

# Heavy flavour production measurements at the CERN-LHC

- motivations
- measuring heavy flavours at the LHC (in short)
- pp collisions at  $\sqrt{s} = 2.76$  & 7 TeV: heavy flavour production cross-sections
- PbPb collisions at  $\sqrt{s} = 2.76$  TeV: heavy flavour nuclear modification factors
- summary

P. Crochet, LPC Clermont-Ferrand, France

## The talk includes:

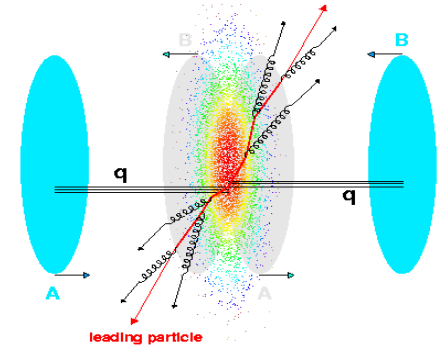
- **only open heavy flavour results**  
(see Raphael's talk for quarkonia)
- **mostly pp results relevant for PbPb collisions**
- **mostly ALICE results**

# Motivations

- **heavy flavours in pp collisions:**
  - **baseline for pA and AA collisions**
  - **test NLO pQCD in a new energy regime**
  
- **heavy flavours in pA collisions:**
  - **shadowing and anti-shadowing**
  - **parton  $k_t$  broadening**
  - **color glass condensate**
  
- **heavy flavours in AA collisions, tomography of QCD medium:**
  - **produced in initial hard scattering with short formation time**
  - **sensitivity to the medium properties**

# Open heavy flavours probe medium density

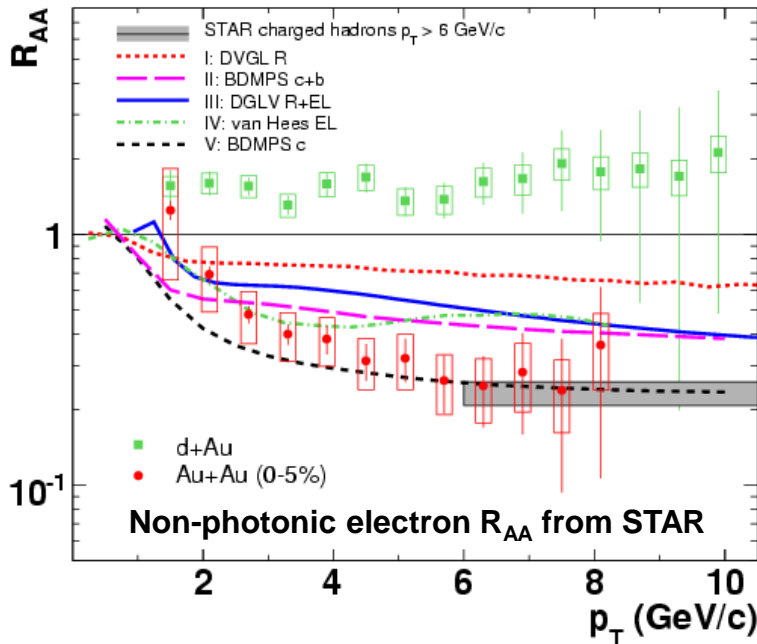
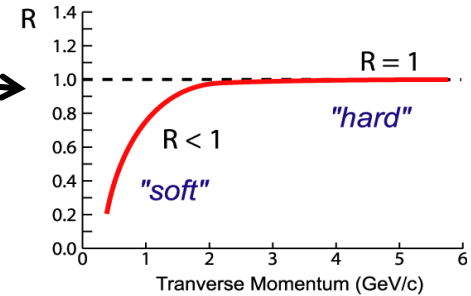
- parton energy loss via medium-induced gluon radiation
- proportional to  $\varepsilon$ ,  $L$ ,  $C_R$  (with  $C_R = 4/3(3)$  for  $q(g)$ ) &  $m_Q$
- gluon radiation suppressed at  $\Theta < m_Q/E_Q$   
 $\rightarrow \Delta E_g > \Delta E_{q\sim c} > \Delta E_b$  expected (“dead cone effect”)



- studied via nuclear modification factor  $R_{AA}$ :

$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp} \times \langle N_{coll} \rangle}$$

if no hot nuclear effects  $\rightarrow$   
 average number of NN collision in a AA collision



dead cone effect:

$$R_{AA}^h < R_{AA}^D < R_{AA}^B$$

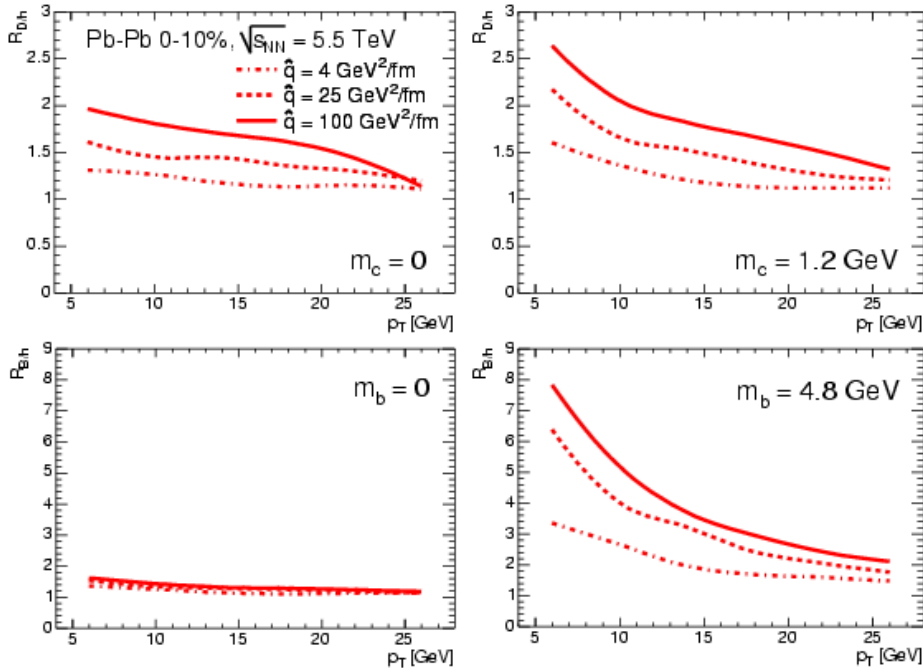
$\rightarrow$  not observed at RHIC!

- very large medium opacity? PLB 637 (2006) 362
- collisional energy loss? PRC 73 (2006) 034913
- early dissociation of heavy mesons? PLB 649 (2007) 139
- baryon enhancement? PRC 74 (2006) 024902

dead cone effect: Phys. Lett. B 519 (2001) 199  
 STAR data: Phys. Rev. Lett. 98 (2007) 192301

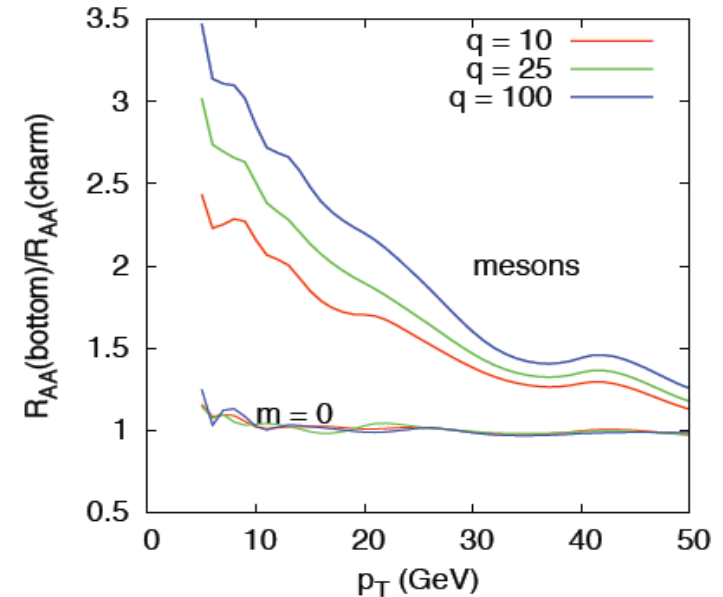
# Heavy quark quenching at the LHC: new ratios

$$R^{D(B)/h} = R_{AA}^{D(B)} / R_{AA}^h$$



- $R^{D/h}$  probes color charge dep. of  $\Delta E$
- $R^{B/h}$  probes mass dep. of  $\Delta E$

$$R_{AA}^{B/D} = R_{AA}^B / R_{AA}^D$$

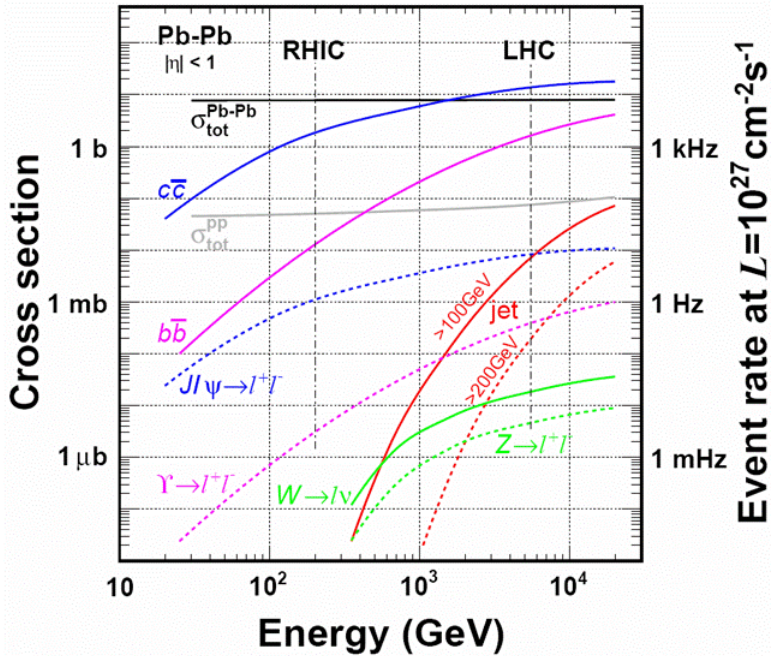


- isolate mass dep. of  $\Delta E$
- sensitivity disappears at large  $p_t$
- lower sensitivity to  $q_{hat}$

More details in Pol-Bernard's talk this afternoon (5.20 pm)



# Heavy flavour cross-section at the LHC



$$\sigma_c(\text{LHC}) = \sigma_c(\text{RHIC}) \times 10$$

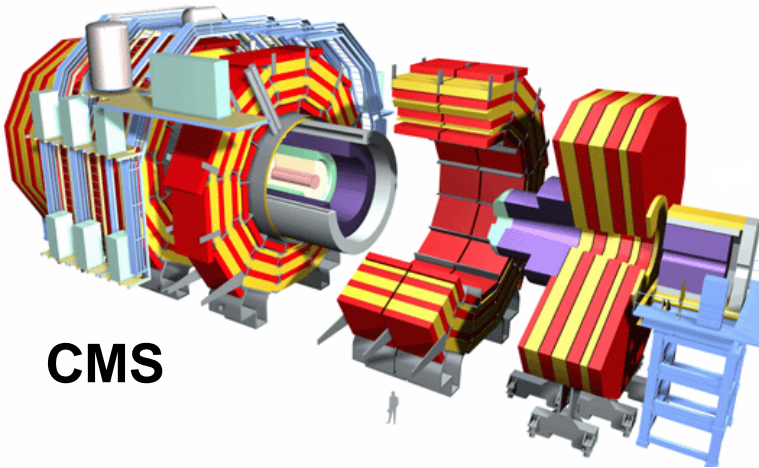
$$\sigma_b(\text{LHC}) = \sigma_b(\text{RHIC}) \times 100$$

NLO predictions for **charm**/**bottom**  
 (+ binary scaling & shadowing (average EKS98 & EPS08) in PbPb)

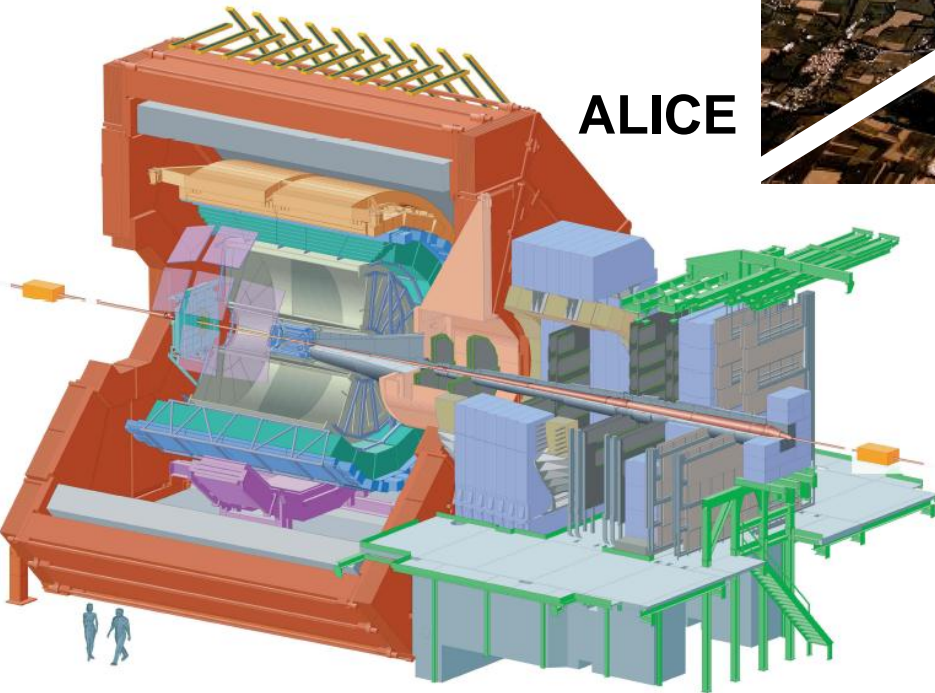
	pp 14 TeV	pp 7 TeV	Pb-Pb (5%) 5.5 TeV	Pb-Pb (5%) 2.76 TeV
$\sigma_{\text{qqbar}}^{\text{NN}}$ (mb)	11.2/0.5	6.9/0.23	3.4/0.14	2.1/0.075
$N_{\text{qqbar}}$ (/event)	0.16/0.007	0.1/0.003	90/3.7	56/2

uncertainty: a factor ~ 2 !

