Charm and Bottom Production Measurements at the LHC

Moriond QCD 2008

12 March 2008

La Thuile

Wolfgang Walkowiak

on behalf of the ATLAS and CMS collaborations

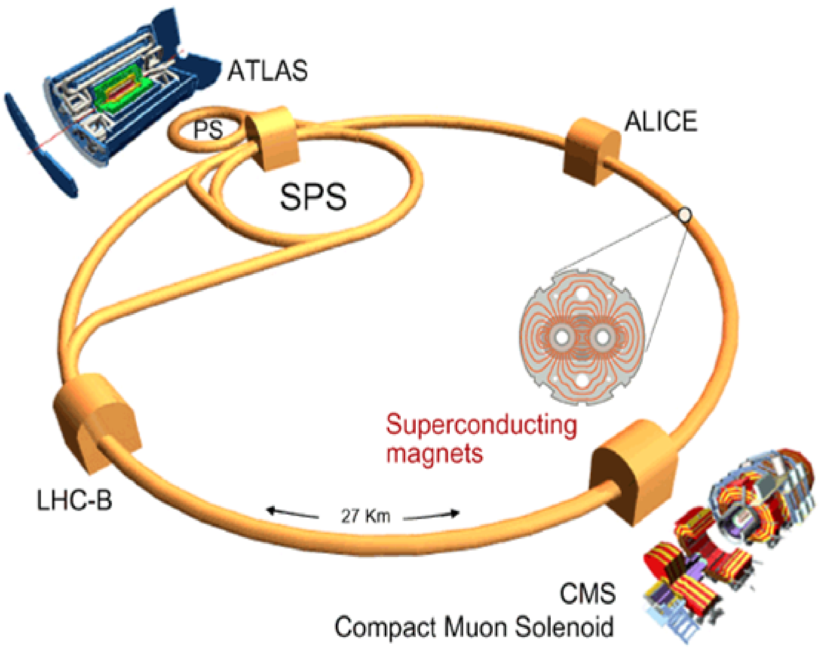
walkowiak@hep.physik.uni-siegen.de

UNIVERSITÄT SIEGEN

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

ATLAS and CMS at the LHC

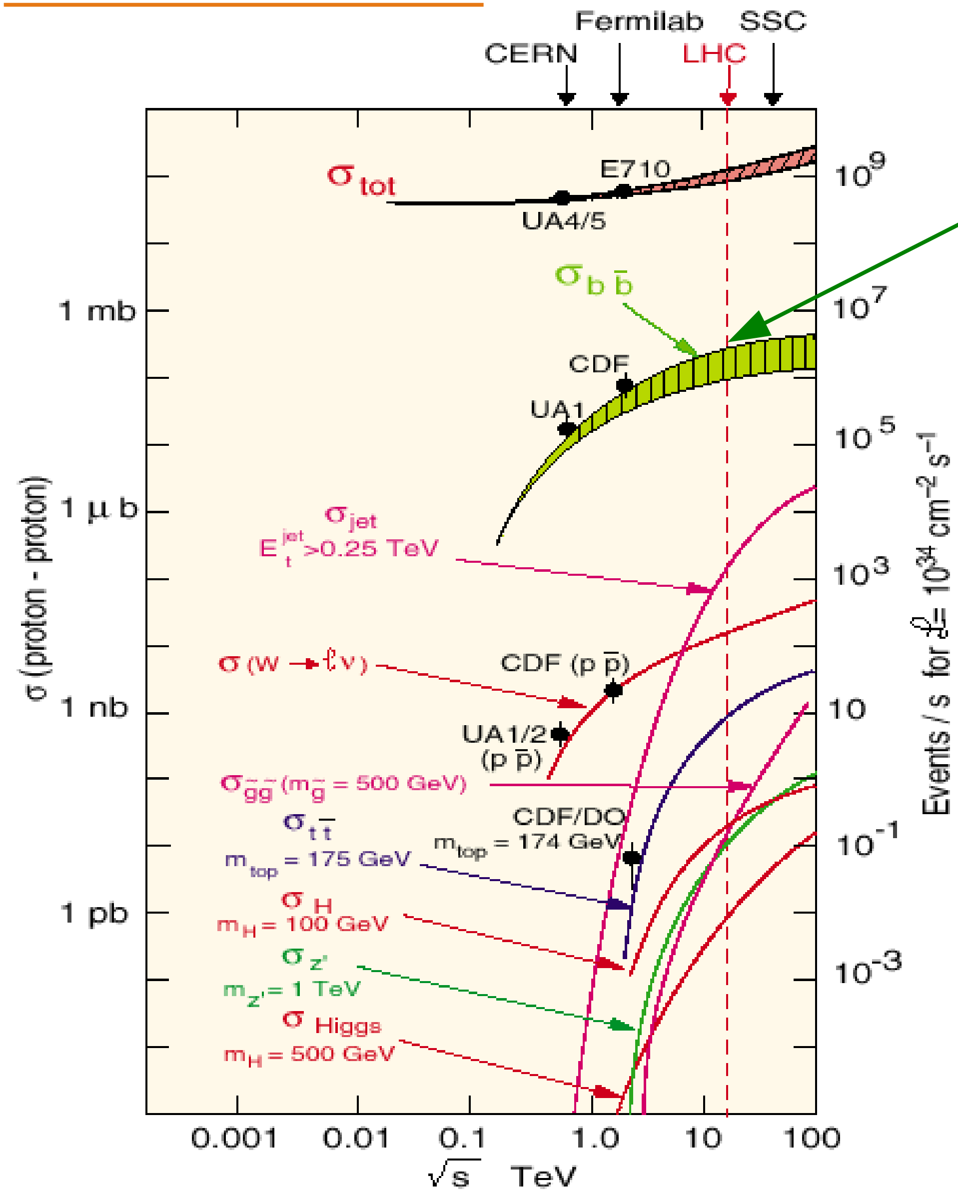


Large Hadron Collider

- E_{CM} = 14 TeV (pp)
- L = 10^{34} $cm^{-2}s^{-1}$ (design)
  ~ 100 fb^{-1}/year
  40 MHz pp bunch crossing rate
- L = 10^{33} $cm^{-2}s^{-1}$ („low“ luminosity)
  ~ 10 fb^{-1}/year
- L = 10^{31} – 10^{32} $cm^{-2}s^{-1}$
  („early“ running)

- Completion expected for 2008!

Beauty Production at LHC



- $\sigma_{b\bar{b}} \sim 500\ \mu b$
- 1 $b\bar{b}$ in 100 pp collisions
- 2 x 10^{12} $b\bar{b}$/year @ L = 10^{33} cm^{-2} s^{-1}

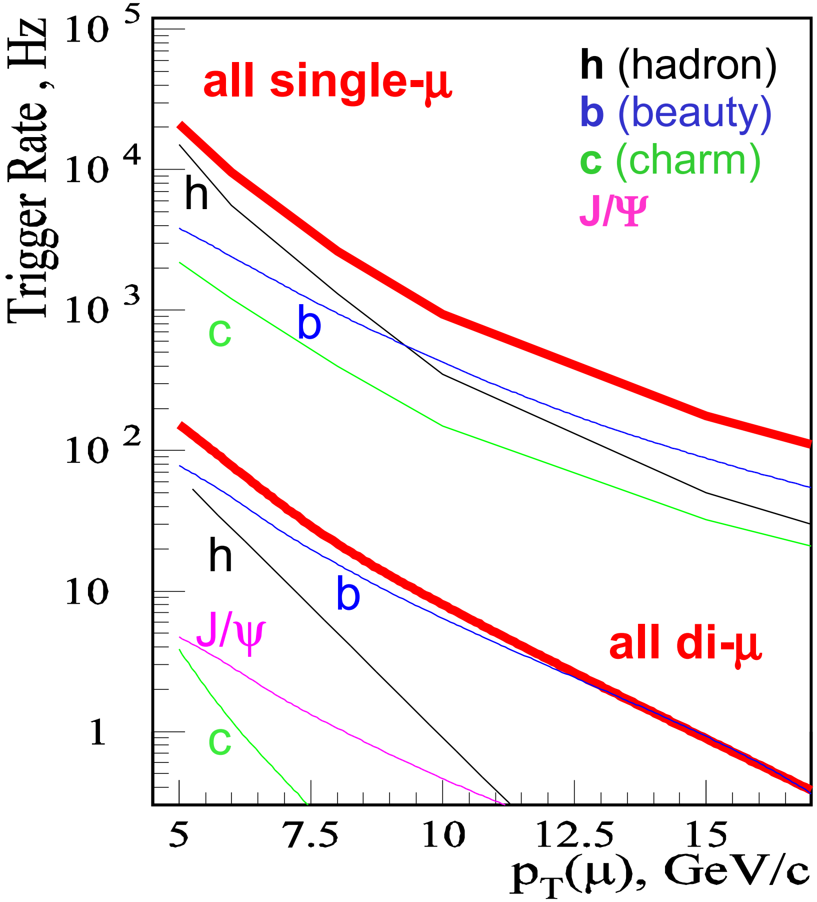
Beauty and Charm Production at LHC

Questions:

- How many **$b\bar{b}$ at 14 TeV**?
  - Inclusive b production with μ, b-jet, μ-in-b-jet, etc.
  - Measure $\sigma_{b\bar{b}}$, $d\sigma/dp_T$, $d\sigma/d\eta$
- From where?
  - Correlated $b\bar{b}$ production with
    $J/\psi+\mu$, $\mu+\mu$, μ+b-jet, etc.
  - Measure $d\sigma/d(\Delta\phi)$ to separate three primary production mechanisms
- How many **prompt quarkonia at 14 TeV**?
  - Measure $\sigma_{J/\psi}$, σ_{Υ}, $d\sigma/dp_T$, $d\sigma/d\eta$
- Which quarkonia production model?
  - Measure polarization of J/ψ and Υ
  - Measure J/ψ and Υ supression in heavy ion collisions

Trigger Strategies for B-physics

ATLAS μ rates for 10^{33} $cm^{-2}s^{-1}$



ATLAS

- Level 1
  - single μ (p_T > 6, 8, 10, 20 GeV)
  - di-μ (p_{T1} > 6 GeV, p_{T2} > 4 GeV)
- Level 2: (starting from LVL1 RoI)
  - $D_s \rightarrow \phi\,\pi$ (hadronic final states)
  - $J/\psi \rightarrow e^+e^-$, $K^*\gamma$, $\phi\,\gamma$ (e/γ final states)
  - $J/\psi \rightarrow \mu^+\mu^-$ ($\mu^+\mu^-$ final states)
- Event Filter (full detector information)

