# Heavy Flavor Production in ATLAS at LHC

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on Behalf of the ATLAS Collaboration

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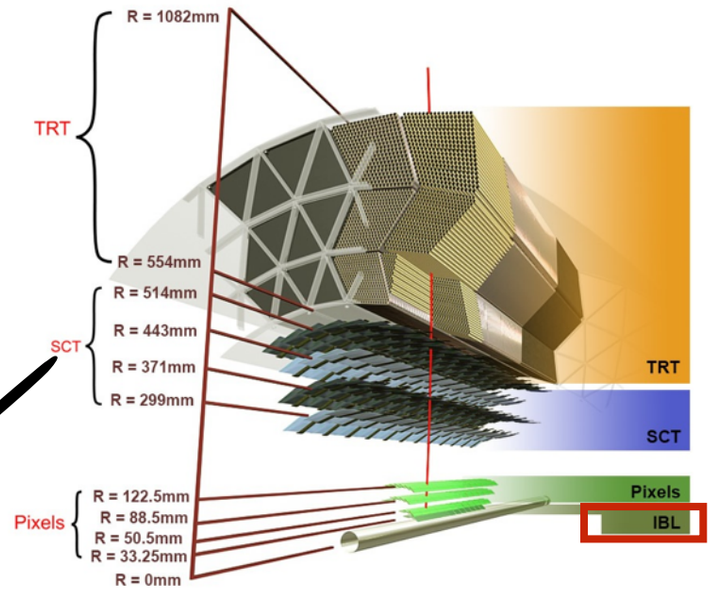
# ATLAS detector

Inner Detector (ID) $|\eta| < 2.5$

Calorimeter (CALO) $|\eta| < 4.9$

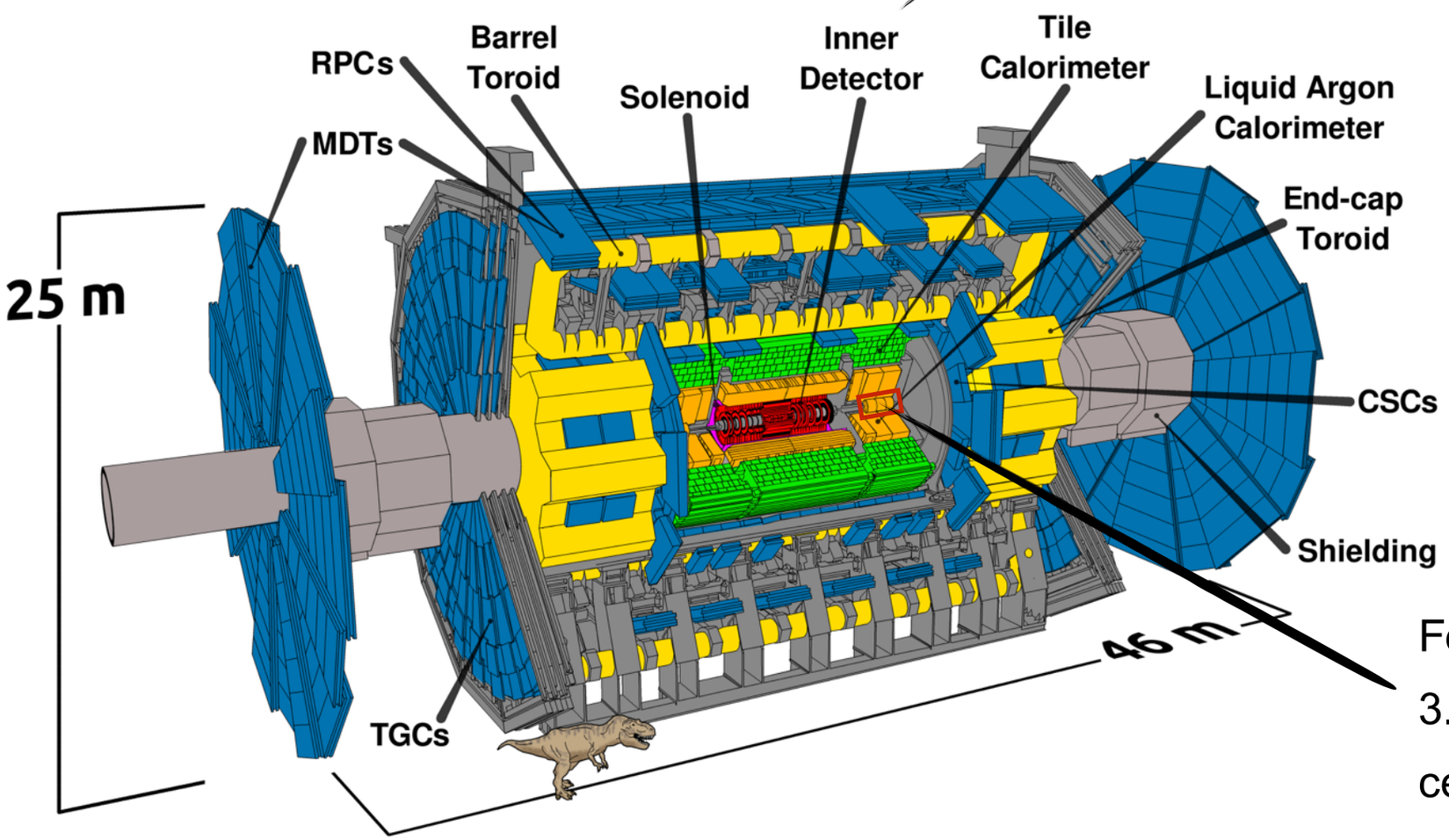
Muon Spectrometer (MS) $|\eta| < 2.7$




Insertable B-layer

New layered at 33 mm installed in 2014

Improve tracking and vertexing

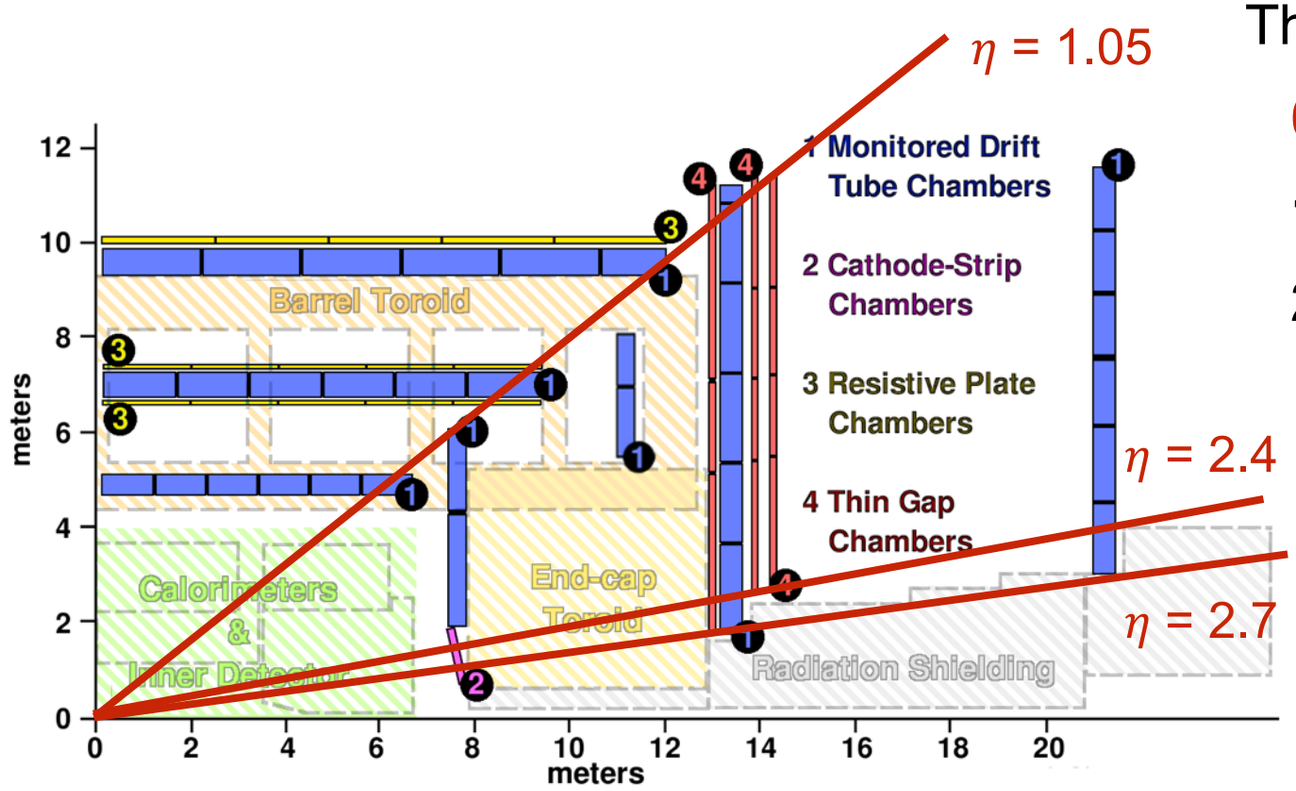



Forward Calorimeter (FCal)

$3.1 < |\eta| < 4.9$

centrality classification

# Muon detecting with ATLAS

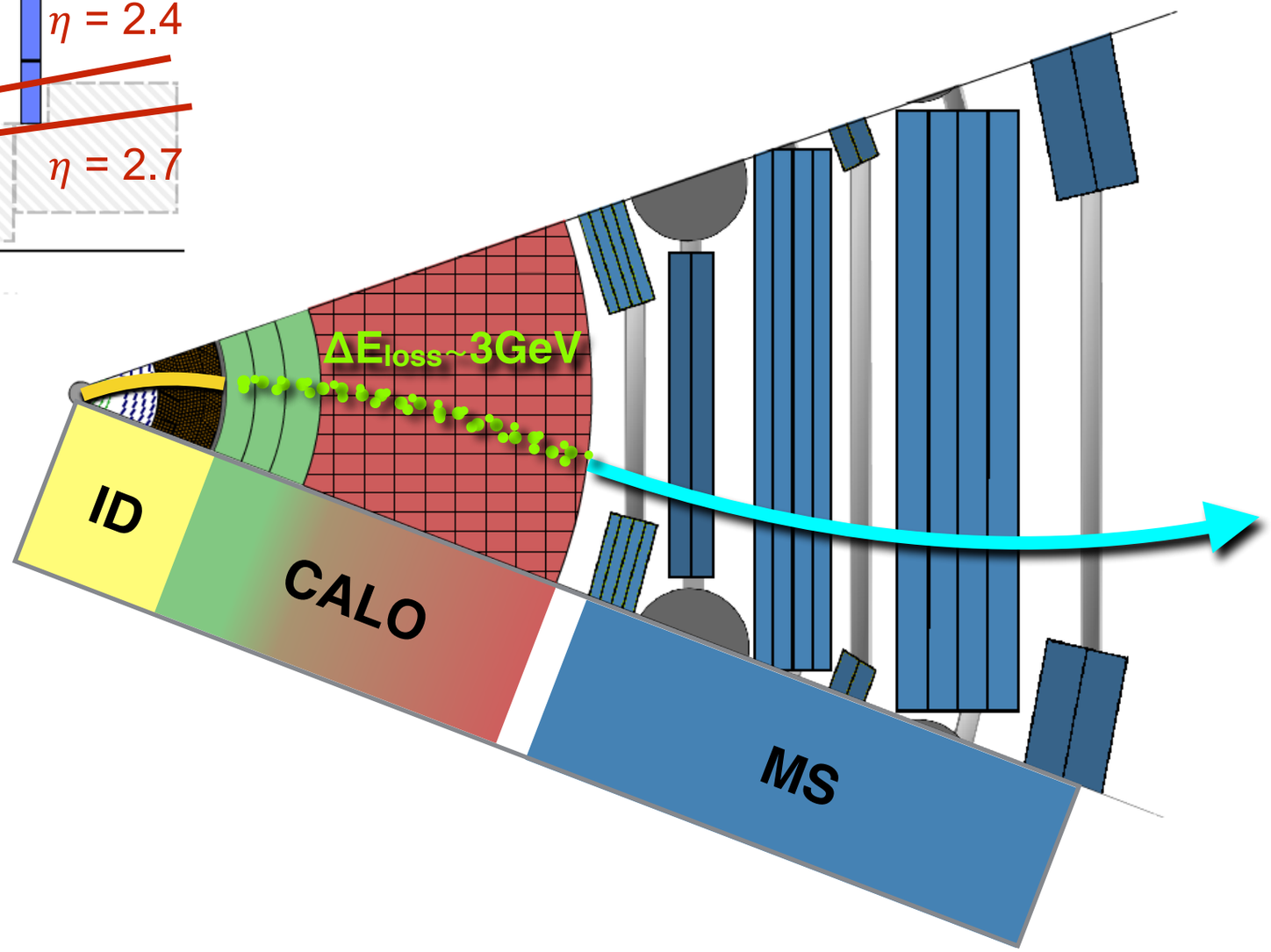



The ATLAS MS covers $|\eta| < 2.7$

**$0 < |\eta| < 1.05$**: best resolution

**$1.05 < |\eta| < 2.4$**: worse resolution; large fake rate

**$2.4 < |\eta| < 2.7$**: no ID tracking, no triggers




All ATLAS HI heavy flavor measurements are based on muon final states

High quality muons leave tracks in **ID** and **MS**, and lose energy in the **Calorimeter**

# Data samples

| Year | Species | $\sqrt{s_{NN}}$ [TeV] | $L_{int}$ [$nb^{-1}$] |
|---|---|---|---|
| 2010 | Pb+Pb | 2.76 | 0.01 |
| 2011 | Pb+Pb | 2.76 | 0.15 |
| 2013 | p+Pb | 5.02 | 28 |
| 2013 | p+p | 2.76 | 5000 |

Heavy flavor muons

- ATLAS-CONF-2012-050
- ATLAS-CONF-2015-053

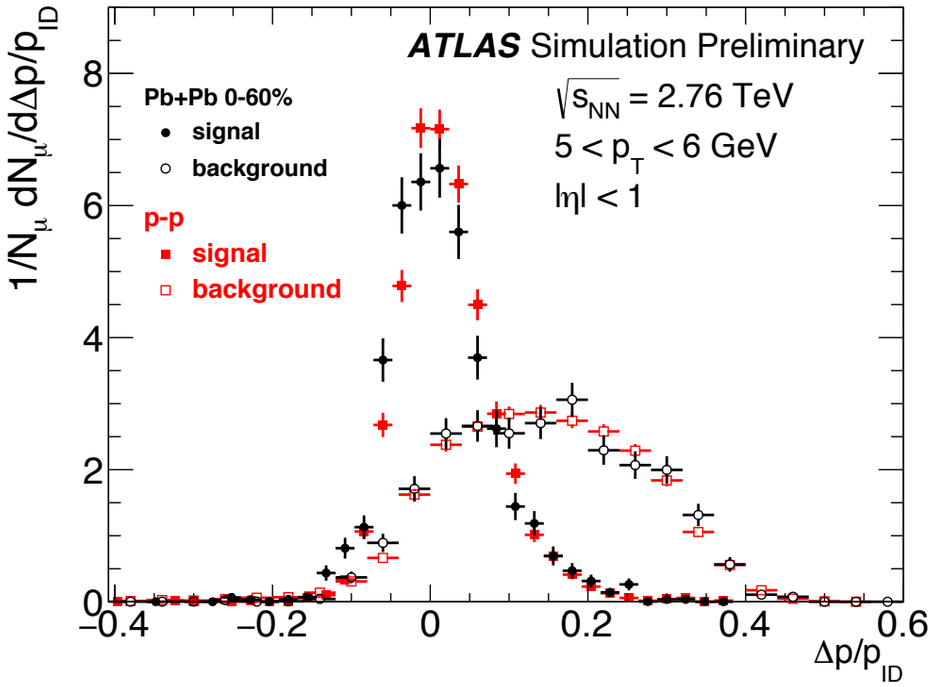
Quarkonia

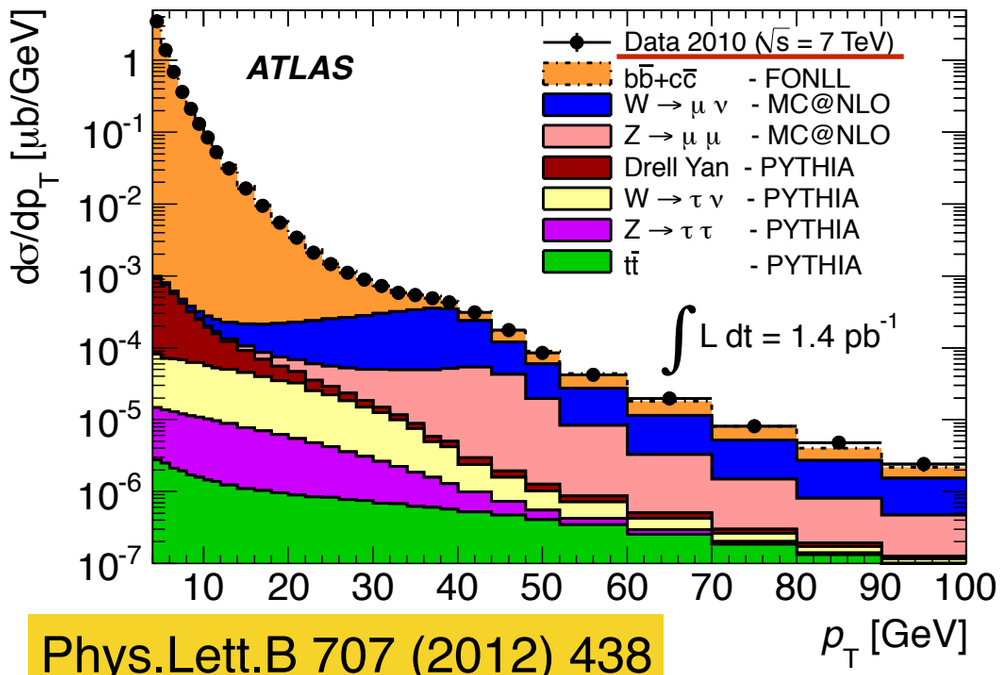
- RPC 92(2015)034904
- ATLAS-CONF-2015-023
- ATLAS-CONF-2015-050

# Hot medium
# Heavy flavor muons in Pb+Pb

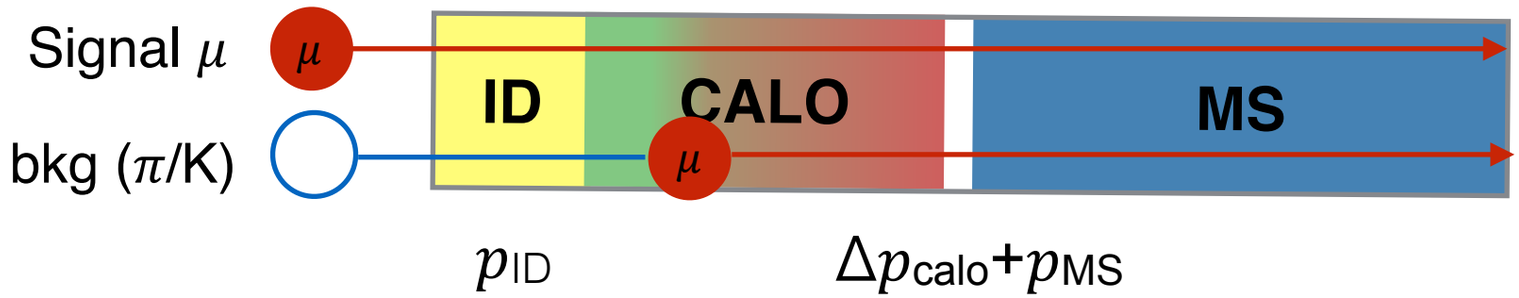
# Heavy flavor signal extraction

ATLAS-CONF-2015-053




Phys.Lett.B 707 (2012) 438




Momentum imbalance:

$$\frac{\Delta p}{p_{\mathrm{ID}}} = \frac{p_{\mathrm{ID}} - (p_{\mathrm{MS}} + \Delta p_{\mathrm{calo}})}{p_{\mathrm{ID}}}$$

