Measurement of the R_{AA} and v_2 of heavy-flavor muons in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76TeV with the ATLAS detector

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IS-2016 Portugal

Why measure heavy-flavor Muons

- Heavy-quarks are produced at early times in the A+A collision

- Masses of heavy quarks are much larger than the temperatures of the Quark-Gluon plasma produced in A+A Collisions
  - T_{QGP}~200-500 MeV
  - Charm mass: 1.275 GeV
  - Bottom mass : 4.18GeV

- High p_T heavy-quarks are expected to lose energy similar to light quarks
  - But with mass dependent modifications
- Low p_T heavy-quarks are expected to partially thermalize

- Measurement of heavy-quark suppression and azimuthal anisotropy can
  - Determine if heavy-quarks couple strongly or weakly to the QGP
  - Constrain transport-coefficient ($\hat{q}$)
  - Constrain heavy-quark diffusion coefficient

Characterizing suppression and azimuthal anisotropy

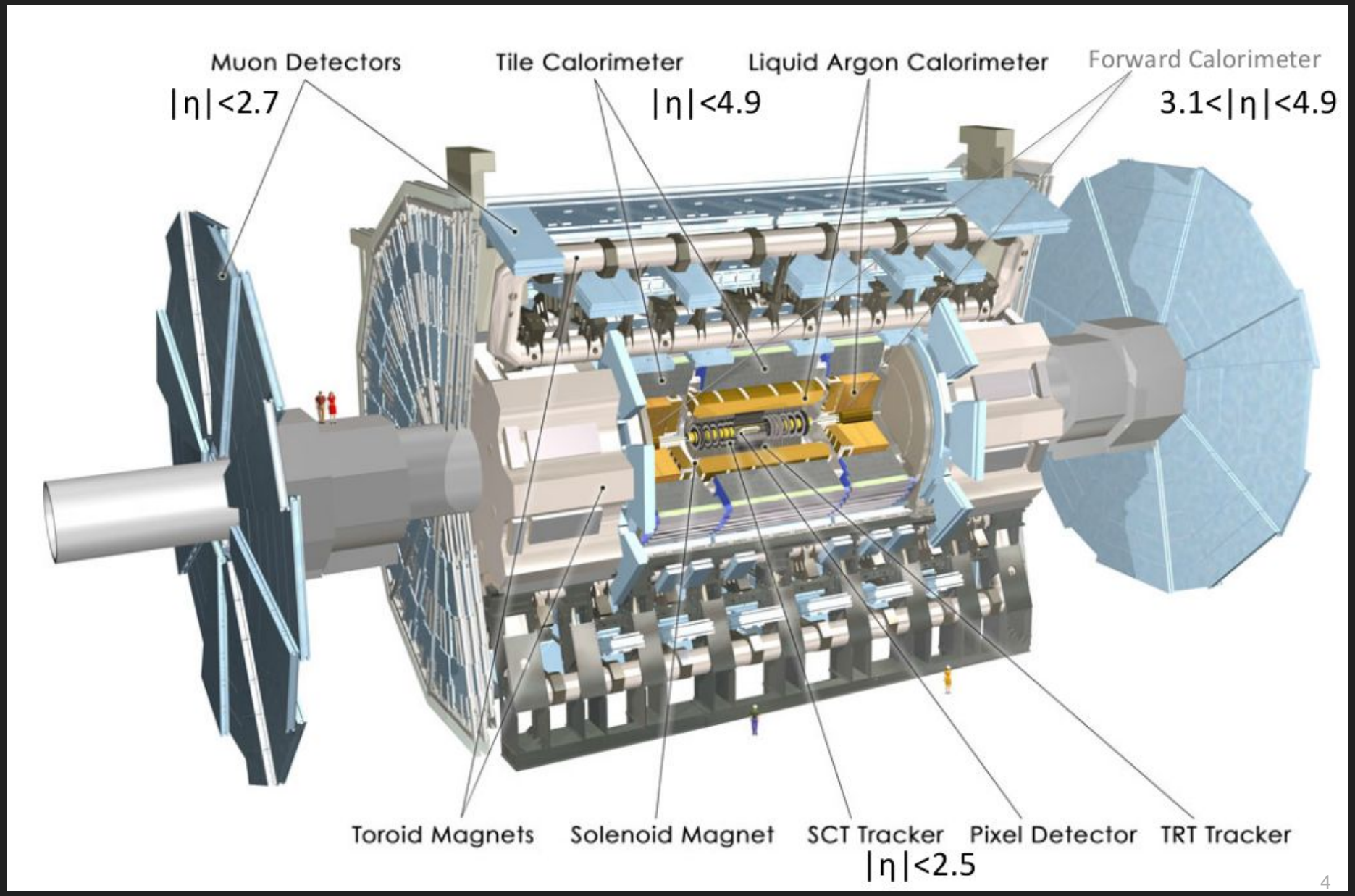
- Suppression is quantified by the nuclear modification factor (R_{AA})

$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}\eta}\Big|_{\mathrm{cent}}}{\frac{\mathrm{d}^2 \sigma^{pp}}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}\eta}}$$

- Azimuthal anisotropy quantified by Fourier harmonics, v_n, of azimuthal angle distribution.
    - Leading anisotropy is 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 Detector



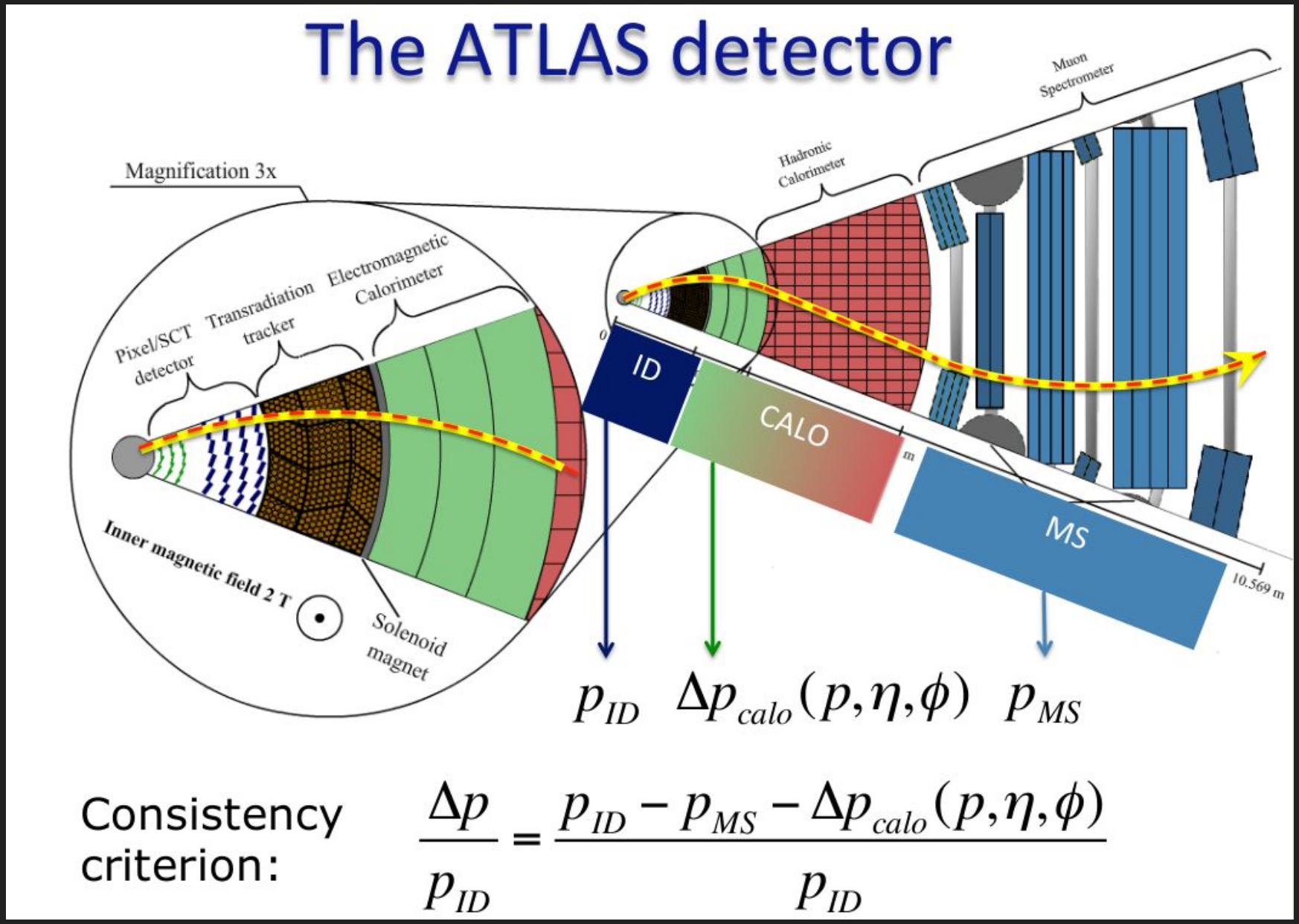
Datasets and muon reconstruction

- Analysis uses
  - 140 mub^{-1} of Pb+Pb data at 2.76TeV
  - 4 pb^{-1} of pp data at 2.76TeV

- Muons are measured over
  - $4<p_T<14$ GeV range
  - $|\eta|<1$
  - (0-60)% centrality
  - 9.2 Million muons in Pb+Pb and 1.8 Million muons in pp

- Muons are reconstructed by associating Muon Spectrometer (MS) muons with Inner Detector (ID) Tracks
  - Signal Muons: Prompt muons produced near the interaction point (dominated by HF muons)
  - Background muons:
    - In-flight decays of π/K,
    - muons produced from secondary interactions
    - mis-associations

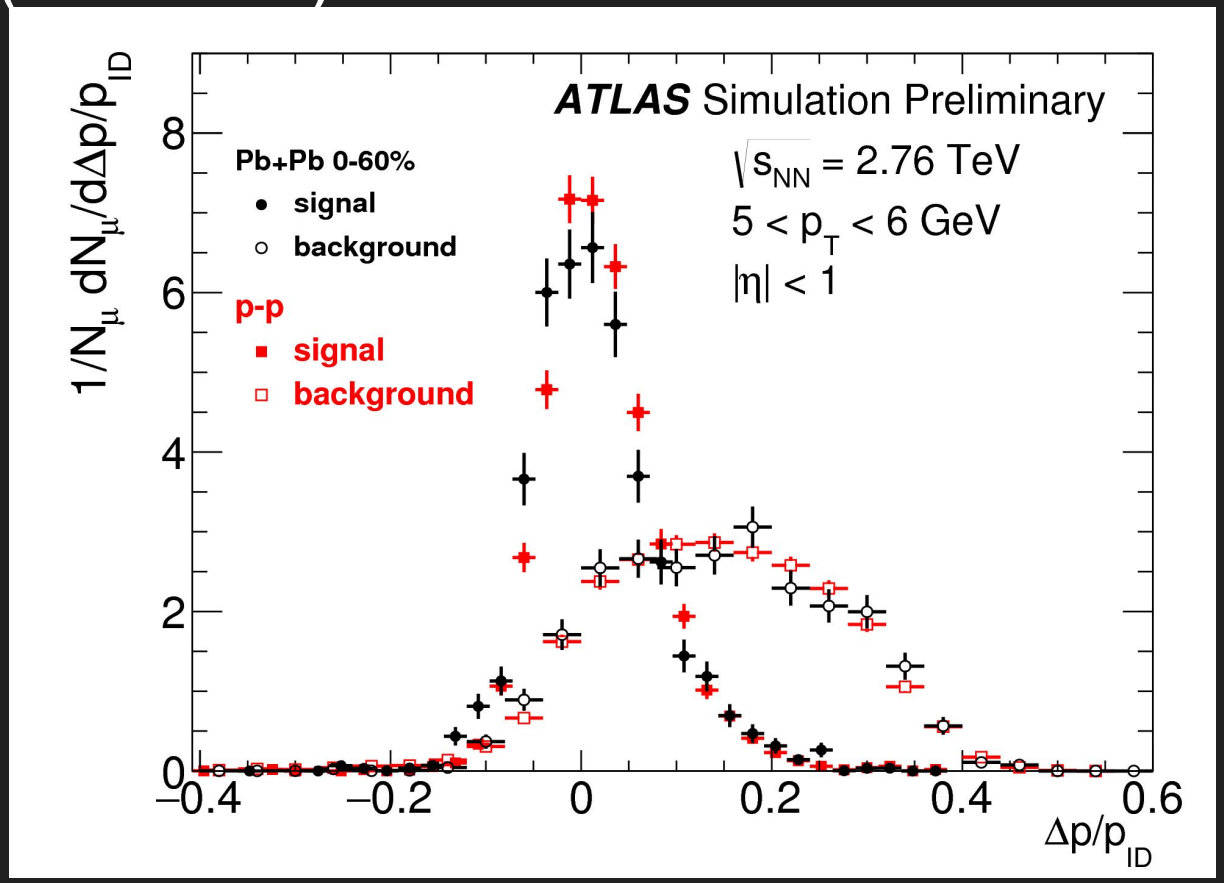
Prompt Muon Identification



Consistency criterion:

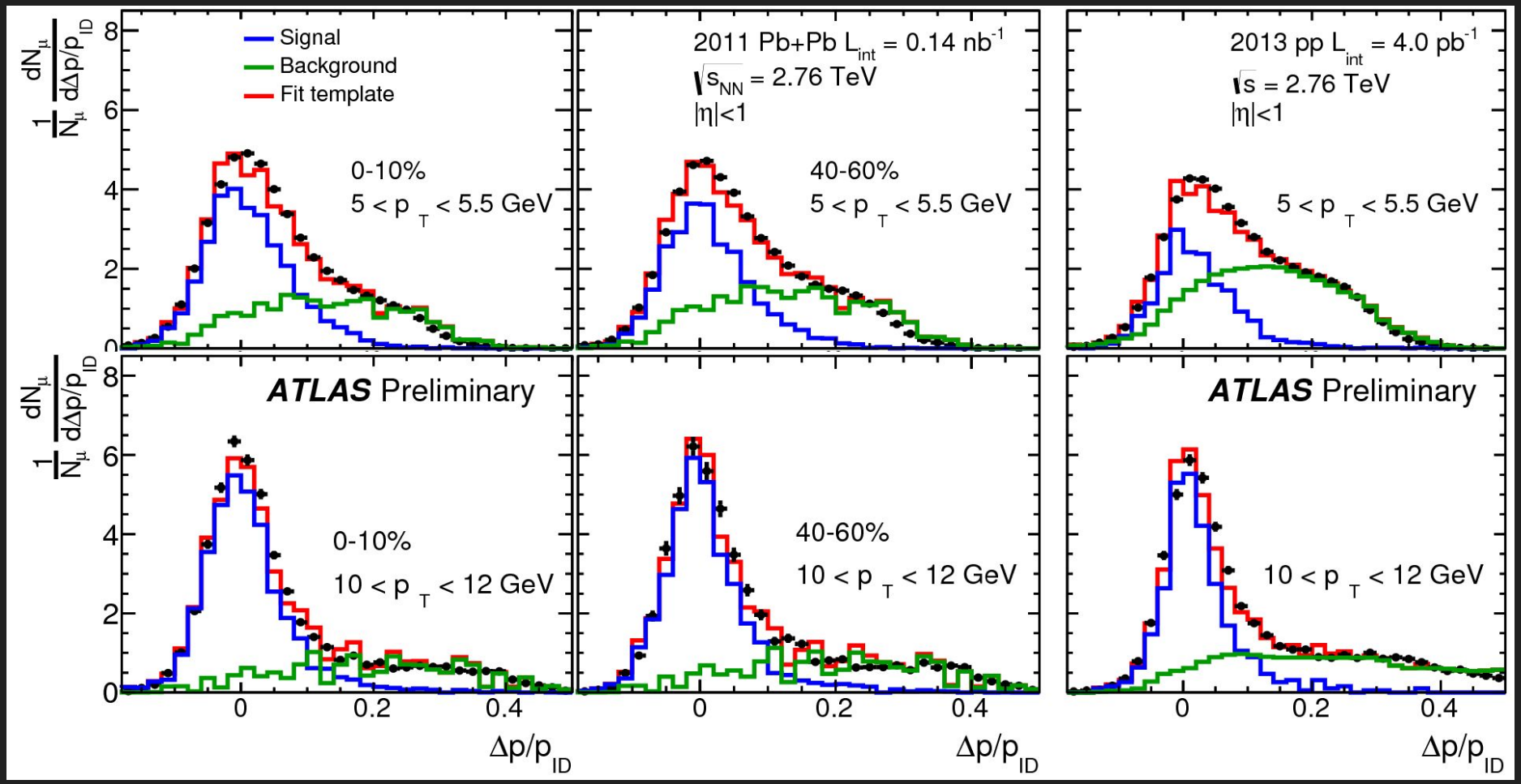
$$\frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - \Delta p_{calo}(p,\eta,\phi)}{p_{ID}}$$

$\Delta p/p_{ID}$ distributions for prompt and non-prompt muons (from MC)



- Signal distributions centered at zero
- Background distributions have large positive value (p_{MS} than expected from prompt muons)

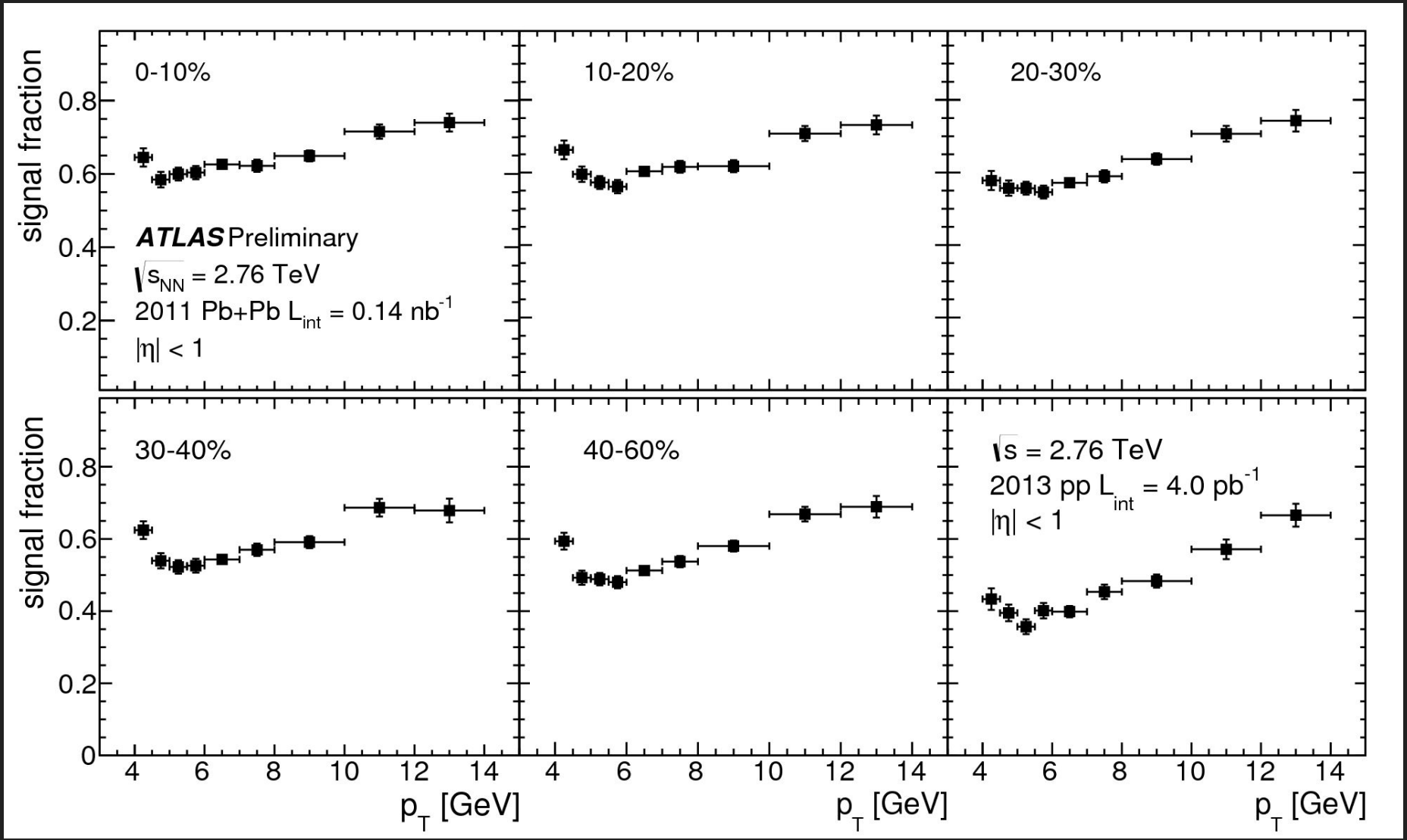
Template fits: Data



$$\frac{dN}{d\Delta p/p_{ID}} = N_\mu \left(f^{sig} \frac{dP^{sig}}{d\Delta p/p_{ID}} + (1 - f^{sig}) \frac{dP^{bkg}}{d\Delta p/p_{ID}} \right)$$

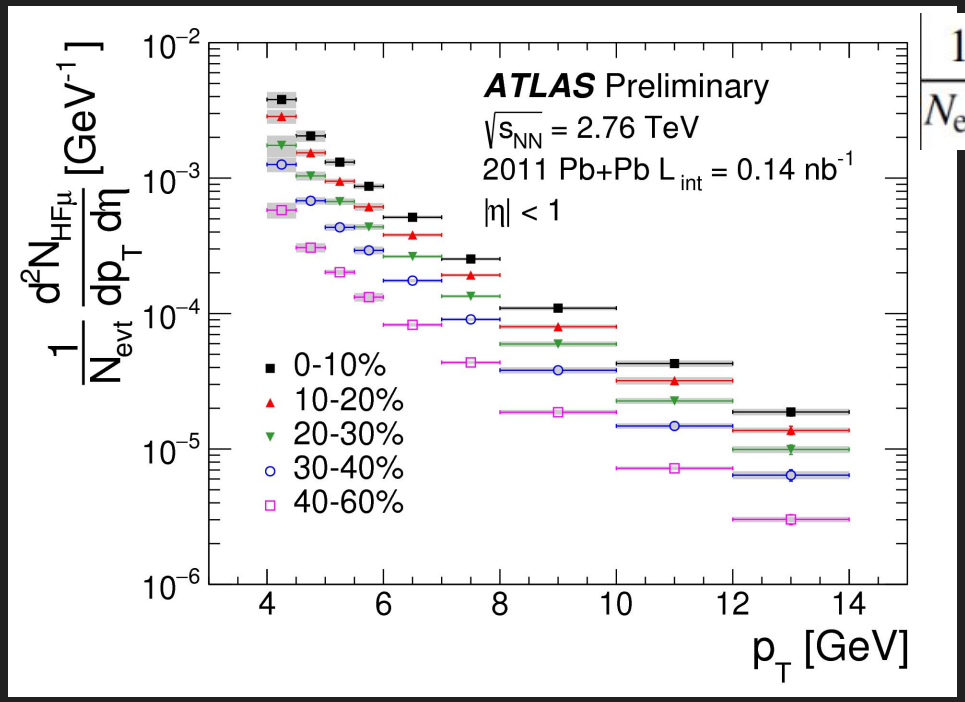
- Panels show $\Delta p/p_{ID}$ distributions in data together with template fits
- Top row $5<p_T<5.5$ GeV, bottom row $10<p_T<12$ GeV
- Left two columns are Pb+Pb, right column is pp

