Heavy Flavour in CMS

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on behalf of the CMS Collaboration

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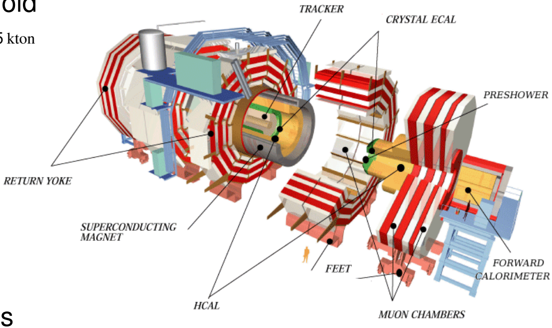
Outline

- Introduction
  - CMS detector
  - Subsystems
  - Start-up scenario
- Overview
  - HF program in CMS
  - Simulation
  - b tagging
- HF Physics in CMS
  - B Physics
  - Heavy Flavour in Heavy Ions
- Conclusion

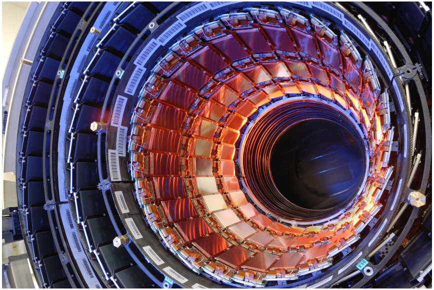
The CMS Experiment

- The Compact Muon Solenoid
  - **Length** 22 **m , diameter** 15 **m,** 12.5 kton
  - **Magnetic field** 4Tesla
- Muon system
  - **DT, CSC, RPC**
  - $p_\perp > 3\text{GeV}$
- All-silicon tracker
  - $|\eta| < 2.5$
  - **pixel: 3 layers**
  - **strip tracker: 10 layers**
- Pixel detector startup plans
  - **2007: minimal commissioning system**
  - **2008: three layers for first physics run**

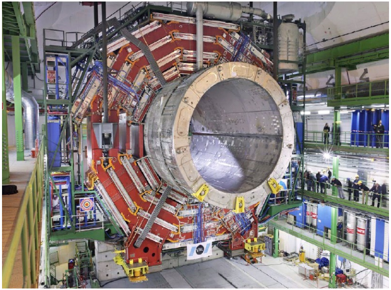


Construction and Installation

Interior of one half of the Tracker Inner Barrel

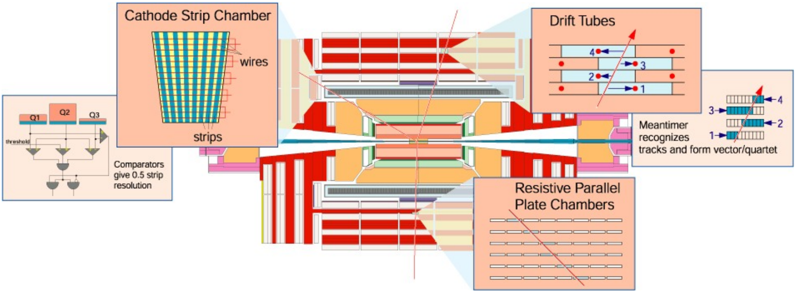


Feb 28 central wheel YB0 touching-down in the UXC55 cavern



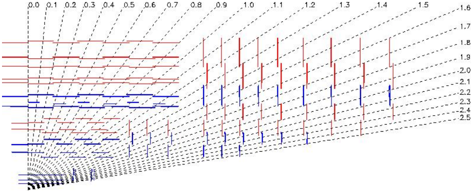
The CMS Muon System

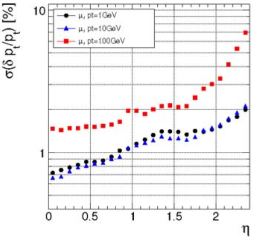
- Three types of gaseous particle detectors for muon identification
  - **Drift Tubes (DT) in the central barrel region: position and momentum measurements**
  - **Cathode Strip Chambers (CSC) in the endcap region: position and momentum measurements**
  - **Resistive Parallel Plate Chambers (RPC) in both the barrel and endcaps: fast information for the Level-1 trigger**

