Recent results from ATLAS: Onia, heavy-flavor, and more

Martin Spousta
for the ATLAS Collaboration

Charles University
Prague

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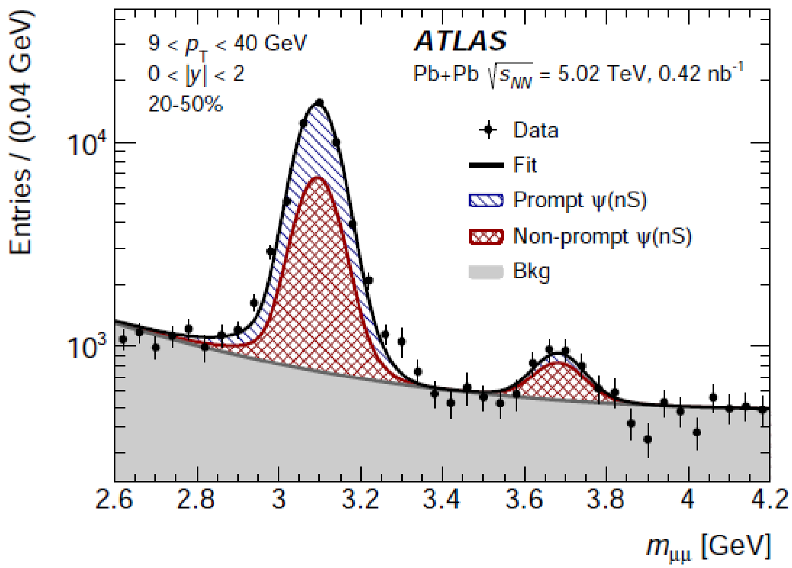
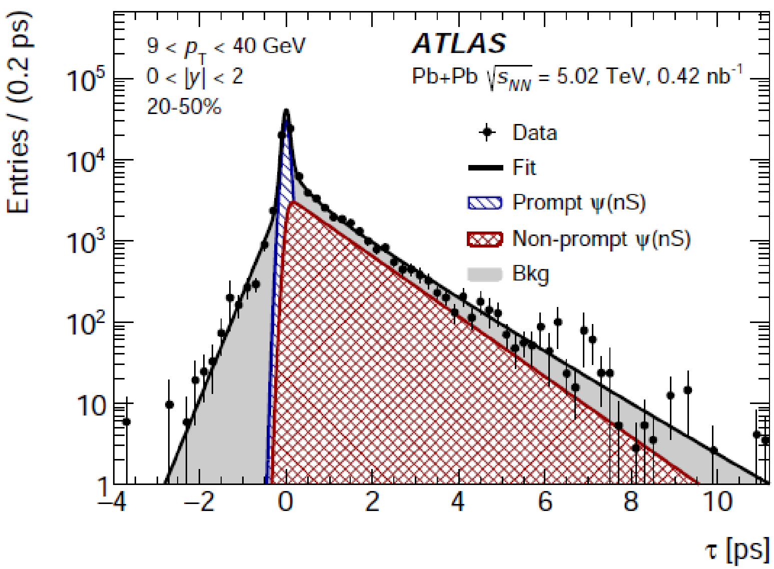
Charmonia, upsilon and heavy flavor

- Brief motivation
  - Pb+Pb: heavy quarks produced early => can help to understand transport properties of the plasma, role of the mass in the high-pt suppression, ...
  - p+Pb: initial state effects (energy loss of incoming partons, nPDFs, ...)
- Summary of results
  - J/ψ and ψ(2S) production in 5.02 TeV Pb+Pb and *pp* [EPJC 78 (2018) 762]
  - J/ψ elliptic flow in 5.02 TeV Pb+Pb [EPJC 78 (2018) 784]
  - R_{AA} and v_2 of muons from heavy-flavor decays in 2.76 TeV Pb+Pb [PRC 98 (2018) 044905]
  - Quarkonia production in 5.02 TeV p+Pb and *pp* [EPJC 78 (2018) 171]
  - D meson production in p+Pb collisions [ATLAS-CONF-2017-073]
  - Muon-hadron correlations in p+Pb collisions [ATLAS-CONF-2017-006]

Quarkonia in **Pb+Pb**

EPJC 78 (2018) 762

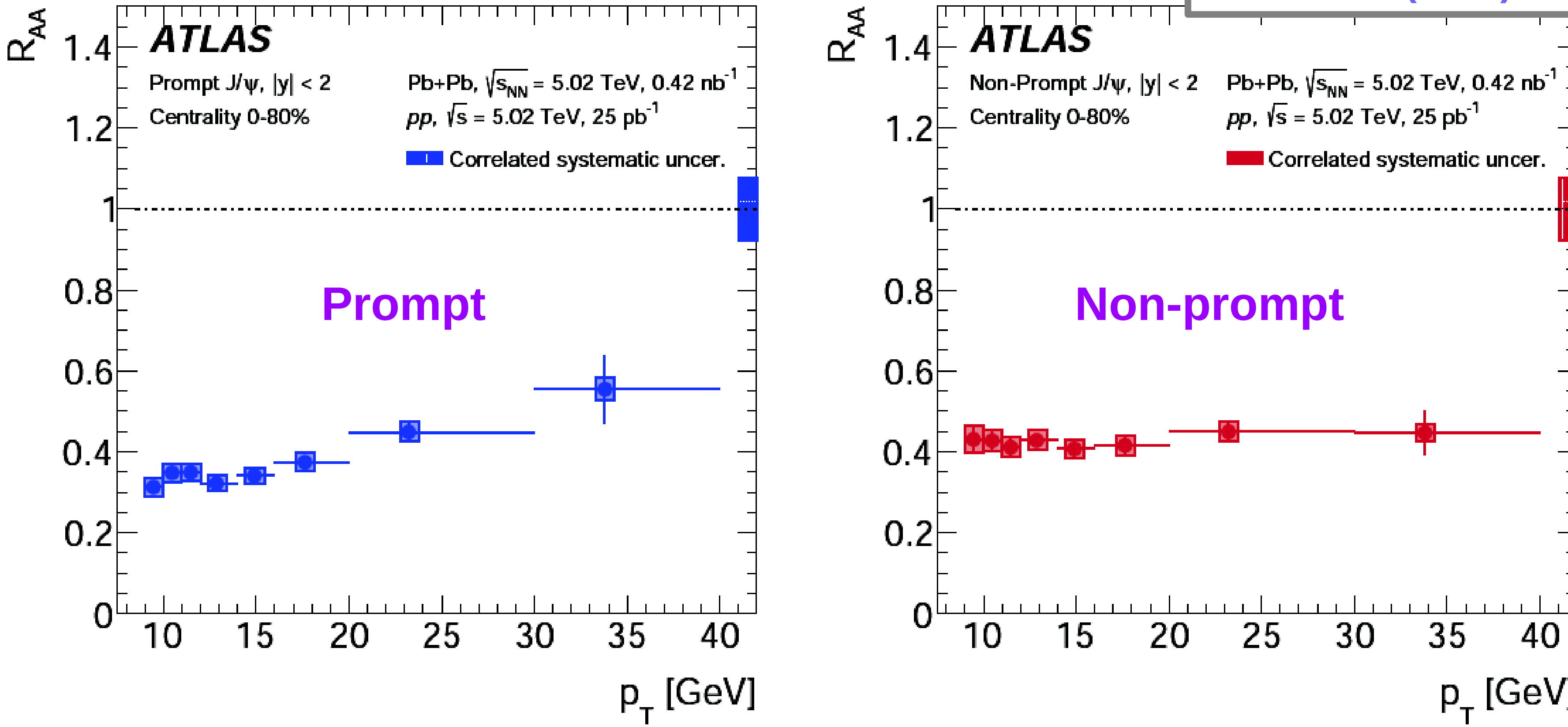




- J/ψ and ψ(2S) in dimuon channel.
- p_T = 9 – 40 GeV, |y| < 2, $\sqrt{s_{NN}}$ = 5.02 TeV.
- Yields from 2D unbinned maximum likelihood fits in $m_{\mu\mu}$ and pseudo-proper decay time τ.
- Prompt and non-prompt (from b-decays) component separated.

Suppression of J/ψ in **Pb+Pb**

EPJC 78 (2018) 762

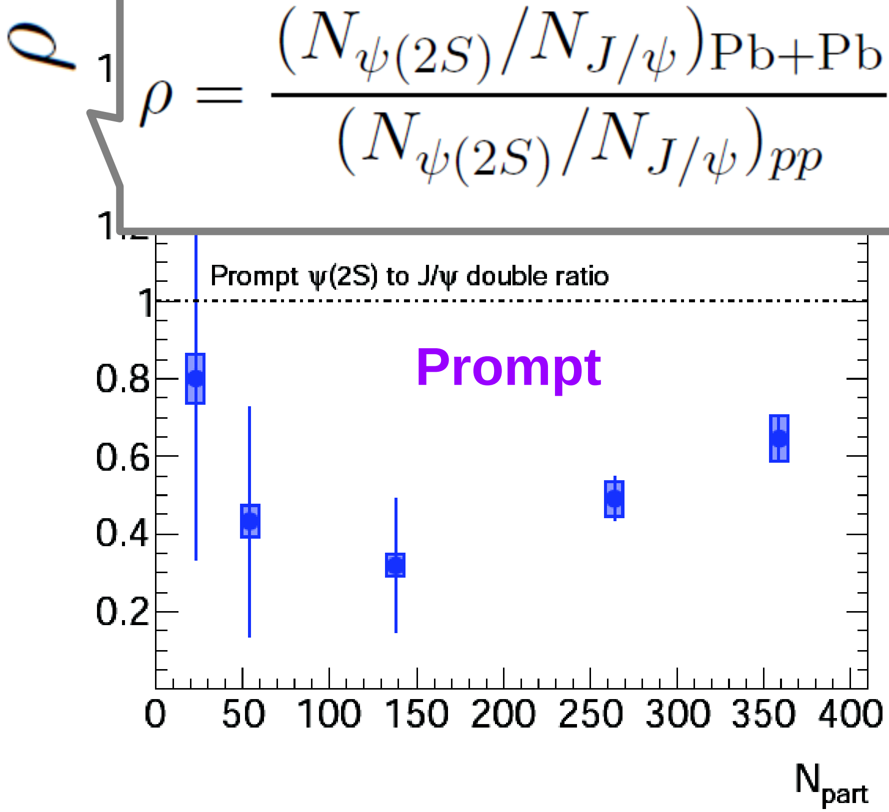


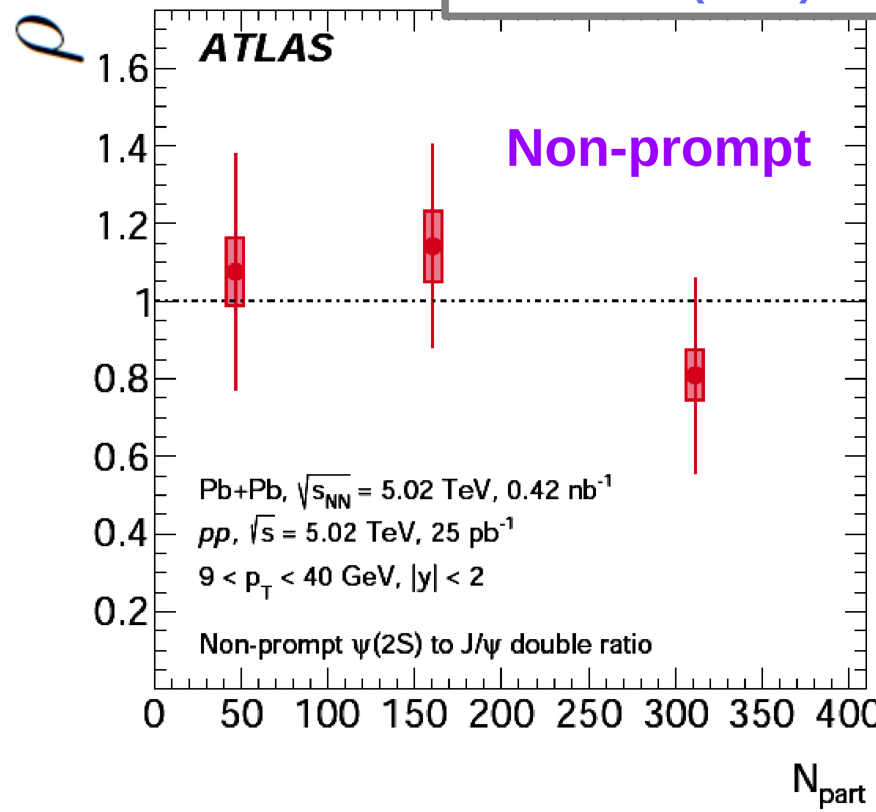
- **Similar suppression** of prompt and non-prompt J/ψ.
- No significant dependence of suppression on rapidity over |y|<2 (not shown).
- No centrality dependence of non-prompt fraction (not shown).

Suppression of ψ(2S) in **Pb+Pb**

EPJC 78 (2018) 762

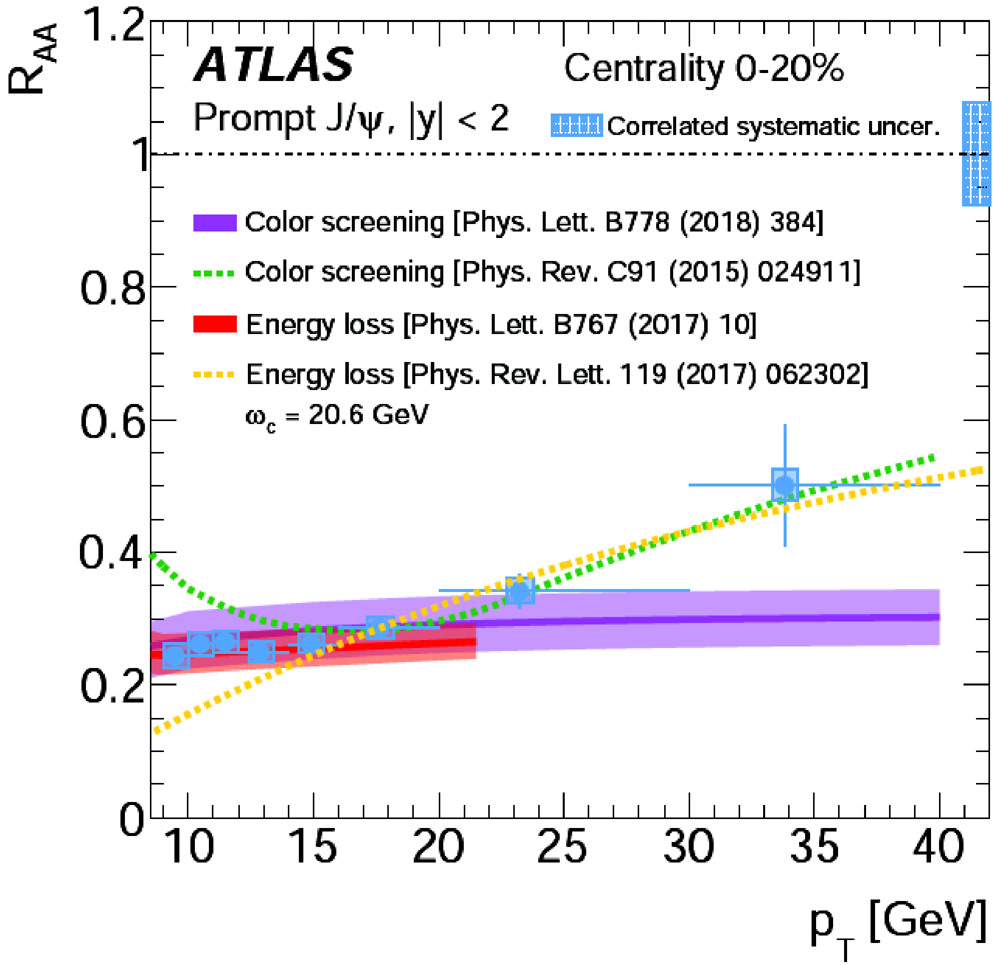
$$\rho = \frac{(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{Pb+Pb}}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}}$$





- **Prompt ψ(2S)** suppressed by a factor of **~2 more** than prompt J/ψ. (expected e.g. from different binding energies)
- **Non-prompt ψ(2S)** exhibits **similar suppression** as non-prompt J/ψ. (expected e.g. from B-hadron decaying outside of the medium)

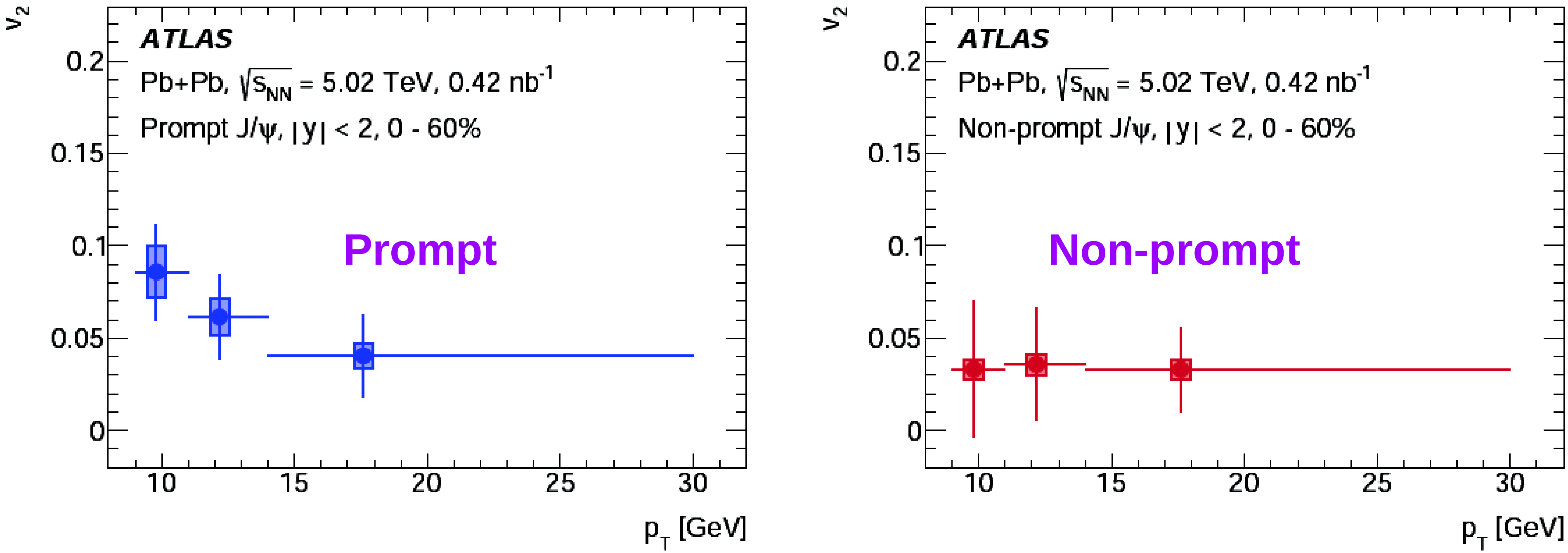
… theory comparison



- Color screening versus energy loss.
- Both of these different mechanisms can reproduce observed suppression, but not in the full range of measurement.
- More precision at high-p_T should allow to discriminate among mechanisms.