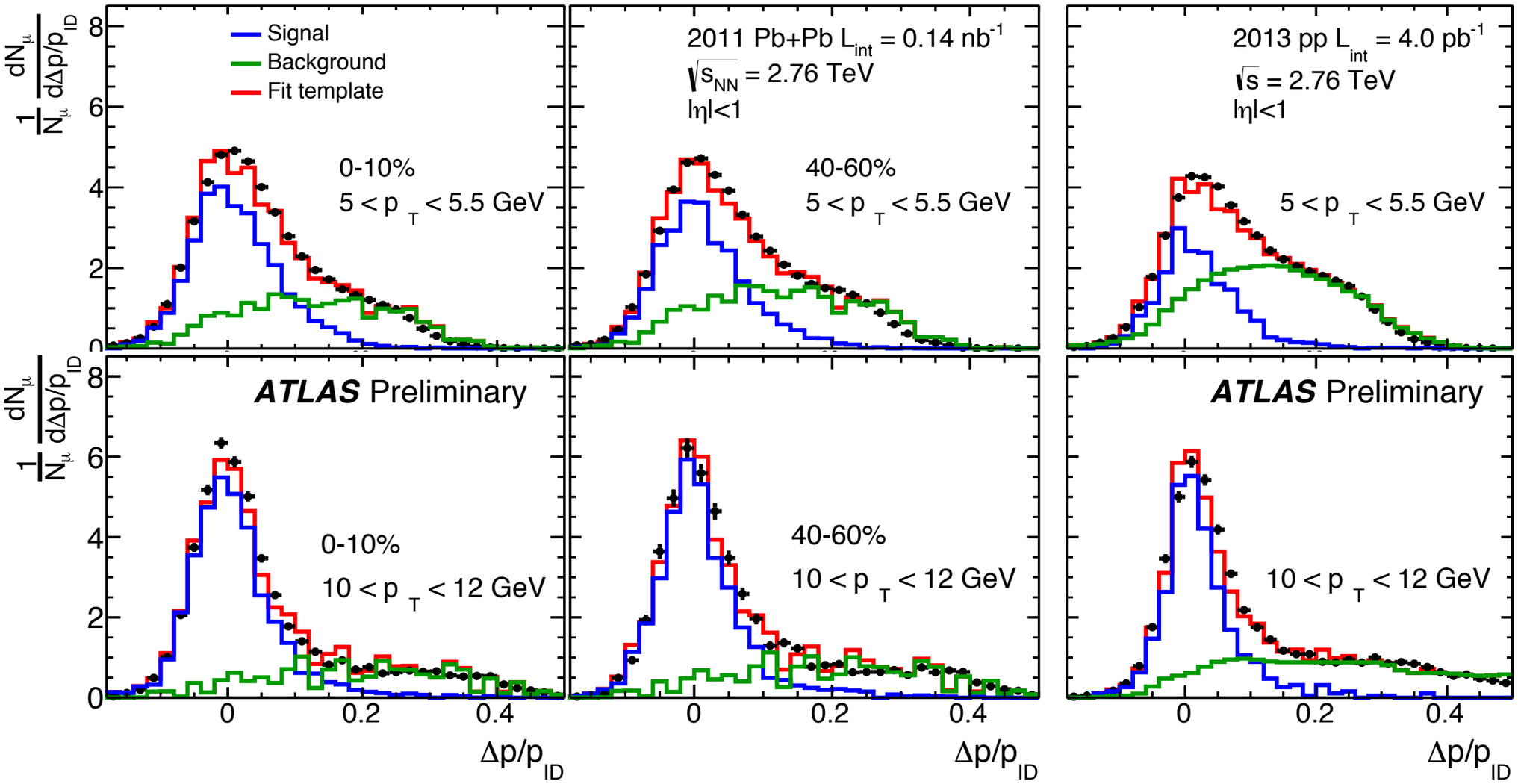
Signal well-separated from background

Very similar for pp and Pb+Pb, no centrality dependence

$|\eta| < 1.05$, $4 < p_T < 14$ GeV

# Signal extraction in data

ATLAS-CONF-2015-053



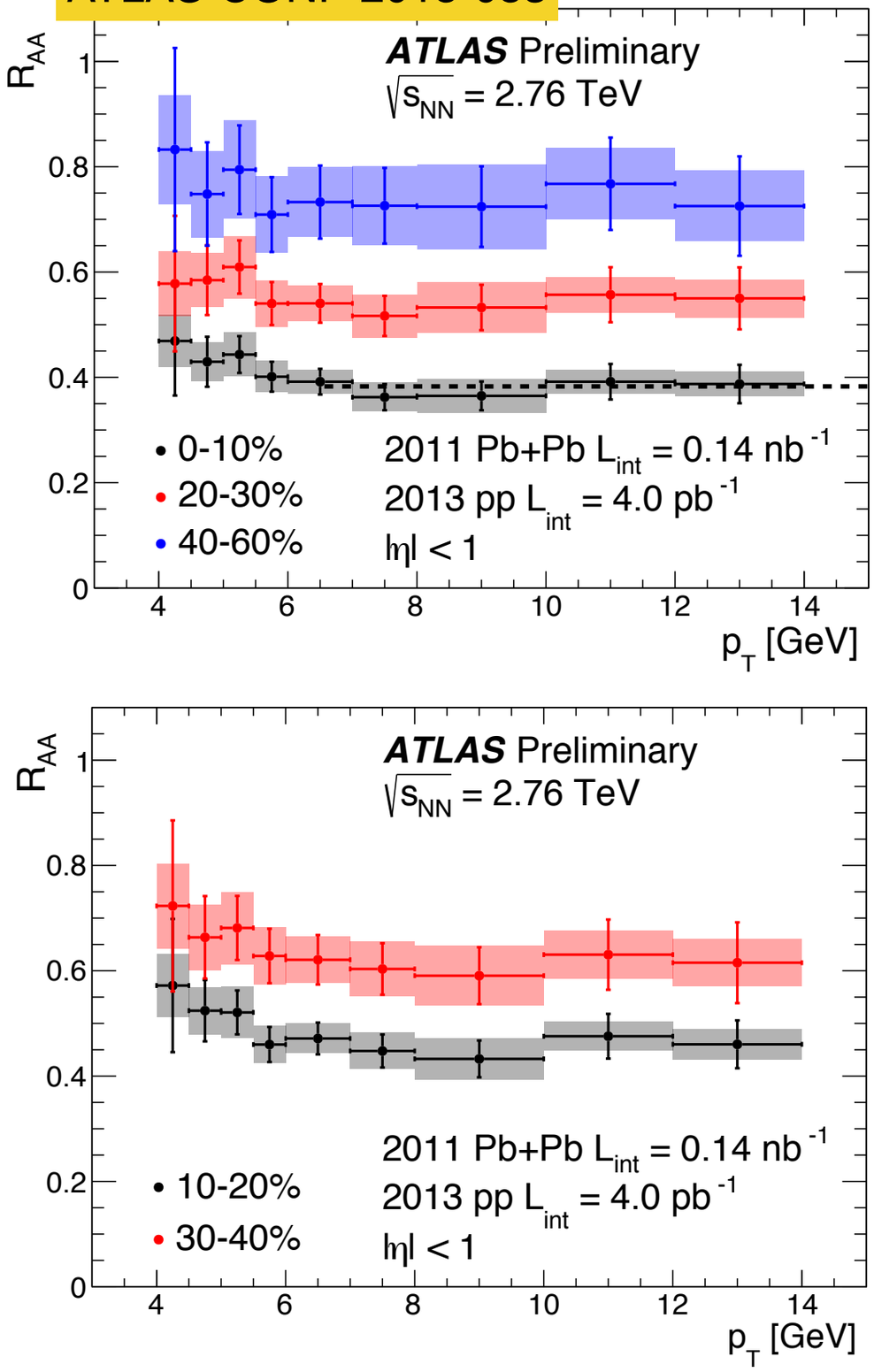

Template fits to extract heavy flavor component from inclusive $\mu^{\pm}$ yield

Good agreements between data and templates

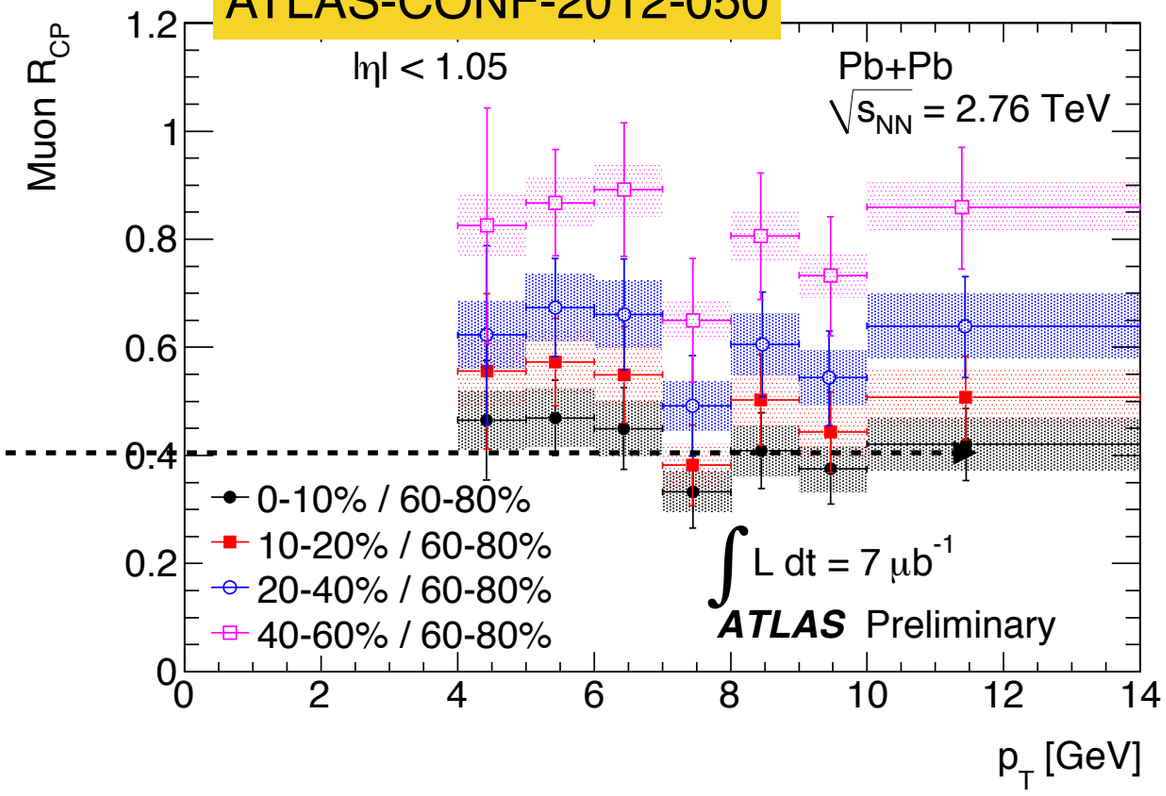
# Nuclear modification factor

ATLAS EXPERIMENT

ATLAS-CONF-2015-053




ATLAS-CONF-2012-050

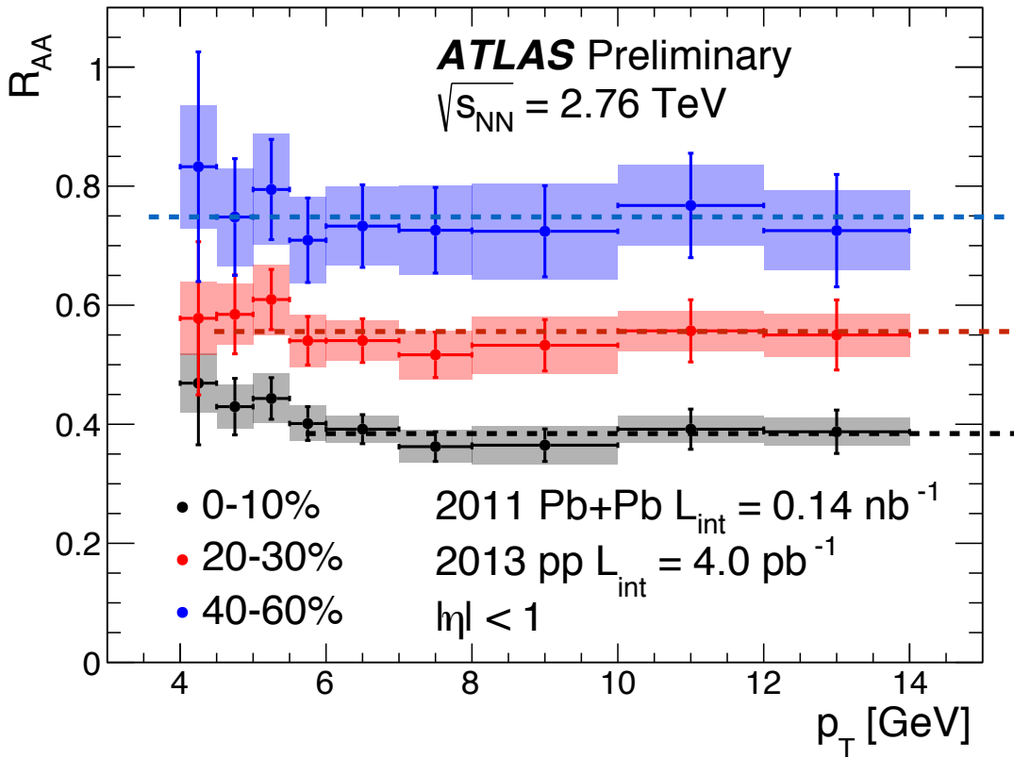


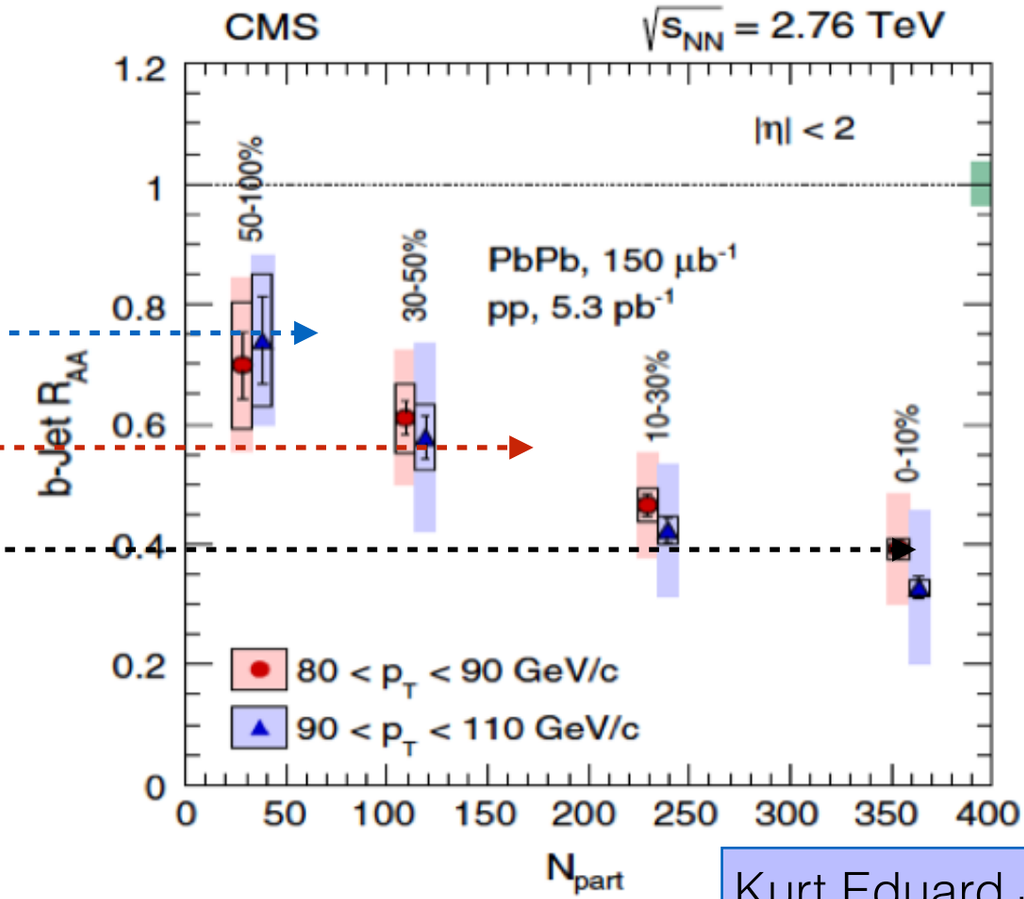

Significant suppression in central

No obvious dependence on $p_T$

2010 and 2011 data shows good consistency

# HF muon $R_{AA}$ vs. b-jet $R_{AA}$



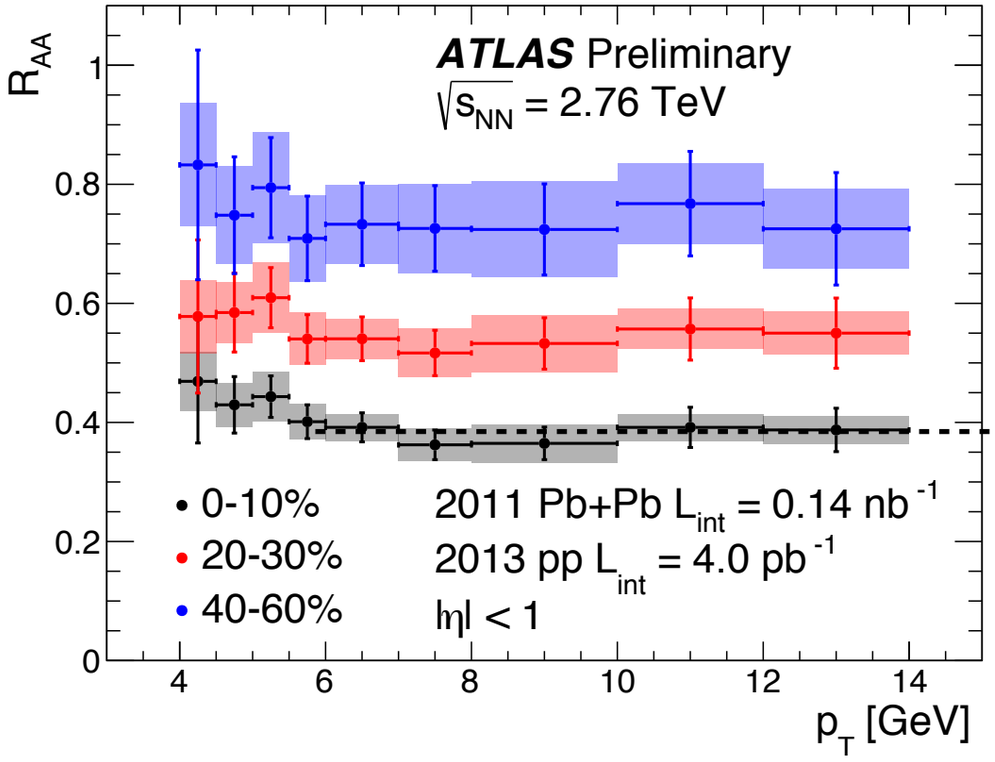

Kurt Eduard Jung

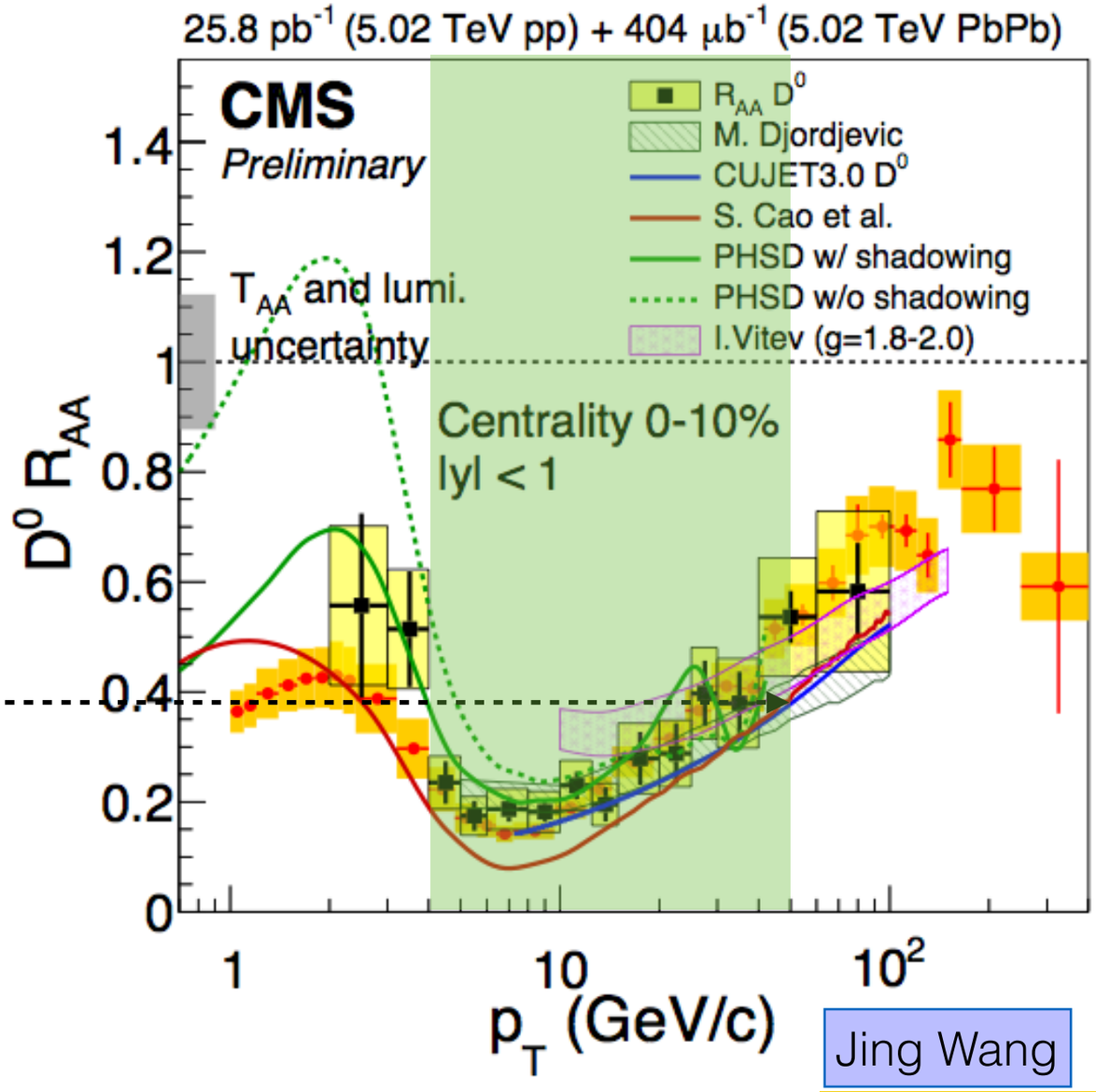
PRL 113(2014)132301

Centralities (averaged over measured ranges) are similar

Weak (or none) $p_T$ dependence in both measurements

# HF muon $R_{AA}$ vs. D meson $R_{AA}$




Jing Wang

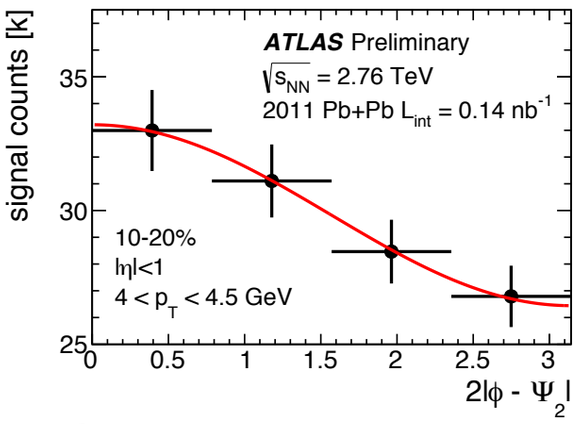
CMS-HIN-16-001

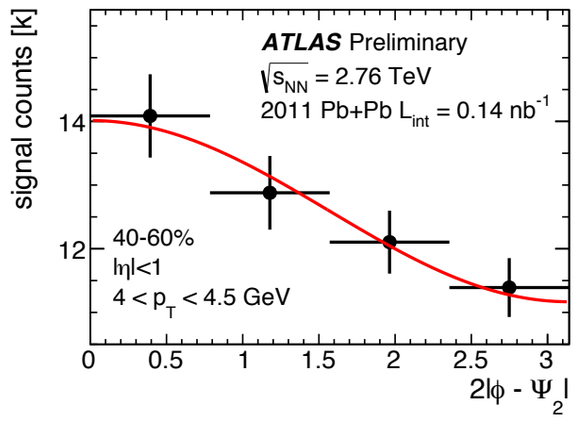
Very different behavior compared to the $D^0$ or inclusive hadron

