Top quark and quarkonia production in heavy-ion collisions with the ATLAS experiment

Yue Xu
On behalf of the ATLAS Collaboration

University of Washington

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Outline

- Observation of $t\bar{t}$ production in $p + Pb$ collisions at 8.16 TeV arXiv:2405.05078 (submitted to JHEP)

- $\Upsilon(nS)$ nuclear modification factors at 5.02 TeV Phys. Rev. C 107 (2023) 054912

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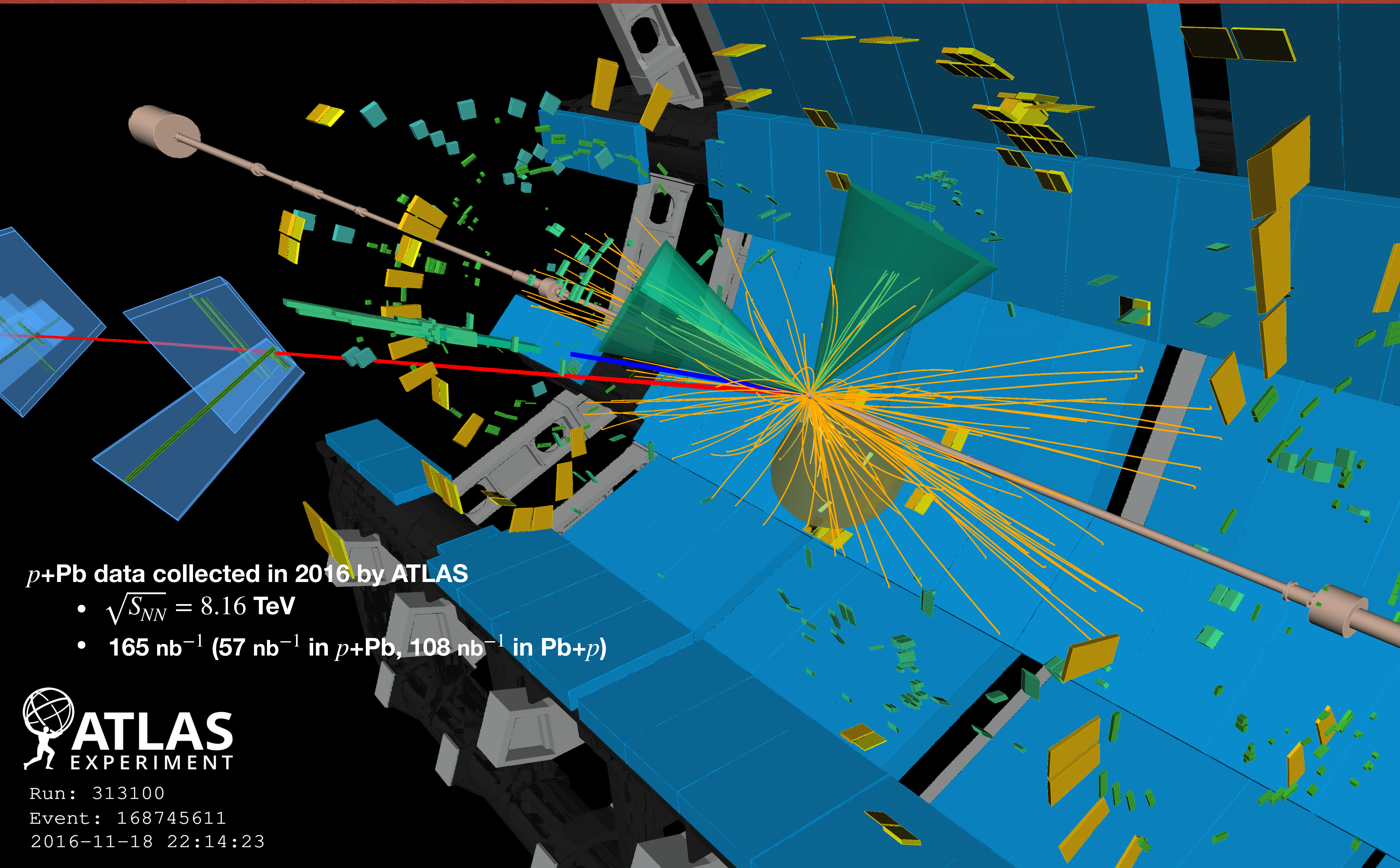
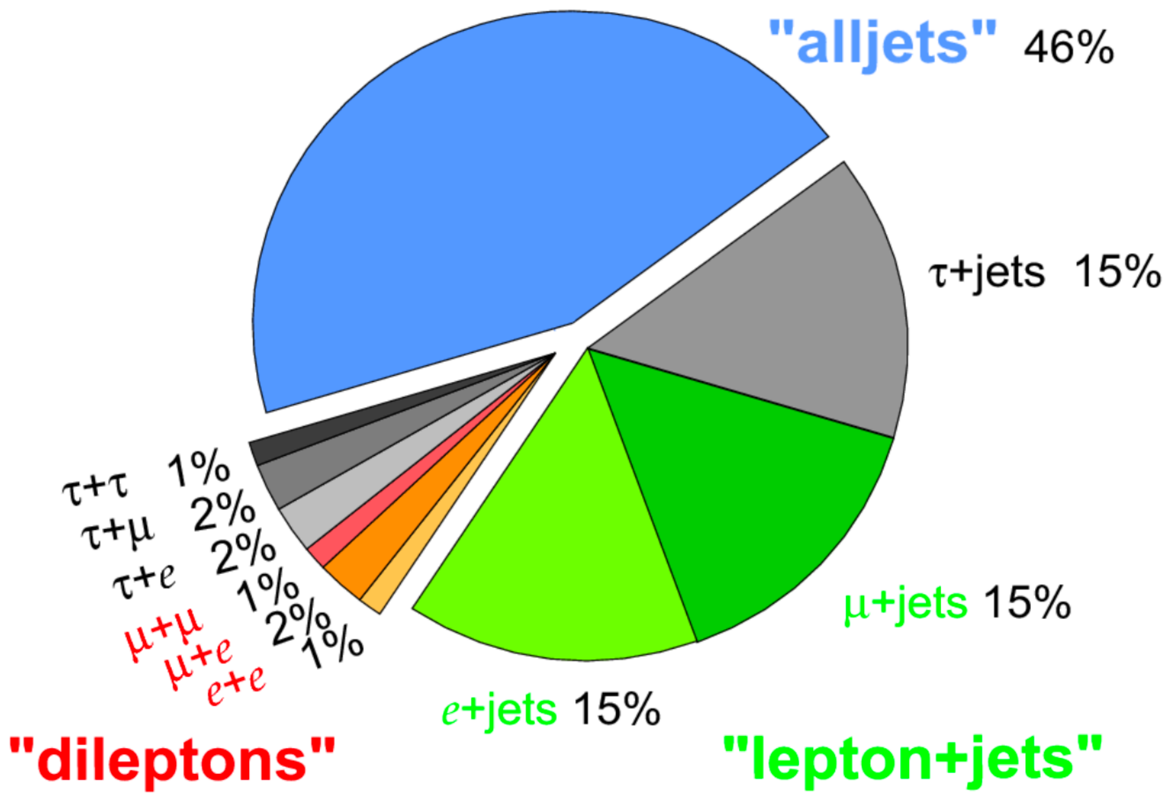
Event candidate for $t\bar{t}$ process in $p + Pb$



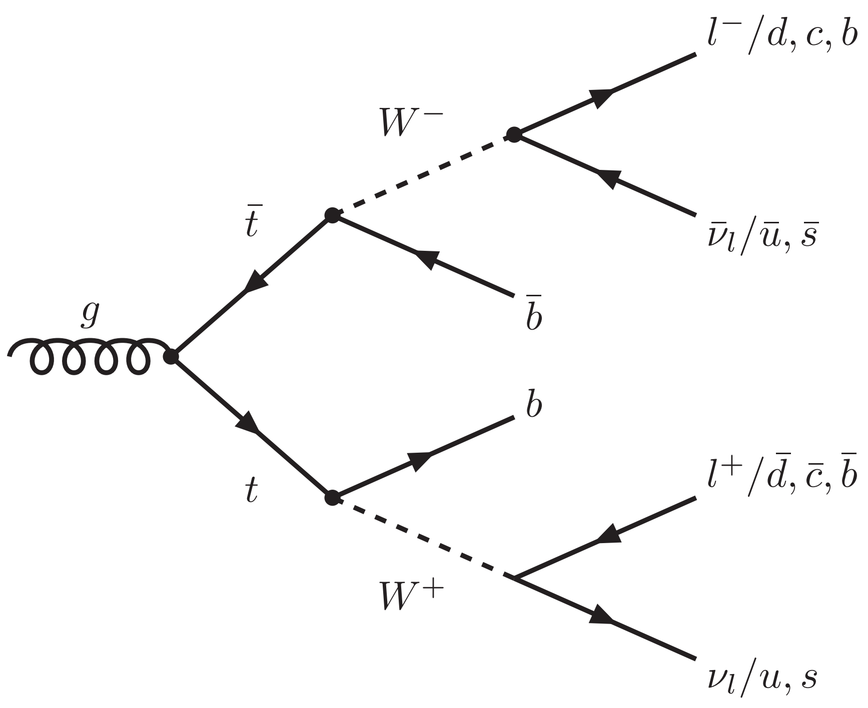
Motivation

- Top quark is the heaviest elementary particle, $m_t \approx 172.5$ GeV, and is an important probe of:
  - Nuclear parton distribution functions (nPDFs) in a poorly constrained kinematic region
  - Gluon nPDF in the unexplored high Bjorken-x region
- $t\bar{t}$ cross section measured in two channels:
  - **ℓ+jets** channel (reported by CMS [PRL 119, 242001 (2017)](#))
  - **dilepton** channel (**firstly measured**)



ℓ+jets: $t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell bq\bar{q}'\bar{b}$

dilepton: $t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell b\ell\bar{\nu}_\ell\bar{b}$

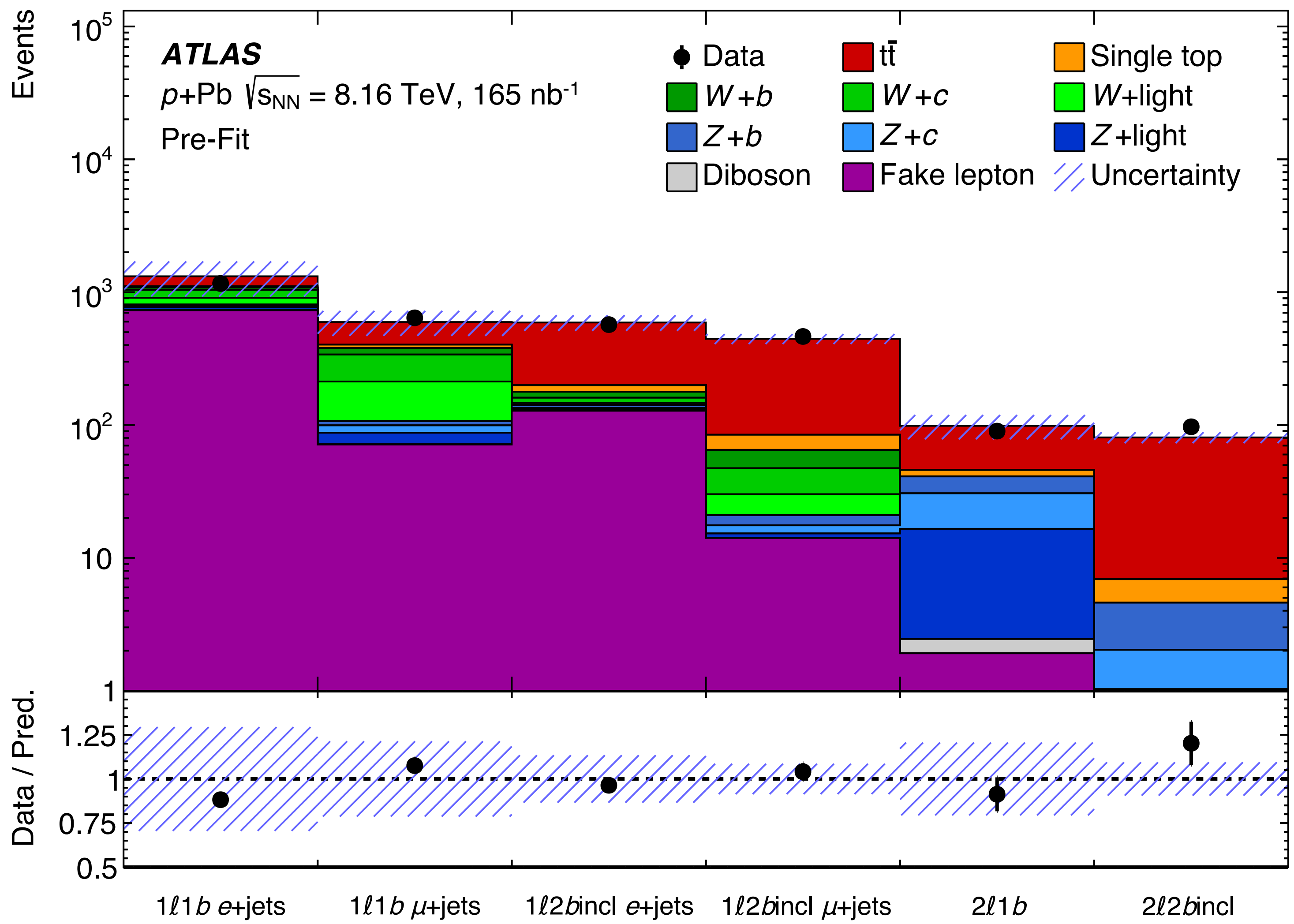


Event selection

- Objects:
  - Lepton ($\ell = e$ or μ): $p_T > 18$ GeV and $|\eta| < 2.5$ ($|\eta| < 2.47$ for e)
  - Jet: $p_T > 20$ GeV and $|\eta| < 2.5$
- **Signal regions** are defined according to number of leptons, number of jets and number of b-tagged jets
  - Six signal regions:
    - **Four** in **ℓ+jets** channel: $1\ell 1b$ e+jets, $1\ell 1b$ μ+jets, $1\ell 2b$incl e+jets, $1\ell 2b$incl μ+jets
    - **Two** in **dilepton** channel: $2\ell 1b$, $2\ell 2b$incl

