Heavy Flavour production at LHC

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Outline

Introduction

- Why heavy flavours physics at LHC?.
- Few words about Tevatron and RHIC.

Heavy Flavour production (c, b):

- Cross section measurements in pp
- Production in Heavy-Ion collisions.
- Why heavy flavour in Heavy-Ion collisions.

Experimental challenges:

- What we can do with the first data
- Examples from ALICE, CMS and ATLAS

Outlook

Many thanks to:

Andrea Dainese and Andre' Mischke (ALICE collaboration), Paula Eerola and Jim Olsen(CMS collaboration), Samira Hassani and Chara Petridou (ATLAS collaboration)

Why Heavy Flavour production at LHC?

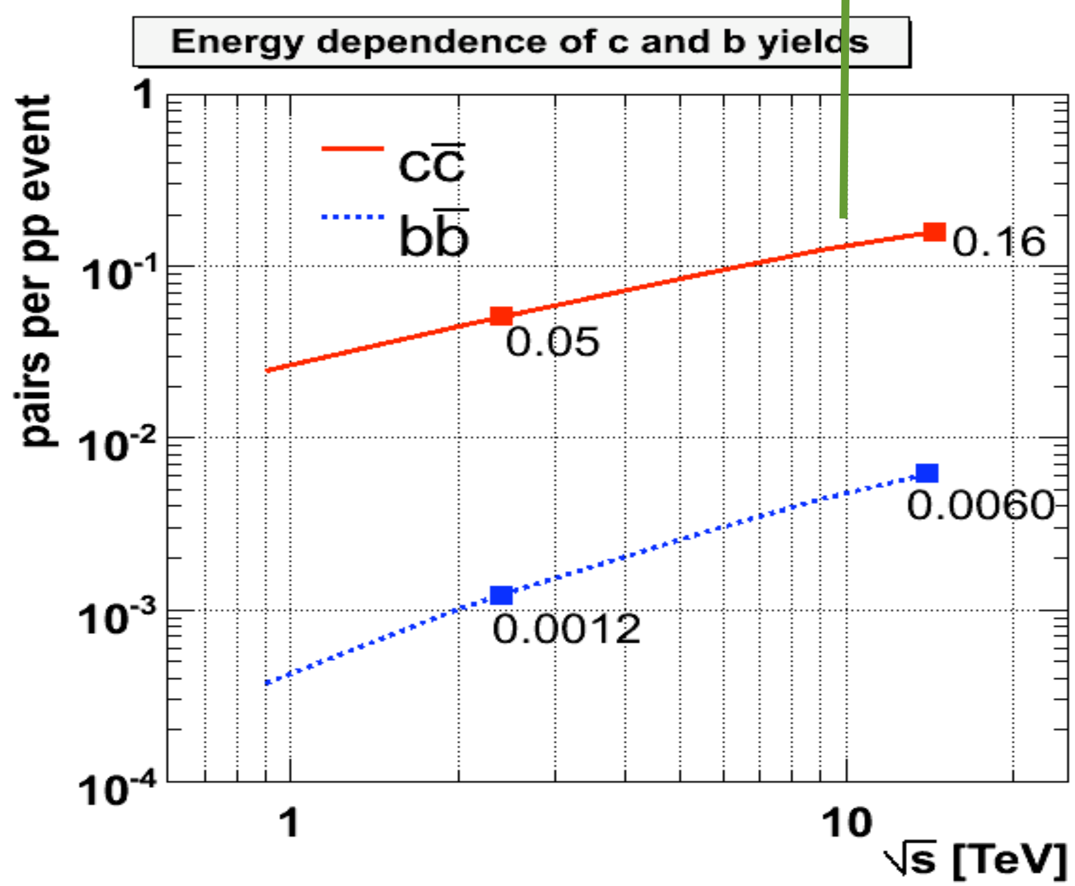
- Heavy flavour production provide a QCD test tool.
  - p-p : test the QCD prevision.
  - p-A : initial state effects.
  - A-A : probe the high density medium.

- Large Hadron Collider.
  - Large cross section, heavy flavour factory
  - NLO production processes became important.

$$\sigma^{c\bar{c}}_{LHC} \approx 10 \times \sigma^{c\bar{c}}_{RHIC}$$

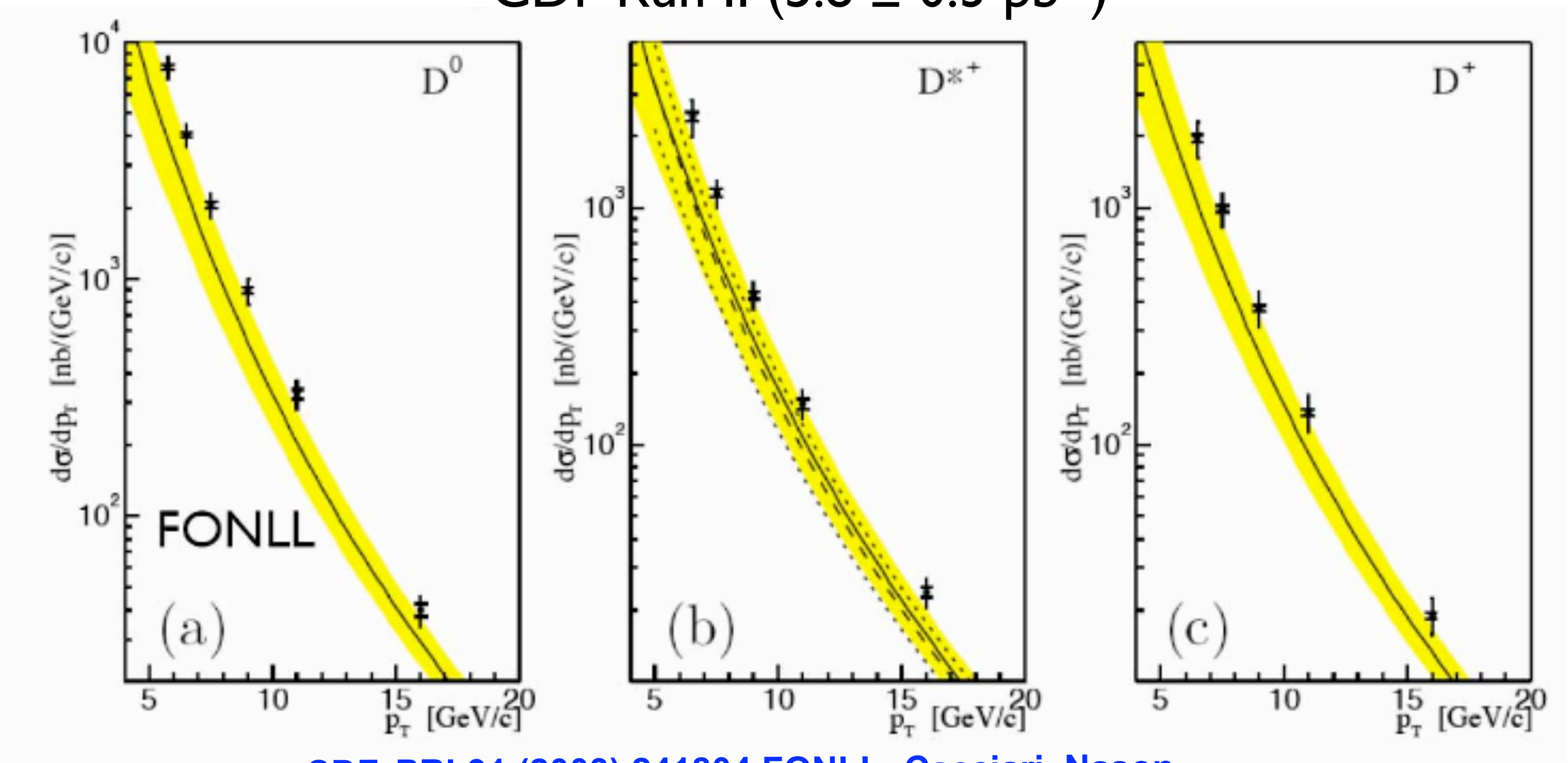
$$\sigma^{b\bar{b}}_{LHC} \approx 100 \times \sigma^{b\bar{b}}_{RHIC}$$

At $\sqrt{s}$ = 10 TeV
→ yields lower by ≈25%



Charm and Bottom @ Tevatron

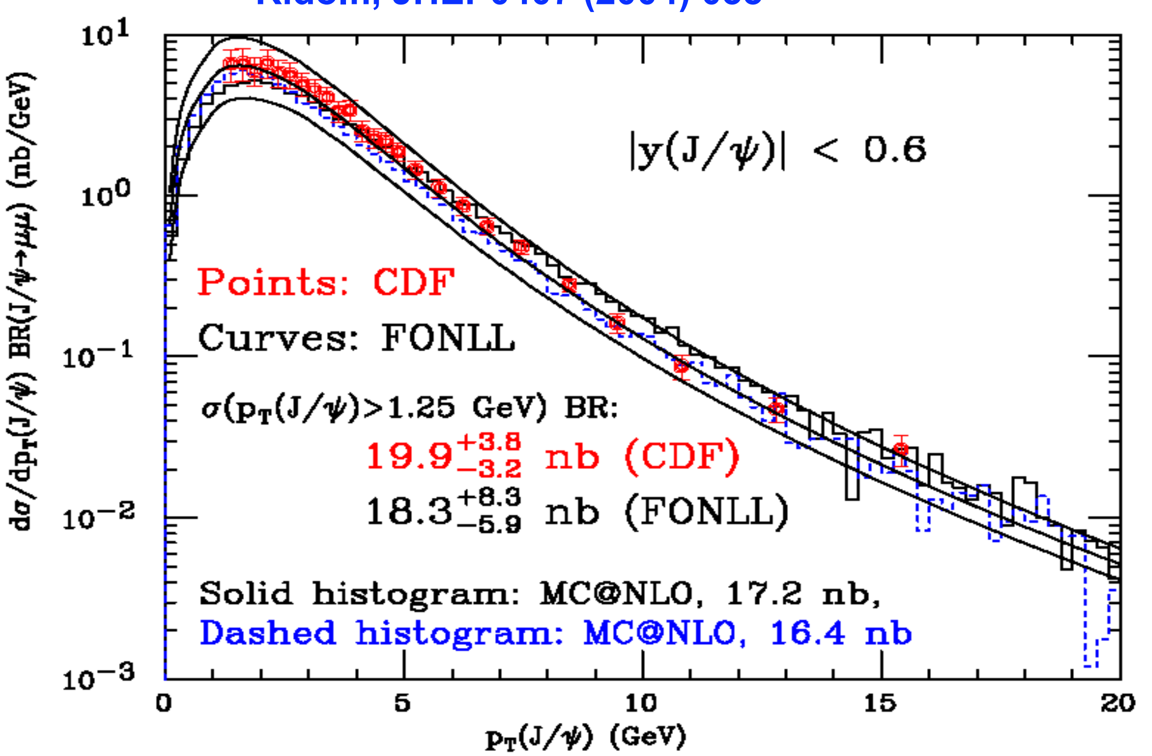
CDF Run II (5.8 ± 0.3 pb^{-1})



CDF, PRL91 (2003) 241804 FONLL: Cacciari, Nason

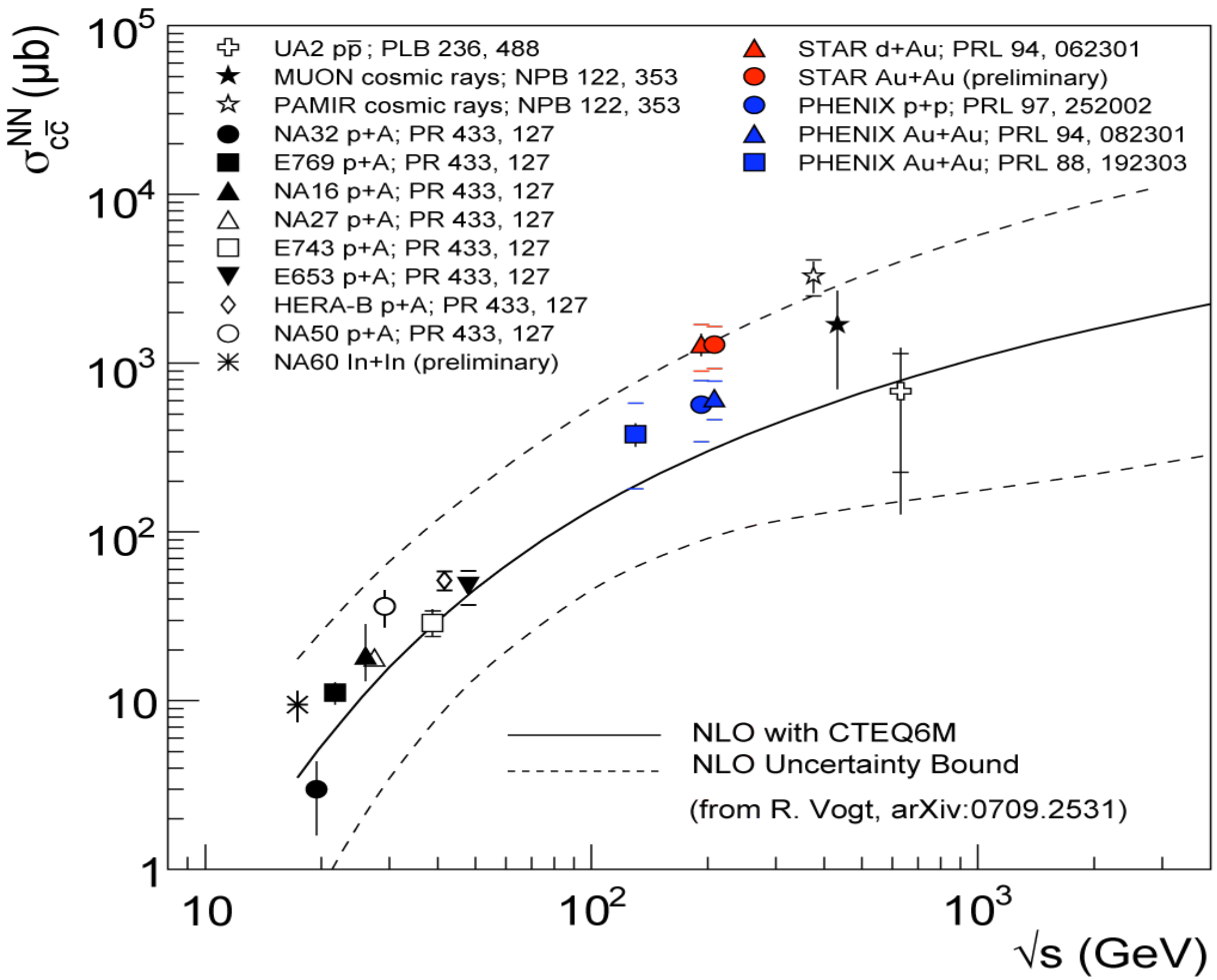
Measurements are at the edge of theoretical errors.

FONLL, MC@NLO:
Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033



- ☑ At the end of b production saga: Good understanding, inside the errors, of b production.
- ☑ Charm cross section studies, more complex, available since Run II - but not low pt!.

Charm @ RHIC



- ☑ STAR and PHENIX are self-consistent
- ☑ STAR data factor of ~2 larger than PHENIX data but both consistent with NLO pQCD calculation **(uncertainties primarily from scale choice and PDF)**

What we expect @ LHC

- NLO predictions (ALICE baseline for **charm** & **beauty**)

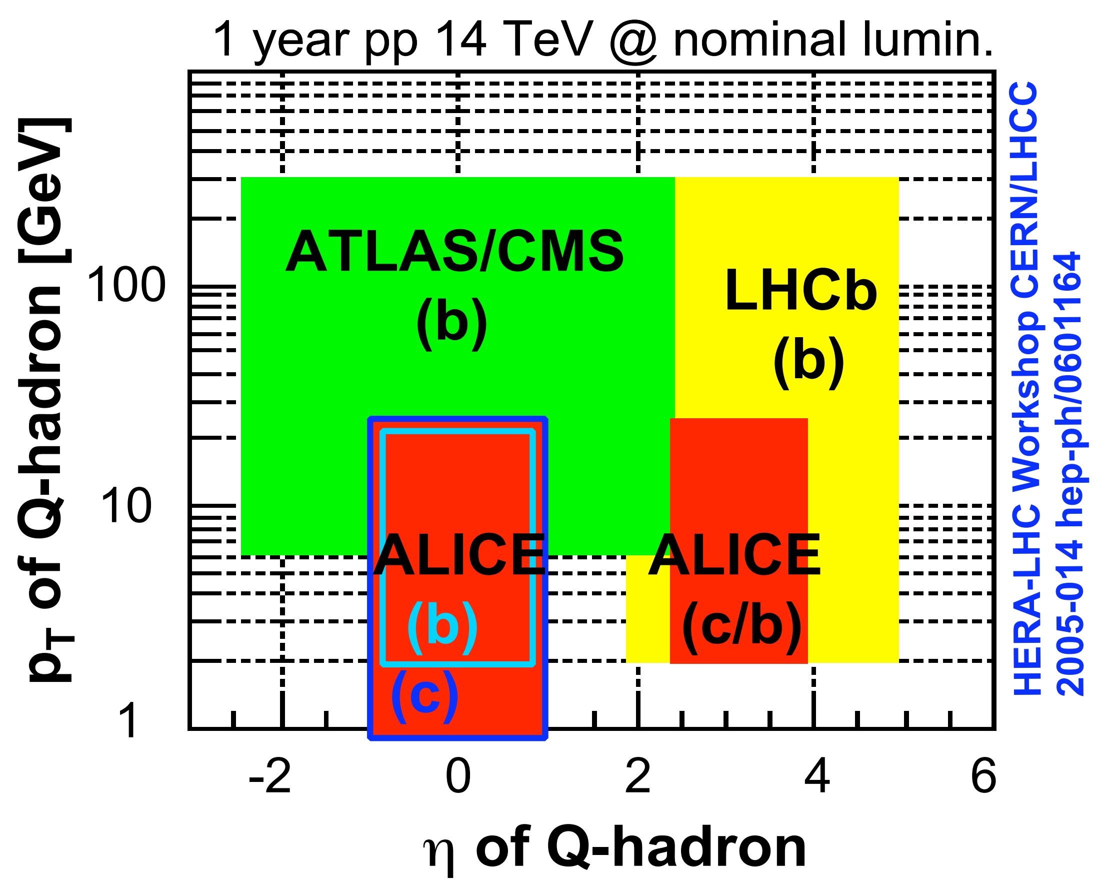
system : $\sqrt{s_{NN}}$:	Pb-Pb (0-5% centr.) 5.5 TeV	p-Pb (min. bias) 8.8 TeV	pp 14 TeV
$\sigma_{NN}^{Q\overline{Q}}$ [mb]	4.3 / 0.2	7.2 / 0.3	11.2 / 0.5
$N_{tot}^{Q\overline{Q}}$	115 / 4.6	0.8 / 0.03	0.16 / 0.007

MNR code (FO NLO): Mangano, Nason, Ridolfi, NPB373 (1992) 295. With EKS98 shadowing.