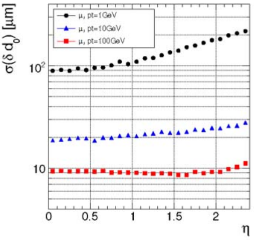


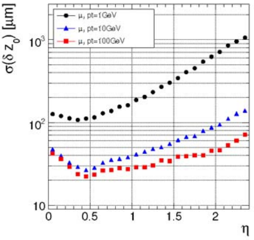
The CMS Tracker

- All-silicon tracker
  - Few measurement layers
  - Very precise measurements
- Pixel Detector
  - hit resolution: 10 –15 μm
- Silicon Strip Detector
  - 10 –14 points



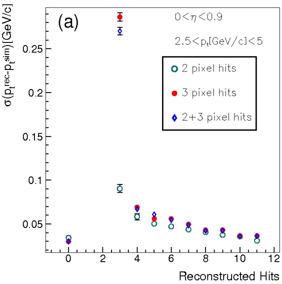


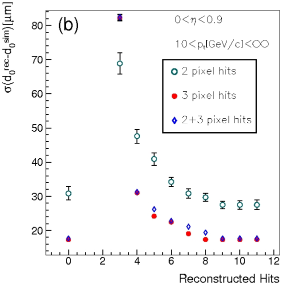




The CMS Trigger Strategy

- Level 1
  - **muons and calorimeters**
    Latency: 3.2μs
    40 MHz $\longrightarrow$ 100 kHz
- High-level trigger (HLT)
  - **fast (local) reconstruction**
    100 kHz $\longrightarrow$ 100 Hz
- B-physics triggers
  - **Level 1: single- or di-muon trigger**
    single-muon: $p_T > 14GeV/c$
    di-muons: $p_T > 3GeV/c$
  - **HLT: exclusive and inclusive b, c triggers at $\sim$ 5Hz**
    exclusive B decays: partial (local) reconstruction





LHC start-up and CMS objectives

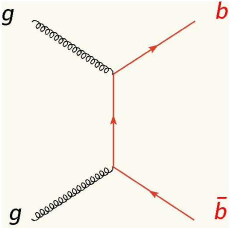
- 2007 - 900GeV Collision:
  - **Engineering Run $\longrightarrow$ few days (?)**
  - **Nominal luminosity** $(10^{28} \longrightarrow 10^{32})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ **[R.Bailey]**
  - **Initial detector commissioned, learn how to operate it**
- 2008 - 14TeV Collision:
  - **Pilot Run $\longrightarrow$ 1 fb^{-1} [J. Virdee]**
  - **Nominal luminosity** $(10^{28} \longrightarrow 10^{32})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**, bx=**$75 - 25$ **ns [R.Bailey]**
  - **Low luminosity detector commissioned, calibration and alignment**
- 2009 - 14TeV Collision:
  - **Physics Run $\longrightarrow$ 5 fb^{-1} [J. Virdee]**
  - **Nominal luminosity** $(4 \times 10^{32} \longrightarrow 10^{33})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$**, bx=25 ns [R.Bailey]**
  - **Detector calibrated and aligned, physics data taking**
- Bottom production
  - $\sigma_{b\bar{b}} \sim 500\,\mu$**b**
  - $N_{b\bar{b}} = 5 \times 10^{11}\,/\,$**fb**$^{-1}$

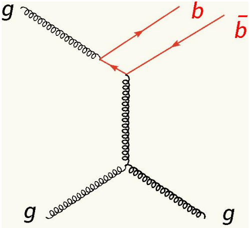
HF program in CMS

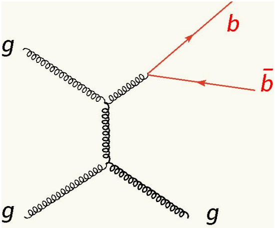
- B Physics
  - $b\bar{b}$ production x-section @ 14TeV (low p_T)
  - $b\bar{b}$ production mechanisms @ 14TeV
  - inclusive and exclusive B decays (CP, CKM, FCNC, NP ...)
  - HF spectroscopy
- b jets
  - $b\bar{b}$ production x-section @ 14TeV ($50\,\mathrm{GeV}/c < p_T < 1500\,\mathrm{GeV}/c$)
  - crucial ingredient in many physics studies and searches
    - $t\bar{t} \to W^+W^-b\bar{b}$
    - Higgs searches: $H \to b\bar{b}$, $t\bar{t}H$, $b\bar{b}H(A)$ etc
    - b jets in decays of SUSY particles
- Heavy ions
  - production x-section of J/Ψ and Υ families (with $\mu^+\mu^-$ final state) in PbPb @ 5.5TeV
  - direct probe of QGP formation
  - sensitive to “Colour Glass Condensate”

