Top-pair & single-top production in nuclear collisions at the LHC & FCC

Workshop on ions at the FCC
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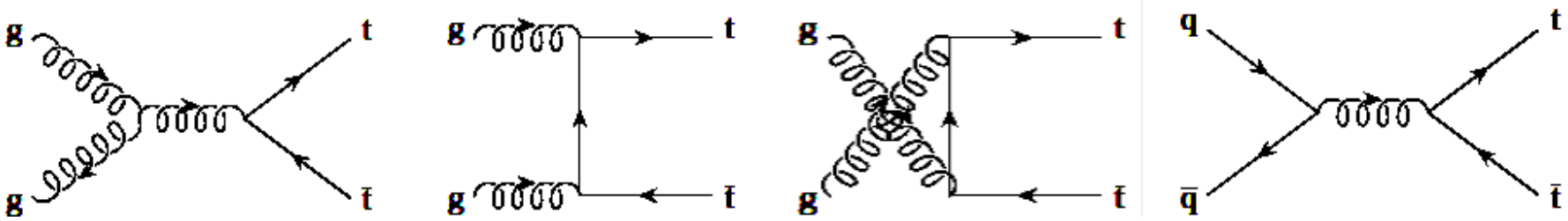
CERN

Top-quark production in hadronic collisions

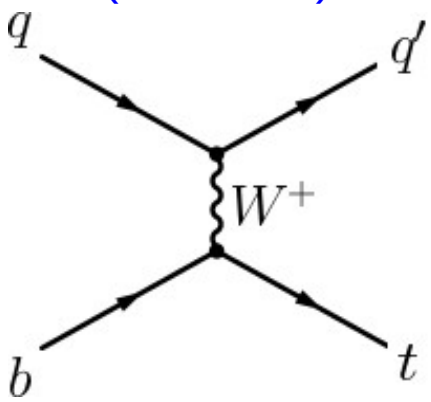
- Top-pair production: QCD interaction dominated by gluon-induced processes (+80%,+90% at LHC,FCC energies at NLO):

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

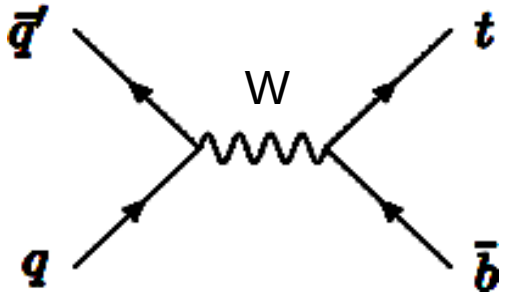


- Single-top production: Electroweak process sensitive to b-quark (from g→b$\bar{b}$) PDF:

(t-channel)



(s-channel)



(contributes a few % of the total)

Top-quark in nuclear collisions

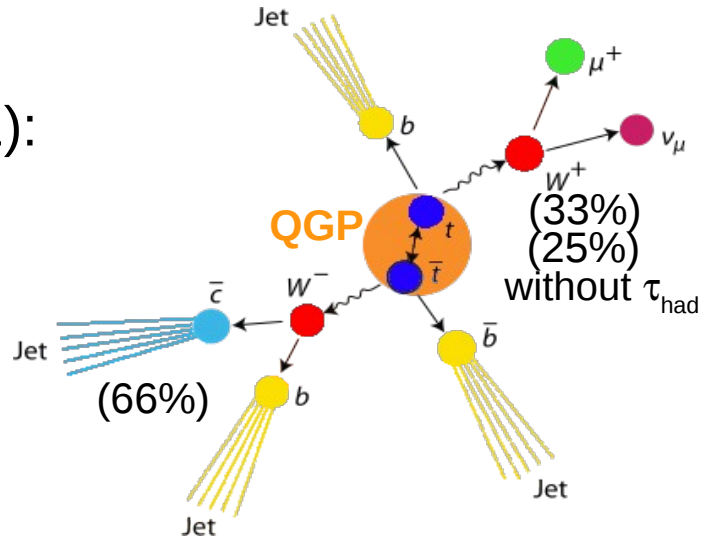
- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b (BR~100%,V_{tb}~1):

  ttbar → bbar + 4jets (44%)

  ttbar → bbar + 2jets + 1ℓ + MET(ν) (44%)

  ttbar → bbar + 2ℓ + MET(2ν) (11%,6%)

  single t → b + 1ℓ + MET(ν) (33%,25%)



- Motivations for measurement:

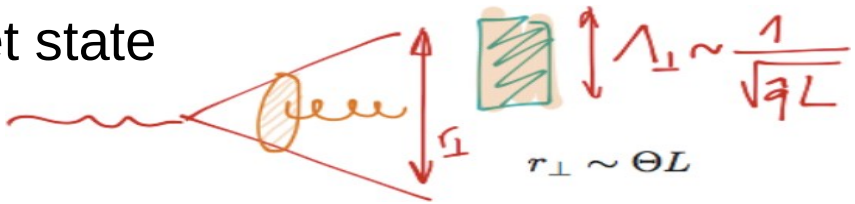
→ One of the few elementary particles (with τ,H) experimentally unobserved so far in A-A collisions.

→ Probes gluon nPDF in unexplored range: $x \sim m_t/\sqrt{s} \sim 10^{-2}$, $Q \sim m_t \sim 173$ GeV

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

→ Boosted single-top (e.g. 1 TeV): τ~1 fm/c (g radiation in QGP)

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



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):

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

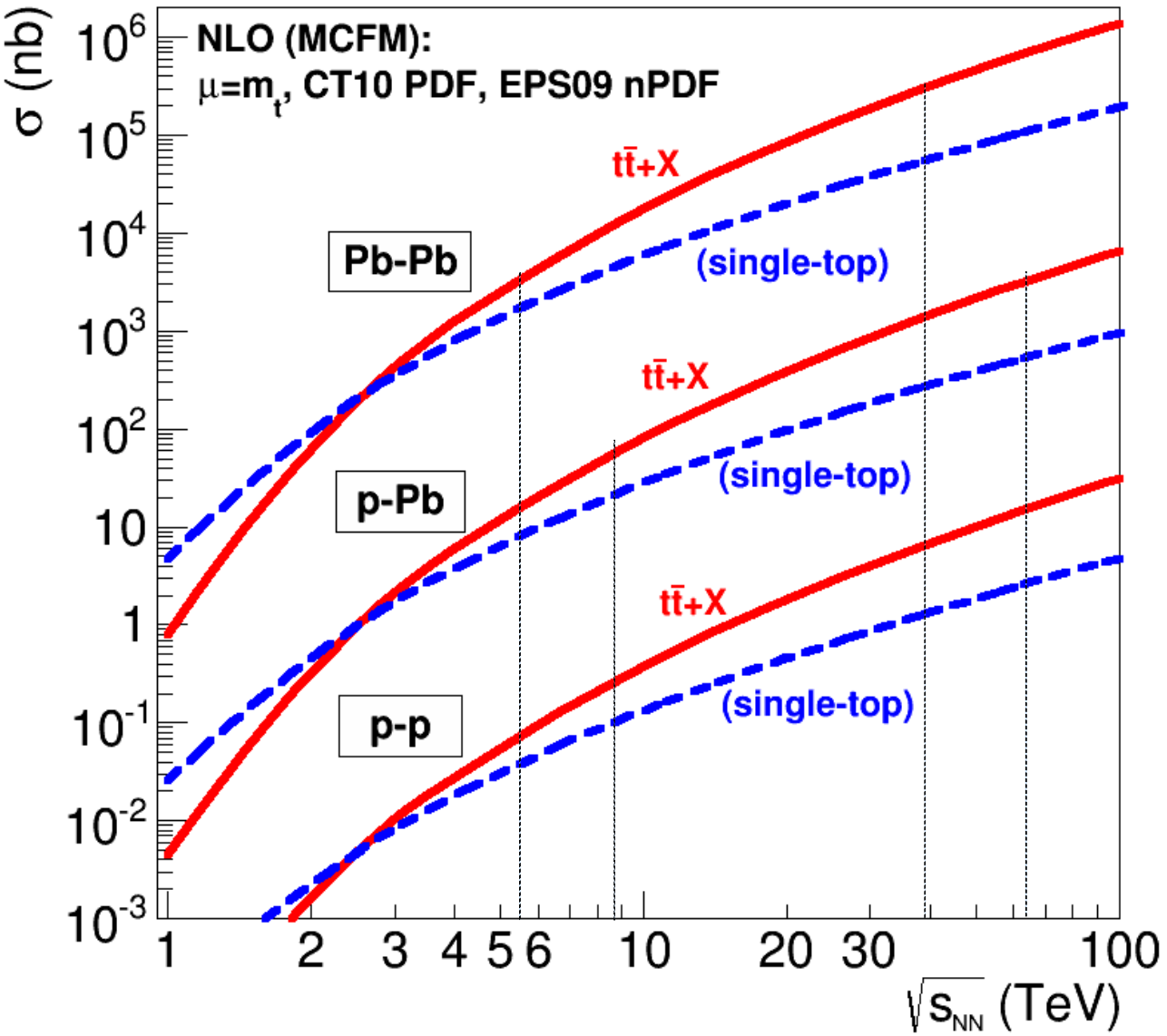
  Single-top: nproc = 161,171; 166,776 (total & semileptonic decay):