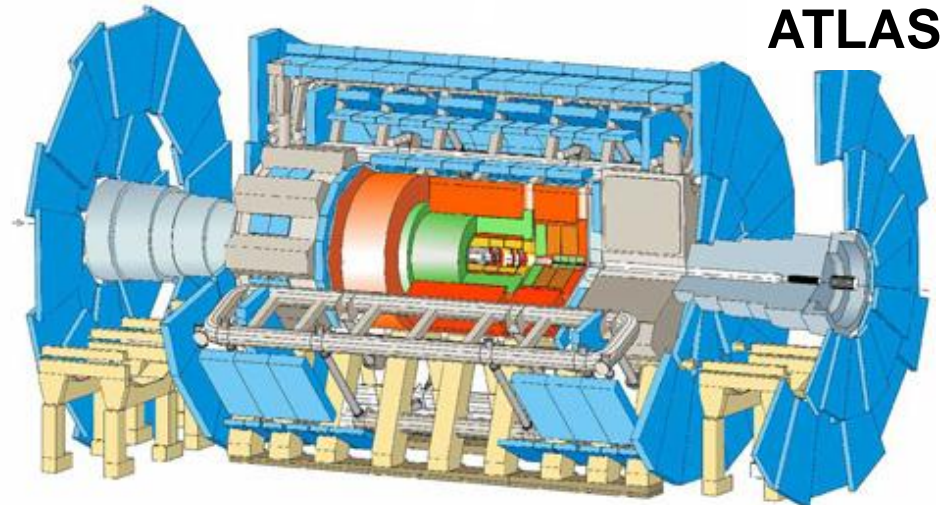
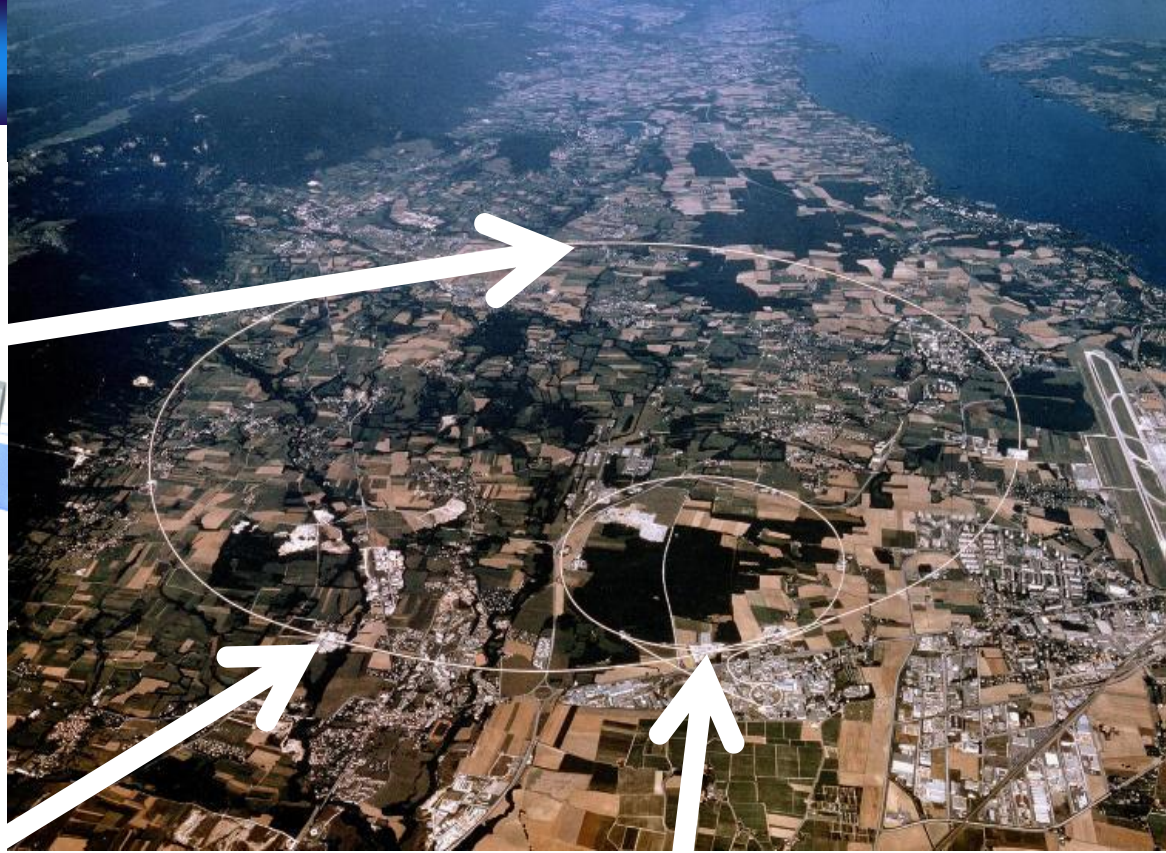
# Heavy ions at the LHC



**CMS**



**ALICE**



**ATLAS**



ITS, TPC, TRD, ToF, EMCal ( $|\eta| < 0.9$ )

(di-)electrons:  $J/\psi$ ,  $\psi'$ ,  $\Upsilon$ ,  $\Upsilon'$ ,  $\Upsilon''$ ,  
open charm, open bottom,  $W^\pm$ ,  $Z^0$

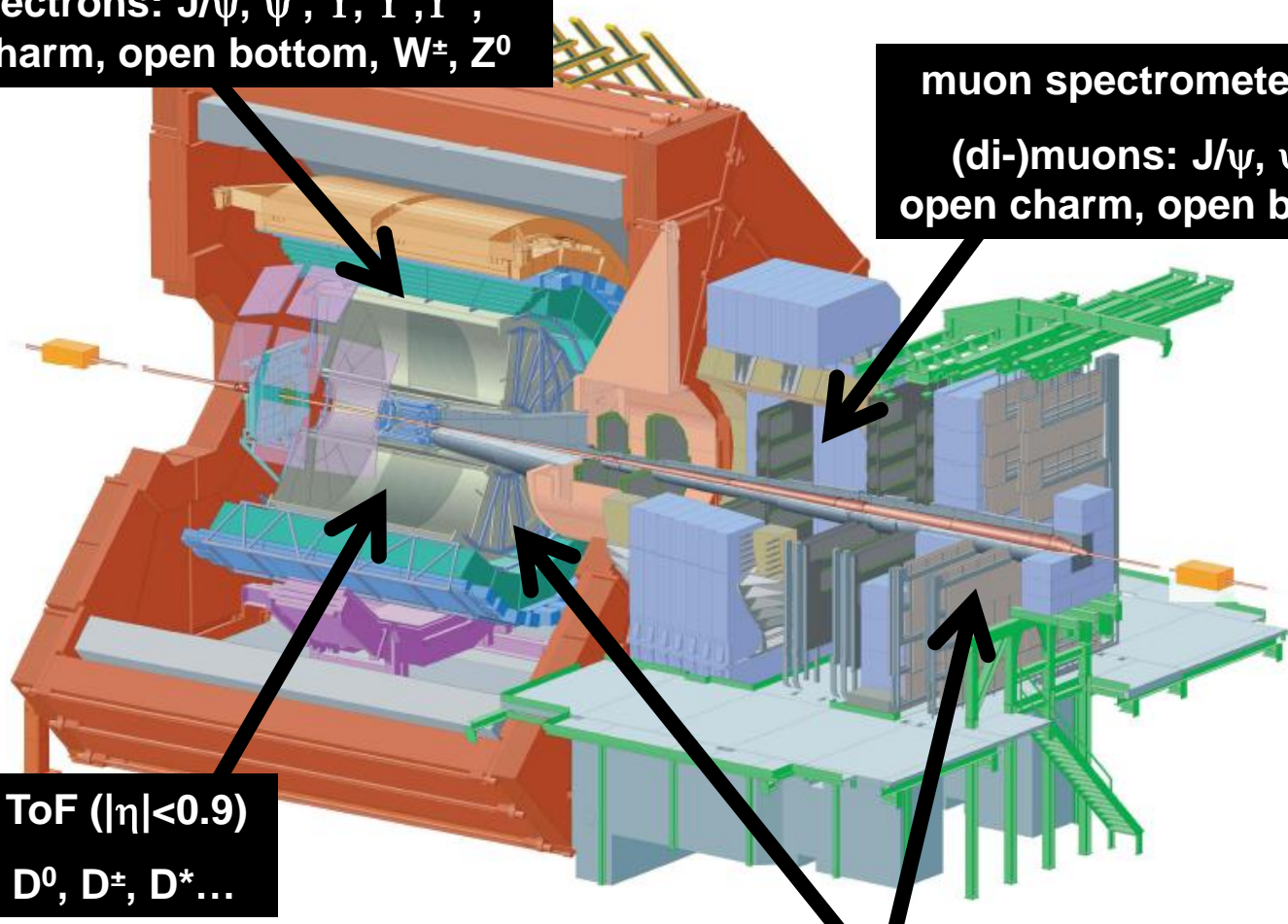
muon spectrometer ( $-4 < \eta < -2.5$ )

(di-)muons:  $J/\psi$ ,  $\psi'$ ,  $\Upsilon$ ,  $\Upsilon'$ ,  $\Upsilon''$ ,  
open charm, open bottom,  $W^\pm$ ,  $Z^0$

ITS, TPC, ToF ( $|\eta| < 0.9$ )

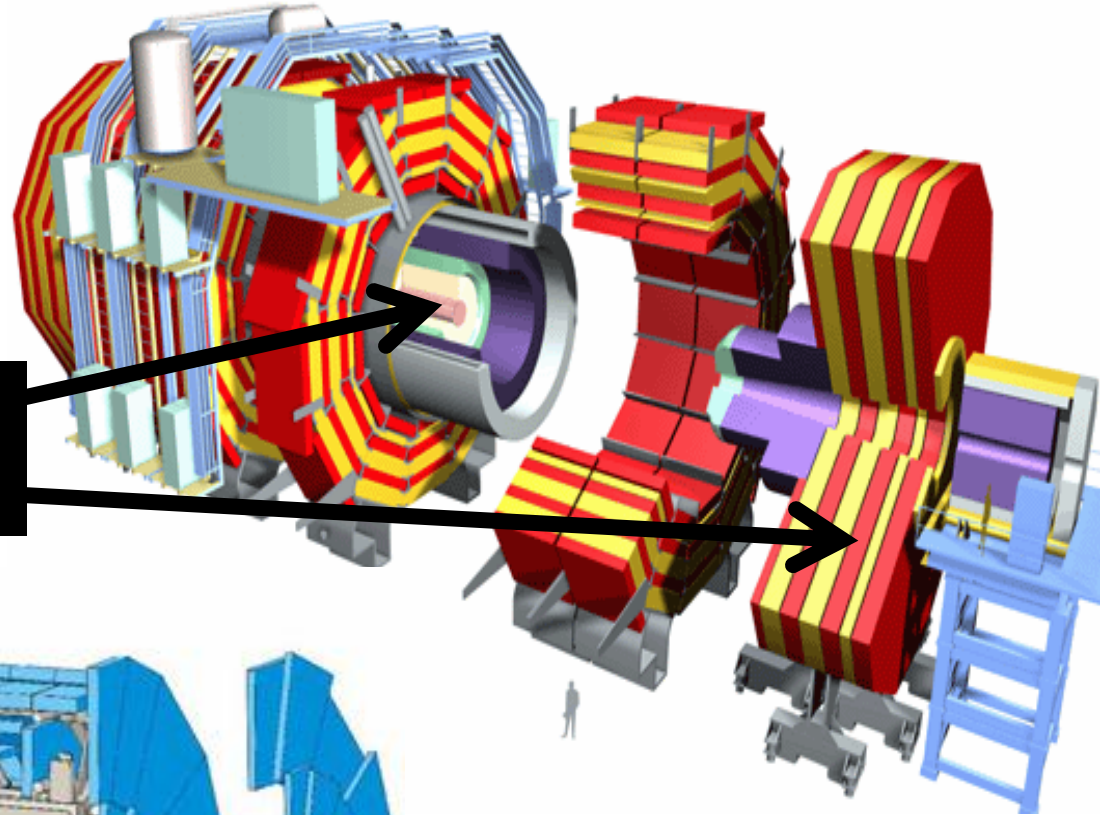
hadrons:  $D^0$ ,  $D^\pm$ ,  $D^*$  ...

electron-muon coincidences:  
open charm & bottom

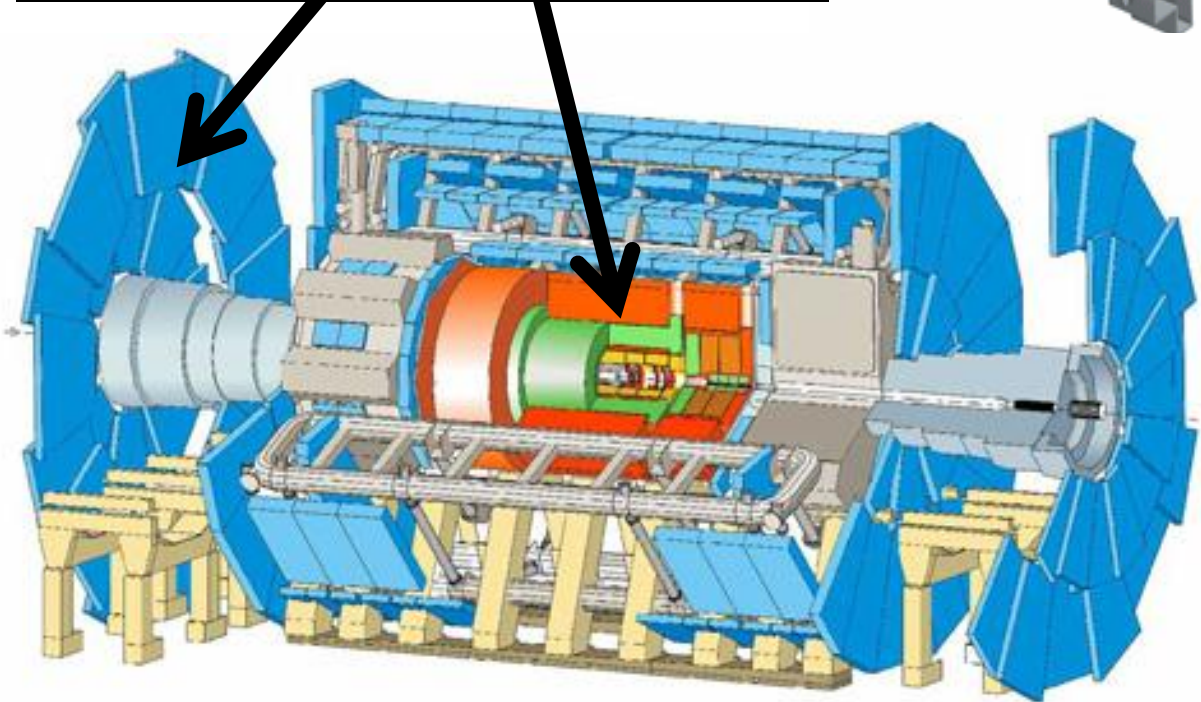




# Heavy flavours with CMS & ATLAS



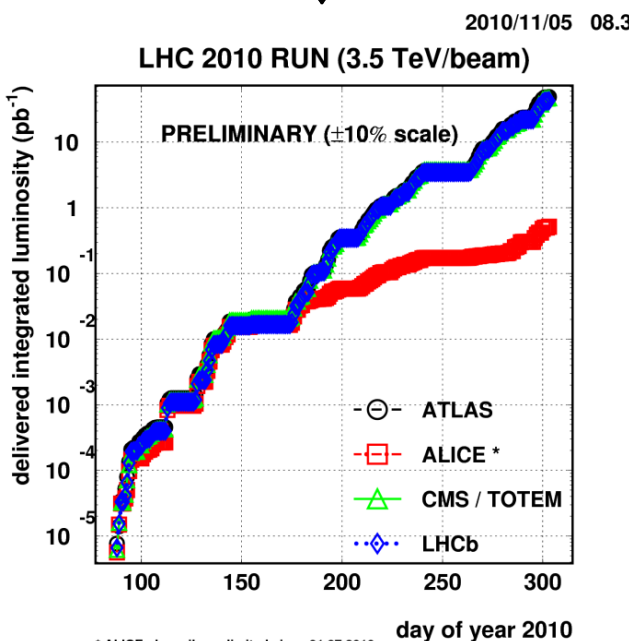
muon spectrometer & silicon tracker  
in central barrel & end-caps ( $|\eta| < 2.4$ )  
TRT+EMCal (ATLAS, electrons,  $|\eta| < 2$ )



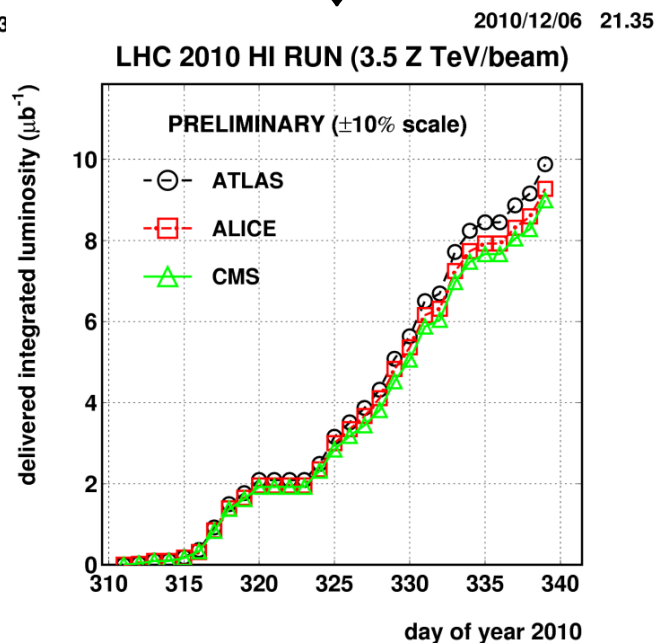
$J/\psi$ ,  $\psi'$ ,  $\Upsilon$ ,  $\Upsilon'$ ,  $\Upsilon''$ ,  
open charm, open bottom,  
 $W^\pm$ ,  $Z^0$ ,  $D^0$ ,  $D^\pm$ ,  $D^*$  ...,  $B^0$ ,  $B^\pm$  ...