Uncertanties factor ~2

Acceptance (pp) of experiments at LHC allows:

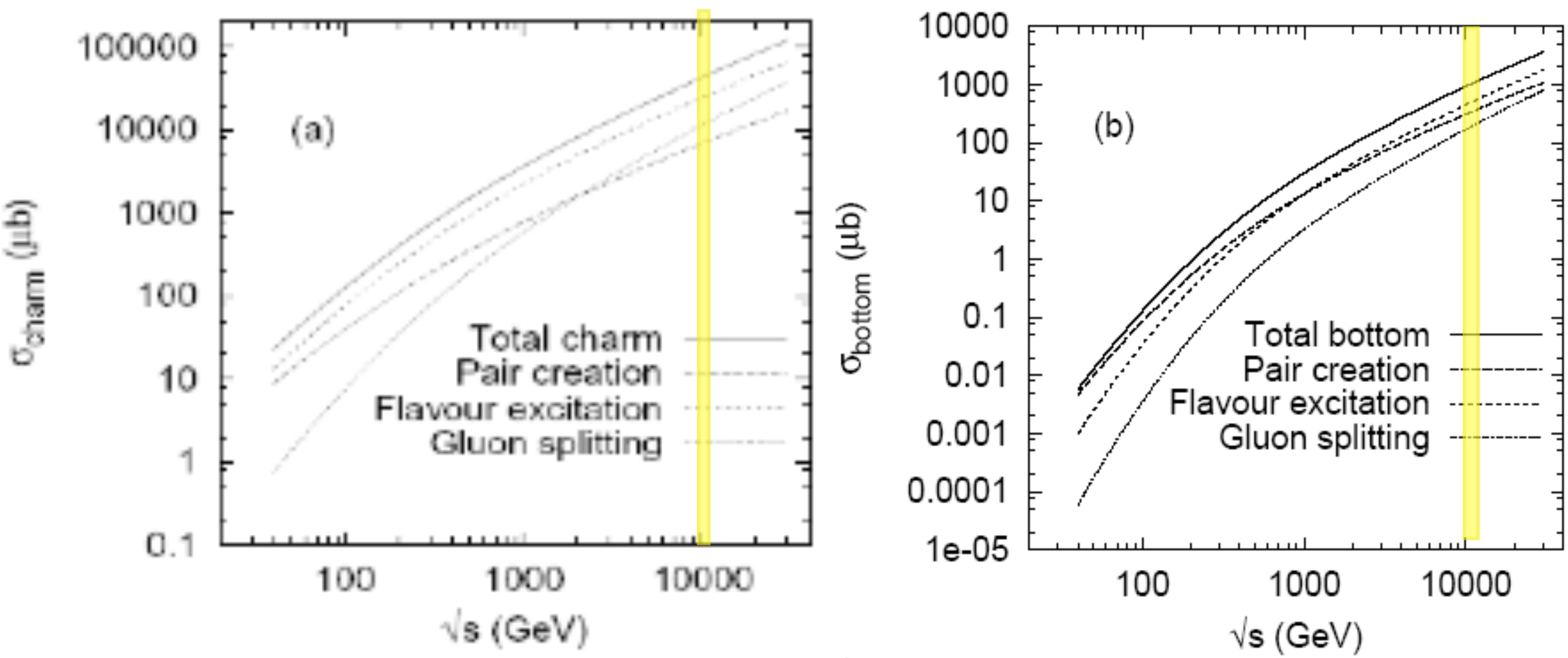
- ☑ Large η - pt coverage
- ☑ ALICE pt acceptance below 1 GeV for Charm !
- ☑ A new x range available ~10^{-6}



NLO contribution became important

- At LHC energies NLO processes are expected to be dominant.
  $K=\sigma_{NLO}/\sigma_{LO}$ = *1.4 - 3.2 for b production* hep-ph/0311225

E. Norrbin, T. Sjostrand, Eur. Phys. J. C17, 137 (2000)



Heavy Flavour production in Nucleus-Nucleus

☑ **large virtuality Q → happen at $t = 0$**

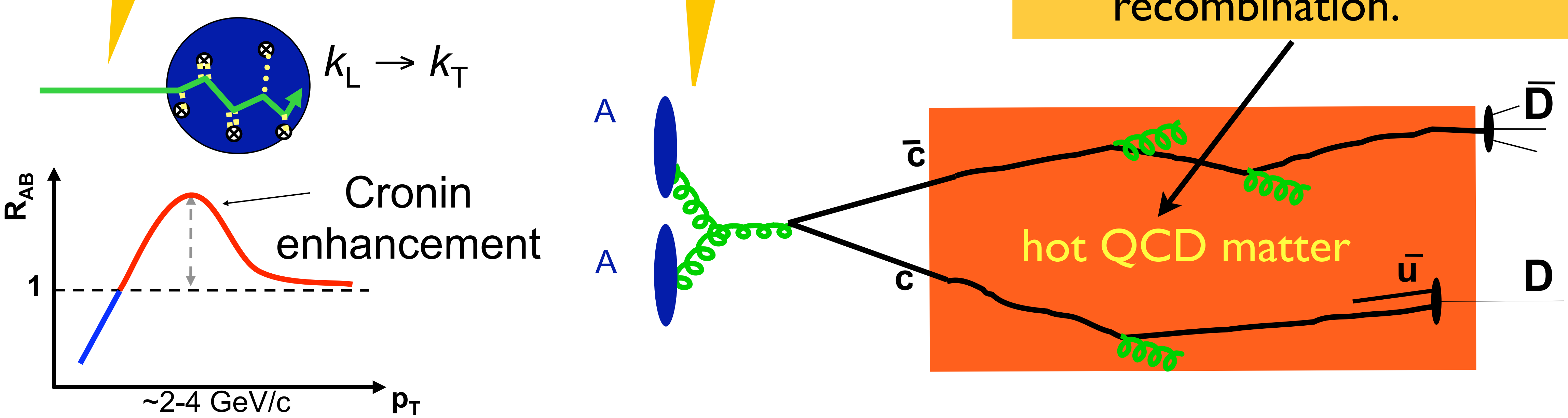
→ small "formation time" $\Delta t \sim 1/Q$

- **for charm: $\Delta t < 1/2m_c \sim 0.1$ fm/c << $\tau_{QGP} \sim 5$–10 fm/c**
- **for beauty: $\Delta t < 1/2m_b$ << 0.1 fm/c << $\tau_{QGP} \sim 5$–10 fm/c**

⇨ Probe the full collision history!

Initial state effects
- PDF shadowing.
- kt broadering.

Final state effects:
- Energy Loss.
- hadronization/ recombination.



A.Dainese - Workshop on High Density QCD at LHC and in Cosmic Rays -2009

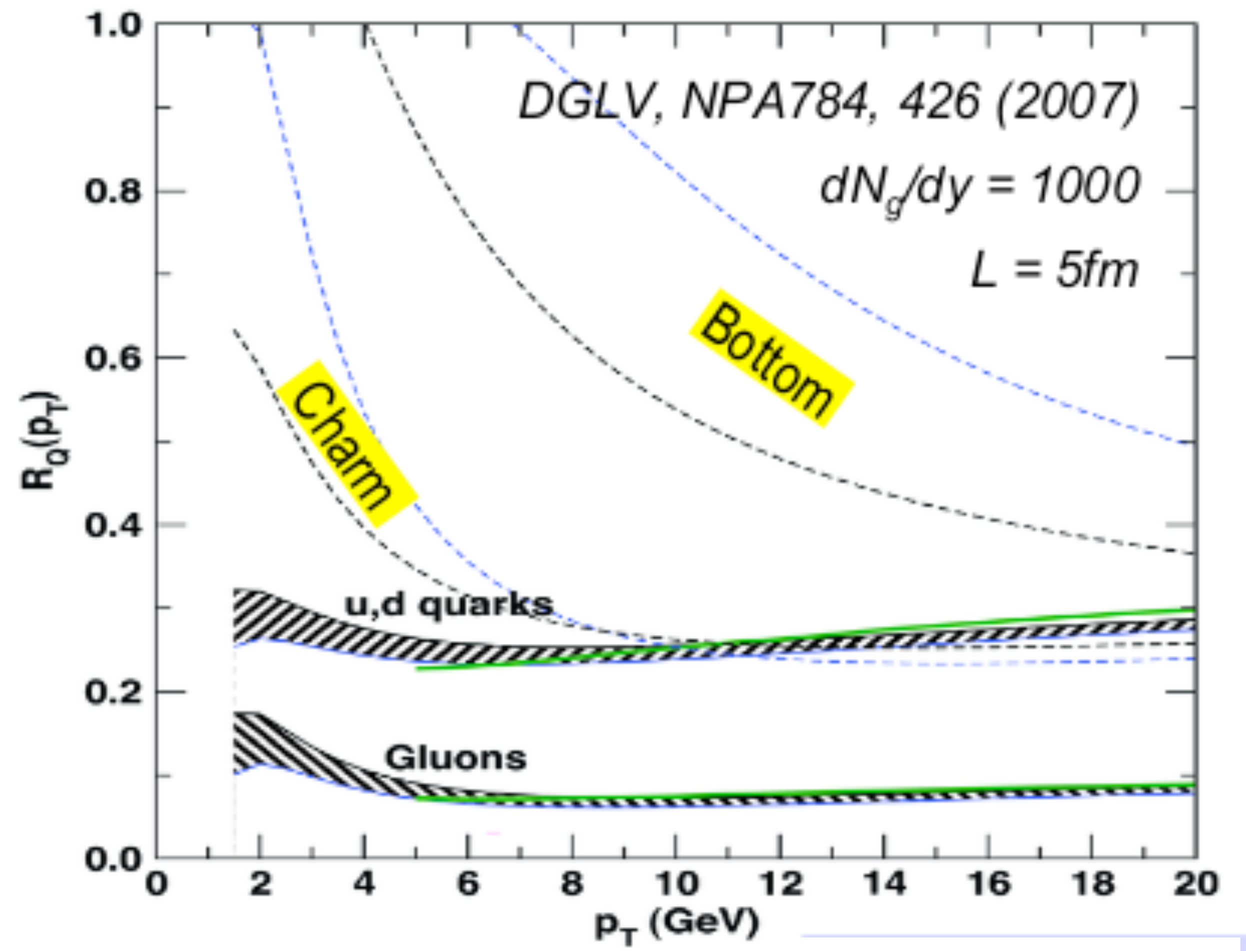
Hard Probes: Energy Loss

For **c** and **b** less energy loss is expected. **$\Delta E_g > \Delta E_{LQ} > \Delta E_{HQ}$**

→ dead cone effect

Y. Dokshitzer & D. Kharzeev PLB 519(2001)199

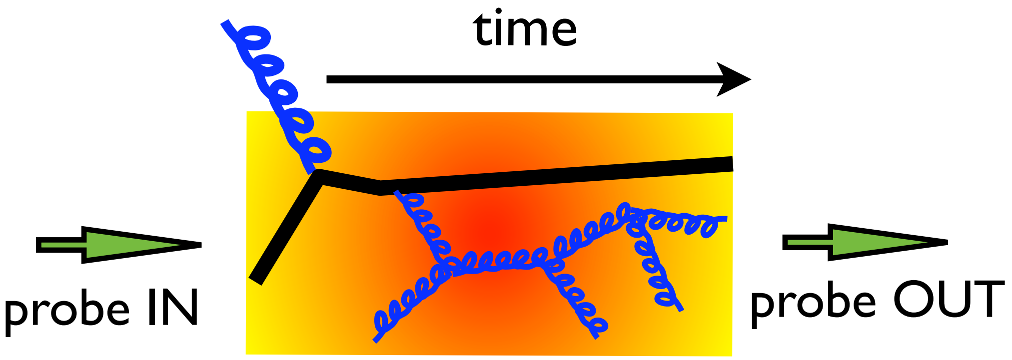
$$R_{AA}^{D,B}(p_t) = \frac{1}{N_{coll}} \times \frac{dN_{AA}^{D,B}/dp_t}{dN_{pp}^{D,B}/dp_t}$$



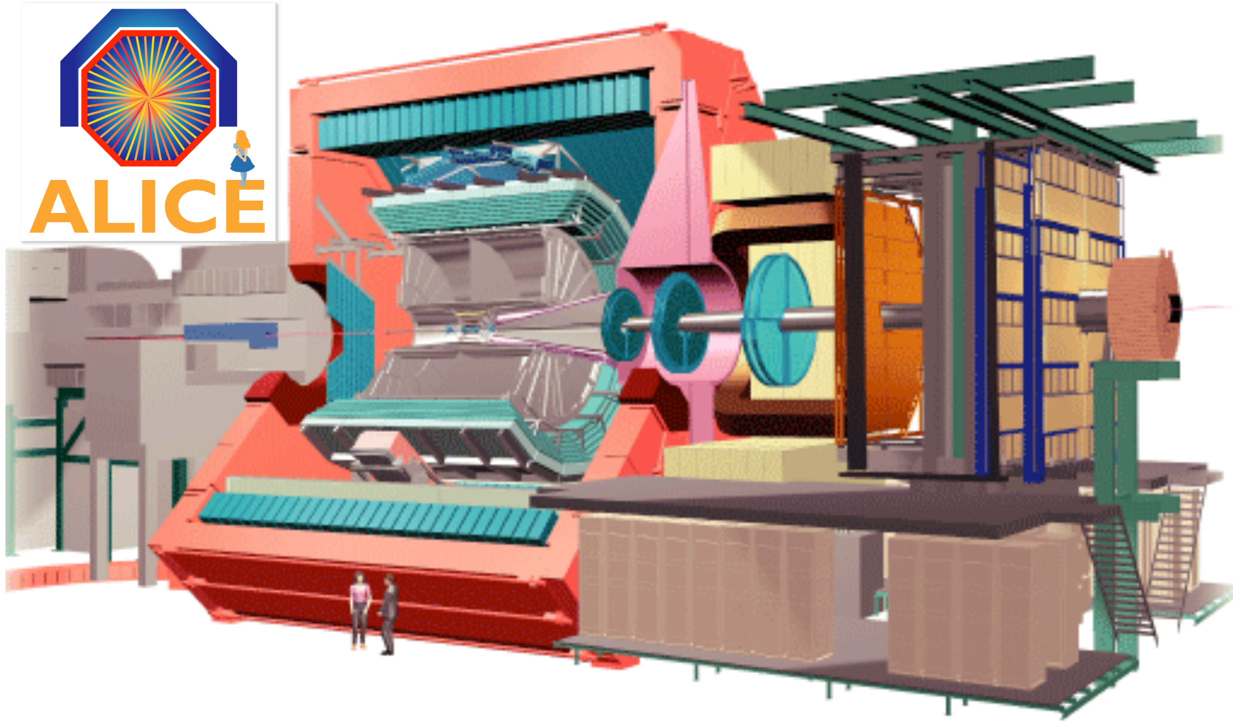
- ☑ Radiative parton energy loss is both color charge & mass dependent.