More details in backup

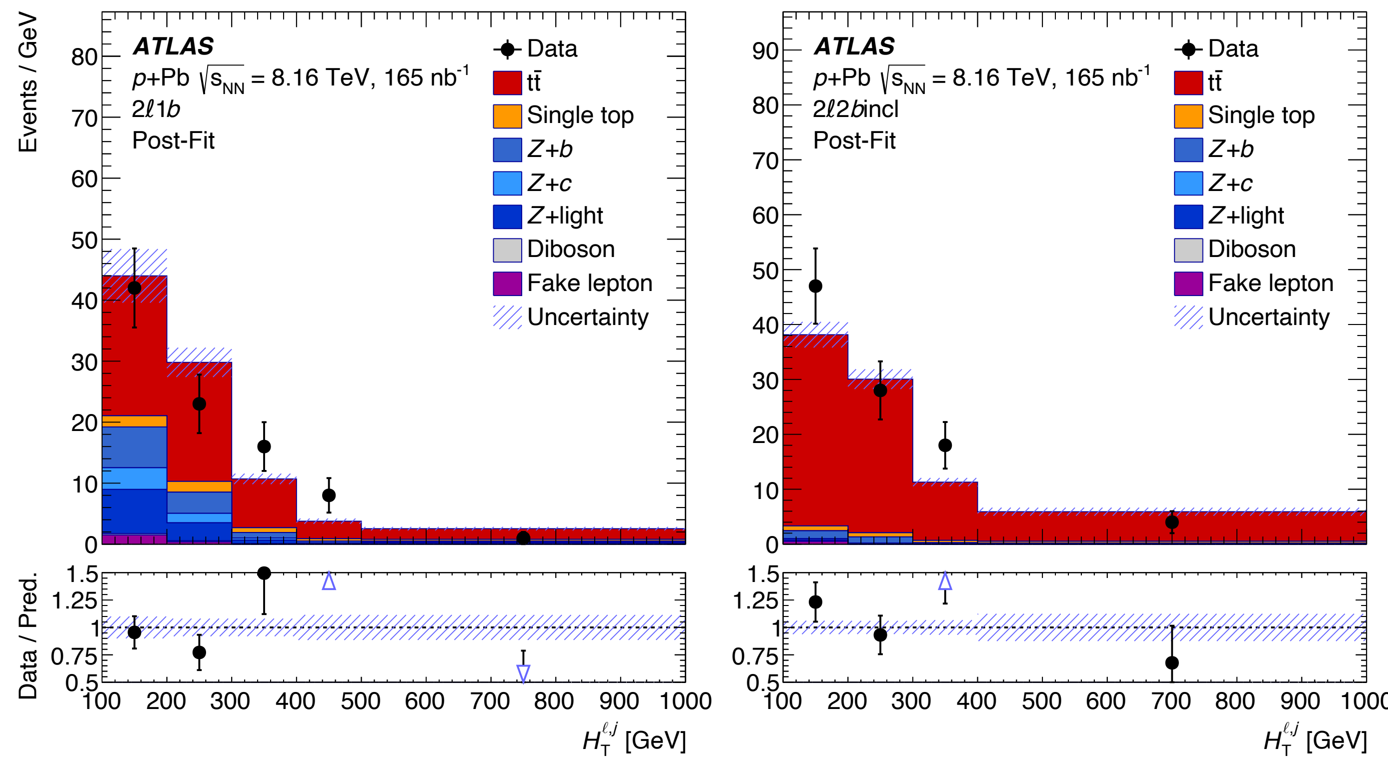
Backgrounds

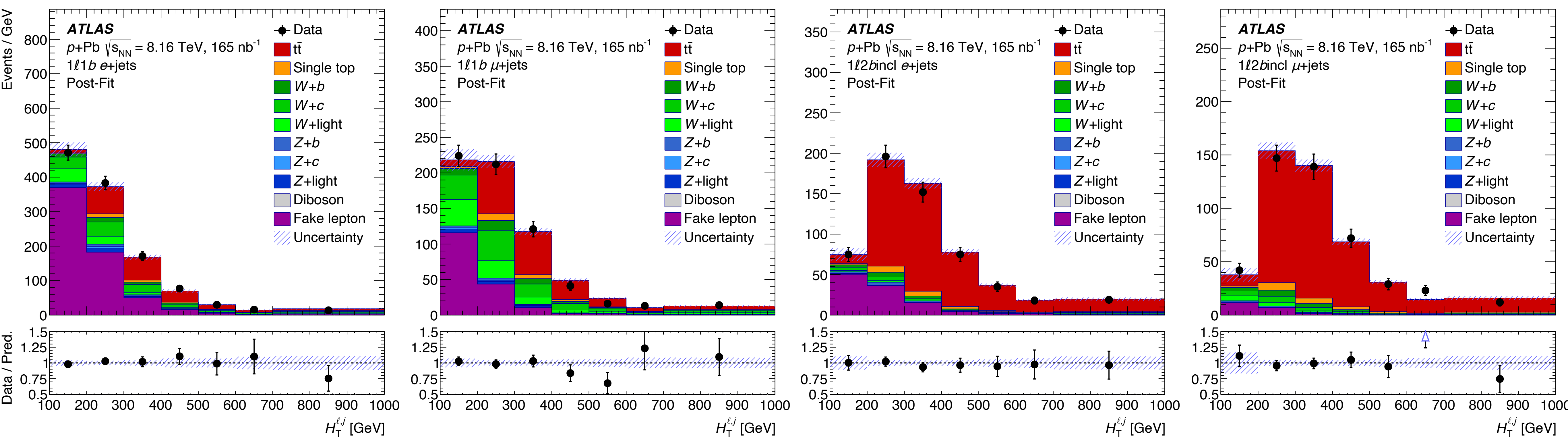


- Main backgrounds:
  - Fake-lepton contributions: estimated with data-driven method
  - W+jets process: estimated based on MC simulations
  - Z+jets process: estimated based on MC simulations

Fit results in signal regions

- Observable: $H_T^{\ell,j} = \sum p_T^{\text{lepton}} + \sum p_T^{\text{jet}}$
- A profile likelihood fit is performed to extract the signal strength $\mu_{t\bar{t}}$
  - Six signal regions fitted simultaneously
  - $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\text{measured}} / \sigma_{t\bar{t}}^{\text{theory}}$



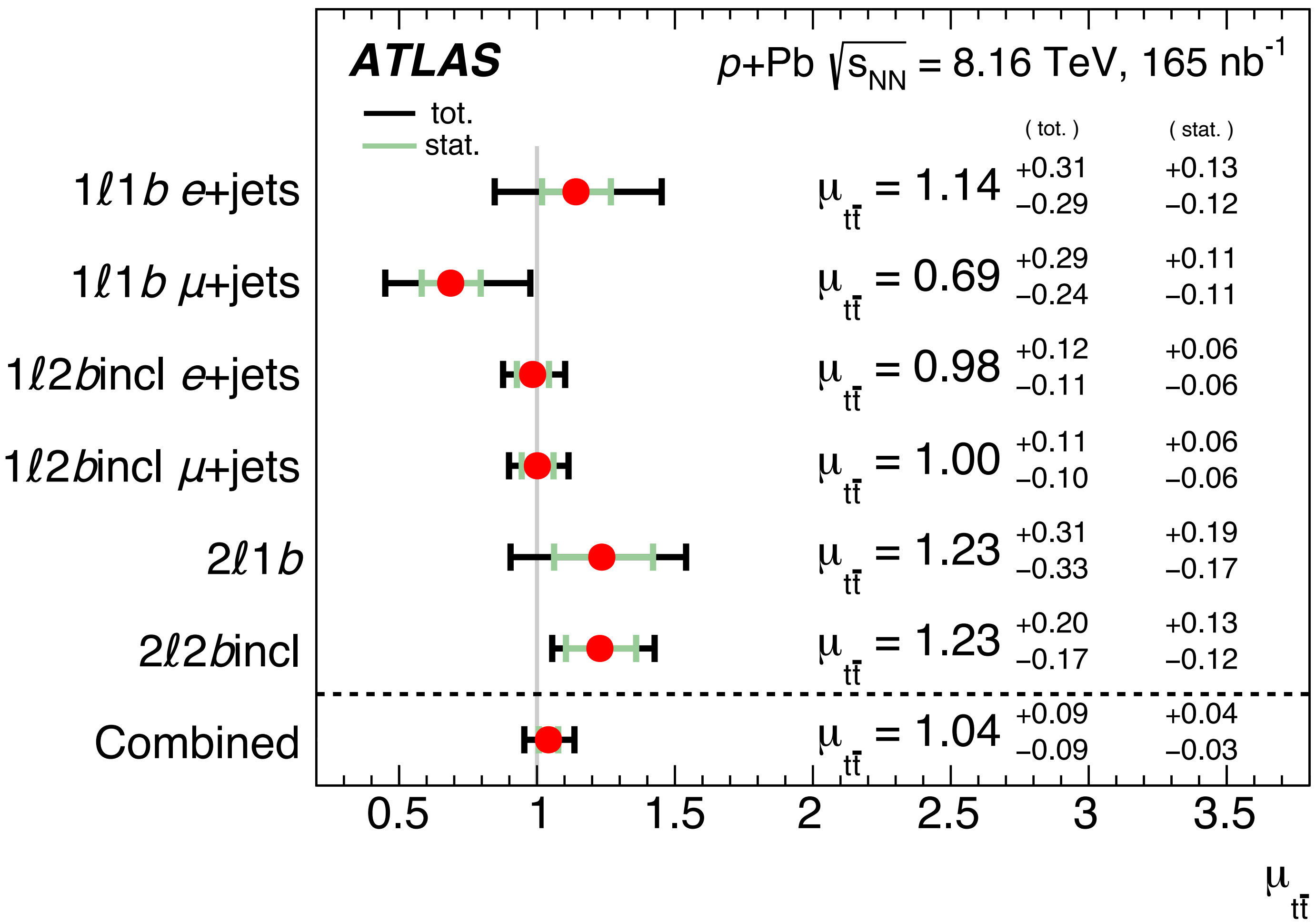


Systematic uncertainties

- Sources of systematic uncertainties:
  - Experimental systematics: lumi, jet, muon, electron…
  - Signal and background modelling
  - Systematics from data-driven background
- Dominant systematics: jet energy scale and signal modelling
- Total relative systematic uncertainty: 8%

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$	
	unc. up [%]	unc. down [%]
Jet energy scale	+4.6	-4.1
$t\bar{t}$ generator	+4.5	-4.0
Fake-lepton background	+3.1	-2.8
Background	+3.1	-2.6
Luminosity	+2.8	-2.5
Muon uncertainties	+2.3	-2.0
W+jets	+2.2	-2.0
b-tagging	+2.1	-1.9
Electron uncertainties	+1.8	-1.5
MC statistical uncertainties	+1.1	-1.0
Jet energy resolution	+0.4	-0.4
$t\bar{t}$ PDF	+0.1	-0.1
Systematic uncertainty	+8.3	-7.6