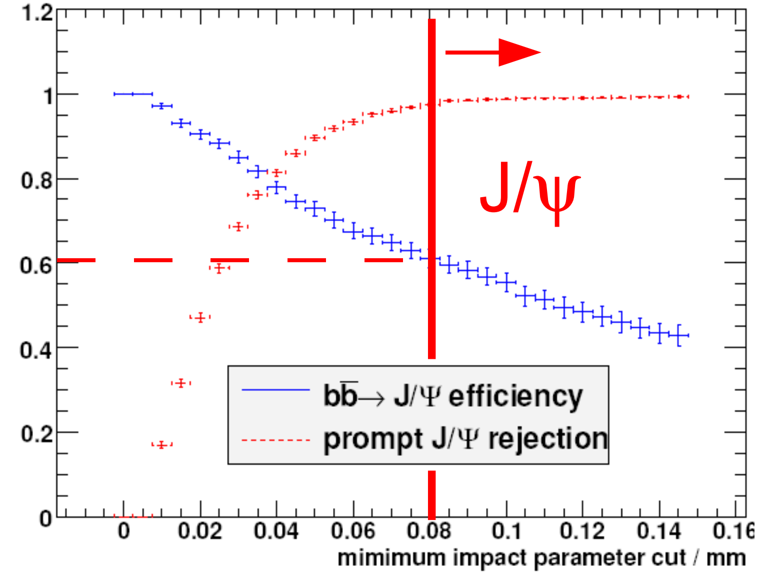
CMS

- Level 1
  - single μ (p_T > 14 GeV)
  - di-μ (p_T > 3 GeV)
- HLT
  - inclusive b, c trigger with b-tagging
  - partial reconstruction of exclusive B decays

Inclusive b Cross Section (low p_T)

Strategy 1: $b\bar{b} \rightarrow J/\psi(\mu^+\mu^-)\,X$

- Di-muon J/ψ trigger
  ($p_T(\mu_1) > 6$ GeV, $p_T(\mu_2) > 4$ GeV)
- Detached J/ψ vertex
- $\varepsilon_{b\bar{b}\rightarrow J/\psi X}$ ~ 60%
  $r_{\text{prompt } J/\psi}$ ~ 100%



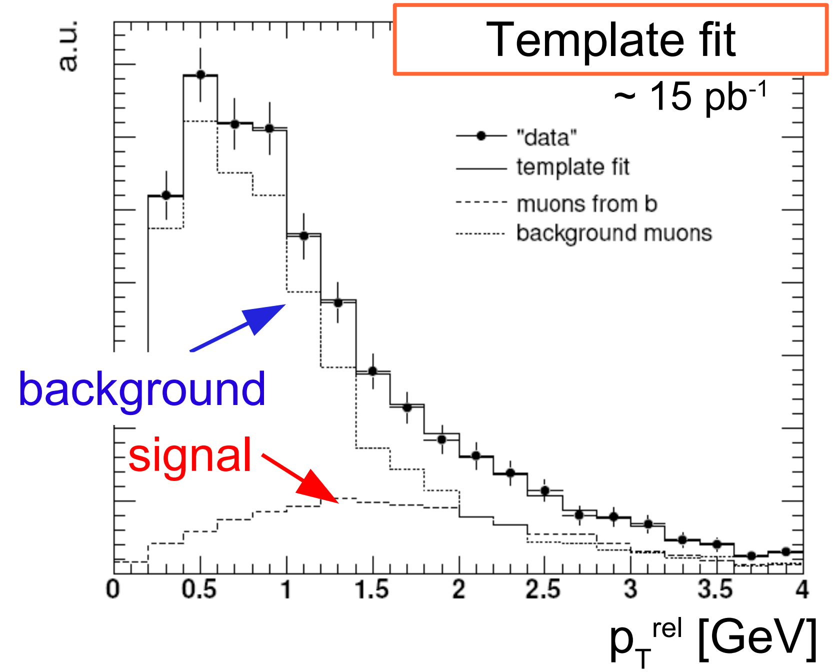
leading μ impact parameter cut [mm]

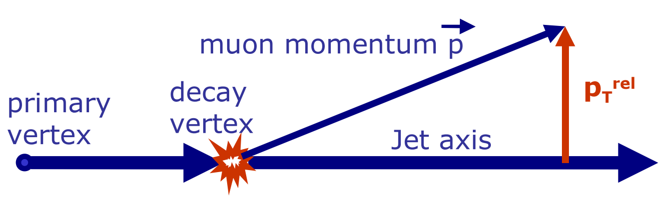
Inclusive b Cross Section (low p_T)

Strategy 2: μ + b-jet based

- Single-muon & jet RoI trigger ($p_T(\mu)$ > 6 GeV), ε_b^{trig} = 13.5%
- b-jet weight tagging and jet-μ assignment ($\Delta R < 0.5$), ε_b^{rec} = 85%

$\Delta R = \mathrm{sqrt}(\Delta\phi^2+\Delta\eta^2)$





Template fit:

- b-fraction: 23 ± 2 %
  ($b \rightarrow \mu$ & $b \rightarrow c \rightarrow \mu$)
- background: 77 ± 4 %
  ($c \rightarrow \mu$ & π, $K \rightarrow \mu$)
- ➔ Agrees well with MC input

Inclusive b Production Cross Section

- Estimated time for O(1%) measurement (statistical error only)

	channel	specific luminosity [$cm^{-2}s^{-1}$] $\mathscr{L} = 10^{31}$	$\mathscr{L} = 10^{32}$	$\mathscr{L} = 10^{33}$
1	$b\bar{b} \to J/\psi(\mu 6 \mu 4) + X$ with 2 μ LVL1	1 year (PS 1)	1 month (PS 1)	1 month (PS 10)
2	$b\bar{b} \to \mu(6) + b - \text{jet} + X$	1 month (PS 10)	1 month (PS 100)	1 month (PS 1000)

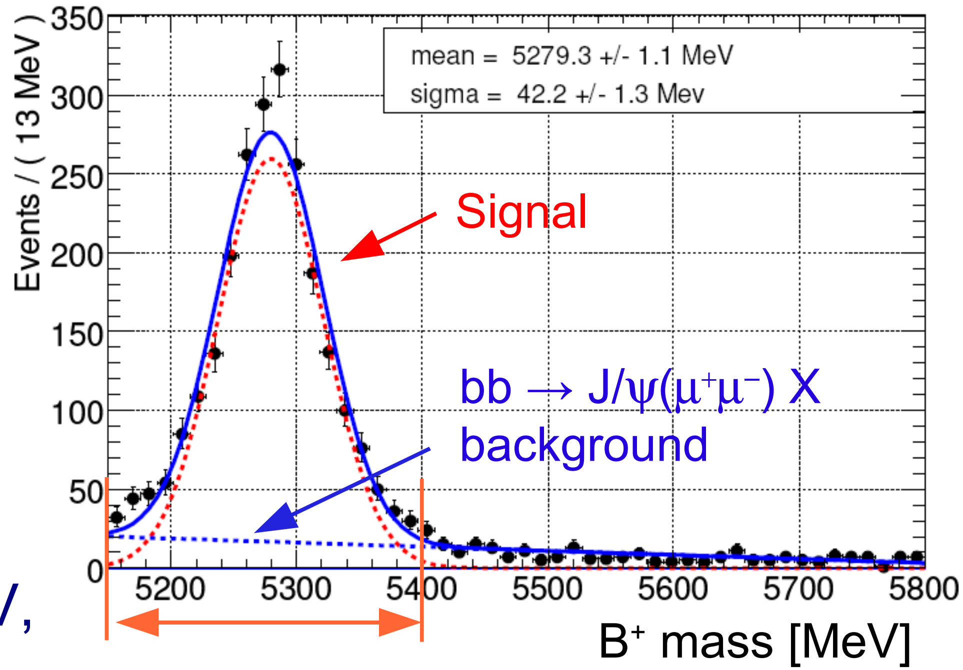
[Trigger pre-scale factors (PS) applied.]

- Typically one month of data

- Systematical error ~ 9 % (with 300 pb^{-1})

b Cross Section ($B^+ \rightarrow J/\psi\, K^+$)

- Reference channel
- Di-μ J/ψ trigger, $\varepsilon_{J/\psi}^{trig} \sim 82\%$
- J/ψ: ($p_T(\mu_{1,2}) > 6$ GeV, 3 GeV) displaced vertex $\lambda > 100$ μm $\varepsilon_{J/\psi}^{rec} = 55.8\%$
- B^+: J/ψ + 1 track ($p_T > 1.5$ GeV, large impact parameter) displaced vertex $\lambda > 100$ μm mass in ±120 GeV around m_{B^+}
- $\varepsilon^{total} = 29.8 \pm 0.84$ % $\sigma(m_{B^+}) = 42.2 \pm 1.3$ MeV



With 13.2 pb^{-1}:

- ~ 2100 signal events
- cross section to ~ 3 %
- mass resolution ~ 3 %
- signal lifetime to ~ 2 %

Inclusive b-jet Cross Section

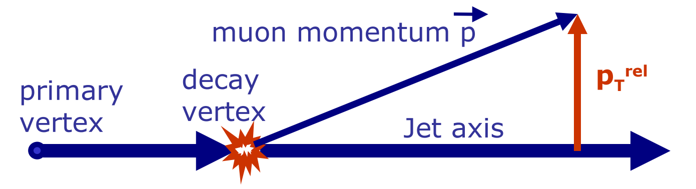
[CMS Note 2006/120]

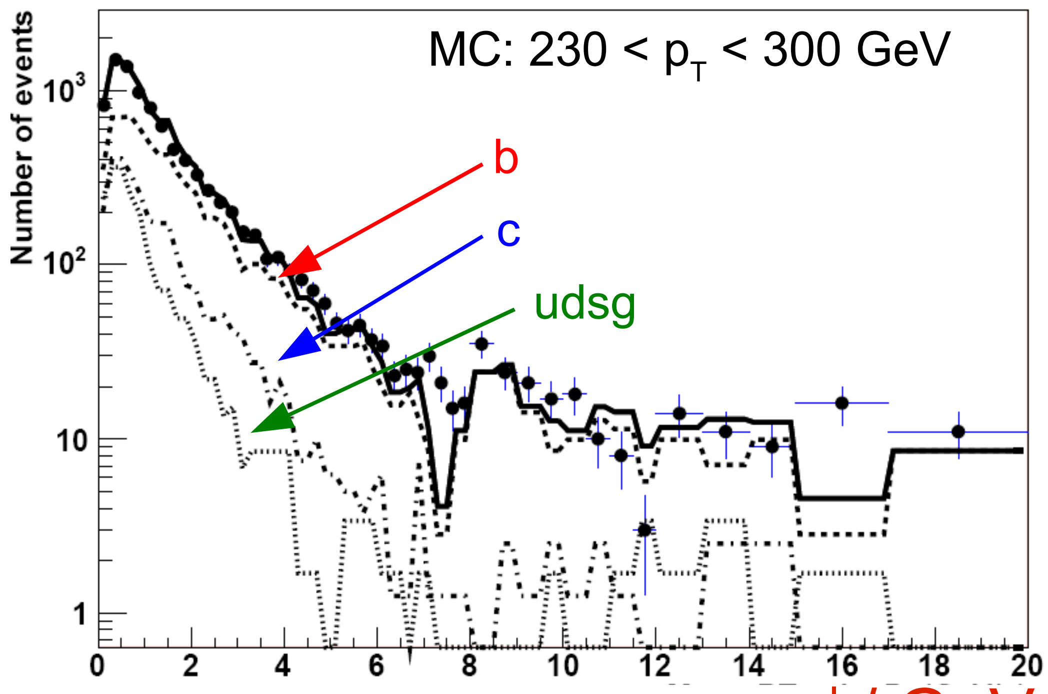
- Trigger:
  - L1: „single muon“
    $p_T^{\mu} > 14$ GeV, $|\eta| < 2.1$
    $\varepsilon = 18$ %
  - HLT: „muon + b-jet“
    $p_T^{\mu} > 19$ GeV, $E_T^{jet} > 50$ GeV, $|\eta| < 2.4$
    $\varepsilon = 60$ %
- Offline selection:
  - b-tagged jet
    $E_T^{jet} > 50$ GeV, $|\eta| < 2.4$
    $\varepsilon = 65$ % (barrel), 55 % (endcap)
  - muon associated to b-tagged jet
    $\varepsilon = 75$ %

