Top & Higgs physics with ions at the FCC & HL/HE-LHC

Ions at the Future Circular Collider

CERN, 29th Sept. 2017

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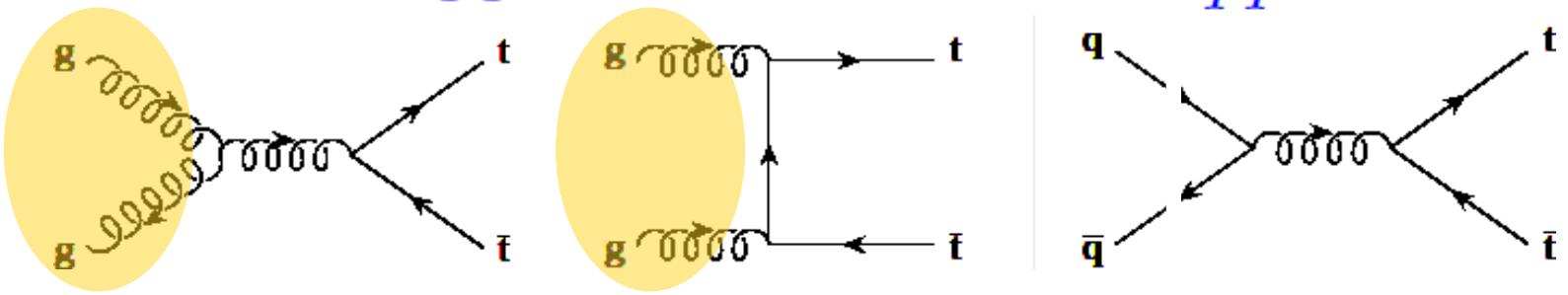
CERN

[Based mostly on: DdE et al., arXiv:1501.05879, arXiv:1701.08047, arXiv:1706.09521]

Top-quark in nuclear collisions

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

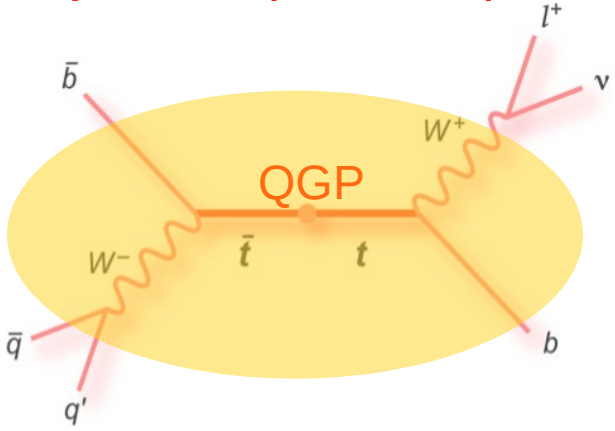
$gg \rightarrow t\bar{t}$ $q\bar{q} \rightarrow t\bar{t}$



- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b (BR~100%,V_{tb}~1). 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%)



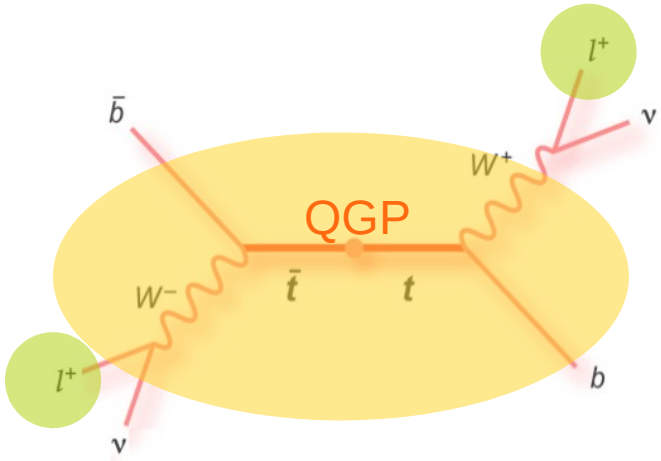
t-tbar (dileptons, AA): high-x gluon nPDFs probe

- 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%)

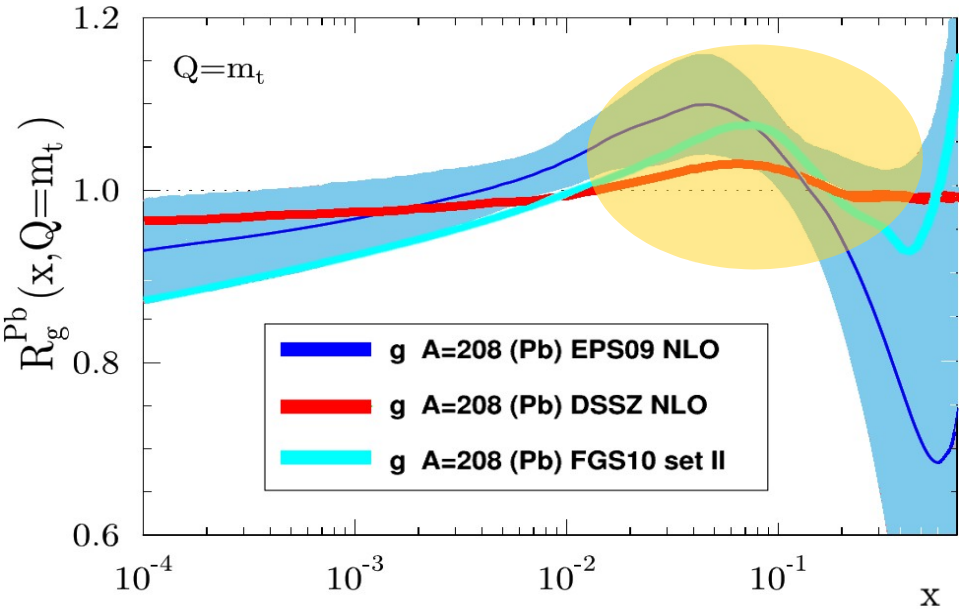


Cleanest decay channels: μ+μ,μ+e,e+e (BR~5%)

- Motivations for leptonic measurement:

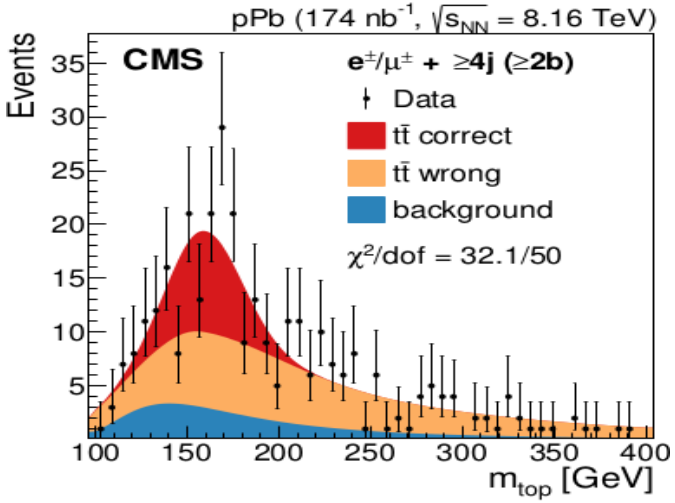
  → Cleanest channel for its first discovery in A-A collisions.

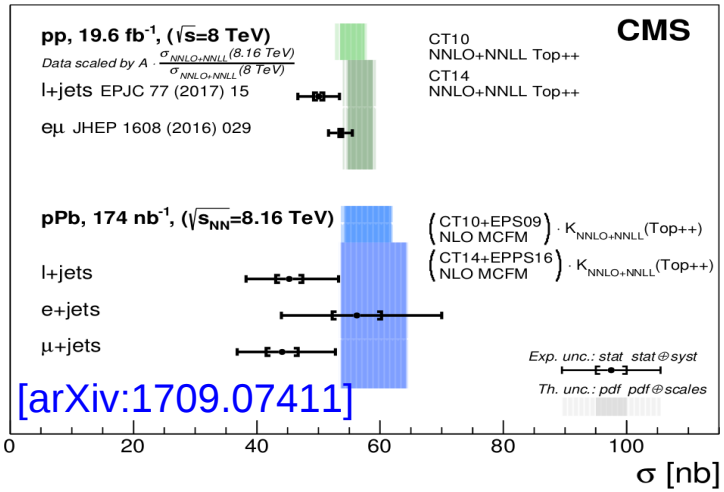
  → Probes gluon nPDF in unexplored high-x range: x~0.3–10^{-3},Q~m_t~173 GeV



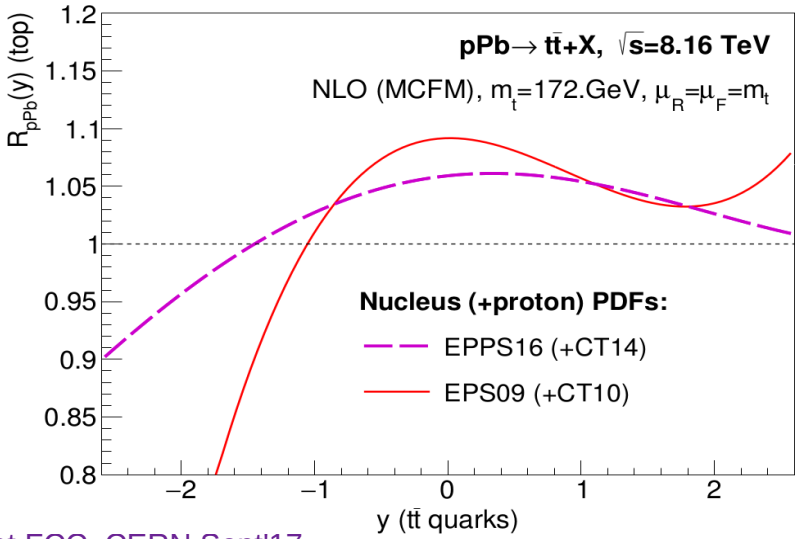
t-tbar (ℓ+jets, pA): high-x gluon nPDFs probe

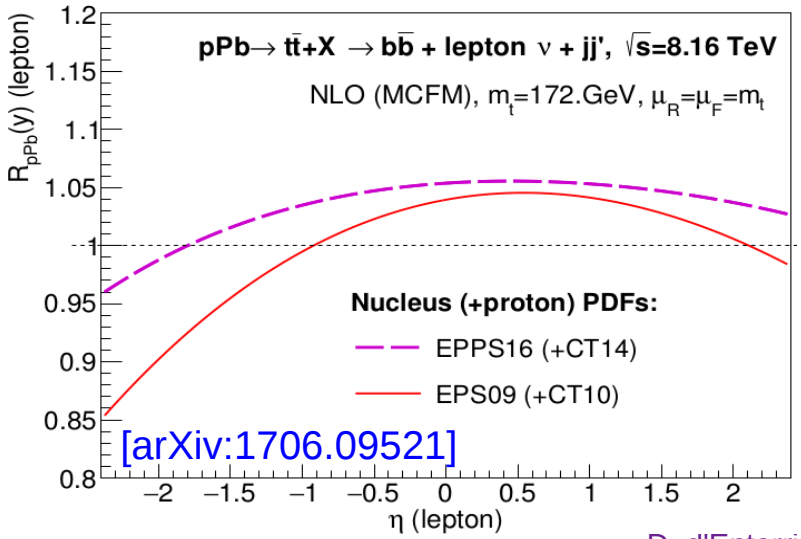
- In p-A collisions one can easily measure ttbar cross sections in the lepton+4jets channel, as demonstrated by CMS in pPb(8.16 TeV):





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





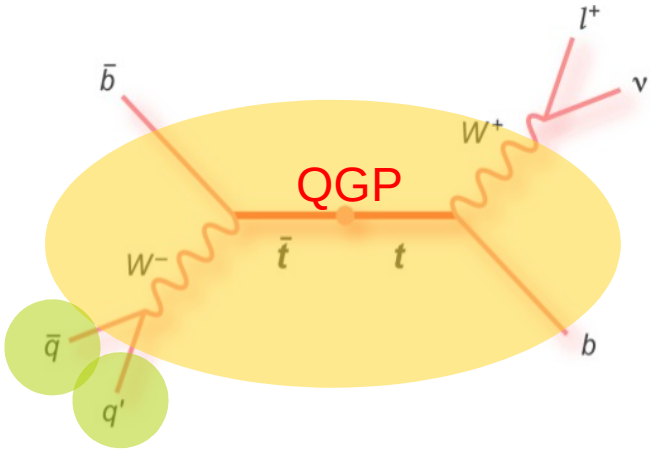
t-tbar (ℓ+jets, AA): QGP parton radiation probe

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

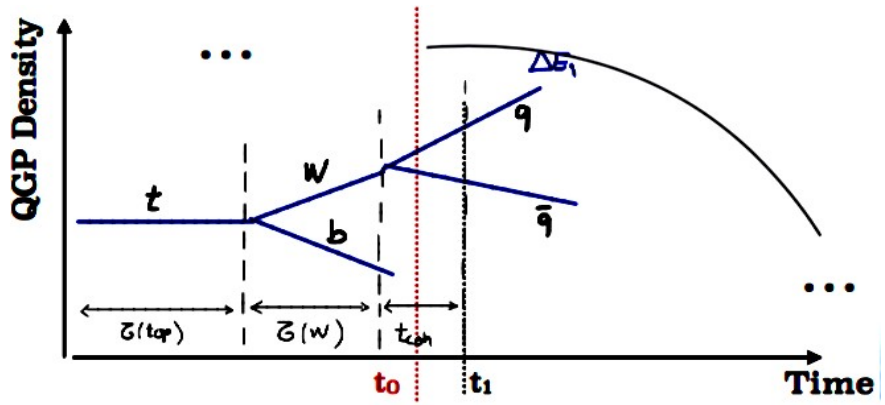
  t → b + 2jets (66%)
  ttbar → bbar + 2jets + 1ℓ + MET(ν) (45%)