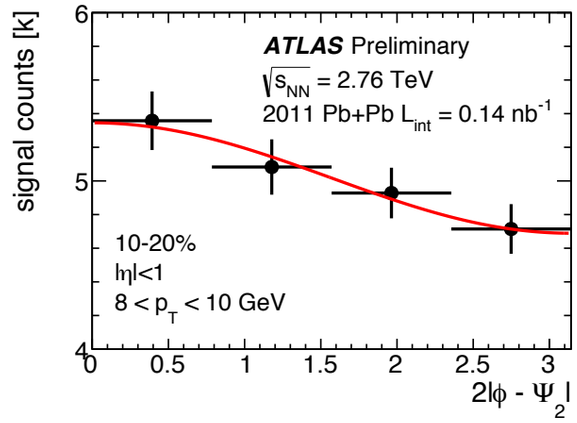
Significantly smaller suppression for inclusive HF muons

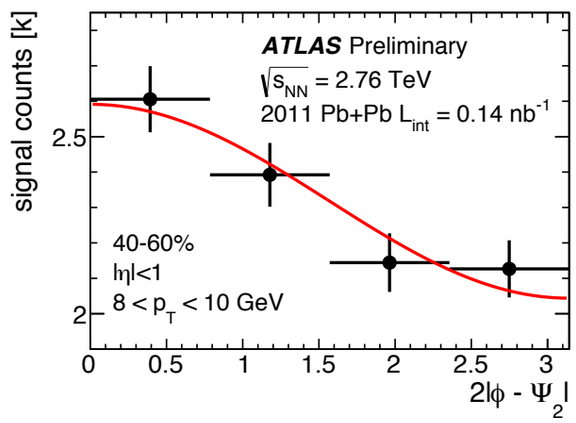
Strong momentum dependence for hadrons and c-jets

# HF muon $v_2$

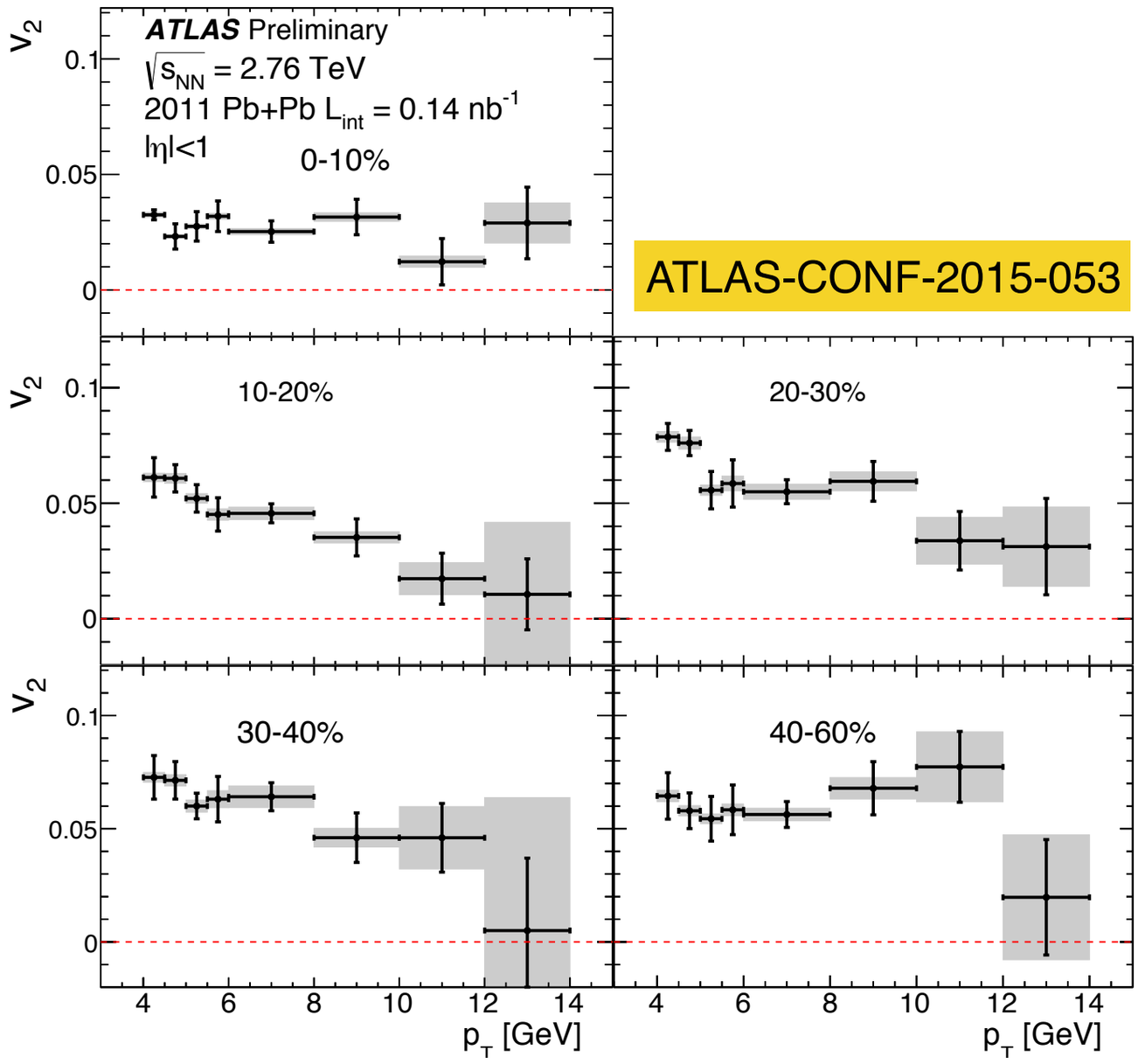



$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left( 1 + \sum_{n \geq 1} 2 v_n \cos\left( n \left[ \phi - \Phi_n \right] \right) \right)$$



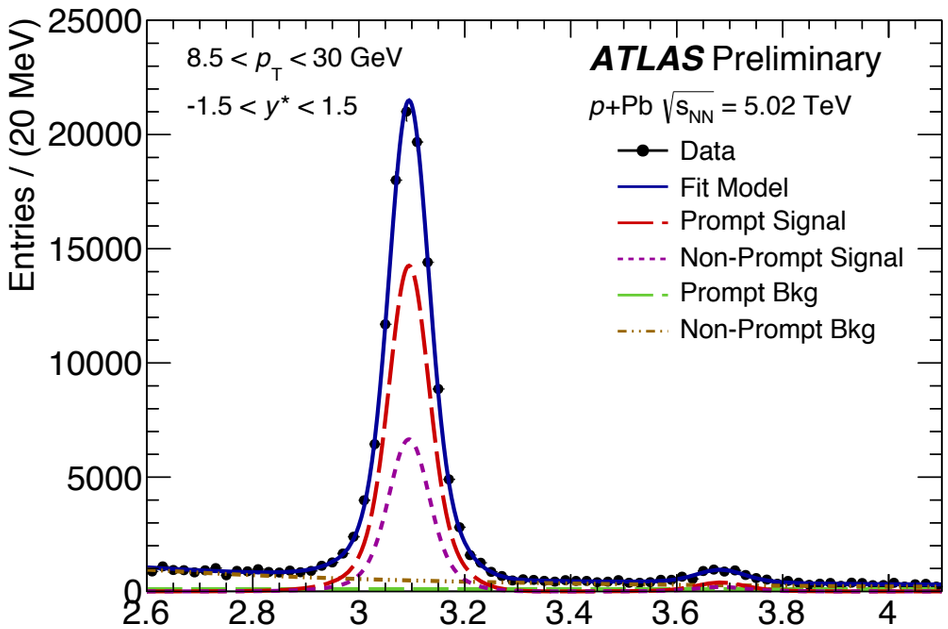

ATLAS-CONF-2015-053

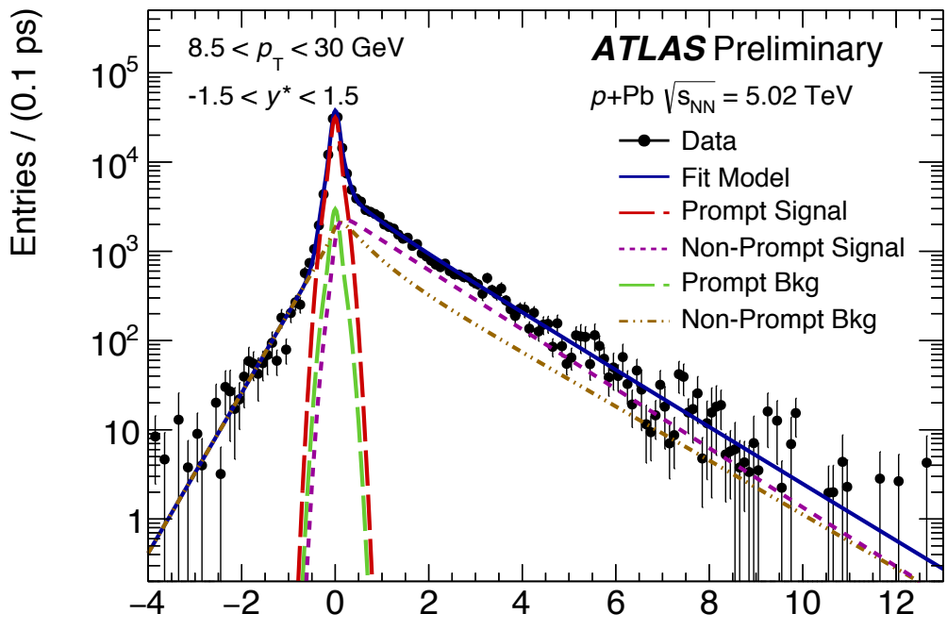
$v_2$ is extracted based on event plane method

Significant $v_2$ (~8%) at lower $p_T$, still significant at $p_T$ ~10 GeV

# “Cold” medium Quarkonia production in p+Pb

# Charmonium extraction



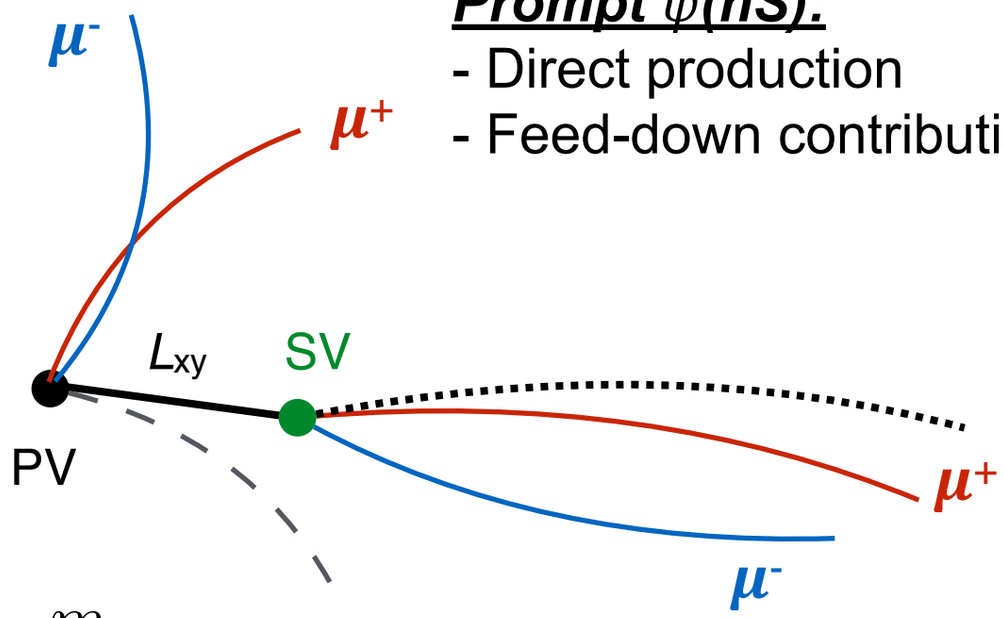




ATLAS-CONF-2015-023

2D ML fit to weighted data corrected for detecting efficiency and acceptance event-by-event

Prompt and non-prompt charmonia are discriminated based on the pseudo-proper lifetime of dimuon vertex

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_{\mathrm{T}}^{\mu\mu}}$$




***Prompt ψ(nS):***
- Direct production
- Feed-down contribution

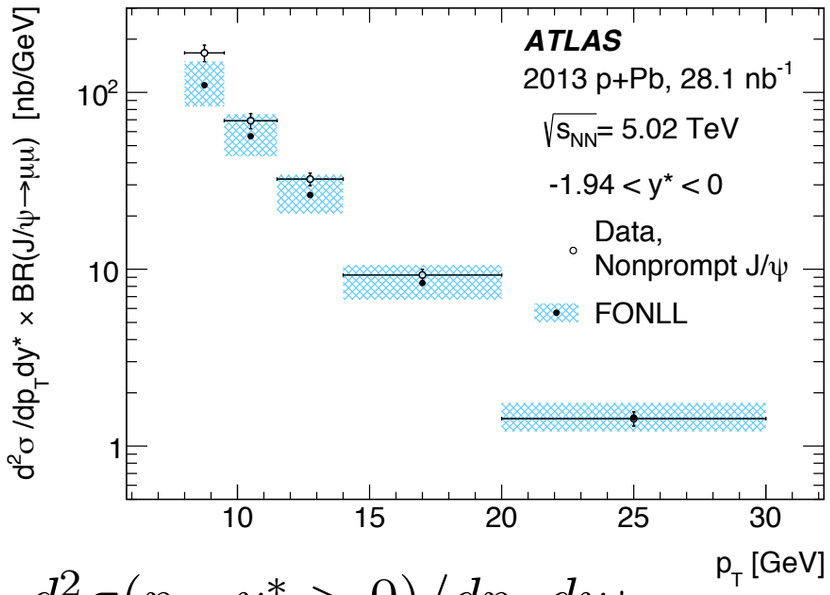
***Non-prompt ψ(nS):***
- Decays from B hadrons

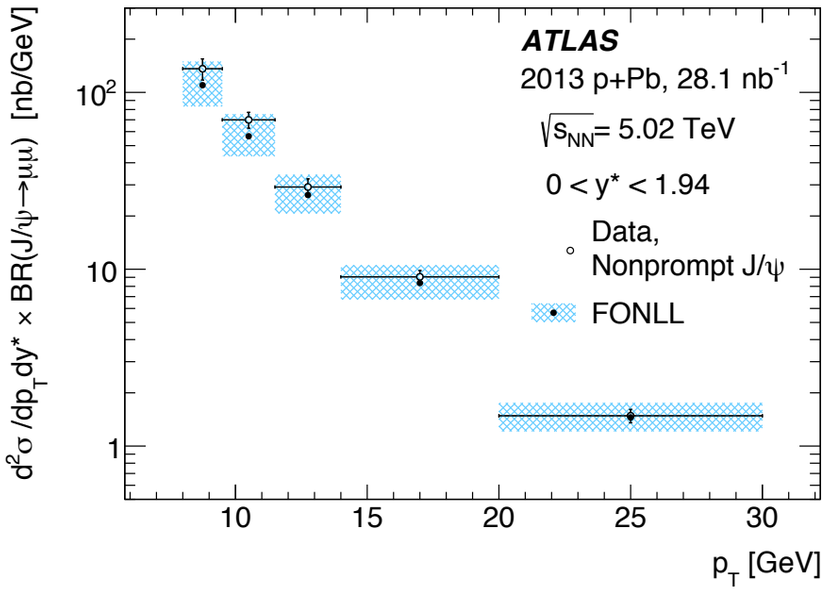
# Non-prompt J/psi $R_{FB}$

Significant production excess wrt. FONLL at low $p_T$

$R_{FB}$ < 1 at low $p_T$

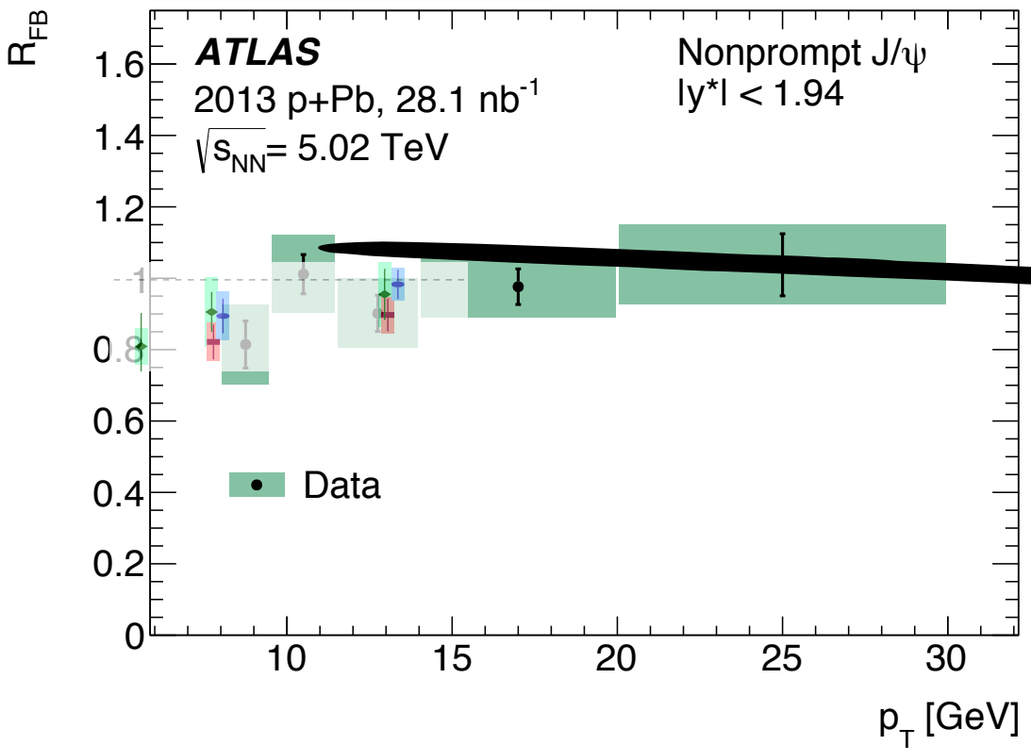
Good agreement between ATLAS and CMS

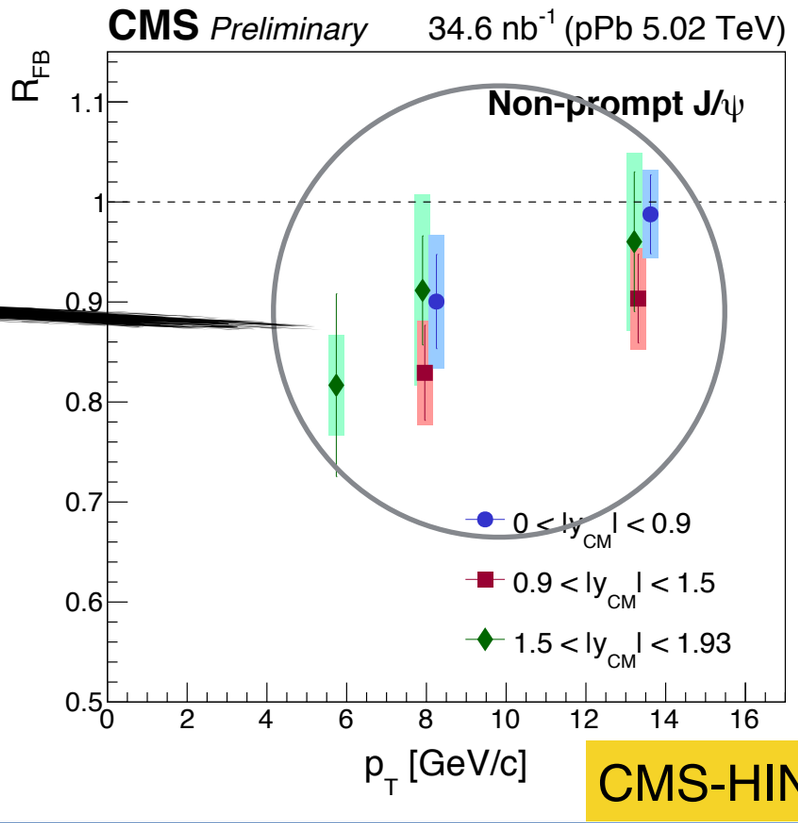



$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y^*) = \frac{d^2\sigma(p_{\mathrm{T}}, y^* > 0)/dp_{\mathrm{T}}dy*}{d^2\sigma(p_{\mathrm{T}}, y^* < 0)/dp_{\mathrm{T}}dy*}$$

