# Physics with ions at the Future Circular Collider (FCC)

## Quark-Matter 2017

## Chicago, 6th–11th Feb. 2017


## David d'Enterria

**(For the FCC-ions team: L.Apolinario, N.Armesto, DdE, A.Dainese, J.Jowett, M.van Leeuwen, J.Ph.Lansberg, S.Masciocchi, G.Milhano, W.Riegler, C.Roland, C.Salgado, M.Schaumann, U.Wiedemann)**

## CERN


*[Based mostly on: A. Dainese et al. arXiv:1605.01389 + new studies]*

# Outline

- Future Circular Collider (FCC) CERN project
- FCC-AA parameters: PbPb(39TeV,33 $nb^{-1}$), pPb(63TeV,8 $pb^{-1}$)

- PbPb(39 TeV): Global properties
- PbPb(39 TeV): Thermalized charm
- PbPb(39 TeV): Quarkonia at $T \sim 5 \cdot T_c$
- pPb(63 TeV): (Very) small-x physics

- Physics with top-quarks
- Physics with Higgs boson
- Physics with $\mathcal{O}$(100-GeV) $\gamma\text{–}\gamma$ collisions

[For FCC detector see: M. Selvaggi https://indico.cern.ch/event/550509/contributions/2413234/]

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**"New (HI) physics"**

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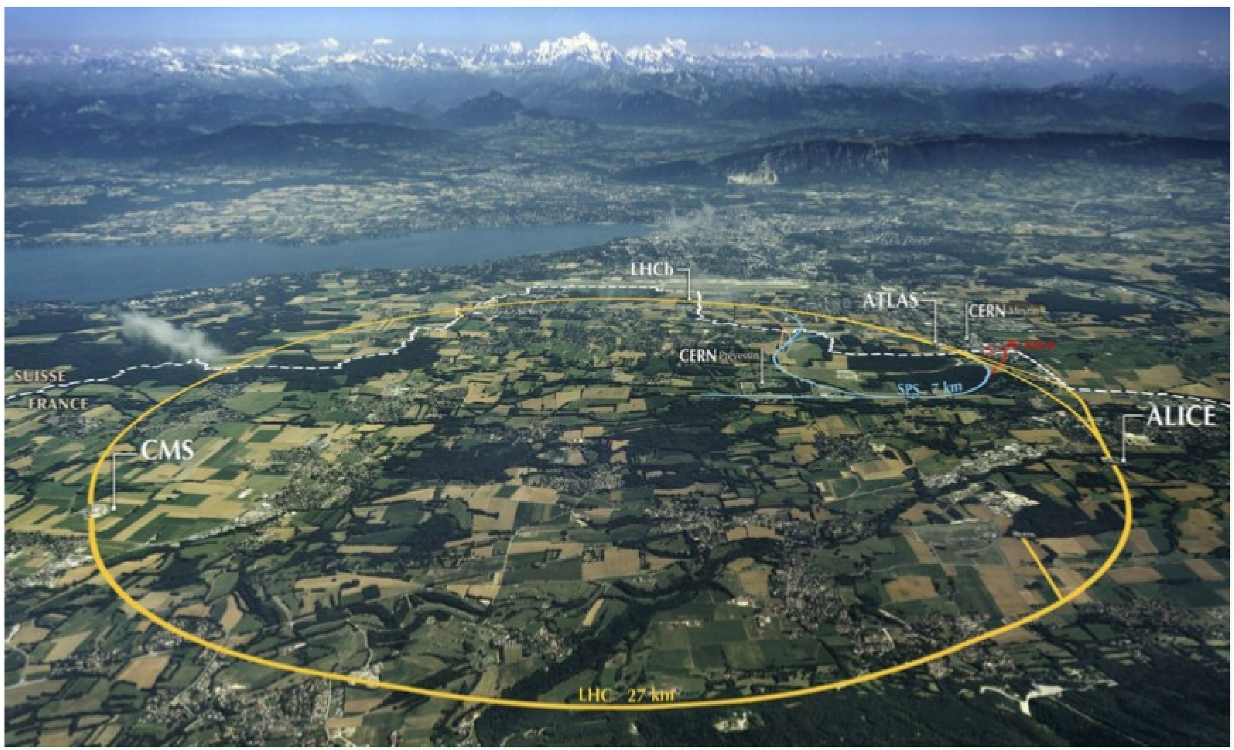
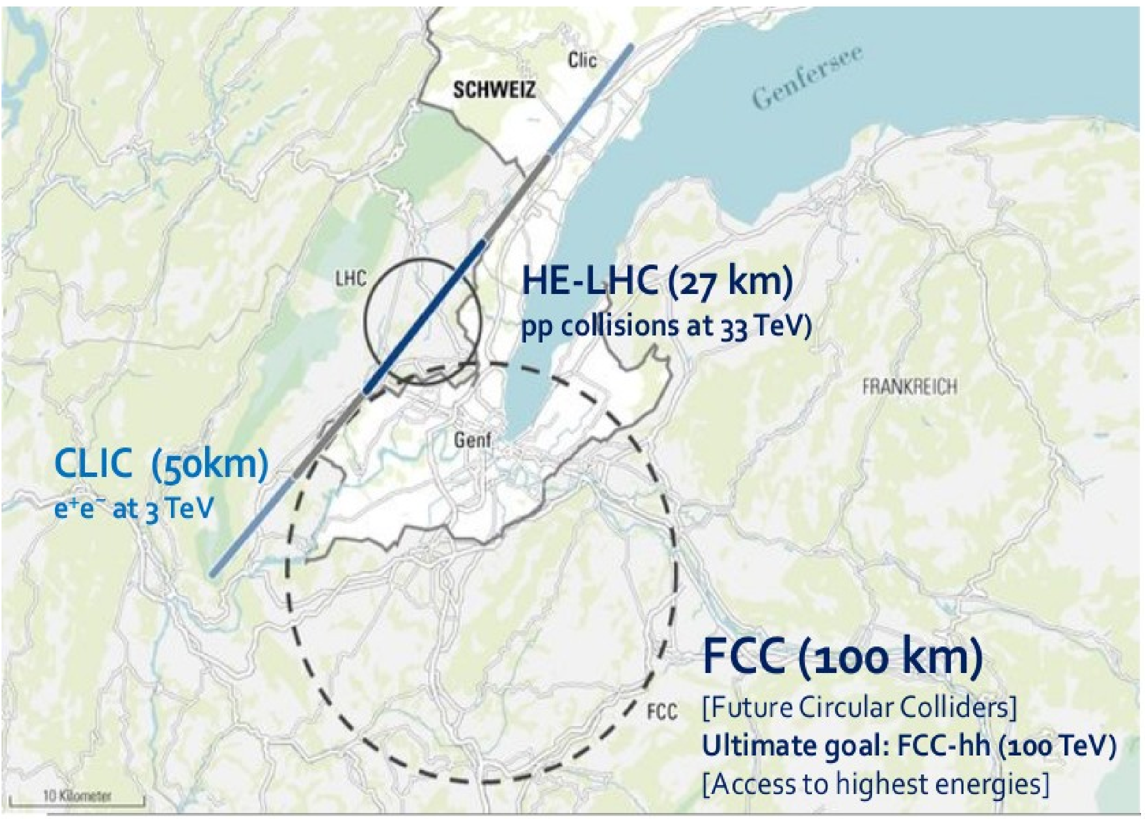
# EU HEP short-term perspectives (2020–2030)

- In May 2013, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 $fb^{-1}$ at 13-14 TeV by 2018 (LHC Run2: running)
    - Get ~300 $fb^{-1}$ at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 $ab^{-1}$ at 14 TeV by 2035 (HL-LHC: project)
      - ➨ A first step towards both energy and precision frontier



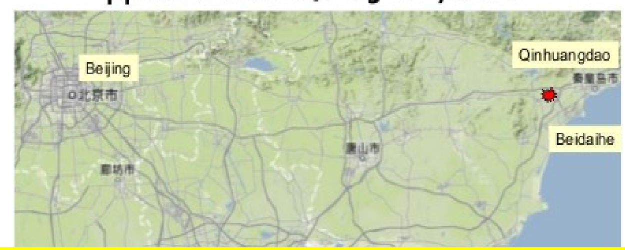
# EU HEP long-term perspectives (2035–2060)

- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines at CERN
    - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV
    - CLIC, an $e^+e^-$ collider project with $\sqrt{s}$ from 0.3 to 3 TeV




Similar circular projects (50 or 70km) in China

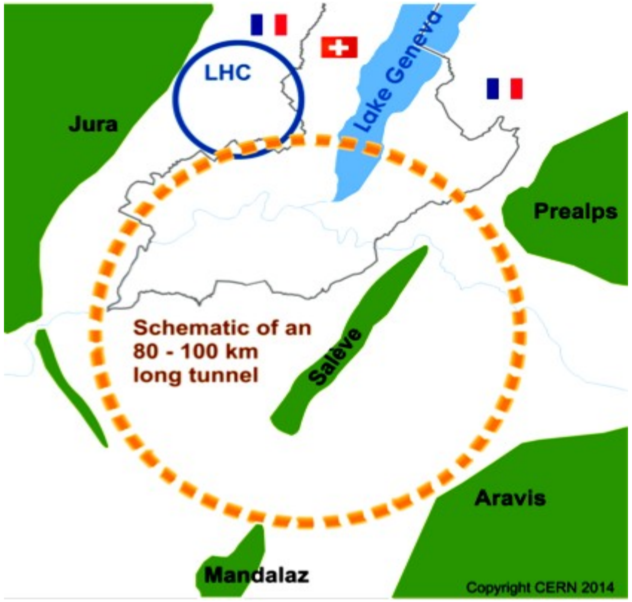
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV




N-b.Chan et al. arXiv:1510.05754 [nucl-th]

# CERN Future Circular Collider

- Reaching $\sqrt{s}$=100-TeV pp requires R=80–100 km collider (16–20 T dipoles).
- $\sqrt{s}$=100-TeV pp → $\sqrt{s_{NN}}$=100 TeV×$\sqrt{[Z_1 \cdot Z_2/(A_1 \cdot A_2)]}$ for p-Pb, PbPb



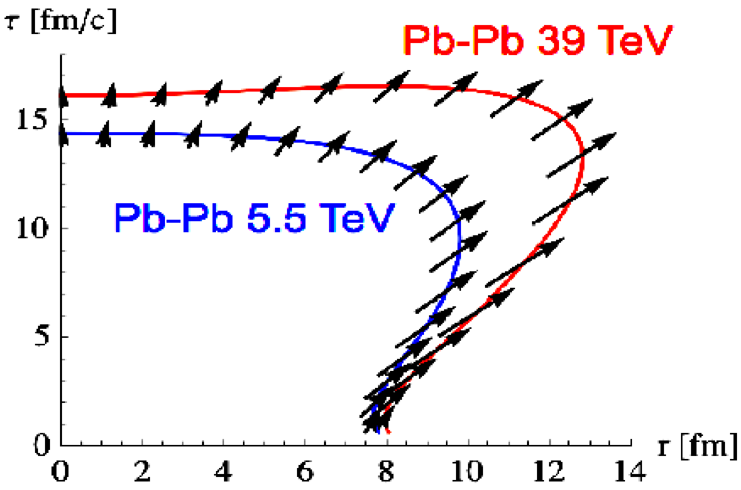

| | Unit | FCC Injection | FCC Collision | |
|---|---|---|---|---|
| Operation mode | | Pb | Pb–Pb | p–Pb |
| Beam energy | [TeV] | 270 | 4100 | 50 |
| $\sqrt{s_{NN}}$ | [TeV] | - | 39.4 | 62.8 |
| No. of bunches per LHC injection | - | 518 | 518 | 518 |
| No. of bunches in the FCC | - | 2072 | 2072 | 2072 |
| No. of particles per bunch | $[10^8]$ | 2.0 | 2.0 | 164 |
| Transv. norm. emittance | [$\mu$m] | 1.5 | 1.5 | 3.75 |
| Number of IPs in collision | - | - | 1 | 1 |
| Crossing-angle | [$\mu$rad] | - | 0 | |
| Initial luminosity | $[10^{27}\text{cm}^{-2}\text{s}^{-1}]$ | - | 24.5 | 2052 |
| Peak luminosity | $[10^{27}\text{cm}^{-2}\text{s}^{-1}]$ | - | 57.8 | 9918 |
| Integrated luminosity per fill | $[\mu\text{b}^{-1}]$ | - | 553 | 158630 |
| Average luminosity | $[\mu\text{b}^{-1}]$ | - | 92 | 20736 |
| Time in collision | [h] | - | 3 | 6 |
| Assumed turnaround time | [h] | - | 1.65 | 1.65 |
| Integrated luminosity/run | $[\text{nb}^{-1}]$ | - | 33 | 8000 |

PbPb(39TeV), $L_{int}$ = 33 $nb^{-1}$
pPb(63TeV), $L_{int}$ = 8 $pb^{-1}$

**×7 larger $\sqrt{s}$ than LHC**
**×10 larger $L_{int}$ than LHC**

# PbPb(39 TeV): Global properties

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



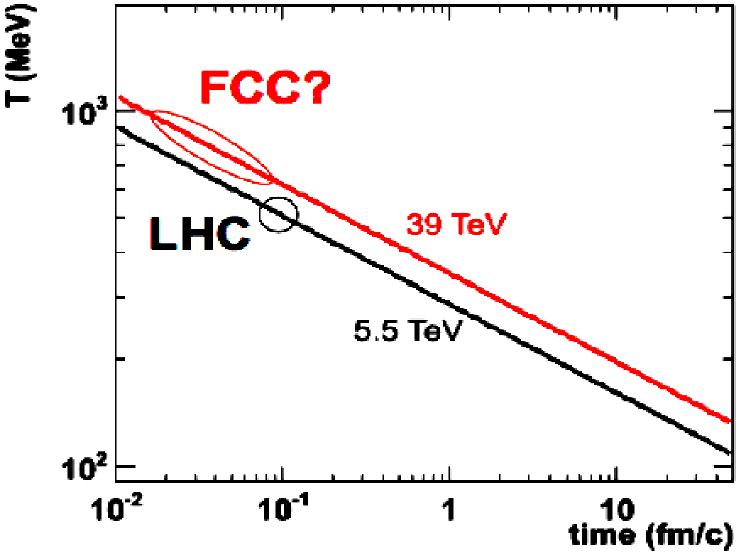
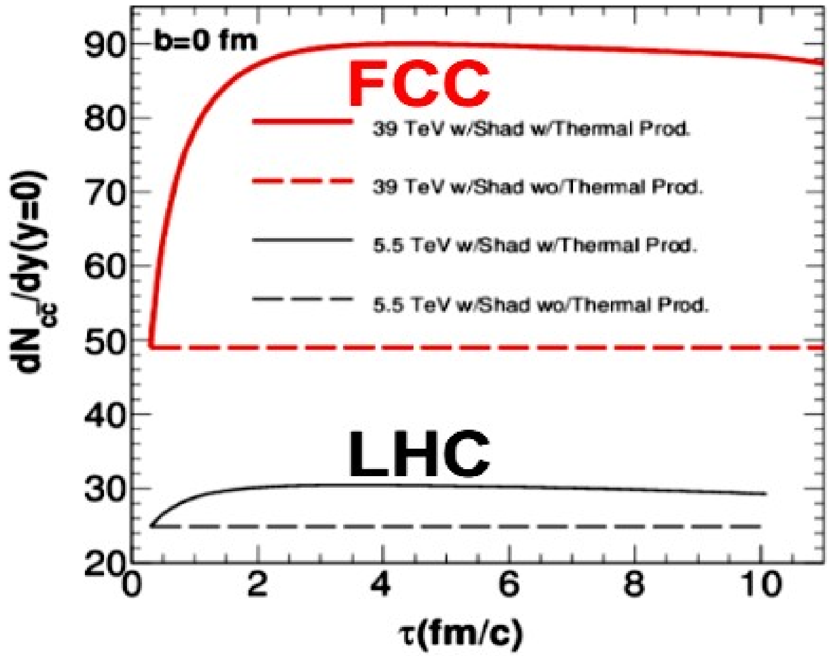




Fig. 2: Left: space-time profile at freeze-out from hydrodynamical calculations for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and 39 TeV. Right: time evolution of the QGP temperature as estimated on the basis of the Bjorken relation and the Stefan-Boltzmann equation (see text for details).