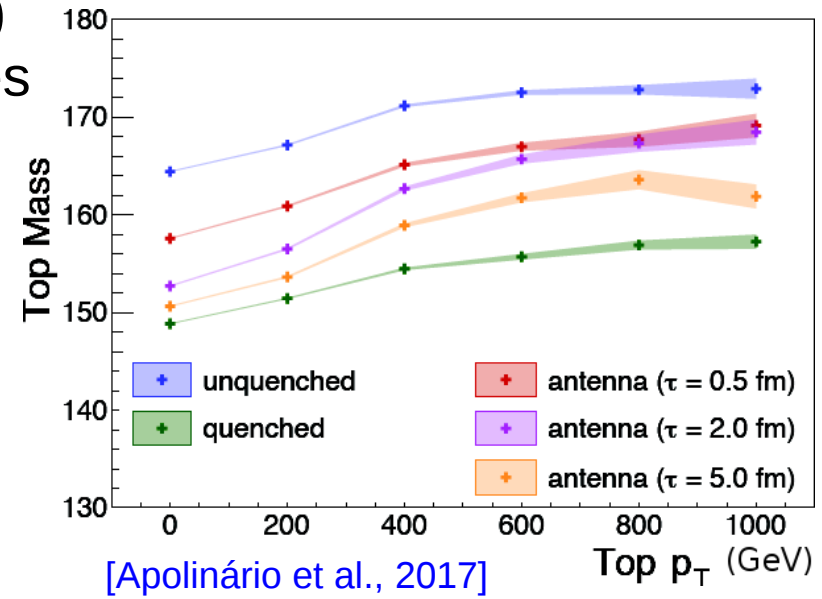
- Motivations for 2j measurement:

→ 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



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





[Apolinário et al., 2017]

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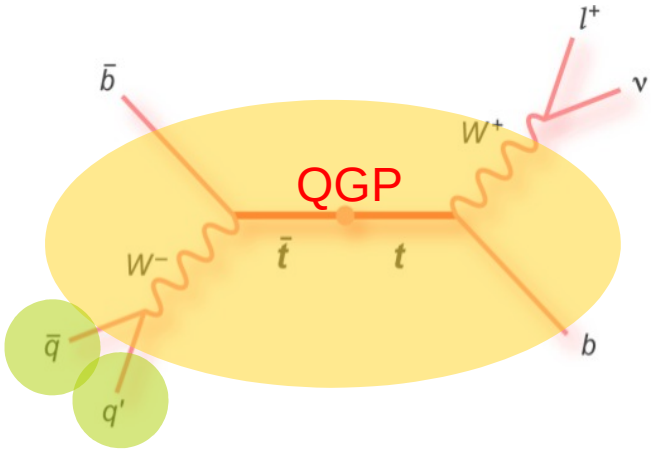

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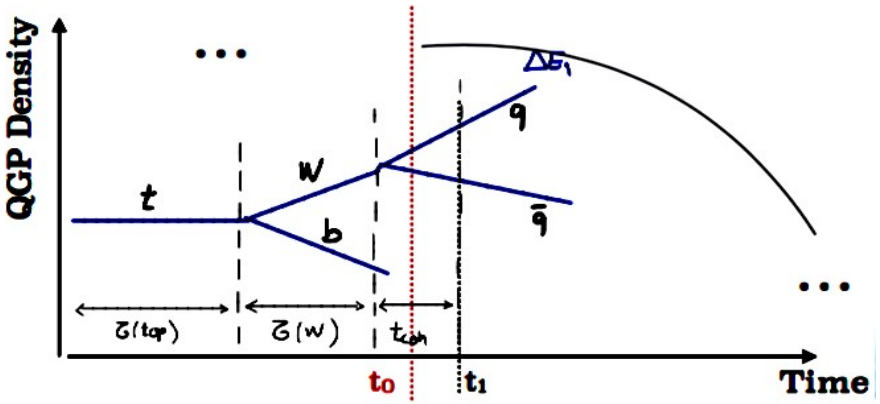
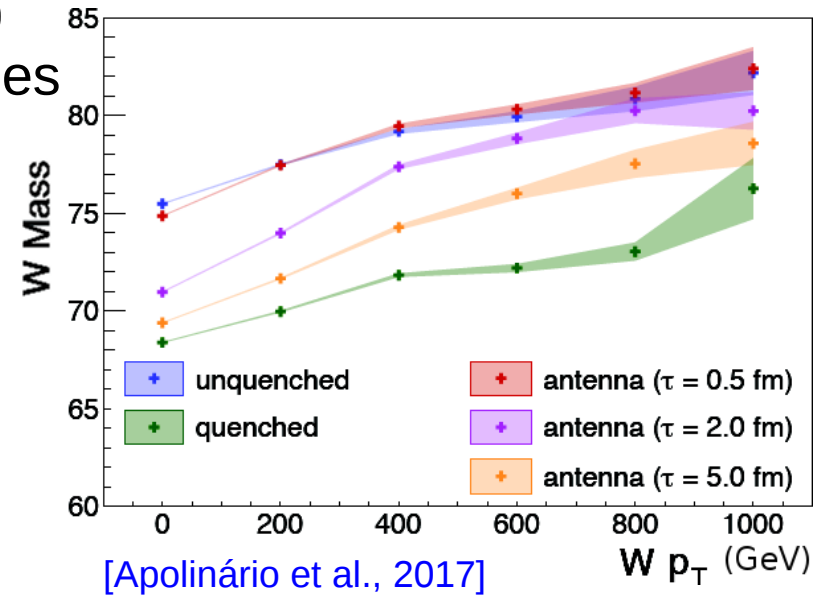
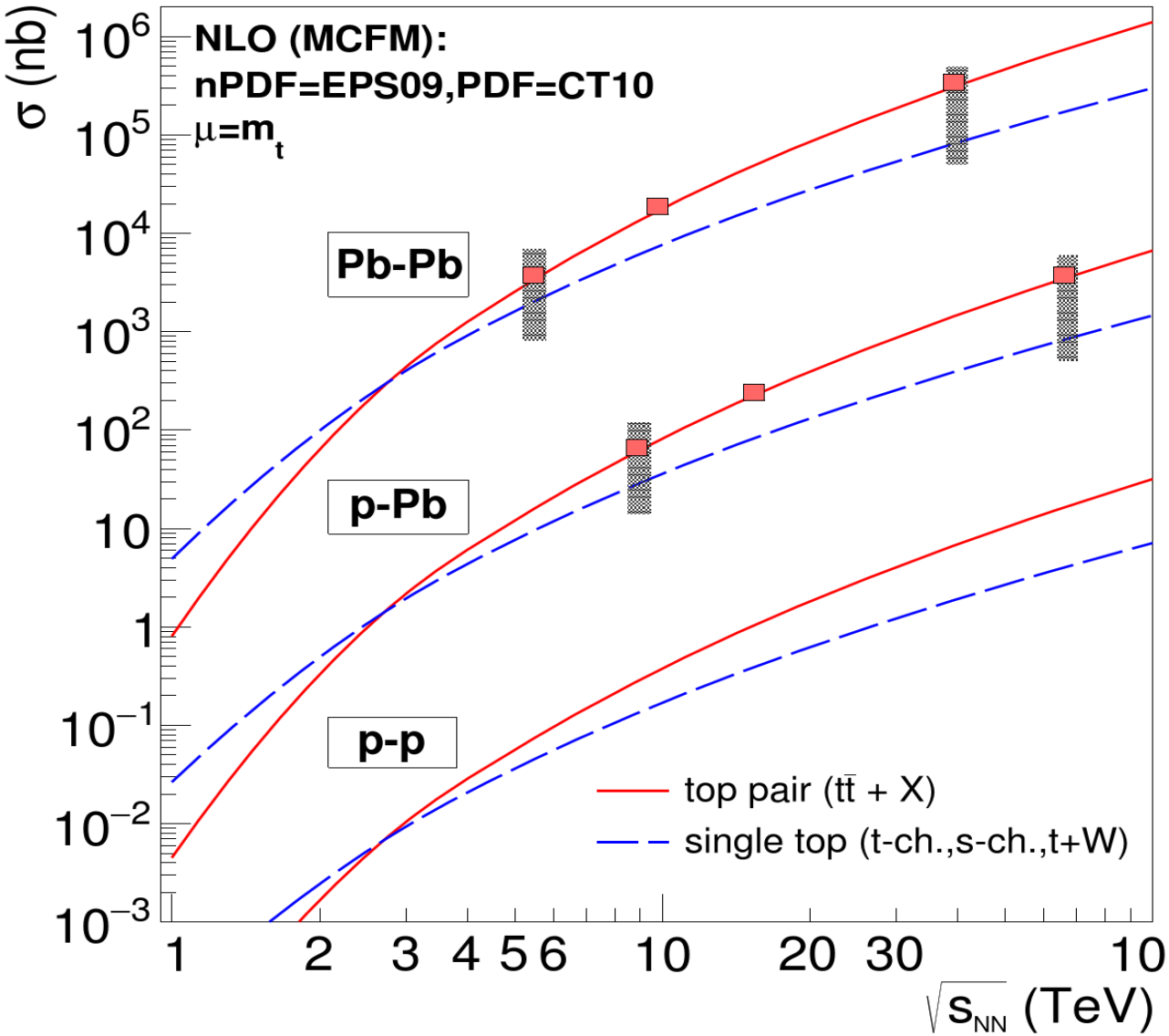




[Apolinário et al., 2017]

t-tbar&single-t total x-sections in p-p,p-Pb,Pb-Pb



- 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

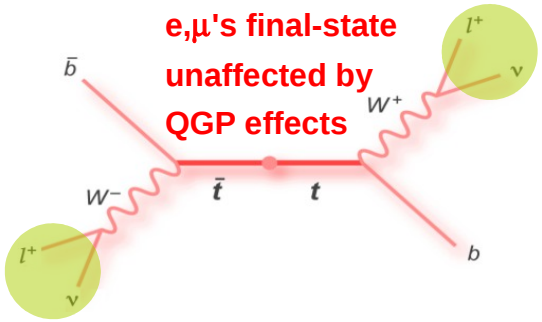
nPDF anti-shadowing increases σ_{tt} by +(2-8)%

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

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

Top-quark dileptons measurement

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



- 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:

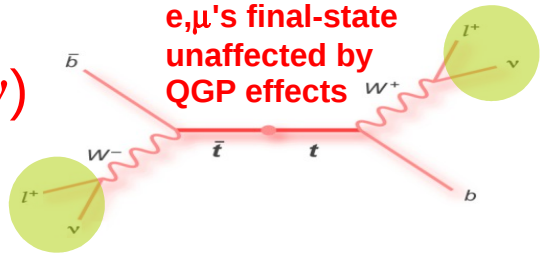
  t-tbar: BR~5%, Acc×Eff ~ 40% (LHC), 50% (FCC)

  Single-top: BR~22%, Acc×Eff ~ 21% (LHC), 30% (FCC)

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

Expected t-tbar & single-t (leptonic) yields

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



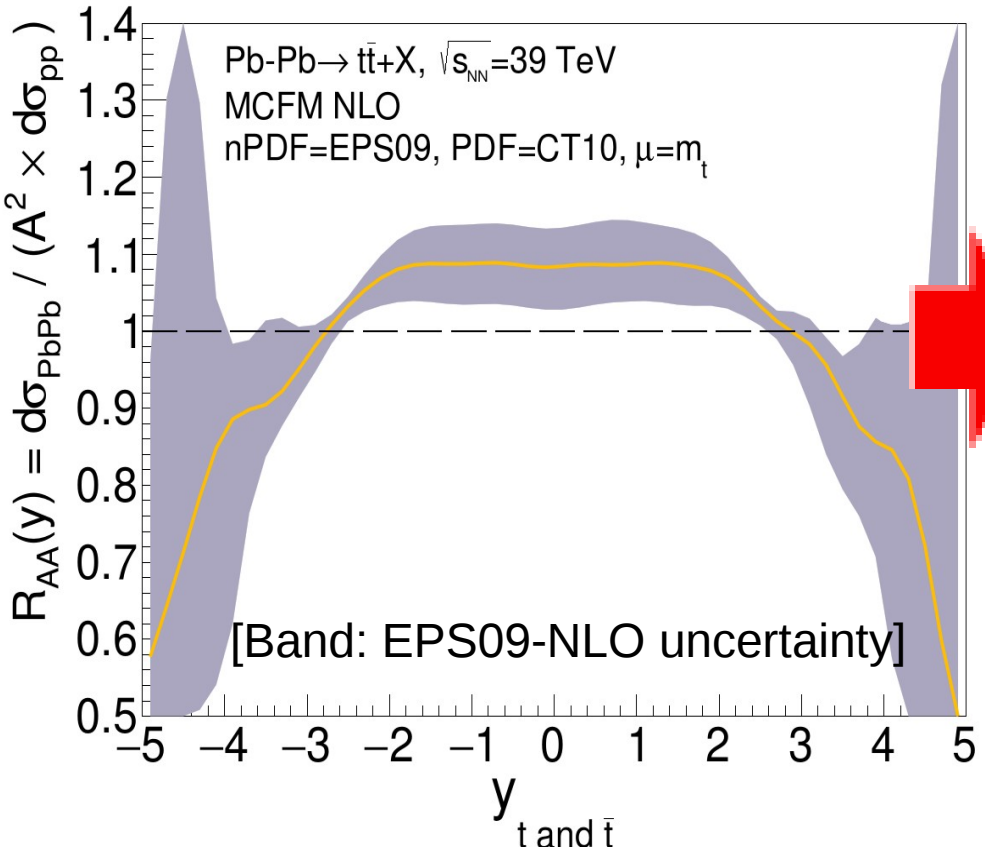
System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{int}$	$t\bar{t}$ σ_{tot}	$t\bar{t} \to b\bar{b}\ell\ell\nu\nu$ yields	single-t σ_{tot}	$tW \to b\ell\ell\nu\nu$ yields
PbPb	5.5	10 nb^{-1}	3.4 μb	450	2.0 μb	30
pPb	8.8	1 pb^{-1}	59 nb	750	27 nb	50
PbPb	39	33 nb^{-1}	300 μb	1.5×10^5	80 μb	8000
pPb	63	8 pb^{-1}	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)
  HL/HE-LHC: Much more at HL? 2.000–5.000 at HE-LHC
- FCC (nominal L_{int}): 0.3–0.8 million t-tbar pairs in Pb-Pb,p-Pb