  $$\begin{array}{l|l|l} 161 & t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)[\text{t-channel}] & \text{NLO} \\ 166 & \bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)[\text{t-channel}] & \text{NLO} \\ \hline 171 & t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + b(p_6))[\text{s-channel}] & \text{NLO} \\ 176 & \bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6))[\text{s-channel}] & \text{NLO} \end{array}$$

- Additional higher-order corrections (not included):

  K-factor=NNLO/NLO ~10% for ttbar & single-t

t-tbar 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) ~ 58 nb
FCC(63 TeV) ~ 3.2 μb

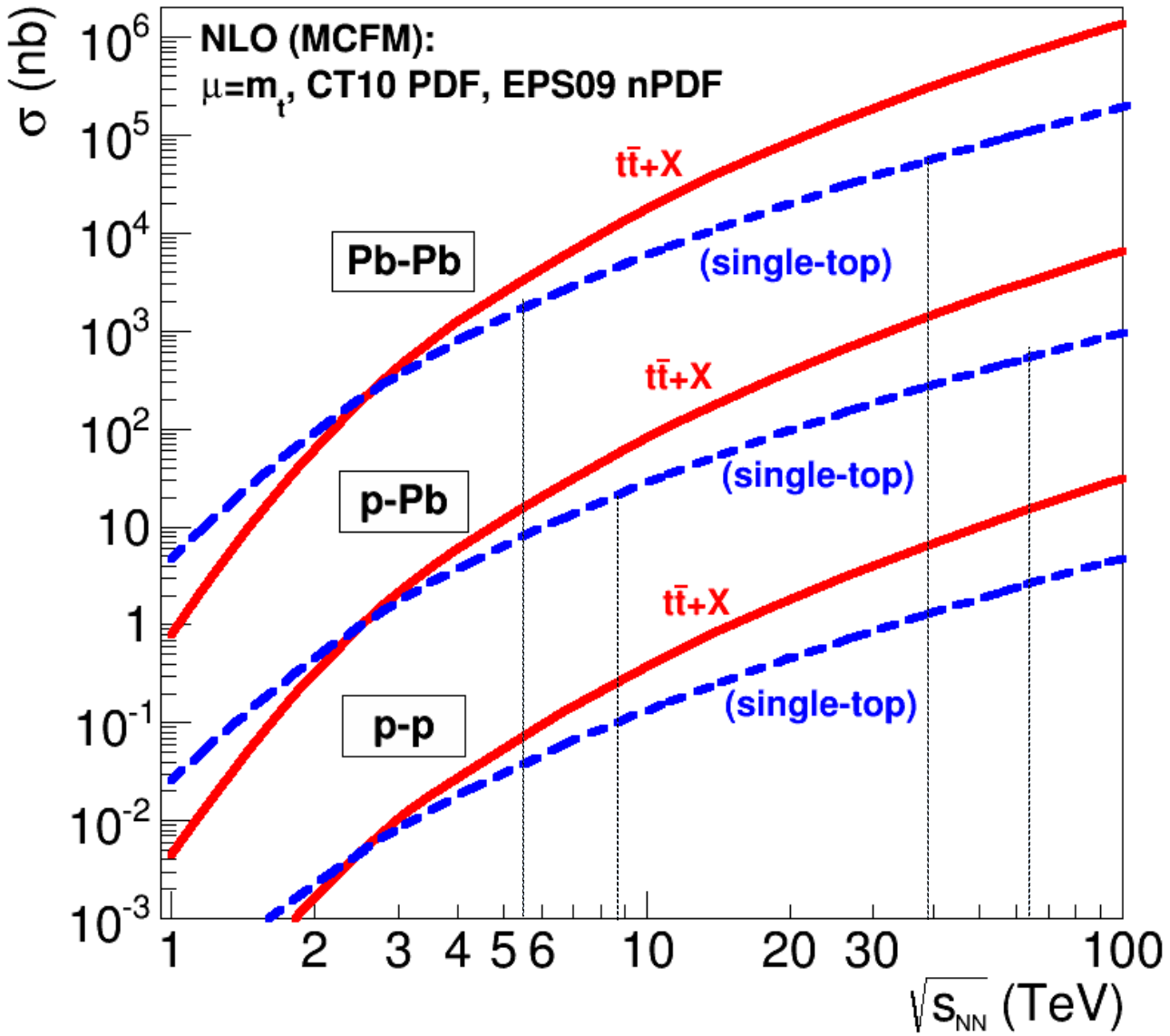
- p-p (reference):

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 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

Experimental top-quark 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: p_T(lepton) > 25 GeV; R_{isol}(b-jet,lepton) = 0.4
  p_T(b-jet) > 60 GeV (t-channel), 40 GeV(s-channel)
  $|\eta$(lepton)$|$ < 2.5 (LHC), 5.0 (FCC)
  $|\eta$(b-jet)$|$ < 4.5 (LHC), 5.0 (FCC)
- Acceptance & efficiency losses:

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

  Single-top: Acc×Eff ~ 21% (LHC), 30% (FCC)
- Backgrounds: Not discussed. Controllable for t-tbar; huge? for single-t

Expected t-tbar & single-top yields

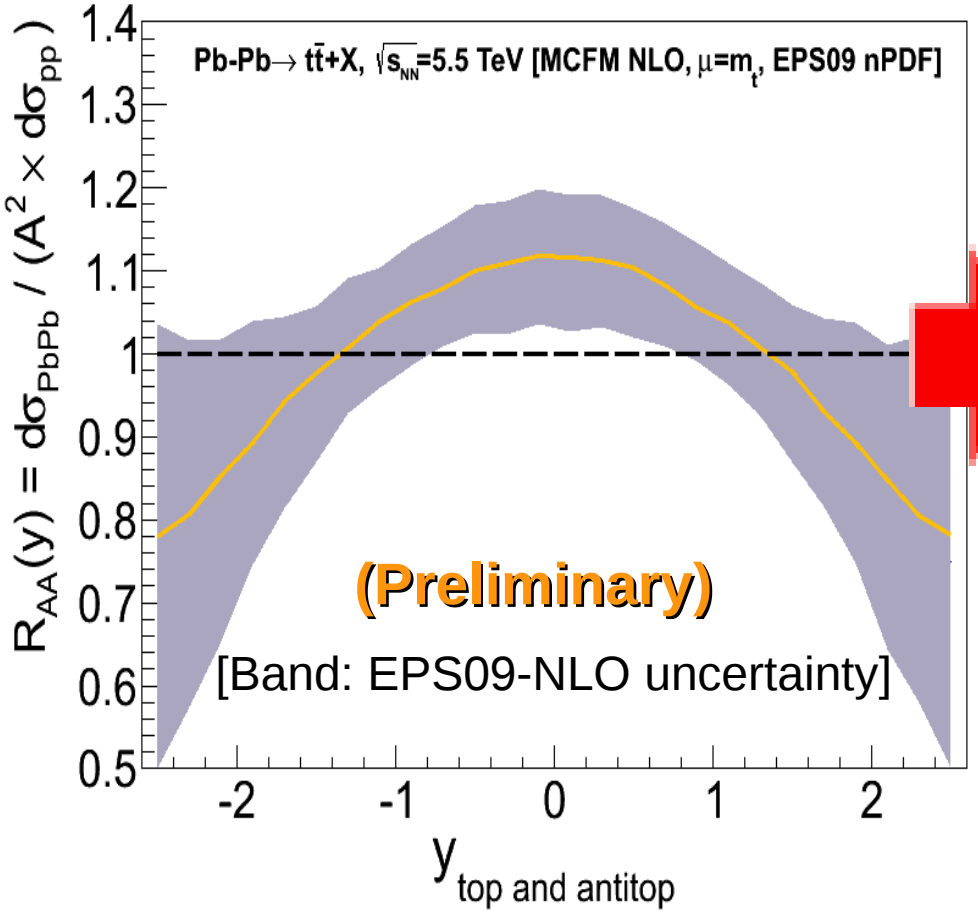
- Final-state: ttbar → bbar + 2ℓ (e,μ) + MET(2ν)
- Final-state: single t → b + 1ℓ (e,μ) + MET(ν)