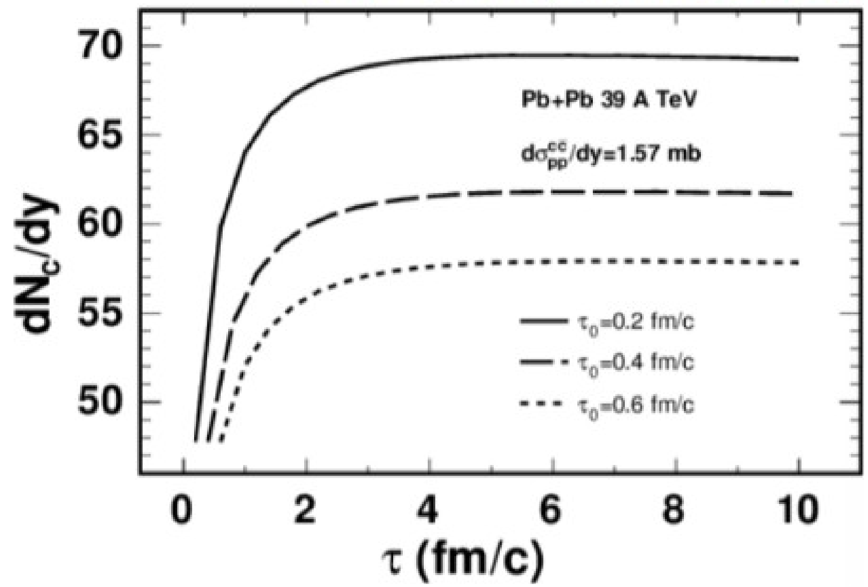
**×2 larger particle & energy densities than in PbPb(5.5 TeV)**

# PbPb(39 TeV): Thermal charm QGP

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium from $gg \rightarrow c\bar{c},\ q\bar{q} \rightarrow c\bar{c}$ + NLO …




K. Zhou et al., arXiv:1602.01667
C.M. Ko, Y. Liu, arXiv:1604.01207



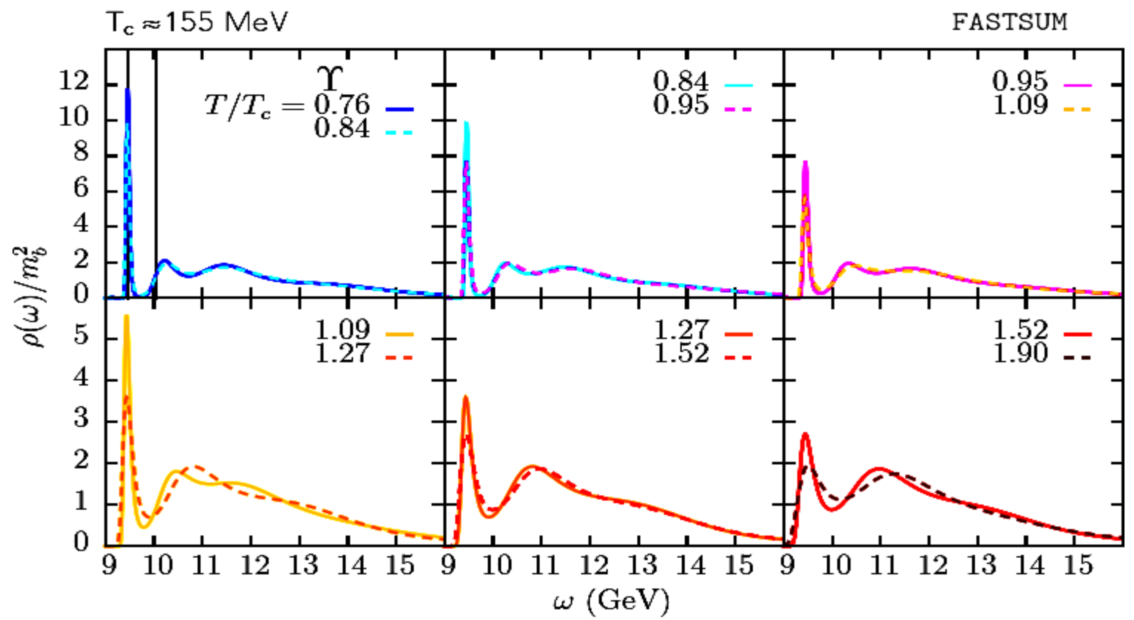

- Up to 50-100% “enhancement” wrt primary charm
- Sensitive to QGP properties: T vs $\tau$, and $\tau_0$ **(affect *ndof* in QGP)**

**×3 larger charm-anticharm densities than in PbPb(5.5 TeV)**

# PbPb(39 TeV): Quarkonia

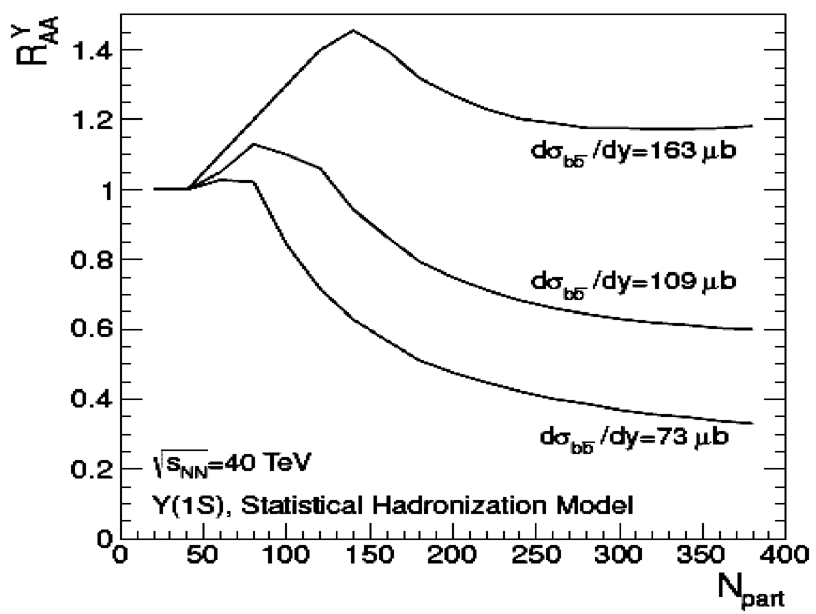
- FCC-AA ($T_0$~1GeV) can probe Y(1S) "melting" expected by latt-QCD at T=4–5 $T_c$

[G. Aarts et al, JHEP 07 (2014) 097]



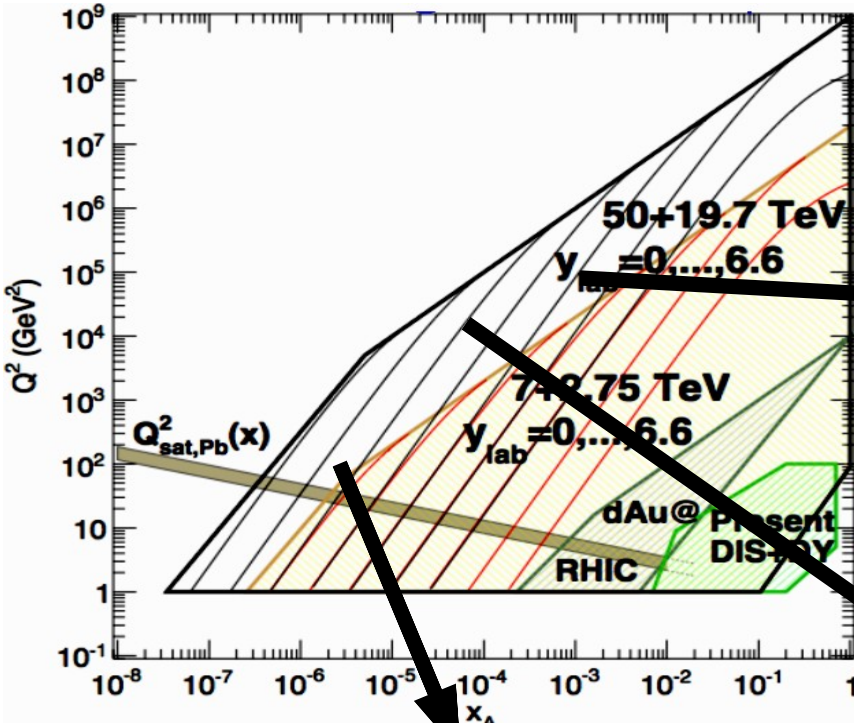

- Density of bbbar pairs large enough for Y(1S) recombination?

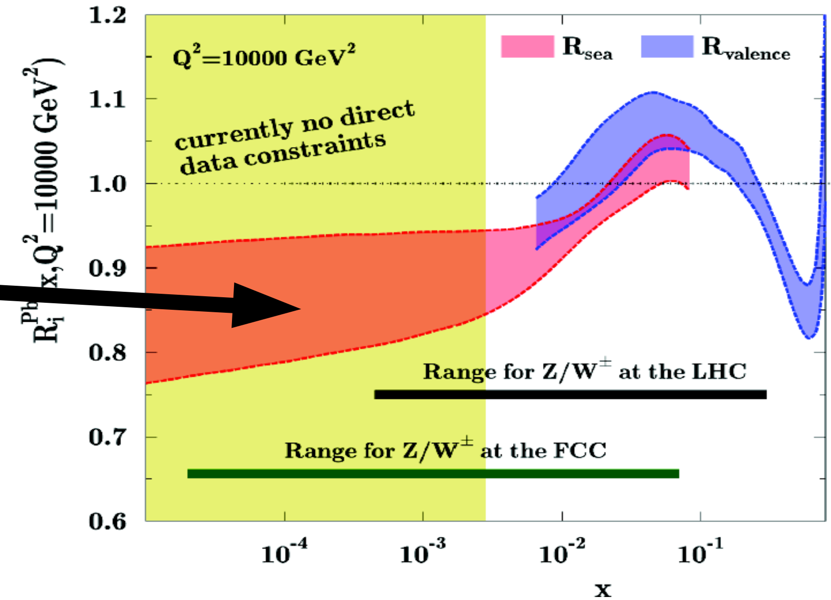
[A.Andronic, et al., JPG38 (2011) 124081]



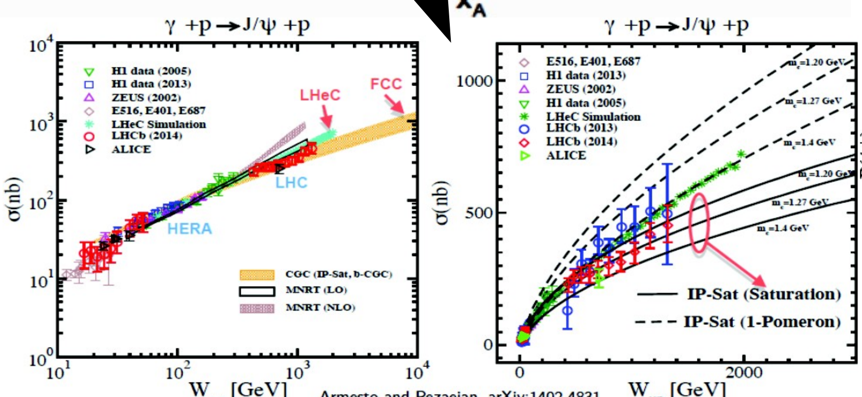
# pPb(63 TeV): Small-x physics

- Kinematical reach at FCC down to $x \sim 10^{-7}$ ($10^{-4}$ with W,Z at y~0)

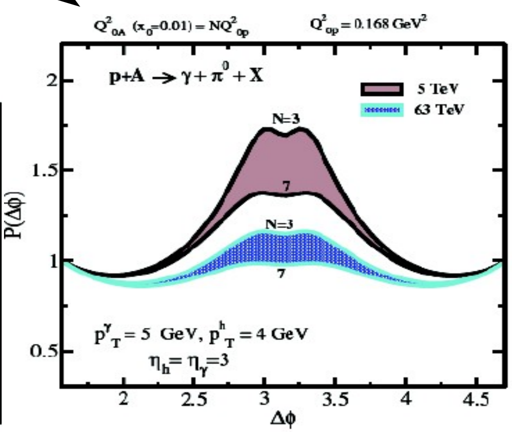


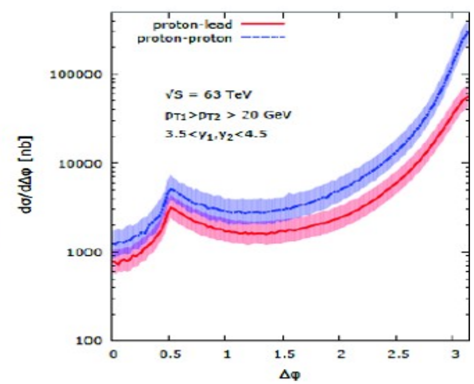

Fwd-Bcwd azimuthal decorrelations:




Exclusive J/ψ photoproduction




γ-π⁰ in pPb




jet-jet in pPb

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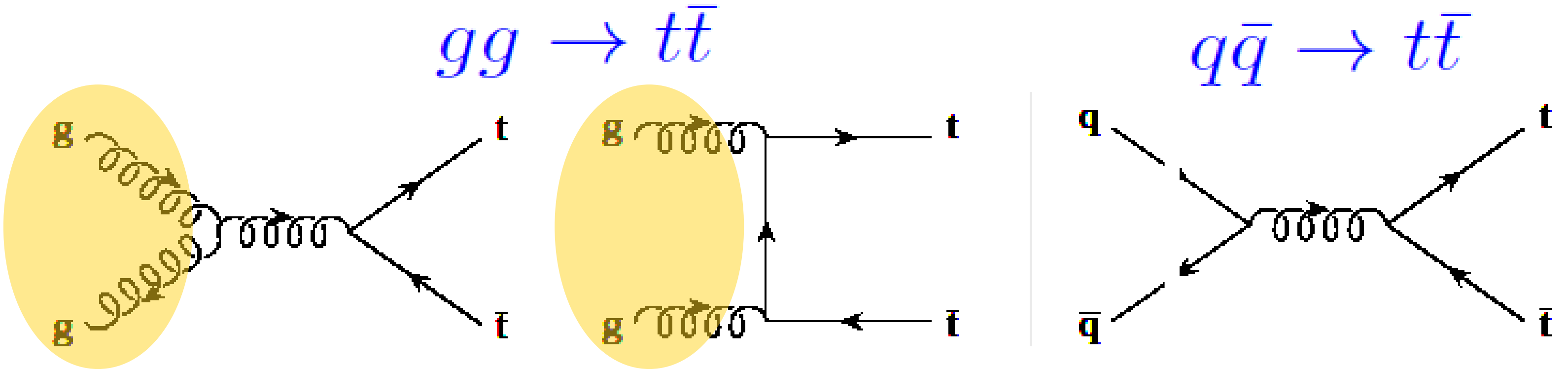
**"New (HI) physics"**

# Top-quark in nuclear collisions

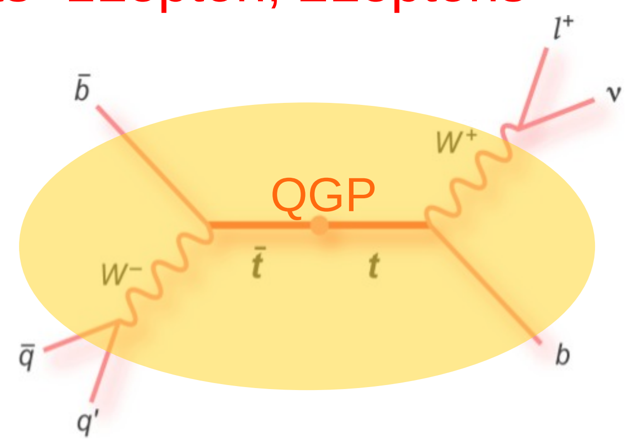
- Top-pair production: QCD interaction dominated by gluon-induced processes (80%→90% from LHC→FCC energies):




- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b (BR~100%,$V_{tb}$~1). 3 final-states: 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%)

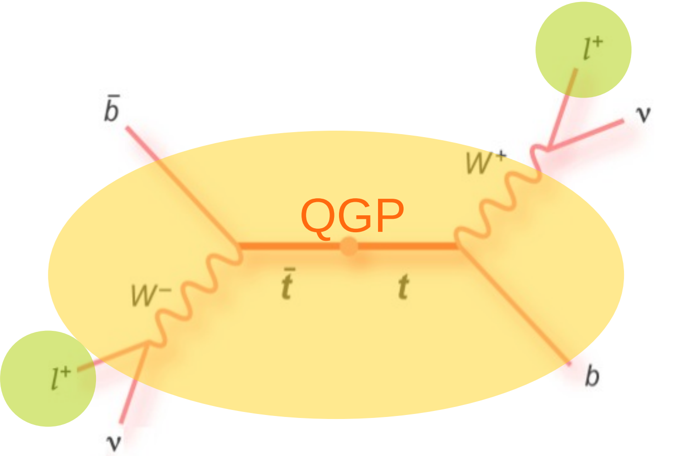


# t-tbar dileptons: high-x gluon nPDFs probe

- 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%)

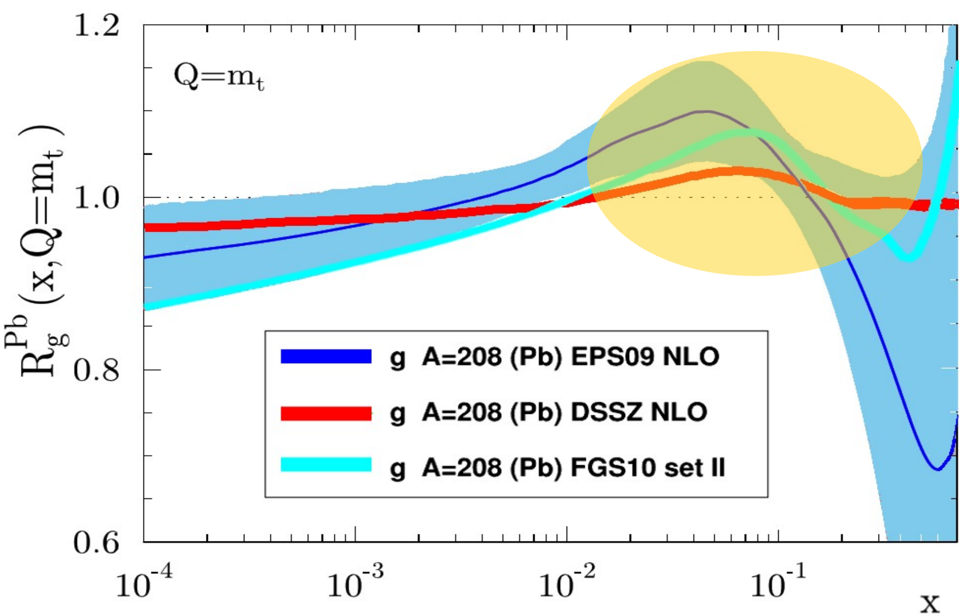



**Cleanest decay channels: μ+μ,μ+e,e+e (BR~5%)**

- Motivations for leptonic measurement:

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

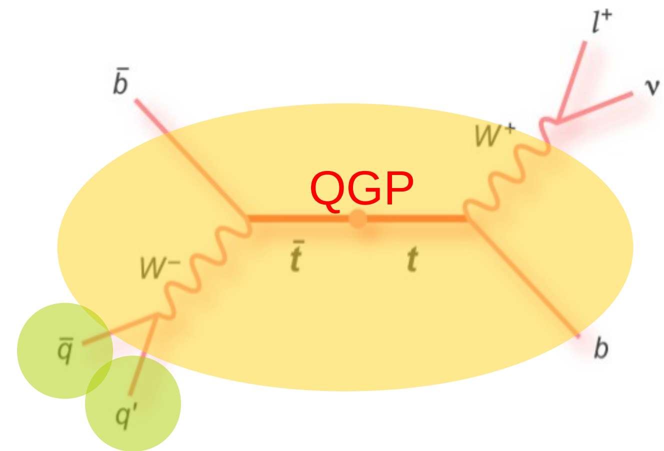
  → Probes gluon nPDF in unexplored high-x range: x~0.3–$10^{-3}$,Q~$m_t$~173 GeV



