Top production in Heavy Ion collisions

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Top LHC WG, 20-21 May 2015

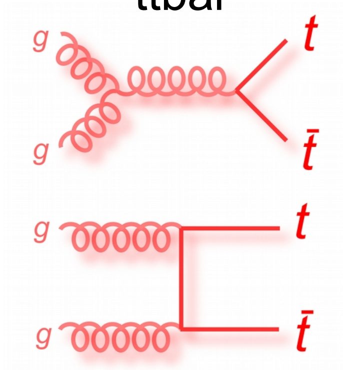
Outline

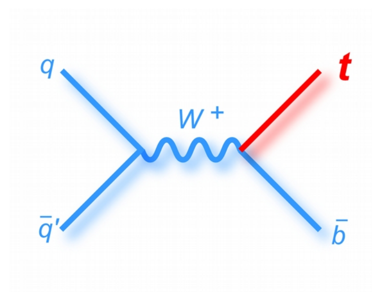
- Introduction & motivations
- Cross section computations with MCFM
- Event selections, expected number of top events
- Pseudodata and nPDF constraints
- Conclusions

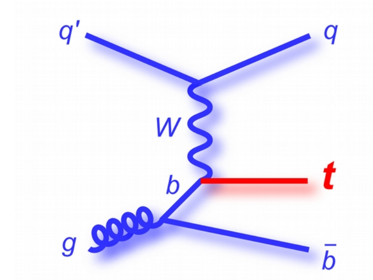
Top quarks in nuclear collisions

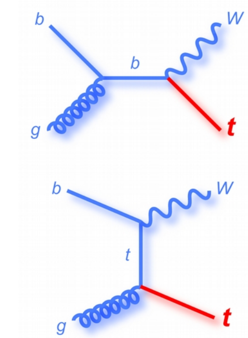
- ttbar: QCD interaction, at LHC dominated by g-induced processes
- Single-top: electroweak process sensitive the b-quark PDF

ttbar | s-channel | t-channel | tW assoc. prod.









- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b (V_{tb}~1)
- t → b + lepton + MET decay channel is promising even in Pb-Pb collisions
  - b-jet measurement in Pb-Pb at LHC: arxiv:1312.4198, PRL 113 (2014) 132301
  - W measurement in Pb-Pb at LHC: arXiv:1205.6334, PLB 715 (2012) 66, arXiv:1408.4674, Eur. Phys. J. C (2015) 75:23

Top quarks in nuclear collisions

- Three elementary particles yet **unobserved** in HI collisions
  - top, tau, H
- Top-quark pairs: constraints for **nuclear PDF**s?
- Top **mass** measurements: systematic uncertainty due to different color reconnection models
  - In HI collisions: top decays in the QGP, color fields are enhanced
- Highly-boosted top quarks with prolonged life time can radiate gluons before hadronization
  - Insight into heavy-quark **energy loss** in QGP and different time scales of HI collisions

Top quarks in nuclear collisions

- Three elementary particles yet **unobserved** in HI collisions
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Main topic of this talk

- Top-quark pairs: constraints for **nuclear PDF**s?

- Top **mass** measurements: systematic uncertainty due to different color reconnection models
  - In HI collisions: top decays in the QGP, color fields are enhanced

Mostly relevant for FCC, see later

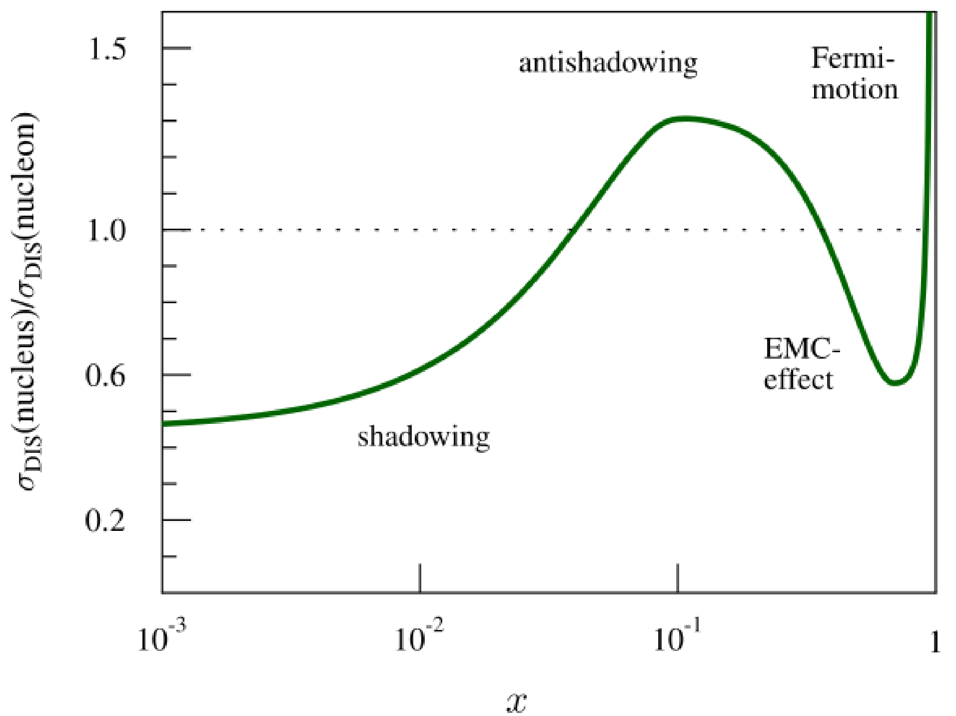
- Highly-boosted top quarks with prolonged life time can radiate gluons before hadronization
  - Insight into heavy-quark **energy loss** in QGP and different time scales of HI collisions

