Nuclear glue from top quark production in ion collisions at the LHC & FCC

Initial Stages 2016
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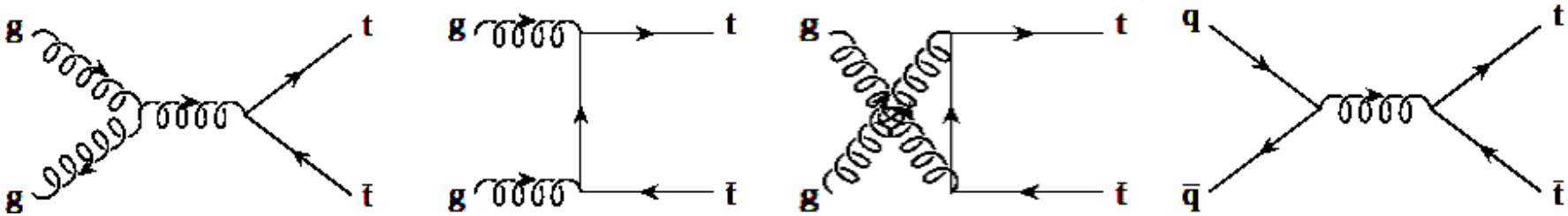
CERN

Based on: D.d'E., K. Krajczar, H. Paukkunen PLB 746 (2015) 64; arXiv:1501.05879 [hep-ph]

Top-quark production in hadron collisions

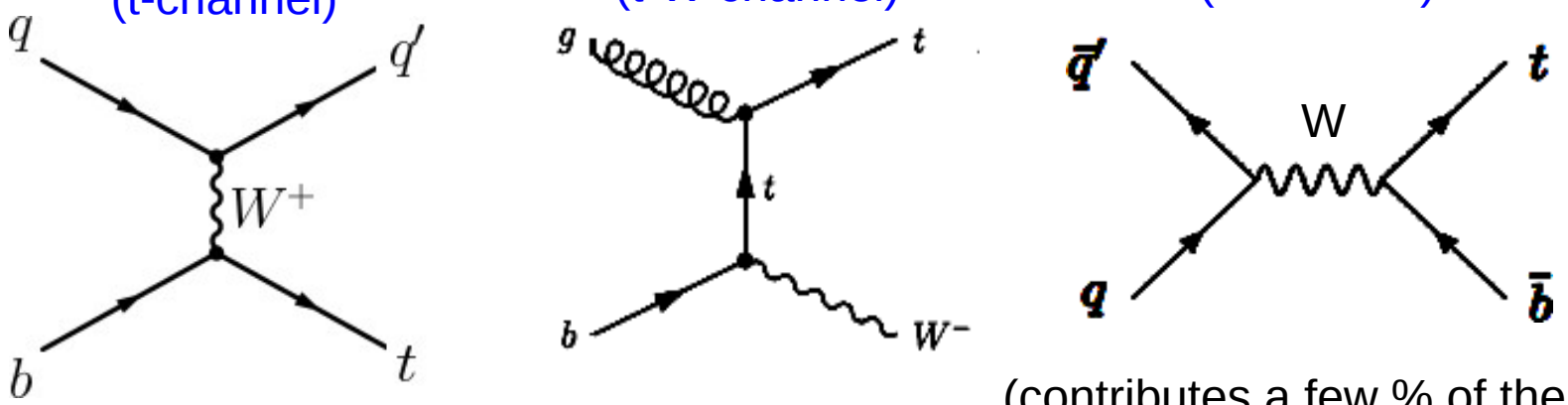
- Top-pair production: QCD interaction dominated by gluon-induced processes (+80%,+90% at LHC,FCC energies at NLO):

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



- Single-top production: Electroweak process sensitive to b-quark (from g→b$\bar{b}$) PDF:

(t-channel) $\qquad$ (t-W channel) $\qquad$ (s-channel)



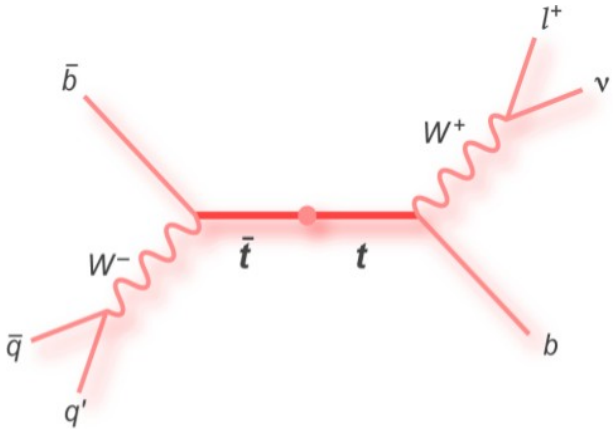
(contributes a few % of the total)

Top-quark decay modes

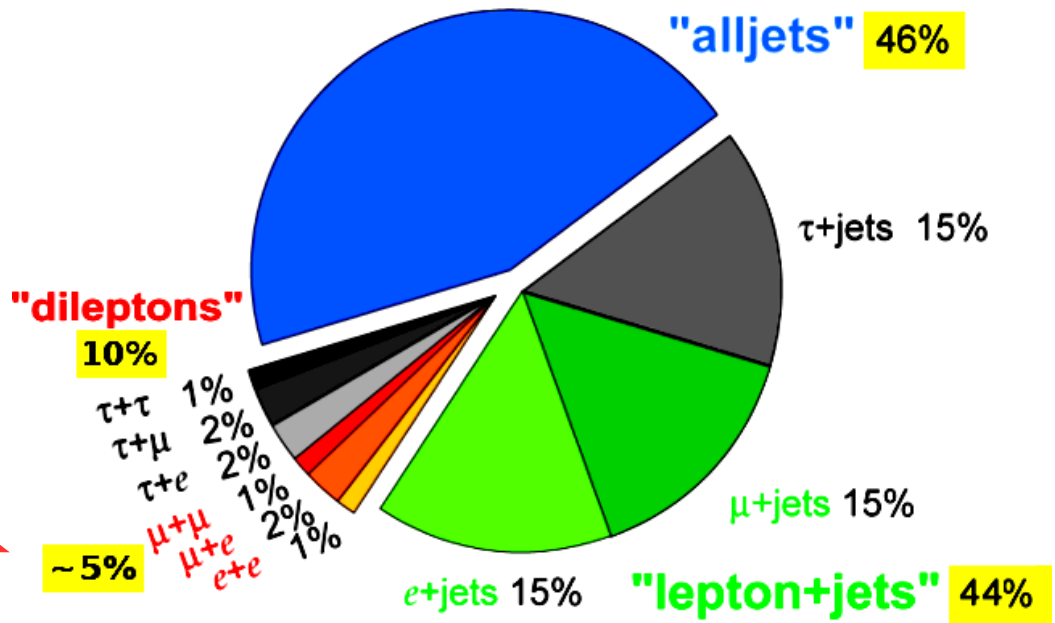
- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b (BR~100%,V_{tb}~1):

  single t → b + 2jets (66%)
  single 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%)



- Top-quark pair decay modes:



Cleanest channels: μ+μ,μ+e,e+e (~5%)

Top-quark in nuclear collisions

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

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

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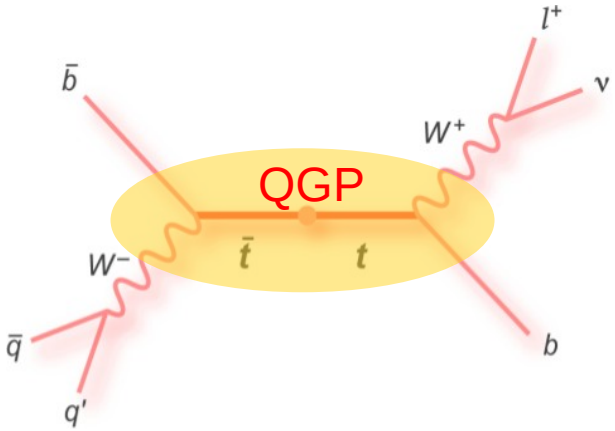


- Motivations for measurement:

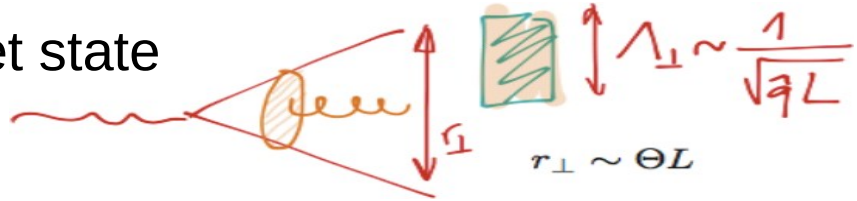
→ One of the few elementary particles (with τ, H) experimentally unobserved so far in A-A collisions.

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

→ Decay within-QGP: Colour reconnection of decay b, q's ?

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

→ Boosted t-tbar pair = color-singlet state probes medium opacity at different time-scales



Top-quark discovery in nuclear collisions

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

  single t → b + 2jets (66%)

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

  ttbar → bbar + 4jets (45%)

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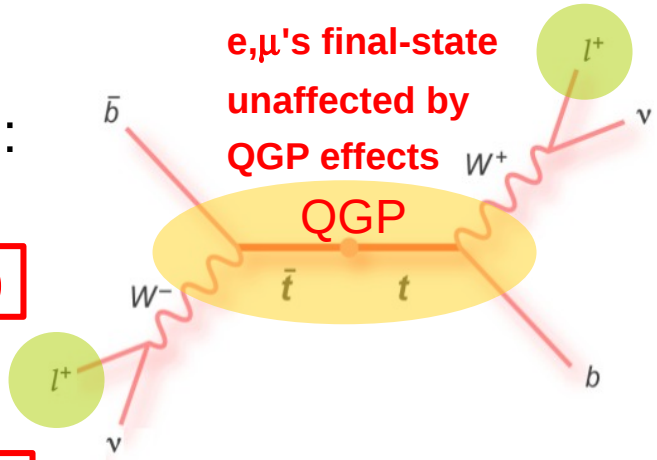

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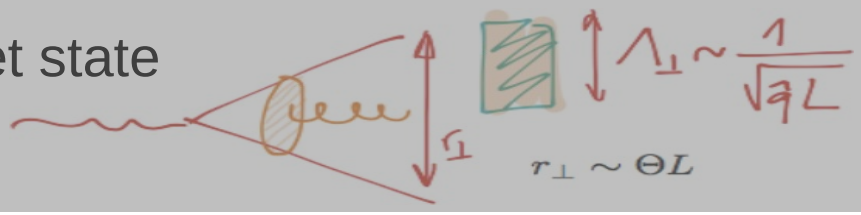
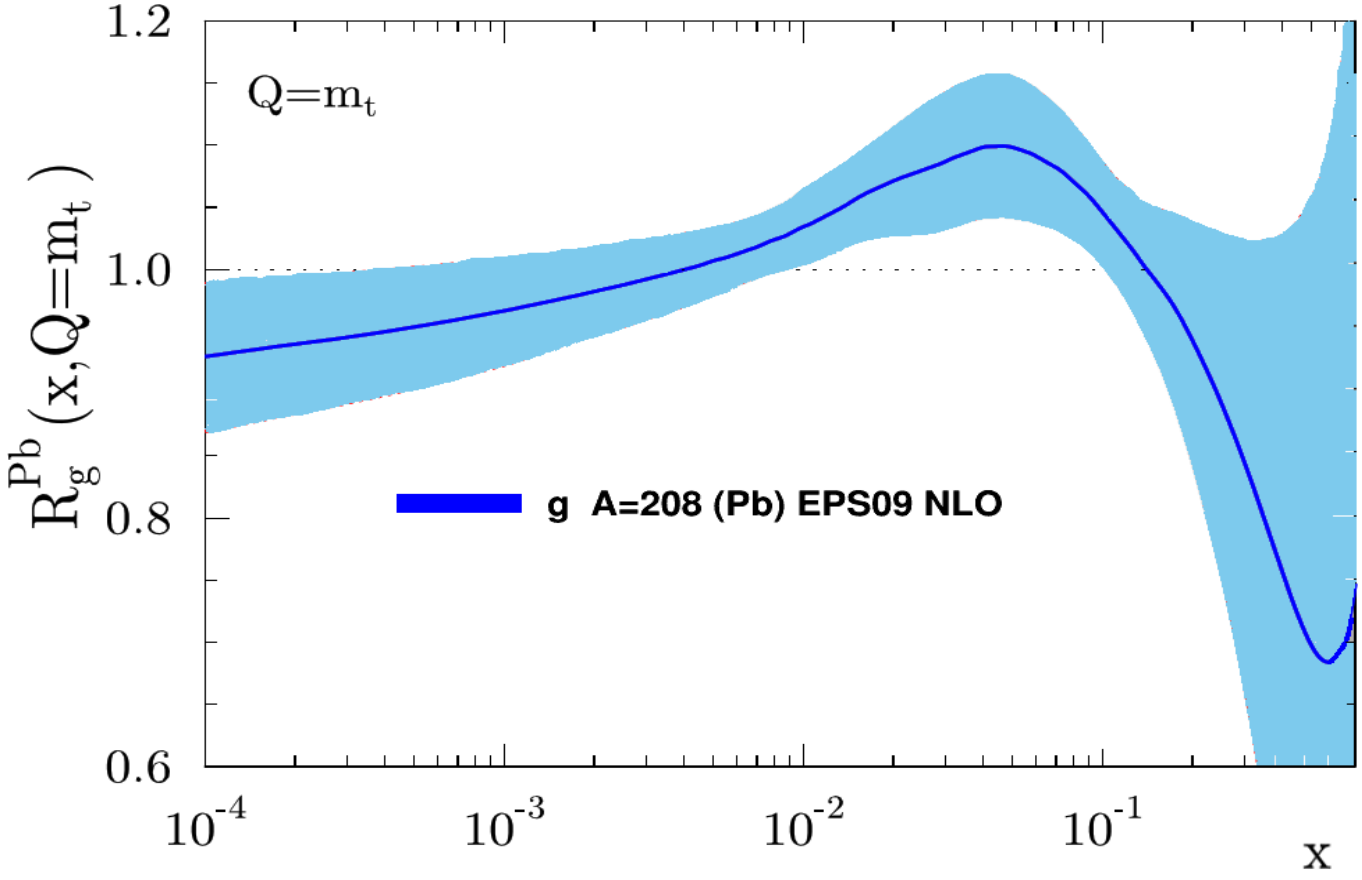