Cross section measurement

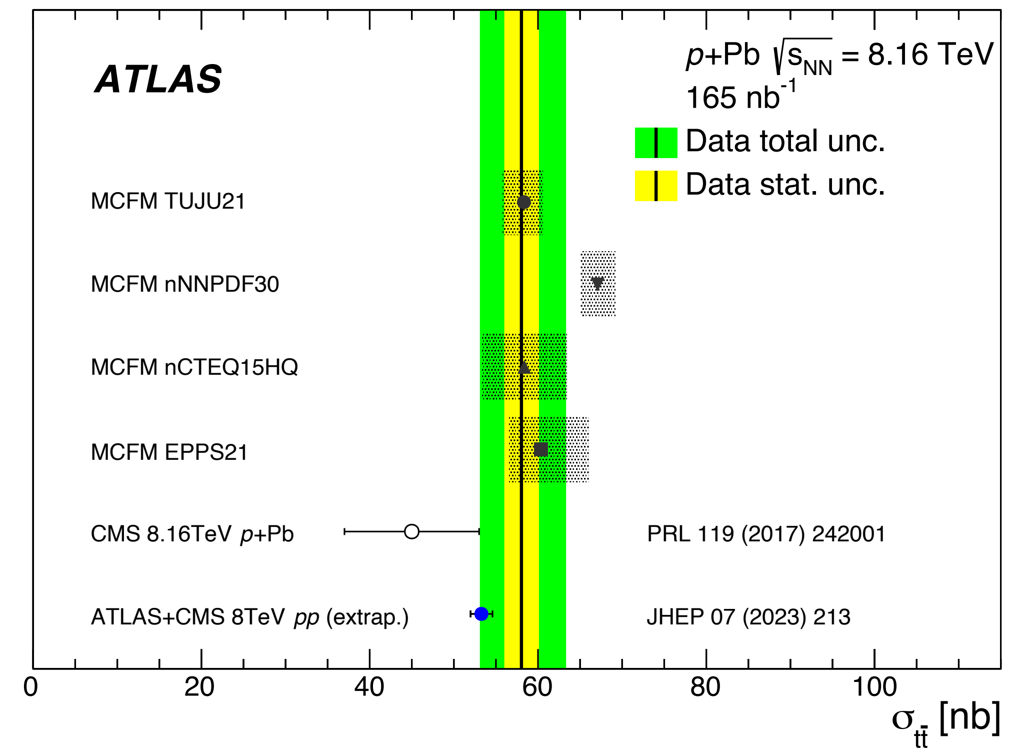


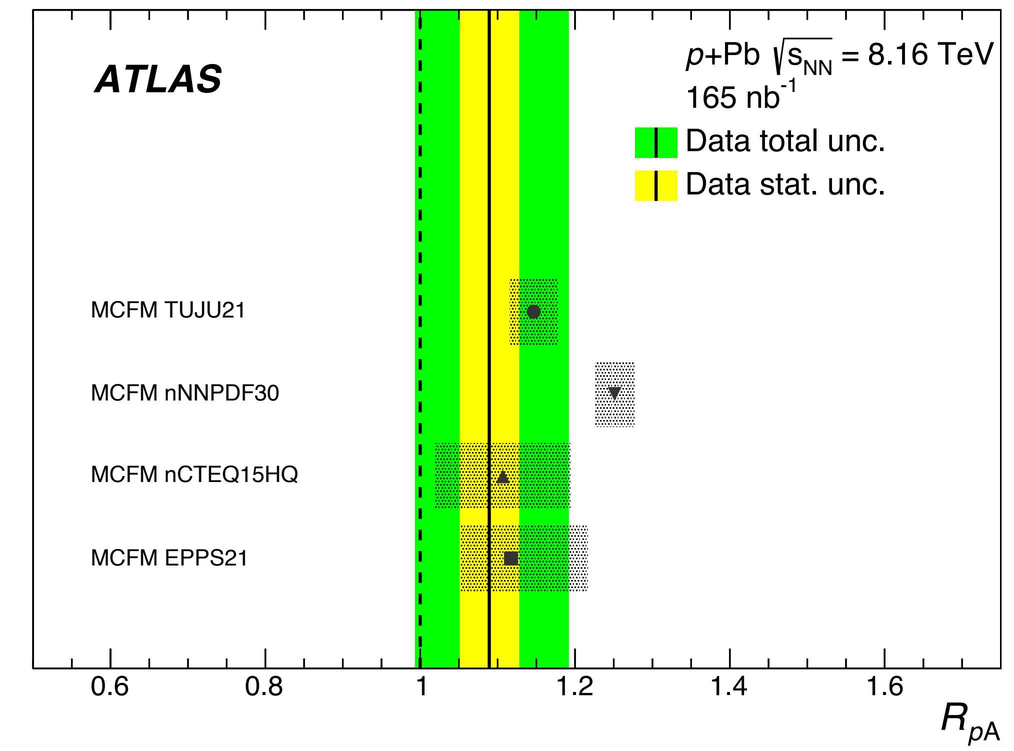
- The $t\bar{t}$ cross section is calculated with the extracted value of $\mu_{t\bar{t}}$ by $\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{Pb} \cdot \sigma_{t\bar{t}}^{\text{th}}$
  - $\sigma_{t\bar{t}} = 58.1 \pm 2.0$ (stat.)$^{+4.8}_{-4.4}$ (syst.) nb
  - The total uncertainty is 9% (3% Stat., 8% Syst.)
  - The most precise $t\bar{t}$ measurement in HI collisions at LHC

- Significances in ℓ+jets and dilepton channels exceed 5σ separately
  - **First observation in dilepton channel with p+Pb collisions**

Comparison

- The measured $\sigma_{t\bar{t}}$ is compared with results from CMS, pp collisions and theory predictions
  - Consistent with the cross section in pp collisions (scaled and extrapolated)
  - Largest discrepancy from nNNPDF30 nPDF set
- Nuclear modification factor $R_{pA} = \dfrac{\sigma_{t\bar{t}}^{p+Pb}}{A_{Pb} \cdot \sigma_{t\bar{t}}^{pp}}$
  - $R_{pA} = 1.090 \pm 0.039$ (stat.)$^{+0.094}_{-0.087}$ (syst.) (**first measurement**)
  - Compared with theory predictions
  - Largest discrepancy also from nNNPDF30





- Observation of $t\bar{t}$ production in $p + Pb$ collisions at 8.16 TeV arXiv:2405.05078 (submitted to JHEP)

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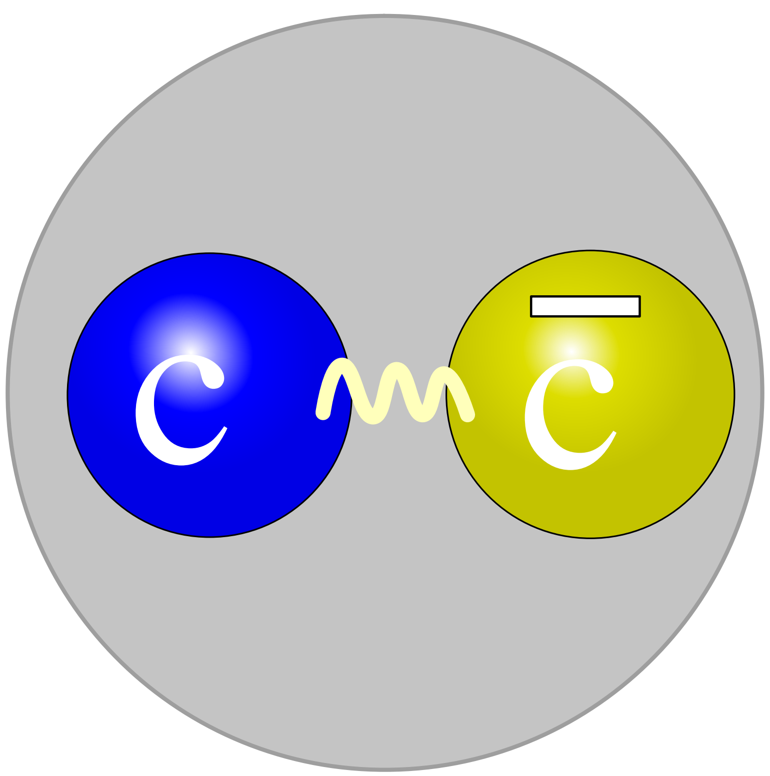
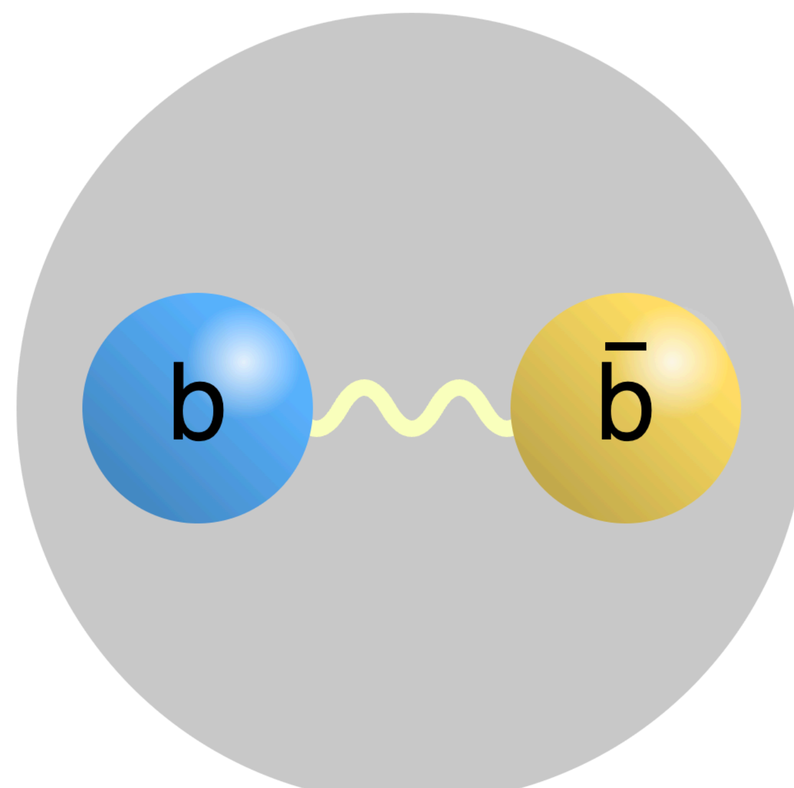
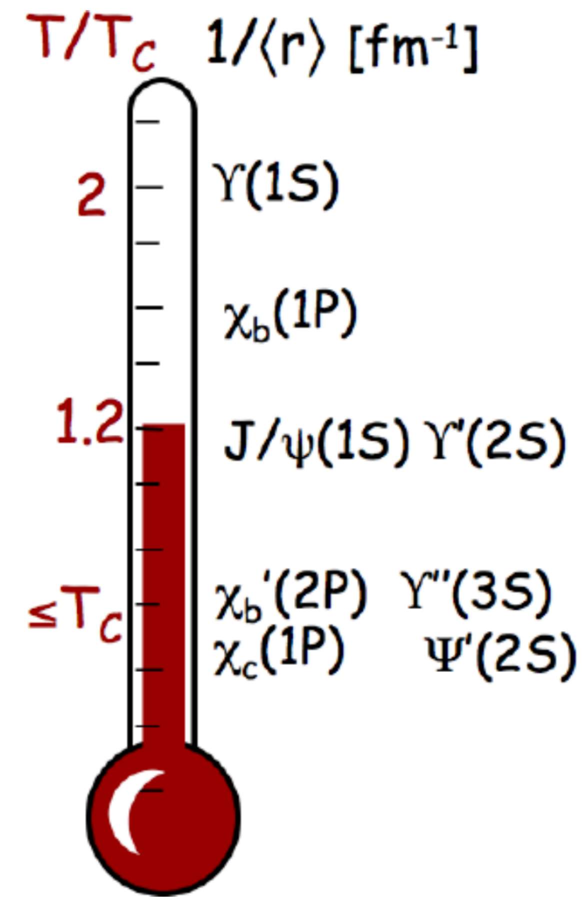
- Quarkonia are important for characterizing the properties of the quark-gluon plasma (QGP)
  - Produced at the very early stage by the hard scattering
  - The sequential melting has been proposed as QGP thermometer