RPC 92(2015)034904

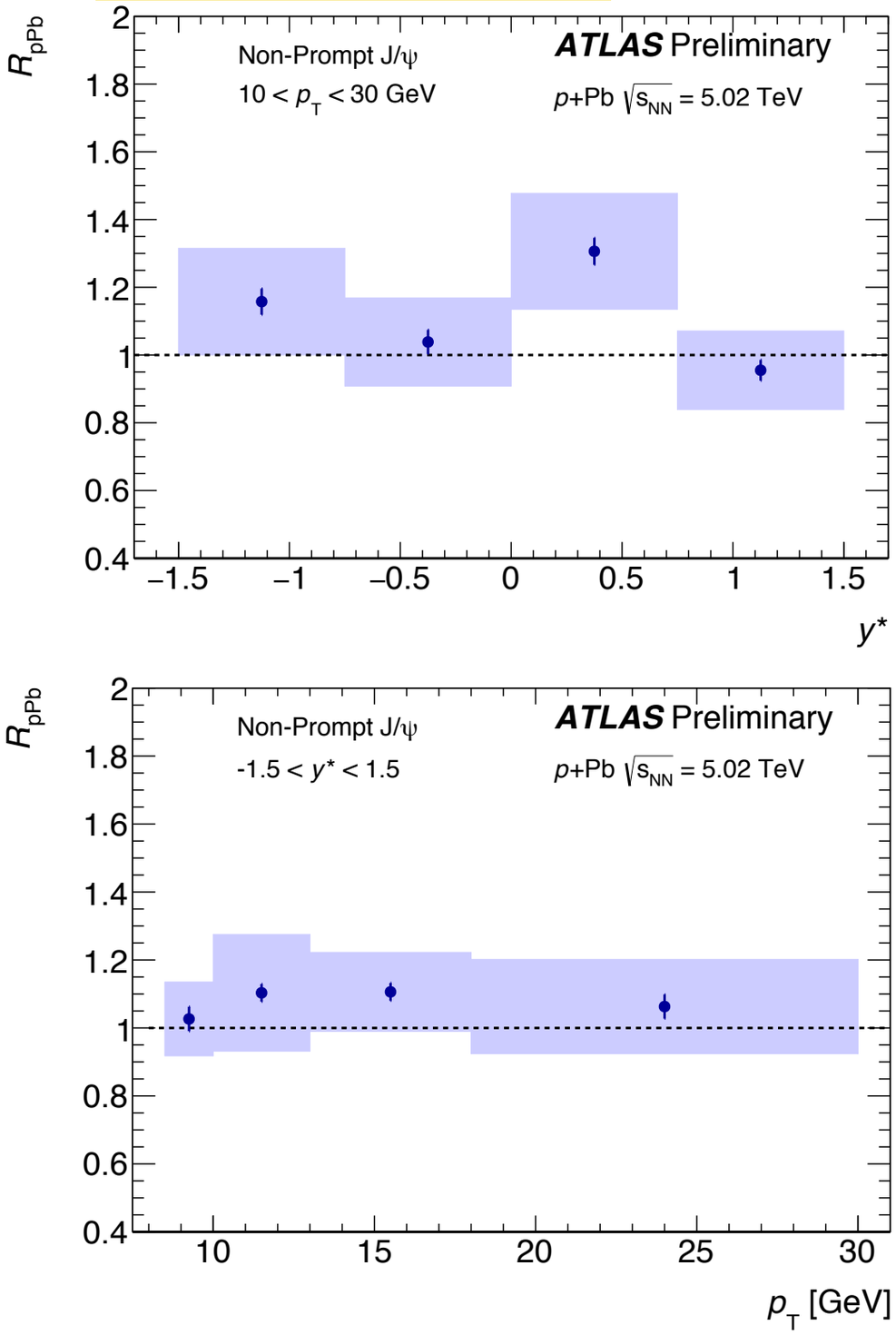



CMS-HIN-14-009

# Non-prompt J/psi nuclear modification factor

ATLAS-CONF-2015-023

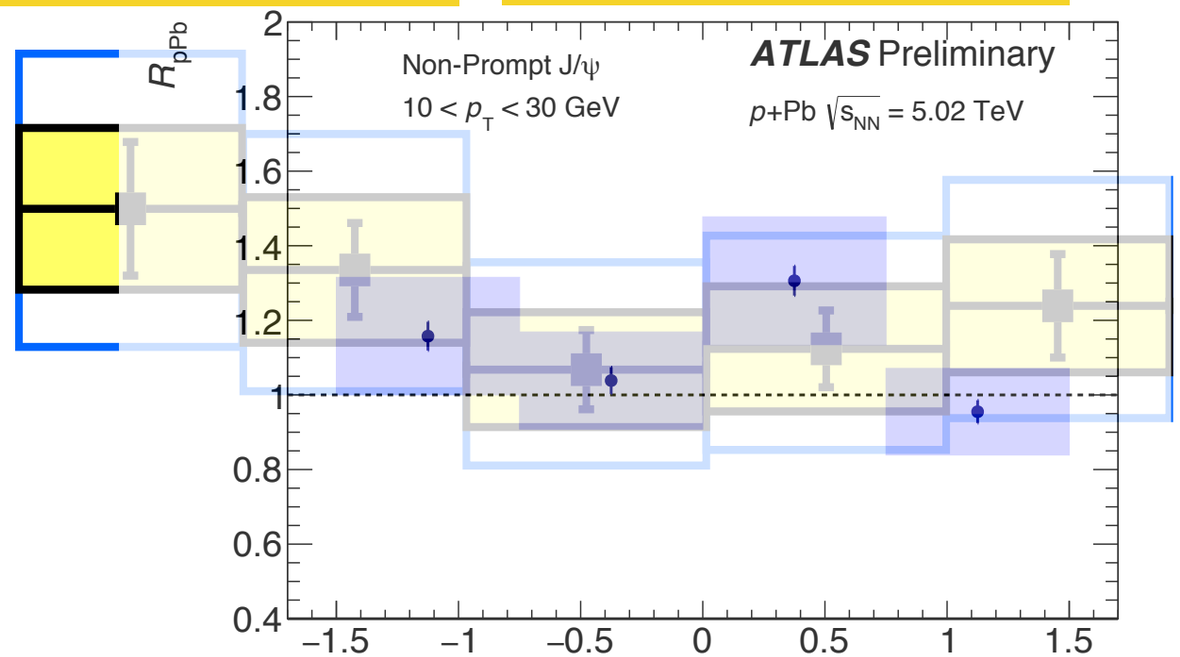



$$R_{p\mathrm{Pb}} = \frac{1}{A^{\mathrm{Pb}}} \frac{d^2\sigma_{\psi}^{p+\mathrm{Pb}}/dy^* dp_{\mathrm{T}}}{d^2\sigma_{\psi}^{pp}/dy dp_{\mathrm{T}}},$$

pp reference determined from interpolation of 2.76, 7 and 8 TeV data

# Non-prompt J/psi vs. B+

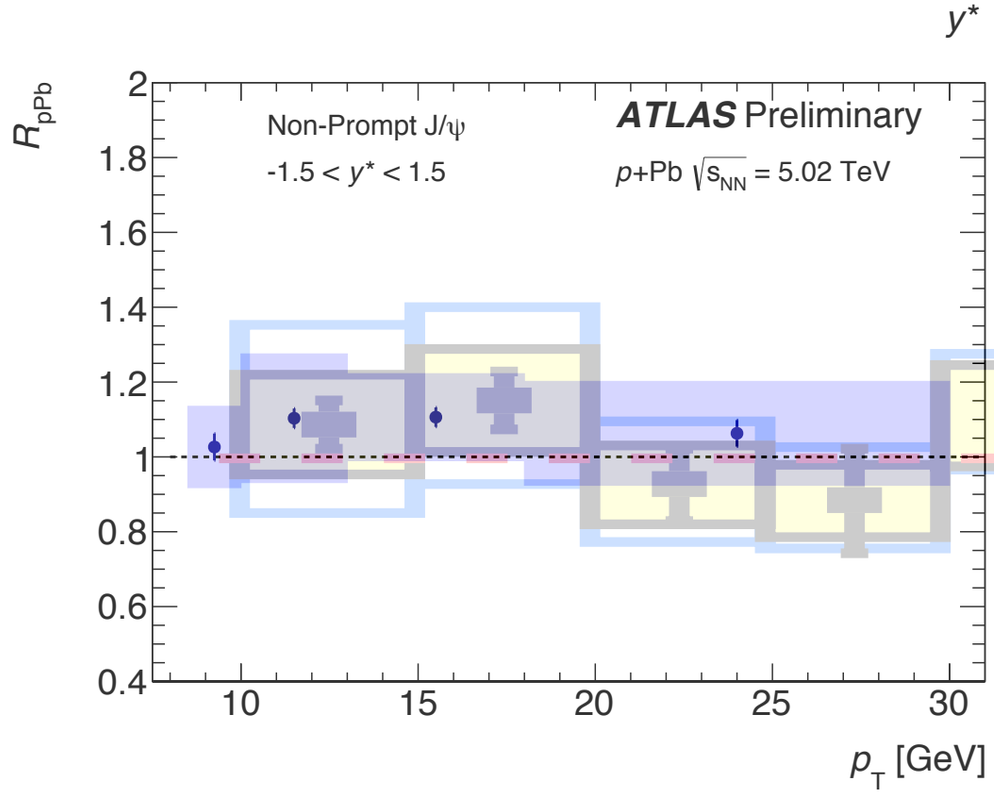
PRL 116 (2016) 032301 ATLAS-CONF-2015-023

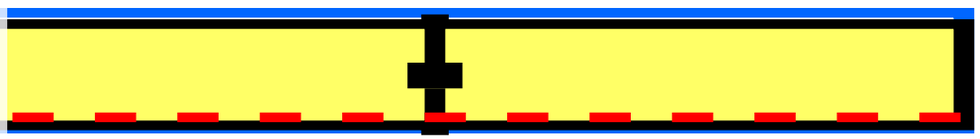



ATLAS: 10 < $p_T$ < 30 GeV

CMS: 10 < $p_T$ < 60 GeV

Non-prompt J/psi $R_{pPb}$ are in good consistency with B+ $R_{pPb}$ measured by CMS