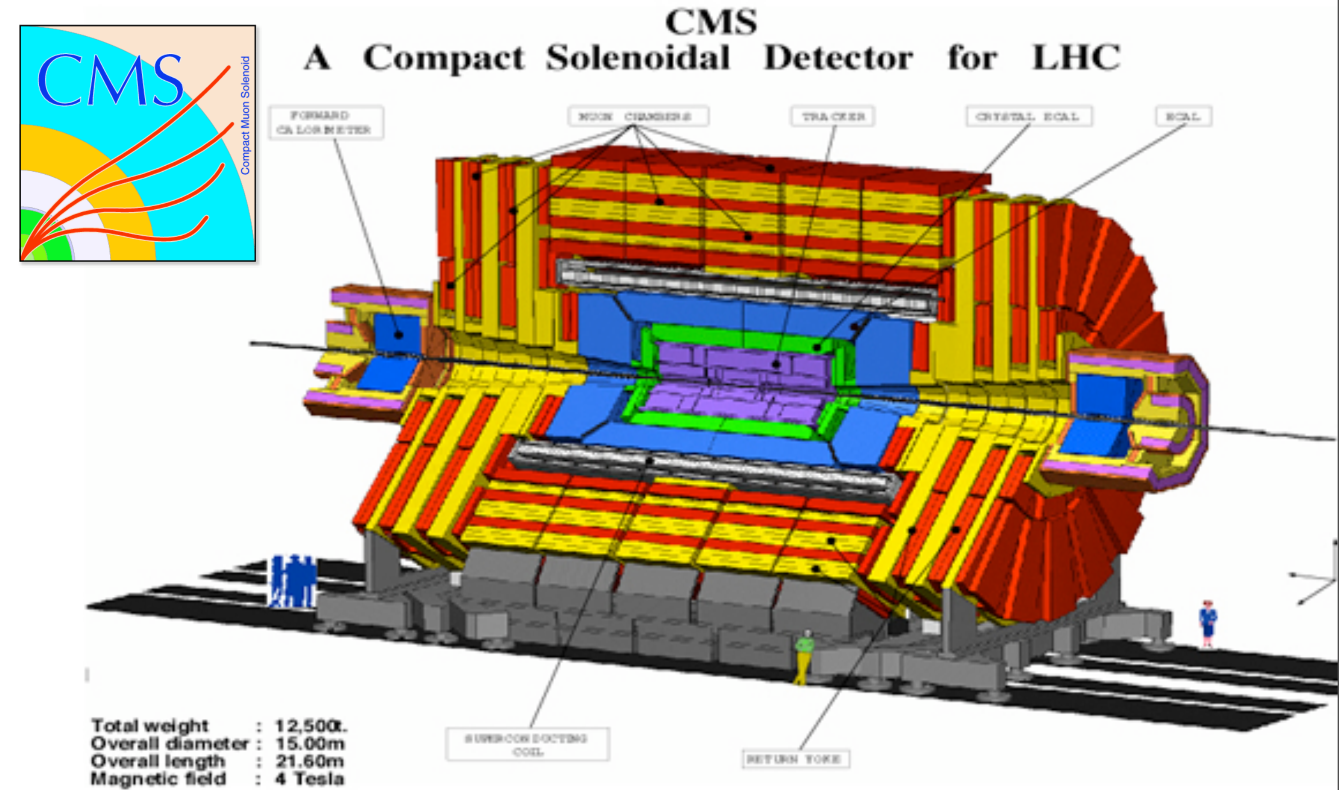
  Phys. Rev. D71 (2005) 054027 see backup

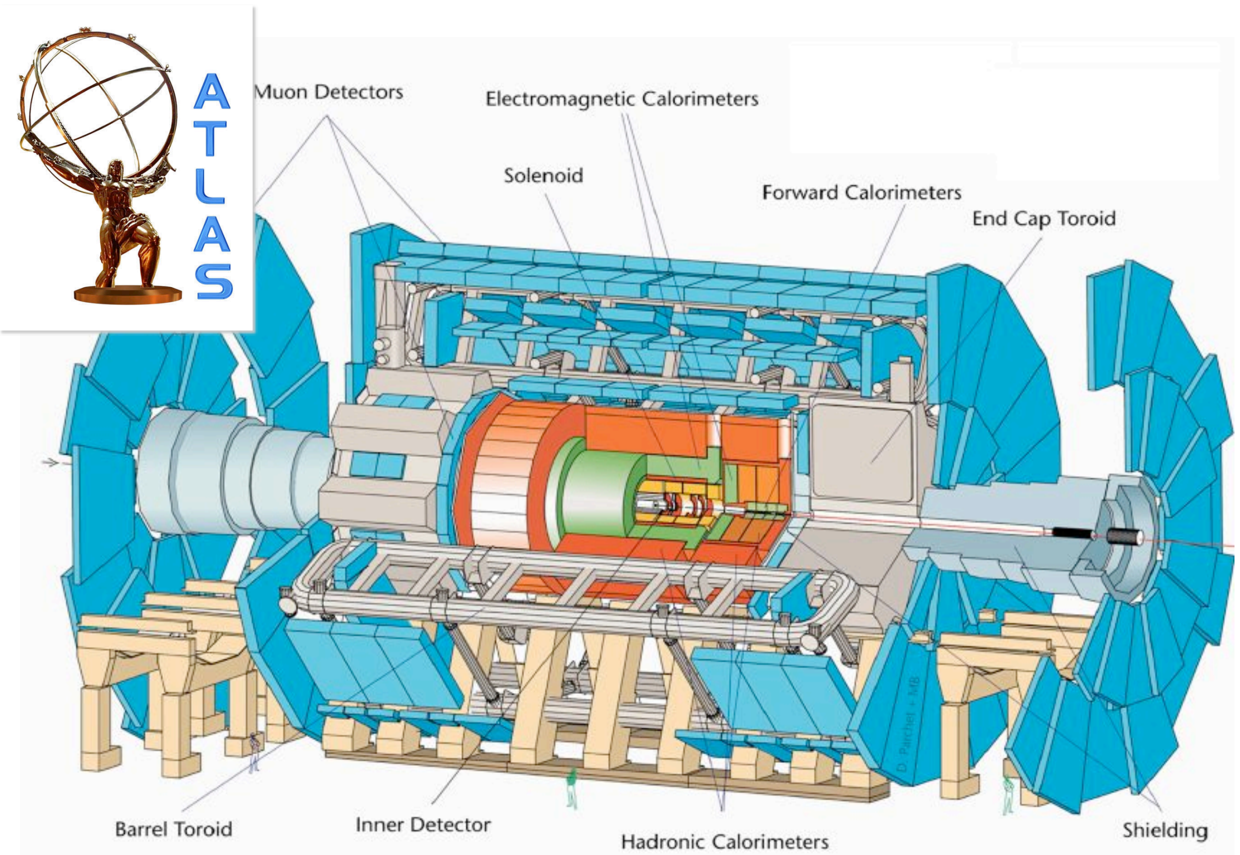
- ☑ Need for a clean “calibration”: **pp and pA as benchmark.**
- ☑ pt distribution sensitive to :
  - **pt<6 GeV non perturbative effects.**
  - **high pt → jet quencing.**
- ☑ Test the medium density.



Heavy Flavour production with early data







Let's concentrate on few examples

- ❑ Open Heavy Flavours - Quarkonia.

  quencing, correlation studies, b tagging

- ❑ Prompt heavy quarkonia.
- ❑ B production.

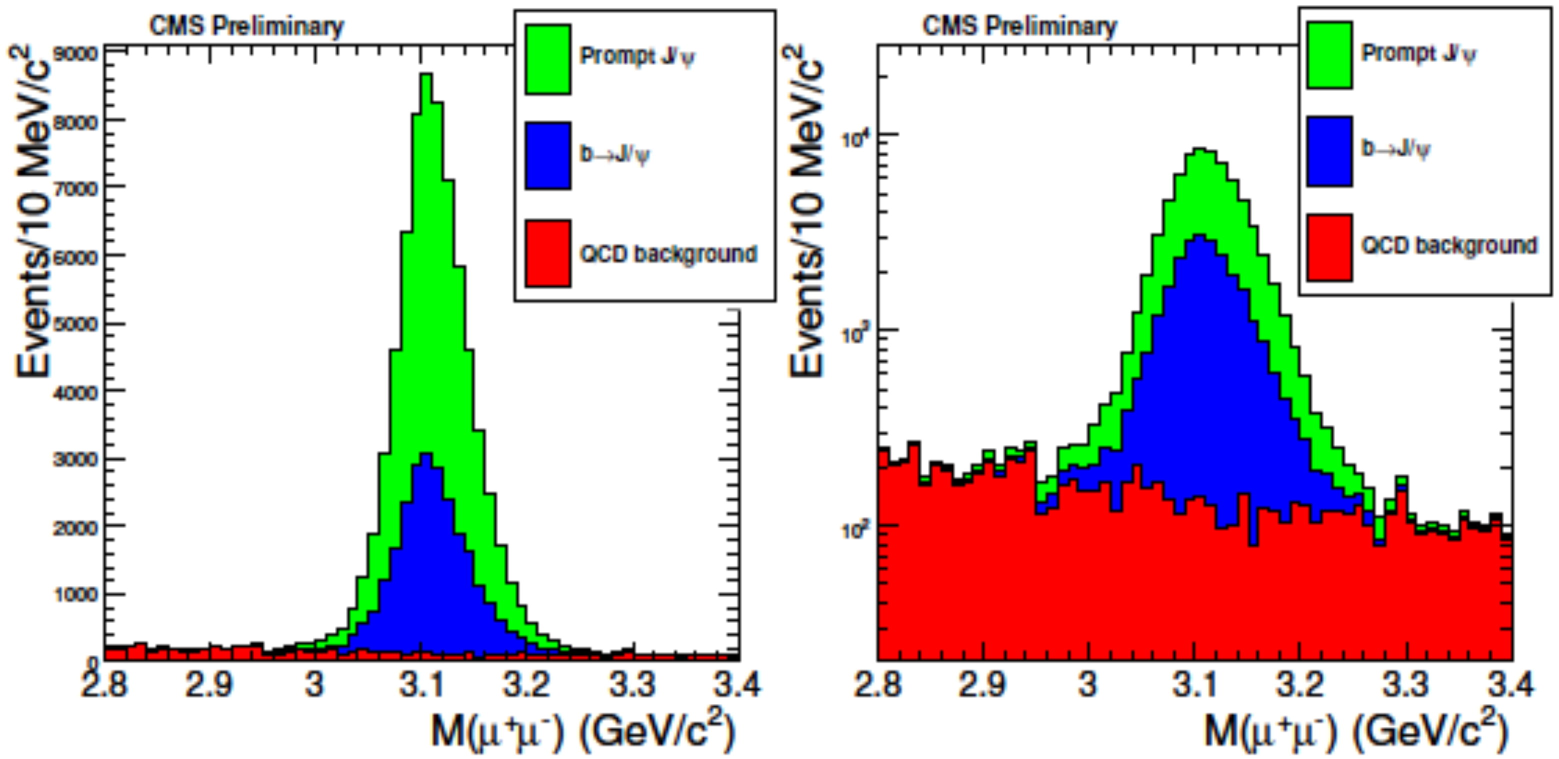
  inclusive, exclusive, b-tagging

J/ψ analysis

14 TeV

- Dimuon invariant mass distributions normalized to 3 pb^{-1}

PAS BPH-07-002

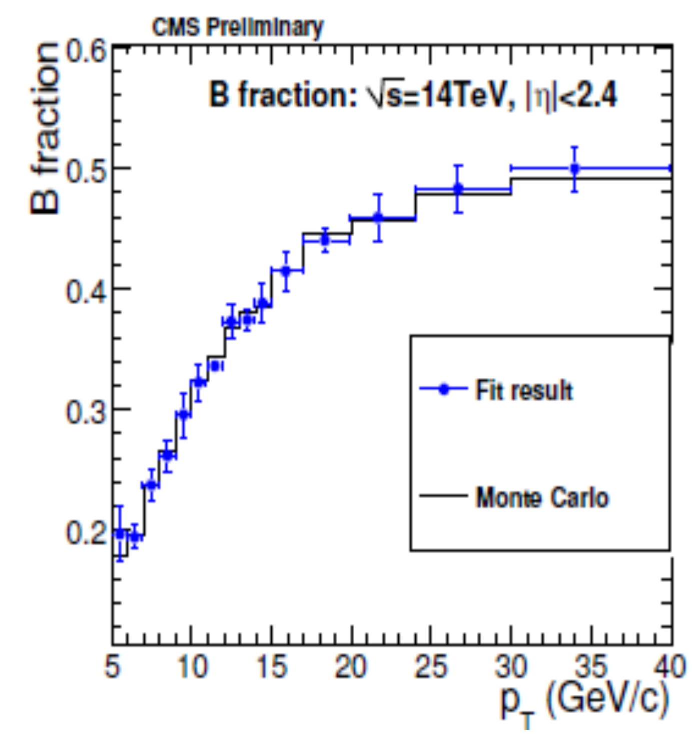


- Dimuon trigger pt>3 GeV
- Dimuon mass resolution:

~17 MeV at η=0
~40 MeV at |η|=2.4

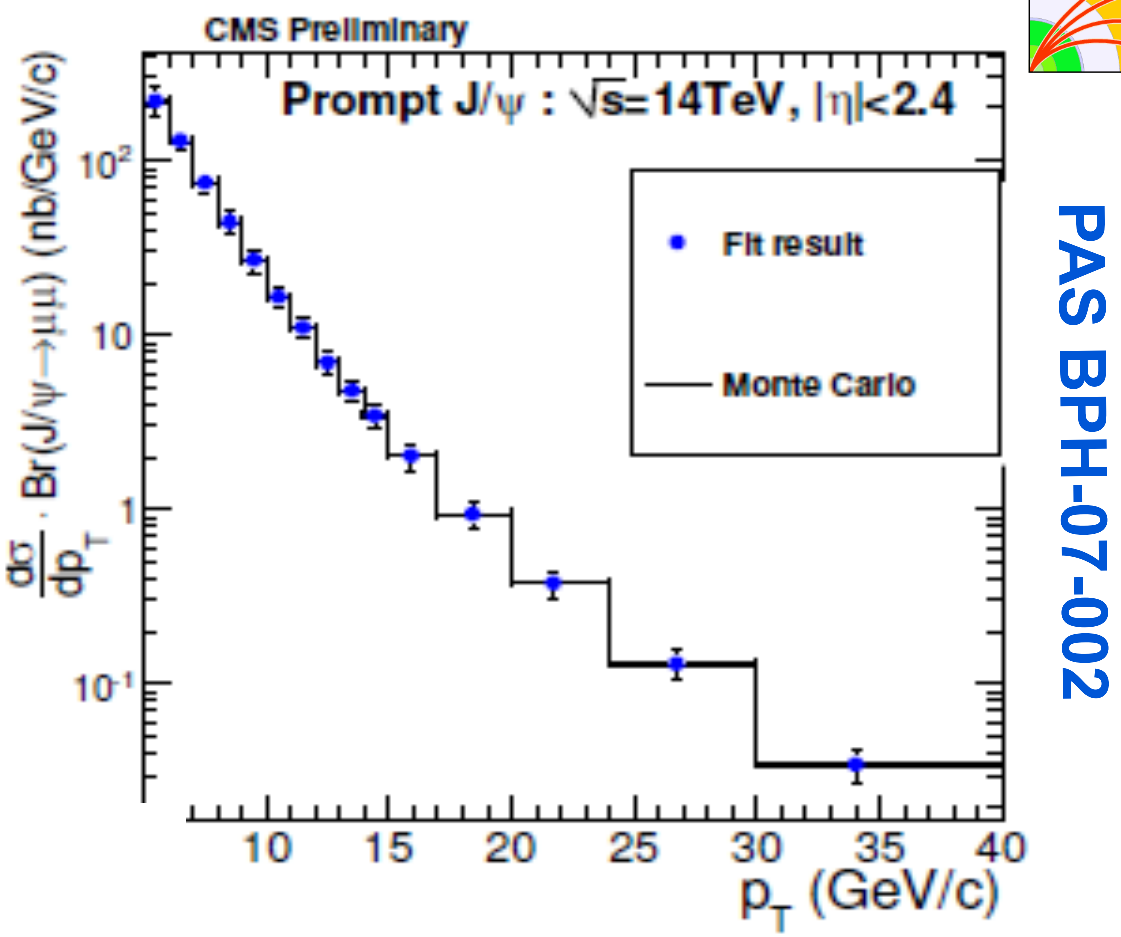
B$^-$ and prompt fractions measured from an unbinned maximum likelihood fit to the mass and the transverse proper decay length.

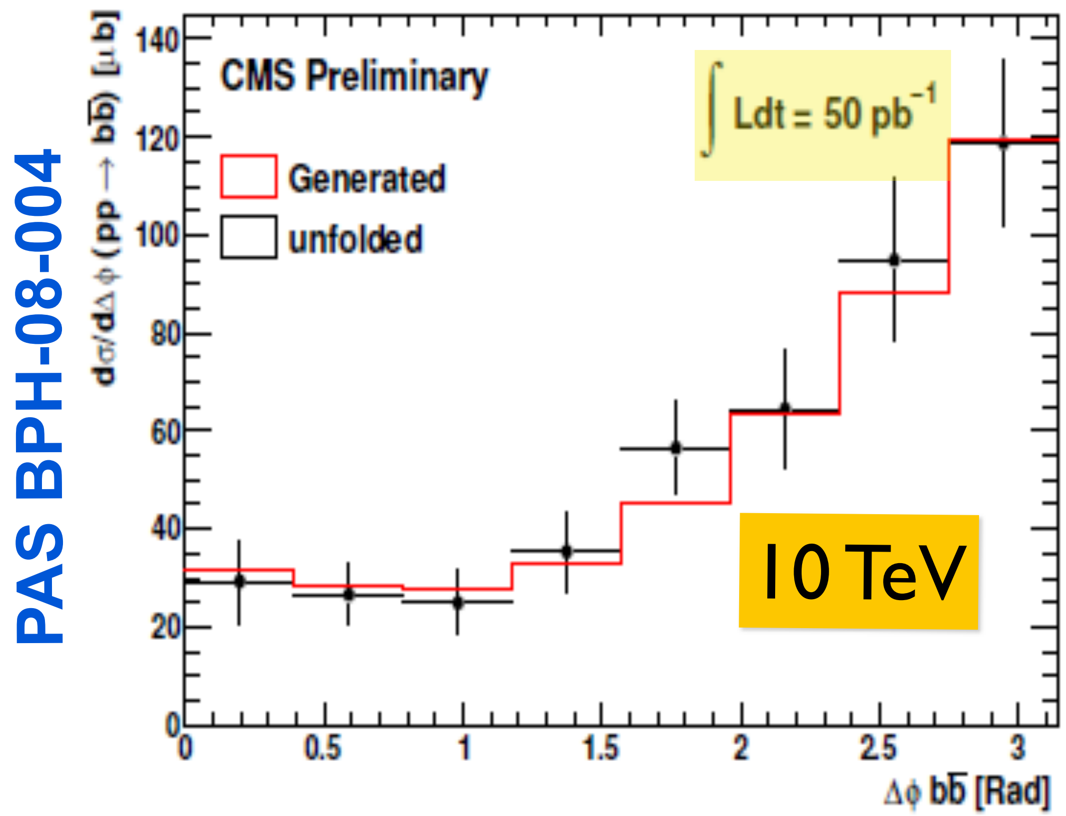
PAS BPH-07-002



J/ψ analysis

- Inclusive differential cross section measured from a fit to the mass distribution.
- The precision is expected to be limited, in this early phase, by systematics at 15% level.