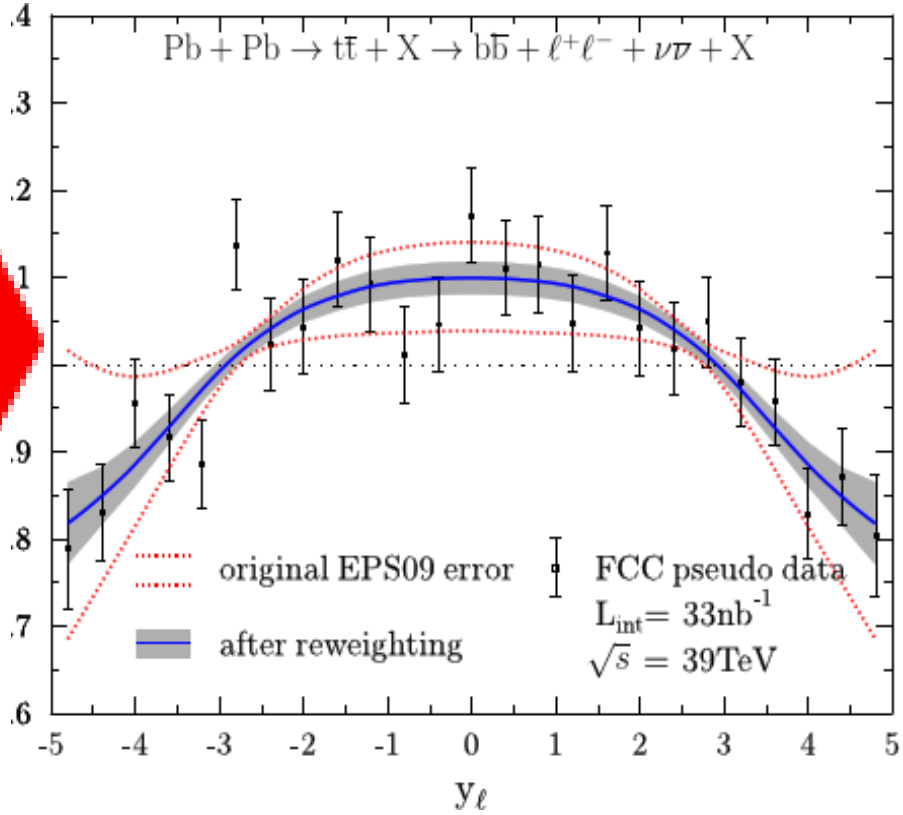
Note: 1.–3. million t-tbar pairs in Pb-Pb,p-Pb w/ updated lumis

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})

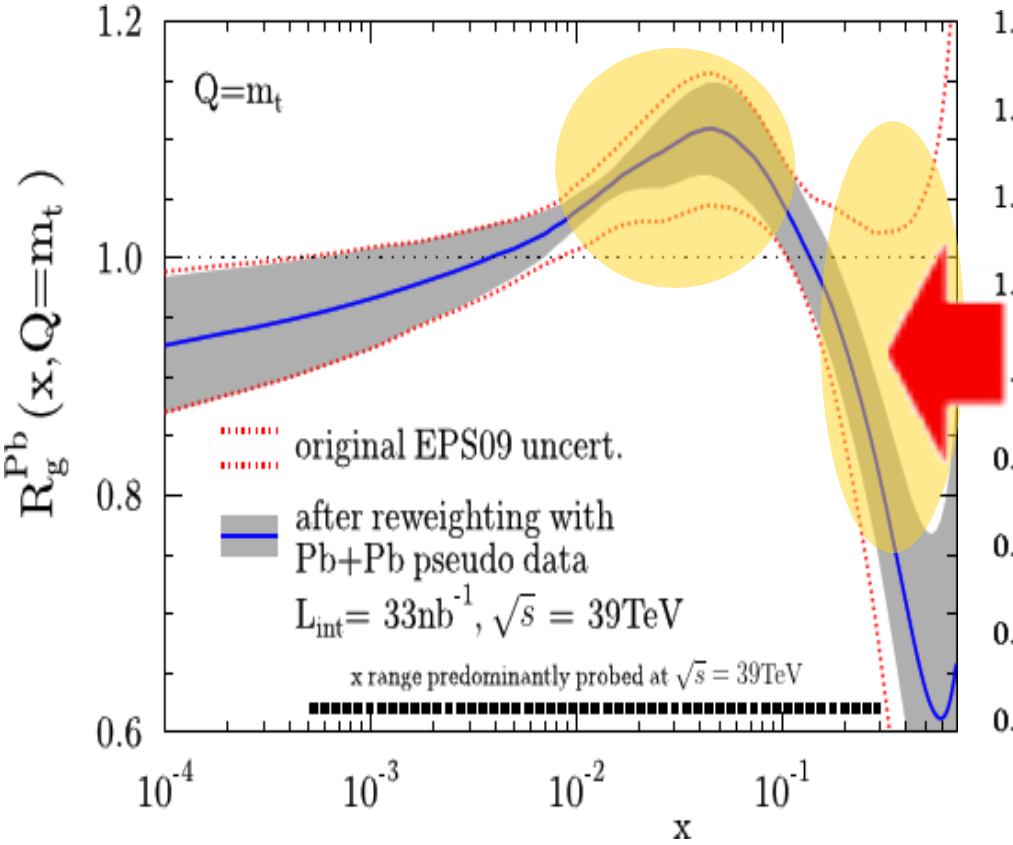


(stat. dominate over syst. uncertainties)

- 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



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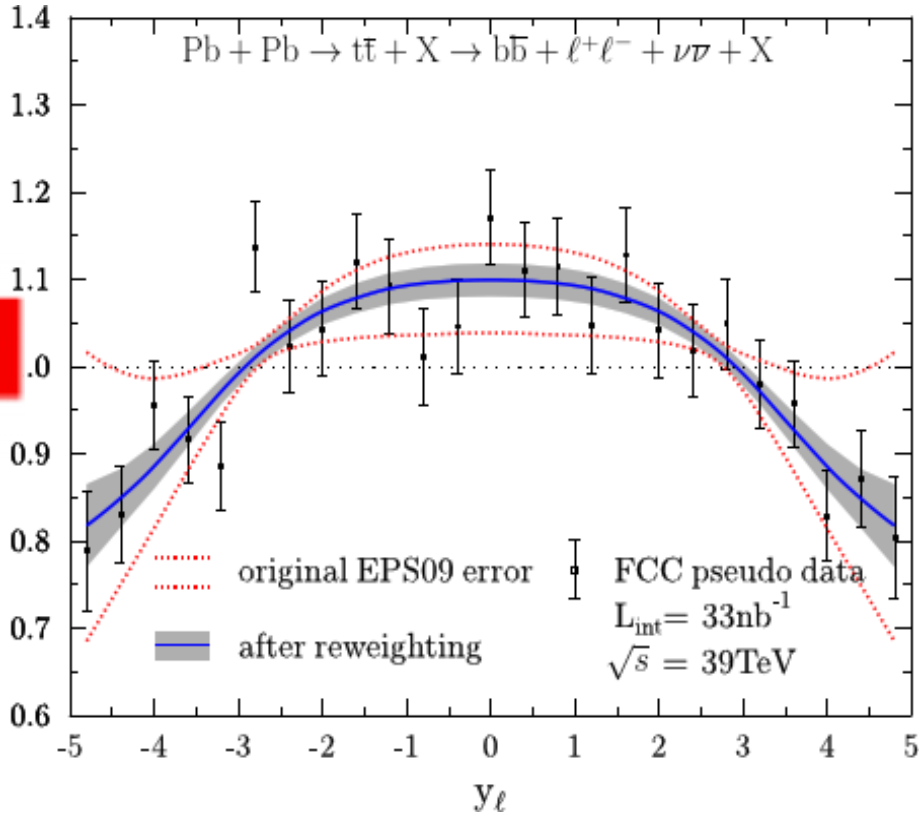


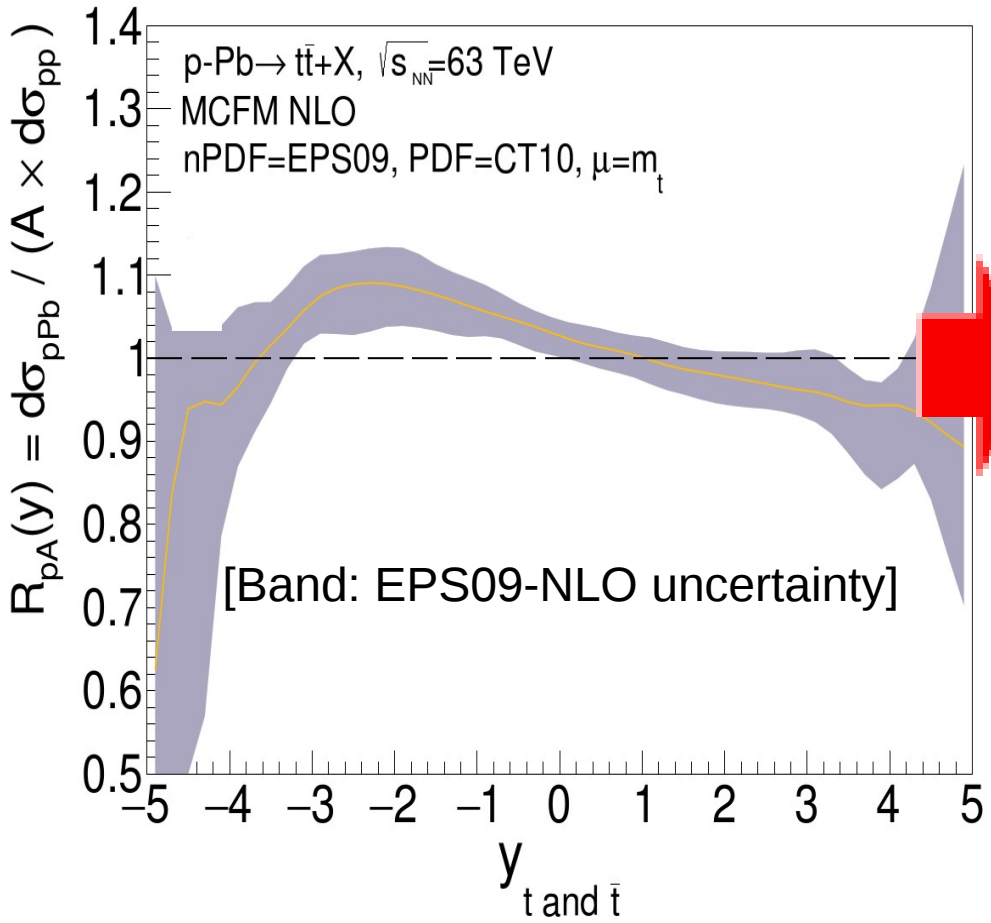
(stat. dominate over syst. uncertainties)

- Significant reduction in uncertainties at antishadowing (x~0.05) and EMC region (x~0.5) regions
- nPDF effects (lepton): ±(10-20)% Strong constraining power

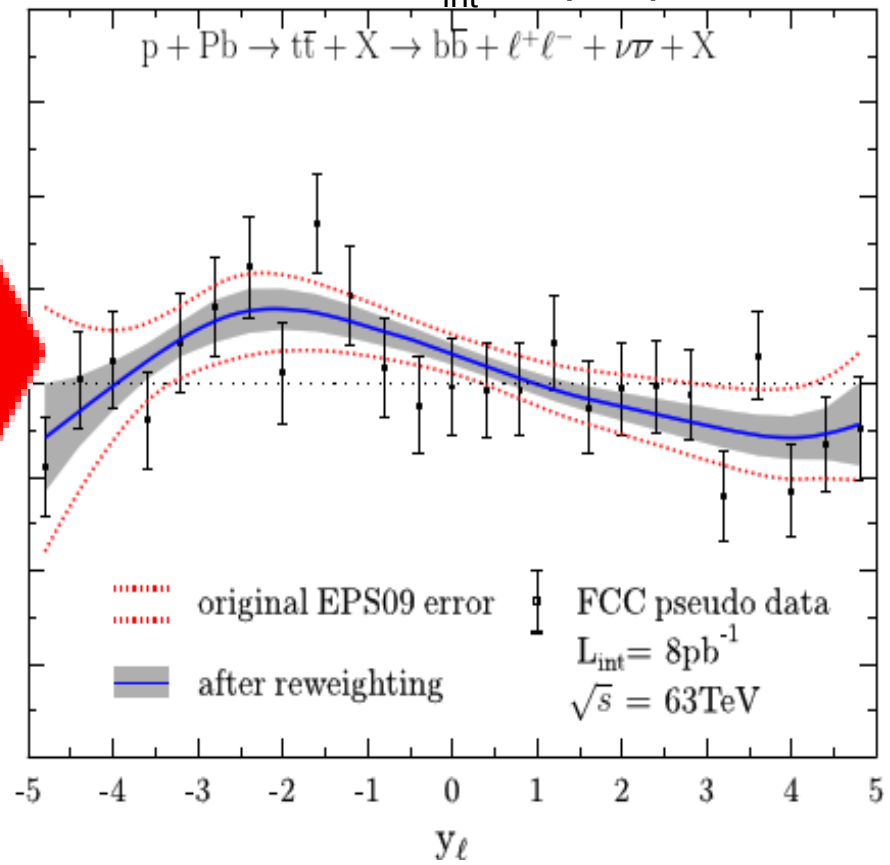
Note: ×3.2 more stats with updated $\mathscr{L}$: ×2 better nPDF improvements