Pb gluon density (high Q^2)

- Gluon density at $Q^2 \sim m_t^2$ badly known, in particular in the antishadowing and EMC regions:



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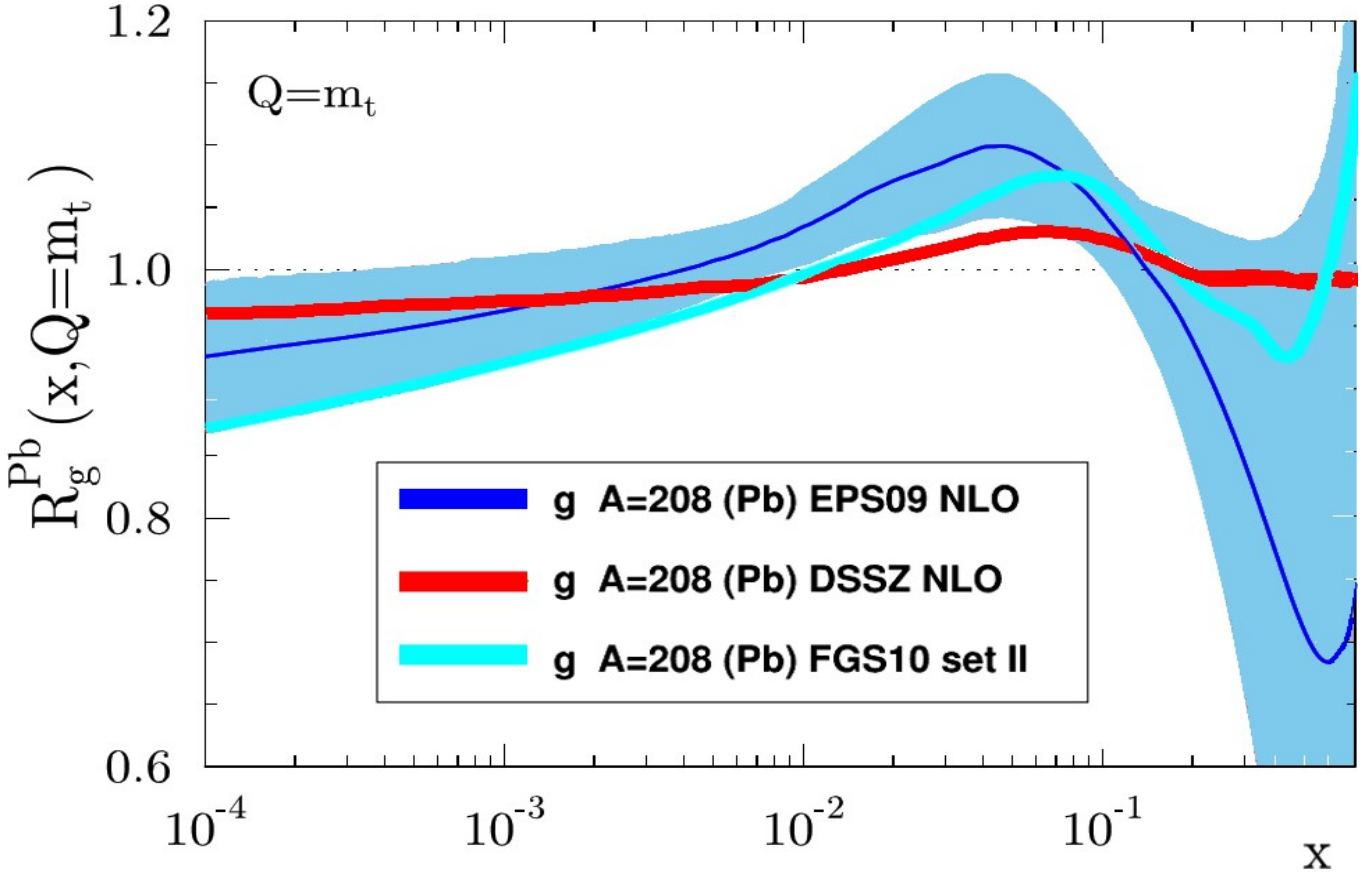


Theoretical setup

- MCFM v6.7 NLO event calculator:
  - → Parton densities:
    Proton PDF: CT10 NLO
    Pb nPDF: EPS09 NLO (central + 30 error sets)
    Isospin (u,d quark) effects included.
  - → Scales choice: $\mu = \mu_F = \mu_R = m_{top}$
    Variations not considered as they mostly cancel in R_{AA} ratios.
- MCFM processes:

t-tbar: nproc = 141 (total & semileptonic decays):

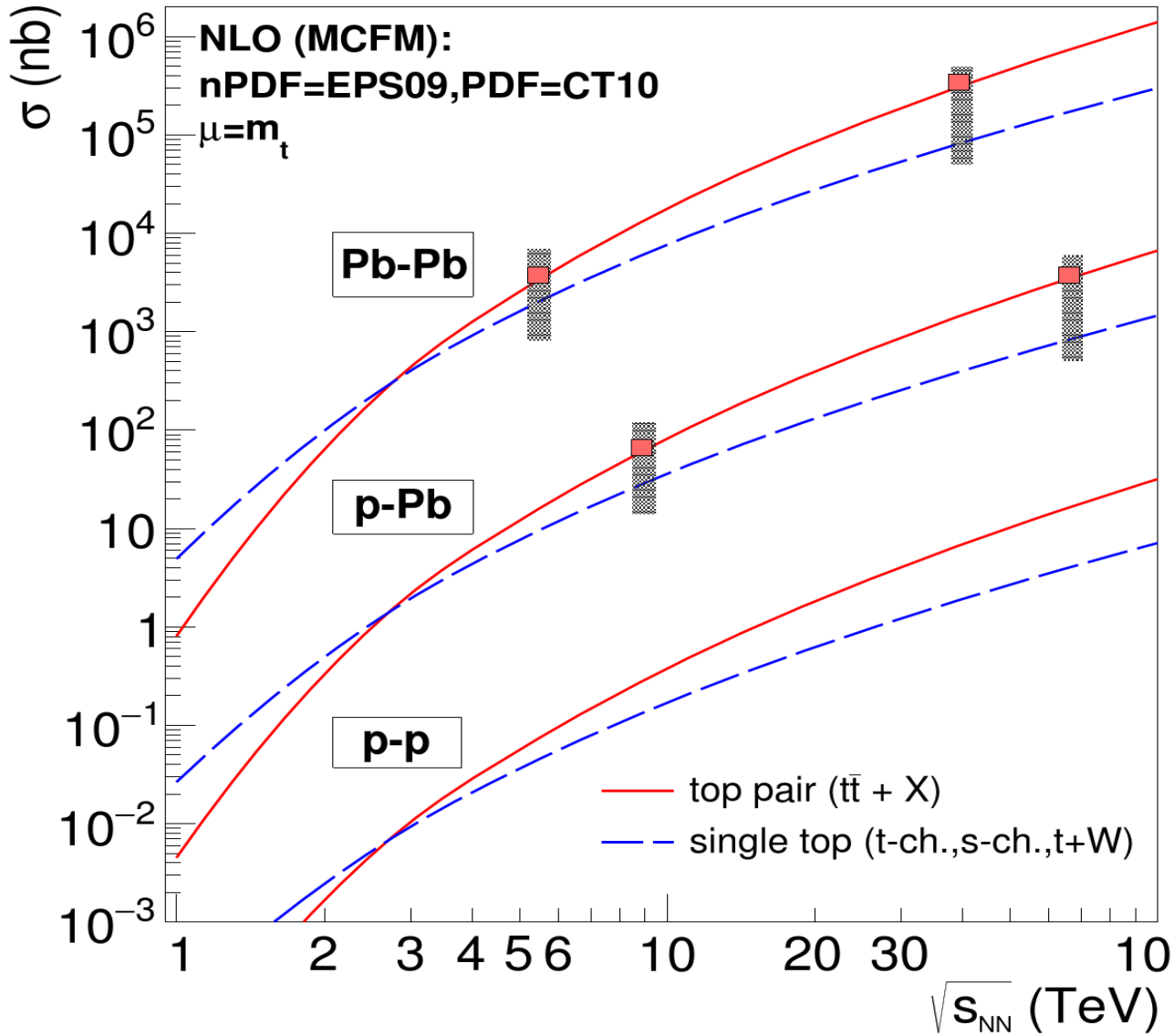
$$141 \mid t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to b\ (p_6) + e^-(p_7) + \bar{\nu}(p_8)) \mid \text{NLO}$$

Single-top: nproc = 161,171; 166,776 (total & semileptonic decay):

161	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$[t-channel]	NLO
166	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$[t-channel]	NLO
171	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + b(p_6))$[s-channel]	NLO
176	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6))$[s-channel]	NLO

- Additional higher-order corrections (not included) are small:
  K-factor=NNLO/NLO ~10% for ttbar & single-t

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

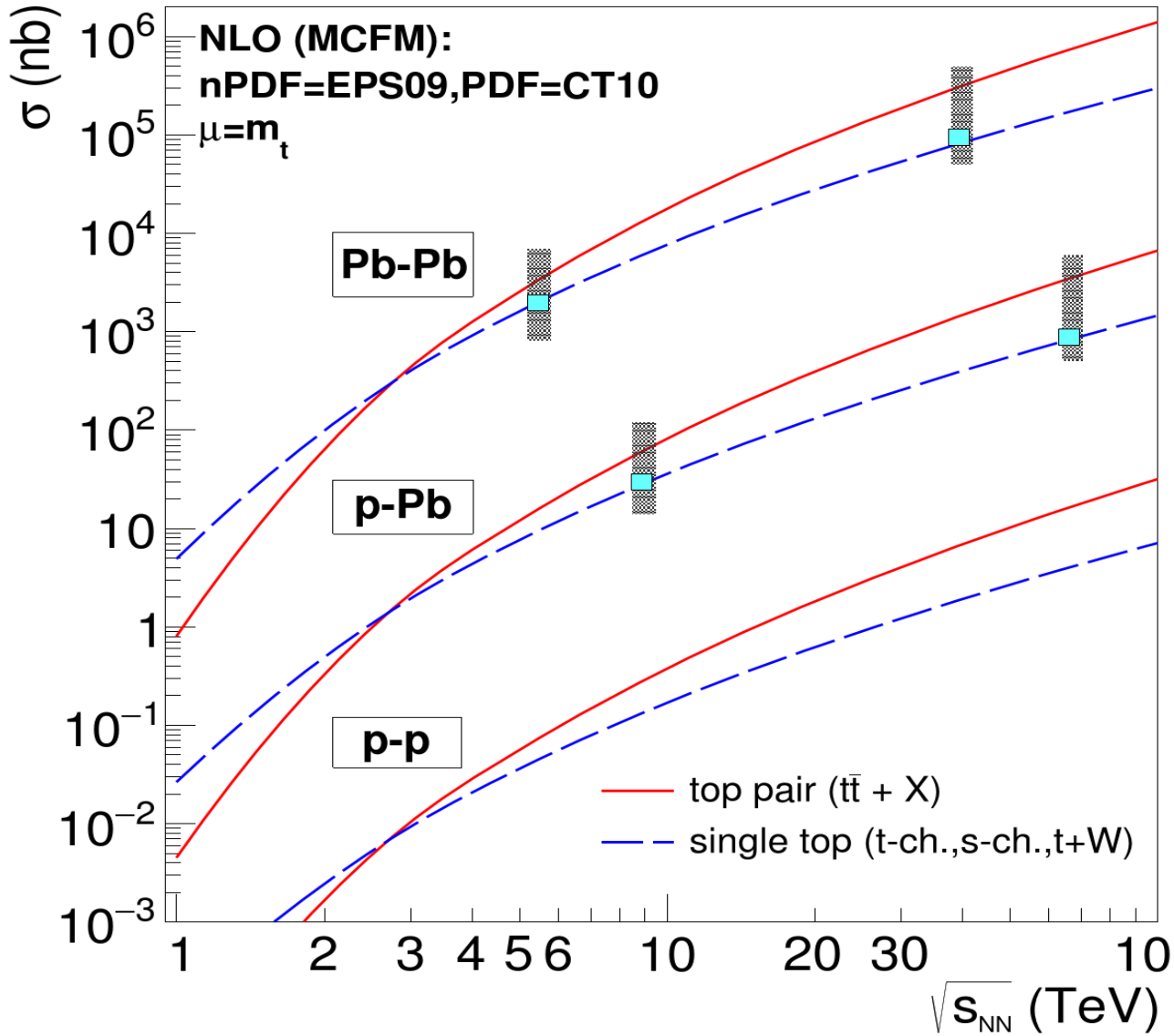
- p-p (reference):