# Data samples

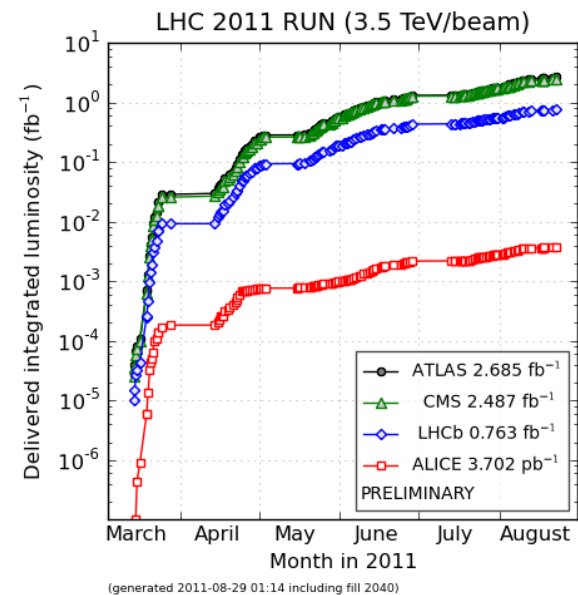
proton-proton at 7 TeV  
April - October 2010



PbPb at 2.76 TeV  
November 2010



proton-proton at 7 TeV  
from April 2011 on



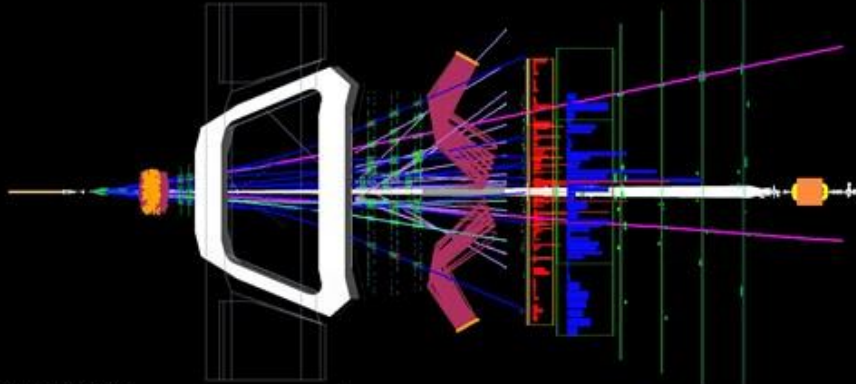
plus 3 days of proton-proton beams at 2.76 TeV (March 2011)



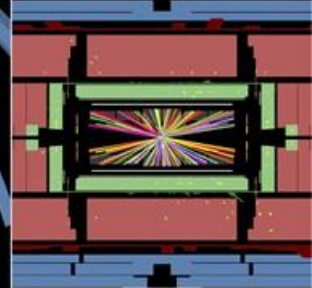
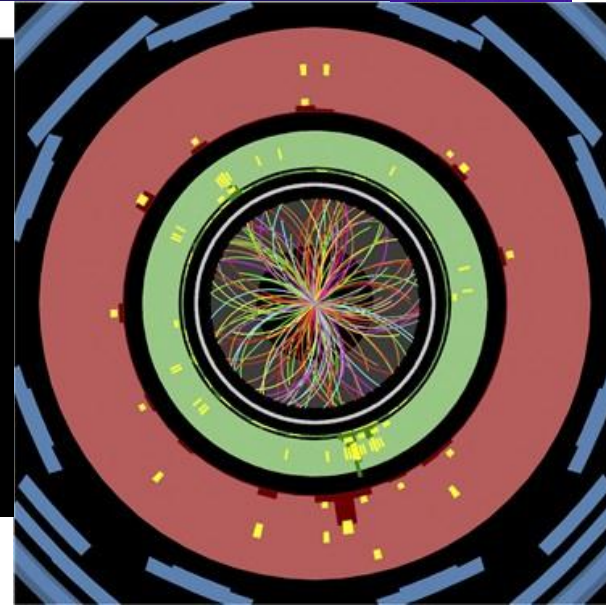
# Proton-proton collisions



LHCb Event Display



14.6.2011 18:57:08  
Run 93593 Event 1179897868 bld 1140

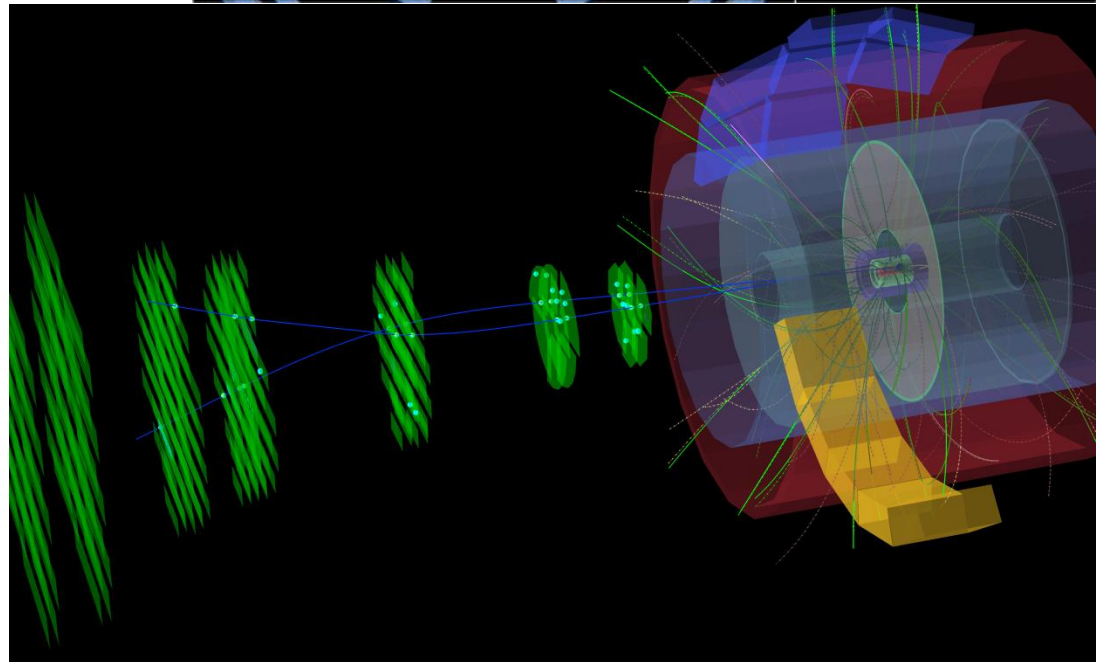
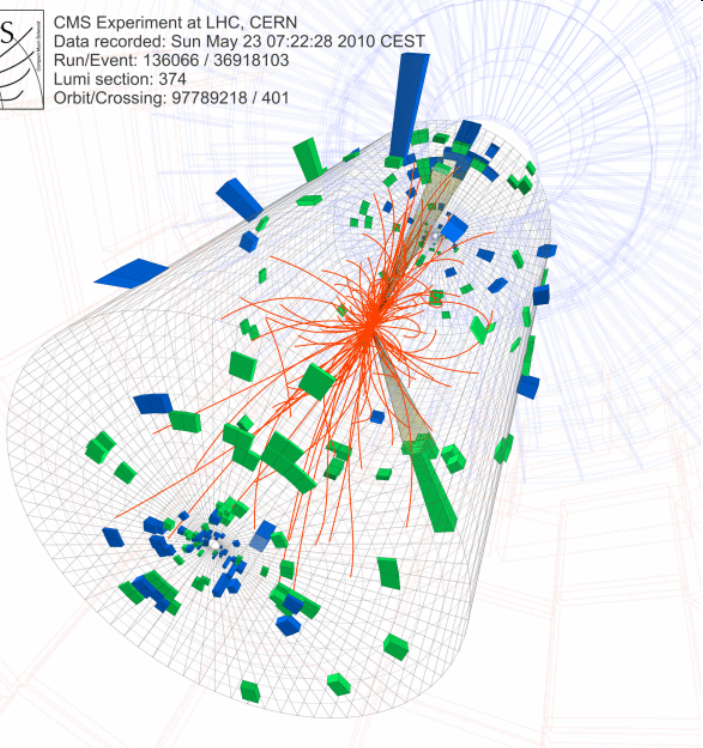


**ATLAS**  
EXPERIMENT

Run Number: 177531, Event Number: 183764  
Date: 2011-03-13 18:20:50 CET



CMS Experiment at LHC, CERN  
Data recorded: Sun May 23 07:22:28 2010 CEST  
Run/Event: 136066 / 36918103  
Lumi section: 374  
Orbit/Crossing: 97789218 / 401





# J/ψ from b differential cross-section



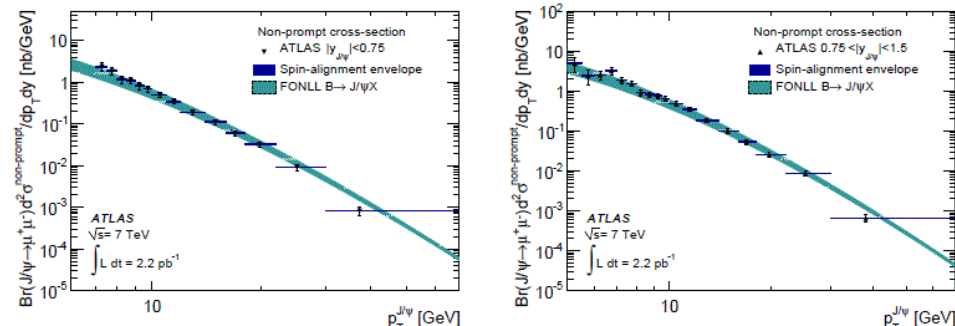
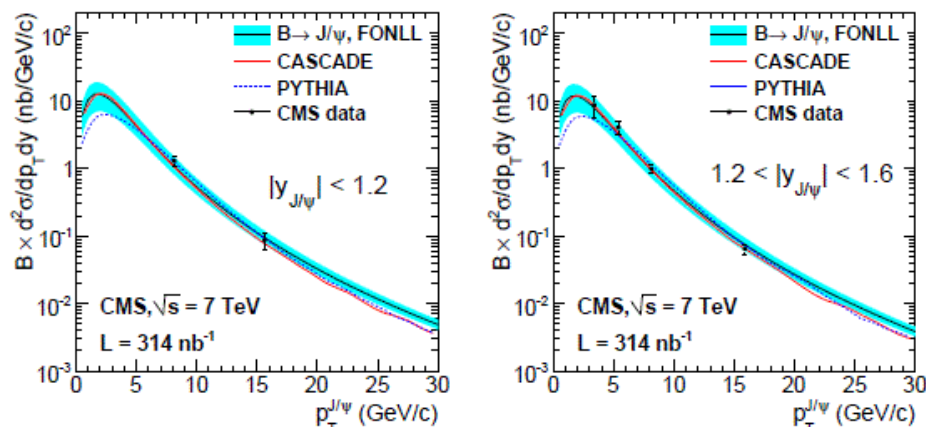
**CMS**

**pp collisions @ 7 TeV**

**ATLAS**

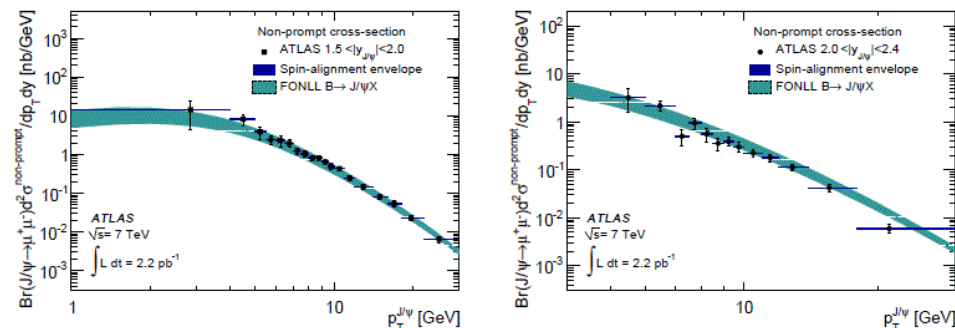
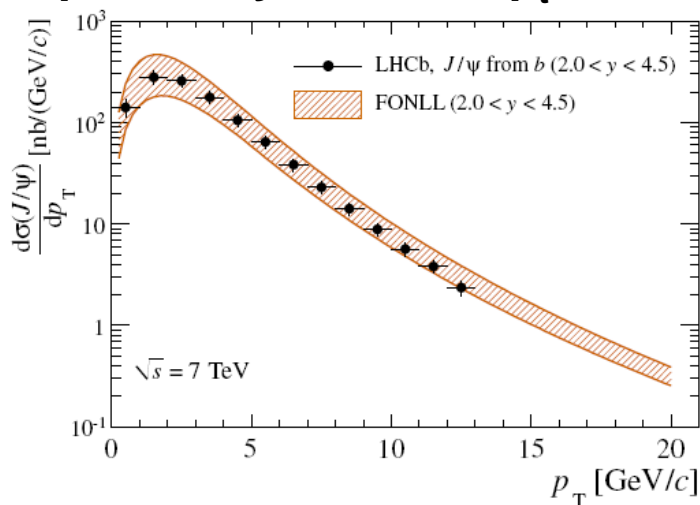
**314 nb<sup>-1</sup>, |y| < 2.4, 6.5 < p<sub>T</sub> < 30 GeV/c**