Flow of J/ψ in **Pb+Pb**

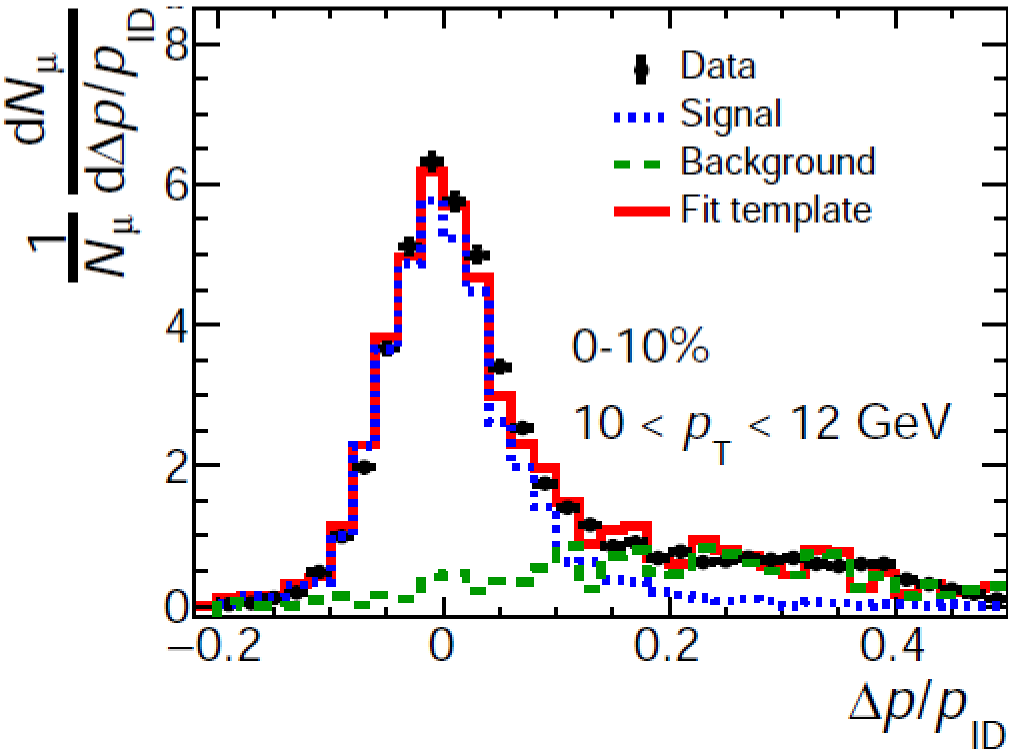
EPJC 78 (2018) 762



- Decreasing v_2 with increasing p_T for prompt J/ψ.
- No significant rapidity and centrality dependence seen (not shown).
- At high-p_T **similar v_2** between prompt and non-prompt => similar suppression mechanism at high-p_T?

Heavy flavor muons

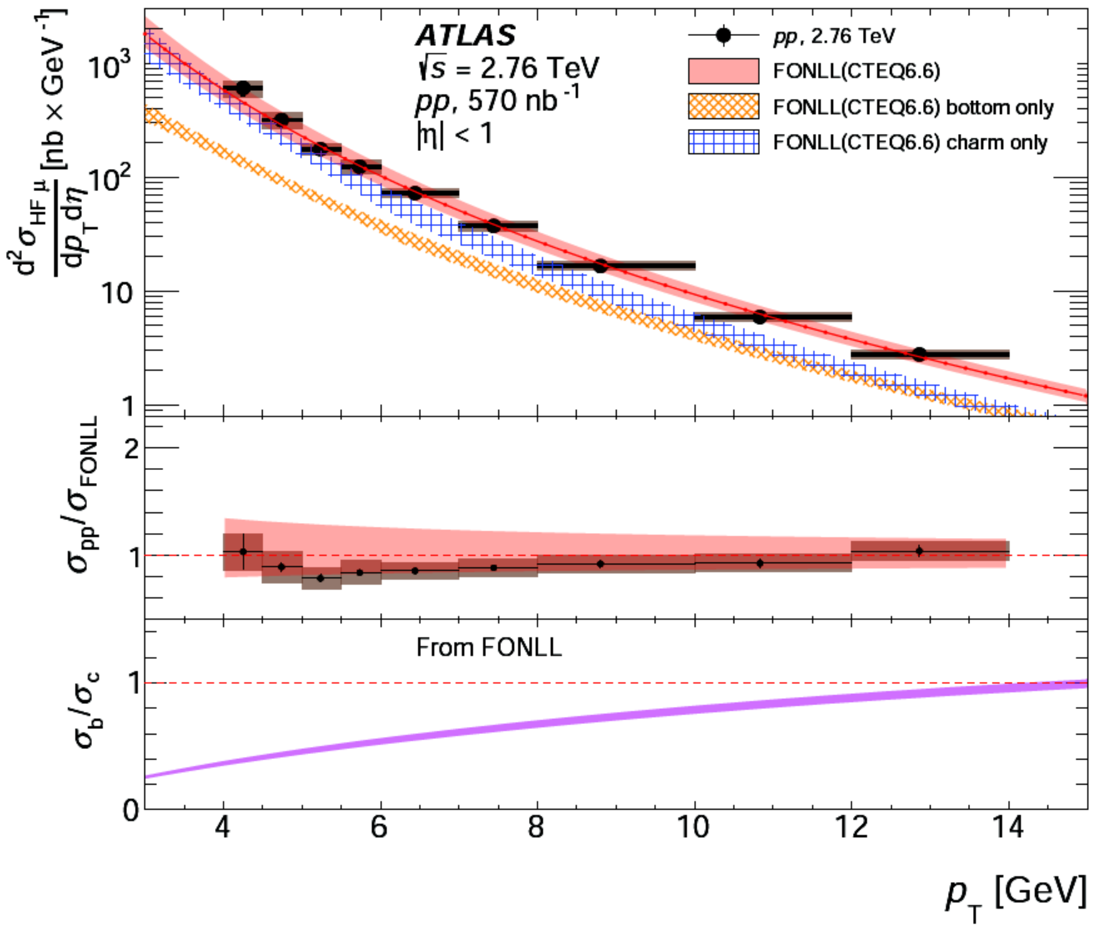
PRC 98 (2018) 044905



- Heavy flavor muons from template fits using **momentum imbalance** between inner detector and muon spectrometer to separate background (π, K decays, hadronic interaction)
- 2.76 TeV *pp* and Pb+Pb collisions
- 4 < p_T < 14 GeV
- Non-heavy flavor contamination (e.g. J/ψ) < 1%
- Flow coefficients v_2 – v_4 measured using Event Plane and Scalar Product methods

Heavy flavor muons in **pp**

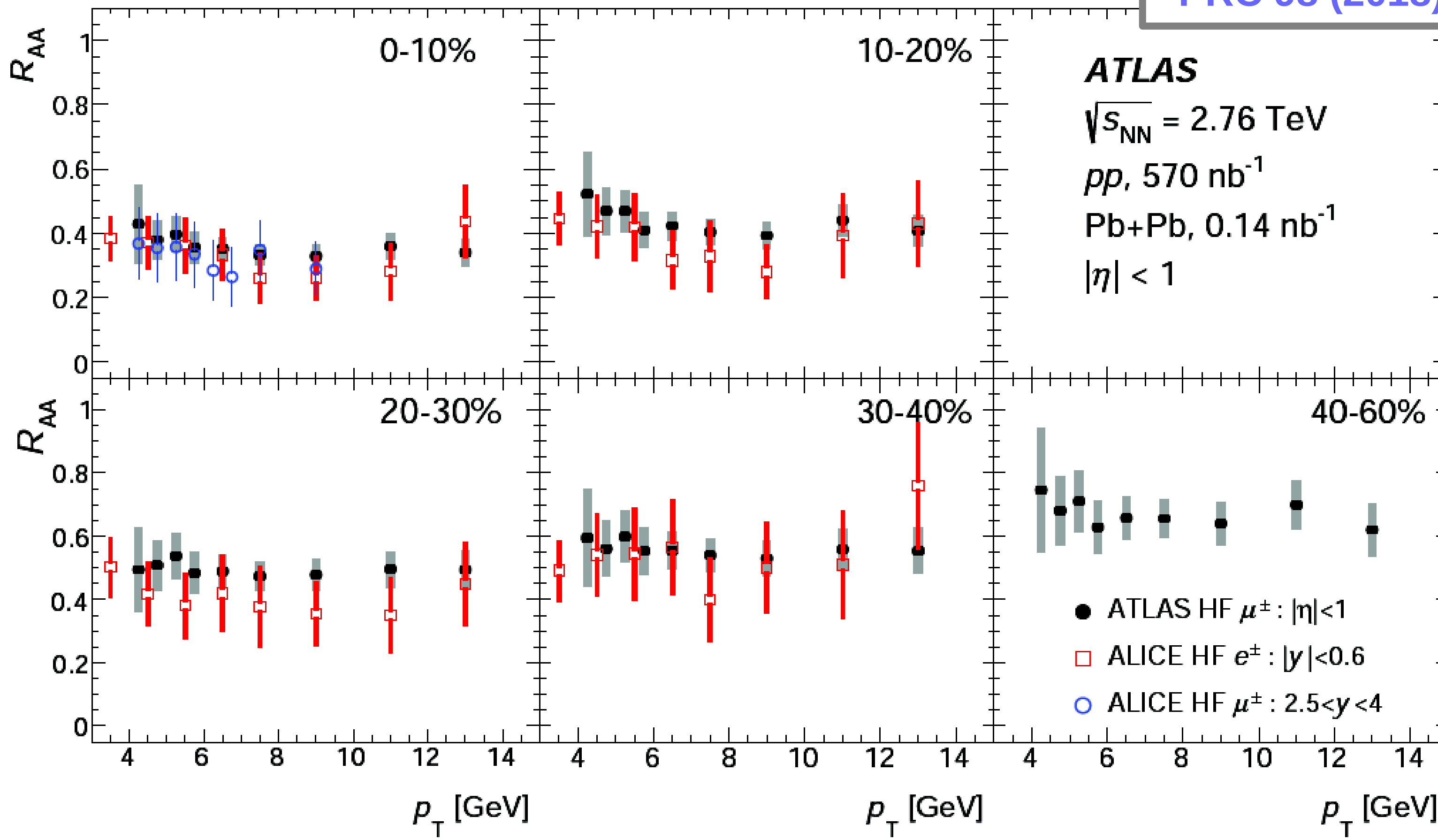
PRC 98 (2018) 044905



- Measured cross-section **consistent with FONLL** calculations
- Significant **variation of c/b** ratio in the kinematic window of the measurement

Suppression of HF muons in Pb+Pb

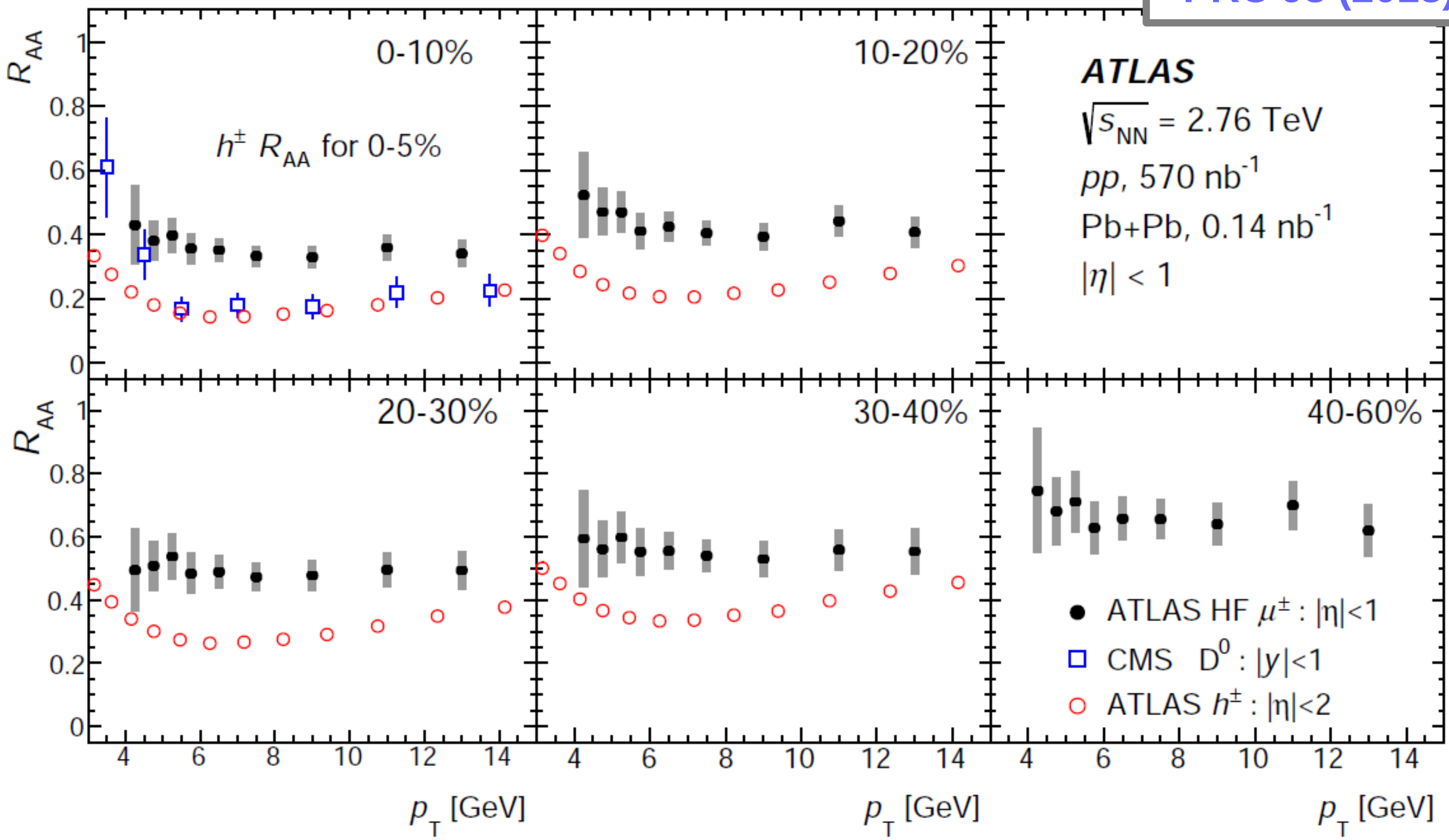
PRC 98 (2018) 044905



- Significant suppression, flat with p_T
- Consistent with ALICE measurements

Suppression of HF muons in Pb+Pb

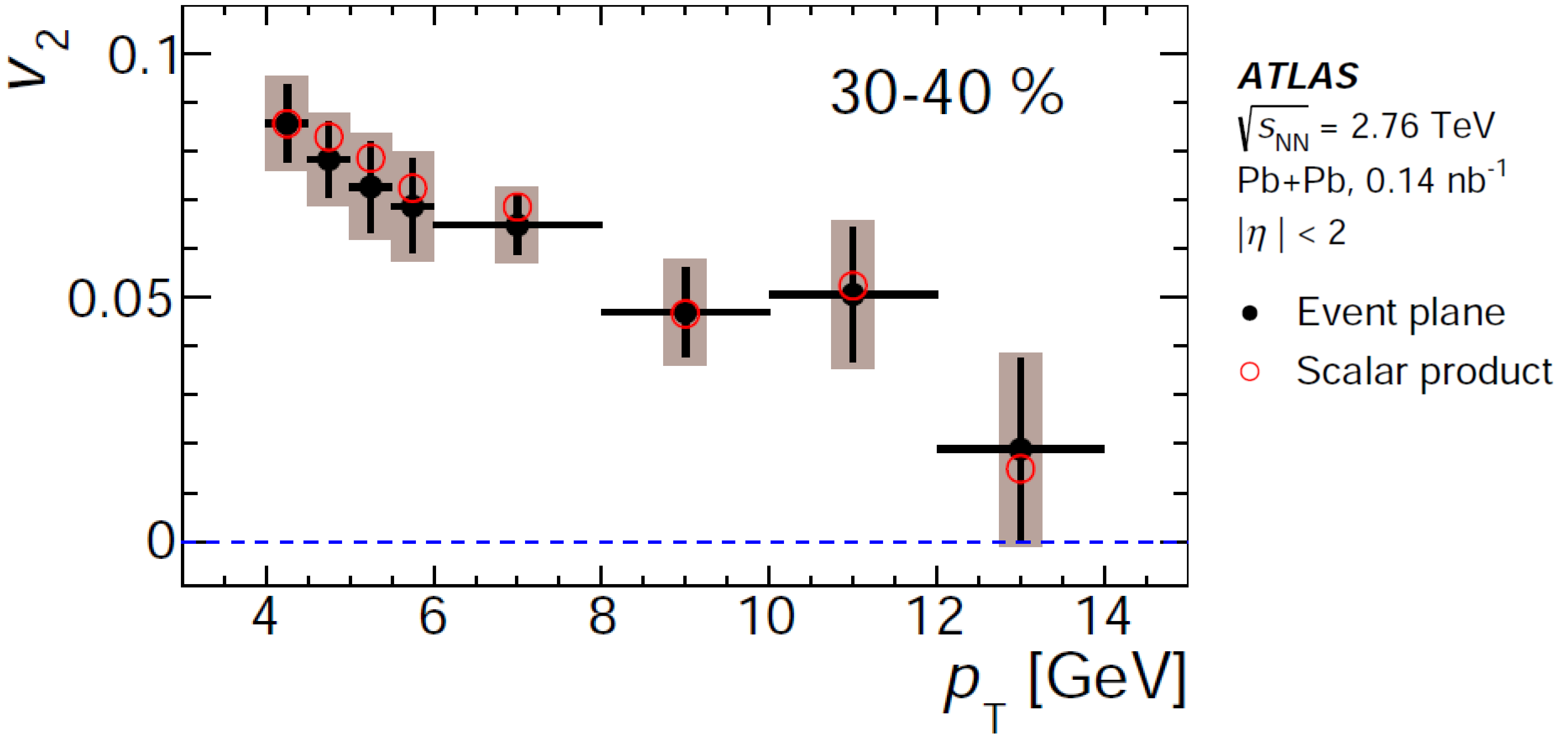
PRC 98 (2018) 044905



- HF significantly less suppressed compared to D^0 and inclusive hadrons.
- Different initial parton p_T? Different suppression mechanism?

Flow of HF muons in **Pb+Pb**

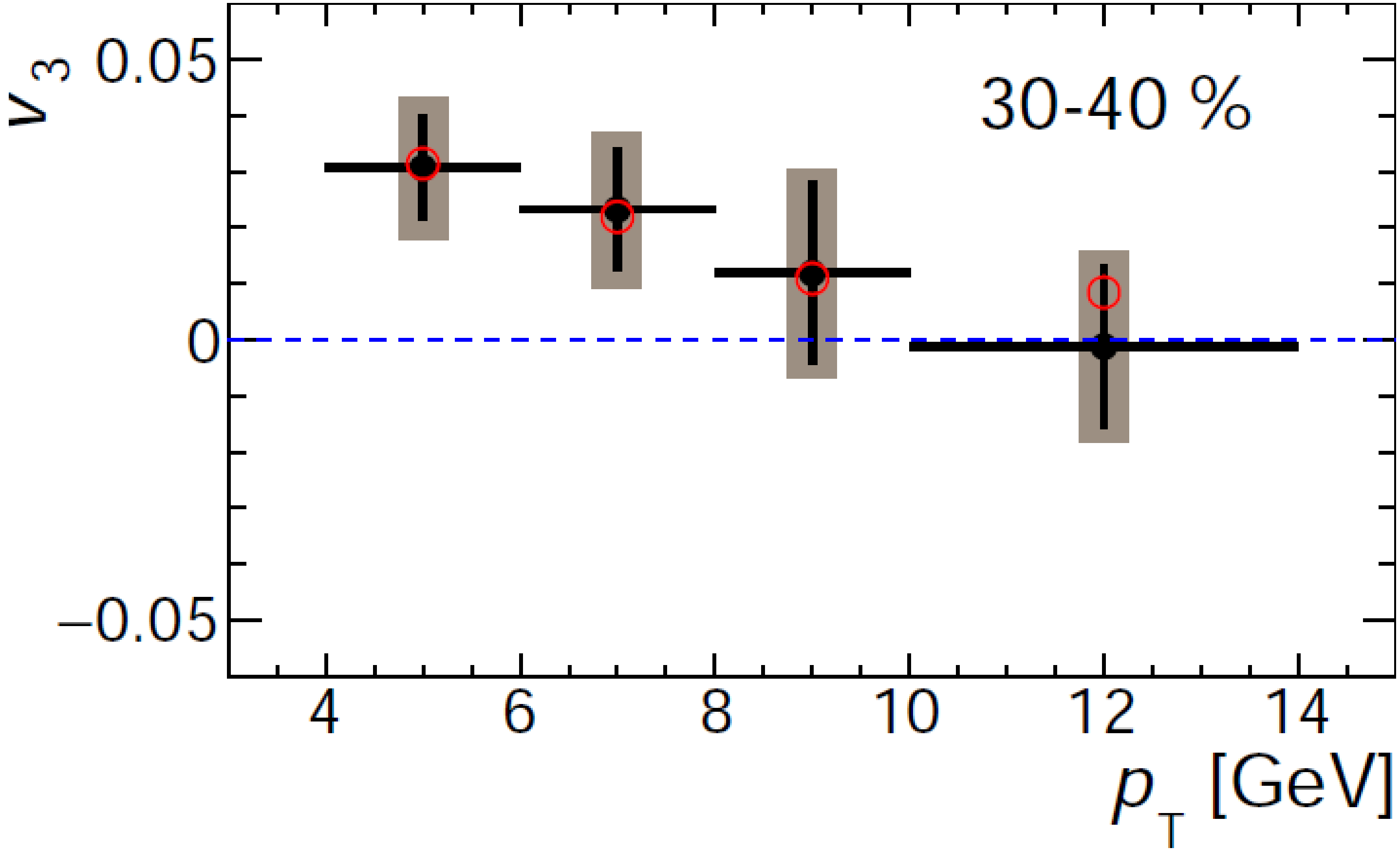
PRC 98 (2018) 044905



- Non-zero v_2 up to 14 GeV
- Similar trends (p_T, centrality dependence) but smaller magnitude compared to inclusive hadrons