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 σ_{tt} by +(2-8)%

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

Single-top total x-sections in p-p, p-Pb, Pb-Pb



- Pb-Pb:

LHC(5.5 TeV) = 1.7 μb
FCC(39 TeV) = 55 μb

- p-Pb:

LHC(8.8 TeV) = 22 nb
FCC(63 TeV) = 530 nb

- p-p (reference):

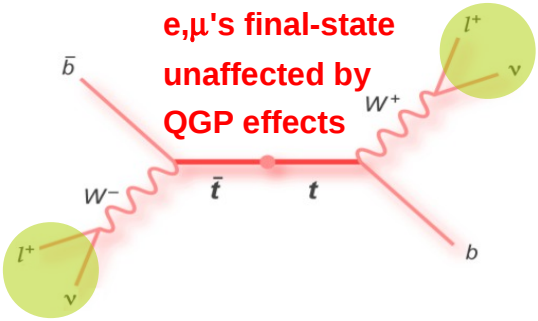
LHC(5.5 TeV) = 39 pb
LHC(8.8 TeV) = 105 pb
FCC(39 TeV) = 1.3 nb
FCC(63 TeV) = 2.6 nb

nPDF (anti)shadowing changes $\sigma_{single\text{-}t}$ by ±2%

➜ Cross-sections increase by ×25-30 from LHC to FCC

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, lepton=e,μ):

  t-tbar: p_T(lepton),p_T(b-jet) > 20,30 GeV; R_{isol}(b-jet,lepton) = 0.3
  $|\eta$(lepton)$|,|\eta$(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)

- Acceptance & efficiency losses:

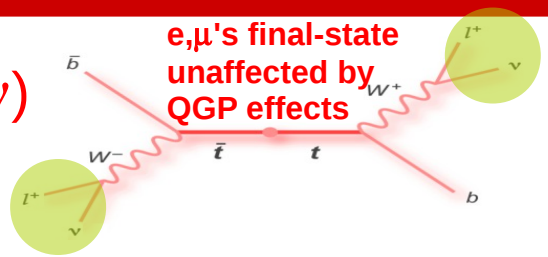
  t-tbar: Acc×Eff ~ 40% (LHC), 50% (FCC)

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

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

Expected t-tbar & single-top yields

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

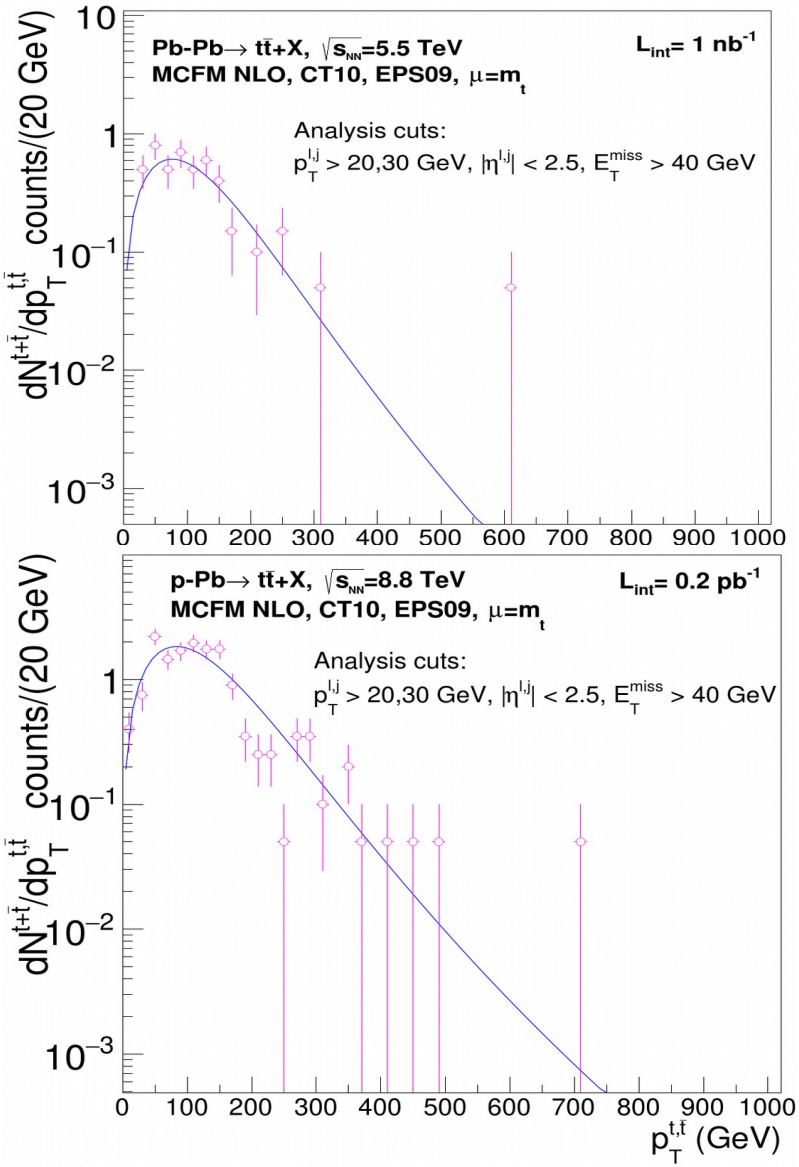


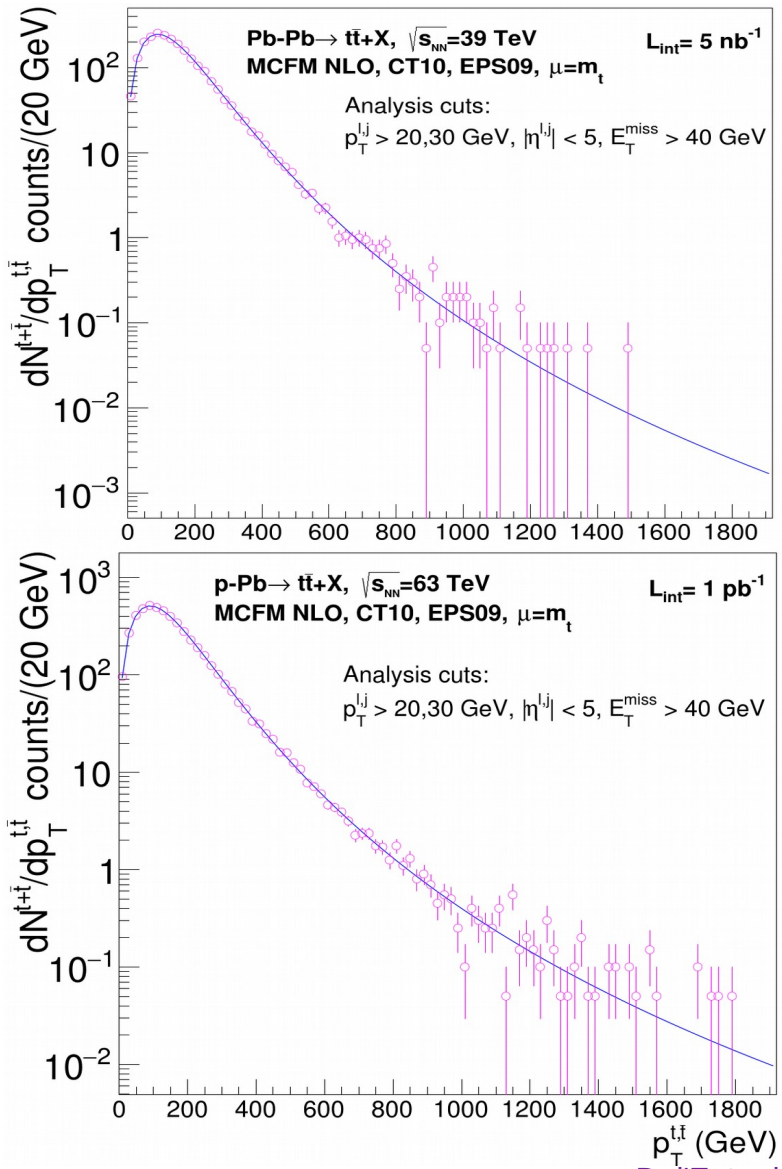
System	$\sqrt{s_{NN}}$	L_{int}	N(t-tbar)	N(t+W)
Pb-Pb	5.5 TeV	1 nb^{-1}	**90**	**3**
		10 nb^{-1}	*900*	*30*
p-Pb	8.8 TeV	0.2 pb^{-1}	**300**	**10**
		1 pb^{-1}	*1.500*	*50*
Pb-Pb	39 TeV	33 nb^{-1}	**310.000**	**8.600**
p-Pb	63 TeV	8 pb^{-1}	**800.000**	**21.500**

- LHC (nominal L_{int}): ~100 t-tbar pairs in Pb-Pb, p-Pb
  O(10^3) tops for enhanced lumis.
- FCC (nominal L_{int}): 0.3–0.8 million t-tbar pairs in Pb-Pb, p-Pb

Differential top-pair p_T distributions

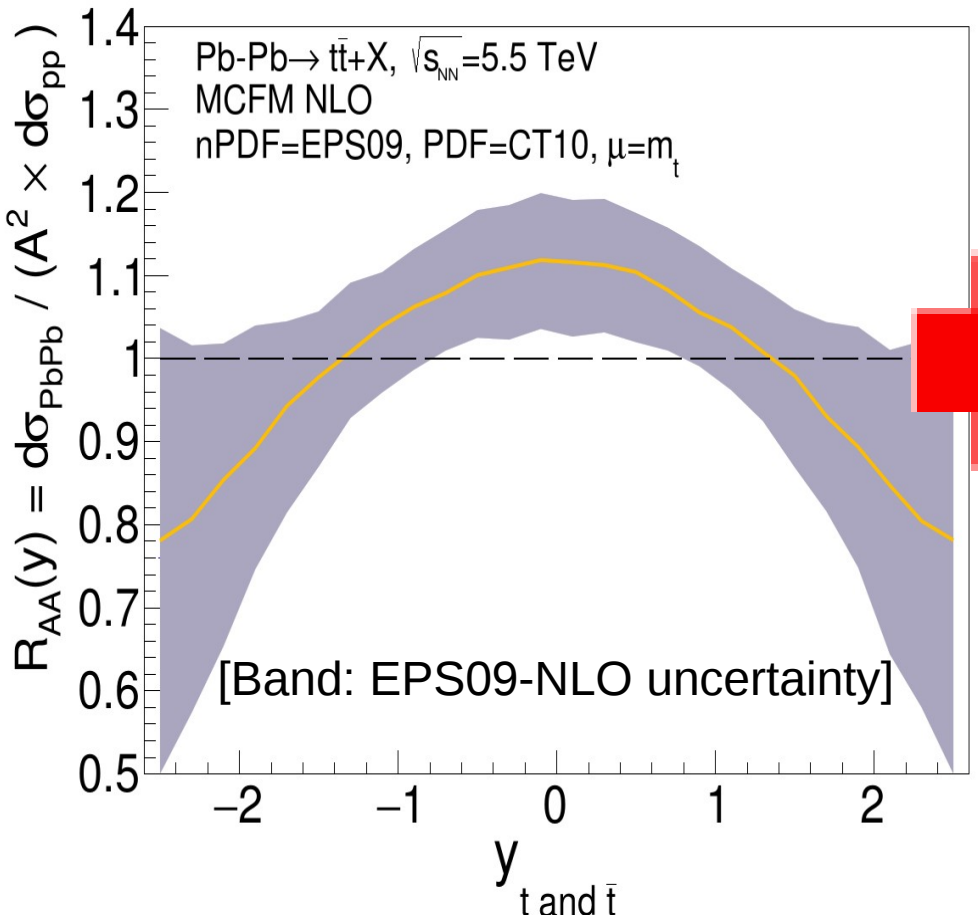
- LHC: p_T reach up to ~500 GeV
- FCC: p_T reach up to ~2 TeV