Charmonium



Bottomonium





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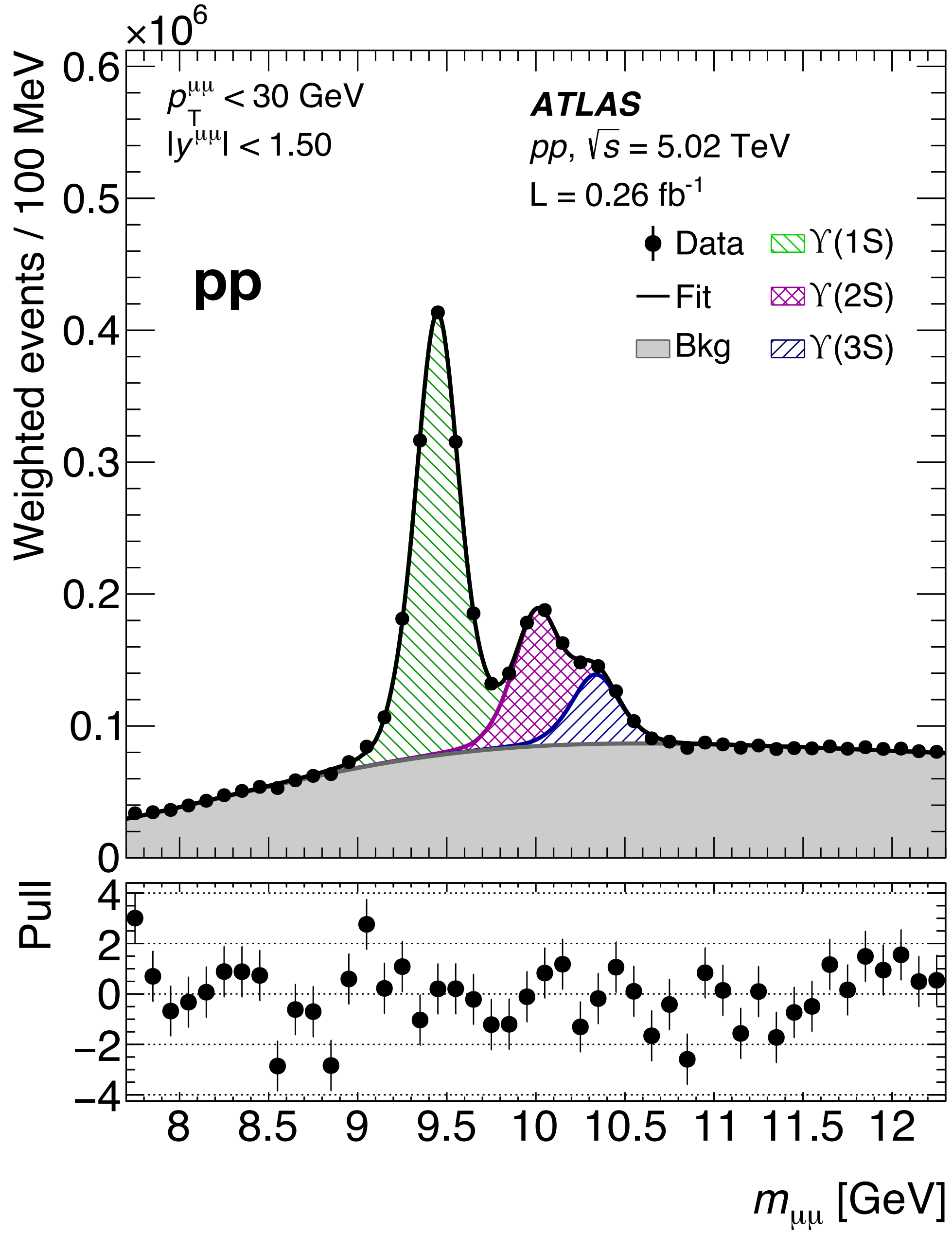
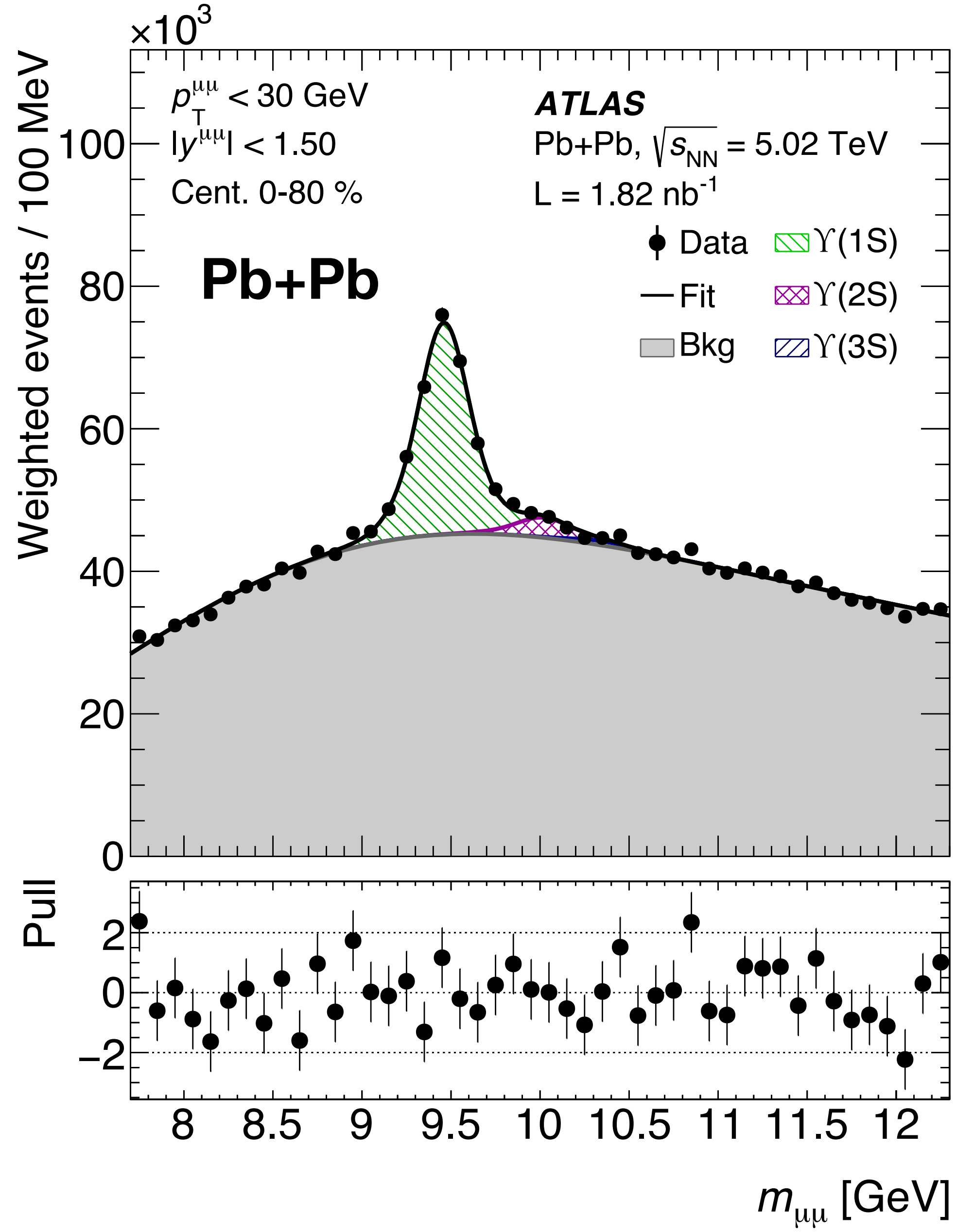
Bottomonium signal



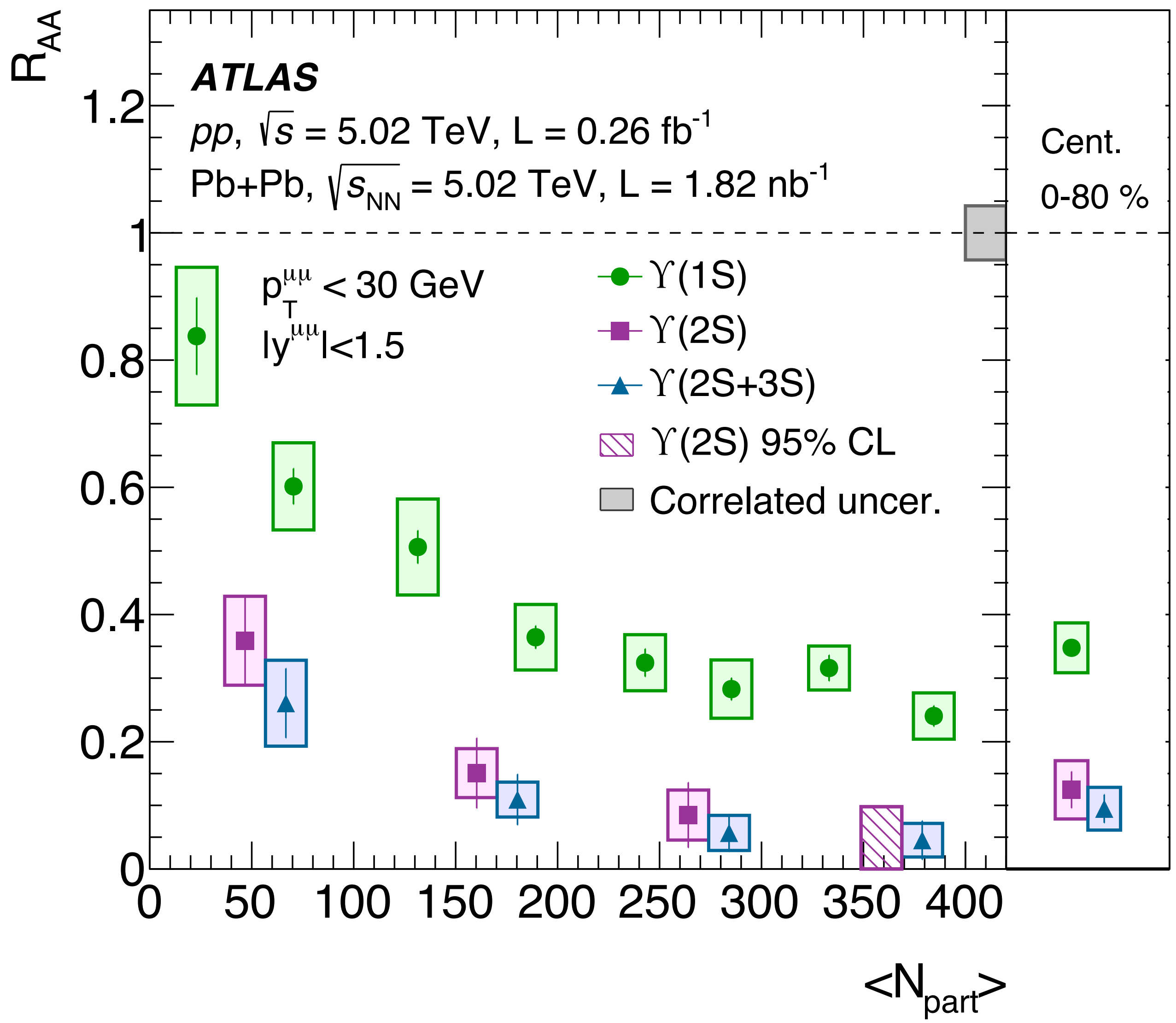


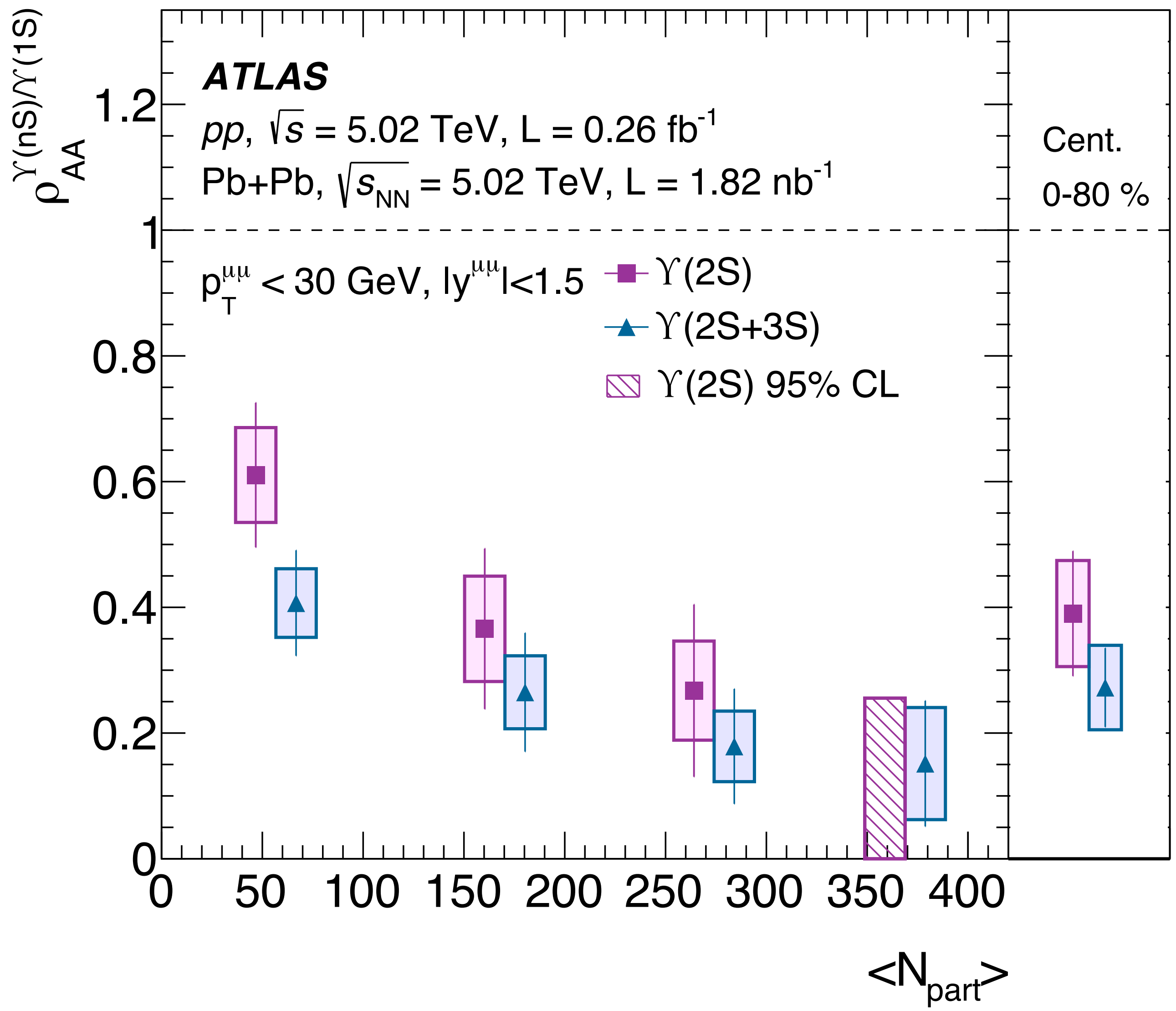
- Υ mesons are reconstructed via $\Upsilon \to \mu\mu$ decay
- Υ mass spectra in pp and Pb+Pb collisions
- Production is suppressed in Pb+Pb, especially $\Upsilon(3S)$