nPDFs

- Collinear-factorization-based expectation:

$$\sigma^{A+B\to\mathcal{O}} = \sum_{i,j} \underbrace{f_i^A(\mu_{\rm fact}^2)}_{\substack{\text{nuclear PDFs, obey} \\ \text{the usual DGLAP}}} \otimes \underbrace{\hat{\sigma}^{i+j\to\mathcal{O}}(\mu_{\rm fact}^2,\mu_{\rm ren}^2)}_{\substack{\text{usual pQCD} \\ \text{coefficient functions}}} \otimes \underbrace{f_j^B(\mu_{\rm fact}^2)}_{\substack{\text{nuclear PDFs, obey} \\ \text{the usual DGLAP}}},$$

- PDFs in nuclei differ from those in free nucleons → nuclear PDFs



LHC HI program

- HI data taken so far
  - Pb-Pb: $\sqrt{s_{NN}}$= 2.76 TeV, ~0.16 nb^{-1} (2010, 2011)
  - p-Pb: $\sqrt{s_{NN}}$= 5.02 TeV, ~35 nb^{-1} (2013)
  - p-p: $\sqrt{s}$ = 2.76 TeV, ~5.4 pb^{-1} (2011, 2013)

- HI data planned for 2015:
  - Pb-Pb: $\sqrt{s_{NN}}$= ~5.1 TeV, ~1 nb^{-1}
  - p-p: $\sqrt{s}$ = ~5.1 TeV, lumi=? (PbPb-equiv. = 43 pb^{-1})

- Together with HL-HI-LHC (Run3 + Run4)
  - Pb-Pb: 10 nb^{-1}
  - p-Pb: 1 pb^{-1}

Theoretical setup

- MCFM v6.7 NLO event calculator
  - Parton densities:
    - Proton PDF: CT10 NLO (central + 52 error sets)
    - Pb nPDF: EPS09 NLO (central + 30 error sets)
  - Scale choices:
    - $\mu_F = \mu_R = m_{top}$ (for ttbar, single top t-channel and s-channel)
    - $\mu_F = \mu_R = p_{Tmin;b\text{-}jet}$ = 50 GeV (for tW assoc prod, $p_{Tmin;b\text{-}jet}$ veto is to avoid double counting with ttbar)
- MCFM processes: 141, 161, 166, 171, 176, 181, 186 (total & fully-leptonic)

141	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to b\ (p_6) + e^-(p_7) + \bar{\nu}(p_8))$	NLO
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
181	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$	NLO
186	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)$	NLO

Cross sections

- Inclusive cross sections for top-pair and single top production
  - The computed cross sections are scaled by the mass numbers

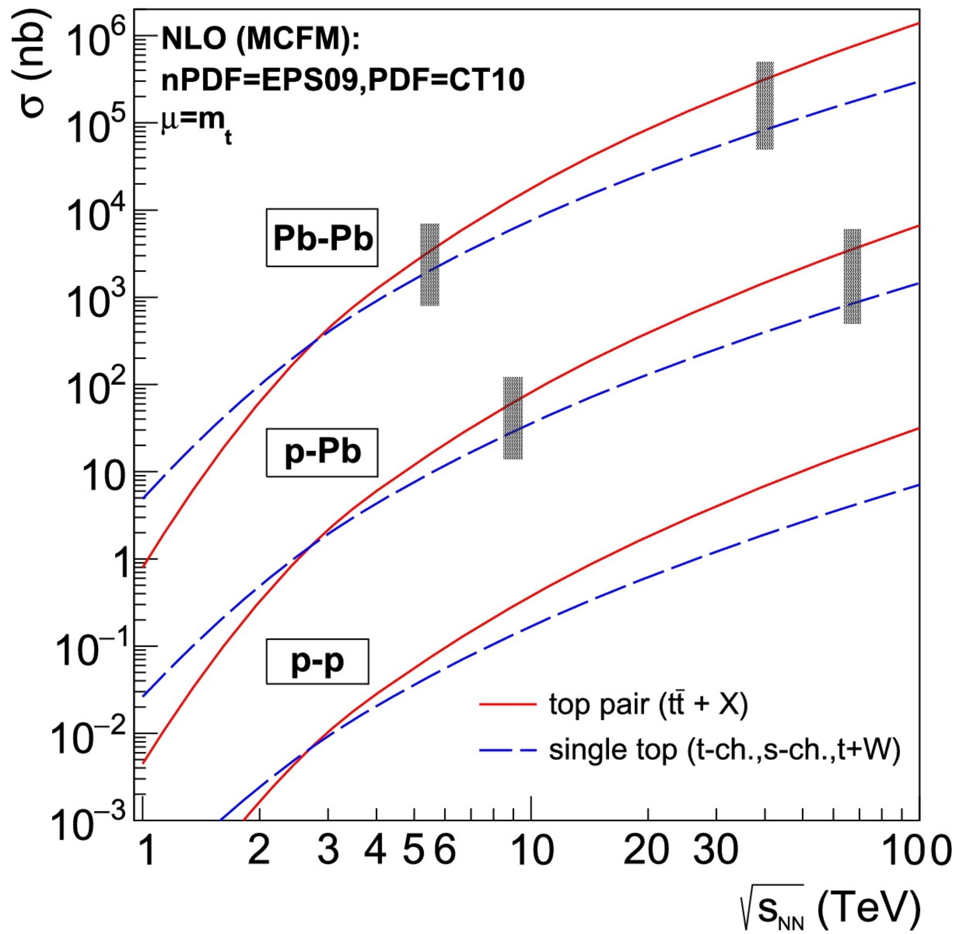
System / Process: (MCFM process)	top pair ($t\bar{t}$) (141)	single-top (t-channel) (161,166)	single-top (s-channel) (171,176)	single-top ($t\,W$) (181,186)
Pb-Pb $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV	$3.40 \pm 0.42 \pm 0.37$ μb	$1.61 \pm 0.05 \pm 0.08$ μb	$110 \pm 4 \pm 6$ nb	$313 \pm 13 \pm 41$ nb
p-Pb $\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV	$58.8 \pm 7.1 \pm 3.8$ nb	$21.1 \pm 0.63 \pm 0.63$ nb	$1.09 \pm 0.03 \pm 0.04$ nb	$5.26 \pm 0.21 \pm 0.37$ nb

