Heavy Quark Production in Pb-Pb Collisions at the LHC with the ATLAS Detector

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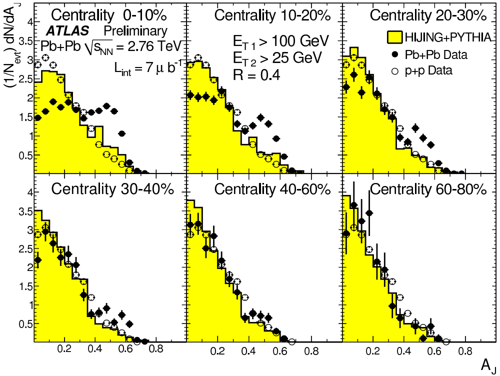
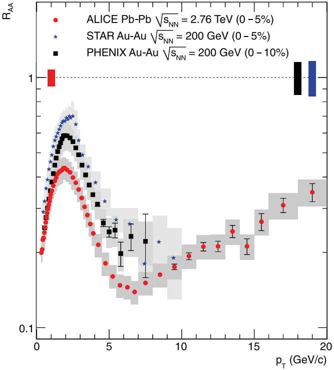
Introduction

- Heavy quark measurements complement light quark/gluon dominated measurements (jets, leading hadrons):
  - larger mass, different formation time, etc.
  - essential for full picture of jet quenching.
- Are heavy quarks suppressed at the same level as light quarks/gluons?
- Is heavy flavour suppression at RHIC and the LHC similar?

ATLAS-CONF 2011-075



Phys. Lett. B696 (1011) 30



ATLAS detector

Detector coverage:

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

Calorimeter (CAL):
$|\eta| < 3.2$ (EM)
$|\eta| < 4.9$ (HAD)
$3.1 < |\eta| < 4.9$ (FCal)

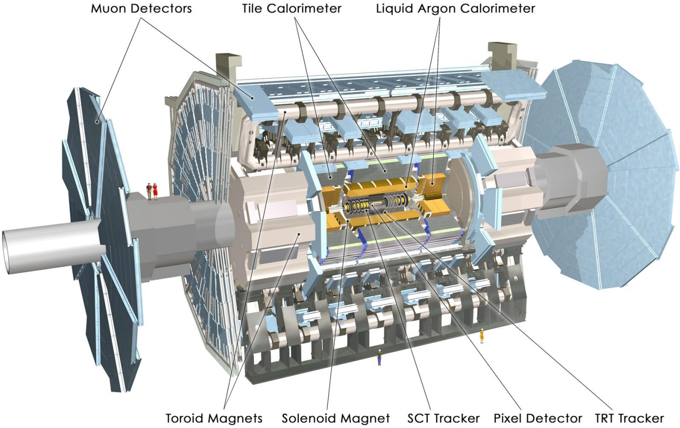
Muon Spectrometer (MS):
$|\eta| < 4.9$

Zero Degree Cal. (ZDC):
$|\eta| > 8.3 \quad @z = \pm 140$ m

MB Trig. Scint. (MBTS):
$2.1 < |\eta| < 3.9$

Magnetic fields:

- 2T solenoid field in ID
- Toroidal field in MS



Muon reconstruction: combined measurements by silicon pixel detectors / silicon microstrip detectors / straw tube tracker (ID) and muon spectrometer.

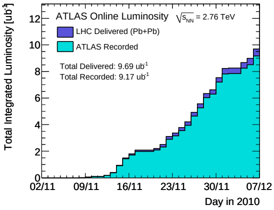
Centrality determination: Forward calorimeters (FCal).

Identification of minimum-bias Pb+Pb Collisions: measurement of spectator neutrons in Zero Degree Calorimeters (ZDCs) and charged particles (pulse hight and arrival times) in Minimum Bias Trigger Scintillators (MBTS).

