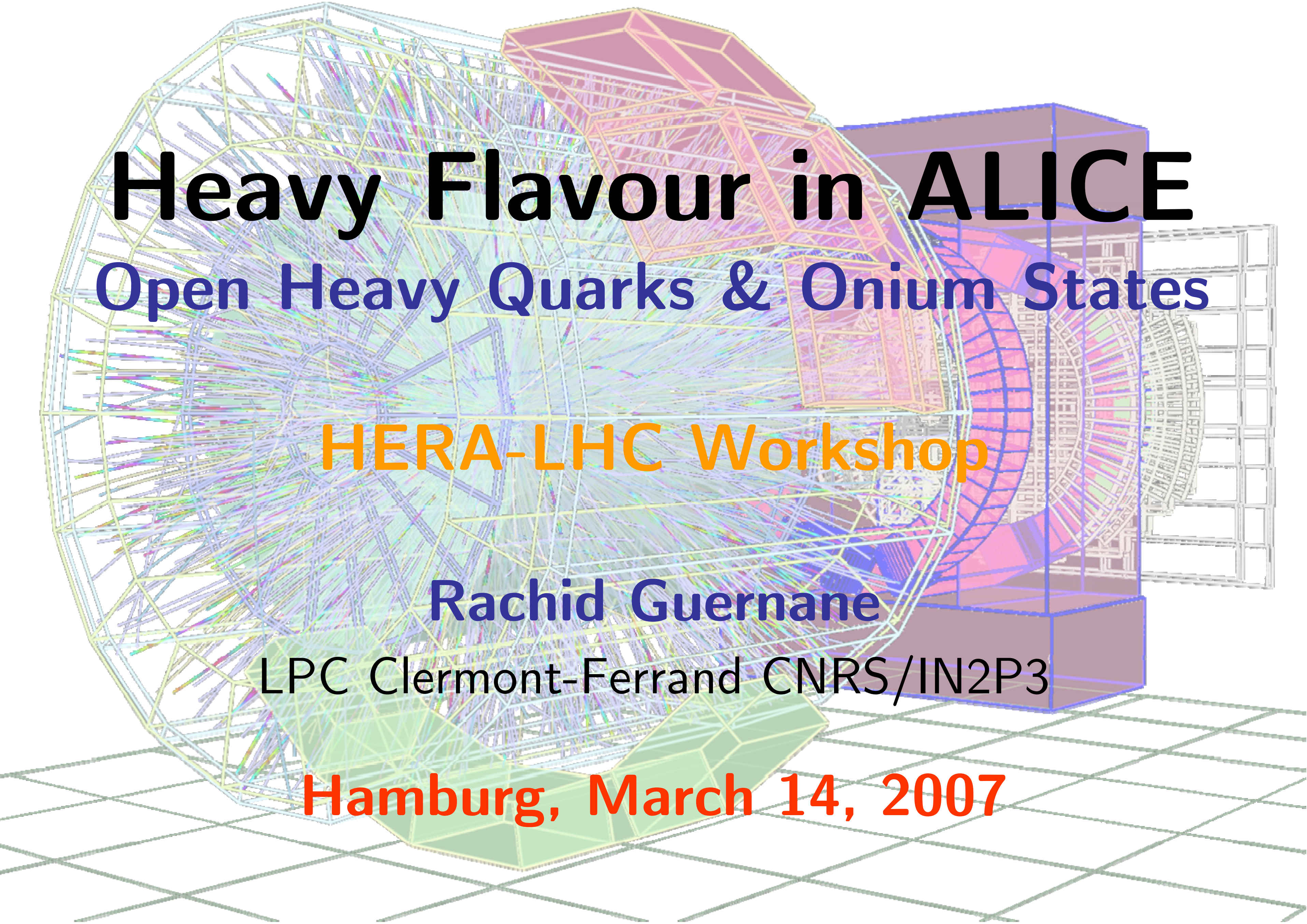

Heavy Flavour in ALICE

Open Heavy Quarks & Onium States

HERA-LHC Workshop

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LPC Clermont-Ferrand CNRS/IN2P3

Hamburg, March 14, 2007

Outline

- Heavy flavour production at the LHC
- The ALICE detector
- ALICE heavy flavour measurements
  - **charm** reconstruction via **hadronic decays**
  - **beauty** detection in **semileptonic** modes
  - **quarkonia** detection in **di-lepton** channels
- Summary & outlook

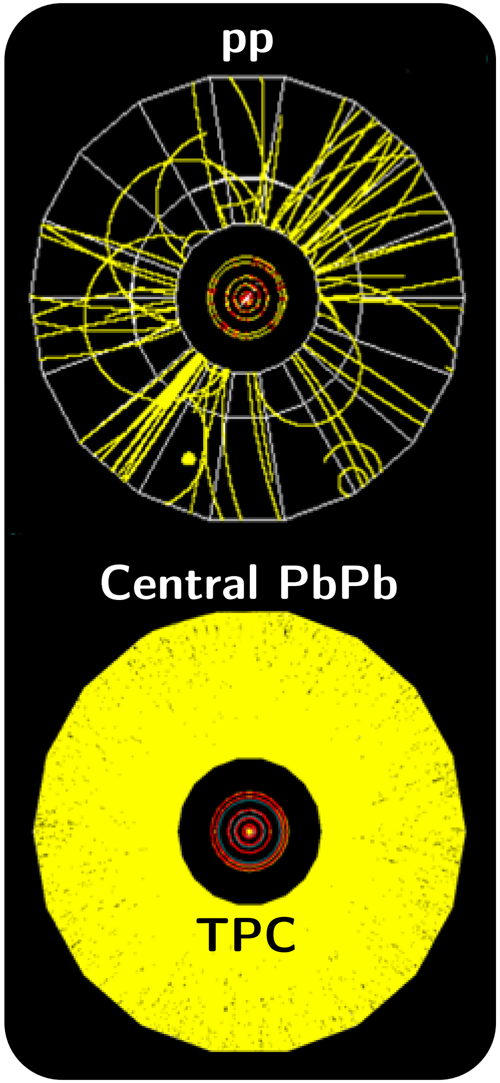
Major part of the material presented hereafter is published in the ALICE "Physics Performance Report",

J. Phys. G30 1517-1763 & J. Phys. G32 1295–2040

Heavy flavour production at the LHC

Introduction

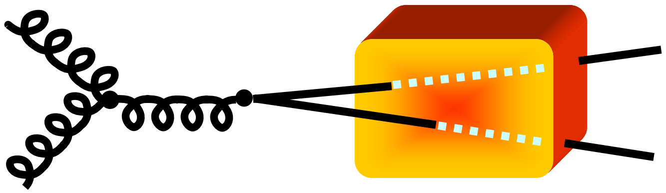
- What for?
  - heavy flavour production in hadron collisions provides a rich QCD phenomenology
    - **pp** → test reliability of **pertubative calculations**
    - **pA** → assess **initial state effects**
    - **AA** → probe the **high colour-density** medium
- LHC's novelties
  - **hard cross section dominates**
    - $\sigma_{\text{hard}} / \sigma_{\text{tot}}$ $\sim$ **98 %** VS **50 % at RHIC**
    - **copious production** of both c & b quarks
  - large inelastic background
    - messy environnement with **large combinatorics**
      $\propto (dN_{ch}/dy)^2$ with $dN_{ch}/dy = 6000$ in central Pb-Pb!
- ALICE's plus points
  - **muti-purpose** → several heavy flavour measurements within **the same experiment**
  - **precise tracking & vertexing** → resolve D's & B's **decay vertices**
  - **PID** → π/K separation



Heavy flavour production at the LHC

Hard QCD probes

- Sensitive probe of the **collision dynamics**
  - early creation time $\sim 1/m_Q$ (~ 0.1 fm/c $\ll \tau_{QGP} \sim 5 \div 10$ fm/c) in initial parton collisions & **long lifetime**
    - Undergo the **whole collision history**

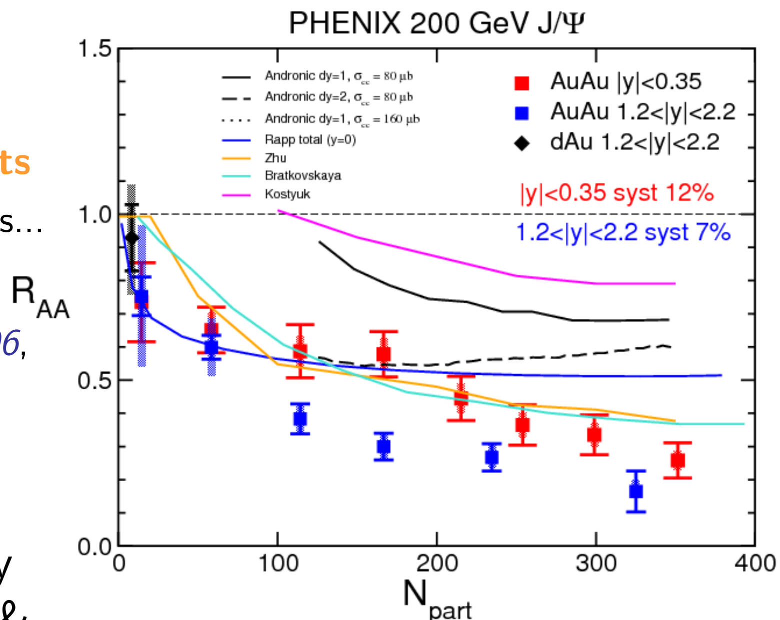


- **Open heavy flavours**
  - **Tomographic** probe
    - Radiative **parton energy loss** is both color charge & mass dependent
      Phys. Rev. D71 (2005) 054027
      - Significantly **larger energy loss** is expected for **light q & g** w.r.t. ***b* quarks** at the LHC
    - Need for a **clean "calibration"**
      - **pp** & **pA** experiments provide a compulsory benchmark
  - Heavy quark **p_T distribution** sensitive to many competing **nuclear effects**
    - Low-p_T (< 6 GeV/c at LHC) region sensitive to **non-perturbative** effects (flow, quark coalescence, gluon shadowing, CGC state...)
    - High-p_T region sensitive to **jet quenching**
  - **Baseline** for quarkonia production

Heavy flavour production at the LHC
Hard QCD probes

- Quarkonium dissociation by **color screening** in a deconfined medium *Phys. Lett. B178 416 (1986)*
  - ℓQCD predicts a **sequential dissolution** of onium states with increasing **temperature** or **energy density** (hierarchy of their sizes)
    - Quarkonium states **do not melt at T_c**
      - J/ψ could survive up to $1.6\,T_c$ Phys. *Rev. Lett. 92 (2004) 012001*
      - Υ up to $2.3\,T_c$ *PoS LAT2005 (2006) 153* $\longrightarrow$ **Good probe for LHC!**
  - A **"smoking gun"** of QGP?

    A puzzle instead... clearly data-driven
    - Poorly constrained **cold or "normal" nuclear effects**
      - Shadowing, saturation, nuclear absorption, co-movers...
    - **Recombination** mechanisms
      - Statistical hadronization *Phys. Lett. B490 (2000) 196*, Kinetic formation *Phys. Rev. C63 (2001) 054905*)
      - Might be **a significant effect at the LHC** for **charmonium** but marginal for bottomonium
  - Study **quakonium yields VS centrality** to clarify the interplay of **true QGP-related suppression** & heavy quark pair **recombination**



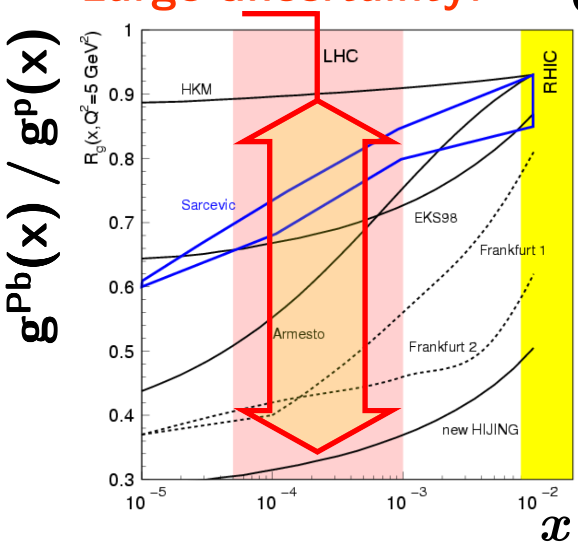
Preliminary, Mike Leitch, QM06

Heavy flavour production at the LHC

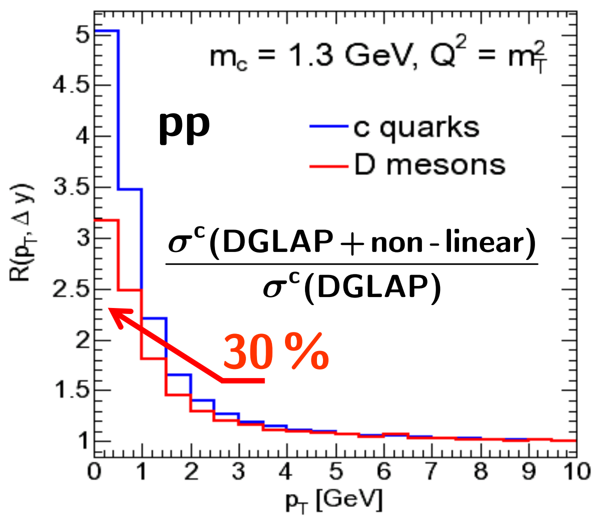
A novel range of accessible x

- ALICE probes a continuous range of x **as low as about 10^{-5}** w/ HQs at low p_T and/or forward y
  - **explore QCD** in the new regime of **"small" x** & **"large" Q^2** where a breakdown of the standard collinear factorization approach is expected
    - deep **nuclear gluon shadowing** at high rapidity in pA
    - **gluon saturation** at $Q_s^2\,(5.5\,\text{TeV}, \text{Pb}) \sim 10 \div 20\ \text{GeV}^2$
    - non-linear terms in the gluon evolution
      - possible **low-p_T charm enhancement** Phys. Lett. B582 (2004) 157