➜ $\varepsilon^{tot} \sim 5$ %
16 mio. $b\bar{b}$ events/10 fb^{-1}

Inclusive b-jet Cross Section

- Shape template fit in p_T^{rel}





[CMS Note 2006/120]

- Fit reproduces fractions:

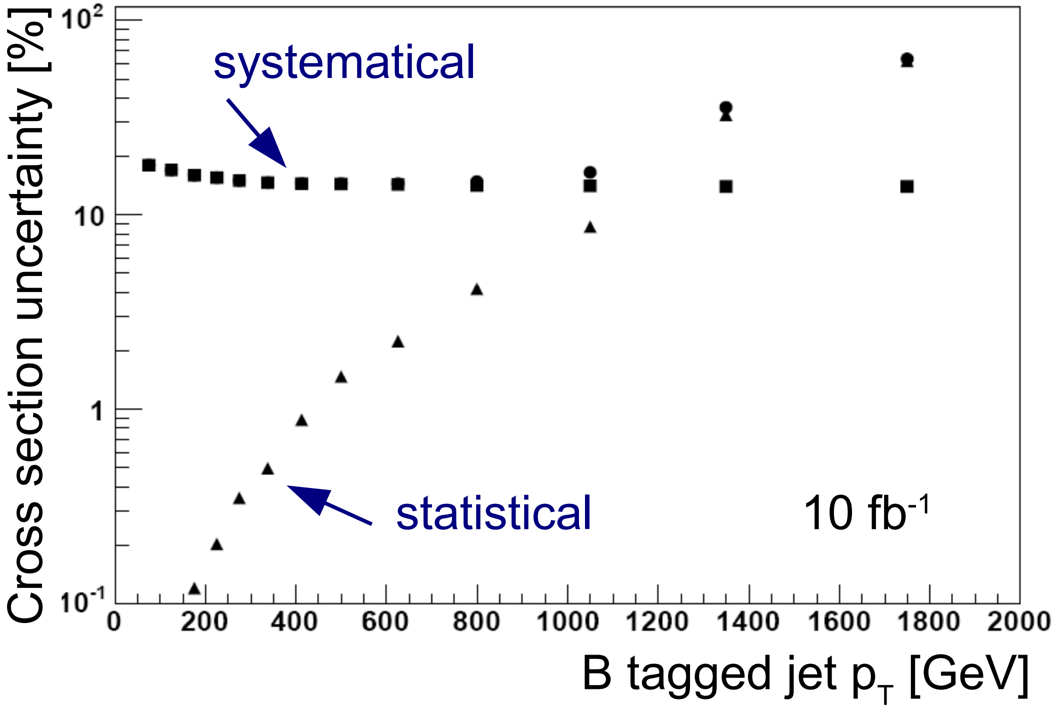
b	56%
c	26%
udsg	18%

- ~ 9400 events ($10\ fb^{-1}$)

Inclusive b-jet Cross Section

[CMS Note 2006/120]

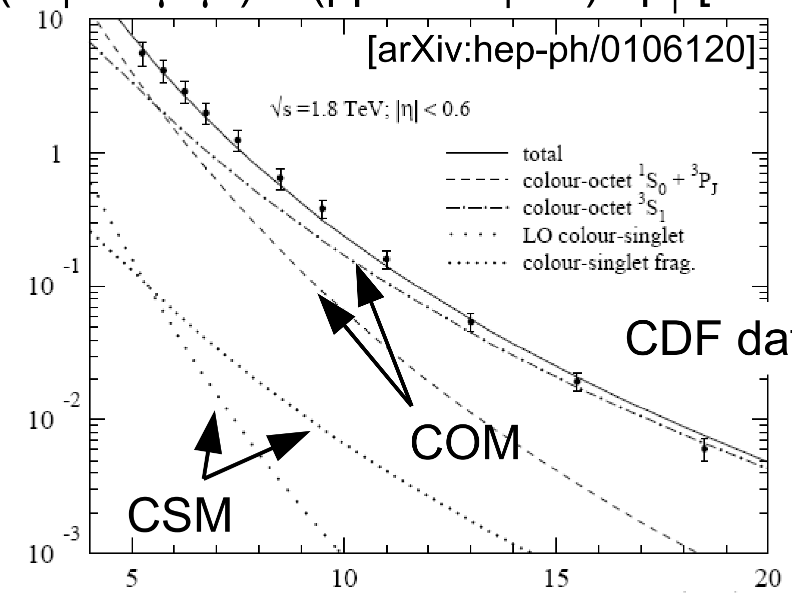
- B-hadron
  $p_T > 50$ GeV
  $|\eta| < 2.4$
- p_T reach up to 1.5 TeV

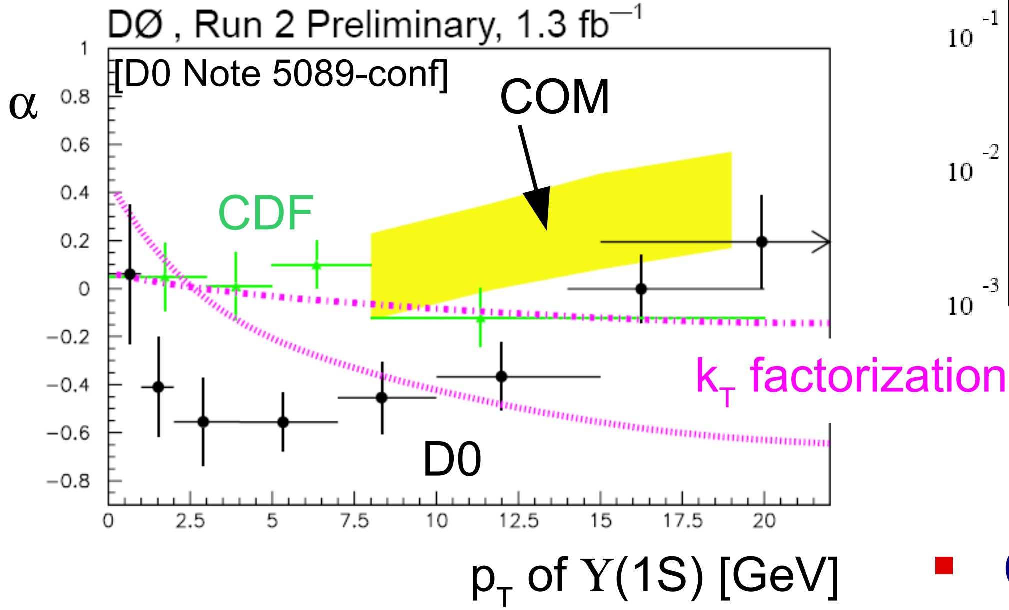


- Dominant systematics:
  - Uncertainties in jet energy scale
  - Uncertainties in fragmentation modelling

Heavy Quarkonia – Motivation

- J/ψ cross section at 1.8 TeV requires Color Octett Model contributions.



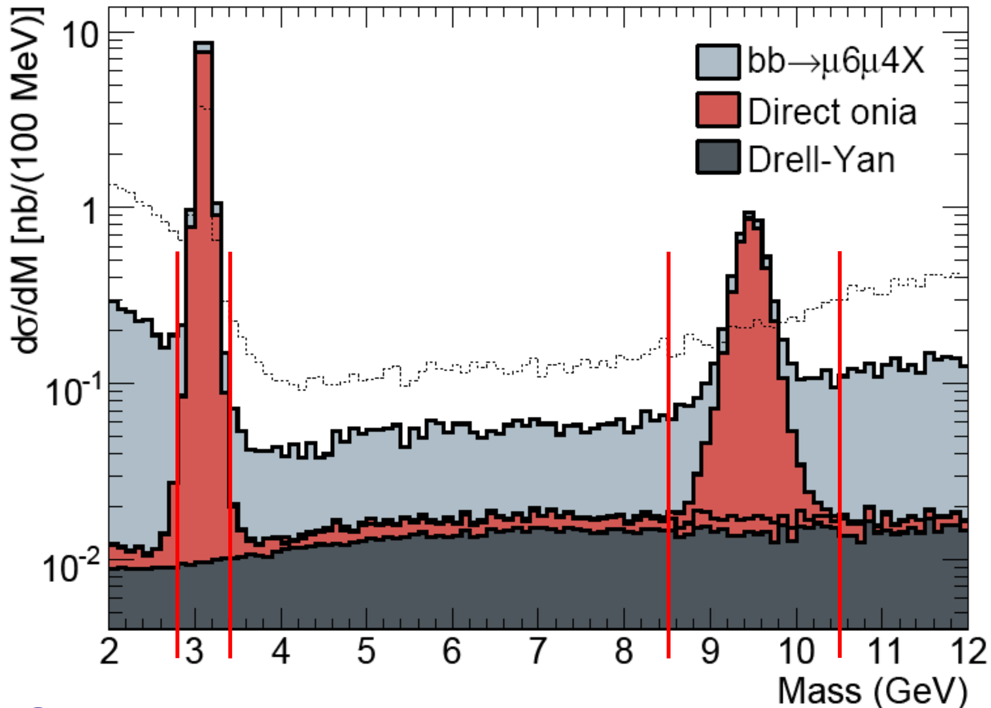


- Polarization in $\Upsilon \rightarrow \mu^+\mu^-$ is not described by Color Octett Model.

- Color Singulet (CSM) and Color Octett Model (COM) predictions from M. Kramer, Prog. Part. Nucl. Phys 47 (2001) 141.

Heavy Quarkonia – Cross Section

- Di-μ trigger, ε^{trig} = 83.7 % ($p_T(\mu_{1,2})$ > 6 GeV, 4 GeV)
- μ tracks from prim. vertex
- Pseudo-proper time < 0.2 ps
- Mass windows:
  $m_{J/\psi}^{PDG}$ ± 300 MeV
  m_{Υ}^{PDG} ± 1 GeV
- 150 000 J/ψ, 25 000 Υ per 10 pb^{-1}
- S/B = 60 (J/ψ), 10 (Υ)
- Combined for 10 pb^{-1}:
  $d\sigma/dp_T$ ~ 1 % level (J/ψ)
  5 % level (Υ)

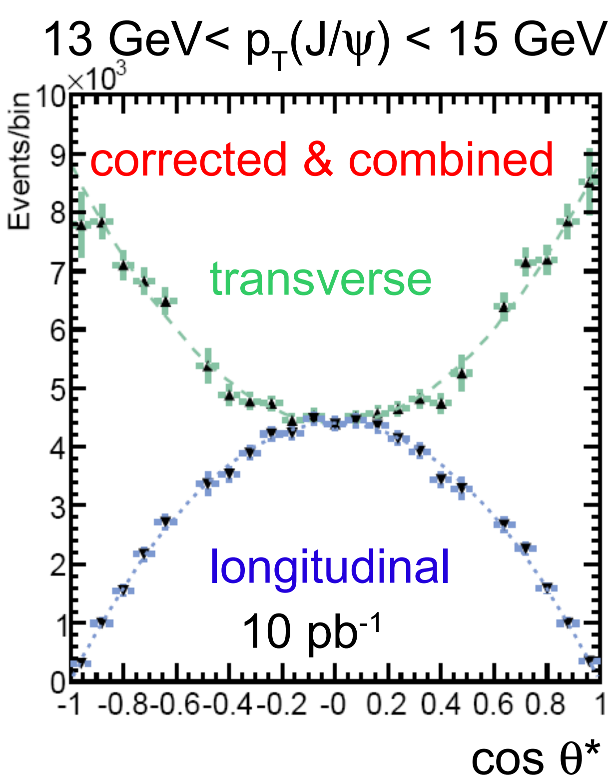


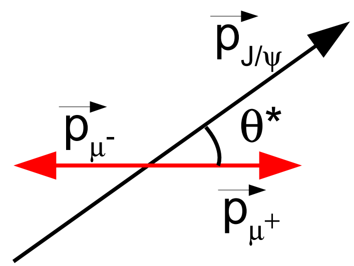
Second method:

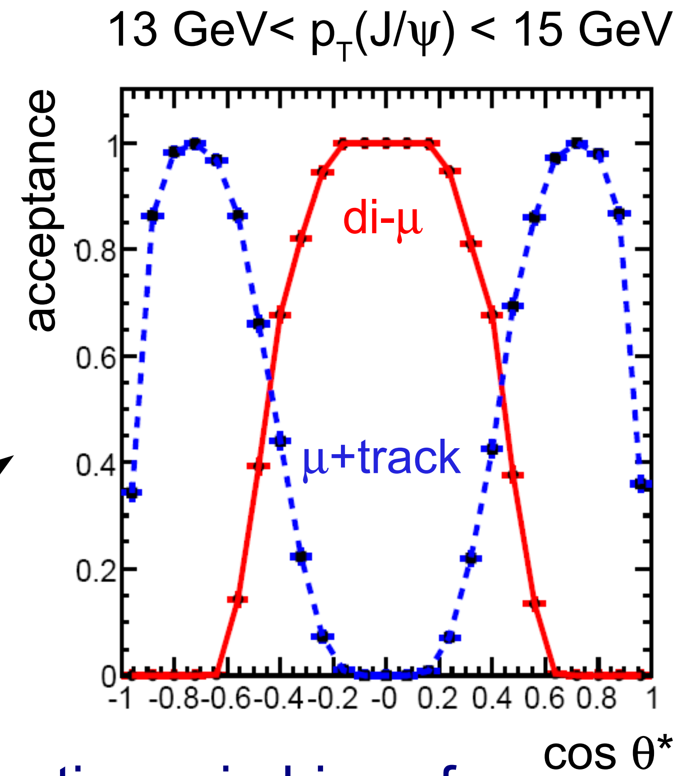
- Single μ-trigger (10 GeV)
- Track in cone $\Delta R_{\mu\text{-track}}$ < 3
- μ and track from prim. vertex
- 160 000 J/ψ, 20 000 Υ per 10 pb^{-1}
- S/B = 1.2 (J/ψ), 0.05 (Υ)

J/ψ and ϒ Polarization

- Different acceptances for di-μ and μ+track samples
- May use combination







- Fit polarization α in bins of p_T

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

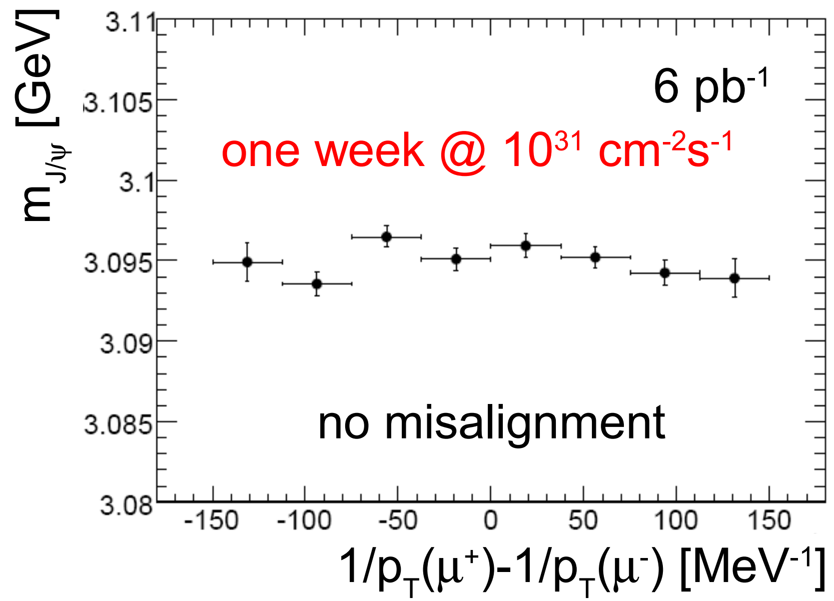
$$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$$

- Precision in α of 0.02 – 0.06 (J/ψ) and 0.2 (ϒ) with 10 pb⁻¹ in p_T up to 20 GeV and beyond

Offline Monitoring with Heavy Quarkonia

Mass shifts in $m_{\mu\mu}$ (J/ψ or Υ)

- vs. p_T :
  μ p_T scale,
  energy loss corrections
- vs. η and ϕ:
  material effects in simulation, magnetic field uniformity
- vs. $1/p_T(\mu^+)-1/p_T(\mu^-)$:
  detector misalignment



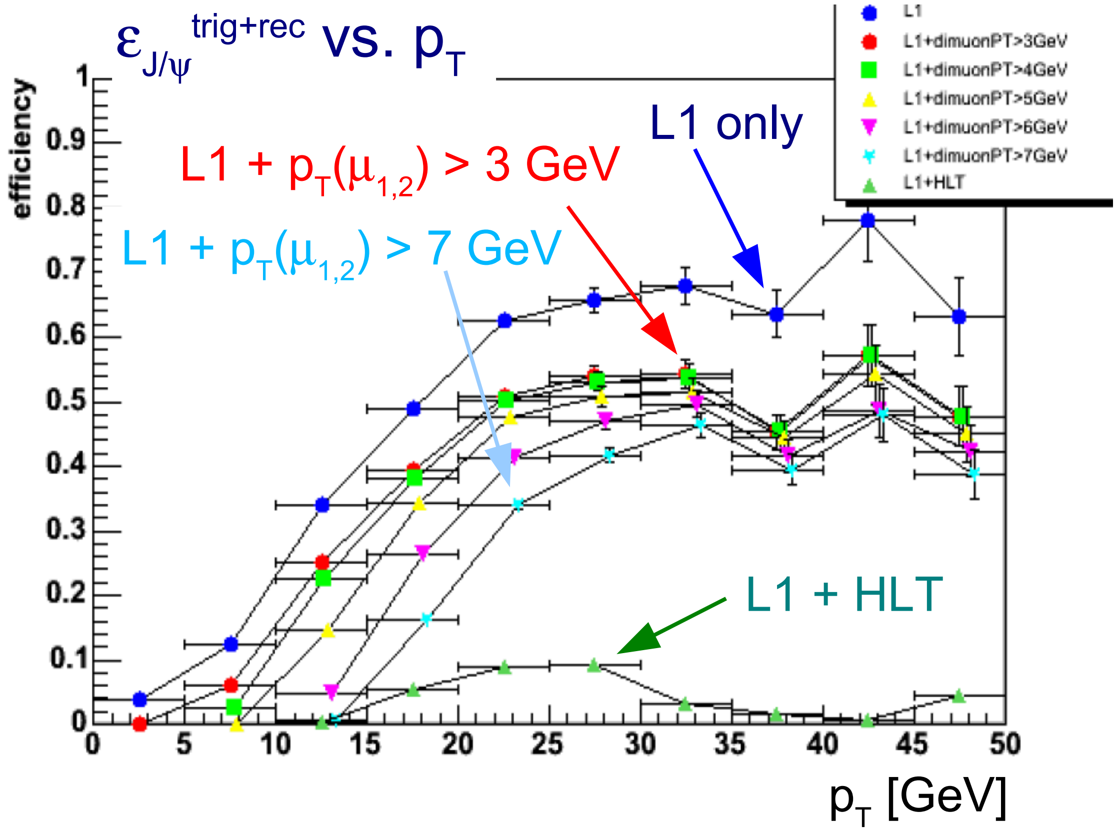
- Quarkonia decays provide low p_T data for monitoring
- Complementary to Z boson decays (higher p_T)
- Quarkonia will also be used for online monitoring (trigger, detector calibration).

Reconstruction of $J/\psi \rightarrow \mu^+\mu^-$

[CMS Note 2007/017]

- MC: ~ 200 000
  $B_s \rightarrow J/\psi\ \phi$ with
  $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$
- LVL1:
  $p_T(\mu_{1,2}) > 3$ GeV,
  $\varepsilon_\mu^{L1} = 36.9\%$
- Reconstruction:
  $\mu^+\mu^-$ pair within
  $2.95 < m_{\mu\mu} < 3.25$ GeV
  $\varepsilon_{J/\psi}^{rec} = 27.4\%$
- $\varepsilon_{J/\psi}^{L1+rec} = 10.1\%$
- HLT:
  specialized HLT trigger under development