Nuclear modification factor

$$R_{AA} = \frac{N_{AA}}{< T_{AA} > \sigma^{pp}}$$

$$\rho_{AA}^{\Upsilon(nS)/\Upsilon(1S)} = R_{AA}[\Upsilon(nS)]/R_{AA}[\Upsilon(1S)]$$

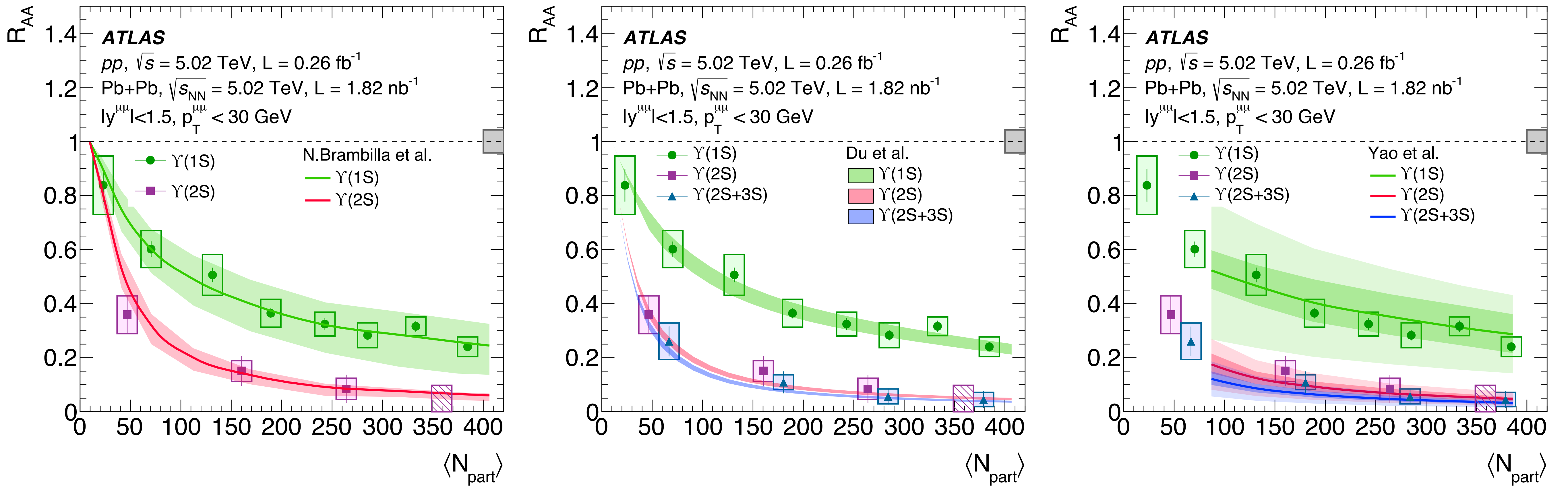




- $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
- R_{AA} smoothly decreases with increasing centrality (increasing centrality means that collisions are more central)

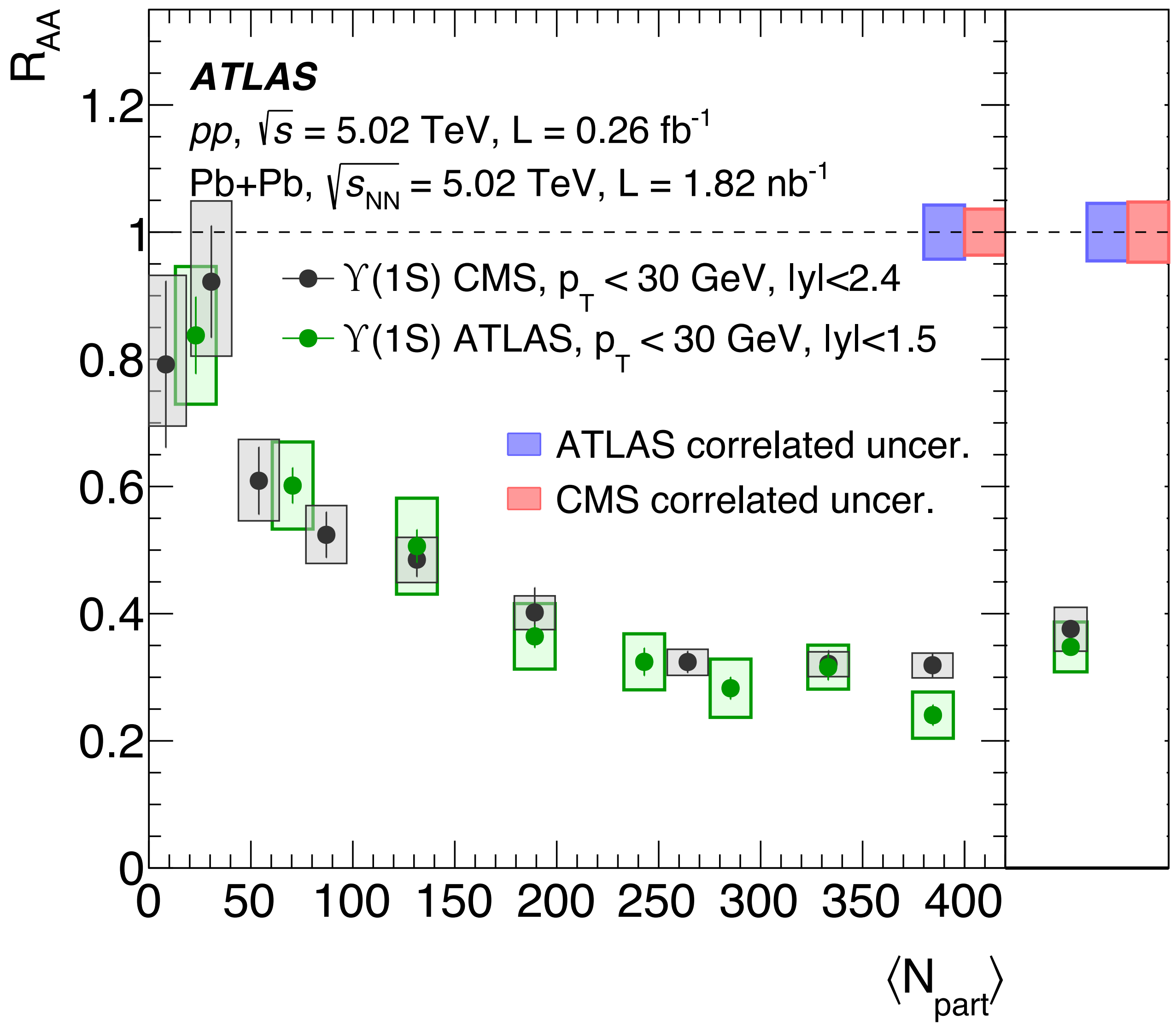
- Excited states are more suppressed than the ground state

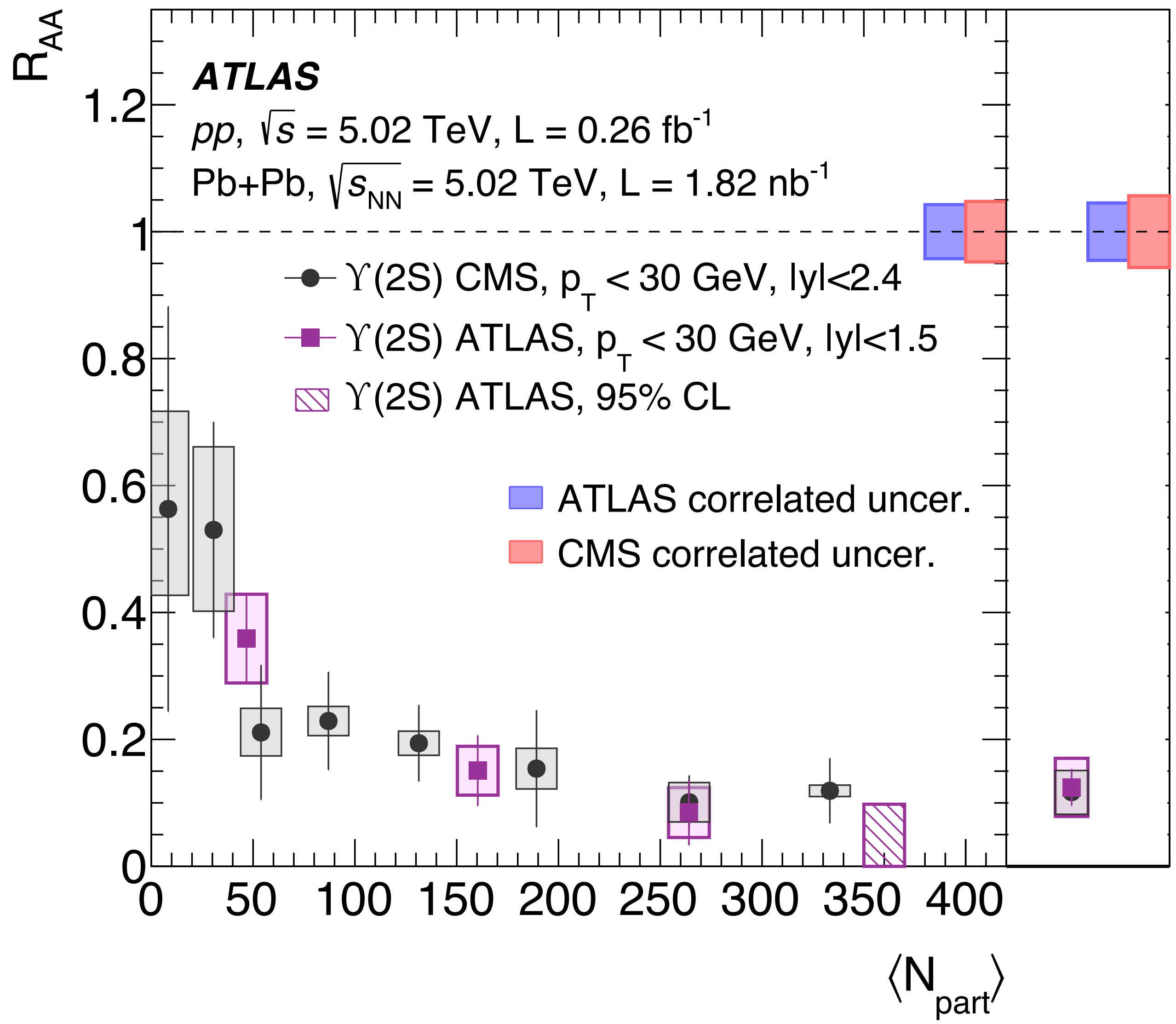
Theory comparisons



- Compare to 3 theory models:
  - Potential Non-relativistic quantum chromodynamics — N.Brambilla et al.
  - Kinetic-rate equation approach including regeneration — Du et al.
  - Cold nuclear matter effects — Yao et al.
- All in agreement with data within experimental and theoretical uncertainties

Comparison to CMS





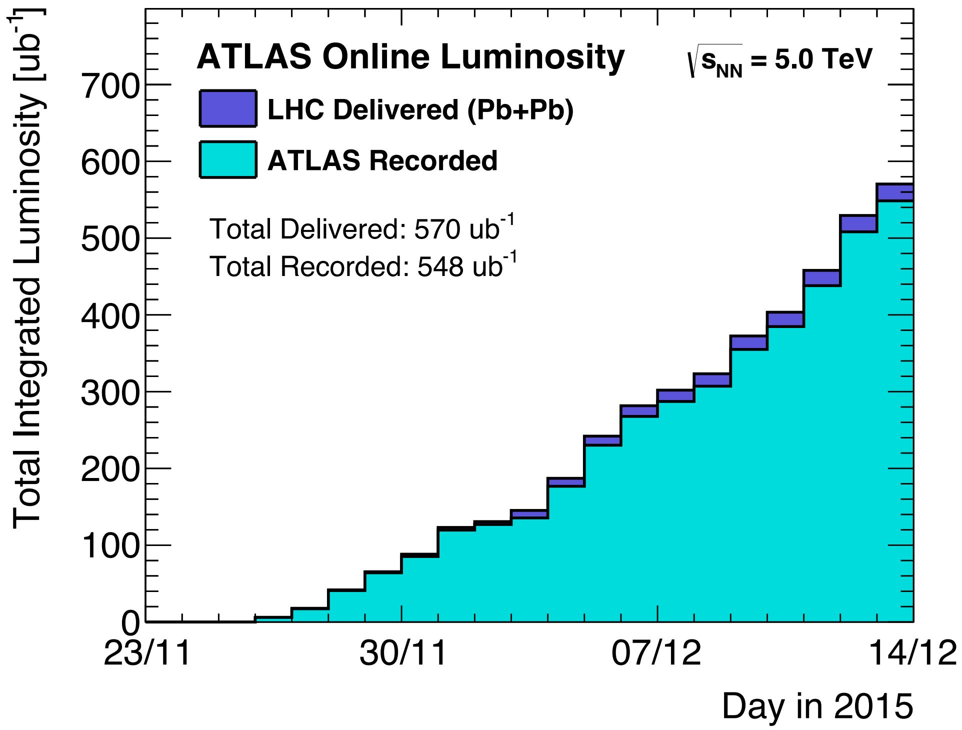
- ATLAS and CMS results seem consistent within uncertainties