# t-tbar jets: Probe of parton radiation in QGP

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

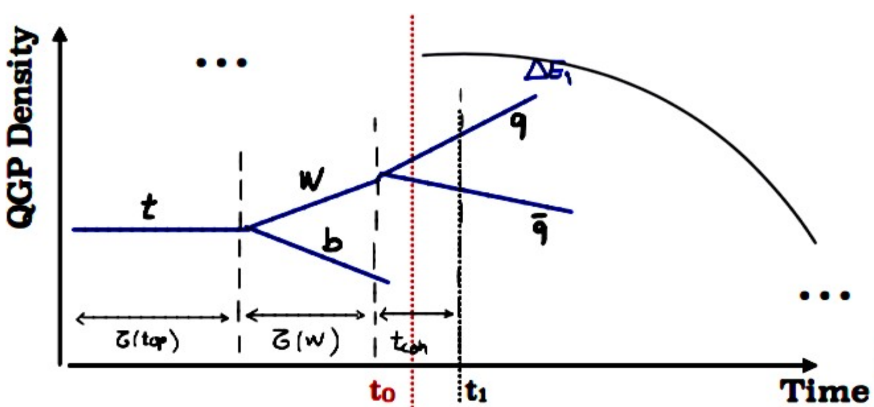
  t → b + 2jets (66%)
  ttbar → bbar + 2jets + 1ℓ + MET(ν) (45%)

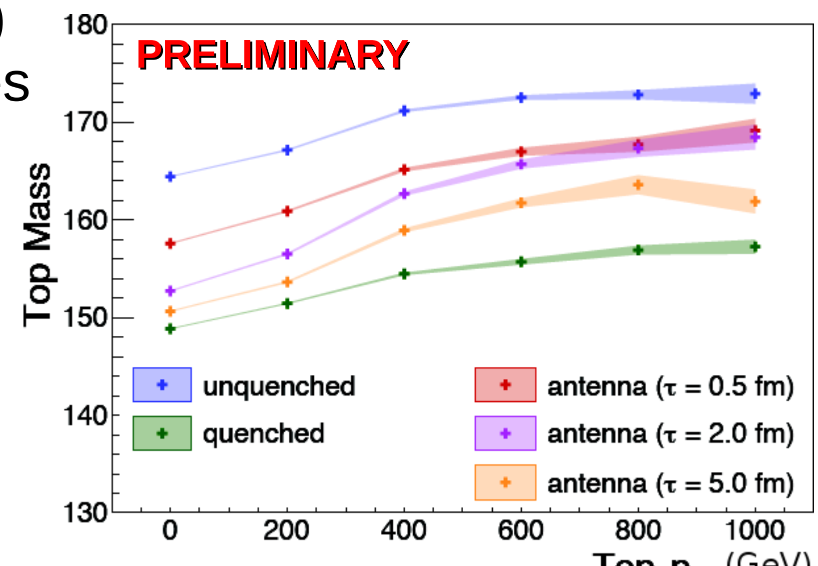



**High-stats decay channel: 2jets+2ℓ (BR~45%)**

- 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]

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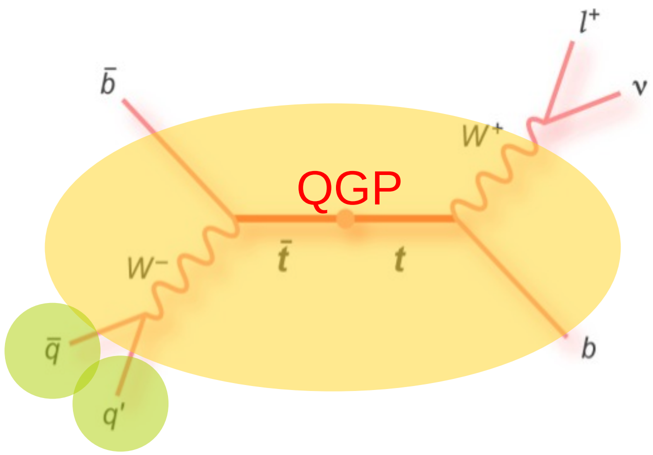


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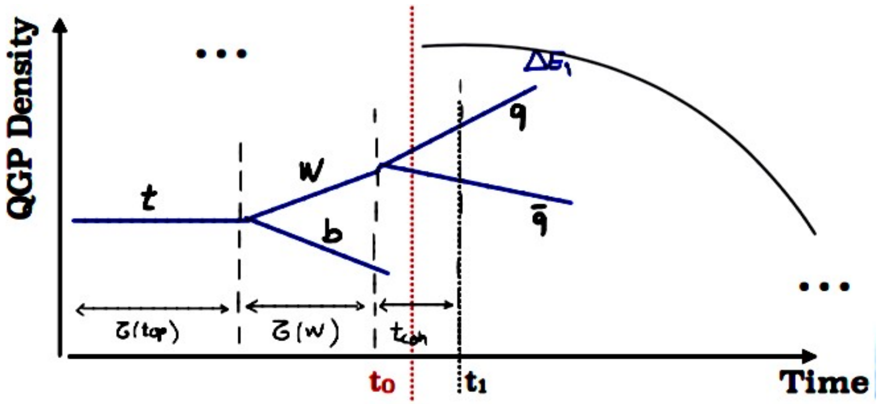
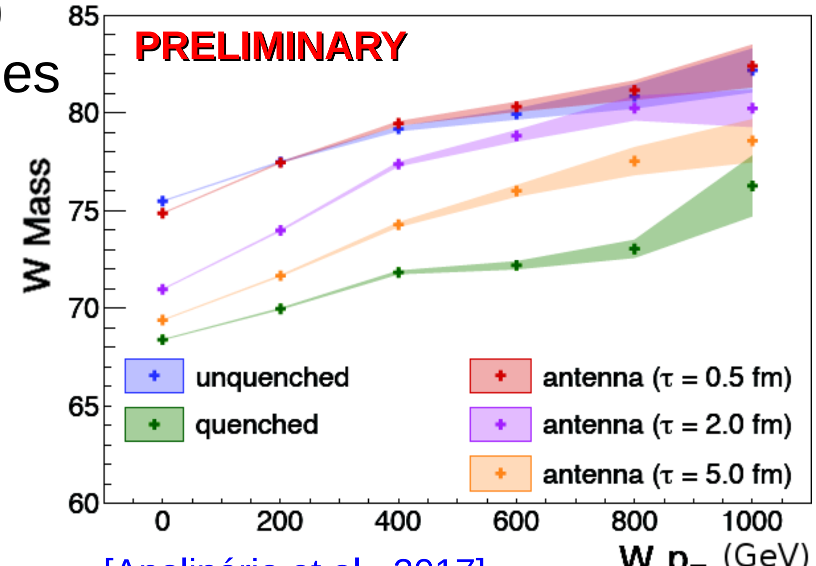
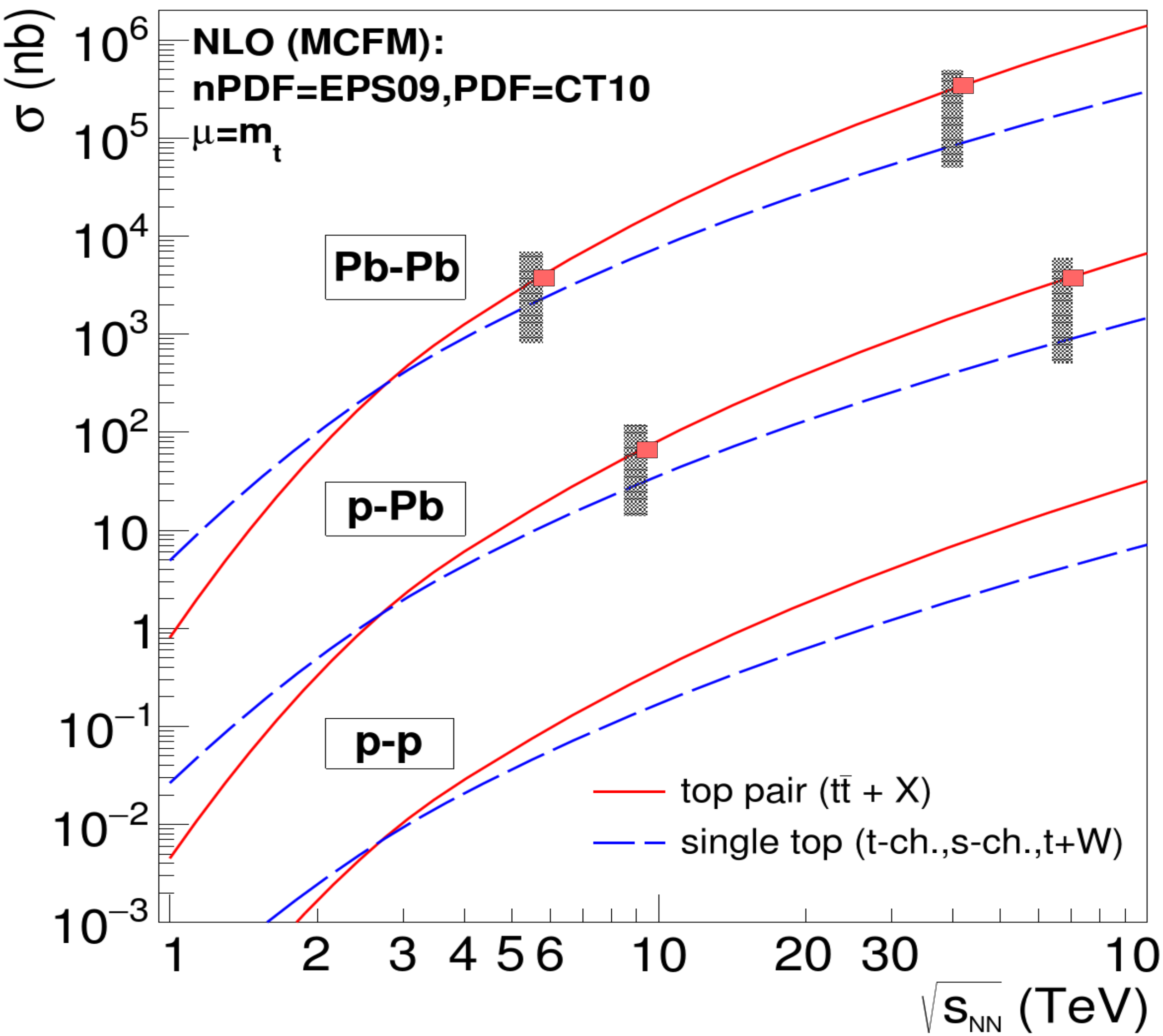



[Apolinário et al., 2017]

# 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

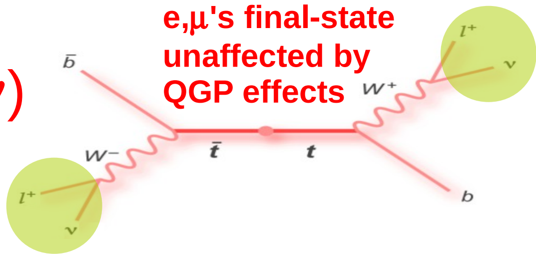
nPDF anti-shadowing increases $\sigma_{tt}$ by +(2-8)%

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

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

# 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)

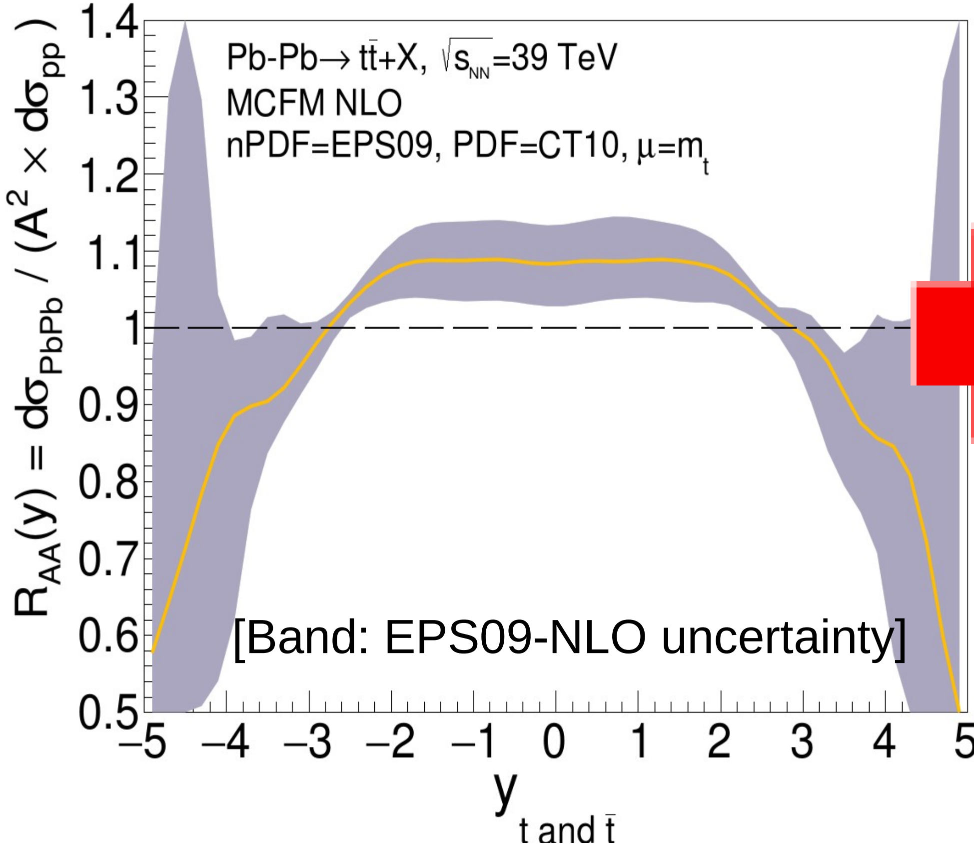



| System | $\sqrt{s_{NN}}$ (TeV) | $\mathcal{L}_{int}$ | $t\bar{t}$ $\sigma_{tot}$ | $t\bar{t} \to b\bar{b}\,\ell\ell\,\nu\nu$ yields | single-t $\sigma_{tot}$ | $tW \to b\,\ell\ell\,\nu\nu$ yields |
|---|---|---|---|---|---|---|
| PbPb | 5.5 | 10 $nb^{-1}$ | 3.4 $\mu b$ | 450 | 2.0 $\mu b$ | 30 |
|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

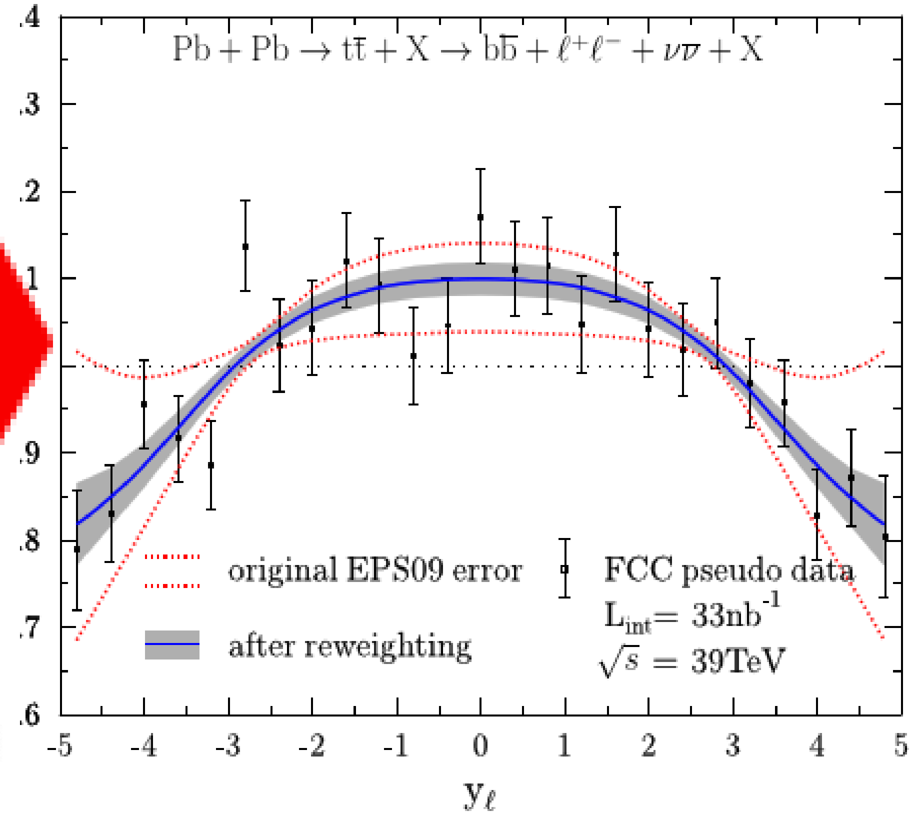
- LHC (nominal $L_{int}$): ~500 t-tbar pairs in Pb-Pb, p-Pb
  (Note: +5000 in ℓ+jets, measurable in p-Pb)
- FCC (nominal $L_{int}$): 0.2–0.4 million/month t-tbar pairs in Pb-Pb,p-Pb

# 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 $nb^{-1}$)

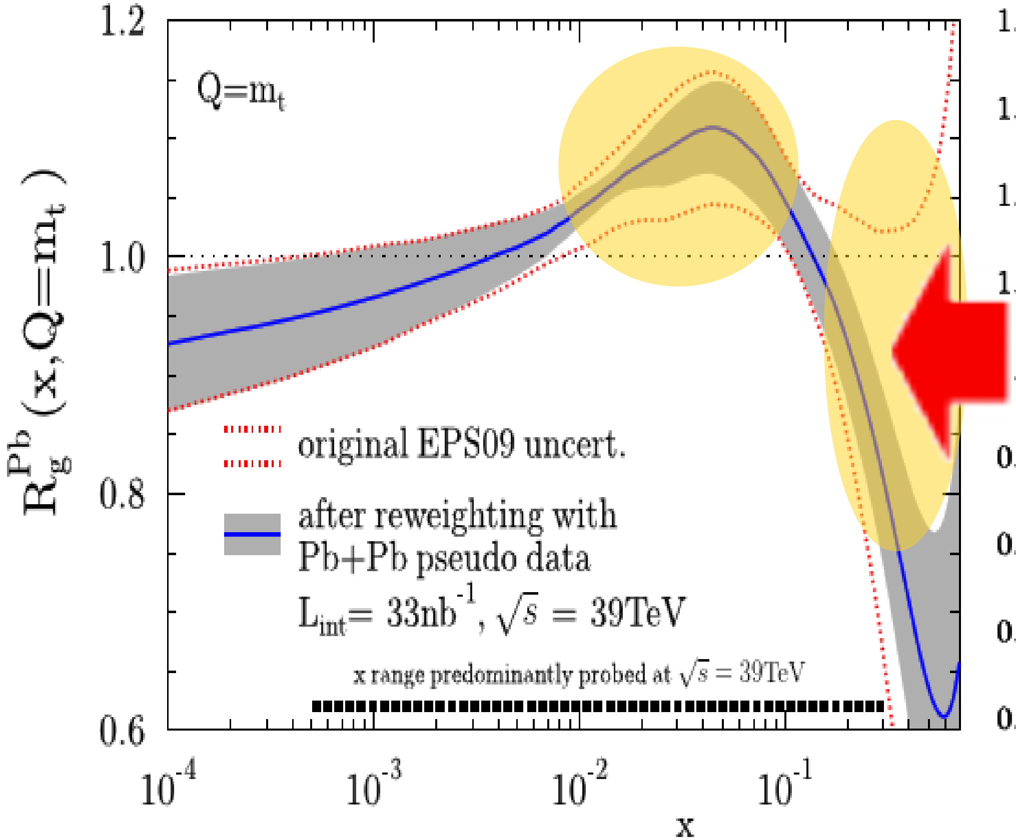



(stat. dominate over syst. uncertainties)

