# Open heavy flavor measurements with ATLAS

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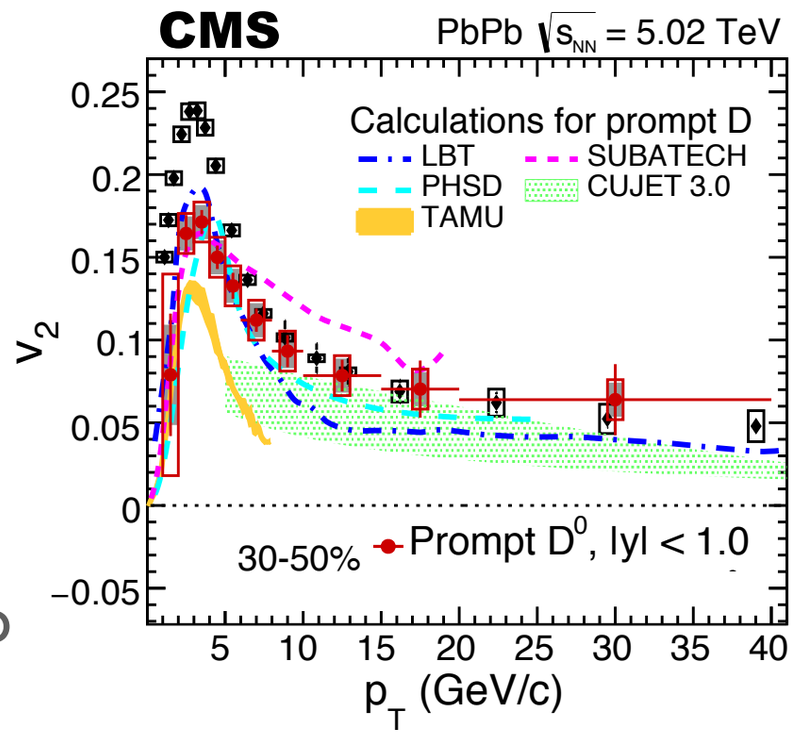
University of Colorado **Boulder**

ATLAS EXPERIMENT

# Motivation

- Heavy flavors (HF) have large masses and are produced at the early stage of heavy ion collisions. Unique tool to study QGP and parton energy loss
- HF measurements in p+A would be helpful to understand shadowing
- Heavy flavor meson flows in A+A. Do they have the same sinusoidal modulations in smaller systems?




arXiv:1708.03497

HF probes in ATLAS:

Non-prompt charmonia in p+Pb and Pb+Pb

Muons from HF decays

- HF muon $R_{AA}$ in Pb+Pb (2.76 TeV)
- HF muon $v_2$ in Pb+Pb (2.76 TeV)
- HF muon $v_2$ in $p$+Pb (8.16 TeV)

Identified HF mesons

- D meson $R_{FB}$ and flow in $p$+Pb (8.16 TeV)

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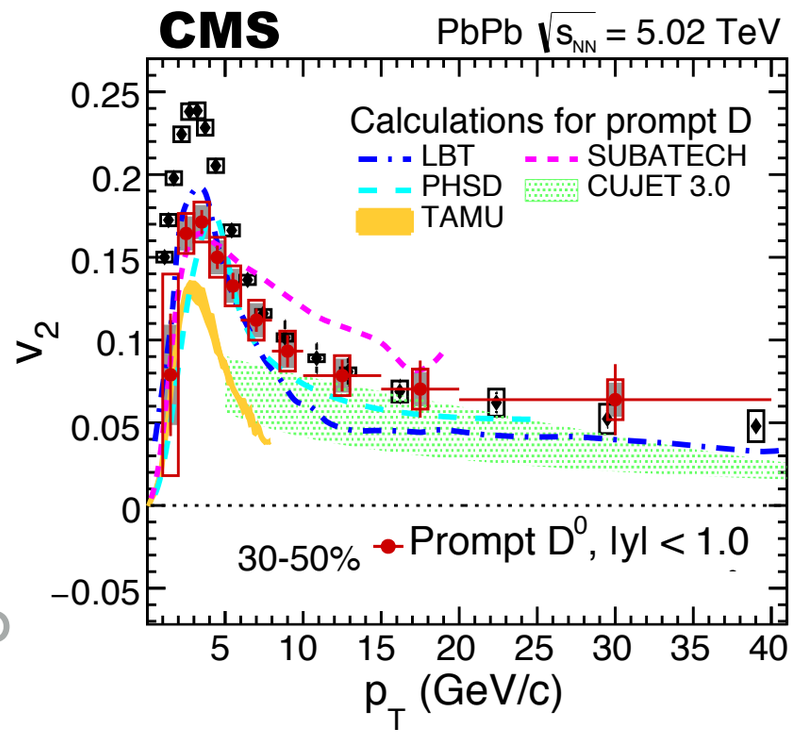


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# D meson production in 8.16 TeV *p*+Pb

# Analysis methodology

$D^0 \rightarrow K\pi$

$D^* \rightarrow D^0\pi \rightarrow K\pi\pi$

Event collected by MinBias trigger

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} = \frac{f_\mathrm{prompt} \times N^\mathrm{corr.}}{\Delta p_\mathrm{T} \times \Delta y^* \times B \times \mathscr{P} \times \int \mathscr{L}\,\mathrm{d}t}$$

$B$: branching fraction

$\mathcal{P}$: trigger prescale factor

$f_\mathrm{prompt}$: prompt D meson fraction estimated based on FONLL

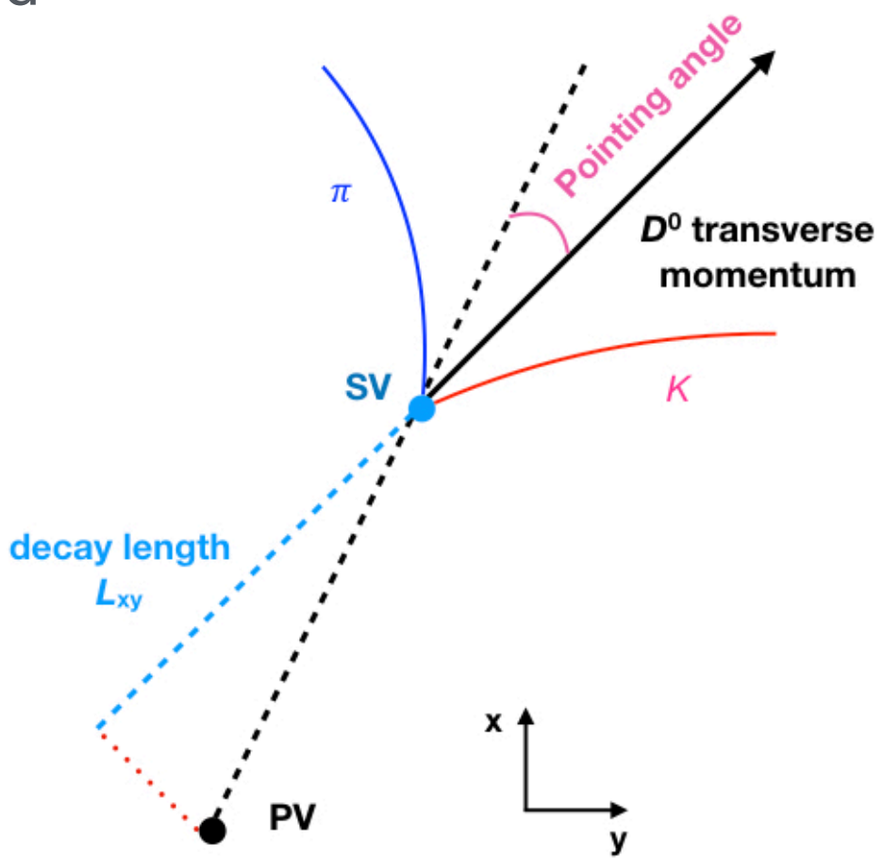
$N^\mathrm{corr}$: corrected yields taking into account trigger, reconstruction and selection efficiency and acceptance

No PID, all possible candidate track pairs with $p_T$ > 1GeV from the same vertex are considered

$D^0$ vertex selection optimized based on:

- Vertex probability
- Pointing angle
- Decay length significance $L_{xy}$ / σ($L_{xy}$)

For $D^*$, the third soft track with $p_T$ > 400 MeV is required



# $D^0$ and D* fits

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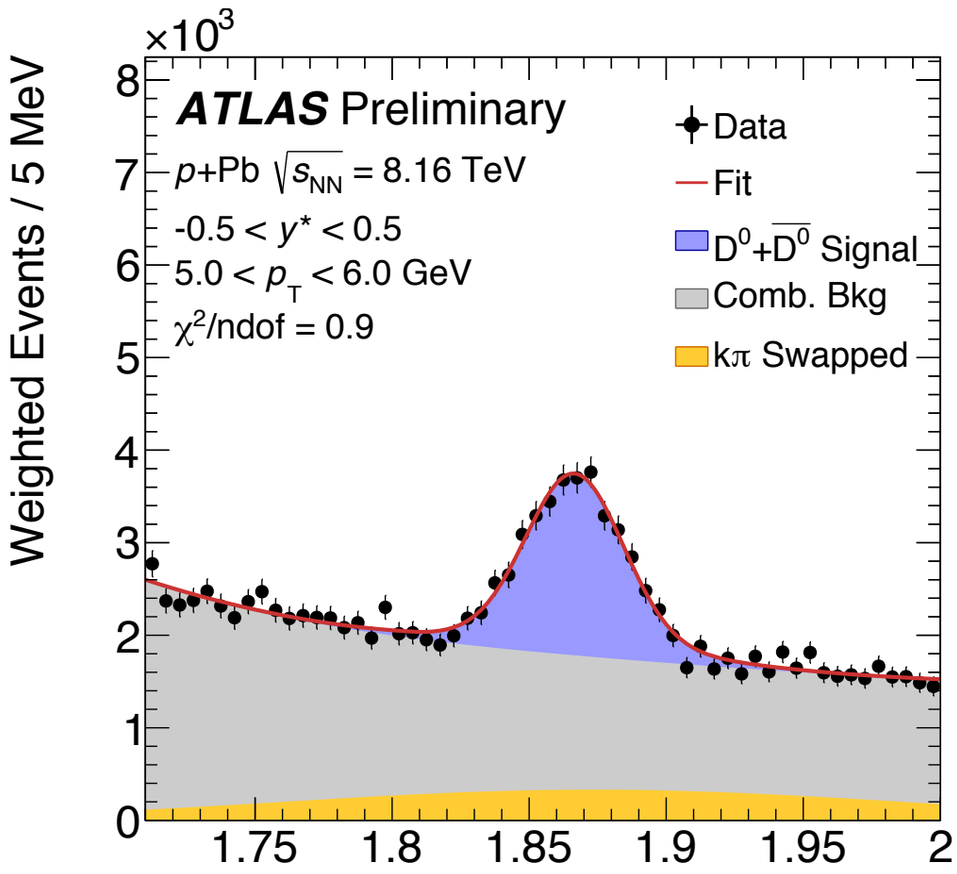
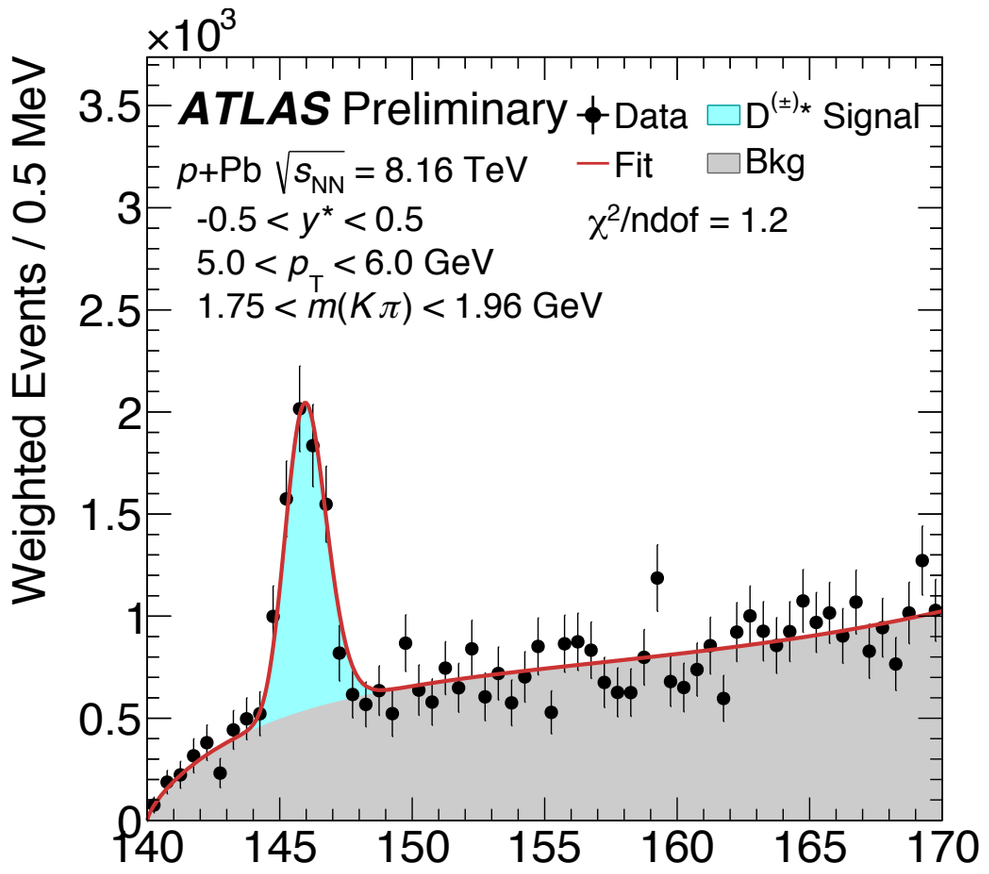



$D^0$ invariant mass

- CB+Gaussian signal
- Gaussian swapped bkg
- third-order polynomial bkg

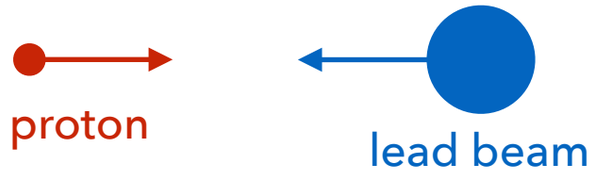
D* mass difference:

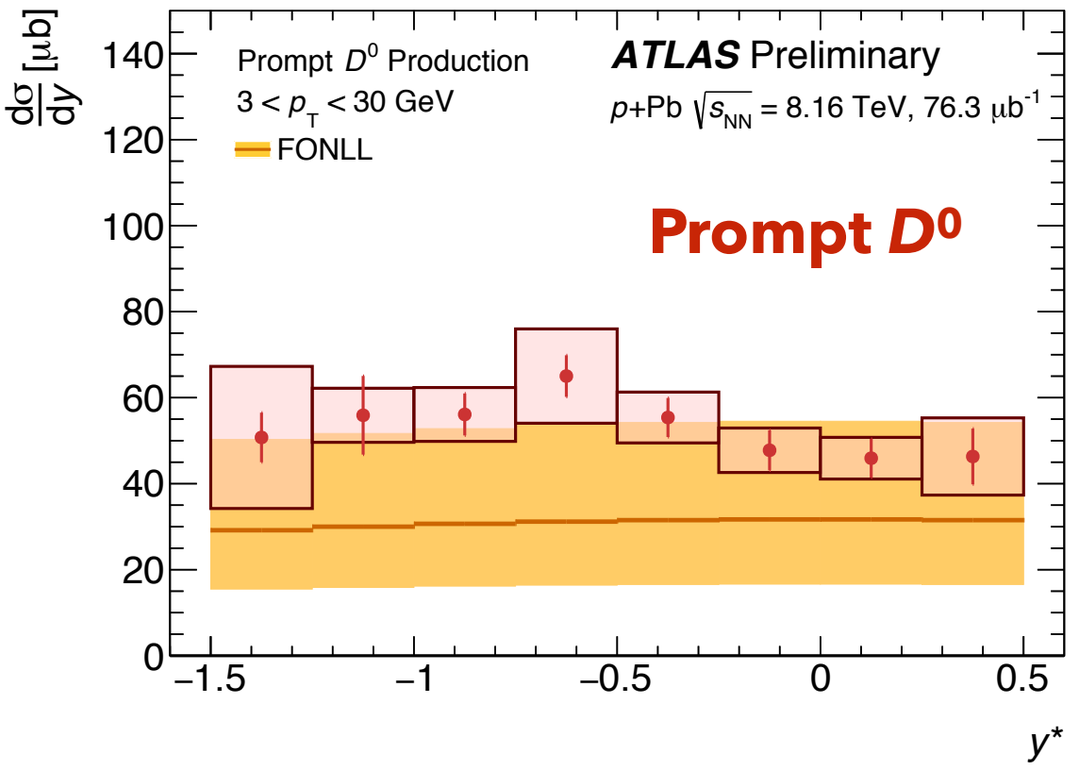
- Novosibirsk signal
- Generic bkg function obtained from control sample