- Differential cross section measurement $d\sigma/d\Delta\Phi$.
  - NLO production mechanisms

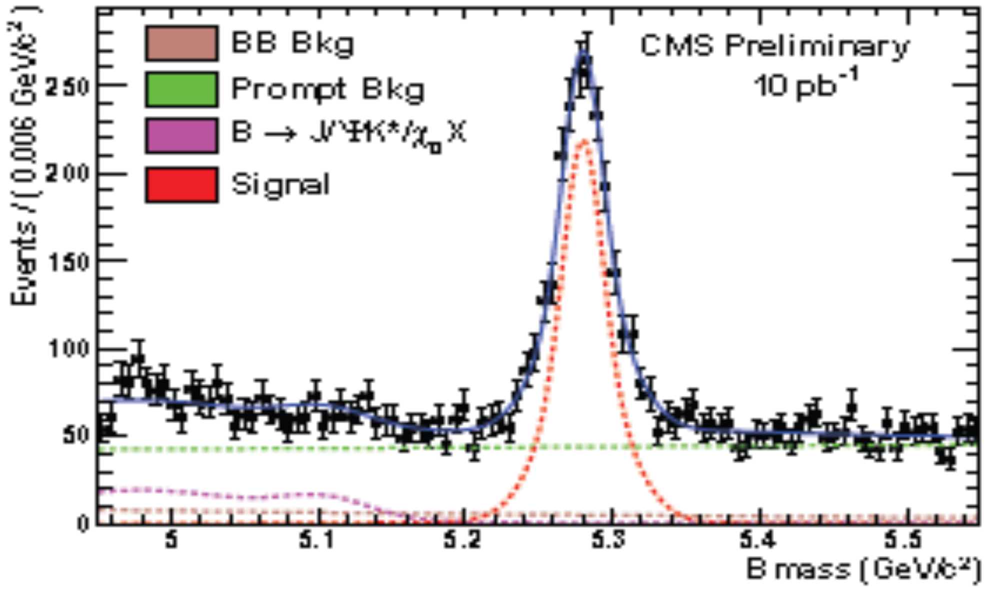
$$b\bar{b} \to (J/\psi X)(\ell X')$$

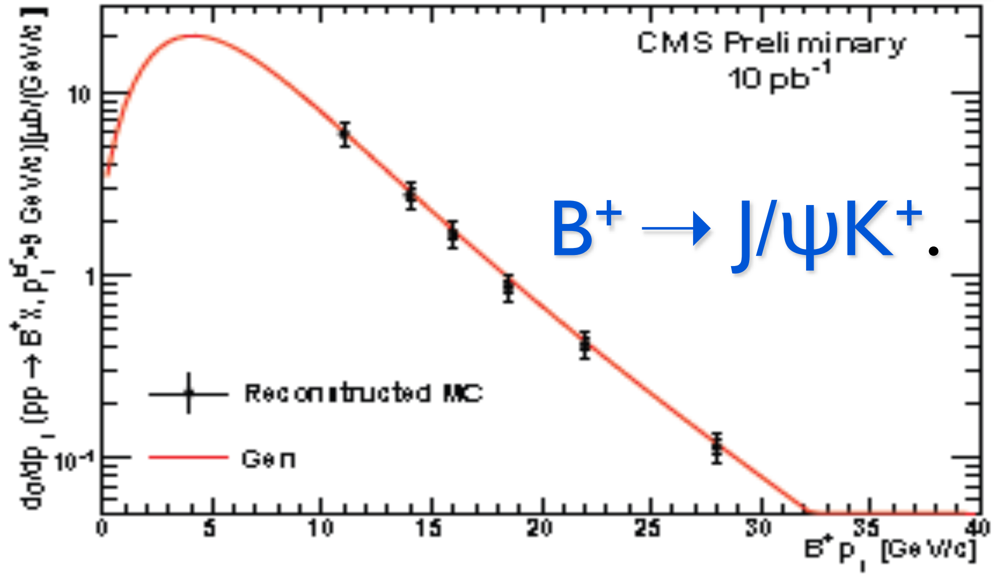
μ

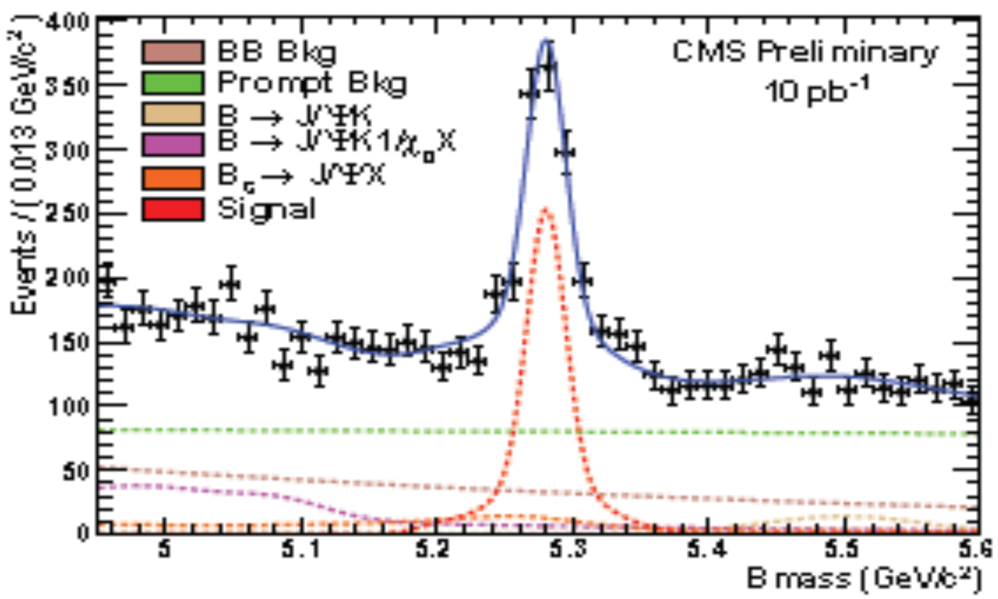
Exclusive B production

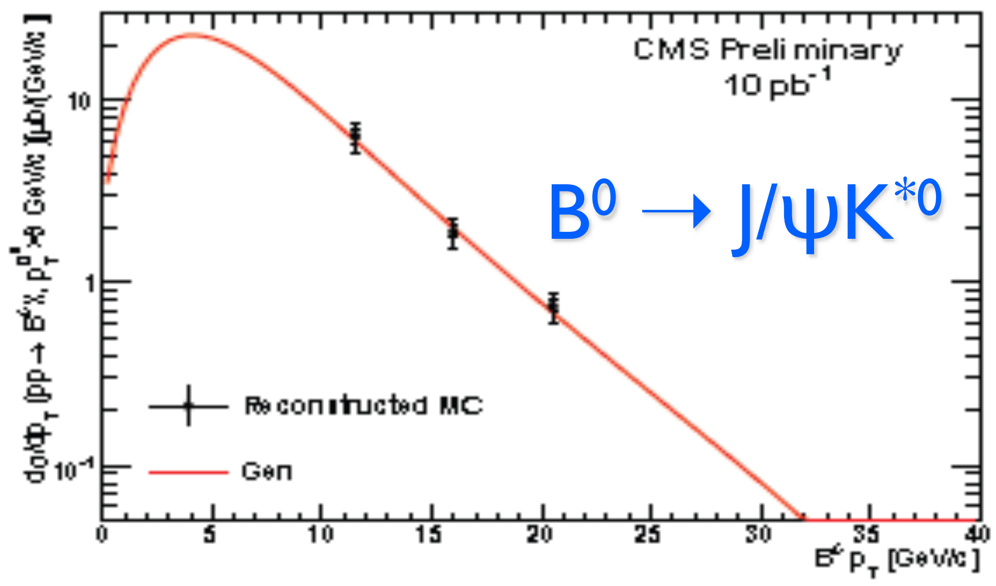
PAS BPH-09-001

10 TeV









☑ The $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ differential cross sections can be measured with early data (10pb^{-1}) with a statistical precision better than 10%.

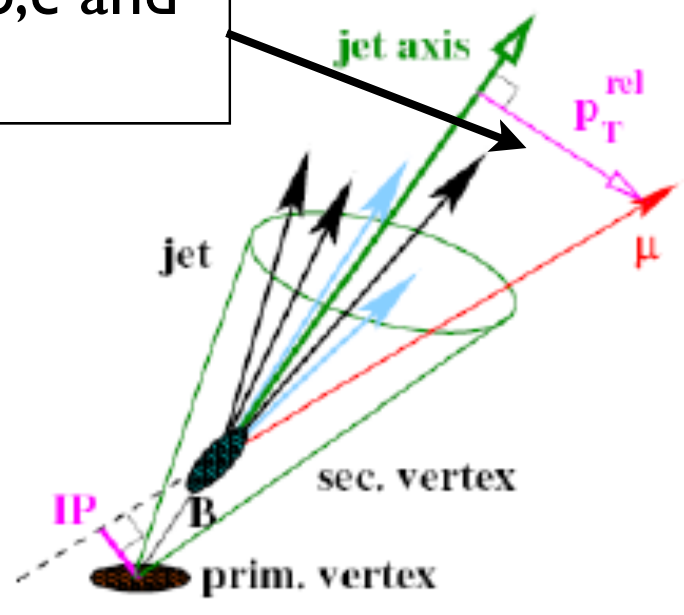
Inclusive B production

- L1 trigger:
  - single μ p_T > 14GeV
- High Level Trigger:
  - single μ p_T > 19 GeV a
  - b-tagged jet with p_T > 50 GeV
- b-tagging:
  - Inclusive secondary vertex reconstruction in jets.
- b-tagging efficiency:
  - ~ 65% in the barrel.
  - ~ 55% in the end-cap.

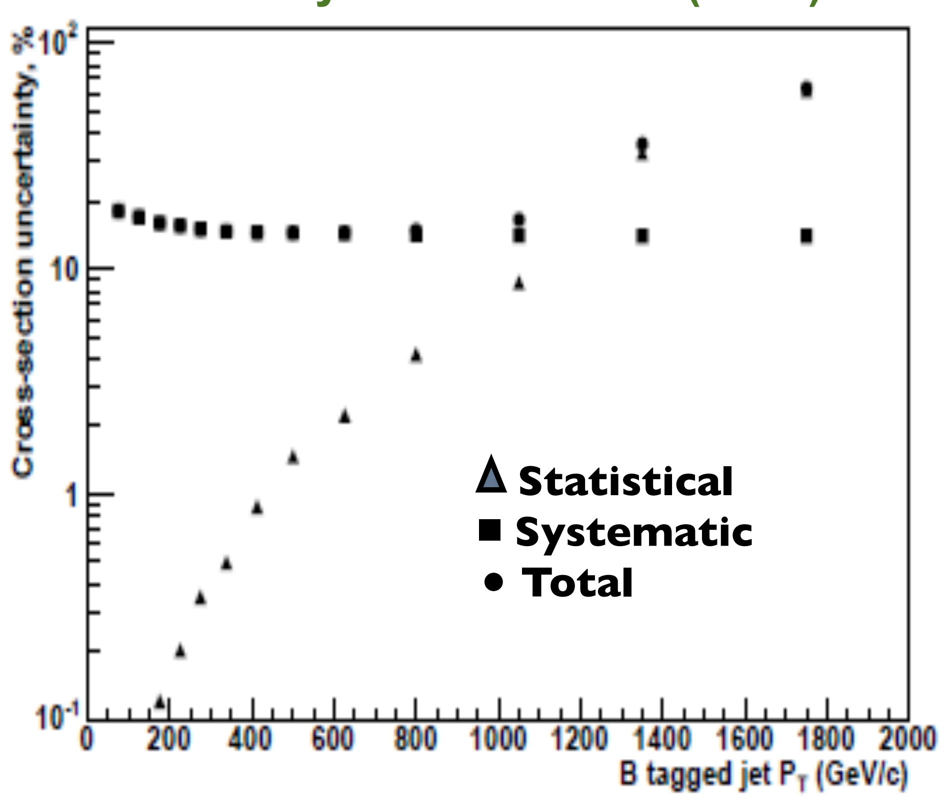
Updated in 2008 PAS BTV-07-003

b-tagging with different misalignment scenario. **PAS BTV-07-003**

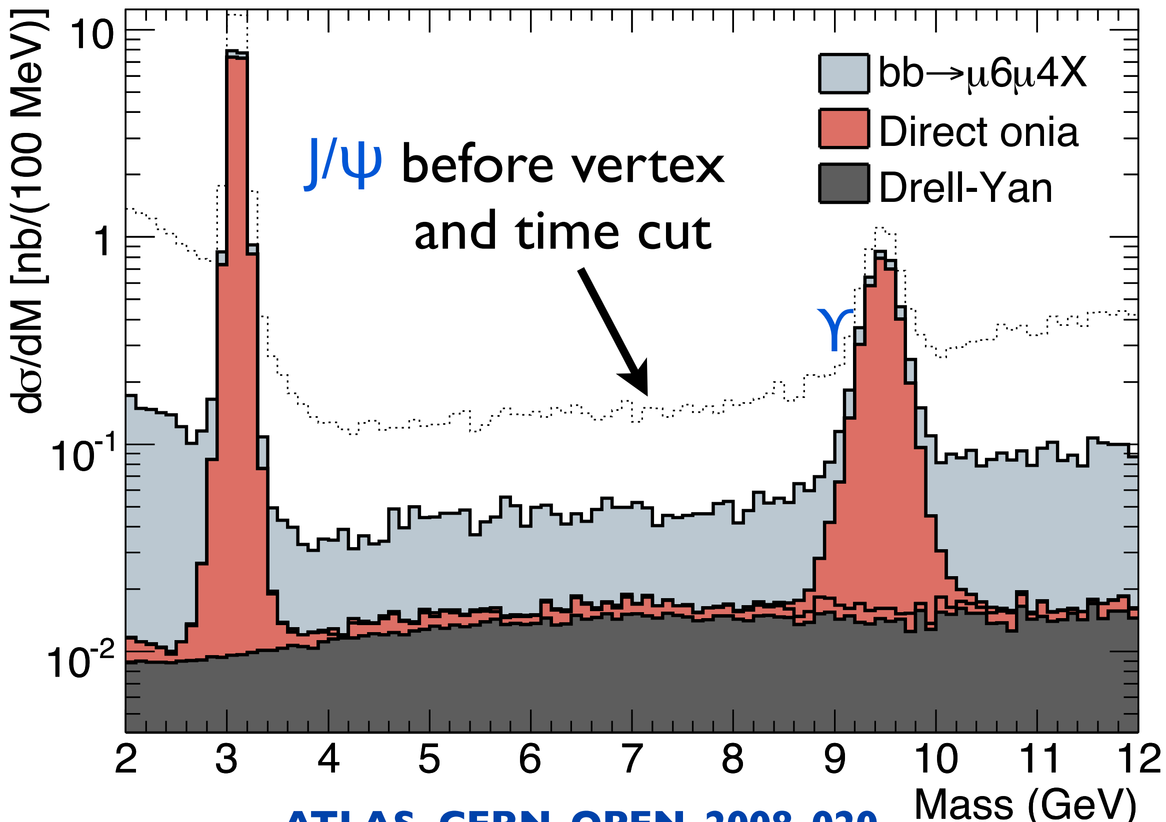
P_T^{rel} used to fit b,c and LQ/g events



CMS Physics TDR Vol II (2006)



J/ψ and Υ analysis

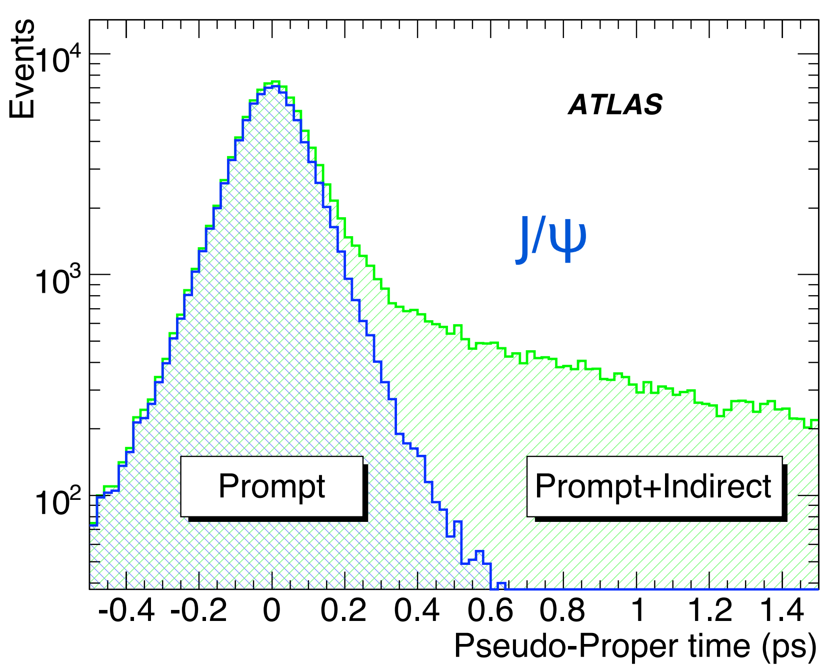


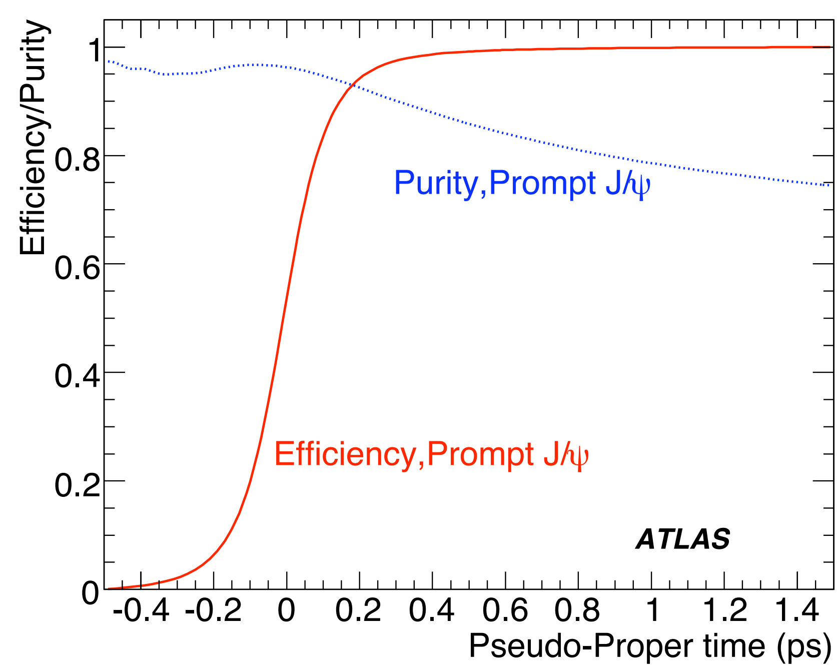
ATLAS, CERN-OPEN-2008-020

In summary

10pb^{-1}

- ☑ prompt J/ψ and Υ
- ☑ di-muon or single muon trigger
- ☑ secondary decay vertex
  - **cut on pseudo proper time t**
- ☑ Additional cut for single muon trigger:
  - **|d0| <0.04 mm for mu**
  - **|d0| <0.1 mm for 2nd track**