- Uncertainties:
  - Theoretical scale variations (factor of 2)
  - CT10 and EPS09 PDF errors added in quadrature

- NNLO/NLO K-factors would enhance cross sections by ~10%

ttbar cross sections

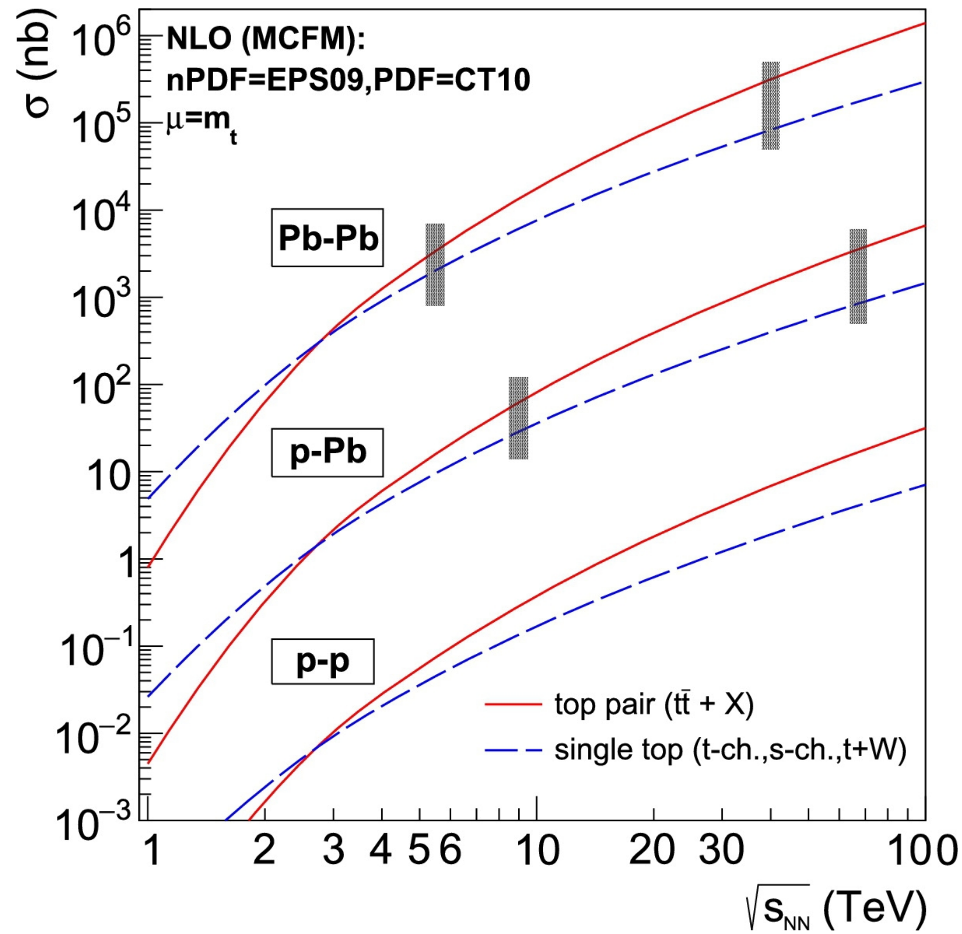
- Pb-Pb:
  - $\sqrt{s_{NN}}$ = 5.5 TeV ~ 3.4 μb
- p-Pb:
  - $\sqrt{s_{NN}}$ = 8.8 TeV ~ 59 nb
- p-p:
  - $\sqrt{s}$ = 5.5 TeV ~ 74 pb
  - $\sqrt{s}$ = 8.8 TeV ~ 270 pb