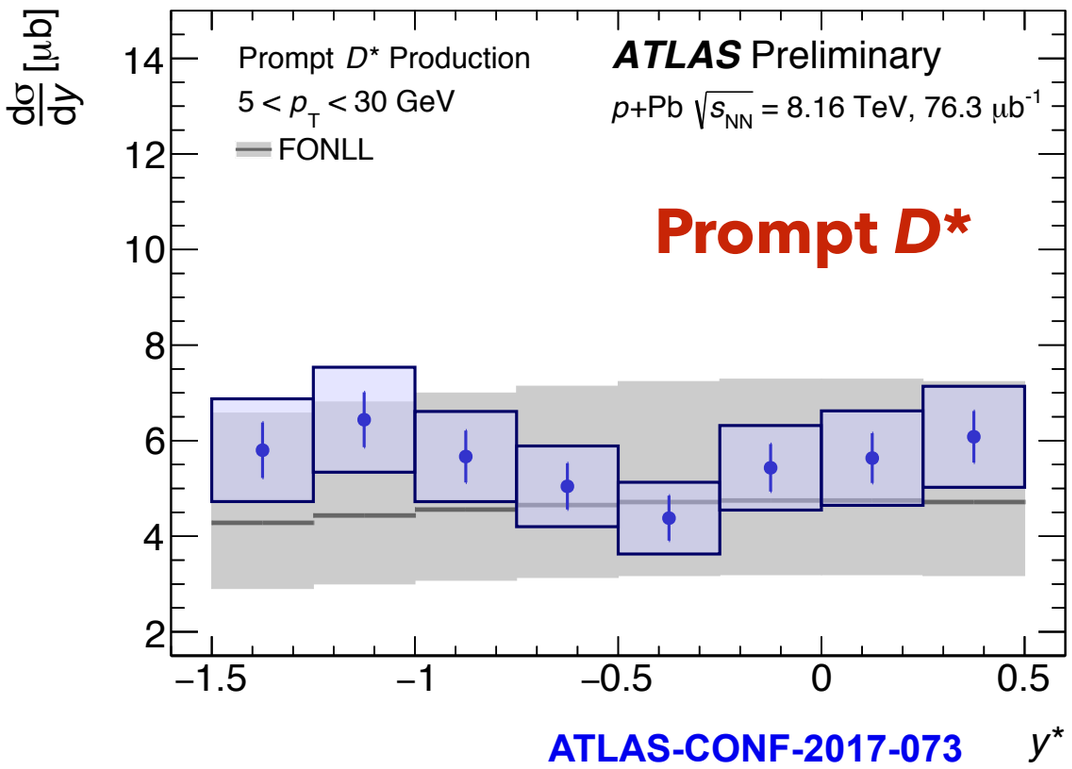
# Cross sections

FONLL uncertainties

- renormalisation scale
- factorization scale
- charm quark mass
- pdf



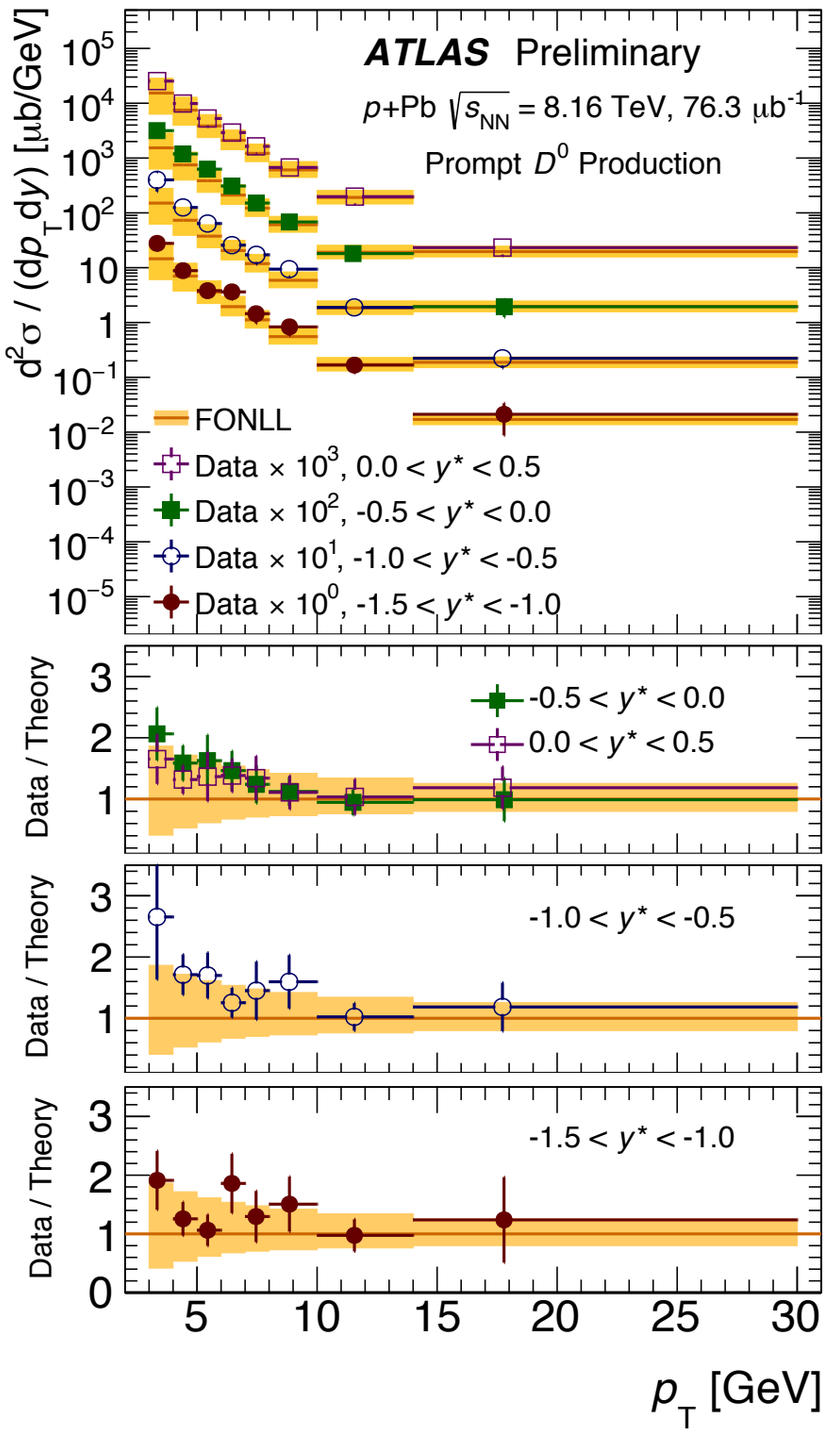




- Prompt $D^0$ ($3 < p_T < 30$ GeV) and prompt $D^*$ ($5 < p_T < 30$ GeV)
- $|y_{lab}(D)| < 1.0$ for better mass resolution ⟶ $-1.5 < y^* < 0.5$
- FONLL (fixed-order next-leading-logarithm) prediction extrapolated from 7 and 8 TeV calculates, and scaled by 208
- Relatively small modification in $p$+Pb

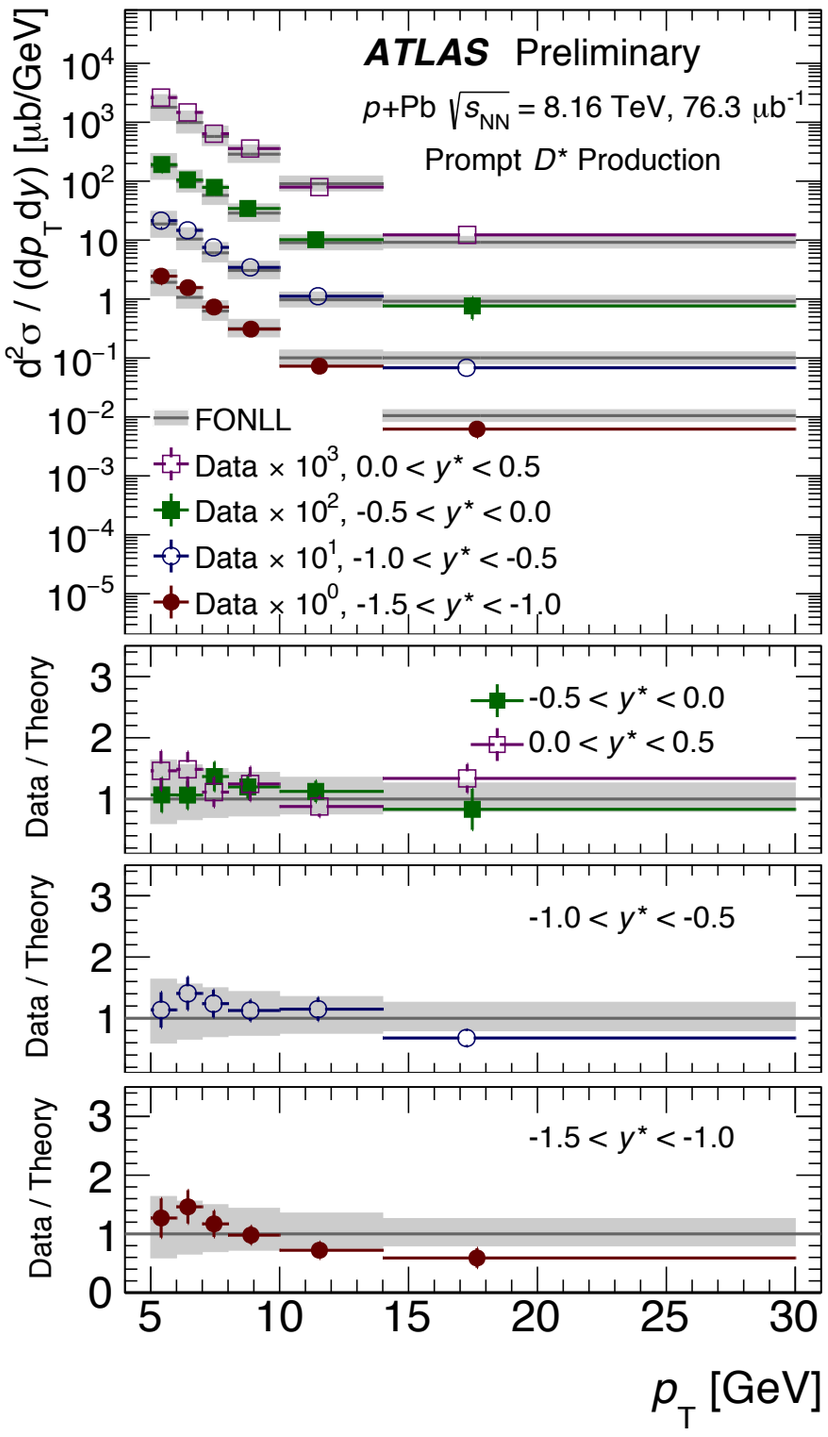
# Cross sections

- Data and FONLL are comparable in whole kinematic range
- Relatively small modification in $p$+Pb