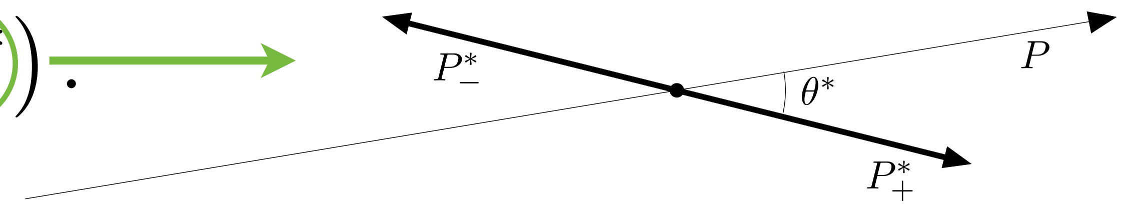
$$\mathbf{t} = \frac{L_{xy} \cdot M_{J/\psi}}{p_T(J/\psi) \cdot c},$$

J/ψ and ϒ analysis

10pb^{-1}

☑ prompt quarkonia polarization as discrimination between models.

$$\frac{dN}{d\cos\theta^*} = C\,\frac{3}{2\alpha+6}\left(1+\alpha\cos^2\theta^*\right).$$



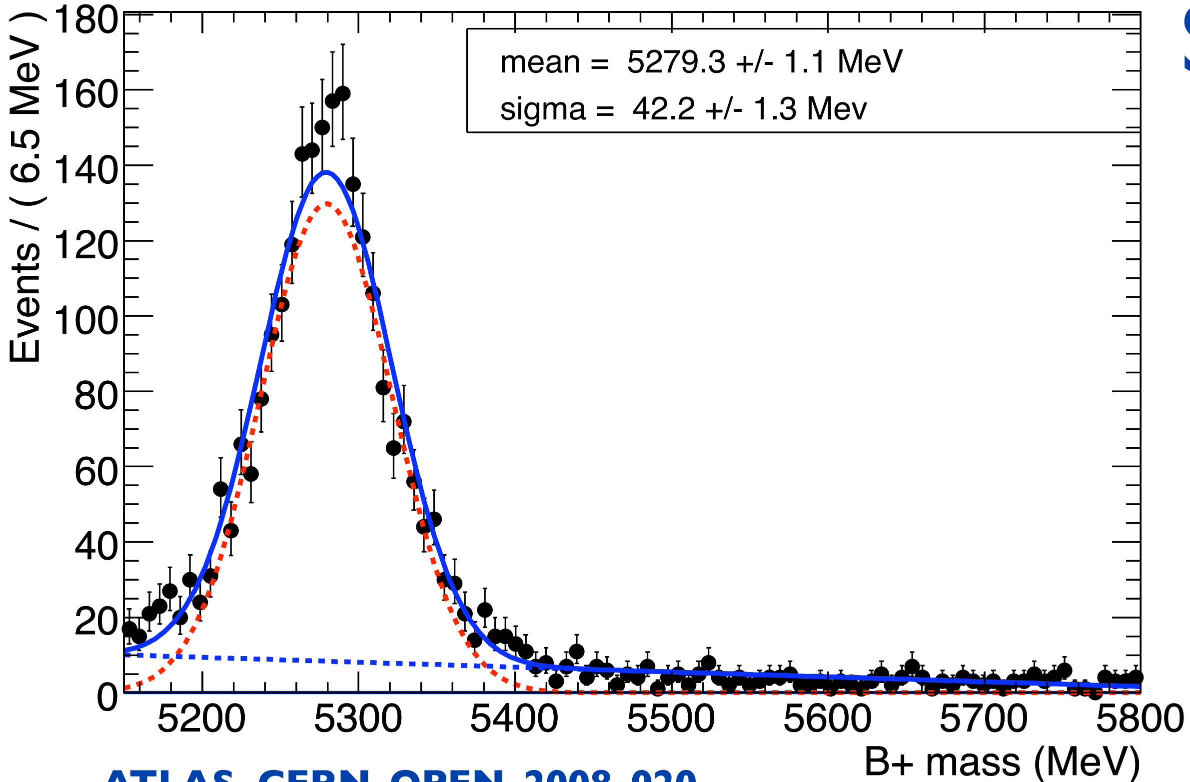
Sample	p_T, GeV	$9-12$	$12-13$	$13-15$	$15-17$	$17-21$	>21
J/ψ, $\alpha_{gen}=0$	α	0.156 ±0.166	−0.006 ±0.032	0.004 ±0.029	−0.003 ±0.037	−0.039 ±0.038	0.019 ±0.057
	σ, nb	87.45 ±4.35	9.85 ±0.09	11.02 ±0.09	5.29 ±0.05	4.15 ±0.04	2.52 ±0.04
J/ψ, $\alpha_{gen}=+1$	α	1.268 ±0.290	0.998 ±0.049	1.008 ±0.044	0.9964 ±0.054	0.9320 ±0.056	1.0217 ±0.088
	σ, nb	117.96 ±6.51	13.14 ±0.12	14.71 ±0.12	7.06 ±0.07	5.52 ±0.05	3.36 ±0.05
J/ψ, $\alpha_{gen}=-1$	α	−0.978 ±0.027	−1.003 ±0.010	−1.000 ±0.010	−1.001 ±0.013	−1.007 ±0.014	−0.996 ±0.018
	σ, nb	56.74 ±2.58	6.58 ±0.06	7.34 ±0.06	3.53 ±0.04	2.78 ±0.03	1.68 ±0.02

α parameter:

- -1 longitudinal ,
- +1 traversal,
- 0 unpolarized

☑ for ϒ more difficult due to lower cross section at high pt and higher backgound.

$B^+ \rightarrow J/\psi K^+$



ATLAS, CERN-OPEN-2008-020

Summary

10pb^{-1}

- ☑ J /ψ combining mu.
- ☑ trigger pt > 6(3)GeV.
- ☑ cut on decay length to reject prompt J /ψ
- ☑ common vertex K$^+$ and J /ψ
- ☑ cuts on K+:
  - **- pt>1.5 GeV, $|\eta|<2.5$, $|d_0|/\sigma_{d0}>1$**

➡ Detector understanding, reference, cross section.

$$\frac{d\sigma(B^+)}{d\,p_T} = \frac{N_{sig}}{\Delta p_T \cdot \mathscr{L} \cdot \mathscr{A} \cdot \mathrm{BR}}$$

Max likelihood fit to invariant mass spectrum in different pt regions

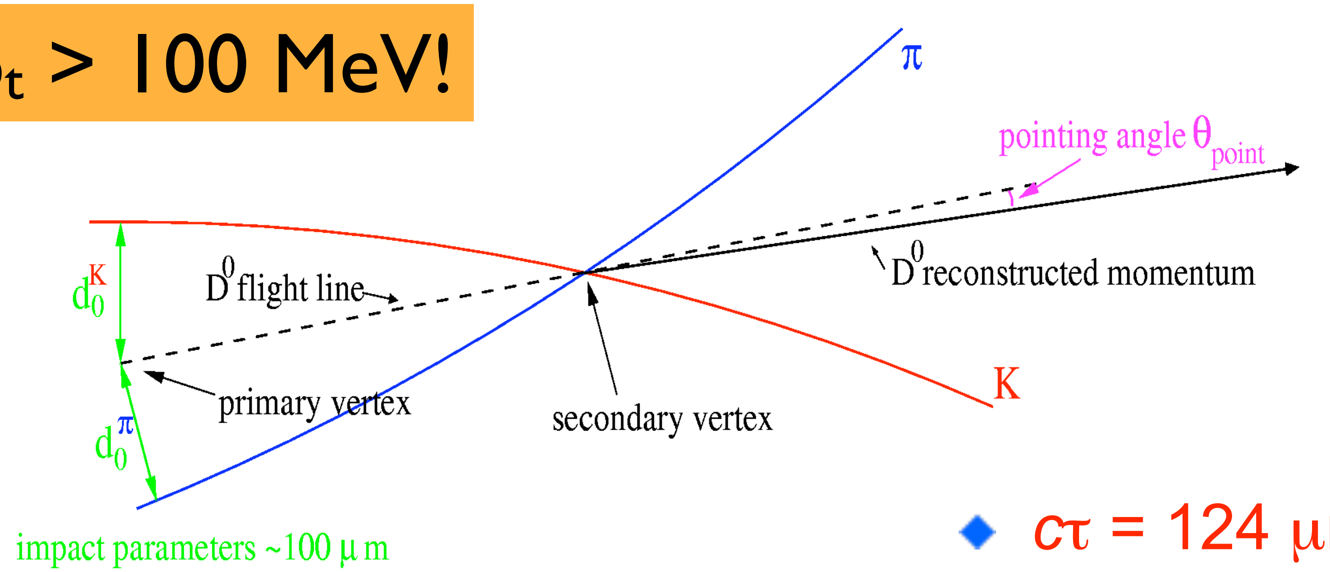
total cross-section	
$\mathscr{A}$ [%]	29.8 ± 0.8
$\sigma(B^+)$ [MeV]	42.2 ± 1.3

Uncertanties

- Statistical: total < 5%, differential ~10 %
- Systematic: dominated by luminosity (~10%) and BR (~10%).

Exclusive Charm: $D^0 \rightarrow K^- \pi^+$

p_t > 100 MeV!



◆ $c\tau$ = 124 μm

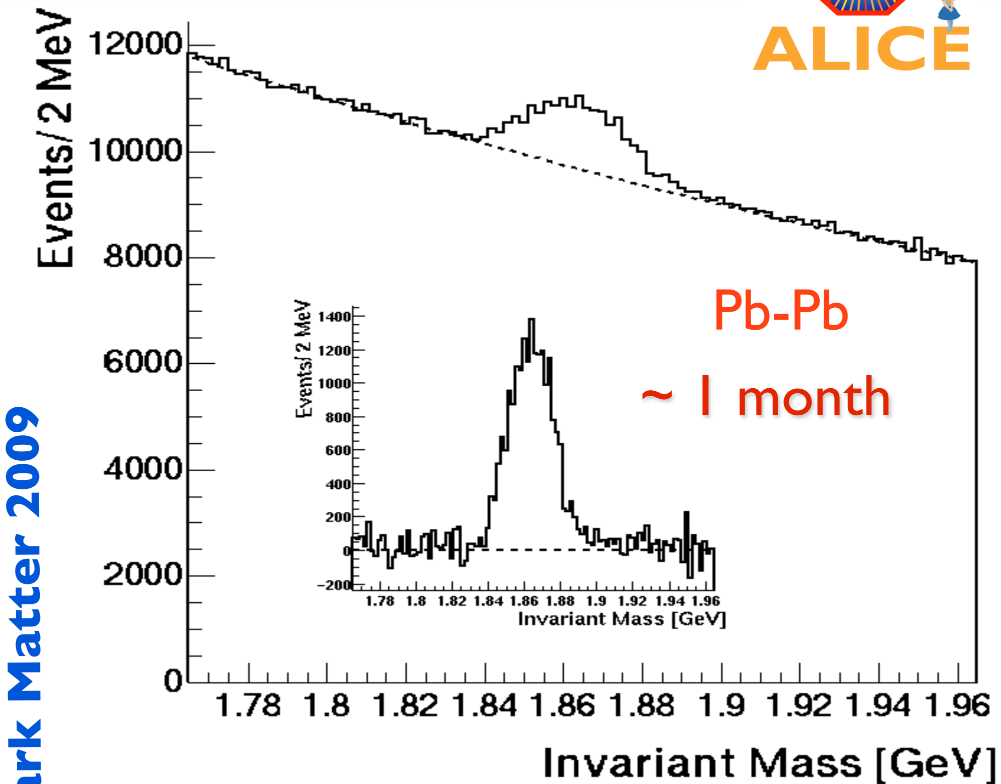
Based on displaced vertex reconstruction.

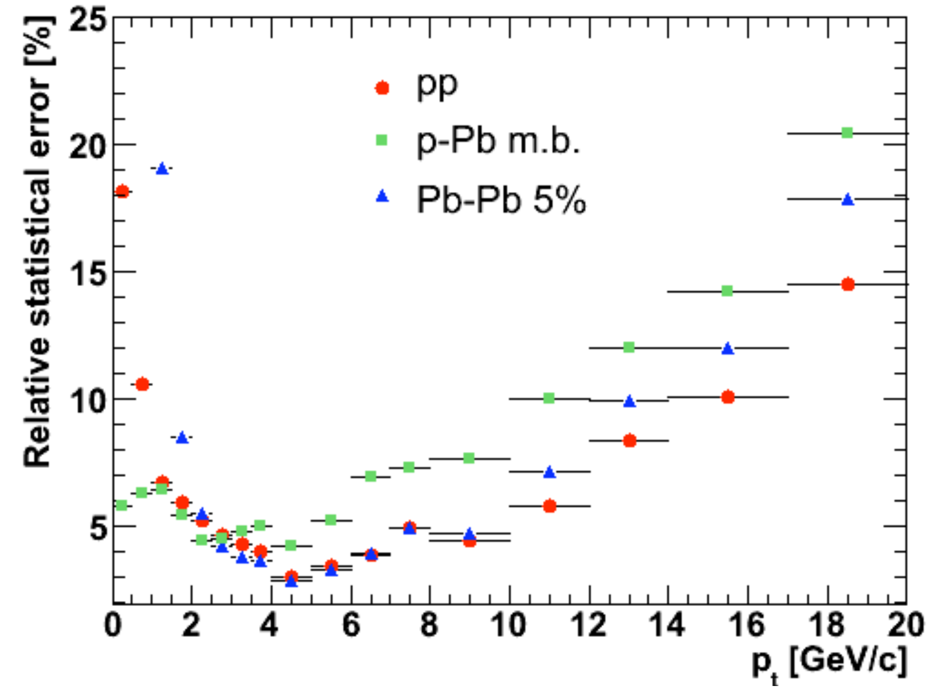
- ☑ single track quality cuts
- ☑ topological cuts:
  - **- dca, pointing angle..**

Many others channels under study!!

$D^+ \rightarrow K\pi\pi$, $D_s \rightarrow KK\pi$, $D^* \rightarrow D^0\pi$,
$D^0 \rightarrow K\pi\pi\pi$, $\Lambda_c \rightarrow \pi K p$

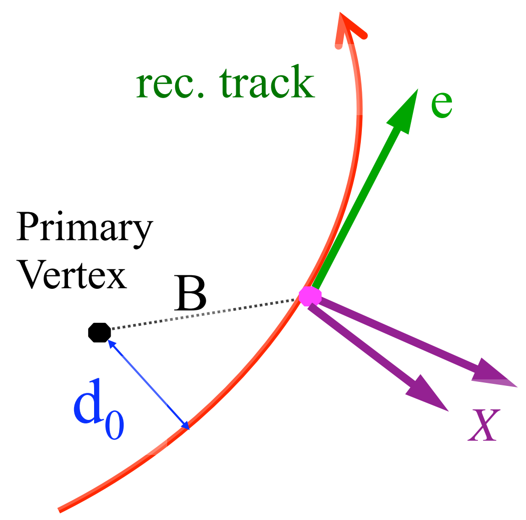
A. Dainese Quark Matter 2009





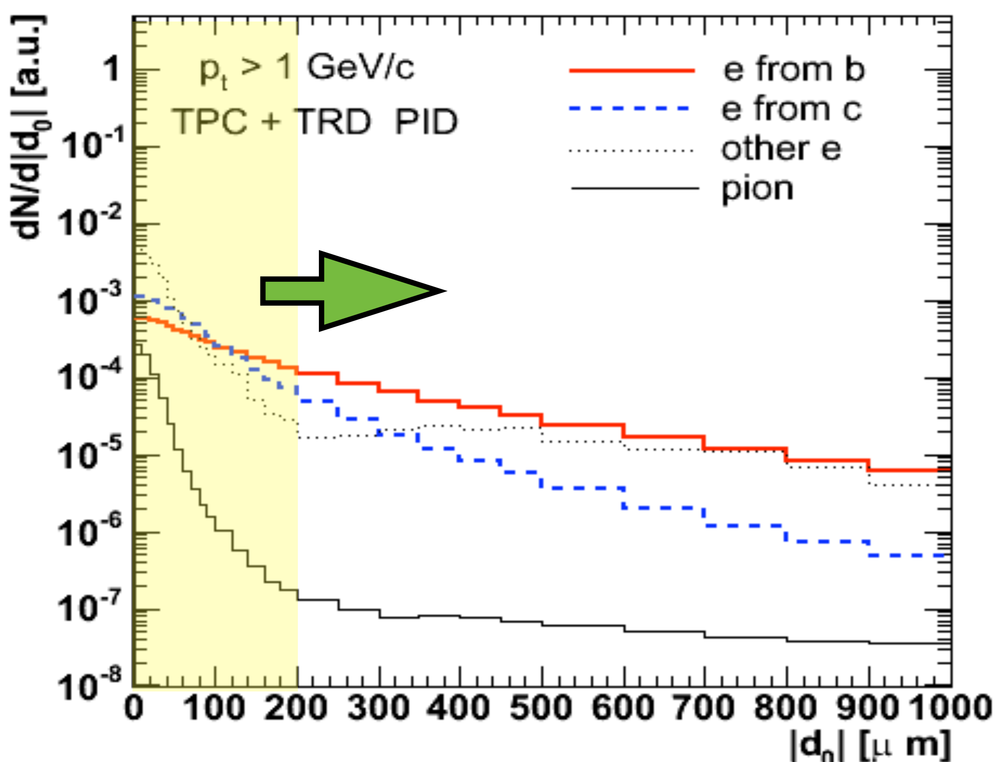
pp, Pb-Pb: 1 year at nominal luminosity
(10^9 pp events, 10^7 central Pb-Pb events)
p-Pb: 1 month (10^8 events)

