W & HF→ μ in Heavy Ion Collisions

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Outline

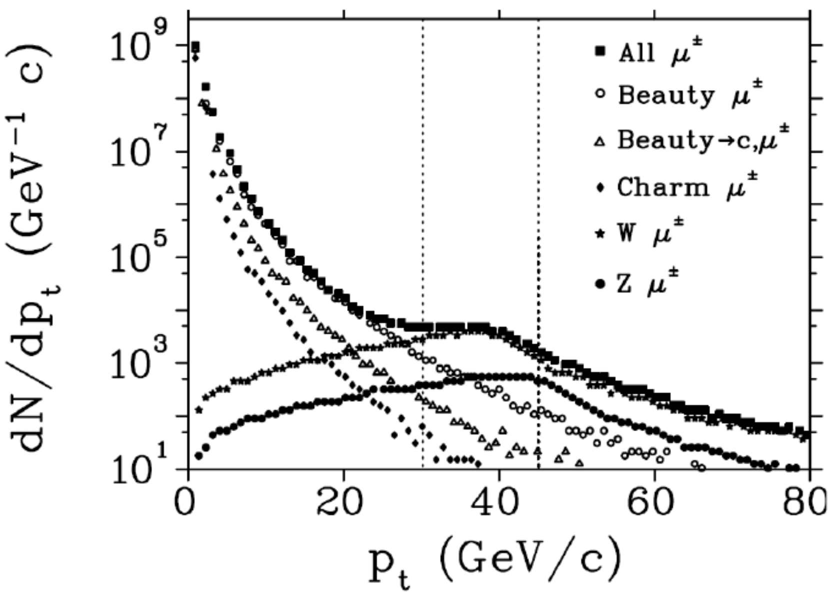
- Introduction
- W → mu analysis
  - Two methods of evaluating number of W bosons
  - W suppression
  - W charge asymmetry
  - W/Z ratio
- Heavy flavour → mu analysis
  - Analysis method
  - Discriminants
  - Test of method
  - Prompt fraction vs pT
  - Heavy flavour suppression
- Summary & conclusions

Introduction

- This analysis is using single muons to probe physics in ATLAS PbPb collisions from 2010.
  - Previous publication used dimuons, to study J/psi and Z events.
- Muons do not interact strongly and can therefore be used to study production of particles at central collisions.
  - Electroweak bosons should not interact with the medium once produced and we should hence see not centrality effects for W → mu and Z → mumu.
  - Heavy flavour (b/c) interact strongly with the medium. The expectation that their heavier masses may lead to a smaller gluon radiation than light flavour due to a suppression of small angle gluon radiation that is known in the literature as the ”dead cone effect”.
    - This topic has been extensively studied at RHIC.

W → mu analysis

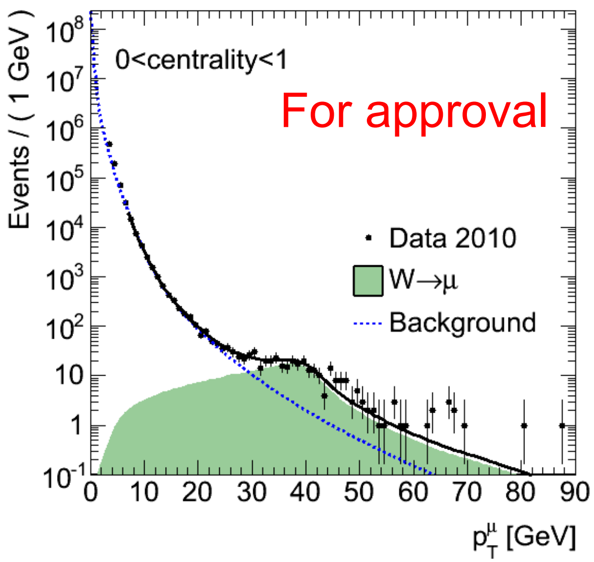
Principle behind W identification

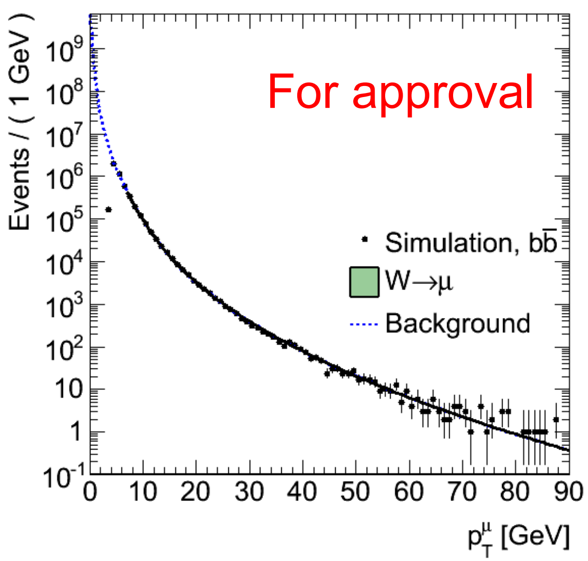


(From ALICE publication)

- Muons from W are in average more energetic than muons from QCD processes.
- At high transverse momenta, the two dominating sources of single muons are b-quark decays and W decays.
- The muons from W creates a "shoulder" in the pT spectrum.
- By comparing the how much the W component must be scaled compared to the background we can determine the number of W on data.

Fitting method





1) Veto dimuons with m>66 GeV (Z/DY candidates)
2) Veto obvious decays in flight.
   - Efficiency loss on W MC <0.3%.
3) Build a template from W → mu MC @ 2.76 TeV pp.
4) Use a function with two free parameters to describe background.

$$b(x) = a \cdot \frac{e^{k\sqrt{x}}}{x^{2.5}}$$

   - Tested on 5M bbbar events, chi2/dof = 1.4.
5) Find the best estimate on number of W but fitting signal+background to data.
   - Log-likelihood fit with MINOS errors.

Cut & count method

- The fitting method works fine, but the low number of peripheral W events gives large statistical uncertainty.
- A cut & count method used in many other ATLAS papers was performed as a cross check.
  - n = number of events on data at pt>30 GeV (signal region).
  - nctrl = number of events in a control region 7<pt<20 GeV.
  - fsig = fraction of W muons at pt>30 GeV from MC.
  - fctrl = fraction of background events in control region, determined from global fit
  - fbkg =fraction of background events in signal region, determined from global fit
  - nbkg =fbkg/fctrl*Nctrl = expected number of background events in signal region.
  - **nsig = n-nbkg = number of observed events after background subtraction.**
  - nW = nsig/fsig = number of W at any pT.
- This reduces statistical uncertainty, but the uncertainty on the background estimate must be propagated into the total uncertainty.