Signal Fractions



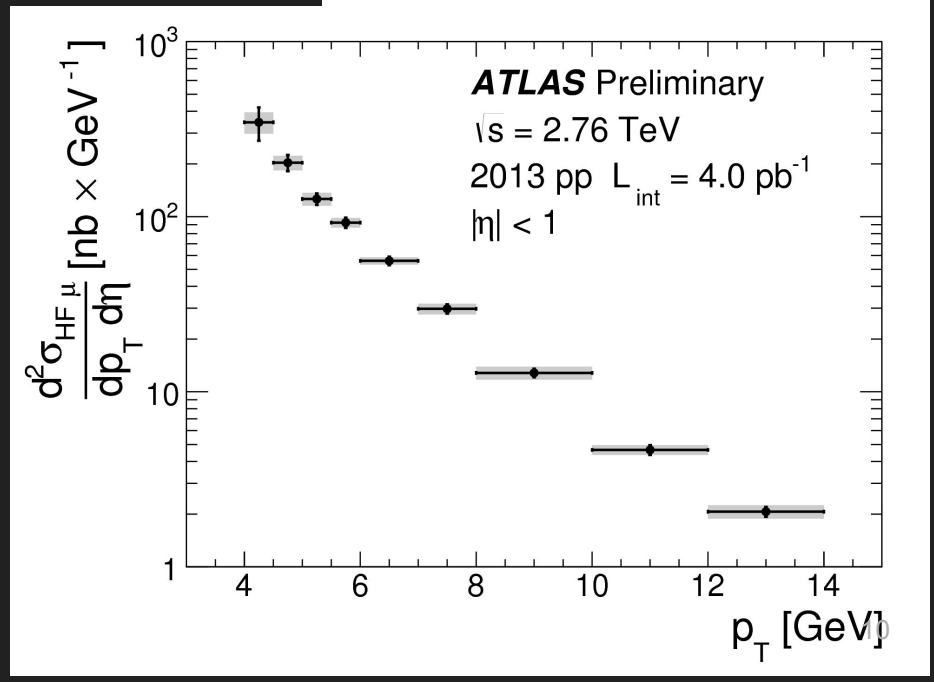
Fraction of prompt muons as function of p_T

Corrected spectra and cross-section of HF muons

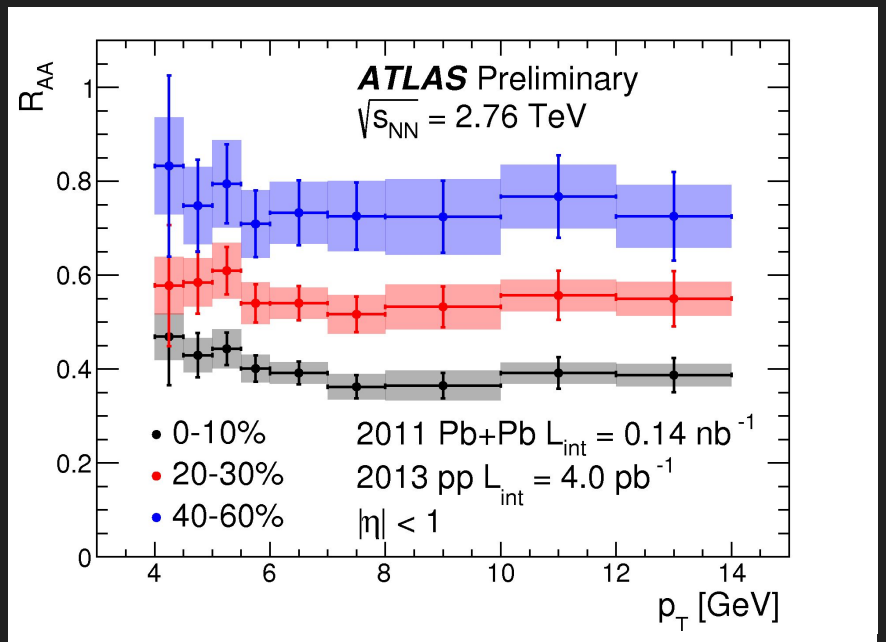


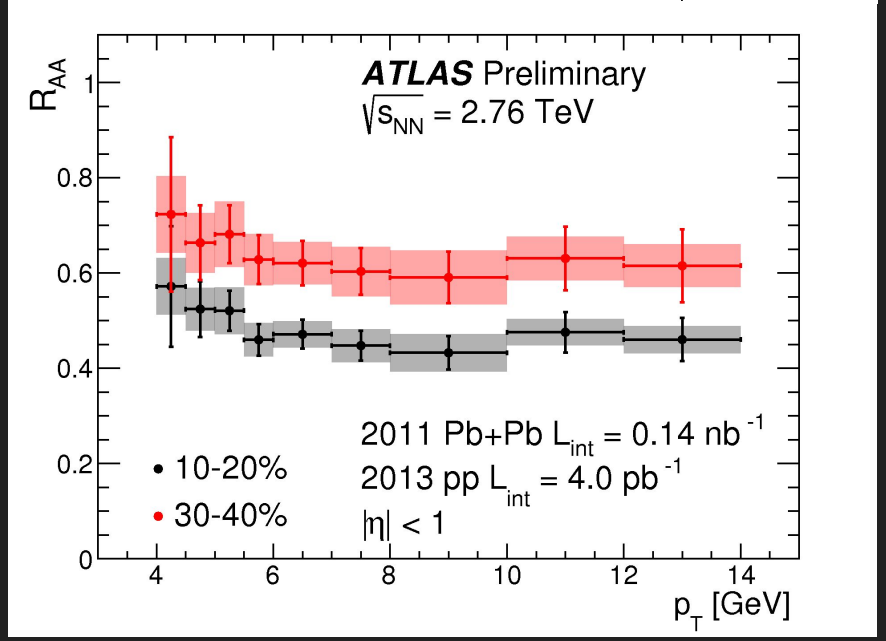
$$\left.\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}^2 N_{\mathrm{HF}\mu}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}\right|_{\mathrm{cent}} = \frac{1}{N_{\mathrm{evt}}^{\mathrm{cent}}}\frac{\Delta N_{\mu}^{\mathrm{cent}} f^{\mathrm{sig}}}{\Delta p_{\mathrm{T}}\Delta\eta}\frac{1}{\varepsilon_{\mathrm{trig}}\varepsilon_{\mathrm{rec}}}$$

$$\frac{\mathrm{d}^2\sigma_{\mathrm{HF}\mu}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} = \frac{1}{\mathcal{L}}\frac{\Delta N_{\mu} f^{\mathrm{sig}}}{\Delta p_{\mathrm{T}}\Delta\eta}\frac{1}{\varepsilon_{\mathrm{trig}}\varepsilon_{\mathrm{rec}}}$$



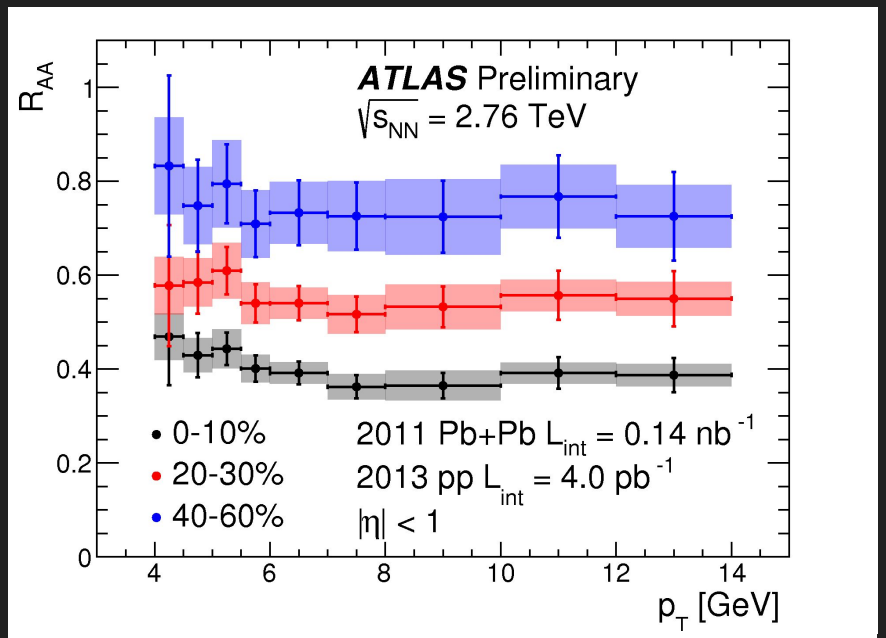
Nuclear modification factor: R_{AA}

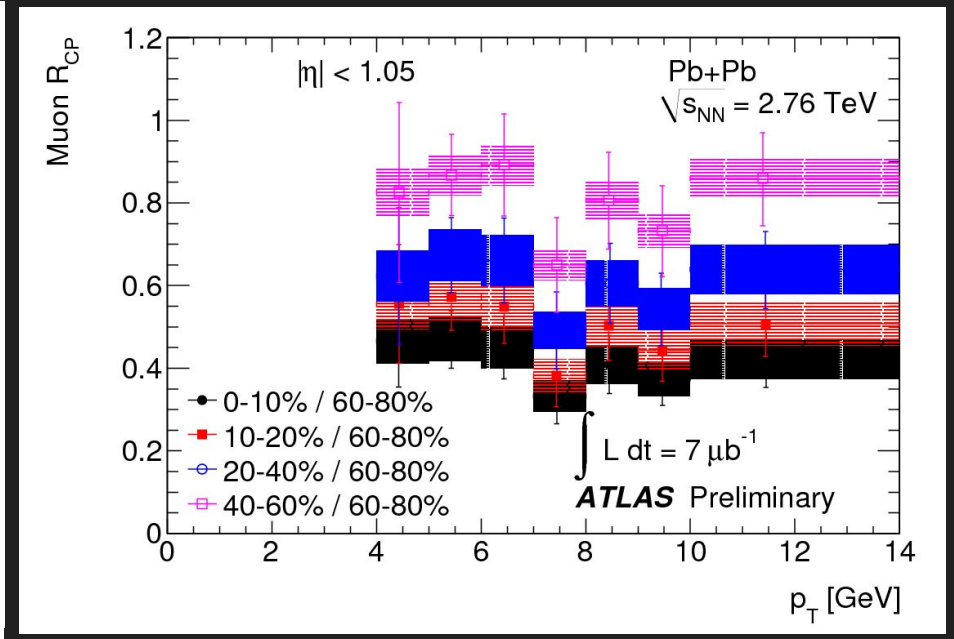


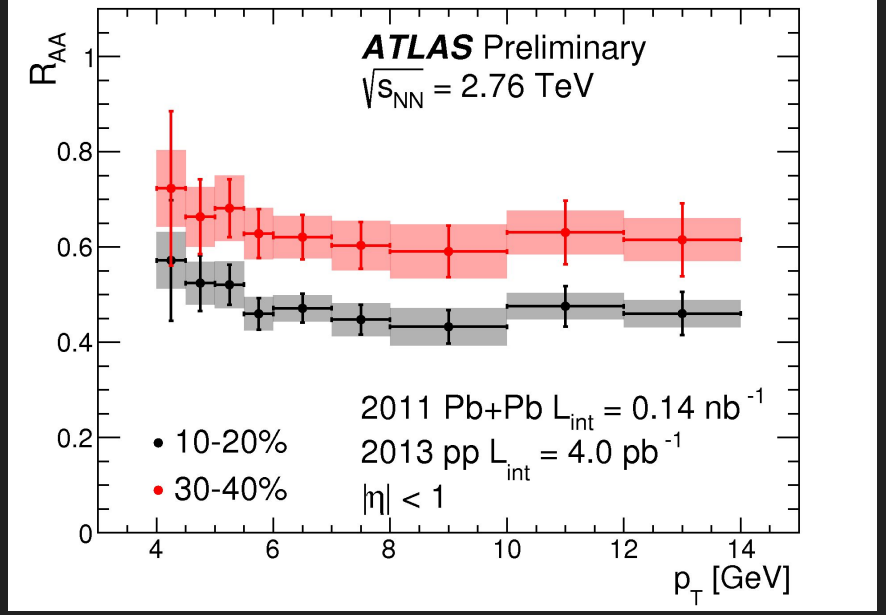


- Significant suppression is observed
- Suppression increases with centrality
- No pT dependence!