Open Beauty in electron channel



H.Yang, R.Bailhache, poster QM 2009

B→e +X in Pb-Pb



ALICE-INT-2006-015

Strategy:

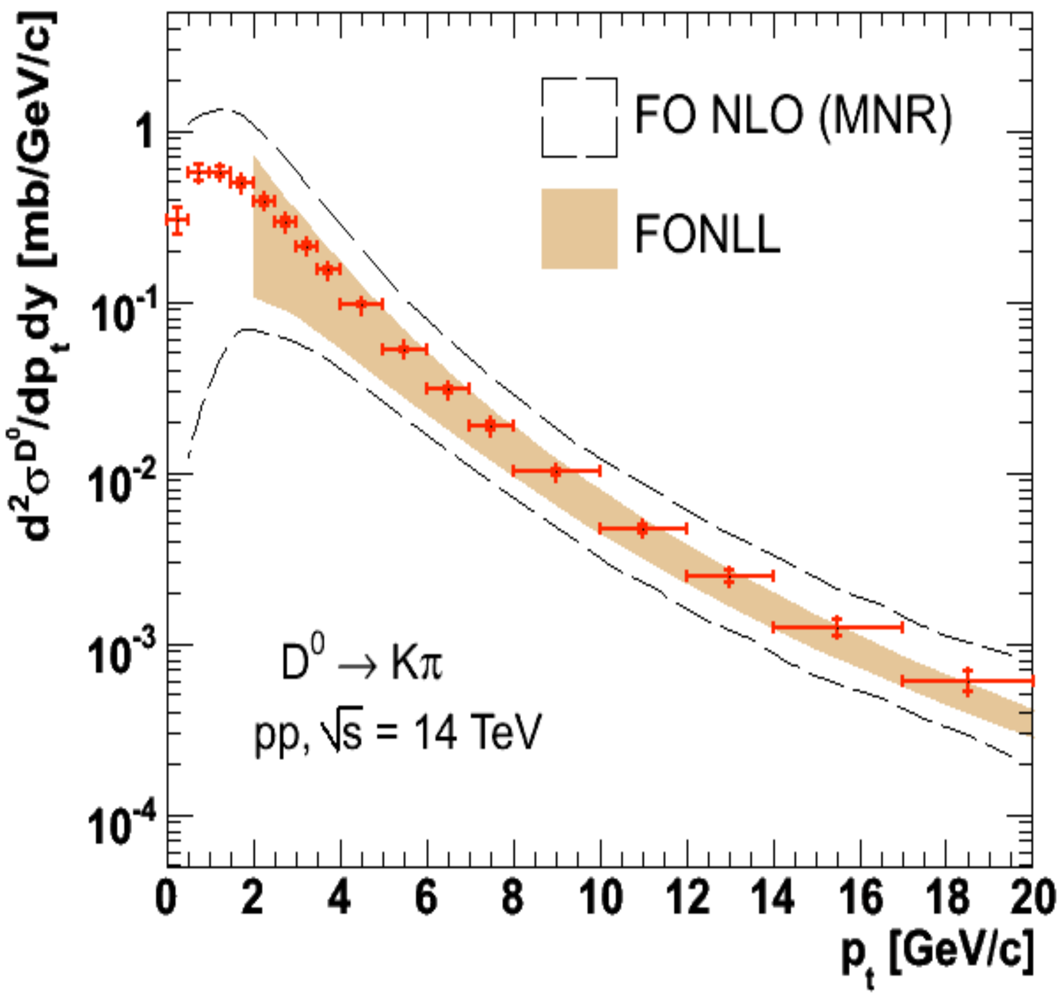
- ☑ Electron PID (TPC+TRD):
  - **- reject most of the hadrons**
- ☑ d_0 cut (200 μm):
  - **- reduce charm and bkg electrons (Dalitz, γ conv.)**
- ☑ Subtract (small) residual background (ALICE data + MC)

Many others channels under study!!

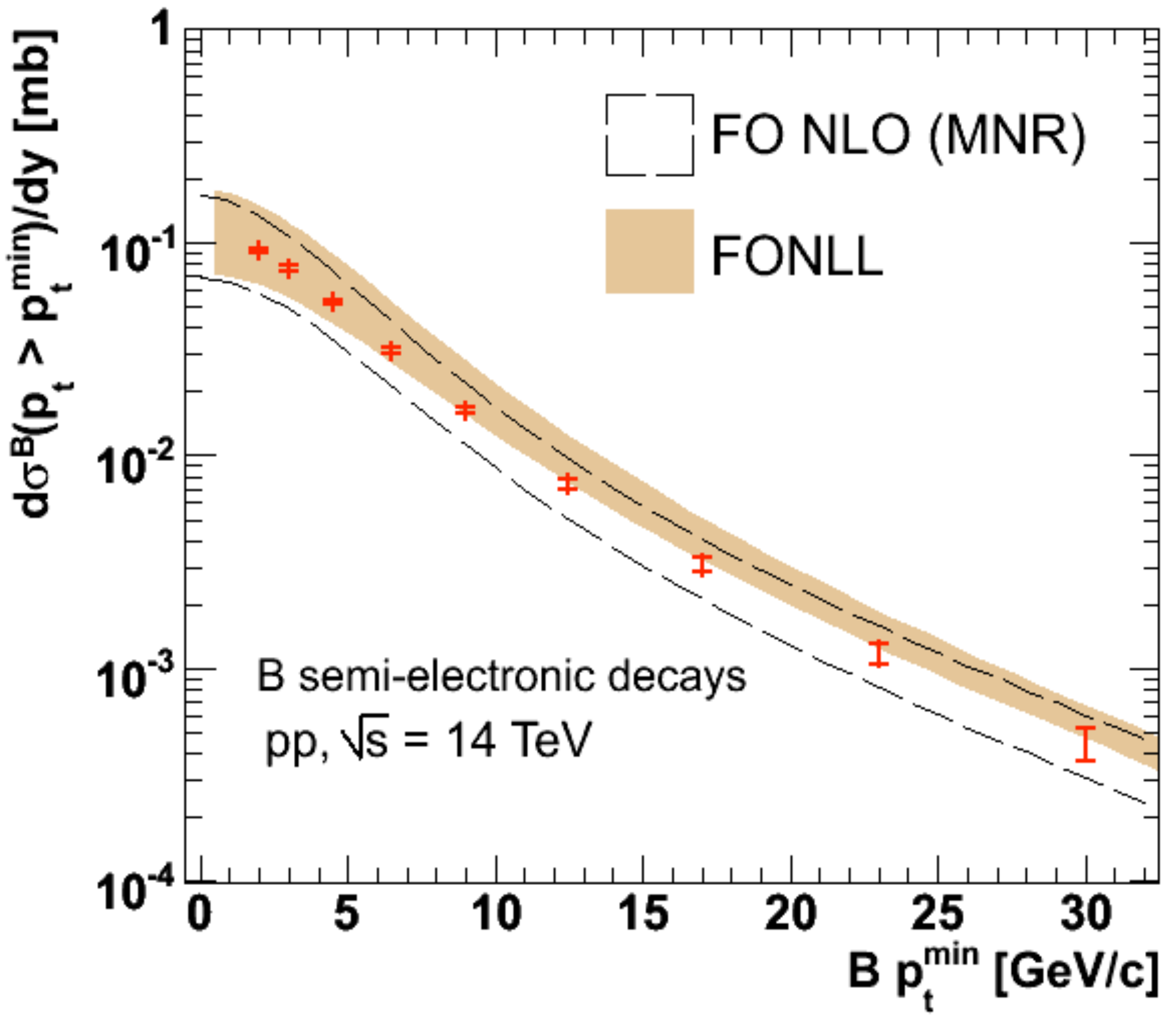
B → ≥5 prongs, B → J/ψ→ee, tagged b-jets, B → μ(μ)+X ....

Expected precision

charm ($D^0 \rightarrow K\pi$)



beauty ($B \rightarrow e+X$)

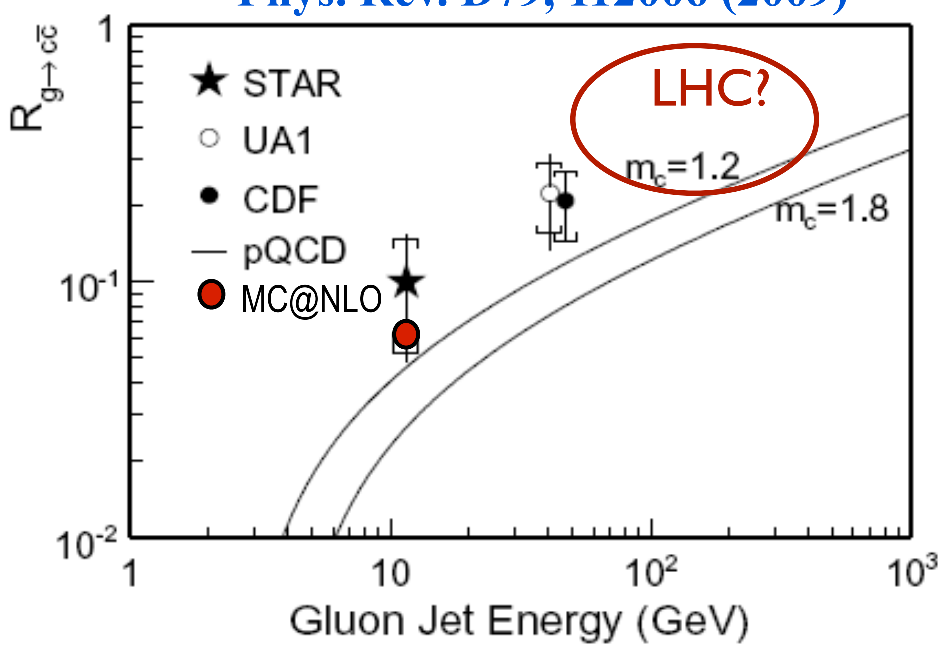


1 year at nominal luminosity (3×10^{30} $cm^{-2}s^{-1}$) (10^9 pp events)

Charm below 1 GeV, Beauty ~1 GeV!

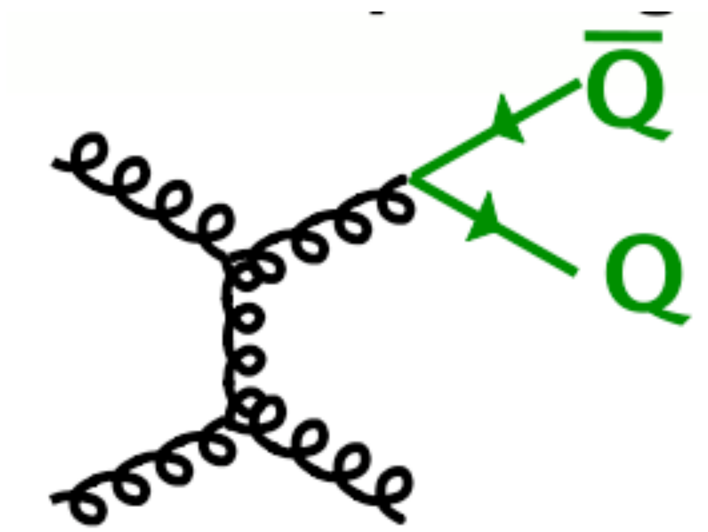
NLO - Gluon Splitting in $c\bar{c}$

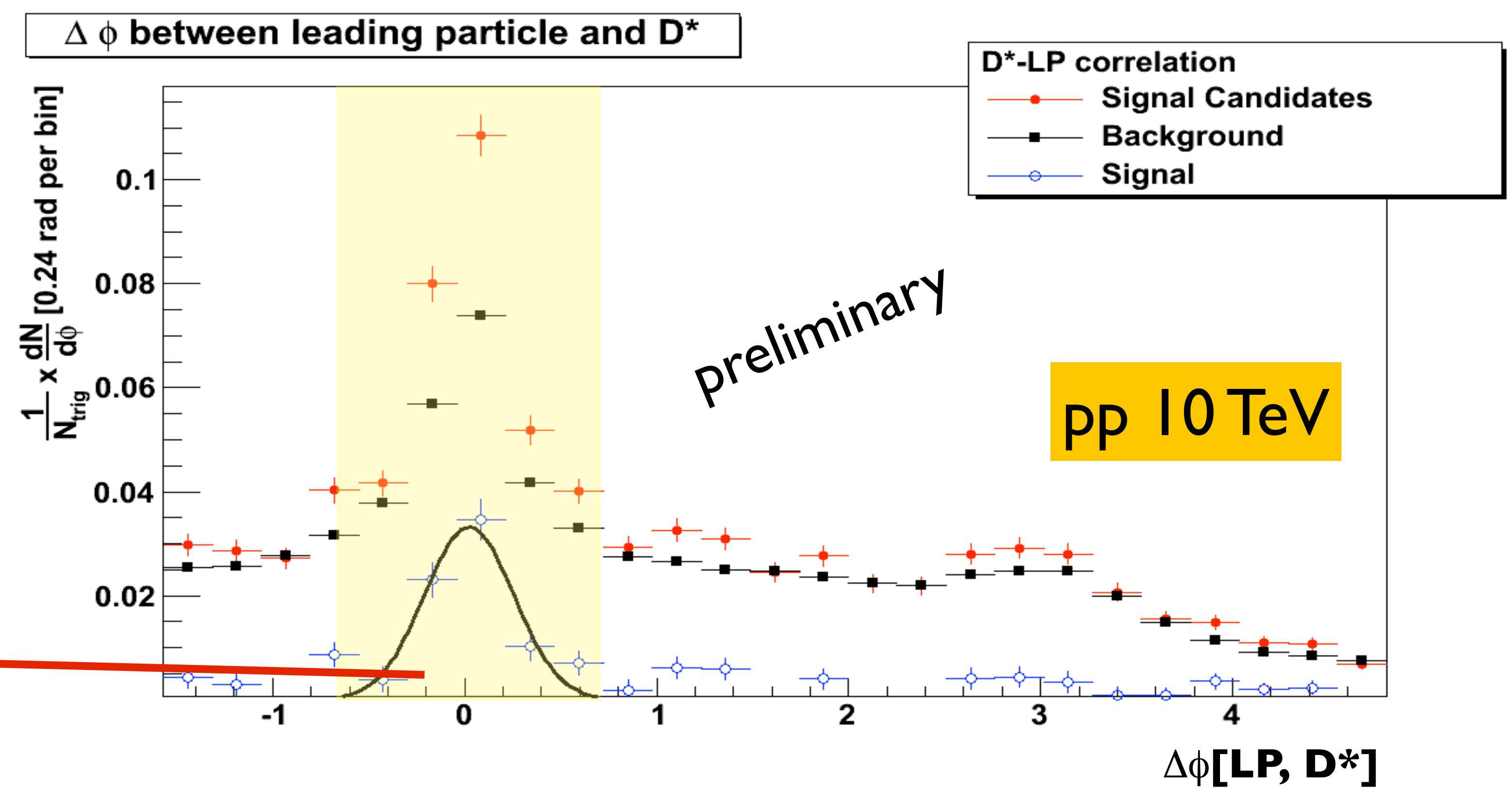
Phys. Rev. D79, 112006 (2009)



- ☑ Azimuthal angular correlation of charm quark pairs
  - GS peaks around $\Delta\phi = 0$
  - FC peaks around $\Delta\phi = \pi$

- ☑ Gluon splitting in c-cbar pairs → near-side azimuthal correlation between jet axis (leading particle) and D*.





Leading particle $p_T > 5$

Different fragmentation characteristic: soft charm FF in gluon jet.