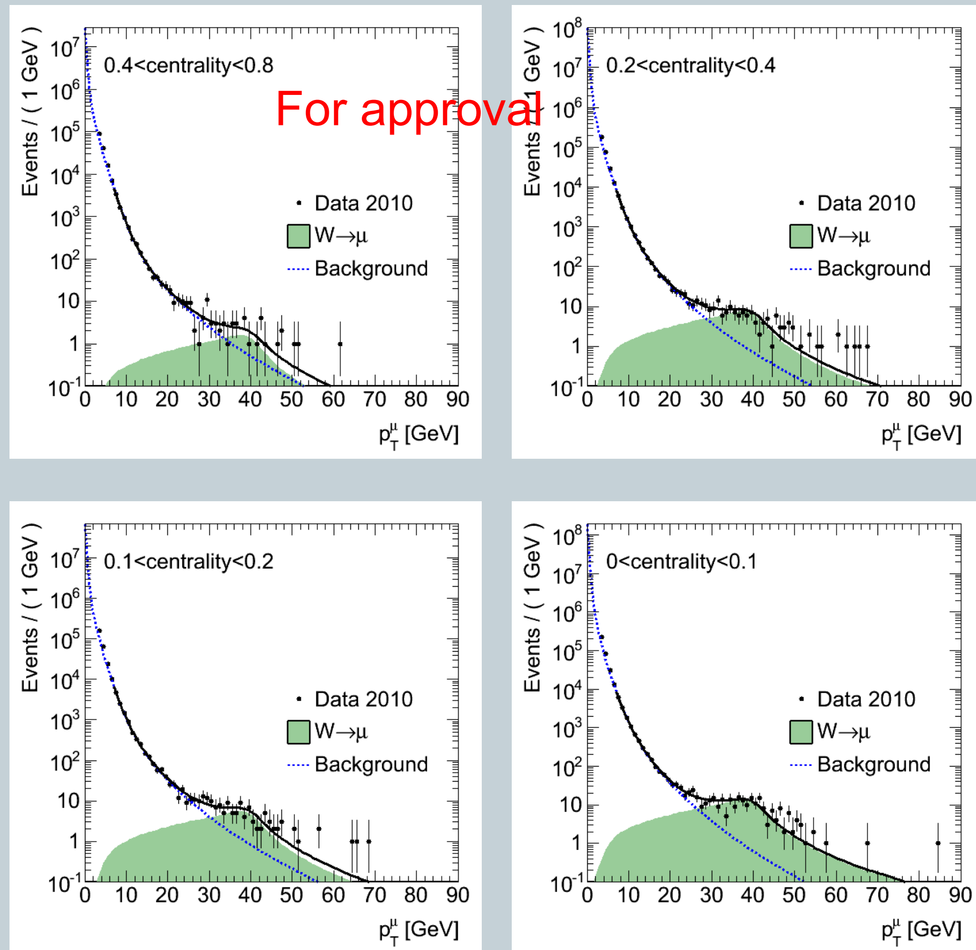
Per centrality bin

- We use both fitting and cut&count methods for all centrality subsets.
  - Results are very similar.

Centrality	$N^{\text{fit}}(W)$	$N^{\text{count}}(W)$
0-10%	$165 + 23 - 18$	$165 \pm 15.3\ (\pm 12.8)$
10-20%	$97 + 16 - 18$	$96 \pm 11.7\ (\pm\ 9.8)$
20-40%	$115 + 19 - 21$	$118 \pm 13.3\ (\pm 10.9)$
40-80%	$12 + 13 - 13$	$12 \pm\ 5.8\ (\pm\ 3.5)$
0-100%	$399 + 38 - 36$	$393 \pm 26.9\ (\pm 19.8)$

Statistical uncertainty

Uncertainty due to background modeling



W → mu suppression

- We investigate a potential suppression by counting the number of events per centrality bin normalized by the binary collisions.
- If the ratio compared to the most central bin is constant we do not observe any suppression.

$$R_{PC} = \frac{< N_{coll}^{C} >}{< N_{coll}^{P} >} \cdot \frac{N_{AA}^{P}}{N_{AA}^{C}}$$

- The no suppression hypothesis (flat line) is fitted to the data with chi2/dof = 1.3.
  - Results are consistent with no suppression of W bosons.