R_{AA}: comparison to R_{CP}

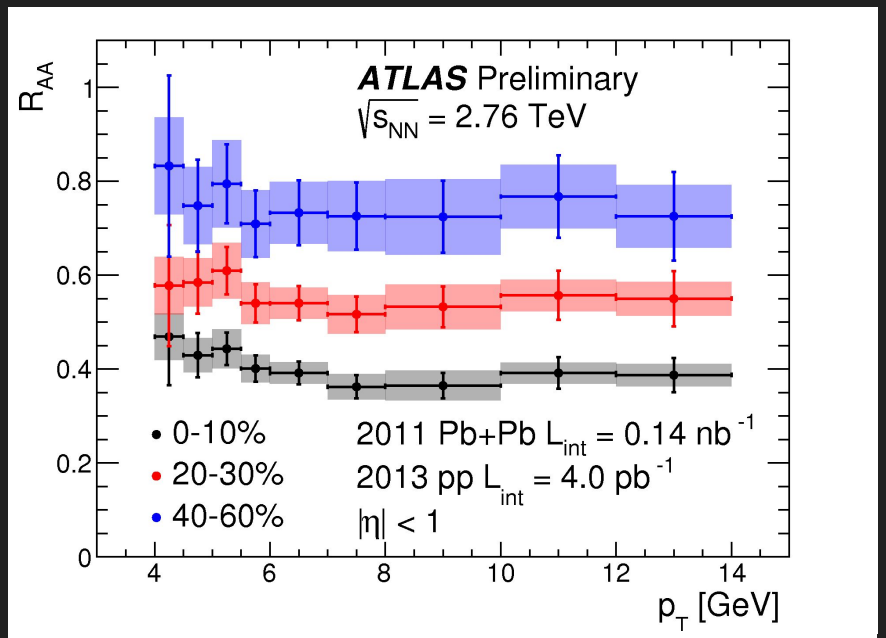


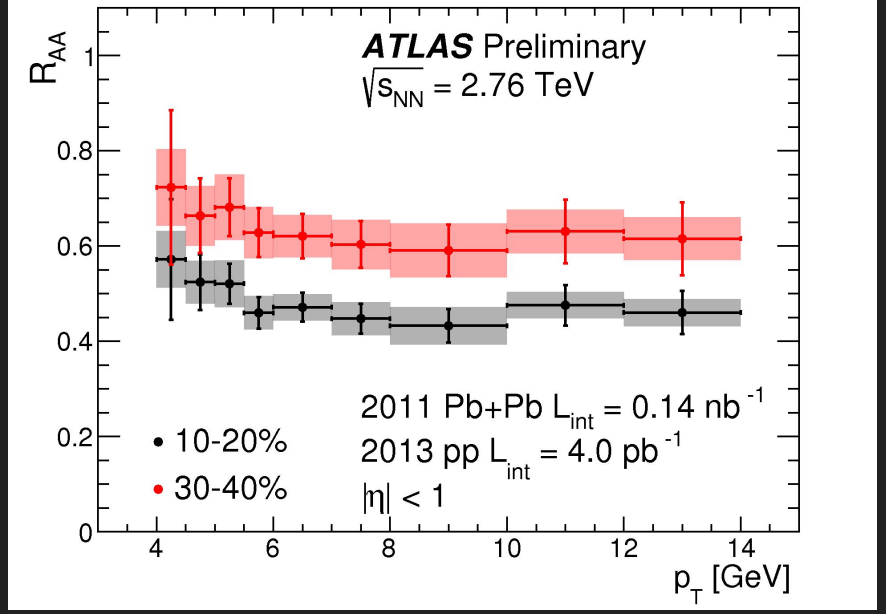


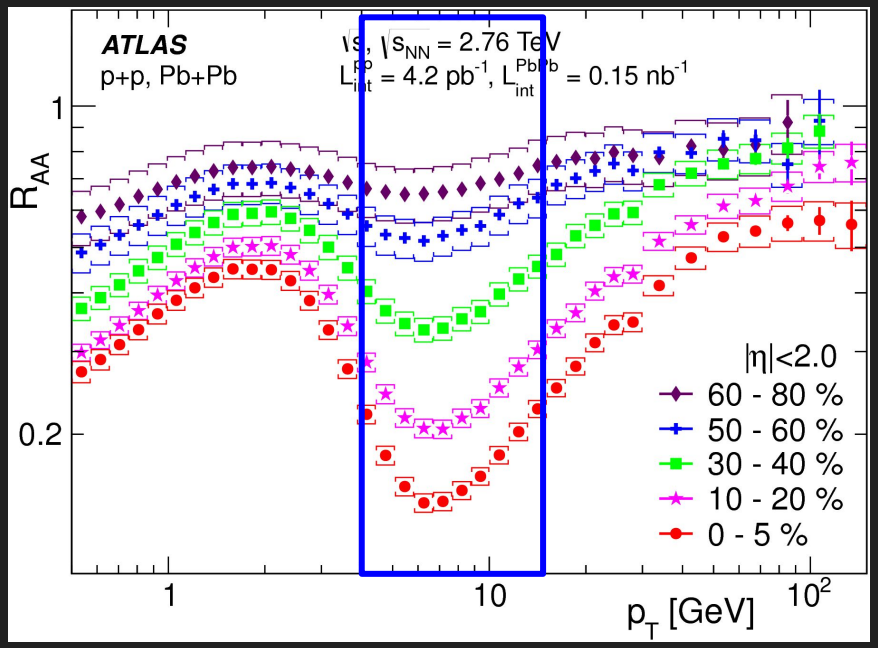


Quite Consistent with previous R_{CP} measurements

R_{AA}:comparison to inclusive hadrons



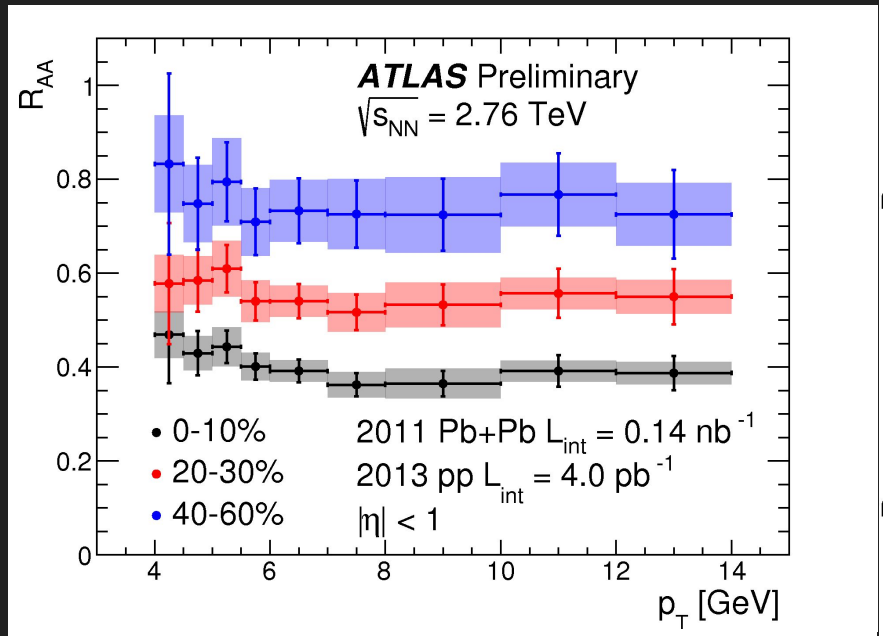


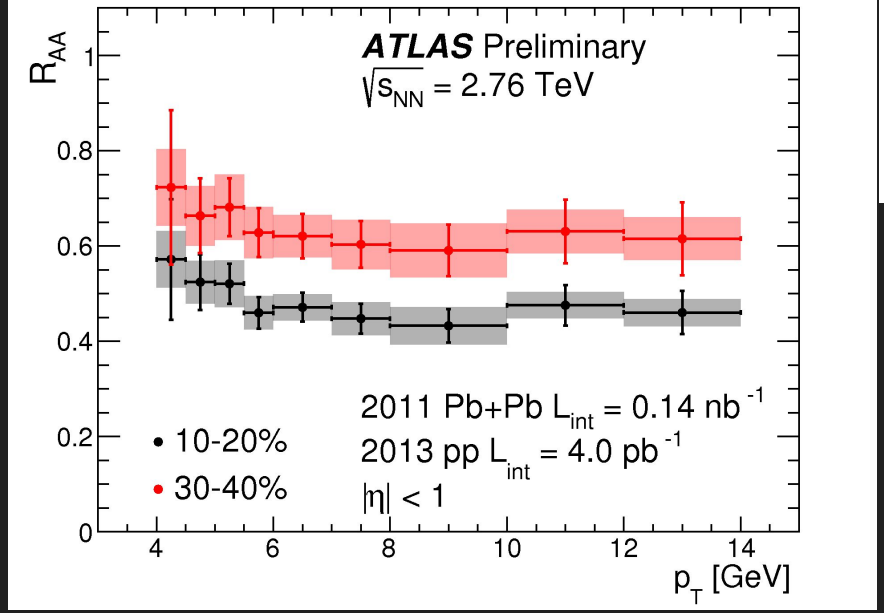


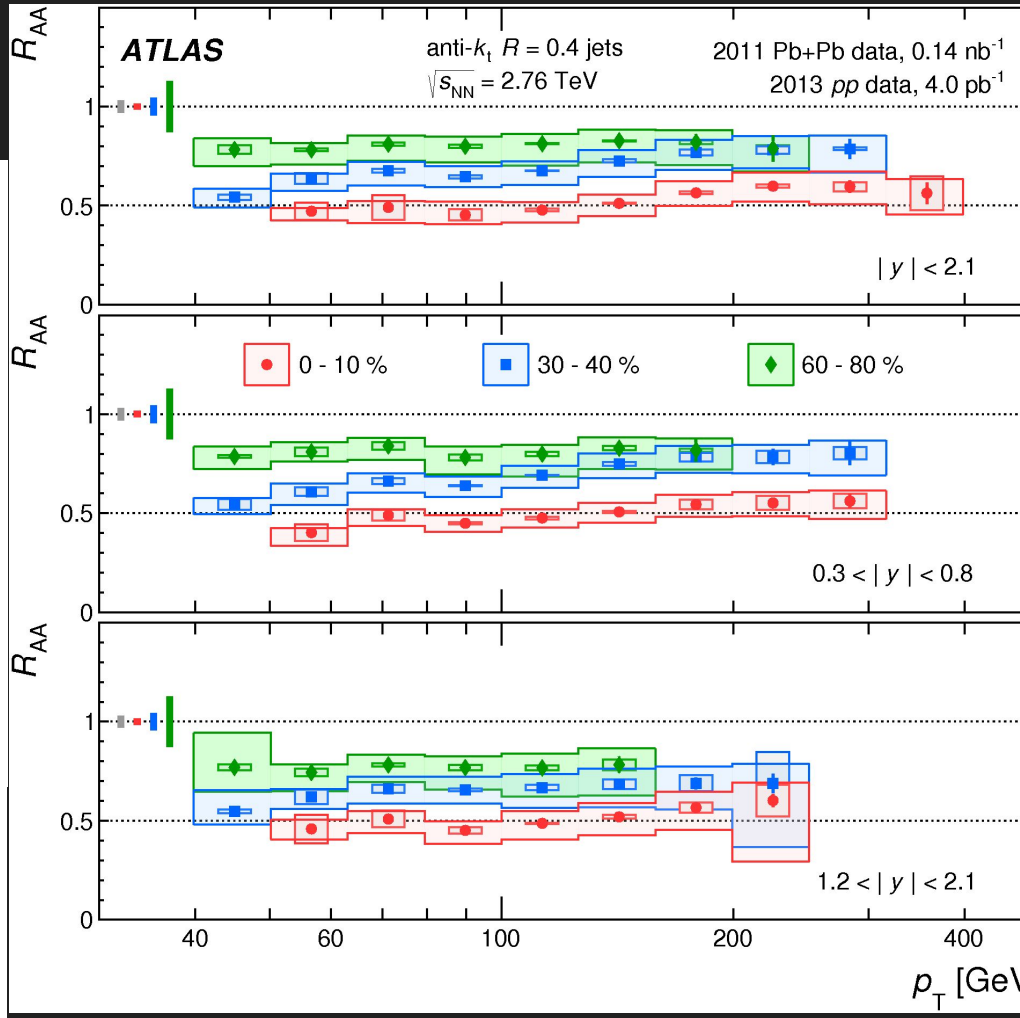
JHEP09 (2015) 050

Smaller suppression is seen for muons compared to hadrons, over the same pT range