Flow of HF muons in **Pb+Pb**

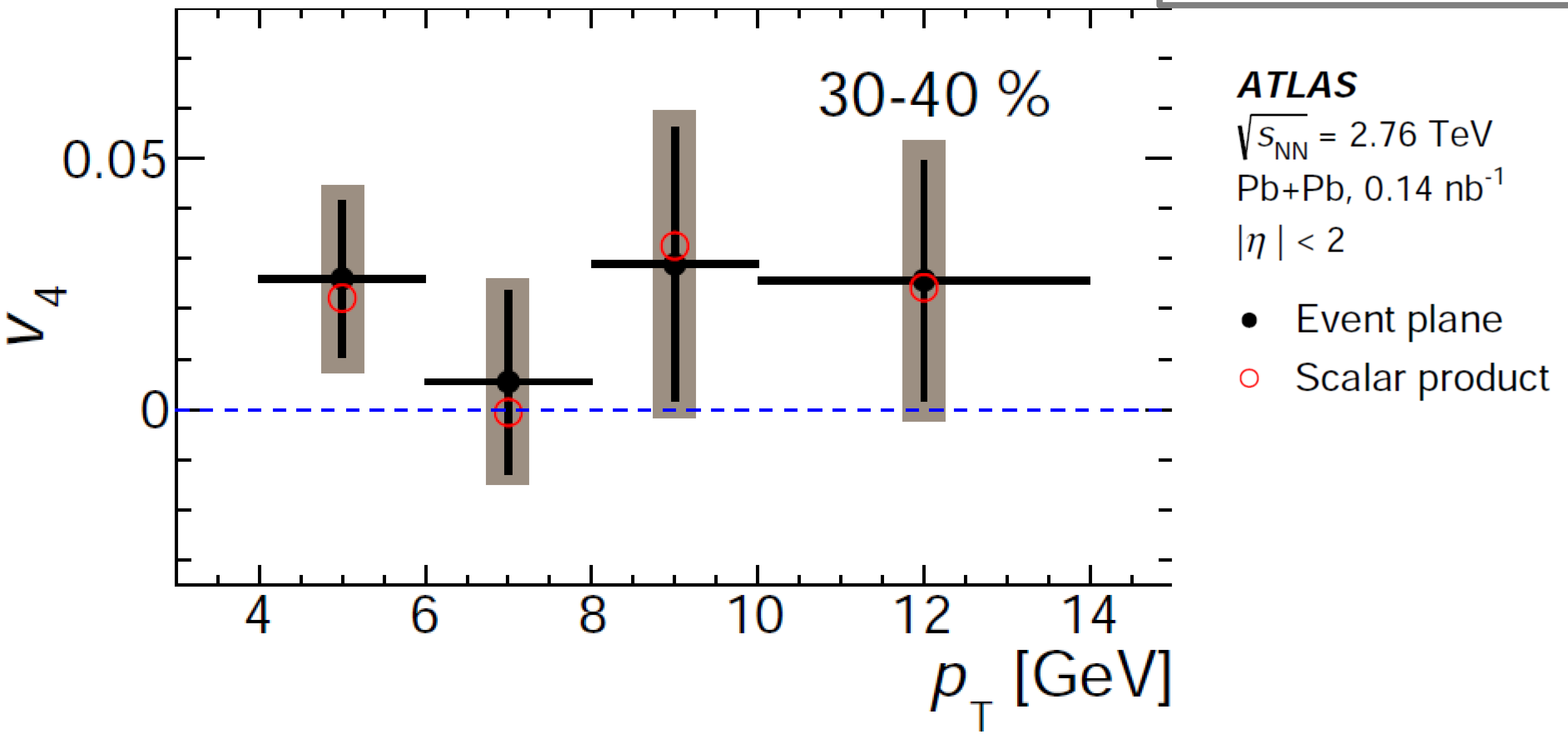
PRC 98 (2018) 044905



- Weak dependence on centrality
- Similar trends (p_T, centrality dependence) but smaller magnitude compared to inclusive hadrons

Flow of HF muons in **Pb+Pb**

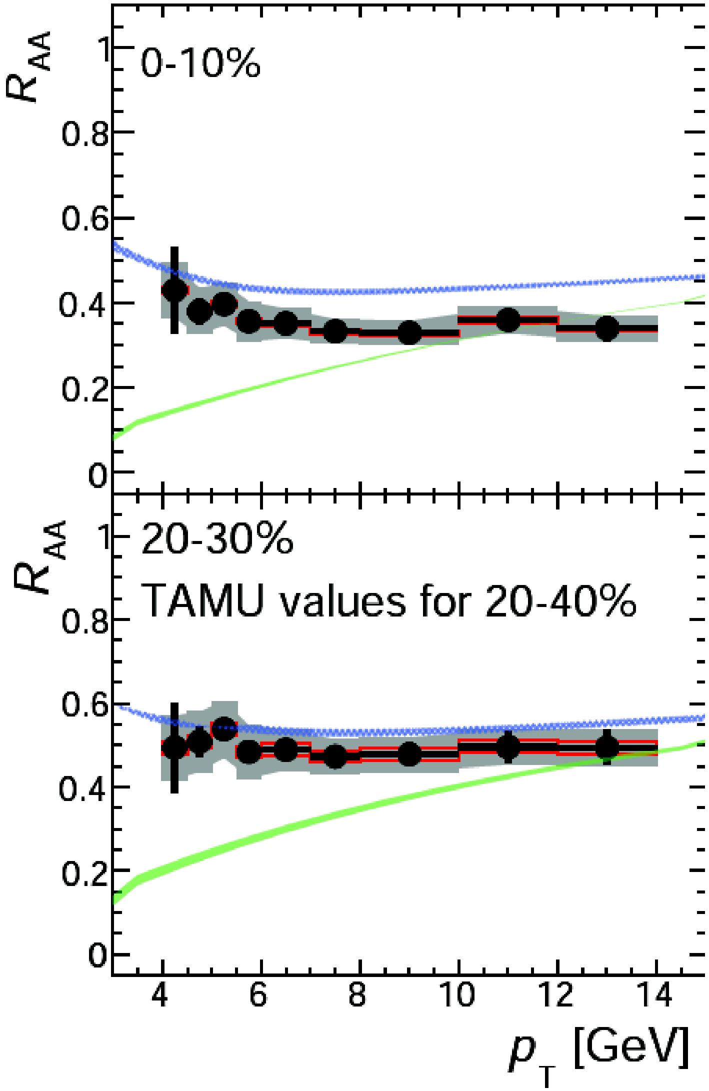
PRC 98 (2018) 044905

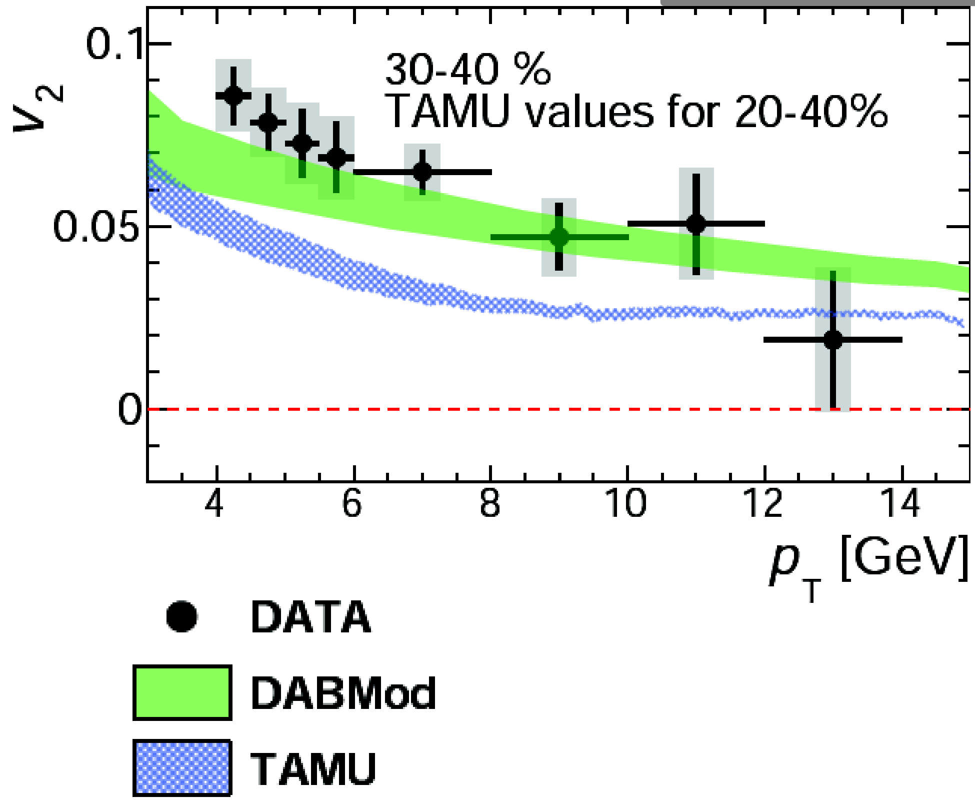


- Uncertainties do not allow to distinguish trends.

… theory comparison

PRC 98 (2018) 044905



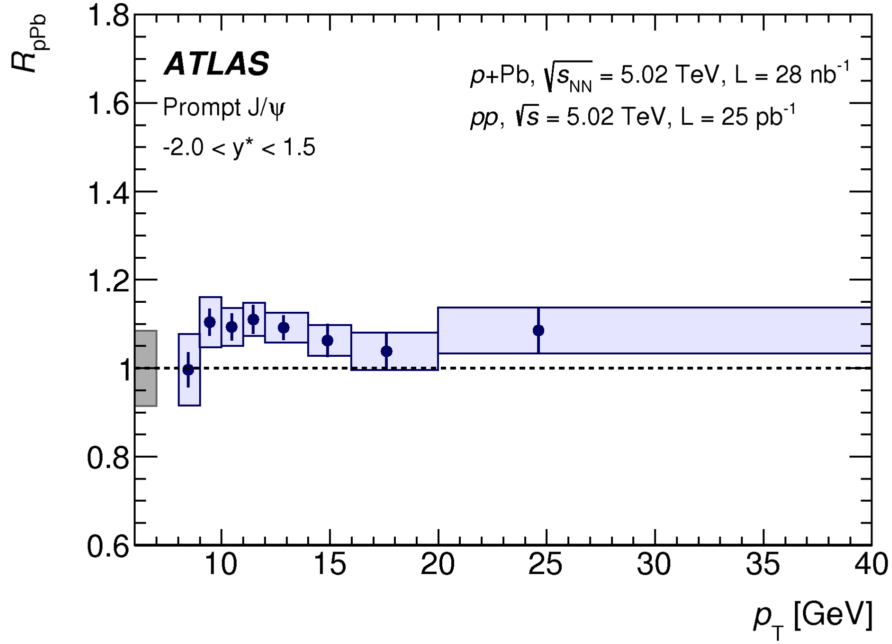


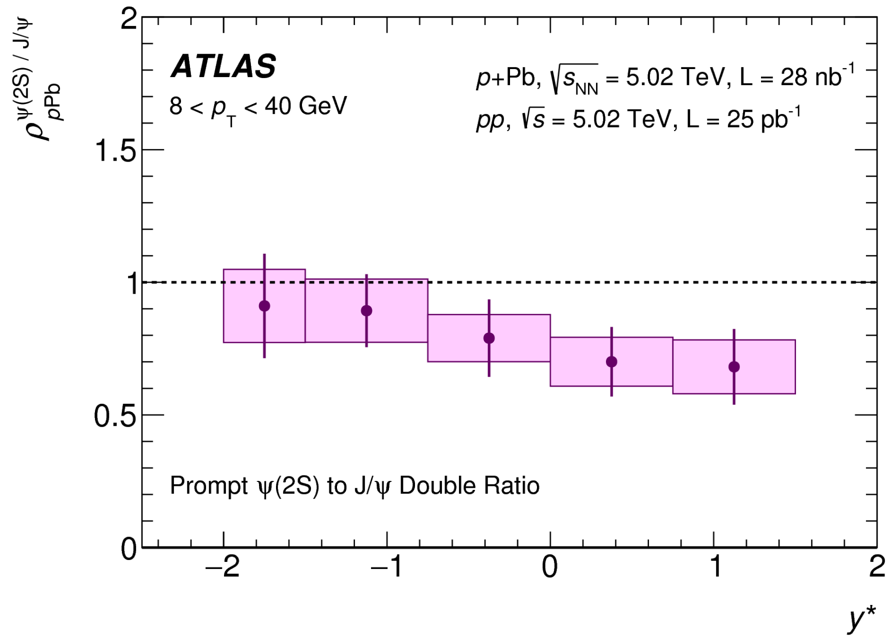
… neither Transport model (TAMU) nor Energy loss model (DABMod) successful in reproducing both the R_{AA} and v_2

Quarkonia in **p+Pb**

~ ratio of R_{pPb}

EPJC 78 (2018) 171



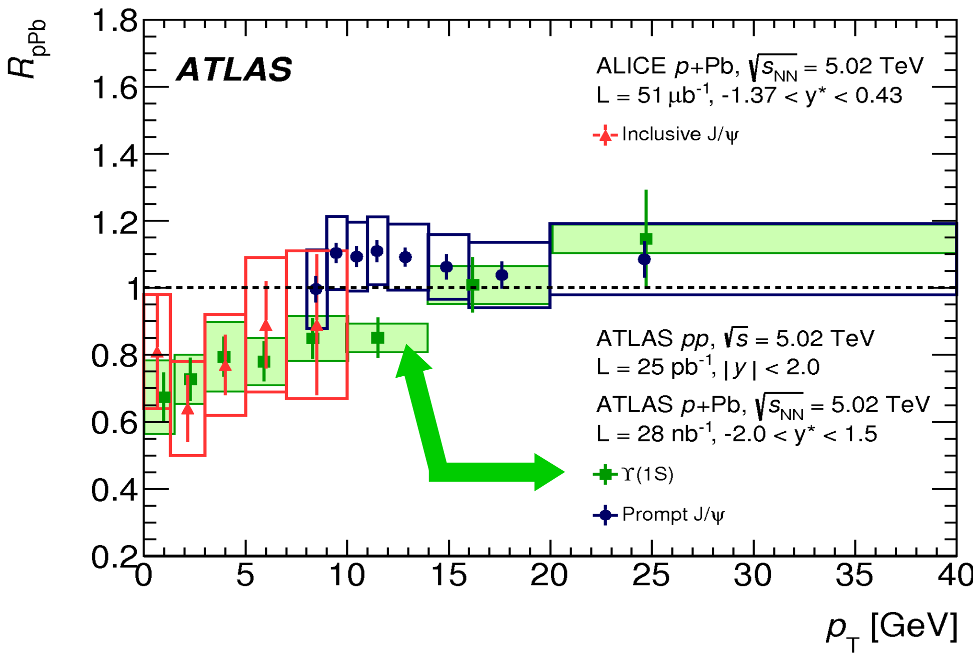


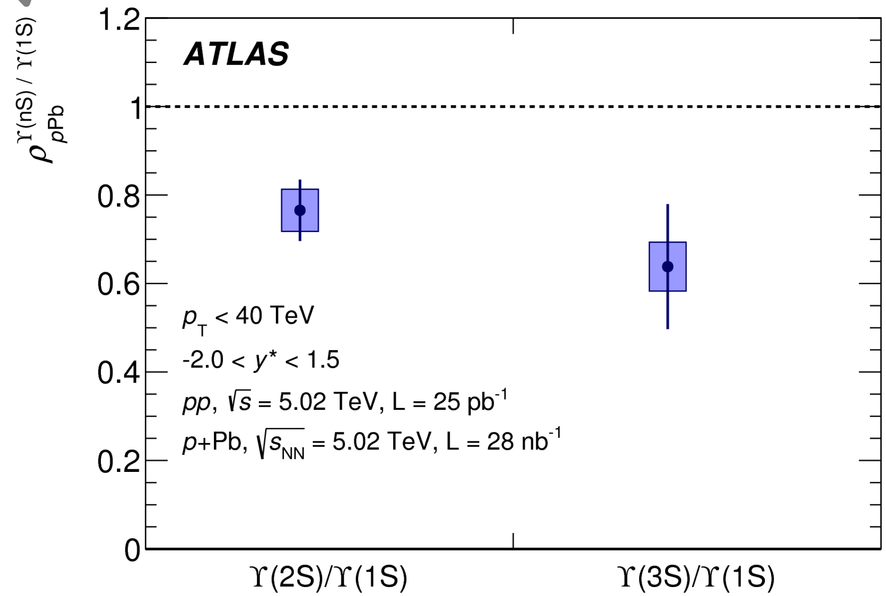
- J/ψ R_{pPb} consistent with unity, **ψ(2S) suppressed** wrt J/ψ (1σ).
- Prompt and non-prompt J/ψ, ψ(2S), cross-sections **consistent with NRQCD and FONLL** predictions, respectively (not shown).

Quarkonia in **p+Pb**, 5.02 TeV

~ ratio of R_{pPb}

EPJC 78 (2018) 171



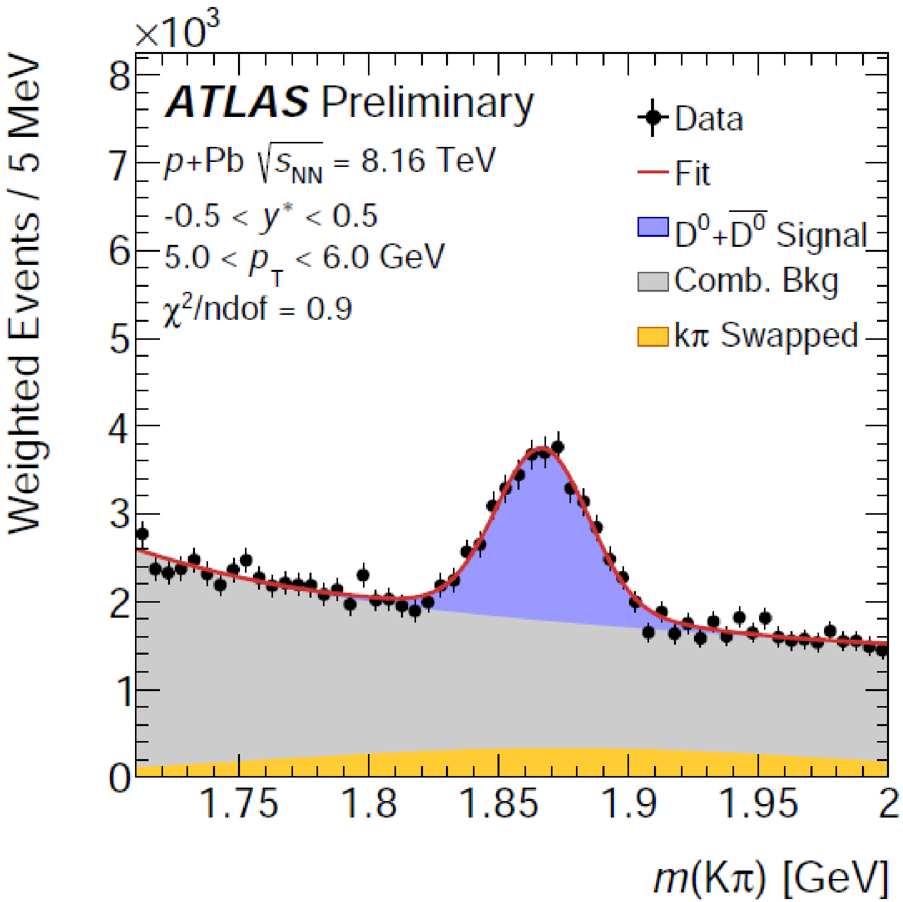


- ϒ(1S) suppressed at low-p_T.
- ϒ(2S),ϒ(3S) suppressed with respect to ϒ(1S).