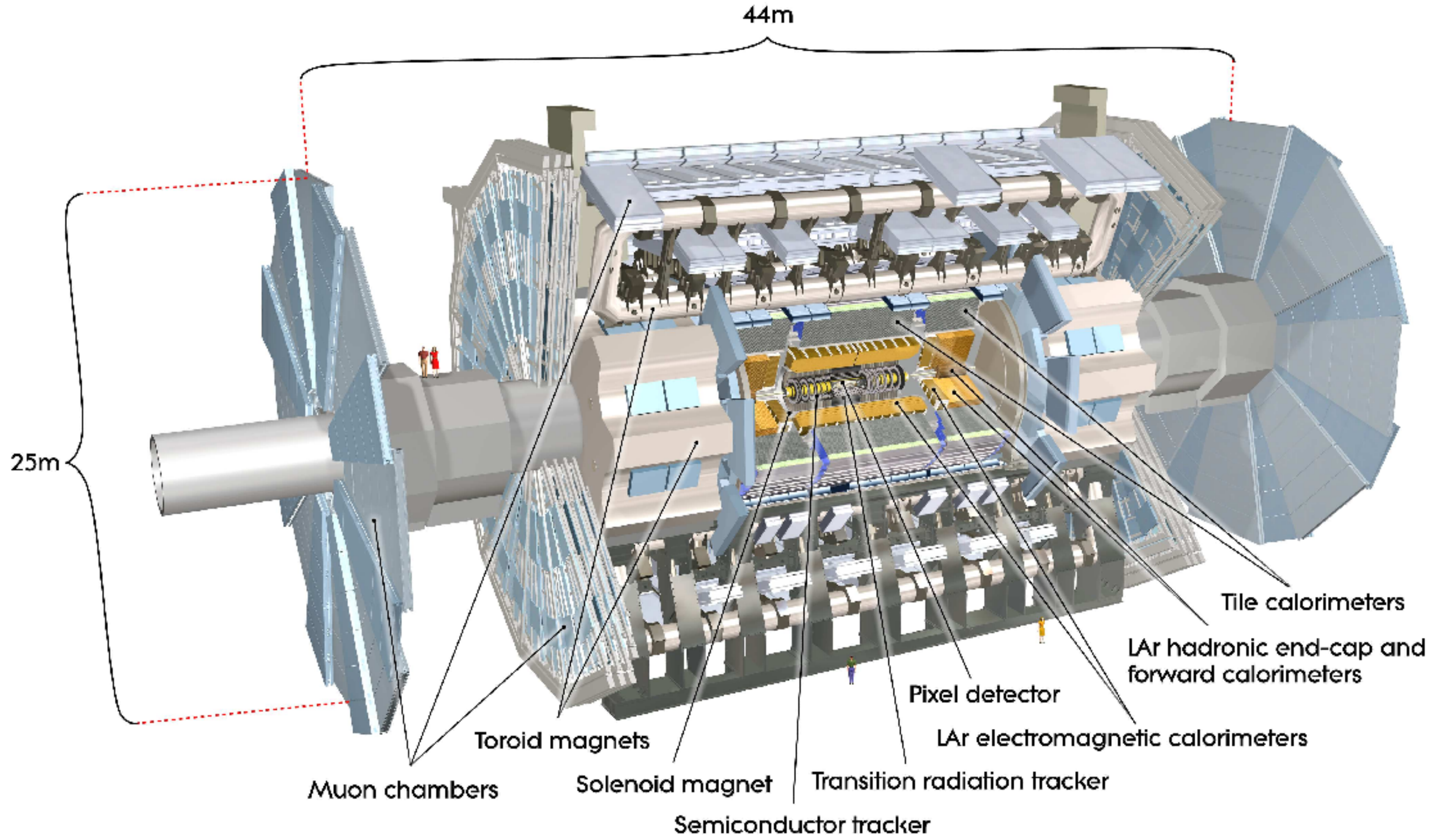
Summary

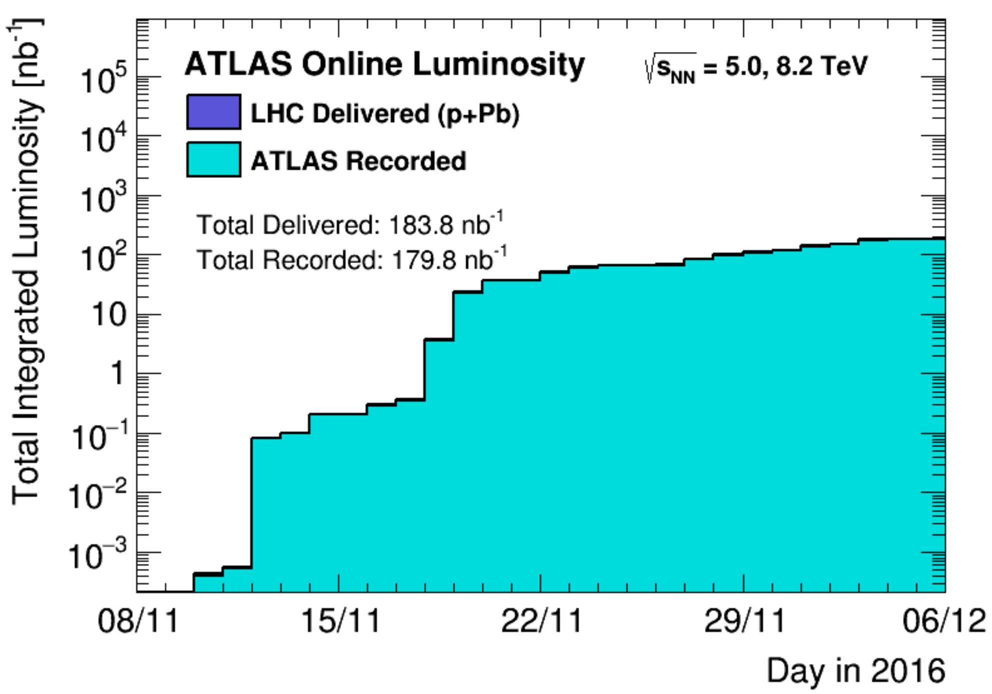
- Observation of $t\bar{t}$ production in $p + Pb$ collisions at 8.16 TeV
  - Provides the most precise cross section measurement in HI collisions at LHC
  - $t\bar{t}$ is firstly observed in dilepton channel in p+Pb collisions
  - R_{pA} is measured for the first time
- $\Upsilon(nS)$ nuclear modification factor at 5.02 TeV
  - R_{AA} <1 for all states and smoothly decreases with increasing centrality
  - The excited states are shown to be more strongly suppressed than the ground state

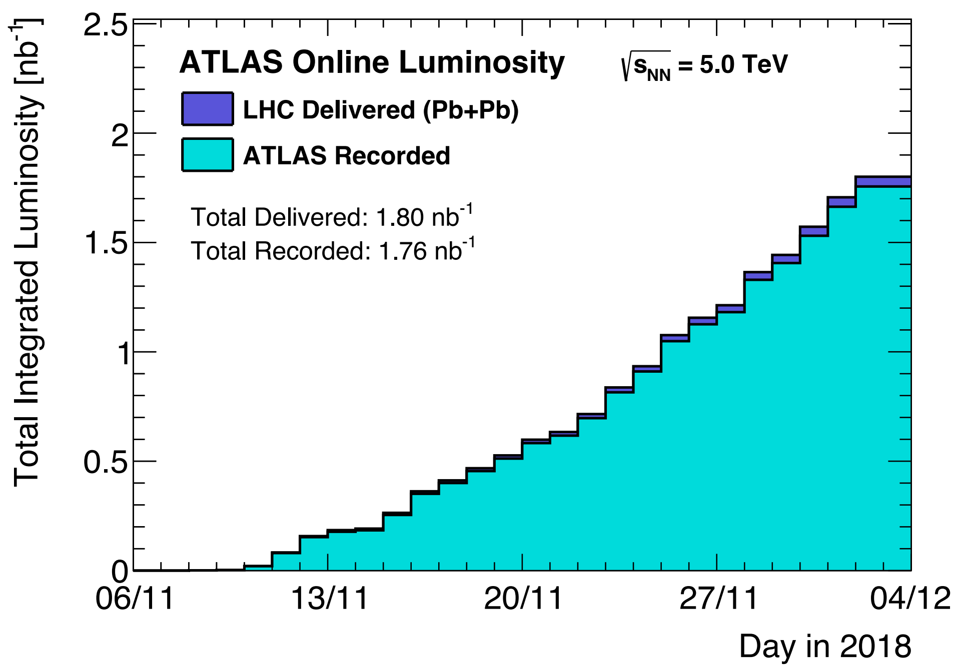
Thanks

Nuclear collisions in ATLAS







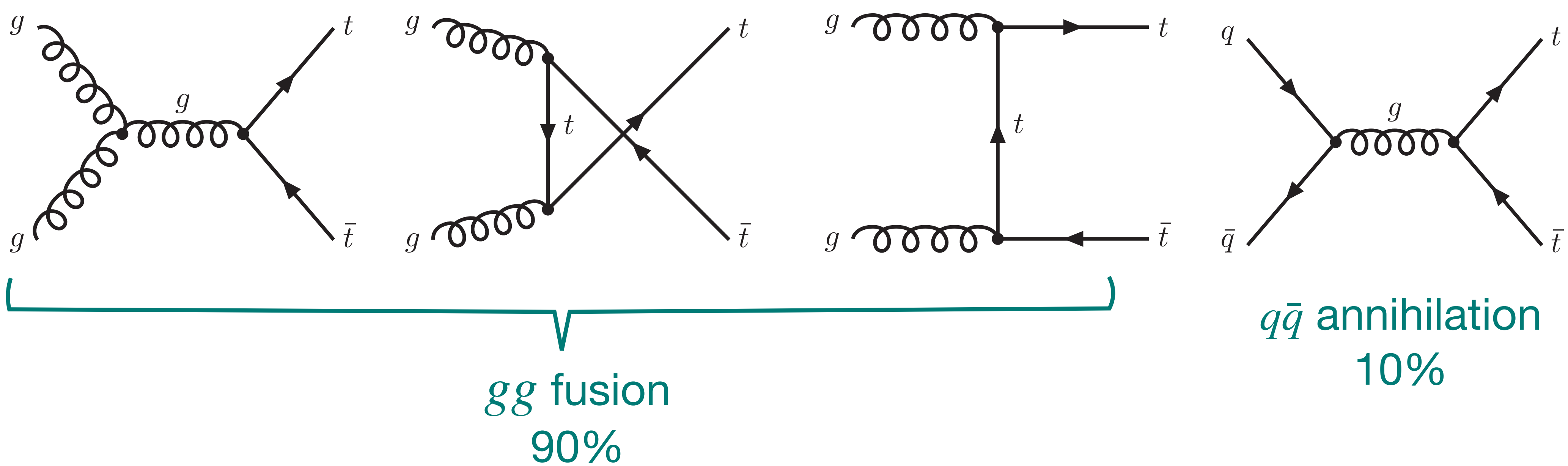


Pb+Pb @ 5.02 TeV

p+Pb @ 5.02/8.16 TeV

Motivation

- Top quark is the heaviest elementary particle, $m_t \approx 175$ GeV
- The production modes of top and anti-top pair at LHC:
  - Gluon-gluon fusion (dominated)
  - Quark-antiquark annihilation
- An important probe of:
  - Nuclear parton distribution functions (nPDFs) in a poorly constrained kinematic region
  - Gluon nPDF in the unexplored high Bjorken-x region