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

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



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

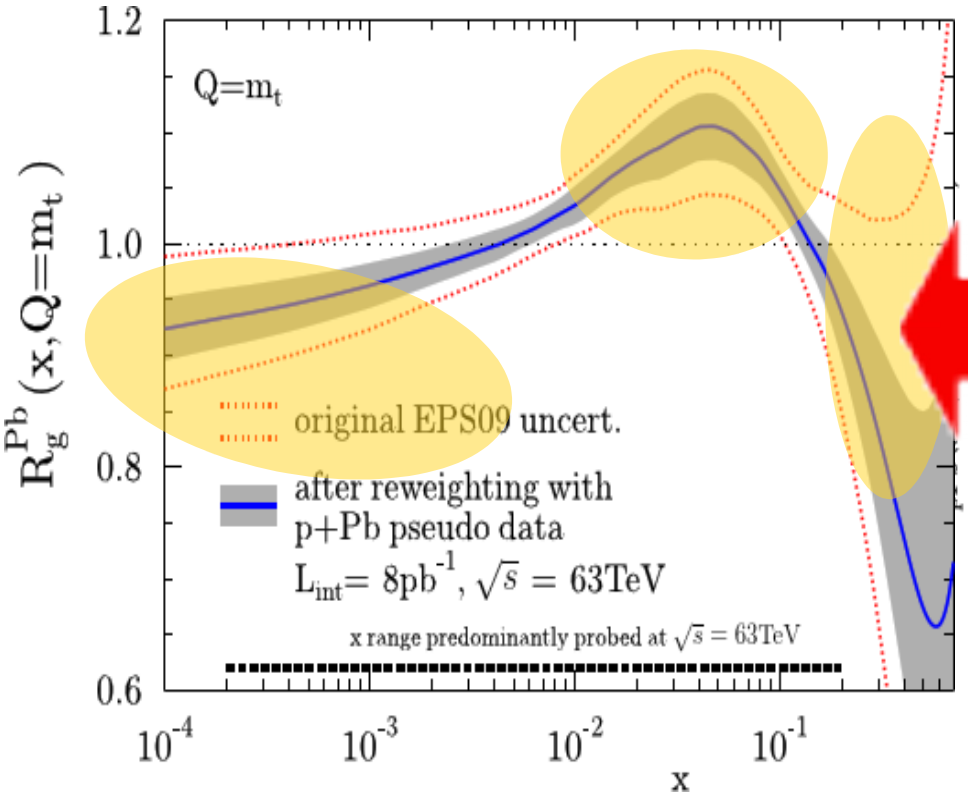


(stat. to dominate over syst. uncertainties)

- nPDF effects (top): -30% (bckwd)
  ±10% (fwd/cent)
- nPDF effects (lepton): ±10%
  Strong constraining power

pPb(63 TeV)→ t-tbar: $R_{AA}(y)$ for $\ell^{\pm}$ & $R_g^{Pb}(x,Q^2)$

- Improved gluon density via Hessian PDF reweighting



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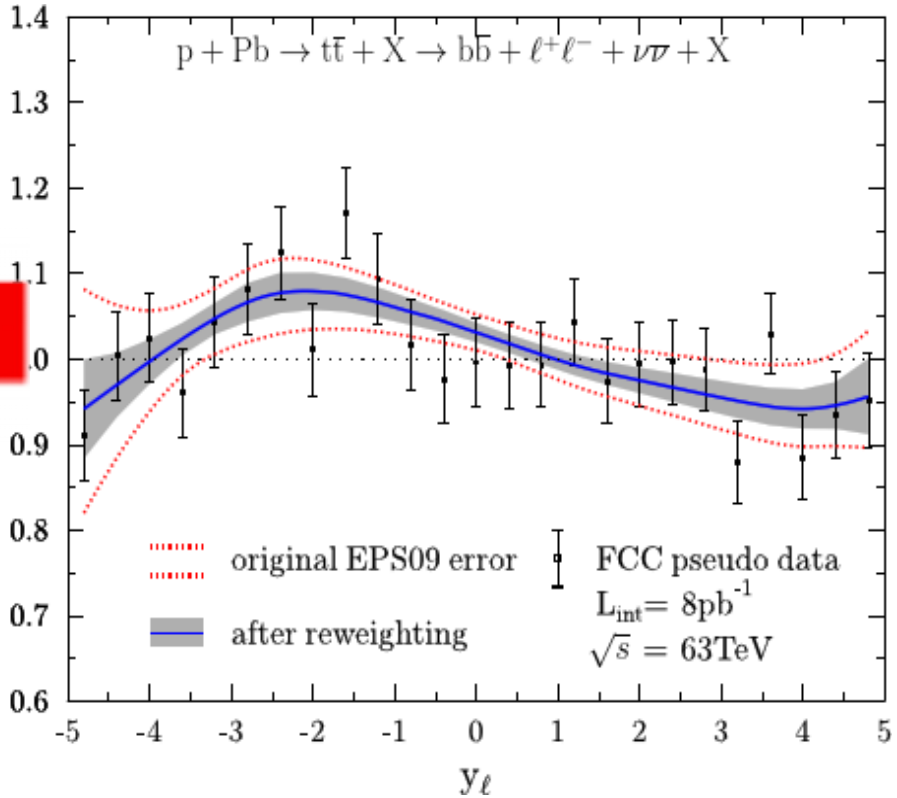


- Significant reduction in uncertainties at low-x ($x<10^{-2}$), antishadowing ($x\sim0.05$) and EMC ($x\sim0.5$) regions

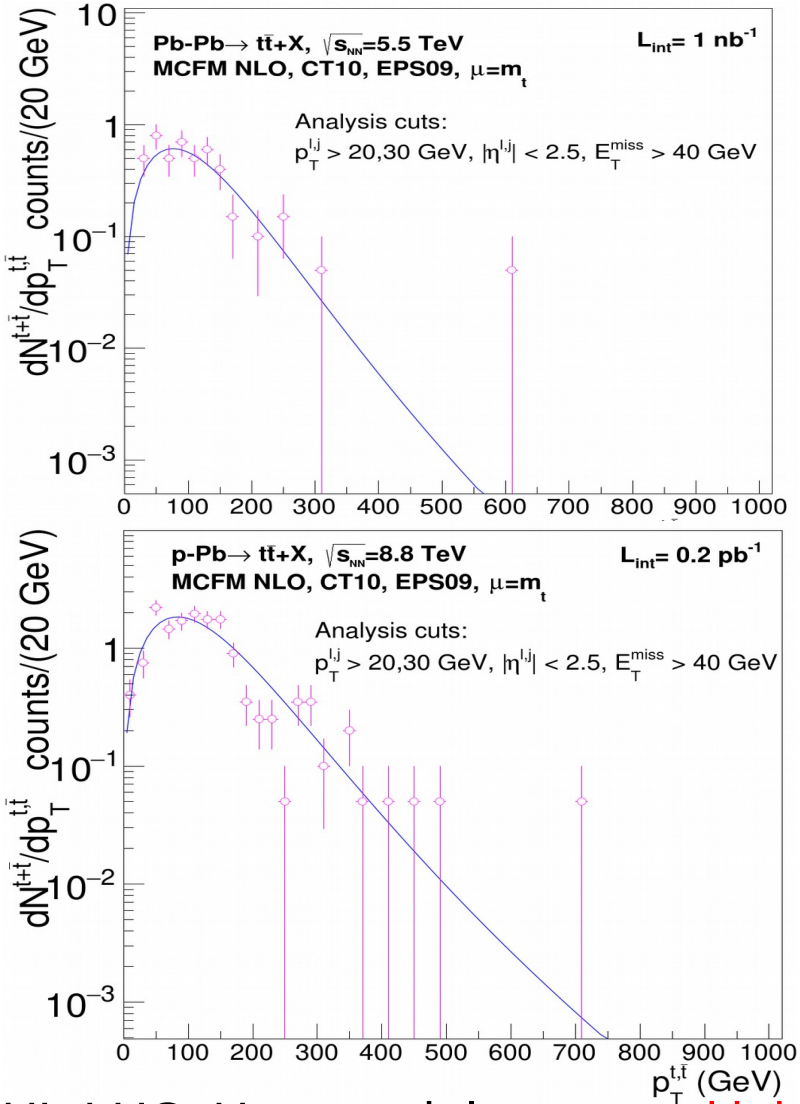
(stat. to dominate over syst. uncertainties)

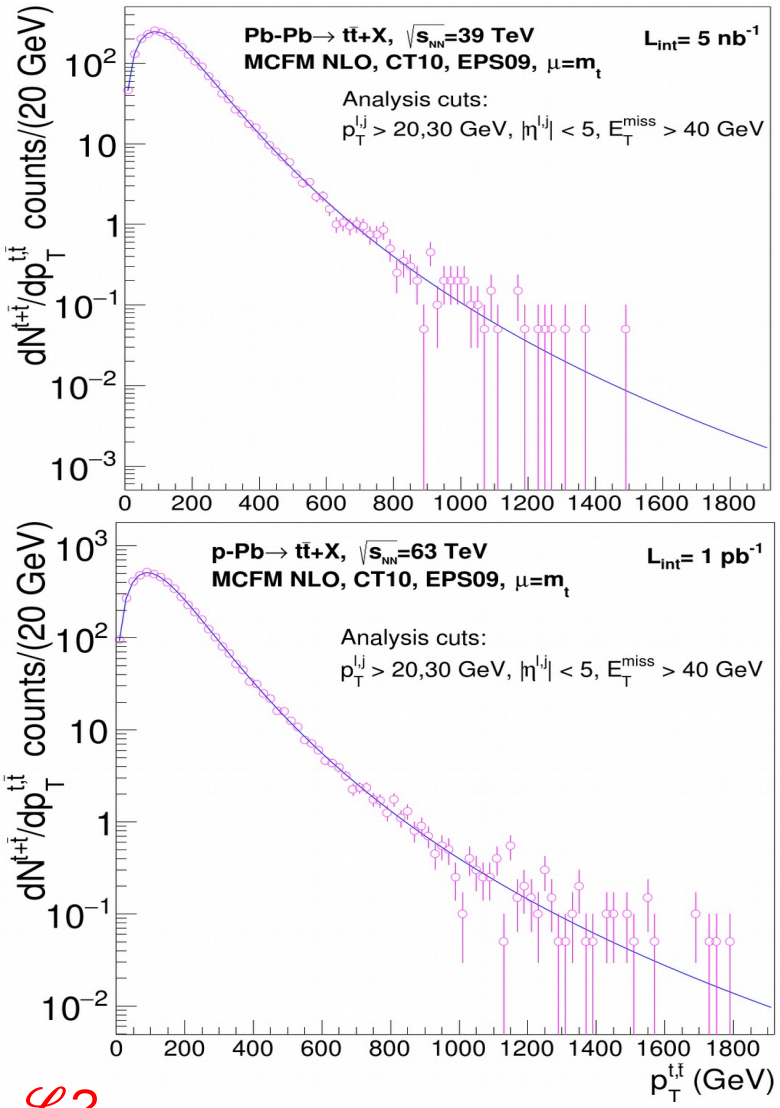
- nPDF effects (lepton): ±10% Strong constraining power

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

Differential top-pair p_T distributions

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





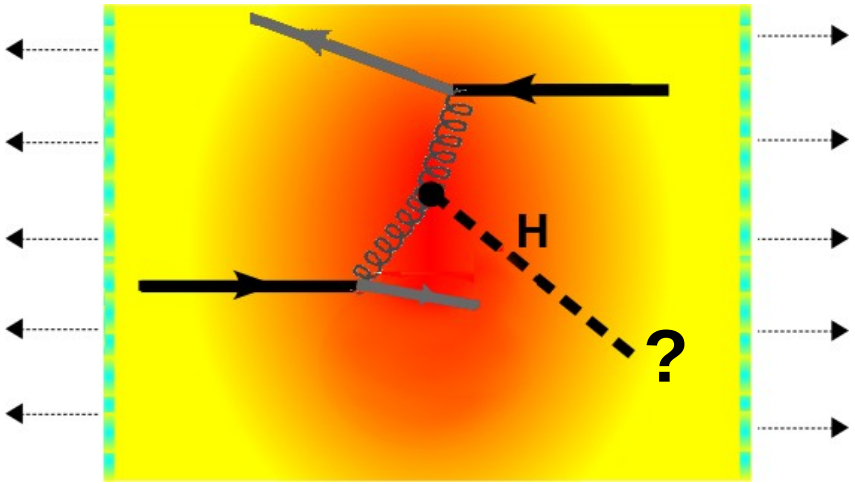
HL-LHC: How much larger p_T with higher $\mathscr{L}$?

HE-LHC: ×4–6 larger cross sections: p_T>1 TeV (boosted top studies possible)

H boson quenching in the QGP ?