- nPDF antishadowing increases $\sigma_{t\bar{t}}$ by 2-8% wrt to (scaled) p-p
- NNLO/NLO K-factors would enhance cross sections by ~10%

Single-top cross sections

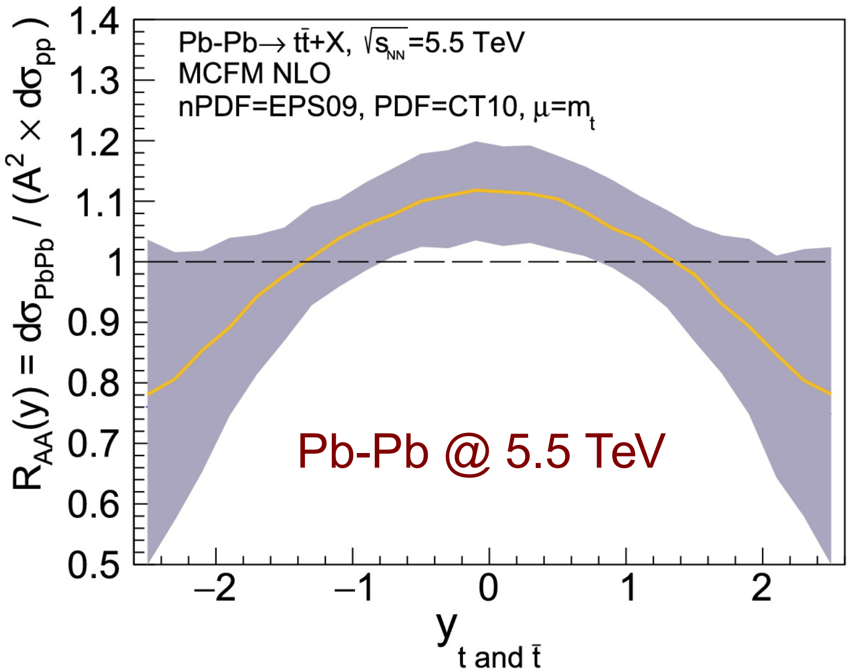
- Pb-Pb:
  - $\sqrt{s_{NN}}$ = 5.5 TeV ~ 2 μb
- p-Pb:
  - $\sqrt{s_{NN}}$ = 8.8 TeV ~ 28 nb
- p-p:
  - $\sqrt{s}$ = 5.5 TeV ~ 45 pb
  - $\sqrt{s}$ = 8.8 TeV ~ 130 pb

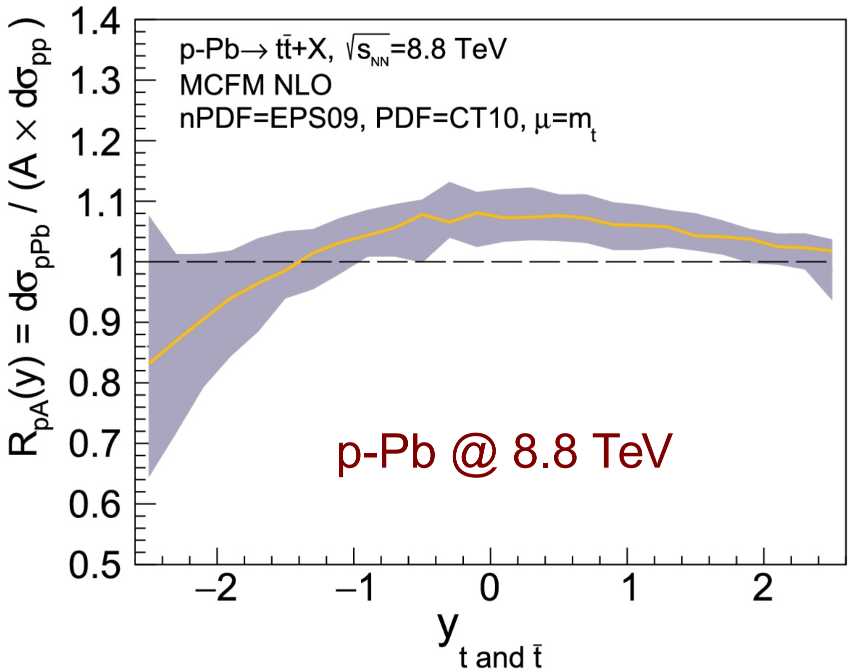


- nPDF antishadowing increases $\sigma_{\text{single-top}}$ by 2% wrt to (scaled) p-p
- NNLO/NLO K-factors would enhance cross sections by ~10%

Theoretical $R_{AA}(y)$

- Nuclear modification factor: $R_{AA}(y) = \frac{d\sigma_{AA}/dy}{A^2 d\sigma_{pp}/dy}$
  - HI = independent superpositions of nucleon-nucleon collisions → $R_{AA}(y) = 1$
- Theoretical nuclear modification factors in ttbar collisions at LHC
  - Function of the y of individual top and antitop quarks
  - Central curve and error bands: results with the EPS09 parametrization