**2.3 pb<sup>-1</sup>, |y| < 2.4, 1 < p<sub>T</sub> < 70 GeV/c**



**LHCb**

**5.2 pb<sup>-1</sup>, 2 < y < 4.5, 0 < p<sub>T</sub> < 14 GeV/c**

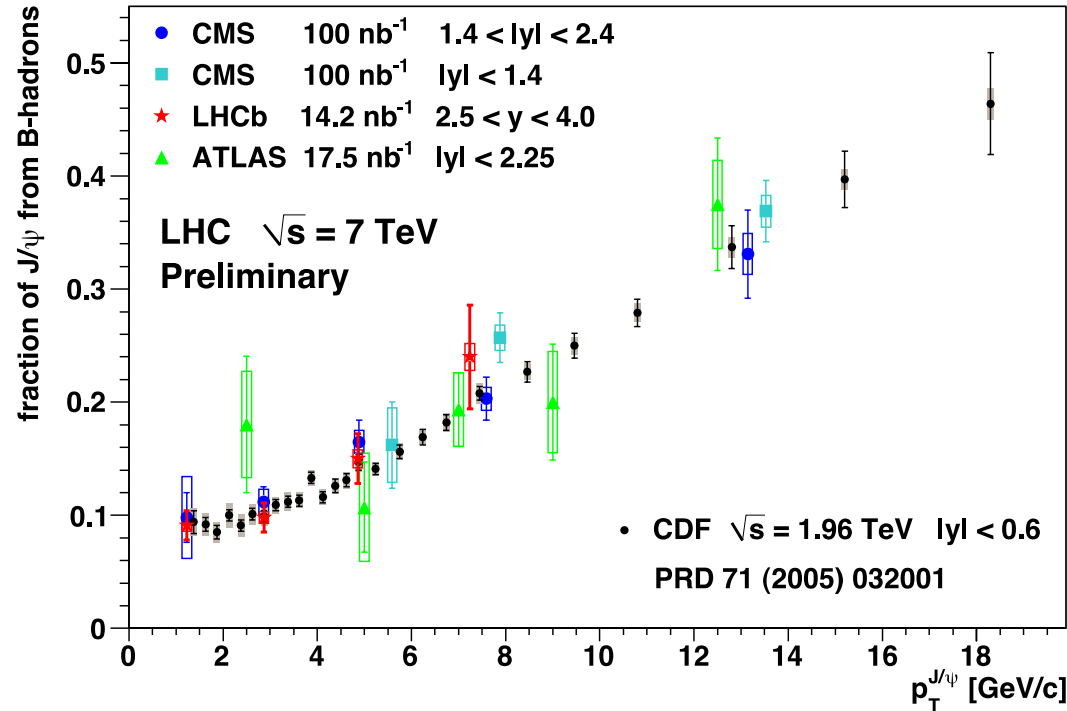
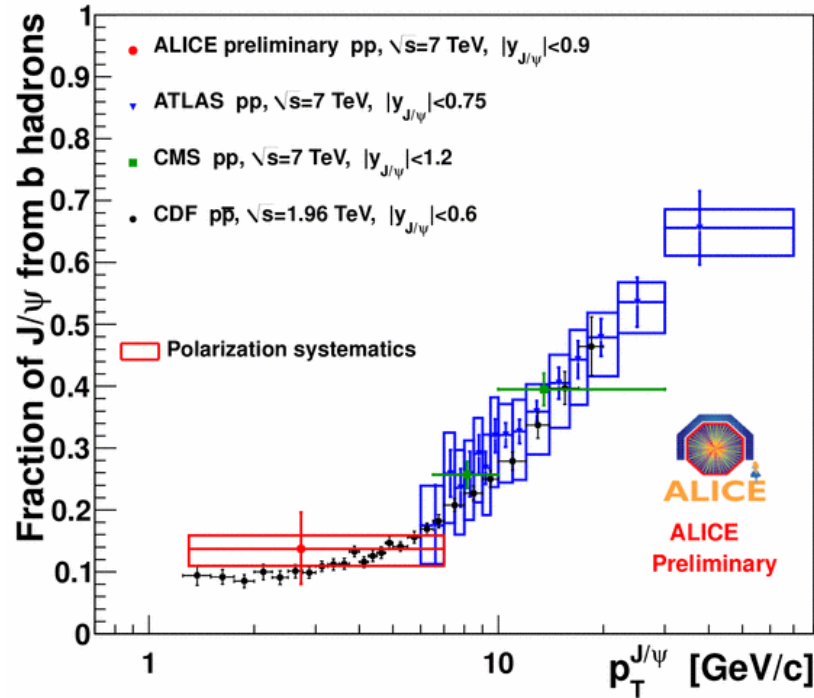


- prompt and non-prompt J/ψ yield unraveled via vertex unfolding (slide # 27)
- nice agreement with FONLL
- CMS data used as reference for J/ψ from b in PbPb collisions (slide # 27)

CMS: EPJC 71 (2011) 1515, ATLAS: arXiv:1104.3038, Nucl. Phys. B in press, LHCb: EPJC 71 (2011) 1645

# Fraction of $J/\psi$ from b hadrons

pp collisions @ 7 TeV



nice agreement between various experiments

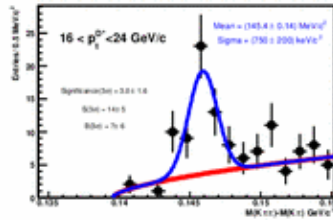
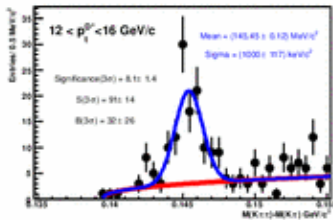
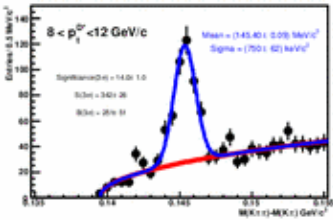
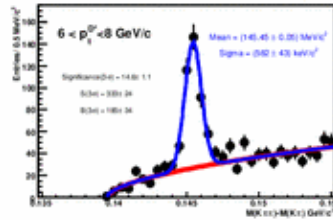
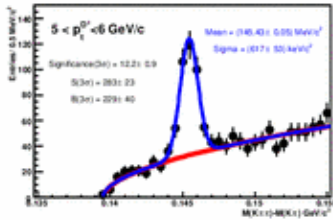
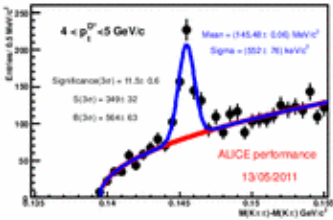
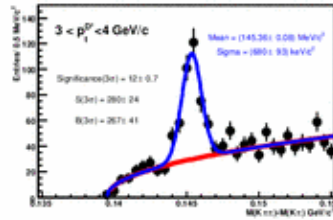
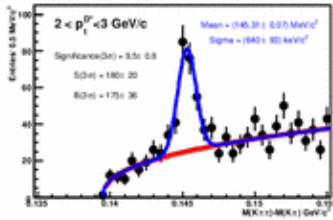
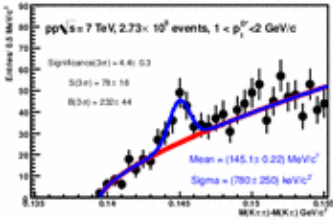
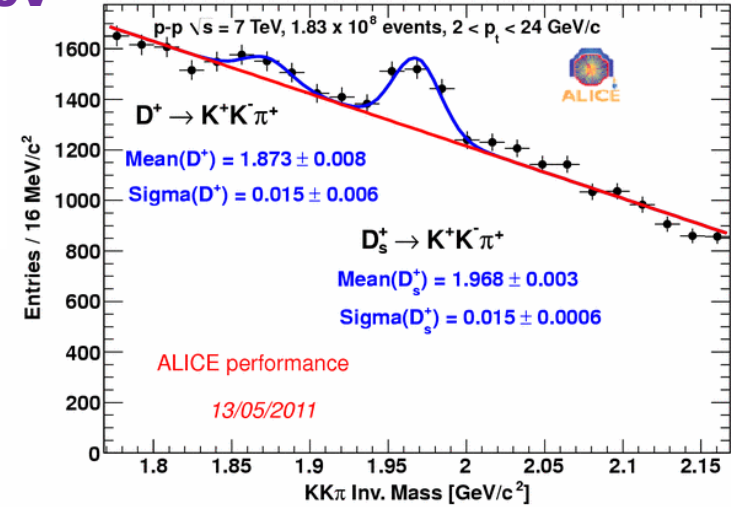
CMS: EPJC 71 (2011) 1515, ATLAS: arXiv:1104.3038, Nucl. Phys. B in press,  
 LHCb: H. Woehri, Quarkonium Production Workshop, Vienna, April 2010

# D meson invariant masses



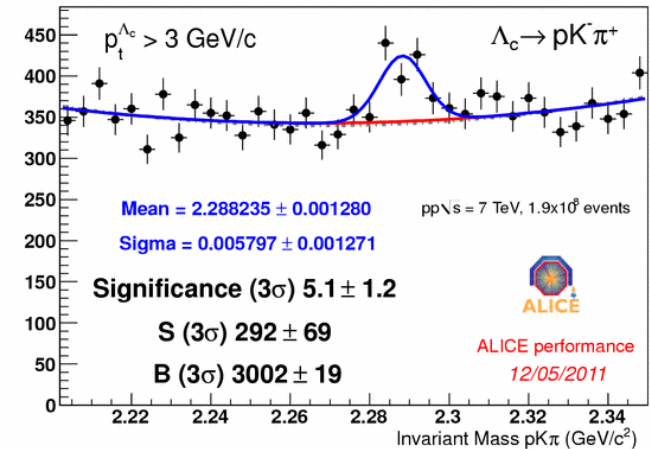
pp collisions @ 7 TeV

$D^0, D^+, D^*$  &  $D_s$  from 1 to 20 GeV/c  
with the full 2010 data sample



ALI-PERF-2047

$\Lambda_c$  showing up



ALI-PERF-1925

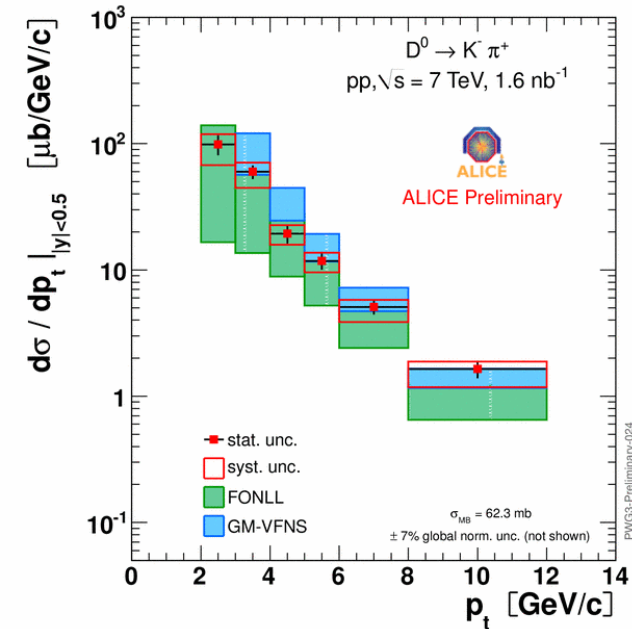
more to come from 2011 data

ALI-PERF-1875

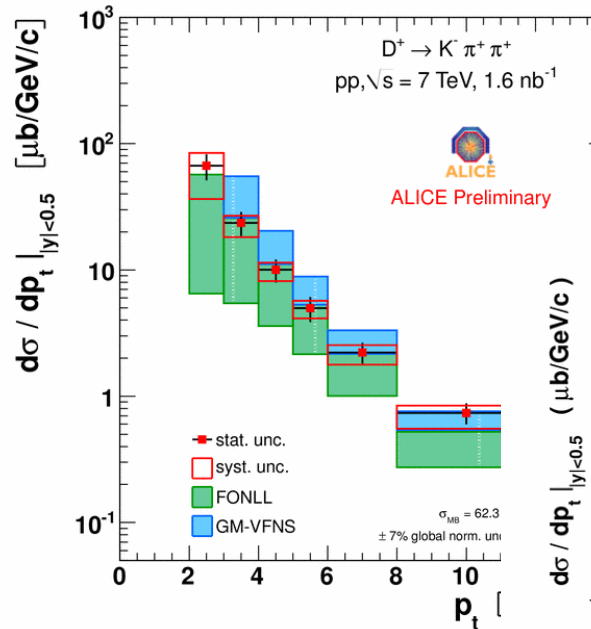


# D meson differential cross-section

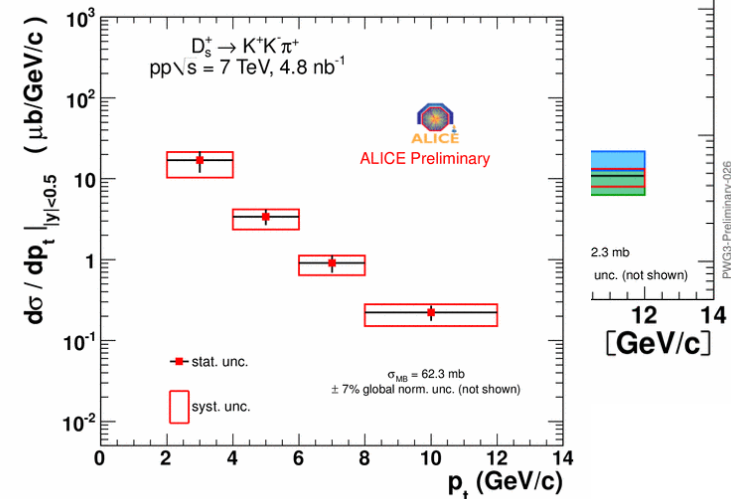
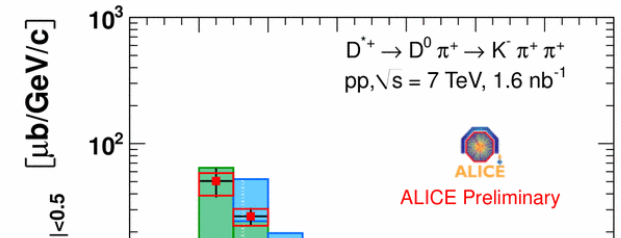
## pp collisions @ 7 TeV



ALI-PREL-9022



ALI-PREL-8170



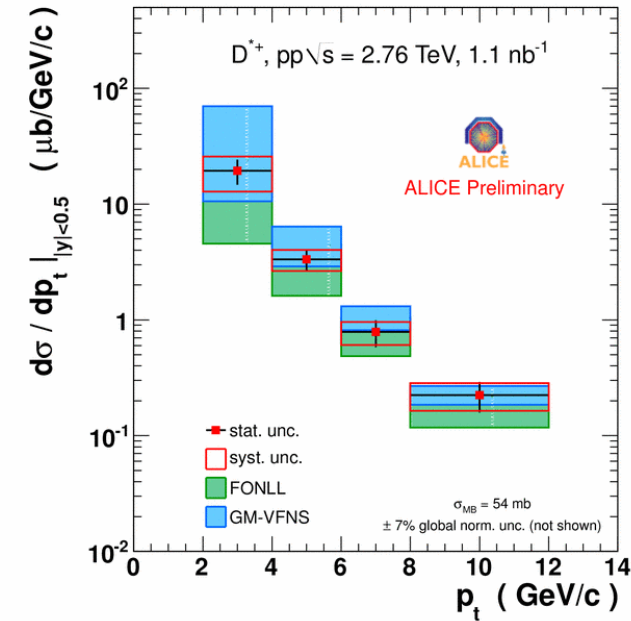
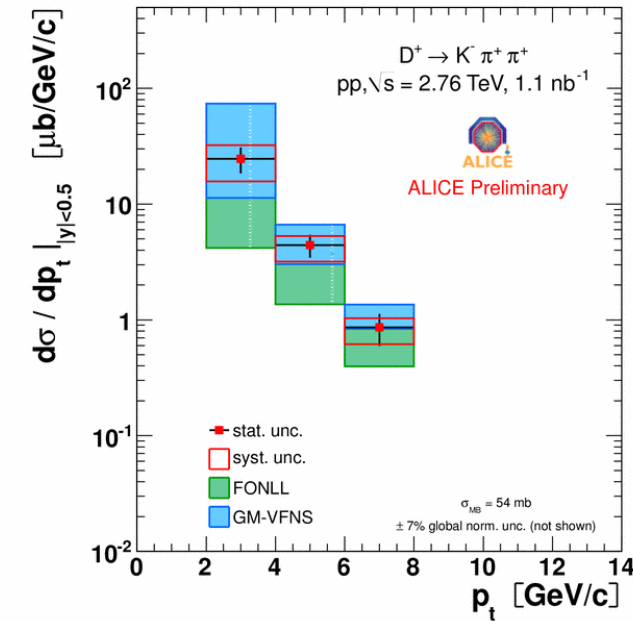
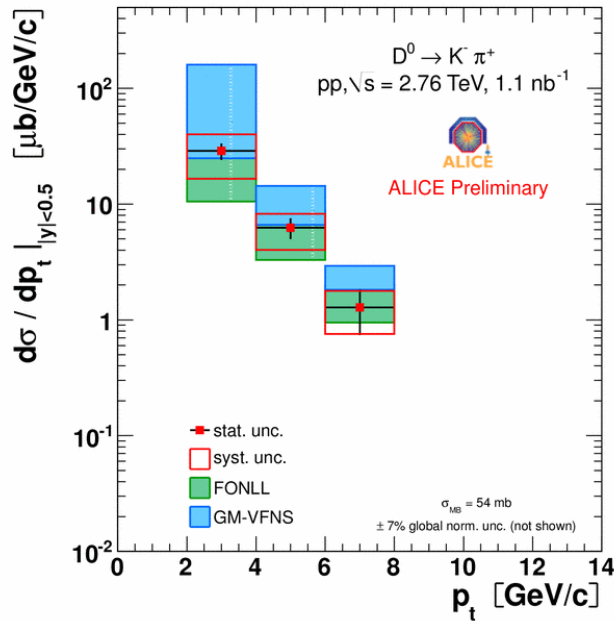
ALI-PREL-9496

- $2 < p_t < 12 \text{ GeV/c}$  with  $1.6 \text{ nb}^{-1}$  (30% of 2010 statistics),  $4.8 \text{ nb}^{-1}$  for  $D_s^+$
- prompt D meson yield obtained after pQCD (FONLL) driven feed-down subtraction (checked against data using impact parameter distributions)
- data well described by pQCD predictions (FONLL & GM-VFNS) within errors (seem to lie systematically in the upper part of FONLL and lower part of GM-VFNS)

FONLL: M. Cacciari et al., private comm., GM-VFNS: B.A. Kniehl et al., private comm.