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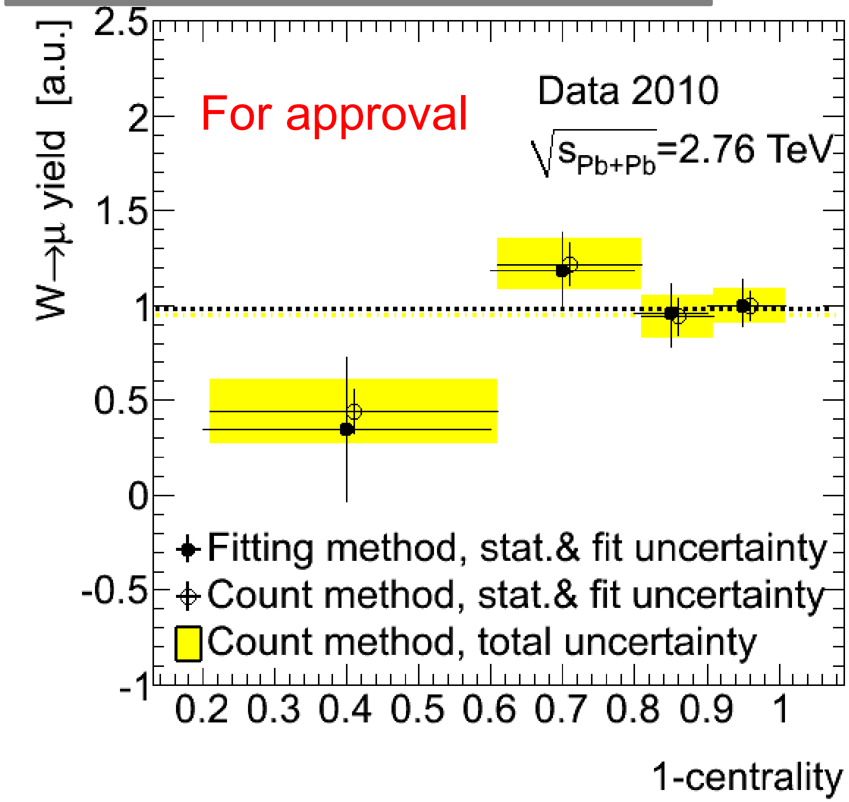
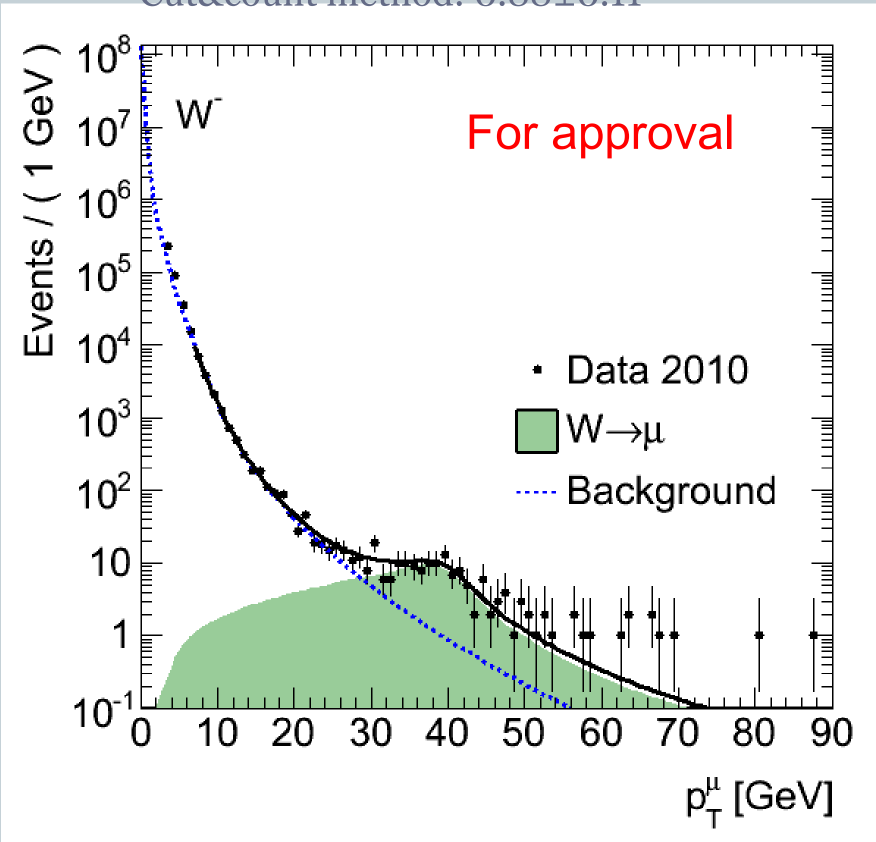
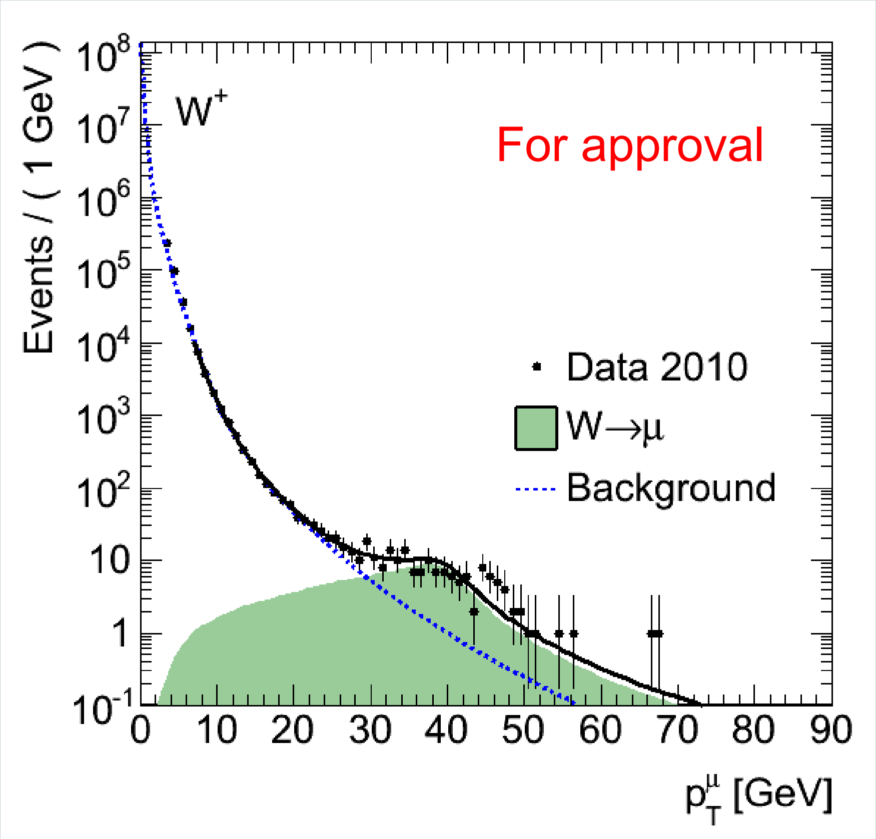


W+ & W-

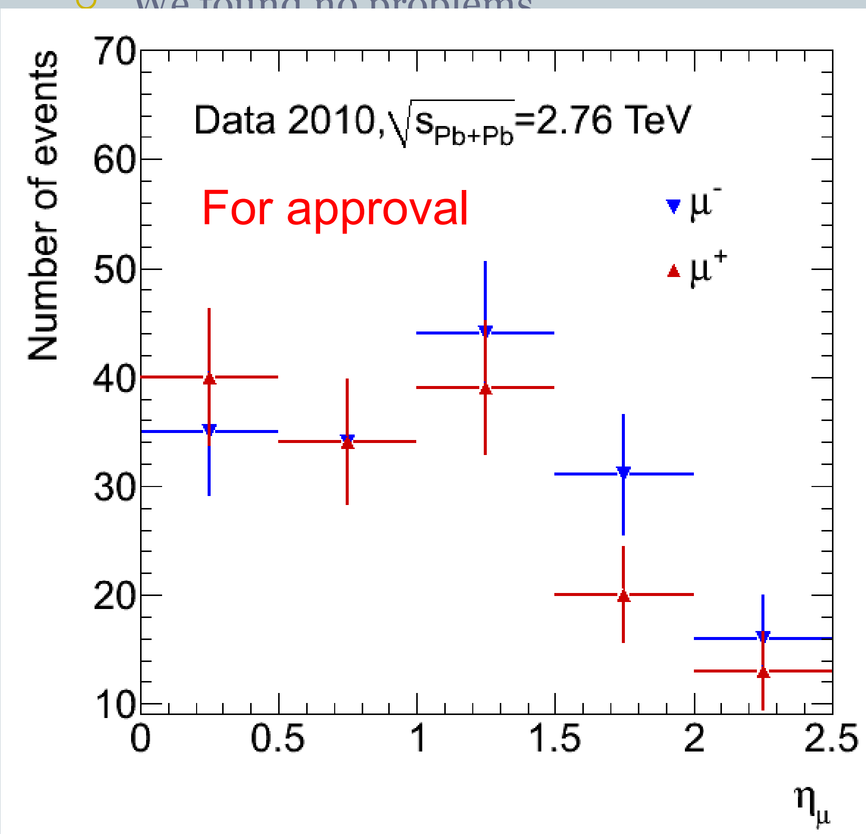
- Due to more d-quarks than u-quarks, theory predicts W+/W- = 0.90±0.04
  - Fitting method: 0.93±0.14
  - Cut&count method: 0.88±0.11