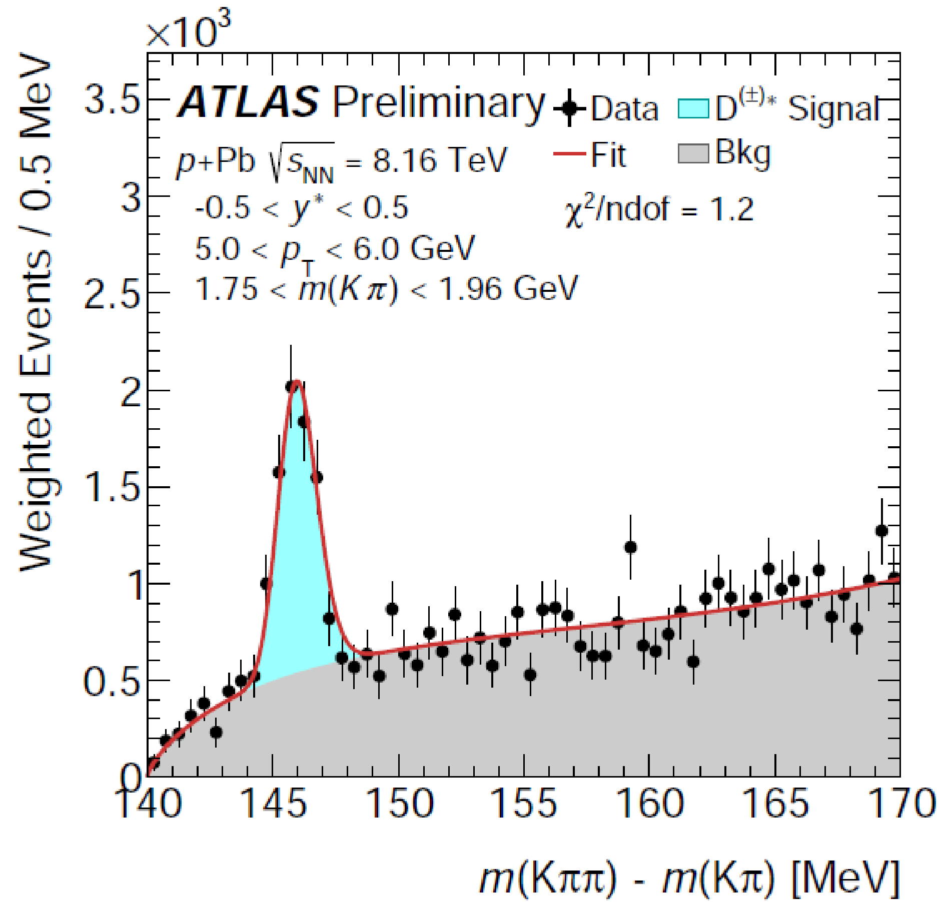
D meson in **p+Pb**, 8.16 TeV

ATLAS-CONF-2017-073

$D^0 + \overline{D^0}$

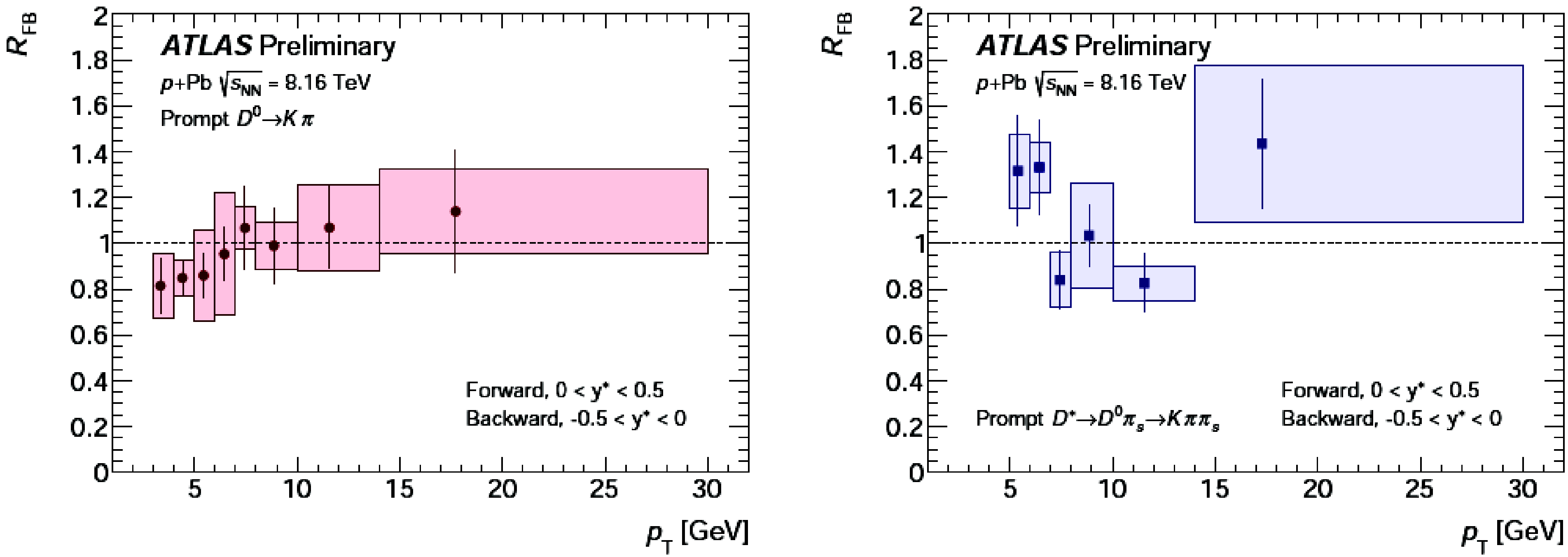


$D^{(\pm)*}$



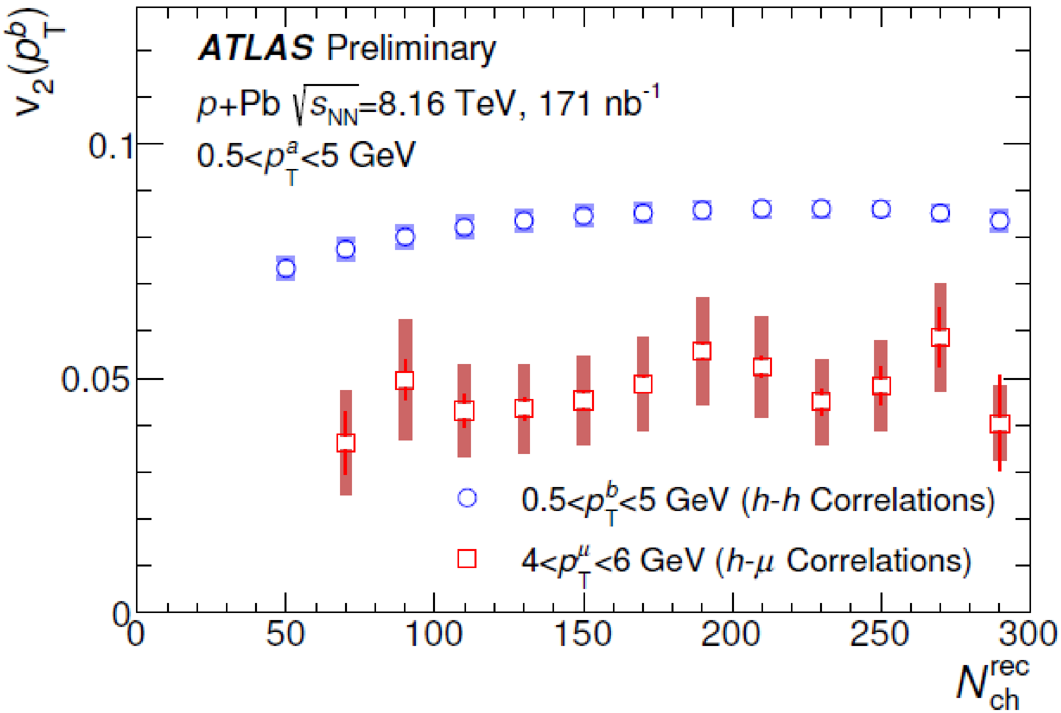
D meson in **p+Pb**, 8.16 TeV

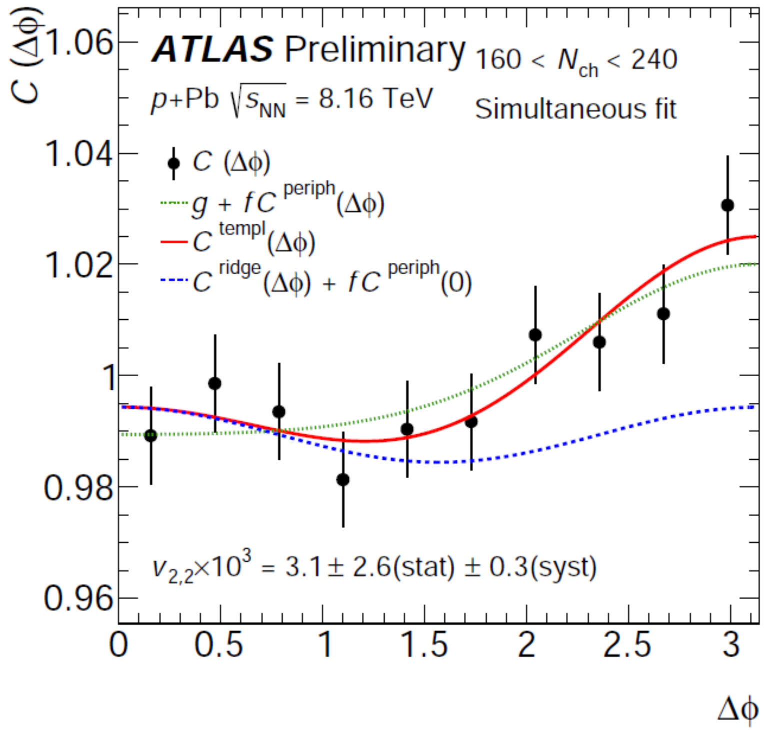
ATLAS-CONF-2017-073



- Forward-backward ratio, **R_{FB} consistent with unity** for both D^0 and D*.
- Cross-sections **consistent with FONLL** predictions (not shown).

Flow of heavy flavor in **p+Pb**





- Flow also present **for heavy flavor**:
  - muon-hadron correlations
  - D*-hadron correlations
- Extracted from long-range two-particle correlations (ridge)

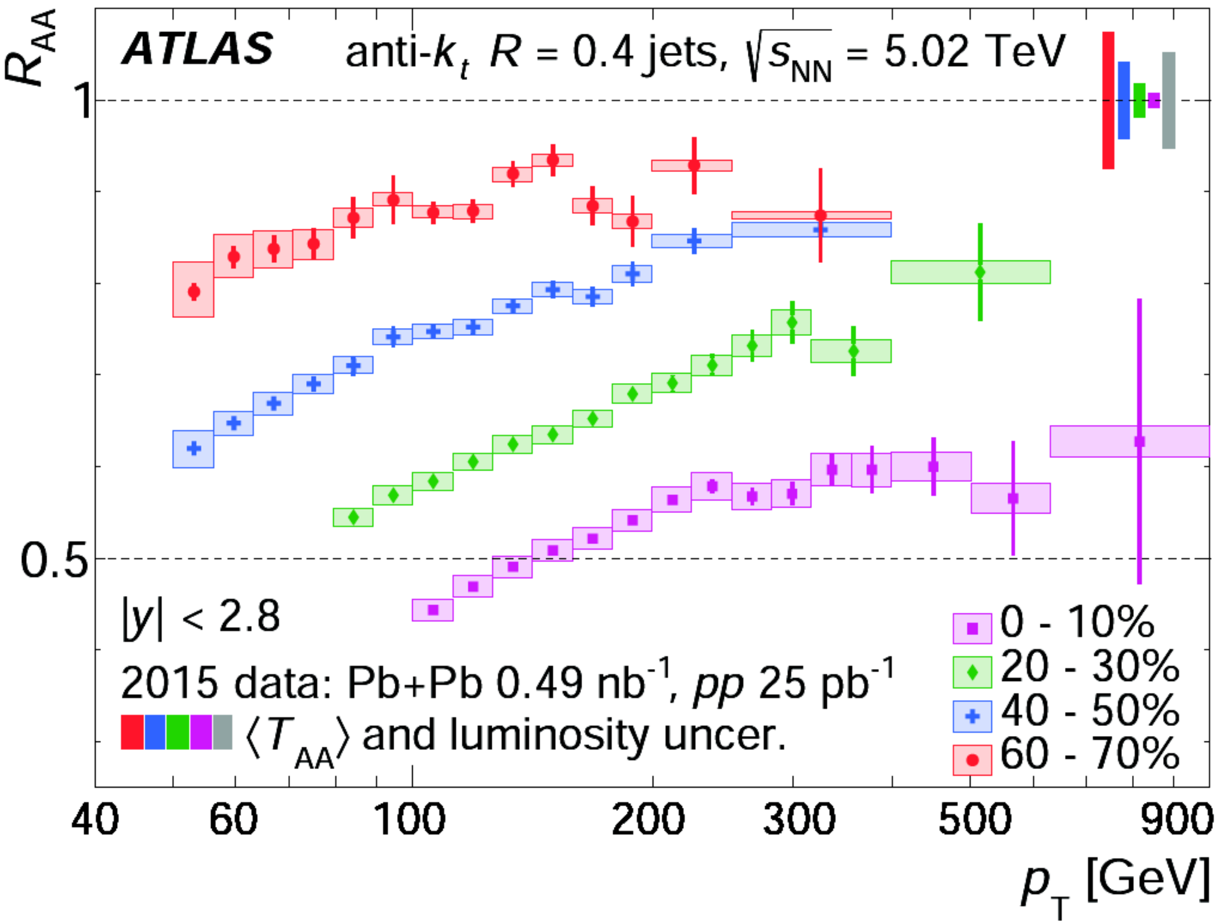
ATLAS-CONF-2017-073

ATLAS-CONF-2017-006

Other highlights: Jets

Jet R_{AA}

PLB 790 (2019) 108-128

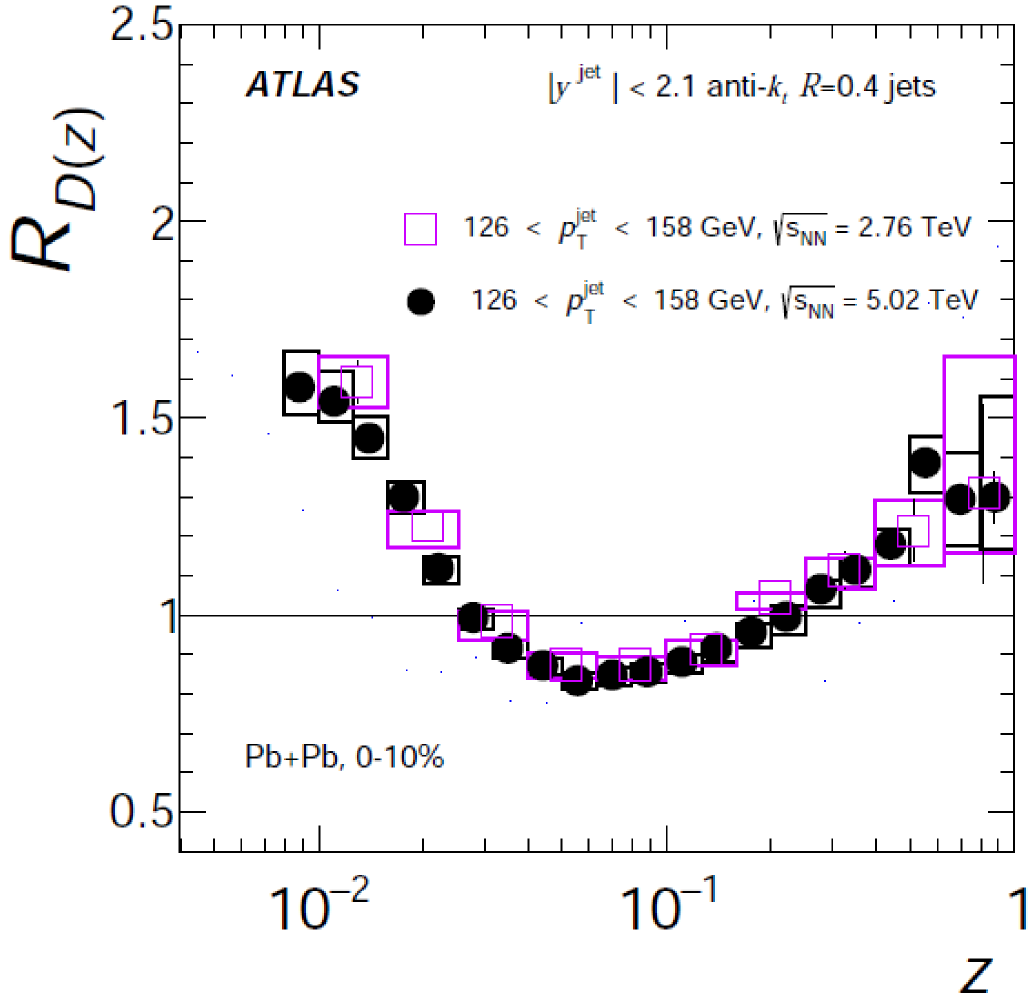


- Jet R_{AA} in 5.02 TeV data.
- Central collisions (0-10%): R_{AA} ~ 0.6 **up to TeV scale**.
- Peripheral collisions (60-70%): still significant suppression.
- More suppression in the forward region (not shown).
- No $\sqrt{s_{NN}}$ dependence (not shown).

Internal structure of jets

PRC 98 (2018) 024908

EPJC 77 (2017) 379

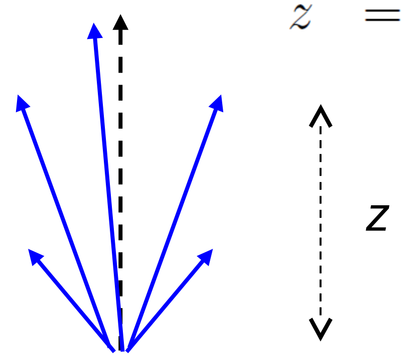


- Precision measurements of fragmentation functions

$$R_{D(z)} = \frac{D(z)|_{cent}}{D(z)|_{pp}}$$

$$D(z) = \frac{1}{N_{jet}} \frac{dN}{dz}$$

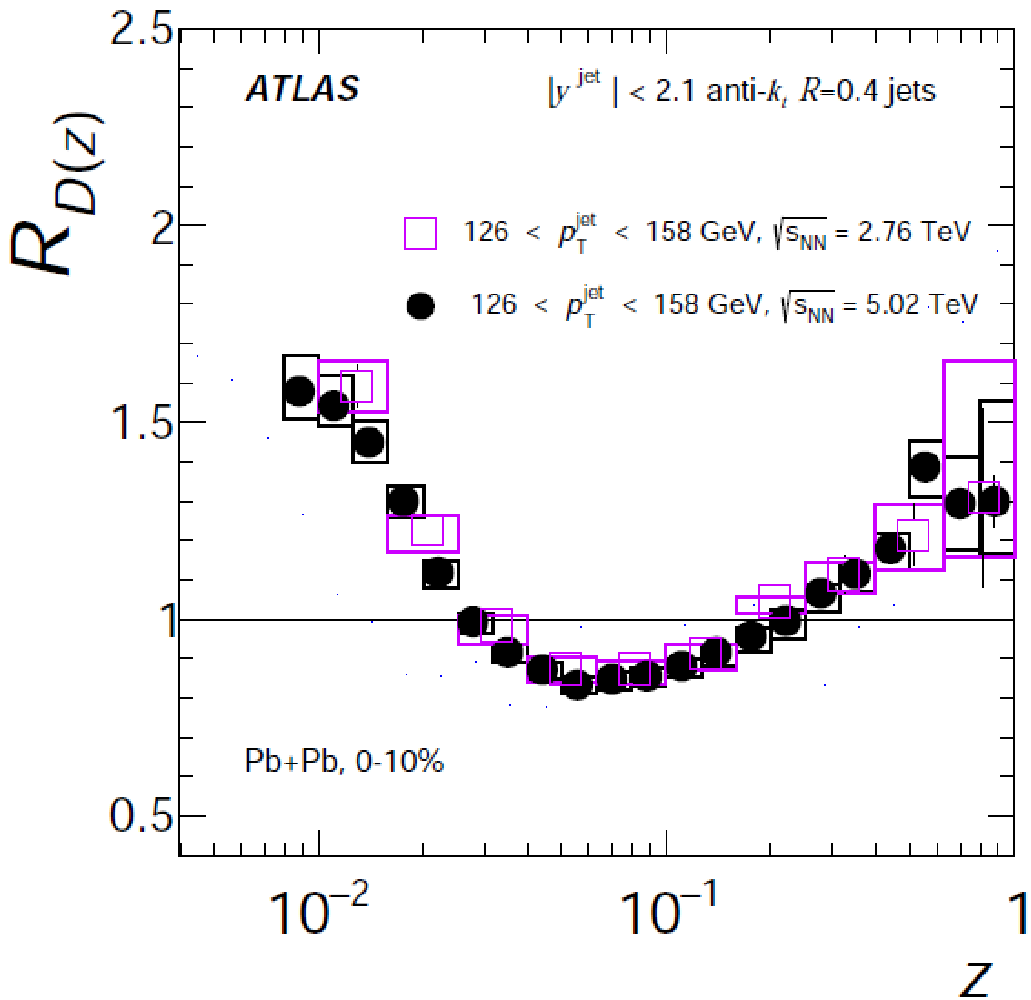
$$z = \frac{p_T}{p_T^{jet}} \cos \Delta R$$