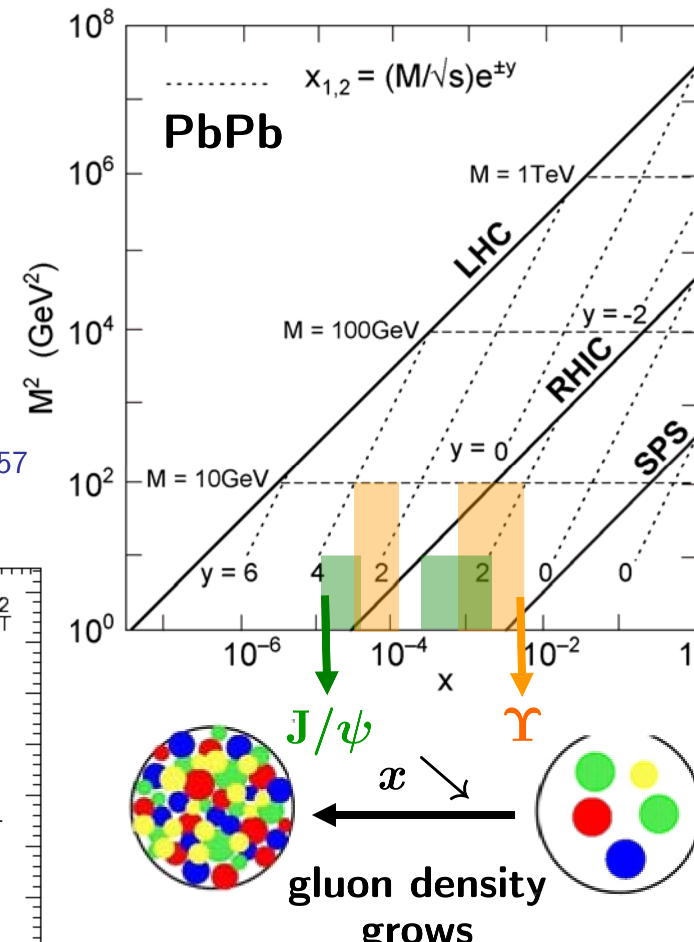
Large uncertainty!



Charm



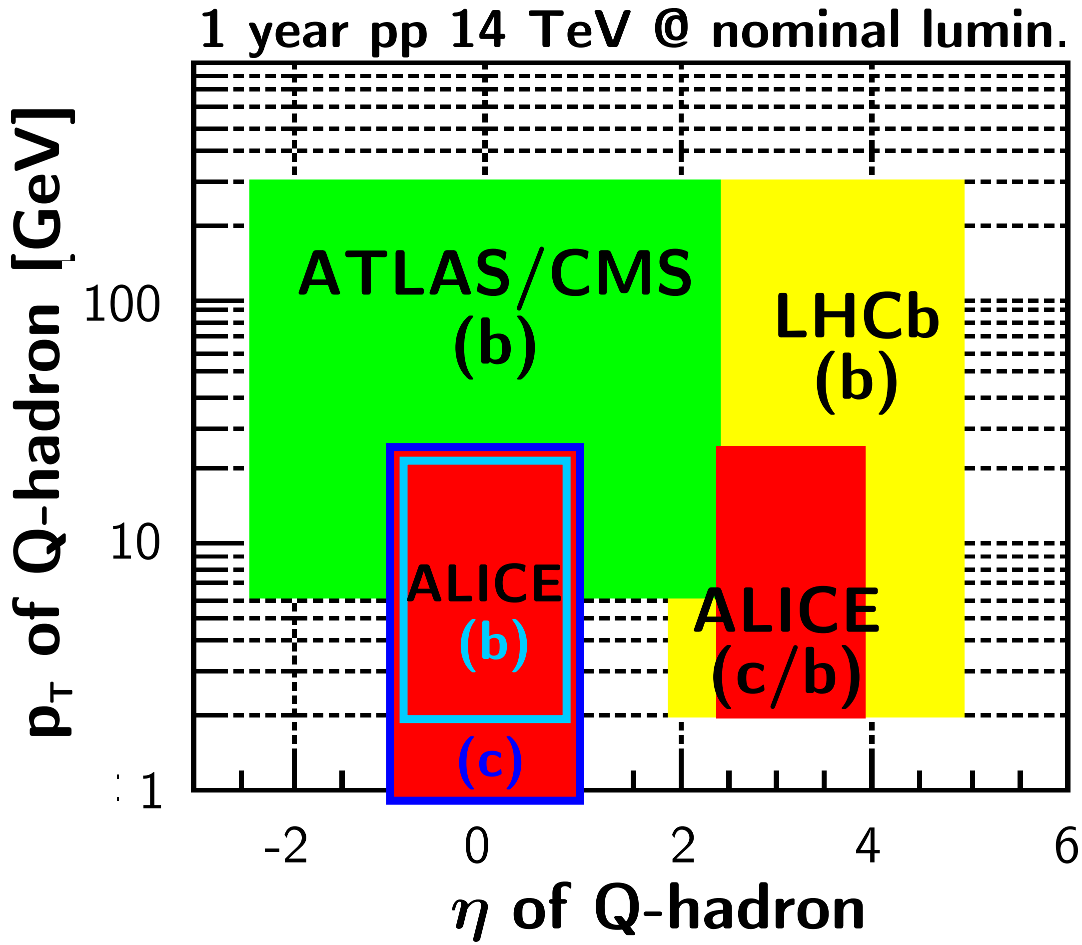
ALICE kinematic reach



EKS98: 35 % (20 %) reduction of charm (beauty) cross section in PbPb & 15 % (10 %) in pPb

Open heavy flavour production at the LHC

pp acceptances



Complementarity of the four LHC experiments

ALICE's specific features

- ▷ both **central** & **forward** coverage
- ▷ both **c** & **b** measurements

HERA-LHC Workshop
CERN-2005-014

ALICE has acceptance down to very low p_T!

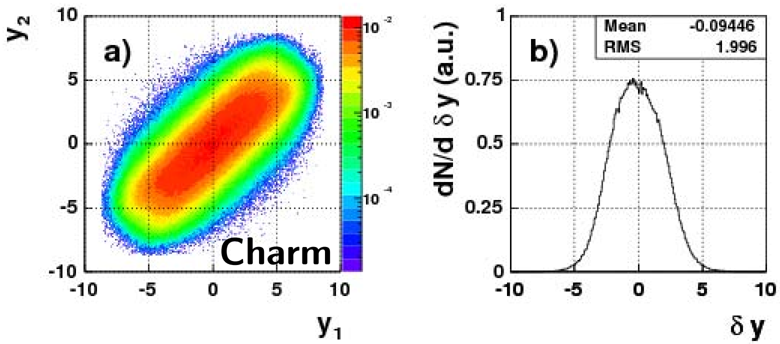
Open heavy flavour production at the LHC

Outbreak of large higher order corrections

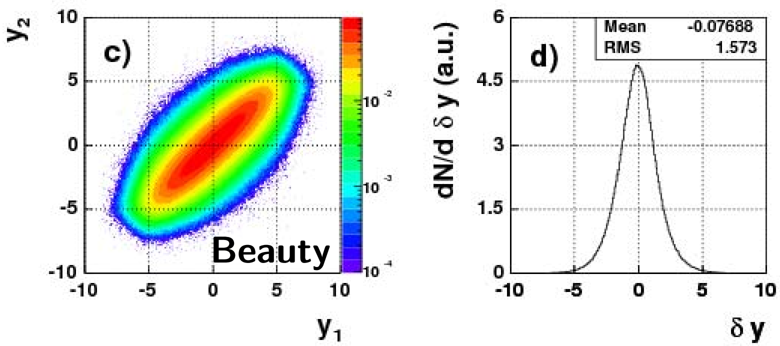
- **LO processes** result in topologies where the $\mathbf{Q}$ and the $\bar{\mathbf{Q}}$ quarks are produced **back-to-back** and necessarily have **similar p_T** ($\Delta\varphi = \pi$ & $p_T^{Q\bar{Q}} = 0$)
- **Higher order contributions**
  - can produce much more **complicated topologies**
  - become **dominant at LHC energies**, $K = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} = 1.4 \div 3.2$ for b production *hep-ph/0311048*
  - in the following, heavy quarks have been **generated using PYTHIA (*)**, tuned to reproduce kinematic distributions given by **NLO pQCD** *hep-ph/0311225*

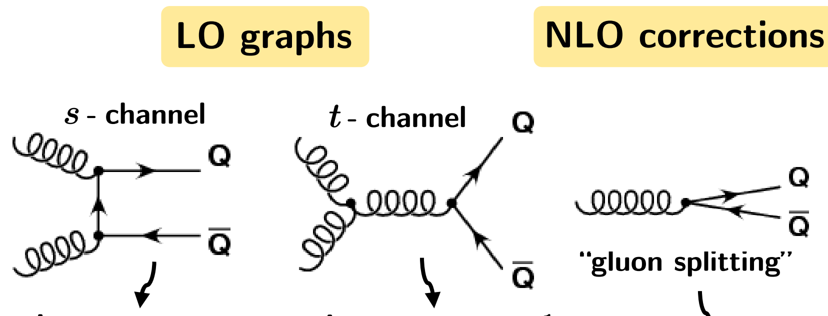
    (*) NLO pertubative processes approximated in the PS approach by LO hard scattering (QCD $2 \to 2$ processes) plus initial & final-state cascades

$-4 \leq \eta^{\mu} \leq -2.5$



ALICE muon spectrometer design adapted to **heavy quark detection**





$\frac{d\sigma}{d\hat{t}} \sim (\cosh\delta y)^{-2}$ $\frac{d\sigma}{d\hat{s}} \sim (\cosh\delta y)^{-1}$ $\delta y \sim 0$

Heavy flavour production at the LHC

The ALICE baseline

Unpreceding large cross sections!

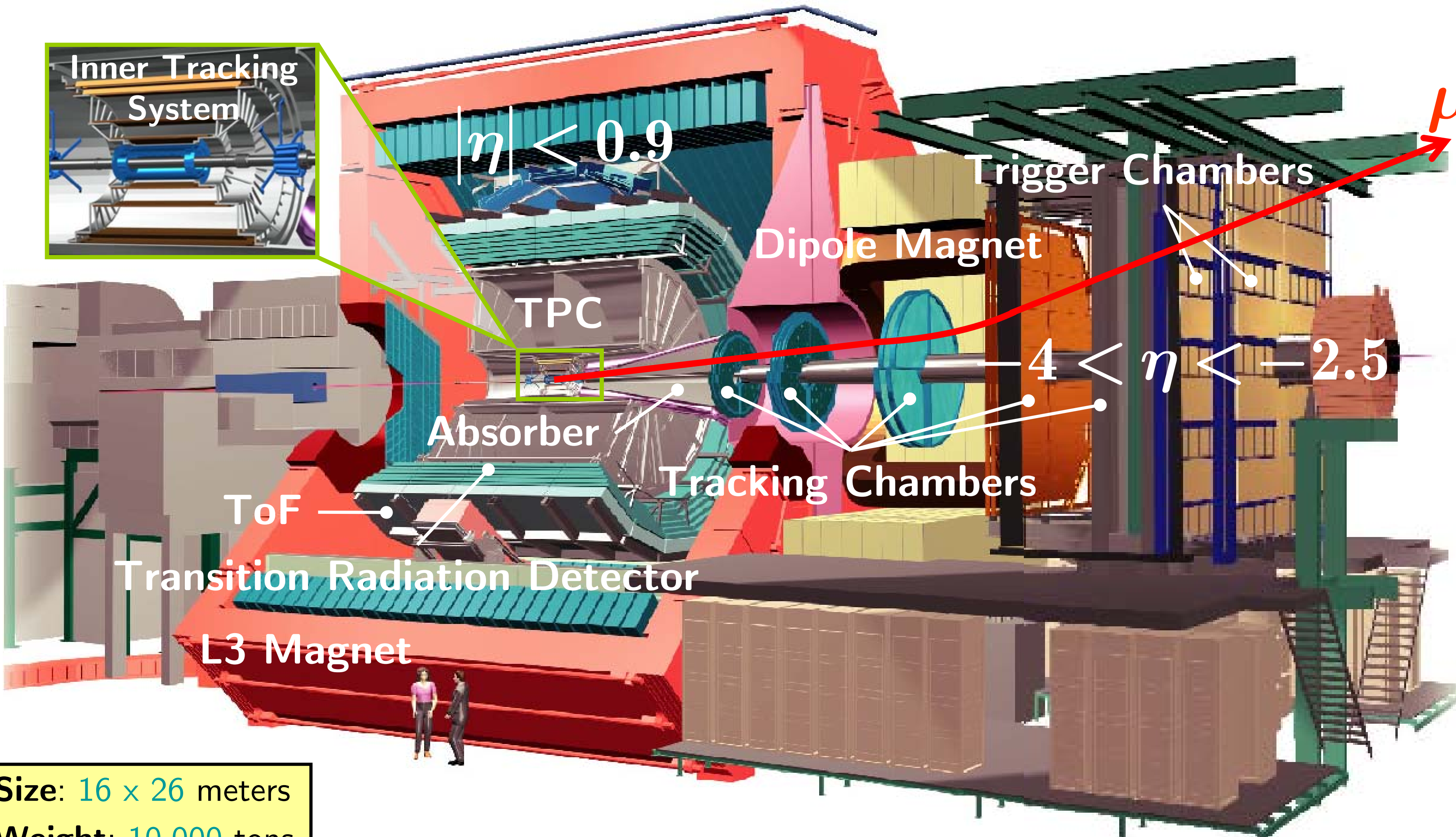
	PbPb 5.5 TeV					pp 14 TeV				
	0-5% centr.									
	$c\bar{c}$		$b\bar{b}$			$c\bar{c}$		$b\bar{b}$		
σ(NN) [mb] (*)	6.64		0.21			11.2		0.51		
EKS98 shadowing	0.65		0.86							
N per collision	115		4.56			0.16		0.0072		
	J/ψ	ψ'	Υ	Υ'	Υ''	J/ψ	ψ'	Υ	Υ'	Υ''
σ (AA) [μb] (**)	48930	879	420	109	61	3.18	0.0057	0.028	0.0069	0.0041