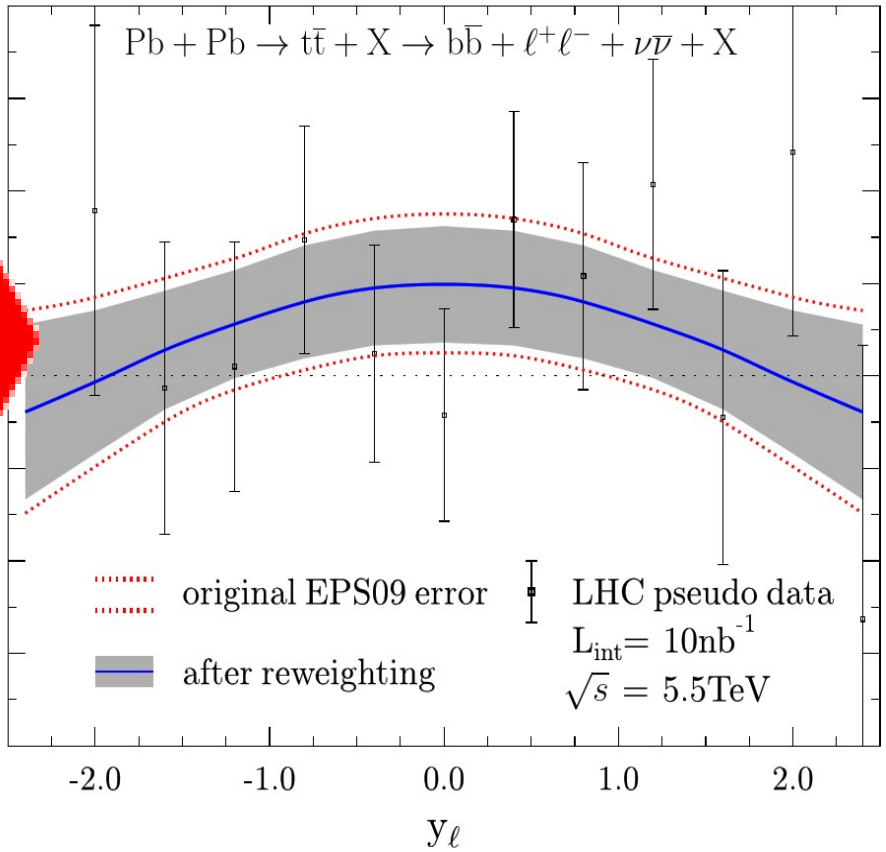


PbPb→ttbar+X (5.5 TeV): Nuclear modif. factor

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



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



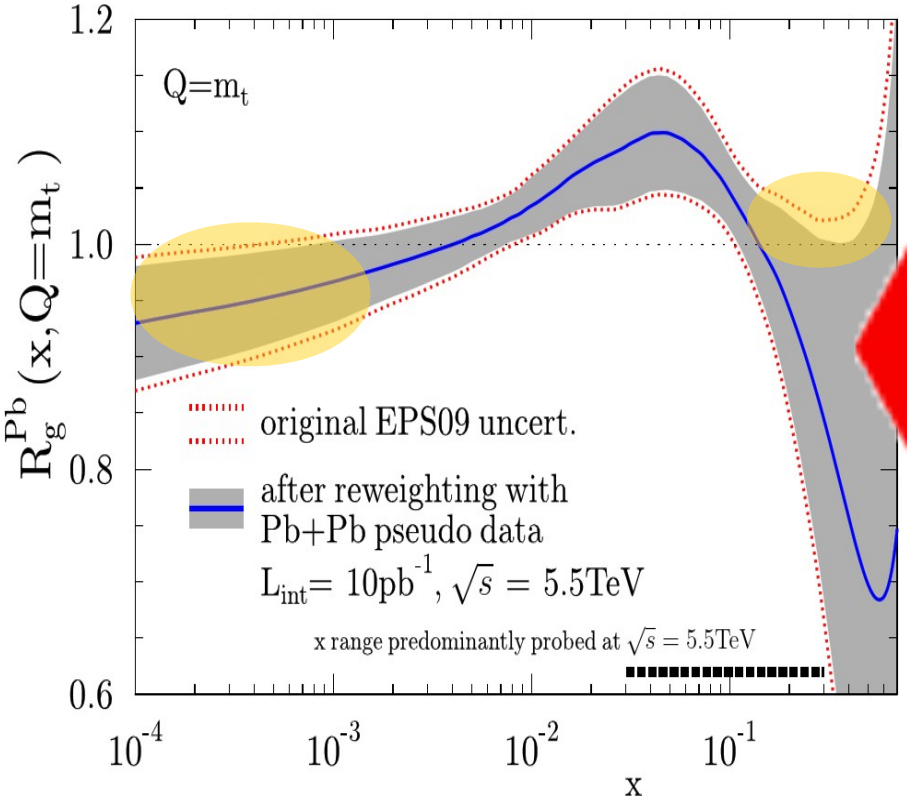
(stat. to dominate over syst. uncertainties)

- 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



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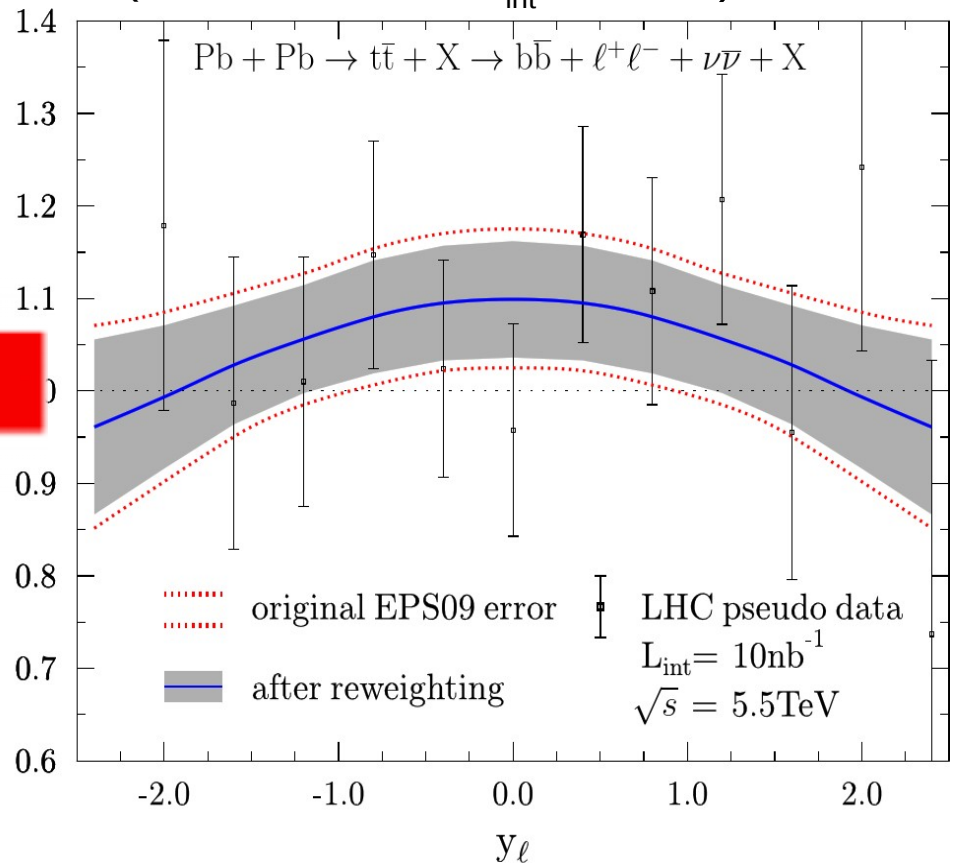


- ~10% reduction in uncertainties at low x (x~10^{-4}-10^{-2}) and EMC (x~0.3) regions

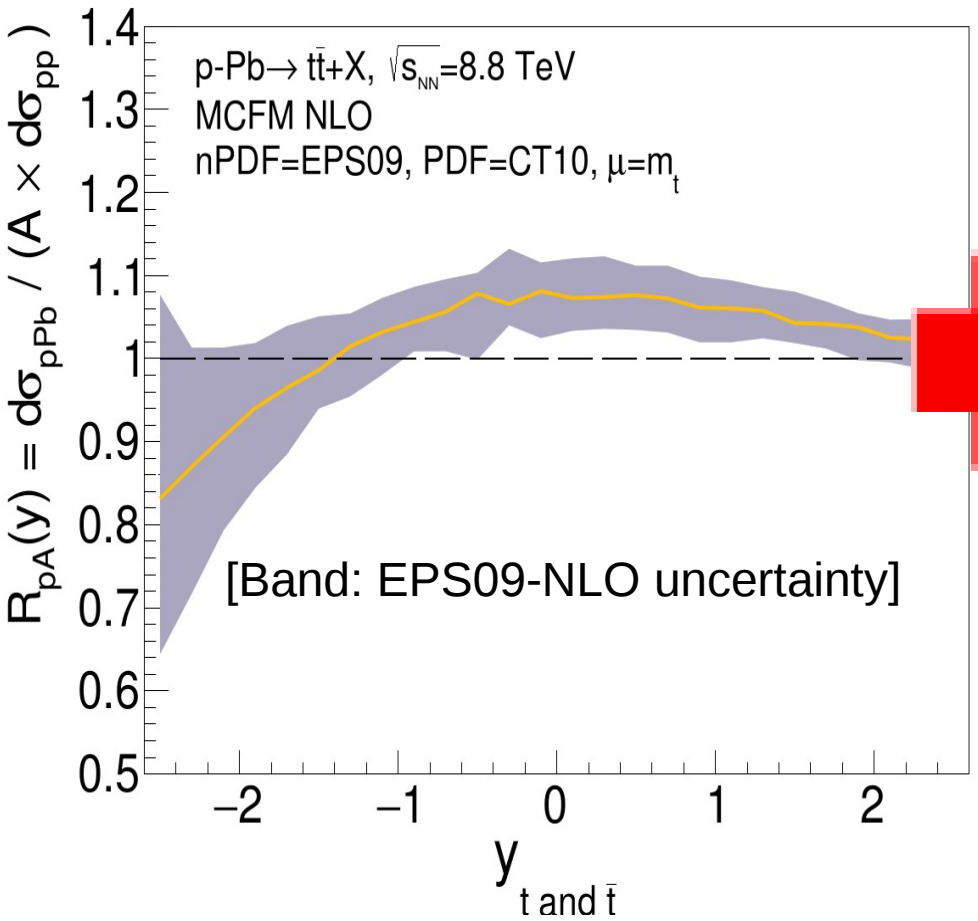
(stat. to dominate over syst. uncertainties)

- nPDF effects (lepton): ±10%

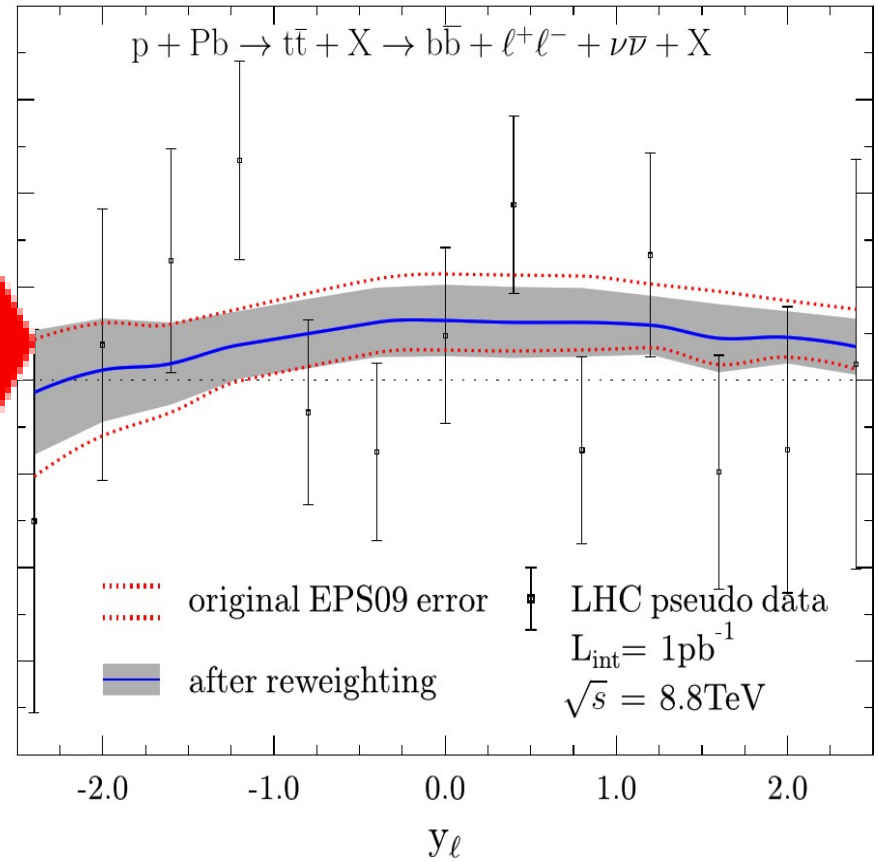
L_{int}=10 nb^{-1}: some constraining power

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})



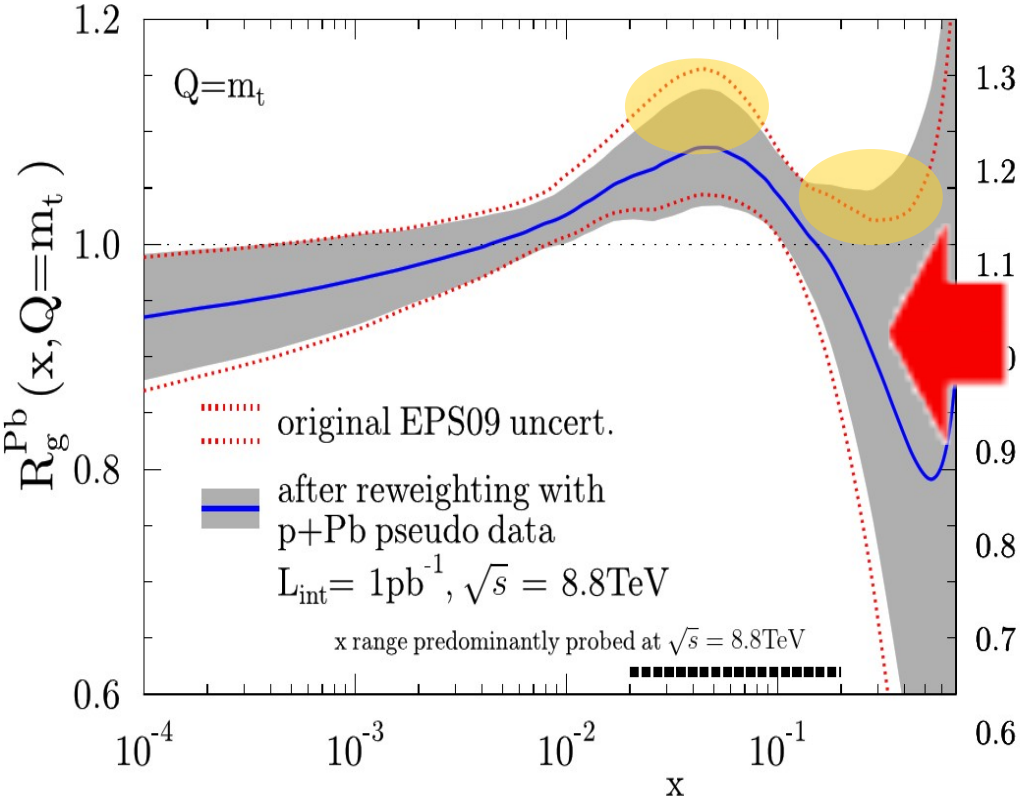
(stat. to dominate over syst. uncertainties)