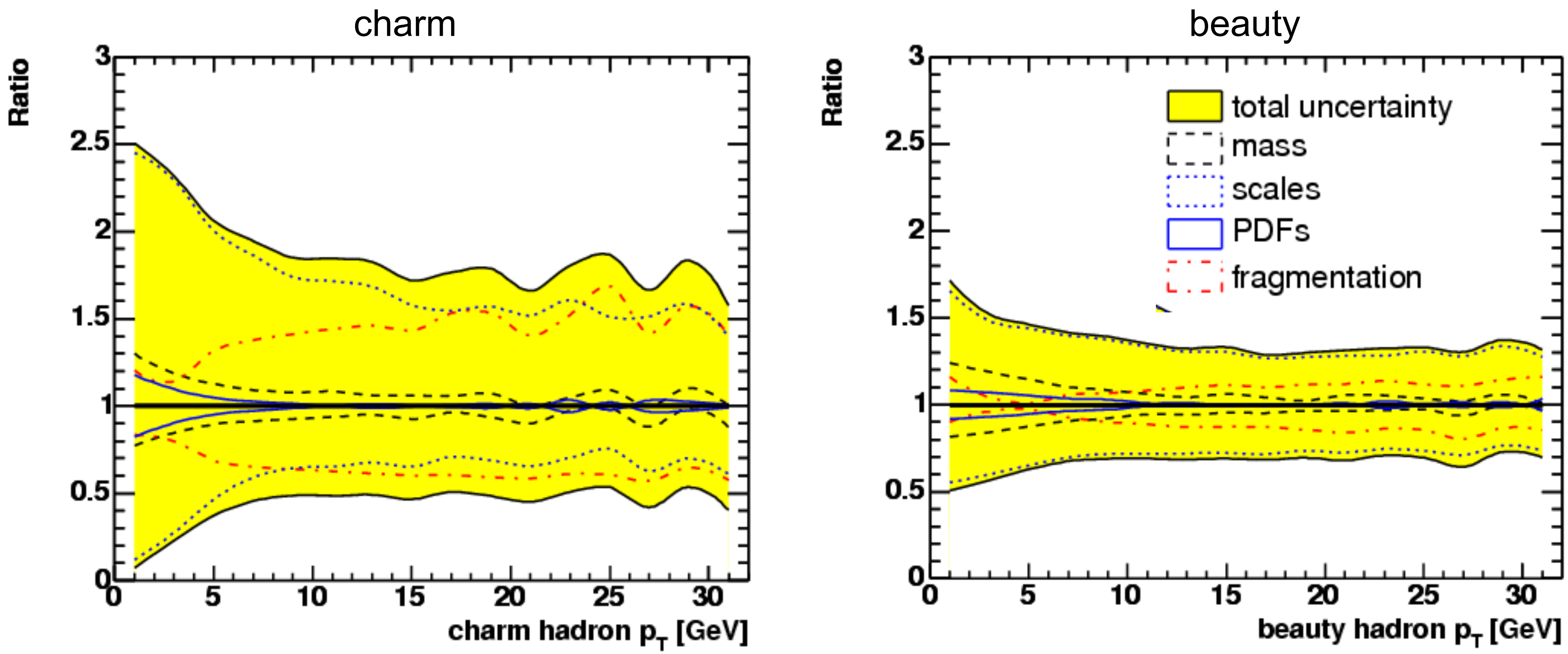
Outlook

- ☑ LHC heavy quark factory
- ☑ Significant contribution from NLO processes at LHC energies.
- ☑ ALICE, CMS and ATLAS have intense HF programs.
- ☑ Charm cross section below 1GeV with ALICE
- ☑ Basic to understand the production mechanism in heavy ion.
  - **heavy quarks used as probe for Quark-Gluon Plasma properties**
- ☑ With the early data:
  - **Powerful test of QCD.**
  - **Understanding of heavy quark cross sections in hadronic collisions.**
- ☐ Rare B channels. Not covered in this presentation.

Backup Slides

Theoretical Uncertainties (HERA-LHC Workshop)

CERN/LHCC 2005-014hep-ph/0601164



$1.3 < m_c < 1.8\,\text{GeV}$ $\quad 0.5 < \mu_{F,R} / m_T < 2$ $\quad 0.002 < \varepsilon_c < 0.11$

$4.5 < m_b < 5.0\,\text{GeV}$ $\quad 0.5 < \mu_F / \mu_R < 2$ $\quad 0.0002 < \varepsilon_b < 0.004$

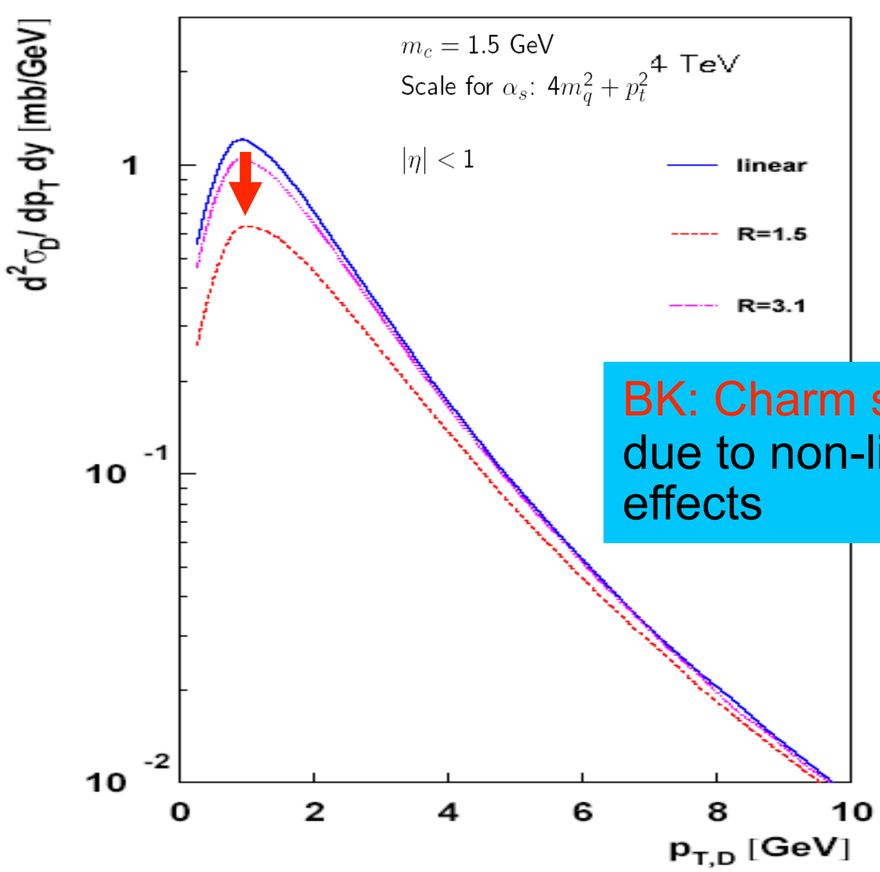
PDFs : CTEQ4, CTEQ5, CTEQ6, MRST2001

MNR code: Mangano, Nason, Ridolfi, NPB373 (1992) 295.

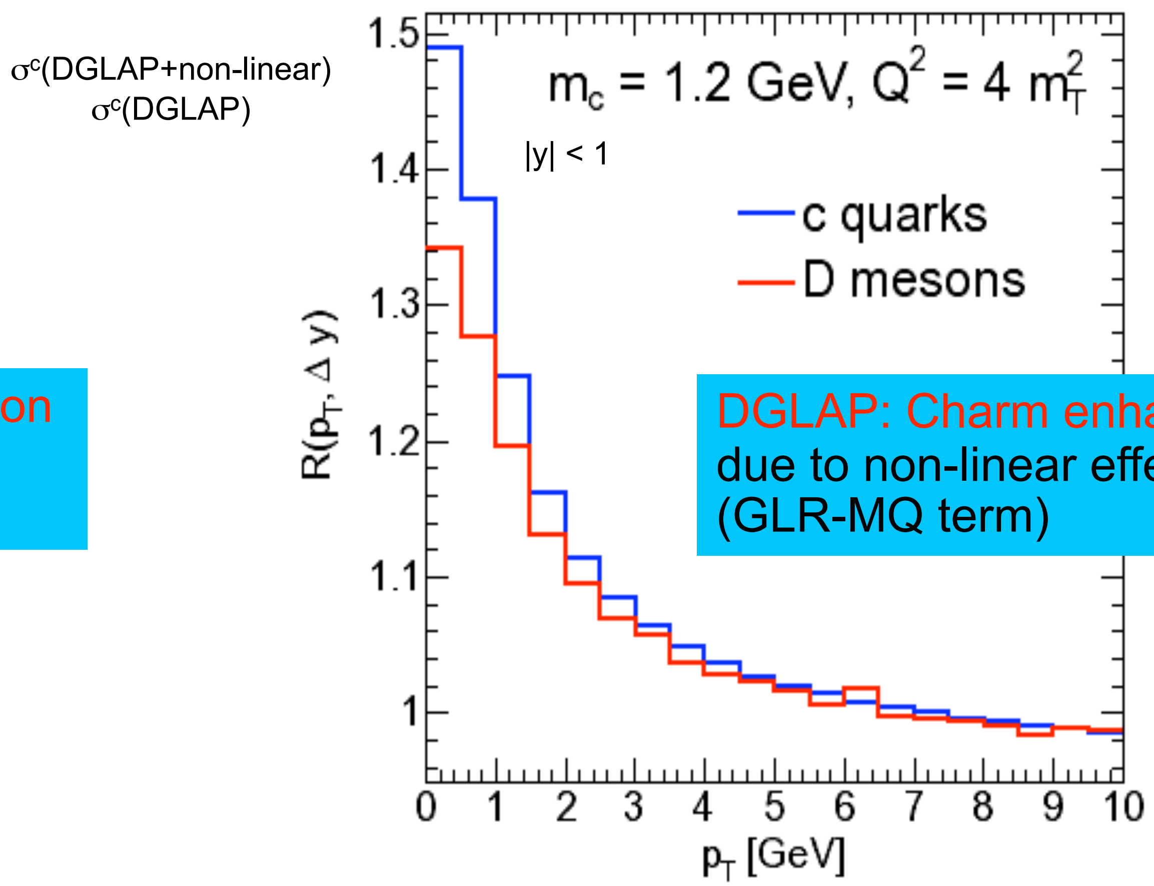
Non linear term in gluon evolution - hints

- Large pQCD uncertainties for charm $p_T \rightarrow 0$
- Two attempts to include non-linear terms in evolution equations:

  - DGLAP+GLRMQ Eskola et al., NPB660 (2003) 211
  - BK Kutak, Kwiecinski, Martin, Stasto

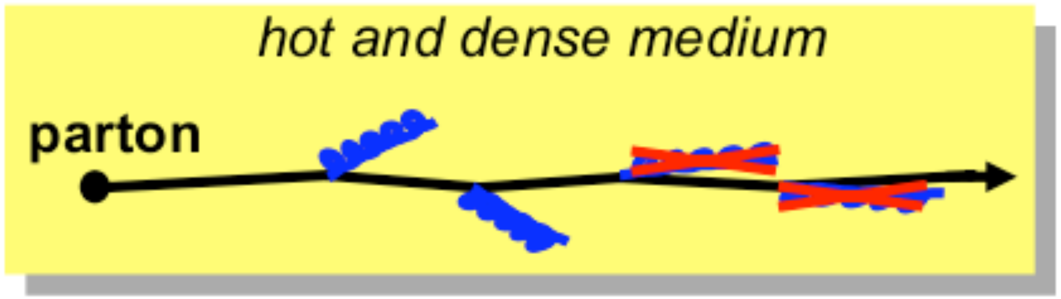


BK: Charm suppression due to non-linear effects



DGLAP: Charm enhancement due to non-linear effects (GLR-MQ term)

Energy Loss of Heavy Quarks in the medium



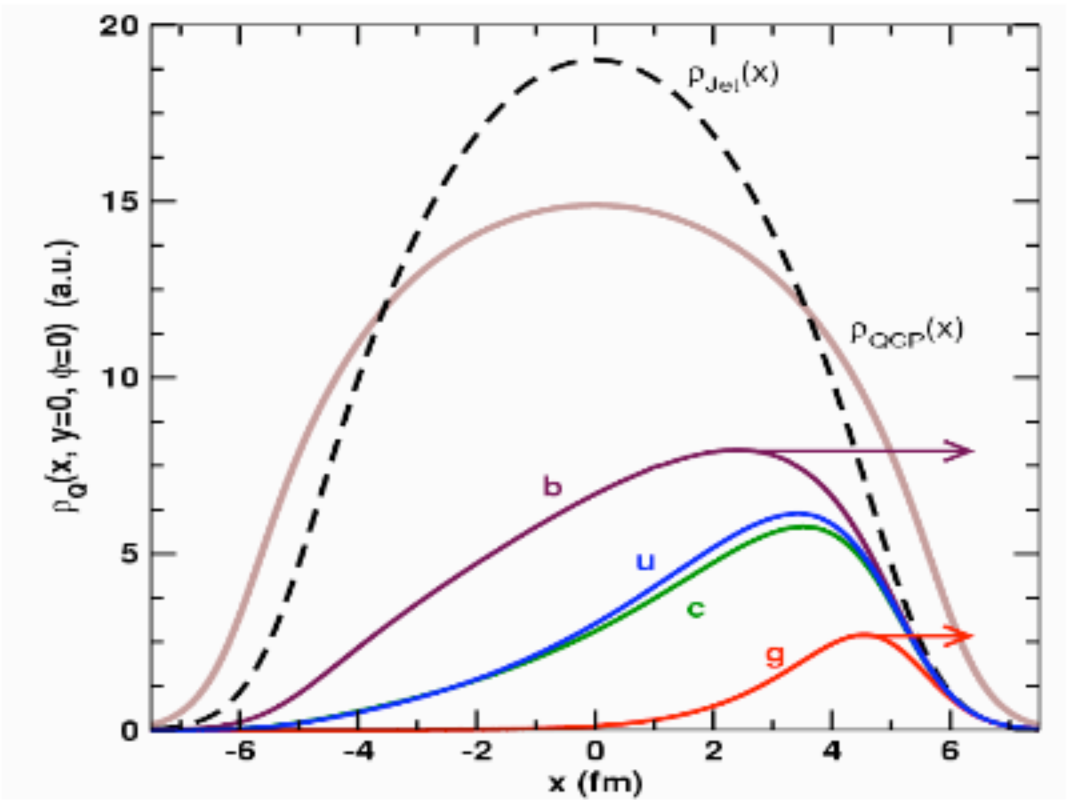
Gluon radiation probability

$$\omega \frac{dI}{d\omega}\Big|_{HEAVY} = \frac{\omega \frac{dI}{d\omega}\Big|_{LIGHT}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

Gluon radiation suppressed at $\theta < m_Q/E_Q$

(dead-cone effect) *Dokshitzer & Kharzeev, PLB 519, 199 (2001)*

Probe deeper into the medium



Production in AA prevision at LHC

☑ R_{AA} of D or B mesons produced in AA and pp → **quark energy loss**

$$R_{AA}^{D,B}(p_t) = \frac{1}{N_{coll}} \times \frac{dN_{AA}^{D,B}/dp_t}{dN_{pp}^{D,B}/dp_t}$$