(*) NLO in pQCD calculations from M. Mangano, P. Nason, and G. Ridolfi, *Nucl. Phys. B 273 (1992) 295*
Theoretical uncertainty of a factor 2-3 (cf. CERN–2005–014)

(**) Inclusive lepton pair cross-sections from the Color Evaporation Model, *Phys. Lett. B 91 (1980) 253*

The ALICE detector

Only dedicated HI experiment at the LHC with a **large suite of detectors** optimized for **high efficiency tracking** and **particle identification** across large range of **momenta** from below **100 MeV** to above **100 GeV**

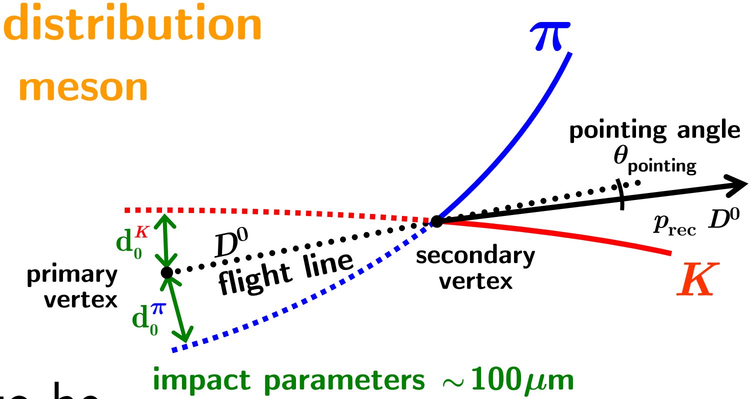


Size: 16 x 26 meters

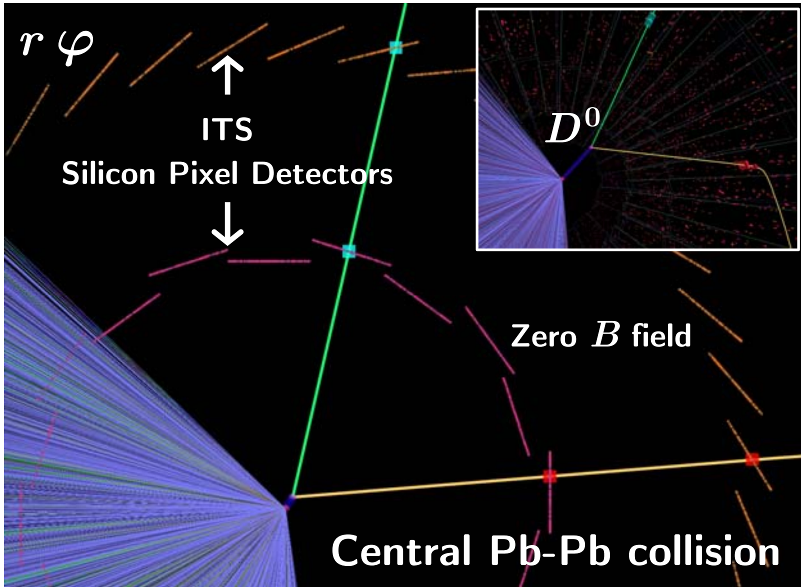
Weight: 10,000 tons

Direct charm reconstruction in ALICE
The $D^0 \to K^- \pi^+$ "golden" mode

- **Direct measurement** of the charmed meson **p_T distribution**
  - measure the nuclear modification factor **R_{AA} of D meson**
- **Very challenging** in an heavy-ion environment
  - $S/B \sim 10^{-6}$ in $M_{D^0} \pm 3\sigma$ before selection
  - need for a **drastic selection procedure** to reduce the background by **6-7 orders of magnitude!**
- **Secondary production** from **b-hadron decays** to be subtracted from direct production



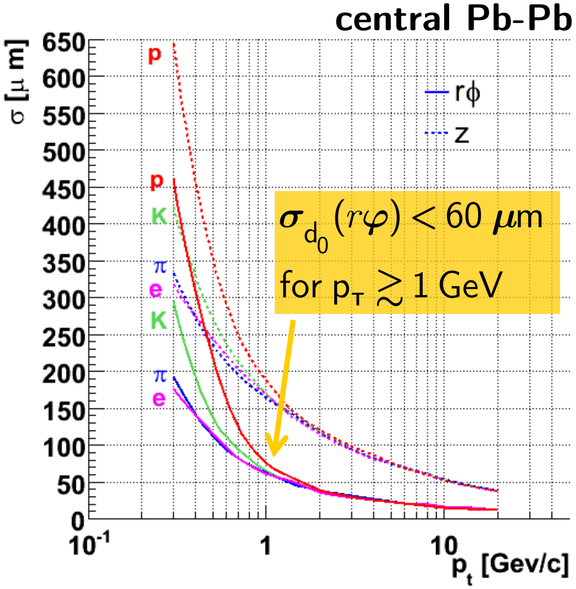
- Detection strategy
  - exploit the **long c lifetime** ($c\tau = 124\ \mu$m)
    - events containing hadronic decays of charmed hadron are selected by requiring
      - two opposite-sign tracks displaced from the primary vertex *i.e.* w/ **large impact parameters d_0**
  - D^0 reconstructed momentum should **point to the primary vertex** ($\theta_{pointing} \approx 0$)
  - (K, π) **invariant mass analysis** to extract the D^0 yield



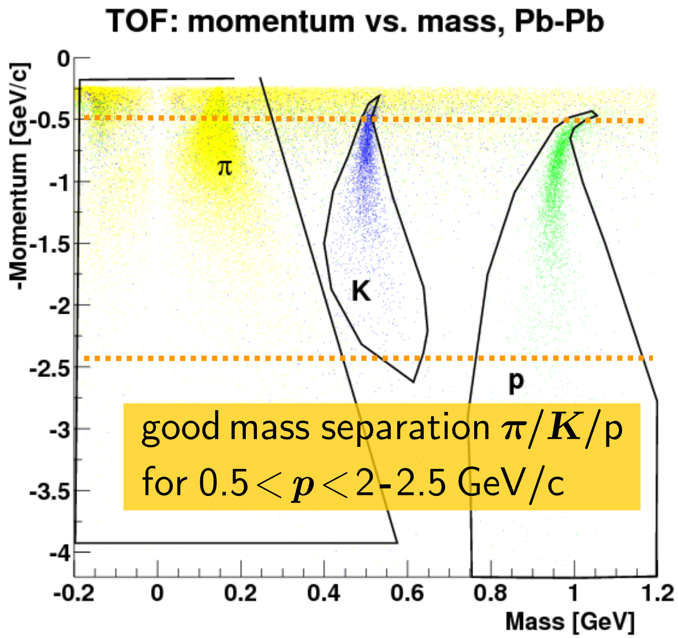
$D^0 \rightarrow K^- \pi^+$

D^0 candidate reconstruction

Measurement of the track impact parameter
- track reconstruction in ITS + TPC
- d_0 resolution given by ITS SPD layers



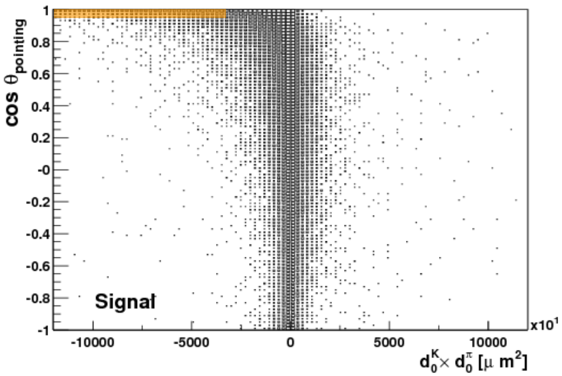
PID
- TOF tag decay products

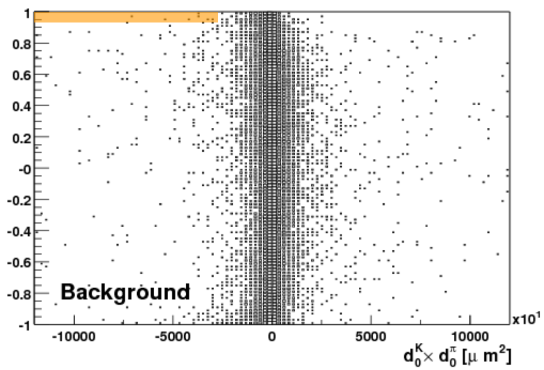


D^0 candidate selection

$d_0^K \times d_0^\pi <$ -40,000 μm^2 & $\cos\theta_{point} \geq 0.98$

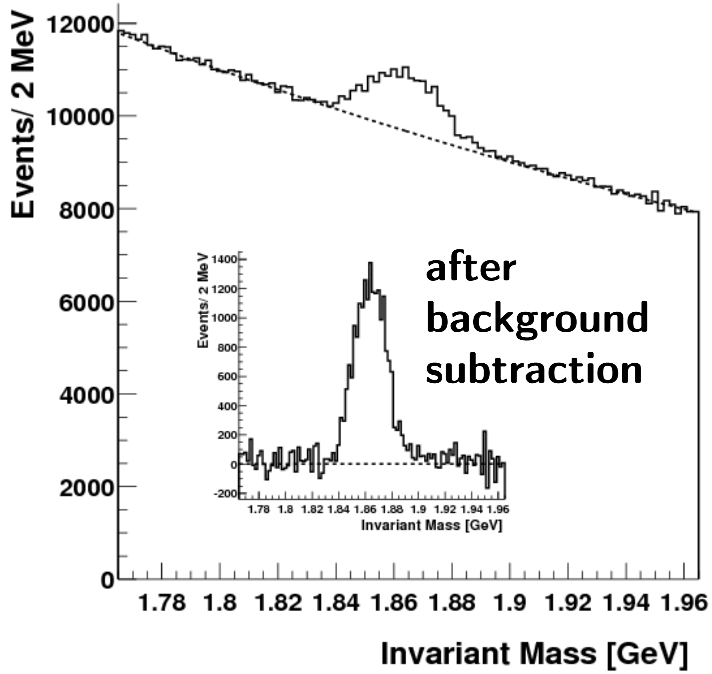
increase S/B by a factor $\sim 10^3$!