Event selection and centrality determination

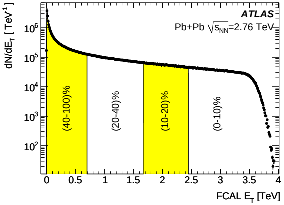
Data:

- Pb+Pb run in 2010, $\sqrt{s_{NN}} = 2.76$ TeV, $L = 7\mu b^{-1}$
- minimum-bias: ZDC .and. MBTS coincidence triggers
- timing requirement $\Delta t_{\mathrm{MBTS}} < 3$ ns
- primary vertex from tracks with $p_T > 500$ MeV
- efficiency $98 \pm 2\%$ (ineficiency concentrated in most peripheral bin, not used in the analysis)



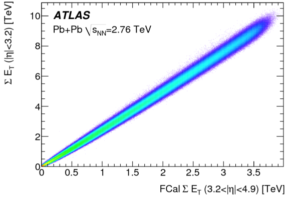
Monte Carlo:

- 5×10^6 Pythia $p + p \rightarrow$ dijets events, p_T=17-560 GeV overlayed with 10^6 Hijing Pb+Pb events.



Centrality determination (PRL 105 (2010) 252303):

- $\sum E_T^{\mathrm{FCal}}$ used for centrality categorization,
- use convolution of Glauber model with parameterized $p + p$ FCal response,
- used bins: 0-10%, 10-20%, 20-40%, 40-60%, 60-80%,
- $60 - 80\%$ used as a common peripheral reference in the analysis.



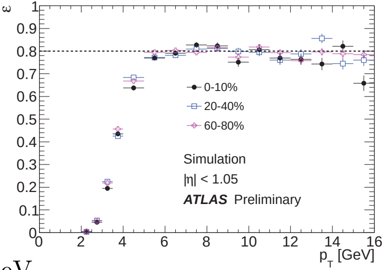
Muon reconstruction and efficiency

- Combining separate measurements of the muon trajectory in ID and MS.
- Using the same algorithm as in $p + p$ collisions (PLB 707 (2012) 438)

- tracks required to point within 5 mm of the primary vertex,
- $p_T > 4$ GeV (good reconstruction efficiency),
- $p_T < 14$ GeV (limitted statistics, contribution from $W^{\pm}$ decays is less than 1%),
- $|\eta| < 1.05$ (to avoid transitional region in calorimeter coverage),
- p_T resolution is about 5% in HI collisions.

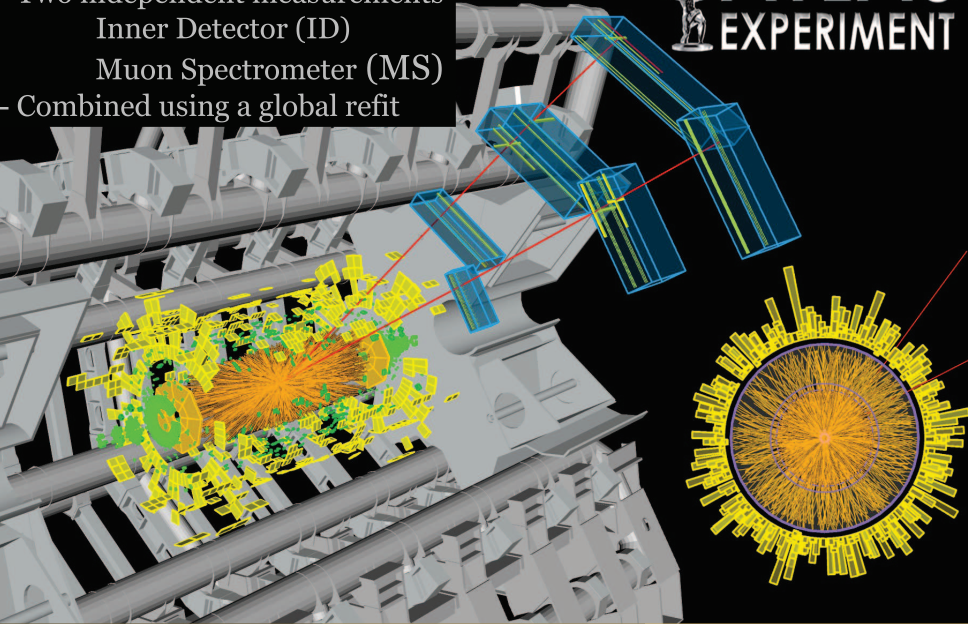
p_{T} [GeV]	Centrality [%] 0–10	10–20	20–40	40–60	60–80
4–5	49k	36k	43k	17k	4.7k
5–6	19k	15k	18k	7.4k	2.0k
6–7	8.6k	6.5k	8.2k	3.4k	0.93k
7–8	4.1k	3.1k	3.9k	1.6k	0.46k
8–9	2.2k	1.7k	2.1k	0.78k	0.21k
9–10	1.2k	0.93k	1.1k	0.46k	0.13k
10–14	1.7k	1.31k	1.5k	0.62k	0.15k