Experimental measurement

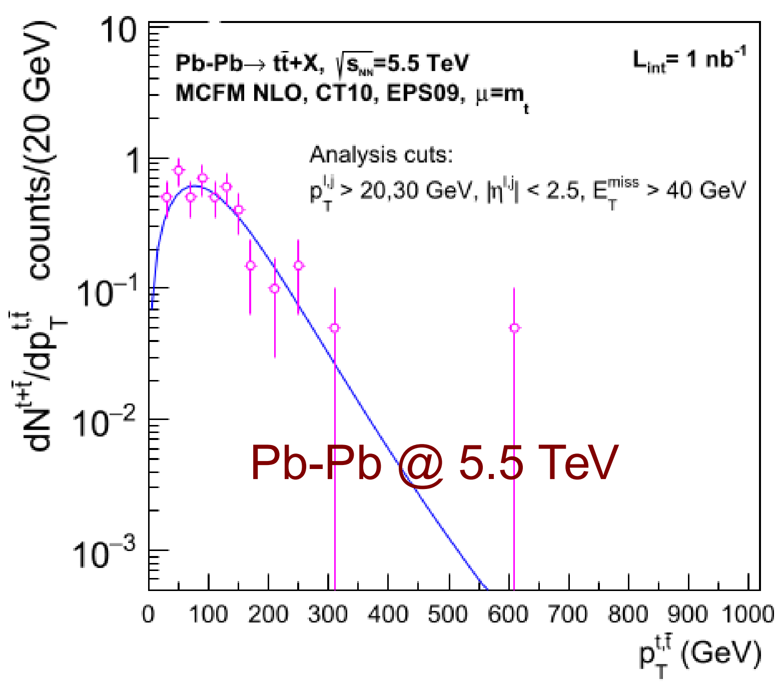
- Experimental setup:
  - Gen-level analysis cuts, ATLAS/CMS-like conditions
  - Anti-kT jet algo, R=0.5
  - Charged leptons: $|\eta_{leptons}|<2.5$, $p_T>20$ GeV
  - b-jets: $|\eta_{b\text{-}jet}|<2.5$, $p_T>30$ GeV
  - Neutrinos: $E_{miss}>40$ GeV
  - b-jet tagging efficiency: 50%
    - For ttbar: only 1 b-jet is required: 50% → 75%
  - Estimated total efficiency·acceptance in the fully-leptonic channel:
    - ttbar: ~30%, tW: ~20%
- Single-top t-channel and s-channel: large expected background, out of the scope of this work

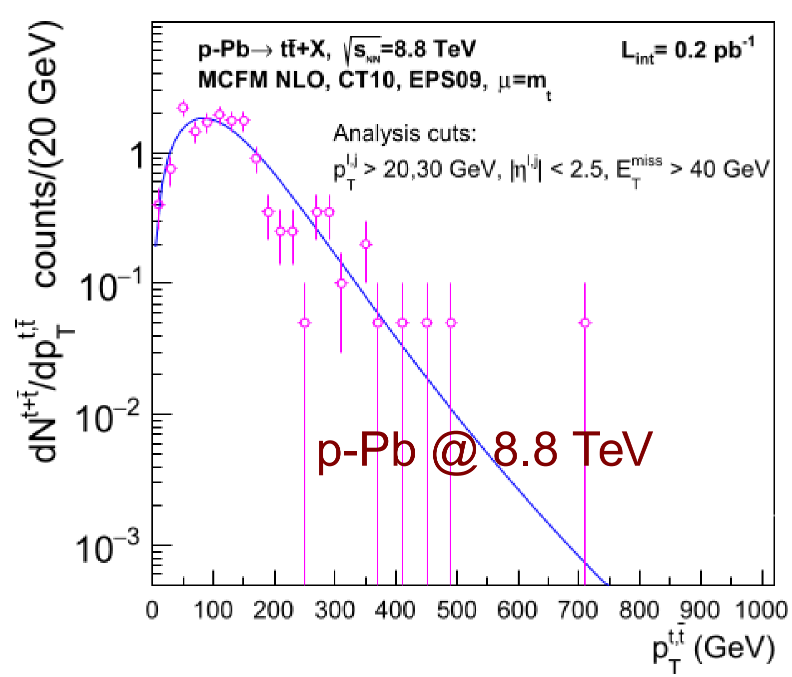
Number of top quarks

- Number of top and antitop quarks per run after analysis selections

System	$\sqrt{s}$	$\mathcal{L}_{\rm int}$	Number of top+antitop quarks $t\bar{t} \to b\,\bar{b}\,\ell\ell\,\nu\nu$	Number of top+antitop quarks $t\,W \to b\,\ell\ell\,\nu\nu$
Pb-Pb	5.5 TeV	1 nb^{-1}	90	3
p-Pb	8.8 TeV	0.2 pb^{-1}	300	10