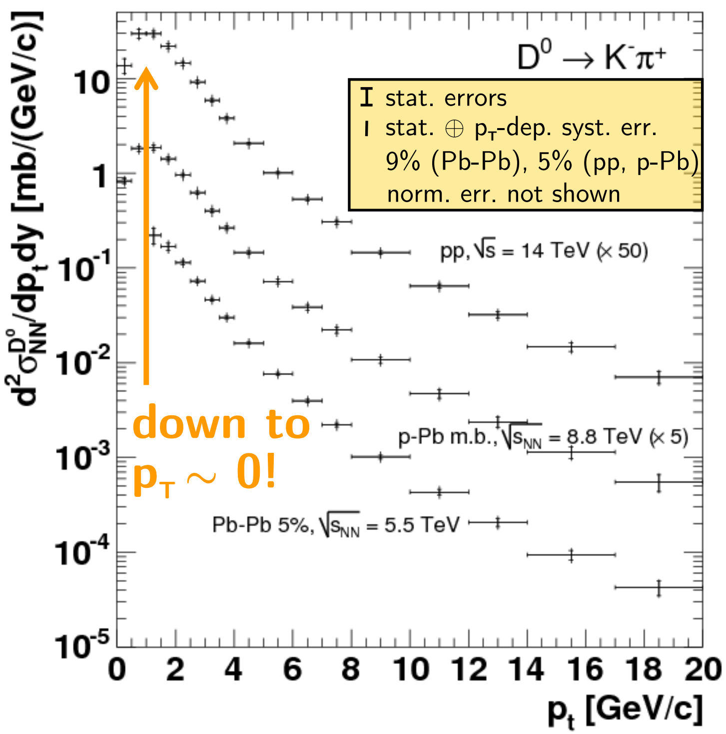




$D^0 \rightarrow K^- \pi^+$

The results



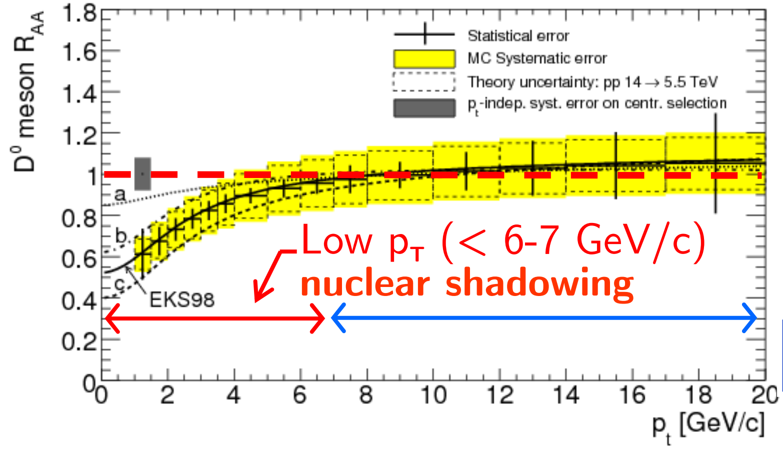


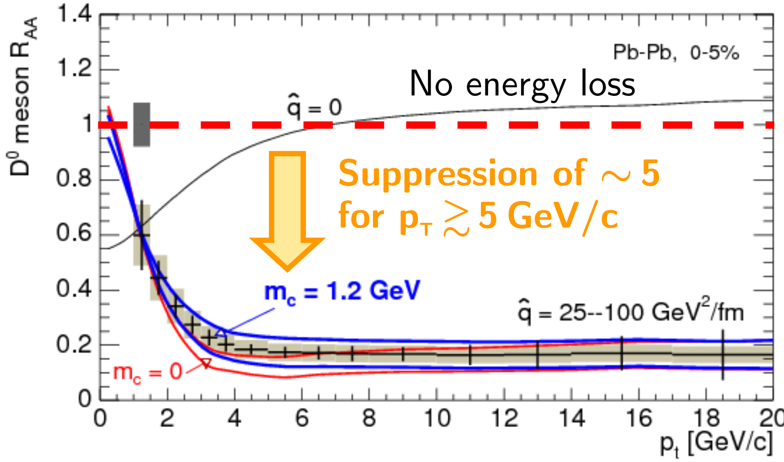
	S/B initial ($M \pm 3\sigma$)	S/B final ($M \pm 1\sigma$)	Significance $S/(S+B)^{1/2}$ ($M \pm 1\sigma$)
Pb-Pb central	$5 \cdot 10^{-6}$	10%	~ 35 (for 10^7 evts, $\sim$1 month)
pPb min. bias	$2 \cdot 10^{-3}$	5%	~ 30 (for 10^8 evts, $\sim$1 month)
pp	$2 \cdot 10^{-3}$	10%	~ 40 (for 10^9 evts, $\sim$7 months)

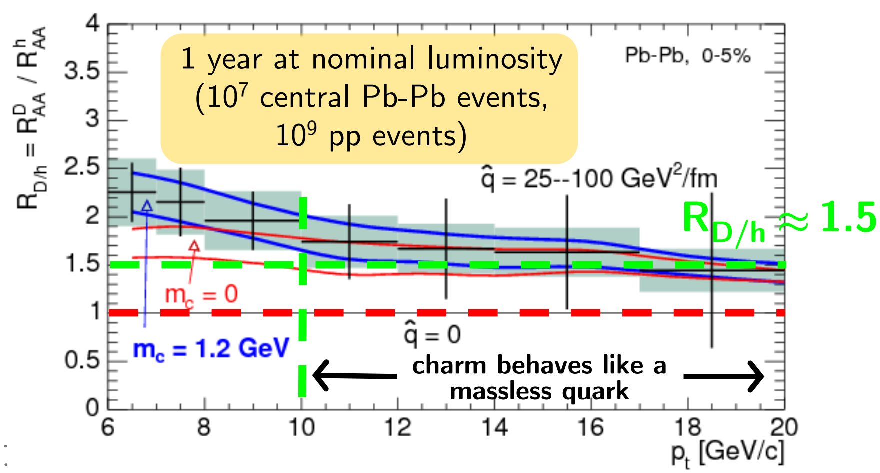
Note

w/ $dN_{ch}/dy = 3000$, S/B larger by $\times 4$ & significance larger by $\times 2$

Perspectives for the study of charm quenching







- The method
  - compare D^0 mesons p_T distributions in **pp** & **AA**

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

"High" p_T (> 6 - 7 GeV/c)

▷ here **energy loss** can be studied

▷ **only** expected effect?

in-medium hadronisation...

  - "heavy-to-light" ratios

$$\Delta E_g > \Delta E_q^{m=0} > \Delta E_q^{m\neq 0}$$

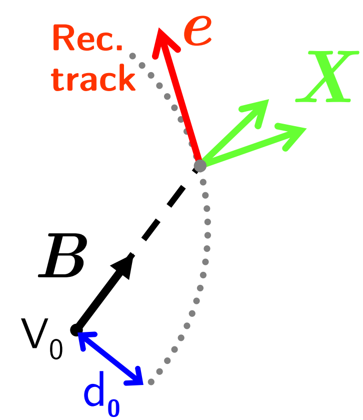
$$R_{D/h}(p_T) = R^D_{AA}(p_T) \,/\, R^h_{AA}(p_T)$$

test the **color-charge dependence** of QCD energy loss

$$R_{B/h}(p_T),\ R_{B/D}(p_T)$$

test the **masse dependence** of QCD energy loss

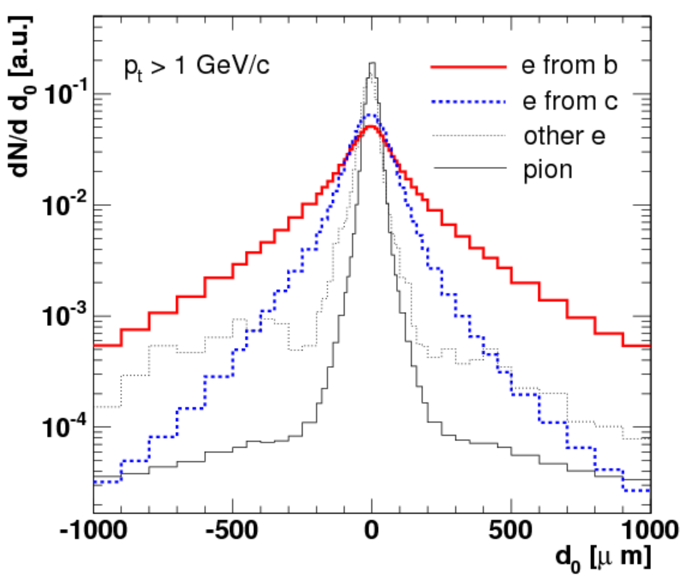
Beauty via single electrons in central Pb-Pb collisions

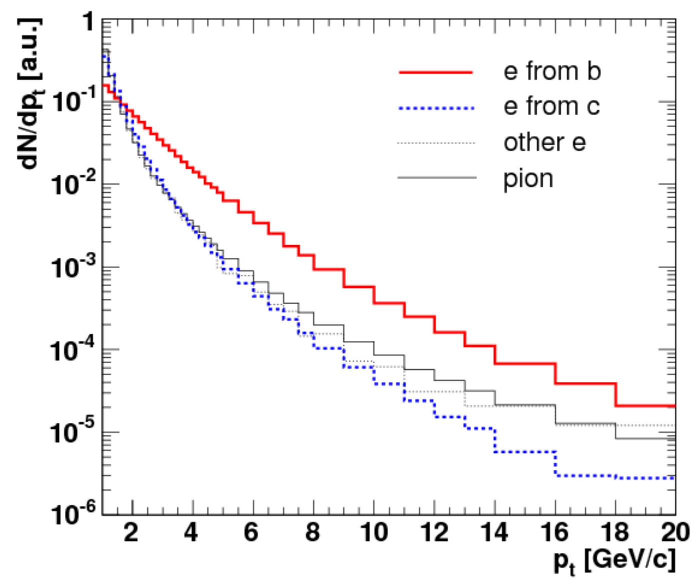


- Main **sources of background**
  - pions misidentified as electrons
  - charm decay electrons
  - Dalitz decays
  - photon conversions
  - strangeness decays

e signal	e backg	π
0.4	**$\sim 10^3$**	**$\sim 10^4$**

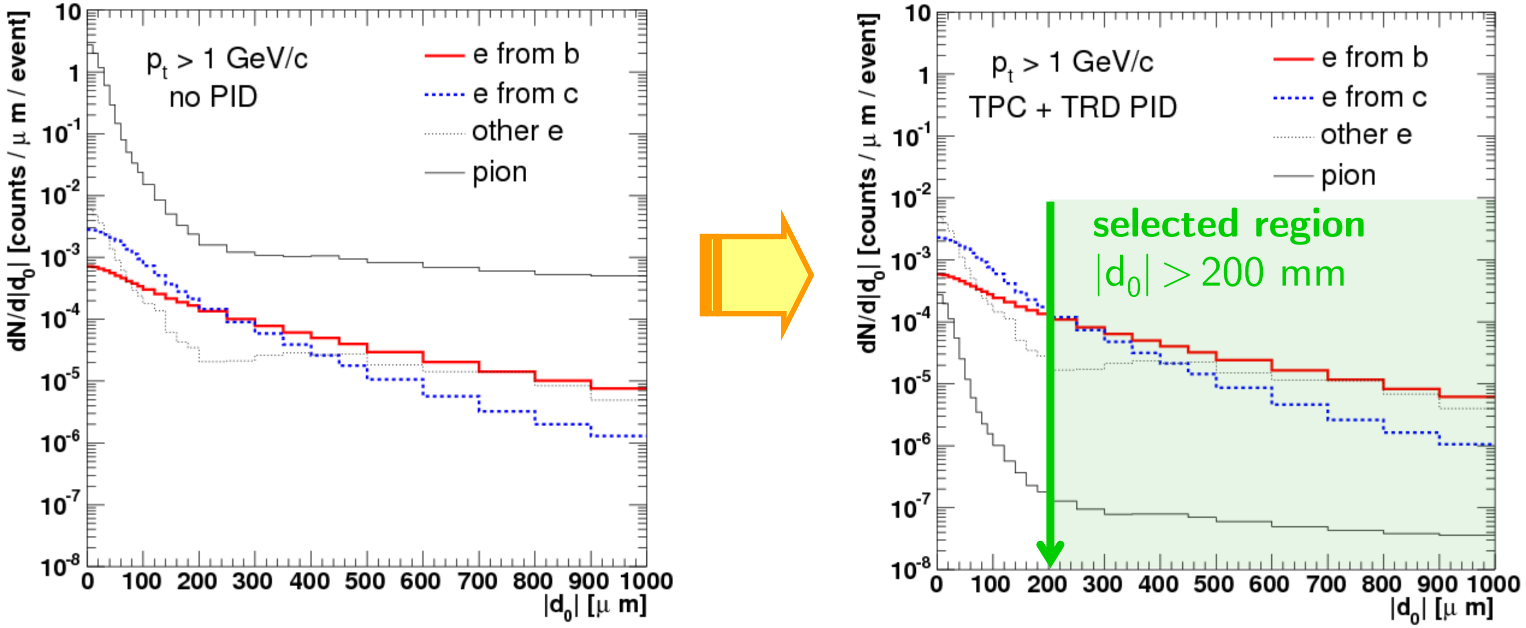
- Detection strategy
  - **electron ID** in TPC + TRD
  - **impact parameter** cut-off
    - B's $c\tau \sim 500\mu$m
  - **p_T** cut-off
    - large b-quark mass $\rightarrow$ hard spectrum