Simulation I

- MC generator - PYTHIA 6.227, CTEQ5L
  - **MSEL 5 for fast study and debugging**
    Gluon-gluon Fusion (GF): $gg(q\bar{q}) \longrightarrow b\bar{b}$
  - **MSEL 1 with $b\bar{b}$ selection for real study (∼1% initial efficiency)**
    GF +
    Flavour Excitation (FE) $gb \longrightarrow gb$ **+**
    Gluon Splitting (GS) $g \longrightarrow b\bar{b}$

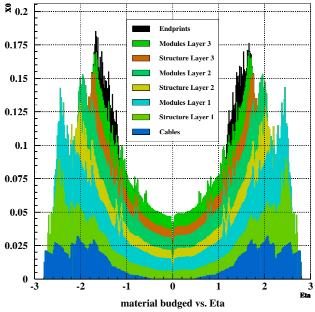


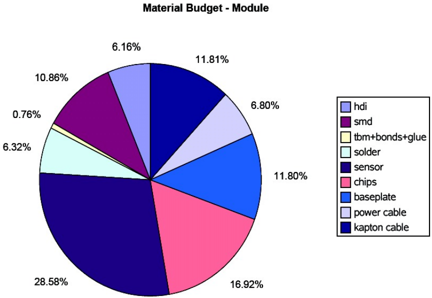




Simulation II

- MC generator - plans
  - PYTHIA 6.4 with Color Octet Mechanism, CTEQ6.1
  - EvtGen plugin
- Detector simulation
  - GEANT4 based CMSSW
  - Detailed detector geometry description
  - Realistic material budget
  - Beam test based detector response



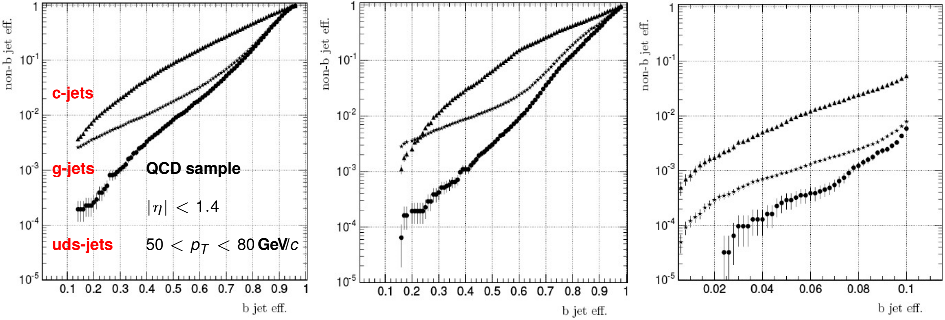


b-jets tagging

- Track counting (TC)
  - measurement of charged tracks Impact Parameter (IP), $< n_b^{ch} > \sim 5$
  - n (2 or 3) tracks with $IP > IP_{cut}$
  - decreasing order, IP of n-th track is discriminant
  - extra cut: dist(track-jet axis)<0.65mm
- Track probability (TP)
  - measurement of charged tracks (IP)), $< n_b^{ch} > \sim 5$
  - include all charged tracks in a jet
  - probability to originate from primary vertex P_{tr}
  - $-logP_{jet}$ is a discriminant
- Combined secondary vertex (CSV)
  - fully reconstructed secondary decay vertex: $100\ \mu$m $< L_t < 2.5cm$, $L_t/\sigma_t > 3$
  - invariant mass of charged tracks: 1.5 GeV/$c^2 < M < 6.5$ GeV/c^2
  - several other cuts (IP, energy ratio etc)
  - discriminating variable based on Likelihood ratio technique
- Soft lepton (SL) b tag
  - electrons or muons inside hadronic jets (20%)
  - several other variables (IP, rel. p_T etc)