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

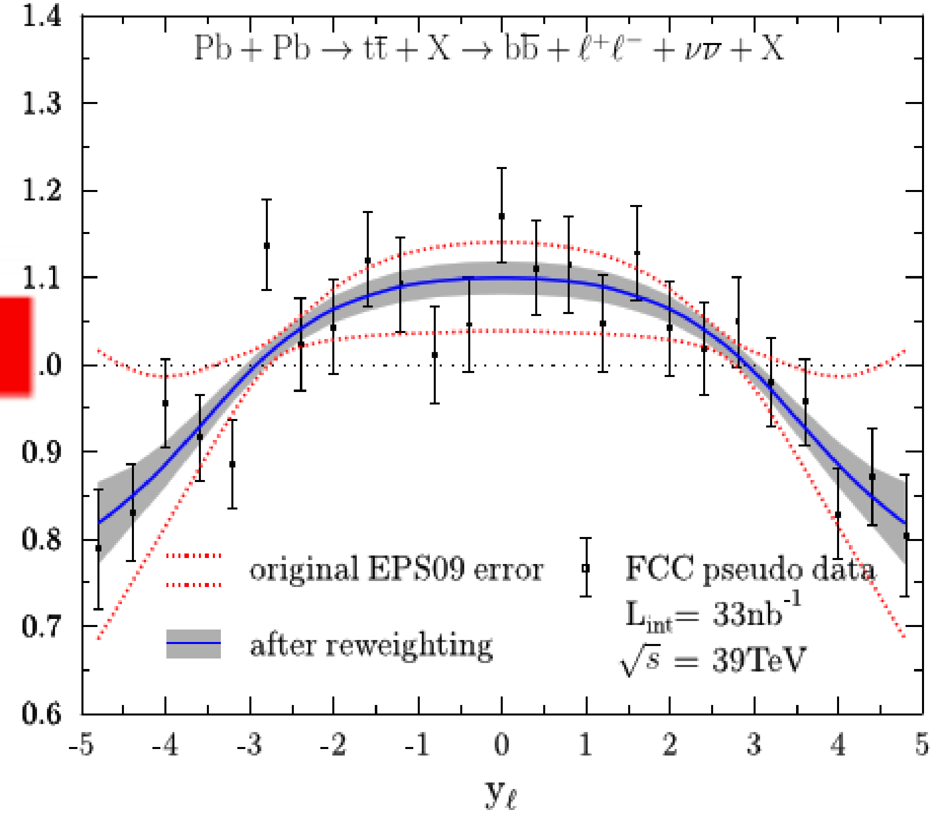
# Pb-Pb(39 TeV)→ t-tbar: $R_{AA}(y)$ for $\ell^{\pm}$ & $R_g^{Pb}(x,Q^2)$

- Improved gluon density via Hessian PDF reweighting




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

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

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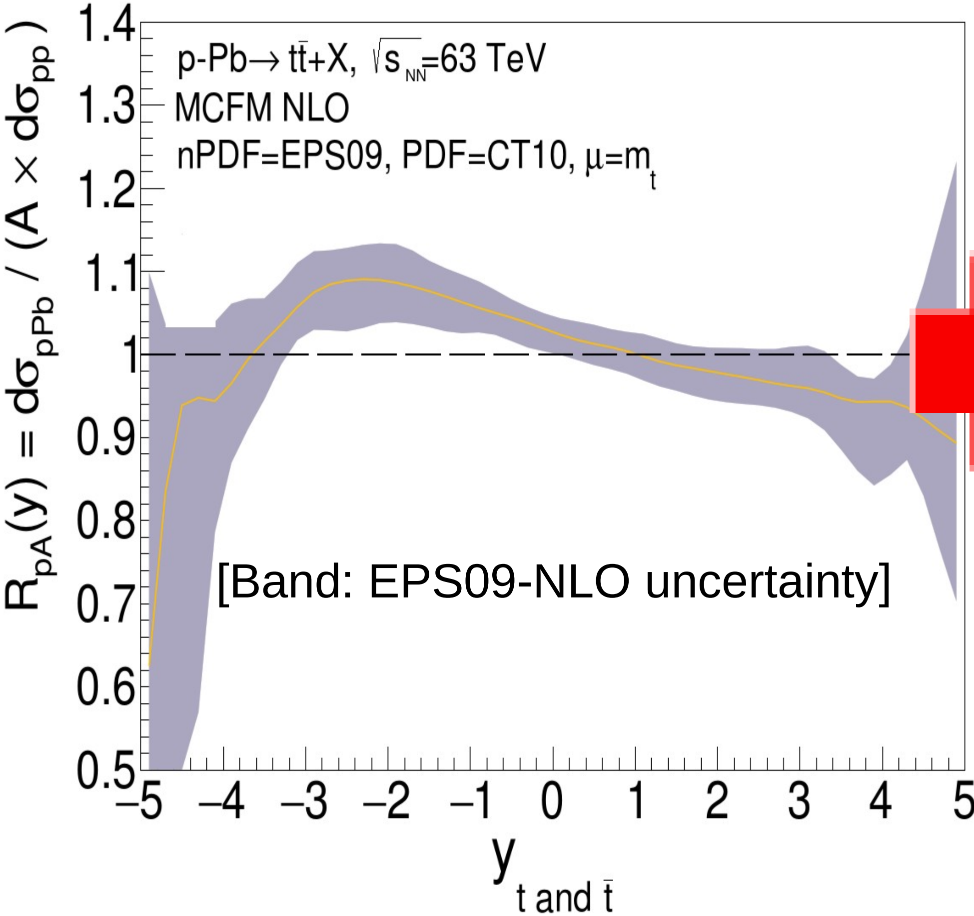
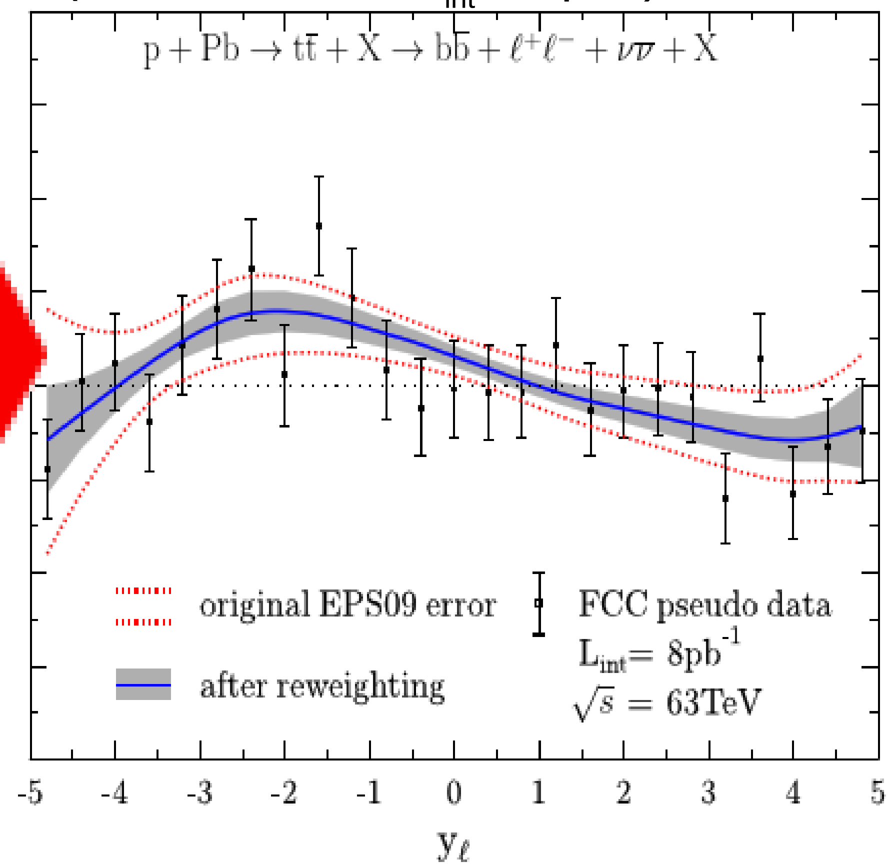



■ Isolated lepton y-distrib. after cuts: (Pseudodata for $L_{int}$= 8 $pb^{-1}$)

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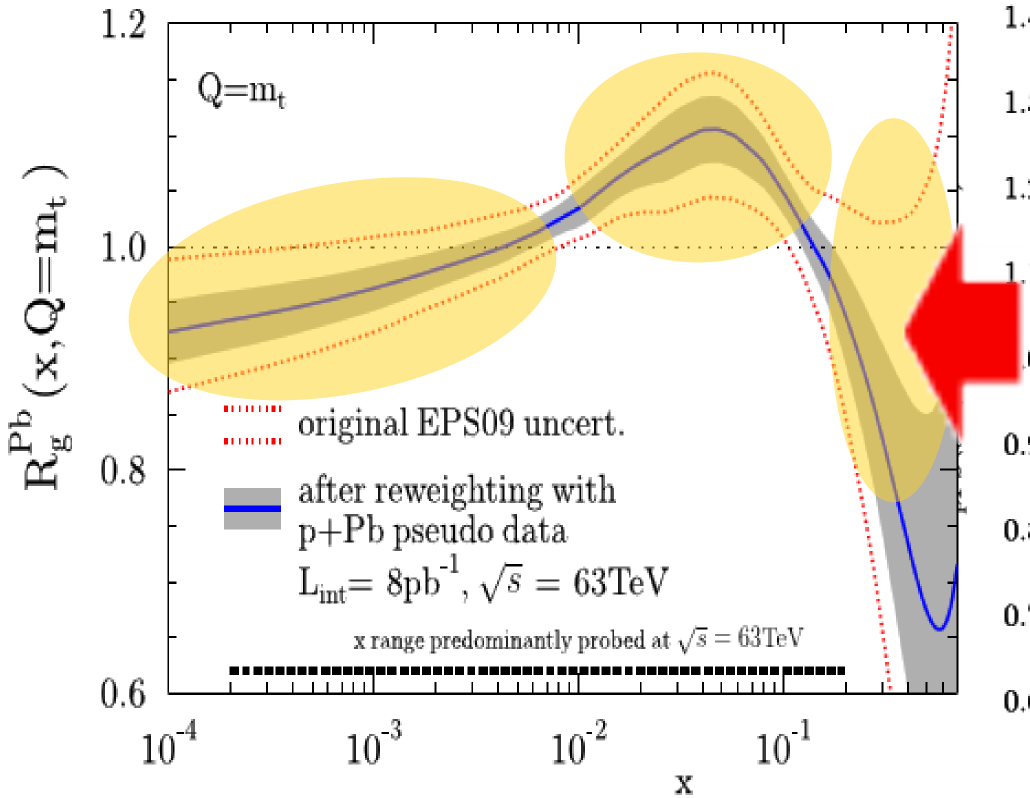
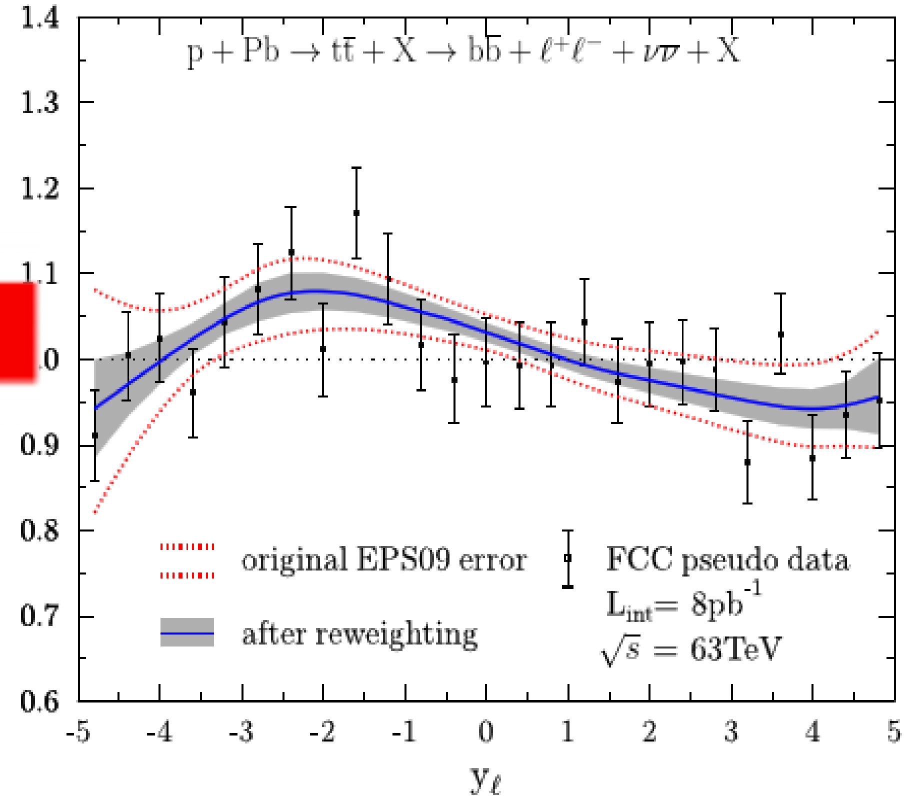



- Significant reduction in uncertainties at low-x ($x<10^{-2}$), antishadowing ($x\sim0.05$) and EMC ($x\sim0.5$) regions

- 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

[Note: 1-month pPb data alone. Lepton+jets adds ×10 more data]

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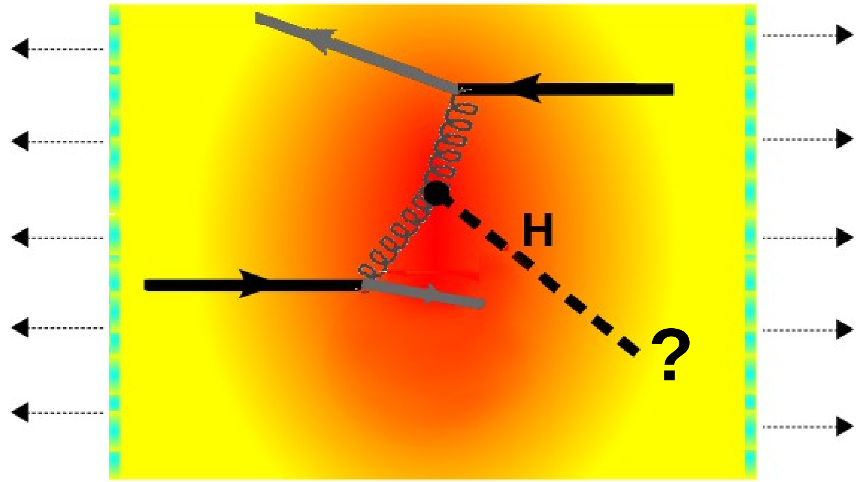
- Physics with $\mathcal{O}$(100-GeV) $\gamma$–$\gamma$ collisions

**"New (HI) physics"**

# H boson quenching in the QGP ?

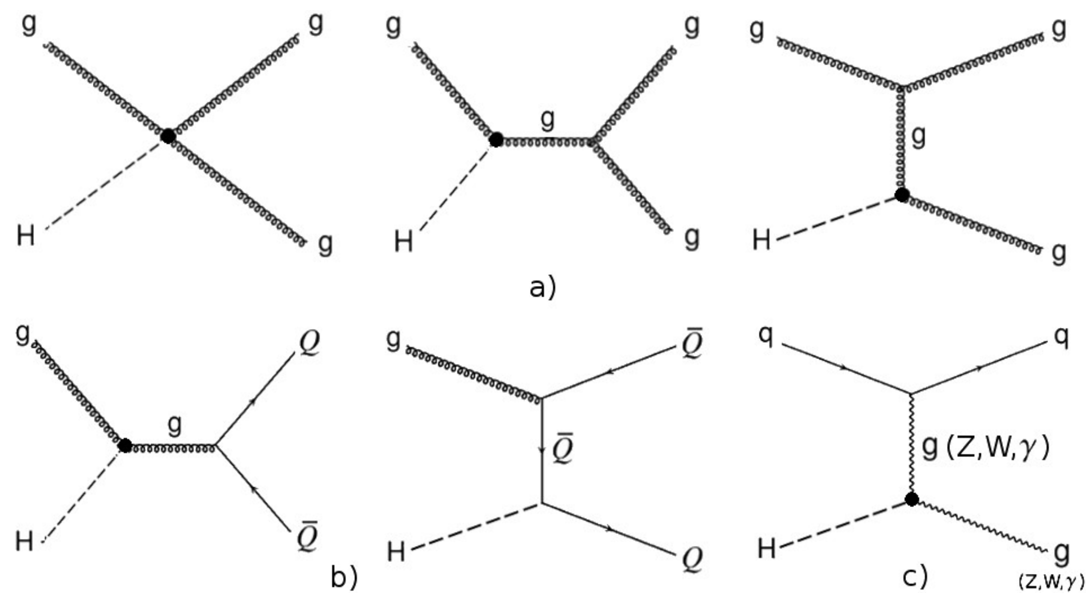
[DdE,C.Loizides, to be submitted]