$B \to e\, X$
e identification in TPC + TRD

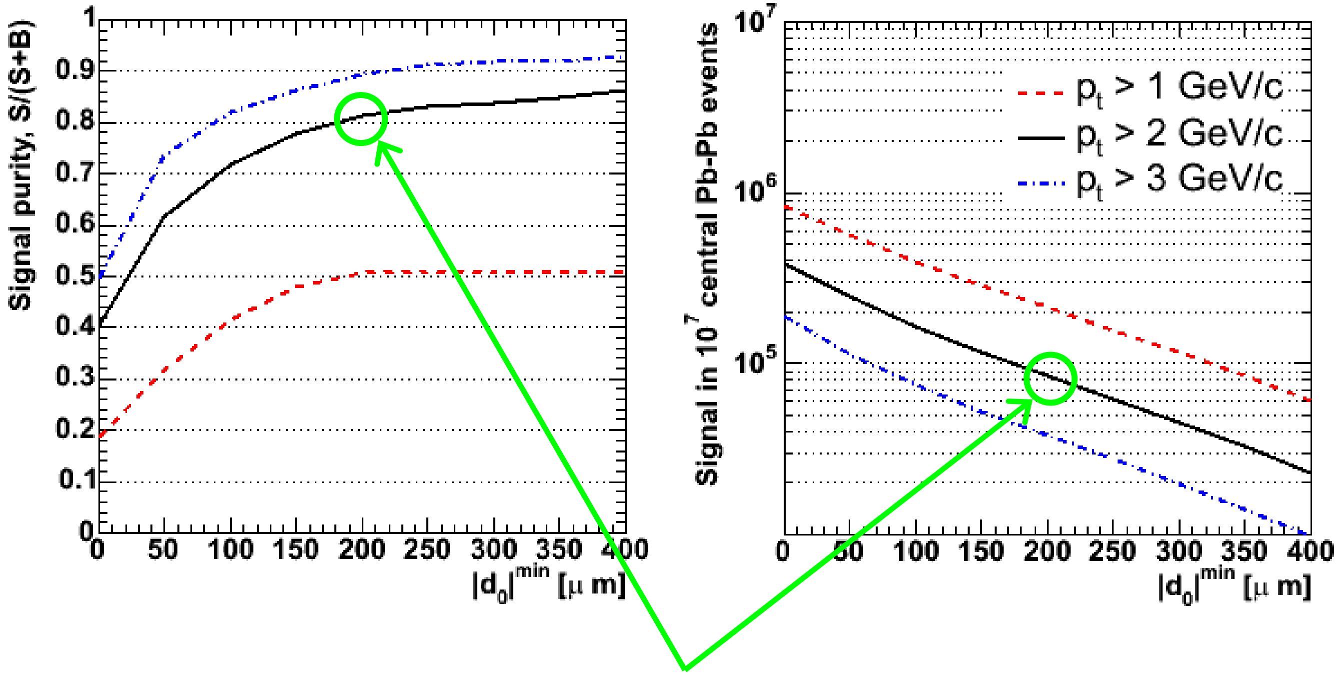
- **Charged pion contamination** reduced by **4 orders of magnitude** after electron ID w/ a combined **dE/dx** and **transition radiation** selection



$B \to e\, X$

Purity & statistics

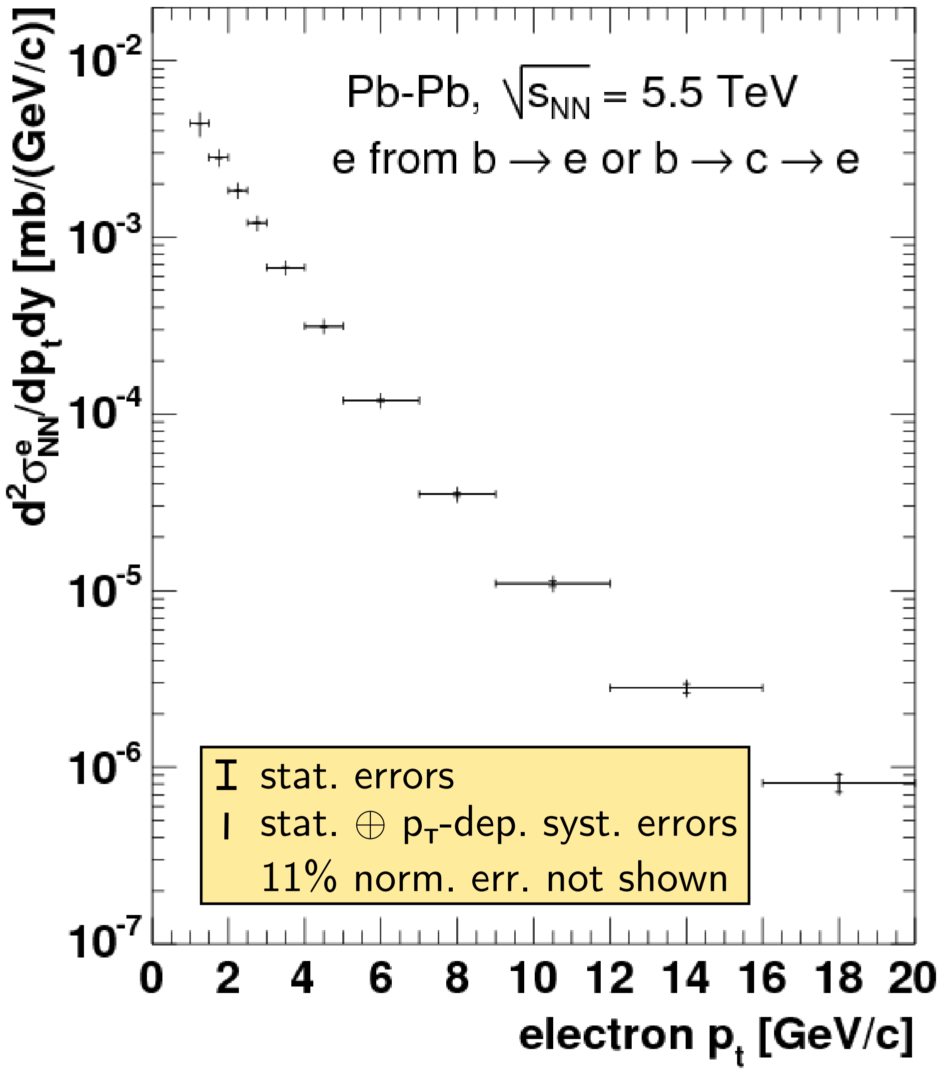
- **Signal-to-total ratio** & **expected statistics** in 10^7 central Pb-Pb events

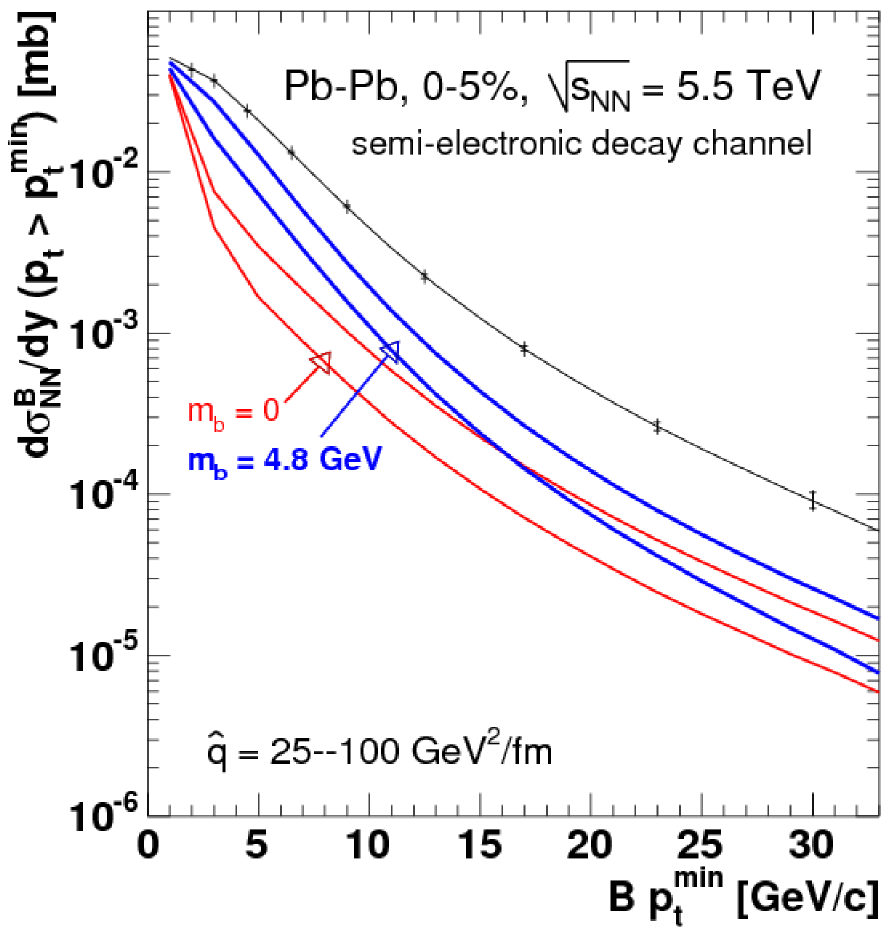


$p_T > 2$ GeV/c and $200 \leq |d_0| \leq 600\,\mu$m
80,000 electrons from B decays with a 80 % purity

$B \to e\,X$

p_T - differential cross sections





Beauty measurement using muons in central Pb-Pb collisions

- A representative fraction of b-quarks is detected in ALICE through their **semileptonic decays**

5 $b\bar{b}$ pairs / central Pb-Pb collision (5 %)

$$B^+ \to \overline{D^0}\, \ell_1^+ \nu_\ell, \quad \overline{D^0} \to \ell_2^- X'$$

$$\overline{B^0} \to D^+\, \ell_3^- \overline{\nu_\ell}, \quad D^+ \to \ell_4^+ X''$$

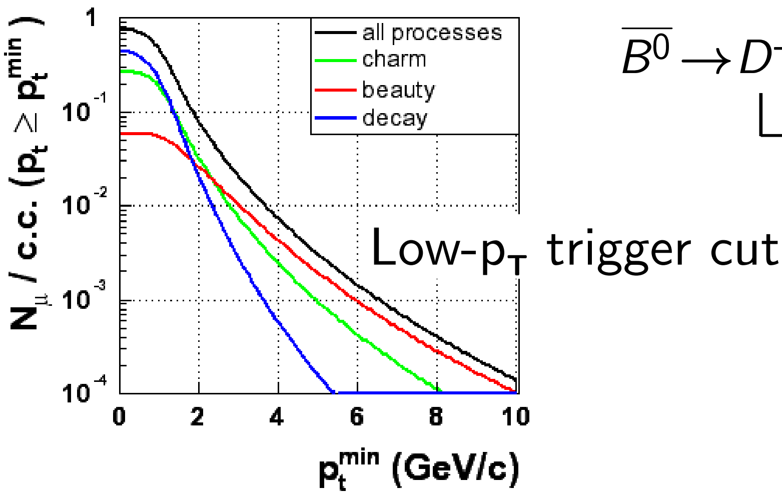
$$B^+ \to \overline{D^0}\, \ell_1^+ \nu_\ell, \quad \overline{D^0} \to \ell_2^- X'$$

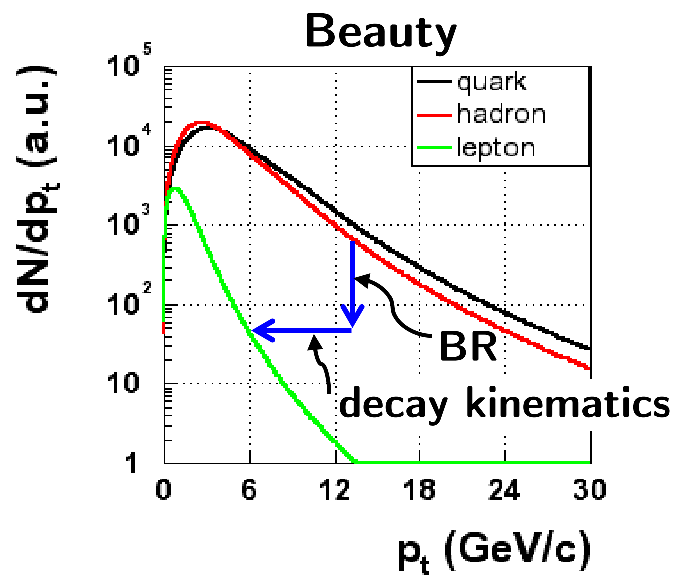
Large BR ~ 10 %

$$\overline{B^0} \to B^0 \to D^- \, \ell_3^+ \nu_\ell, \quad D^- \to \ell_4^- X''$$

oscillations

! correlated LS muon pairs from $b\bar{b}$ decays !