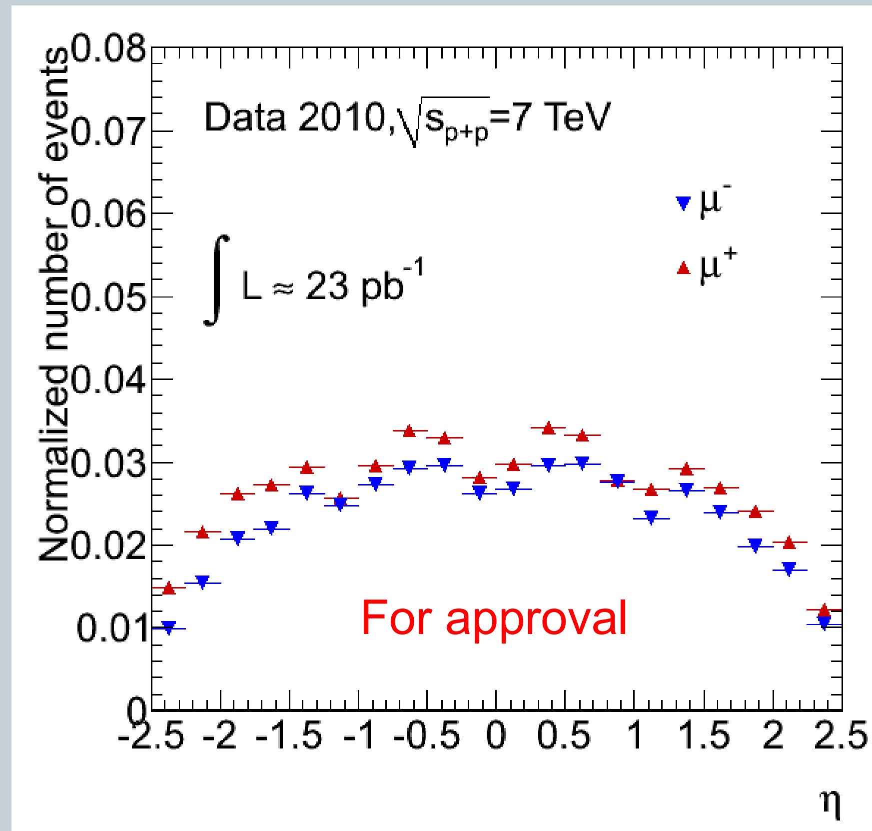




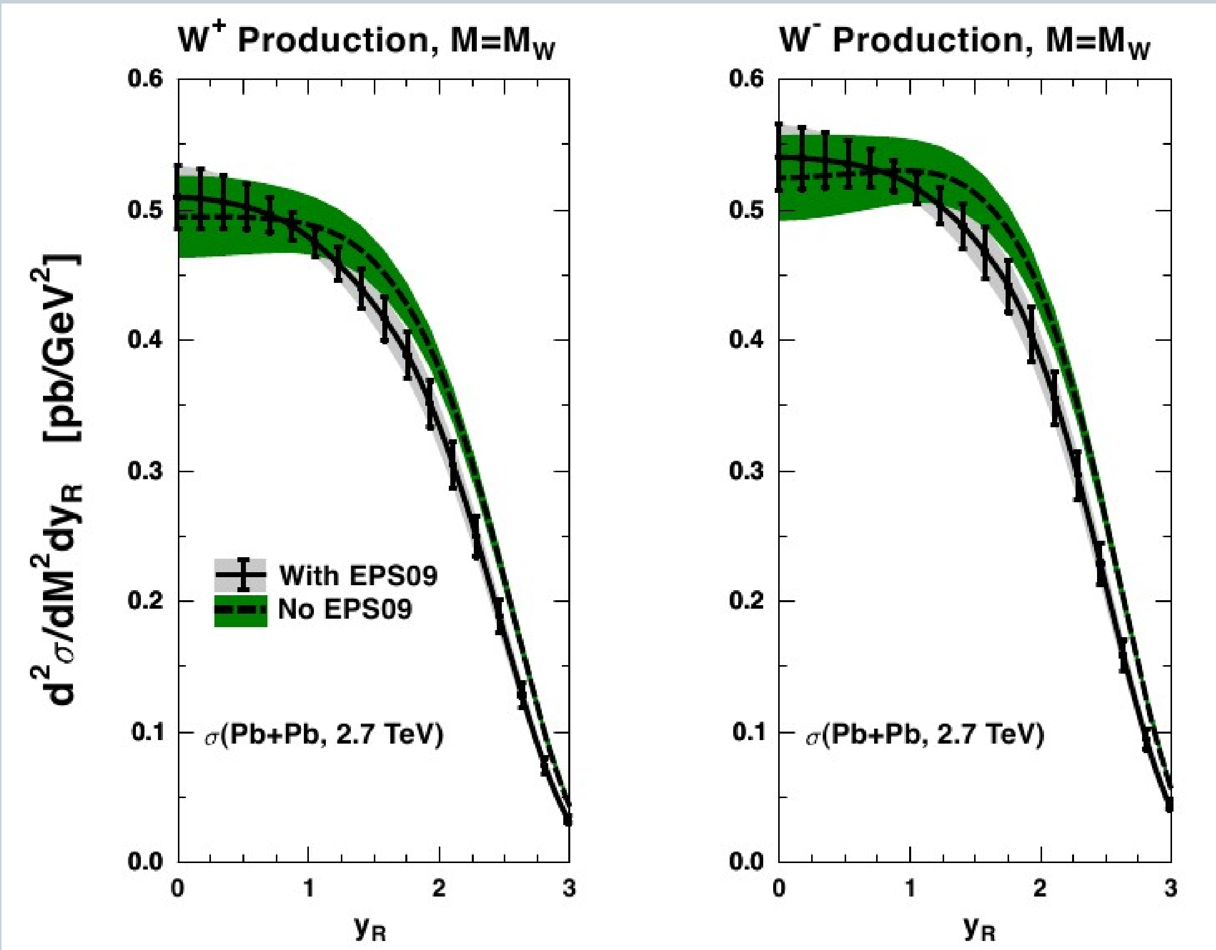
Muon charge vs pseudorapidity

- To spot potential problems we compared the kinematic distributions for muons with pT > 30 GeV with pp-data.
  - We found no problems