R_{AA}:comparison to jets





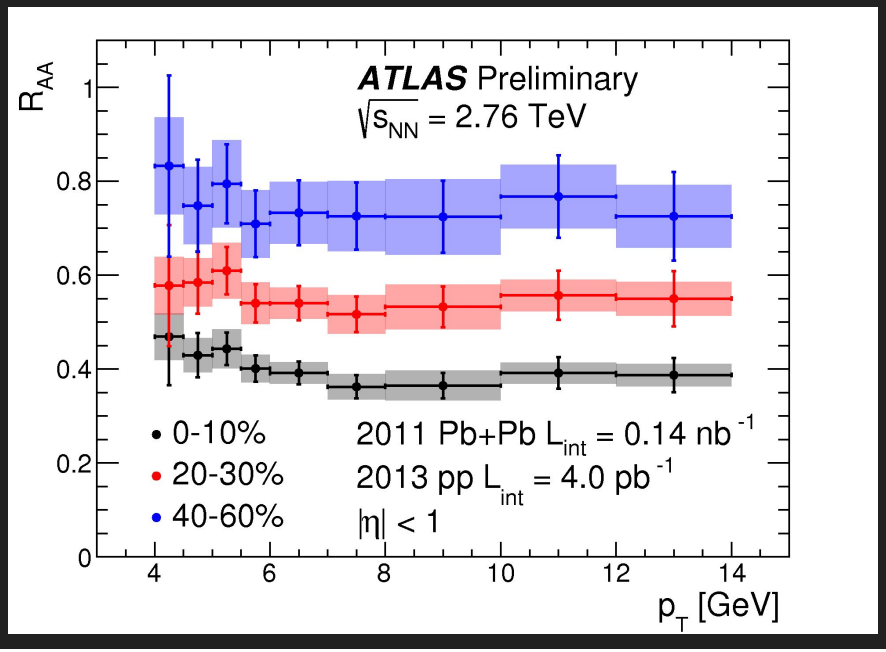


PRL 114 (2015) 072302

Similar suppression to Jets: weak pT dependence!

(Not apples to apples comparison)

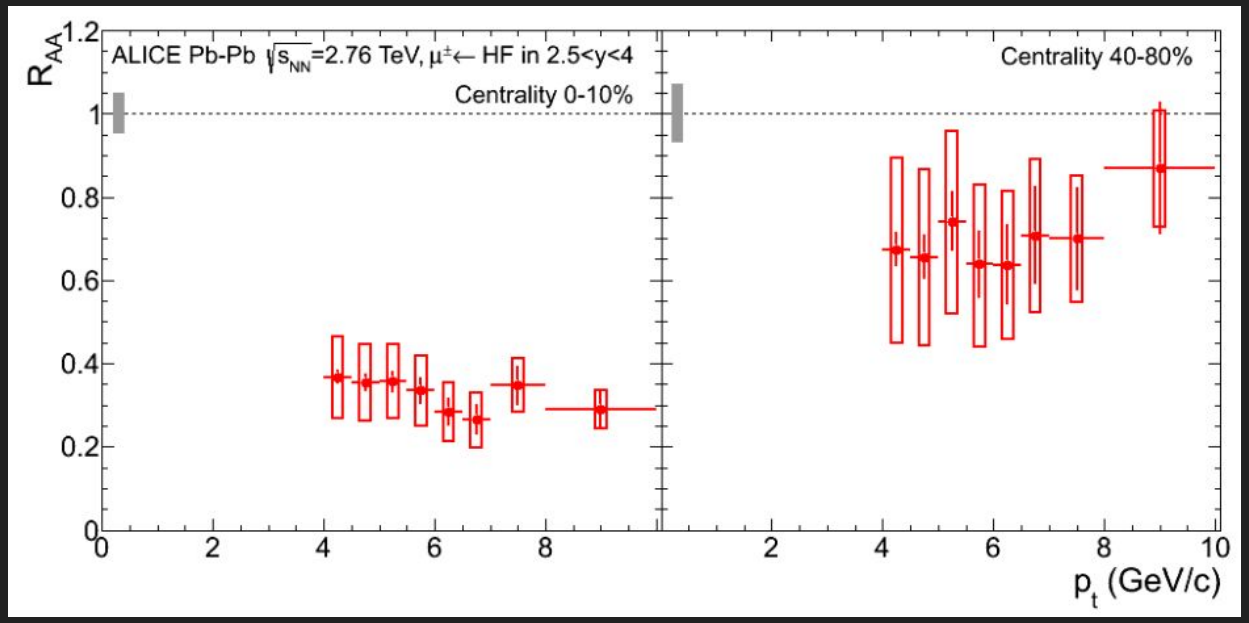
R_{AA}:mid vs forward rapidity



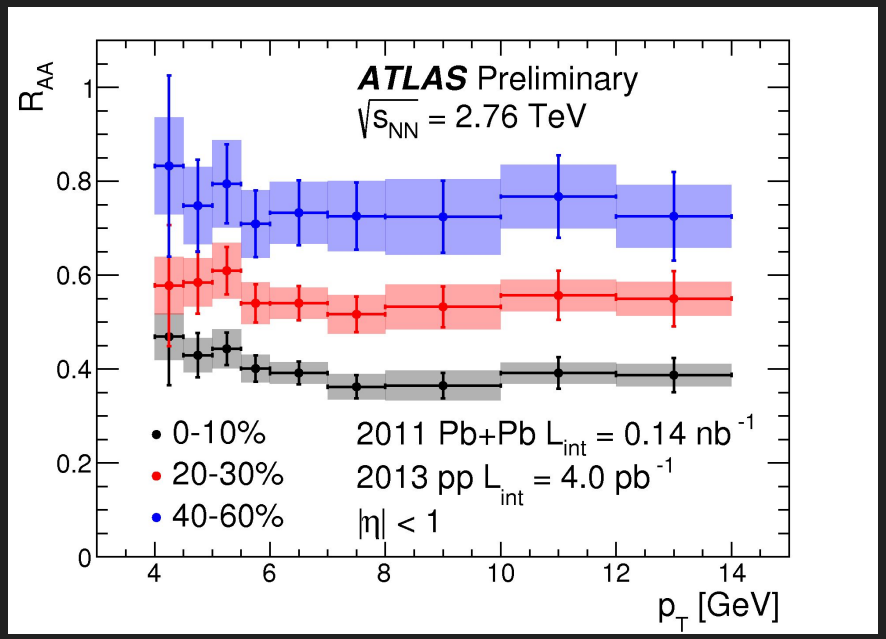
Consistent with suppression at forward rapidity (ALICE)

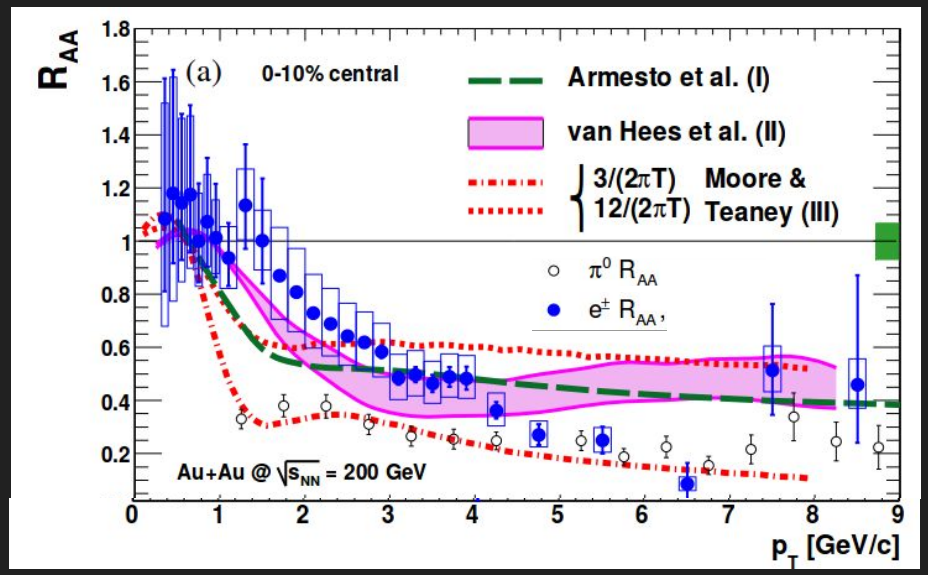
No p_T dependence seen there as well

ALICE results: PRL 109, 112301 (2012)



R_{AA}:comparison to RHIC



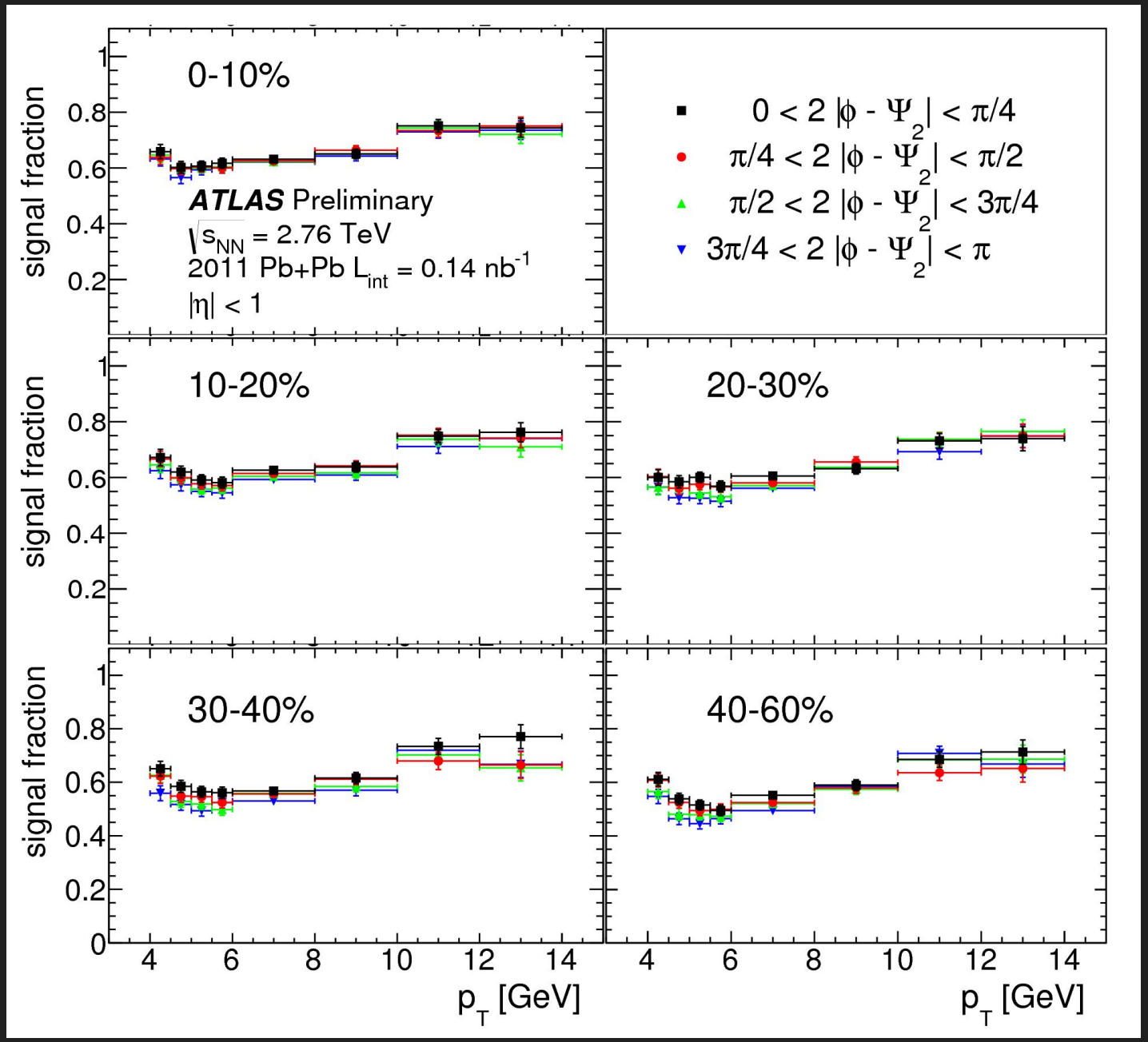


PHENIX Results: PRL.98, 172301 (2007)