$\varepsilon_{J/\psi}^{trig+rec}$ vs. p_T



- $\sigma(m_{J/\psi}) = 34$ MeV

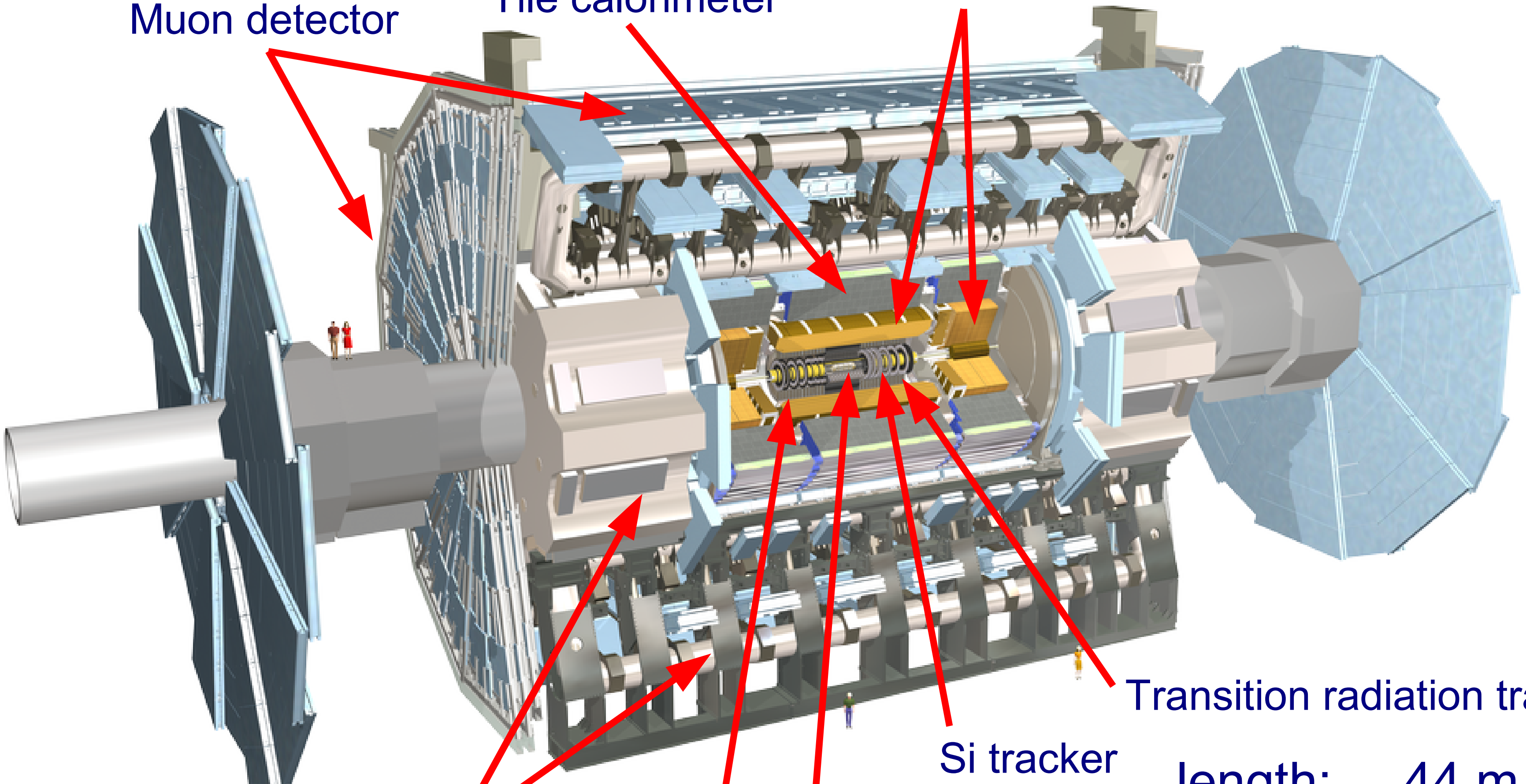
Conclusions

- ATLAS and CMS will measure beauty and onia production cross sections at low p_T (via muonic decays or p_T^{rel}) and for higher p_T (using b-tagging methods):
  - σ, $d\sigma/dp_T$, $d\sigma/d\eta$
  - early data will already provide sufficient statistics
- ATLAS and CMS plan J/ψ and Υ polarization measurements
- Onia properties may be used for offline-monitoring of detector performance (e.g. mass distributions, asymmetries in μ track curvature)
- CMS studied measurement of J/ψ and Υ production in heavy ion collisions (not shown here)
- New tests of QCD are coming with LHC!

Backup Slides

Backup slides

A Toroidal Lhc ApparatuS (ATLAS)

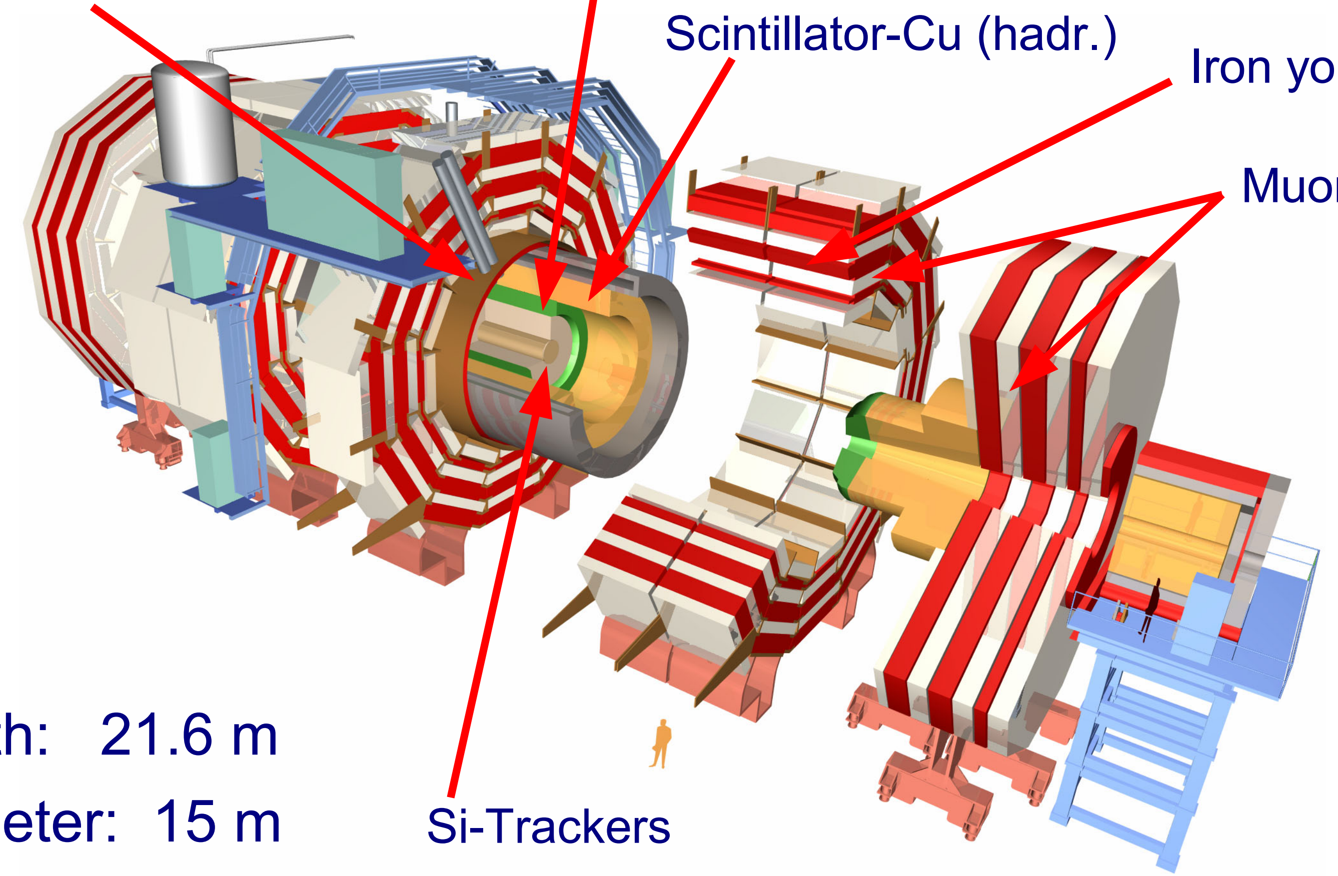


length: 44 m

diameter: 22 m

weight: 7 000 t

Compact Muon Solenoid (CMS)

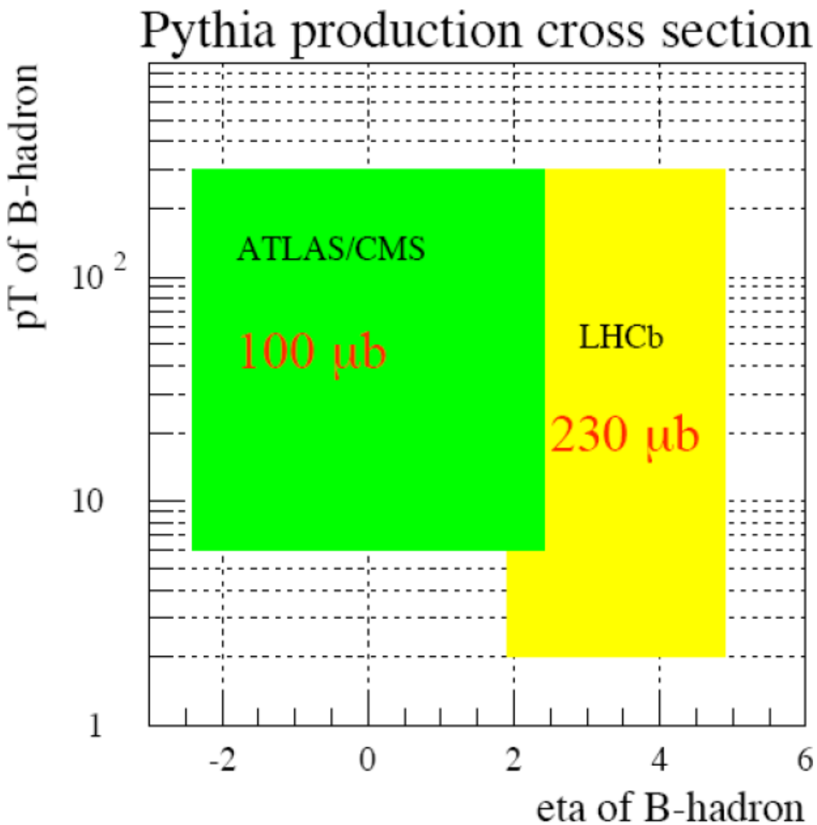


length: 21.6 m

diameter: 15 m

weight: 12 500 t

Beauty Acceptance



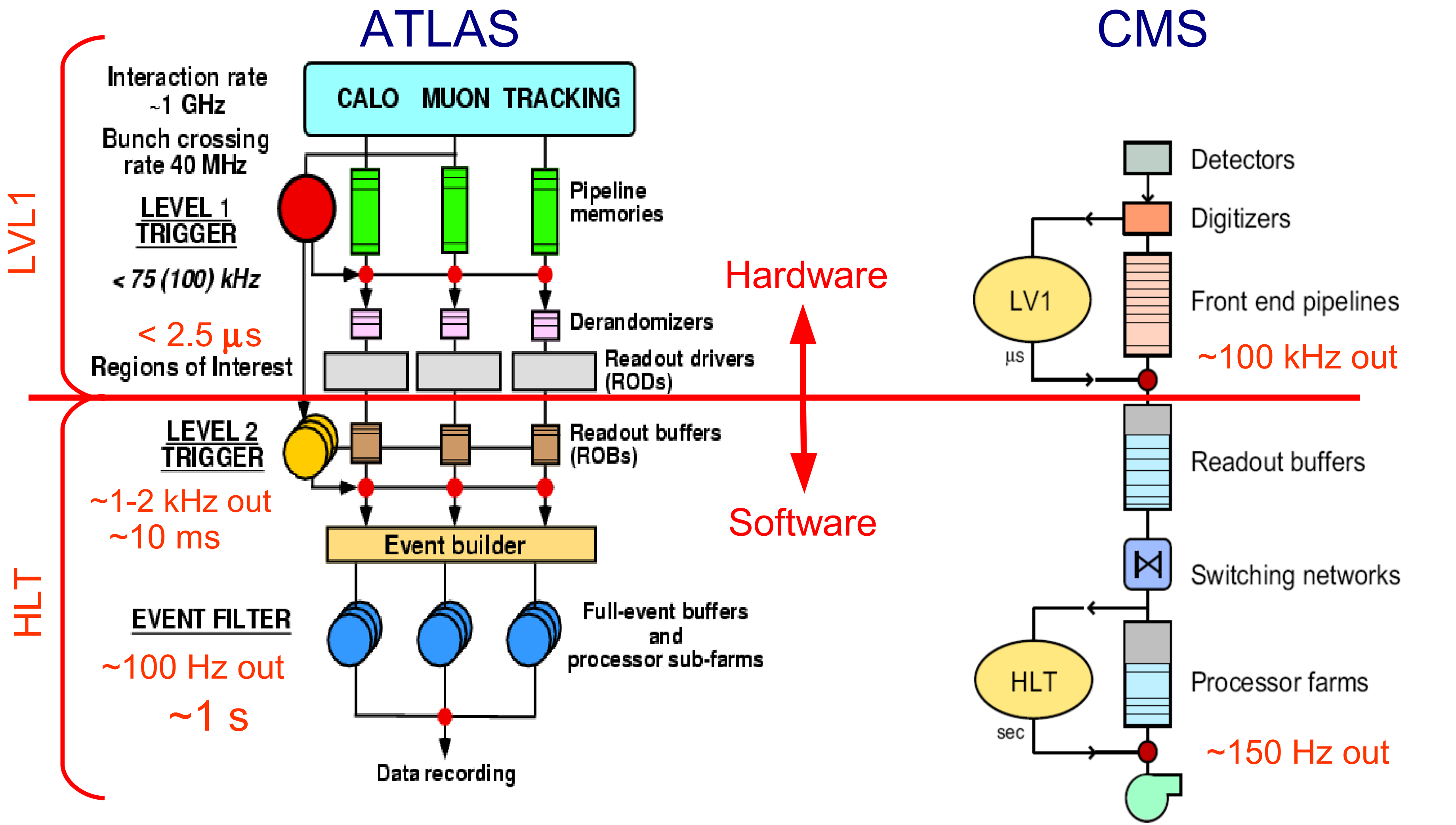
- ATLAS/CMS
  - $|\eta| < 2.5$ / 2.4 (tracker/muon detector acceptance)
  - muon trigger $p_T(\mu) > 4$ GeV
  - jet trigger with b recognition
- LHCb
  - forward spectrometer $1.9 < |\eta| < 4.9$
  - $p_T(\mu) > 2$ GeV