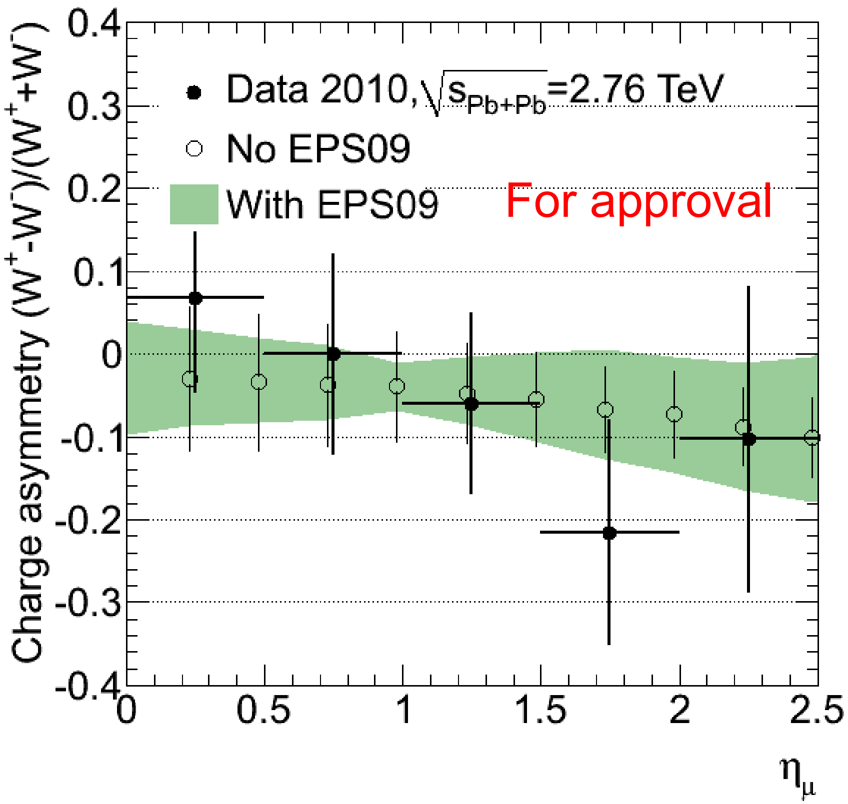


Theoretical cross section



- According to theory, the excess of d valence quarks in Pb atoms produces different cross section as function of eta for W+ and W-.
  - This could be observed as a eta dependent muon charge asymmetry.

W charge asymmetry



- We measure the charge asymmetry for muons with pT > 30 GeV as a function of pseudorapidity.

$$A_{\mu} = \frac{d\sigma_{W_{\mu^+}}/d\eta_{\mu} - d\sigma_{W_{\mu^-}}/d\eta_{\mu}}{d\sigma_{W_{\mu^+}}/d\eta_{\mu} + d\sigma_{W_{\mu^-}}/d\eta_{\mu}}$$

  - The two theory predictions from the previous slide is shown in the same figure.
  - Our result is compatible with theory, but we need more statistics to be able to discriminate between theory models.

W/Z ratio

- With slightly tighter cuts on the W analysis than what was used for the J/psi & Z paper we count 32 Z boson events on the same data.
  - Mass window 66<m<116 GeV.
- After correcting for geometrical acceptance and reconstruction efficiency we can derive the ratio of W and Z bosons.

$$R = \frac{N_W}{N_Z} \cdot \frac{A_Z}{A_W} \cdot \frac{C_Z}{C_W}$$

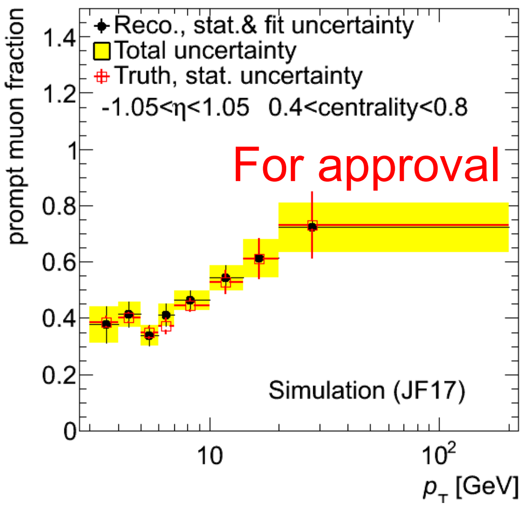
  - We assume that single muon acceptance and reconstruction efficiency for muons in the signal region is independent for $W \rightarrow$ mu and $Z \rightarrow$ mumu.
  - We measure $R^{fit} = 11.0 \pm 2.2$ ($R^{count} = 10.9 \pm 1.8$)
    - Theory pp: R = 11.2
    - Theory PbPb: R = 11.5

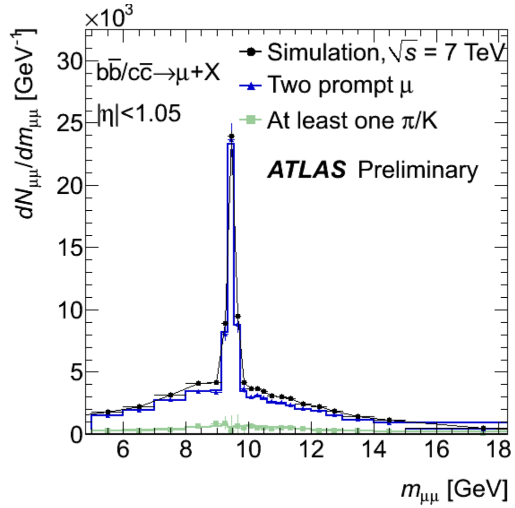
Heavy flavour → mu analysis

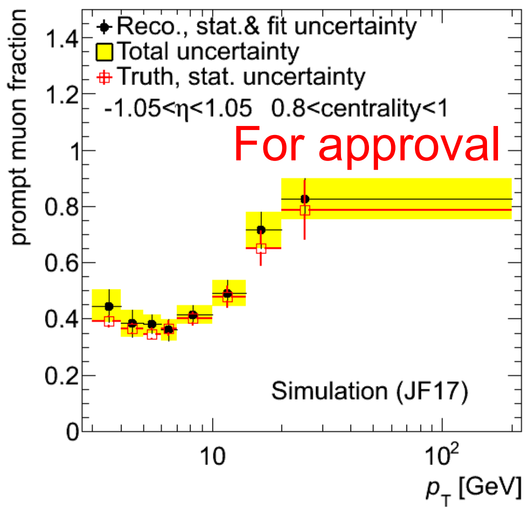
The method and its history

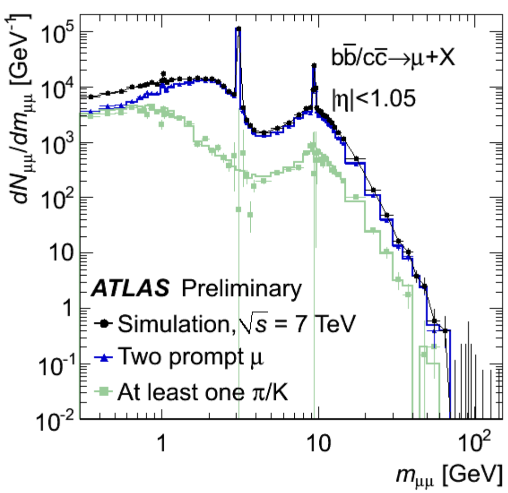
- We are identifying "prompt" muons by separating them from decays in flight using template fitting techniques.
  - These techniques were first used in ATLAS-CONF-2010-075.
  - I improved the method and used it to identify di-muons in ATLAS-CONF-2011-003.
  - This analysis uses *identical* method as ATLAS-CONF-2011-003, so the method is already approved.
- Prompt muons include muons from phi, W etc, but at 4<pt<10 GeV heavy flavour (b,c) dominates.
  - We can therefore interpret the prompt muon fraction as heavy flavour.
- Decays in flight is always a subset of total number of decays in flight, since muon reconstruction vetoes obvious decays.
  - Hence we cannot directly interpret suppression of pi/K → mu as light flavour suppression (it will always be a subset).