Event selection

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- **Signal regions** are defined according to number of leptons, number of jets and number of b-tagged jets
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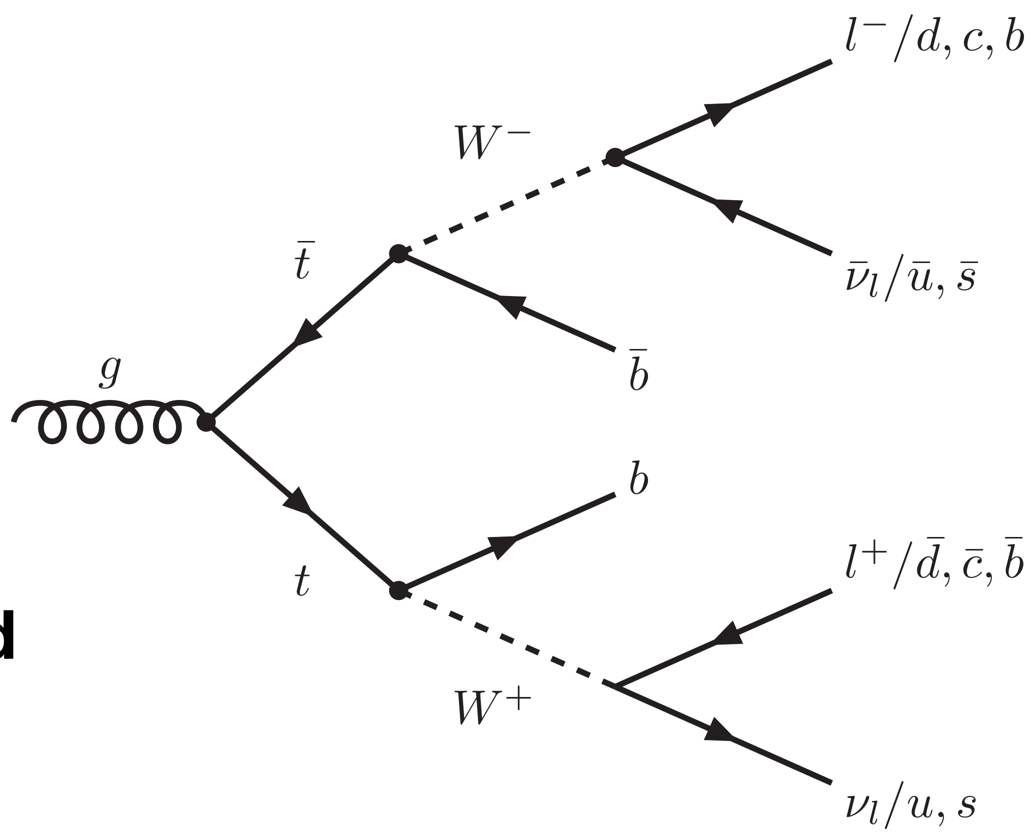
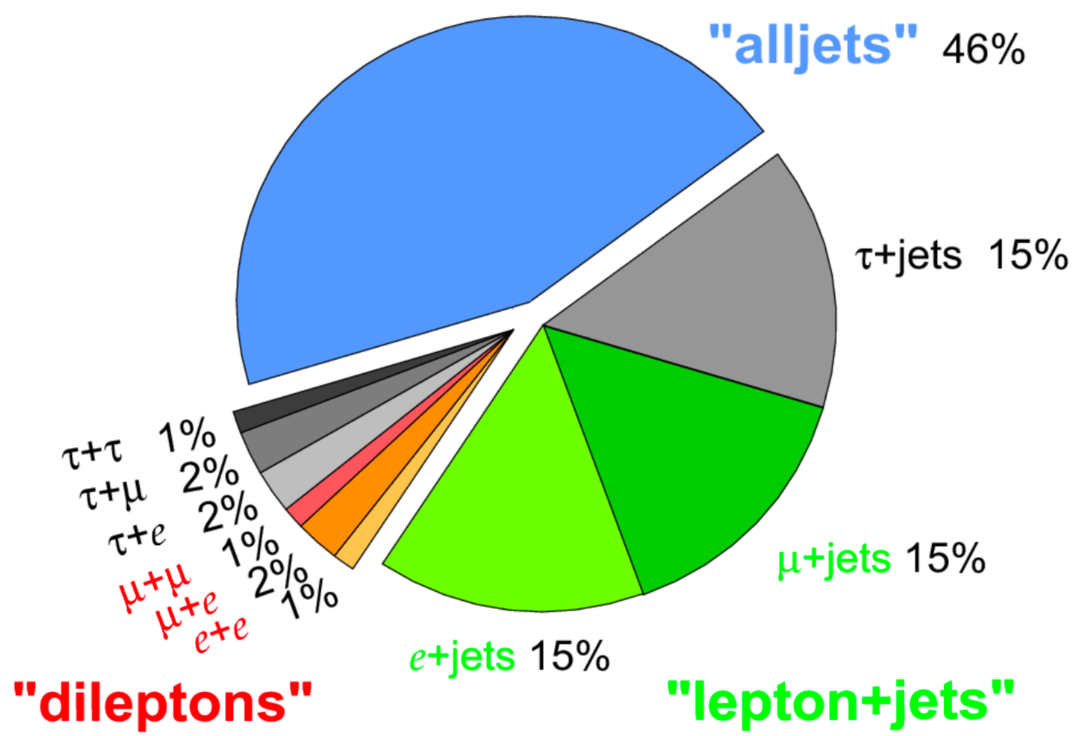
lepton+jets		dilepton			
e/mu		**ee/mumu**		**emu**	
1b	**2bincl**	**1b**	**2bincl**	**1b**	**2bincl**
1 electron / 1 muon		2 electrons / 2 muons		1 electron + 1 muon	
		opposite charge		opposite charge	
		$m_{\ell\ell} > 45$ GeV		$m_{\ell\ell} > 15$ GeV	
		$m_{\ell\ell} \notin (80{,}100)$ GeV			
>= 4 jets		>= 2 jets		>= 2 jets	
1 b jet	>= 2 b jets	1 b jet	>= 2 b jets	1 b jet	>= 2 b jets

Top quark pair decay channels

- Measure $t\bar{t}$ cross section in two channels:
  - **ℓ+jets** channel
  - **dilepton** channel
- The ℓ+jets has been reported by CMS
- **The dilepton channel is firstly measured**





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dilepton: $t\bar{t} \to WbW\bar{b} \to \ell\nu_\ell b\ell\bar{\nu}_\ell\bar{b}$

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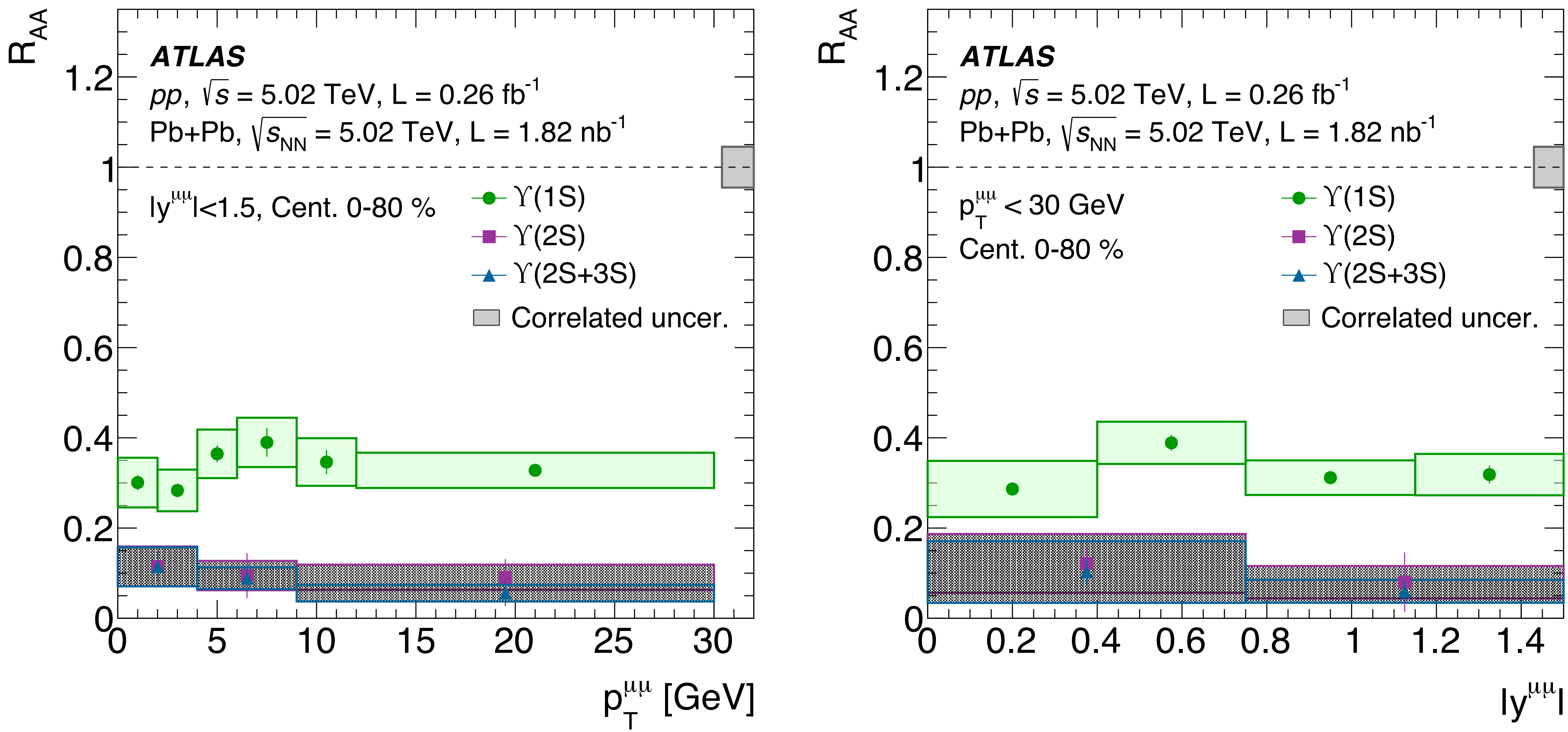
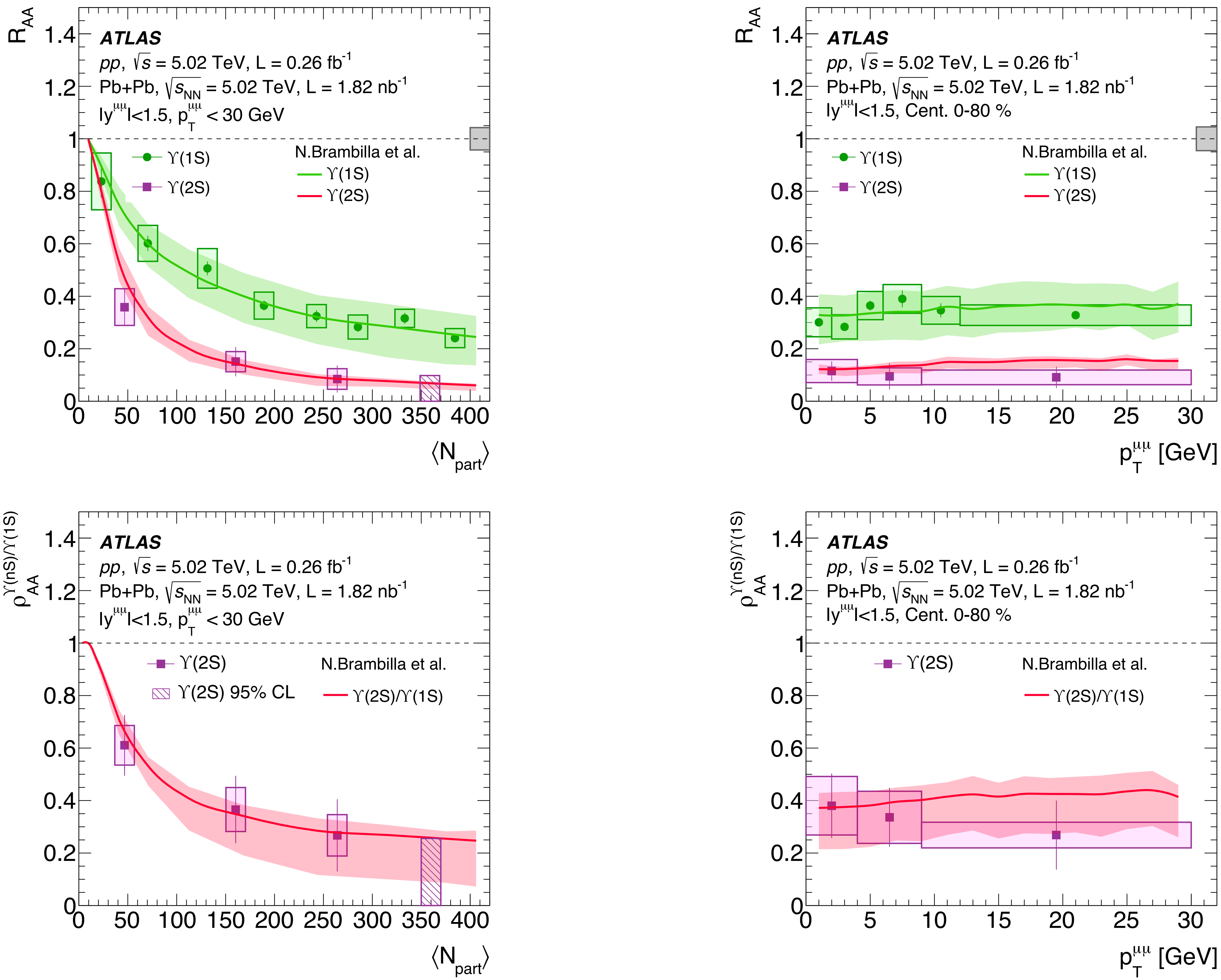
lepton+jets		dilepton			
e/mu		ee/mumu		emu	
1b	2bincl	1b	2bincl	1b	2bincl
1 electron / 1 muon		2 electrons / 2 muons		1 electron + 1 muon	
		opposite charge		opposite charge	
		$m_{\ell\ell} > 45$ GeV		$m_{\ell\ell} > 15$ GeV	
		$m_{\ell\ell} \notin (80,100)$ GeV			
>= 4 jets		>= 2 jets		>= 2 jets	
1 b jet	>= 2 b jets	1 b jet	>= 2 b jets	1 b jet	>= 2 b jets