b-tagging performance

TP b tag | CSV b tag | SL b tag

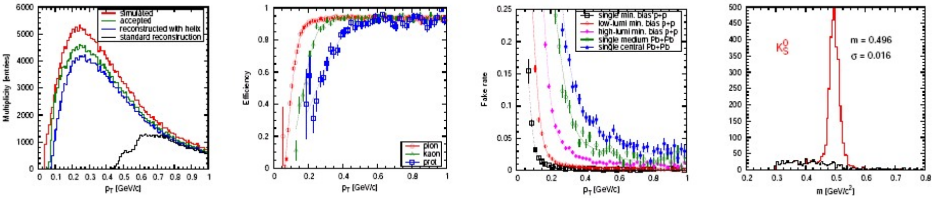


B Physics Menu

- Past
  - $B_d \to \pi^\pm \pi^\mp$ and $B_s \to K^\pm K^\mp$: CP violation, angles α and γ
  - $B_d \to J/\Psi K_s \to \mu^+\mu^-\pi^+\pi^-$: CP violation, angle β, NP(?)
  - $B_s - \bar{B}_s$ mixing in $B_s \to D_s^- \pi^+ \to K^- K^+ \pi^- \pi^+$
- Present
  - Inclusive b production: differential x-sections
  - $B_s \to J/\Psi\phi \to \mu^+\mu^- K^+ K^-$: measurement of $\Delta\Gamma_s$
  - $B^0 \to \mu^+\mu^-$: FCNC rare decay, possible hint for NP
  - $B_c^\pm \to J/\Psi\pi^\pm \to \mu^+\mu^-\pi^\pm$: mass and lifetime of B_c
- Future (planned topics)
  - $B^\pm \to J/\Psi K^\pm \to \mu^+\mu^- K^\pm$: measurement of $\sigma_{b\bar{b}}$ (14 TeV)
  - $B \to \mu + X$: lifetime measurements, early 'engineering physics'
  - J/Ψ vs μ: $b\bar{b}$ correlation studies, $b\bar{b}$ production mechanisms
  - $B_s^0 \to \phi\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$: search for NP
  - B_c, η_b, $X(3872)$ ...: spectroscopy
  - $\tau \to 3\mu$: lepton flavour violation

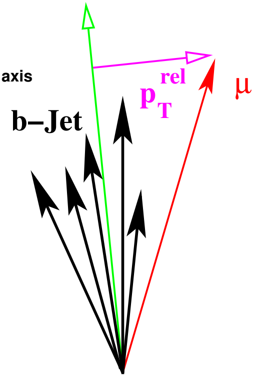
$B_d \to J/\Psi K_s$ and low p_T reconstruction

- $A_{CP} = A_{CP}^{mix-ind} \oplus A_{CP}^{dir}$, $A_{CP}^{dir} \sim 0_{SM}$
  - **2000: CMS planned $\delta(sin2\beta)_{CMS} = 0.015_{stat}$ in 30 fb^{-1} ($p_T^{\pi} > 0.7$ GeV/c)**
  - **2006: HFAG quoted $\delta(sin2\beta)_{exp} = 0.040(0.023)_{stat}$**
  - **2009: CMS can probe NP measuring A_{CP}^{dir} at level of 1-2% (?)**
- New method for low $p_T > 0.2$ GeV/c hadron reconstruction
  - **only silicon pixel hits used (3 layers), simple helix**
  - **good efficiency, high resolution and negligible fake rate (proved by full simulation)**



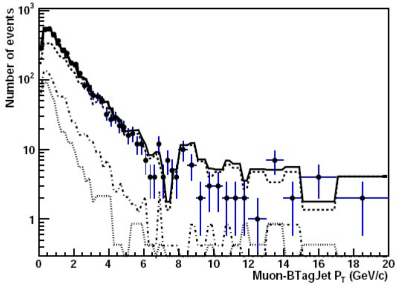
Inclusive b production [V.Andreev, 2 HERA-LHC]