# D meson differential cross-section

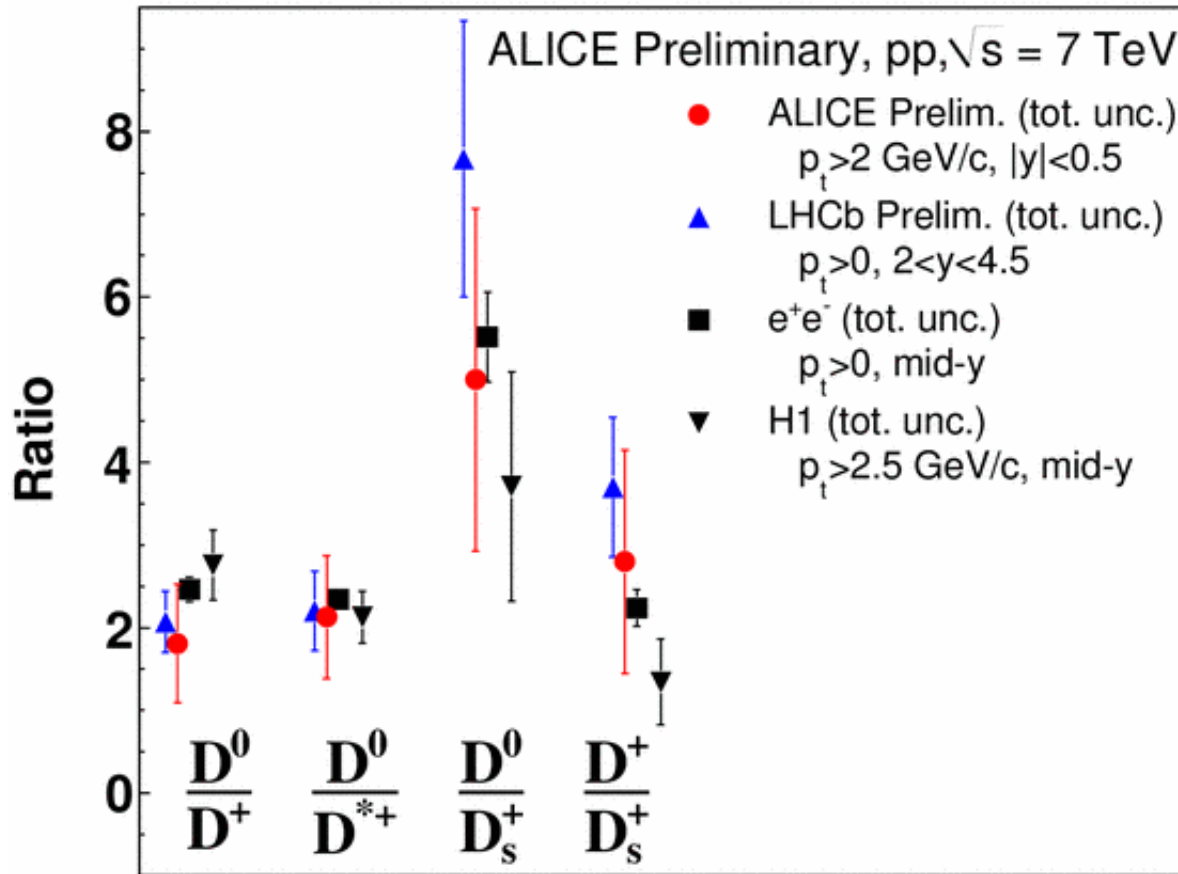
pp collisions @ 2.76 TeV



- $2 < p_t < 8-12$  GeV/c with  $1.1 \text{ nb}^{-1}$  (3 days of data taking in 2011)
- prompt D meson yield obtained after pQCD (FONLL) driven feed-down subtraction (checked against data using impact parameter distributions)
- data well described by pQCD predictions (FONLL & GM-VFNS) within errors (seem to lie systematically in the upper part of FONLL and lower part of GM-VFNS)

FONLL: M. Cacciari et al., private comm., GM-VFNS: B.A. Kniehl et al., private comm.

pp collisions @ 7 TeV

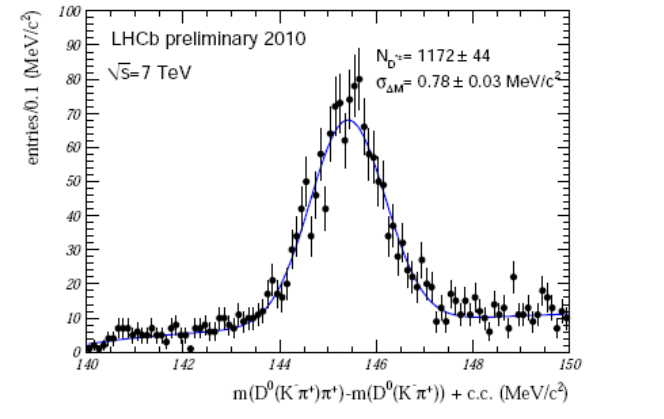
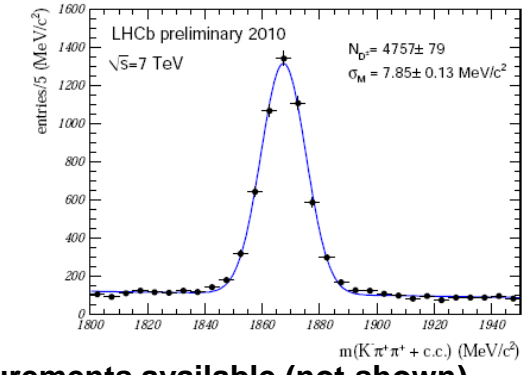
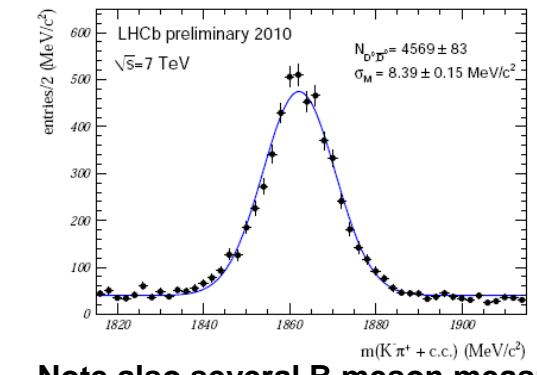
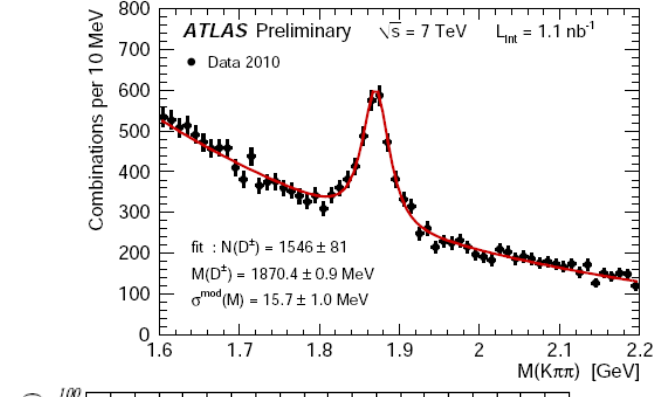
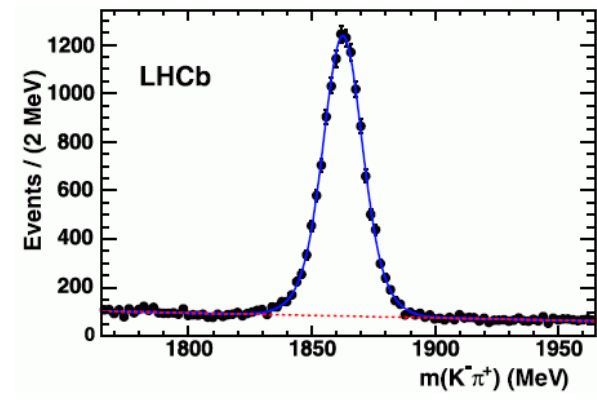
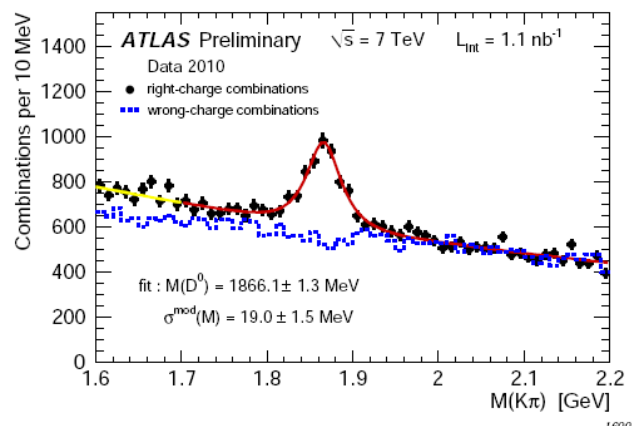
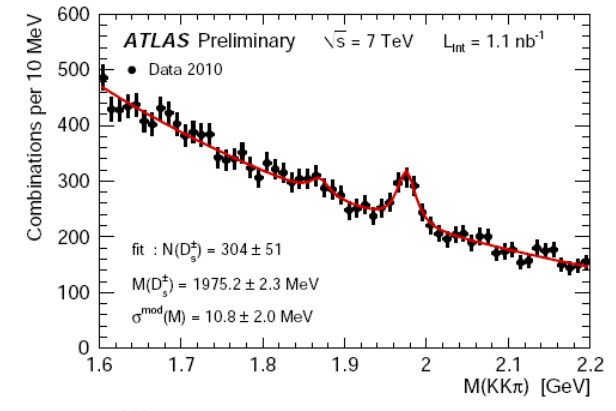
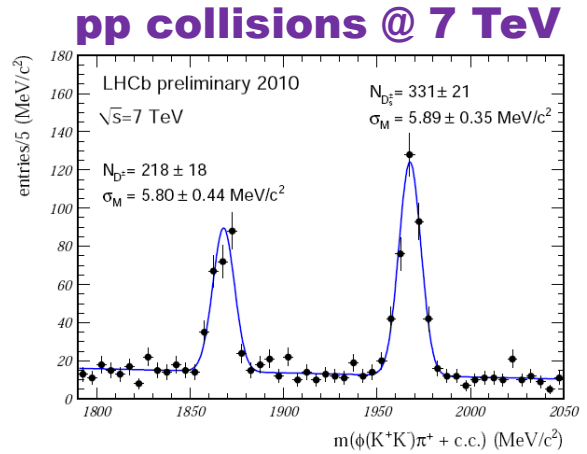
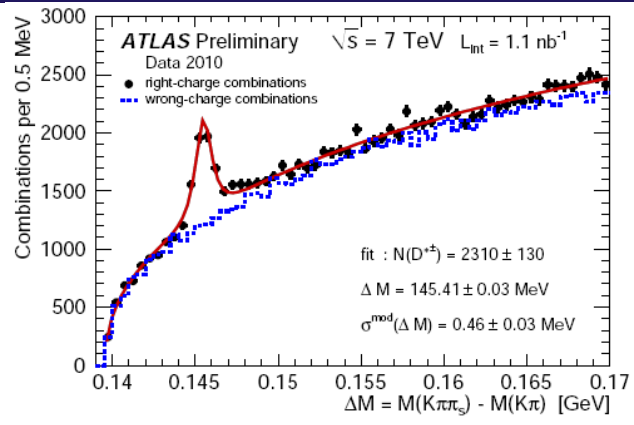


ALI-PREL-9458

nice agreement between various experiments



# Other D meson measurements



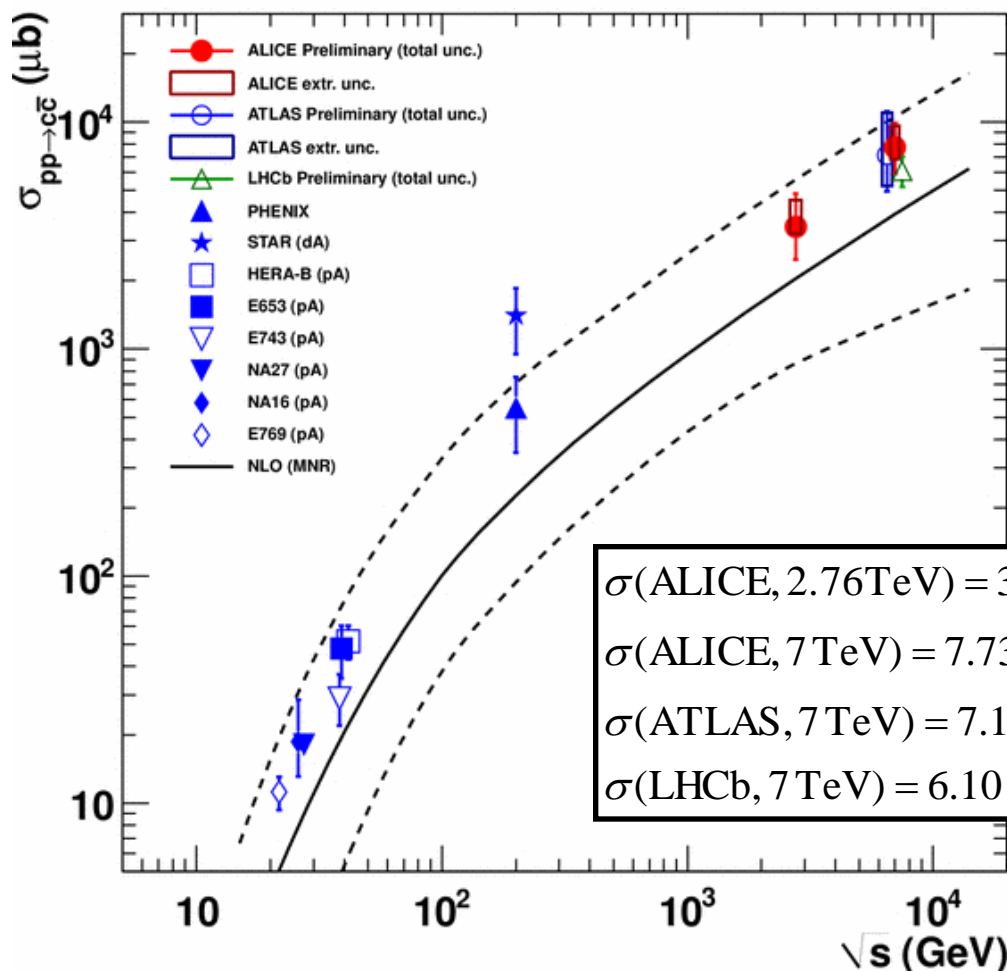
Note also several B meson measurements available (not shown)

ATLAS-CONF-2011-017, LHCb-CONF-2010-013

# Total charm cross-section in pp collisions



- extrapolation of D mesons data over full  $p_t$  and  $\eta$  range using FONLL