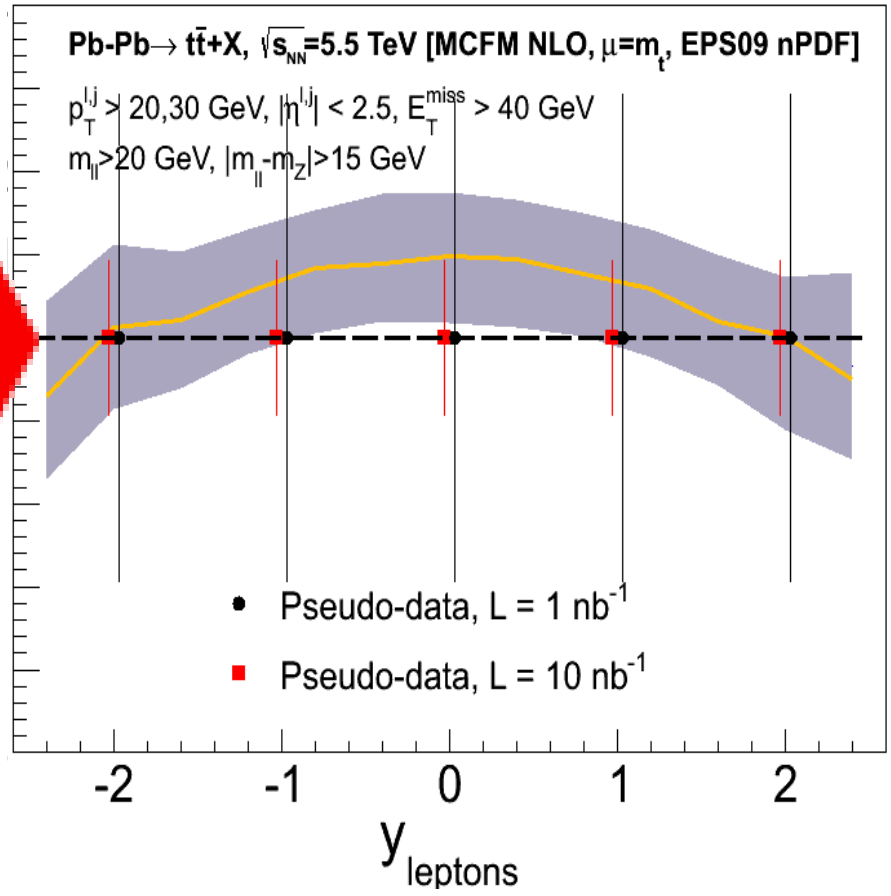
System	$\sqrt{s_{NN}}$	L_{int}	N(t-tbar)	N(single-t)
Pb-Pb	5.5 TeV	1 nb^{-1}	**57**	**73**
		10 nb^{-1}	**566**	**730**
p-Pb	8.8 TeV	0.2 pb^{-1}	**196**	**185**
		1 pb^{-1}	**979**	**930**
Pb-Pb	39 TeV	5 nb^{-1}	**31.500**	**16.900**
p-Pb	63 TeV	1 pb^{-1}	**66.650**	**31.900**

- LHC (nominal L_{int}): 50-200 t-tbar pairs & single-t in Pb-Pb, p-Pb
  O(10^3) tops for enhanced lumis.
- FCC: (15-60)×10^3 t-tbar pairs & single-t in Pb-Pb, p-Pb

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

- Top quarks y-distrib. (no cuts):
- Isolated lepton y-distrib. after cuts:

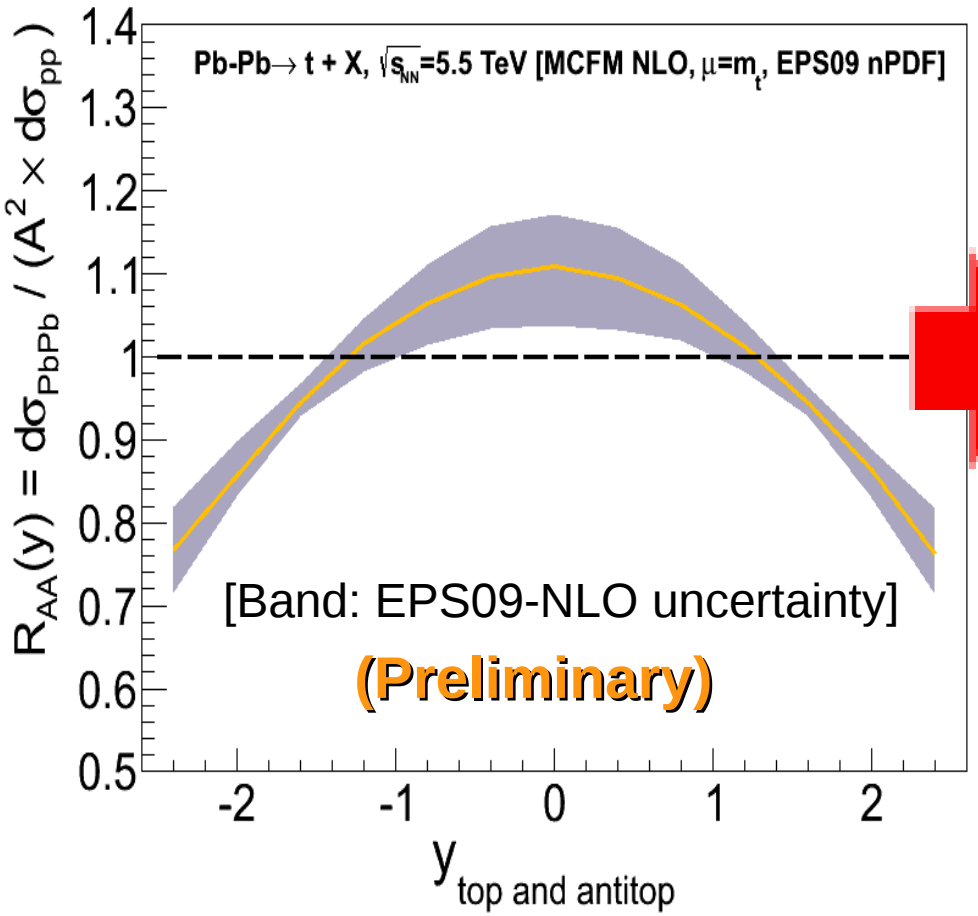




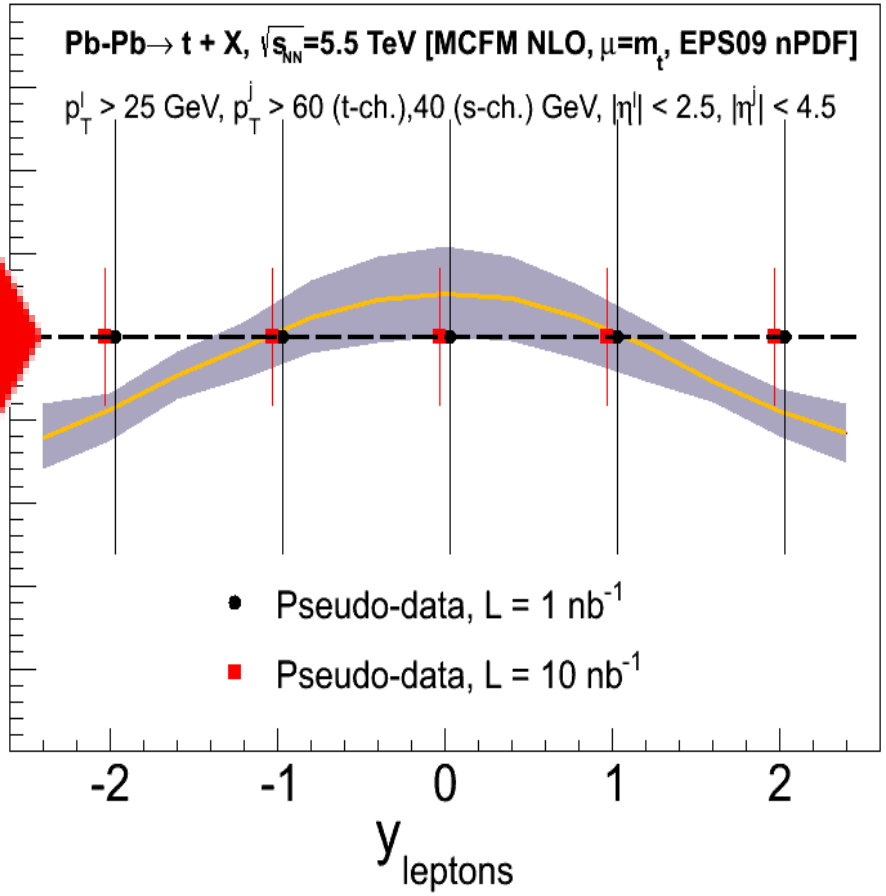
- nPDF effects (top): ±20% (central/fwd. rapidities)
- nPDF effects (lepton): ±10%
  L_{int}=10 nb^{-1}: some constraining power

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

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



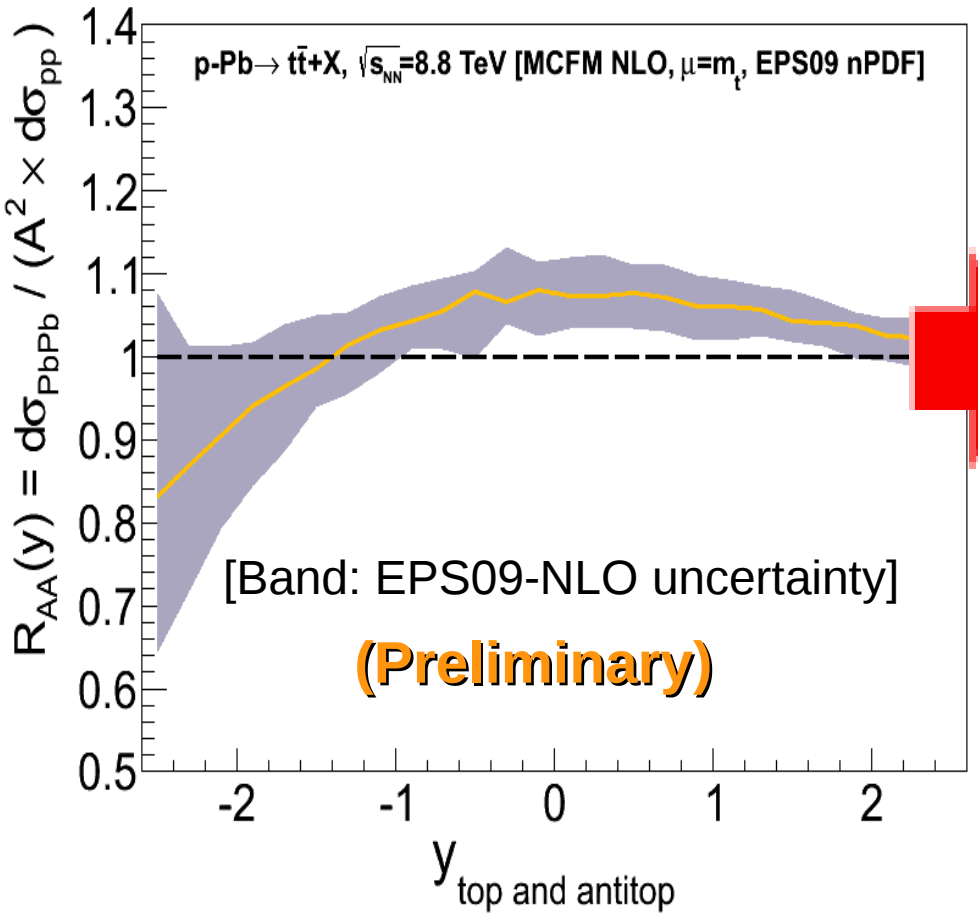
- Isolated lepton y-distrib. after cuts:

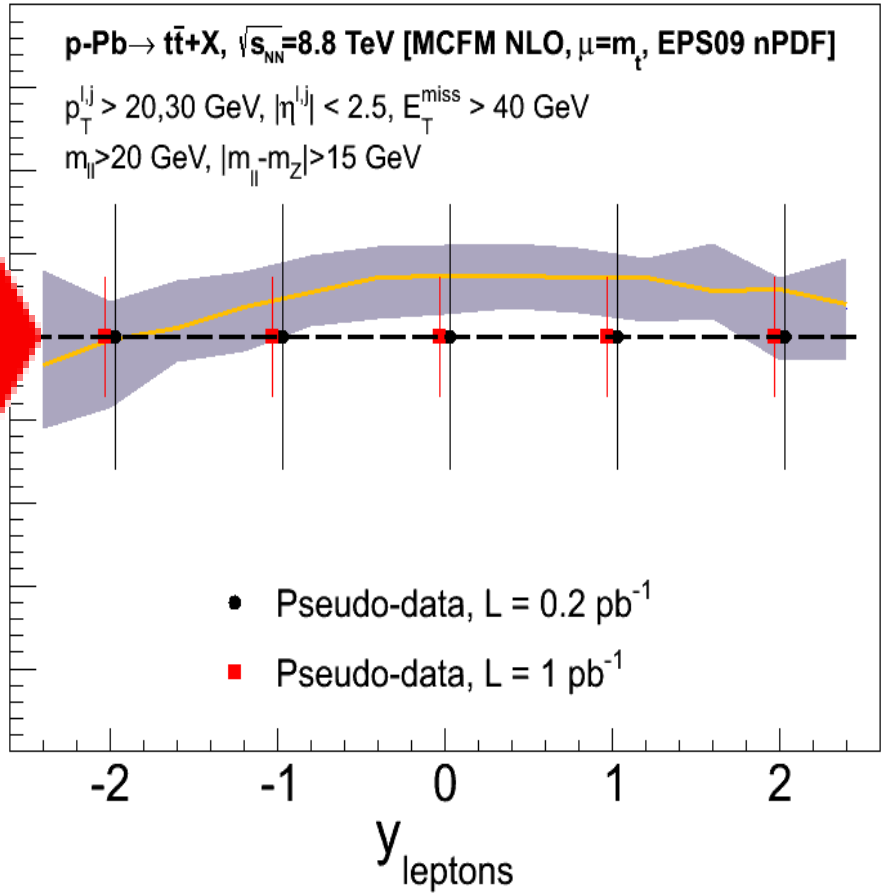


- nPDF effects (top): ±20 (cent./fwd)
  Smaller nPDF uncertainties than t-tbar
- nPDF effects (lepton): ±10%
  L_{int}=10 nb^{-1}: some constraining power (iff large background controlled)

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

- Top quarks y-distrib. (no cuts):
- Isolated lepton y-distrib. after cuts:

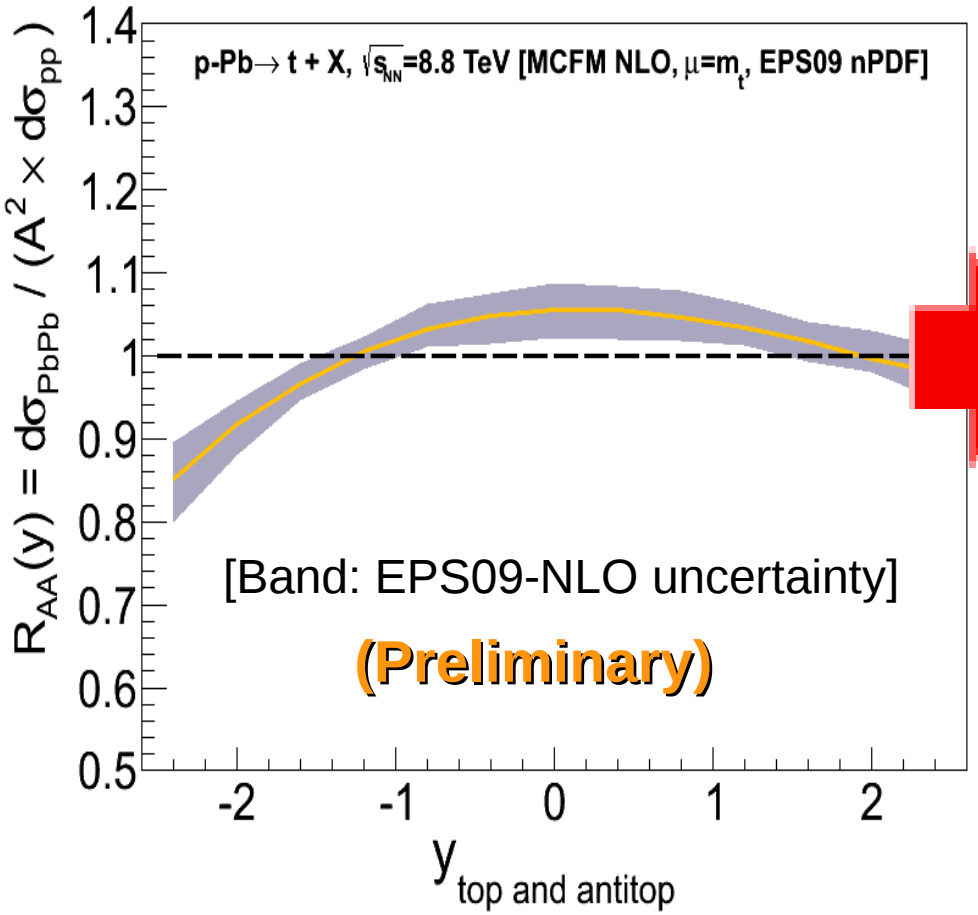




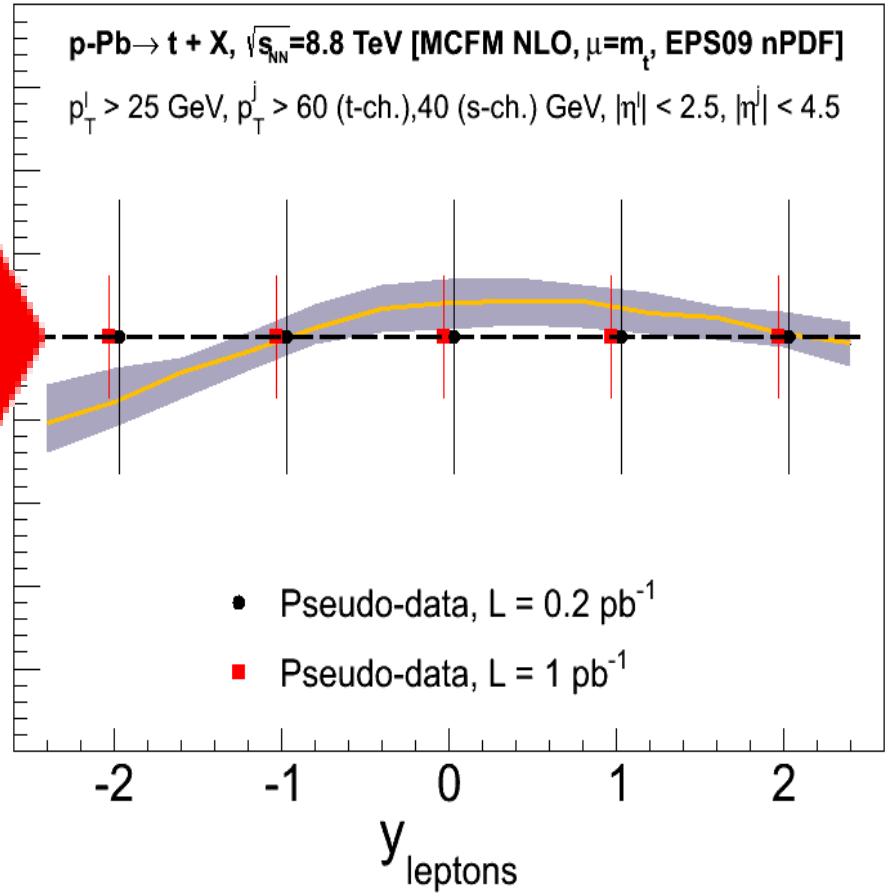
- nPDF effects (top): ±10% (central/fwd. rapidities)
- nPDF effects (lepton): ±10%
  L_{int}=1 pb^{-1}: some constraining power

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

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



- Isolated lepton y-distrib. after cuts:

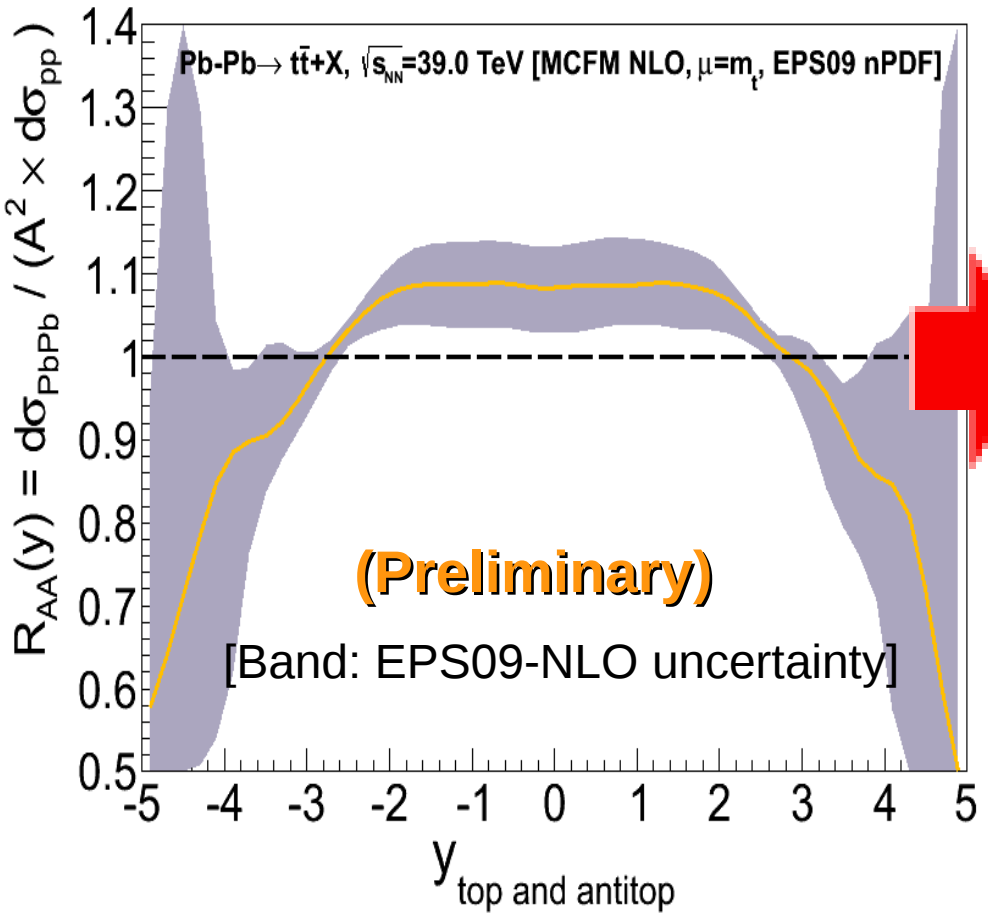


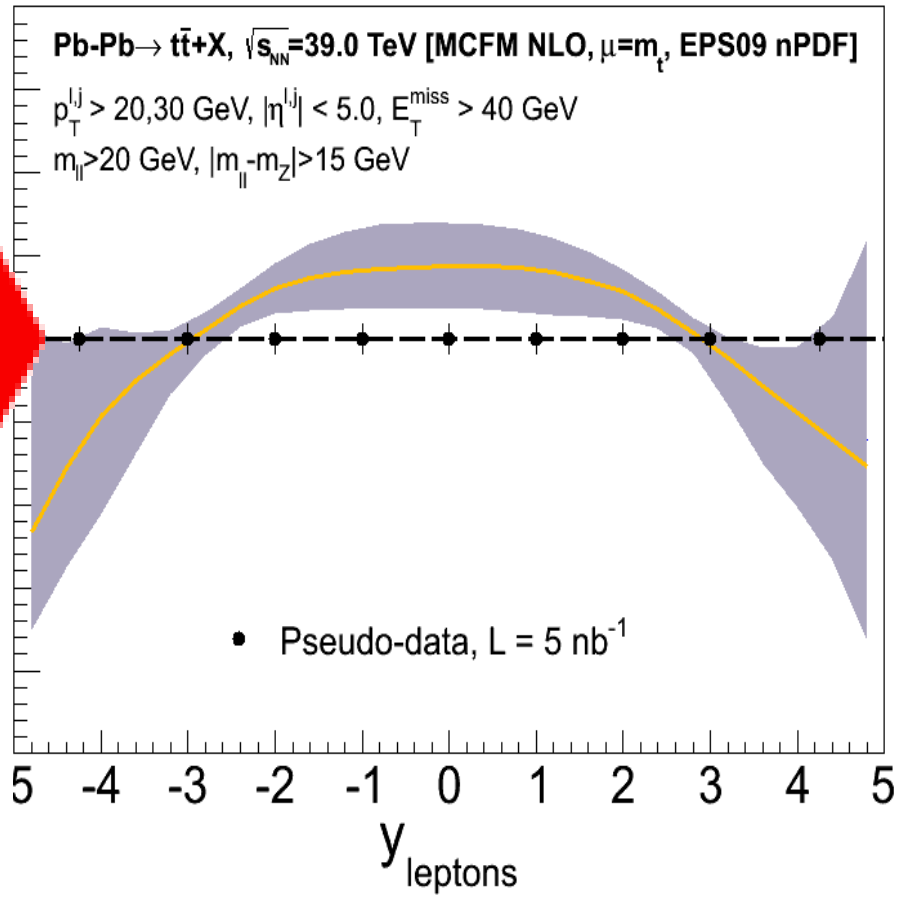
- nPDF effects (top): ±10 (cent./fwd.)
  Smaller nPDF uncertainties than t-tbar

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

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

- Top quarks y-distrib. (no cuts):
- Isolated lepton y-distrib. after cuts:

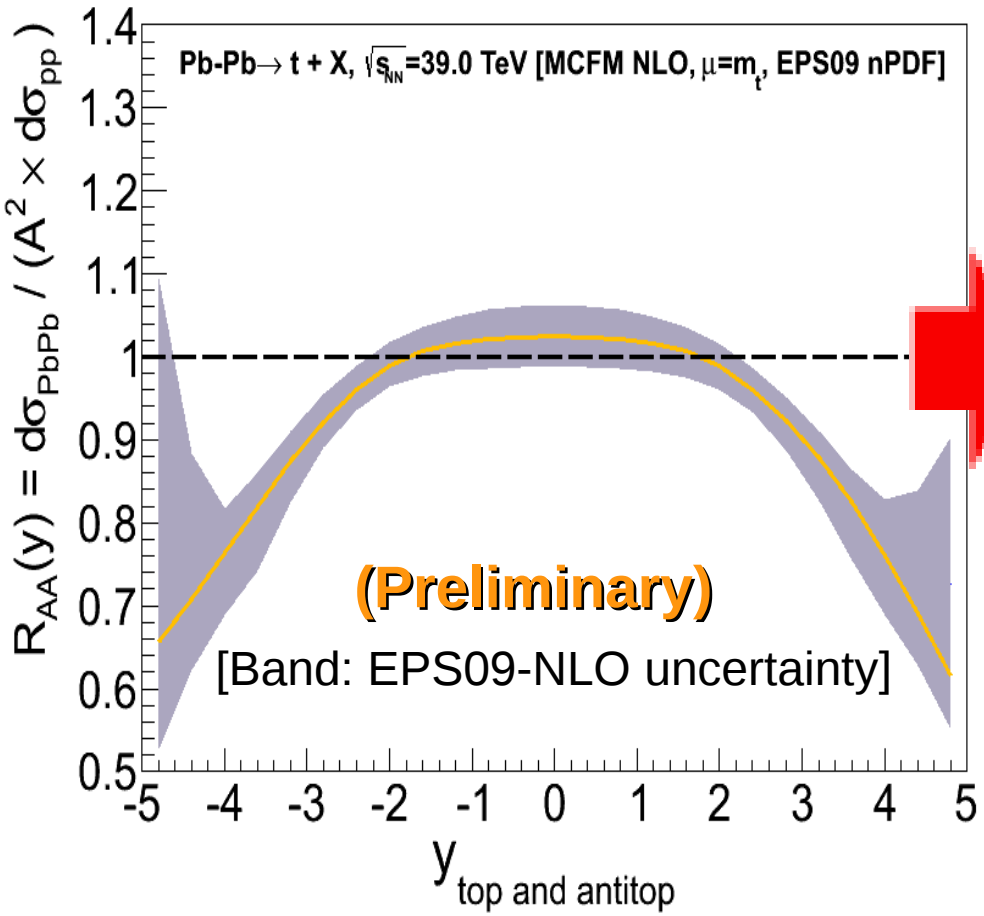


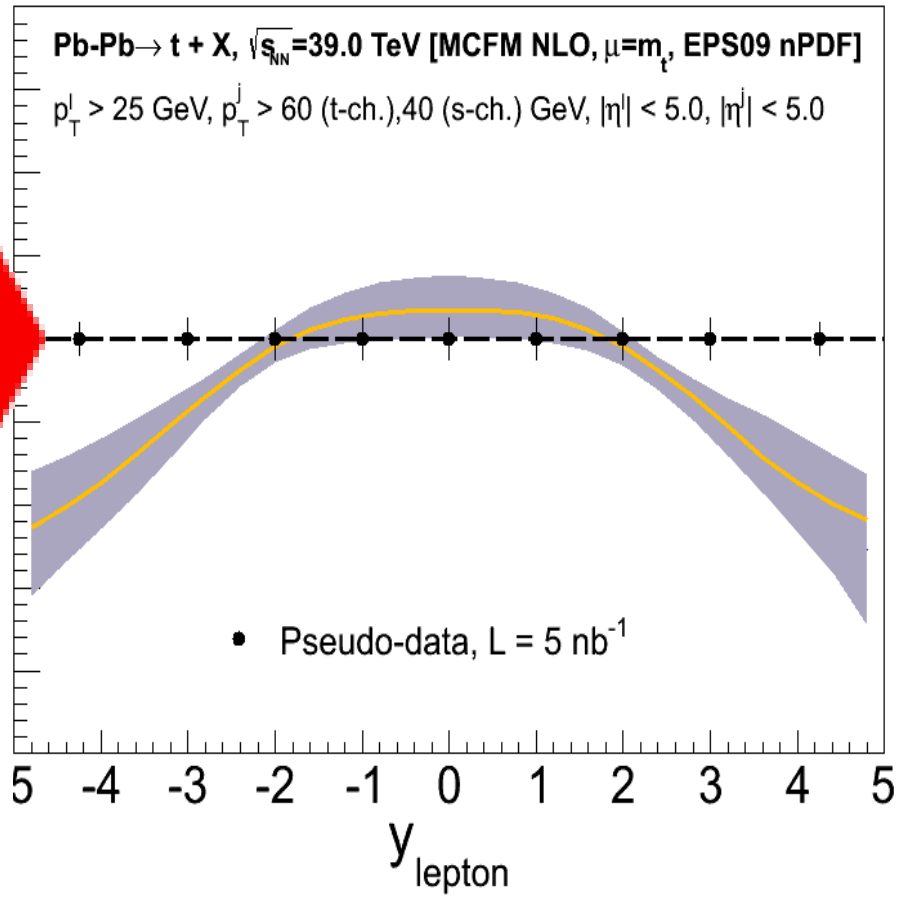


- nPDF effects (top): -20% (fwd/backwd.) +10% (central)
- nPDF effects (lepton): ±(10-20)% Strong constraining power