- Expected p_T reach: boosted top quarks with p_T>1 TeV not accessible at LHC





Constraints on nPDFs

- ~80% of the top pair production comes from gluon-gluon fusion
  - ttbar cross section to constrain gluon densities in Pb
- Demonstrate the effect of ttbar measurement on nPDFs:
  - Generate pseudodata
  - Use the pseudodata to constrain the nPDFs through the Hessian PDF re-weighting technique
- Hessian re-weighting:
  - Also known as PDF profiling in HERAFitter, see arxiv:1503.05221
  - The error sets in Hessian PDF fits correspond to a certain increment in the global χ^2 function
  - Thus, the error sets parametrize the original χ^2 function
  - New PDFs are obtained by reweighting to the previous PDFs
  - See the details in JHEP 1412 (2014) 100

Constraints on nPDFs

- Total cross section: nPDF effects enhance σ_{tot} by 2-8% compared to pp
  - Hard to differentiate from overall normalization uncertainties

    → differential cross sections are needed

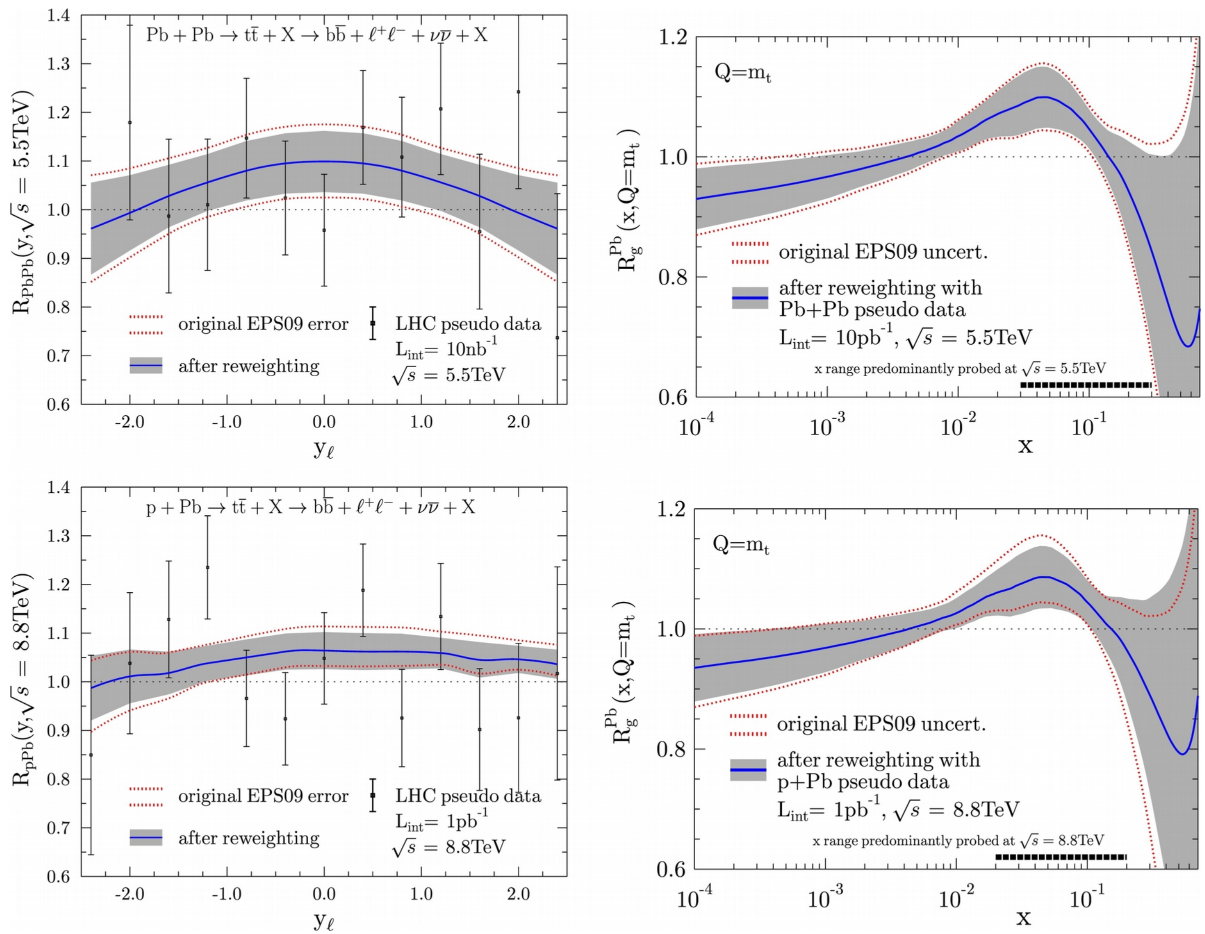
- Mimic experimental situation:
  - Use the distribution of the decay leptons (unaffected by final state interactions)
  - Statistical uncertainties from total number of events, and shape of σ(y)
  - Uncorrelated systematics: 5%
  - Normalization uncertainty: 5%
  - Pseudodata: $D_i = T_i^{EPS09} + \delta_i^{uncorr} r_i + \delta_i^{norm} r^{norm}$, where r factors are from Gaussians of σ=1 and μ=0
  - Covariance matrix: $C_{ij} = \delta_i^{uncorr} \delta_j^{uncorr} \delta_{ij} + \delta_i^{norm} \delta_j^{norm}$