☑ R_{AA} beauty/charm ratio

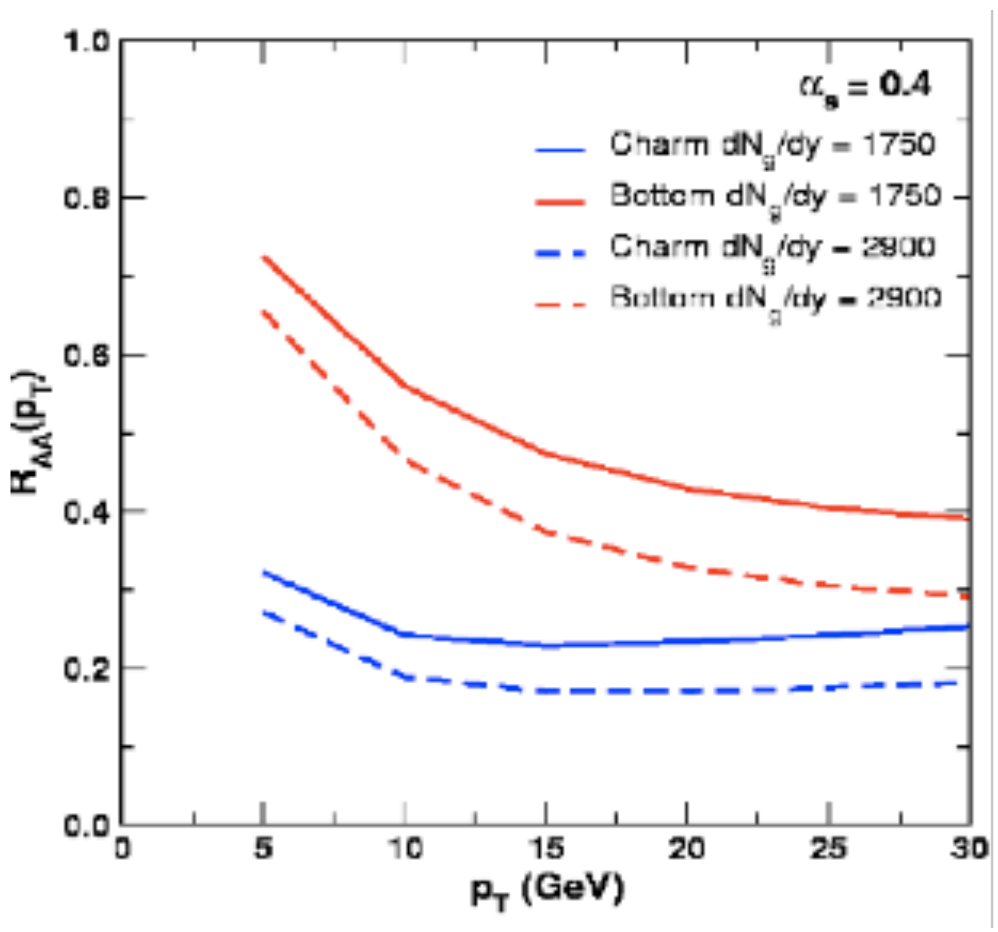
→ **mass dependence**

$$R_{D(B)/h}(p_t) = R_{AA}^{B}(p_t) \big/ R_{AA}^{D}(p_t)$$

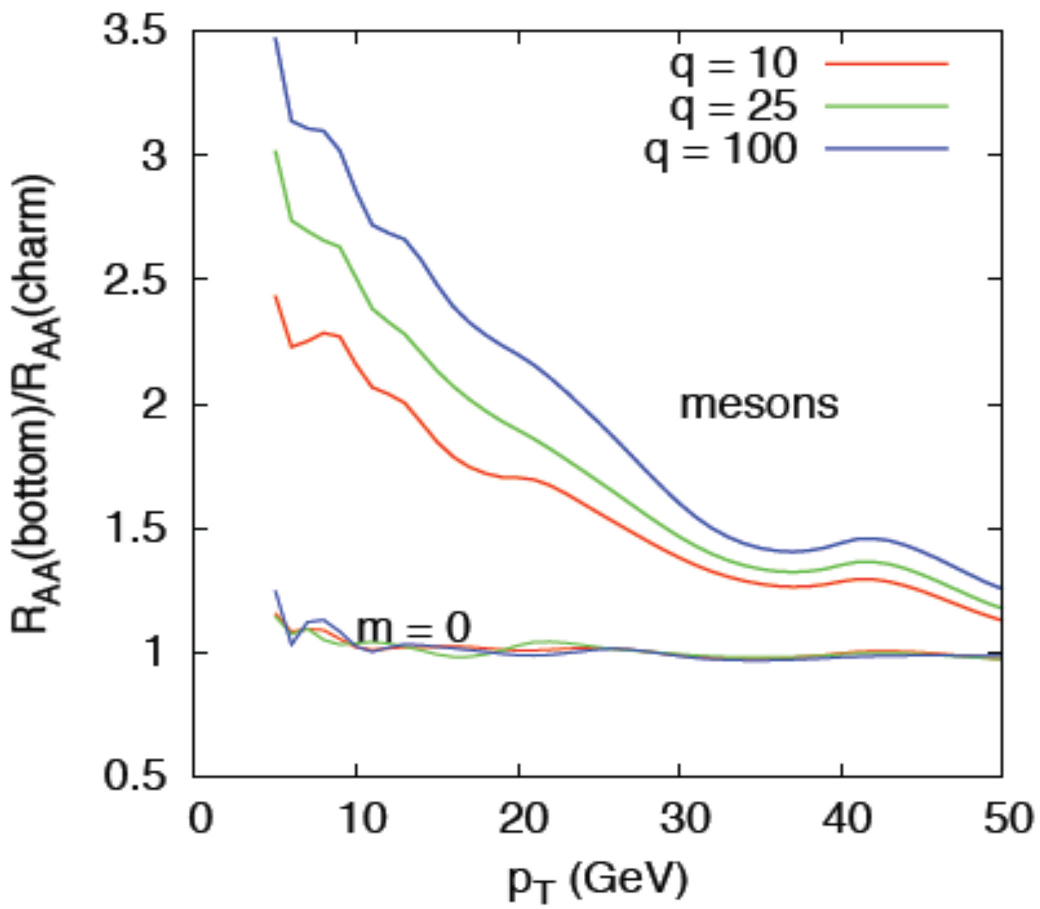
☑ R_{AA} hravy/light ratio

→ **color charge dependence**

$$R_{D(B)/h}(p_t) = R_{AA}^{D(B)}(p_t) \big/ R_{AA}^{h}(p_t)$$

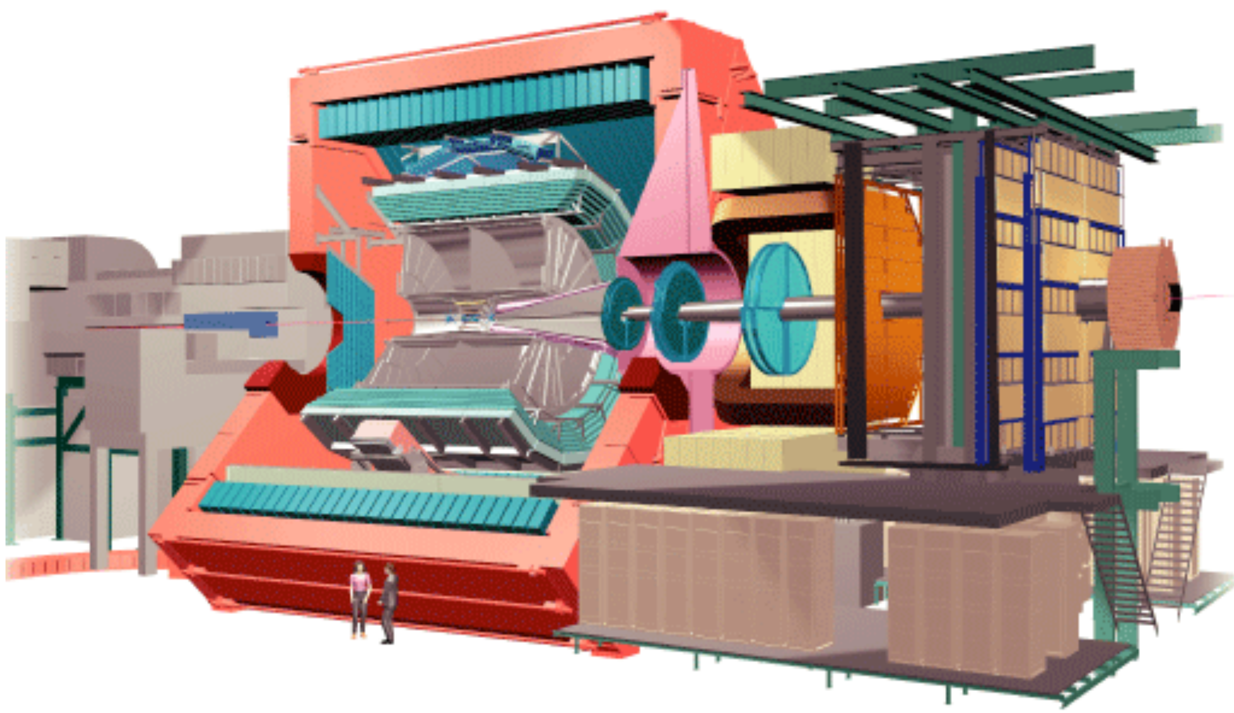


Wicks, Gyulassy, "Last Call for LHC Predictions" workshop



Armesto, Cacciari, Dainese, Salgado, Wiedemann, "Last Call for LHC Predictions" workshop

Heavy Flavour production with early data



Rich Heavy flavour physics program.

In pp:

- Calibrations - baseline for AA
- Open Heavy Flavours - Qarkonia

In pA:

- Initial state effects.

In AA:

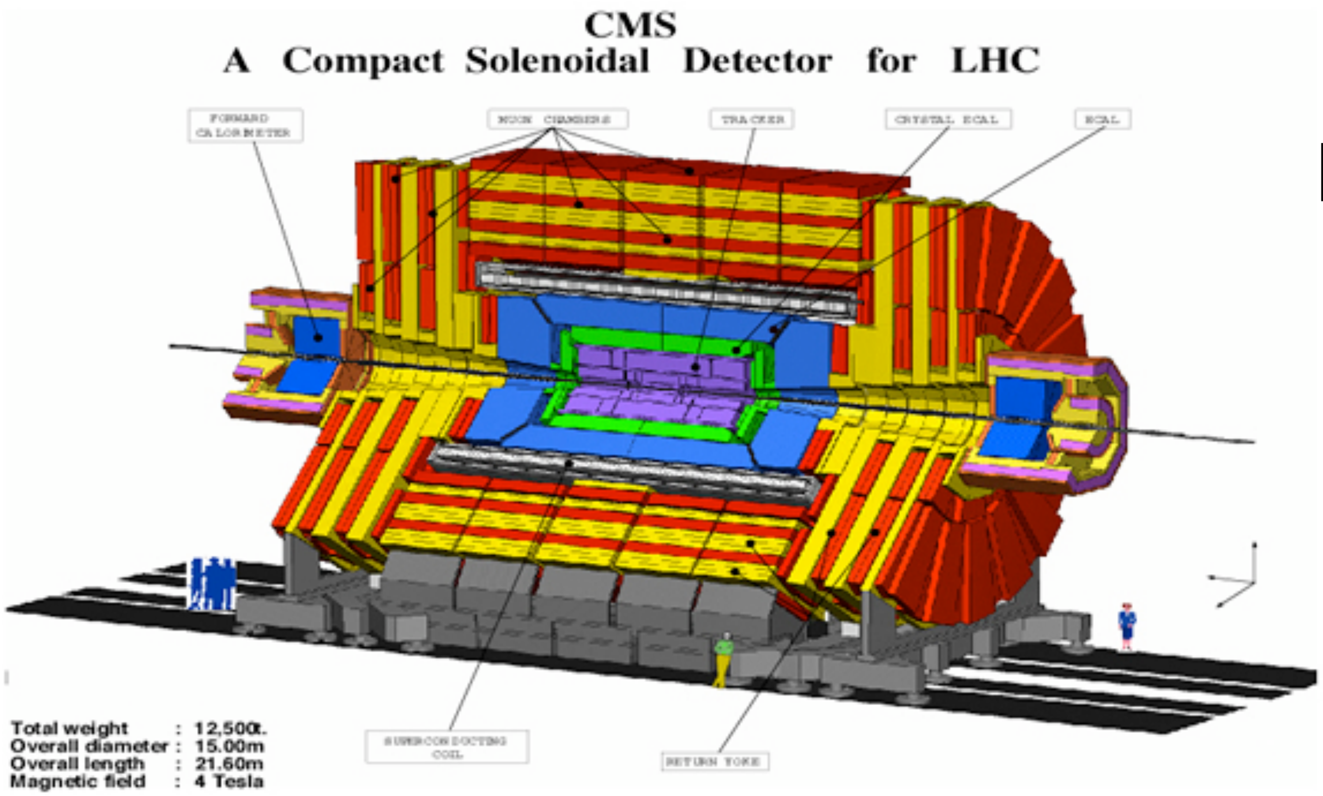
- Production in AA , Hard Probes ......

HF production with early data:

Large program : barrel and forward

- Open Heavy Flavours - Qarkonia
  quencing, correlation studies, b tagging
- Heavy Flavoured Hadrons Cross sections

Heavy Flavour production with early data



Rich Heavy flavour physics program.

- Calibrations
- Heavy Flavour production
- New Physics - rare channels

HF production with early data:

☑ J/ψ analysis:

- **Cross section measurements**

☑ Inclusive B production:

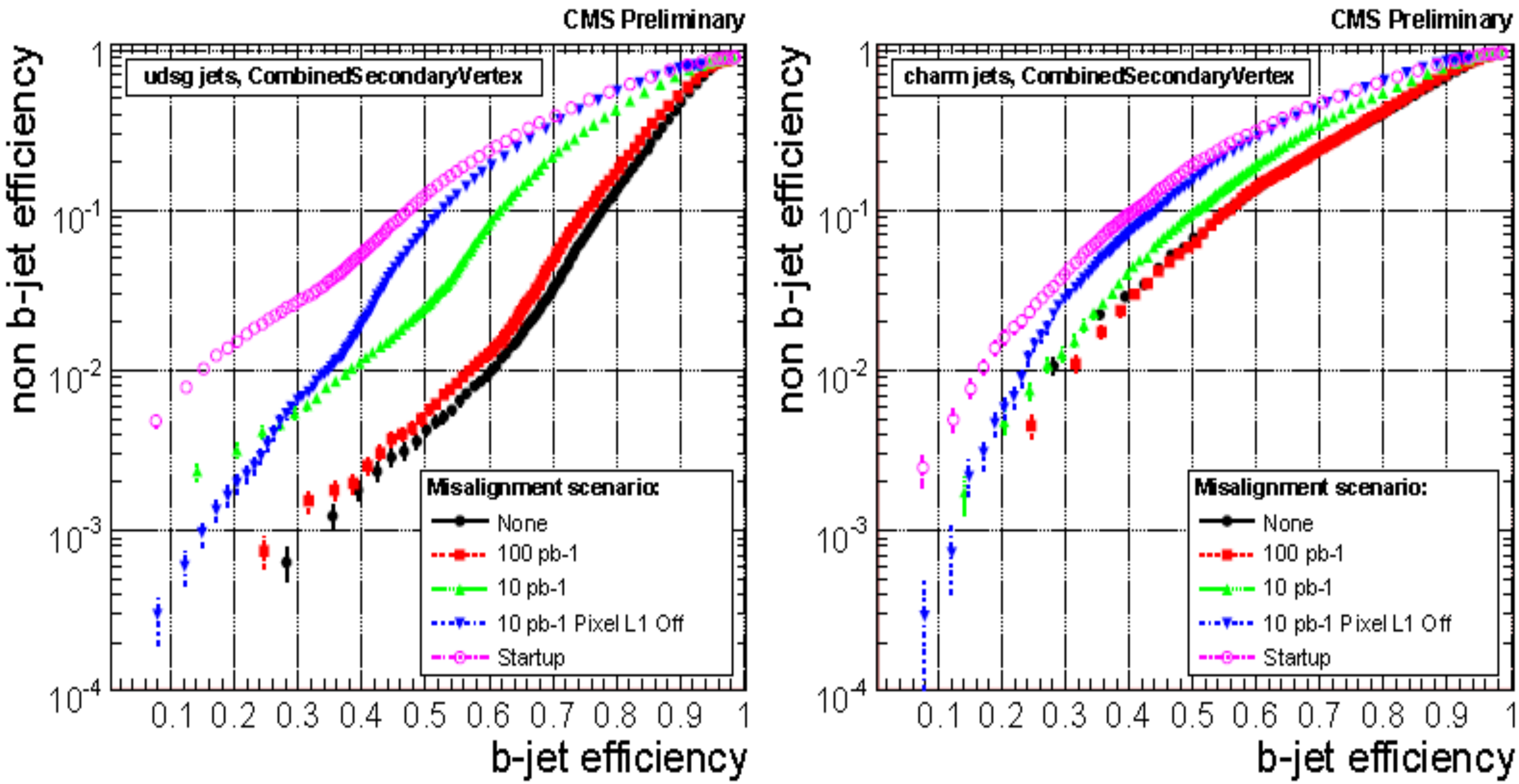
- **Inclusive μ + b-tagged jets**

☑ Exclusive B production:

- **Calibrations, control samples, cross sections**

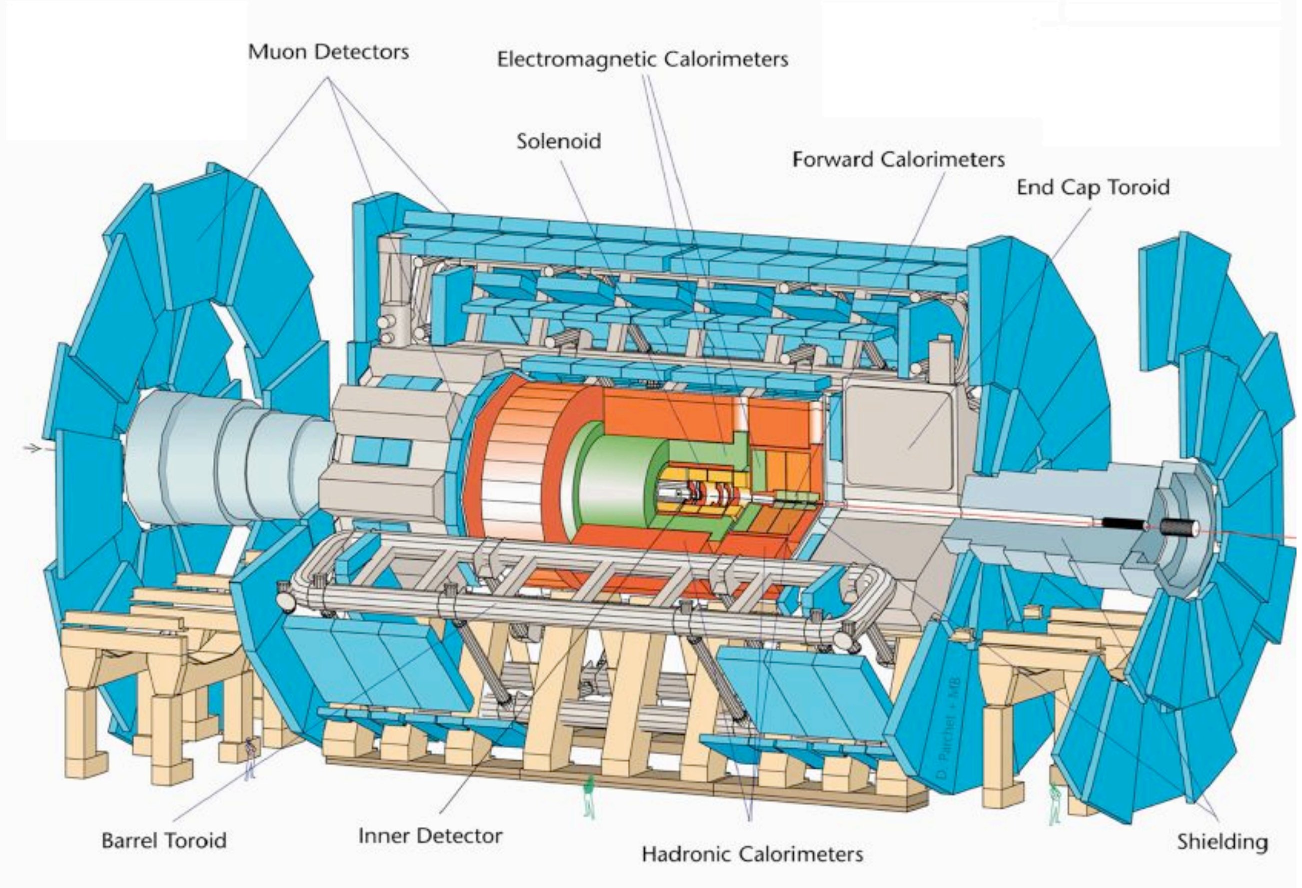
B-tagging efficiencies with different alignment scenarios.

PAS BTV-07-003



☑ CMS has already been aligned with cosmic data with a precision corresponding to the 10 pb^{-1} scenario!

Heavy Flavour production with early data



Rich Heavy flavour physics program.

- Calibrations
- Heavy Flavour production
- New Physics - rare channels

HF production with early data:

☑ Prompt heavy quarkonia

- **Cross section measurements**
- **Reference channel $B^+ \to J/\psi K^+$ for future meas.**

☑ Test for QCD calculations

- **Prompt heavy quarkonia cross sections**

$B^+ \rightarrow J/\psi K^+$

Systematics:

- ~ 160 B^+ candidate per pb^{-1}
- Reliable cross section in few months of data taking
- Results valid even in a low luminosity scenario <= 10^{32} cm^{-2} s^{-1}
- Total extimated systematic uncertanty ranging from 9.5%-12%:
  - **Luminosity 10% (6.5 after 0.3fb^{-1})**
  - **PDFs 3%**
  - **Scale 5%**
  - **Muon ID 3%**

Statistical:

- Expected O(1%) already at 0.1 fb^{-1}