**Prompt $D^0$**




**Prompt $D^*$**

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# Forward to backward ratio

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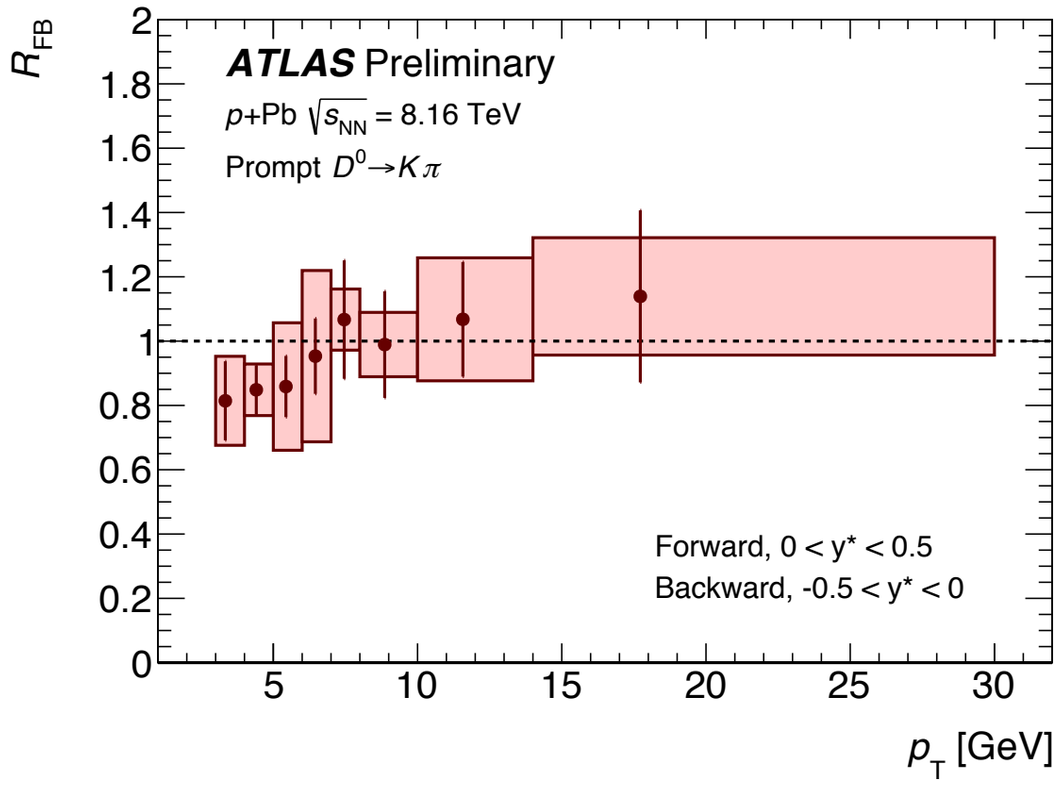
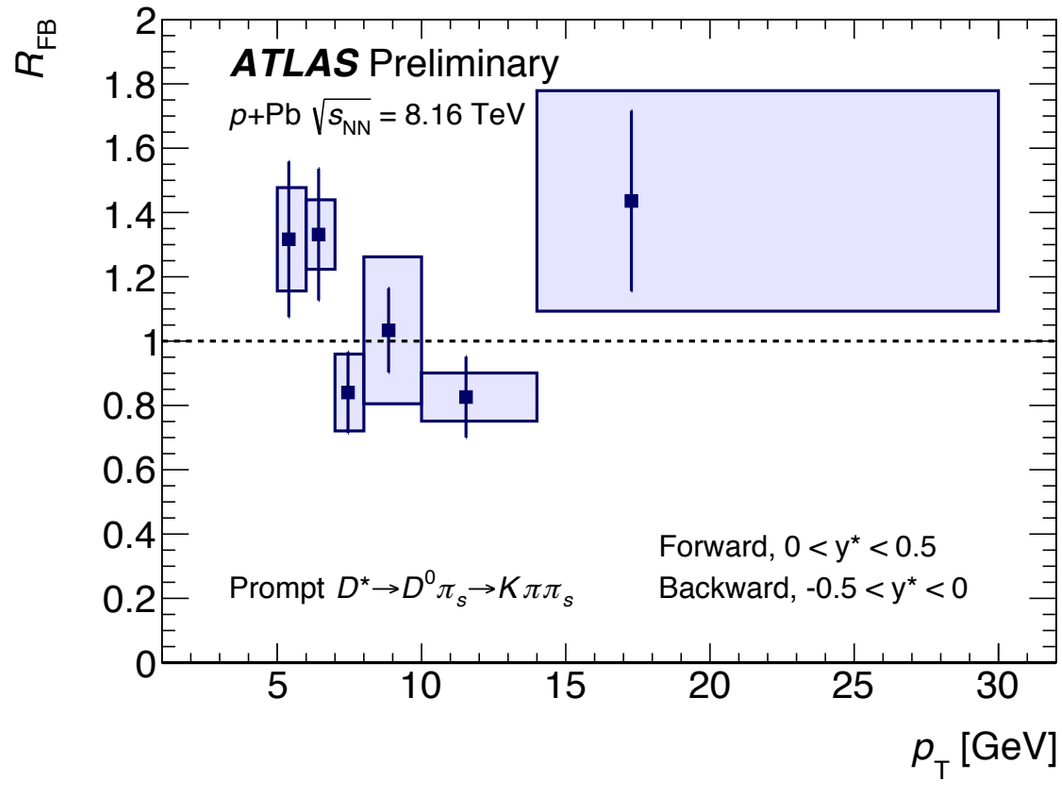
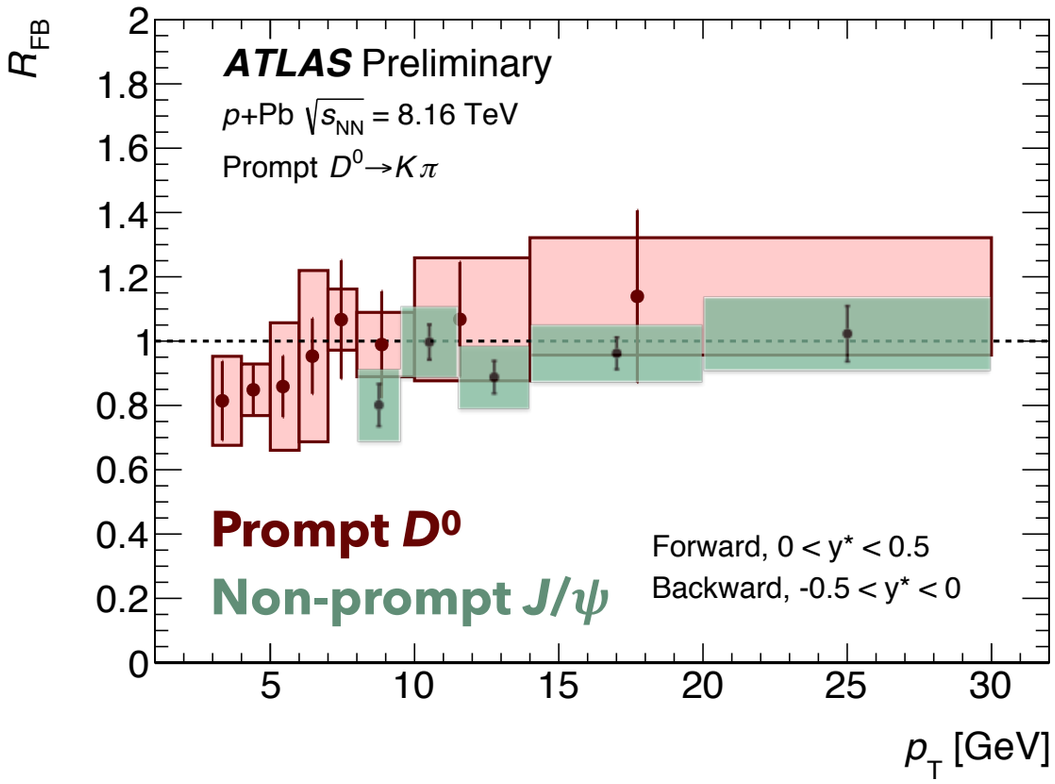


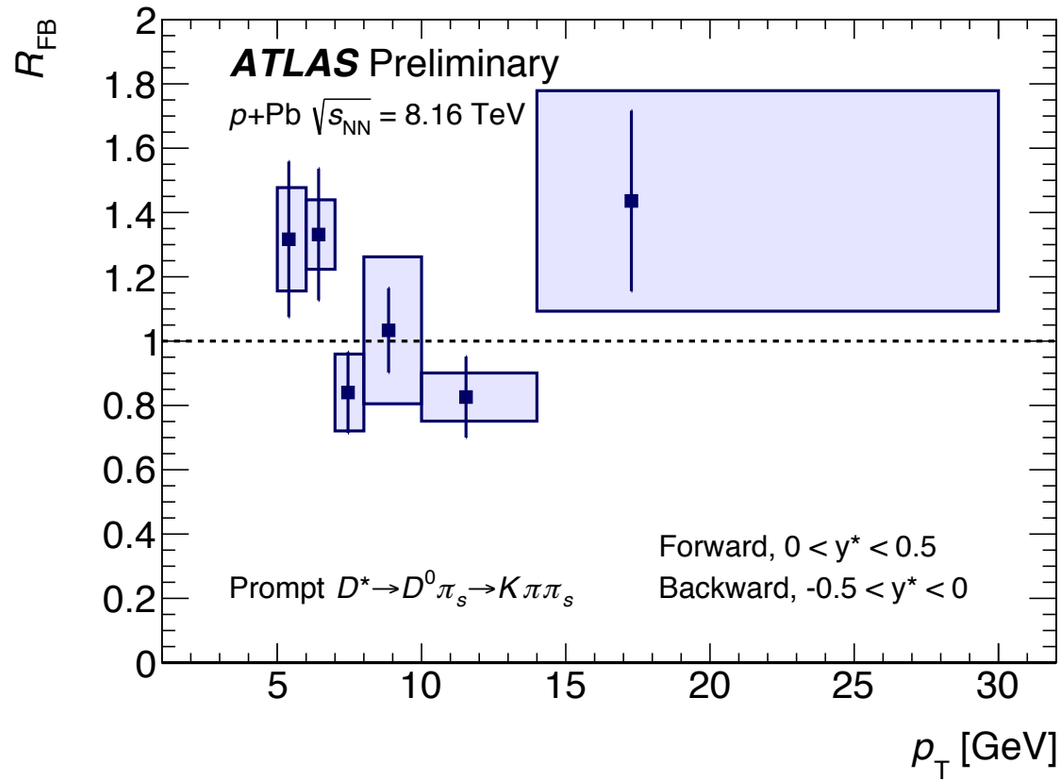




- Consistent with unity for the investigated kinematic range
- No obvious modification in forward wrt. backward for prompt D* and $D^0$

# Forward to backward ratio

ATLAS-CONF-2017-073
Phys. Rev. C 92, 034904 (2015)

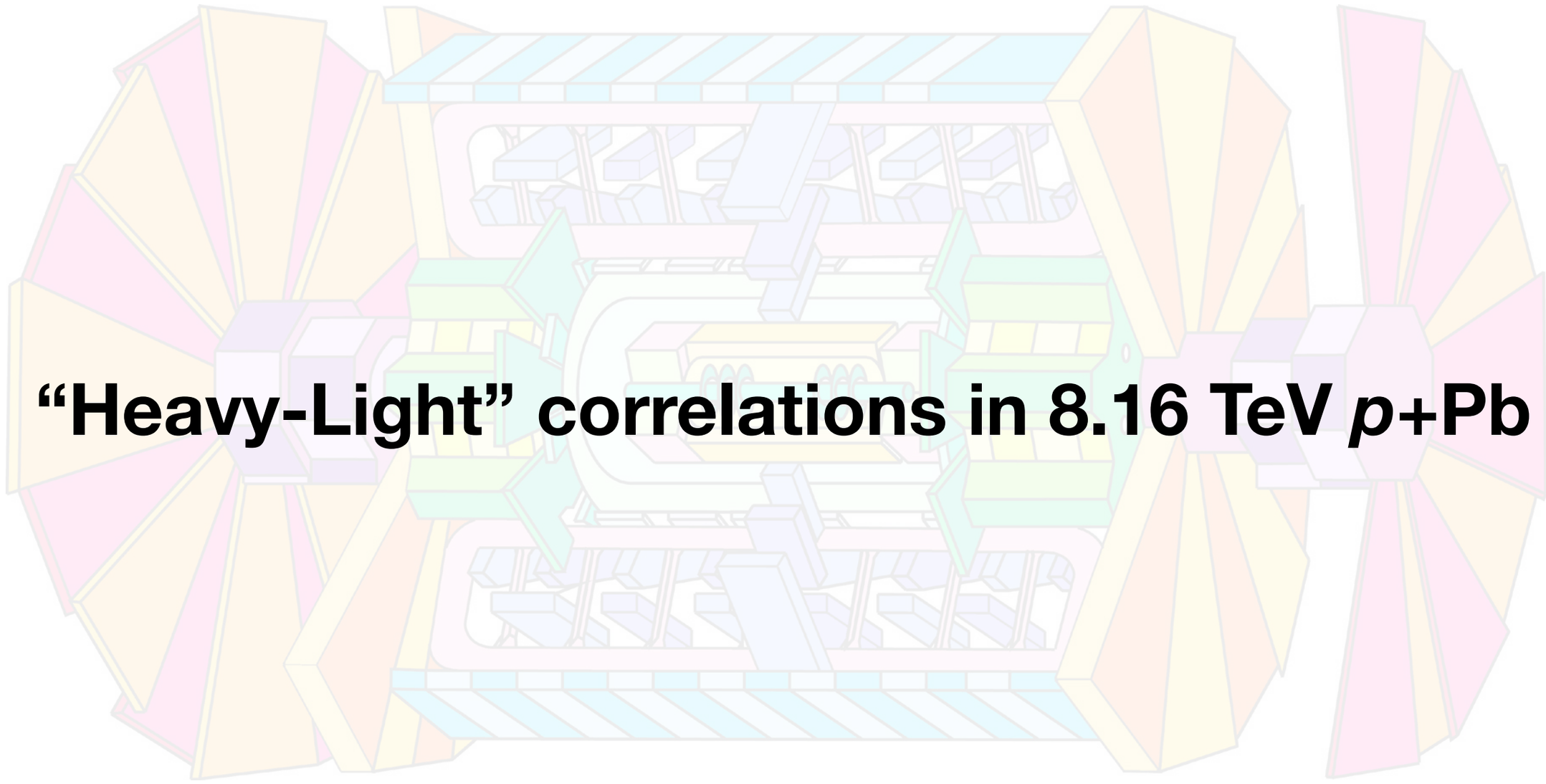



- Consistent with unity for the investigated kinematic range
- No obvious modification in forward wrt. backward for prompt D* and $D^0$
- $R_{FB}$(prompt $D^0$) ~ $R_{FB}$(non-prompt $J/\psi$)

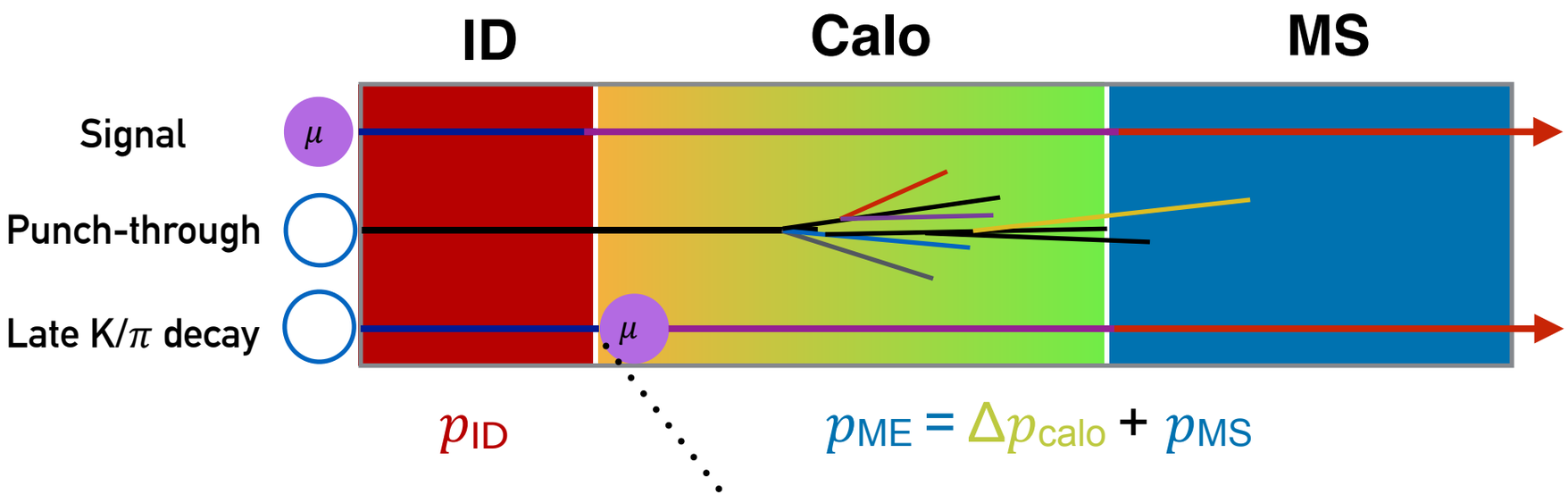


William Brooks 31/10, 9:30 ATLAS quarkonium measurements



# “Heavy-Light” correlations in 8.16 TeV *p*+Pb

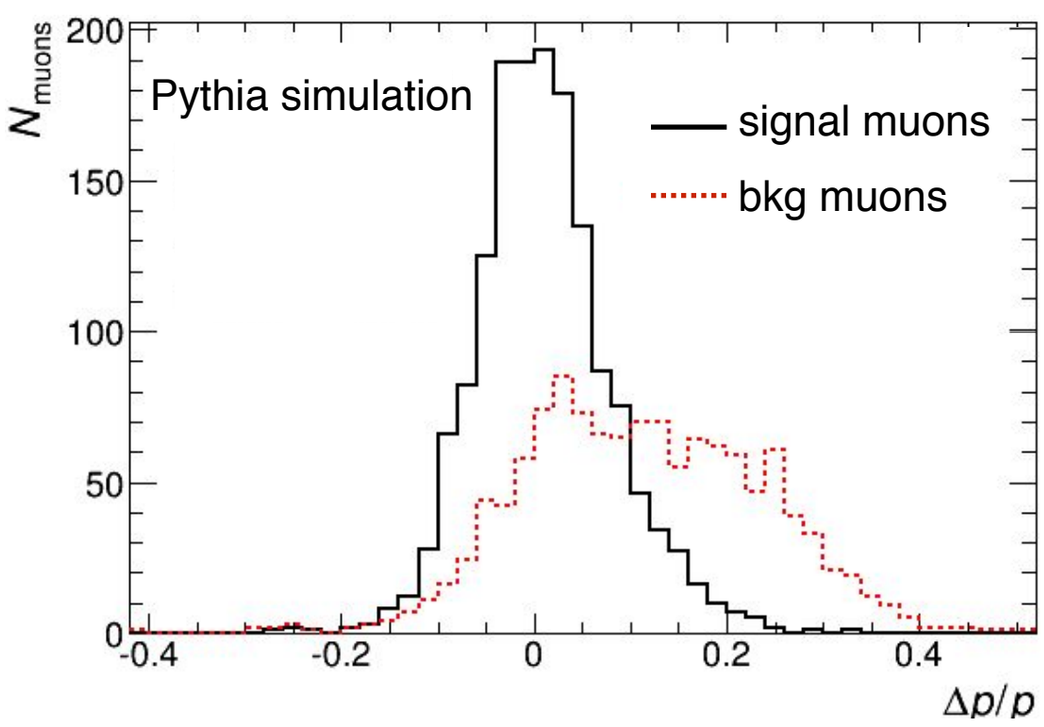
# Heavy flavor muon




Momentum imbalance

$$\frac{\Delta p}{p_{\mathrm{ID}}} = \frac{p_{\mathrm{ID}} - p_{\mathrm{ME}}}{p_{\mathrm{ID}}}$$