Constraints on nPDFs (pseudodata)

- ttbar decay-lepton R_{AA} pseudodata and impact on the gluon nPDFs based on the full HI LHC program
  - ~10% reduction of uncertainties

Pb-Pb @ 5.5 TeV

p-Pb @ 8.8 TeV



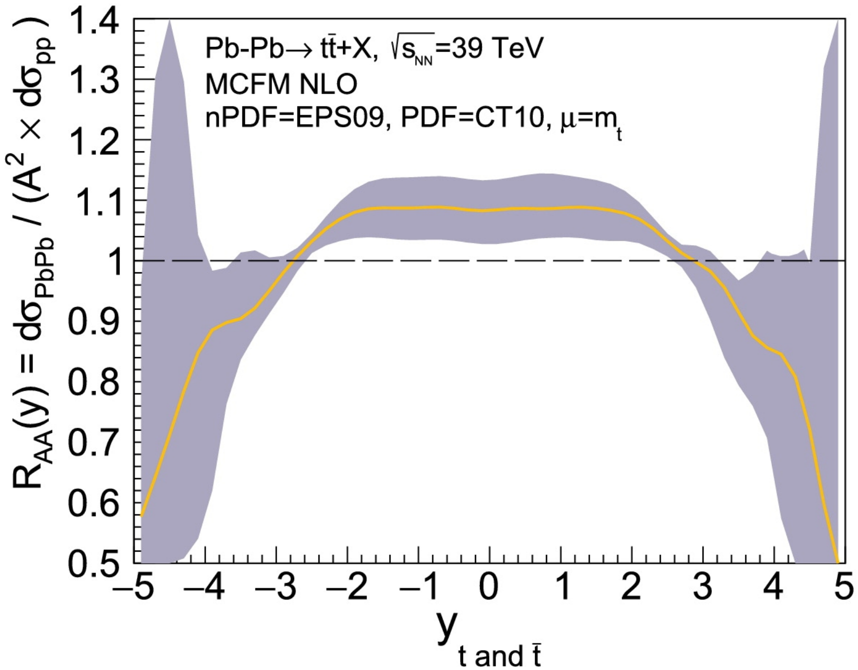
Conclusions

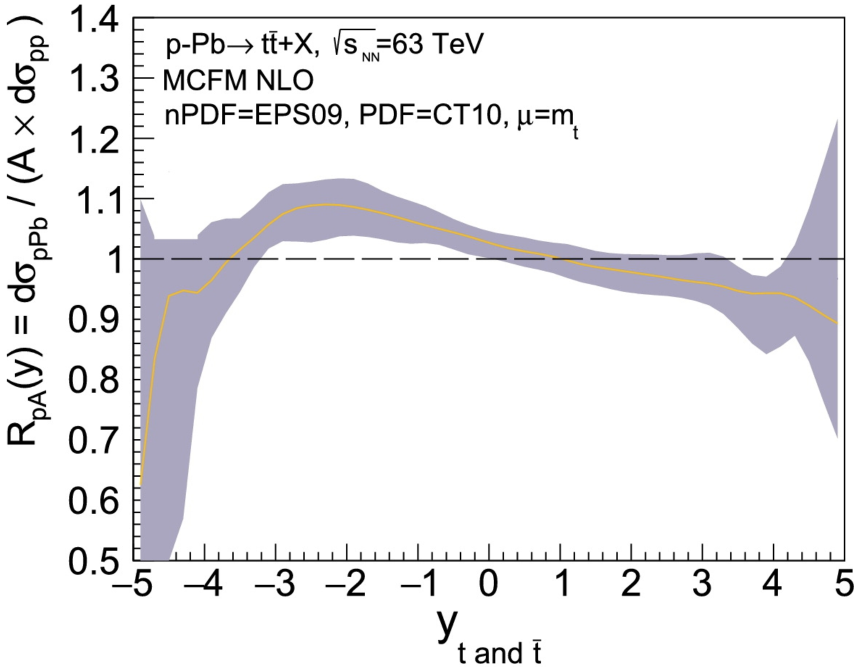
- ttbar and single-top production cross sections in HI collisions
  - Computed with MCFM, NLO accuracy
  - Using CT10 free proton PDF and nuclear modifications from EPS09
- Top quark production is observable in nuclear collisions at the LHC
  - After typical analysis cuts in the leptons + b-jet final state: ~100 (PbPb) and ~300 (pPb) top and antitop quarks per LHC-year
  - To be compared with <100 top-quarks (in all decay channels) reconstructed by CDF and D0 at Tevatron during Run-1.
- Impact on the gluon nPDF of the y distribution of decay leptons:
  - Combining PbPb and pPb data, and ATLAS+CMS measurements
    → 30% reduction of uncertainties
- Further information: arXiv:1501.05879, Physics Letters B 746 (2015) 64-72