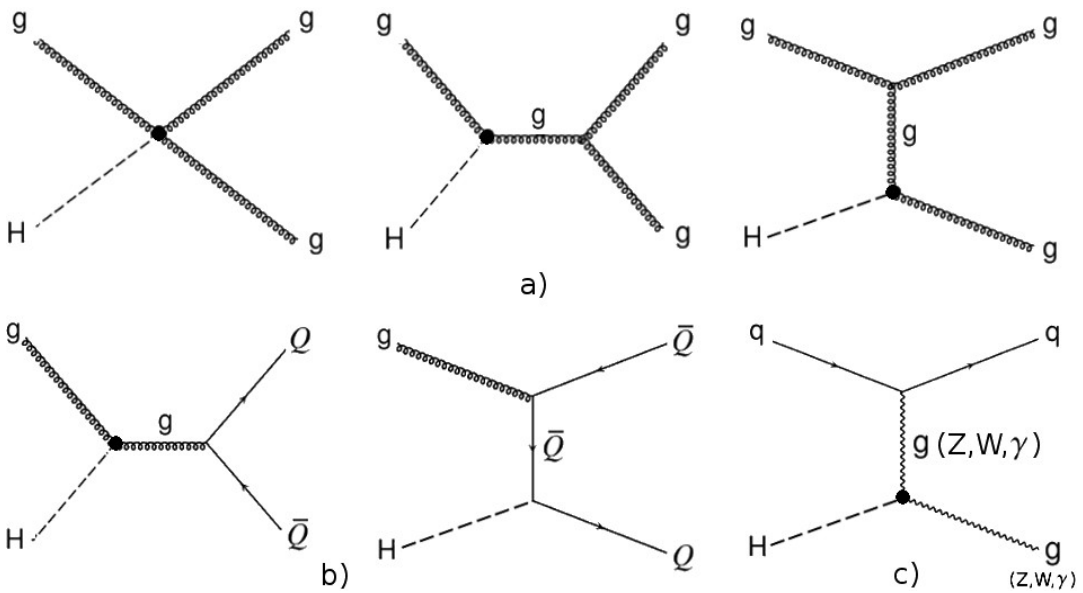
[DdE,C.Loizides, to be submitted]

- 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 (thru 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: **σ~𝒪(10 μb)**

H boson quenching 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.
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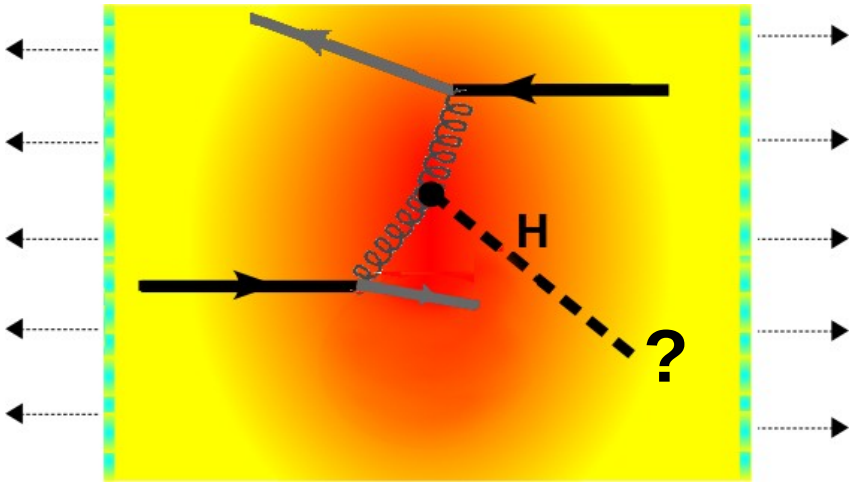
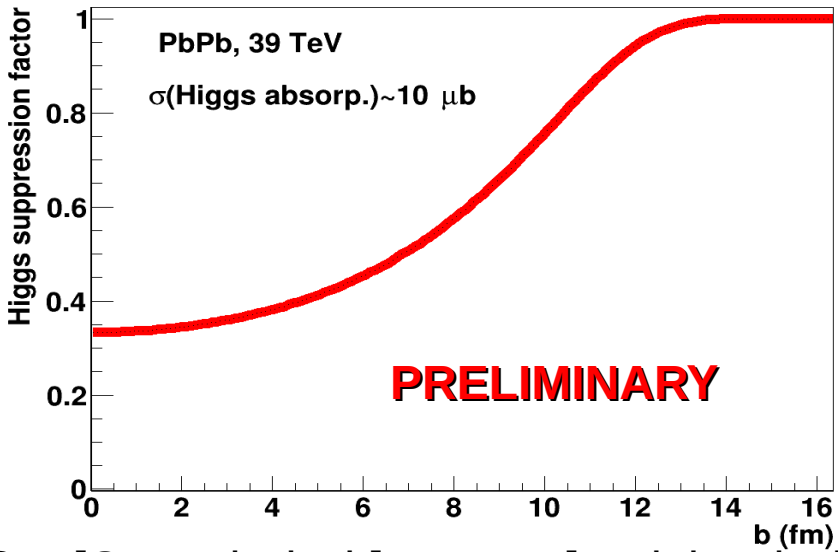


- Survival probability computed combining σ = 10 μb Higgs "absorption" x-section in QGP (1+1D-Bjorken expansion Glauber MC model):

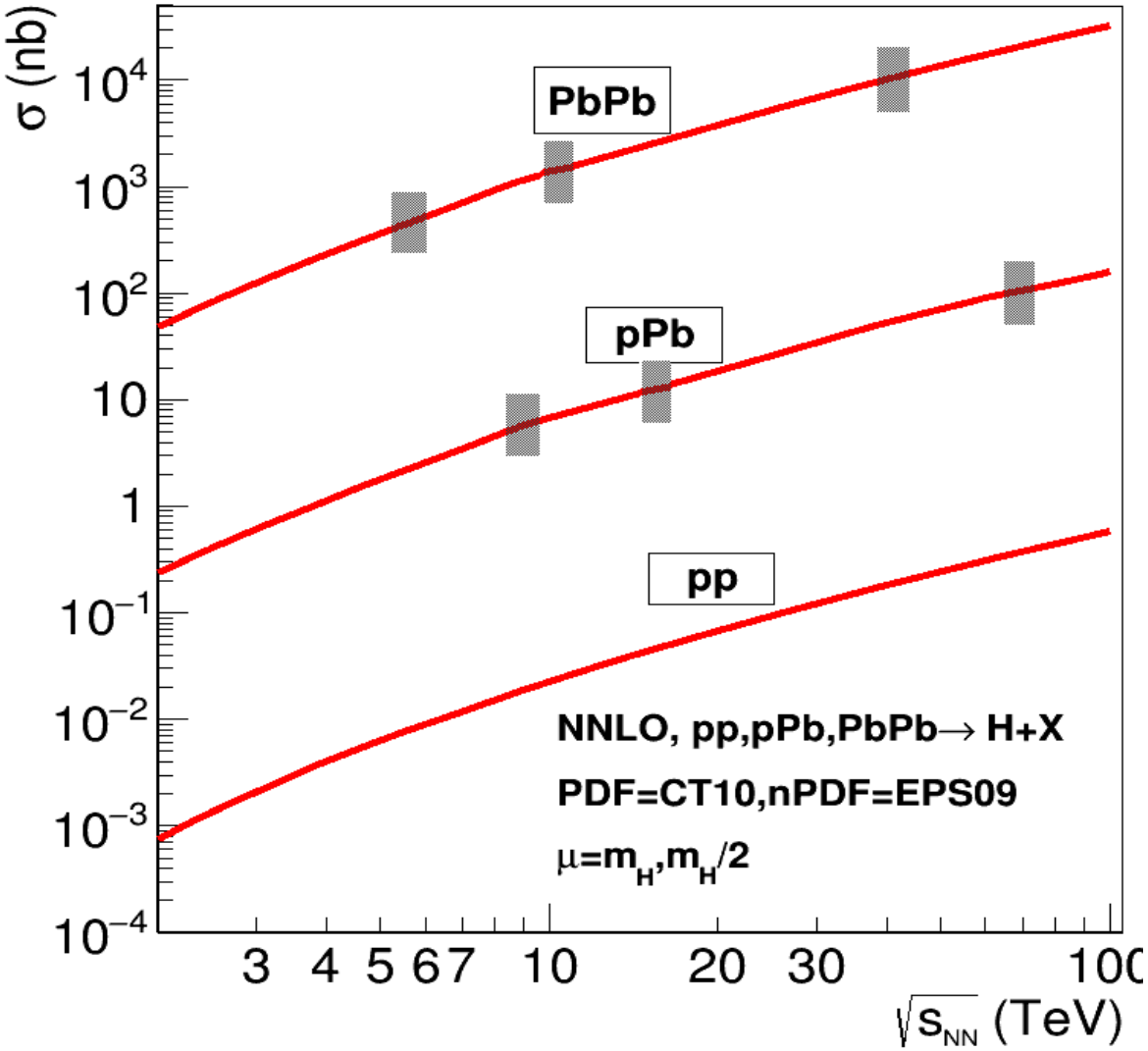
  → Average Higgs suppression factor in PbPb(39 TeV): ~25%



- Is the H boson observable at FCC? [Central PbPb] [Periph. PbPb]

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
HE-LHC(10 TeV)= 1.8 μb
FCC(39 TeV) = 12 μb

- p-Pb:

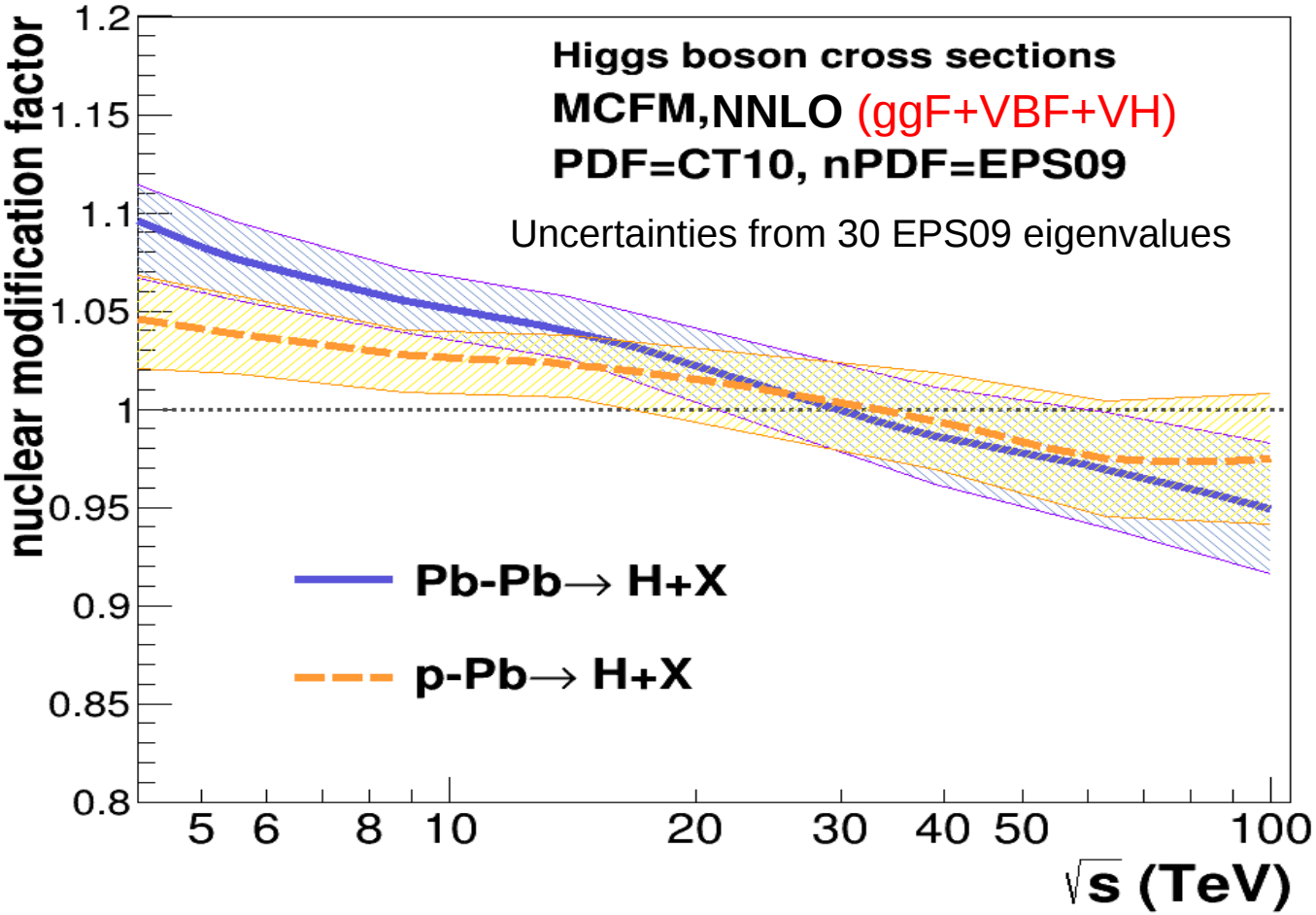
LHC(8.8 TeV) = 6 nb
HE-LHC(16 TeV) = 17 nb
FCC(63 TeV) = 120 nb

[DdE, arXiv:1701.08047]

➜ Cross-sections increase by ×3.5, ×20 from LHC to HE-LHC, FCC

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

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

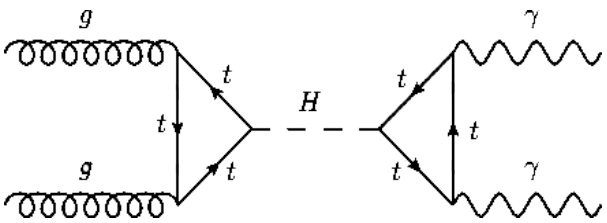


➜ LHC: Small antishadowing: R_{AA}~ 1.07, R_{pA}~1.03

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

[DdE arXiv:1701.08047]

H → 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

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

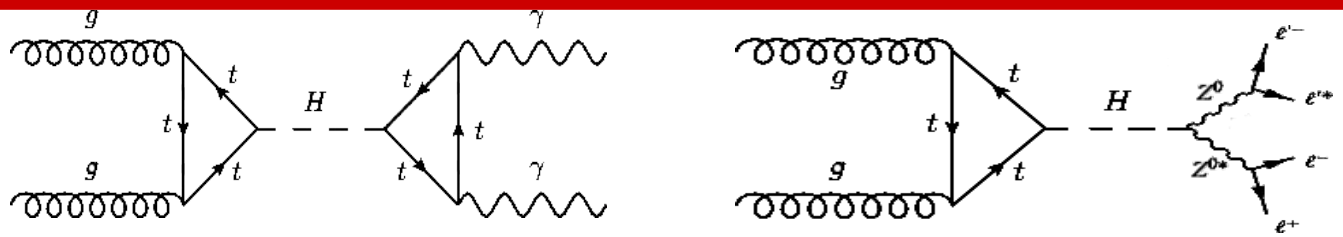
- LHC (nominal L_{int}): ~15 Higgs bosons in Pb-Pb, p-Pb

  Note: ×(30–40) L_{int} needed for evidence. Not for HL, but HE-LHC?