- Backgrounds: late K/$\pi$ decays and punch-through jets
- To enrich signal muons: $\Delta p$ / $p_{ID}$ < 0
- Signal purity ~ 80%
- Comparable *c* and *b* contribution at $p_T$ ~ 5 GeV and *b*-dominated at $p_T$ > 5 GeV



# Muon-hadron correlation

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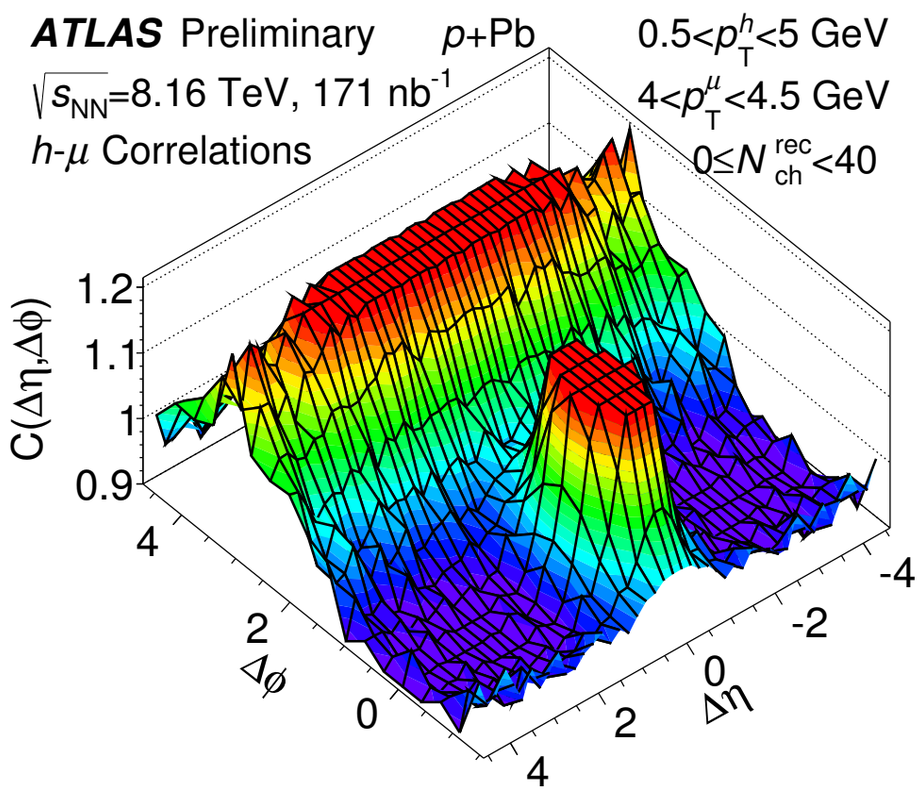
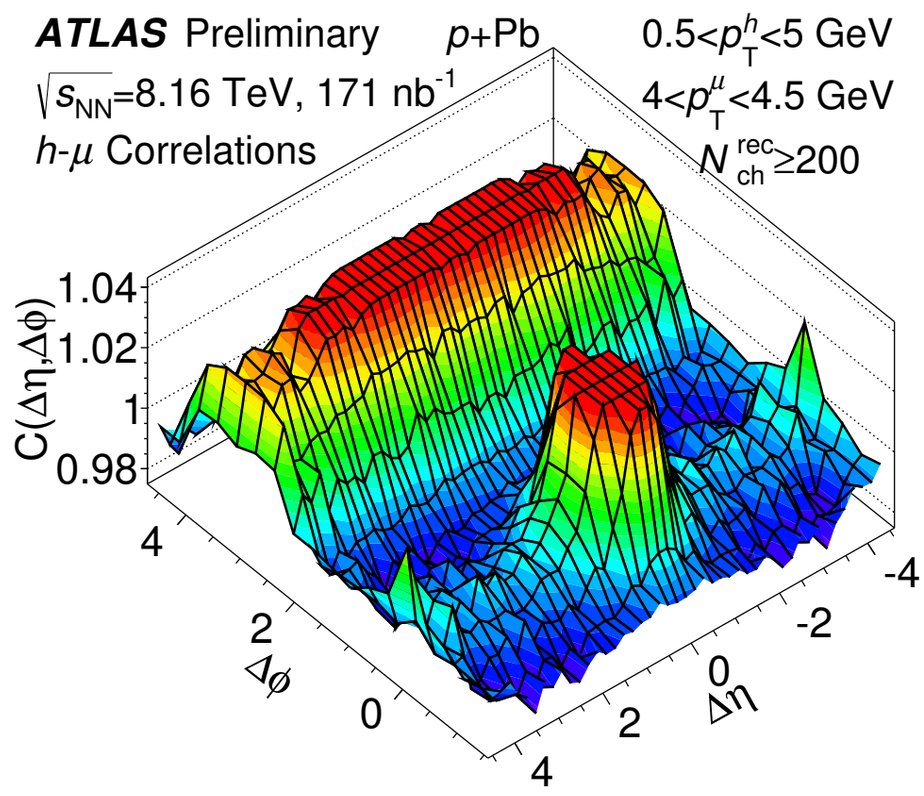



**Low Multiplicity**




**High Multiplicity**

- Event collected by single muon trigger and high multiplicity trigger
- 2PC between HF muon and charged hadrons
- Multiplicity dependence of ridge strength but limited

# Template fit method

ATLAS-CONF-2017-006

Two assumptions:

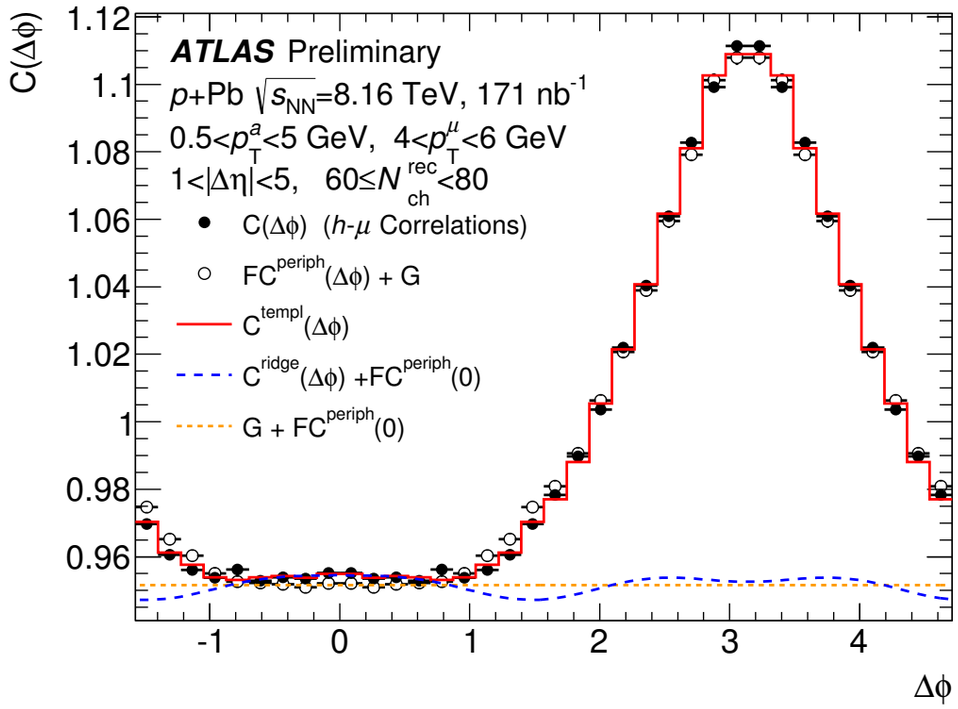
- Universal jet-correlation shape
- Weak/no multiplicity dependence of flow modulation

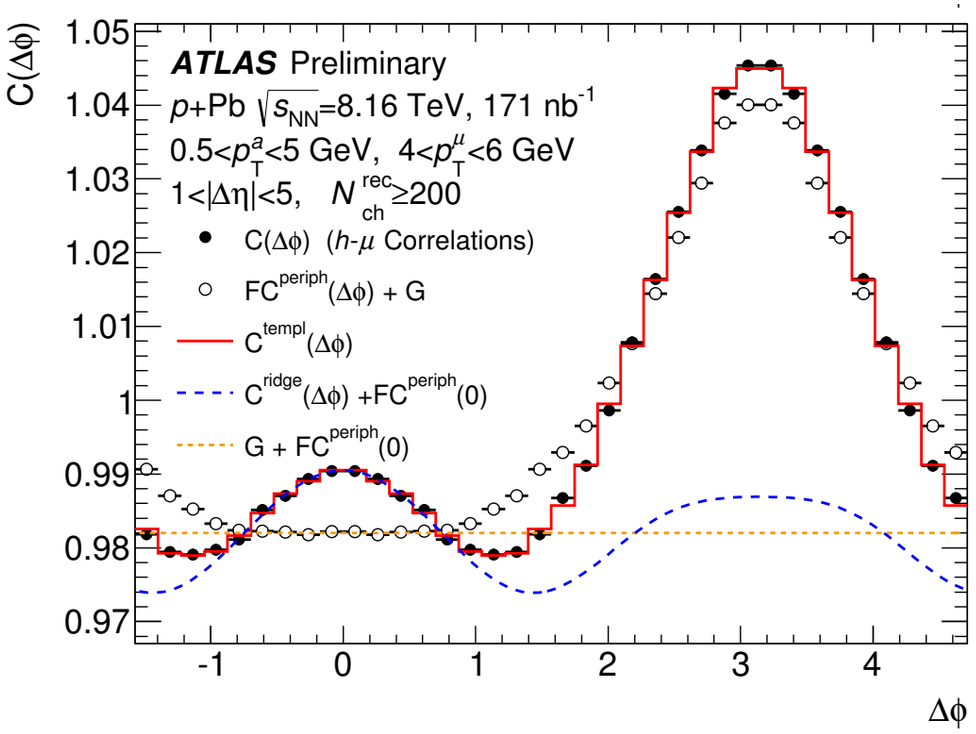
$$Y^{\mathrm{templ}}(\Delta\phi) = Y^{\mathrm{ridge}}(\Delta\phi) + F\,Y^{\mathrm{periph}}(\Delta\phi)$$

where

$$Y^{\mathrm{ridge}}(\Delta\phi) = G\left(1 + \sum_{n=2}^{\infty} 2v_{n,n}\cos\left(n\Delta\phi\right)\right)$$

$v_{n,n}$ factorizes and $v_n$ is extracted.



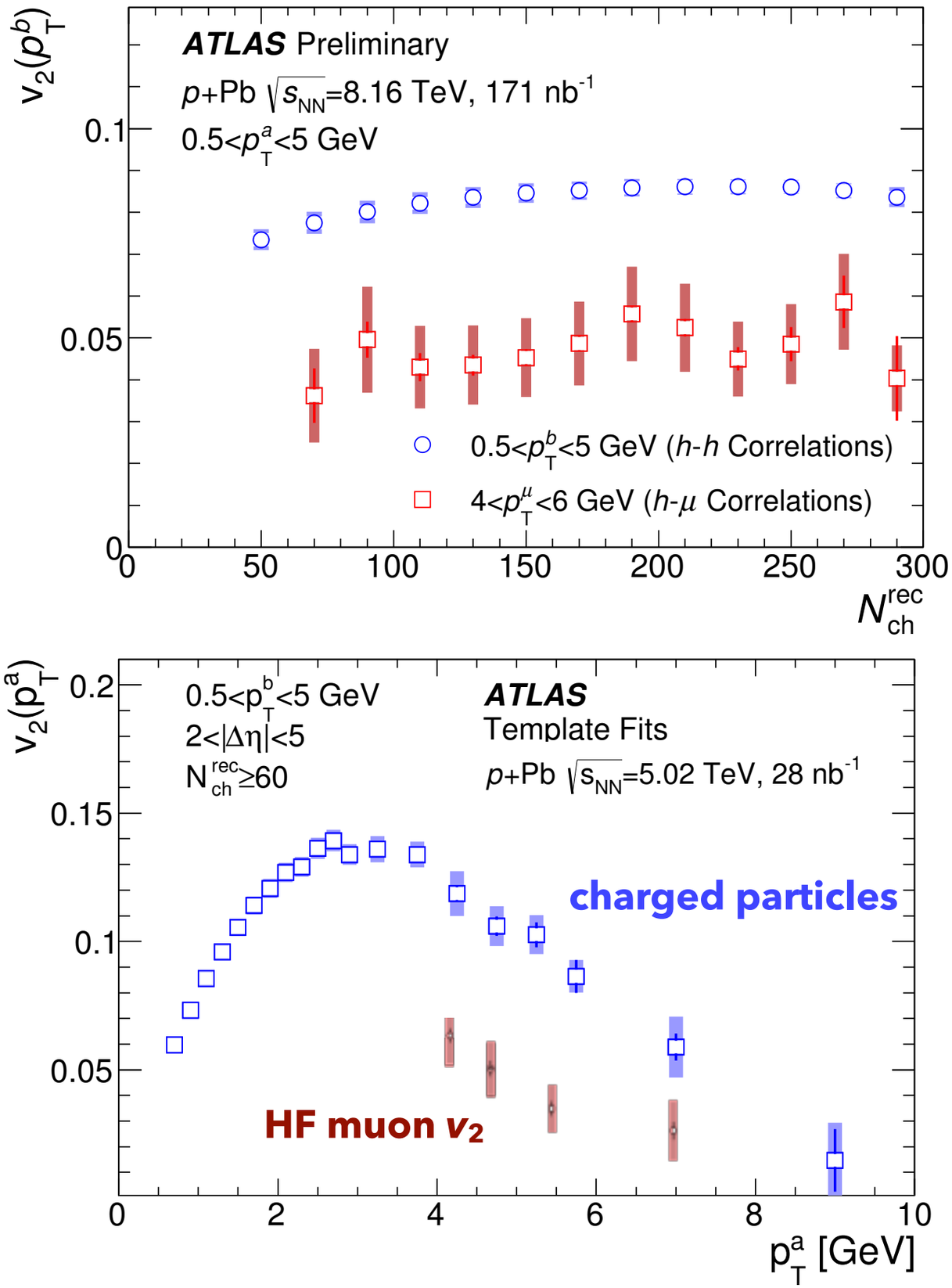




- peripheral interval $0 \leq N_{ch} < 40$
- 2-4 order harmonic considered in fit

# HF muon $v_2$

ATLAS-CONF-2017-006

- No obvious multiplicity dependence of HF muon $v_2$
- $v_2$ (HF muon) ~ 0.6 × $v_2$ (hadron)



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ATLAS-CONF-2017-006
ATLAS-CONF-2015-053