- Reconstruction efficiency for $\mu^{\pm}$ from semi-leptonic c and b decays estimated from MC:
- centrality independent for $p_T > 5$ GeV ($\varepsilon_{\mathrm{plateau}} = 80 \pm 2\%$),
- weak centrality dependence for $4 < p_T < 5$ GeV.



Muon reconstruction:

- Two independent measurements
  - Inner Detector (ID)
  - Muon Spectrometer (MS)
- Combined using a global refit



Muon signal extraction

Signal: muons which originate directly from Pb+Pb collisions, from vector meson decays and from heavy quark decays.

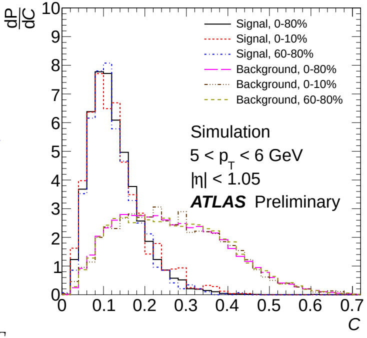
Background: muons from decays of pions and kaons, produced in hadronic showers or misidentified ID or MS tracks.

Statistical discrimination between signal (S) and background (B) based on:

❶ fractional momentum imbalance: $\frac{\Delta p_{\rm loss}}{p_{\rm ID}} = \frac{1}{p_{\rm ID}}\left(p_{\rm ID} - p_{\rm MS} - \Delta p_{\rm calo}(p,\eta,\phi)\right)$

❷ 'scattering significance' - a measure of deflection in azimuthal angle of hit position from fitted muon trajectory, compared to expected deviation from multiple scattering:

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

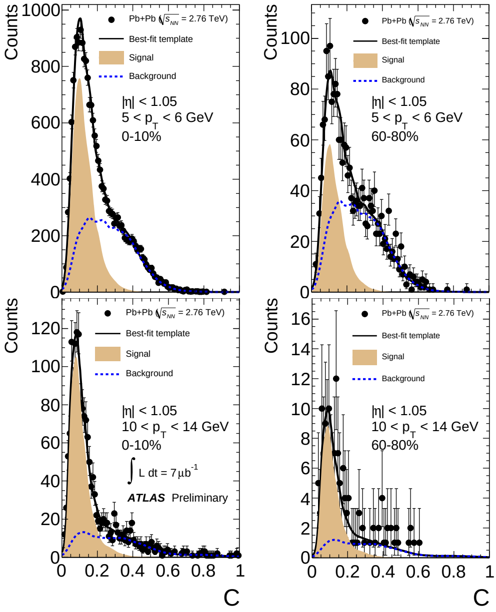


Composite discriminant:

$$C = \left|\frac{\Delta p_{\rm loss}}{p_{\rm ID}}\right| + 0.07\cdot\max(S(k))$$

- no centrality dependence
- increasing separation with increasing muon p_T
- heavy quark signal well separated from $\pi^\pm/K^\pm$ background