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

- Top quark y-distrib. (no cuts):
- Isolated lepton y-distrib. after cuts:

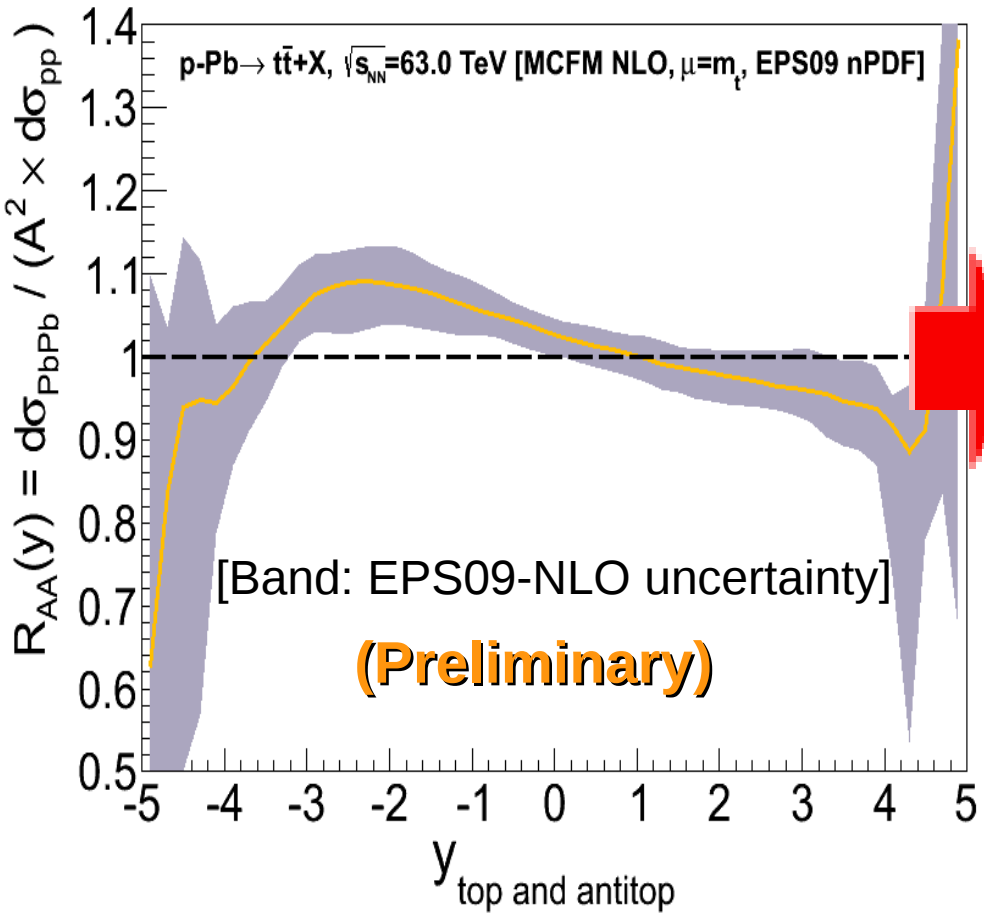


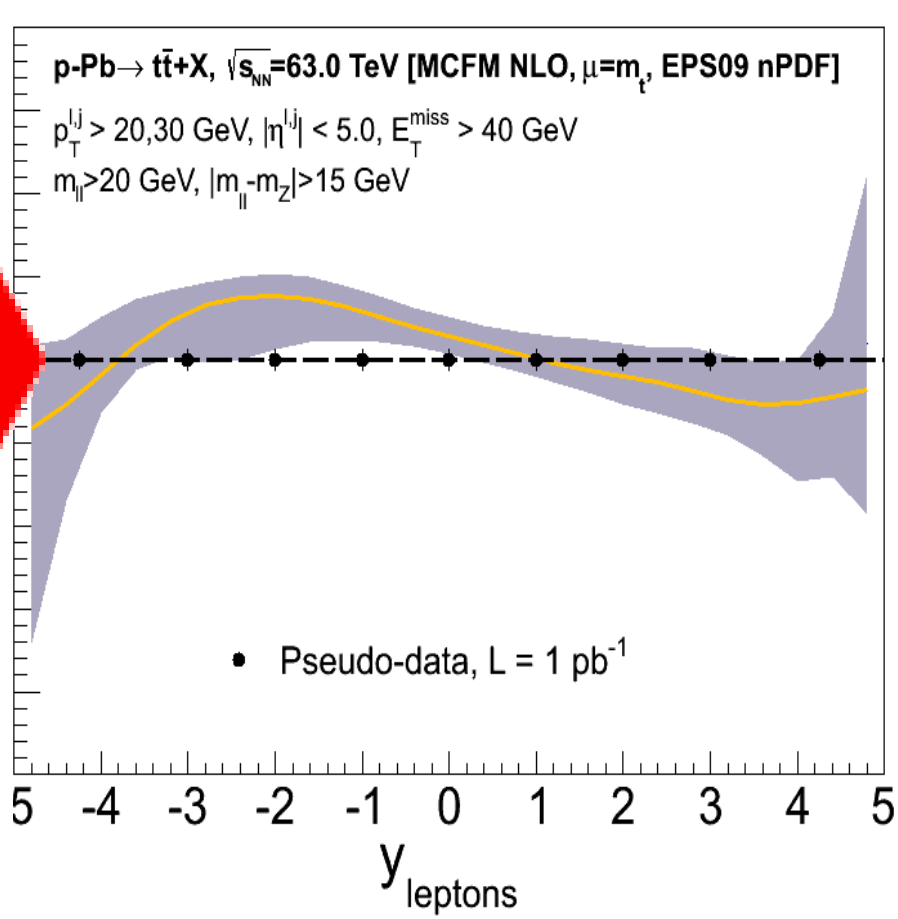


- nPDF effects (top):-30% (fwd/bckwd)
  Smaller nPDF uncertainties than t-tbar
- nPDF effects (lepton):-20% (fwd/bckwd)
  Strong constraining power
  (iff large background controlled)

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

- Top quarks y-distrib. (no cuts):
- Isolated lepton y-distrib. after cuts:

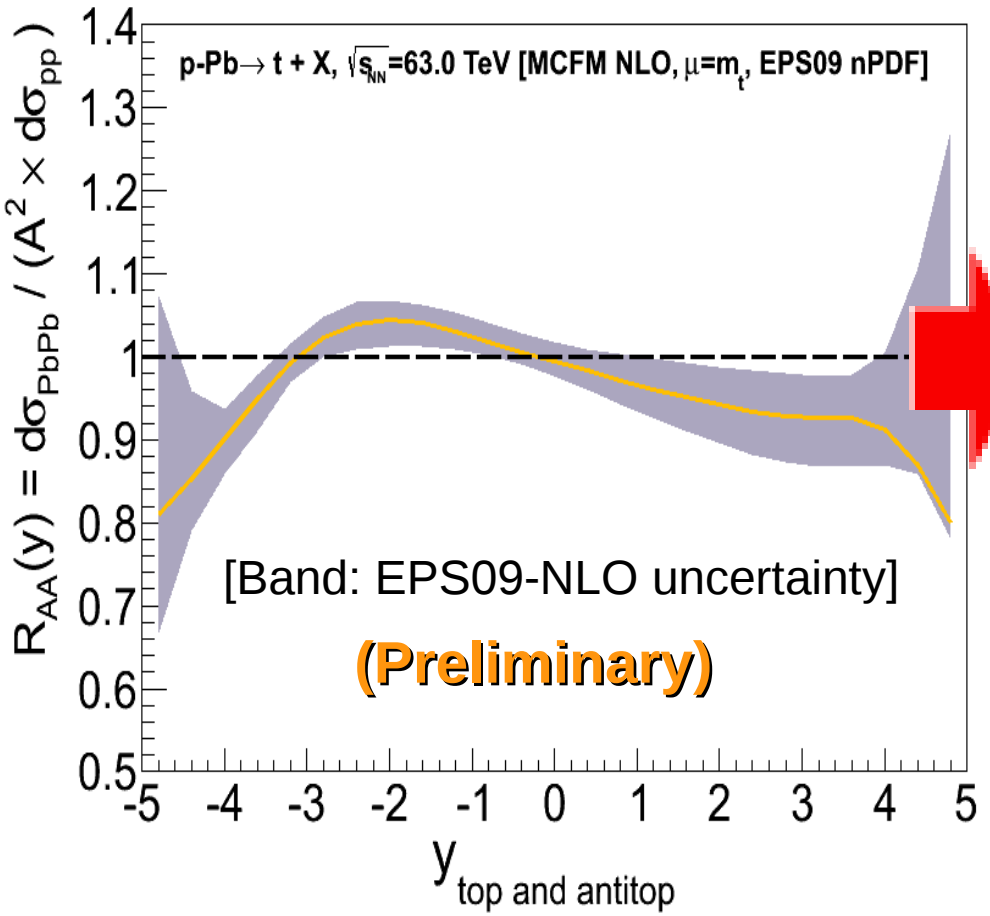


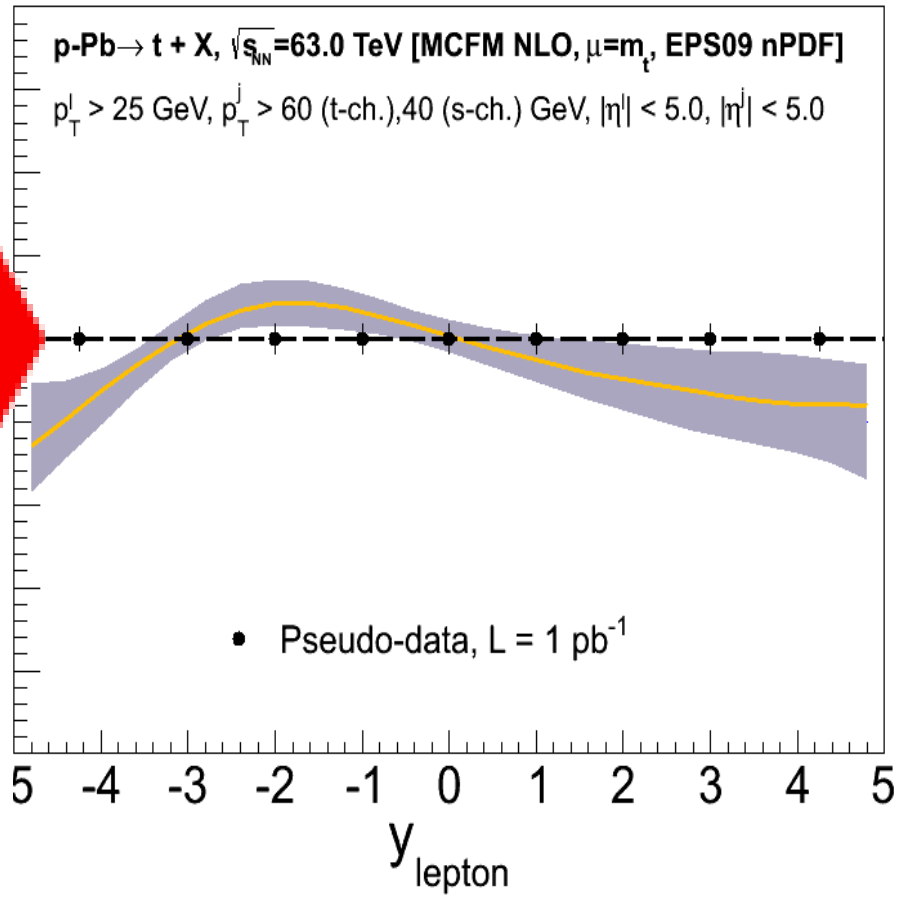


- nPDF effects (top): -30% (bckwd)
  ±10% (fwd/cent)
- nPDF effects (lepton): ±10%
  Strong constraining power

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

- Top quark y-distrib. (no cuts):
- Isolated lepton y-distrib. after cuts:

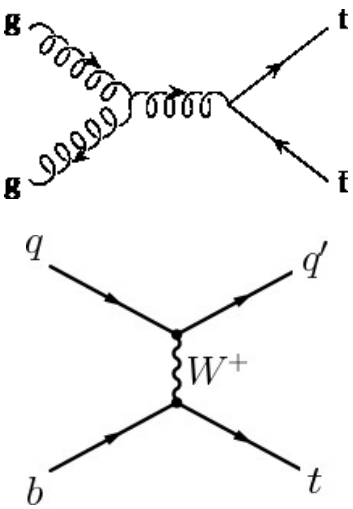




- nPDF effects: -20% (bckwd)
  -10% (forward)
  Smaller nPDF uncertainties than t-tbar
- nPDF effects (lepton): ±10% (fwd/bckwd)
  Strong constraining power
  (iff large background controlled)

Conclusion

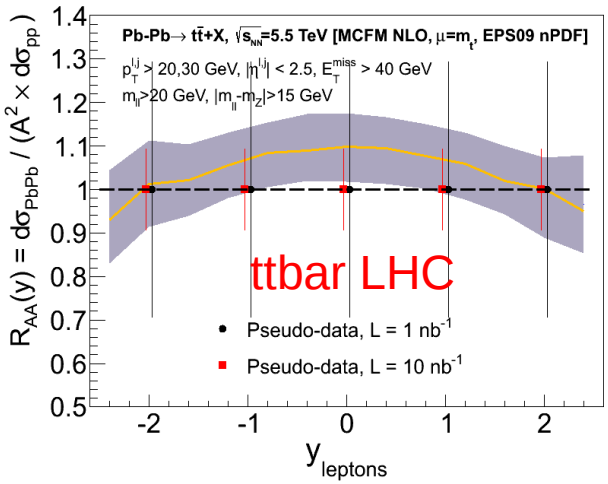
- Top quark (pair & single?) production is clearly observable in nuclear collisions (p-Pb & Pb-Pb) at LHC/FCC.
- MCFM: NLO, CT10 PDF, EPS09 nPDF (30 error sets):

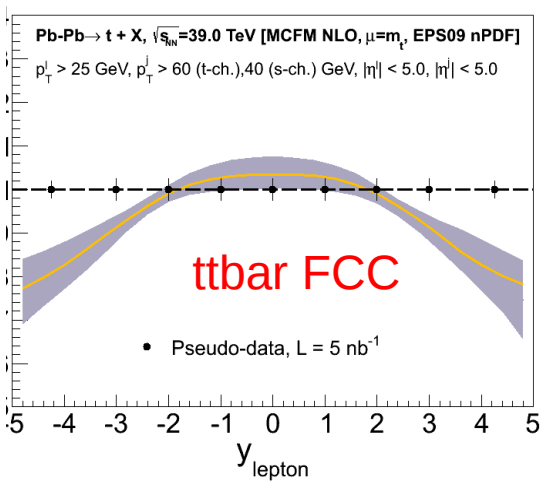


- Yields (semileptonic W decays) after std. cuts:

  LHC: 50-200 t-tbar pairs & single-t (nominal L_{int})
  $O(10^3)$ tops for enhanced lumis.

  FCC: $(15\text{-}60)\times10^3$ t-tbar pairs & single-top





- Novel interesting physics accessible:
  - ➜ LHC: 1st observation of such elementary particle in A-A
  - ➜ FCC: Constrain nPDF in unexplored range: $x\sim m_t/\sqrt{s}\sim10^{-2}$, $Q\sim m_t\sim173$ GeV
  - ➜ FCC: QGP effects: Color reconnect., g-radiation, color-singlet evolution...

Back-up slides