- nPDF effects (top): ±10%
  (central/fwd. rapidities)

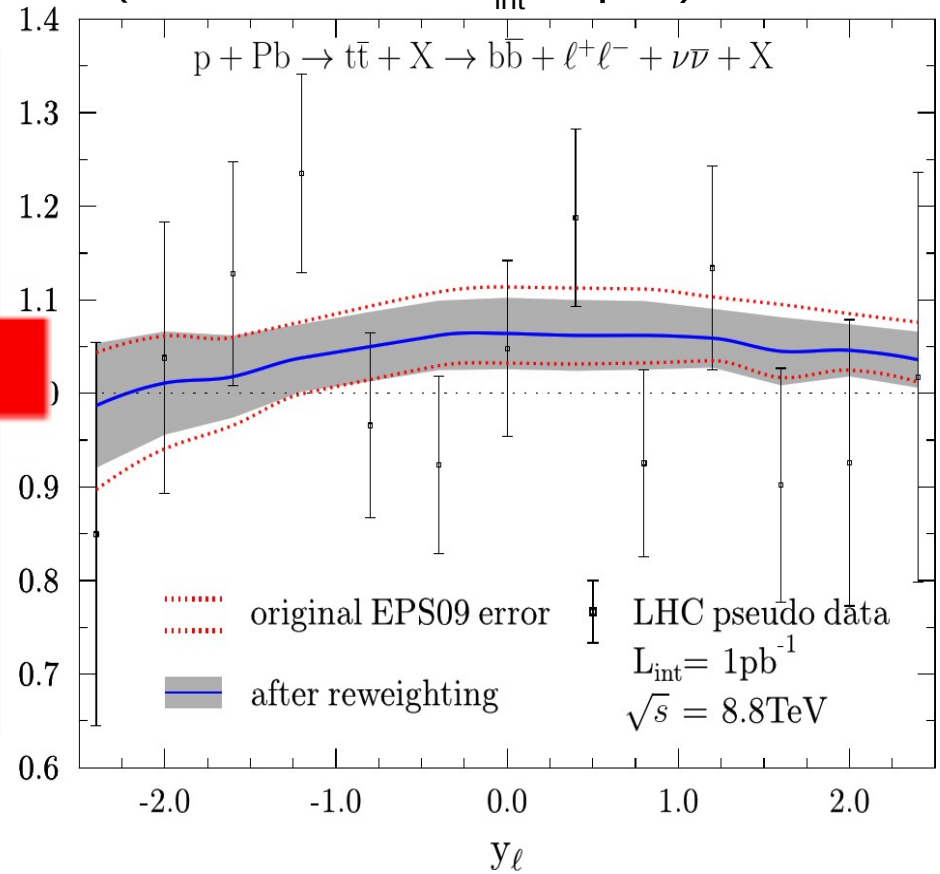
- nPDF effects (lepton): ±10%
  L_{int}=1 pb^{-1}: some constraining power

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.

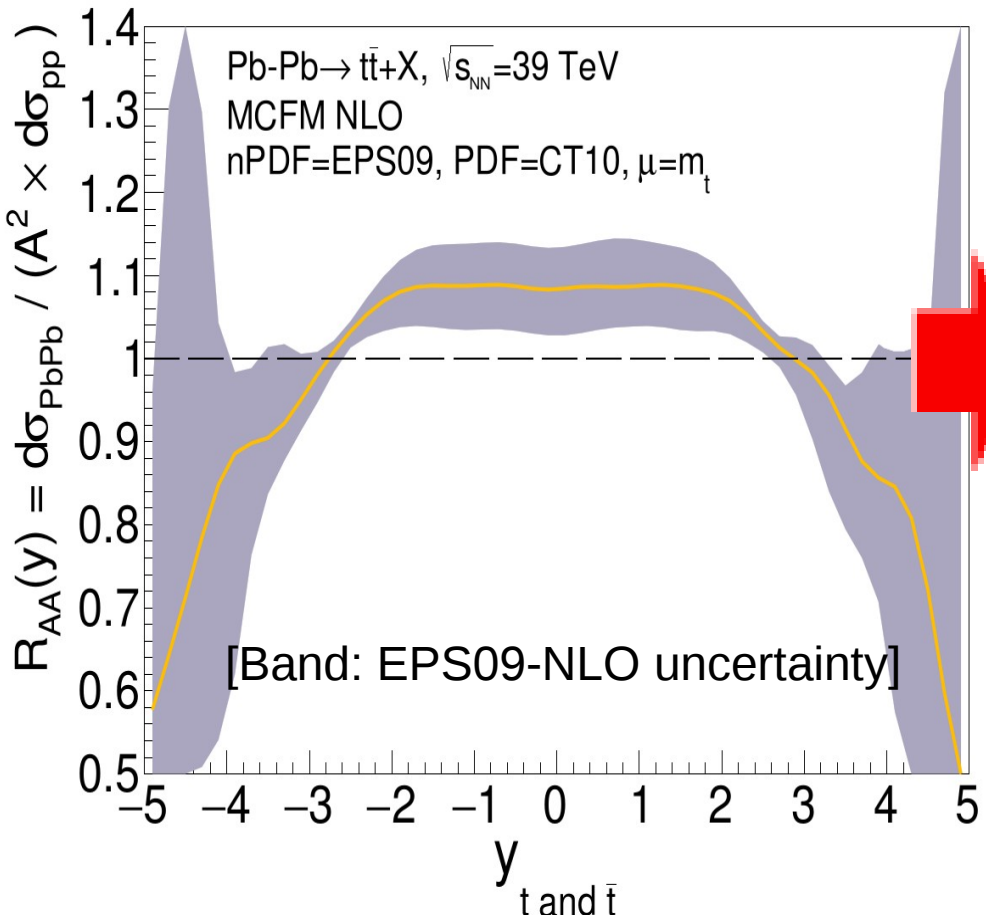
(stat. to dominate over syst. uncertainties)

- nPDF effects (lepton): ±10%

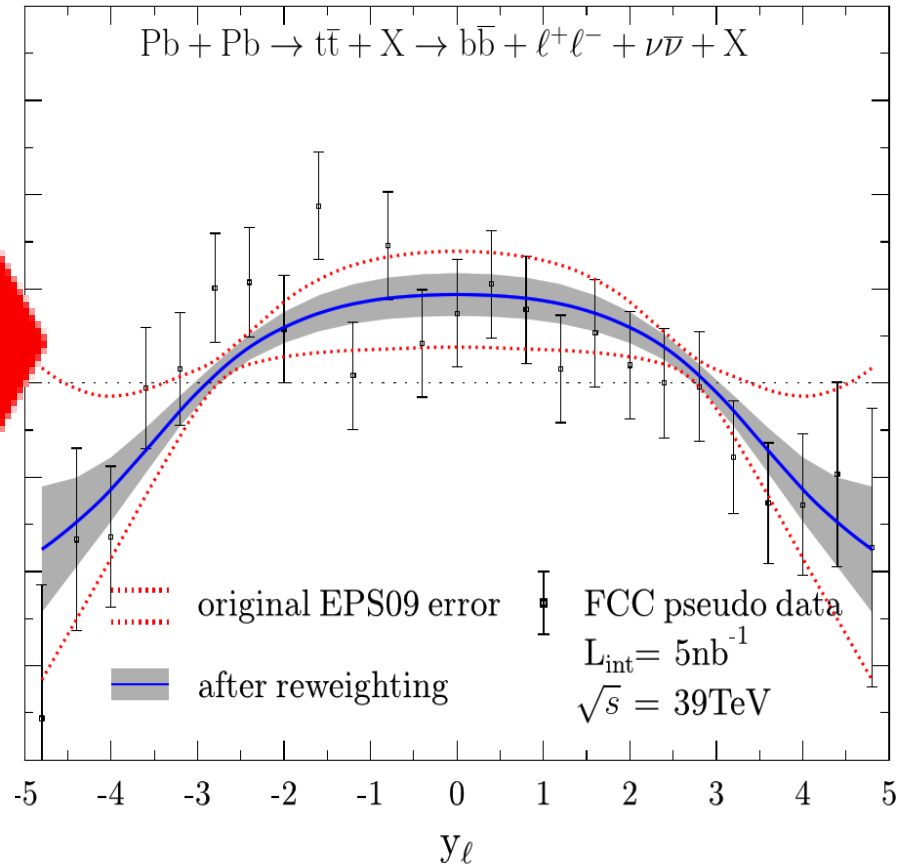
L_{int}=1 pb^{-1}: some constraining power

PbPb→ttbar+X (39 TeV): Nuclear modif. factor

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



- Isolated lepton y-distrib. after cuts:
(Pseudodata for L_{int}=5 nb^{-1})



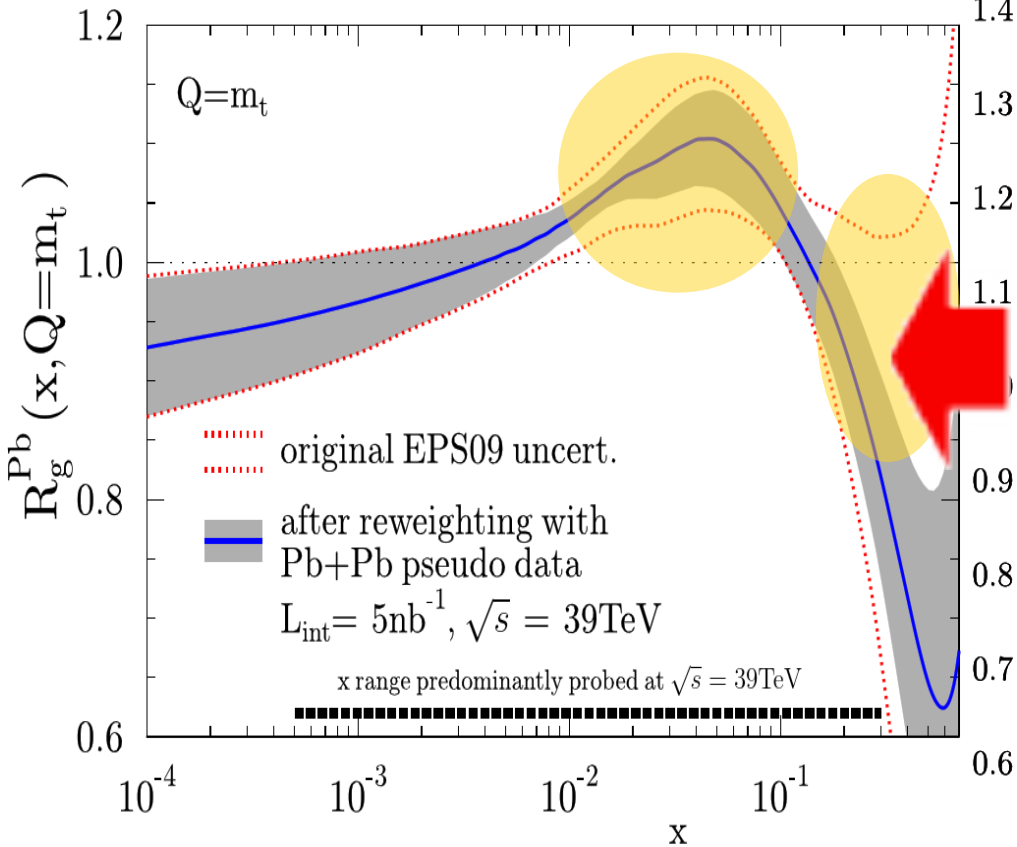
(stat. to dominate over syst. uncertainties)

- nPDF effects (top): -20% (fwd/backwd.)
+10% (central)