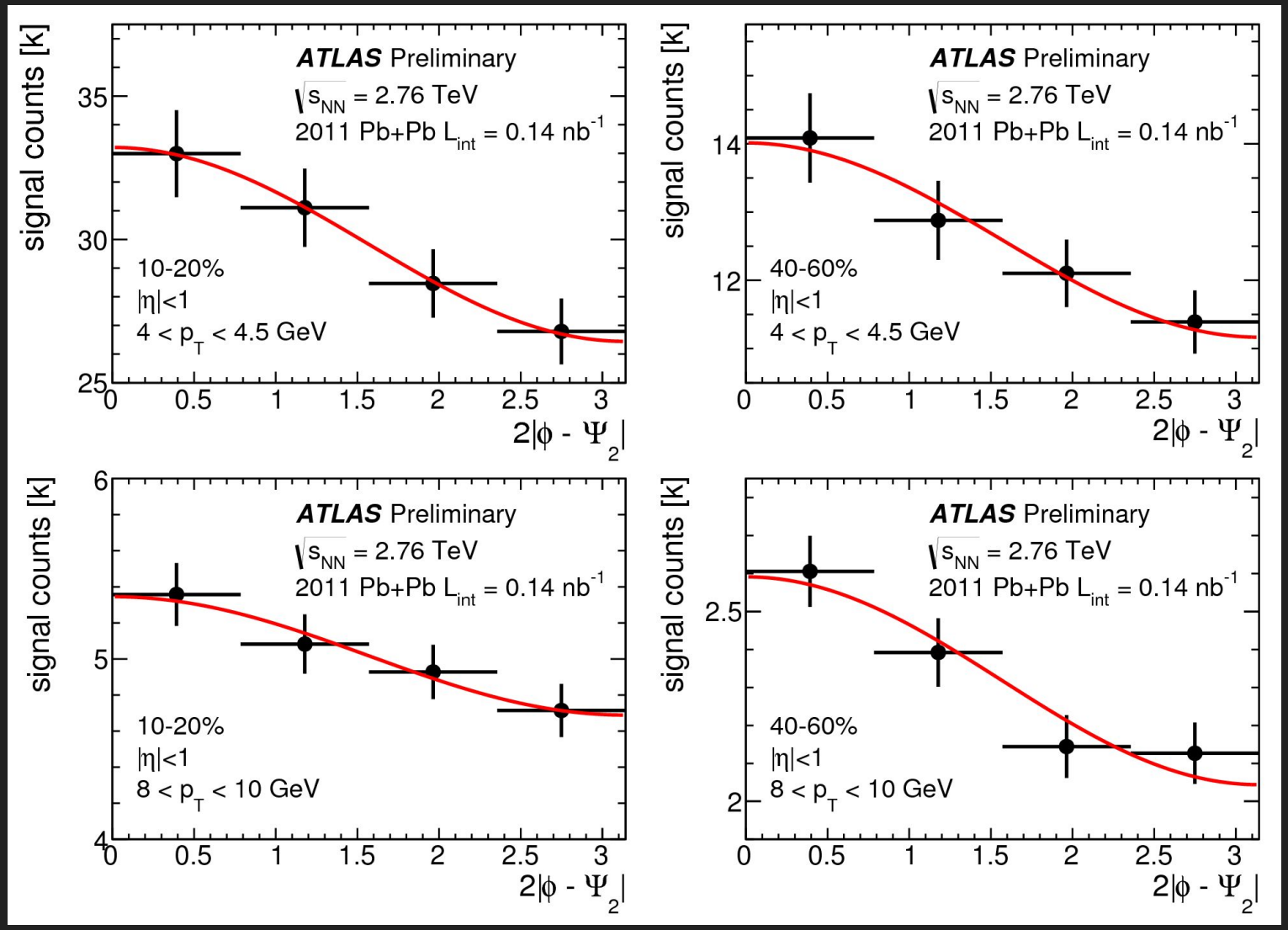
Smaller suppression that what seen at RHIC (over same p_T range)

More consistent with theoretical calculations

Event-plane dependence of signal fractions

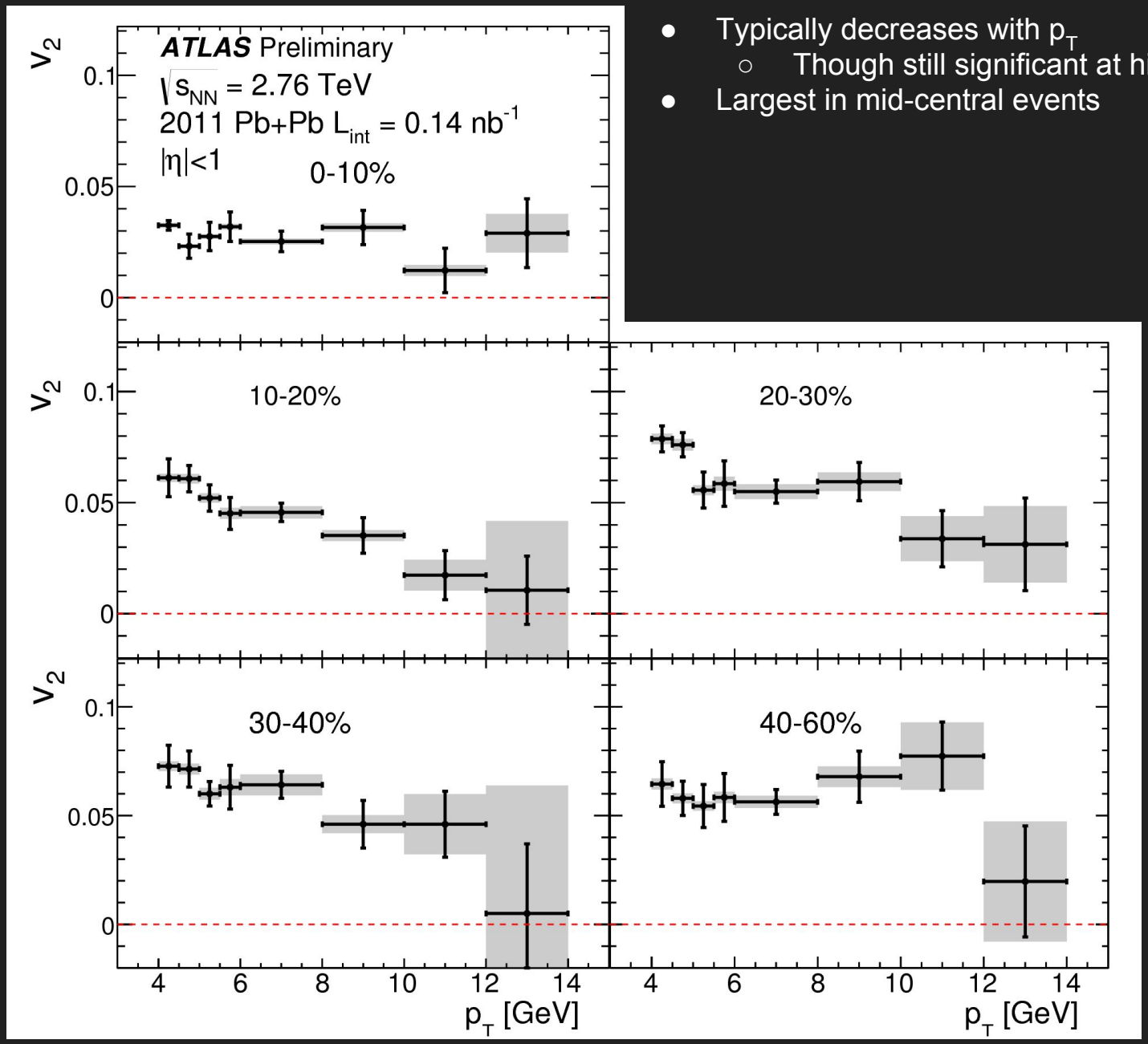


Prompt muon anisotropy wrt ψ_2 plane



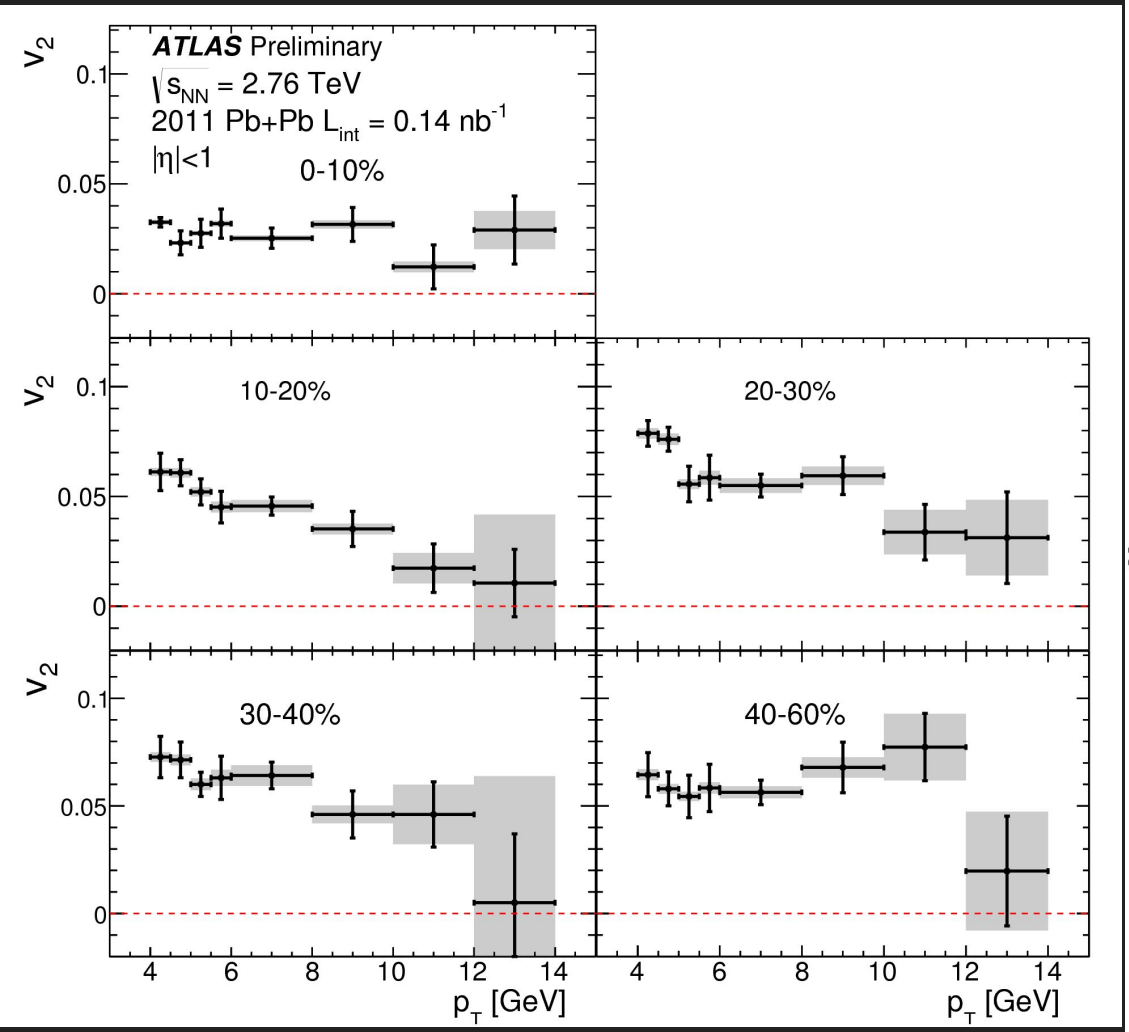
Larger Yields in the “in-plane” direction as compared to “out of plane-direction”