- Different phase space
  → complementary measurements
- Overlap region
  → cross checks

ATLAS Strategy for B-Physics

- Focus on discovery potential for **new physics**:
  - Rare b-decays (multi-μ-, γ-decay channels):
    $B_d \to K^*\gamma$, $B_d \to K^*\mu\mu$, $B_{d,s} \to \mu\mu$, $B_s \to \phi\,\mu\mu$, $B_s \to \gamma\,\mu\mu$, ...
  - CP violation parameters, predicted to be small in SM:
    e.g. $B_s \to J/\psi\,\phi$ ($B_s \to J/\psi\,\eta$) [Φ_s, $\Delta\Gamma_s$, ...]
- Focus on **topics unaccessible at B-factories**:
  - B_s, baryon and double heavy flavor hadrons
    $B_s \to D_s\pi/a_1$, $B_s \to J/\psi\,\phi\,(\eta)$, $\Lambda_b \to \Lambda^0 J/\psi$, $B_c \to J/\psi\,\pi$
    [m_s, Γ_s, Δm_s; a_b, P_b; m_c, ...]
- Concentrate on **channels accessible at 10^{34} cm^{-2} s^{-1}**:
  Di-μ-trigger based decays (low rate)
- **Early measurements**:
  - B-production cross-section measurement

Trigger Systems in ATLAS and CMS



- 10% (5% for CMS) of total trigger resources dedicated to B-physics → fast, efficient and selective trigger needed!

ATLAS B-Physics Trigger Strategies

Flexible B trigger strategies:

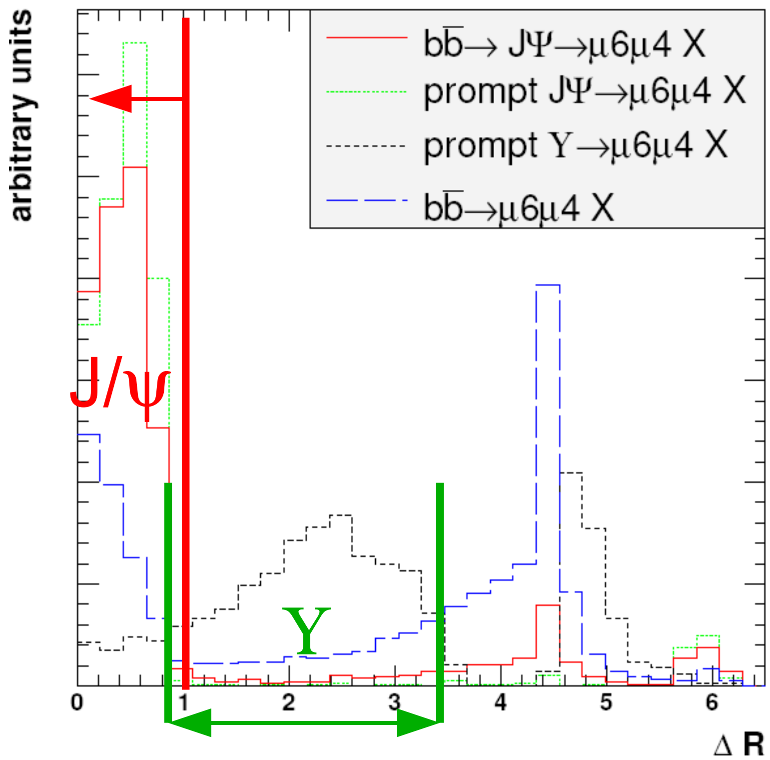
Preliminary!

- Luminosity up to a few times 10^{33} $cm^{-2}s^{-1}$:
  - μ (p_T > 6 GeV) + μ (p_T > 5 GeV) $B_s \to J/\psi\, \phi$, $B_d \to K^{*0} \mu\mu$, $B \to \mu\mu$
  - μ (p_T > 6 GeV) + e/γ (E_T > 6 GeV) $B_d \to K^{*0}\gamma$, $B_s \to \phi\gamma$, $B \to \mu\mu\gamma$
  - μ (p_T > 6 GeV) + Jet (E_T > 10 GeV) $B_s \to D_s\, \pi/a_1$
- Nominal luminosity 10^{34} $cm^{-2}s^{-1}$:
  - 2μ: μ (p_T > 6 GeV) + μ (p_T > 5 GeV) $B \to \mu\mu$
- Low luminosity (end of spill) < 10^{33} $cm^{-2}s^{-1}$:
  - single μ (p_T > 6 - 8 GeV) (+ further selections in HLT)
- ~ 10^8 events/year for specific exclusive B-decay modes to permanent storage

Inclusive b Cross Section (low p_T)

Strategy 1: bb → J/ψ($\mu^+\mu^-$) X

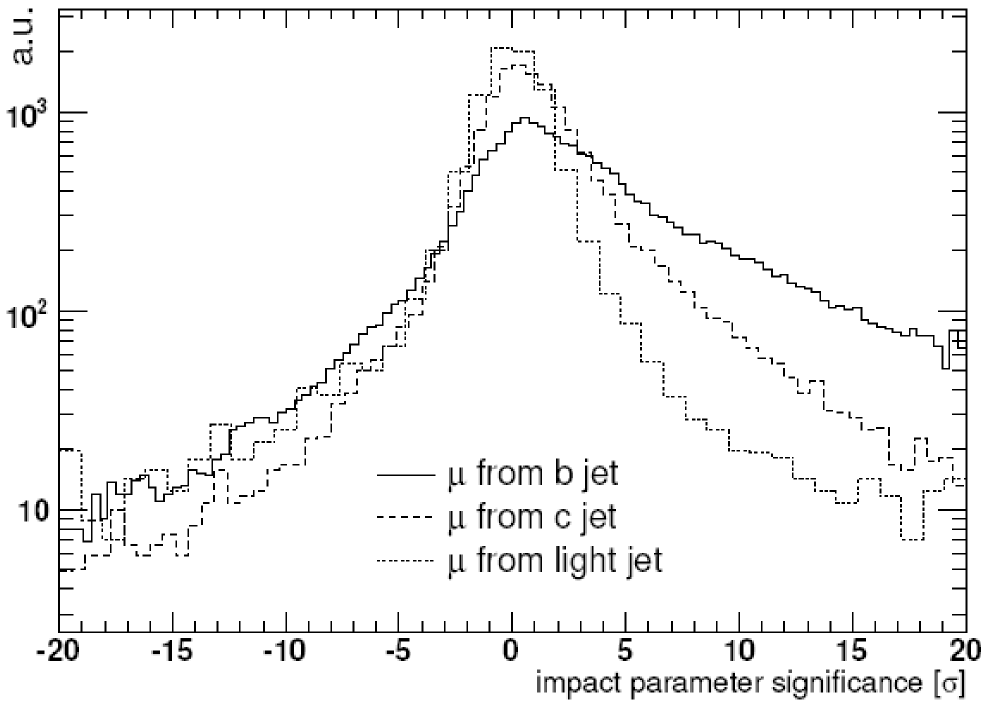
- cut on ΔR



b-Production X-Section (low p_T)

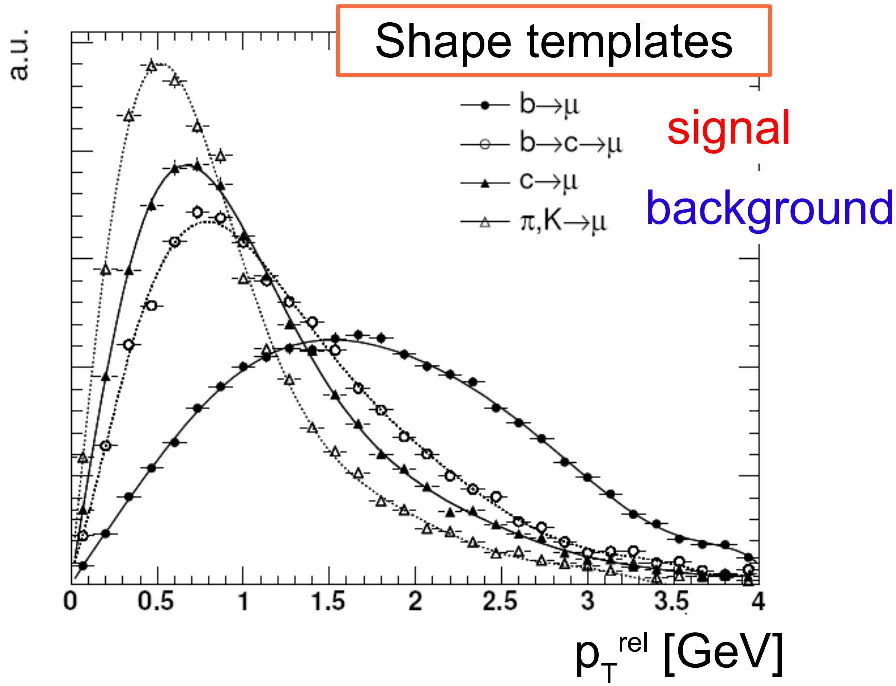
Strategy 2: μ + b-jet based

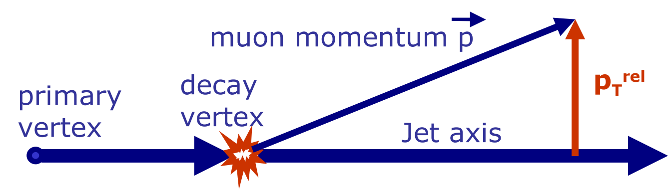
- Impact parameter significance



Inclusive b Cross Section (low p_T)

- **Strategy 2:** μ + jet based





Inclusive b Production Cross Section

- Estimated rates for μ + jet trigger for $L = 10^{33}\ cm^{-2}s^{-1}$ (for bb $\rightarrow \mu^+$ + b-jet X)

Level	Condition	Rate [kHz]
LVL1	6 GeV μ + 17 GeV jet	9.0
LVL2	6 GeV μ + 30 GeV jet	3.2
	+ b-jet	3.0
	+ b-weight cut	1.6
EF	6 GeV μ	1.4

Pre-scale factors (PS) necessary!