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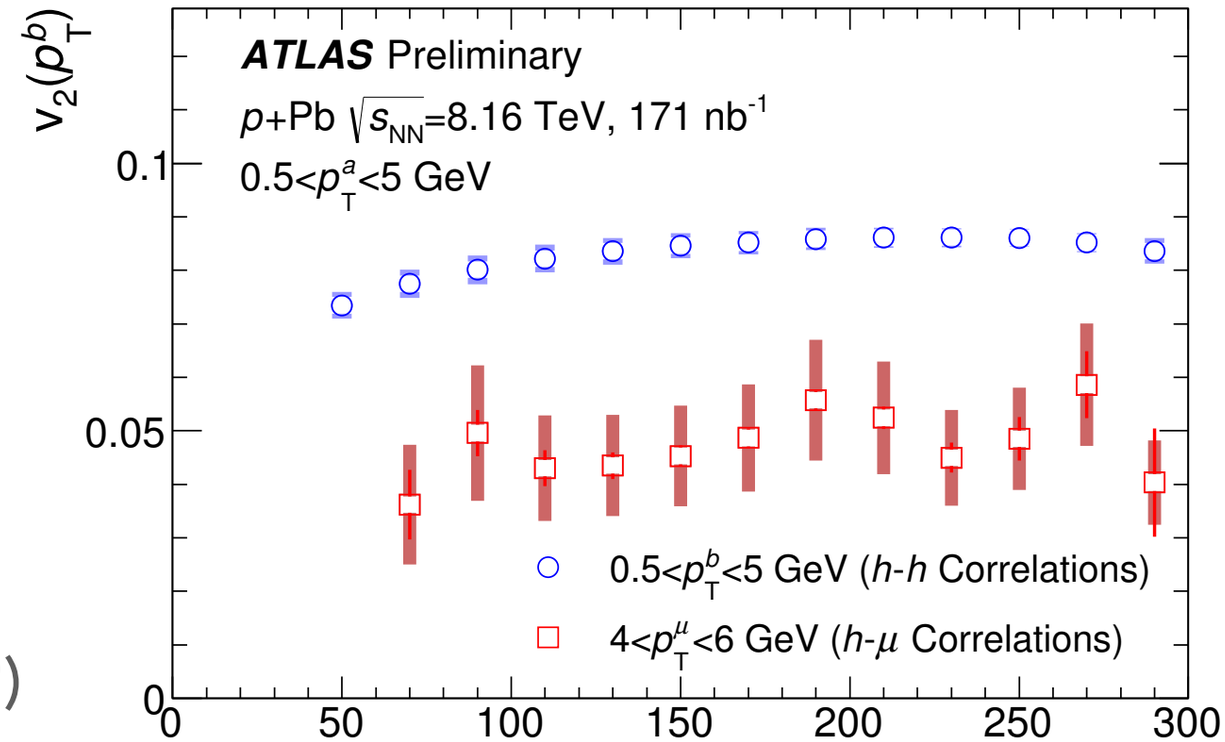
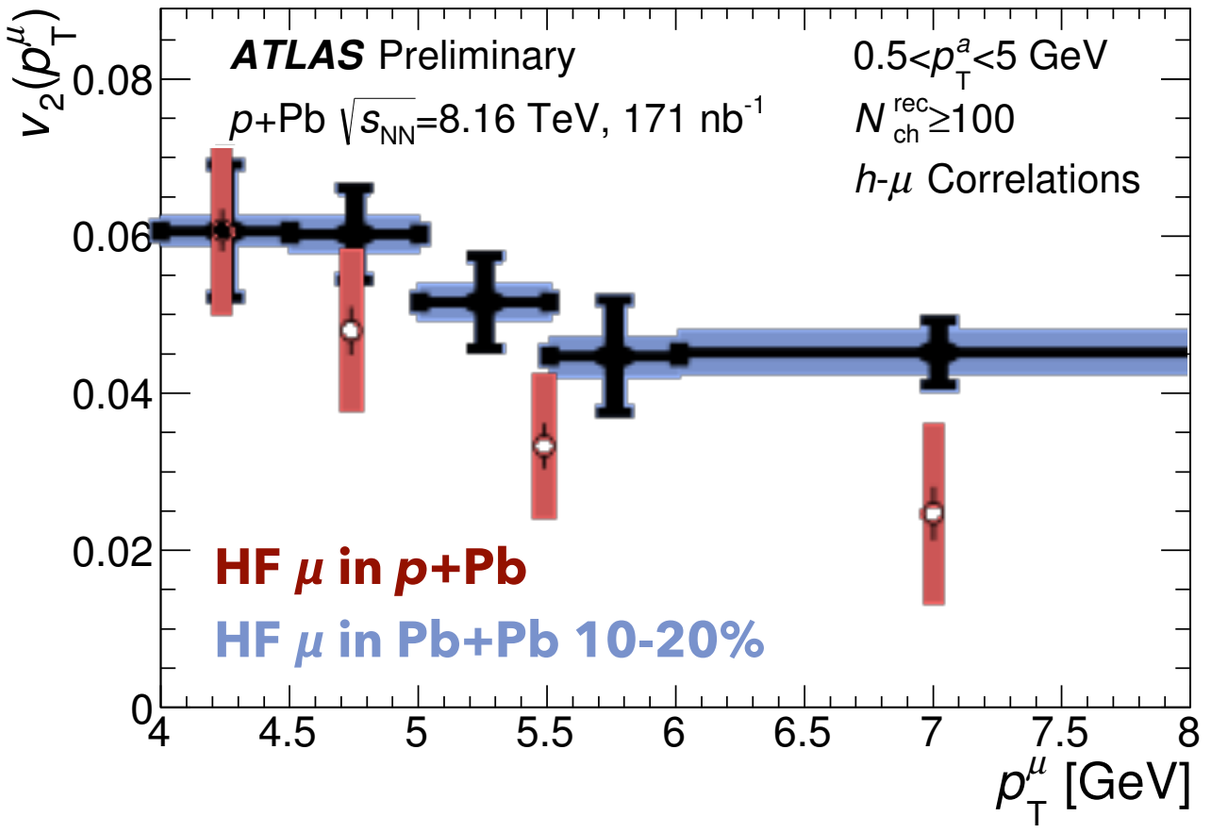
- $v_2$ (HF muon) ~ 0.6 × $v_2$ (hadron)
- $v_2$ (p+Pb; 2PC) ~ $v_2$ (Pb+Pb; 10-20%, EP)



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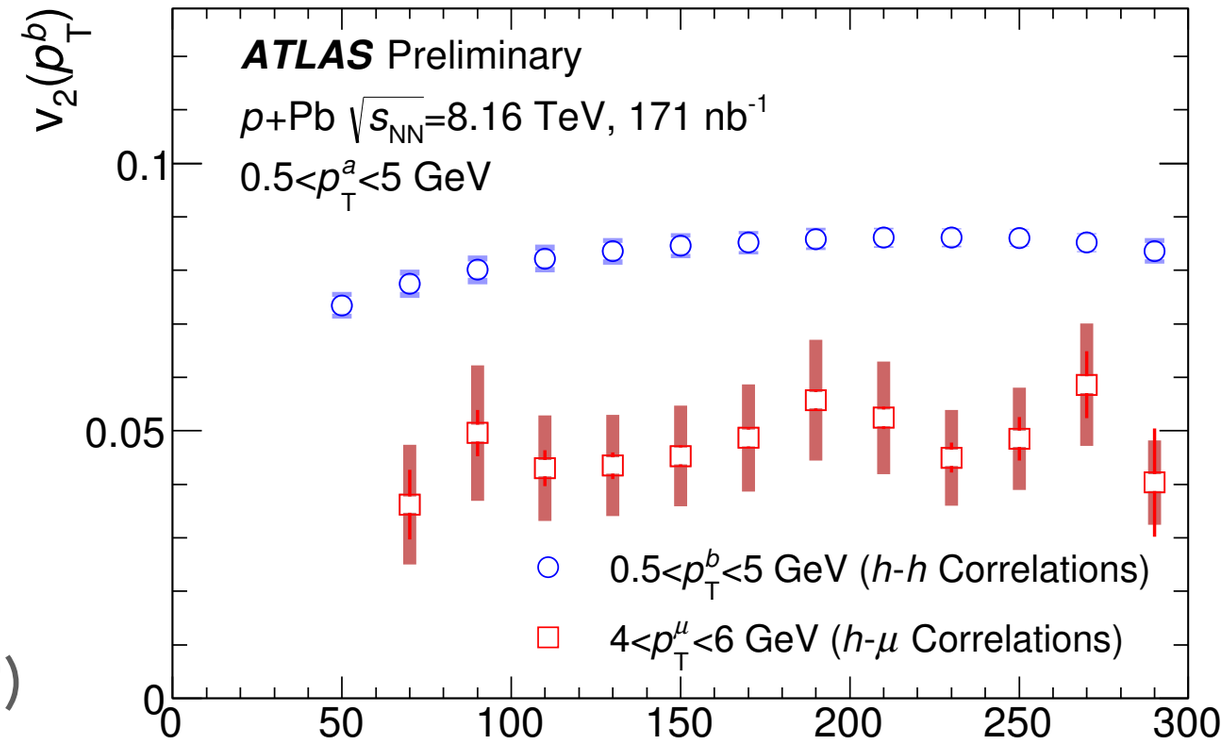
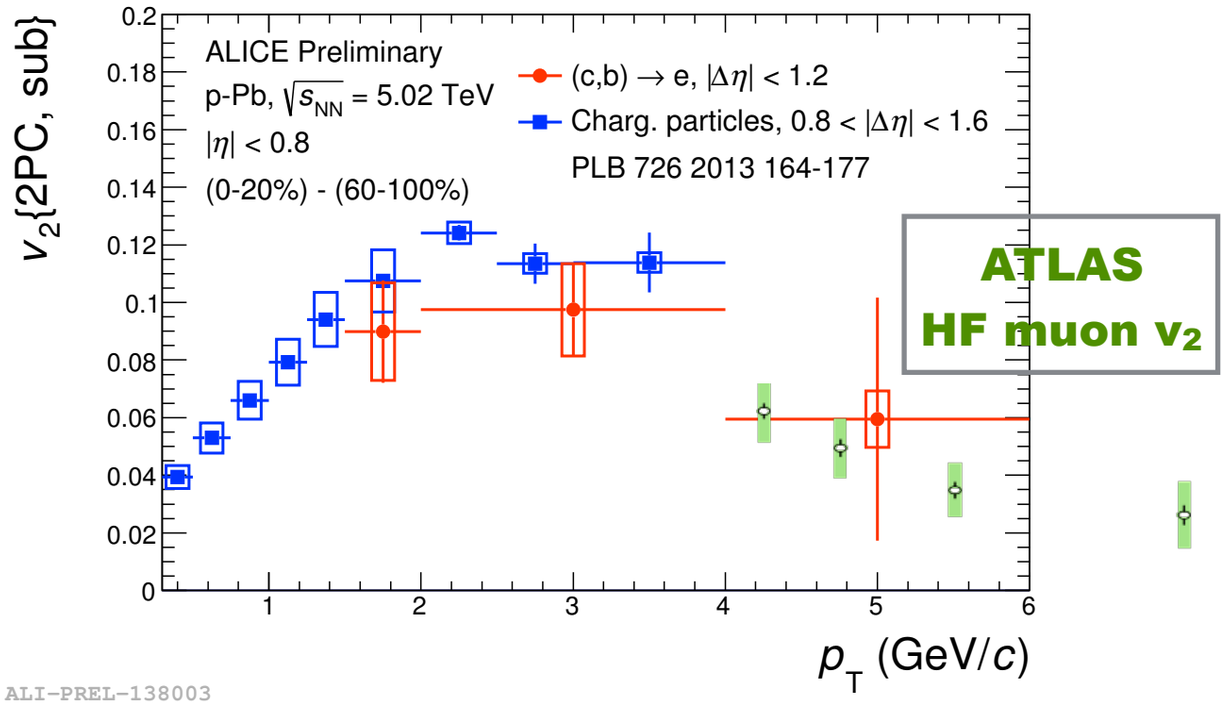



✦ Smear of similar anisotropy due to decay (different pT and angle)?

✦ Smaller HF anisotropy?

HF meson-hadron correlation



# D*-hadron correlation

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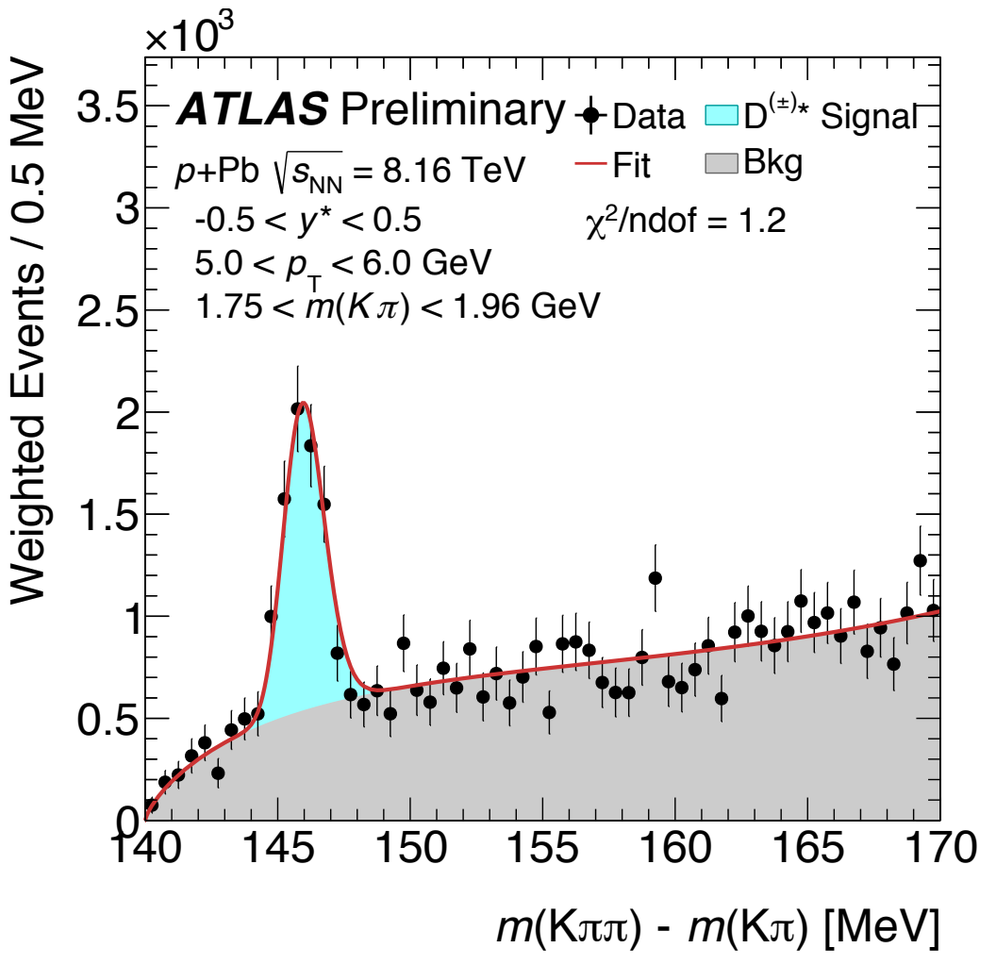


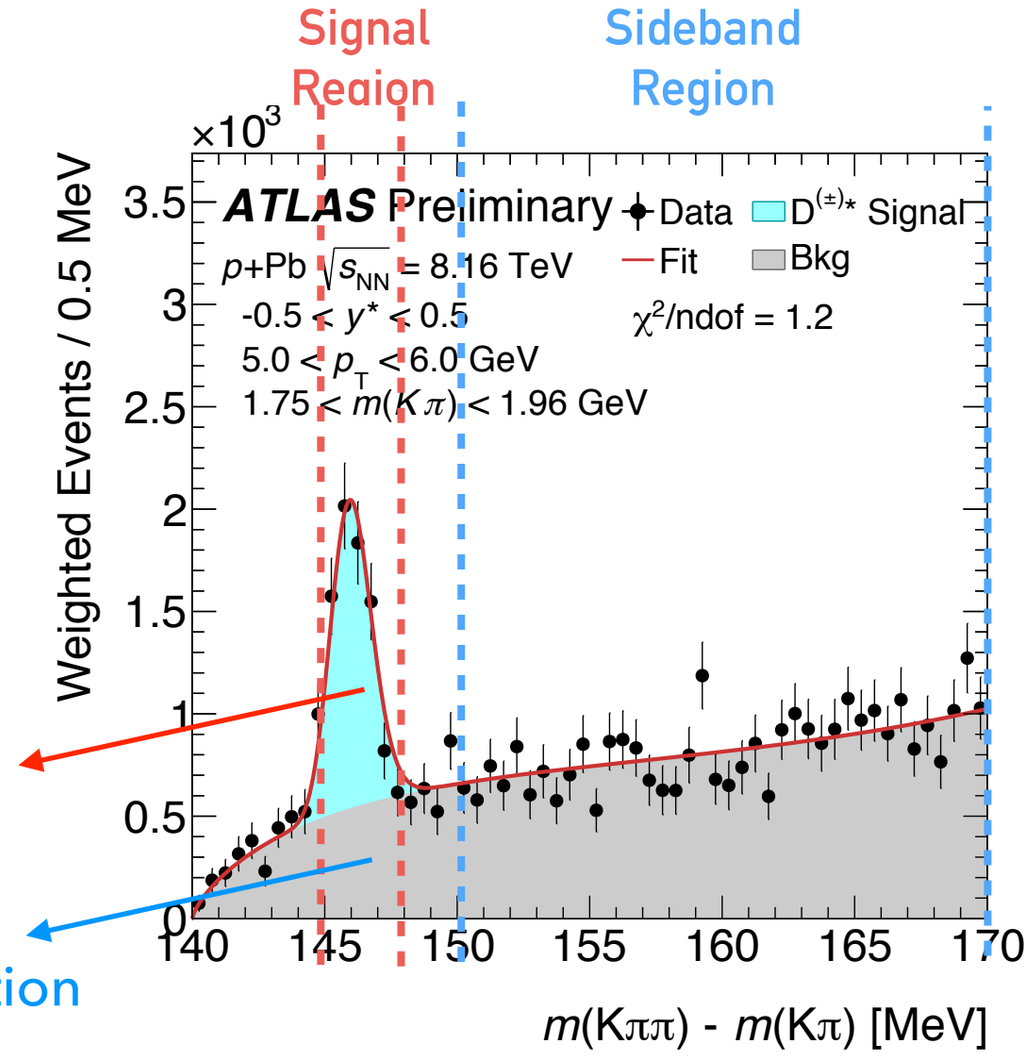

- Event collected by MinBias and high multiplicity triggers
- Third soft pion from *D** decay with $p_T$ > 250 MeV for larger *D** fiducial volume ( **3** < $p_T$ < 30 GeV and -1.5 < y* < 0.5 )
- Charged particles $p_T$ > 0.25 GeV, $\Delta\eta$ > 1 for more statistics for 2PC