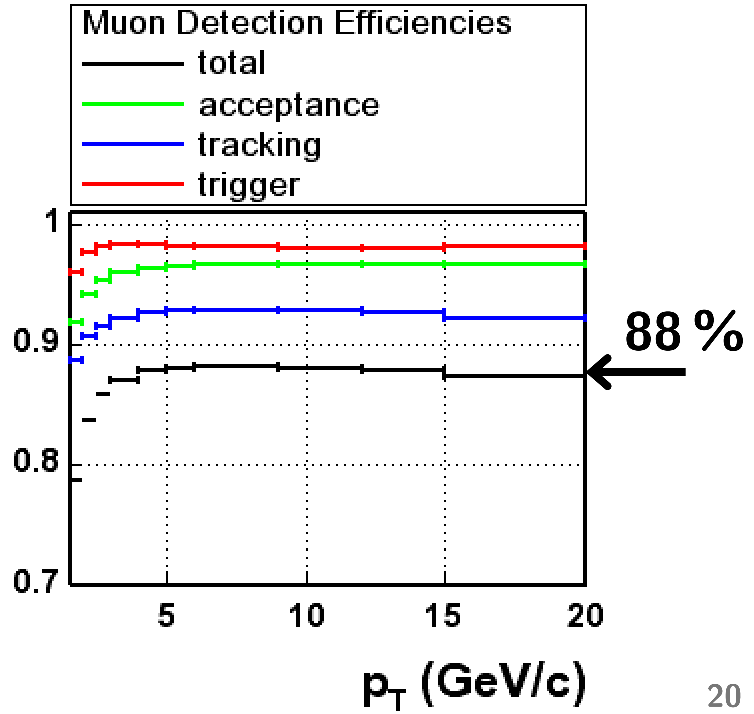


- How to **enhance b signal?**
  - muon p_T cut-off $\langle p_t^Q \rangle \sim m_Q$ & **harder fragmentation**

$B \to \mu\ X$
Muon detection

- Muons are **identified** with a **high *p* resolution ∼ 1-2 %** by their ability to **punch through** more than **15 interaction lengths** of materials
- Acceptance $\mathcal{A}_{\text{track}}$ is the fraction of **"trackable tracks"** (1/2 TC1-3, 3/4 TC4-5, 3/4 MT1-2)

	Charm		Beauty		
%	$\mu^{\pm}$	$\mu^{+}\mu^{-}$	$\mu^{\pm}$	$\mu^{+}\mu^{-}$	$\mu^{\pm}\mu^{\pm}$
$\mathcal{A}_{\text{geom}}$	13	3	12	5	3
$\mathcal{A}_{\text{track}}$	42	19	75	46	51
$\varepsilon_{\text{track}}$	27	8	62	29	34
$\varepsilon^{\text{Low}}_{\text{trigger}}$	13	2	53	17	23
$\varepsilon^{\text{High}}_{\text{trigger}}$	4	0.3	29	4	7



$B \to \mu X$

Invariant mass selection

$B^+ \to \overline{D^0} \mu^+ \nu_\ell$

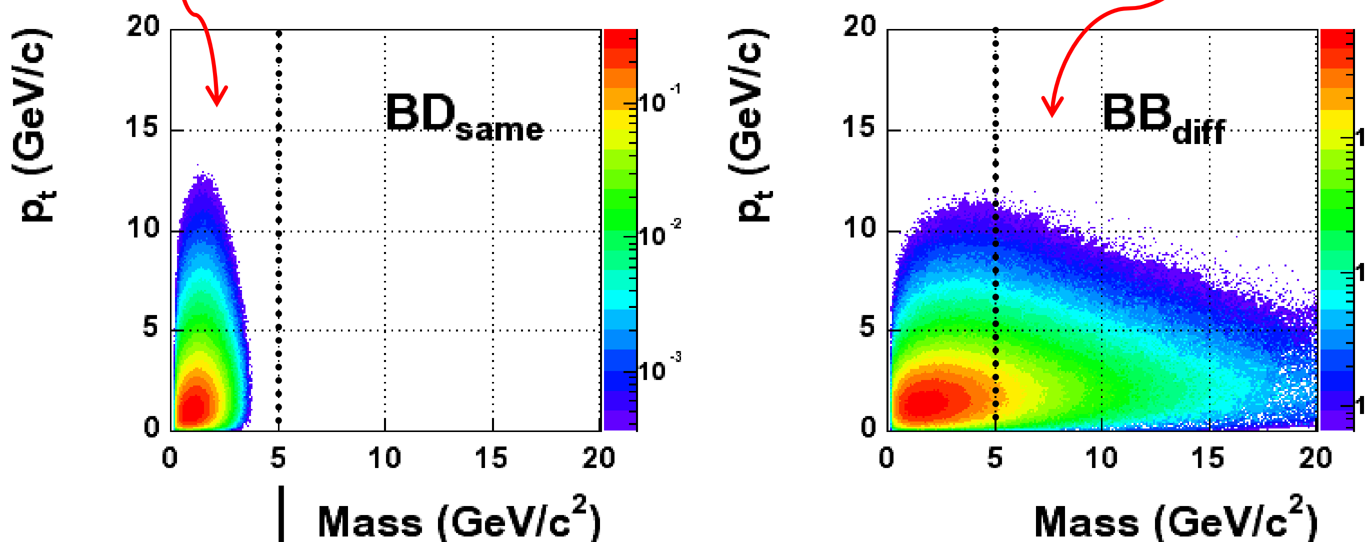
$\quad \hookrightarrow \mu^- X'$

$B^+ \to \mu^+$

$\overline{B^0} \to \mu^-$

Opposite sign dimuons

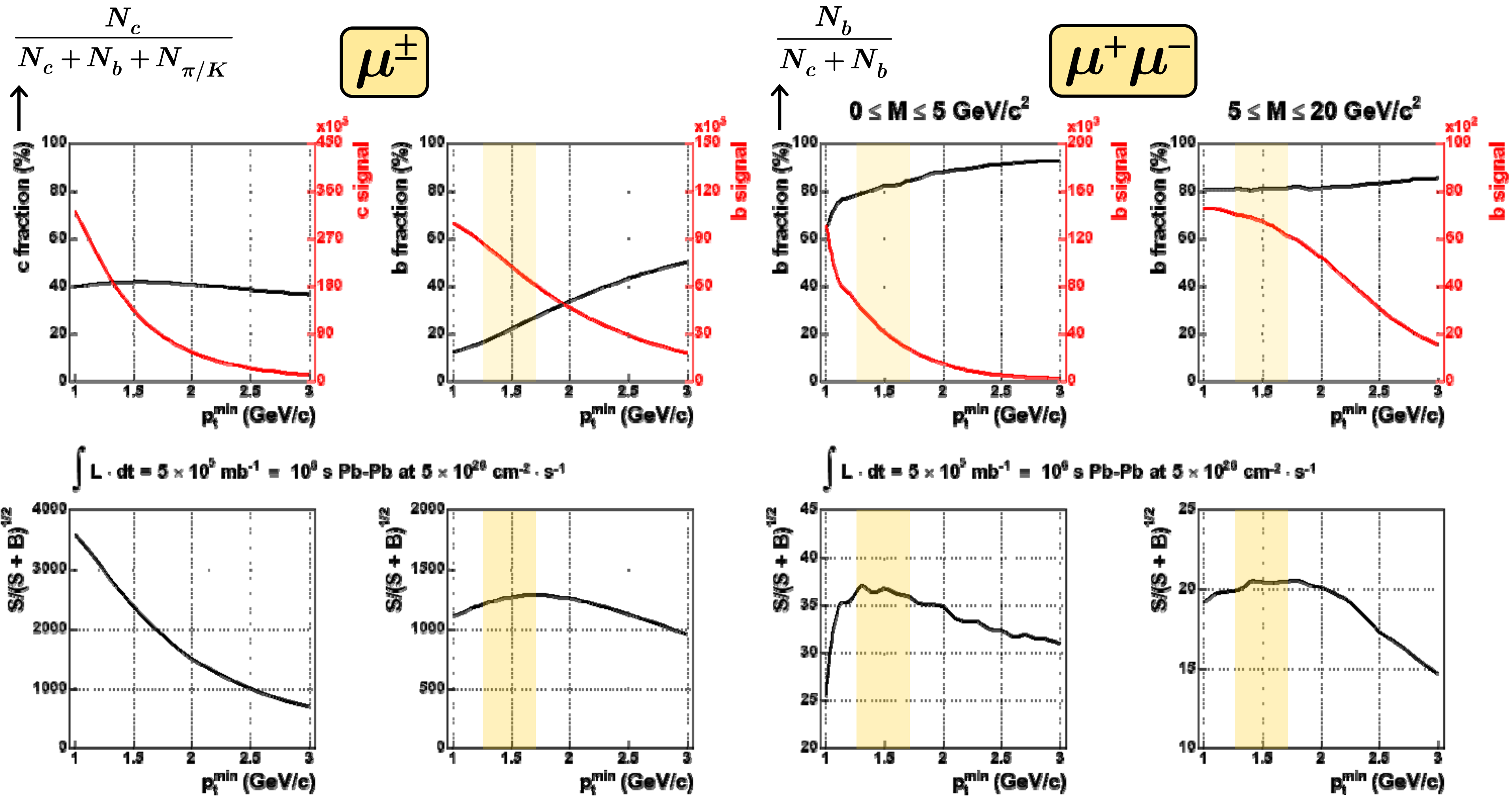
Sensitive to different processes according to the muon pair mass



Low Mass	$M \leq 5\ \mathrm{GeV}/c^2$	sensitive to BD_{same}
High Mass	$M \geq 5\ \mathrm{GeV}/c^2$	sensitive to BB_{diff}

$B \to \mu\ X$

Beauty signal selection

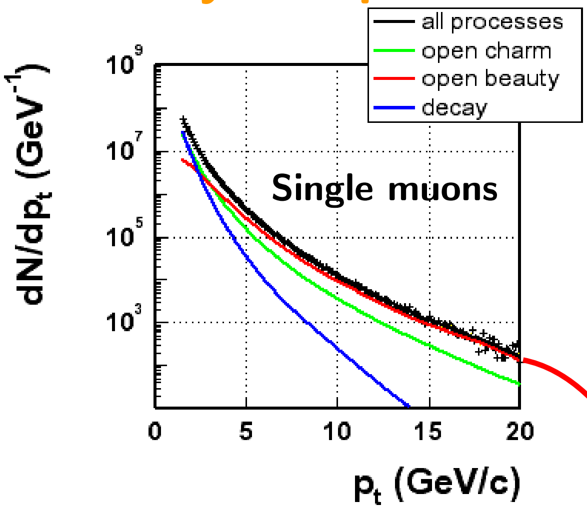


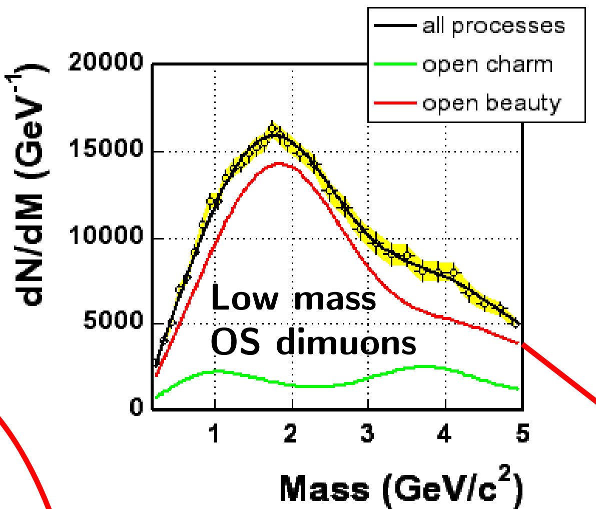
$p_T^{\mu} >$ **1.5** GeV/c is optimal to enrich the **3 data samples** (single μ & di-μ) with ***b* signal**

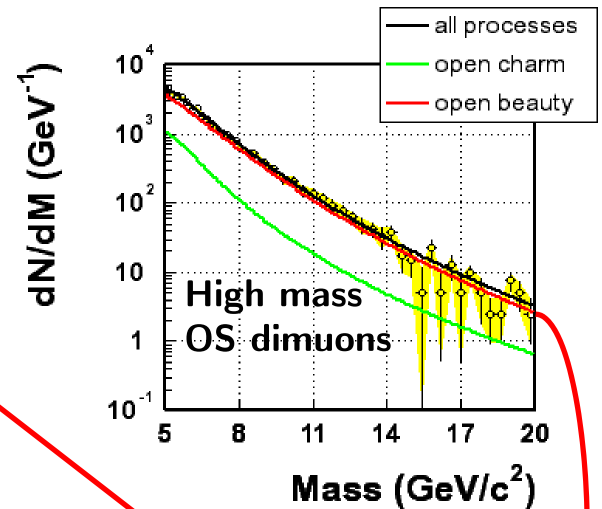
$B \rightarrow \mu X$

Muon raw yields

- Uses **3** different **data samples**
- Fits with fixed shapes from the Monte Carlo & **beauty amplitude** as the **only free parameter**







- ▷ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 6000$
- ▷ **No energy loss**
- ▷ **Centr. 0 – 5 %**
- ▷ **500 μb^{-1} collected**