- SM boson ($\Gamma_H$=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: $\sigma \sim \mathcal{O}(10\ \mu b)$

# H boson quenching in the QGP ?

[DdE,C.Loizides, to be submitted]

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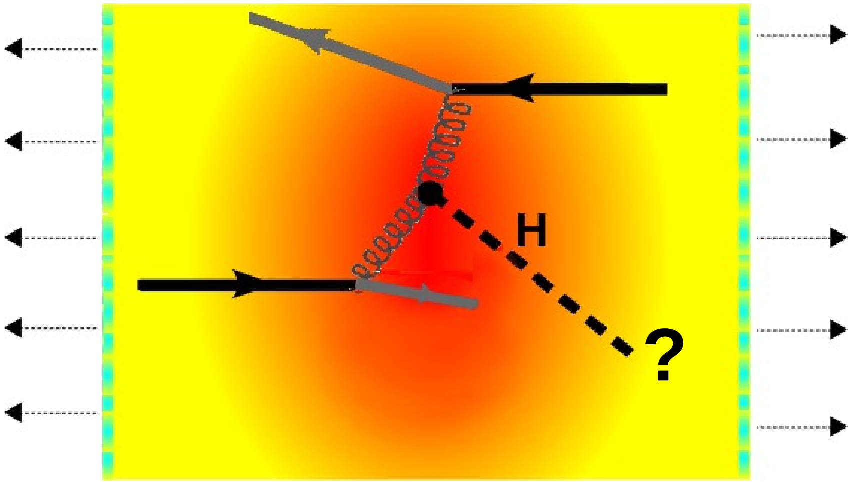
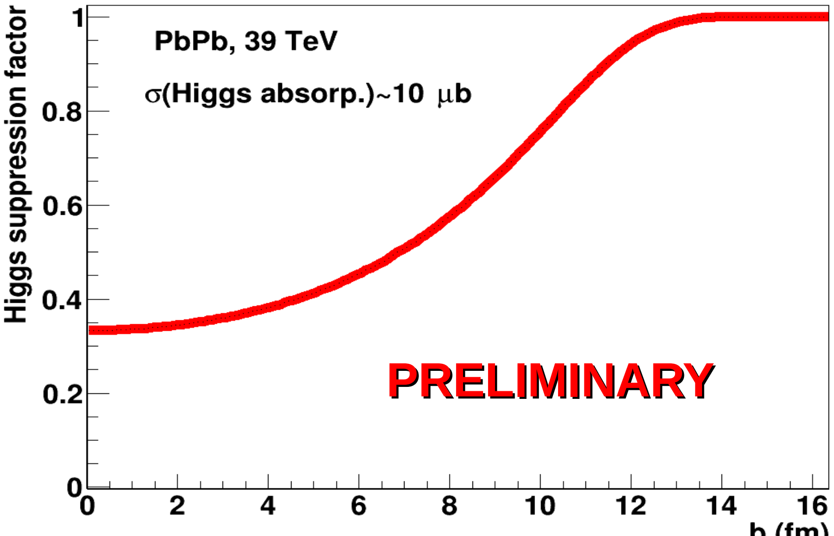



- Survival probability computed combining $\sigma \approx 10\ \mu b$ Higgs "absorption" x-section in QGP (1+1D-Bjorken expansion Glauber MC model):

→ Average Higgs suppression factor in PbPb(39 TeV): ~20%

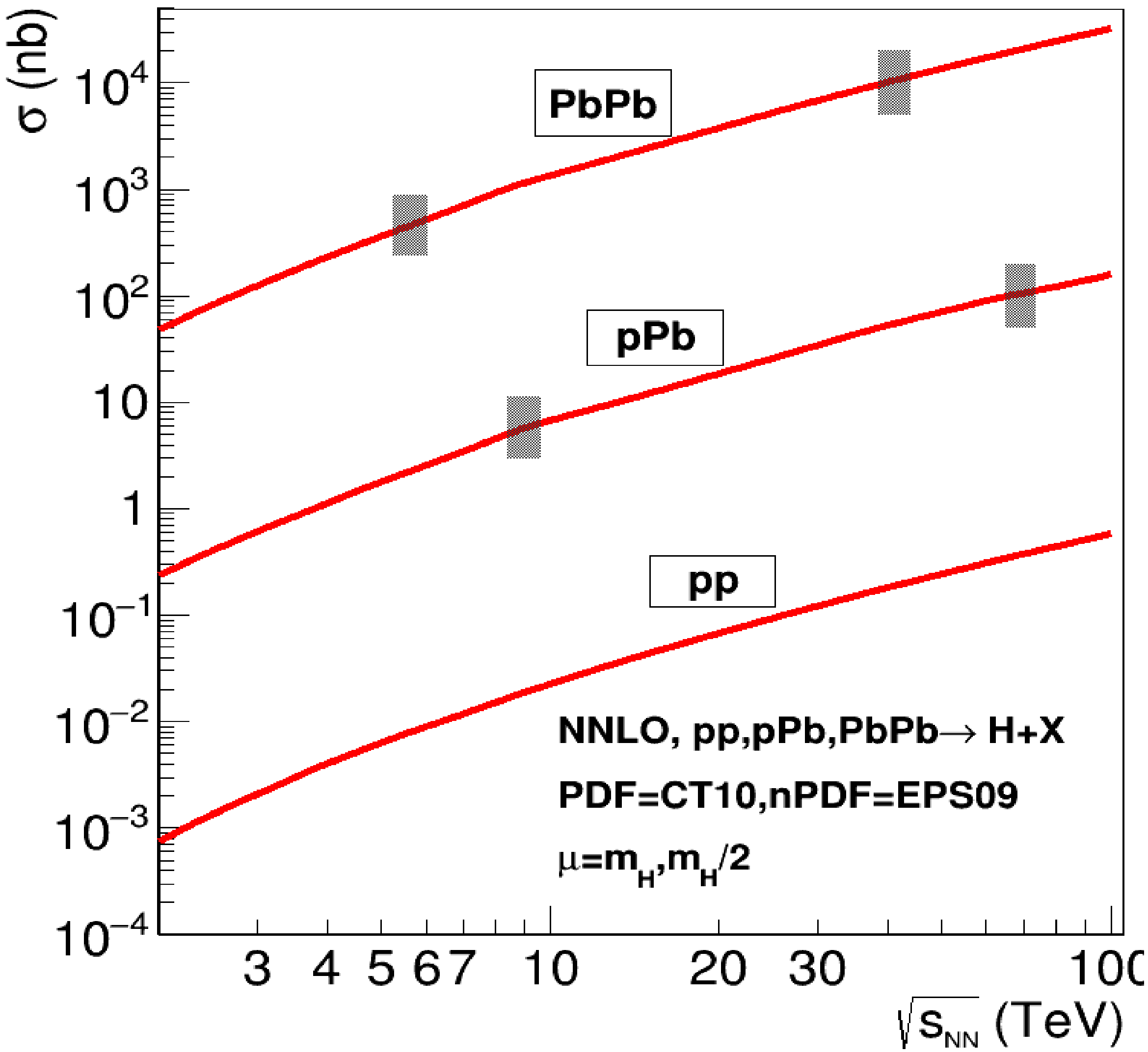



[Central PbPb] [Periph. PbPb]

- Is the H boson observable at FCC?

# 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
FCC(39 TeV) = 12 μb

- p-Pb:

LHC(8.8 TeV) = 6 nb
FCC(63 TeV) = 120 nb

- p-p (reference):

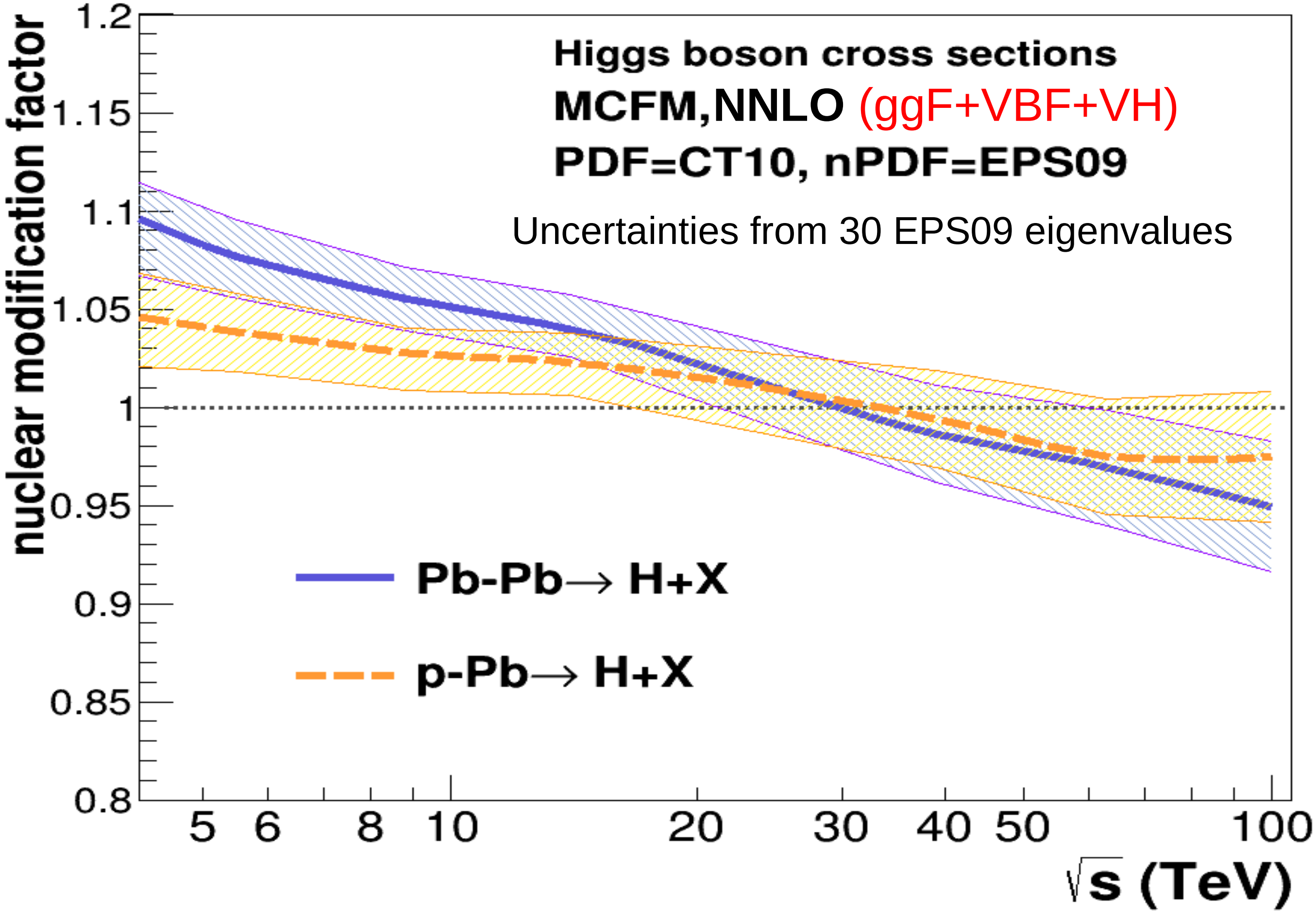
LHC(5.5 TeV) = 12 pb
LHC(8.8 TeV) = 27 pb
FCC(39 TeV) = 270 pb
FCC(63 TeV ) = 490 pb

[DdE, arXiv:1701.08047]

→ Cross-sections increase by about ×20 from LHC to FCC

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

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



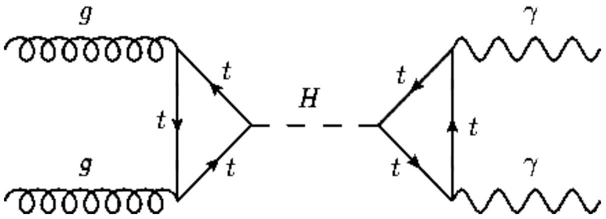

→ LHC: Small antishadowing: $R_{AA}$~ 1.07, $R_{pA}$~1.03

→ 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 $\sigma_{tot}$ | $\to\gamma\gamma$ yields | $\to ZZ^*(4\ell)$ 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 $\mu$b | 450 | 25 |
| pPb | 63 | 8 $pb^{-1}$ | 115 nb | 950 | 50 |

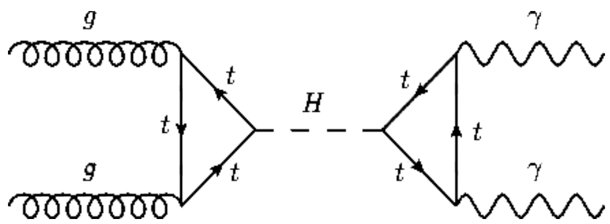
- LHC (nominal $L_{int}$): ~15 Higgs bosons in Pb-Pb, p-Pb

  Note: ×(30–40) $L_{int}$ needed for evidence at LHC

- FCC (nominal $L_{int}$): 500-1000 H bosons/month in Pb-Pb, p-Pb

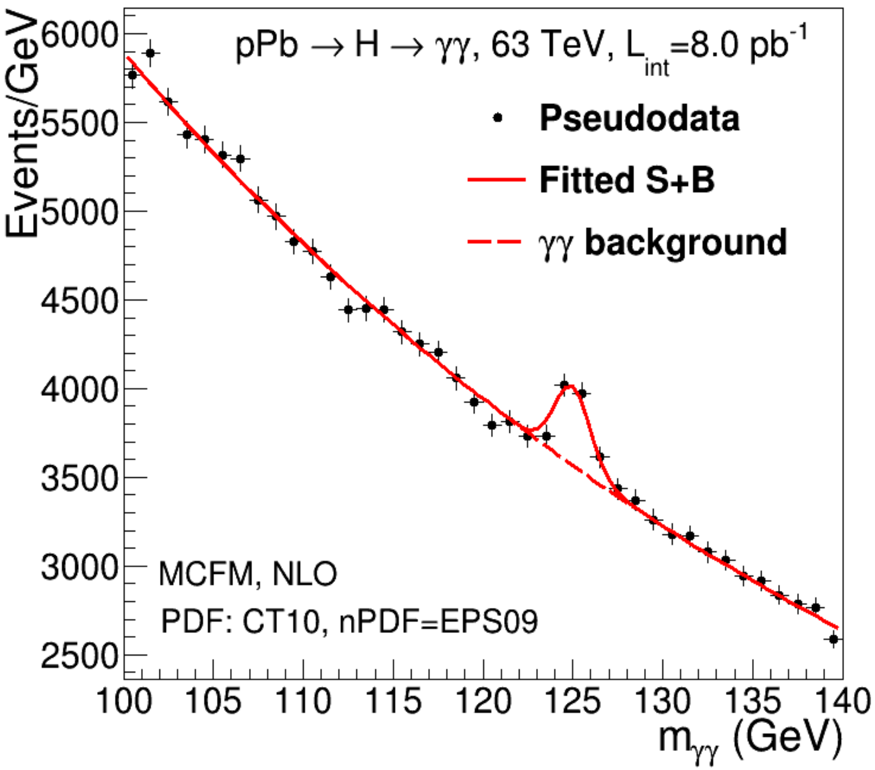
# $H \rightarrow \gamma\gamma$ observation at FCC

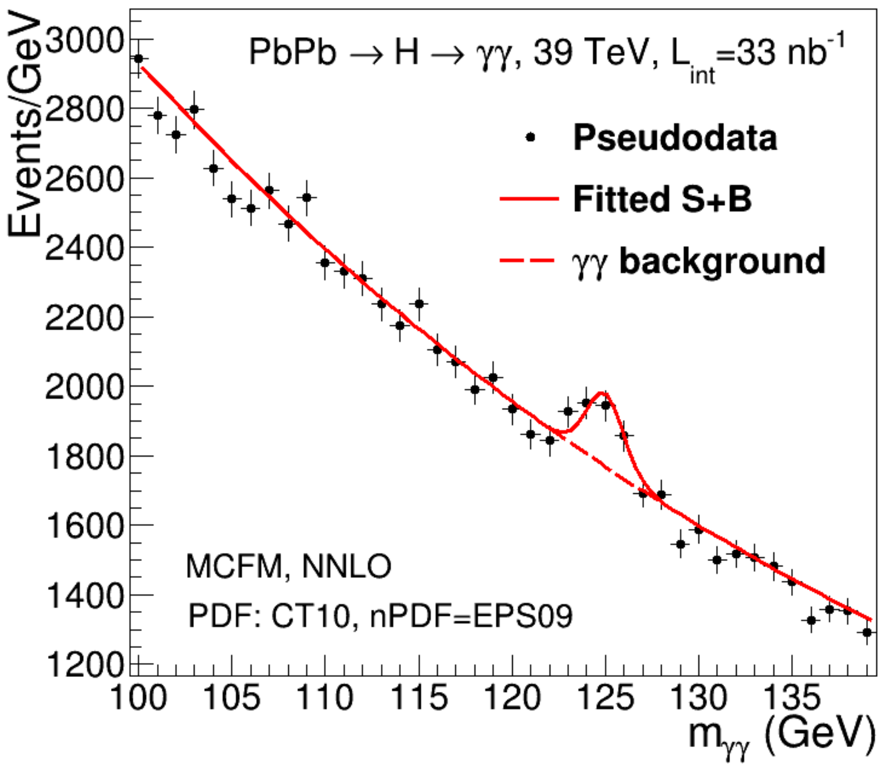
[DdE, arXiv:1701.08047]




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




S/√B~7.7σ observation

S/√B~5.2σ observation

# Outline

- Future Circular Collider (FCC) CERN project
- FCC-AA parameters: PbPb(39TeV,33 $nb^{-1}$), pPb(63TeV,8 $pb^{-1}$)