Internal structure of jets

PRC 98 (2018) 024908

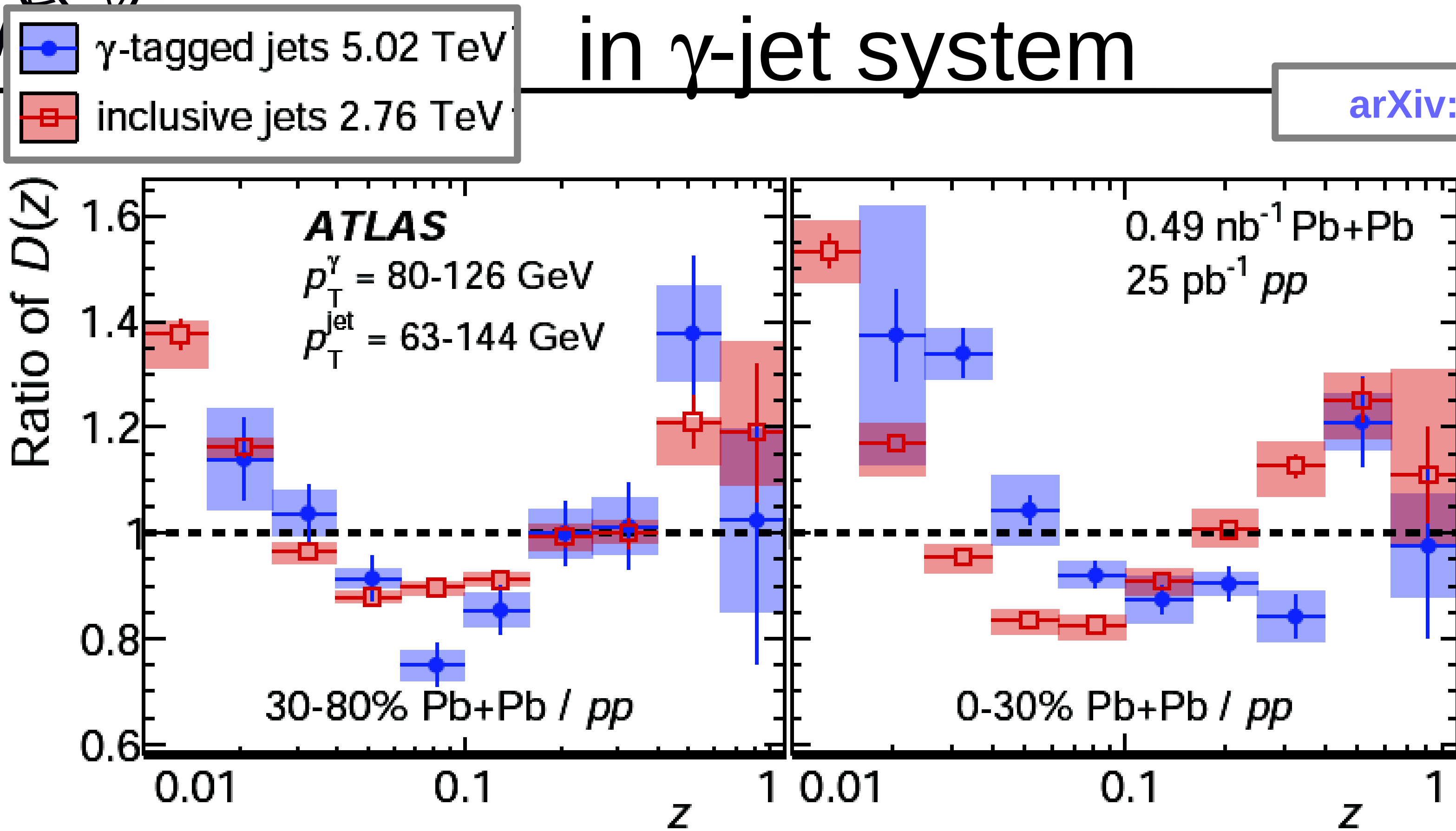
EPJC 77 (2017) 379



- Precision measurements of fragmentation functions
- **Enhancement** at low z and at high z, **suppression** at intermediate z
- Result **fully corrected** to particle level
- **No √s** dependence
- **No $p_{T,jet}$** dependence observed (not shown)
- Also done in γ-jet system ...

Internal structure of jets in γ-jet system

arXiv: 1902.10007

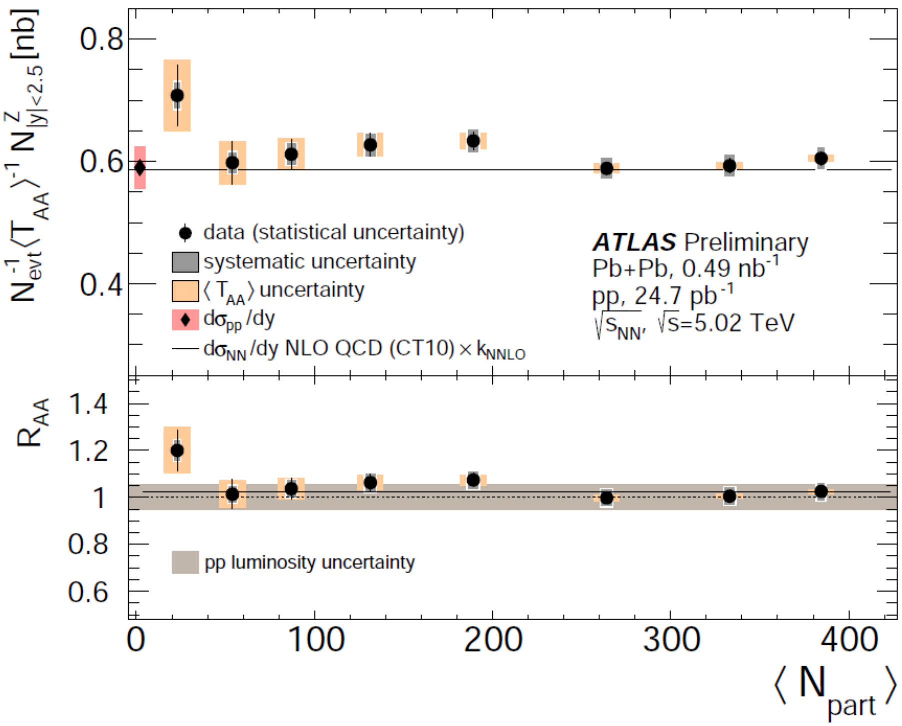


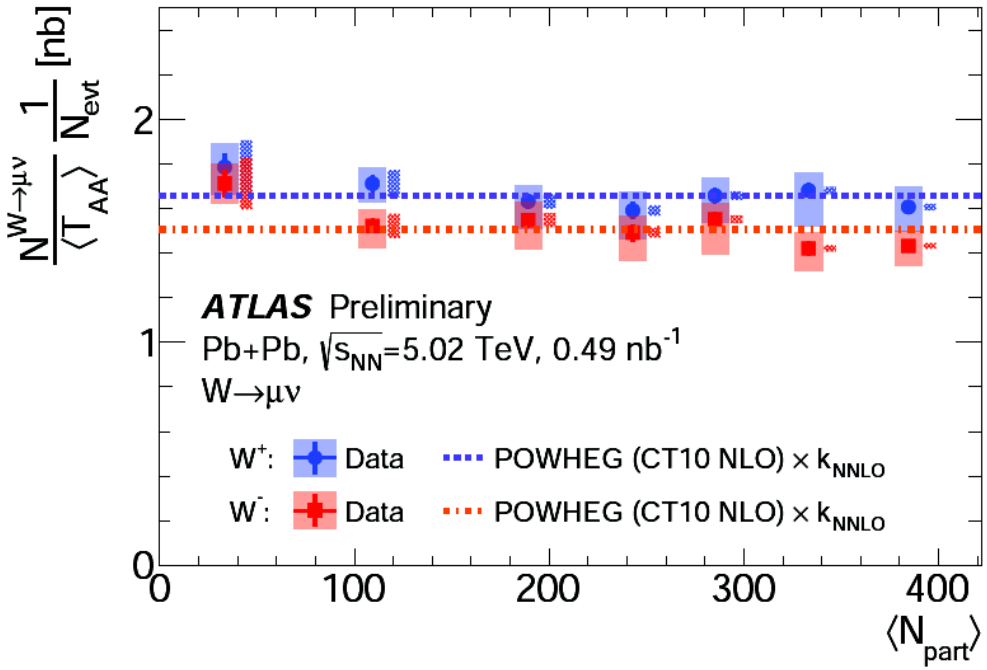
- Photon-tagged jet fragmentation: **quark/gluon dependence**.
- More peripheral bin: ratios similar between photon-tagged and inclusive.
- **Central bin: ratios different** between photon-tagged and inclusive.
- Result **fully corrected** to particle level.

Other highlights: Electroweak bosons

Z & W in Pb+Pb, 5.02 TeV

ATLAS-CONF-2017-010
ATLAS-CONF-2017-067

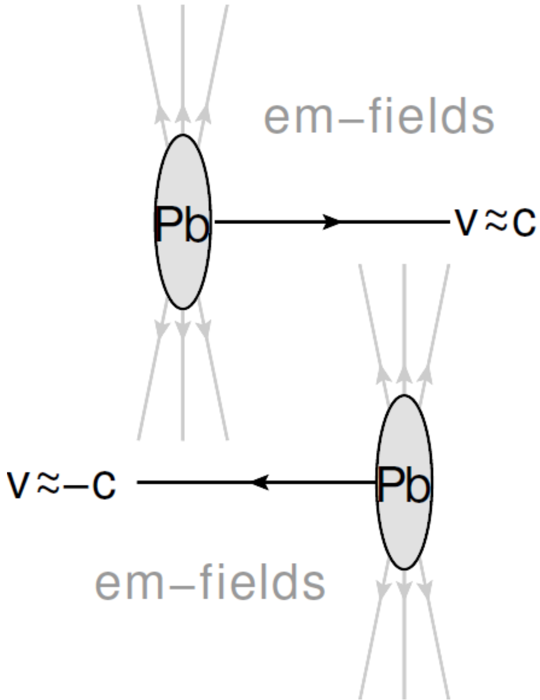


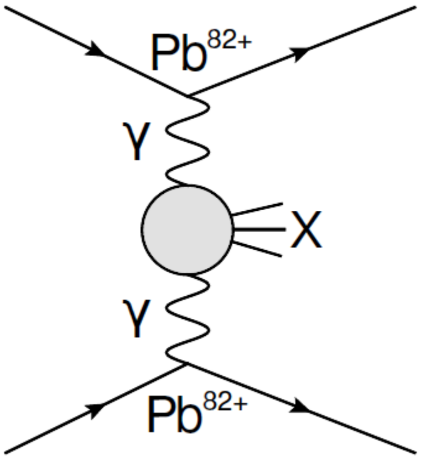


- Consistent with POWHEG scaled to NNLO accuracy.
- No significant modifications seen in T_{AA}-scaled yields – good **understanding of geometry**.
- No precision to **distinguish nPDF effects** yet.
- Final results coming soon!

Other highlights:
Ultra-peripheral collisions

UPC

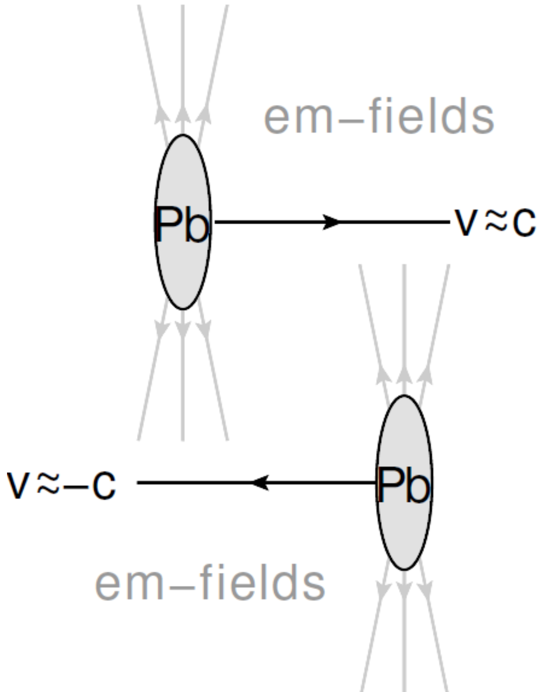


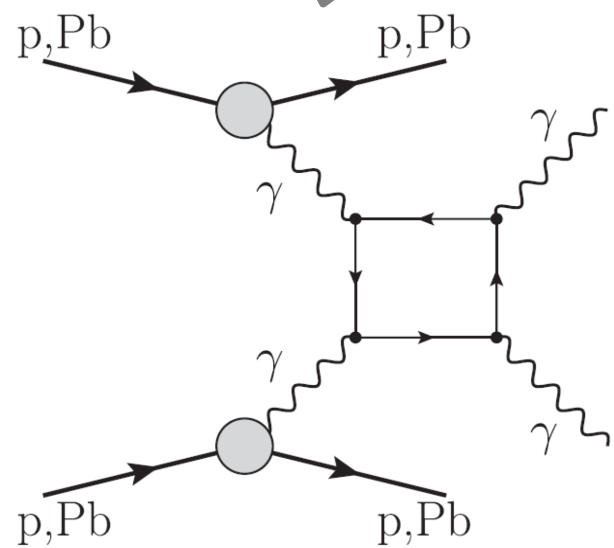


- Boosted protons / nuclei are source of photons of small virtuality ($Q^2 < 1/R^2 = 10^{-3}$GeV^2) described using equivalent photon approximation.
- Electromagnetic interactions dominate at large impact parameters.

UPC

One of processes:
light-by-light scattering



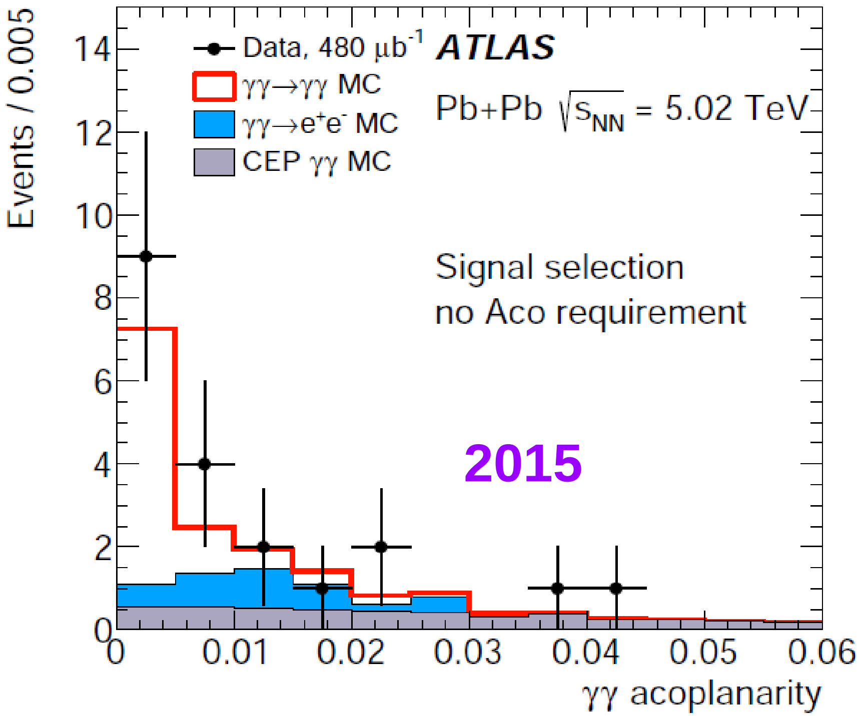


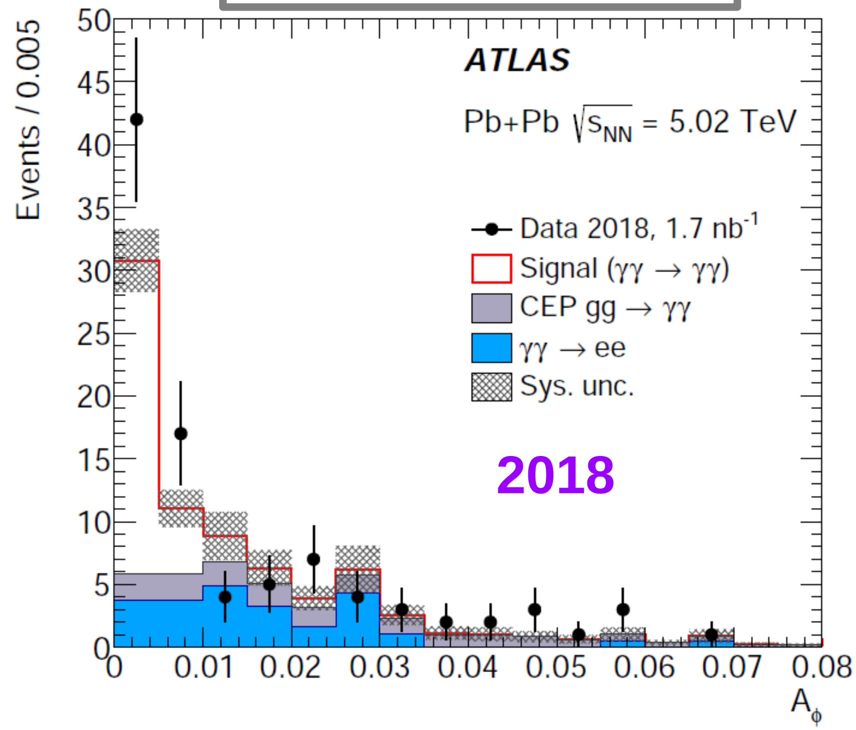
- Boosted protons / nuclei are source of photons of small virtuality ($Q^2 < 1/R^2 = 10^{-3}GeV^2$) described using equivalent photon approximation.
- Electromagnetic interactions dominate at large impact parameters.