Nuclear modification factor



Theory comparisons



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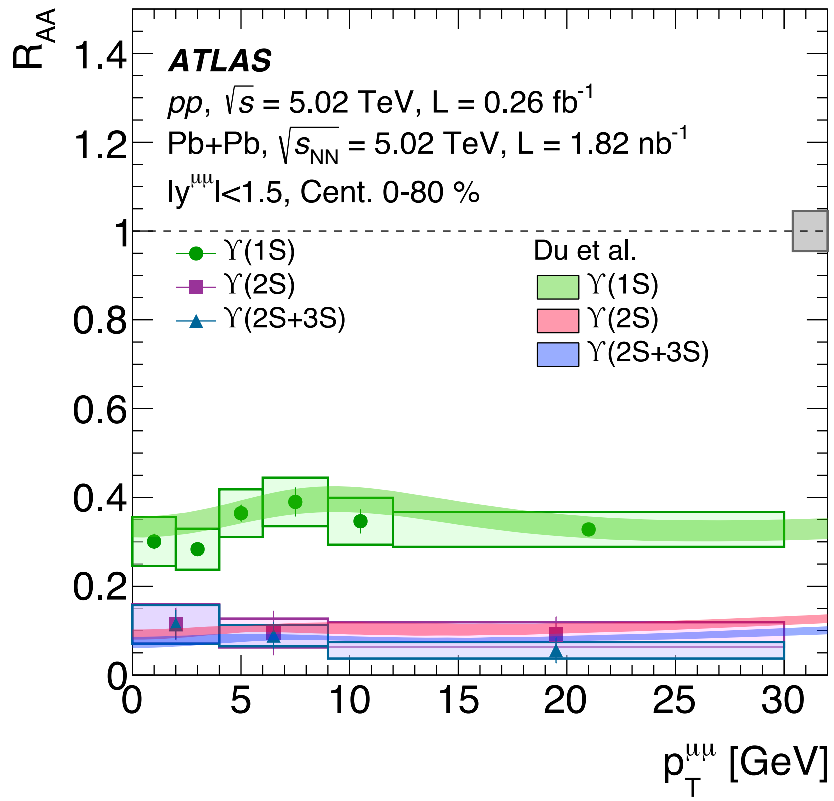

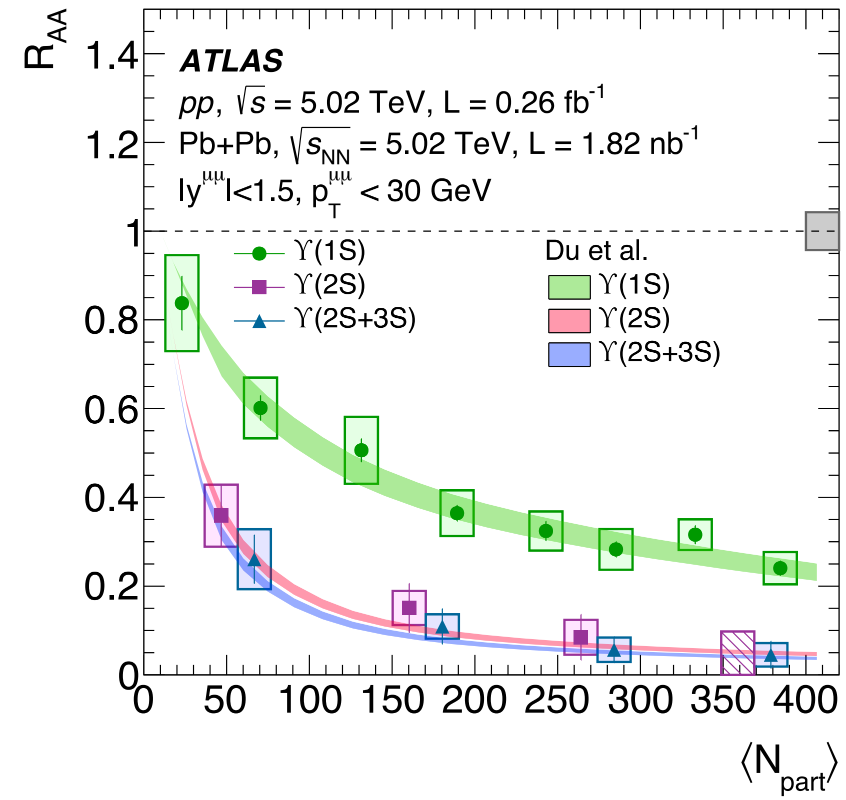

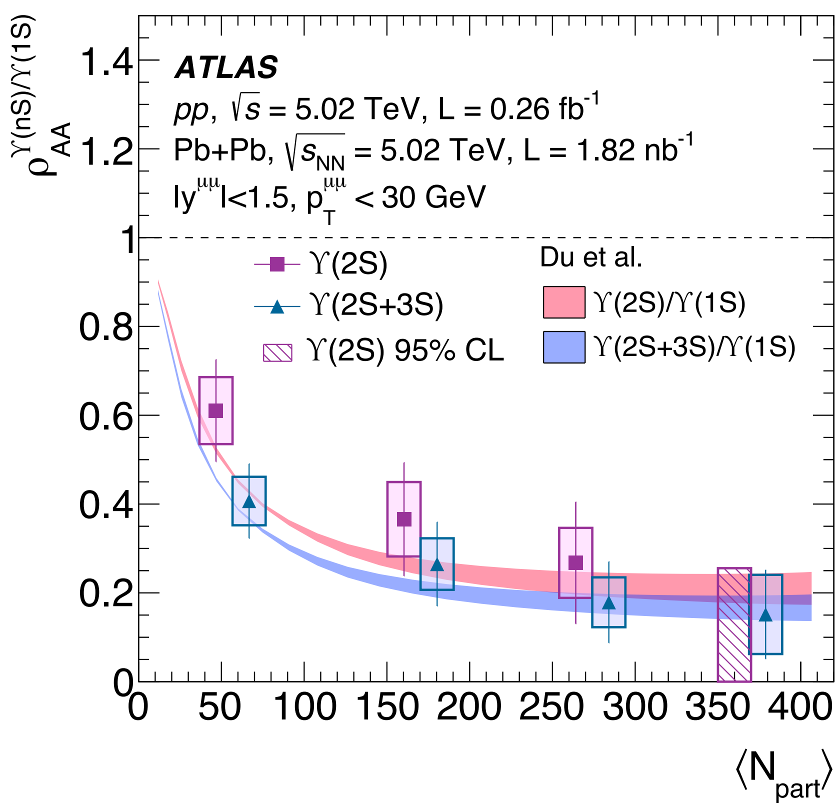

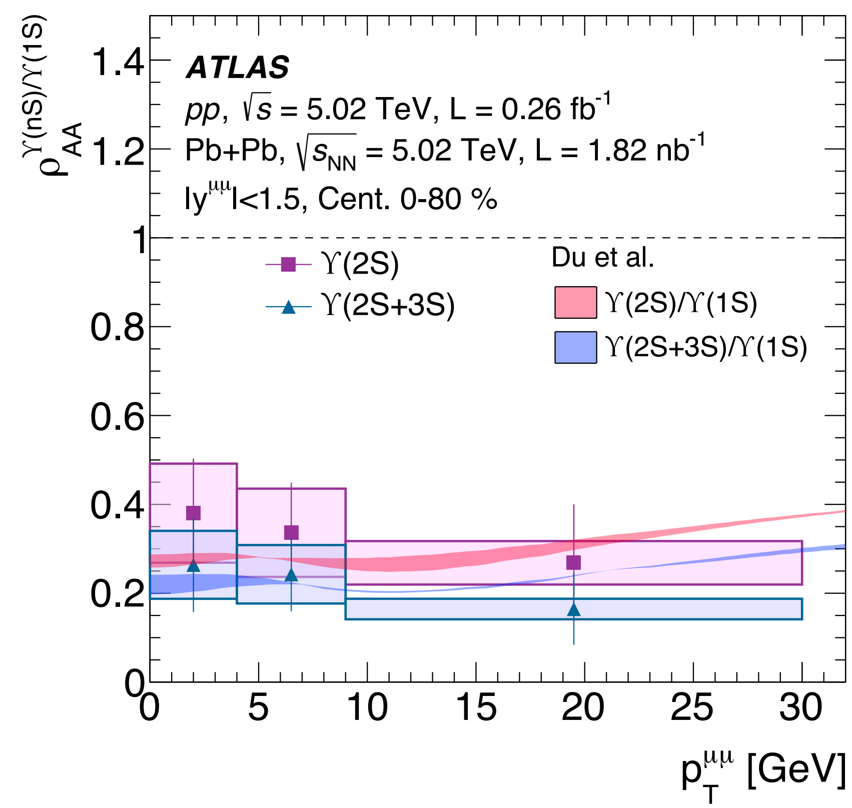

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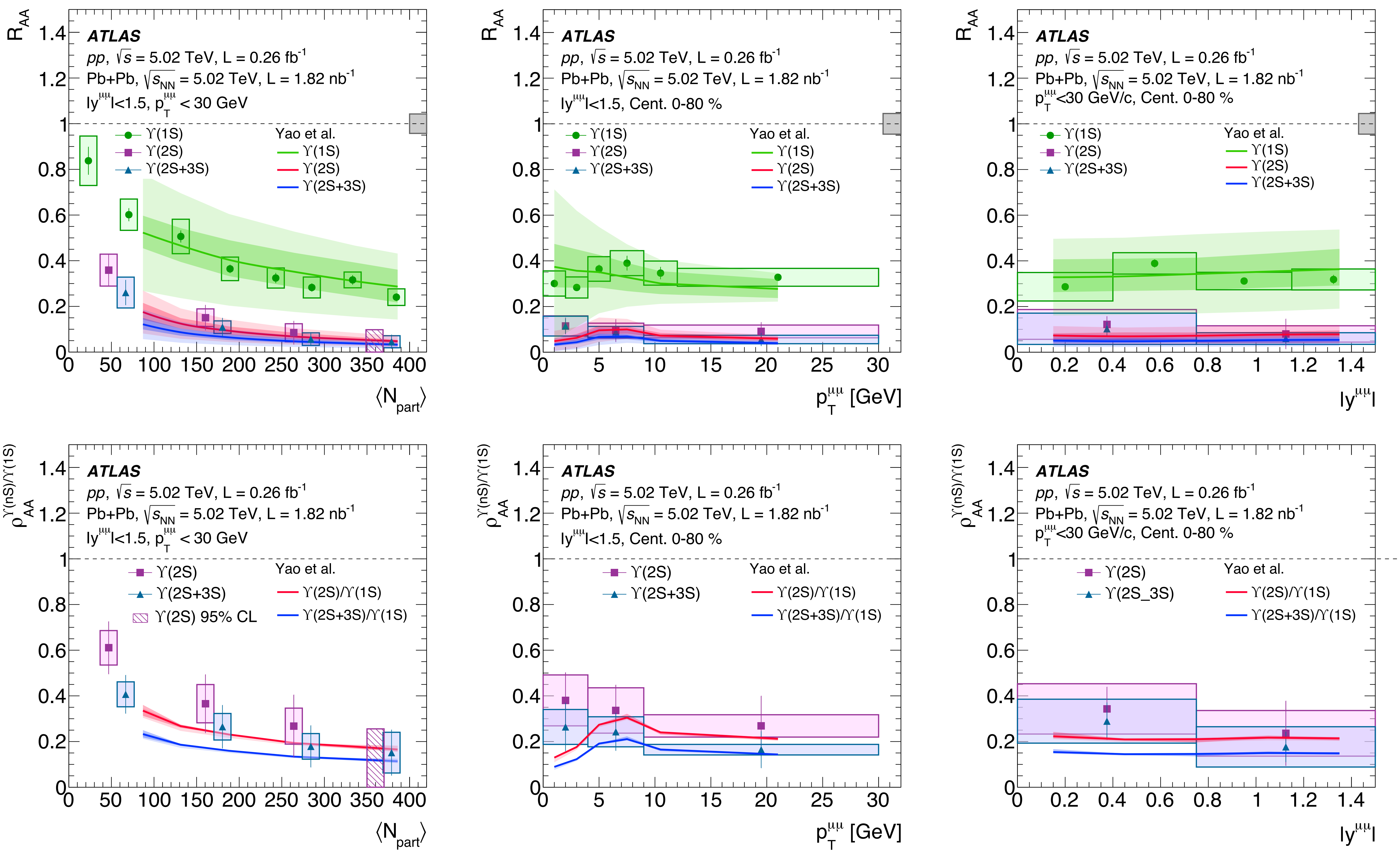

CMS comparisons