Heavy flavour extraction: template fitting



Fit the template S+B distribution to the C distribution in the data:

$$\frac{\mathrm{d}P}{\mathrm{d}C} = f_\mathrm{S}\,\frac{\mathrm{d}P}{\mathrm{d}C}\Big|_\mathrm{S} + (1 - f_\mathrm{S})\,\frac{\mathrm{d}P}{\mathrm{d}C}\Big|_\mathrm{B}$$

Allow for possible differences in the C distribution between data and MC by shifting and scaling:

$$C' = a + \langle C \rangle + b(C - \langle C \rangle)$$

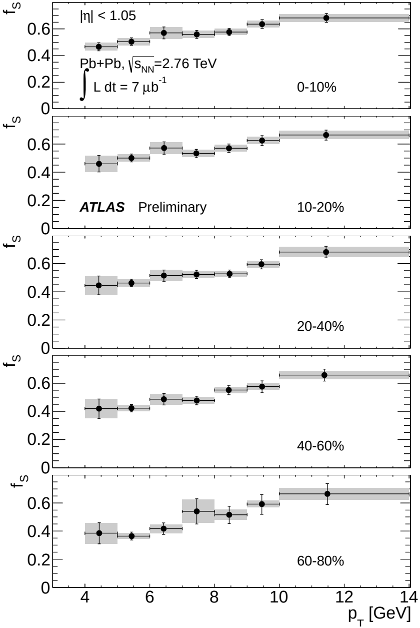
and include Gaussian smearing of the MC C distribution:

$$\frac{\mathrm{d}P'}{\mathrm{d}C'} = \frac{\mathrm{d}P}{\mathrm{d}C'} \otimes \frac{e^{-C'^2/2\sigma^2}}{\sqrt{2\pi}\,\sigma}$$

Typical fitted values:

$$a \sim 0.02, \quad b \sim 0.95 - 1.05, \quad \sigma \sim 0.002$$

Signal fraction



Extract heavy flavour component from inclusive $\mu^{\pm}$ yield.

Shaded boxes indicate systematic uncertainty due to possible data-MC template mismatch and the template fitting ($\mathrm{d}P/\mathrm{d}C$ and "Fit" - next slide).

Error bars show combined statistical and systematic uncertainties.

Systematic uncertainty

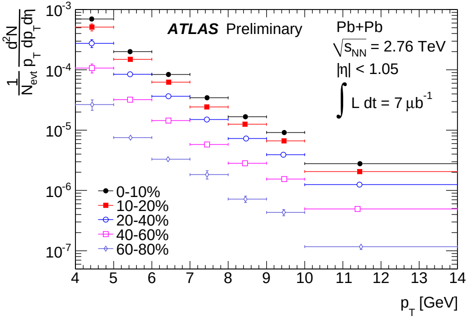
Main sources of systematic uncertainty on f_S:

- $\mathrm{d}P/\mathrm{d}C$ - possible mismatch betwen C distributions in data and MC:
  - performing fits with fixing a and σ to zero and b to one,
  - use centrality integrated MC C distribution in template fitting,
- Fit - uncertainy due to template fitting procedure:
  - use $C < C_{\mathrm{cut}}$ for $C_{\mathrm{cut}} = 0.15$, 0.2, 0.25 as alternate signal definition,
- K/π - possible mismatch of the primary hadron composition in data and MC:
  - new MC background C distributions were obtained by separately dubling the π and K contributions,
  - new C_B distributions were used in the template fits,
- ε - $\mu^{\pm}$ reconstruction efficiency uncertainty.

Centrality [%]	p_{T} [GeV]	Uncertainty [%]				
		dP/dC	Fit	K/π	ε	Total
0-10	4–5	4	0	5	3	7
	7–8	5	0.5	0.5	2	5.5
	10–14	4	1	1	2	5
60-80	4–5	18	1	5	3	19
	7–8	14	5	0.5	2	15
	10–14	4	4	2	2	6

Invariant differential per-event muon yield for a given centrality:

$$\frac{1}{N_{\mathrm{evt}}} \left. \frac{\mathrm{d}^2 N}{p_T \, \mathrm{d}p_T \mathrm{d}\eta} \right|_{\mathrm{cent}} = \frac{1}{N_{\mathrm{evt}}^{\mathrm{cent}}} \frac{N_S^{\mathrm{cent}}(p_T)}{\varepsilon^{\mathrm{cent}}(p_T)\, p_T \Delta p_T \Delta\eta}$$



The yields increase by more than an order of magnitude between peripheral and central collisions as expected from geometrical enhancement of hard scattering rates.