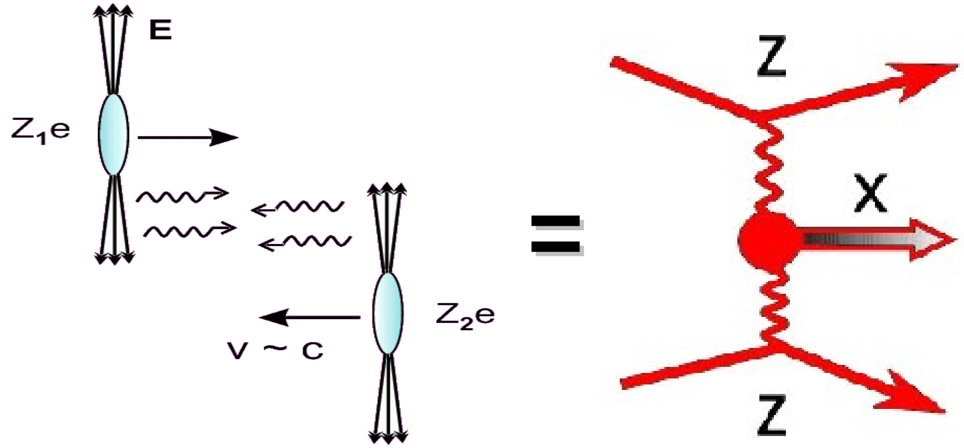
- PbPb(39 TeV): Global properties
- PbPb(39 TeV): Thermalized charm
- PbPb(39 TeV): Quarkonia at $T \sim 5 \cdot T_c$
- pPb(63 TeV): (Very) small-x physics

- Physics with top-quarks
- Physics with Higgs boson
- Physics with $\mathcal{O}$(100-GeV) $\gamma$–$\gamma$ collisions

**"New (HI) physics"**

# γ-γ collisions at FCC-ions

- Electromagnetic ultra-peripheral collisions (UPC): $b_{min} > R_A + R_B$
- HE ions generate huge EM fields ($10^{14}$ T) from coherent action of Z=82 p:



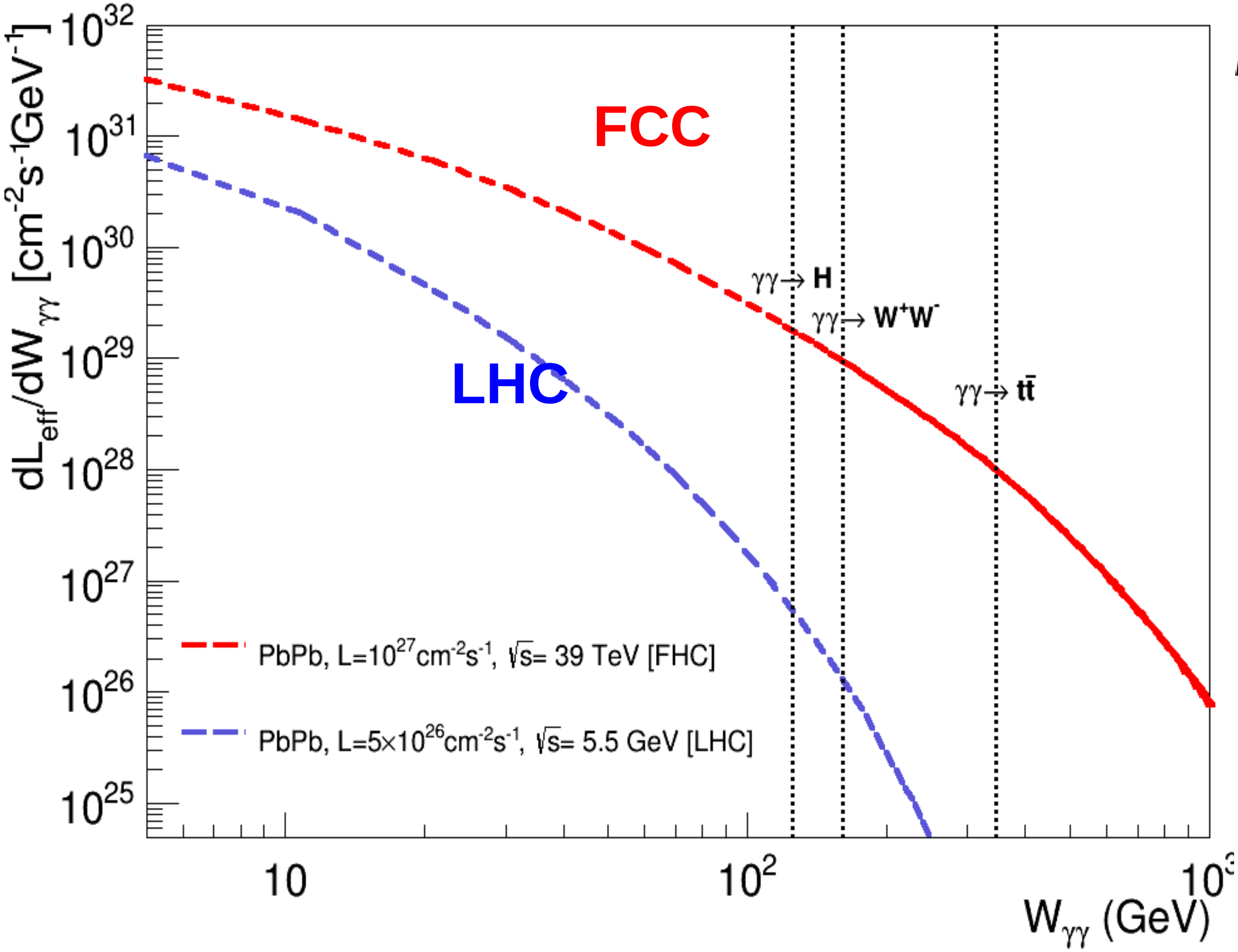

- Huge photon fluxes:
  $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5 \cdot 10^7$ for PbPb) larger than p,$e^\pm$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

- Quasi-real photons (coherence): Q ~ 1/R ~ 0.06 GeV (Pb), 0.28 GeV (p)
- Maximum γ energies (FCC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 0.6 TeV (Pb), ~ 18 TeV (p)

| System | $\sqrt{s_{NN}}$ (TeV) | $\mathcal{L}_{AB} \cdot \Delta t$ (per year) | $\gamma$ ($\times 10^3$) | $\omega_{max}$ (TeV) | $\sqrt{s_{\gamma\gamma}^{max}}$ (TeV) |
|---|---|---|---|---|---|
| p-p | 100 | 1 $fb^{-1}$ | 53. | 17.6 | 35.2 |
| p-Pb | 64 | 1 $pb^{-1}$ | 33.5 | 0.95 | 1.9 |
| Pb-Pb | 39 | 5 $nb^{-1}$ | 21. | 0.60 | 1.2 |

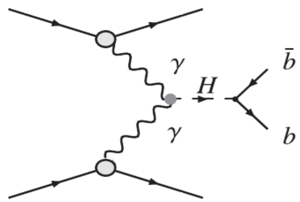
# γ-γ luminosity & physics at FCC-ions

- "Low masses": x4 higher effective lumi than at PbPb(5.5 TeV)
  Huge stats for: $\gamma\gamma \to \gamma\gamma$, double VM ($\gamma\gamma \to \rho\rho$, J/ψJ/ψ, ϒϒ),...
- High masses : x400 more lumi than LHC for Higgs
  x700 more lumi than LHC for W+W- (anomalous QGC)

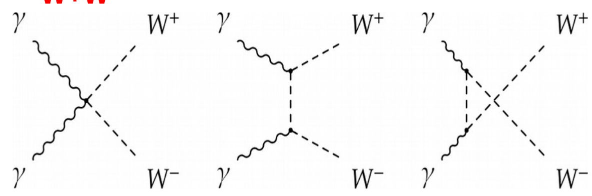



$$N_X = \int \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} W_{\gamma\gamma} \sigma_X^{\gamma\gamma}(W_{\gamma\gamma})$$

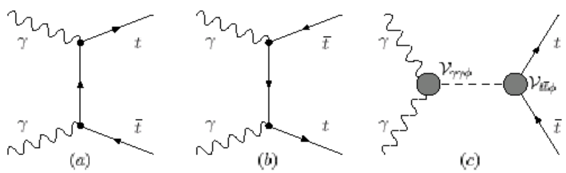
**$N_{Higgs}$ ~ $10^2$ counts/month**



**$N_{W+W-}$ ~ $10^3$ counts/month**



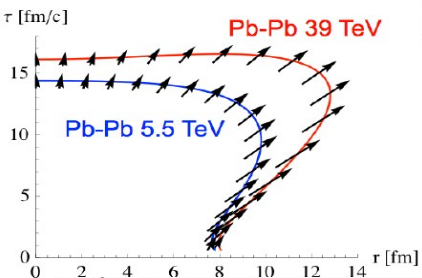
**$N_{t\text{-}tbar}$ ~ few counts/month**

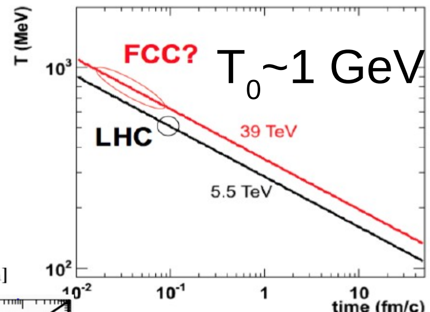


# FCC summary: pPb(63 TeV), PbPb(39 TeV)

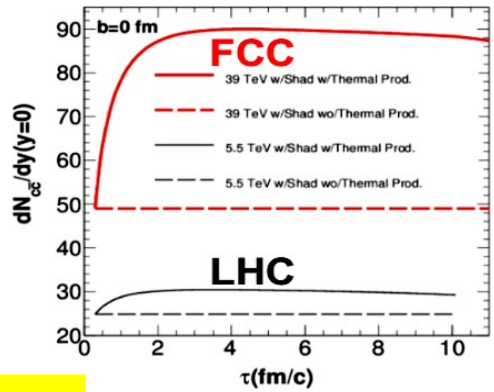
- Accessible HI physics at ×7 larger √s and ×10 larger $L_{int}$ than LHC:

**×2 larger particle & energy densities**

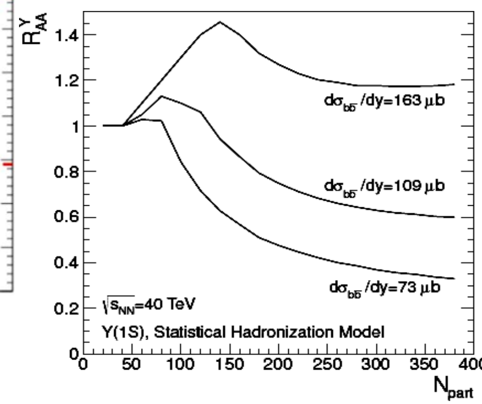


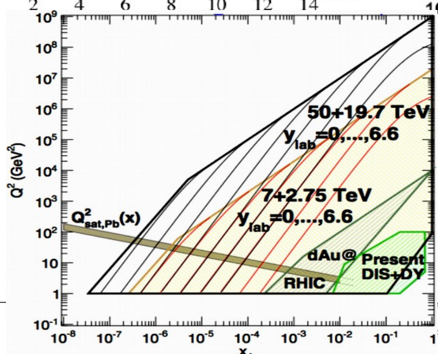




**×3 larger ccbar densities**



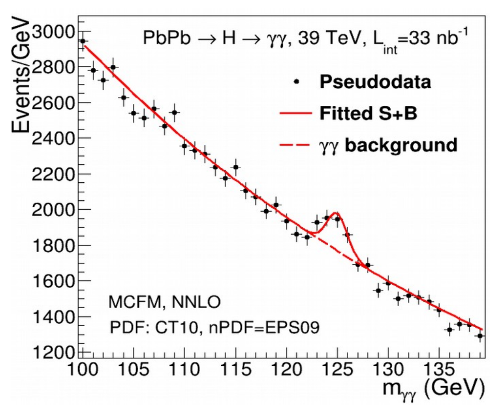

**Υ(1S) melt.+recomb.?**



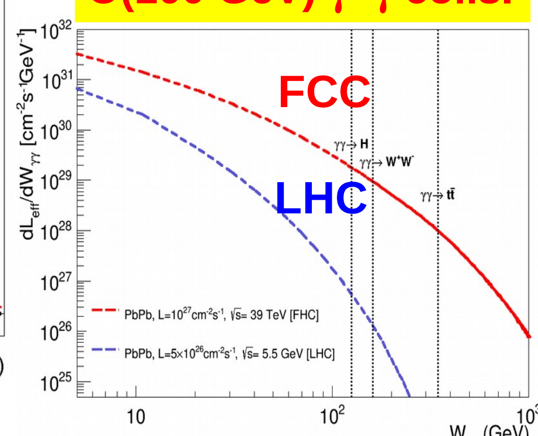



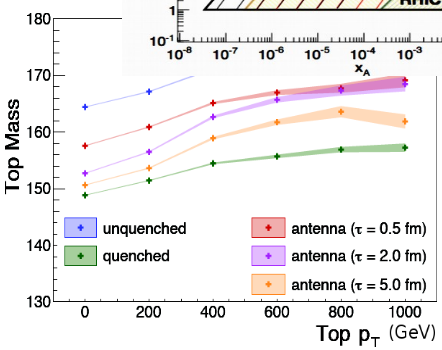

**Low-x phys. to x~$10^{-7}$**

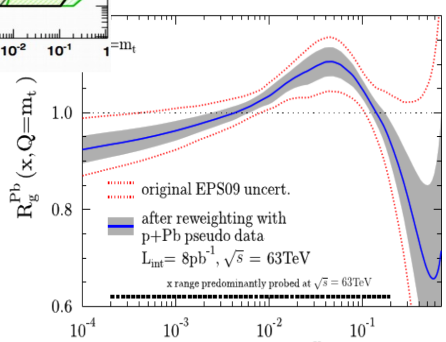
**Higgs suppression?**




**O(100 GeV) γ–γ colls.**



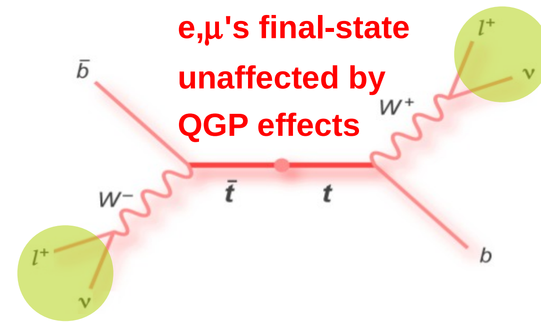




**Top quark = Parton rad. "chrono-fmeter"**
**= high-x gluon nPDF probe**

# Back-up slides

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

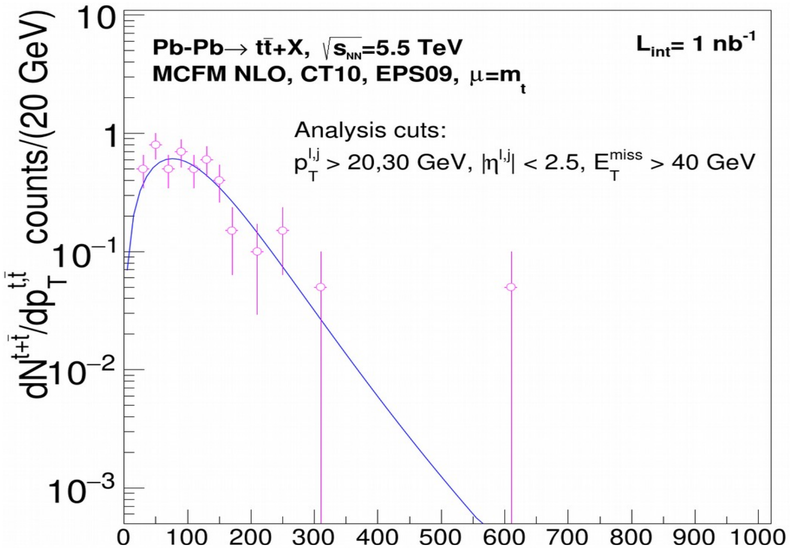
- **Branching ratios, acceptance & efficiency losses**:

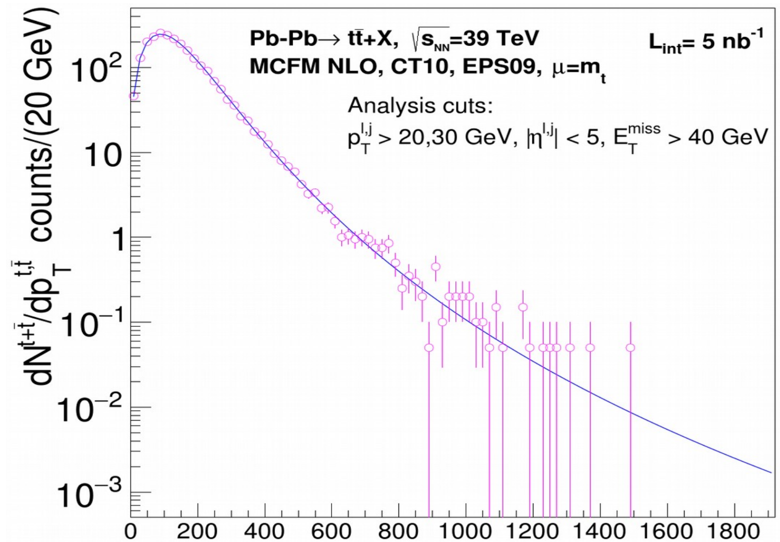
| | |
|---|---|
| t-tbar: | BR~5%, Acc×Eff ~ 40% (LHC), 50% (FCC) |
| Single-top: | BR~22%, Acc×Eff ~ 21% (LHC), 30% (FCC) |

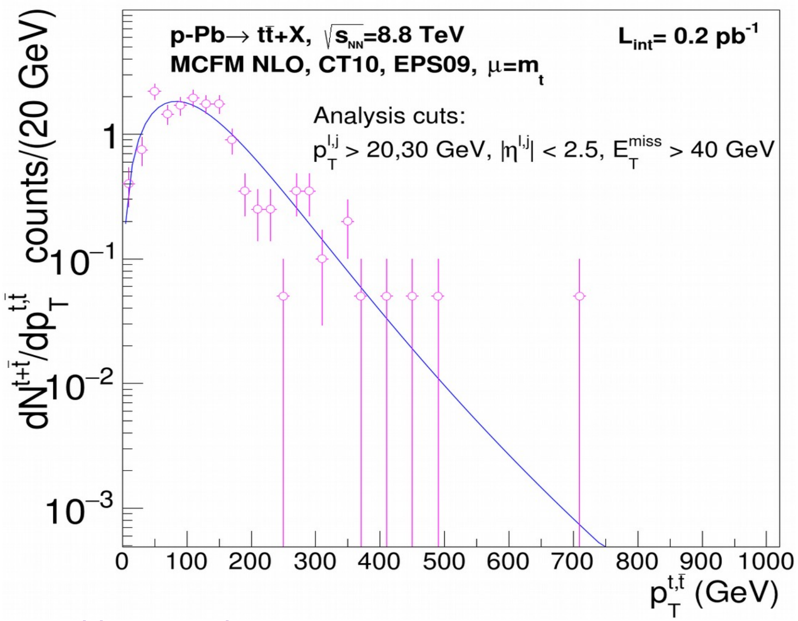
- **Backgrounds** (W,Z+j): Controllable for t-tbar (much worst for single-t)