- Measure differential b-jet x-section: $d\sigma/dp_T$ and $d\sigma/d\eta$
- Key issue is data purity
  - select b-jets with muon inside
  - fit data with MC shapes of muon transverse momentum with respect to b-jet axis
- Trigger
  - L1: single muon with $p_T > 19\,\text{GeV}$
  - HLT: muon + b-jet of $E_T > 50\,\text{GeV}$
- Off-line Analysis
  - b-jet tagging with CSV b tag algorithm
  - take most energeric b-jet in event as B-particle candidate
  - apply muon tag (muon in b-jet)
- 16M b-events collected @ $10\,\text{fb}^{-1}$

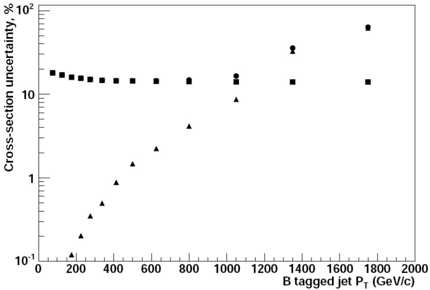


Inclusive b production

muon p_T spectrum fit:
b (dash), c (dot-dash), uds (dot)



x-section uncertainties:
stat (▲), sys (■), total (•)

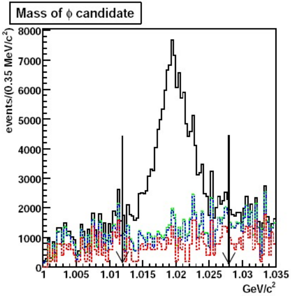


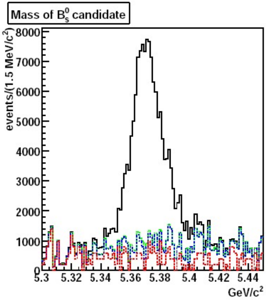
$B_s \to J/\Psi\phi$

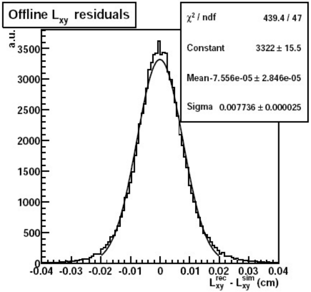
- Study properties of B_s system
  - width and mass difference of two weak eigenstates: $\Delta\Gamma_s$, Δm_s
  - height of the Unitarity Triangle (η) and possible hint for NP: $\phi_{CKM} = 2\lambda^2\eta \sim 0.03_{SM}$
- Trigger
  - L1: dimuon with $p_T > 3$ GeV
  - HLT 1: partial ($\sim$6hits) track reconstruction
  - HLT 2: J/Ψ and vertices reconstruction
  - HLT 3: kinematical (p_T, mass) and topological (L_{xy}, $\Delta\alpha$ etc) cuts
  - HLT 4: ϕ and B_s reconstruction and corresponding cuts
- Off-line Analysis
  - almost the same as HTL but with complete information
  - angular analysis to measure $\Delta\Gamma_s$
- Results
  - $\sim$10k events collected @ 1.3 fb^{-1}
  - Rel. errors on $\bar{\Gamma}_s$, $\Delta\Gamma_s$, $\Delta\Gamma_s/\bar{\Gamma}_s$ are 3.4%, 19%, 20%

$B_s \longrightarrow J/\Psi\phi$

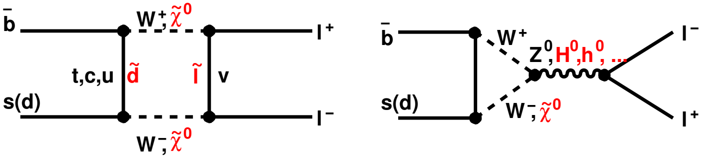
$\Delta m_\phi \sim 3\,\text{MeV}/c^2$ | $\Delta m_{B_s} \sim 14\,\text{MeV}/c^2$ | $\sigma_{sv} \sim 77\,\mu\text{m}$







$B^0 \to \mu^+\mu^-$: Motivation



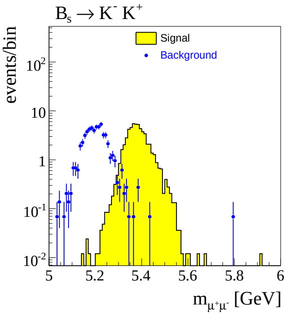
- Highly supressed in SM: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$= $(3.42 \pm 0.54) \times 10^{-9}$
- Sensitive to BSM: $\mathcal{B} \propto \tan^6\beta$ (MSSM) or $\tan^4\beta$ (2HDM)
- 'Measurements' of $\tan\beta$
- Current limit: $\mathcal{B} \leq 0.8 \times 10^{-7}$ at 90% C.L. (CDF public note 8176)