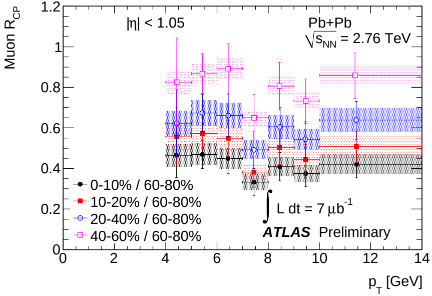
Define ratio of the invariant yields with respect to paripheral collisions:

$$R_{\mathrm{CP}}^{\mathrm{cent}} = \frac{1}{R_{\mathrm{coll}}^{\mathrm{cent}}} \frac{(1/N_{\mathrm{evt}}^{\mathrm{cent}})(\mathrm{d}N^{\mathrm{cent}}/\mathrm{d}p_T)}{(1/N_{\mathrm{evt}}^{60-80\%})(\mathrm{d}N^{60-80\%}/\mathrm{d}p_T)}$$

where $R_{\mathrm{coll}}^{\mathrm{cent}}$ is the ratio of the numbers of binary collisions between central and peripheral collisions:

$\Rightarrow$ $R_{\mathrm{coll}}^{\mathrm{cent}}$=56.7±6.2 (0−10%), 34.9±3.5 (10−20%), 16.7±1.5 (20−40%), 4.9±0.2 (40−60%)

Results: $R_{CP}(p_T)$ from heavy flavour decays



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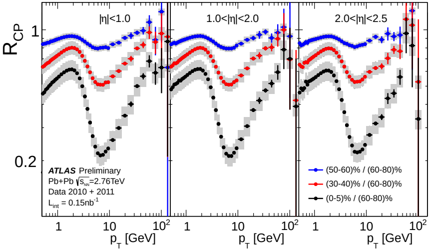
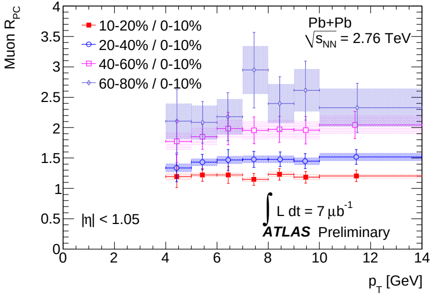


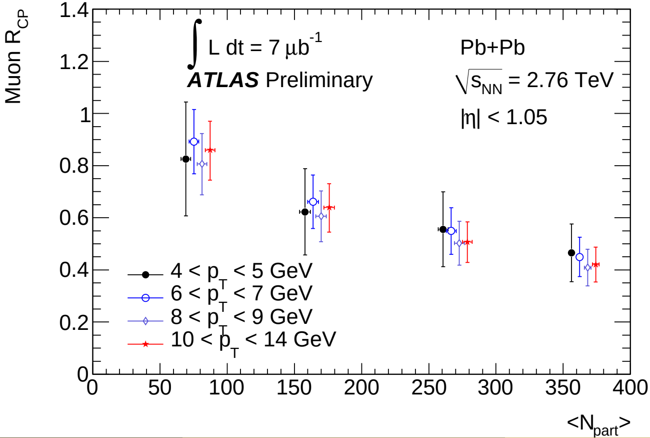


- shaded boxes - contrib. from $R_{\rm coll}$ and ε, error bars include both stat $\oplus$ sys,
- suppression increasing with centrality, $R_{\rm CP}^{0-10\%}/R_{\rm CP}^{60-80\%} \simeq 0.45$,
- almost no p_T dependence,
- different suppression than in single hadron (upper right),
- $R_{\rm PC}$ uses central bin $(0-10\%)$ as reference - smaller uncertainties.