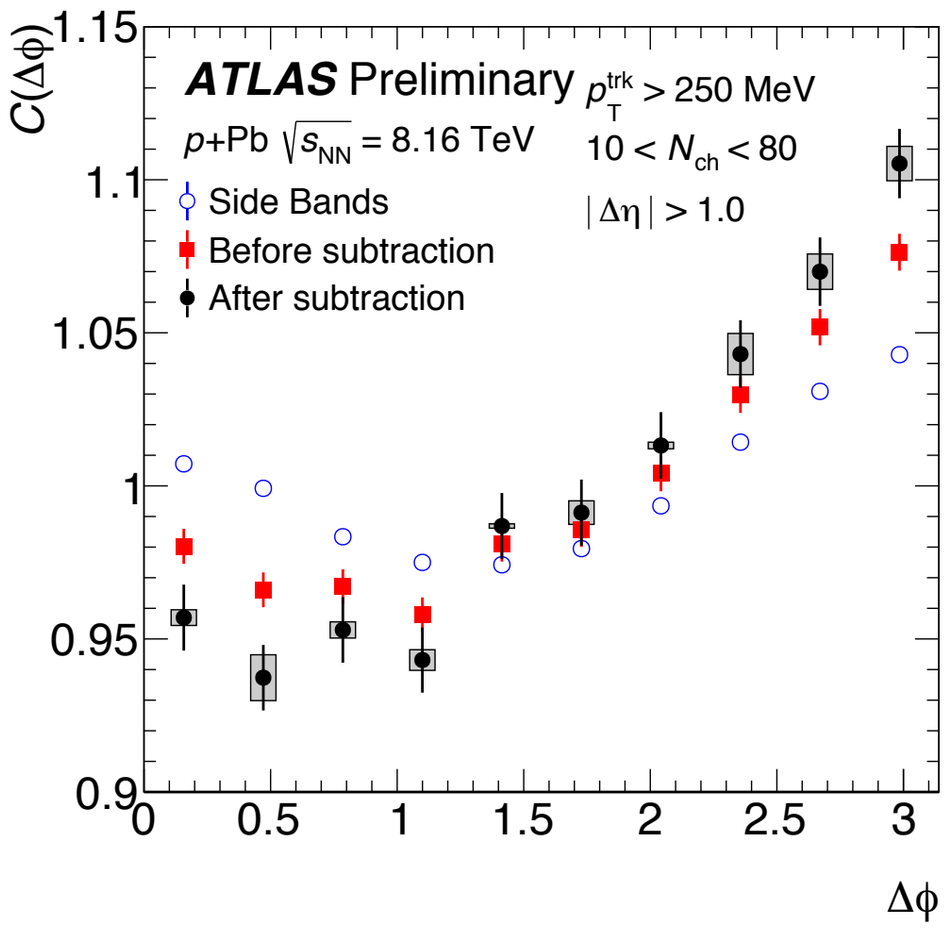
# D*-hadron correlation

ATLAS-CONF-2017-073

D*-h correlation

h-h correlation

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- Charged particles $p_T$ > 0.25 GeV, $\Delta\eta$ > 1 for more statistics for 2PC
- Using sideband region 150 < Δm < 170 MeV to estimation the background correlation function

# D*-h correlation fit

- Assuming weak multiplicity dependence of near-side D*-h long range correlation
- Peripheral reference bin $10 < N_{ch} < 80$
- Simultaneous template fit method applied to low and high $N_{ch}$ single correlation functions

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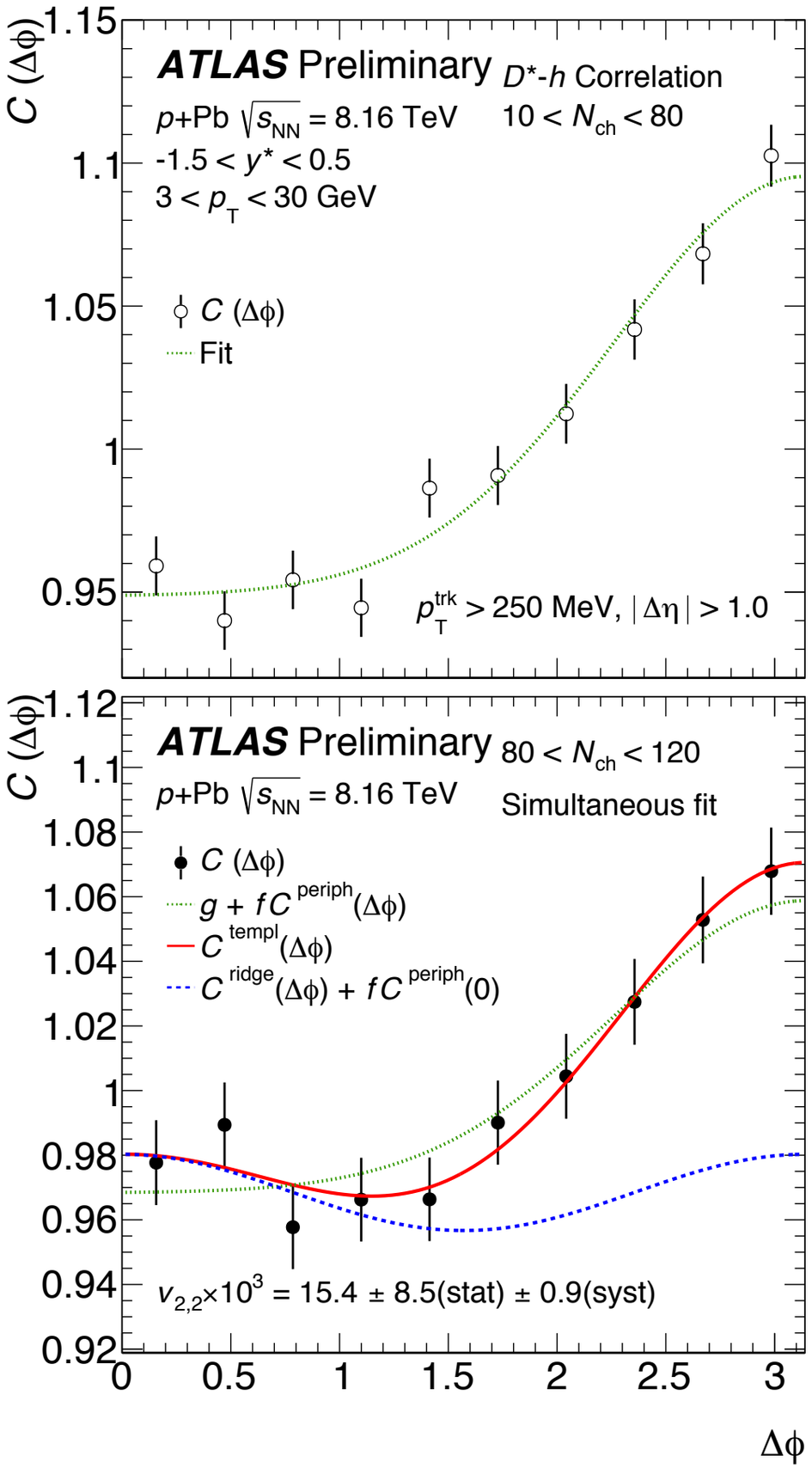
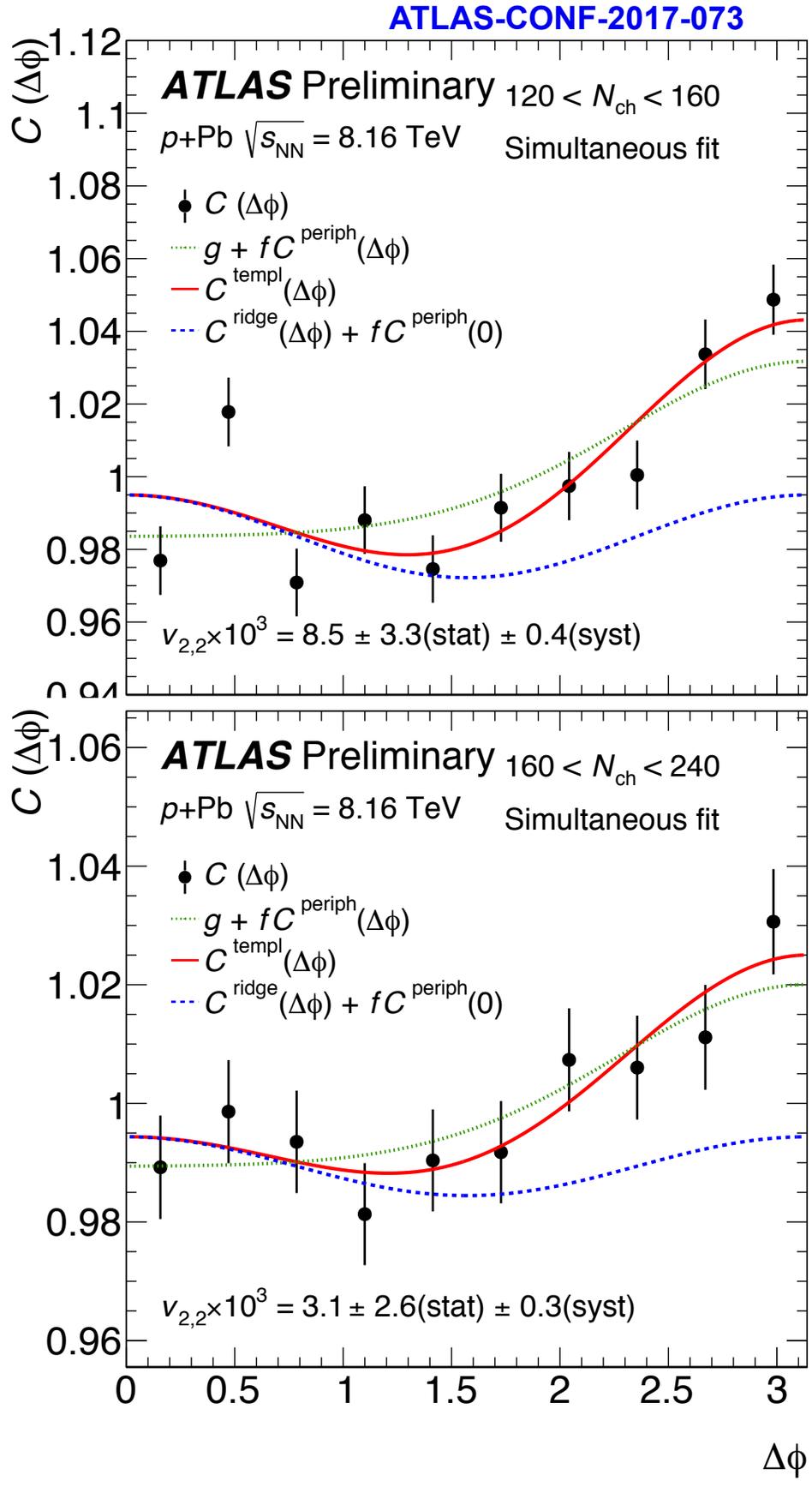


# D*-h correlation results

| $N_{ch}$ | $v_{2,2}$ ×10³ | Stat. Error ×10³ | Syst. Error ×10³ |
|---|---|---|---|
| 120~160 | **8.5** | ± 3.3 | ± 0.4 |
| 160~240 | **3.1** | ± 2.6 | ± 0.3 |

- Template fit favors $v_{2,2} > 0$
- *1~2σ* hint for cos(2Δ$\phi$) azimuthal angle modulation of *D**
- Broadly consistent with *h-h* and *μ-h* correlations



# Summary

- $D^0$ and $D^*$ productions are measured in $p$+Pb for the first time in ATLAS. No obvious modification observed to due CNM effects

- HF $\mu$-$h$ correlation in $p$+Pb:
  - $v_2$(HF $\mu$) = $0.6 \times v_2$ (hadron), no obvious $N_{ch}$ dependence
  - significant cos(2$\Delta\phi$) modulation of HF $\mu$, evidence for similar modulations of $D/B$ hadrons.

- $D^*$-$h$ correlation in $p$+Pb:

  finite cos(2$\Delta\phi$) modulation of inclusive $D^*$ in $p$+Pb at $1\sim2\sigma$ significance, broadly consistent with $h$-$h$ and $\mu$-$h$ correlations

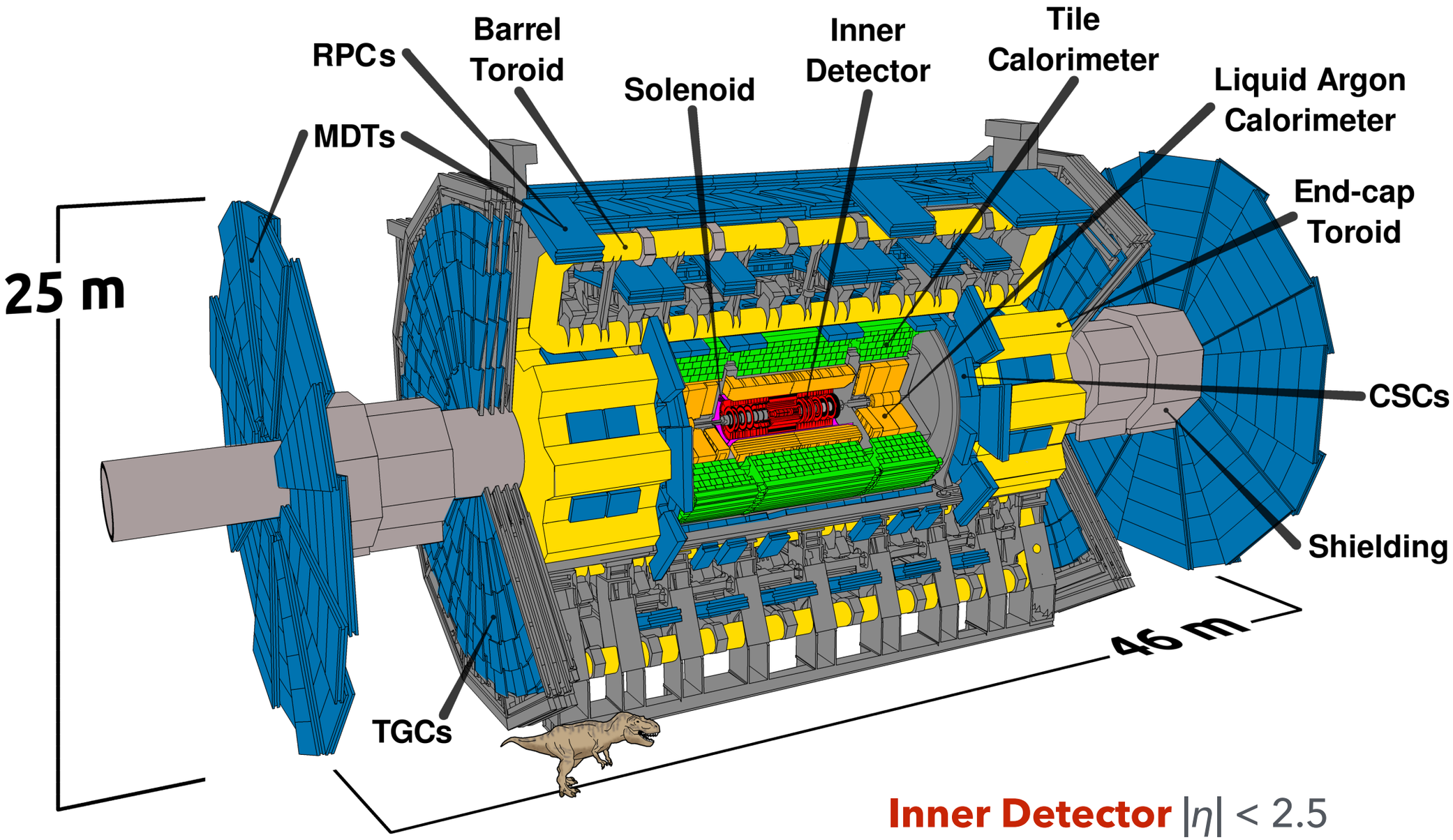
More identified HF meson in p+Pb / Pb+Pb from ATLAS in the near future. So stay tuned!