Backup slides

Theoretical R_{AA}

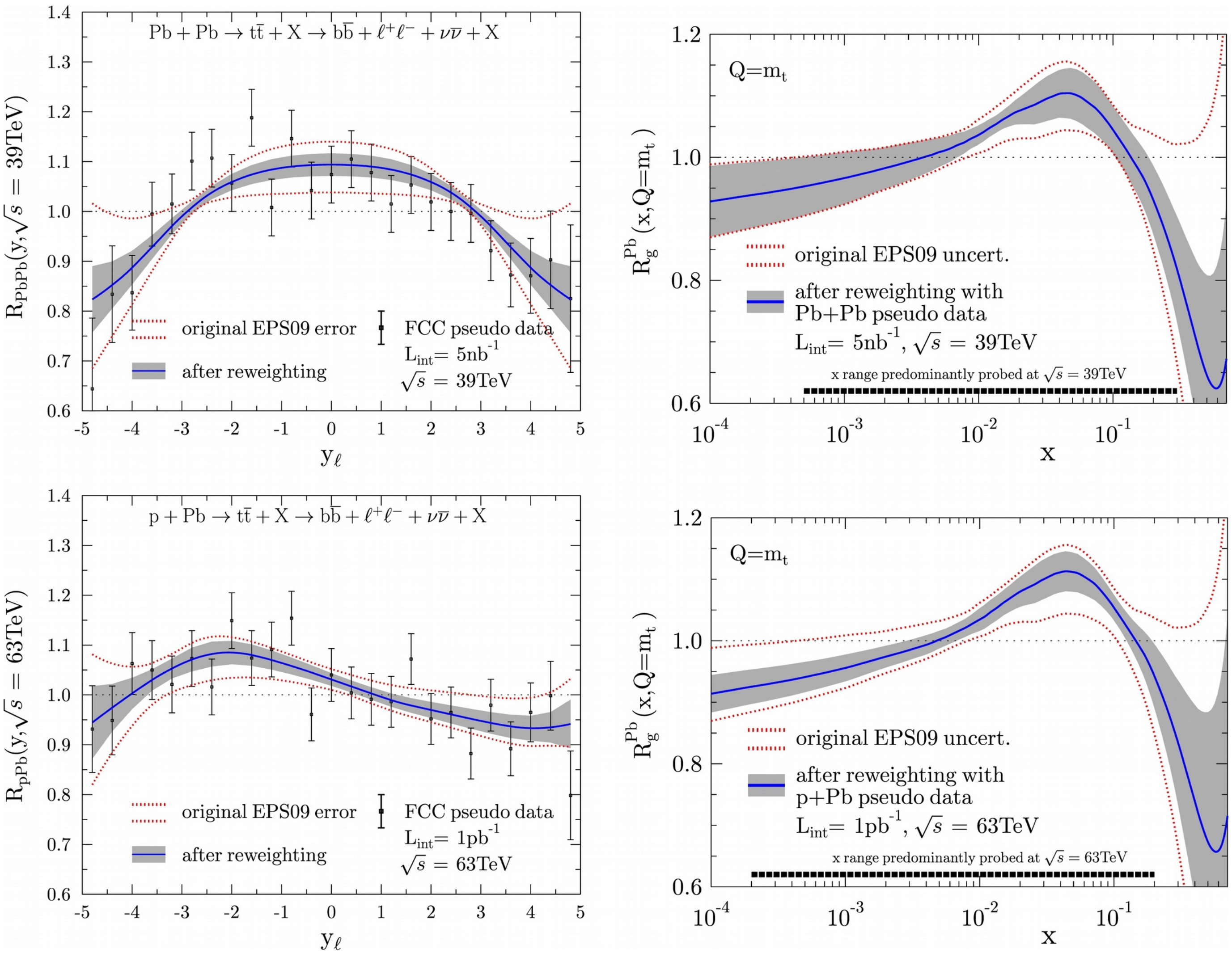
- Theoretical nuclear modification factors in ttbar collisions at FCC
  - Function of the y of individual top and antitop quarks
  - Central curve: results with central EPS09 parametrization
  - Grey band: nPDF uncertainty





Constraints on nPDFs

- ttbar pseudo-data, and improvements in the gluon nPDF



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p-Pb $\sqrt{s_{NN}}$ = 8.8 TeV	58.8±7.1±3.8 nb	21.1±0.63±0.63 nb	1.09±0.03±0.04 nb	5.26±0.21±0.37 nb
Pb-Pb $\sqrt{s_{NN}}$ = 39 TeV	302±33±12 μb	54.6±1.6±2.2 μb	1.31±0.05±0.08 μb	24.2±1.6±1.3 μb
p-Pb $\sqrt{s_{NN}}$ = 63 TeV	3.20±0.35±0.10 μb	518±16±17 nb	10.9±0.5±0.5 nb	246±24±11 nb

- Uncertainties:
  - Theoretical scale variations, and CT10 and EPS09 PDF errors added in quadrature

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Pb-Pb	39. TeV	5 nb^{-1}	47 000	1 300
p-Pb	63. TeV	1 pb^{-1}	100 000	2 600

Top quark p_T distributions

- Top quark p_T distributions for events passing typical analysis cuts