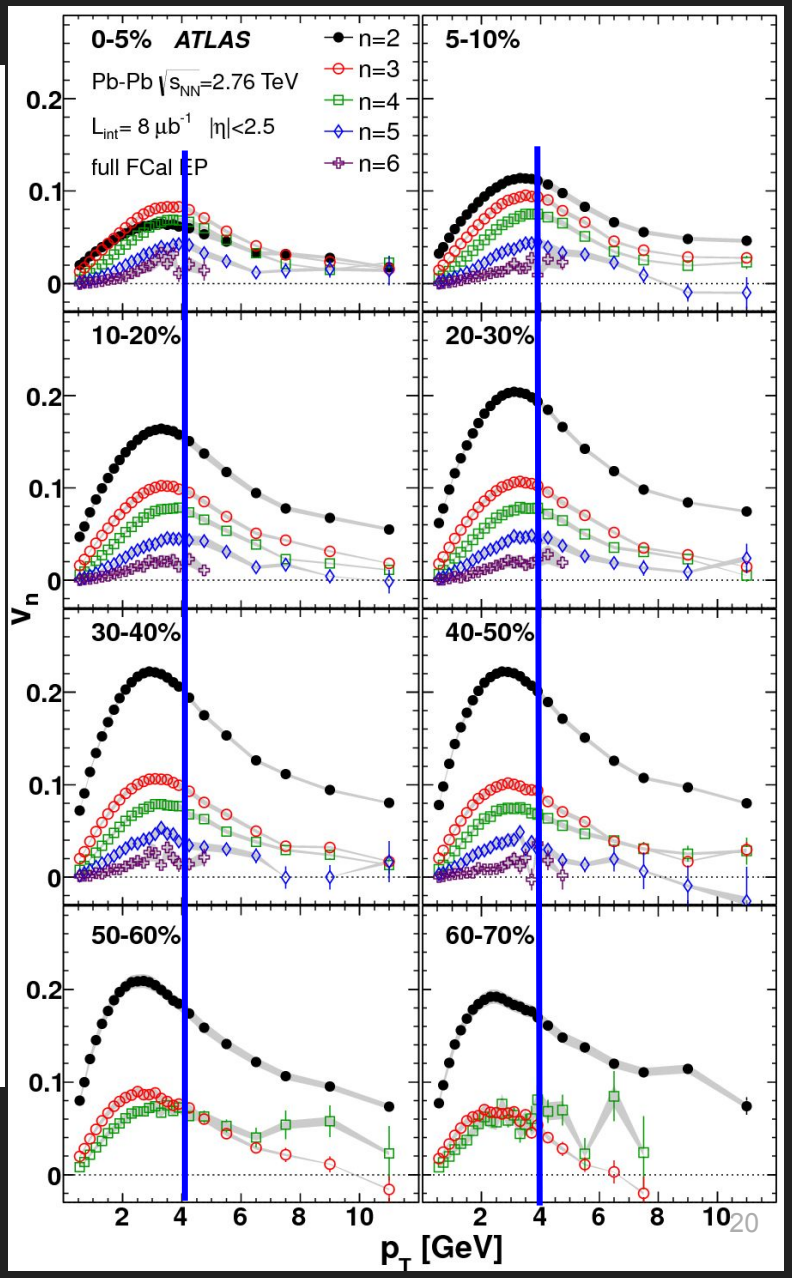
Prompt muon v_2: p_T dependence



- Typically decreases with p_T
  - Though still significant at high p_T
- Largest in mid-central events

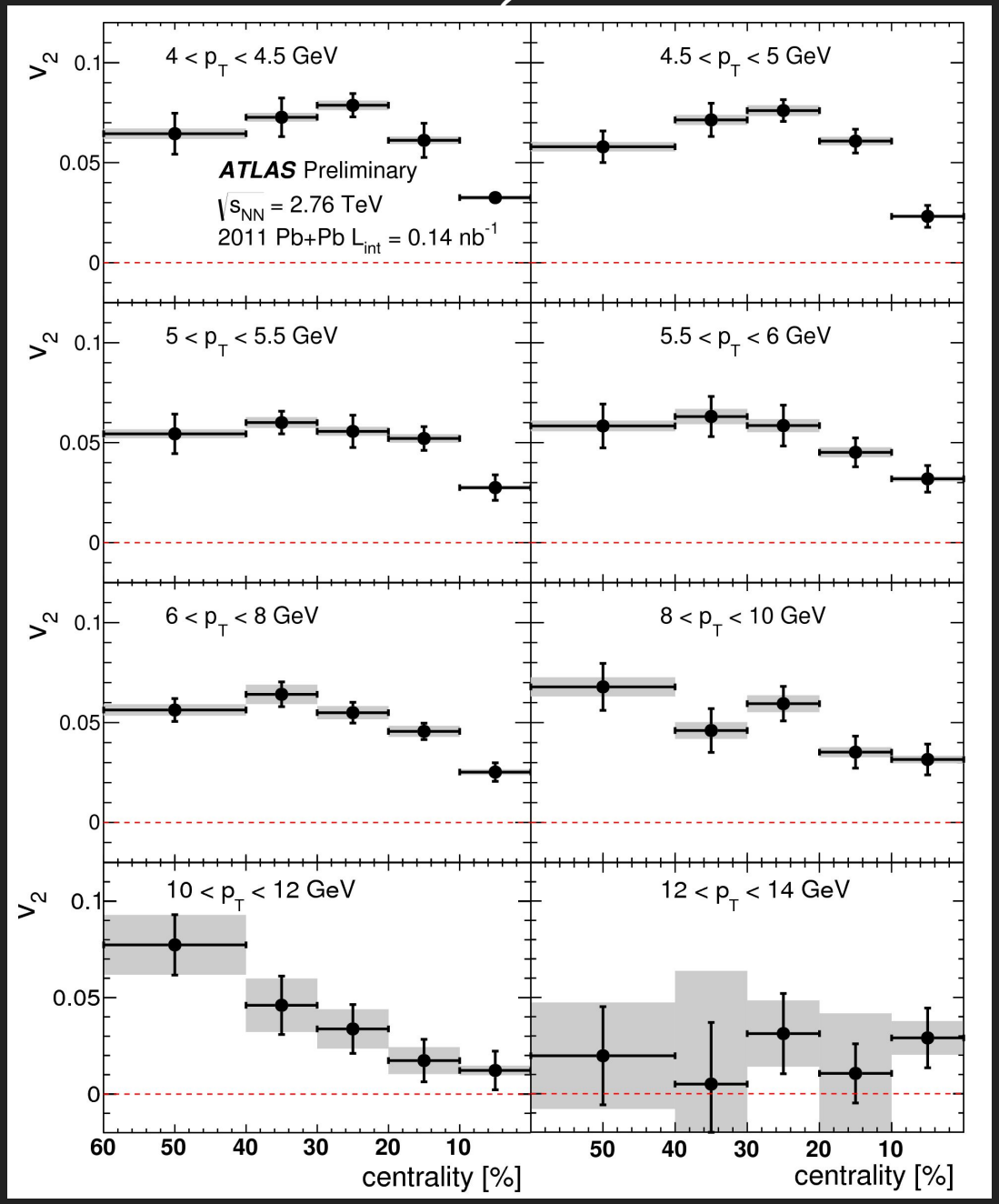
Prompt muon v_2: p_T dependence, comparison to hadrons