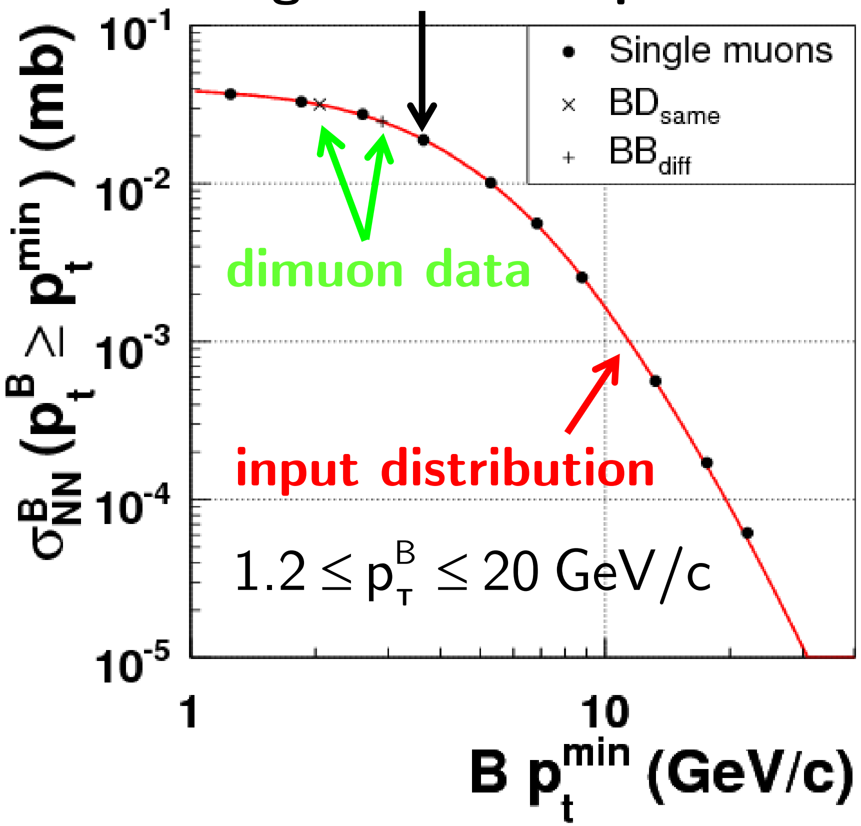
M [GeV/c^2]	0 - 5	5 - 20
$N_{\mu\mu}$ from $b\bar{b}$	41461 ± 1.91%	6983 ± 1.86%

p_T [GeV/c]	1.5 - 2	2 – 2.5	2.5 - 3	3 - 4	4 - 5	5 - 6	6 - 9	9 - 12	12 - 15	15 - 20
N_μ from b	$2.2\ 10^6$ ± 0.03%	$1.5\ 10^6$ ± 0.04 %	$0.9\ 10^6$ ± 0.06 %	$0.9\ 10^6$ ± 0.07%	$3.7\ 10^5$ ± 0.13%	$1.5\ 10^5$ ± 0.2%	$1.2\ 10^5$ ± 0.23%	$1.9\ 10^4$ ± 0.6%	$4.7\ 10^3$ ± 1.26%	$1.8\ 10^3$ ± 2.06%

$B \rightarrow \mu\ X$

b - meson inclusive cross section

“Measured data points” from single muon sample

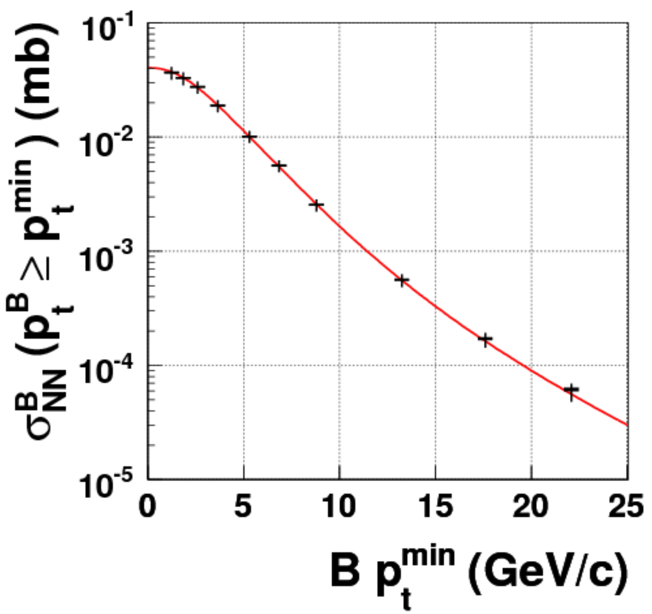


- Beauty inclusive production cross section **measured over a wide p_T region**
- **Any deviation** from pQCD scaled pp measurement could indicate **effects from dense medium**!

$B \to \mu X$

Systematic uncertainties

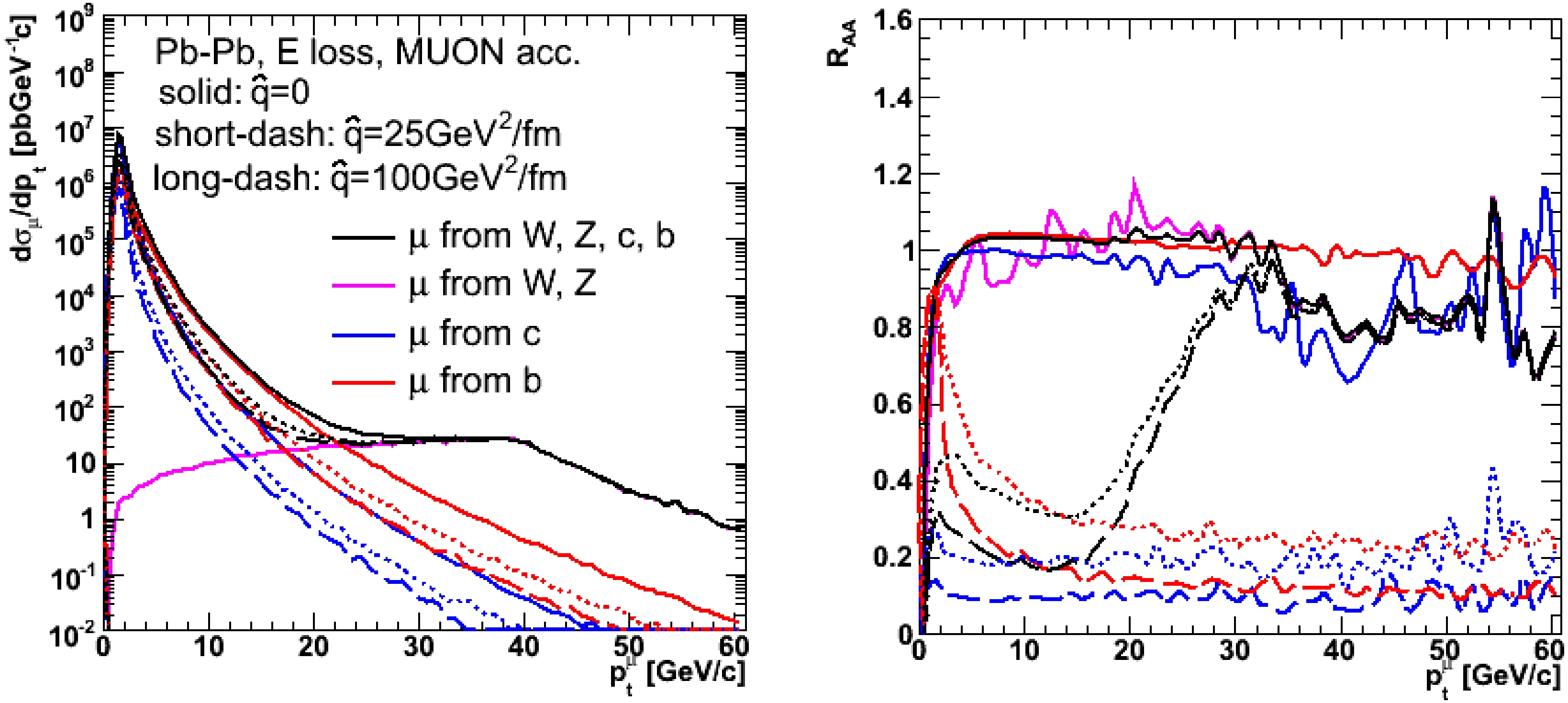
- Besides statistical uncertainties, **systematic errors** arising from **various sources** have been considered
  - Model for **signal**
    - include variations in pQCD scales, strength of nuclear shadowing
  - Model for **background**
    - varying the decay fraction by $\pm 10\,\%$
  - Efficiency
    - typical conservative **10 %**
  - Normalization to one NN collision



p_T[GeV/c]	1.5-2	1-2.5	2.5-3	3-4	4-5	5-6	6-9	9-12	12-15	15-20
Signal	4%	4%	3%	3%	2%	2%	3%	4%	8%	12%
Eff.	10%									
Total p_T-dep.	11%	11%	10%	10%	10%	10%	10%	11%	13%	16%
Decay	4%									
Norm.	9%									
Total p_T-indep	10%									

$B \to \mu\ X$

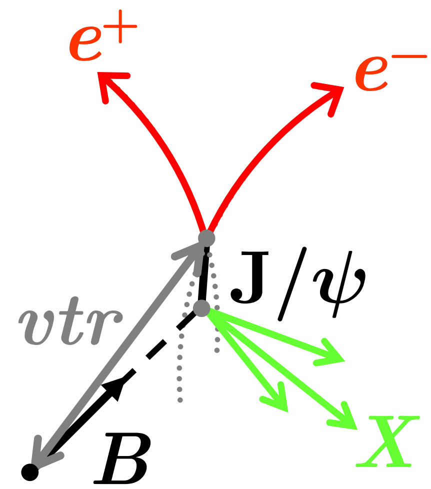
Effect of energy loss in Pb-Pb



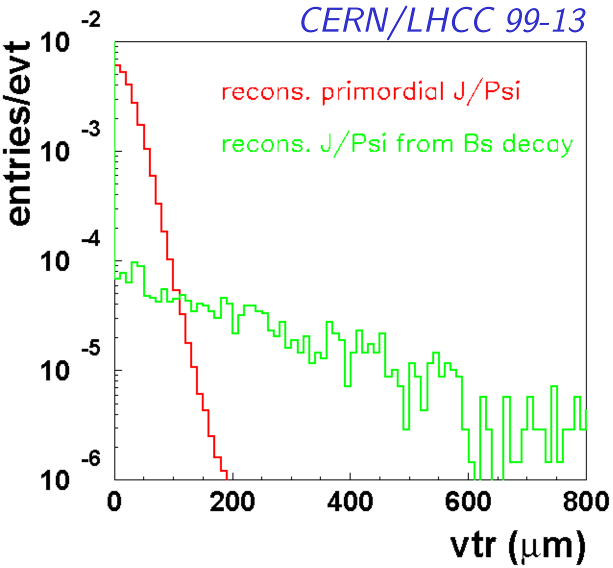
Andrea Dainese, 2nd ALICE Physics Week, Müenster

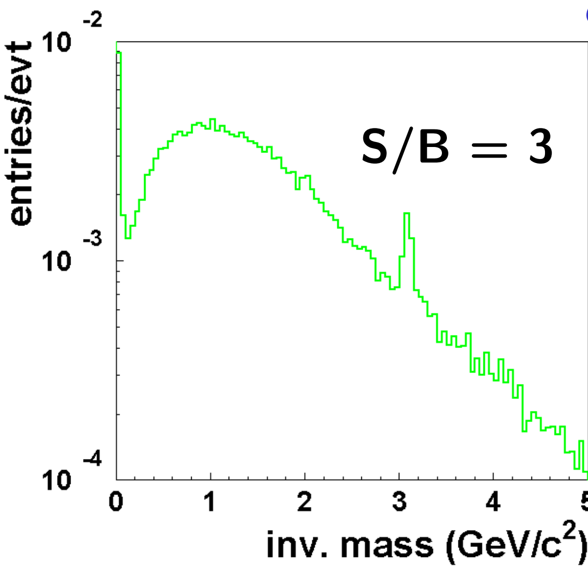
Measuring beauty production using secondary J/ψ from b-hadron decays

- $H_b \to \mathrm{J}/\psi\,(1\mathrm{S})\,X$
  $\mathrm{BR} =$ **1.16 ± 0.10%** (from PDG)
- N($H_b \to \mathrm{J}/\psi$) / N(prompt J/ψ) = **30 %**
- Needed to be disentangled for **QGP direct J/ψ suppression** signature
- Also sensitive to ***b*-quark quenching**