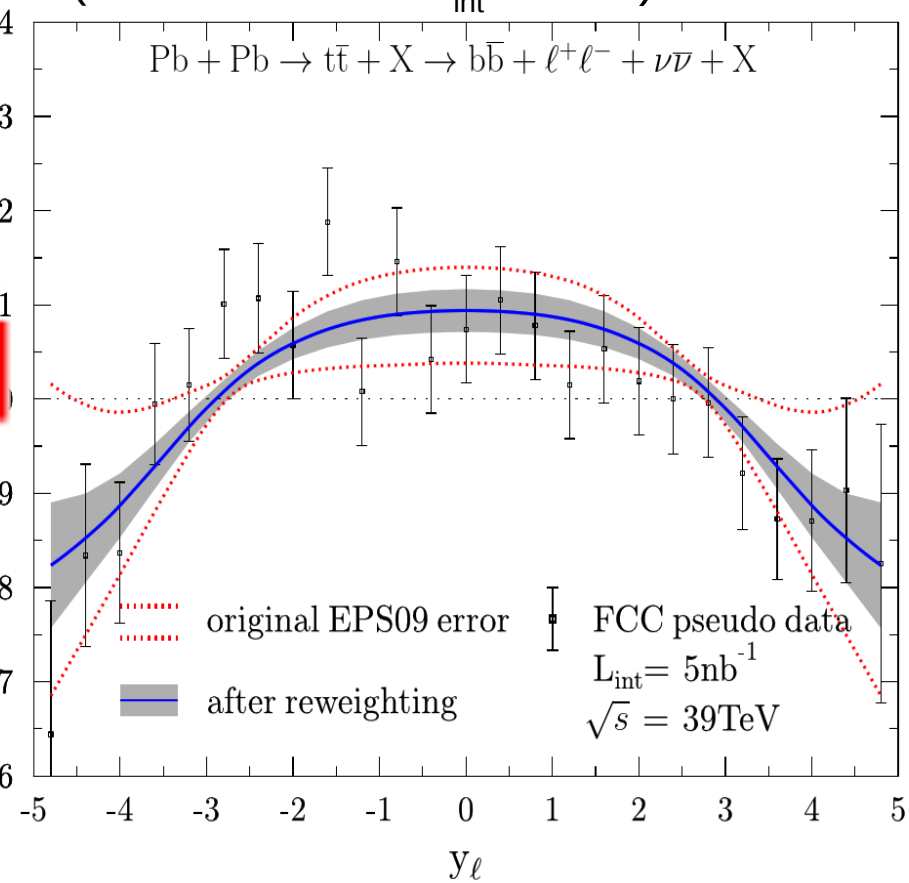
- nPDF effects (lepton): ±(10-20)%
Strong constraining power

PbPb→ttbar+X (39 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting



- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int}=5 nb^{-1})



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

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

pPb→ttbar+X (63 TeV): Nuclear modif. factor

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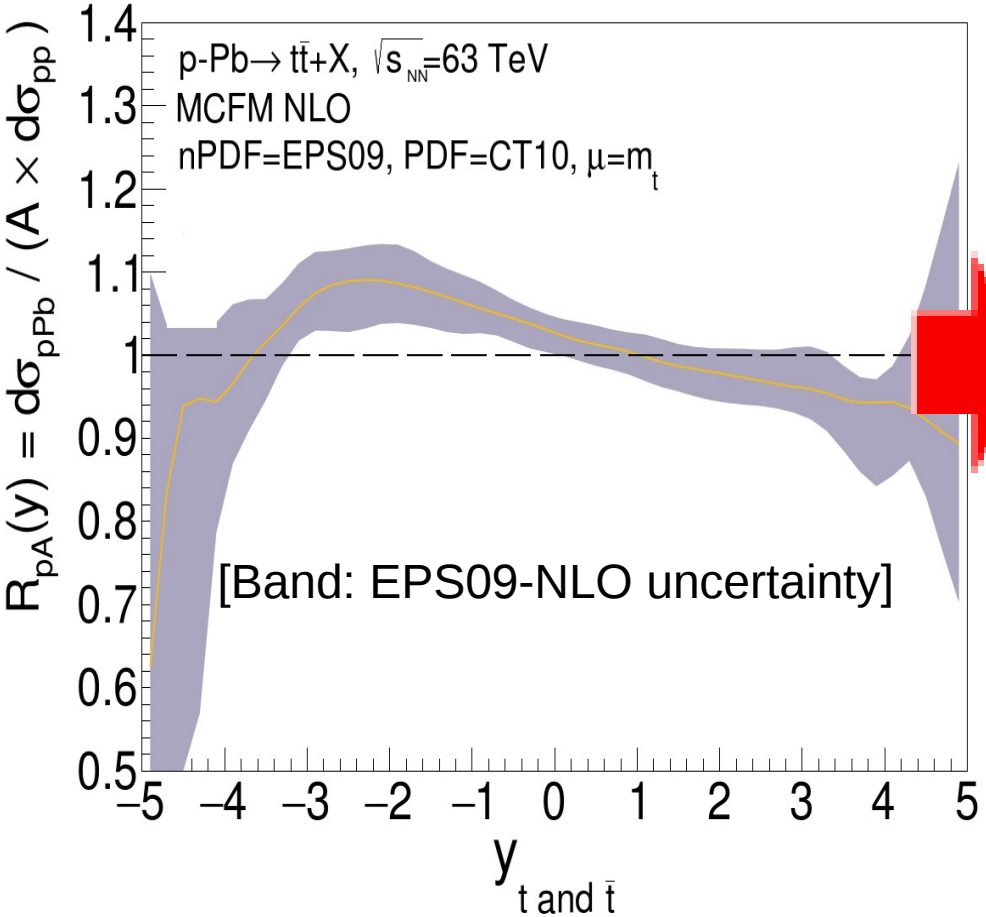
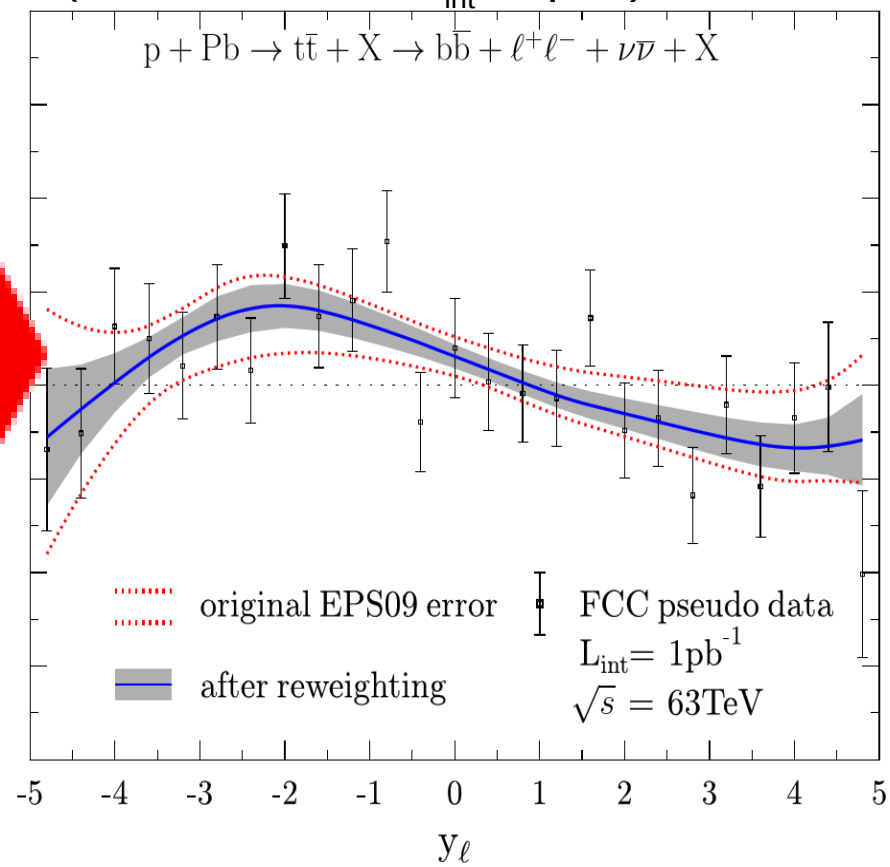


- Isolated lepton y-distrib. after cuts:
  (Pseudodata for L_{int}=1 pb^{-1})



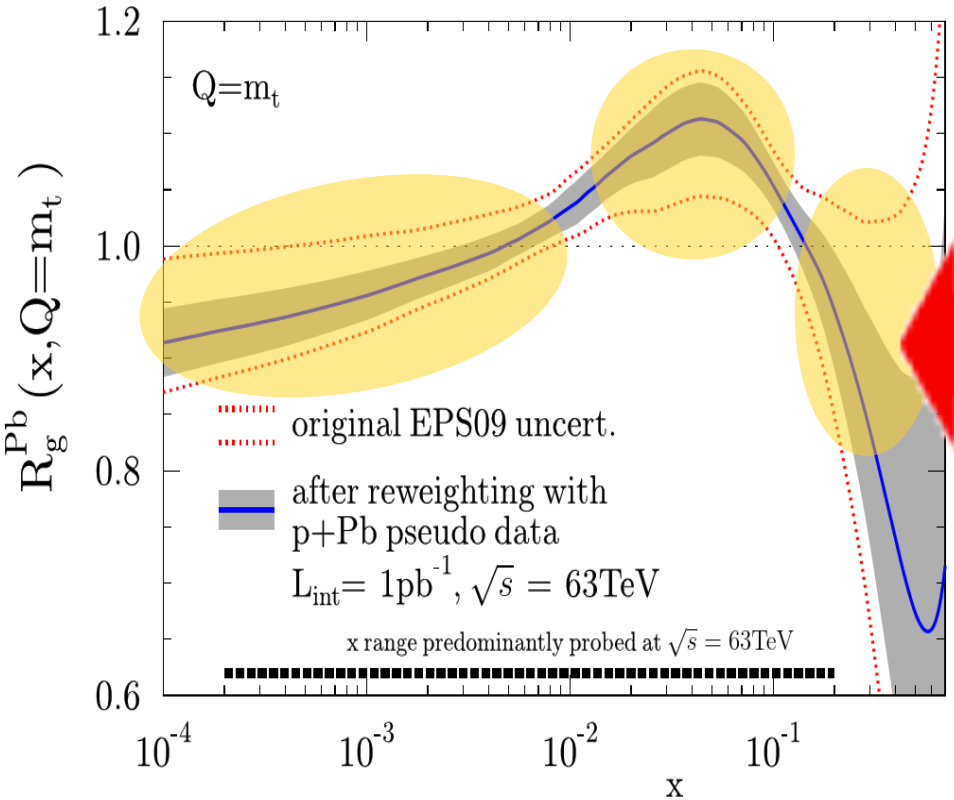
(stat. to dominate over syst. uncertainties)

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

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

pPb→ttbar+X (63 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting



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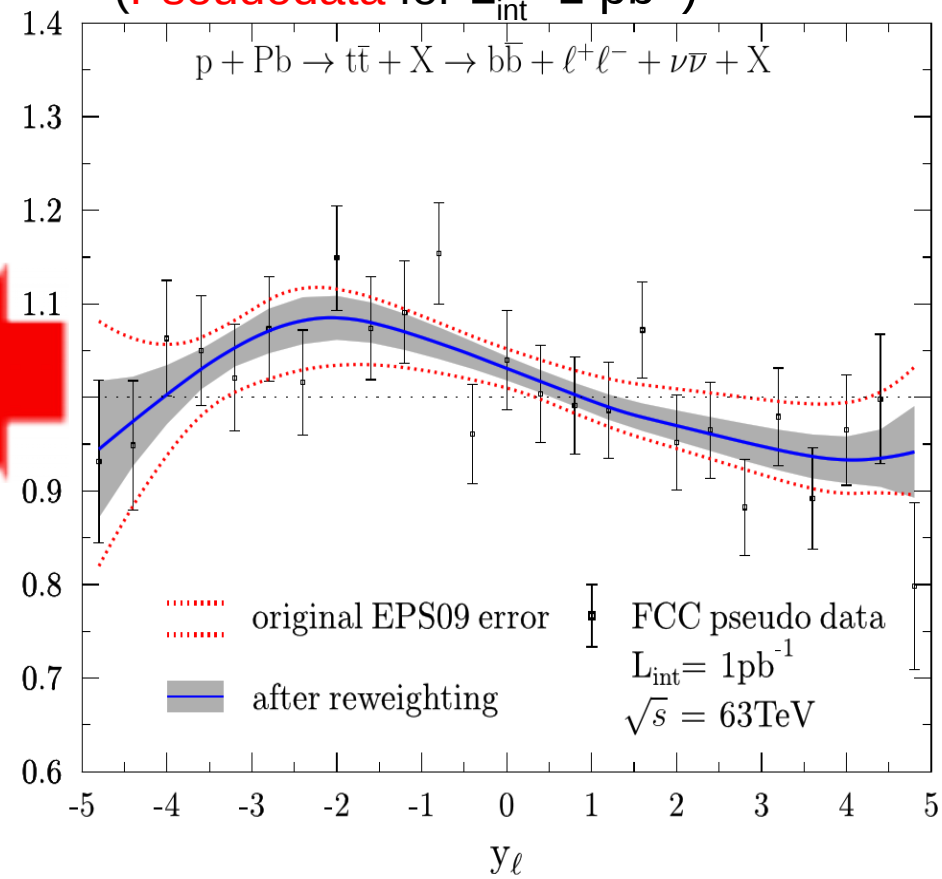


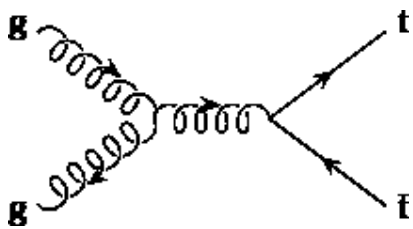
- Significant reduction in uncertainties at low-x ($x<10^{-2}$), antishadowing ($x\sim0.05$) and EMC ($x\sim0.5$) regions