Test of method



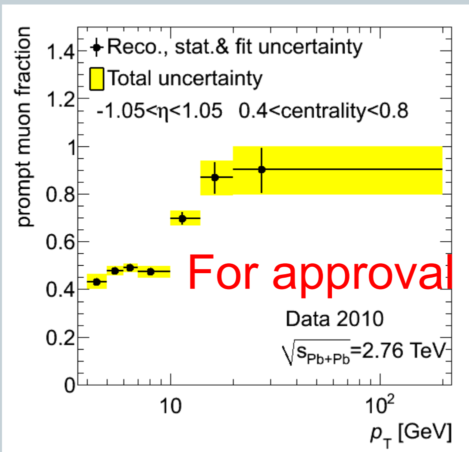


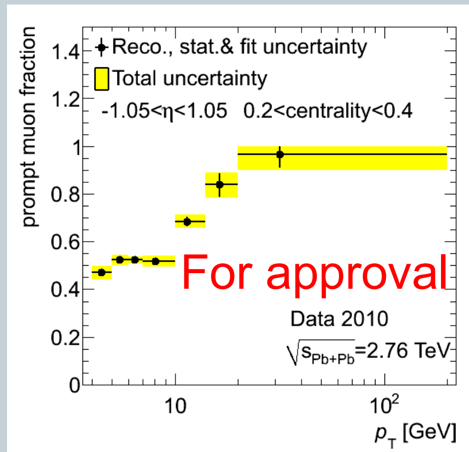


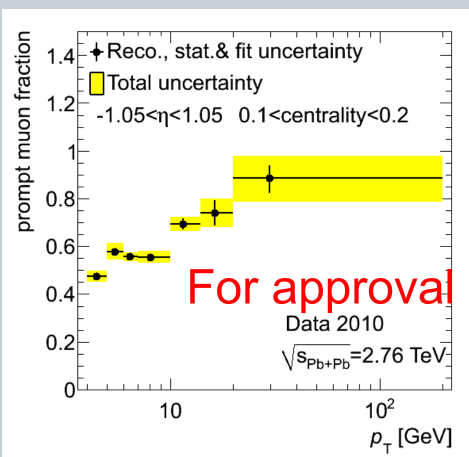


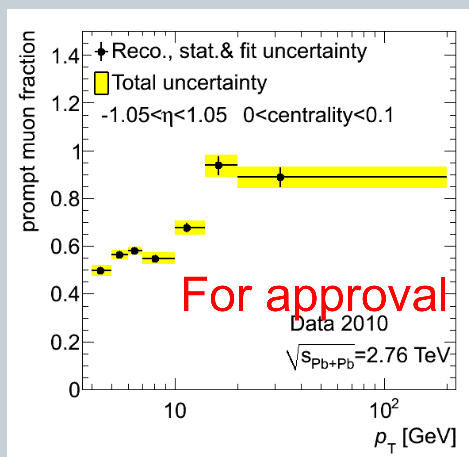
- As a closure test, we treated MC as data and compared the estimated prompt fraction with the MC truth value.
  - This test, together with similar studies in the previously approved dimuon note gives us confidence that the method is valid and accurate.

Prompt muon fraction as function of pT









- General trend is an increase of prompt muons with increasing pT.
  - Just like for pp data and simulation.
  - Hint of a structure within this shape.
- Ideally we want to show the heavy flavour suppression as a function of pT.
  - This requires accurate efficiency maps, since we are operating in the steep turn on curve for the muon reconstruction.
    - This is not done yet.

Heavy flavour suppression

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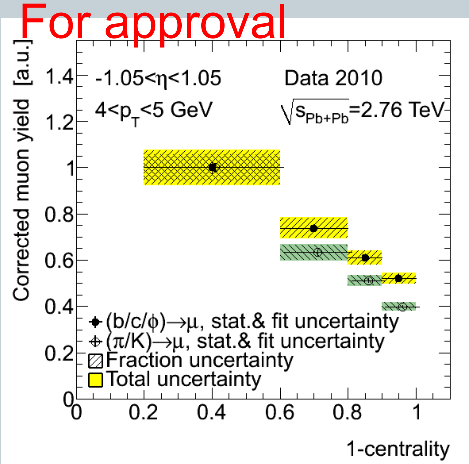

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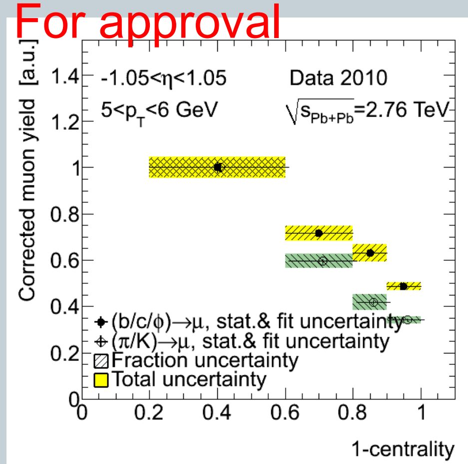

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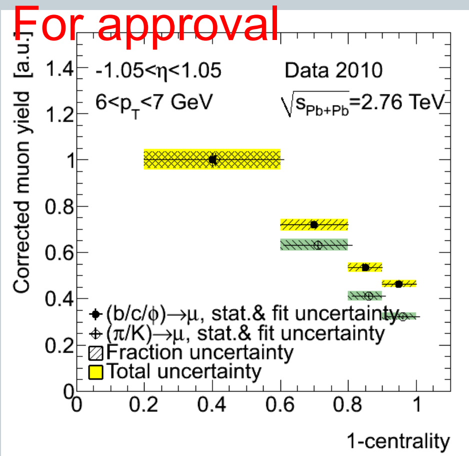

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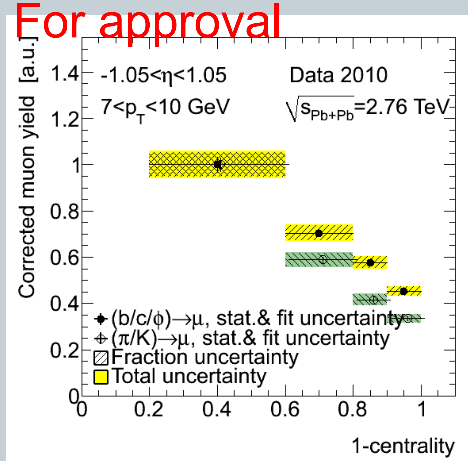


- We observe
  - prompt muon suppression at central collisions
    - Since we have are dominated by b/c in this kinematical range, we observe heavy flavour suppression.
  - stronger suppression for decays in flight
    - Thus heavy flavour is less suppressed than light flavour.
- These observations are agreeing with expectations.