Thanks for your attentions!

ATLAS EXPERIMENT

# BACKUP

# ATLAS detector




By J. Goodson

**Inner Detector** $|\eta| < 2.5$

**Calorimeter** $|\eta| < 4.9$

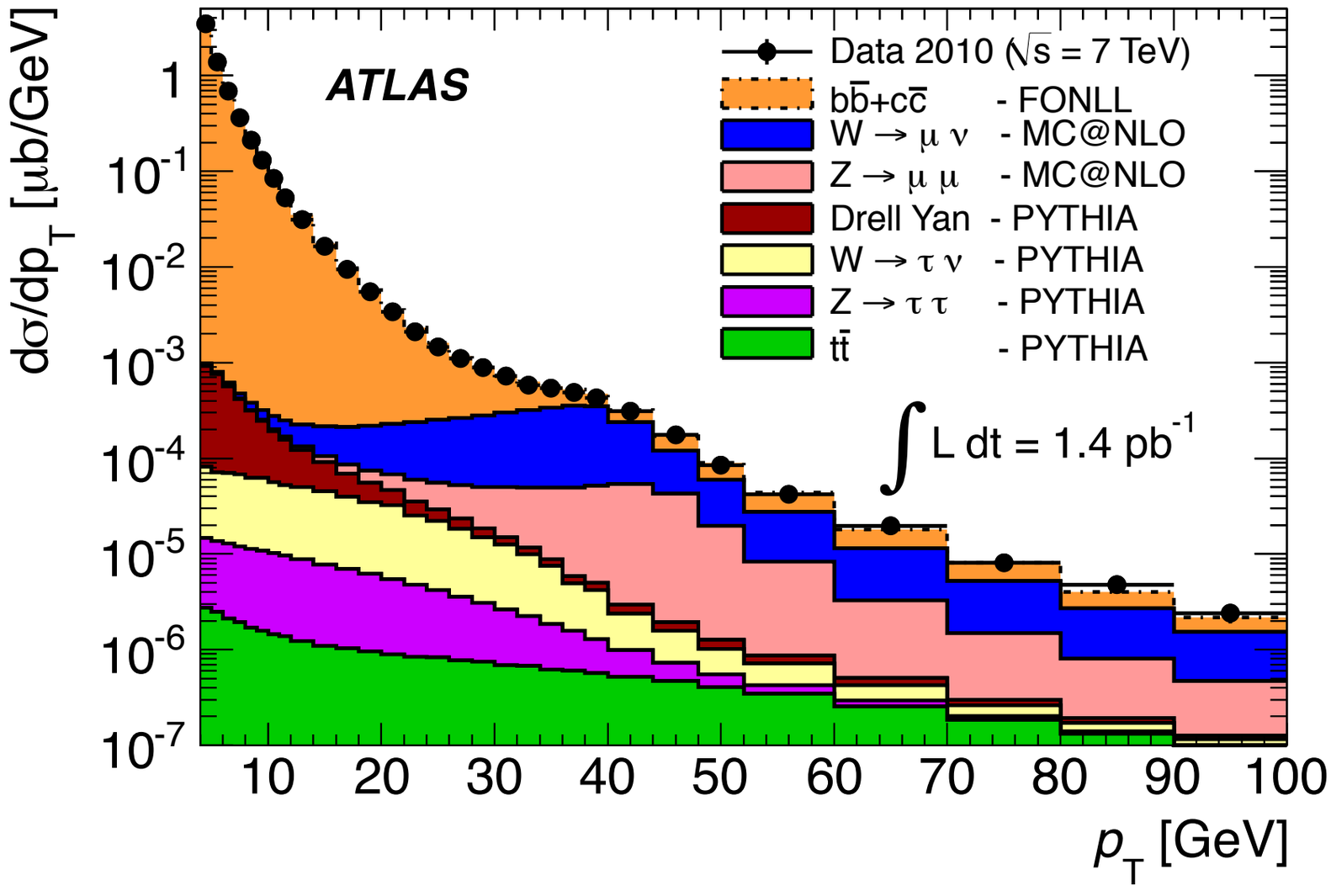
**Muon Spectrometer** $|\eta| < 2.7$

# D reconstruction

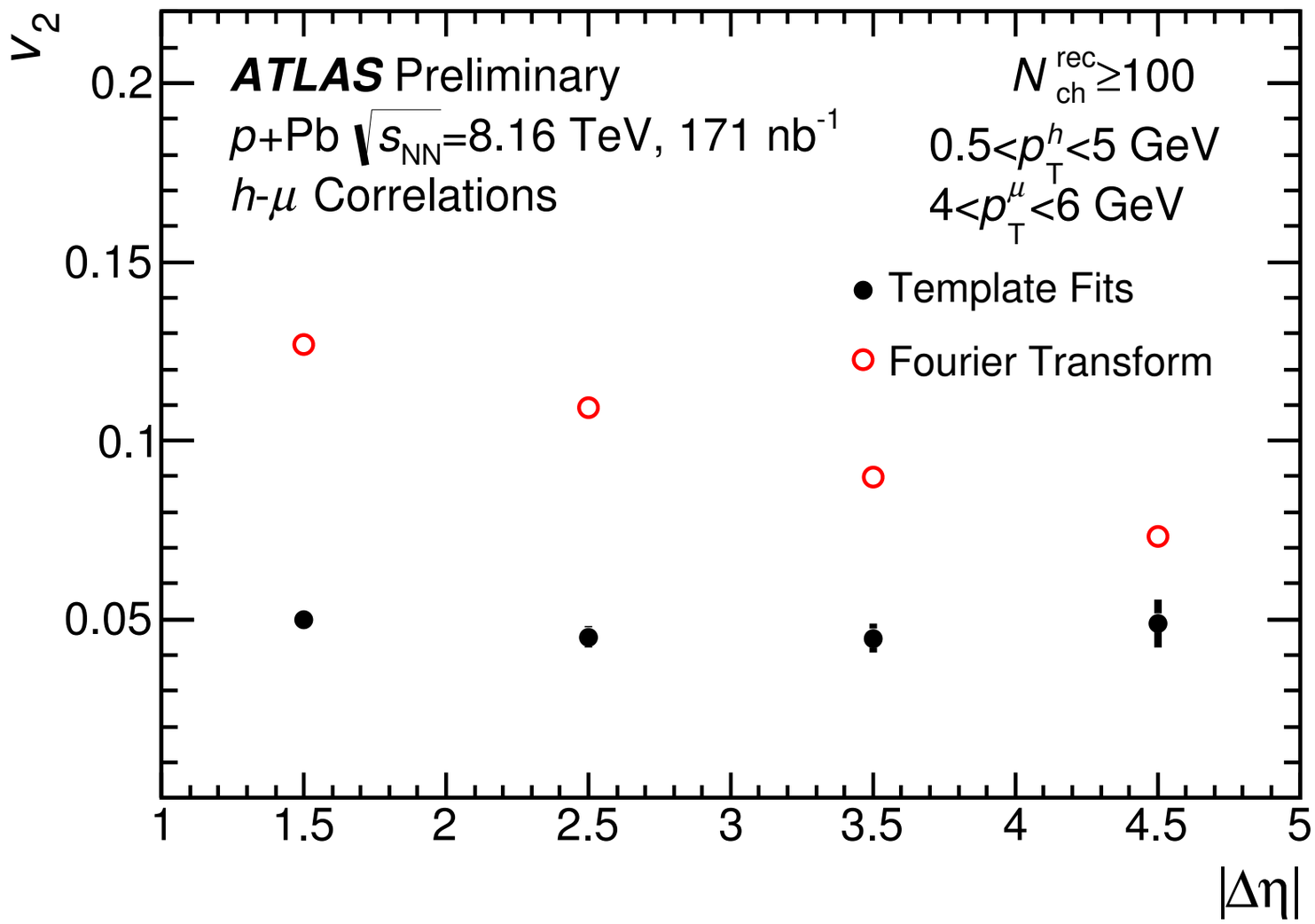
| | |
|---|---|
| Trigger selection | MinBias (+HMT for correlation) |
| $D^0$ selection | Two tracks, $p_T$ > 1GeV<br>$\pi$ and K masses assigned in turn, 1.7 < m(K$\pi$) < 2.0 GeV<br>Vertex probability<br>Pointing angle cos$\alpha_{xy}$<br>$L_{xy}$ / $\sigma(L_{xy})$ |
| D* selection | A selected $D^0$ vertex<br>An additional track ($\pi$ mass), same charge with the $\pi$ in $D^0$ with soft pion $p_T$ > 400 MeV (for yield) or 250 MeV (for correlation)<br>1.75 < m(K$\pi$) < 1.96 GeV as SR, m(K$\pi$) < 1.76 GeV \|\| m(K$\pi$) > 1.96 GeV as CR |