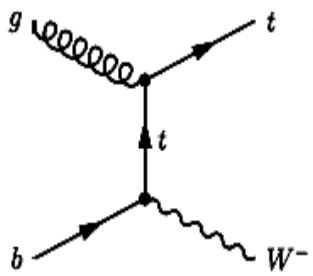
(stat. to dominate over syst. uncertainties)

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

Conclusion

- Top quark (pair & single?) production is clearly observable in nuclear collisions (p-Pb & Pb-Pb) at LHC/FCC.
- MCFM: NLO, CT10 PDF, EPS09 nPDF (30 error sets):

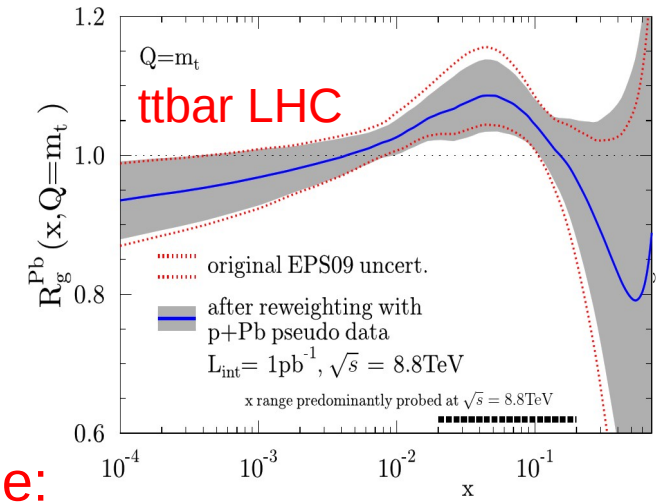


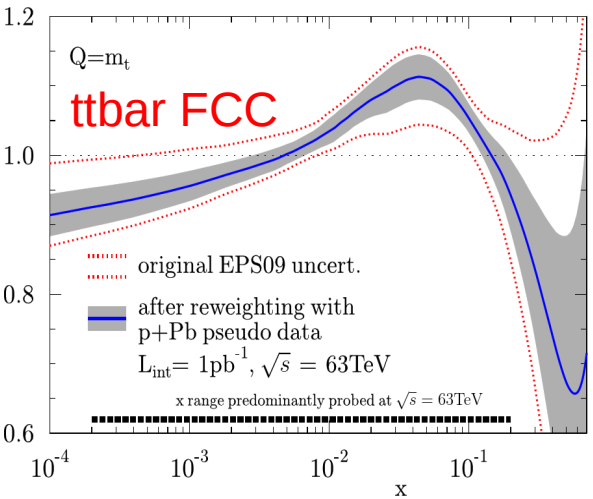


- Yields (semileptonic W decays) after std. cuts:

  LHC: 90-300 t-tbar pairs & few single-t (nominal L_{int})
  $O(10^3)$ top-pairs for enhanced lumis.

  FCC: 0.3–0.8 million t-tbar pairs & ~10^4 single-top



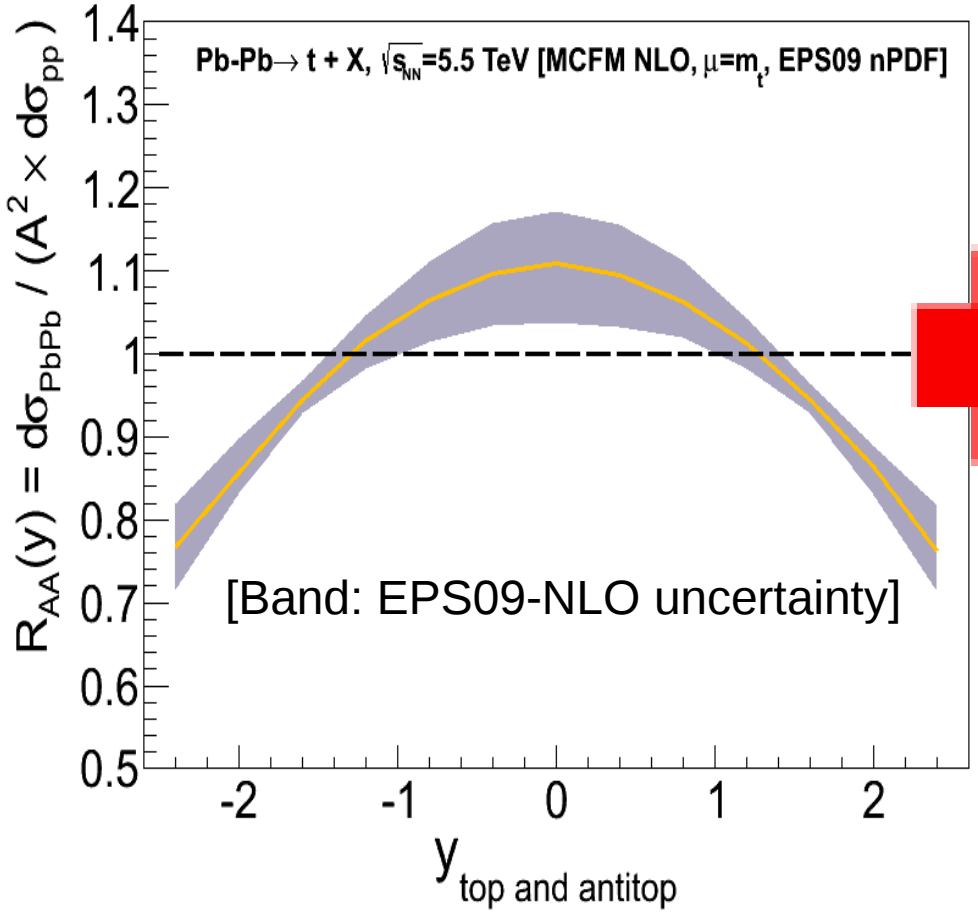


- Novel interesting physics accessible:
  - ➜ LHC: 1st obvs. of heaviest elementary particle in A-A. Mild PDF constraints
  - ➜ FCC: Strong nPDF constraints in unexplored range: $x \sim 10^{-3}$–0.3, $Q \sim m_t$
  - ➜ FCC: QGP effects: Color reconnect., g-radiation, color-singlet evolution...

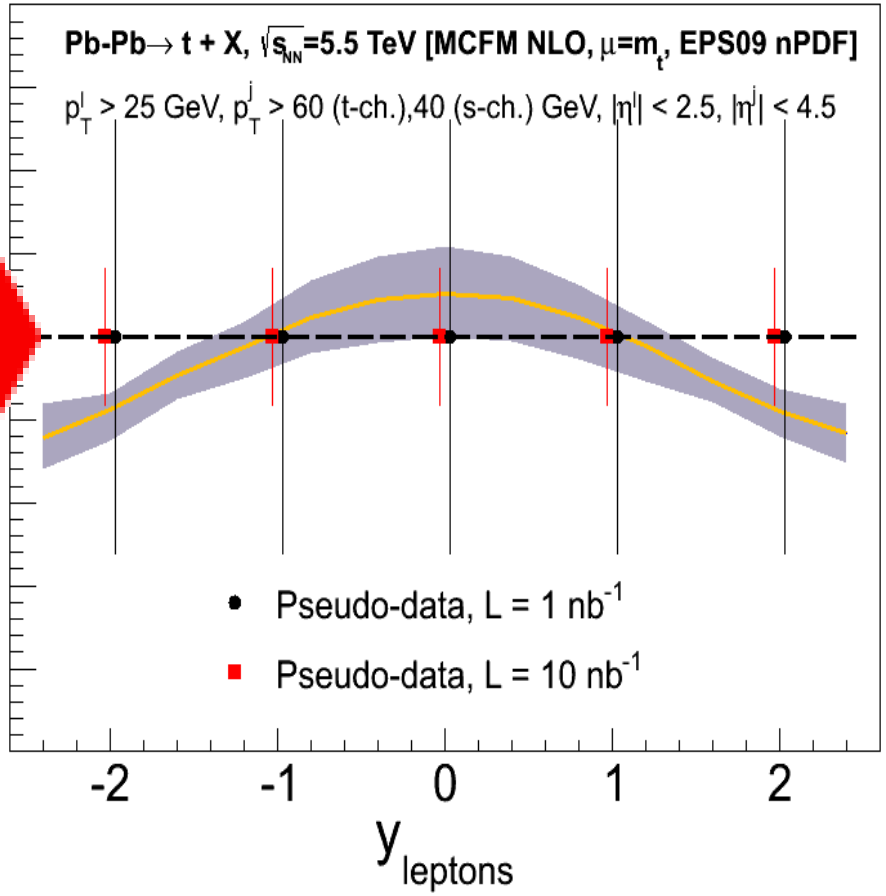
Back-up slides

PbPb→single-t+X (5.5 TeV):Nuclear modif. factor

- Top quark y-distrib. (no cuts):



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



- nPDF effects (top): ±20 (cent./fwd)

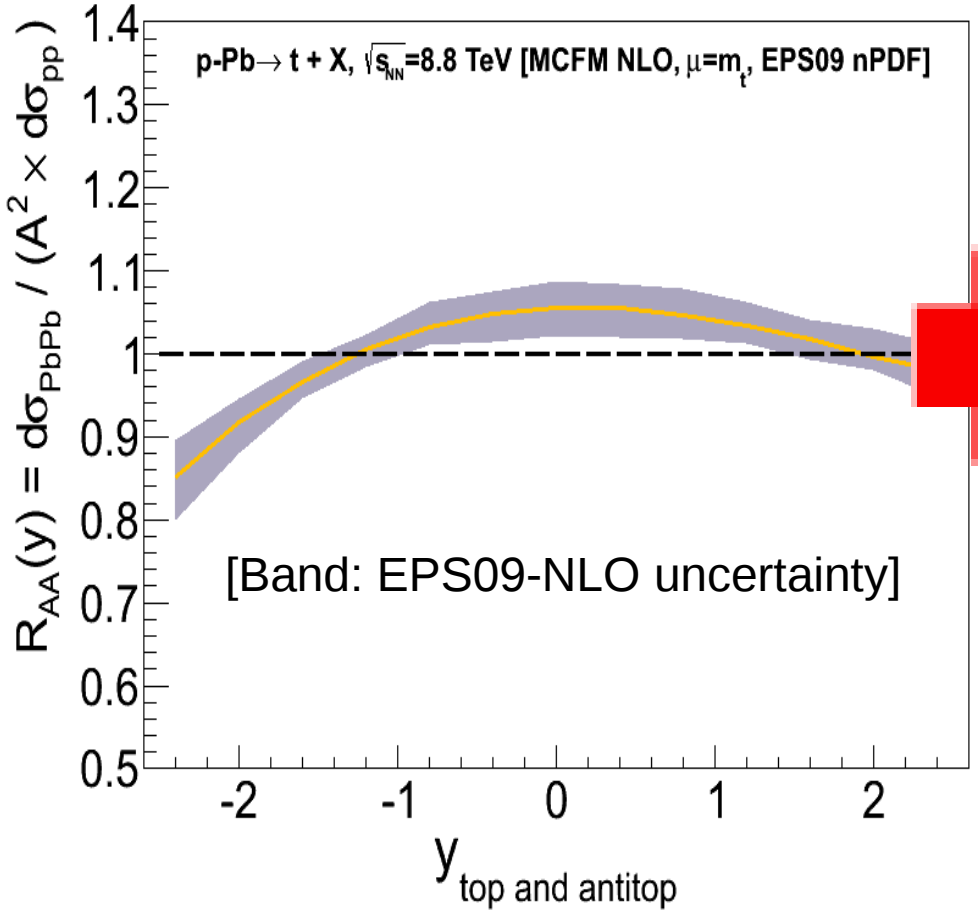
  Smaller nPDF uncertainties than t-tbar

- nPDF effects (lepton): ±10%

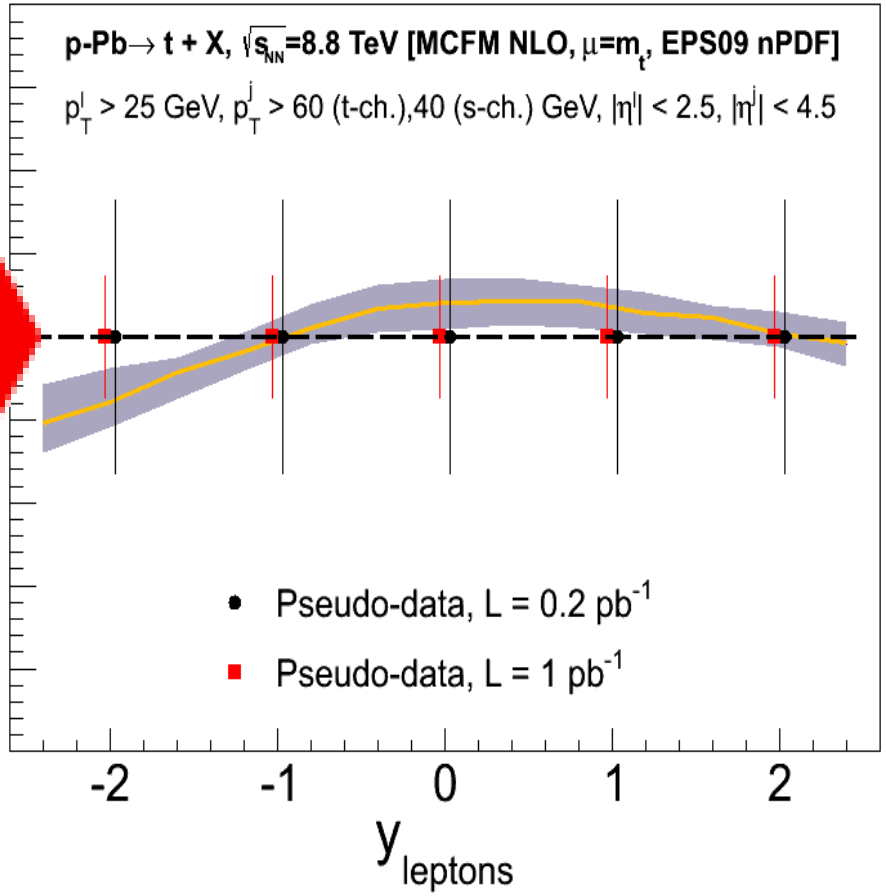
  L_{int}=10 nb^{-1}: some constraining power (iff large background controlled)

pPb→single-t+X (8.8 TeV): Nuclear modif. factor

- Top quark y-distrib. (no cuts):