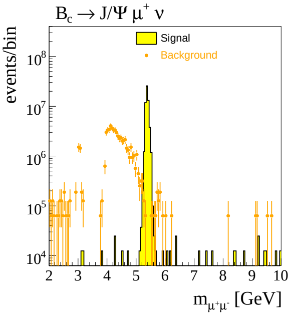
$B^0 \to \mu^+\mu^-$: Fully simulated channels

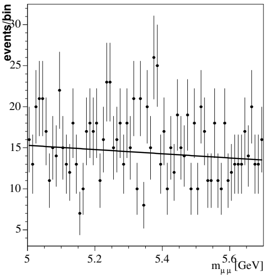
Sample	Generator cuts/channels	N_{Gen}	σ_{vis} [fb]	$N_{\mu ID} in 10\,\mathbf{fb}^{-1}$
$B_s^0 \to \mu^+\mu^-$	$p_\perp{}^\mu > 3$ **GeV**, $\lvert\eta^\mu\rvert < 2.4$	5000		390
$b\bar{b} \to \mu^+\mu^- + X$	$p_\perp{}^{\mu\mu} > 5$ **GeV**, $p_\perp{}^\mu > 3$ **GeV**, $\lvert\eta^\mu\rvert < 2.4$ $5 < m_{\mu\mu} < 6$ **GeV**, $0.3 < \Delta R(\mu\mu) < 1.8$	**14472**	1.74E + 07	1.74×10^8
B_s **decays**	$B_s \to K^- K^+$	1000	2.74E + 05	274
	$B_s \to \pi^-\pi^+$	1000	9.45E + 03	3
	$B_s \to K^-\pi^+$	1000	3.08E + 04	16
	$B_s \to K^-\mu^+\nu$	1000	2.80E + 05	2.80×10^4
	$B_s \to \mu^+\mu^-\gamma$	1000	1.29E + 01	130
	$B_s \to \mu^+\mu^-\pi_0$	1000	3.77E + 01	377
B_d **decays**	$B_d \to \pi^-\pi^+$	1000	8.34E + 04	21
	$B_d \to \pi^- K^+$	1000	3.74E + 05	187
	$B_d \to \pi^-\mu^+\nu$	1000	1.25E + 06	6.25×10^4
B_u **decay**	$B_u \to \mu^+\mu^-\mu^+\nu$	1000	2.24E + 03	2.24×10^4
B_c **decays**	$B_c \to \mu^+\mu^-\mu^+\nu$	1000	2.01E + 01	201
	$B_c \to J/\Psi\mu^+\nu$	1000	1.89E + 03	1.89×10^4
Λ_b **decays**	$\Lambda_b \to p\pi^-$	1000	4.22E + 03	1
	$\Lambda_b \to pK^-$	1000	8.45E + 03	1
QCD hadrons	$5 < M(hh) < 6$ **GeV**	4000	2.24E + 11	1.12×10^8

B decays before selection cuts

$b\bar{b} \to \mu^+\mu^- + X$







$B^0 \to \mu^+\mu^-$: Result

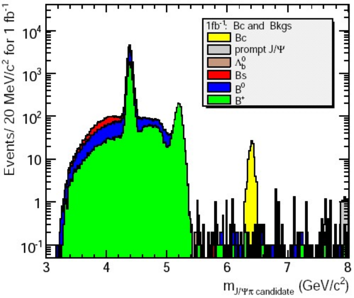
- Signal selection efficiency $\varepsilon_S = 0.019 \pm 0.002_{stat}$
  In 10 fb^{-1}: $n_S = 6.1 \pm 0.6$ signal events
- Background rejection $\varepsilon = 2.6 \times 10^{-7}$
  In 10 fb^{-1}: $n_B = 13.8^{+22.0}_{-13.8}$ background events
- Extract upper limit with Bayesian procedure (CDF)