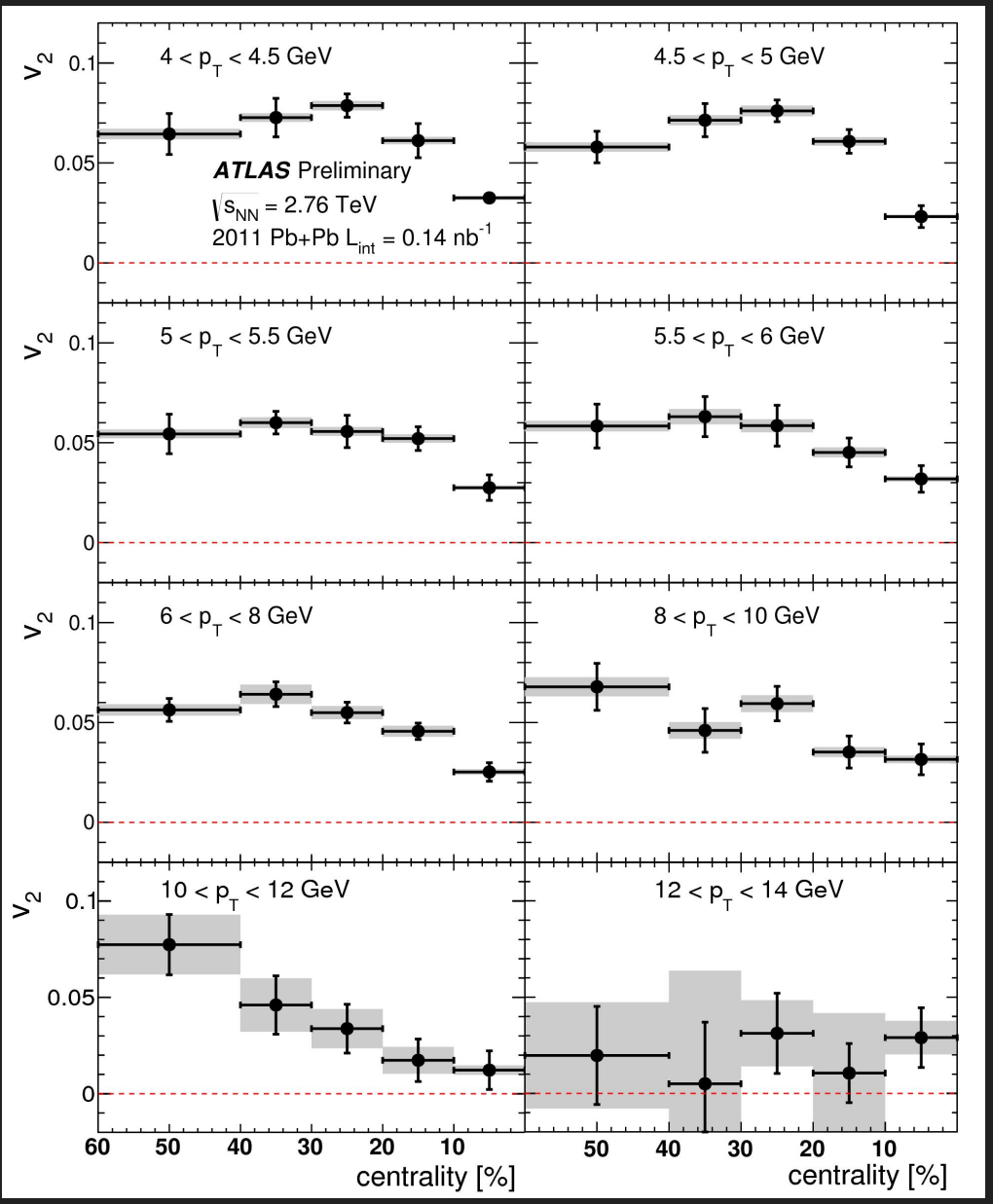


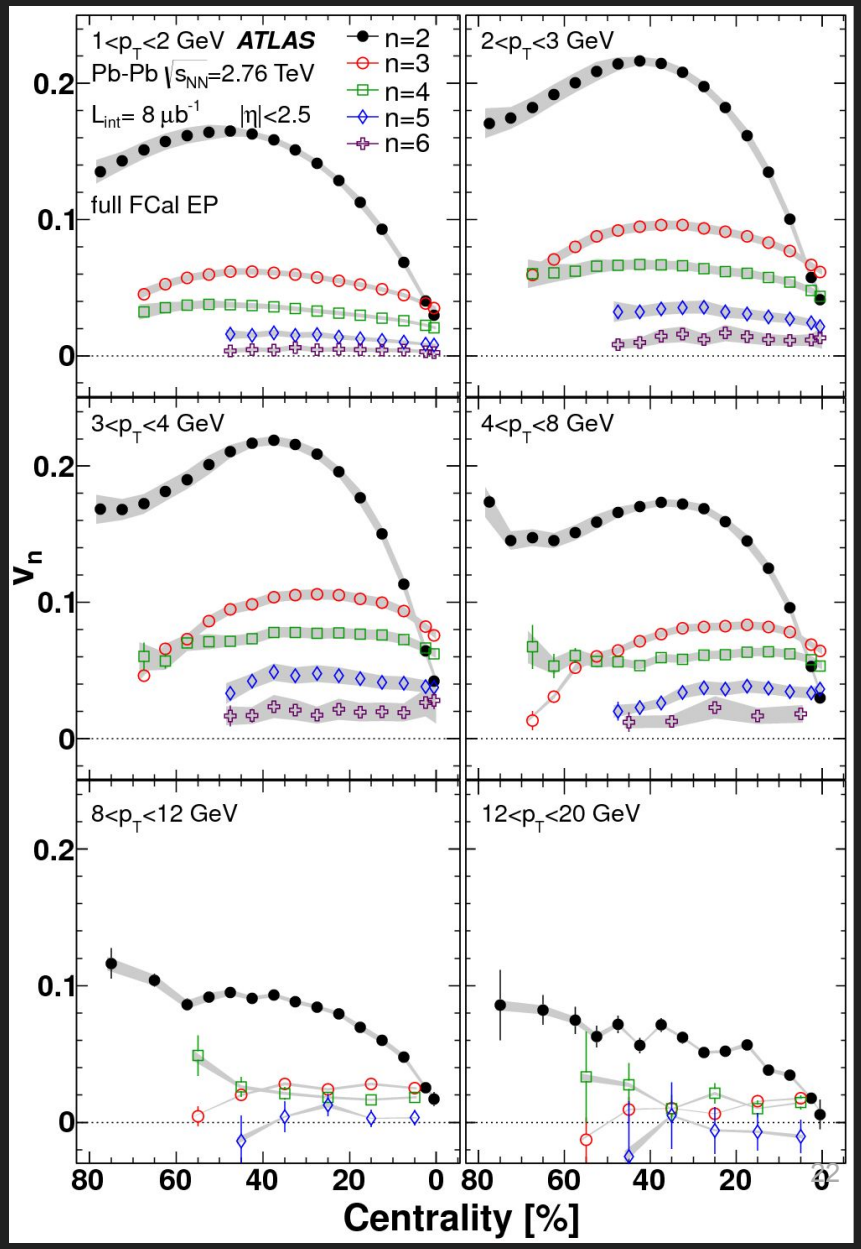
Significantly smaller v_2 compared to inclusive hadrons

Prompt muon v_2: centrality dependence

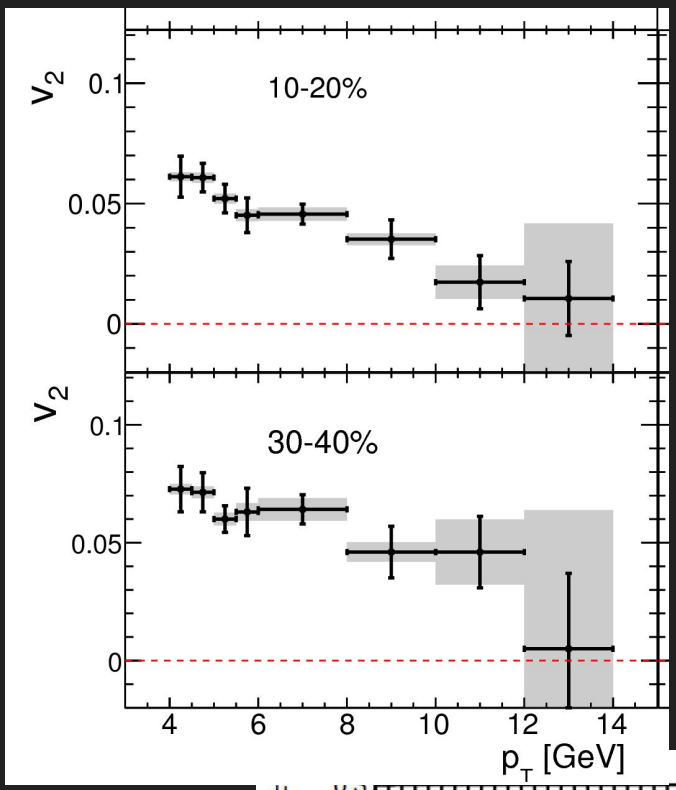


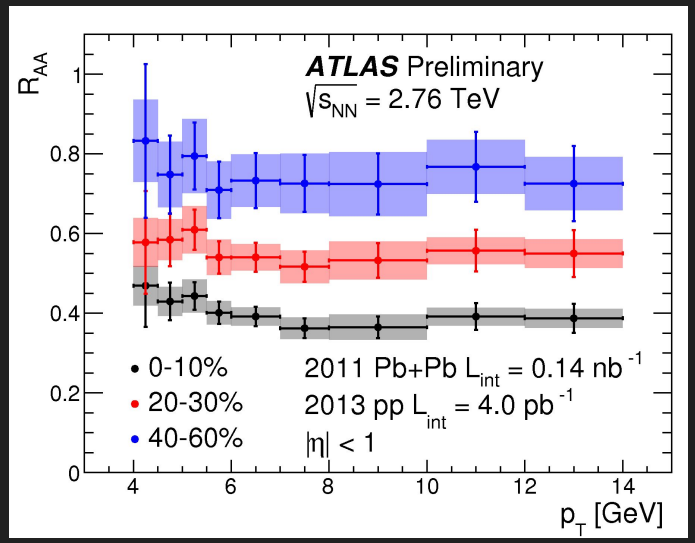
Prompt muon v_2: centrality dependence, comparison to hadrons

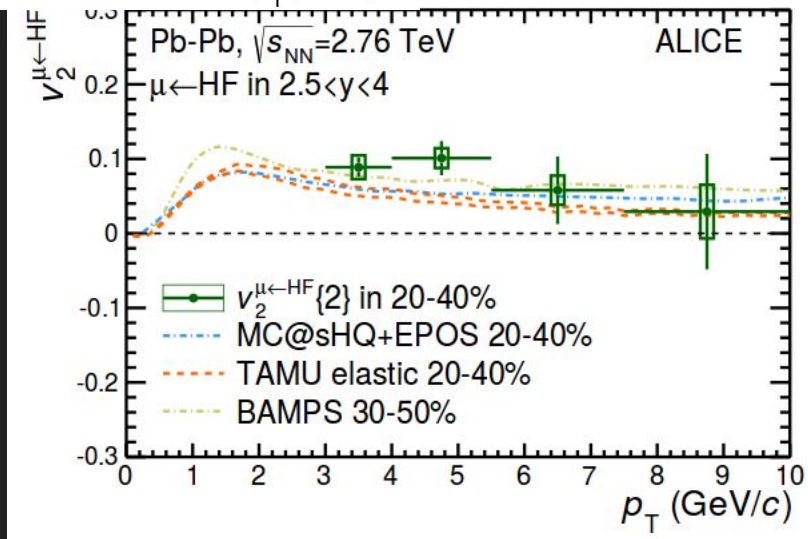


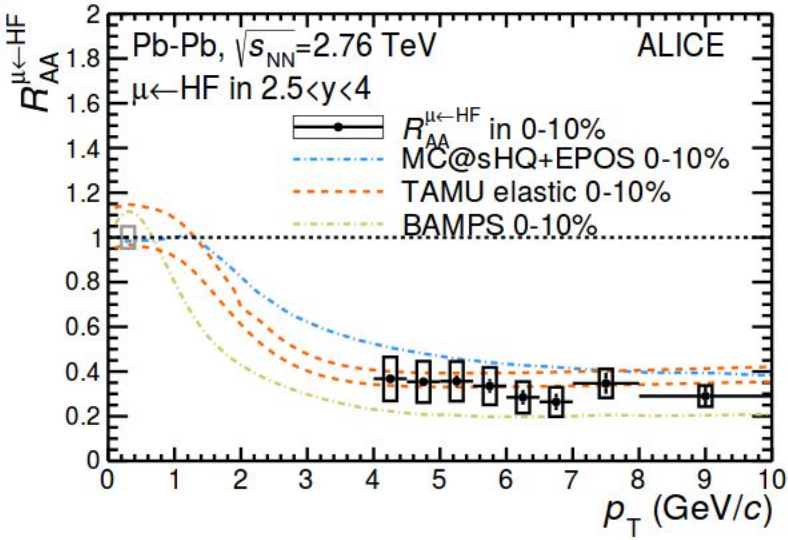


Prompt muon v_2 & R_{AA} : comparisons to ALICE









Summary

- ATLAS has measured prompt muons from HF decays in Pb+Pb and pp collisions at 2.76 TeV

- R_{AA}
  - Centrality dependent suppression is observed
  - Weaker suppression as compared to inclusive hadrons
  - No p_T dependence of suppression, very different than inclusive hadrons
  - Consistent with R_{CP} measurements and with forward rapidity measurements

- v_2
  - Significant v_2 is observed
  - v_2 decreases with increasing p_T (for mid-central events)
  - Smaller than inclusive hadron v_2, but similar shape

Systematic Uncertainties : Yields

Uncertainty	p_T Range [GeV]	Value
Trigger Efficiency	4--14	1--4%
Muon selection cuts	4--4.5, >7	1.5, 3%
P_{MS} cut	4--14	3--1 %
Template (background)	4--14	7--1 %
p_T resolution	4--14	1 (2 for pp) %
Cut Method	4-14	10--6% (15--6 for pp)

Systematic Uncertainties : v_2

p_T interval	$4<p_T<5$ GeV		$6<p_T<10$ GeV		$10<p_T<14$ GeV	
Centrality	0–10%	40–60%	0–10%	40–60%	0–10%	40–60%
Muon selection cuts [%]	2	1	2	2	2	5
p_{MS} cuts [%]	1	4	0	0	0	0
Background Template variation [%]	1	2	2	3	3.5	40
p_T resolution [%]	1	0	4	2	25	70
EP resolution [%]	2.5	4	2.5	4	2.5	4

Table 2: Relative systematic uncertainties on the heavy flavor muon v_2, quoted in percent, for selected p_T and centrality intervals. They are averaged over p_T intervals that are larger than the intervals used for the measurement.

T_{AA} and its uncertainties

Centrality interval [%]	$\langle T_{AA} \rangle$ [mb^{-1}]
0–10	23.45 ± 0.37
10–20	14.43 ± 0.30
20–30	8.73 ± 0.26
30–40	5.04 ± 0.22
40–60	2.02 ± 0.15