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

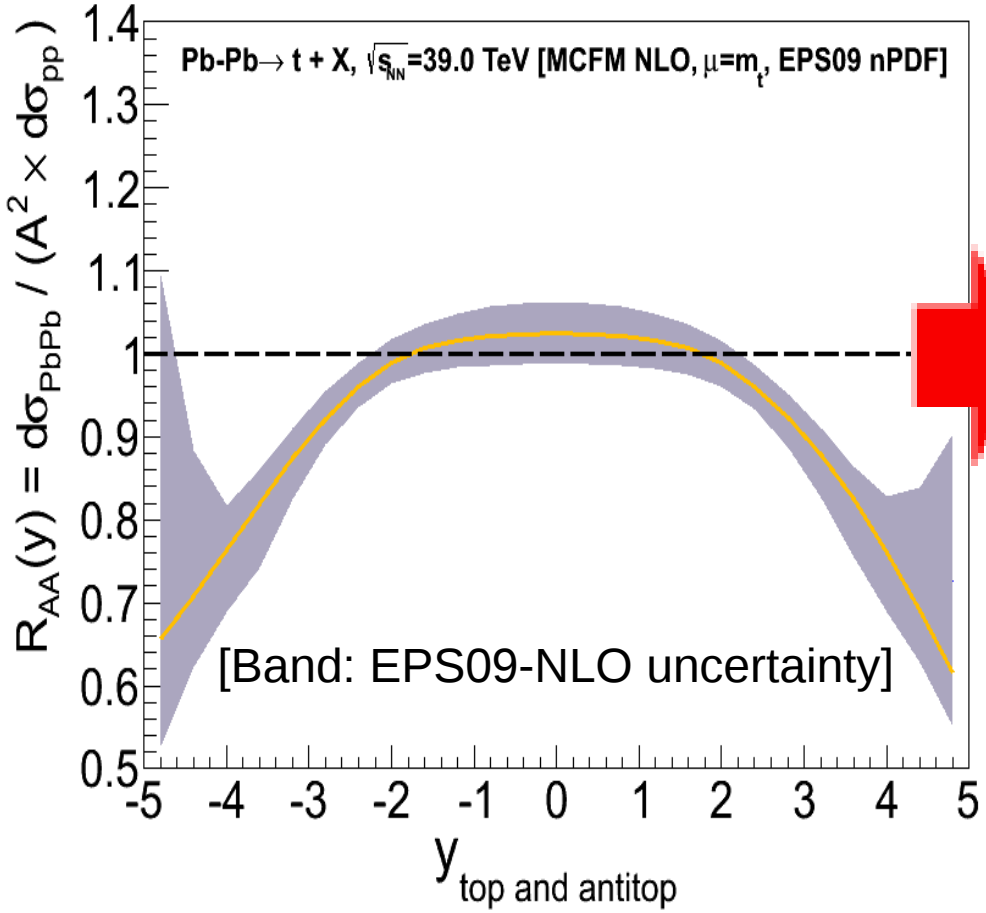


- nPDF effects (top): ±10 (cent./fwd.)
  Smaller nPDF uncertainties than t-tbar

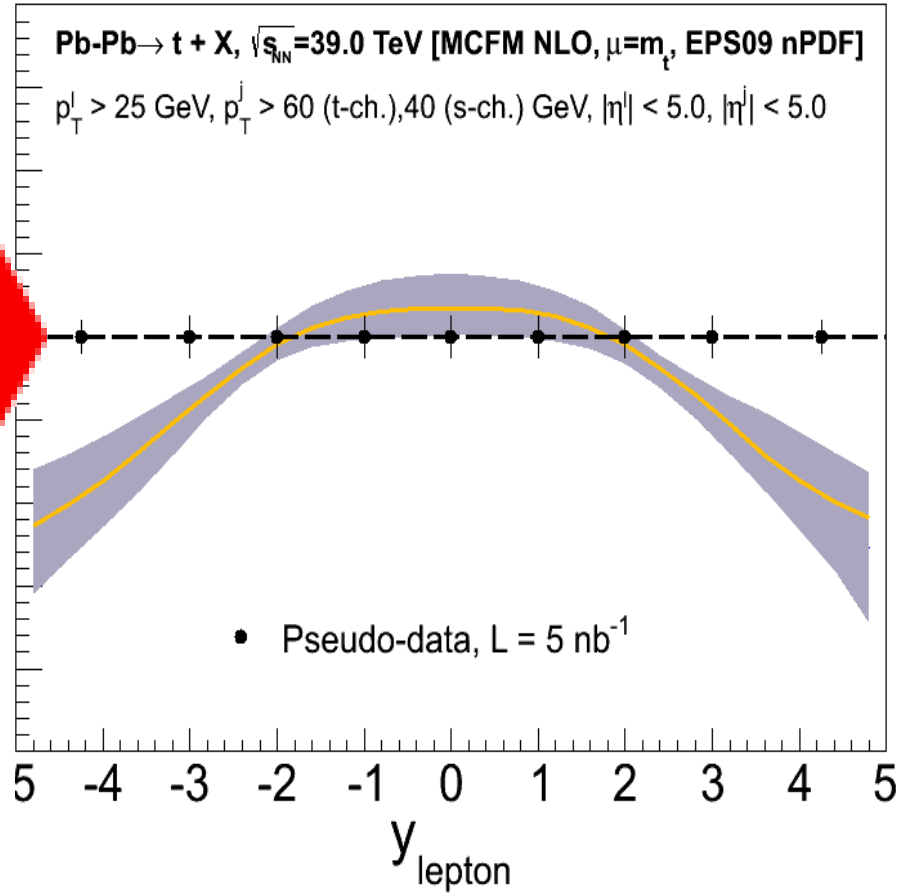
- nPDF effects (lepton): ±10%
  L_{int}=1 pb^{-1}: some constraining power (iff large background controlled)

PbPb→single-t+X (39 TeV):Nuclear modif. factor

- Top quark y-distrib. (no cuts):



- Isolated lepton y-distrib. after cuts:
(Pseudodata for L_{int}=5 nb^{-1})

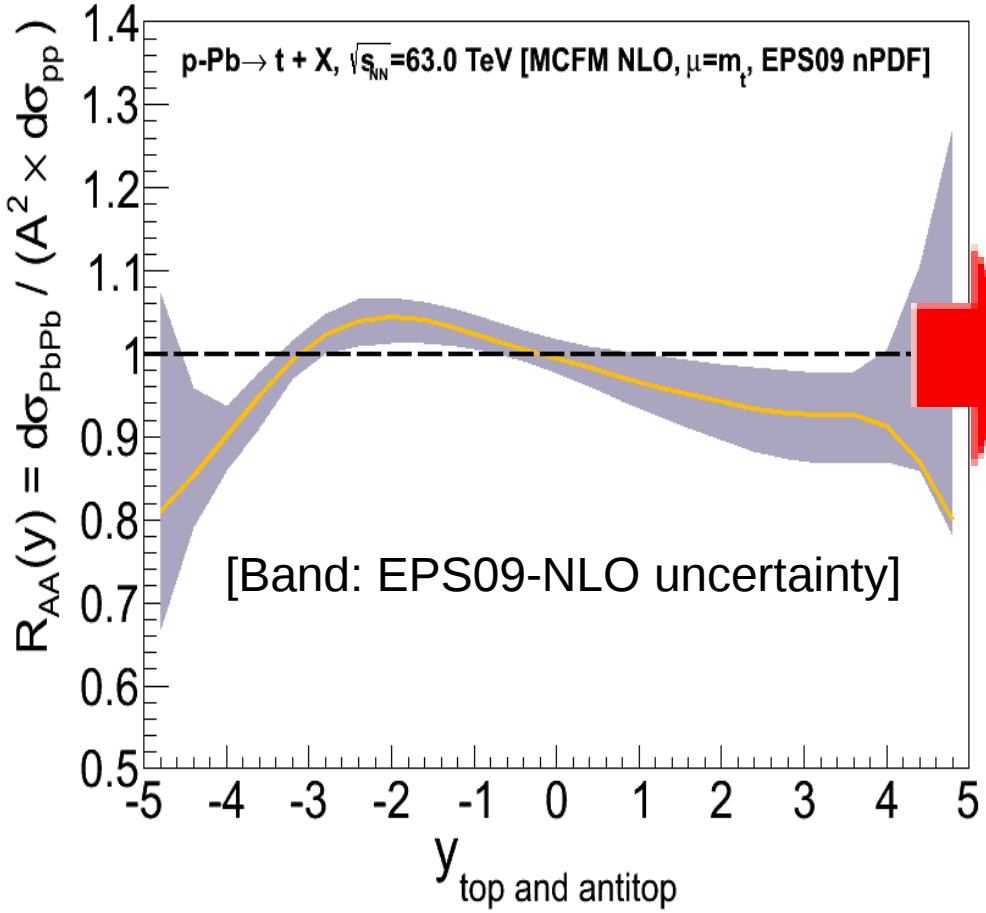


- nPDF effects (top):-30% (fwd/bckwd)
Smaller nPDF uncertainties than t-tbar

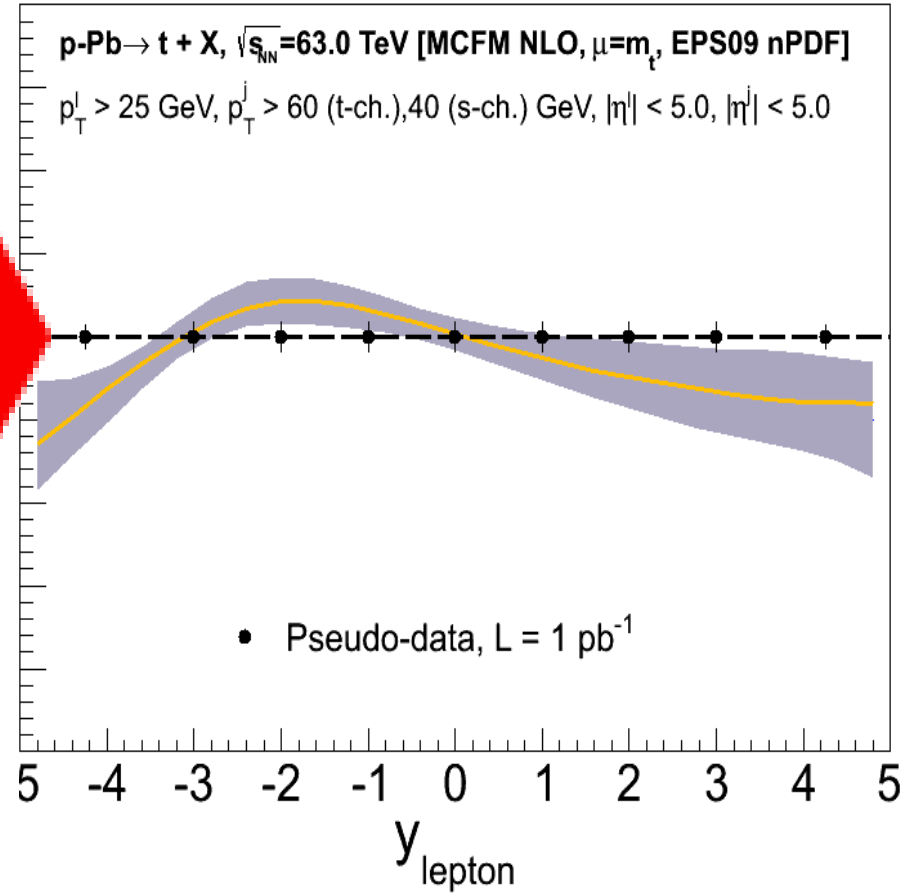
- nPDF effects (lepton):-20% (fwd/bckwd)
Strong constraining power
(iff large background controlled)

pPb→single-t+X (63 TeV): Nuclear modif. factor

- Top quark y-distrib. (no cuts):



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



- nPDF effects: -20% (bckwd)
-10% (forward)
Smaller nPDF uncertainties than t-tbar

- nPDF effects (lepton): ±10% (fwd/bckwd)
Strong constraining power
(iff large background controlled)