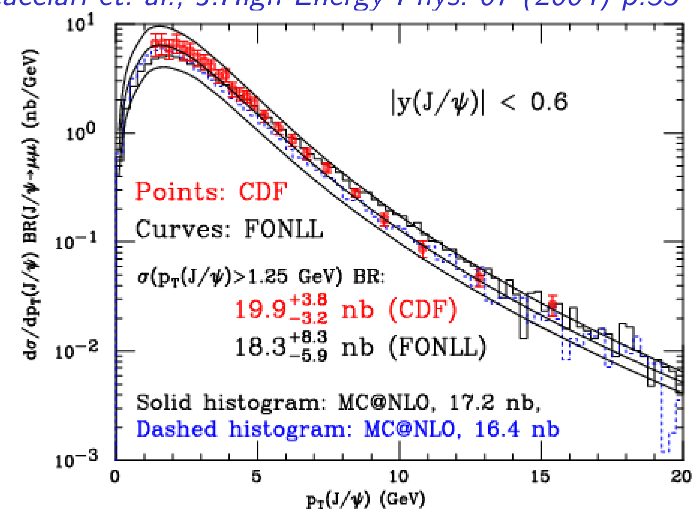


CERN/LHCC 99-13





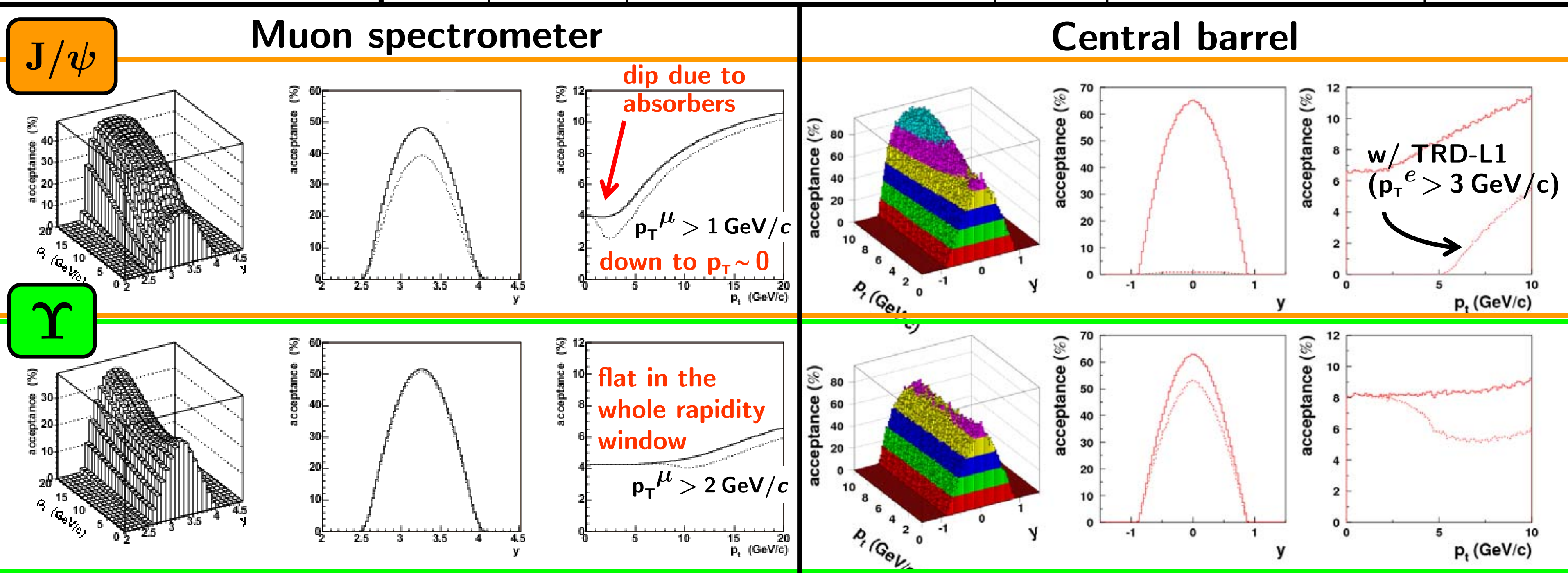
Cacciari et. al., J.High Energy Phys. 07 (2004) p.33



Quarkonium detection in ALICE

Two complementary measurements

	State	y range	$x^{\text{Pb-Pb}}$ range	$\mathcal{A}$	ε p-p	ε Cent. Pb-Pb	$\sigma_{M_{\ell^+\ell^-}}$ (MeV/c^2) p-p	$\sigma_{M_{\ell^+\ell^-}}$ (MeV/c^2) Cent. Pb-Pb
Muon spectrometer $\mu^+\mu^-$ ▷ $B = 0.7$ T	J/ψ	$-4 \le y \le -2.5$	$2.3\times10^{-4} \le x_{1,2} \le 1.4\times10^{-3}$	0.0446	0.67	0.70	72	70
	Υ		$7.0\times10^{-4} \le x_{1,2} \le 4.2\times10^{-3}$	0.0441	0.89	0.83	99	115
Central barrel e^+e^- ▷ e id w/ TRD ($p > 1$ GeV/c) ▷ p meas. w/ ITS + TPC + TRD ▷ $B = 0.5$ T	J/ψ	$\|y\| \le 0.9$	$7.0\times10^{-3} \le x_1 \le 3.1\times10^{-2}$ $1.0\times10^{-5} \le x_2 \le 4.6\times10^{-5}$	0.295				90
	Υ		$2.1\times10^{-2} \le x_1 \le 9.3\times10^{-2}$ $3.1\times10^{-5} \le x_2 \le 1.4\times10^{-4}$	0.266				33



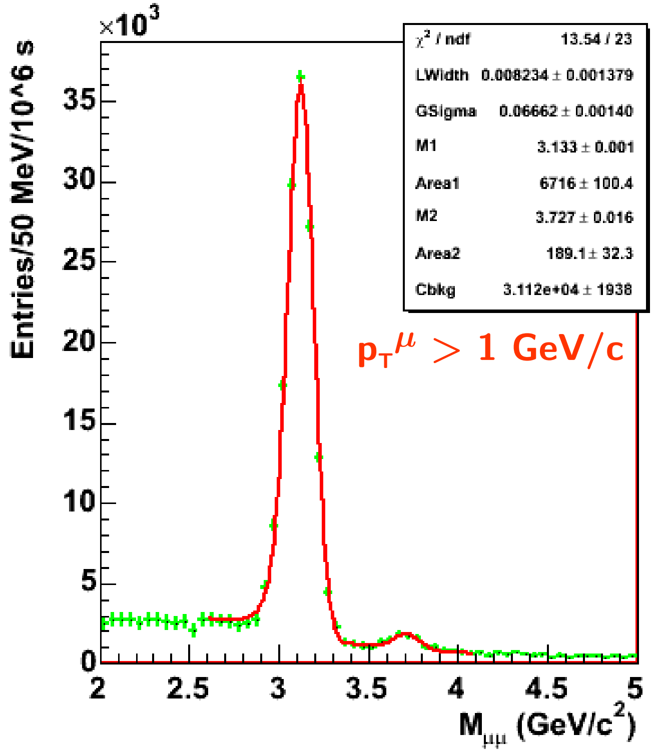
Quakonium detection in ALICE

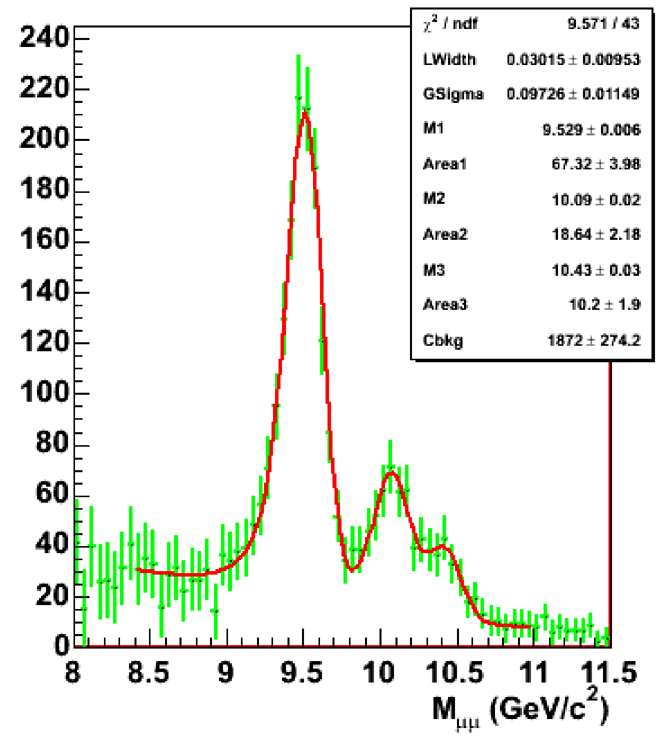
Di-muon spectra in central Pb-Pb

- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 6000$
- Assuming no suppression/enhancement
- Centr. $0-5$ %
- 500 μb^{-1} collected

$\pm 2\sigma$ around the resonance peak

State	S($\times 10^3$)	B ($\times 10^3$)	S/B	S/(S+B)$^{1/2}$
J/ψ	130	680	0.20	150
ψ'	3.7	300	0.01	6.7
Υ	1.3	0.8	1.7	29
Υ'	0.35	0.54	0.65	12
Υ''	0.20	0.42	0.48	8.1





Quakonium detection in ALICE

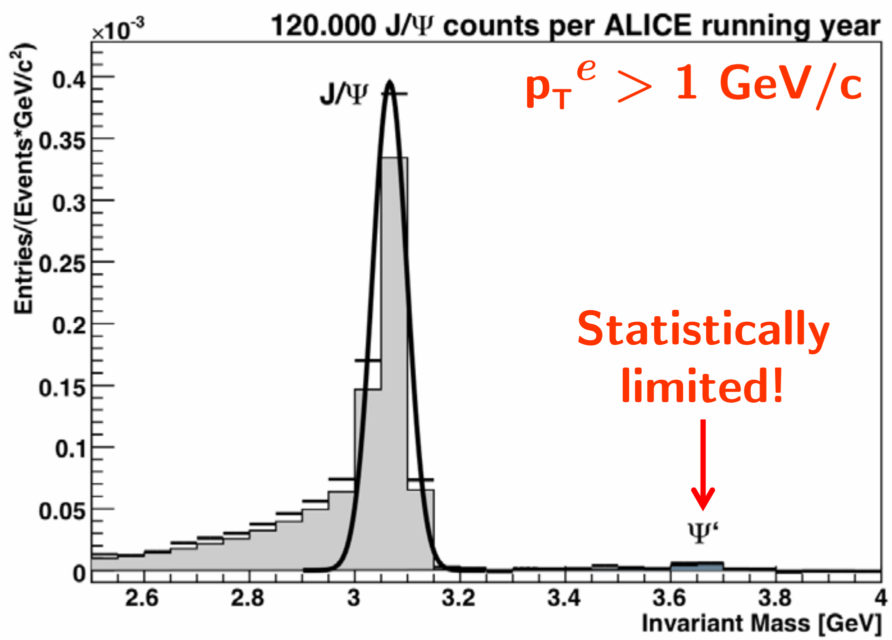
Di-electron spectra in central Pb-Pb

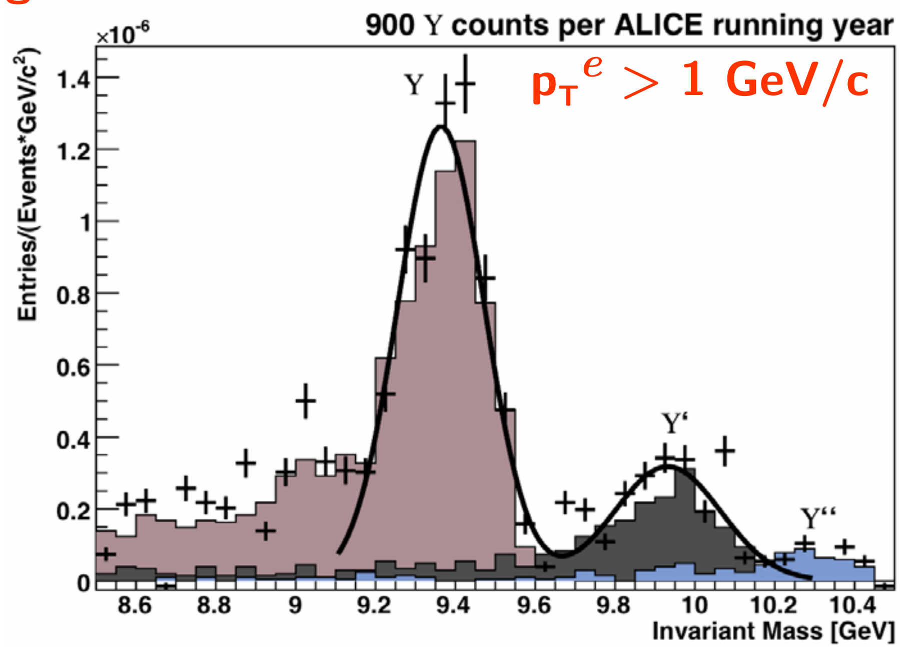
- ▷ $dN_{ch}/dy = 3000$
- ▷ Centr. $0-10$ %
- ▷ 500 μb^{-1} delivered
- ▷ Effective readout rate 200 Hz

$\pm 1.5\sigma$ around the resonance peak

State	S($\times 10^3$)	B ($\times 10^3$)	S/B	S/(S+B)$^{1/2}$
J/ψ	121.1	88.2	1.4	265
Υ	1.3	0.8	1.6	28
Υ'	0.46	0.8	0.6	13

Combinatorial background subtracted





Summary & Outlook

- LHC is definitely a **"hard probes factory"**
  - ALICE despite "non-dedicated" has a **full heavy flavour physics program**
    - ❢ Performance fulfill requirements in the very **demanding** environment of **central Pb-Pb collisions**
      - **The large available statistics** of both hadronic & leptonic heavy flavour decays is reconstructed w/ high **tracking efficiency** & **resolution** and good **particle identification**
      - Heavy flavoured hadron production **cross sections** are assessed w/ **small errors** opening promising perspectives for the study of **heavy quark dynamics in a dense medium**
    - ❢ Measurements presented here for Pb-Pb are also **planned in p-p** with even **better expected performance** (due to lower occupancy) notwithstanding pileup
      - First physics w/ **p-p collisions** ($\sqrt{s} = 0.9$ TeV) is currently under **intensive preparation**...

...new avenues to be investigated

- muon pair **correlations**, a powerful probe of **higher orders**
- **multi-muon** topologies
- ***b*-jet tagging** w/ soft electrons

The countdown to the first collisions has already started... Get ready for **first pp runs!**