Light-by-light scattering

Nat. Phys. 13 (2017) 852

arXiv: 1904.03536





- Event selection: 2 photons: E_T>6 GeV, $|\eta|$<2.37, $m_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < (1)2 GeV, Aco = $(1-\Delta\phi/\pi)$<0.01; no tracks
- **2015:** 13 events (2.6 expected bkgr), **4.4 σ significance**
- **2018:** 59 events (12 expected bkgr), **8.2 σ observation**

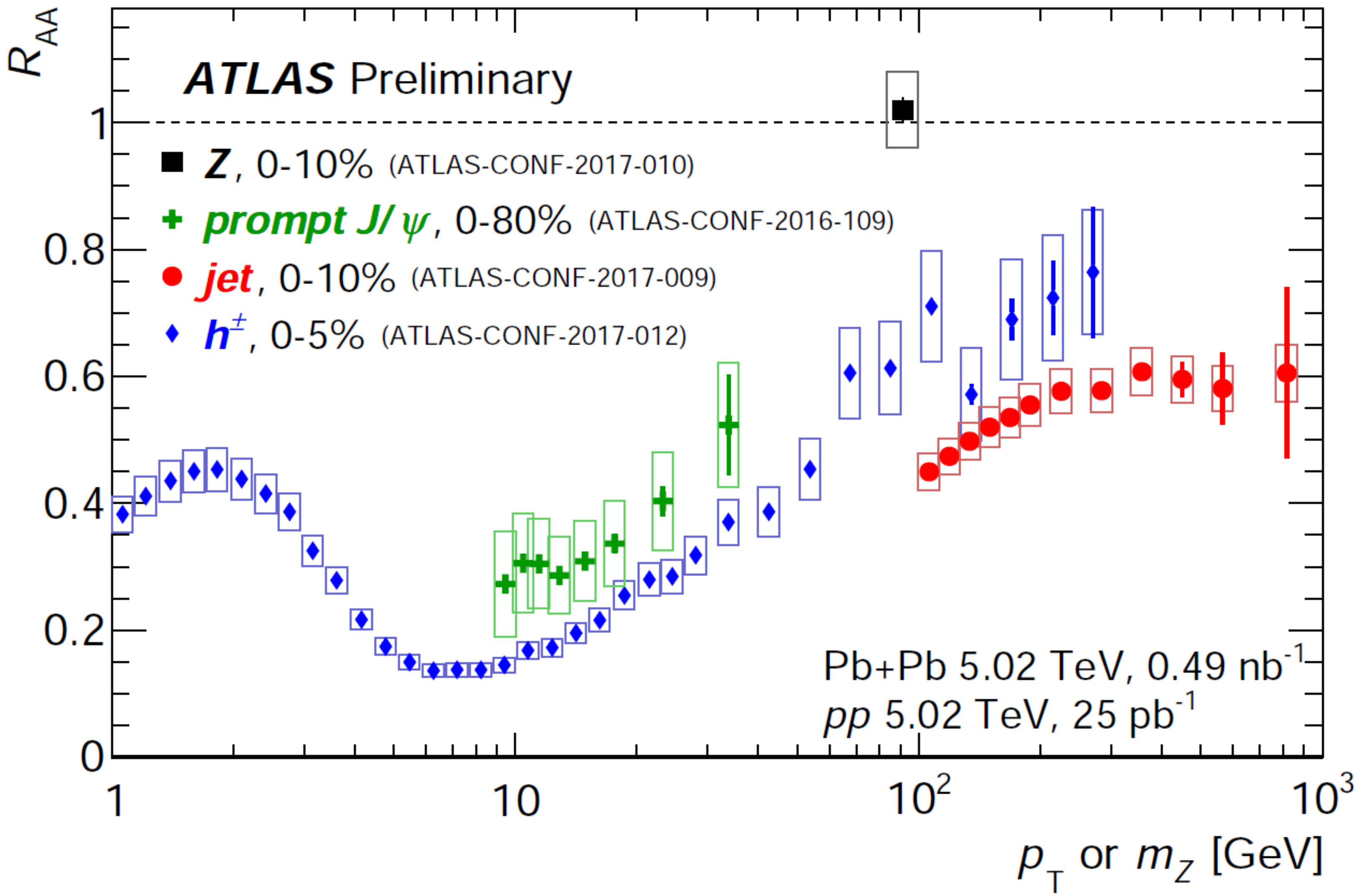
Summary / few basics points

- Similar suppression and v_2 of prompt and non-prompt J/ψ in Pb+Pb
- Prompt ψ(2S) suppressed more than J/ψ
- Non-prompt ψ(2S) suppressed the same as J/ψ
- HF muons are less suppressed and have smaller v_2 compared to inclusive hadrons
- No modification of J/ψ production in p+Pb, but ψ(2S) seems suppressed
- Υ(1S) suppressed at low-pt in p+Pb
- Υ(2S) and Υ(3S) suppressed wrt Υ(1S) in p+Pb
- Heavy flavor flows in p+Pb

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Backup slides

Landscape of the suppression measurements



Other highlights:
Soft processes

Cumulants for flow

- Cumulant method: Fourier harmonics are obtained from **2k-particle azimuthal correlations**

$$\langle corr_n\{2k\}\rangle = \left\langle\left\langle e^{in(\phi_1+\ldots+\phi_k\ -\phi_{k+1}-\ldots-\phi_{2k})}\right\rangle\right\rangle = \left\langle v_n\{2k\}^{2k}\right\rangle$$

example of cumulants:

$$c_n\{2\} = \langle corr_n\{2\}\rangle \qquad c_n\{4\} = \langle corr_n\{4\}\rangle - 2\,\langle corr_n\{2\}\rangle^2$$

$$\downarrow \qquad\qquad \downarrow$$

$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- Cumulants are less sensitive to non-flow effects.

Cumulants for flow

- Cumulant method: Fourier harmonics are obtained from **2k-particle azimuthal correlations**

$$\langle corr_n\{2k\}\rangle = \left\langle\left\langle e^{in(\phi_1+\ldots+\phi_k\ -\phi_{k+1}-\ldots-\phi_{2k})}\right\rangle\right\rangle = \left\langle v_n\{2k\}^{2k}\right\rangle$$

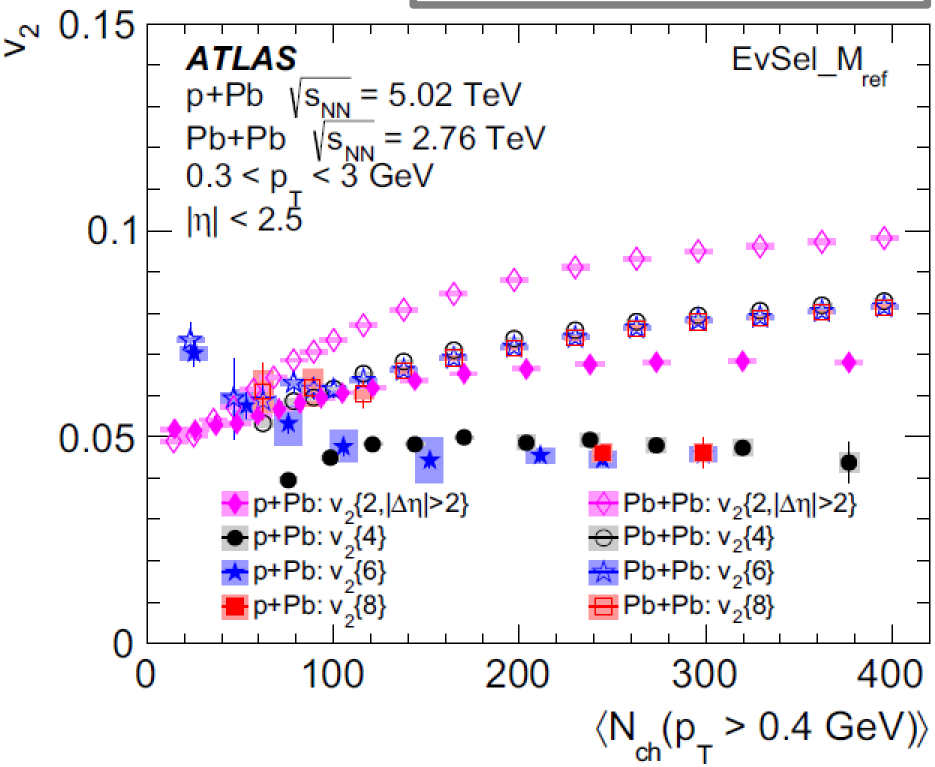
example of cumulants:

$$c_n\{2\} = \langle corr_n\{2\}\rangle$$

$$\downarrow$$

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

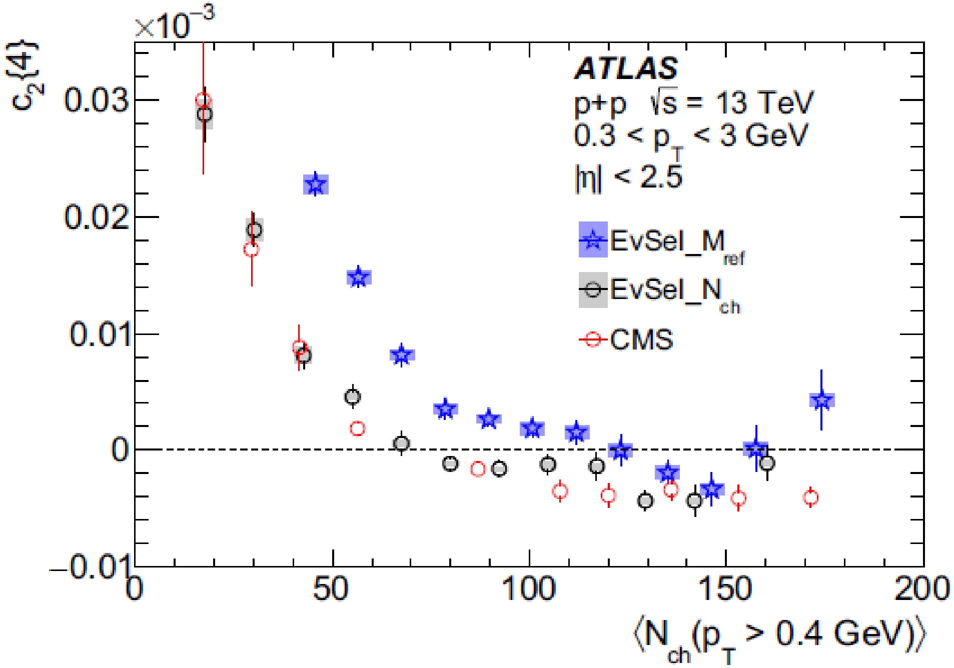
EPJC 77 (2017) 428



- Cumulants are less sensitive to non-flow effects.
- v_2 harmonics from cumulants **larger for Pb+Pb** then for *p*+Pb.
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$.

Cumulants and sub-event cumulants – small systems

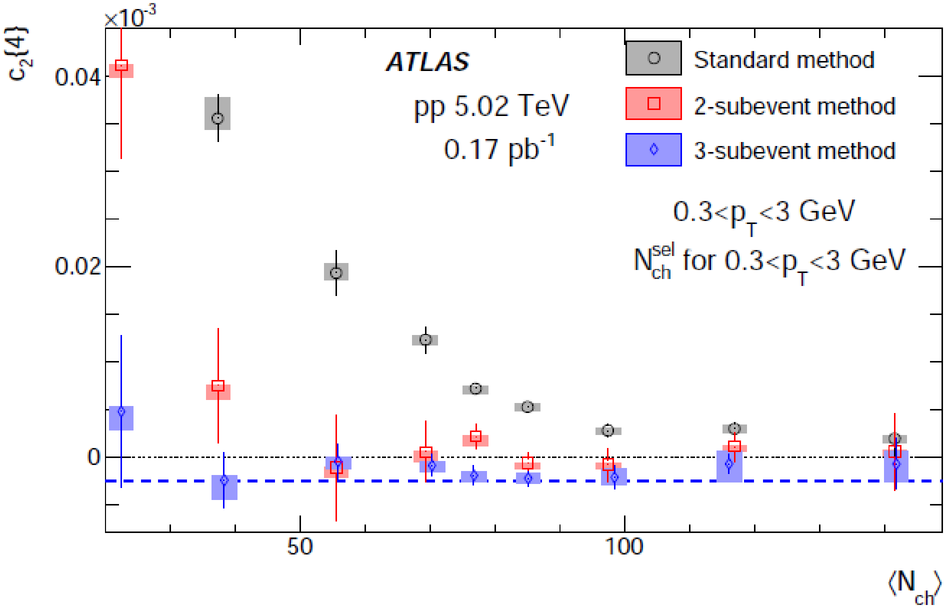
EPJC 77 (2017) 428



- Strong dependence on the definition of the event class.
- Still sensitive to various non-flow effects. Can we do better?
- Is there a collectivity in small systems or not?

Cumulants and sub-event cumulants – small systems

PRC 97 (2018) 024904



- Strong dependence on the definition of the event class.
- Still sensitive to various non-flow effects. Can we do better?
- Is there a collectivity in small systems or not?

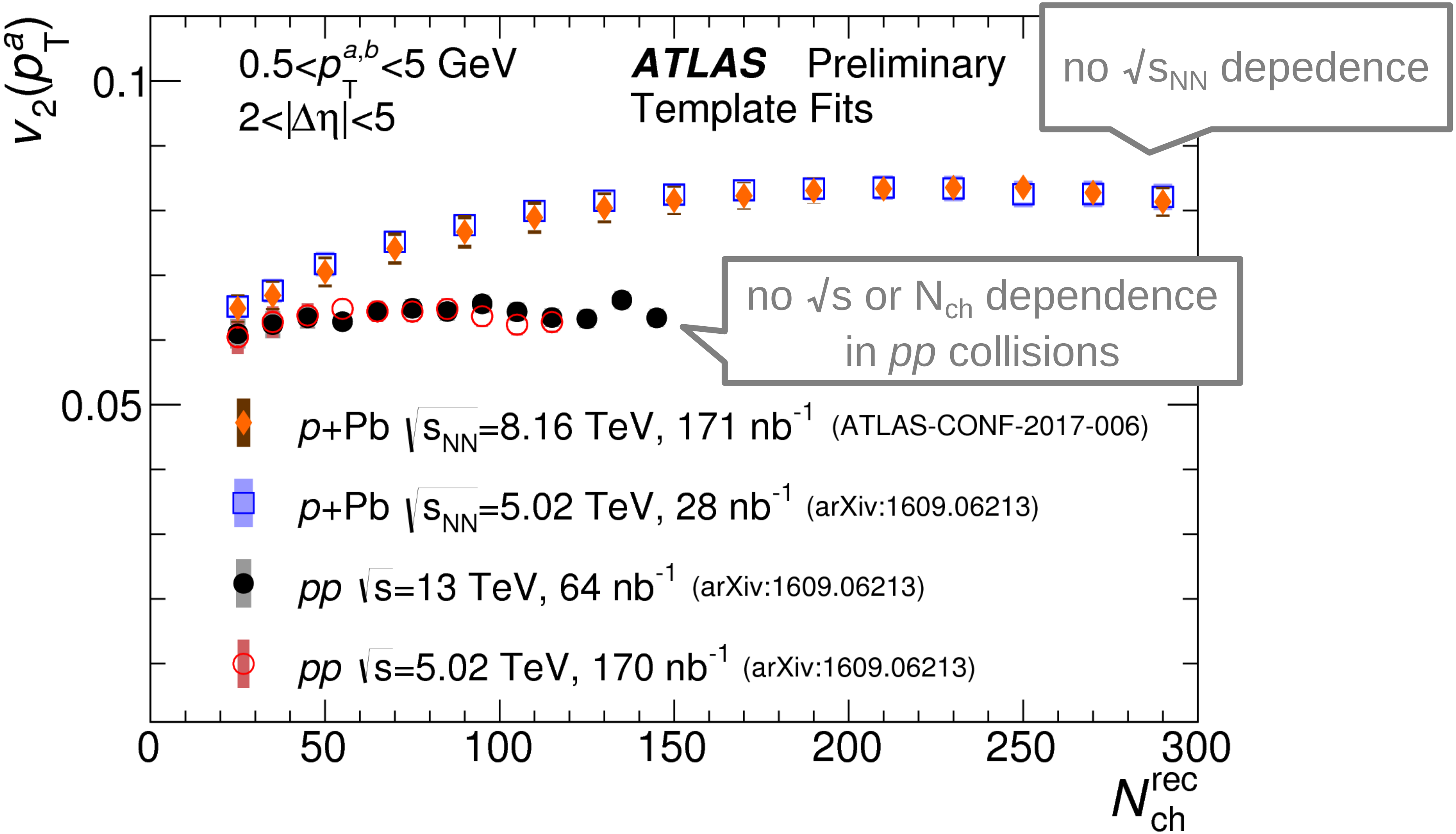
⇓

- **Sub-event cumulants** – correlator calculated using particles from 2 or 3 subevents => removing non-flow contribution

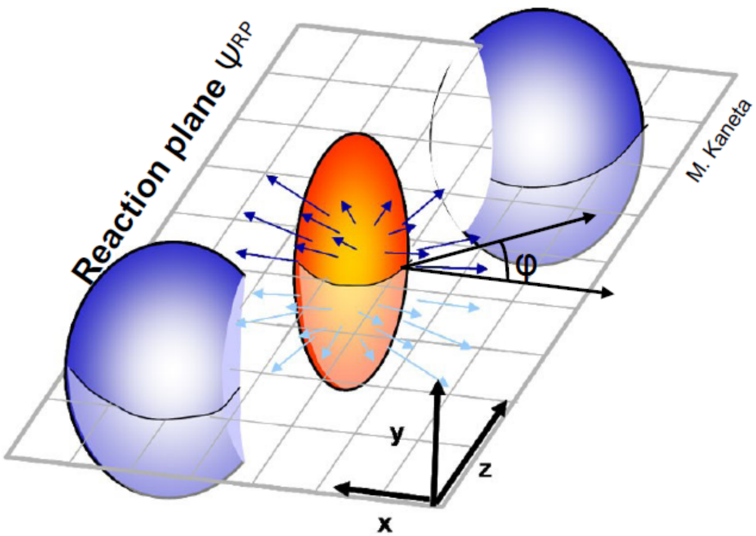
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- … direct evidence for **collectivity in small systems**

Ridge in small systems



Soft processes – azimuthal anisotropies



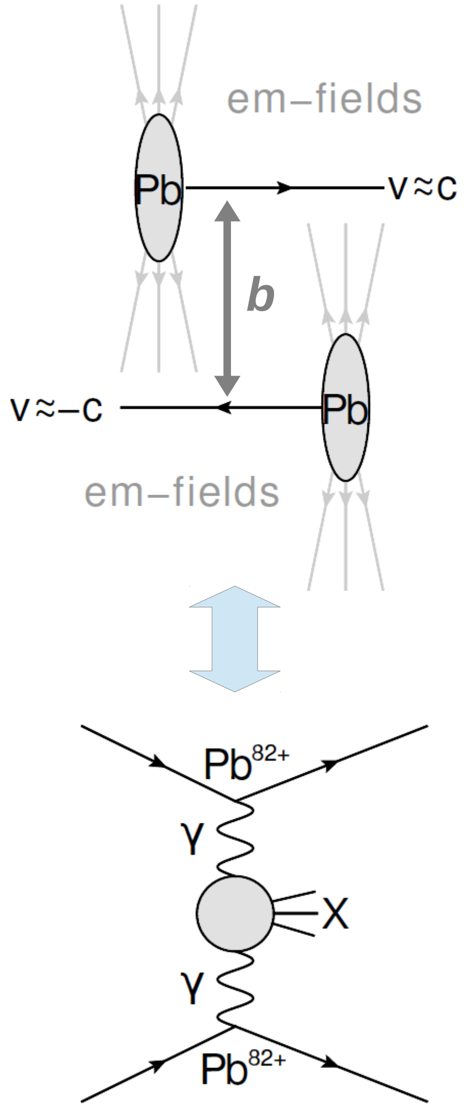
- Initial shape and its fluctuations lead to pressure gradients giving rise to azimuthal anisotropies in particle production.
- Quantified by **Fourier decomposition**:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = N_0\left(1 + 2\sum_{i=1} v_n \cos n(\phi - \Phi_n)\right)$$

$$v_n = \left\langle e^{in(\phi-\Phi_n)}\right\rangle = \langle \cos n(\phi - \Phi_n)\rangle$$

- **Initial shape** of the interaction region drives **elliptic flow**, v_2.
- Initial **spatial fluctuations** of interacting nucleons dictate **higher order flow**, v_n.
- Expected in Pb+Pb. Seen in *pp*, *p*+Pb !? … How about non-flow contributions (di-jets, resonances,…)?

UPC



Boosted protons/nuclei are source of photons of small virtuality ($Q^2<1/R^2=10^{-3}GeV^2$) described using equivalent photon approximation (EPA)

$$n(k,b) = Z^2 \frac{\alpha}{\pi^2} \frac{k}{(\hbar c)^2} \frac{1}{\gamma^2} K_1^2(x)$$

photon number density for one nucleus in EPA

45·10⁶ larger photon density compared to *pp*

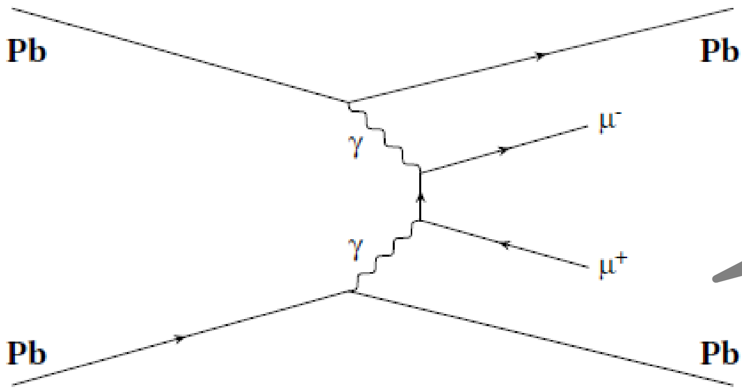
where $x = \dfrac{kb}{\gamma \hbar c}$

e.g. for two photon interaction

$$\sigma^{\mathrm{EPA}}(A_1 A_2 \xrightarrow{\gamma\gamma} A_1 A_2 X) =$$
$$= \int \mathrm{d}k_1 \mathrm{d}k_2 \; f(\mathrm{geometry}) \; n_1(k_1) \; n_2(k_2) \; \sigma(\gamma_1\gamma_2 \to X)$$

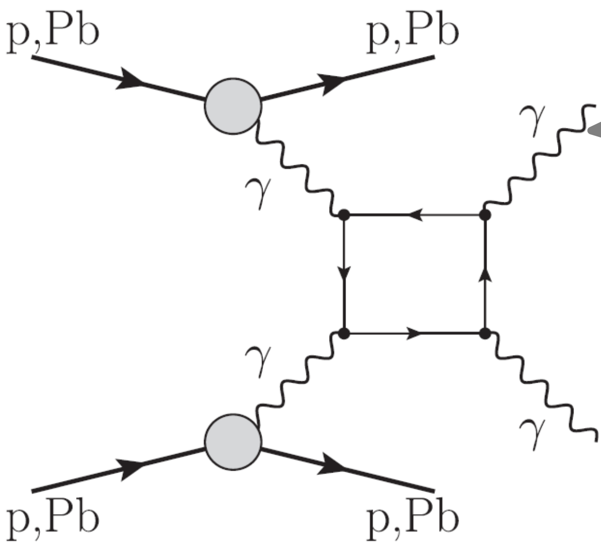
… EM interactions dominate at large *b*, qualitatively different collisions compared to ordinary Pb+Pb

Three UPC measurements ...