Results: $R_{CP}(N_{part})$ from heavy flavour decays

Plot R_{CP} as function of $\langle N_{part} \rangle$:

- $\langle N_{part} \rangle$ - the average number of nucleons participating in the collision was estimated with a standard Glauber MC,
- suppresion decreases smoothly from peripheral to central collisions,
- the same dependence for all p_T bins.



Conclusions

- ATLAS has measured muon yields from heavy quark decays in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:
  - $4 < p_T < 14$ GeV and $|\eta| < 1.05$
  - template fitting method used to extract heavy quark signal from π/K background
- parameter R_{CP} indicates factor of more than two suppression in the yield of muons in the most central $(0-10\%)$ collisions compared to most peripheral $(60-80\%)$ collisions:
  - no significant variation with p_T,
  - R_{CP} decreases smoothly from peripheral to central collisions,
- distinct suppresion pattern from the ATLAS charged hadron R_{CP}, which indicates that heavy flavours behave differently at the LHC than at RHIC (Phys.Rev. C84 (2011) 044905),
- the central muon R_{CP} for $10 < p_T < 14$ GeV agrees with the central $(0-10\%)$ non-prompt J/Ψ R_{AA} measured by CMS (JHEP1205 (2012) 063).

More information in ATLAS-CONF-2012-050

Thank you for your attention!

Heavy flavours at Phenix (Phys.Rev. C84 (2011) 044905)

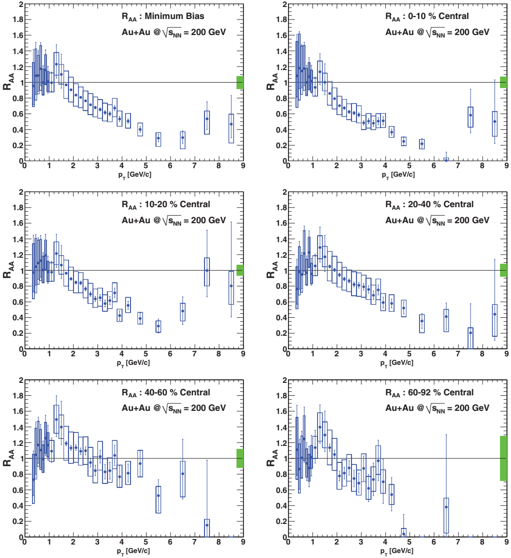


FIG. 34. (Color online) Open heavy-flavor electron R_{AA} for the indicated centralities. The boxes show the point-to-point correlated systematic uncertainty.

Backup slide

Heavy flavours at CMS (JHEP1205 (2012) 063)

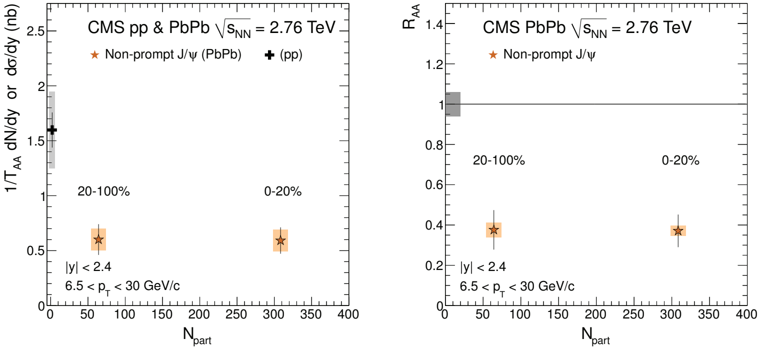


Figure 14. Left: non-prompt J/ψ yield divided by T_{AA} (orange stars) as a function of N_{part} compared to the non-prompt J/ψ cross section measured in pp (black cross). Right: nuclear modification factor R_{AA} of non-prompt J/ψ as a function of N_{part}. A global uncertainty of 6%, from the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Statistical (systematic) uncertainties are shown as bars (boxes).