- FCC (nominal L_{int}): 1.000 Higgs bosons in Pb-Pb, p-Pb

  Note: ×3 updated L_{int} would yield 3.000 Higgs'

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

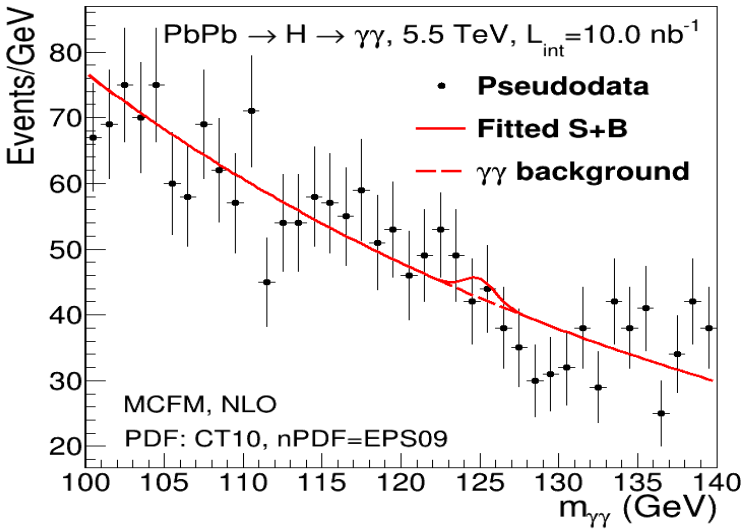
- Backgrounds: As for p-p (under control in pPb,PbPb: high-p_T iso γ,l)

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

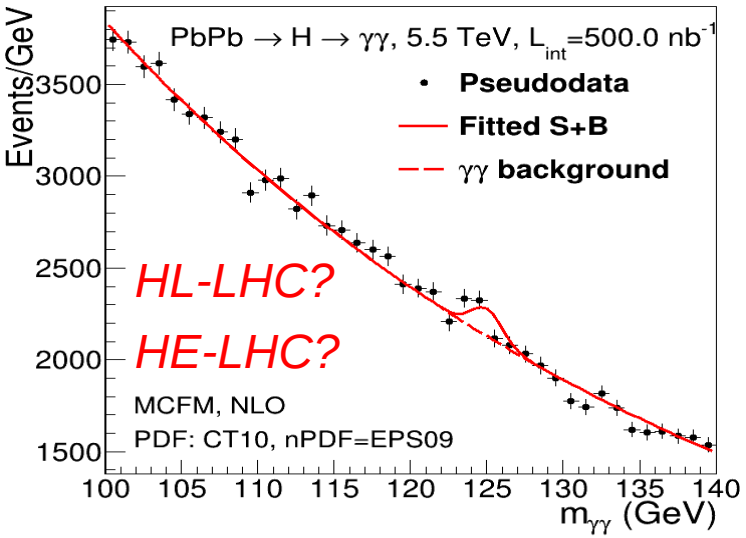
[DdE, arXiv:1701.08047]

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)

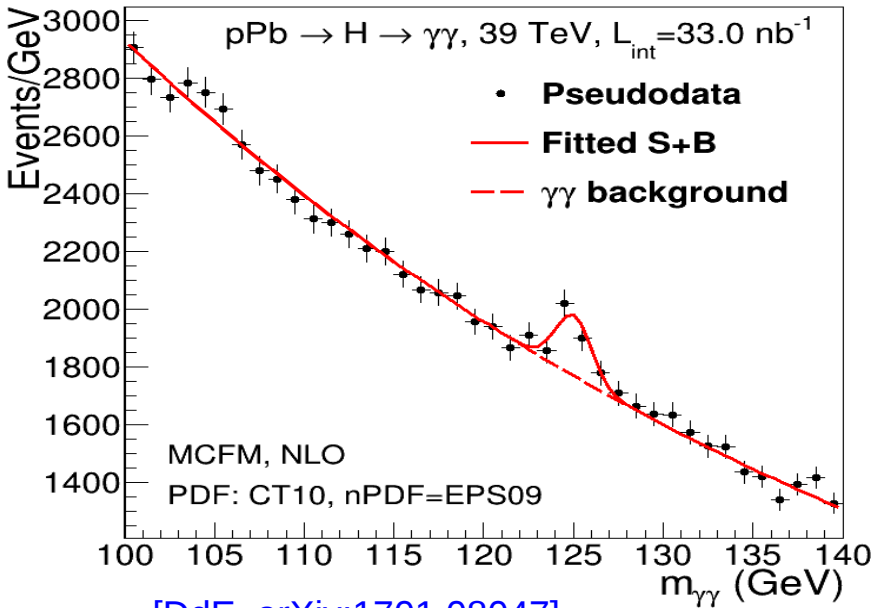
L_{int}= 500 nb^{-1}: 3σ evidence (HL-LHC?)

4.2σ combined with H(4l)

➔ FCC (39 TeV, 33 nb^{-1}):

Nominal lumi: S/√B~5.2σ observation

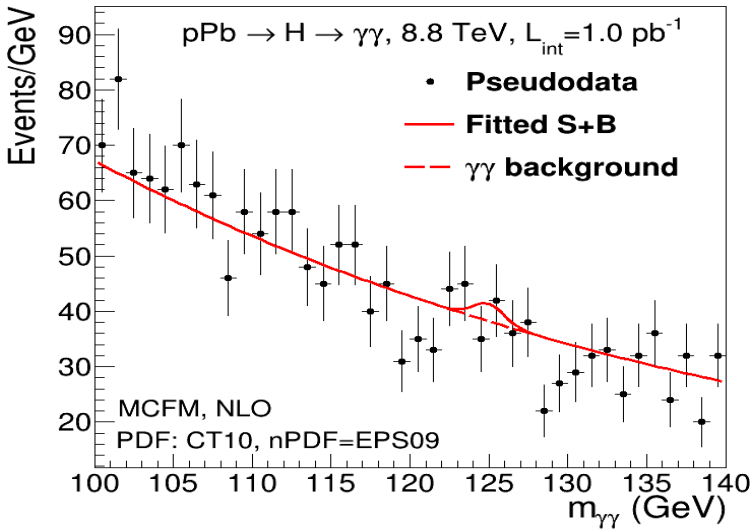
- Pb-Pb @ 39 TeV (L_{int}= 33 nb^{-1})



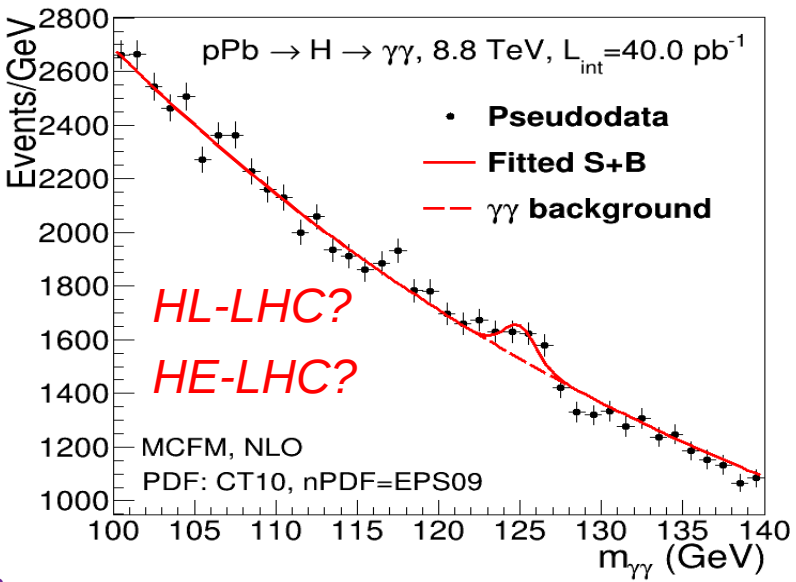
[DdE, arXiv:1701.08047]

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)

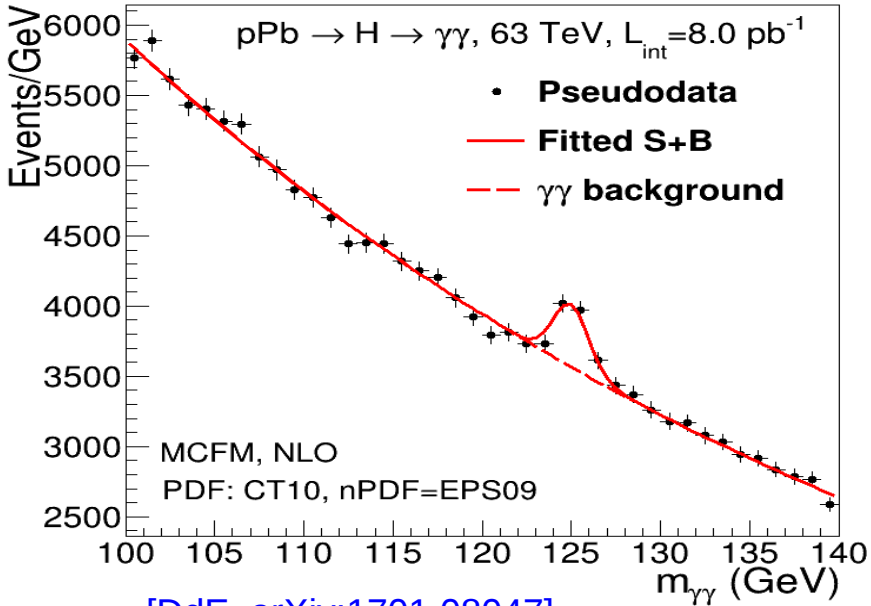
L_{int}= 40 pb^{-1}: 3σ evidence (HL-LHC?)

4.2σ combined with H(4l)

➔ FCC (63 TeV, 8 pb^{-1}):

Nominal lumi: S/√B~7.7σ observation

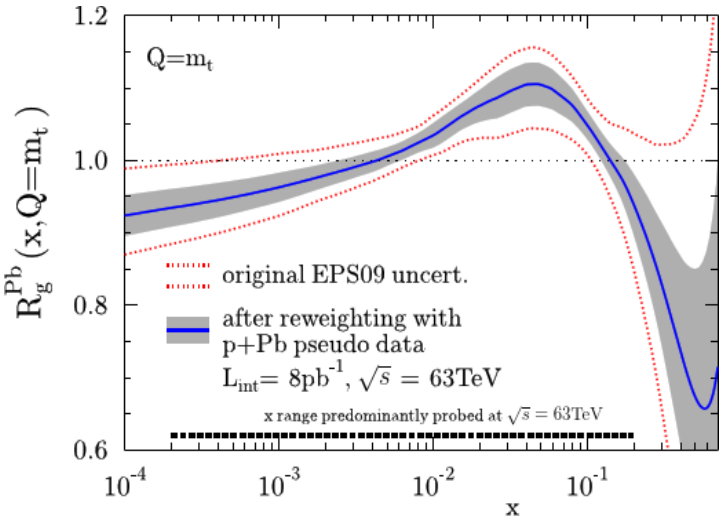
- p-Pb @ 63 TeV (L_{int}= 8 pb^{-1})

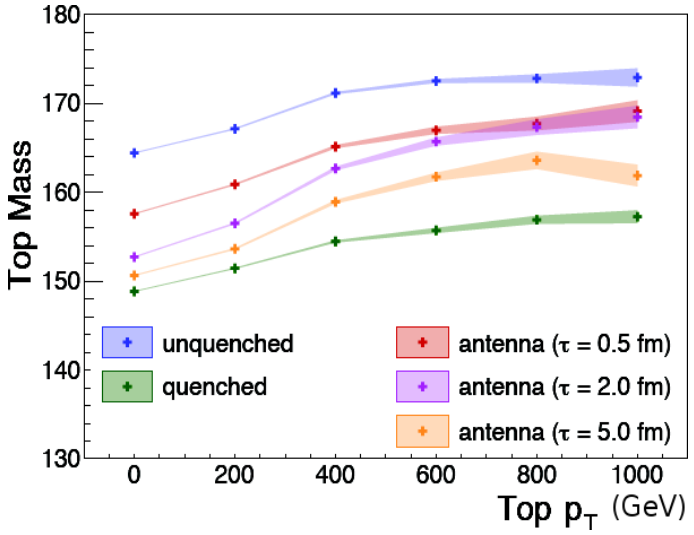


[DdE, arXiv:1701.08047]

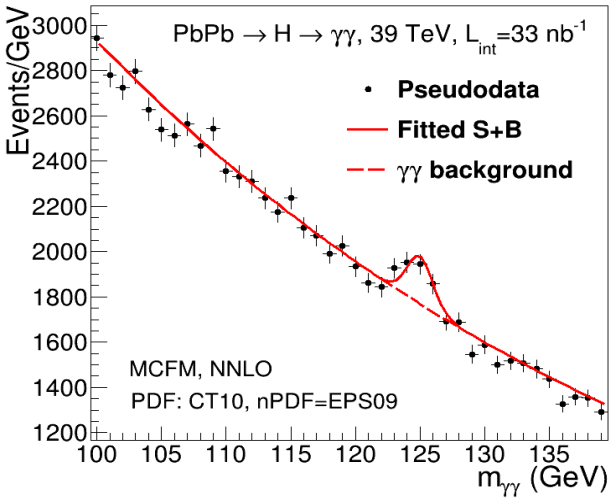
Higgs & top at LHC and FCC

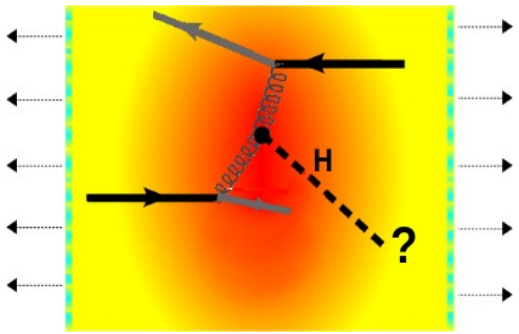
- The top-quark is already a new probe of high-x nPDFs and QGP. Much enhanced possibilities with larger L & √s at HL/HE-LHC and FCC:





- The Higgs boson could be observable at HE-LHC (to be studied), and will become an exciting probe of the QGP at FCC:

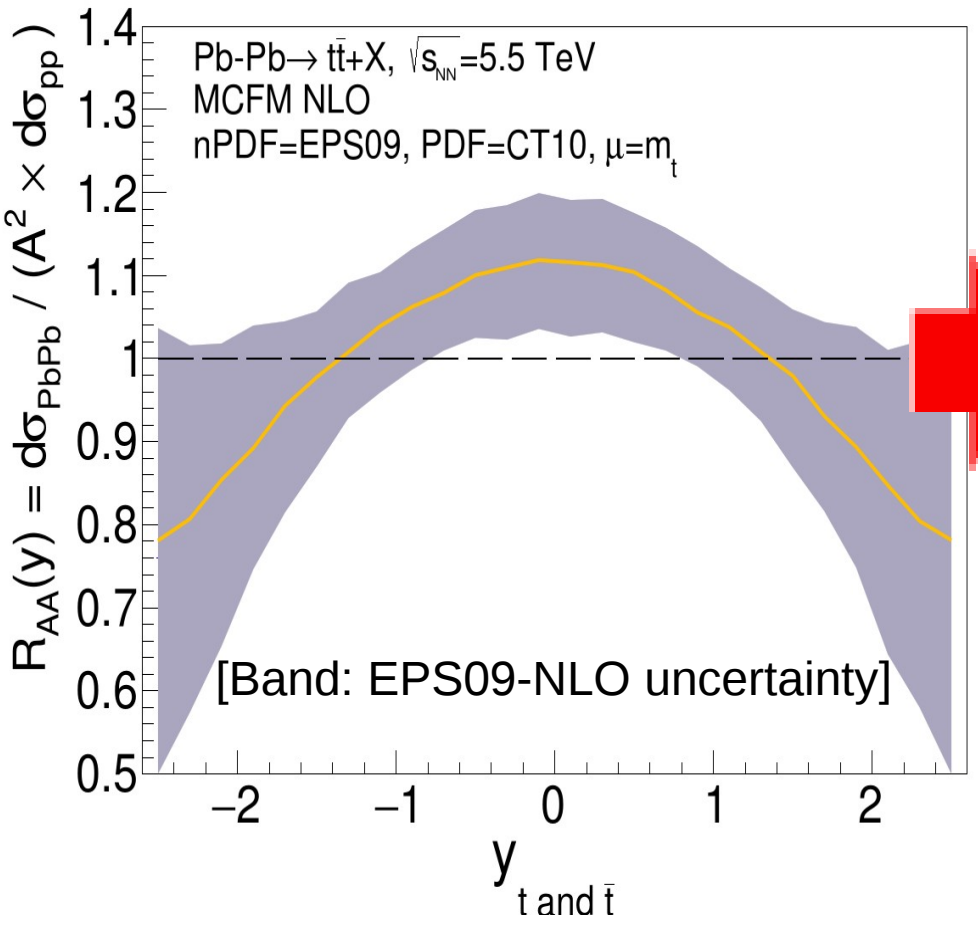




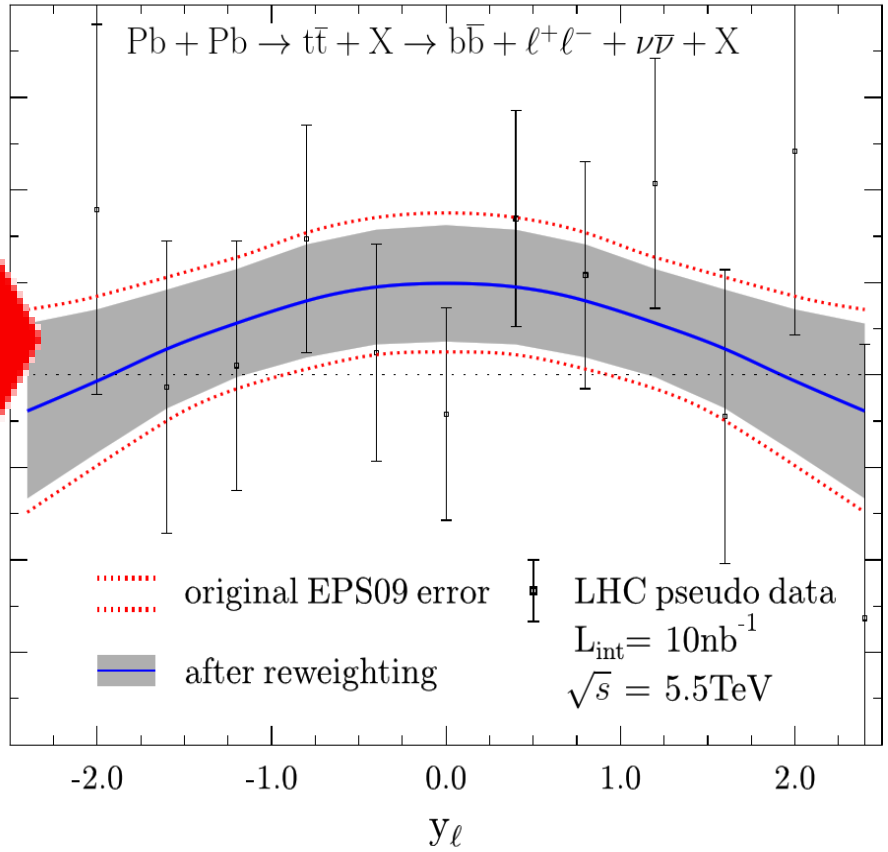
Back-up slides

PbPb→ttbar+X (5.5 TeV): Nuclear modif. factor

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



- Isolated lepton y-distrib. after cuts:
  (Pseudodata for L_{int}= 10 nb^{-1})

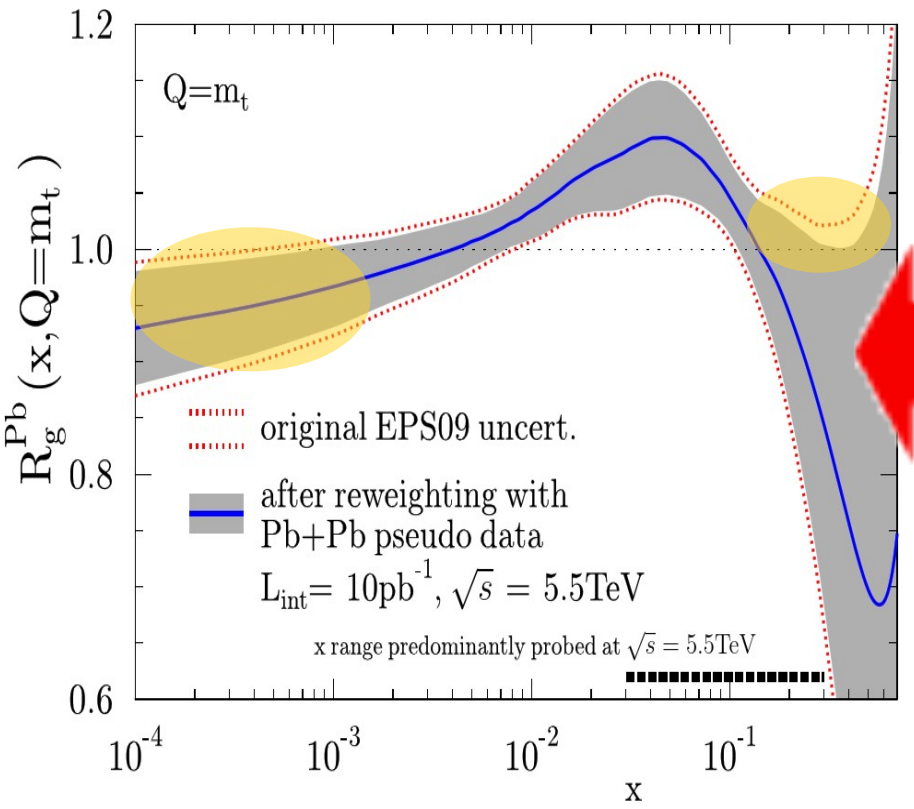


(stat. to dominate over syst. uncertainties)

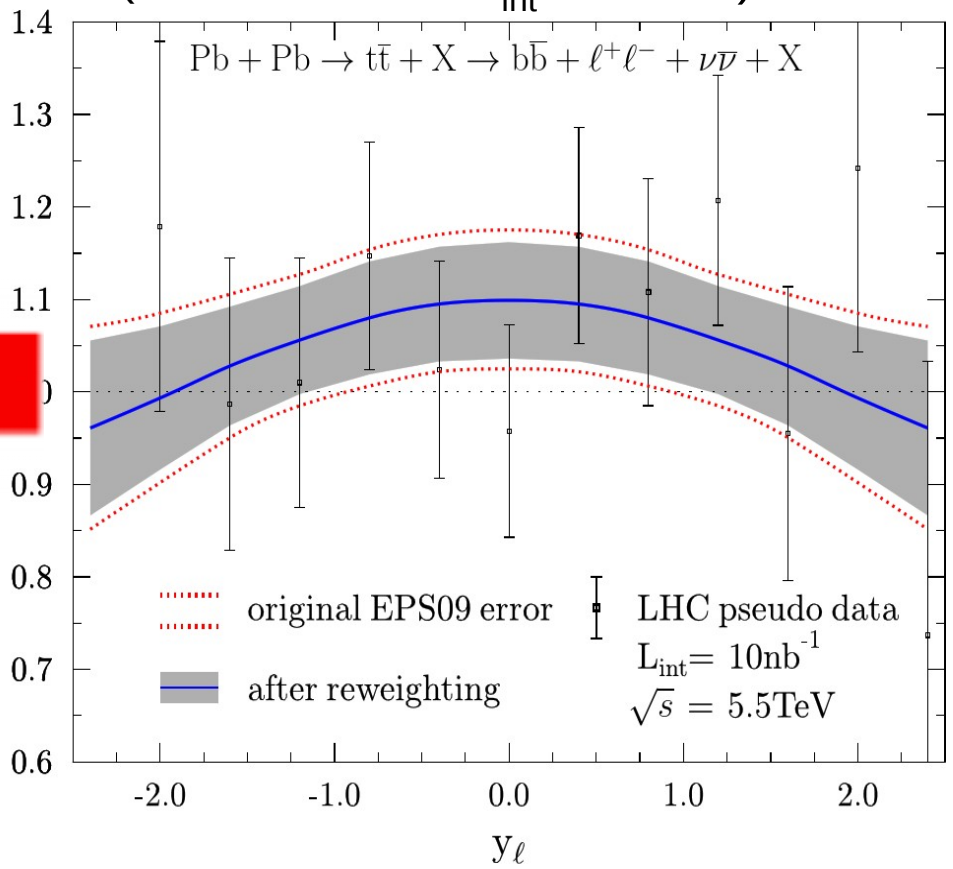
- nPDF effects (top): -20% (fwd)
  +10% (cent.)
- nPDF effects (lepton): ±10%
  L_{int}=10 nb^{-1}: some constraining power

PbPb → ttbar+X (5.5 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting



- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int}= 10 nb^{-1})



- ~10% reduction in uncertainties at low x (x~10^{-4}-10^{-2}) and EMC (x~0.3) regions

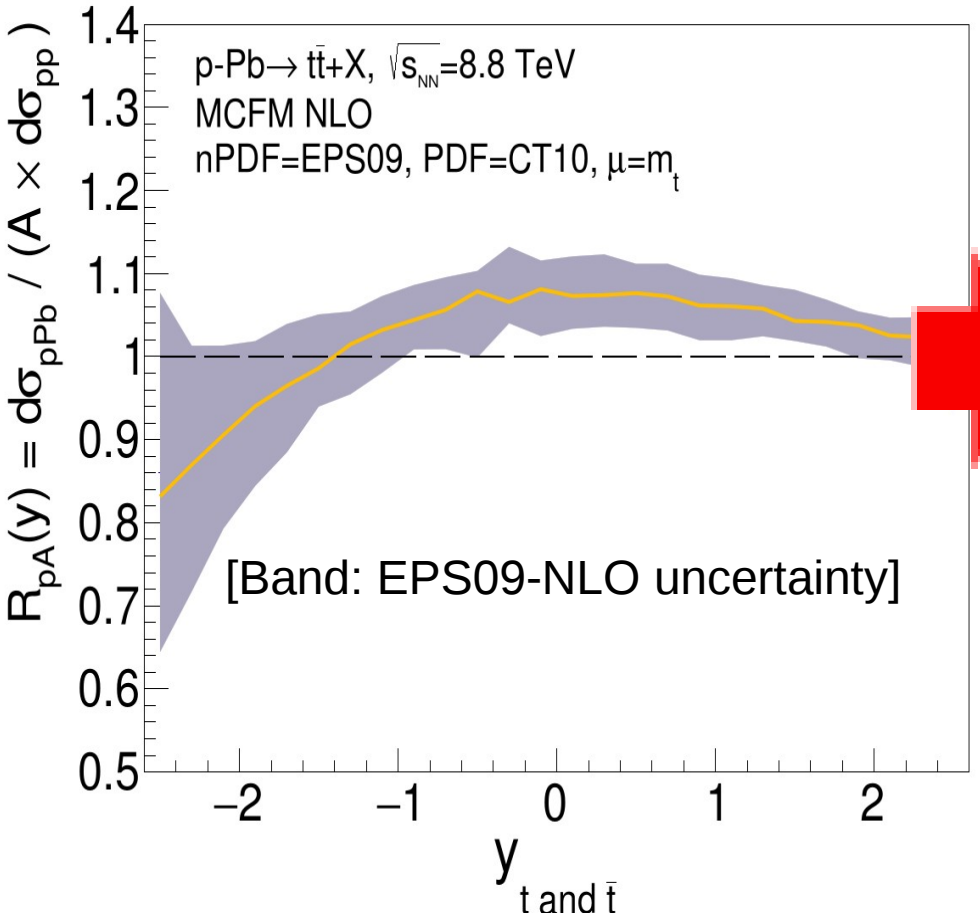
(stat. to dominate over syst. uncertainties)