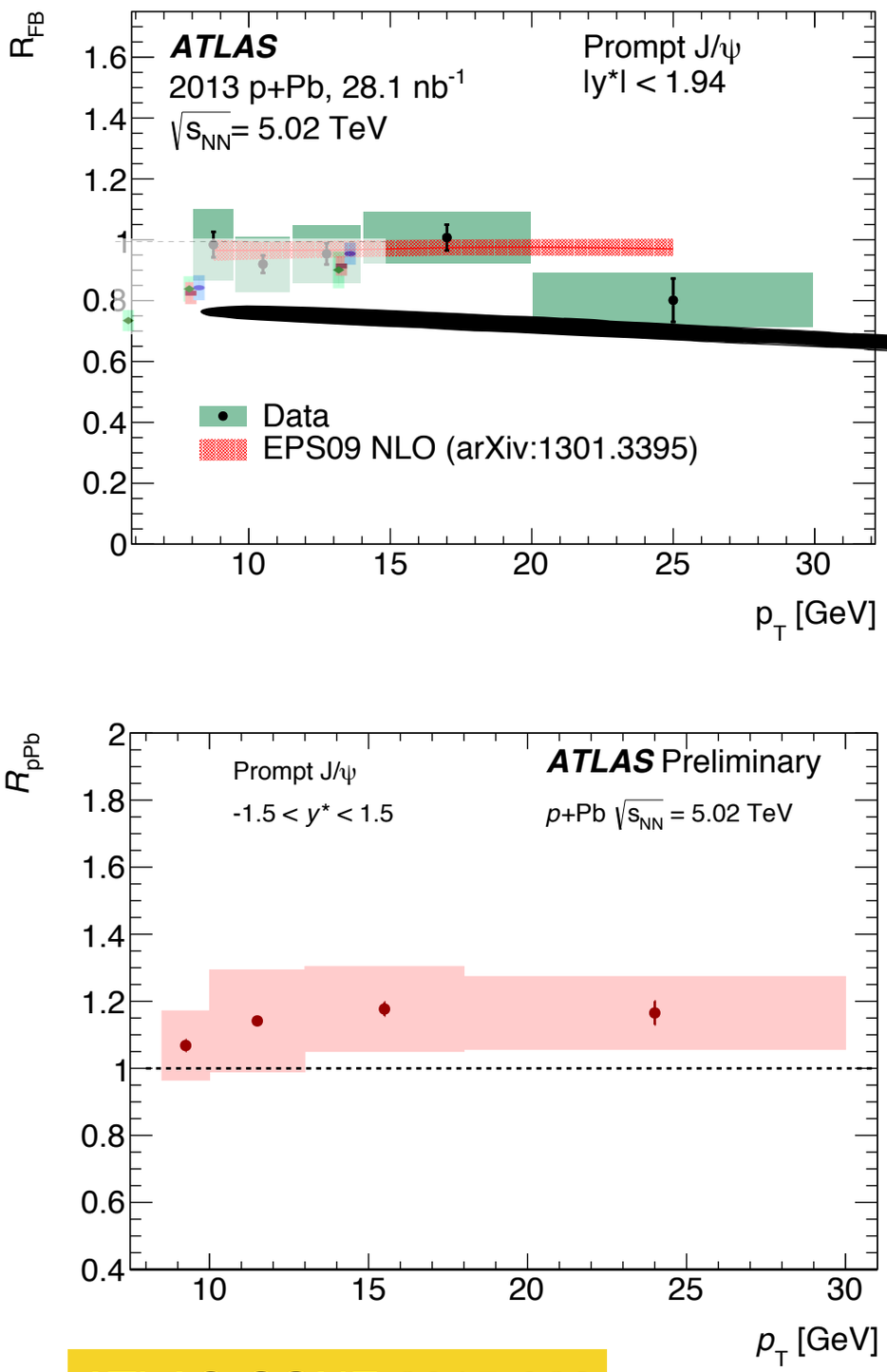



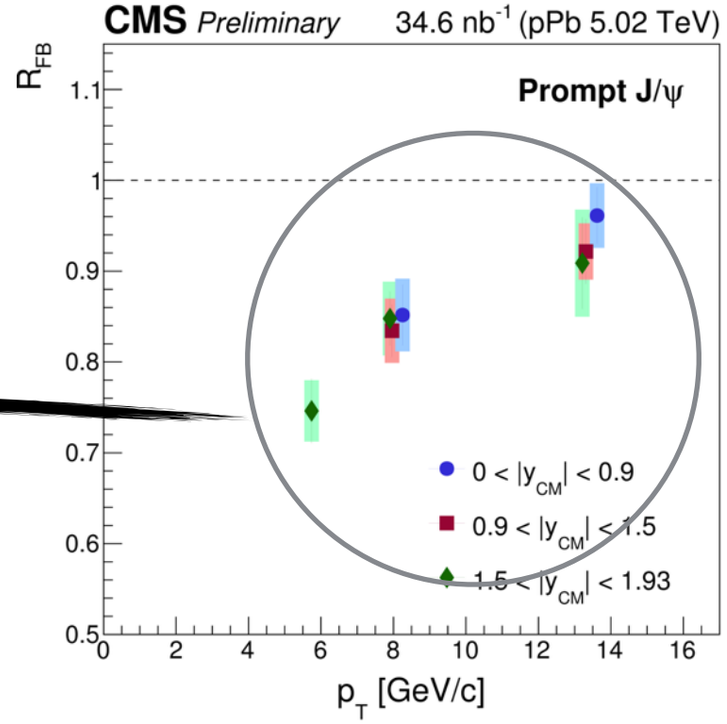
ATLAS: |y*| < 1.5

CMS: $|y_{lab}|$ < 2.4

# Prompt charmonium

RPC 92(2015)034904

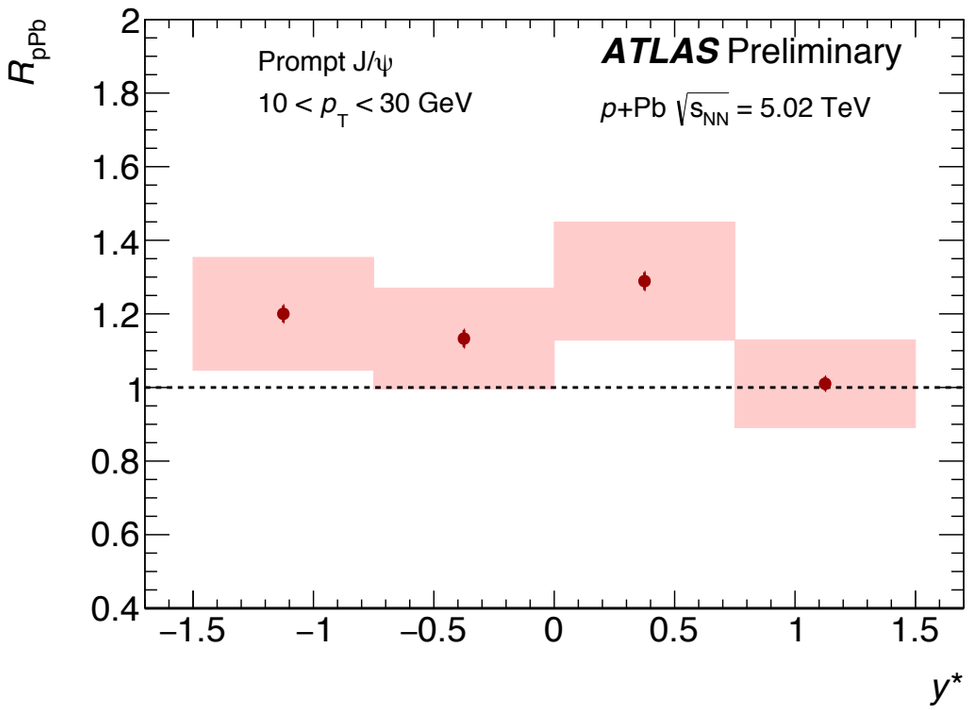



CMS-HIN-14-009

$R_{FB}$ consistent at common $p_T$ between ATLAS and CMS




ATLAS-CONF-2015-023

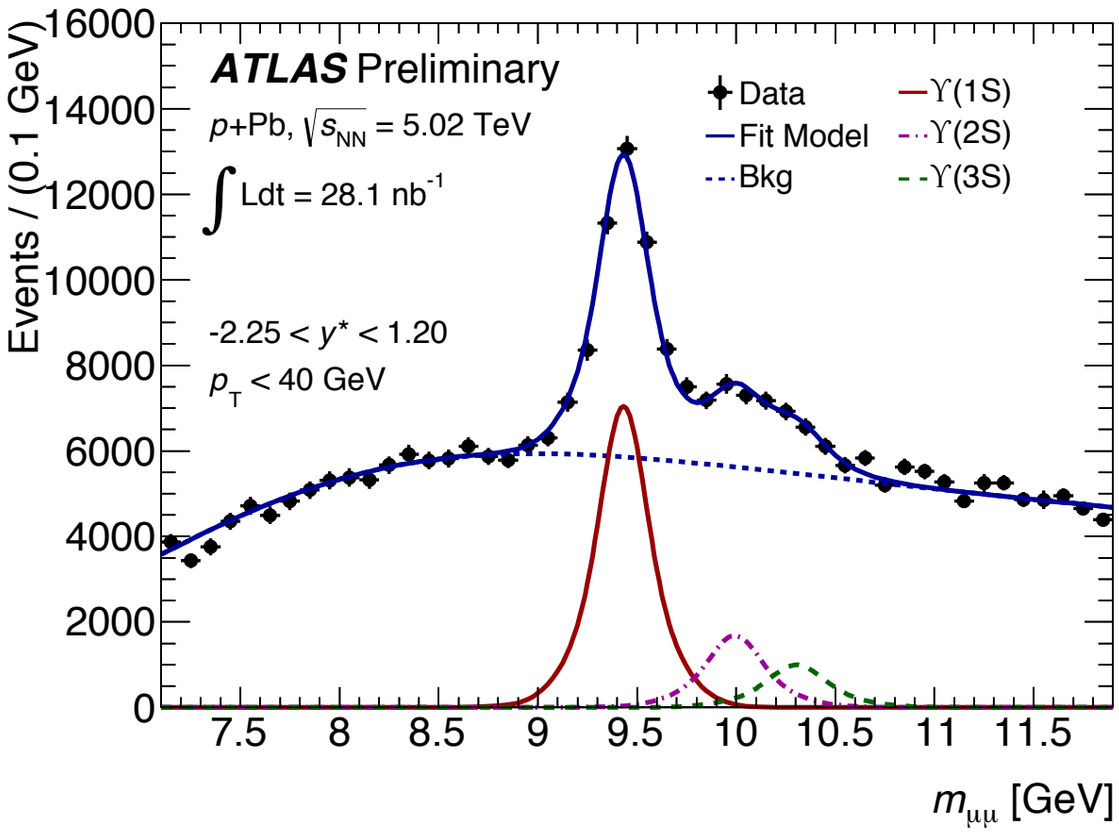
$R_{pPb} > 1$

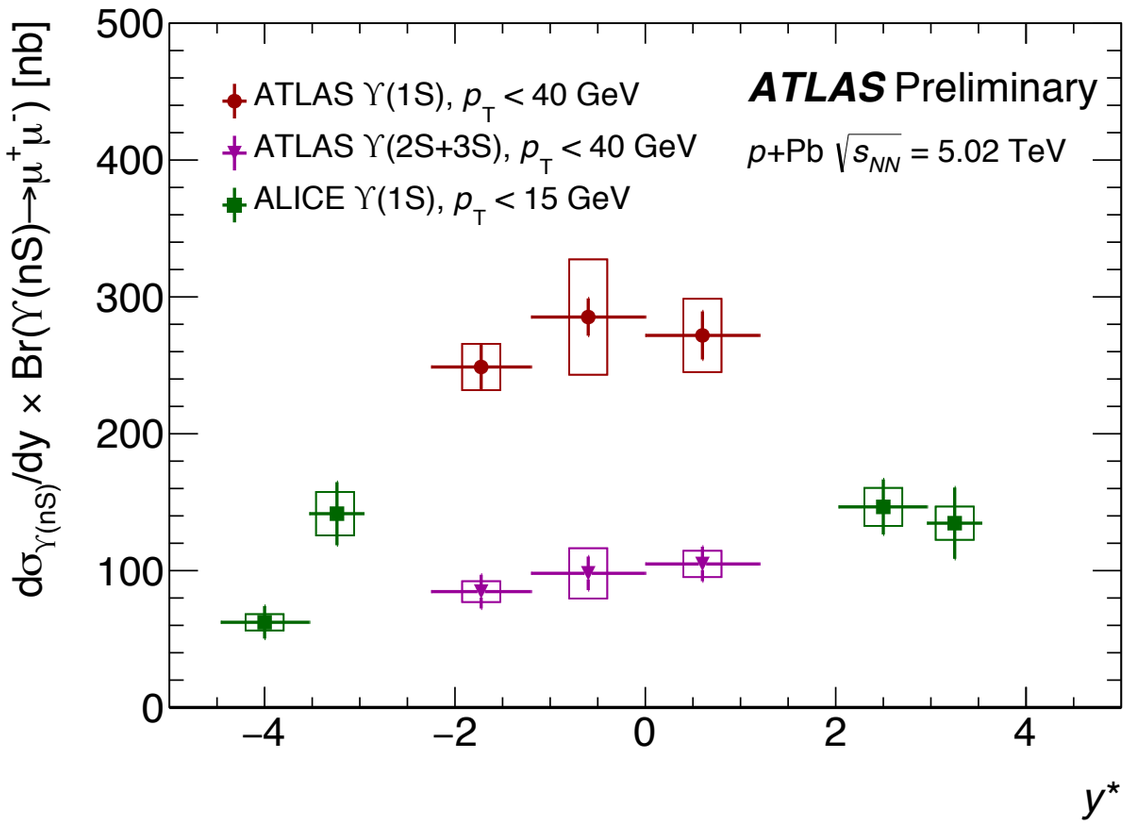
No obvious kinematic dependence

William Brooks

# Bottomonium extraction

ATLAS-CONF-2015-050



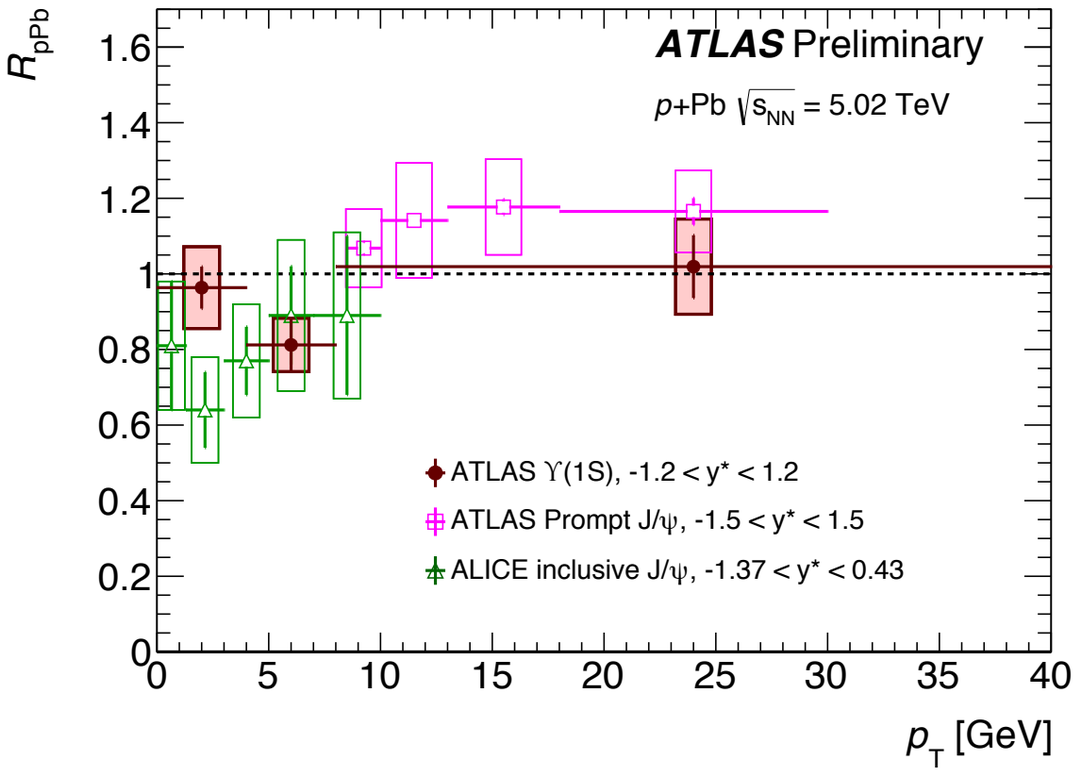

Binned chi2 fit to per-event-corrected data

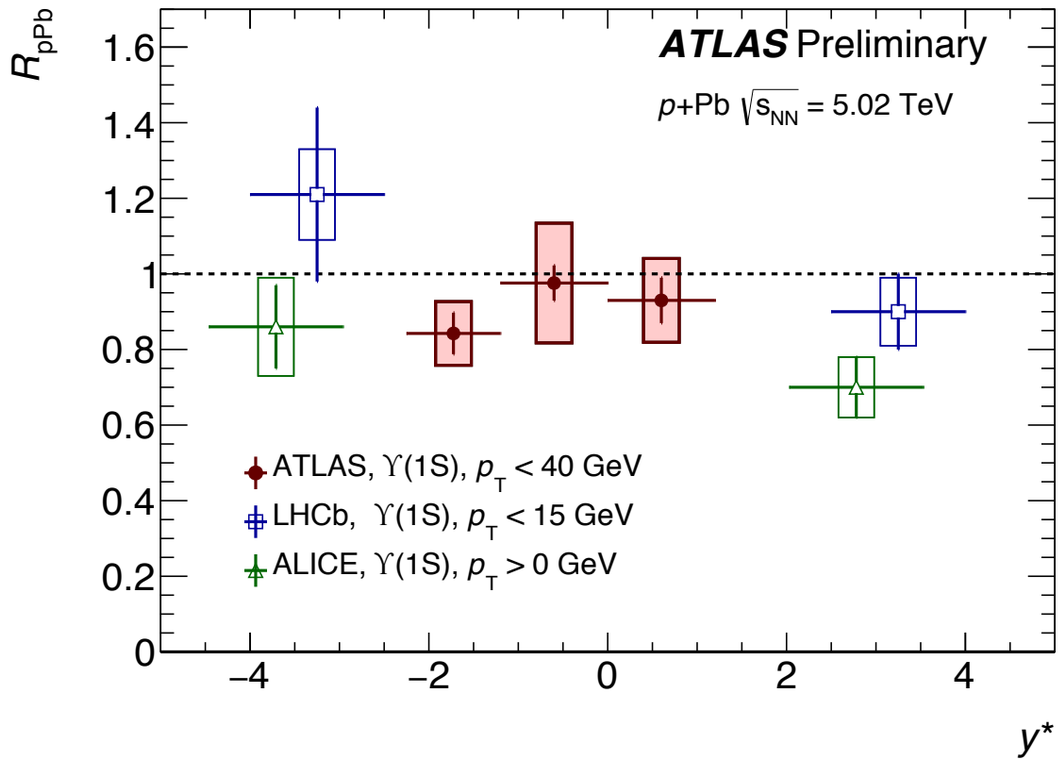
Upsilon(2S) and Upsilon(3S) are combined as Upsilon(2S + 3S)

-2.25 < y* < 1.2 and 0 < $p_T$ < 40 GeV. Thanks to the higher mass, a wider $p_T$ range can be covered for Upsilon states

# Charmonium vs. bottomonium

ATLAS-CONF-2015-050




Reference based on interpolation

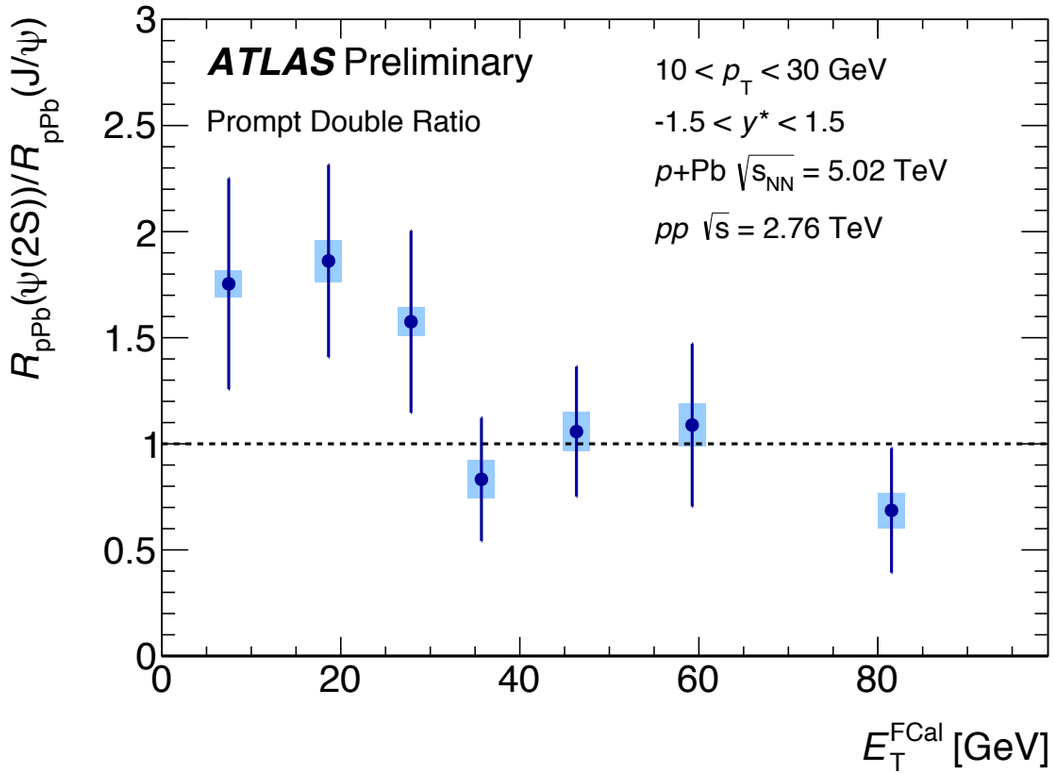
Upsilon vs. inclusive J/psi $R_{pPb}$ at low $p_T$ and prompt J/psi $R_{pPb}$ at higher $p_T$

Charmonium $R_{pPb}$ and bottomonium $R_{pPb}$ show similar $p_T$ dependence

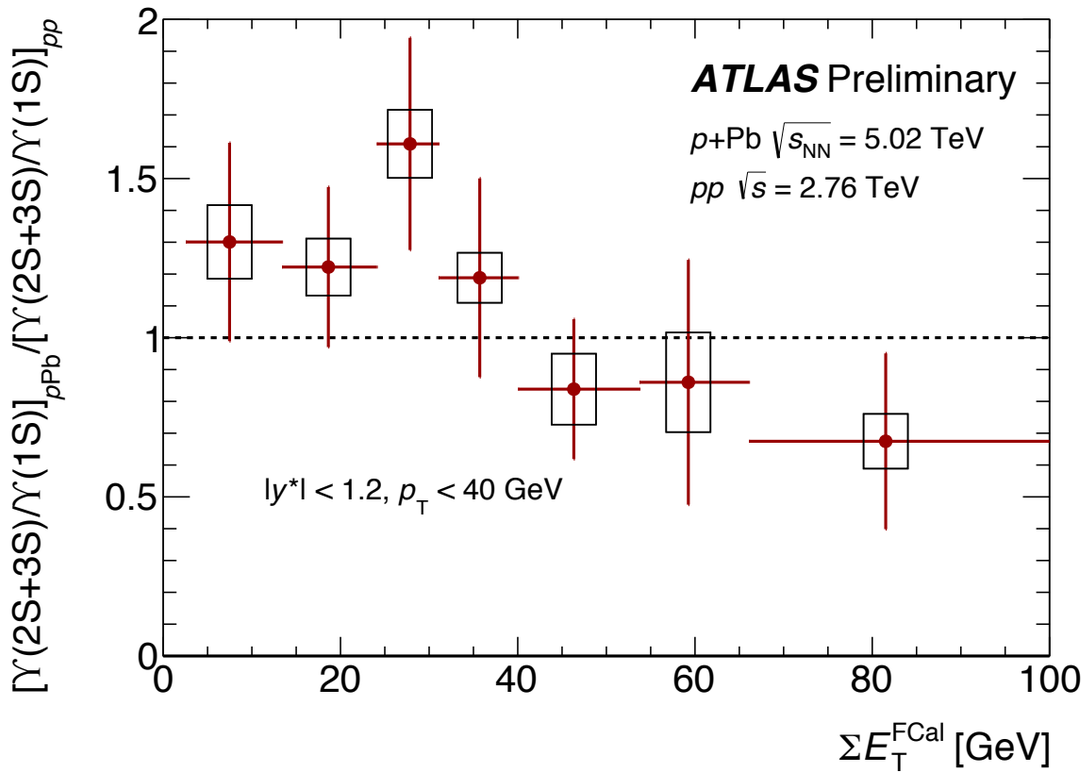
Upsilon $R_{pPb}$ has no strong dependence on rapidity

# Double ratio

ATLAS-CONF-2015-023



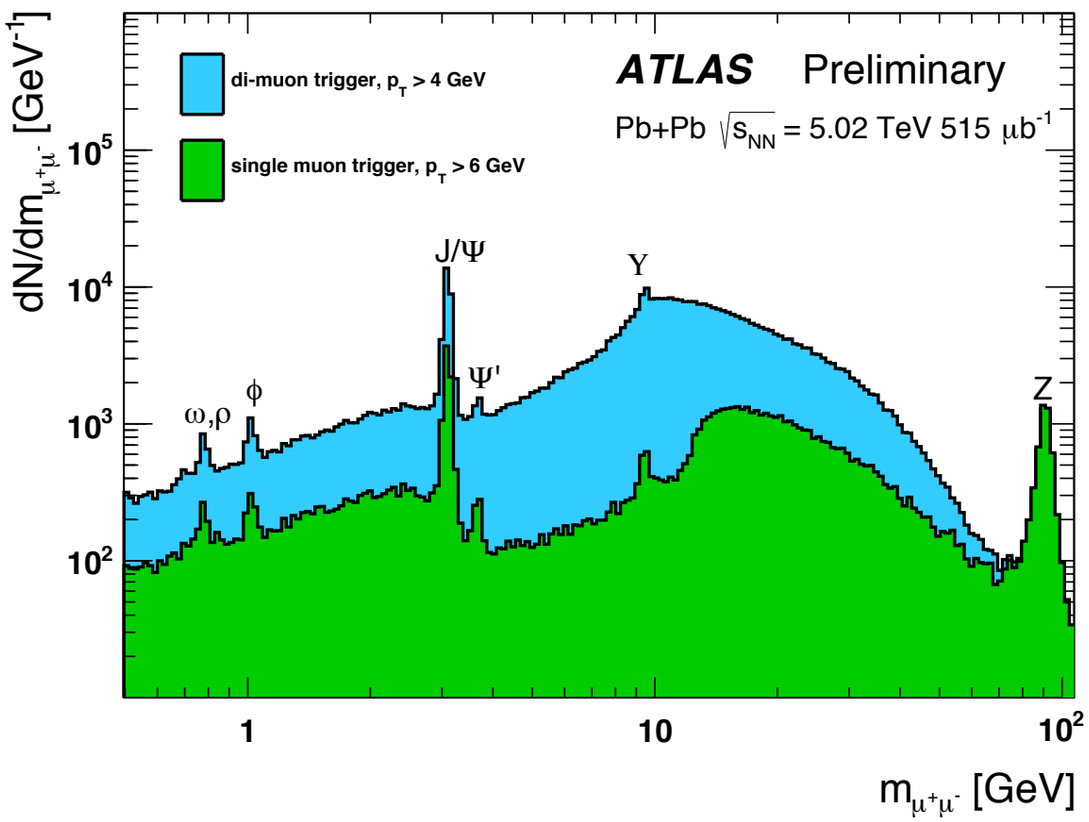

ATLAS-CONF-2015-050

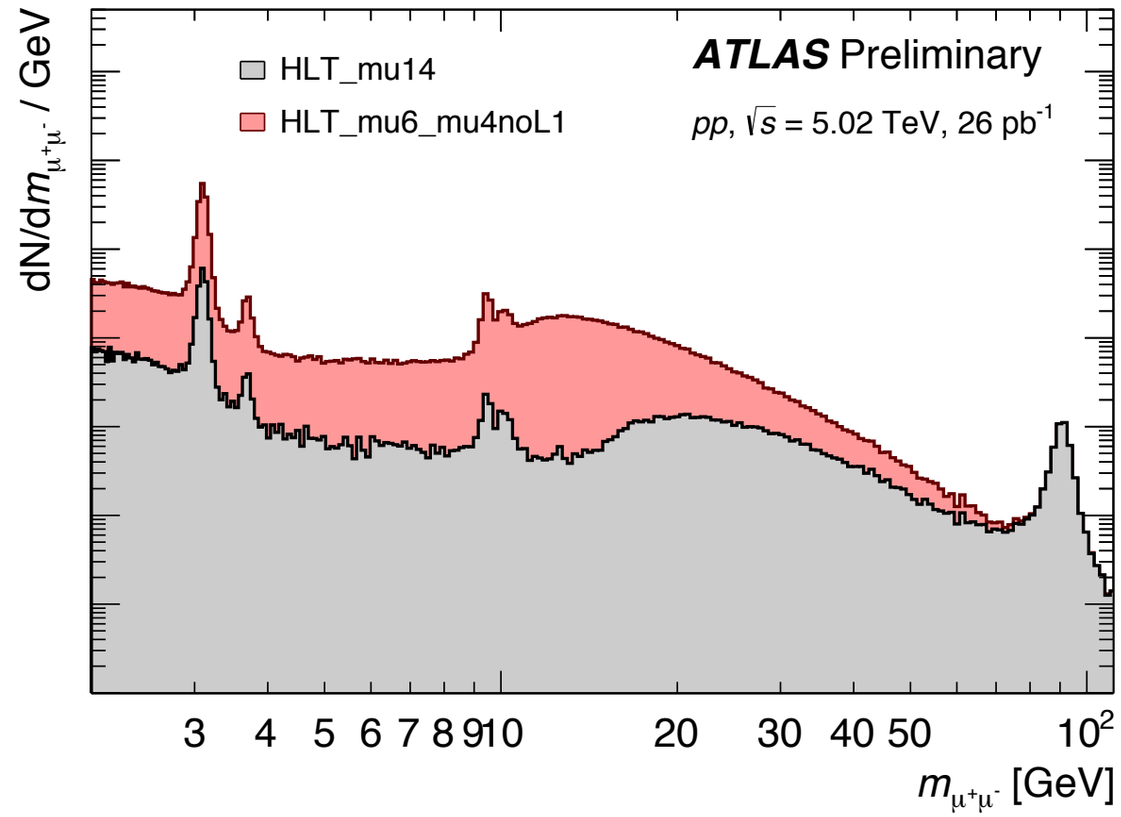



Excited states production is suppressed wrt. ground states in most central p+Pb collisions for both charmonium and botttomonium

May due to interaction with co-movers

# Quarkonia at Run II




What can be expected from ATLAS ?

- ✦ Improved cold quarkonia
- ✦ New results on hot quarkonia

# Summary

HF muon production in Pb+Pb

- HF muon $R_{AA}$ similar with b-jet, but different from $D^0$ and charge hadron
- More suppressed in most central collisions
- Significant $v_2$ up to 10 GeV

Quarkonia production in p+Pb

- Non-prompt J/psi production excess at low $p_T$ wrt. FONLL, more significant in backward
- J/psi and Upsilon(1S) $R_{pPb}$ show no strong kinematic dependence
- Excites states are suppressed in most central collisions wrt. peripheral

0.5 $nb^{-1}$ of Run2 PbPb collisions collected, analyses are in progress

# ATLAS parallel talks

- Measurement of the ridge correlations in pp and pPb collisions with the ATLAS detector at the LHC

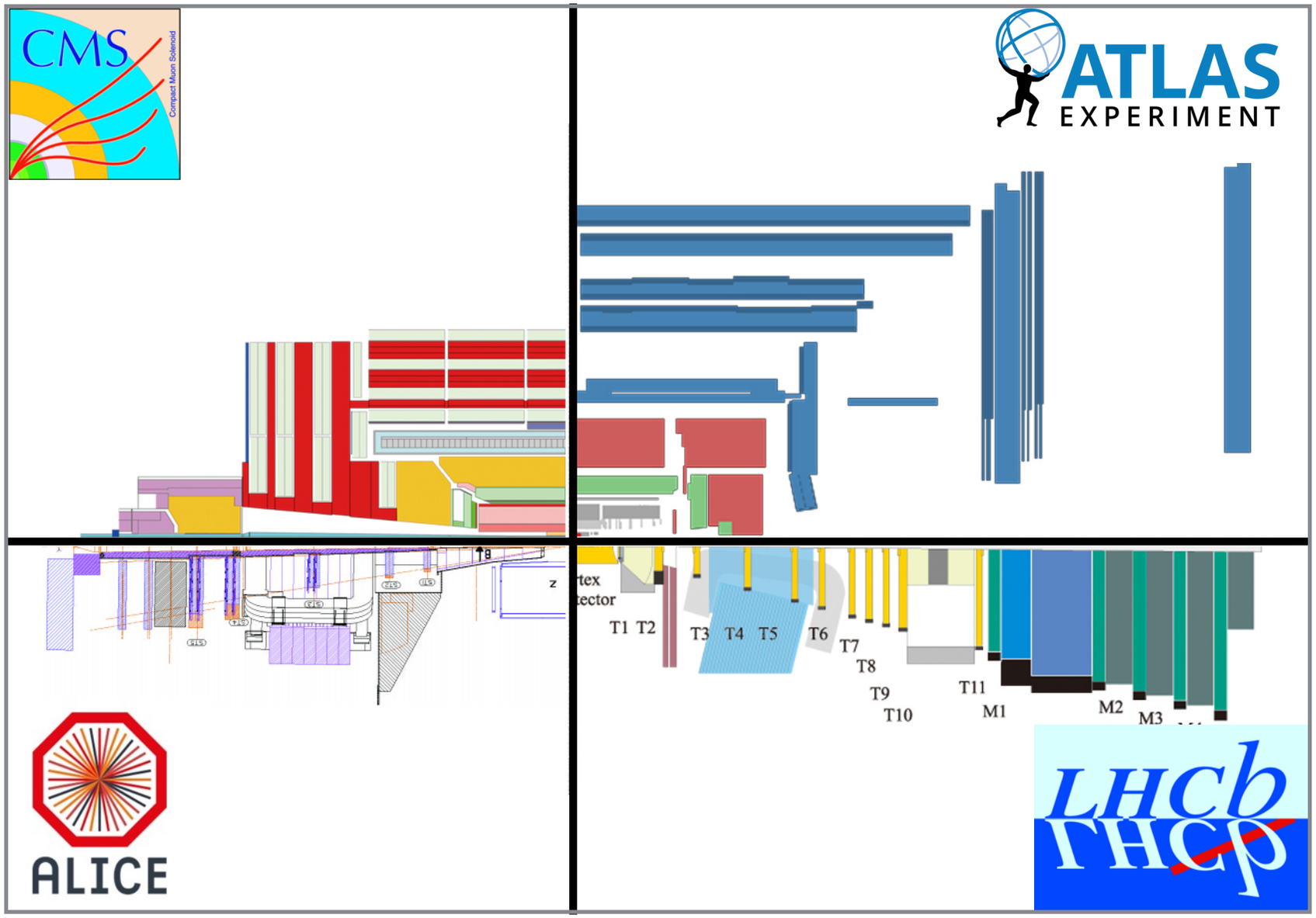
  by Krzysztof Wozniak on Thursday 11:20 in Room 102