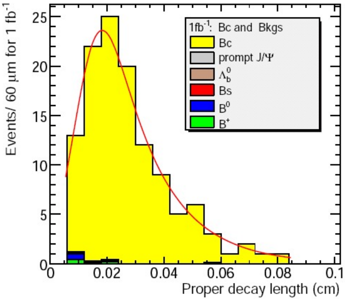
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{\text{gen}}\, \varepsilon_{\text{total}}\, N_{B_s}}$$

$$\leq 1.4 \times 10^{-8} (90\% C.L.)$$

$B_c^{\pm} \to J/\Psi\pi^{\pm}$

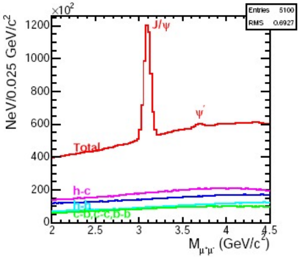
- Measure mass and life time of B_c in decay
  - **120** $J/\Psi\pi^{\pm}$ **selected in 1 fb**$^{-1}$
  - **mass resolution** $22.0(stat) \bigoplus 14.9(sys)$ **MeV/**c^2 **(**$M(B_c) \sim 6.4$ **GeV/**c^2**)**
  - **lifetime error** $44(stat) \bigoplus 10(sys)$ **fs (**$\tau(B_c) \sim 460$ **fs)**

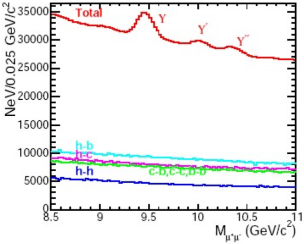




PbPb$\rightarrow Q\bar{Q} + X \rightarrow \mu^+\mu^- + X$

- Measure production x-section of J/Ψ and Υ families
  - **colour screening effect for different $Q\bar{Q}$ states**
  - **gluon saturation effect on low-x nuclear PDFs**
- After 1 month ($0.5\,\mathrm{nb}^{-1}$)
  - **$\sim$180000 J/ψ and $\sim$25000 Υ**
  - **All Υ states measured down to $p_T = 0$ GeV/c**
  - **J/ψ states measured down to $p_T \approx 4$ GeV/c**





Credits

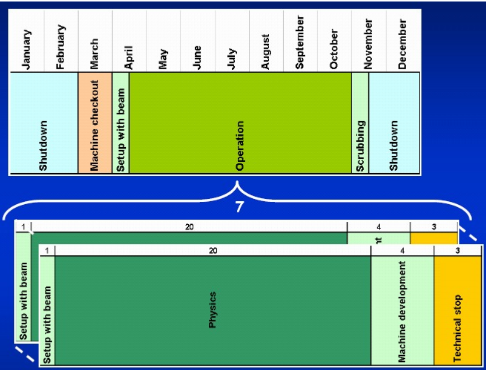
- **Andrea Bocci, CMS TS-2006/004 – Jet flavour tagging with the CMS experiment**
- **Stefan Koenig, pixel material budget plots**
- **Ferenc Sikler, CMS CR 2007/007 – Low p_T Hadronic Physics with CMS**
- **Valery Andreev et al, CMS Note 2006/120 – Measurement of open beauty production at LHC with CMS**
- **Thomas Speer et al, CMS Note 2006/121 – Study of the decay $B_s^0 \rightarrow J/\Psi\phi \rightarrow \mu^+\mu^-K^+K^-$**
- **Urs Langenegger et al, CMS CR-2006/071 – Study of $B^0 \rightarrow \mu^+\mu^-$ in CMS**
- **Guoming Chen et al, CMS Note 2006/118 – Feasibility to study the B_c meson at CMS**
- **Olga Kodolova et al, CMS Note 2006/089 – Quarkonia measurements in heavy-ion collisions in CMS**

Conclusion

- HF plays an important role in Physics programm of CMS
- CMS detector allows successful HF programm thanks to
  - **Muon trigger system: dimuon trigger for very low $p_T(\mu) > 3$ GeV/c**
  - **Tracker system: very good momentum (~1%) and hence mass resolution**
  - **Vertex system: high impact parameter ($20 - 100\ \mu$m) and vertex resolutions**
- CMS is ready to
  - **Study properties of HF states (B_s, B_c etc)**
  - **Search for New Physics in rare B decays**
  - **HF (b jets) is a powerful ingredient for Higgs, SUSY searches**
  - **HF (quarkonia) provide a way to investigate properties of high-density QCD matter**

Backup

Breakdown of a normal year (R.Bailey)



~ 140 days for physics per year
Not forgetting ion and TOTEM operation
Leaves ~ 100 days for proton luminosity running
? Efficiency for physics 40% ?
~ 40 days ~ 1000 h ~ 4 10^6 s of colliding beams / year

PYHTIA 6.2 Tunes

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Use LO α_s with Λ = 192 MeV!