- nPDF effects (lepton): ±10%

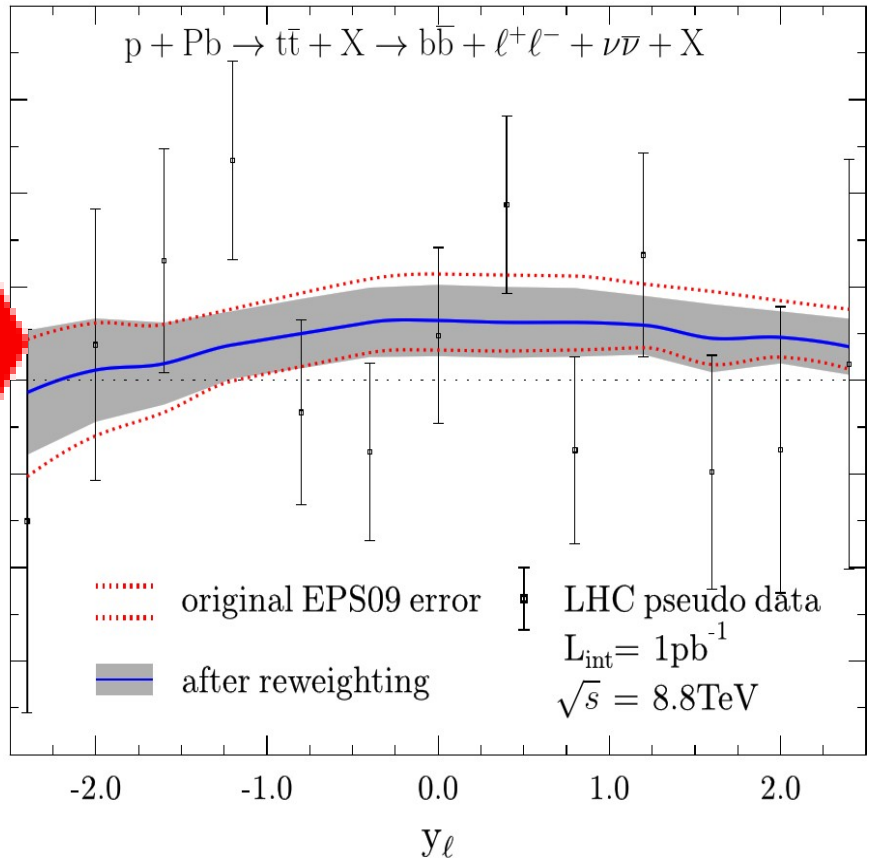
L_{int}=10 nb^{-1}: some constraining power

pPb→ttbar+X (8.8 TeV): Nuclear modif. factor

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



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

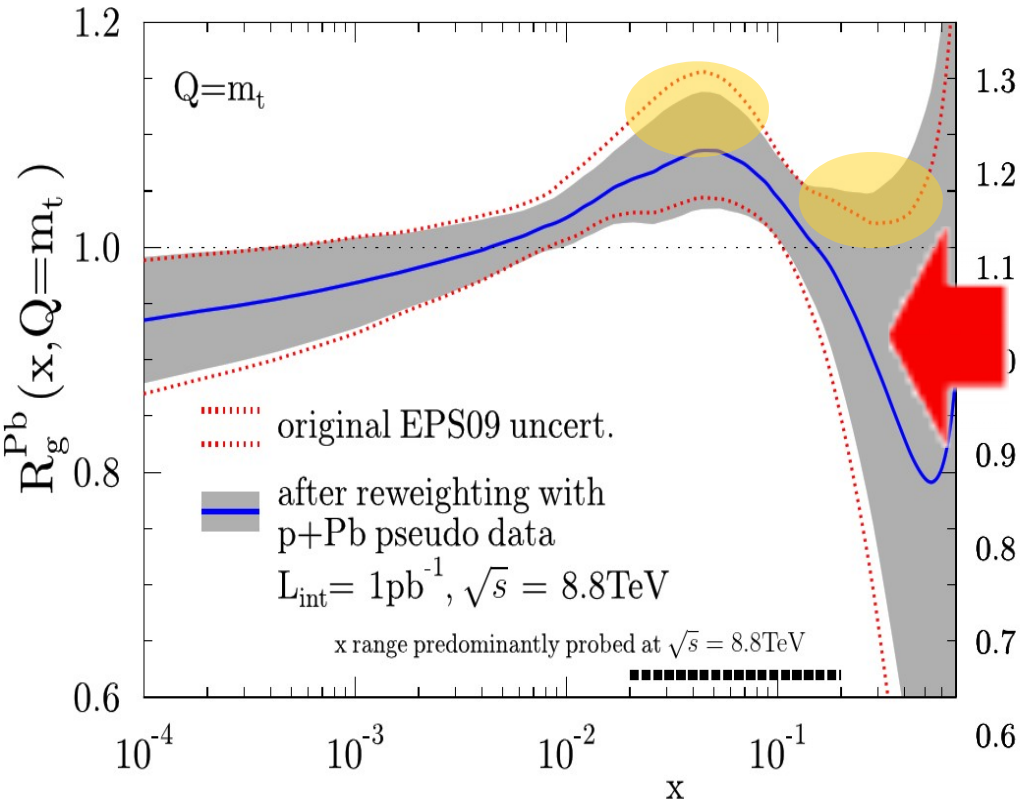


(stat. to dominate over syst. uncertainties)

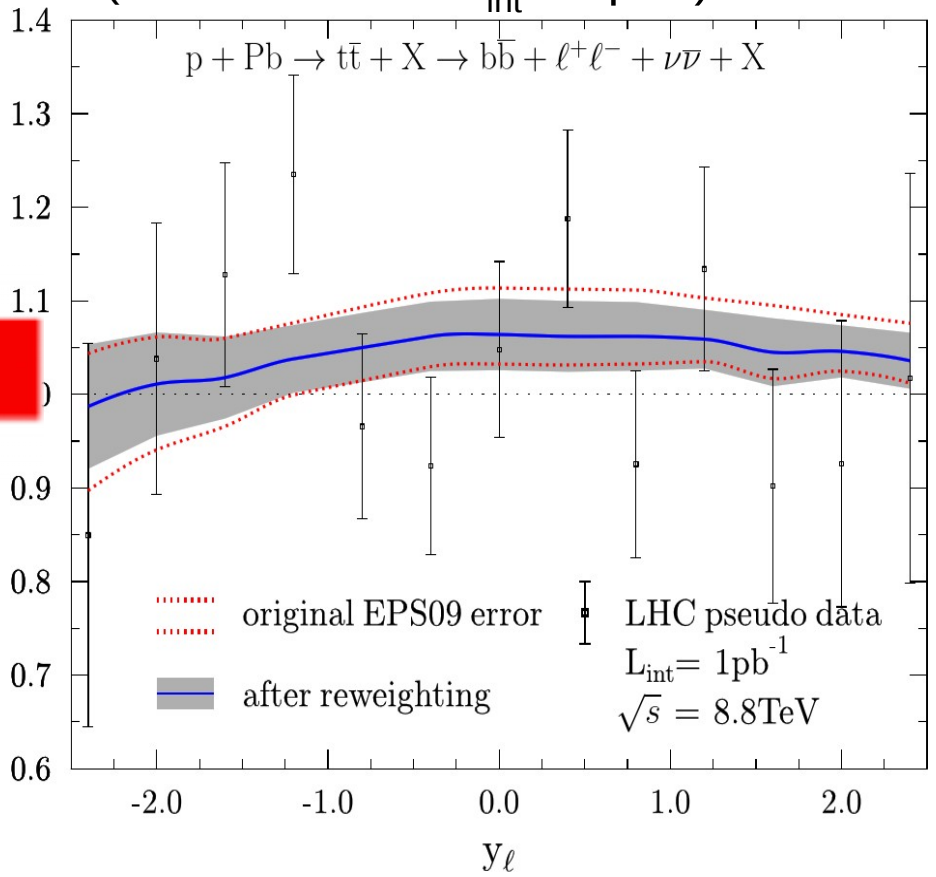
- nPDF effects (top): ±10%
  (central/fwd. rapidities)
- nPDF effects (lepton): ±10%
  L_{int}=1 pb^{-1}: some constraining power

pPb→ttbar+X (8.8 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting



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



- ~10% reduction in uncertainties at antishadowing (x~0.05) and EMC (x~0.4) regions.

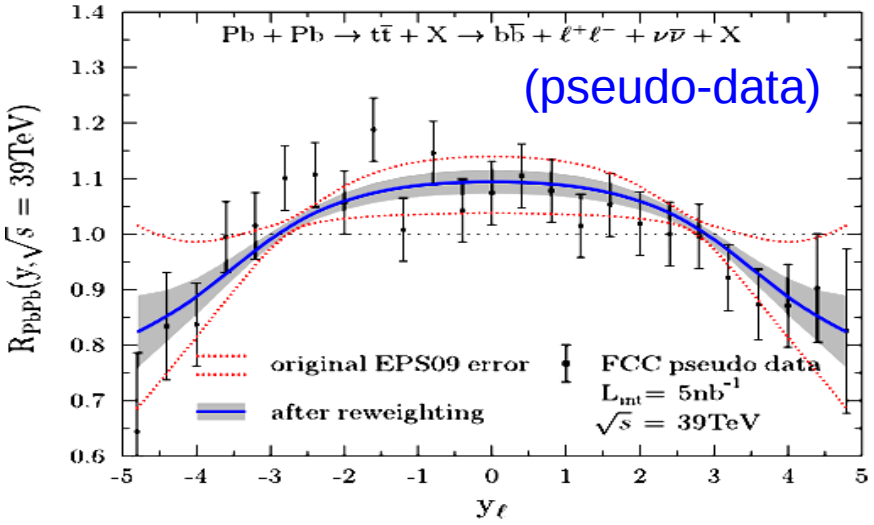
(stat. to dominate over syst. uncertainties)

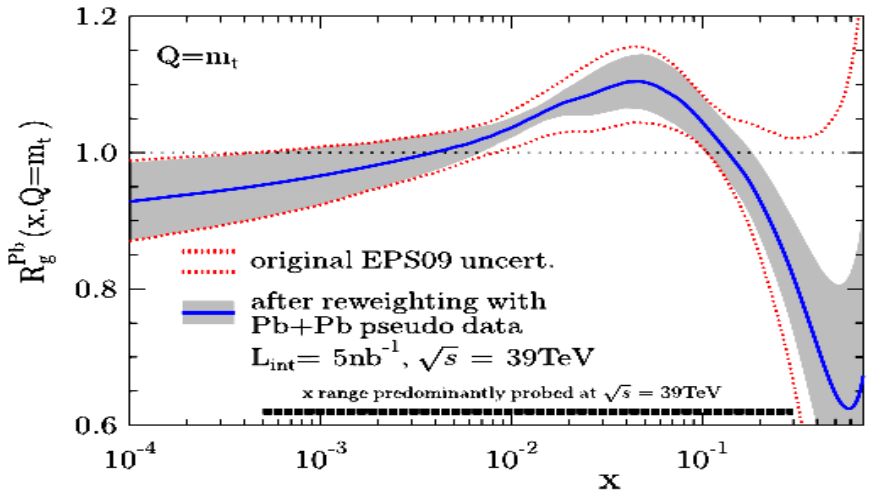
- nPDF effects (lepton): ±10%

L_{int}=1 pb^{-1}: some constraining power

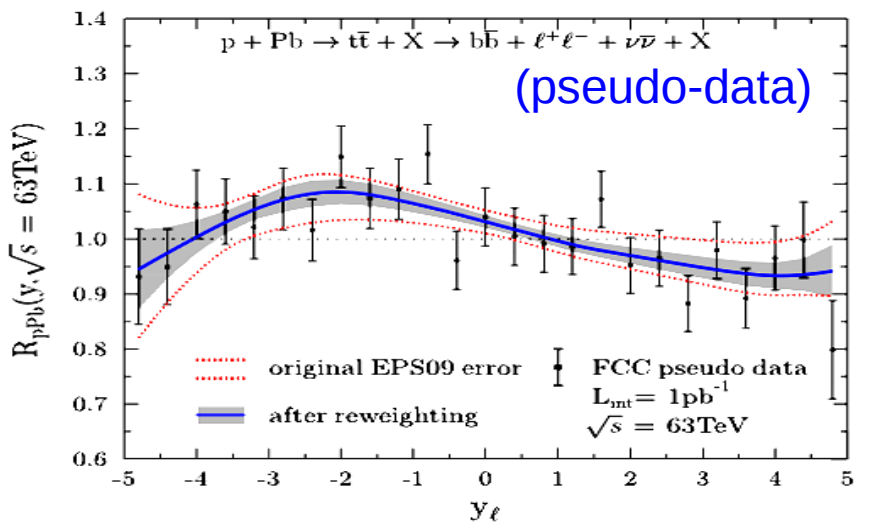
$R_{AA}(y)$ for $\ell^{\pm}$ & R_g^{Pb} from t-tbar in p-Pb, Pb-Pb

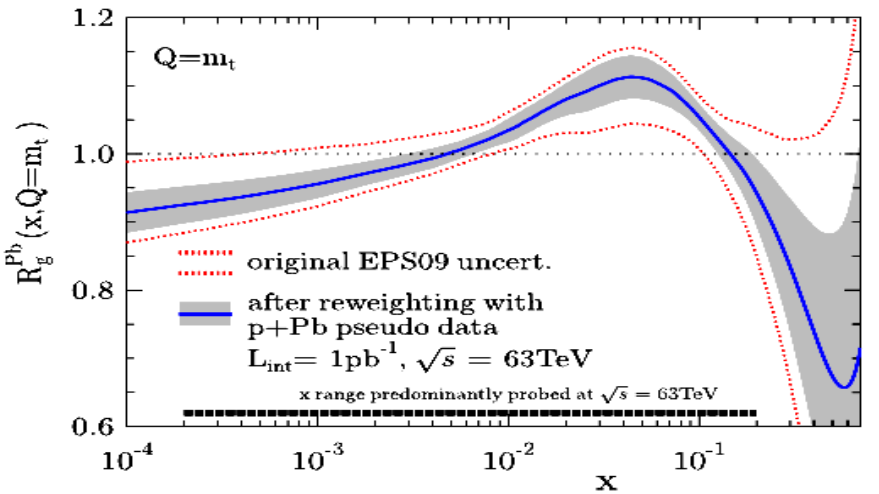
- Pb-Pb at FCC(39 TeV):





- p-Pb at FCC(63 TeV):





- nPDF effects (iso-lepton): ±(10-20)%
- nPDF effects (iso-lepton): ±10%

Nuclear (EPS09 NLO) gluon uncertainties reduced by ~70%.