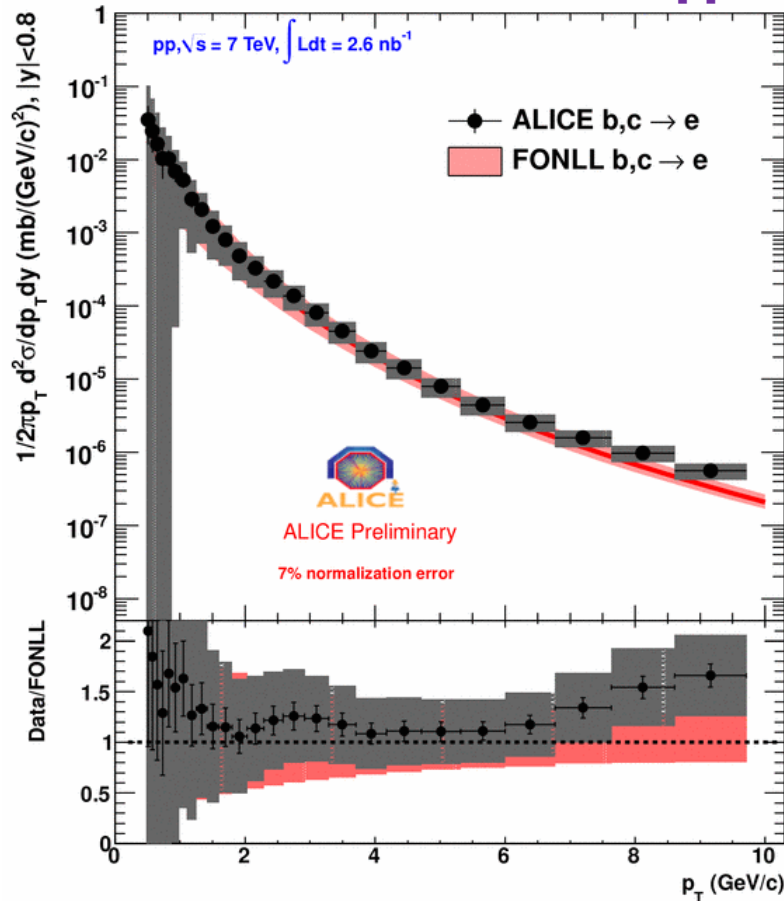


$$\begin{aligned} \sigma(\text{ALICE}, 2.76\text{TeV}) &= 3.45 \pm 0.41(\text{stat.})^{+0.72}_{-0.84}(\text{syst.}) \pm 0.17(\text{lum.})^{+1.09}_{-0.24}(\text{extr.})\text{mb} \\ \sigma(\text{ALICE}, 7\text{TeV}) &= 7.73 \pm 0.54(\text{stat.})^{+0.74}_{-1.38}(\text{syst.}) \pm 0.43(\text{lum.})^{+1.9}_{-0.87}(\text{extr.})\text{mb} \\ \sigma(\text{ATLAS}, 7\text{TeV}) &= 7.13 \pm 0.28(\text{stat.})^{+0.9}_{-0.66}(\text{syst.}) \pm 0.78(\text{lum.})^{+3.82}_{-1.9}(\text{extr.})\text{mb} \\ \sigma(\text{LHCb}, 7\text{TeV}) &= 6.10 \pm 0.93(\text{total})\text{mb} \end{aligned}$$

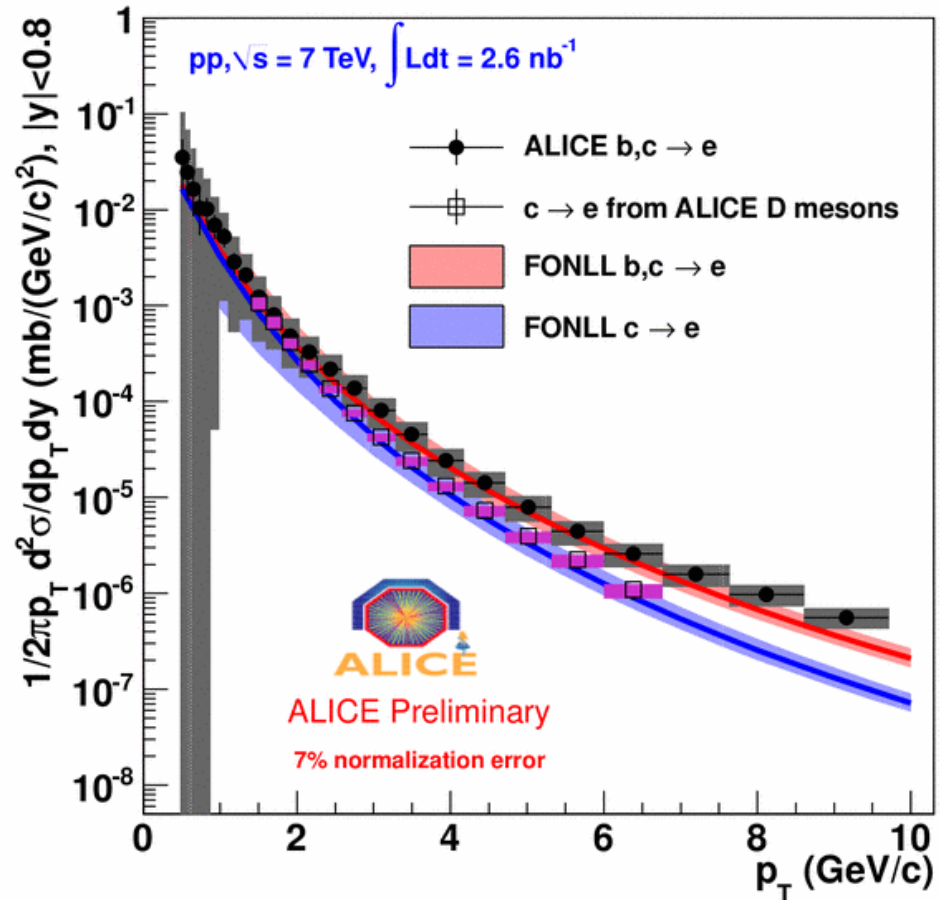
- good agreement between ALICE, ATLAS and LHCb measurements
- data consistent with NLO predictions (upper edge) over 3 orders of magnitude

ATLAS-CONF-2011-017, LHCb-CONF-2010-013

## pp collisions @ 7 TeV



ALI-PREL-3957

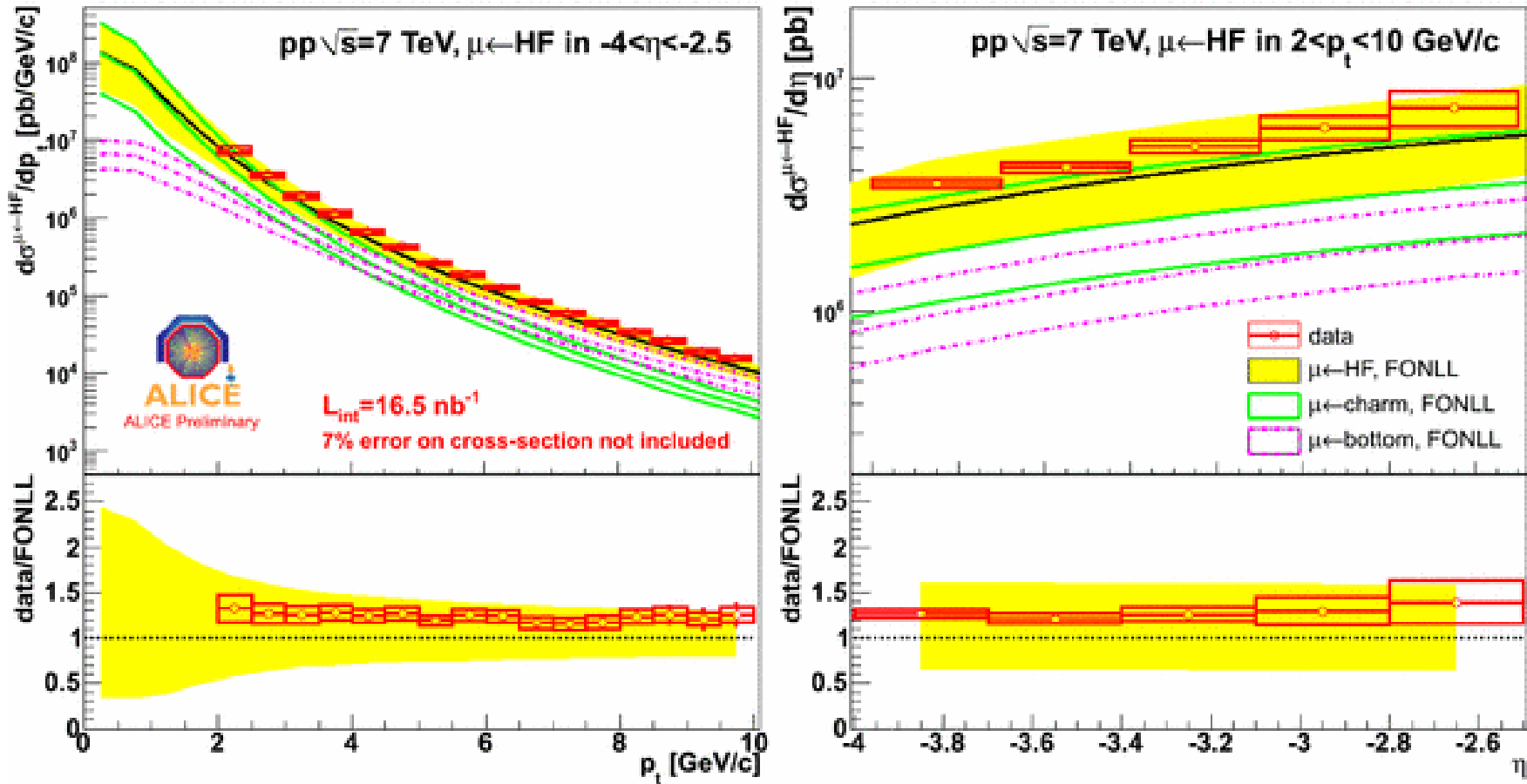


ALI-PREL-3970

- electrons from heavy flavours = inclusive electrons – cocktail (based on measured  $\pi_0 + m_t$  scaling)
- good agreement with FONLL c+b over the full  $p_t$  range
- consistent with the prompt charm measurement from D mesons



pp collisions @ 7 TeV

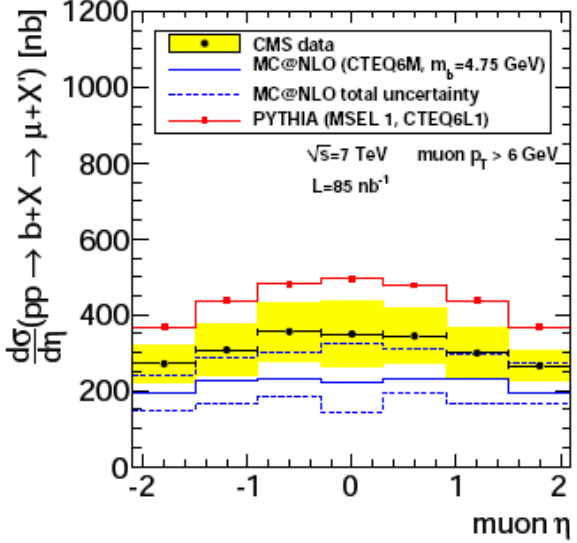
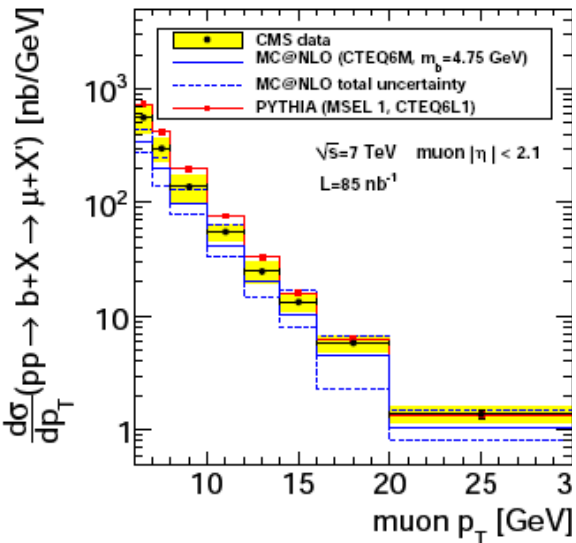
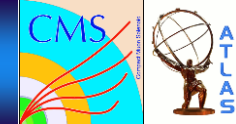


ALI-PREL-2849

- background ( $\mu \leftarrow \pi, K$ ) subtracted using MC normalized to data at low  $p_t$
- data well described by (upper part) of FONLL up to  $p_t = 10$  GeV/c and vs.  $\eta$
- according to FONLL,  $\mu \leftarrow b$  decay dominate for  $p_t > 6$  GeV/c

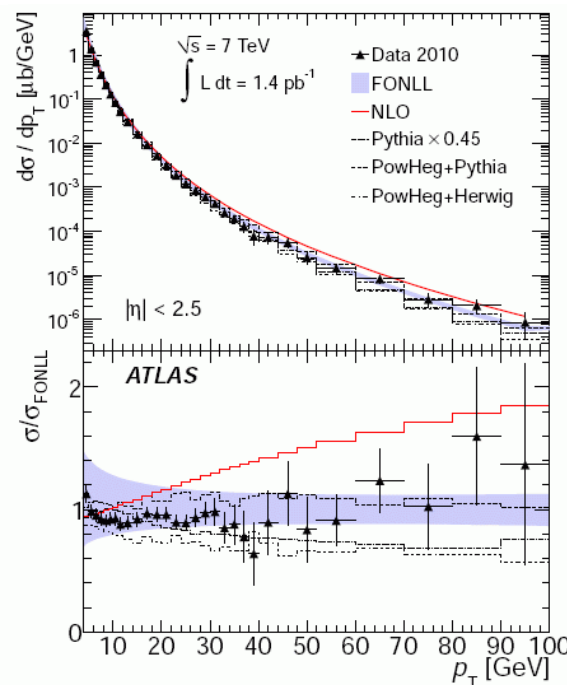
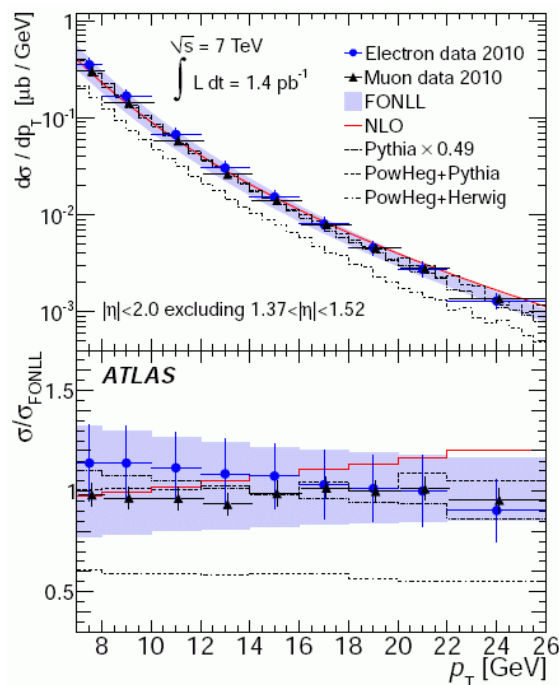
FONLL calculations from M. Cacciari et al.

