Flavor Physics Techniques and Sensitivities At ATLAS and CMS

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LHC Schedule

Month	No. Bunches	Protons per bunch	β* [m]	% Nom	Peak luminosity cm-2s-1	Integrated luminosity
1	Beam Commissioning					
2	43	3×10^{10}	4	0.4	1.2×10^{30}	100 – 200 nb^{-1}
3	43	5×10^{10}	4	0.7	3.4×10^{30}	~2 pb^{-1}
4	156	5×10^{10}	2	2.5	2.5×10^{31}	~13 pb^{-1}
5	156	7×10^{10}	2	3.3	4.9×10^{31}	~25 pb^{-1}
6	720	3×10^{10}	2	6.7	4.0×10^{31}	~21 pb^{-1}
7	720	5×10^{10}	2	11.2	1.1×10^{32}	~60 pb^{-1}
8	720	5×10^{10}	2	11.2	1.1×10^{32}	~60 pb^{-1}
9	720	5×10^{10}	2	11.2	1.1×10^{32}	~60 pb^{-1}
10	Ions					
Total						200 – 300 pb^{-1}

From R.Bailey, April 2009 Oxford IoP

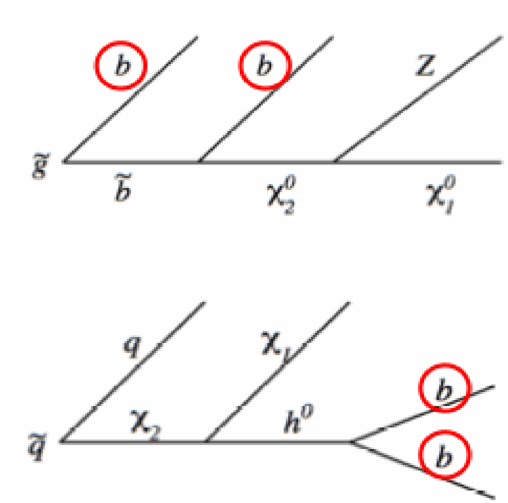
careful: delivered lumi != lumi usable for physics

CMS:
50000 J/Ψ
12000 $b \rightarrow J/\Psi X$
20000 Υ
~350 $B \rightarrow J/\Psi K$
~200 $B \rightarrow J/\Psi K^*$

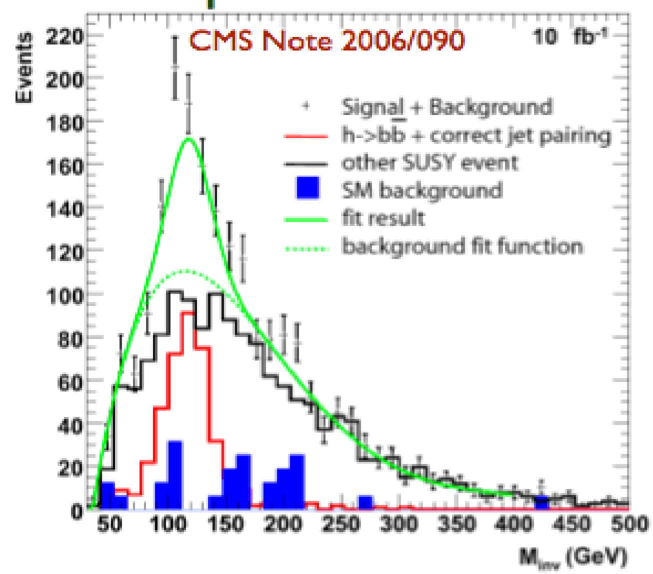
- Collect $\mathcal{O}$(100 pb^{-1}) in 2009-2010 Run @ 10 TeV
- Use them for physics, focus on detector and trigger commissioning
- Getting ready for physics Run in 2011
- Heavy Flavor physics will help!
  Large data samples for quarkonia and B studies within the first month