Conclusions & summary

- First results of W production and heavy quark suppression in lead-lead collisions at the LHC energies by the ATLAS experiment are presented.
  - W and Z bosons are probes that become available at the LHC energies to study the medium produced in heavy ion collisions. They are ideal probes to study the early stages of the system as they do not interact with the medium.
  - Our studies show that W bosons are not suppressed at the most central collisions indicating that their production follow a scaling with the binary collision scaling. We have also established that it is possible to derive both rapidity and charge asymmetry distributions for a subset of the muons that are from the decay of W bosons.
  - In the future these measurements combined from those of Z , should provide means to understand the very early stages of nucleus-nucleus collisions. Statistically significant data will provide information on possible nuclear modifications to the parton distribution functions.
- We have also performed first studies of the in-medium heavy quark suppression at the LHC energies.
  - Extending the heavy flavour particle decay tagging in the single muon decays, we unfold the single muon pT spectrum to obtain the yields for heavy flavoured particle decays. These are compared to decays from π and K decays as function of collisions centrality, showing that heavy flavour is less suppressed than light flavour.

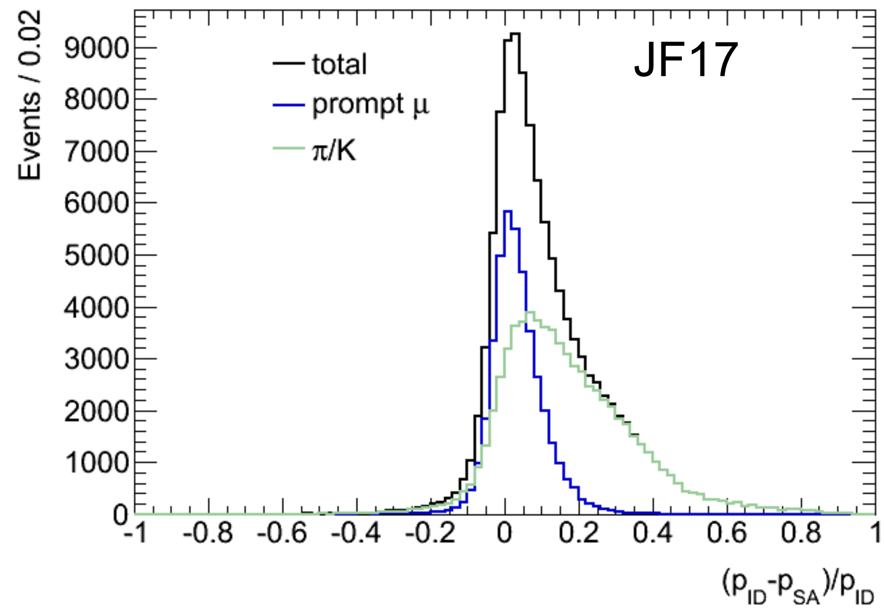
Extra slides

Analysis method

- *Early* decays in flight (inside the beam pipe) are very hard to separate from prompt muons.
- *Late* decays (outside Inner Detector) have the inner detector momentum from the π/K track, and the muon spectrometer momentum from the muon track.
- *Intermediate* decays (inside Inner Detector) can have a noticeable kink on the track.
- By using template fitting techniques we can determine the total amount of π/K.
  - We need a discriminant that gives a good separation between π/K and prompt muons.

Discriminant 1: momentum balance

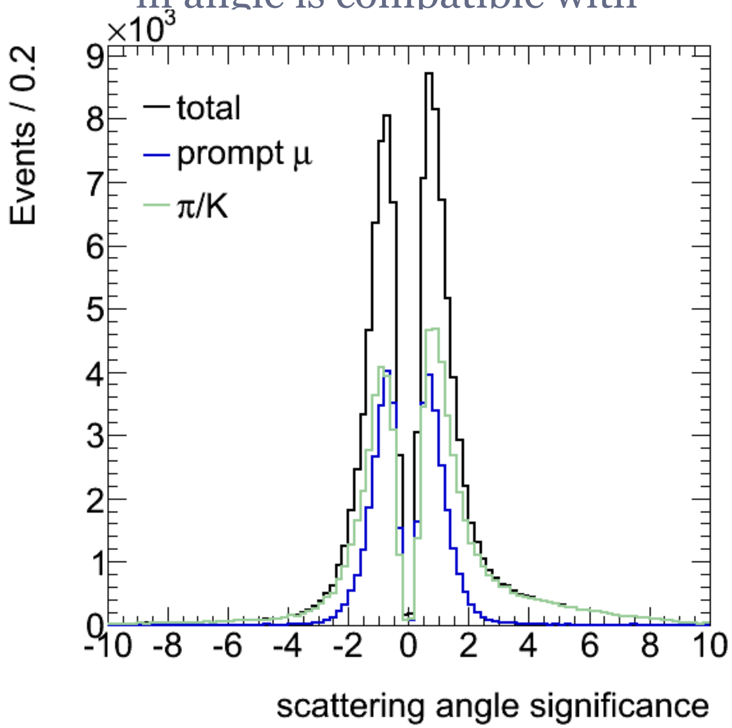
- Pions and kaons decaying to muons in flight will lose a fraction of their energy to neutrinos.
- Late decays, and some intermediate decays:
  - The track parameters measured by the inner detector correspond to the track prior to the decay for late decays, as well as a fraction of the intermediate decays, while the muon spectrometer measures the muon after the decay.
  - If the pion or kaon is very relativistic it will not decay prior to the calorimeter, where it is absorbed. A fraction of its energy can leak out to the muon spectrometer, often in the form of a real muon produced in the calorimeter volume at much lower energy than the particle incident on the calorimeter.