# Heavy flavour muon & electron differential cross-section



pp collisions @ 7 TeV

**CMS: good agreement with MC@NLO**



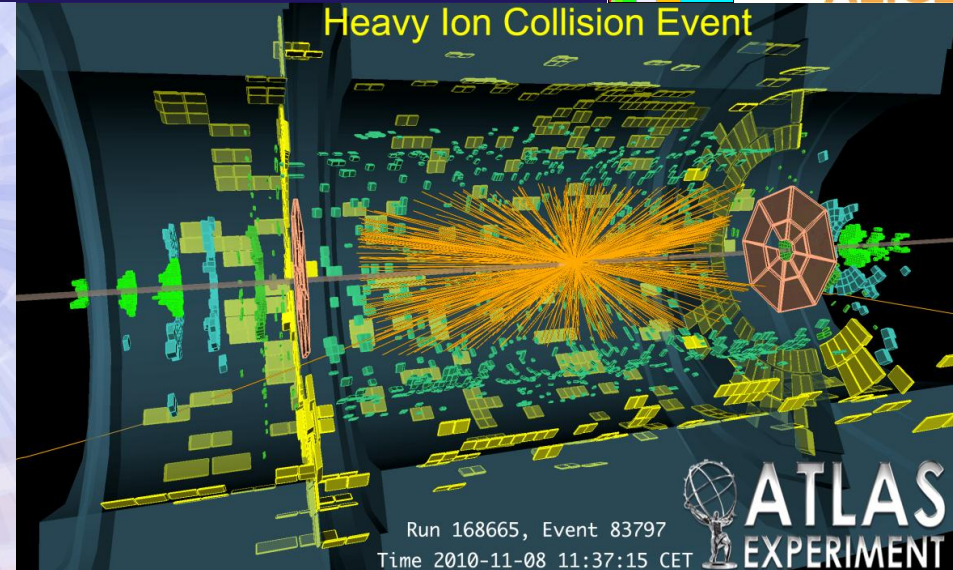
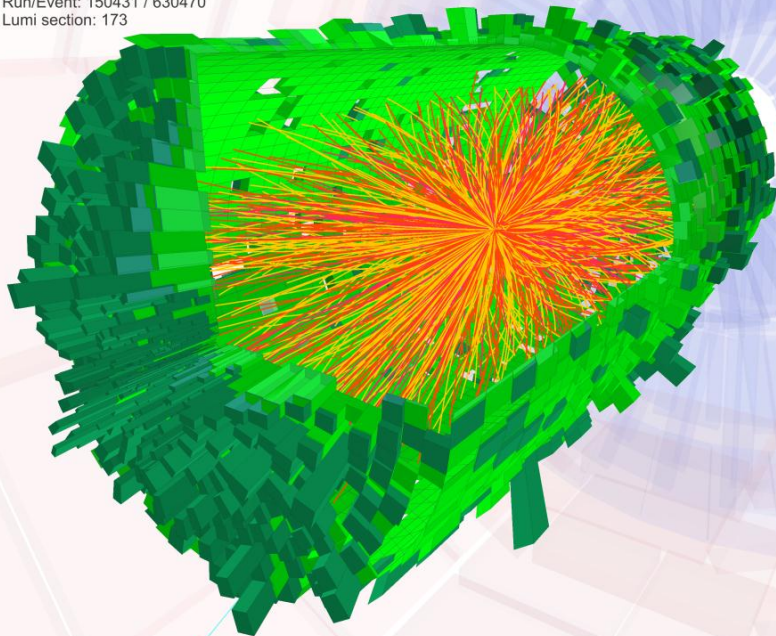
**ATLAS: good agreement with FONLL**

CMS: JHEP03 (2011) 090  
ATLAS: arXiv:1109.0525

# PbPb collisions (2.76 TeV)



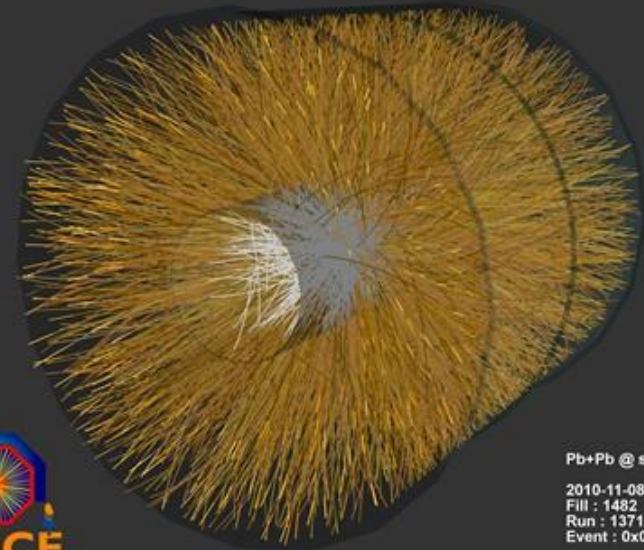
CMS Experiment at LHC, CERN  
 Data recorded: Mon Nov 8 11:30:53 2010 CEST  
 Run/Event: 150431 / 630470  
 Lumi section: 173



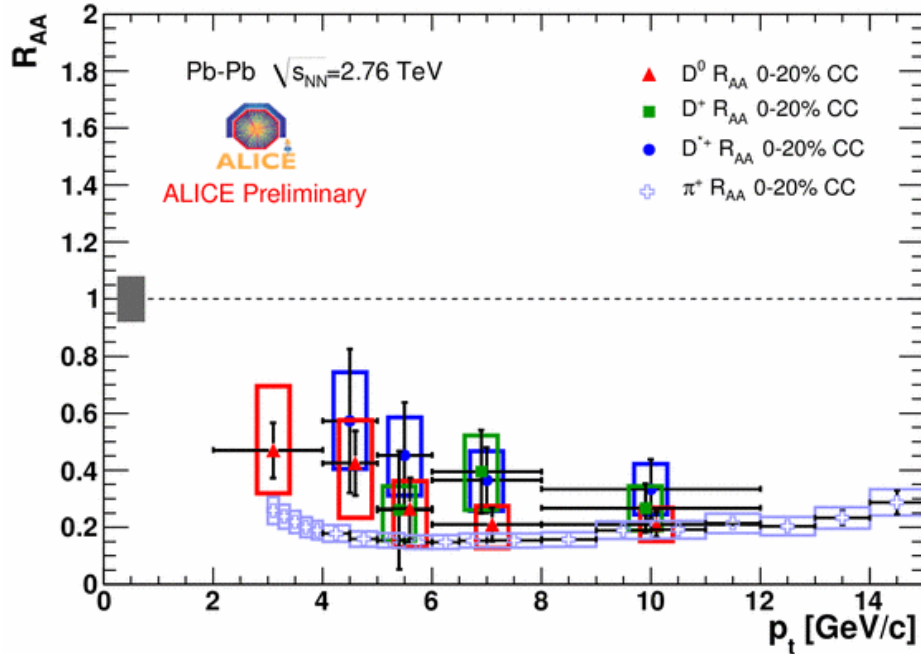
**key observable:  
 nuclear modification factor**

$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \times \frac{dN_{AA} / dp_t}{d\sigma_{pp} / dp_t}$$

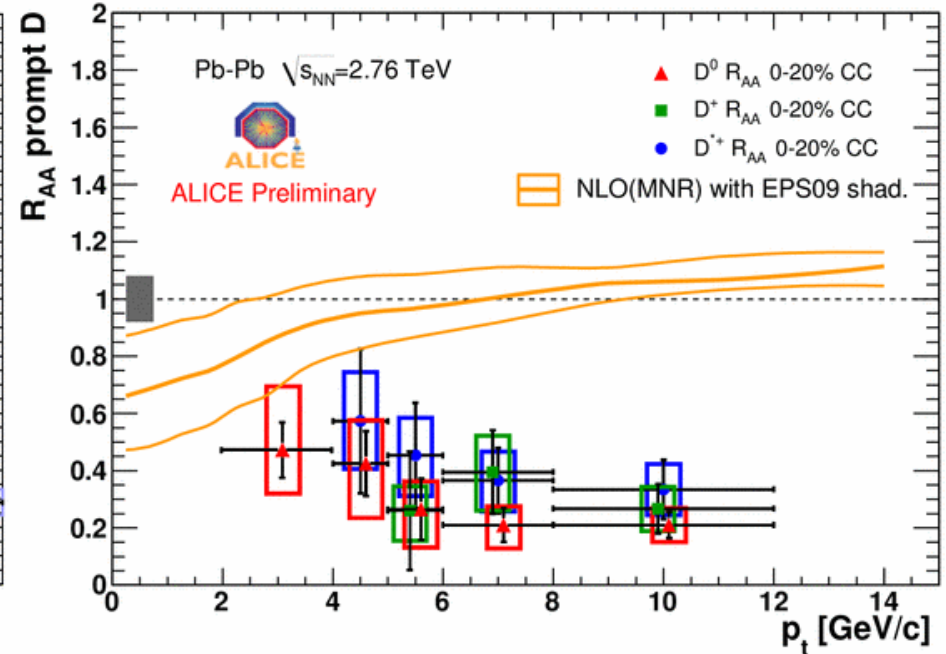
**in most cases, pp data are extrapolated from 7 TeV to 2.76 TeV using pQCD driven  $\sqrt{s}$  scaling**



Pb+Pb @ sqrt(s) = 2.76 ATeV  
 2010-11-08 11:30:46  
 Fill : 1482  
 Run : 137124  
 Event : 0x00000000D3BBE693



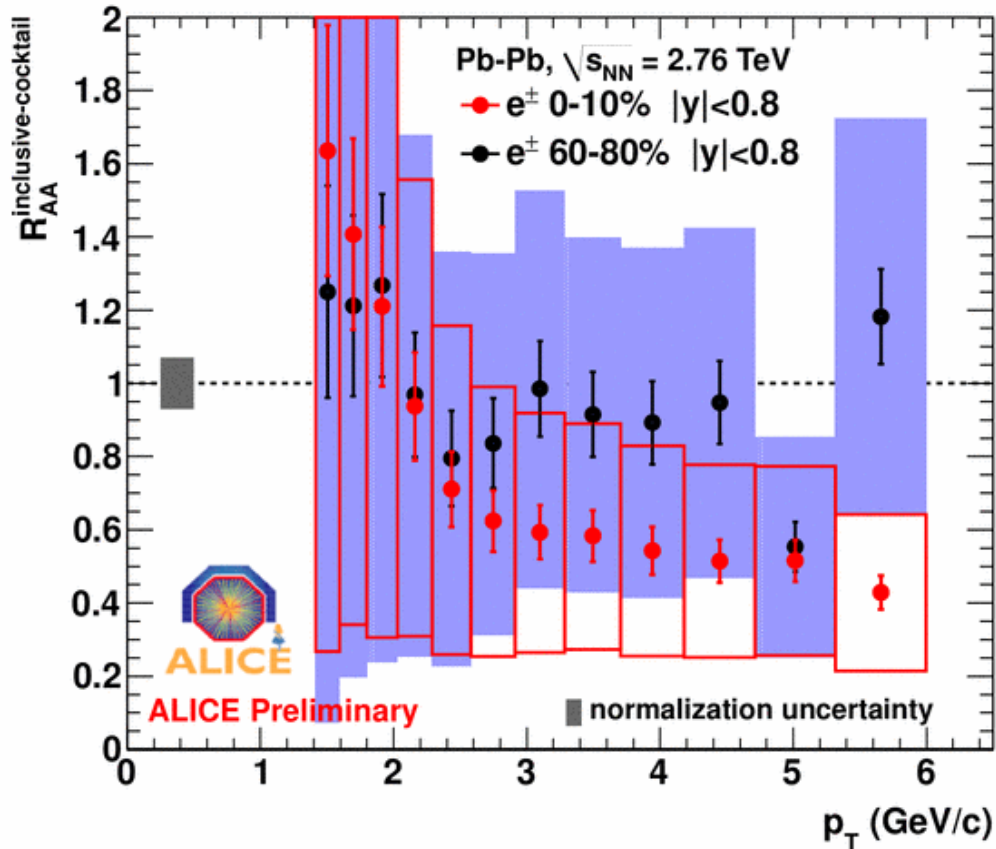
ALI-PREL-10777



ALI-PREL-10749

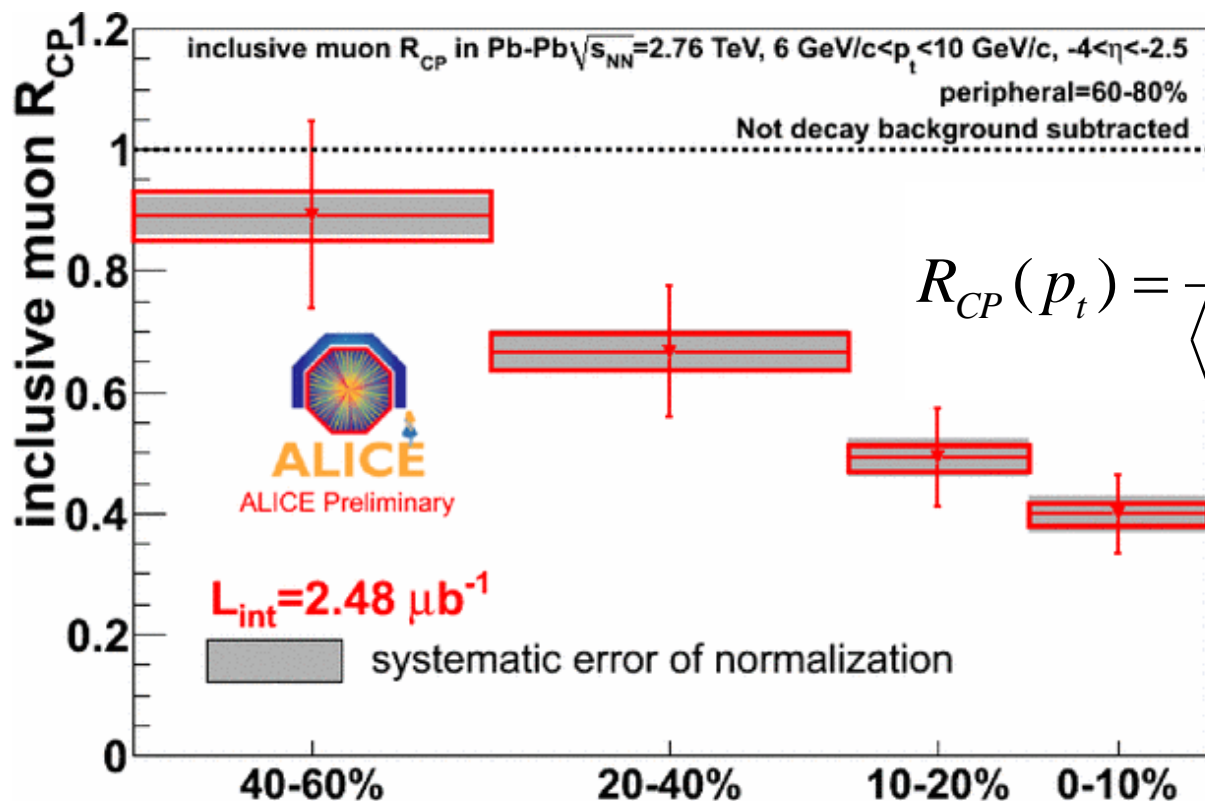
- $p_t > 5$  GeV/c: similar suppression (factor  $\sim 4-5$ ) for  $D^0$ ,  $D^+$ ,  $D^{*+}$  and  $\pi^\pm$
- $p_t < 5$  GeV/c: D  $R_{AA}$  slightly higher than  $\pi^\pm R_{AA}$ , dead cone effect?
- evidence of a hot medium effect from pQCD NLO shadowing calculations
- pPb run crucial to understand these data in details (low  $p_t$  rise?)