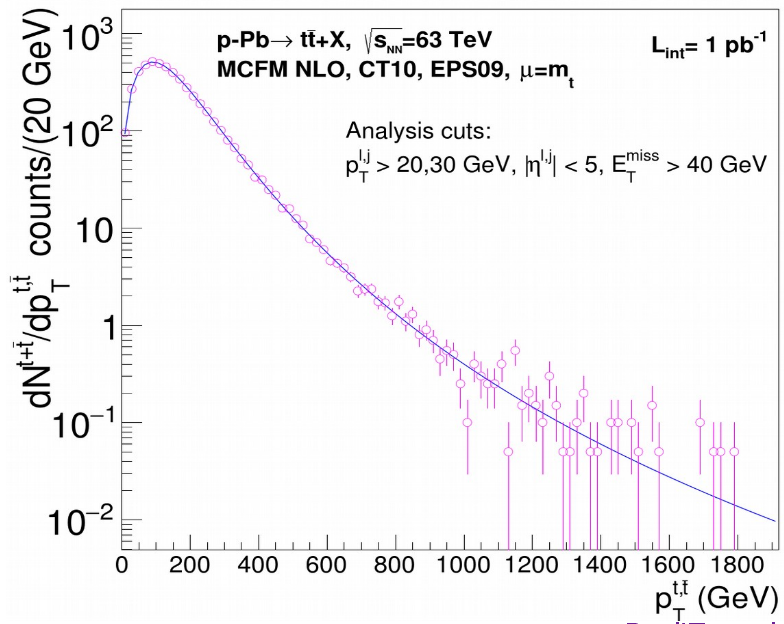
# Differential top-pair $p_T$ distributions

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



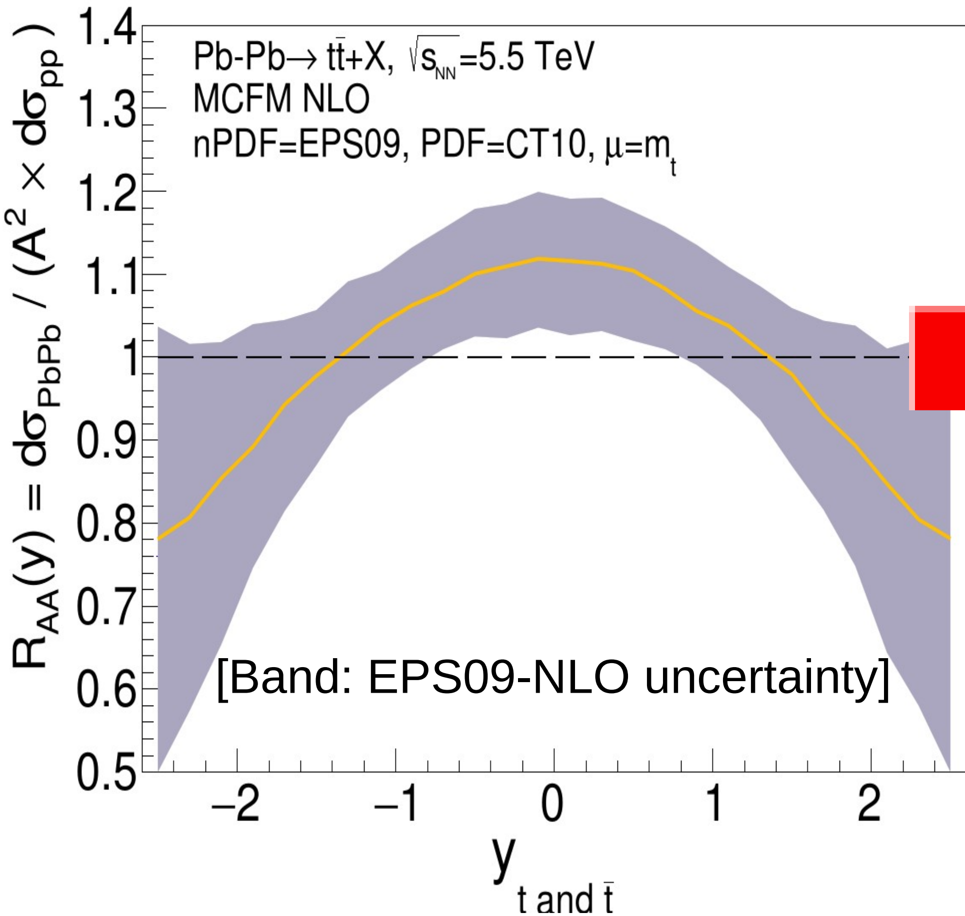



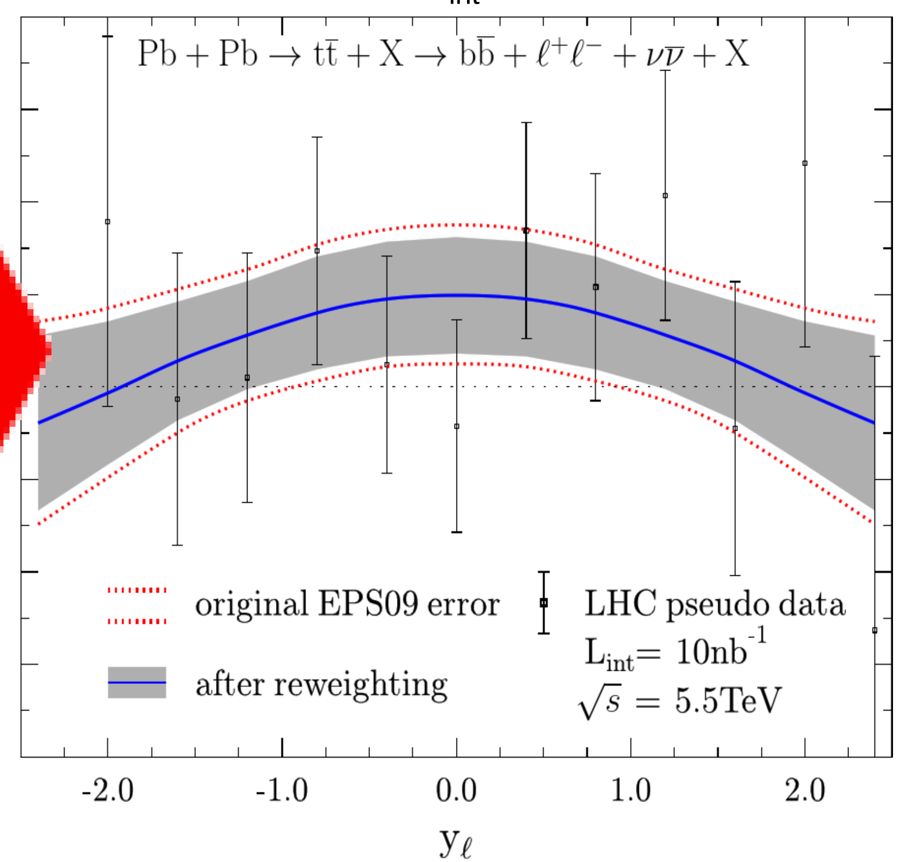
# PbPb→ttbar+X (5.5 TeV): Nuclear modif. factor

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




- nPDF effects (top): -20% (fwd) +10% (cent.)

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



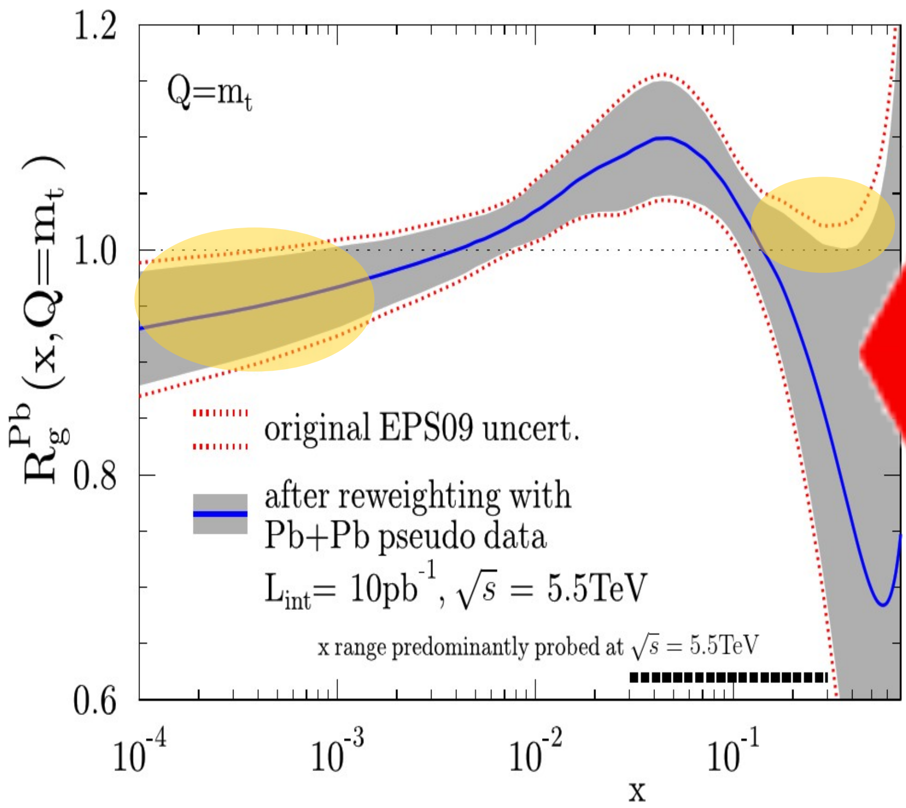

(stat. to dominate over syst. uncertainties)

- nPDF effects (lepton): ±10%

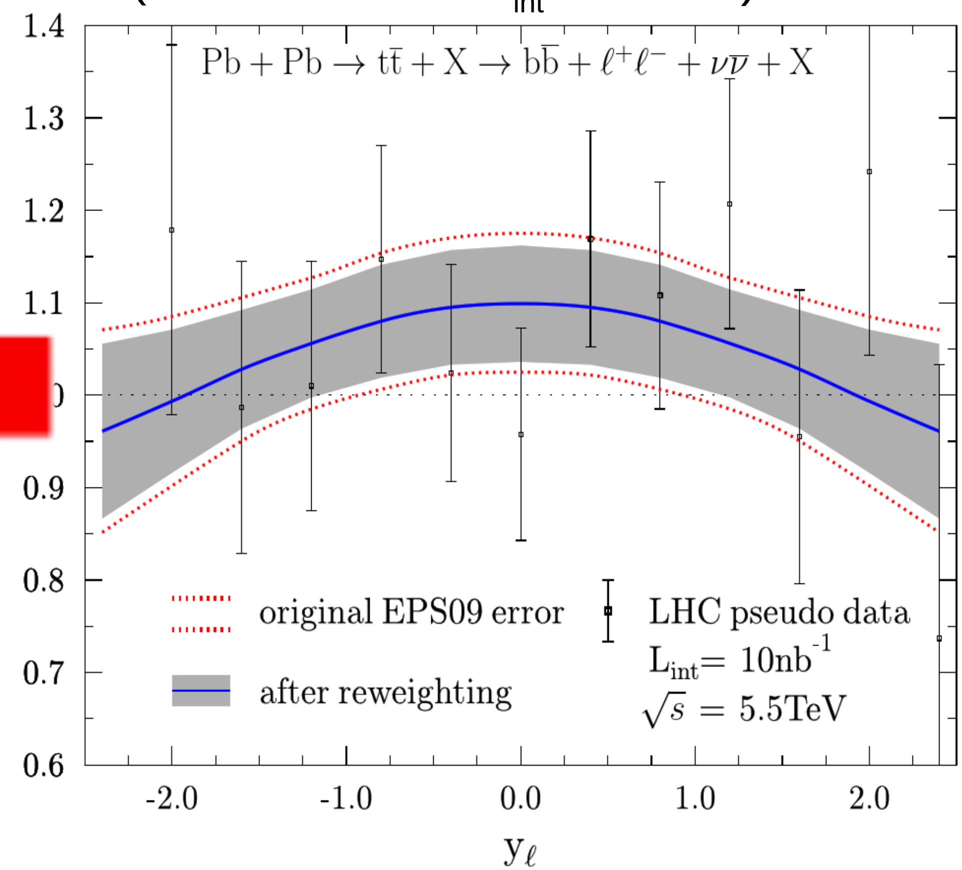
$L_{int}$=10 $nb^{-1}$: some constraining power

# 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$^{-1}$)



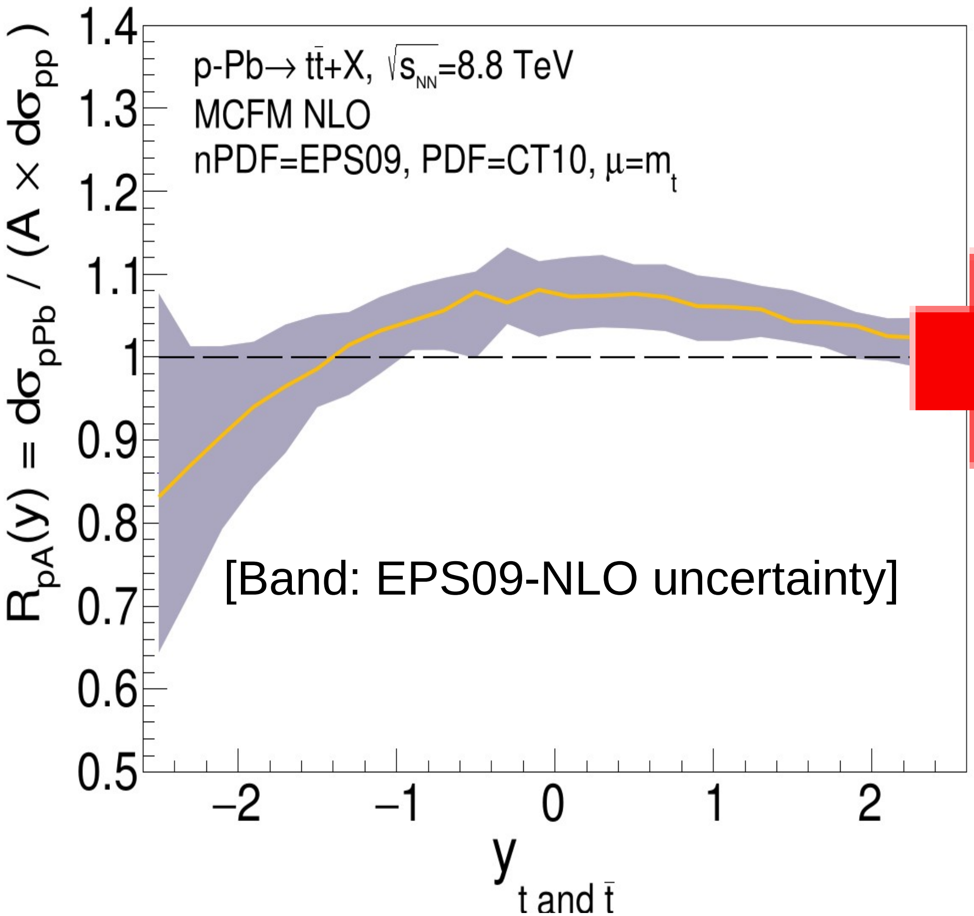

- ~10% reduction in uncertainties at low x (x~$10^{-4}$-$10^{-2}$) and EMC (x~0.3) regions

(stat. to dominate over syst. uncertainties)

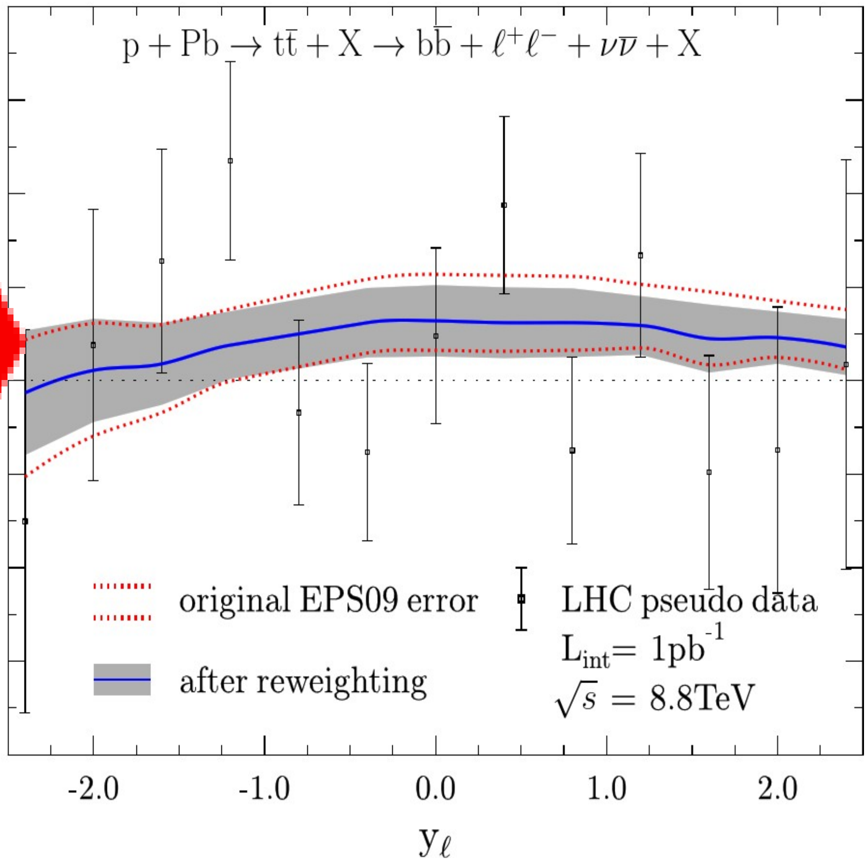
- nPDF effects (lepton): ±10% $L_{int}$=10 nb$^{-1}$: some constraining power