J/ψ and Υ Cross Section and Polarization

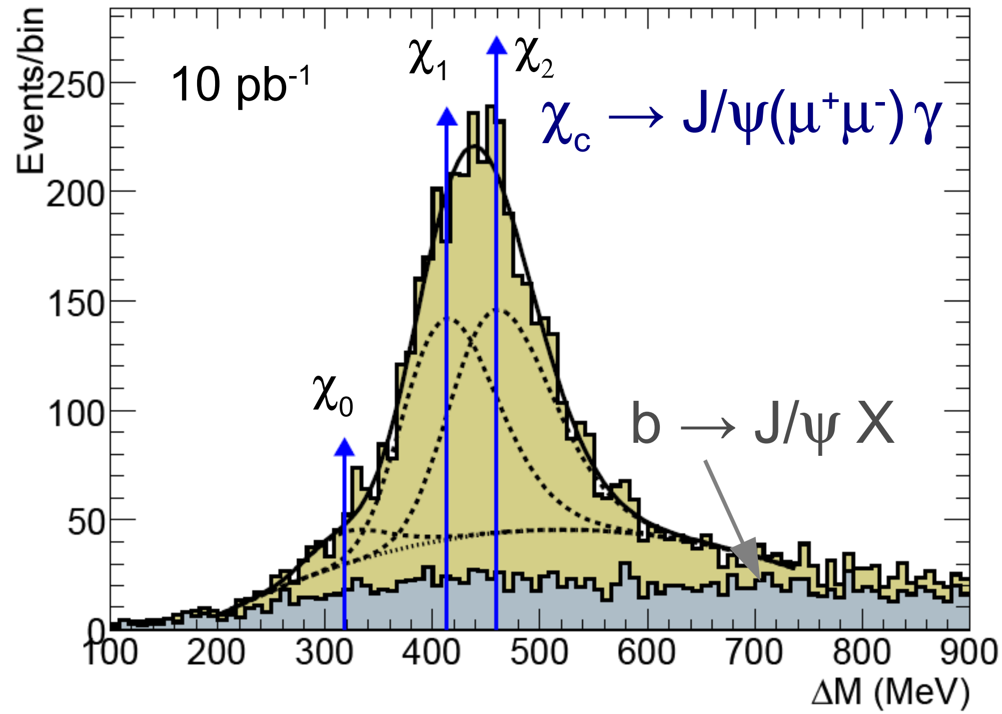
- For 10 pb^{-1}

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
Υ , $\alpha_{gen} = 0$	α	−0.42 ±0.17	−0.38 ±0.22	−0.20 ±0.20	0.08 ±0.22	−0.15 ±0.18	0.47 ±0.22
	σ, nb	2.523 ±0.127	0.444 ±0.027	0.584 ±0.029	0.330 ±0.016	0.329 ±0.015	0.284 ±0.012

Decays of χ_c and χ_b

$\chi_c \to J/\psi(\mu^+\mu^-)\,\gamma$

- Combine J/ψ with soft γ
  - $\cos\alpha(J/\psi,\gamma) > 0.97$
  - $\Delta M = m_{\mu\mu\gamma} - m_{\mu\mu} \in [200, 700\ \text{MeV}]$
- $\varepsilon^{rec} = 4\ \%$
- $\sigma(\Delta M) = 35 - 45\ \text{MeV}$
- Observable at 10 pb^{-1}



$\chi_b \to \Upsilon(\mu^+\mu^-)\,\gamma$

- γ much softer
- $\varepsilon^{rec} = 0.03\ \%$
- Need ~ 1 fb^{-1} to observe

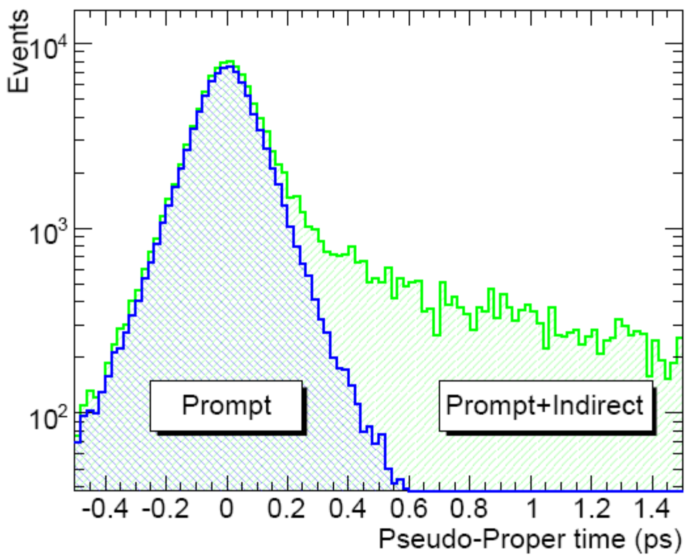
$\chi_b \to J/\psi(\mu^+\mu^-)\,J/\psi(\mu^+\mu^-)$

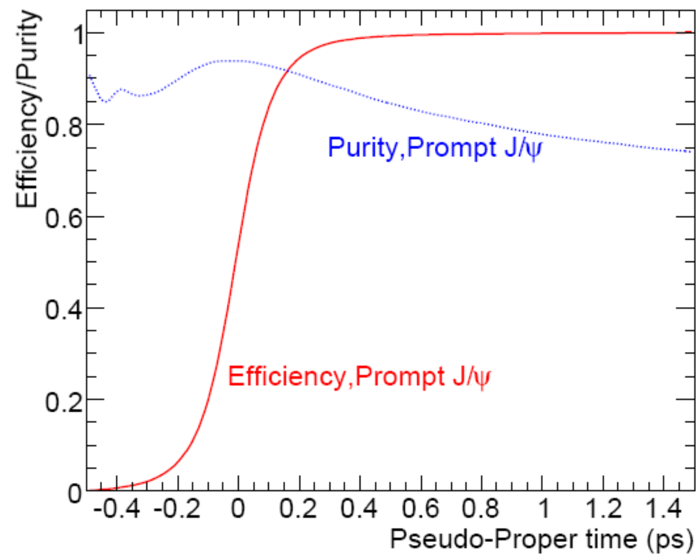
- $\varepsilon^{total} \sim 0.8\ \%$
- Expect ~ 100 events for 10 fb^{-1} (lower bound) and S/B ~ 10 – 20 %

J/ψ and Υ Summary

- With 1 pb^{-1}:
  - 15 000 $J/\psi \rightarrow \mu^+\mu^-$ and 2 500 $\Upsilon \rightarrow \mu^+\mu^-$ with μ6μ4 trigger
  - 10 000 $J/\psi \rightarrow \mu^+\mu^-$ and 2 000 $\Upsilon \rightarrow \mu^+\mu^-$ with μ10 trigger
  - 7 000 $J/\psi \rightarrow \mu^+\mu^-$ from b-decays
  - Use to study detector alignment, acceptance and trigger studies, tracking and muon system performances
  - Try to reconstruct $\chi_c \rightarrow J/\psi(\mu^+\mu^-)\,\gamma$
- With 100 pb^{-1}:
  - several million $J/\psi \rightarrow \mu^+\mu^-$ and > 500 000 $\Upsilon \rightarrow \mu^+\mu^-$
  - p_T spectra up to 100 GeV
  - $\chi_b \rightarrow \Upsilon(\mu^+\mu^-)\,\gamma$ may become observable

Heavy Quarkonia – Cross Section



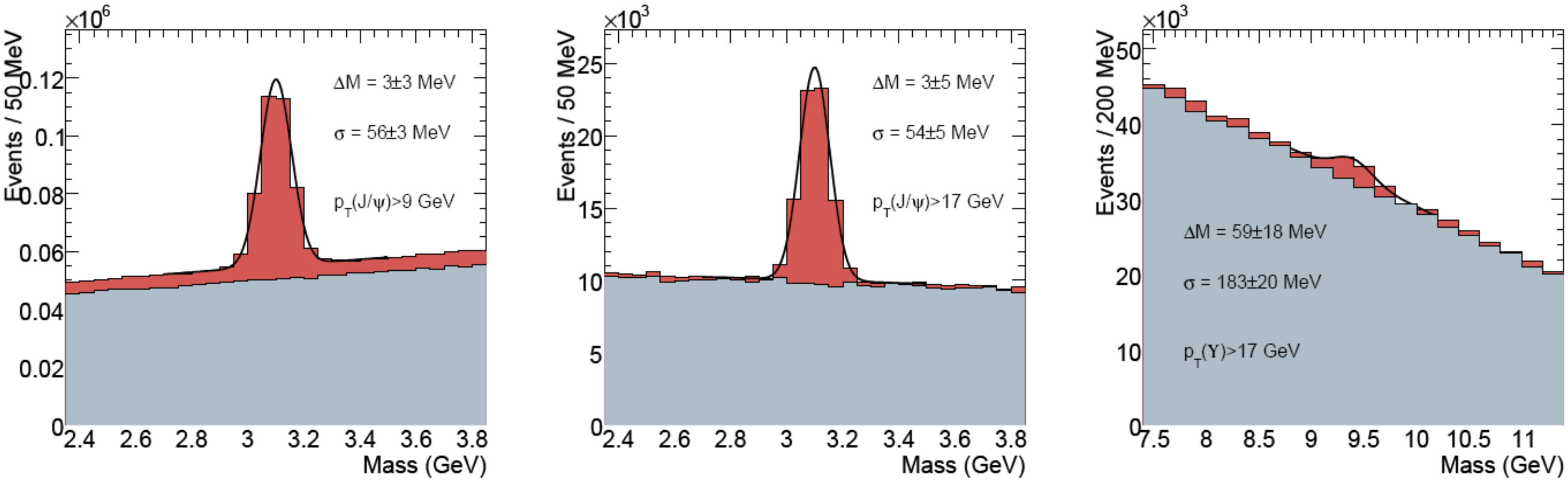


Di-μ method:

- Pseudo proper-time cut (< 0.2 ps)
- 6 pb^{-1}

$$\text{pseudo-proper time} = (L_{xy}\, M_{J/\psi})/(p_{T,J/\psi}\, c)$$

Heavy Quarkonia – Cross Section



Second method:

- Single μ-trigger (10 GeV)
- Track in cone $\Delta R_{\mu\text{-track}} < 3$
- 160 000 J/ψ, 20 000 Υ per 10 pb^{-1}
- S/B = 1.2 (J/ψ), 0.05 (Υ)

Quarkonia in Heavy Ion Collisions

[CMS Note 2006/089]

Motivation

- QCD: Quark deconfinement at T_c ~ 180 MeV
  → Quark Gluon Plasma QGP (?)
- QGP could screen color binding potential
  → measurable suppression of quarkonia yields
  [T. Matsui and H. Satz, Phys. Lett. B178, 416]
  → out of range for RHIC (Pb-Pb at E_{CM} = 200 GeV)?
  [F. Karsch, D. Kharzeev, H.Satz, Phys. Lett B636, 75]
- Other quarkonia (e.g. Υ)?