K-factor (Sjöstrand)

UE Parameters

ISR Parameter

Intrensic KT

Parameter	Tune DW	Tune DWT	ATLAS	Tune QW	Tune QWT	Tune QK	Tune QKT
PDF	CTEQ5L	CTEQ5L	CTEQ5L	CTEQ6.1	CTEQ6.1	CTEQ6.1	CTEQ6.1
MSTP(2)	1	1	1	1	1	1	1
MSTP(33)	0	0	0	0	1	1	1
PARP(31)	1.0	1.0	1.0	1.0	1.0	1.8	1.8
MSTP(81)	1	1	1	1	1	1	1
MSTP(82)	4	4	4	4	4	4	4
PARP(82)	1.9 GeV	1.9409 GeV	1.8 GeV	1.1 GeV	1.1237 GeV	1.9 GeV	1.9409 GeV
PARP(83)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.5	0.4	0.4	0.4	0.4
PARP(85)	1.0	1.0	0.33	1.0	1.0	1.0	1.0
PARP(86)	1.0	1.0	0.66	1.0	1.0	1.0	1.0
PARP(89)	1.8 TeV	1.96 TeV	1.0 TeV	1.8 TeV	1.96 TeV	1.8 TeV	1.96 TeV
PARP(90)	0.25	0.16	0.16	0.25	0.16	0.25	0.16
PARP(62)	1.25	1.25	1.0	1.25	1.25	1.25	1.25
PARP(64)	0.2	0.2	1.0	0.2	0.2	0.2	0.2
PARP(67)	2.5	2.5	1.0	2.5	2.5	2.5	2.5
MSTP(91)	1	1	1	1	1	1	1
PARP(91)	2.1	2.1	1.0	2.1	2.1	2.1	2.1
PARP(93)	15.0	15.0	5.0	15.0	15.0	15.0	15.0

CMS GENERATOR TOOLS Meeting February 27, 2007

Paolo Bartalini on behalf of Rick Field – Florida/CMS

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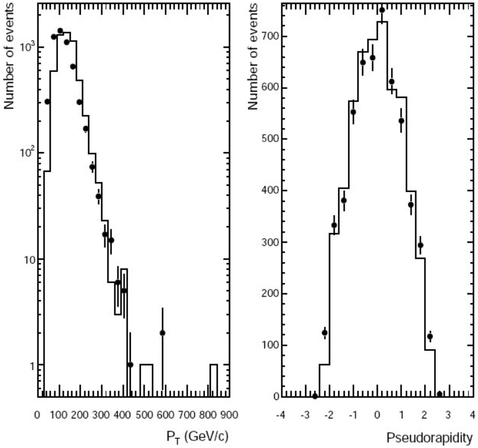
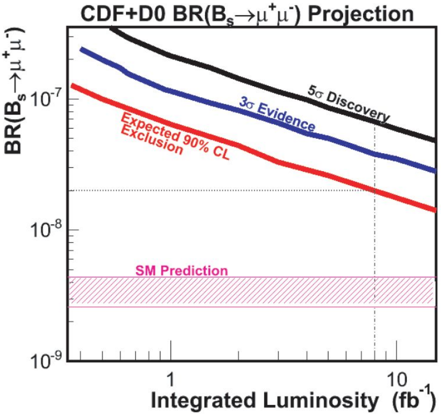
Reco b-jet vs Gen B-particle




CDF+D0 BR($B_s \to \mu^+\mu^-$) Projection
BR($B_s \to \mu^+\mu^-$)
10^{-7}
10^{-8}
10^{-9}
5σ Discovery
3σ Evidence
Expected 90% CL Exclusion
SM Prediction
1
10
Integrated Luminosity (fb^{-1})