# 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 $pb^{-1}$)

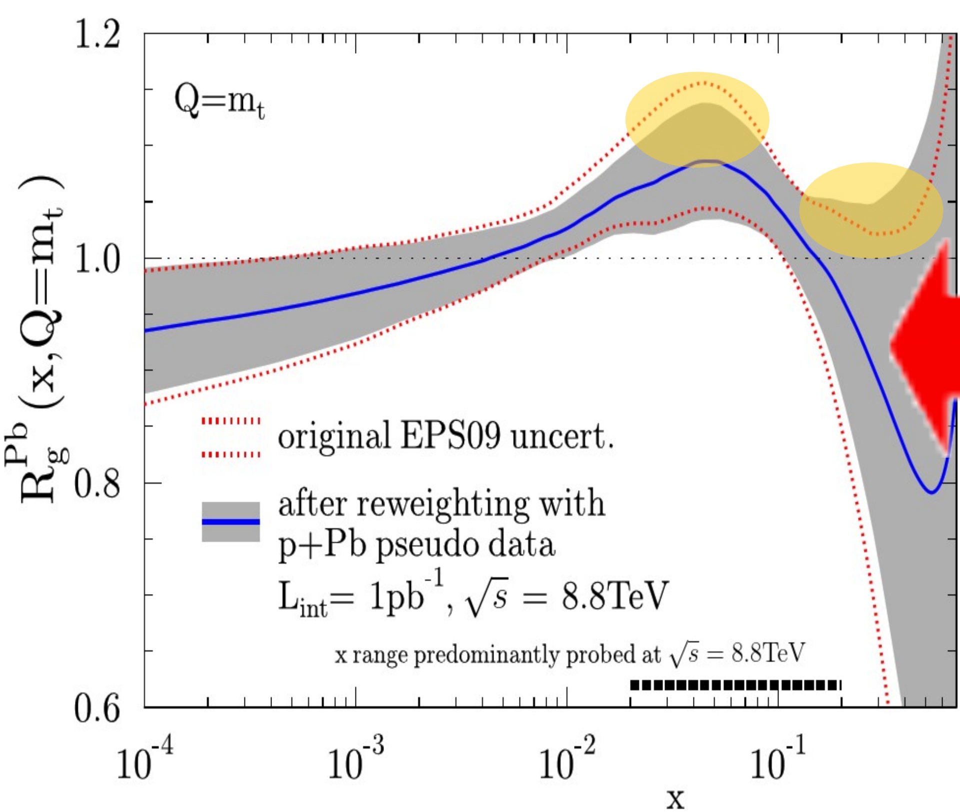



(stat. to dominate over syst. uncertainties)

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

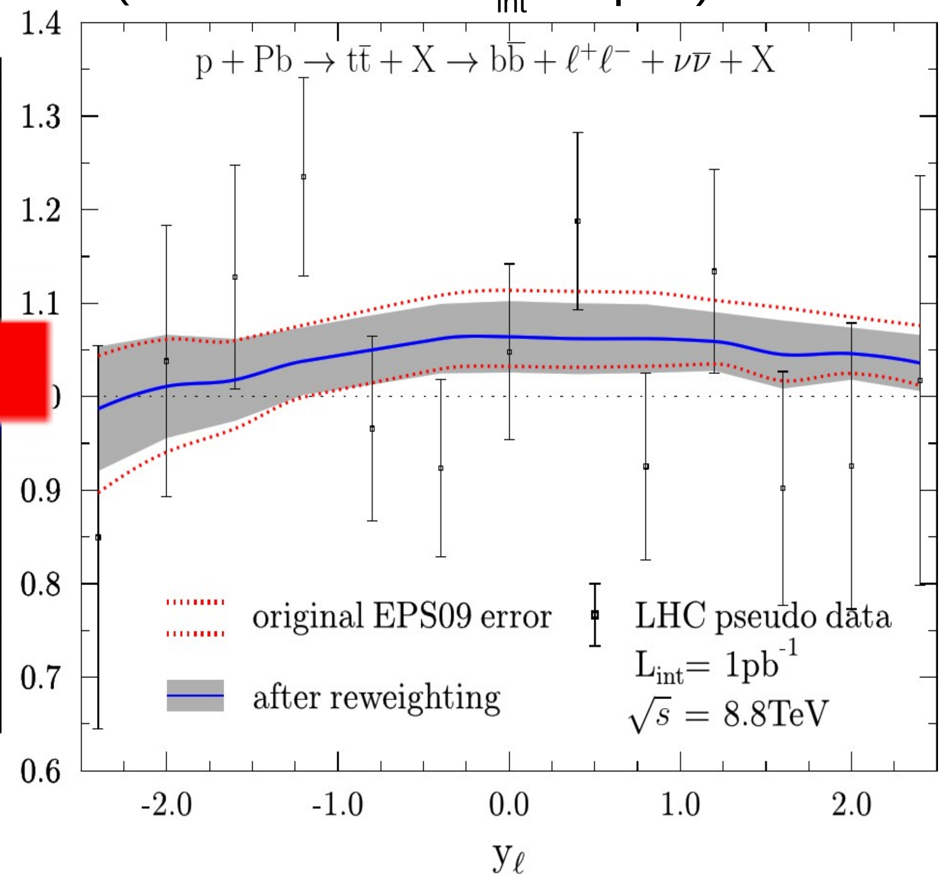
# pPb→ttbar+X (8.8 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting




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

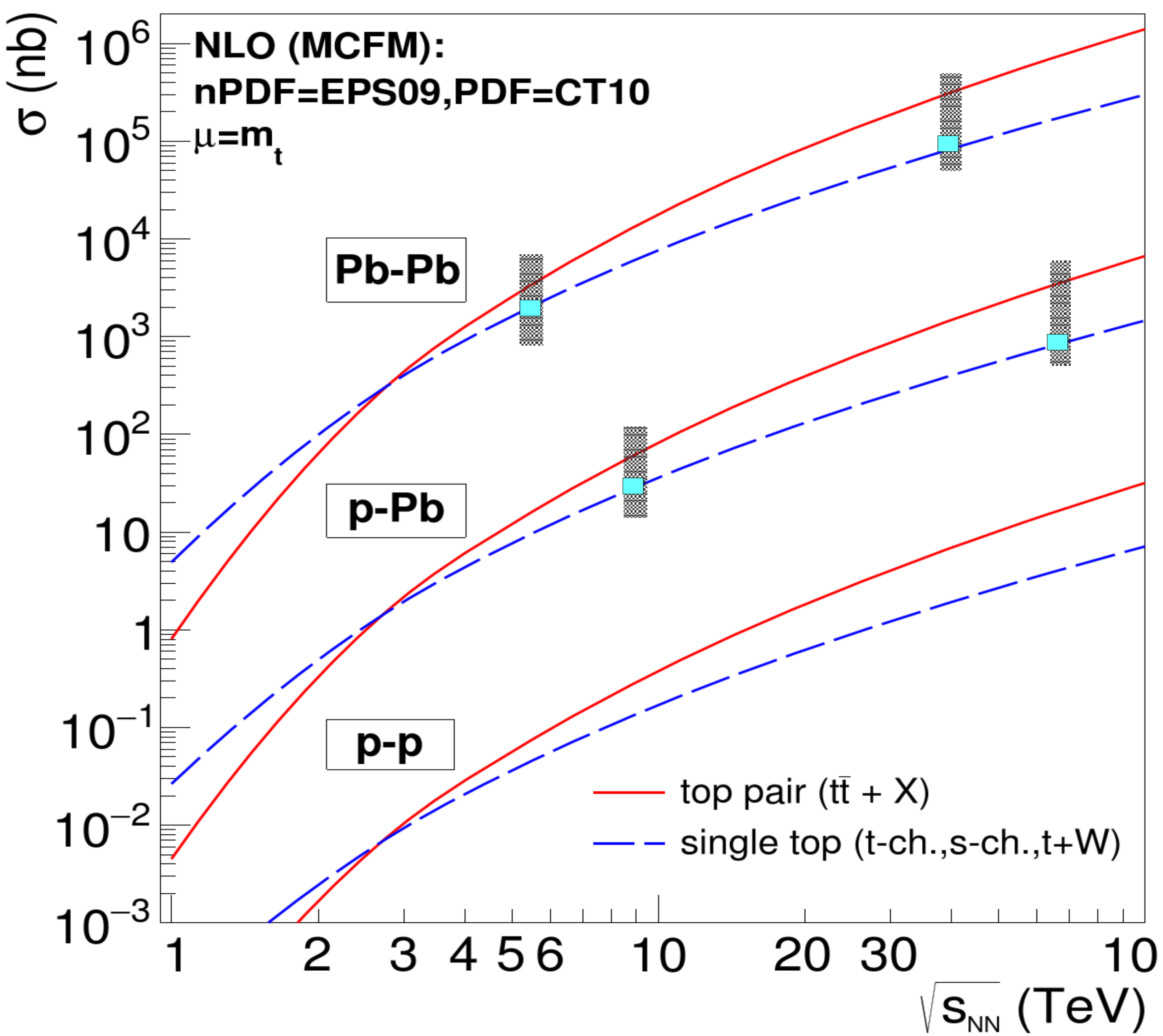
- Isolated lepton y-distrib. after cuts: (Pseudodata for $L_{int}$= 1 $pb^{-1}$)




(stat. to dominate over syst. uncertainties)

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

# 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

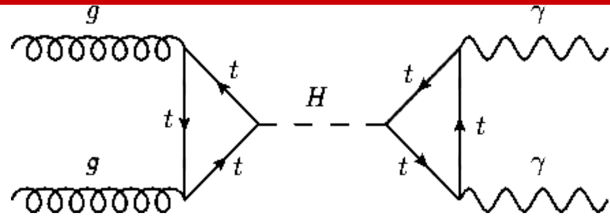
FCC(63 TeV ) = 2.6 nb

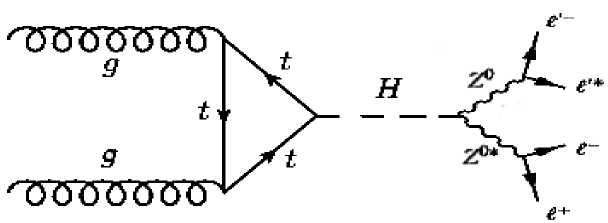
nPDF (anti)shadowing changes $\sigma_{single\text{-}t}$ by ±2%

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

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

# $H \to \gamma\gamma$, $4l$ (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:

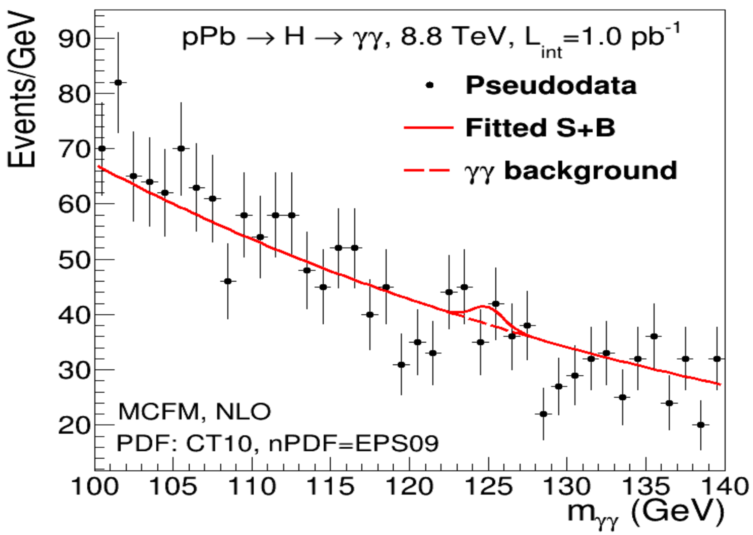
γγ: BR = 0.27%, Acc×Eff ~ 45% (LHC), 60% (FCC)
$ZZ^* \to 4l$: BR = 0.12%, Acc×Eff ~ 60% (LHC), 70% (FCC)

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

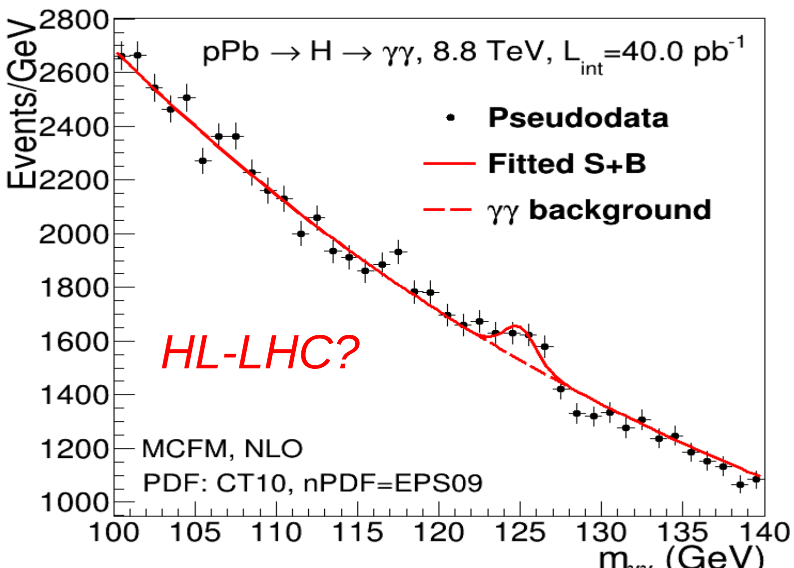
γγ: QCD continuum (MCFM $nproc$=285) +30% $\gamma$-$\gamma^*_{jet}$, $\gamma^*_{jet}$-$\gamma^*_{jet}$
$ZZ^* \to 4l$: ZZ* non-resonant (MCFM $nproc$=90)

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

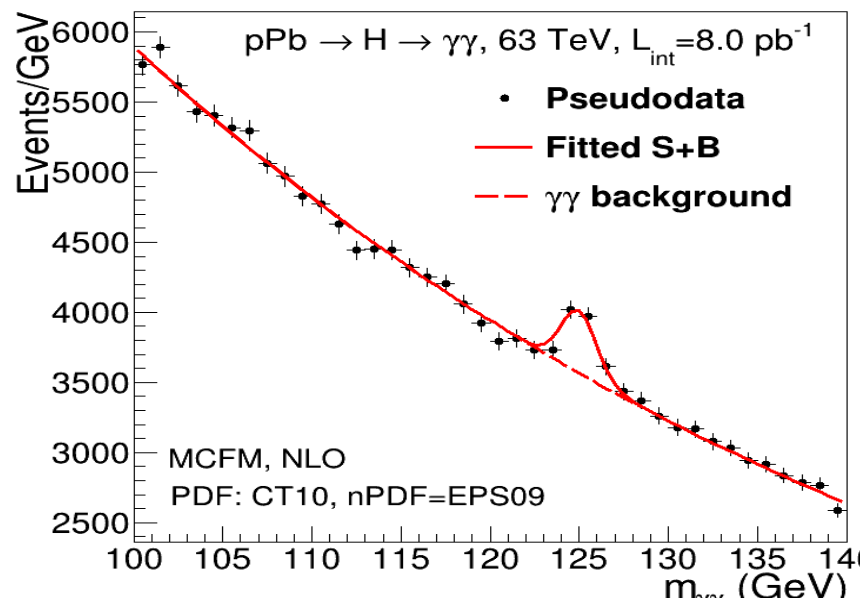
$L_{int}$= 40 $pb^{-1}$: 3σ evidence (HL-LHC?)

4.2σ combined with H(4$l$)

→ FCC (63 TeV, 8 $pb^{-1}$):

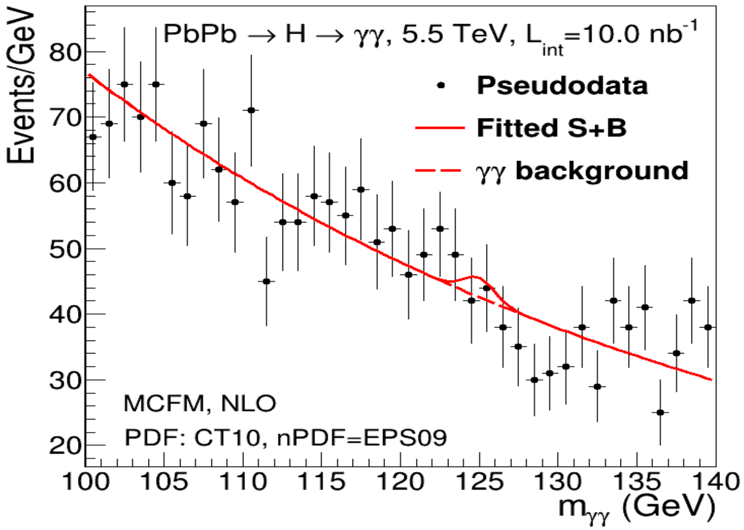
Nominal lumi: $S/\sqrt{B}$~7.7σ observation

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

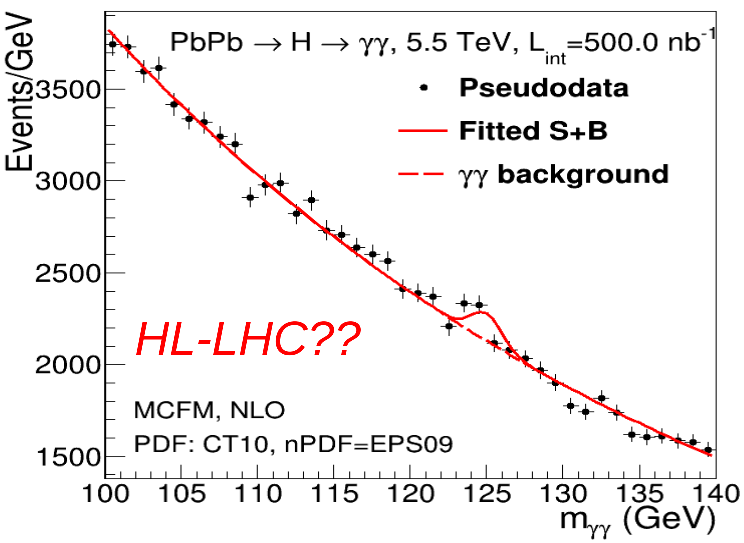


# H→γγ observation in Pb-Pb (LHC, FCC)

- 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: $S/\sqrt{B}$~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: $S/\sqrt{B}$~5.2σ observation

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