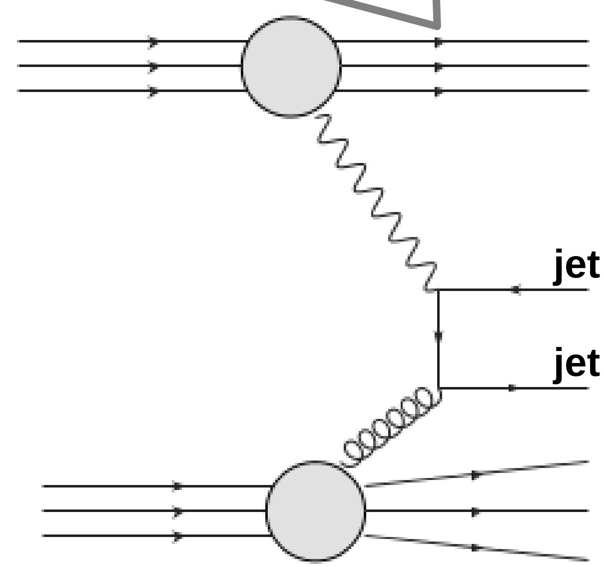


Measurement of high mass dimuons (ATLAS-CONF-2016-025)

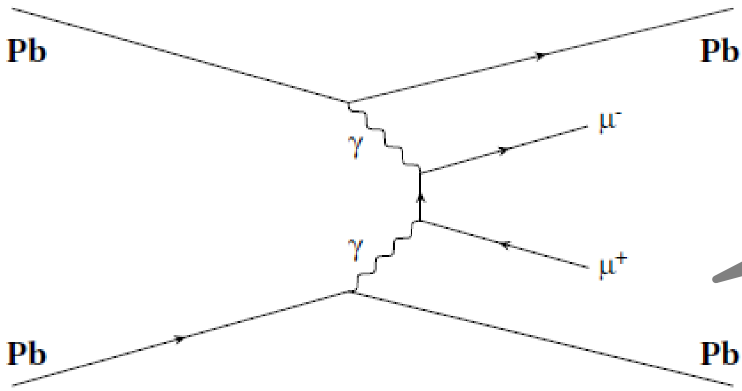
Photo-nuclear dijet production (ATLAS-CONF-2017-011)



Search for light-by-light scattering (Nature Physics 13 (2017) 852)



Three UPC measurements ...



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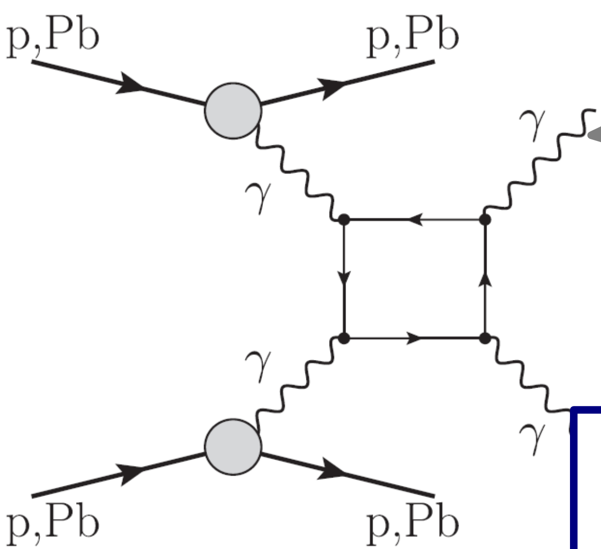
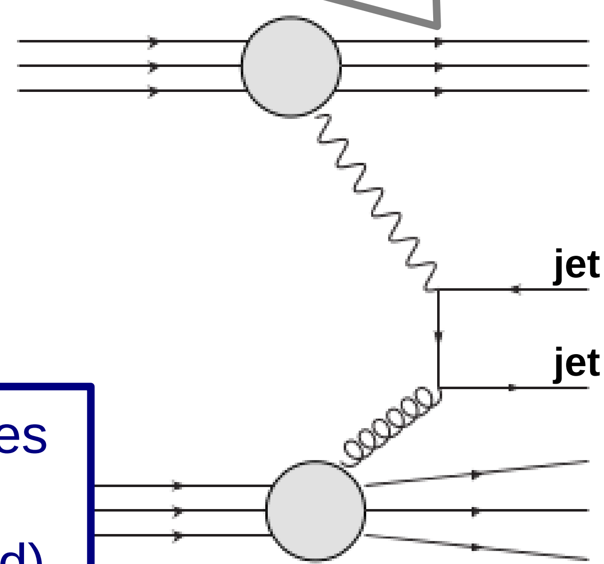
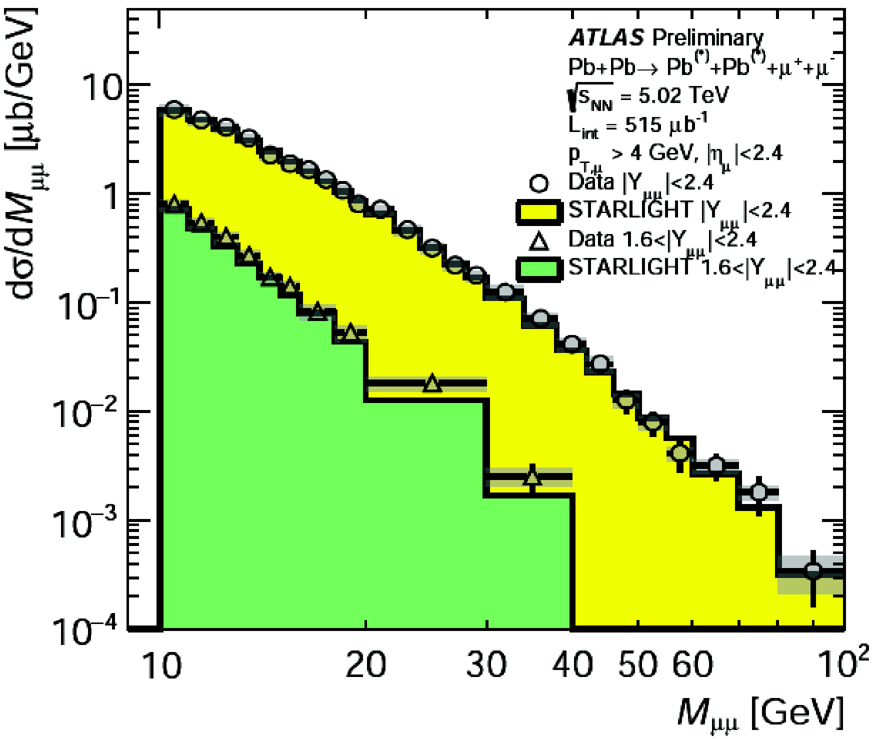


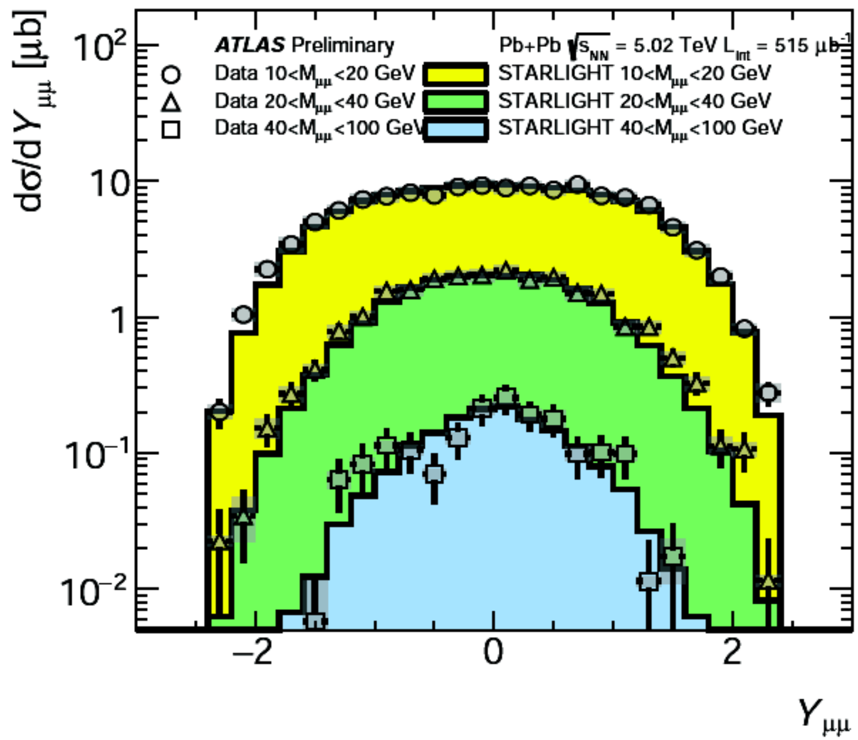
Evidence for light-by-light scattering (Nature Physics 13 (2017) 852)



… all exclusive final states (i.e. nothing else is expected to get produced)

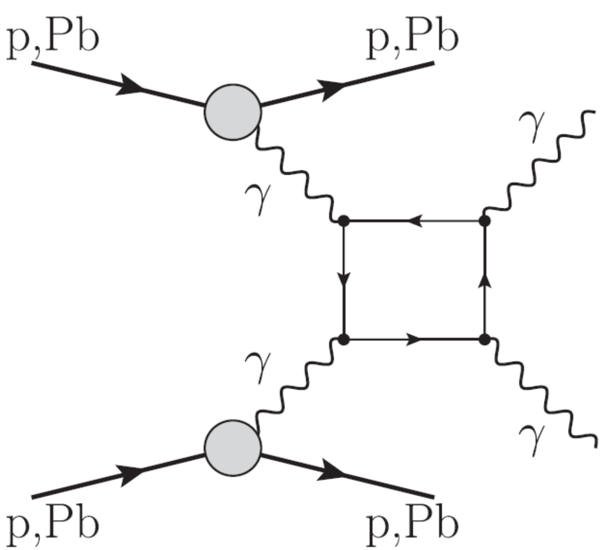
Measurement of high-mass dimuons

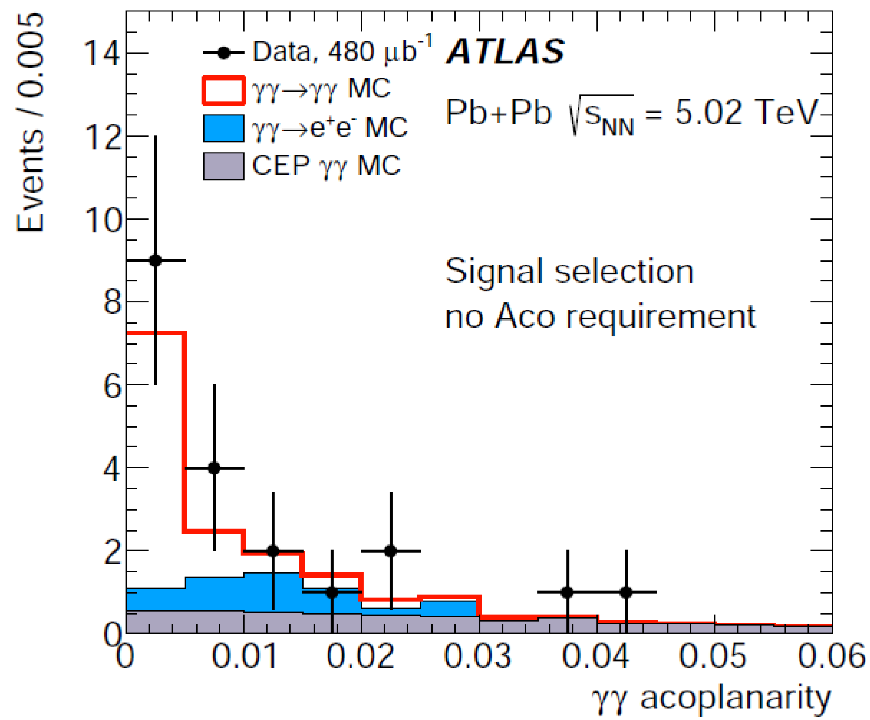




- Good **agreement with Starlight MC** – but the higher order QED corrections needs to be implemented into the MC
- Verifies the **Z^4 scaling** of cross-section and photon flux
- Significant **kinematic extension** over previous measurement by ALICE (EPJC 73 (2013) 2617)

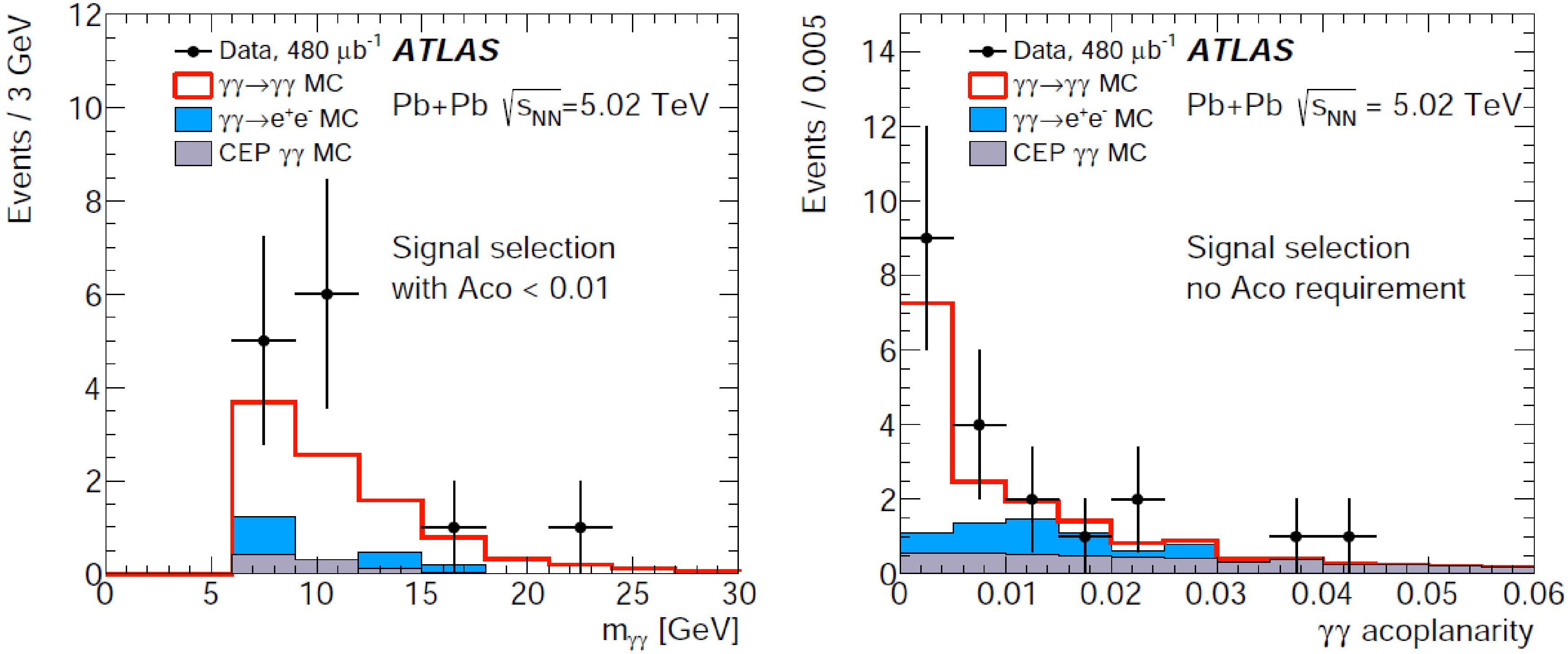
Evidence for light-by-light scattering





- Event selection: 2 photons: E_T>6 GeV, |η|<2.37, $m_{\gamma\gamma}$ > 6 GeV, $p_{T\gamma\gamma}$ < 2 GeV, Aco = (1-Δϕ/π)<0.01; no tracks
- **13 events** seen in the data, expects: 7.3 signal, 2.6 background
- p-value for the background-only hypothesis: 5 x 10^{-6} <=> **4.4 sigma significance** (3.8 sigma expected)

Search for light-by-light scattering



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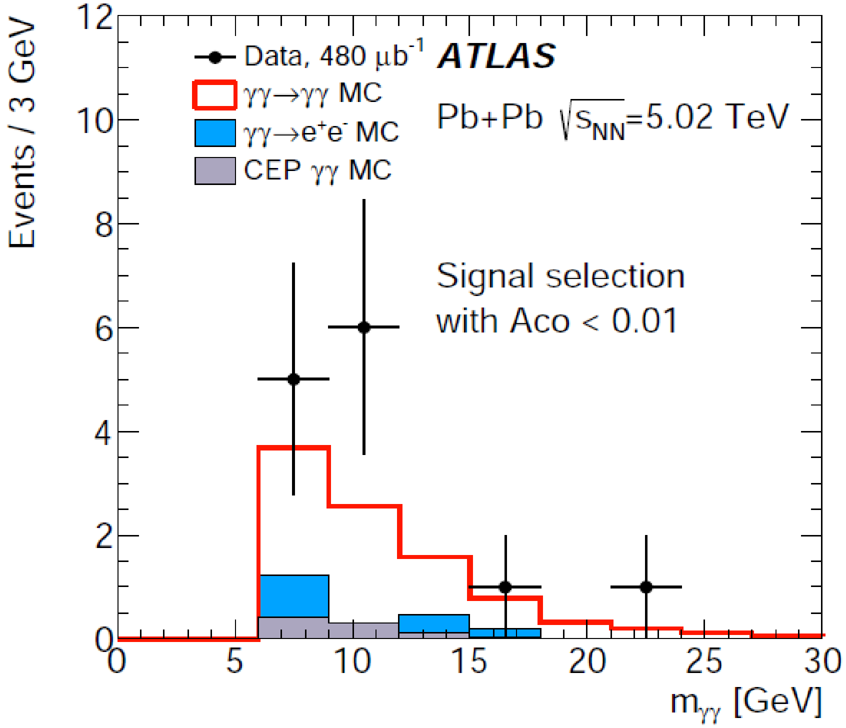
Search for light-by-light scattering



$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt}$$

C=0.31 ± 0.07,
corrects for:
trigger, diphoton, PID efficiencies and photon energy and angular resolutions

- Measured cross-section: **70 ±20 (stat.) ±17 (syst.) nb**
- SM predictions:
  - 45 ± 9 nb (PRL 111 (2013) 080405),
  - 49 ± 10 nb (PRC 93 (2016) no.4, 044907)