ALI-PREL-5138

- electrons from heavy flavours = inclusive electrons - cocktail
- large systematics from electron PID, cocktail and reference spectrum
- dominated by heavy flavour decays for  $p_T > 3-4$  GeV/c
- $R_{AA}$  (0-10%) shows a suppression of about a factor 1-5 for  $3 < p_T < 6$  GeV/c



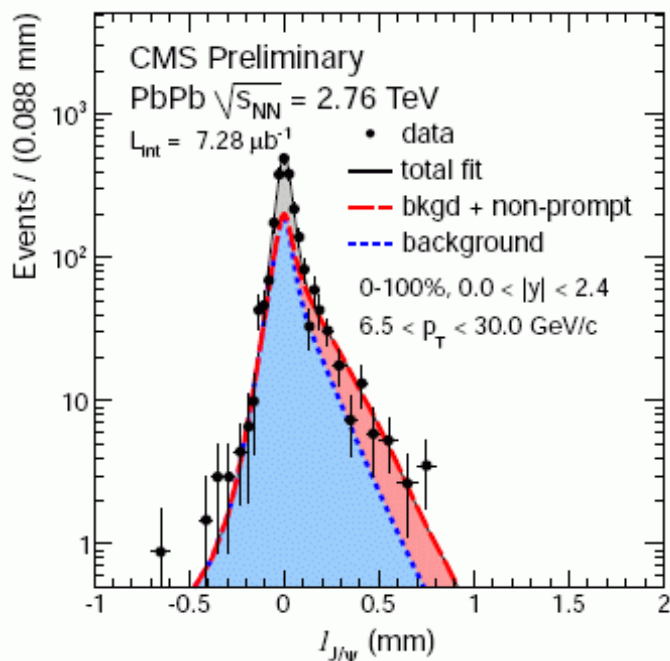
$$R_{CP}(p_t) = \frac{\langle 1/T_{AA} \rangle \times dN^\mu / dp_t \Big|_{central}}{\langle 1/T_{AA} \rangle \times dN^\mu / dp_t \Big|_{peripheral}}$$

ALI-PREL-2937

- systematic uncertainty on normalization from the uncertainty on the ratio of  $T_{AA}$  between the central and peripheral centrality classes
- suppression increases with centrality
- note: muons from primary  $K/\pi$  not subtracted

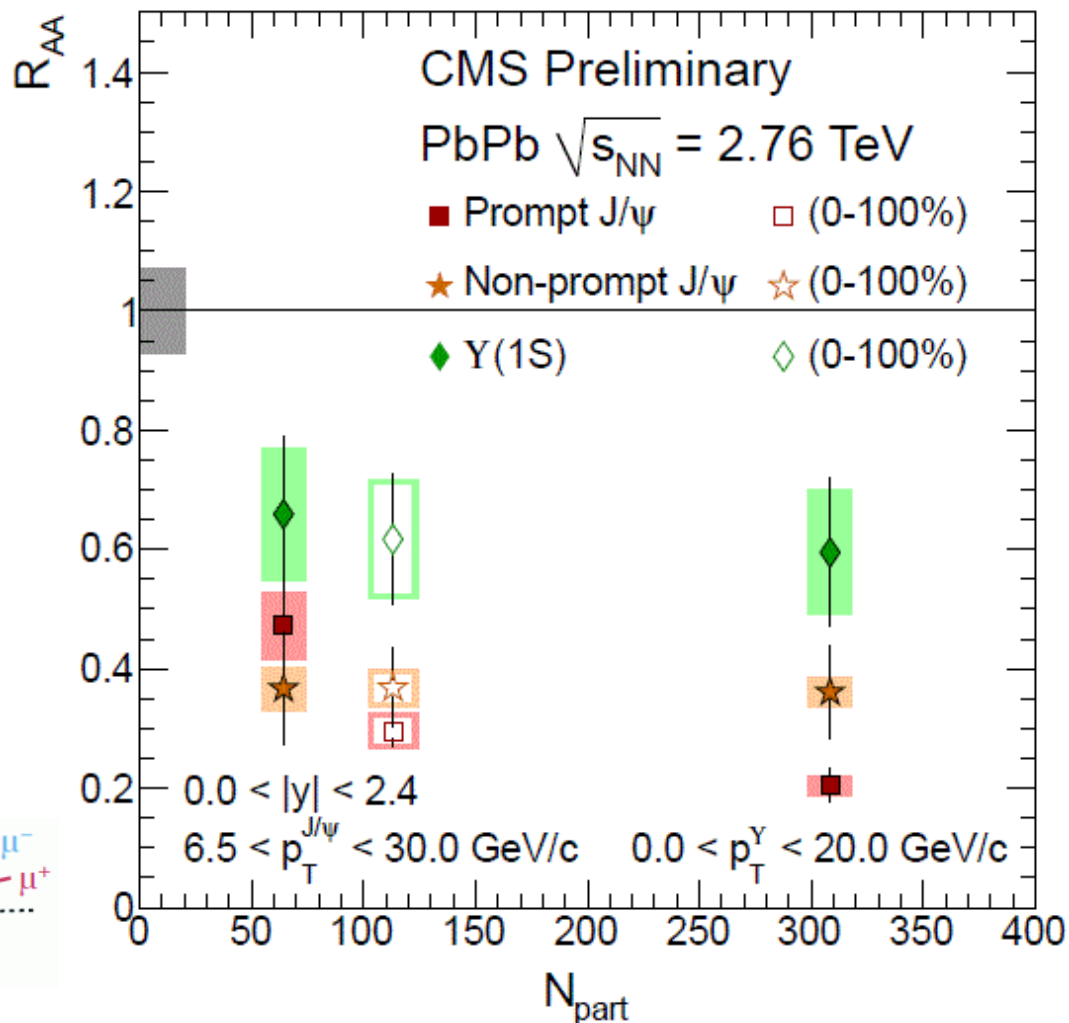
fraction of muons from primary  $K/\pi$  decay (HIJING w/o quenching)

centrality	$p_t > 6 \text{ GeV}/c$
0-10%	$0.09 \pm 0.03$
20-40%	$0.05 \pm 0.02$
40-80%	$0.02 \pm 0.02$



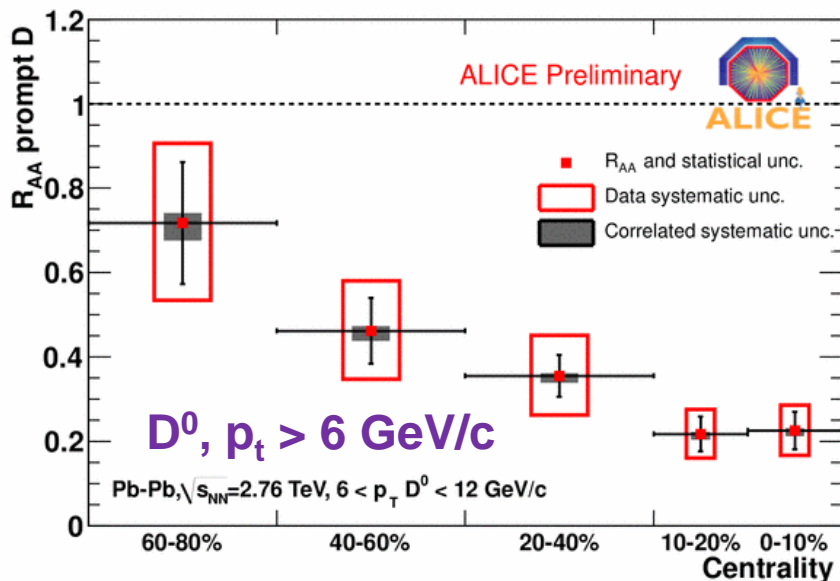
pseudo-proper decay length:

$$l_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$

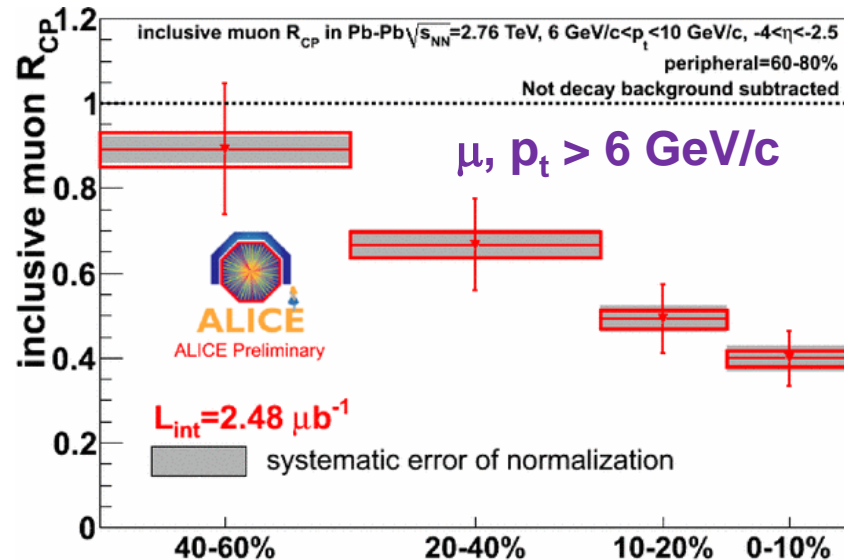


- suppression of non-prompt J/ψ → indication of b-quark quenching
- non-prompt J/ψ less suppressed than prompt J/ψ

# Data comparison: centrality dependence



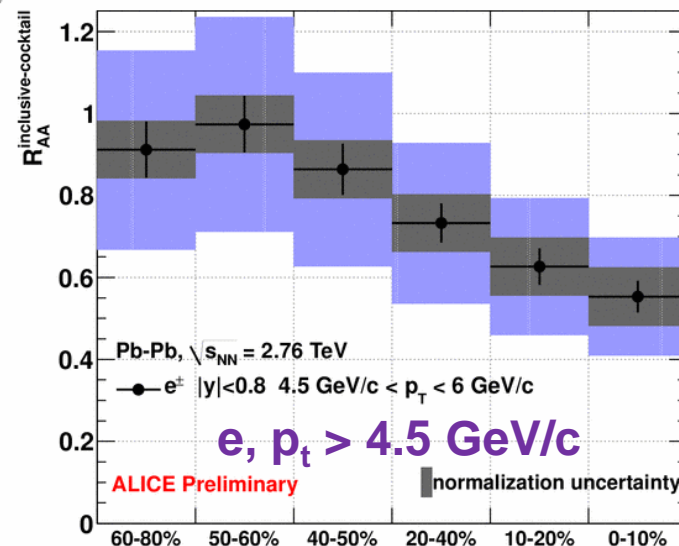
ALI-PREL-3218



ALI-PREL-2937

- consistent centrality dependence
- muons  $\sim$  electrons
- $D^0 R_{AA}$  seems lower (charm versus beauty?)

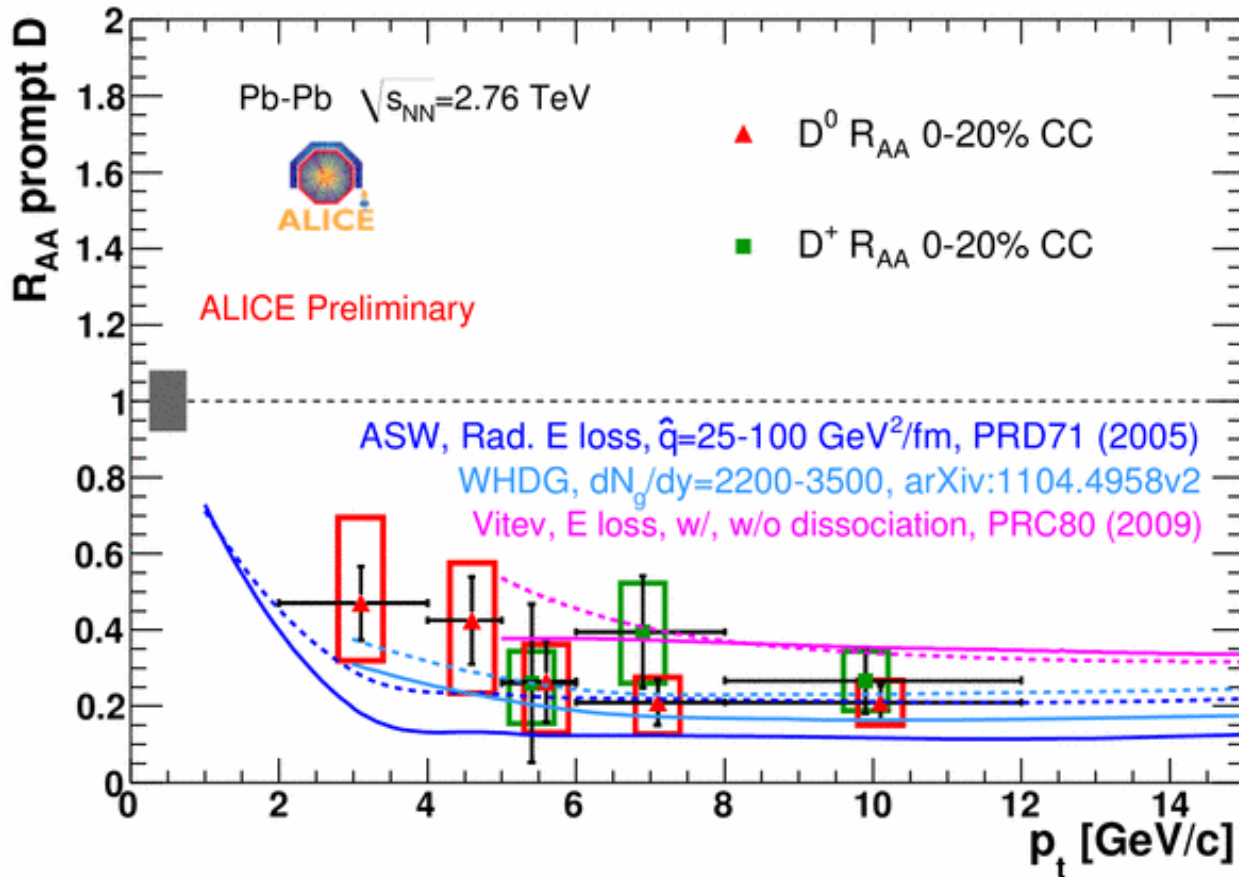
note:  $J/\psi$  from b  $R_{AA} \sim$  flat vs.  $N_{part}$  (slide # 27)



ALI-PREL-7901



# Data versus models (mid-rapidity D mesons)

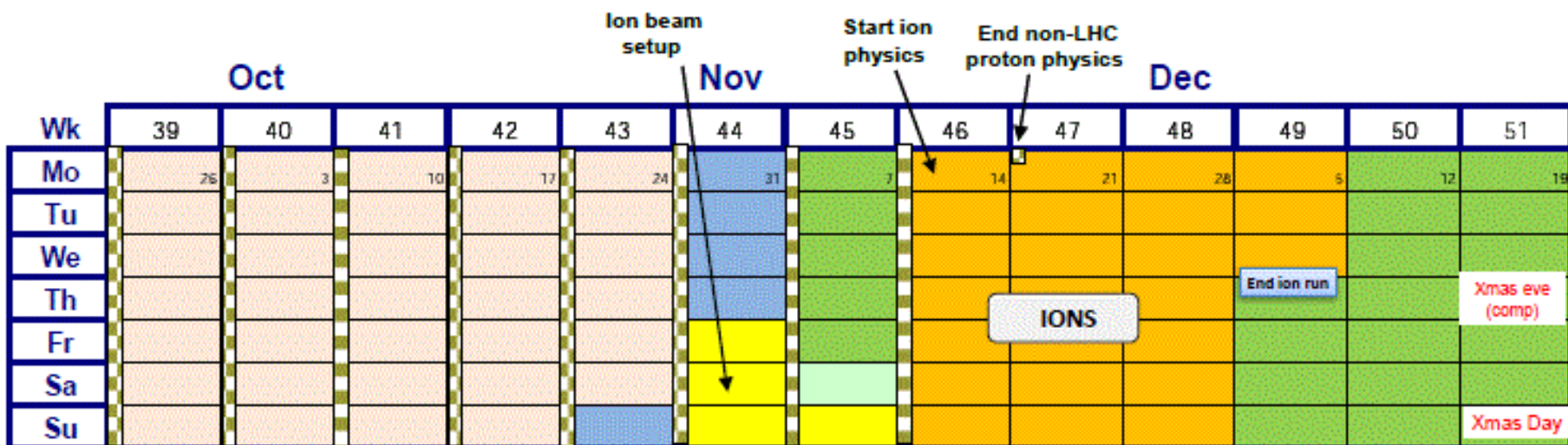


ALI-PREL-5648

- radiative energy loss: overpredict at low  $p_t$
  - radiative + collisional energy loss: fair description
  - light cone wave function with dissociation: underpredict
- warning: most of model predictions concern PbPb collisions at 5.5 TeV

# Summary

- the LHC heavy-ion run has revealed evidence for strong interaction of heavy quarks with the medium formed in PbPb collisions
- hints for different behaviour (suppression) of c, b and light quarks
- more precise results and quantitative statements need inputs from the forthcoming PbPb and pPb runs



next PbPb run in Nov.-Dec. 2011, stay tuned...