- Vector boson and Charmonium production in proton-lead and lead-lead collisions with ATLAS at the LHC

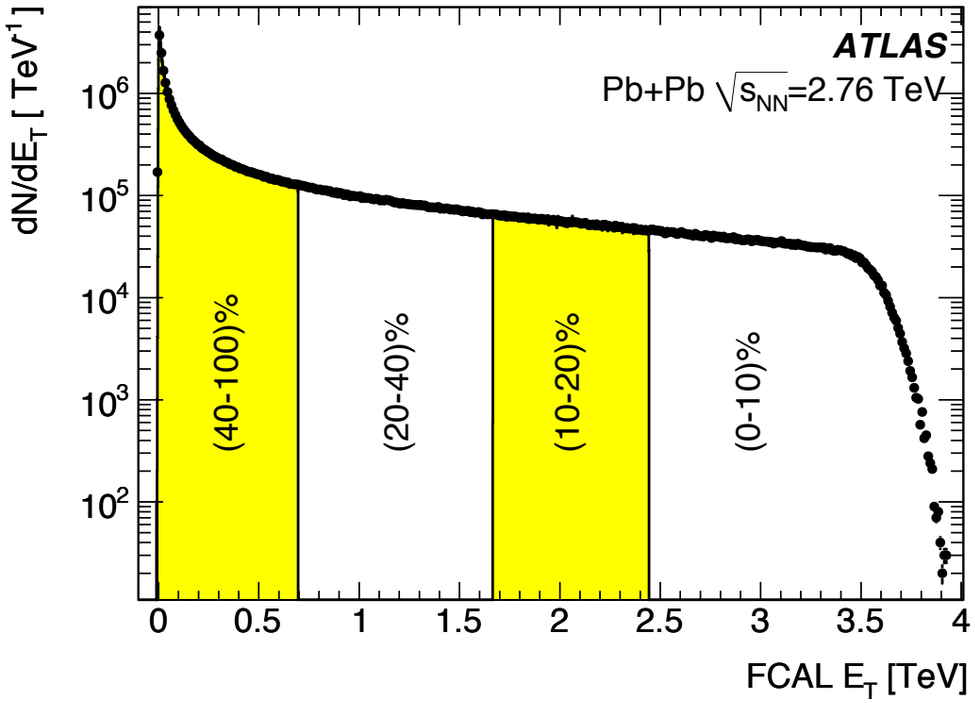
  by William Brooks on Thursday 12:20 in Krutch Theatre

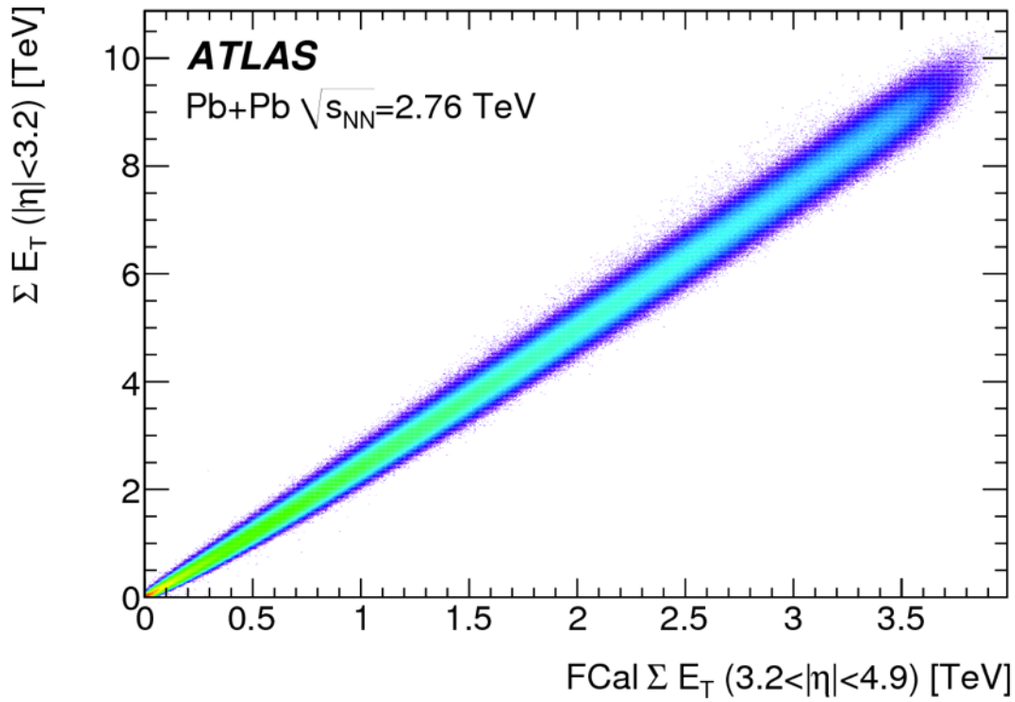
# *Backup*

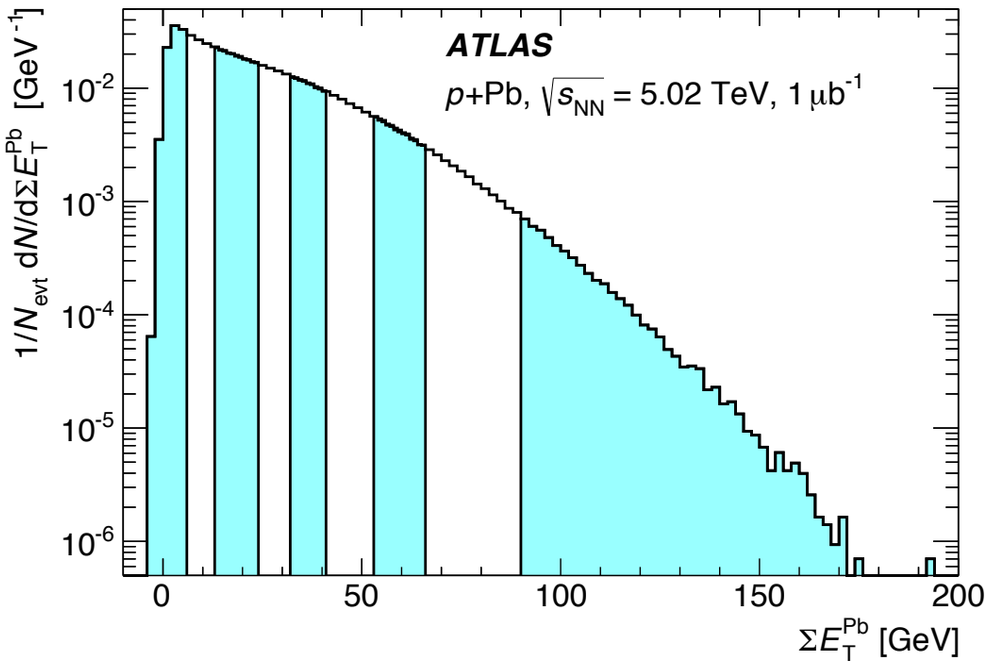
# Experiments at the LHC



# Centrality definition



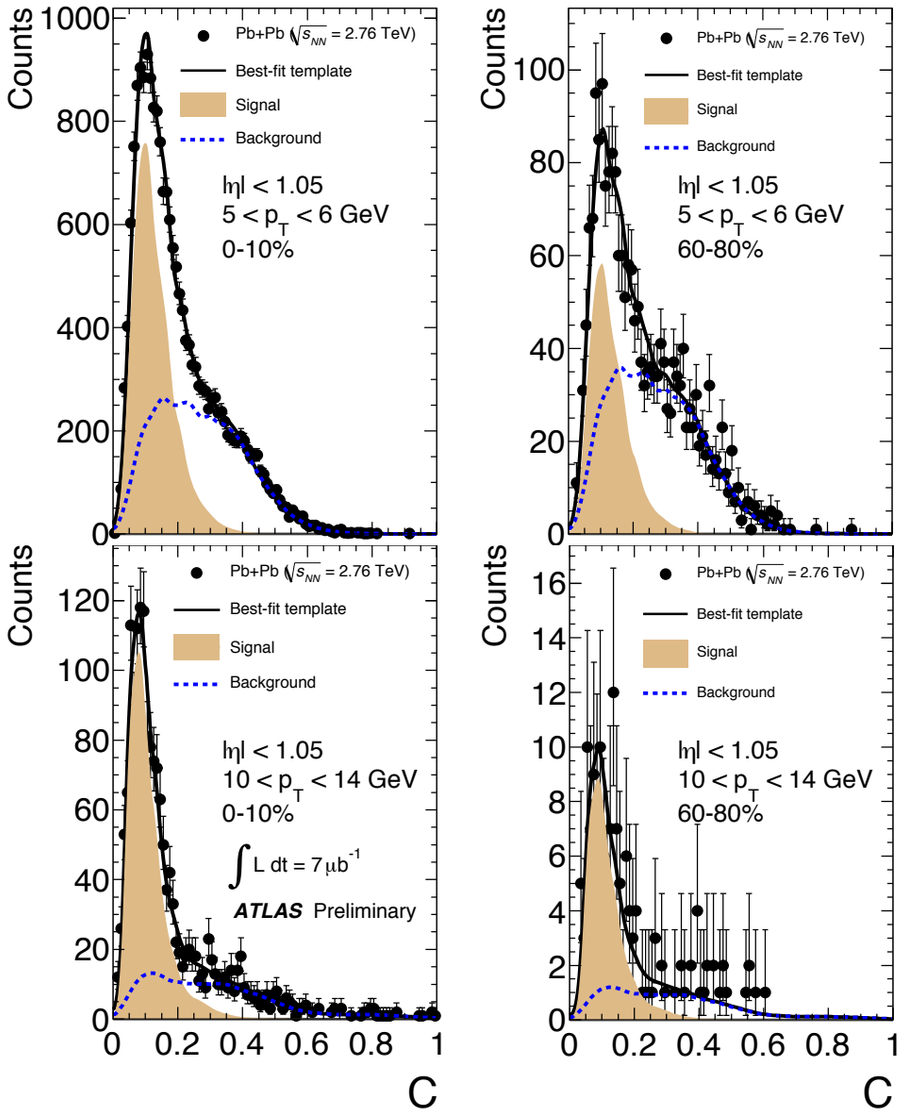



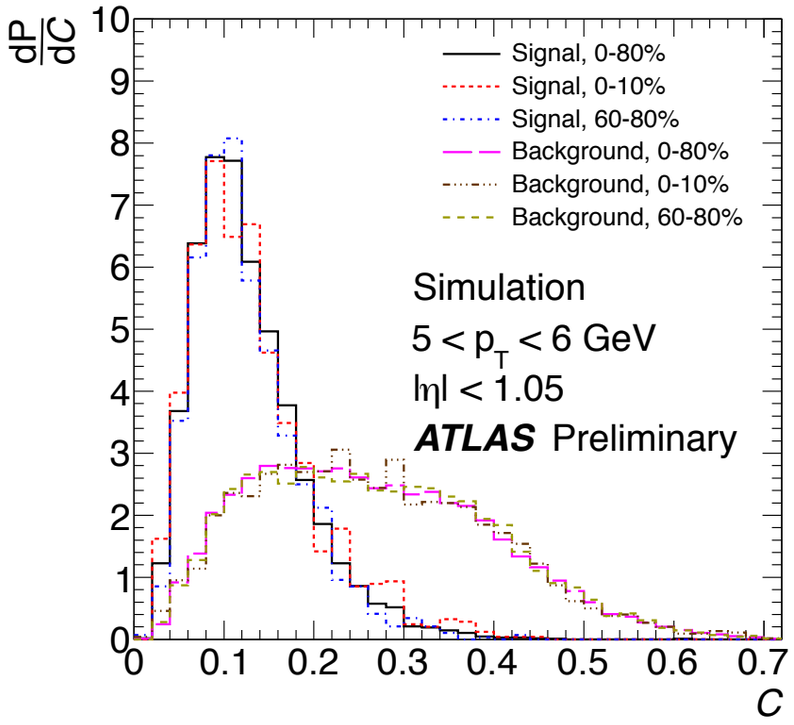




$\sum E_{\mathrm{T}}^{\mathrm{FCal}}$ used to to categorize centrality.

In p+Pb collisions, only the lead going direction $\sum E_{\mathrm{T}}^{\mathrm{FCal}}$ is used.

# HF signal extraction for 2010 data




$$\frac{\Delta p}{p_{\mathrm{ID}}} = \frac{p_{\mathrm{ID}} - (p_{\mathrm{MS}} + \Delta p_{\mathrm{calo}})}{p_{\mathrm{ID}}}$$

momentum imbalance

$$S = \frac{1}{\sqrt{n}}\left(\sum_{1}^{j} s_i - \sum_{j+1}^{k} s_i\right) \quad s_i = q\frac{\Delta\phi_i}{\phi_i^{msc}}$$

scattering angle significance

decay-in-flight would case large deflection, useful for very low $p_T$ (≲ 4 GeV)

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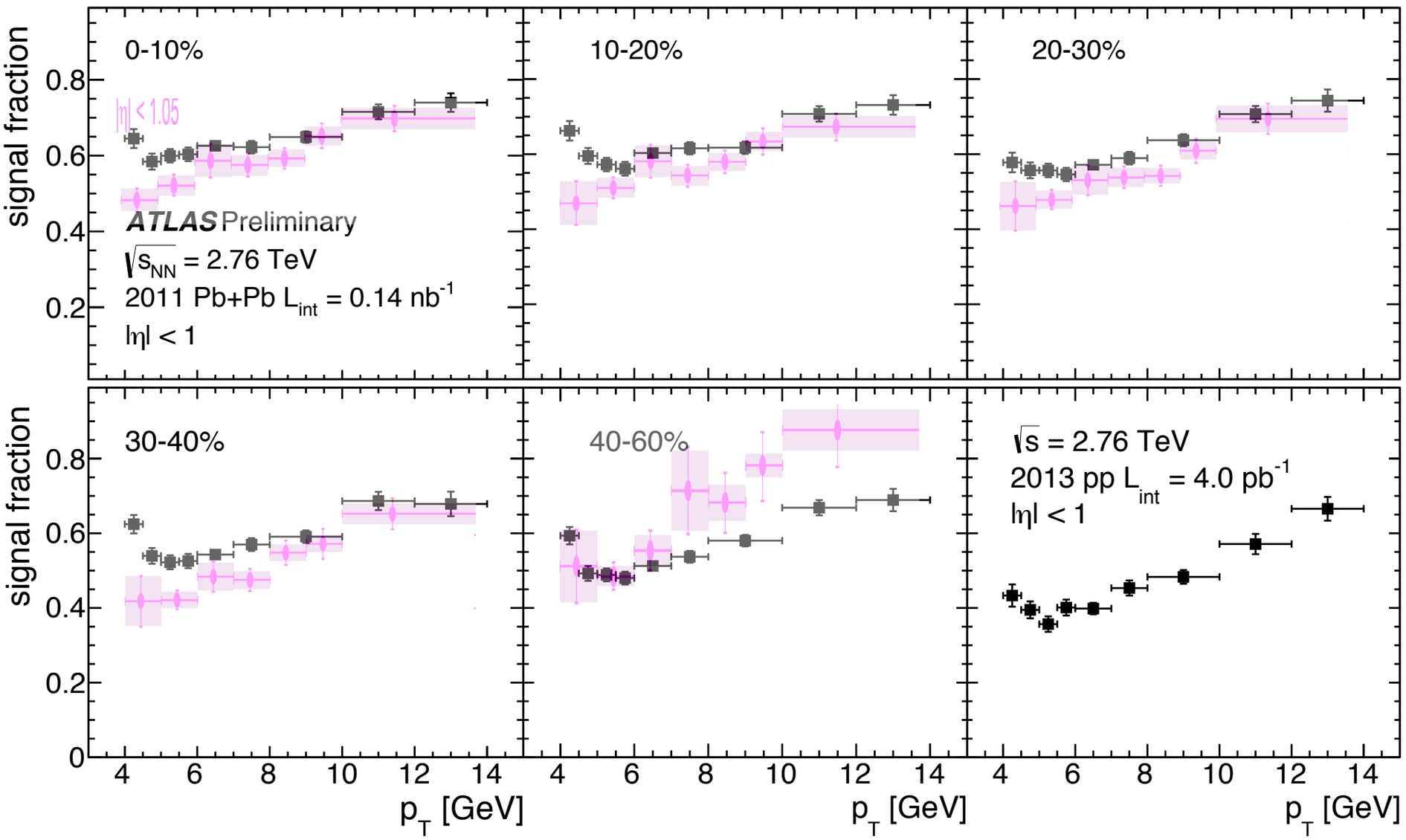
$$C = \left|\frac{\Delta p_{\mathrm{loss}}}{p_{\mathrm{ID}}}\right| + 0.07 \cdot S$$