Photo-nuclear dijet production

- Motivation: restrict nuclear parton distribution functions (nPDF) at low *x*
- **nPDF** exhibit **non-trivial behavior**:
  - suppression at low *x* called “shadowing“
  - enhancement at larger *x* called “anti-shadowing“
  - suppression at the largest *x* called “EMC effect“

$$f_i^{p/A}(x, Q^2) = = R_i^A(x, Q^2) f_i^p(x, Q^2)$$

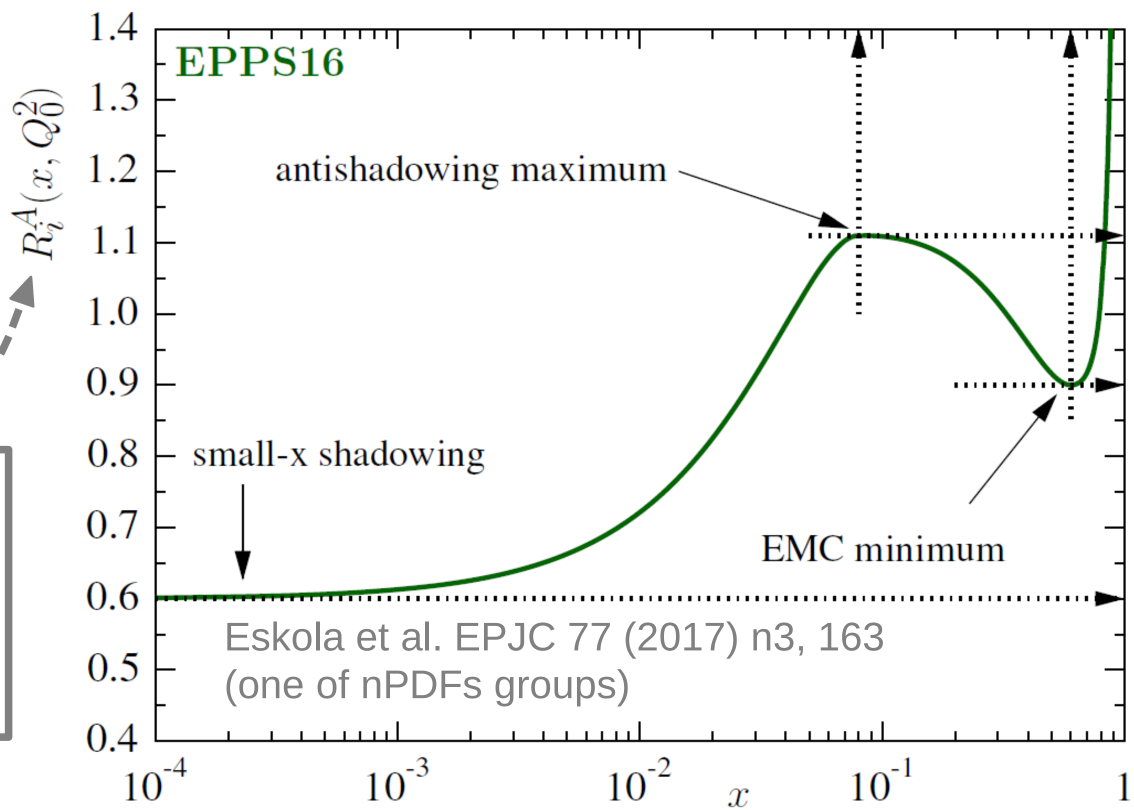
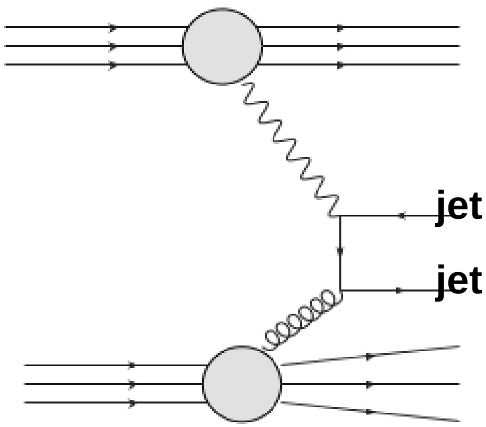


Photo-nuclear dijet production: observables



2 –> 2 scattering limit:

$$H_{\mathrm{T}} \equiv \sum_i p_{\mathrm{T}\,i}$$ → 2Q

$$x_{\mathrm{A}} \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{-y_{\mathrm{jets}}}$$ → x of struck parton in nucleus

$$z_{\gamma} \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{+y_{\mathrm{jets}}}$$ → $x_\gamma\, y_\gamma$ (y_γ … E fraction of γ, x_γ … fraction of γ's E carried by parton in γ)

… where

$$y_{\mathrm{jets}} \equiv \frac{1}{2} \ln \left(\frac{\sum_i E_i + \sum_i p_{z\,i}}{\sum_i E_i - \sum_i p_{z\,i}} \right)$$

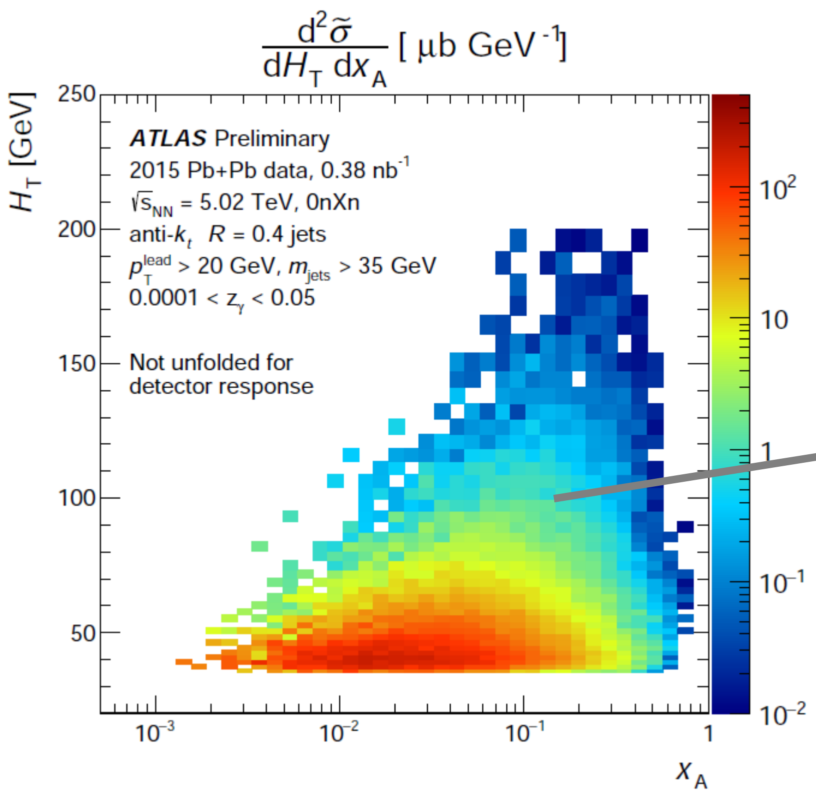
$$m_{\mathrm{jets}} \equiv \left[\left(\sum_i E_i \right)^2 - \left| \sum_i \vec{p}_i \right|^2 \right]^{1/2}$$

… *i* goes through all the jets

Photo-nuclear dijet production: new inputs for nPDF

$$\frac{d^3\tilde{\sigma}}{dH_T x_A dz_\gamma} = \frac{1}{\mathcal{L}} \frac{\Delta N}{\Delta H_T \, \Delta x_A \, \Delta z_\gamma} \frac{1}{\varepsilon_{trig} \, \varepsilon_{sel}}$$

… measuring triple differential cross-section not unfolded for the response –> projections



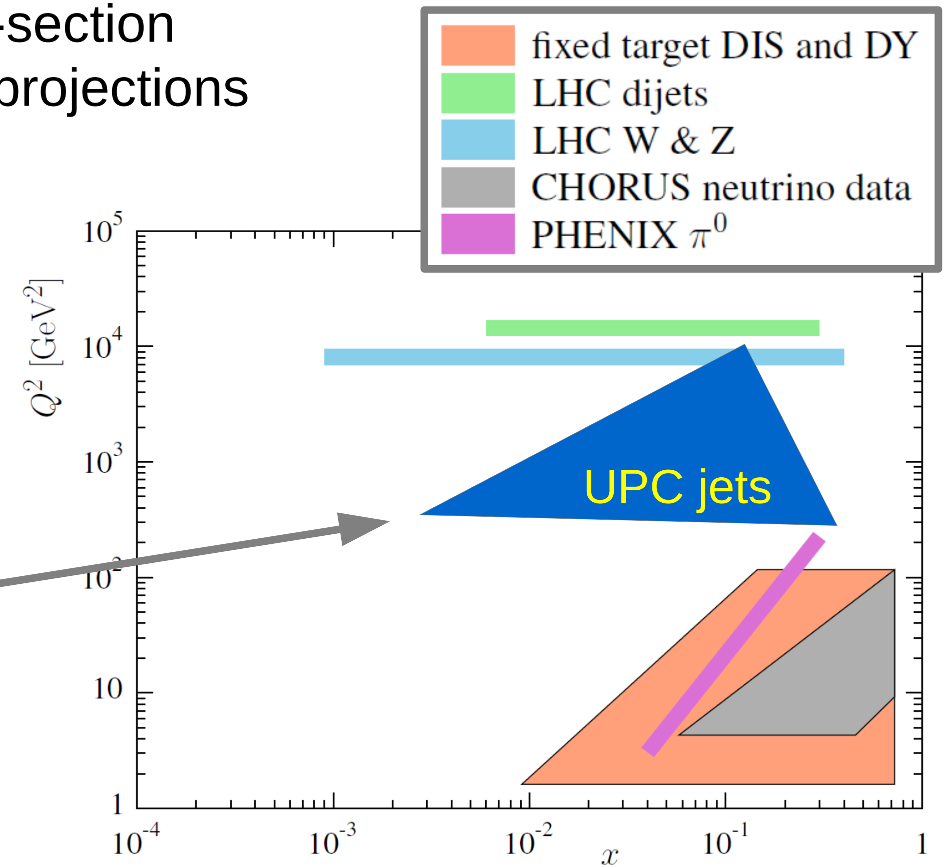
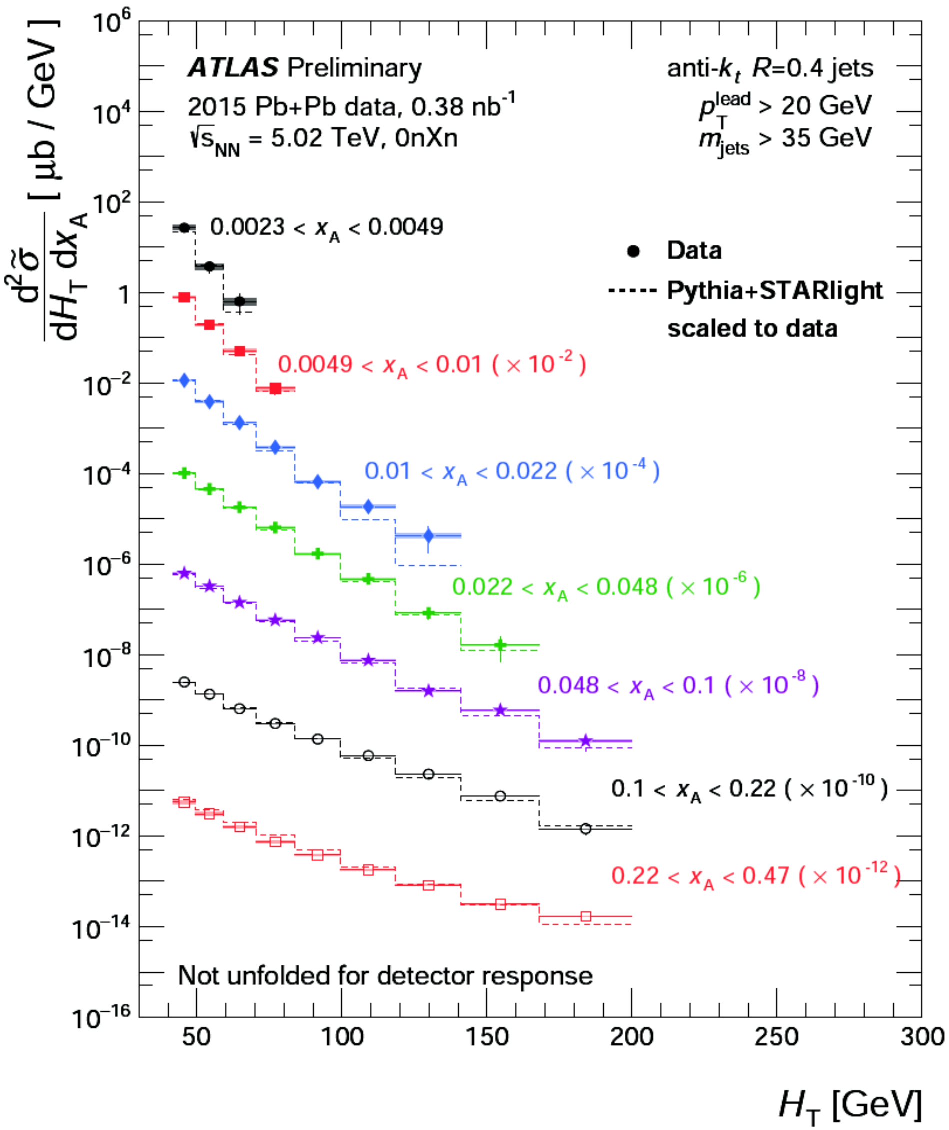
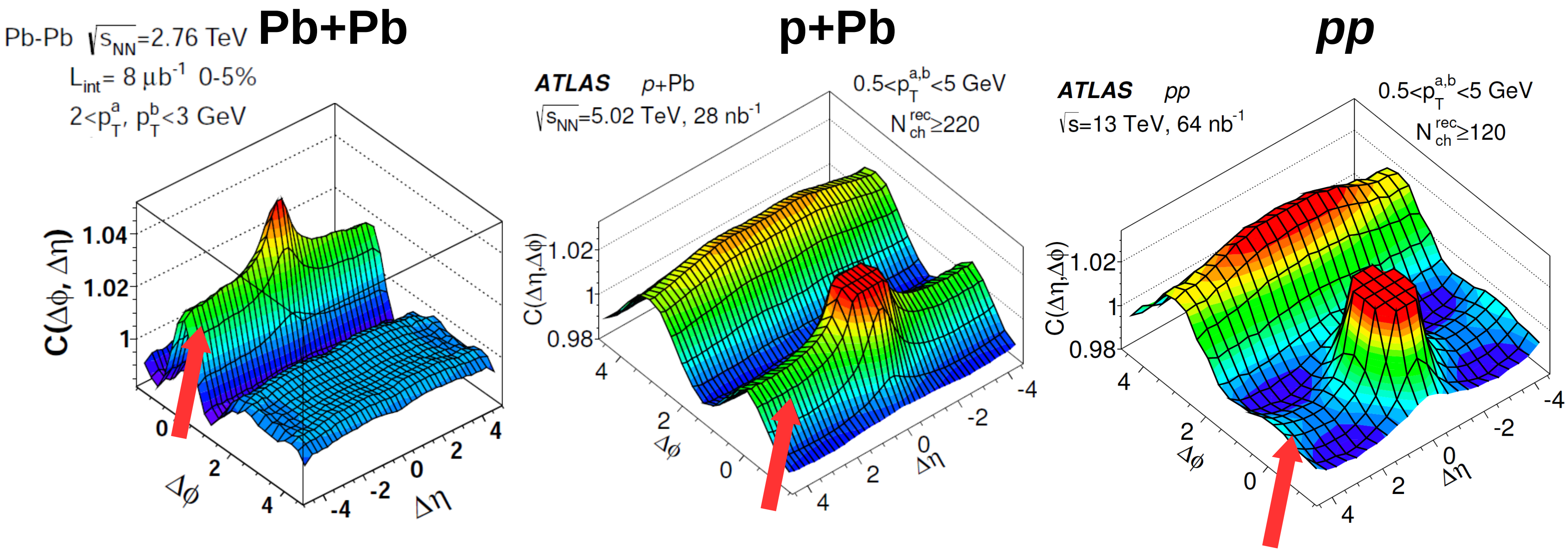


Photo-nuclear dijet production: slices of x_A



- Not the same as $F_2(x,Q^2)$
  - still contains $1/Q^4$ and z_γ dependence
- MC close to data but matching is not expected
- Also measured slices of H_T and z_g

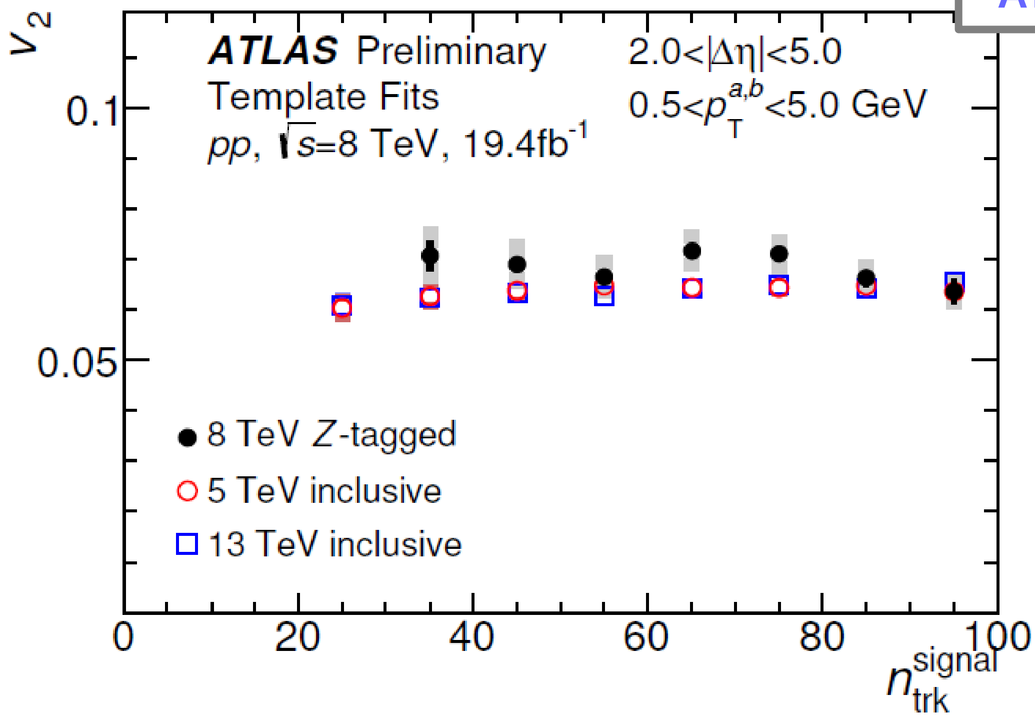
Ridge in small systems



- Two particle correlations in ΔηxΔφ – long range, **near side** and away side correlations = the ridge.
- Seen in Pb+Pb, but also in ***p*+Pb, *pp* collisions**.
- Template fitting method to suppress non-flow contribution.

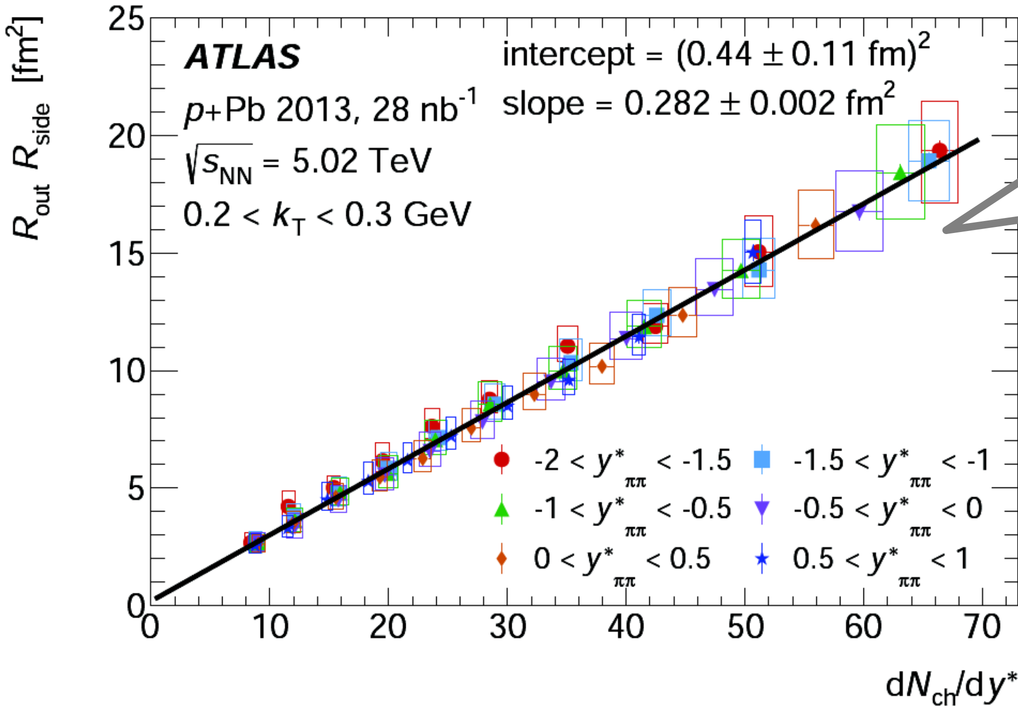
Ridge in small systems: impact parameter dependence

ATLAS-CONF-2017-068



- Selecting on high-Q^2 processes = sampling of **lower impact parameter** *pp* collisions. Here: **Z-tagged ridge**.
- New method to measure the ridge in events with **large pile-up**.
- v_2 **8% ± 6% larger** in Z-tagged events compared to inclusive.

… more results



Femtoscopy with identified charged pions in p+Pb (Phys. Rev. C 96 (2017) 064908)

Longitudinal flow decorrelations in Pb+Pb (arXiv:1709.02301)