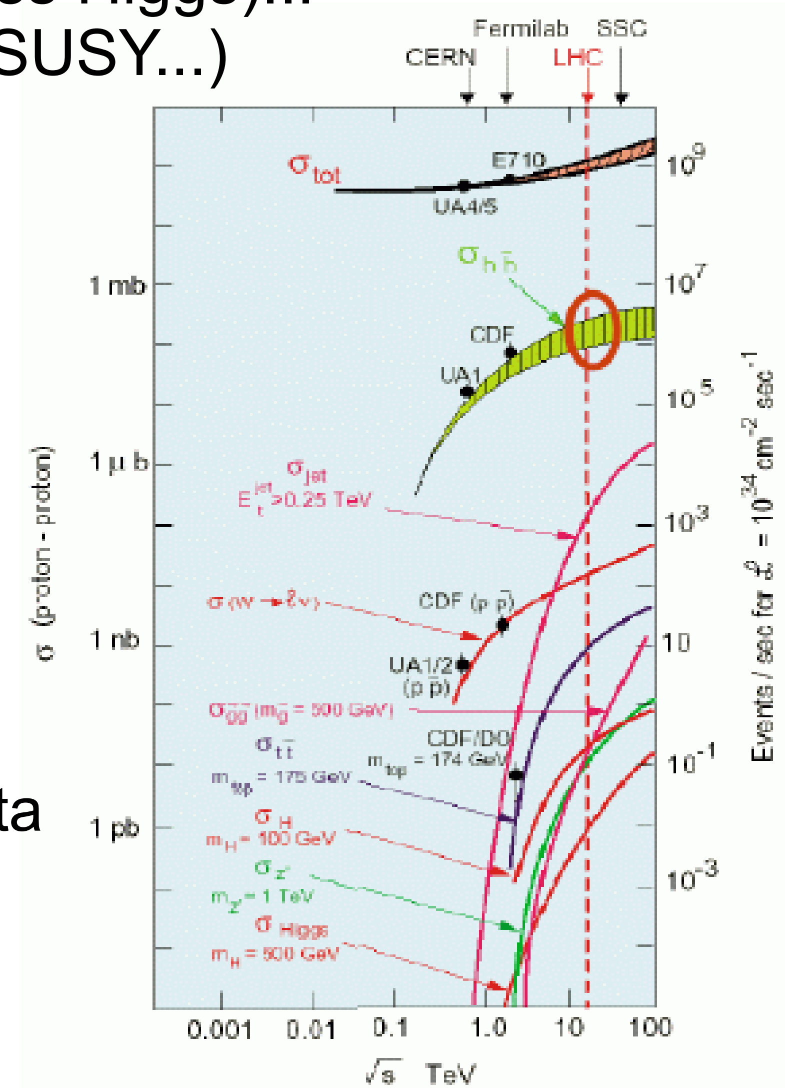
Why study b production at LHC?

- b quarks are a key ingredient at LHC
  either as direct signal (top physics, low mass Higgs)...
  Or background to New Physics searches (SUSY...)



example h^0 at LM5:



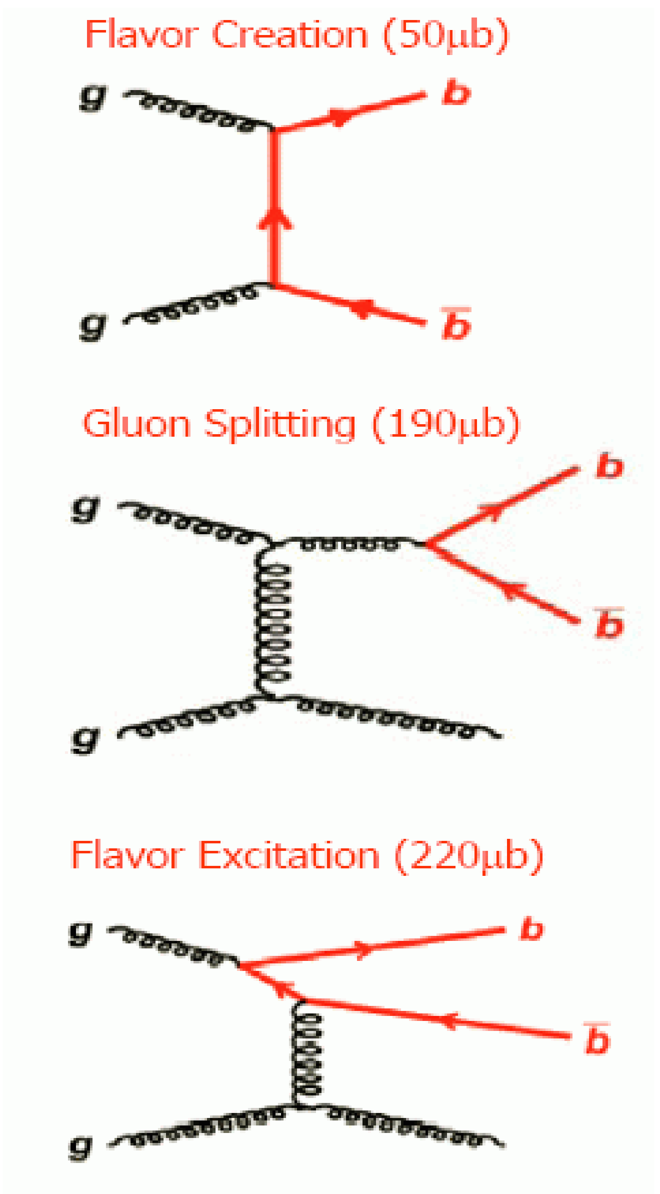


- Large bb cross-section allow study of b production and bb correlations with early data
- Test of QCD predictions at LHC energy
- Test detector performance: help with calibration, alignment, trigger

b production mechanisms

- Three dominant production mechanisms:
  LO:
  Flavor Creation (FC): gluon fusion (dominant) and qq annihilation
  NLO:
  Flavor Excitation (FE): $b\bar{b}$ from the sea, only one b participates to the hard scatter, asymmetric p_T for the b's
  Gluon Splitting (GS): $g \rightarrow b\bar{b}$ in initial or final state, b at low p_T and close in the azimuthal angle ($\Delta\phi$)

- Measurement of b production:
  Differential cross-section $d\sigma/dp_T$, $d\sigma/d\eta$
- $b\bar{b}$ correlations:
  Azimuthal correlation between the two b's (high sensitivity to NLO/LO ratio)



b production at the Tevatron

- Studied since the first data in late 80s
- Single b production

Exclusive, fully reconstructed $B \rightarrow J/\Psi K$ — CDF PRL 75, 1451(1995)

Inclusive $b \rightarrow J/\Psi X$ (lifetime) — CDF PRL 79, 572(1997)

Inclusive $b \rightarrow (e,\mu)X$ (impact parameter) — CDF PRL 71, 2396(1993), D0 PRL 74, 3548 (1995)

Inclusive $b \rightarrow \mu$+jet — D0 PRL 85, 5068(2000)

- Correlated $b\bar{b}$ production

Dimuons (impact parameter) — CDF PRD 55, 2546(1997), D0 PLB 487, 264 (2000)

J/Ψ +lepton (lifetime + impact parameter)

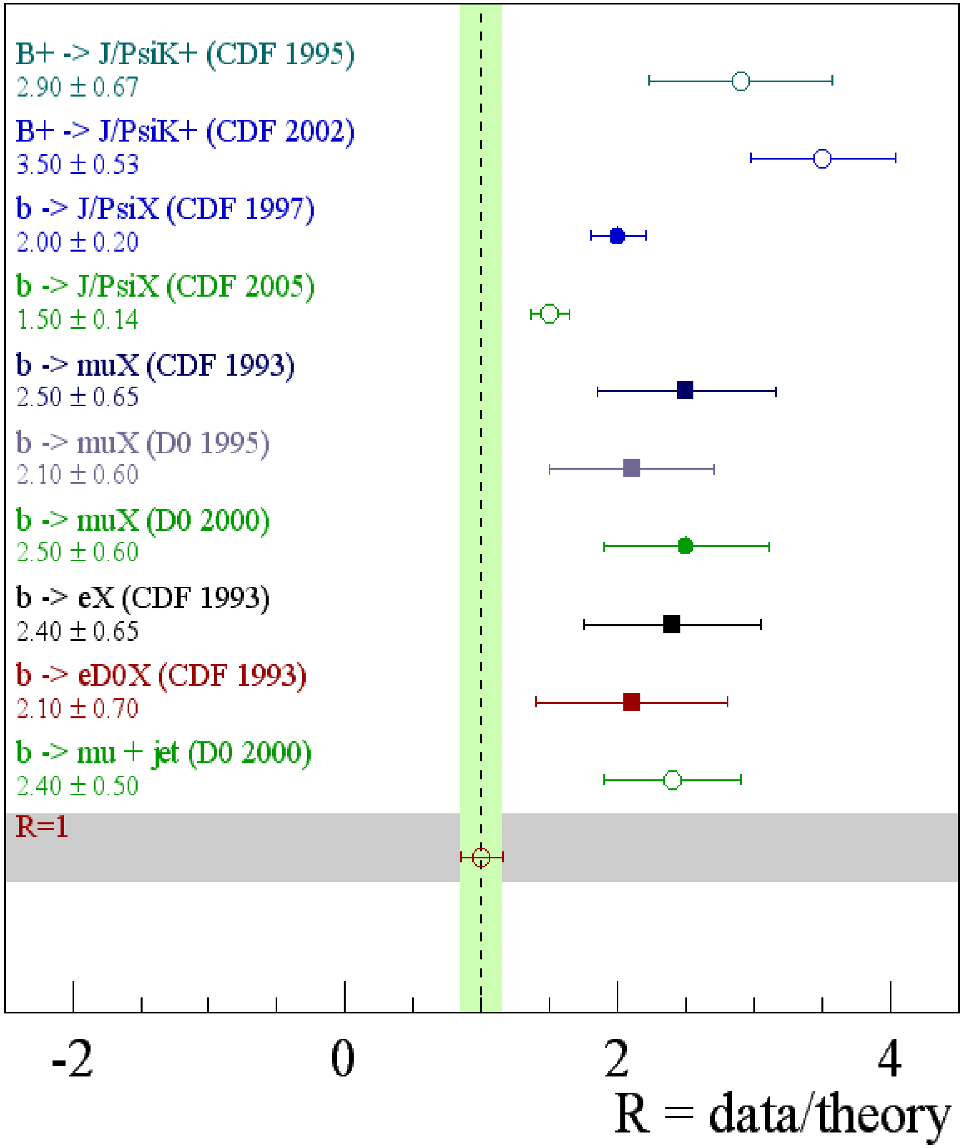
μ + b-tagged jet (secondary vertex) — CDF PRD 53, 1051(1996)