Composite

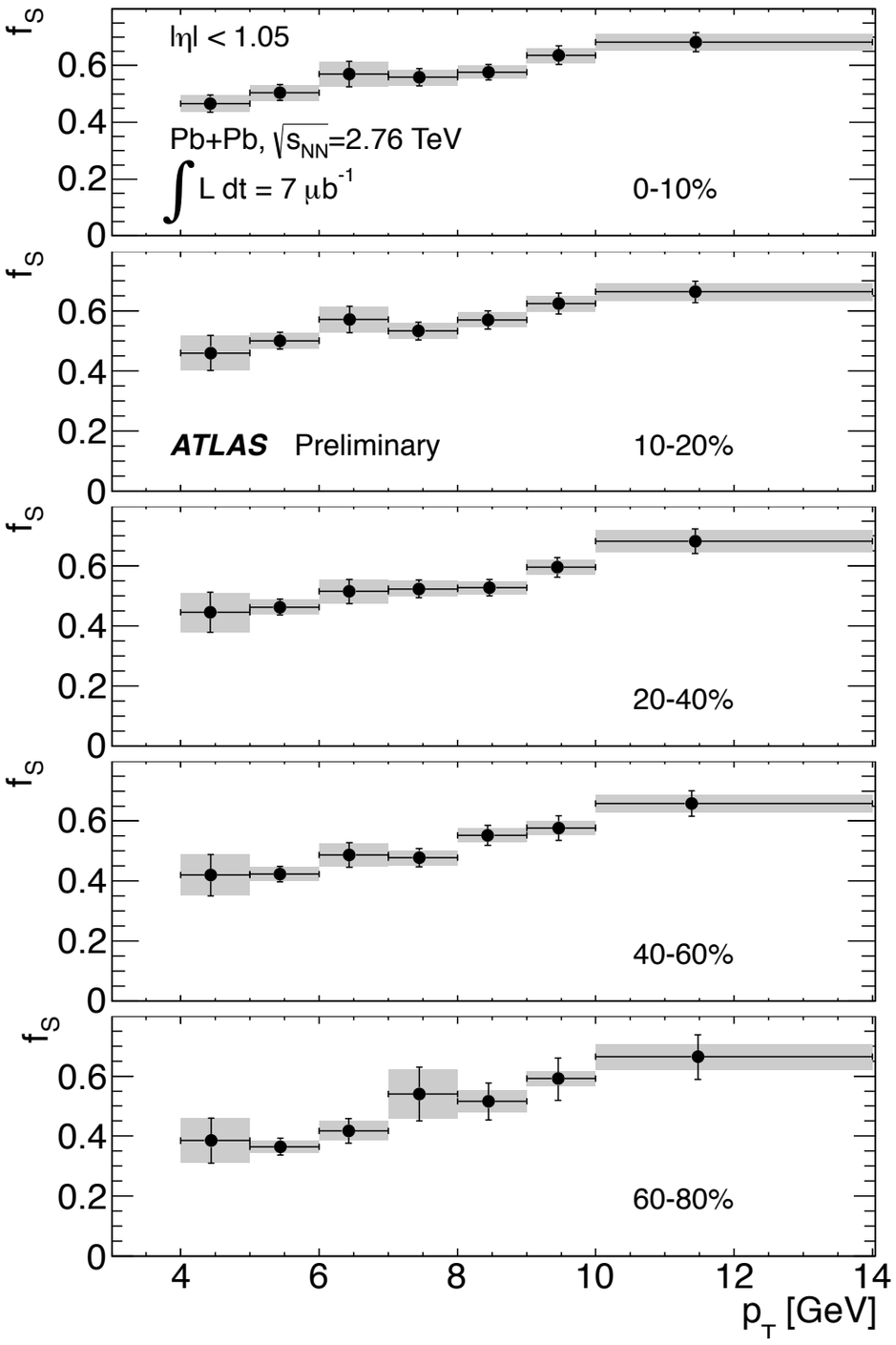
# Signal fraction and spectra

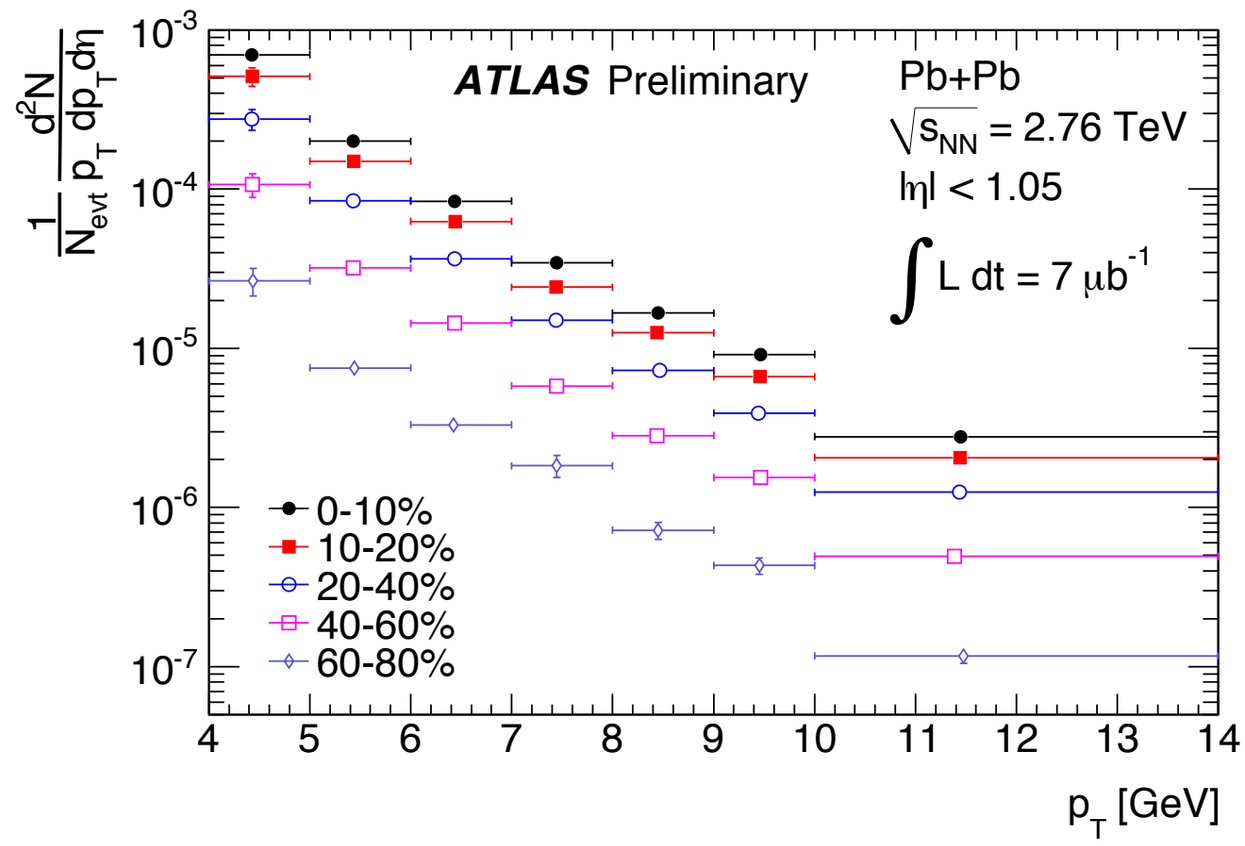



2010 Data

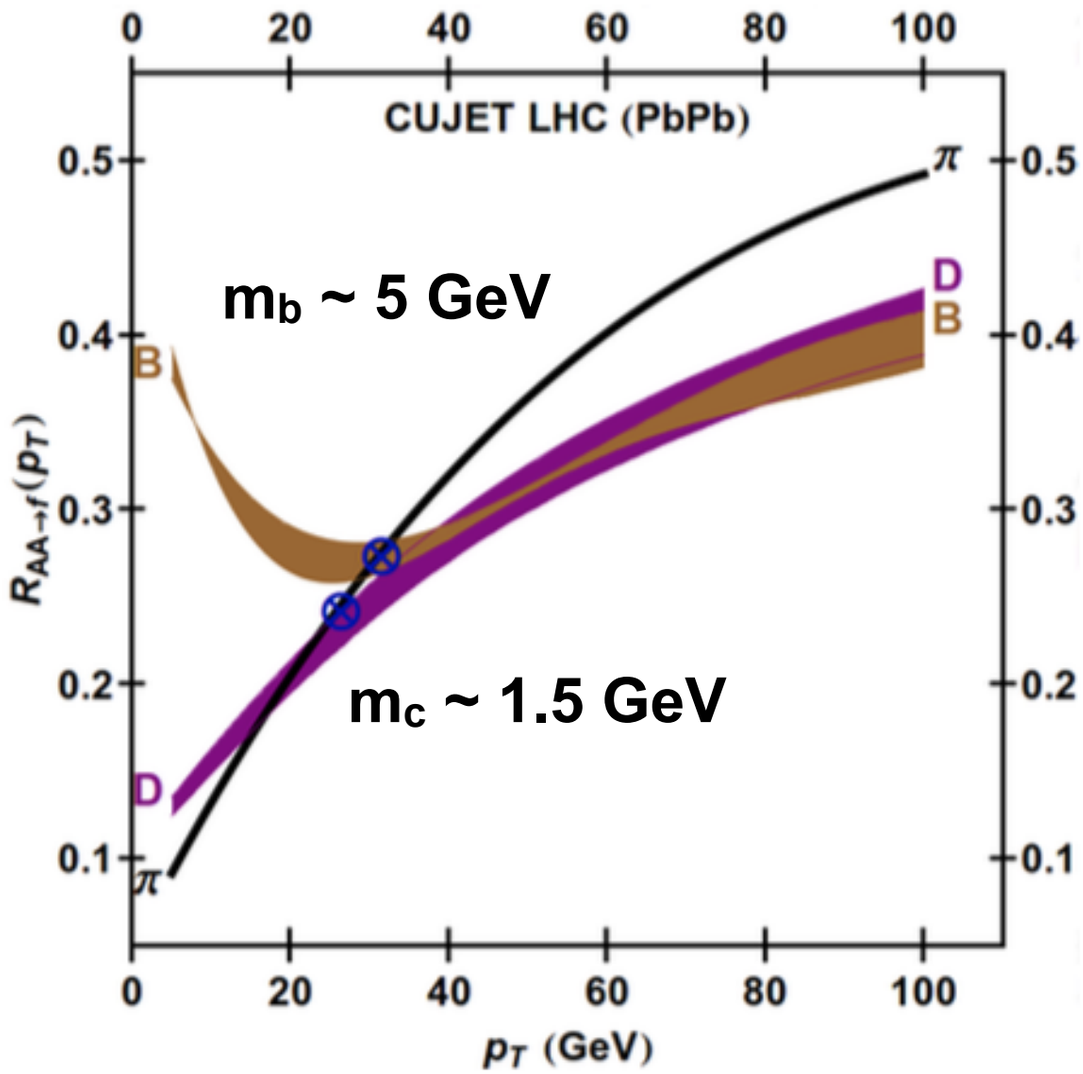
2011 Data

# HF fraction and spectra in 2010 data



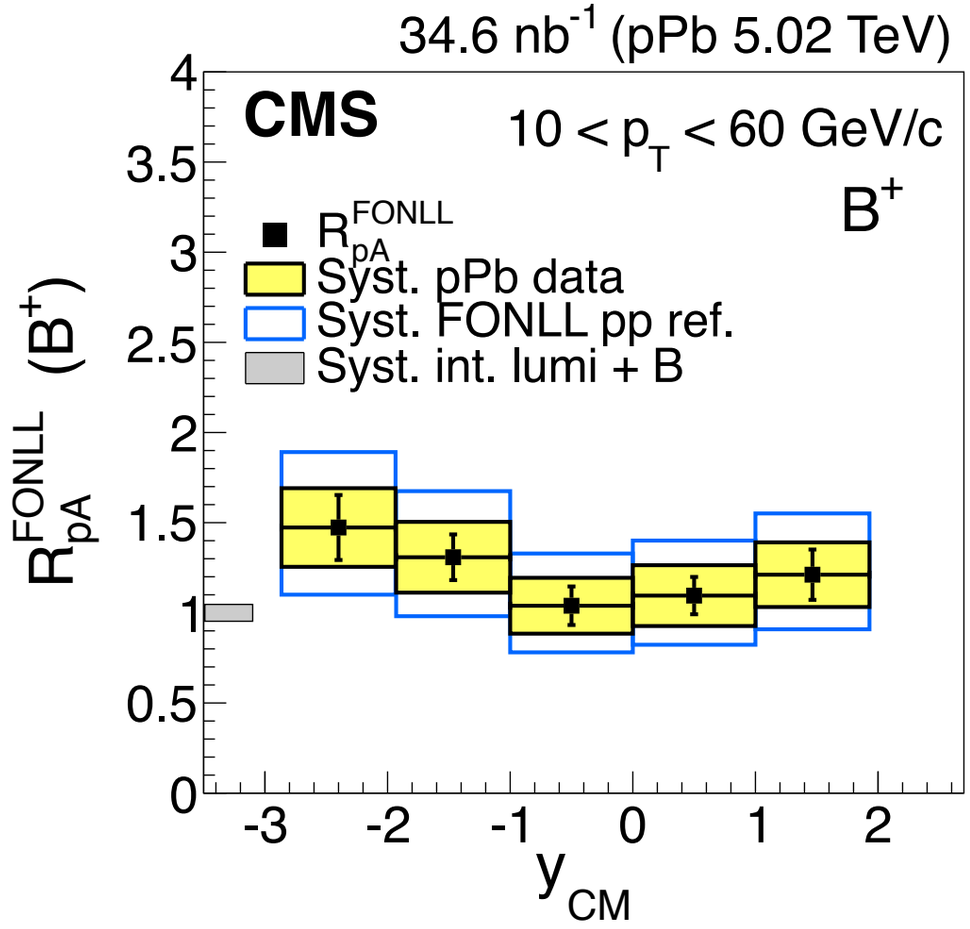



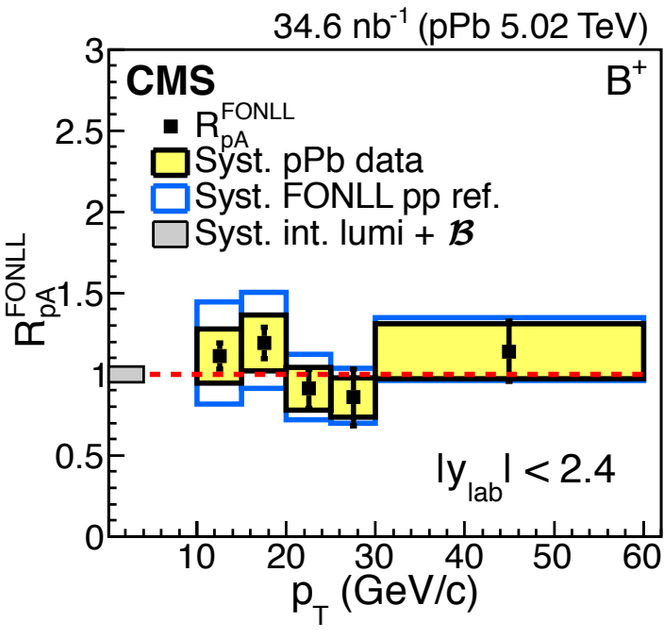
# Mass ordering of $R_{AA}$

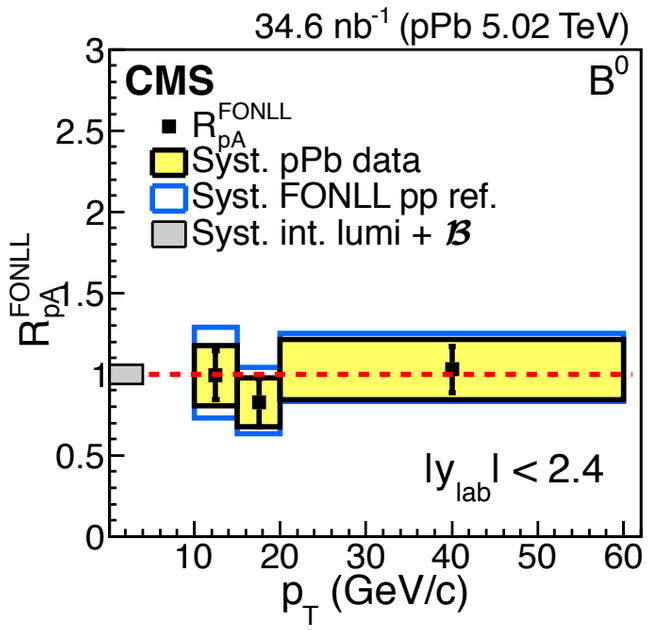


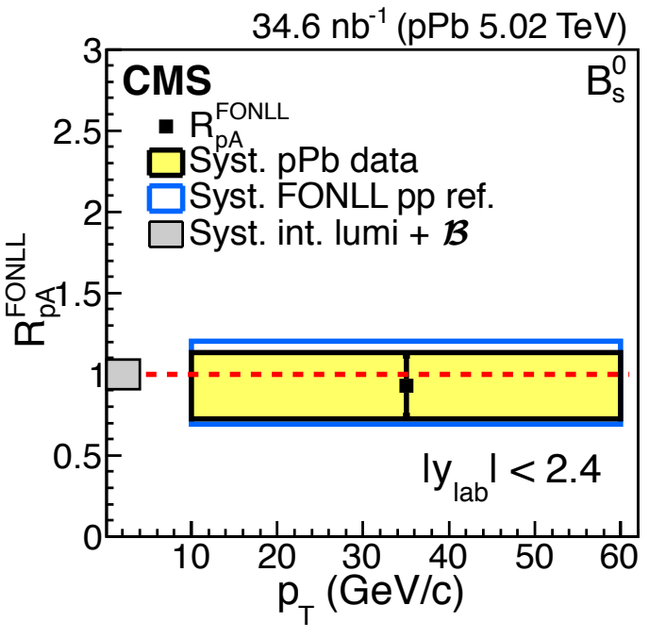

Bugatti, Gyulassy 2011

# CMS B+


34.6 nb-1 (pPb 5.02 TeV)
CMS
10 < pT < 60 GeV/c
B+
RpAFONLL
Syst. pPb data
Syst. FONLL pp ref.
Syst. int. lumi + B
RpAFONLL (B+)
yCM


34.6 nb-1 (pPb 5.02 TeV)
CMS
B+
RpAFONLL
Syst. pPb data
Syst. FONLL pp ref.
Syst. int. lumi + B
|ylab| < 2.4
pT (GeV/c)

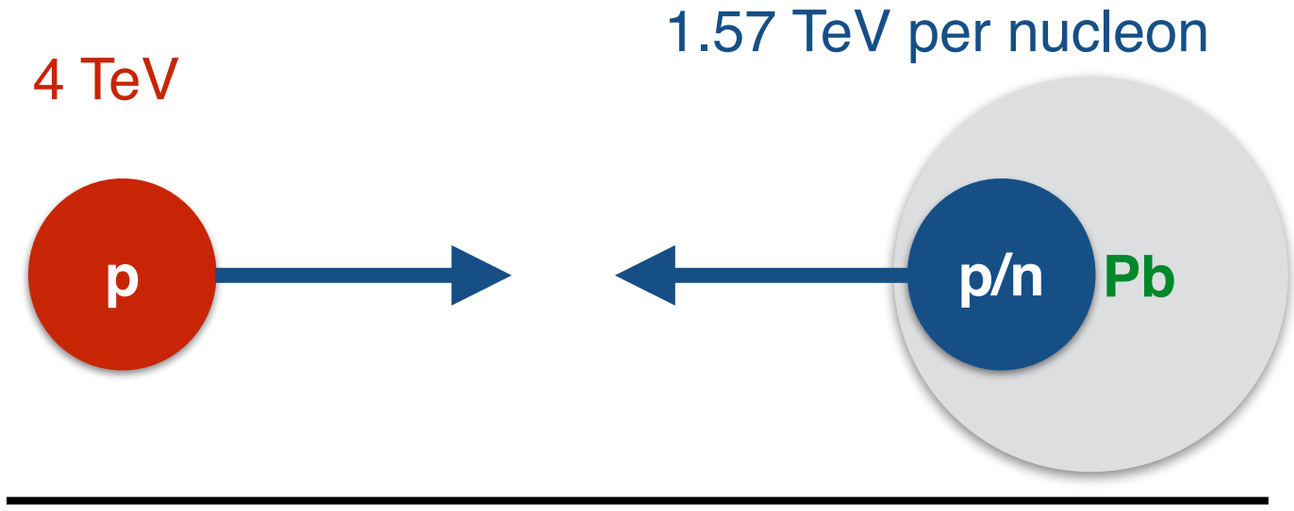

34.6 nb-1 (pPb 5.02 TeV)
CMS
B0
RpAFONLL
Syst. pPb data
Syst. FONLL pp ref.
Syst. int. lumi + B
|ylab| < 2.4
pT (GeV/c)


34.6 nb-1 (pPb 5.02 TeV)
CMS
B0s
RpAFONLL
Syst. pPb data
Syst. FONLL pp ref.
Syst. int. lumi + B
|ylab| < 2.4
pT (GeV/c)

# p+Pb beam configuration

The proton-nucleon center of mass (CM) frame has a shift of 0.465 in rapidity in the proton beam direction.

*y**: CM rapidity being positive in forward (proton beam direction).

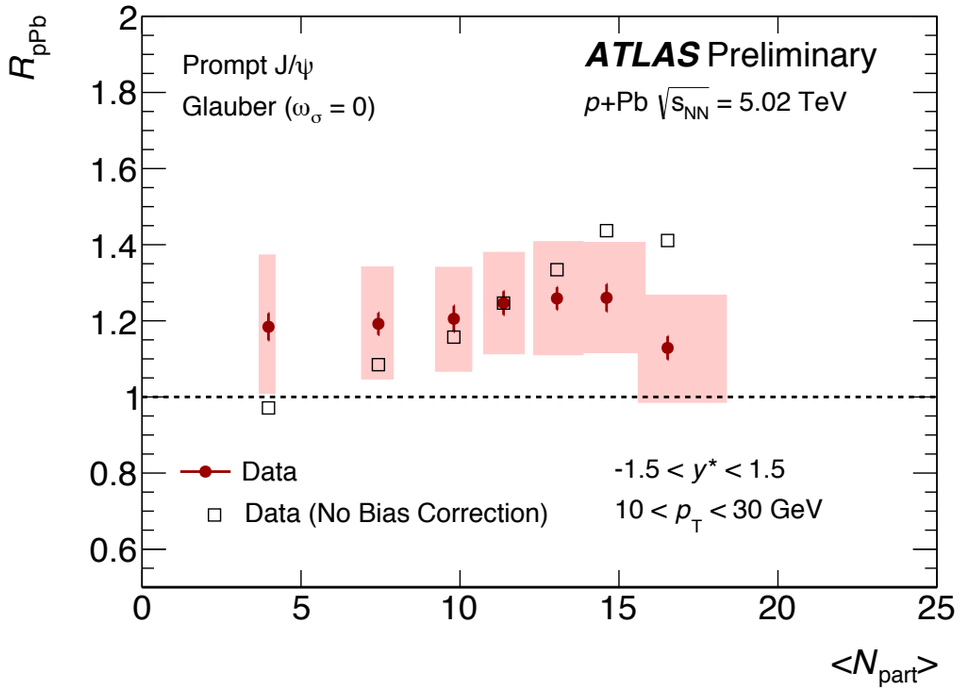


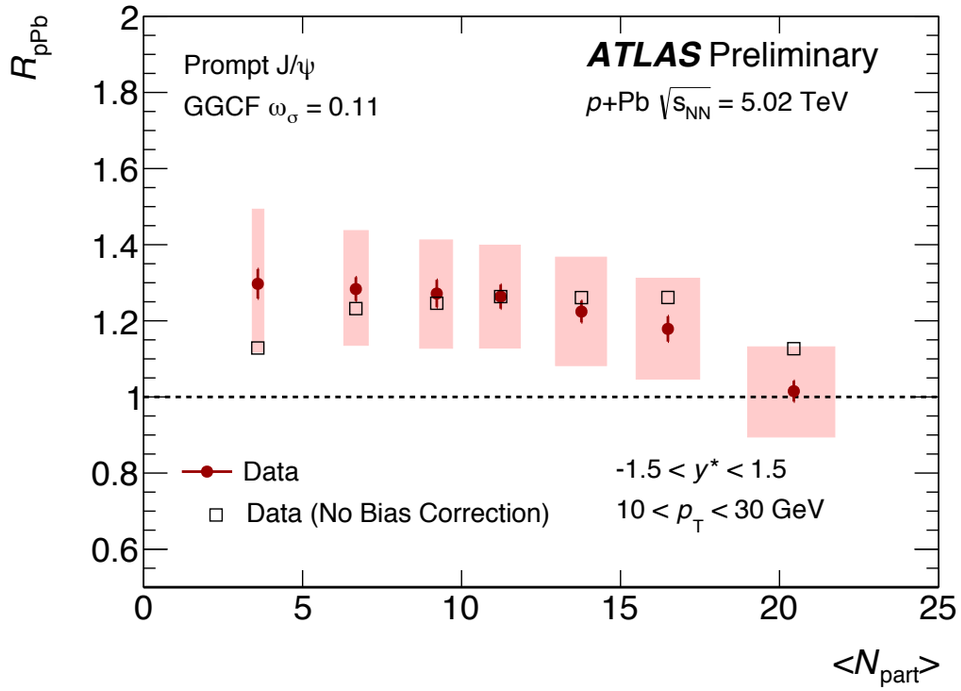

*p*+Pb collision beam configuration

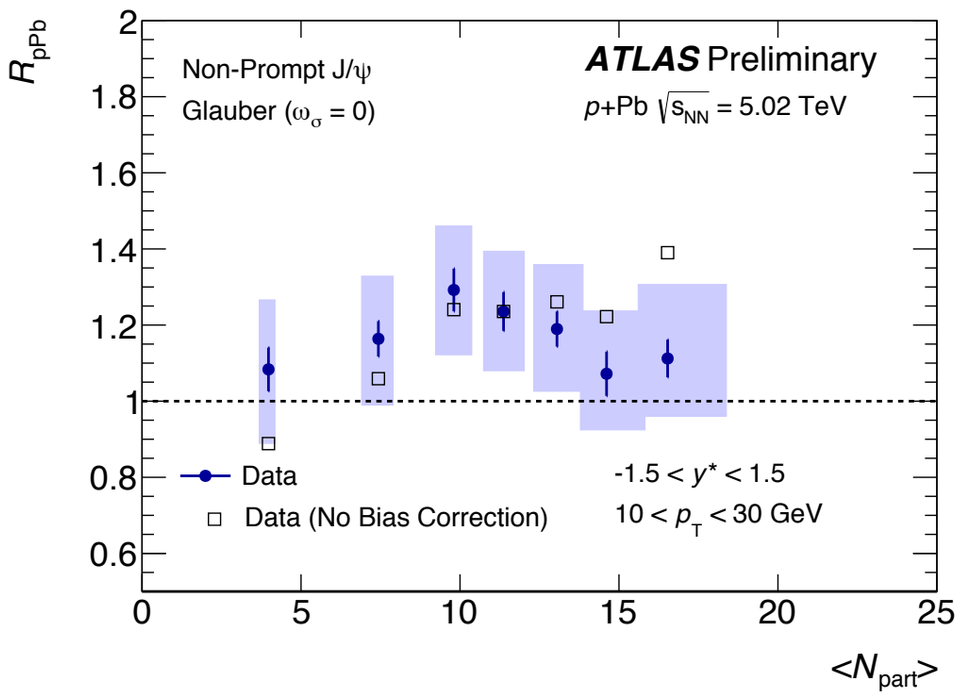
$y^* = -(y_{lab} + 0.465)$ p+Pb run period A