# Signal muon composition

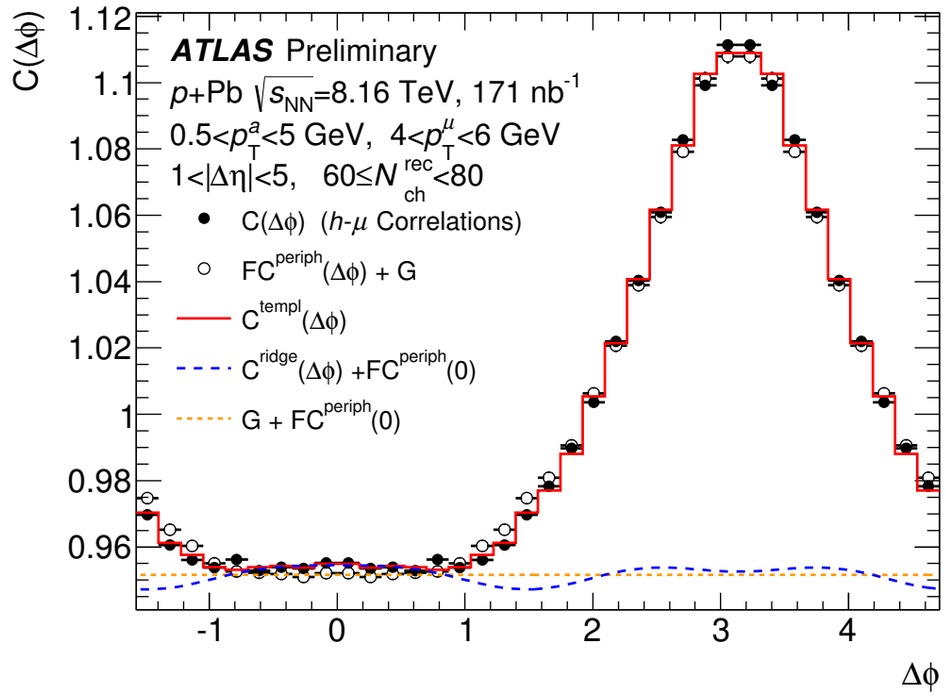
PLB 707 (2012) 438

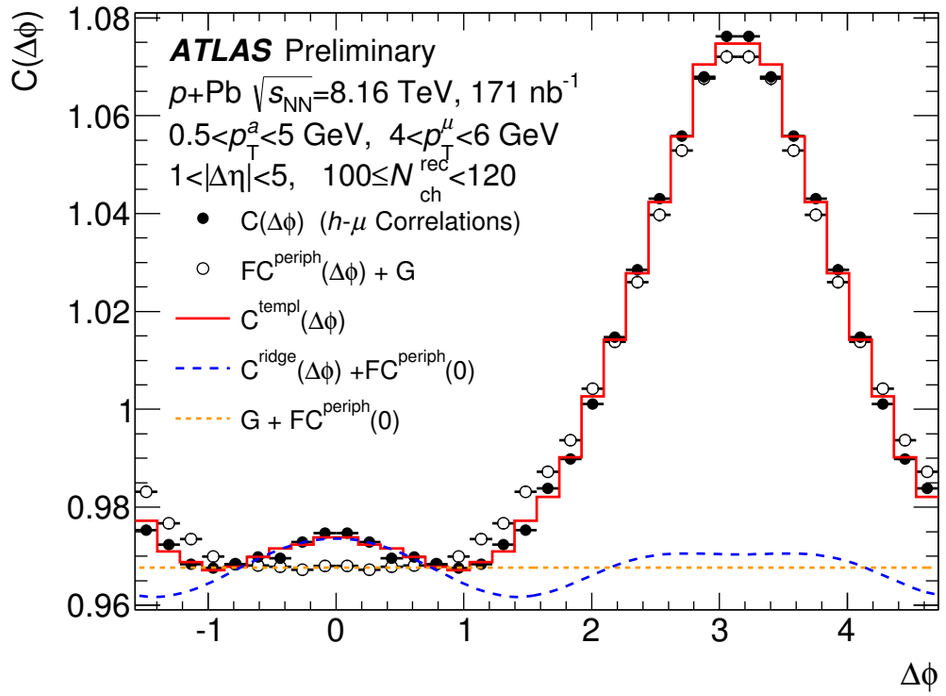


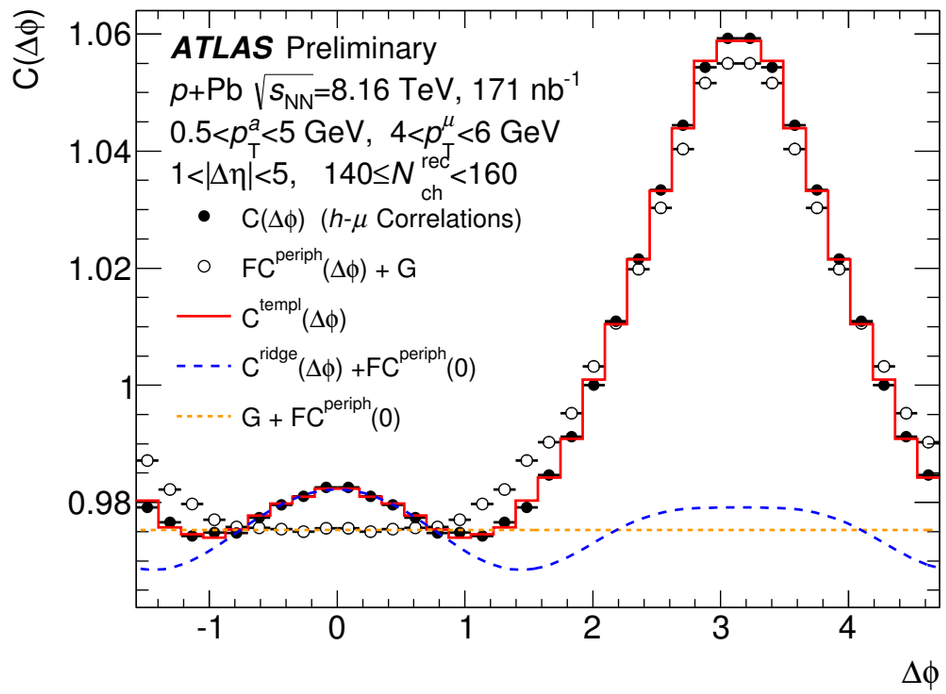
# Stability with different gaps

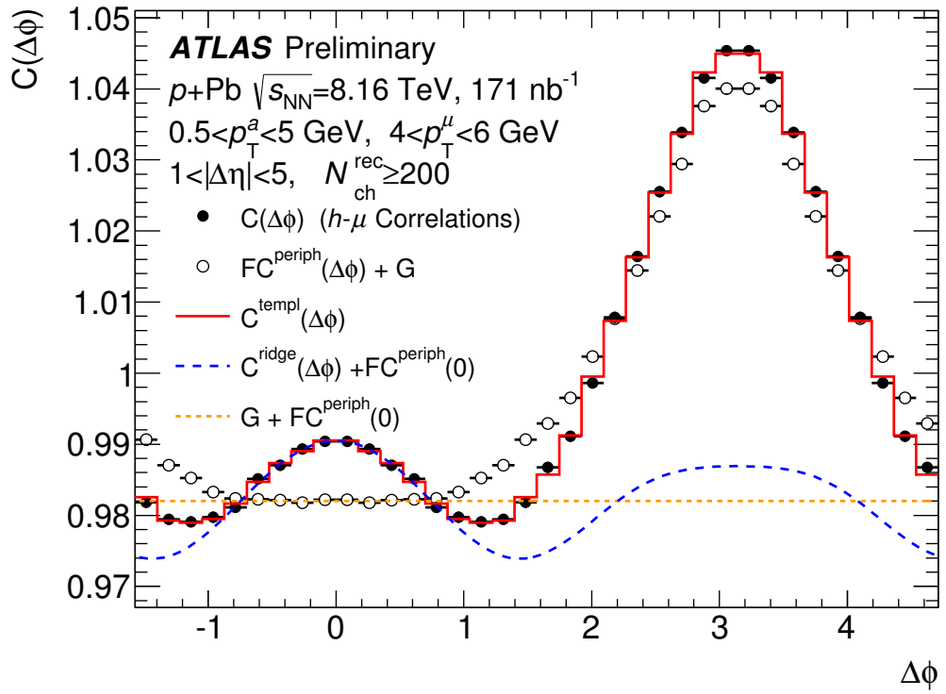


# Template fits — μ-h in p+Pb



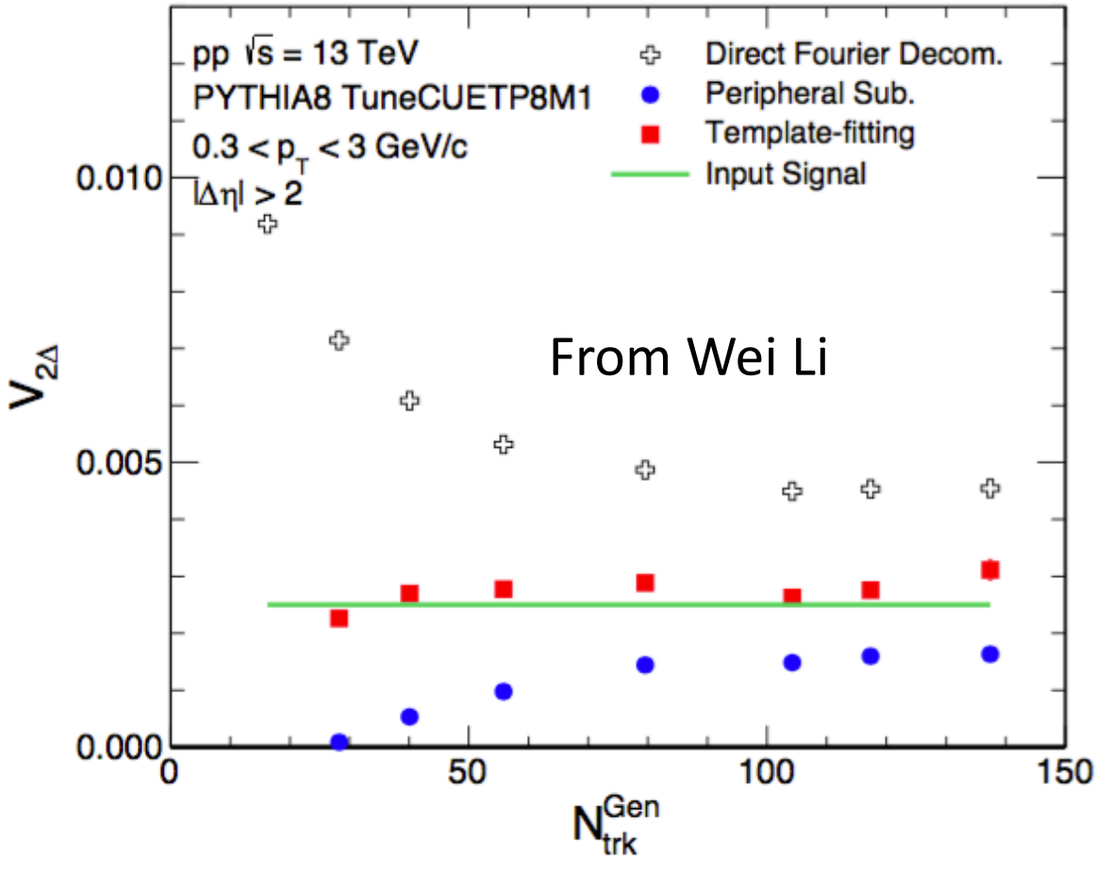



# Closure test of template fit

V2 constant

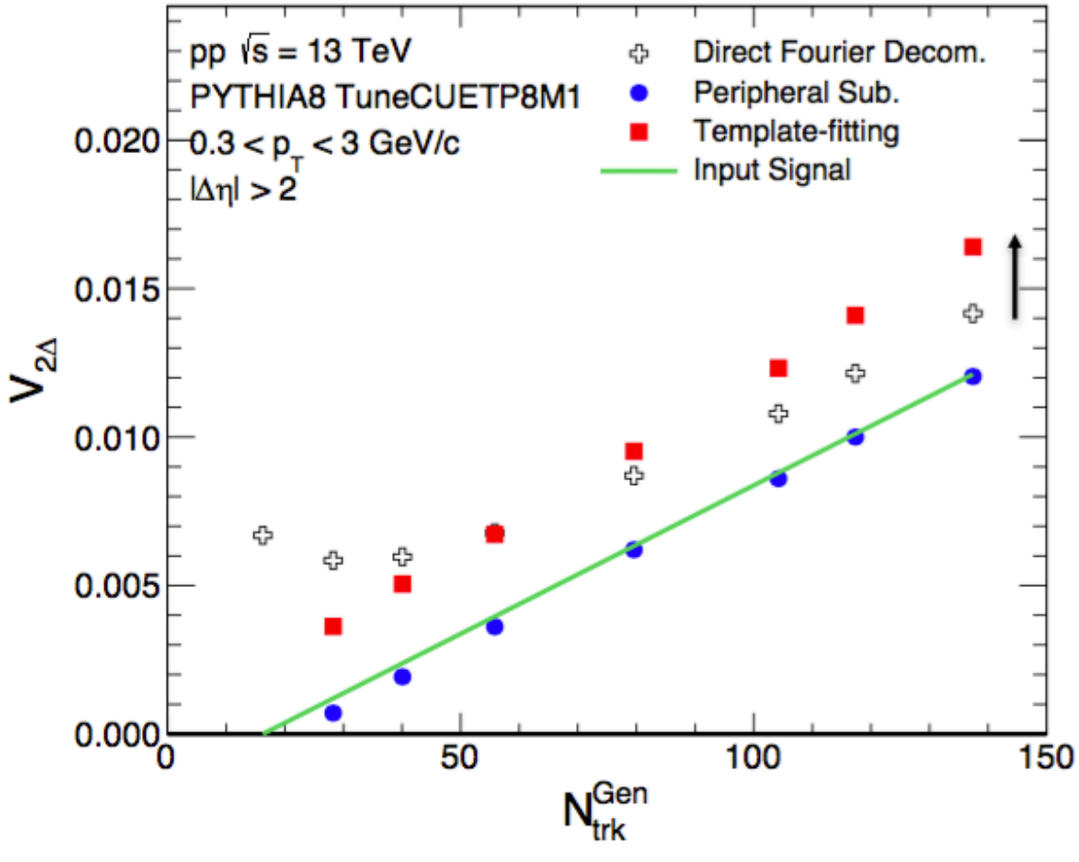
Template fitting works good




From Wei Li

V2 in crease with Nch

Template fitting overestimates v2



# Systematics for mu-h correlation

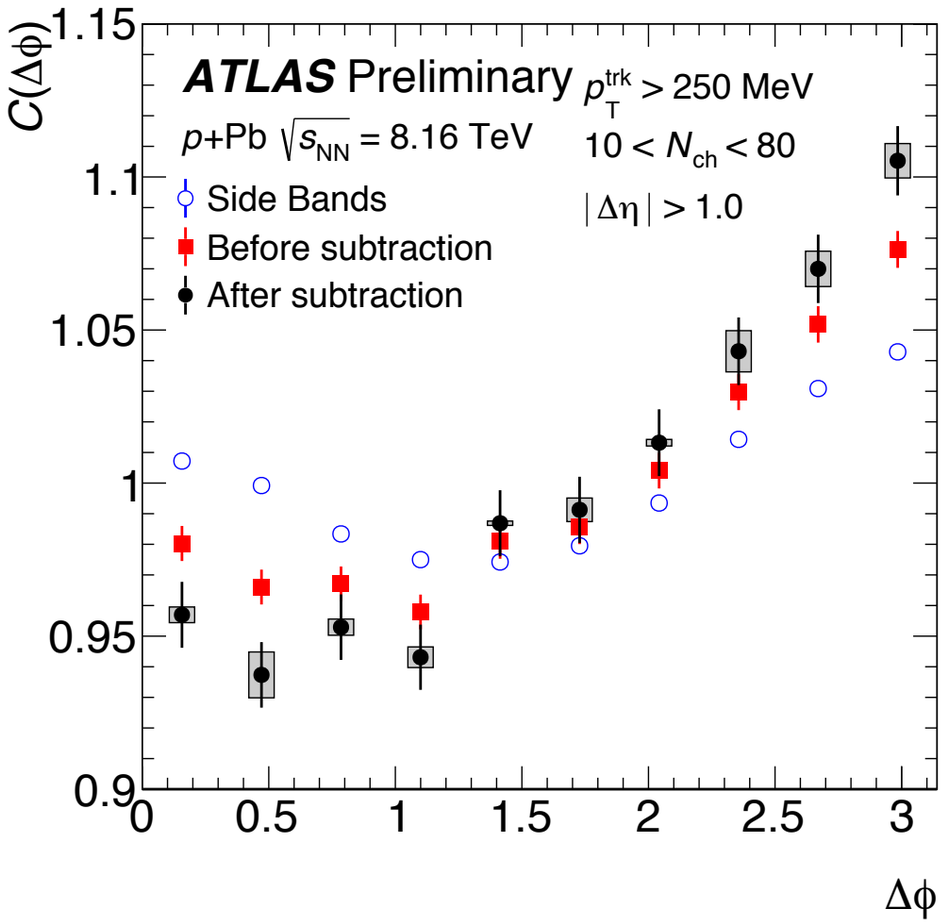
- **Choice of peripheral bin**
  0-20, 20-40, 10-20, 20-30, 30-40
- **Background muons**
- Efficiency correction
- Track/muon selection
- Pileup
- Acceptance

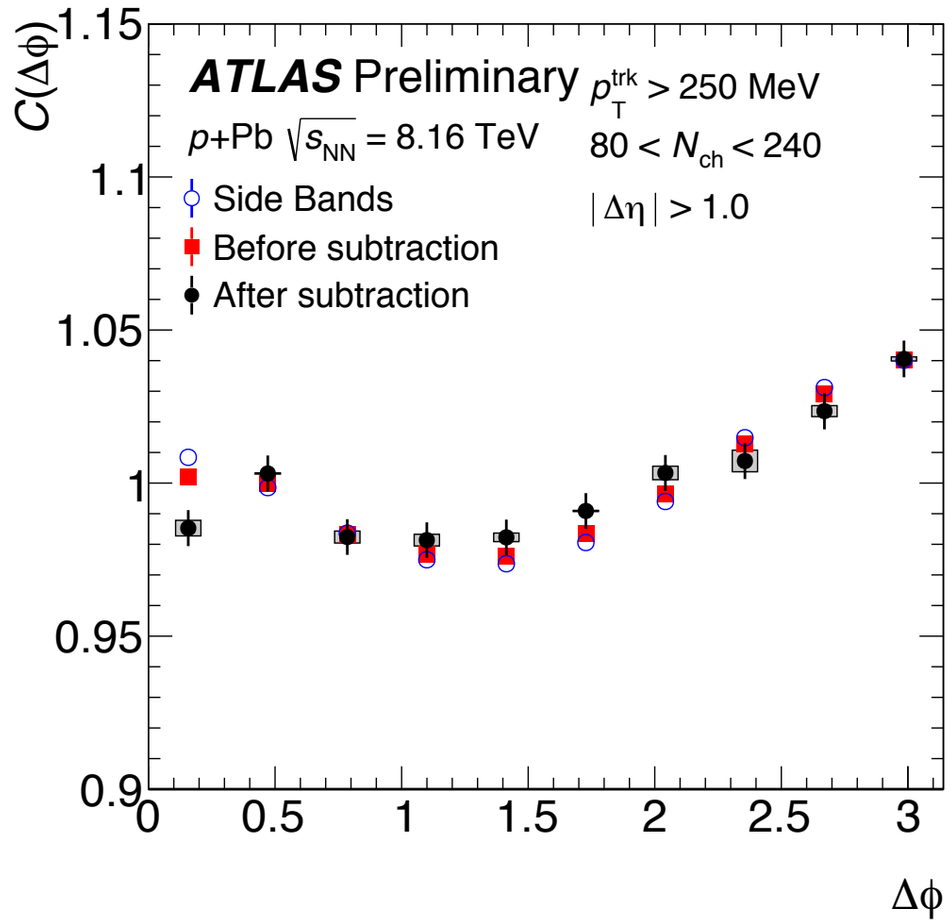
| Syst Uncertainty | Value |
|---|---|
| Peripheral bin | 25-15%: $N_{ch}^{rec} \in(60,100)$<br>15–10%: $N_{ch}^{rec} \in(100,150)$<br>10–6%: $N_{ch}^{rec} \in(150,300)$ |
| Background Muons | 16% |
| Trigger & Tracking Efficiency | 5% |
| Muon Selections | 2% |
| Pileup | 1%<: $N_{ch}^{rec}$<250<br>1-5%: $N_{ch}^{rec} \in(250,300)$ |
| Pair Acceptance | 1% |

**systematics for muon-hadron correlation**

# Sideband subtraction

$$C(\Delta\phi;\text{Signal}) = \frac{1}{f_{sig}} \cdot \{C(\Delta\phi;\text{Signal + Background}) - (1 - f_{sig})C(\Delta\phi;\text{Sideband})\}$$




Systematics:

- Statistical uncertainty in $f_{sig}$
- $N_{ch}$ dependence of $f_{sig}$
- $\Delta m$ dependence of sideband correlation