- LHC heavy ion running ~ 1 month/year (~ 0.5 nb^{-1})
  - ^{208}Pb-^{208}Pb at E_{CM} = 5.5 TeV
  - $L \sim 4 \times 10^{26}\ cm^{-2}\ s^{-1}$

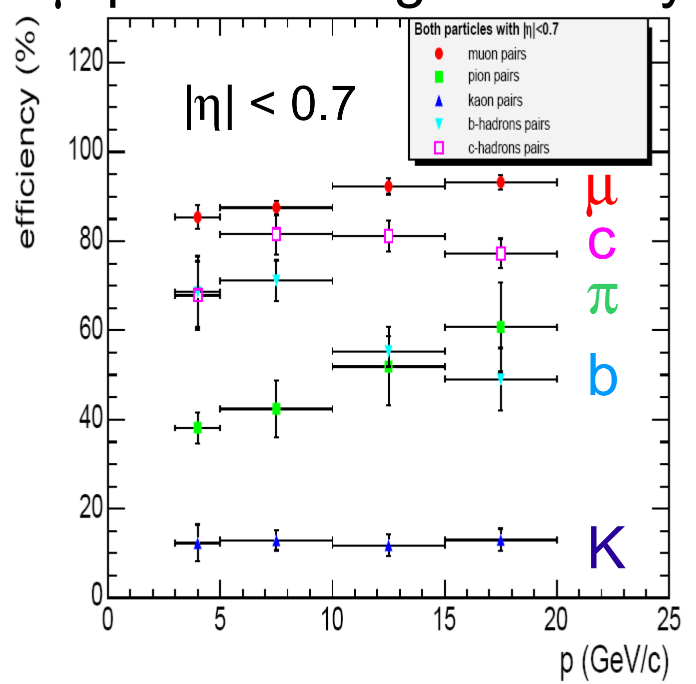
Quarkonia in HI – Event Simulation

[CMS Note 2006/089]

$B_{\mu\mu}\ \sigma_{prod}$ (μb)				
J/ψ	ψ'	Υ	Υ'	Υ''
48930	879	304	78.8	44.4

- $\sigma(J/\psi, \Upsilon, ...) << \sigma_{inel} \Rightarrow$ Fast Monte Carlo
- **Signal:** $J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^-$
- **Backgrounds:**
  - μ from $\pi^\pm$, $K^\pm$ for $dN^\pm/d\eta|_{\eta=0}$ = 2500 (low), 5000 (high)
  - μ from open c and b production
- **Simulation of detector response**
  - μ trigger efficiency tables
  - di-μ efficiency depending on background type, p_T and η
  - smearing according to mass resolutions for ψ and Υ
  - $|\eta| < 2.4$ for both μ tracks
  - ➡ integrated acceptance: 1.3 % (J/ψ), 26 % (Υ)

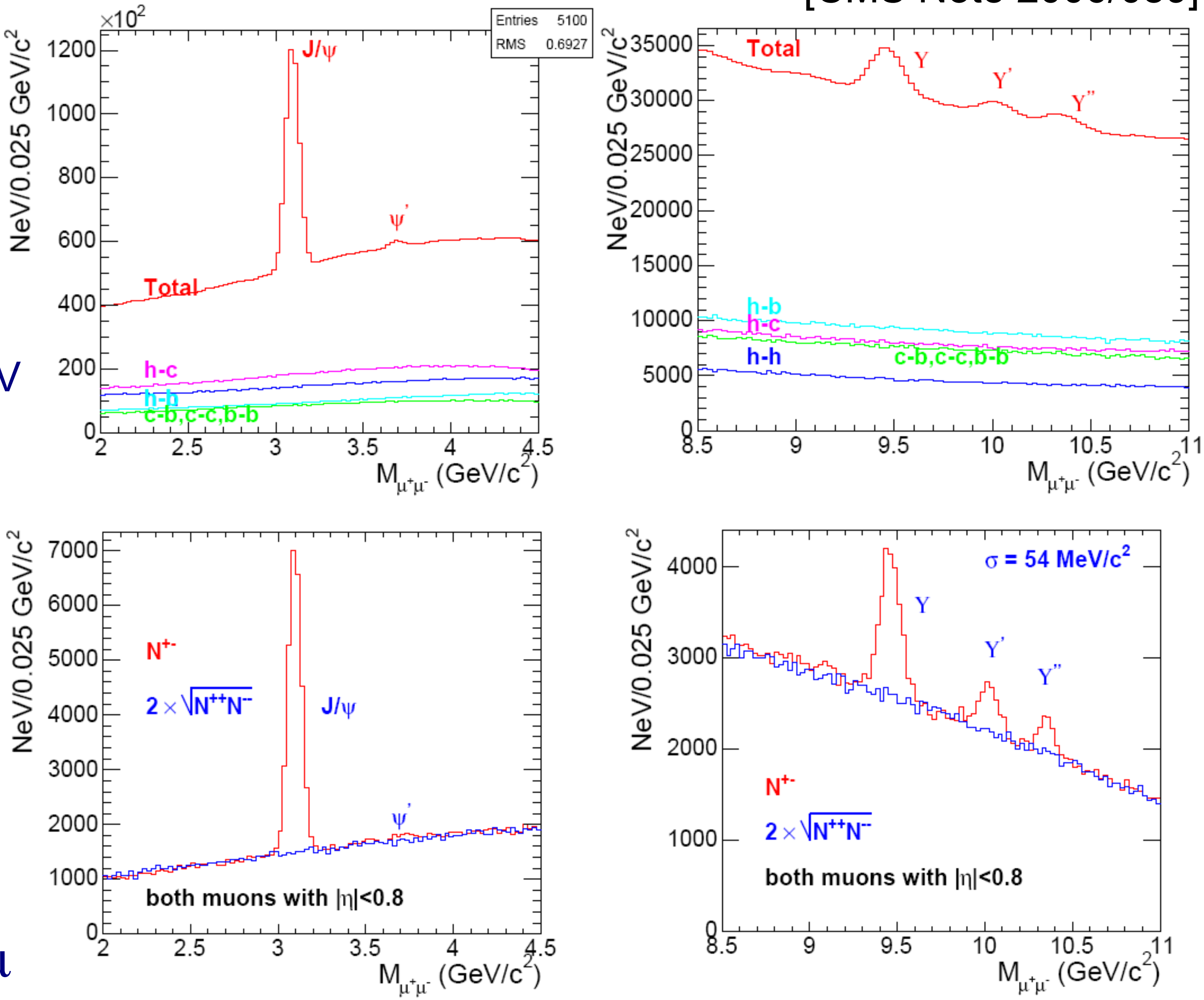
μ-pair tracking efficiency



Quarkonia in HI – Mass Distributions

[CMS Note 2006/089]

- rescaled to 0.5 nb^{-1} (one month)
- Mass regions:
  $2 < M_\psi < 4.5$ GeV
  $8.5 < M_\Upsilon < 11$ GeV
- S/B improved by $|\eta_\mu| < 0.8$ → smaller yields
- Comb. background subtraction by same-sign di-μ



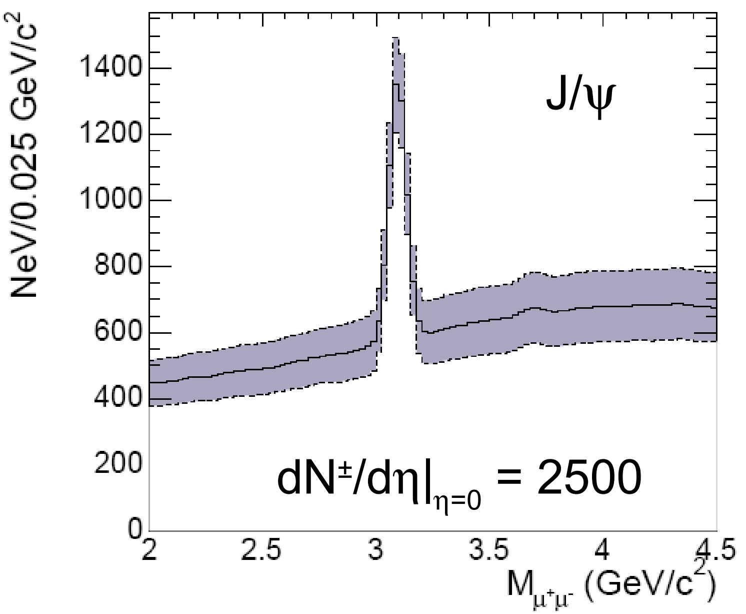
$dN^\pm/d\eta|_{\eta=0} = 2500$

Quarkonia in HI – Yields and Systematics

- Event yields and S/B for 0.5 nb^{-1} (one month Pb-Pb)

	S/B	N(J/ψ)
$dN^{\pm}/d\eta$ =5000	0.6	140 000
$dN^{\pm}/d\eta$ =2500	1.2	180 000

	S/B	N(Υ)	N(Υ')	N(Υ'')
$dN^{\pm}/d\eta$ =5000	0.07	20000	5900	3500
$dN^{\pm}/d\eta$ =2500	0.12	25000	7300	4400

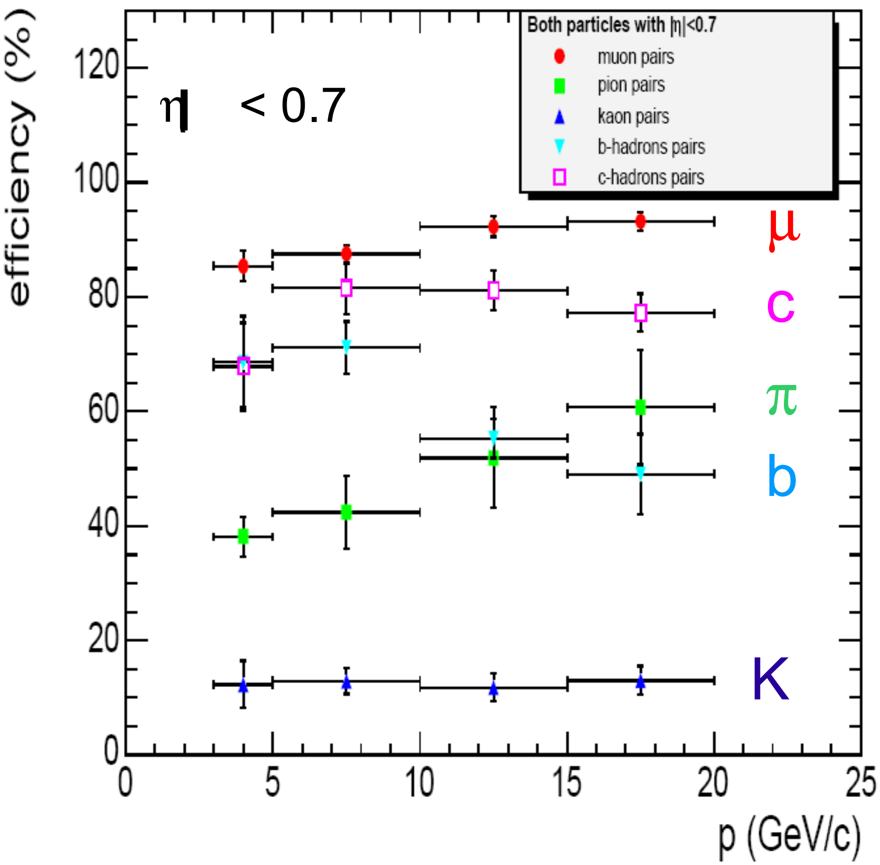


[CMS Note 2006/089]

- Systematic error contributions:
  - limited statistics of „fast“ MC (weighting method) ~ 20 % (J/ψ), ~ 25 % (Υ)
- To be studied:
  - „fast“ vs. full MC comparison
  - limitations in detector description
  - impact parameter dependence

Quarkonia in HI – Detector Response

μ-pair tracking efficiency



[CMS Note 2006/089]