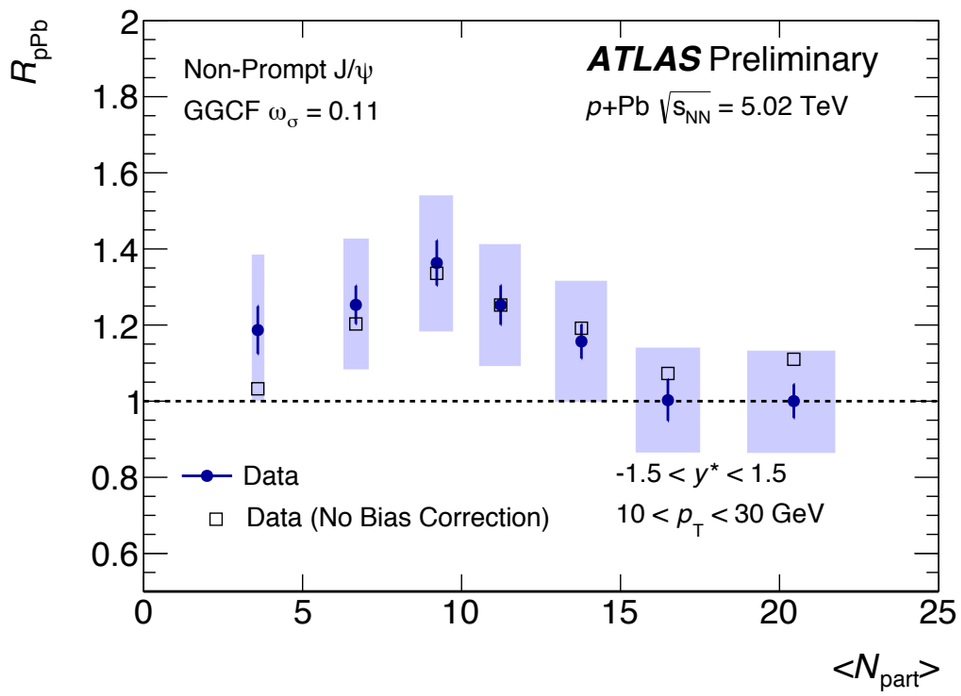
$y^* = y_{lab} - 0.465)$ p+Pb run period B

# $R_{pPb}$ vs. Centrality (I)

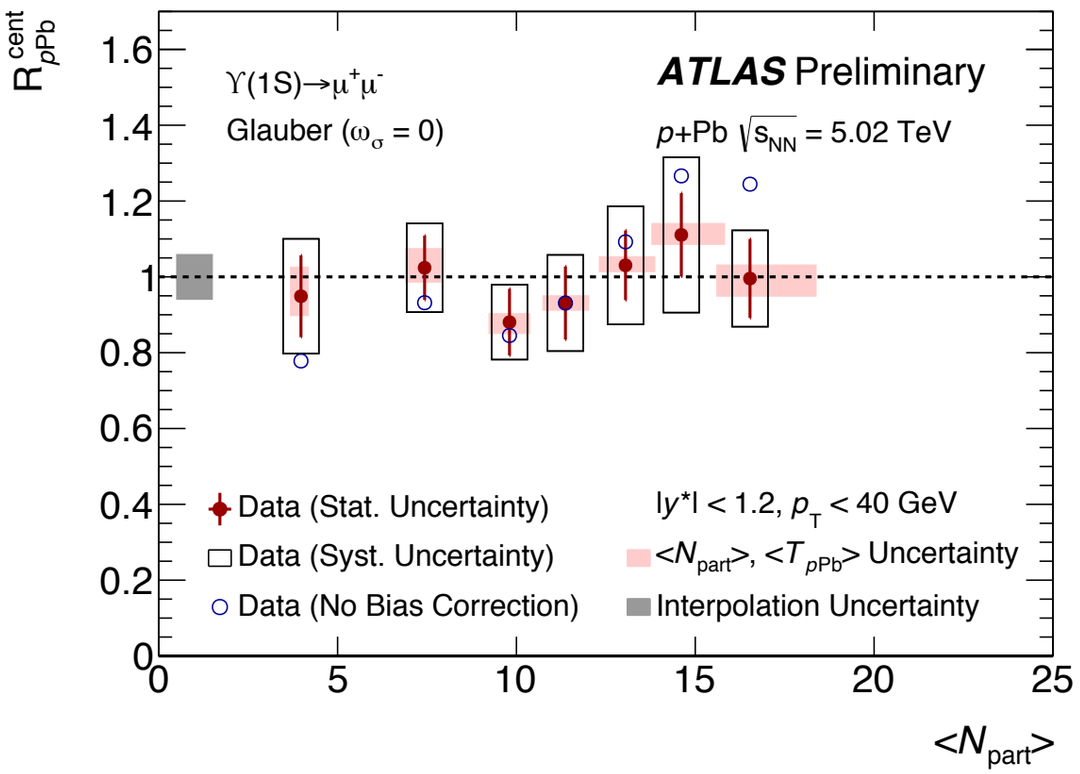


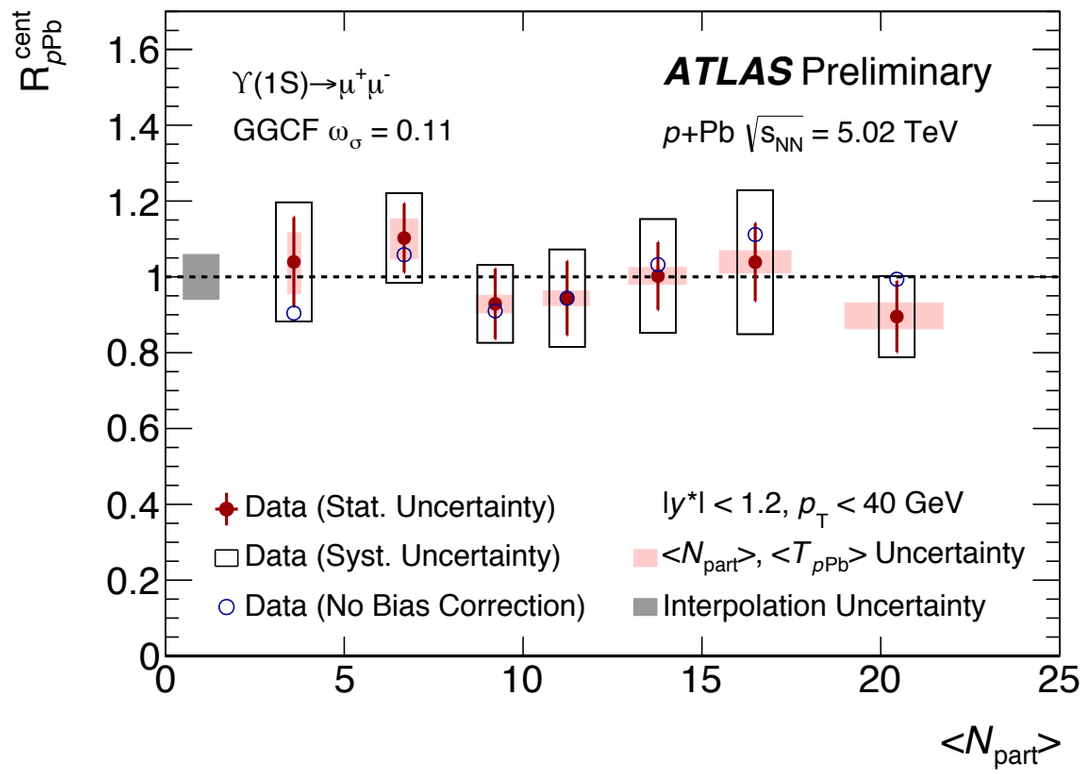



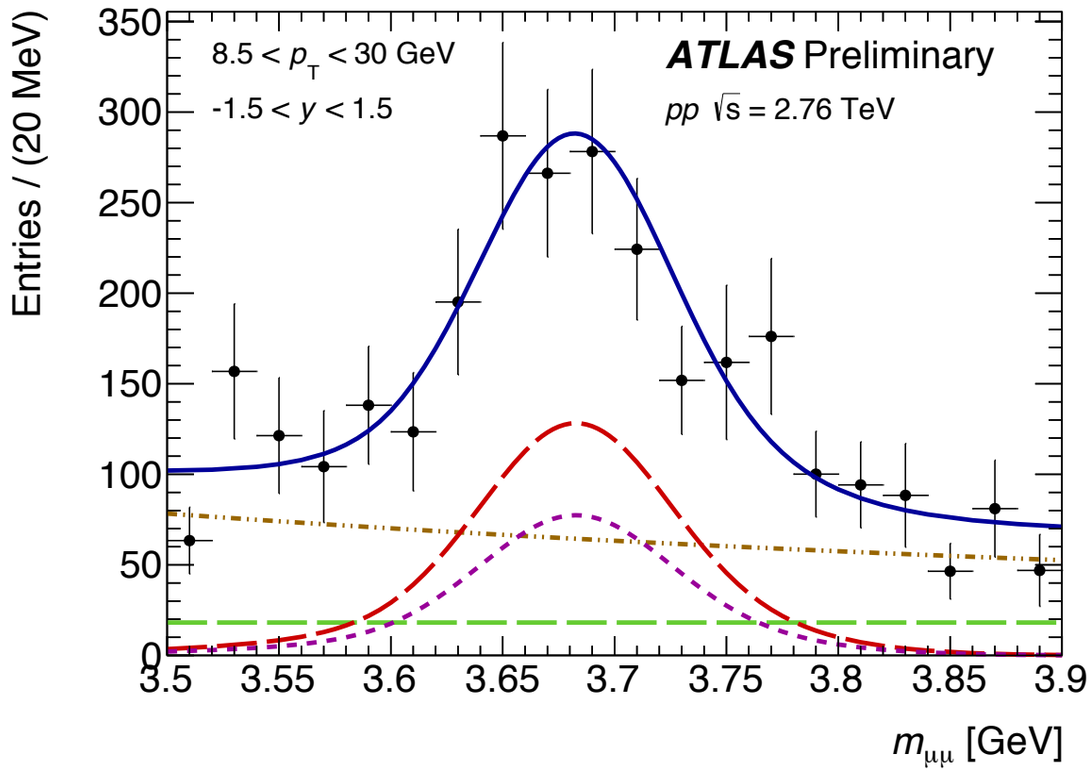



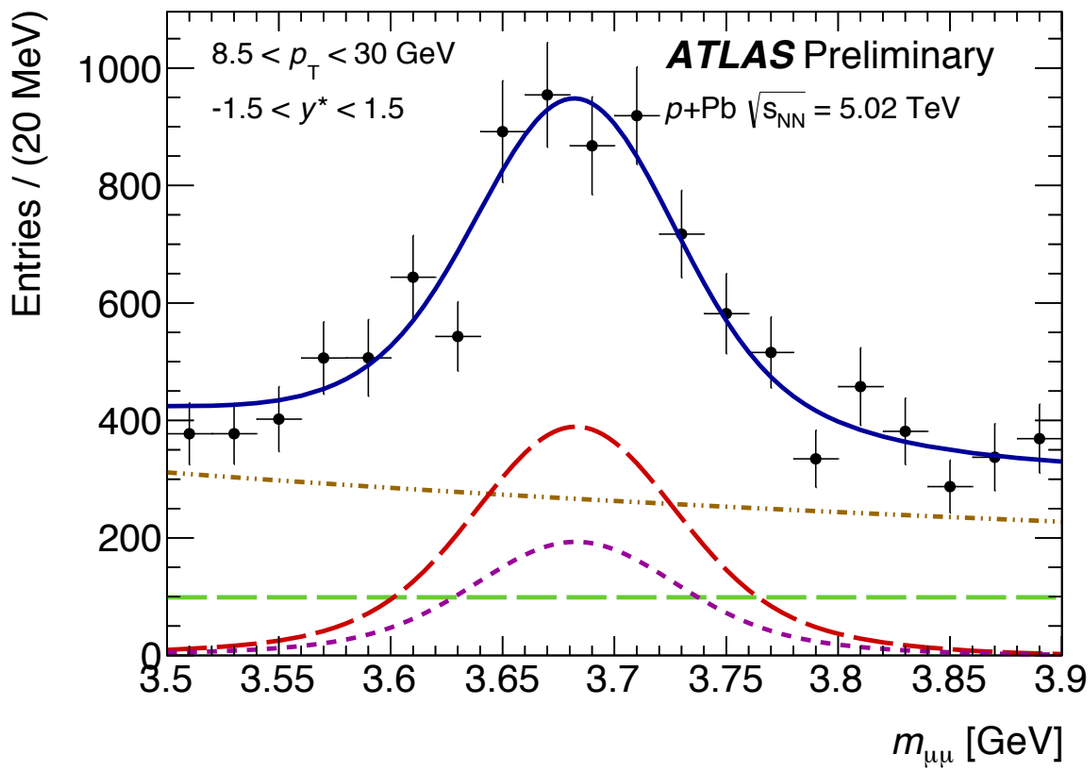
# $R_{pPb}$ vs. Centrality (II)

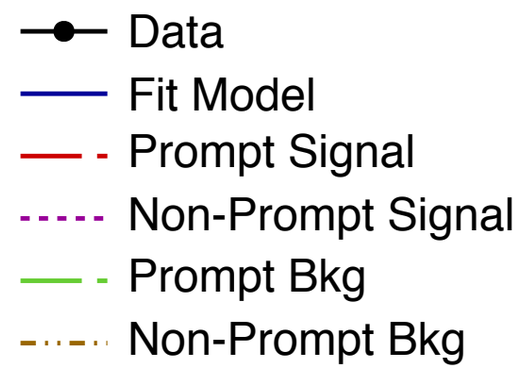


# Psi(2S) fits


8.5 < $p_T$ < 30 GeV
-1.5 < $y$ < 1.5
ATLAS Preliminary
$pp$ $\sqrt{s}$ = 2.76 TeV
Entries / (20 MeV)
$m_{\mu\mu}$ [GeV]


8.5 < $p_T$ < 30 GeV
-1.5 < $y^*$ < 1.5
ATLAS Preliminary
$p$+Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Entries / (20 MeV)
$m_{\mu\mu}$ [GeV]


Data
Fit Model
Prompt Signal
Non-Prompt Signal
Prompt Bkg
Non-Prompt Bkg

# pp reference at 5 TeV

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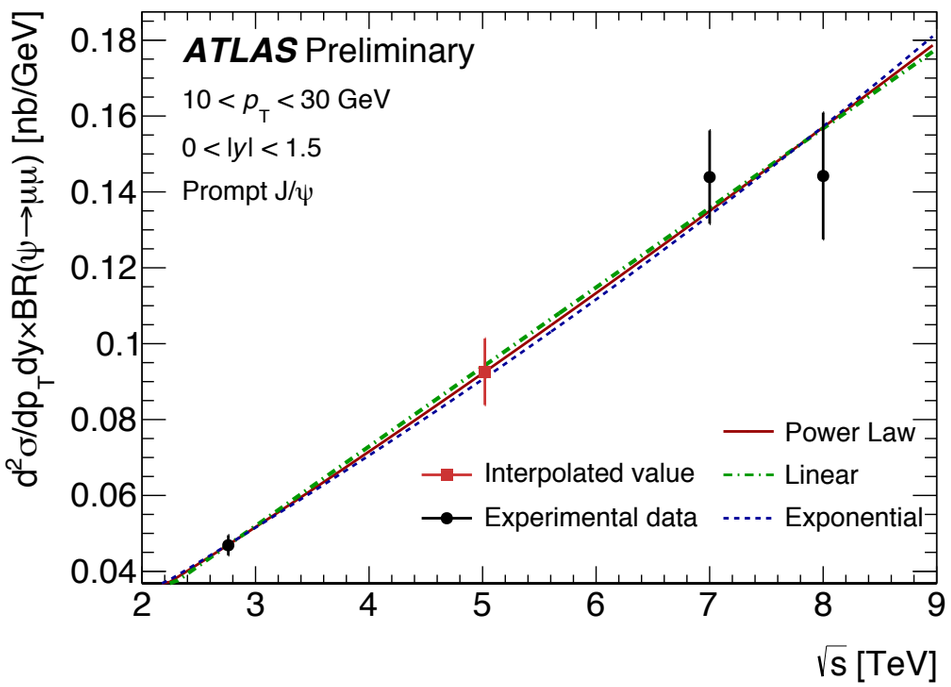


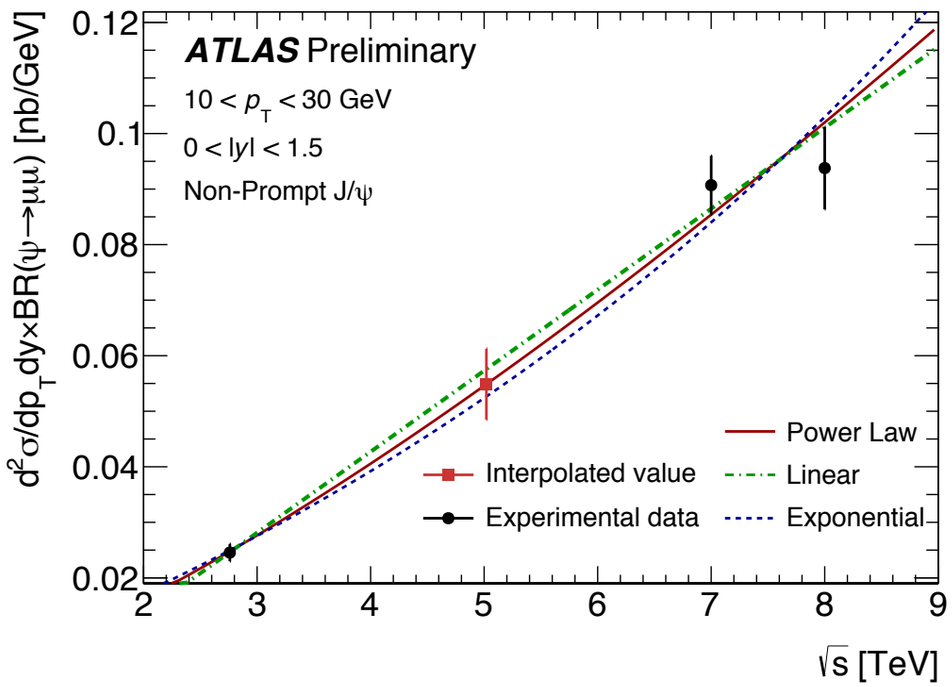


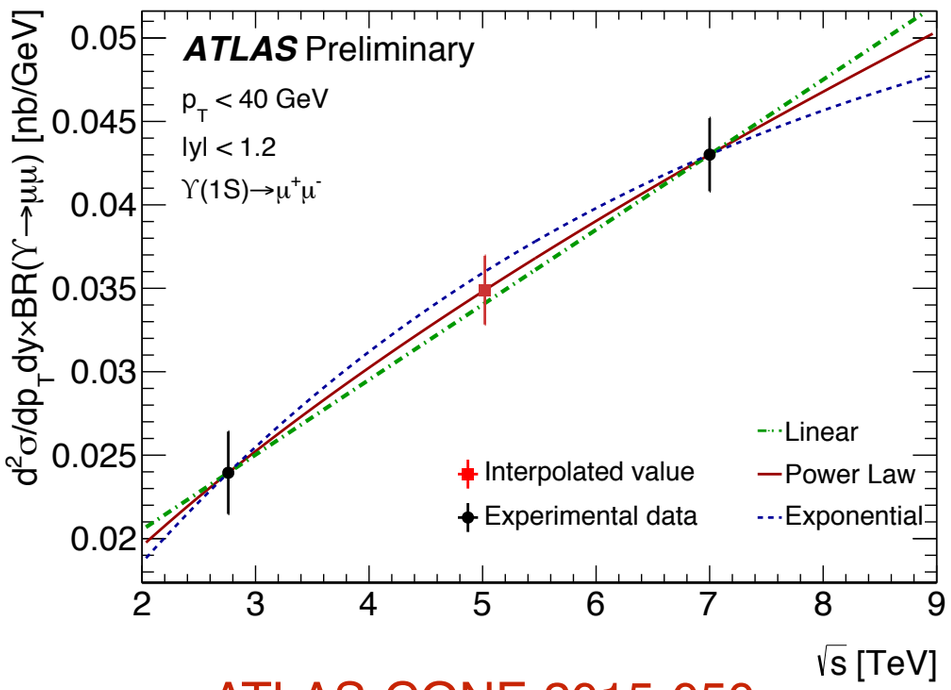


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Three interpolation functions used to calculate pp reference at 5.02 TeV, central values obtained from power law function.

$$\sigma(\sqrt{s}) = \begin{cases} p_0 + \sqrt{s}p_1 & \text{linear} \\ (\sqrt{s}/p_0)^{p_1} & \text{power law} \\ p_0(1-\exp(-\sqrt{s}/p_1) & \text{exponential} \end{cases}$$

Three points for charmoina interpolation
Two points for bottomoina interpolation