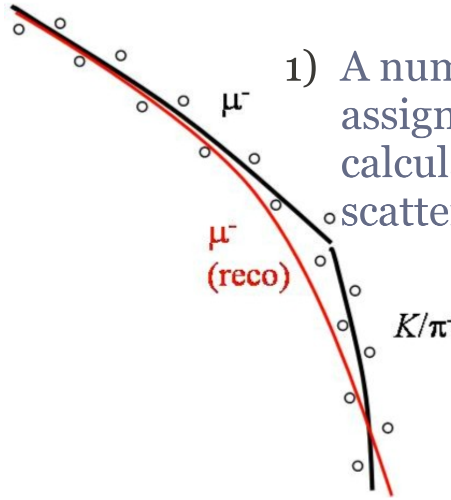


$$\frac{\Delta p_{loss}}{p_{ID}} = \frac{p_{ID} - p_{MS} - p_{param(p_{MS},\eta,\phi)}}{p_{ID}}$$

Discriminant 2: scattering angle significance

- Intermediate decays:
  - A π/K decay inside the inner detector can produce a kink on the track.
  - We test each track to see if a change in angle is compatible with





1) A number of scattering centers is assigned to the track. We calculate a signed residual for the scattering in ϕ-coordinate:

$$s_i \equiv q \frac{\Delta\phi_i}{\phi_i^{msc}}$$

2) For each scattering center the overall significance of the scattering angle in the bending plane are summed up before the center, the corresponding sum after the center is subtracted:

$$S(k) \equiv \frac{1}{\sqrt{n}} \left(\sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j \right).$$

3) We use the center with the highest significance as the decay in flight discriminant.

Composite discriminant

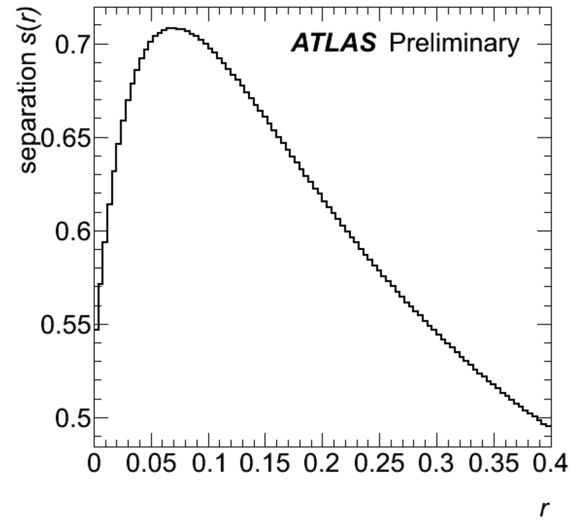
- Scattering significance is better for intermediate decay, momentum balance is better for late decays.

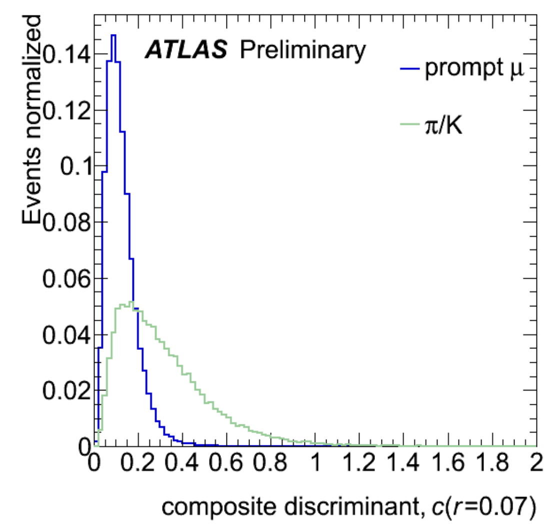
- To cover a larger phase space a linear combination of the two discriminants were made.

$$c(r) = \left|\frac{\Delta p_{loss}}{p_{ID}}\right| + r\left|S\right|$$

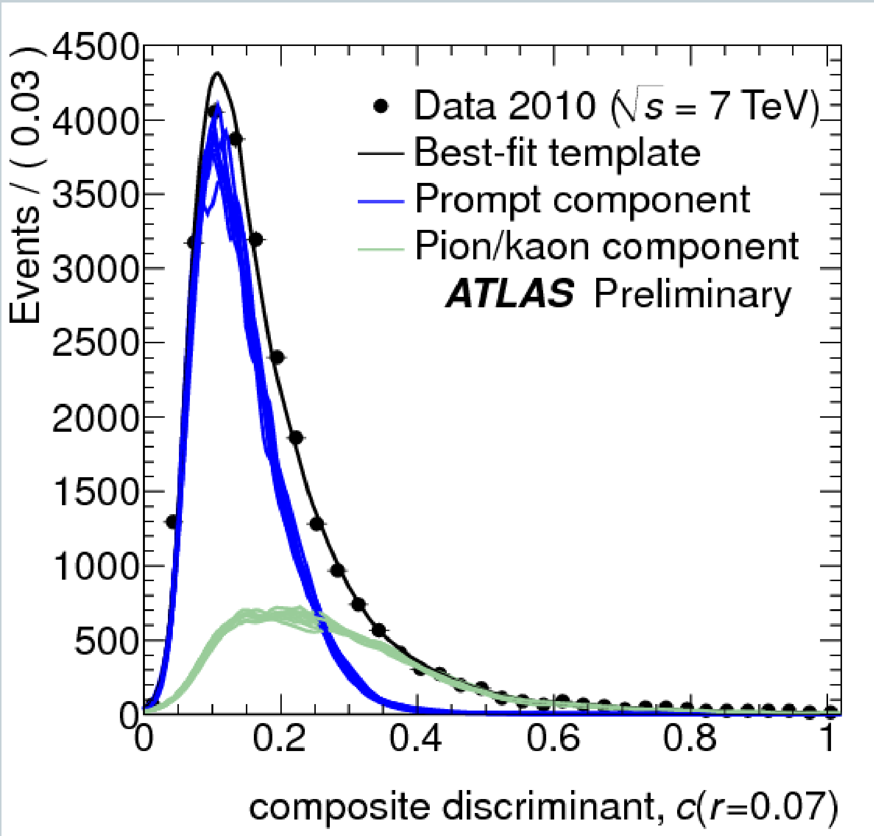
- The constant r was optimized w.r.t. maximum separation

$$s(r) \equiv \int_{-\infty}^{\infty} \frac{\left(f_{prompt}\left(c(r)\right) - f_{\pi/K}\left(c(r)\right)\right)^2}{f_{prompt}\left(c(r)\right) + f_{\pi/K}\left(c(r)\right)} \mathrm{d}c$$





Determining prompt muon fraction - systematics



- The finite statistics in simulation creates an uncertainty of the shape of the probability density functions.
  - By randomly distributing an equal number of muons as was used to build the original template, according to its probability density function, a distribution of c similar to the original probability density function was generated.
  - The new distribution thus obtained was in turn used to build an alternative template that, when fitted to data, gave an individual measurement of the π/K content.
  - This was repeated eight times for every original template fit, and the root mean square was used as a systematic uncertainty.

Future extension to the analysis

- Other experiments have been measuring suppression in heavy ion collisions as a function of transverse momentum.
- Atlas could further extend these studies, but the 3 GeV energy loss in the calorimeters implies that we can only study the higher pT tail.
  - ...or low pT at high eta.