Two b-tagged jet — CDF PRD 69, 072004(2004)

Results have been compared with “classic” NLO QCD (MNR), and newer FONLL (Cacciari et al., JHEP 0407,033) to determine If QCD correctly predicts the data

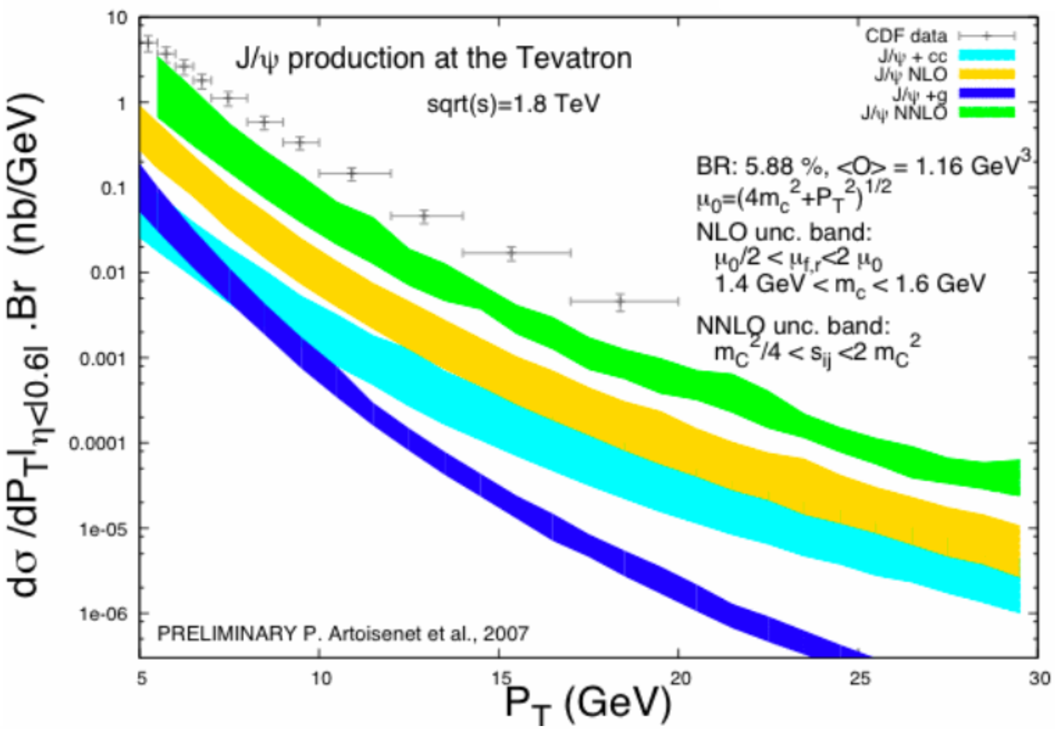
b production at the Tevatron

- We quote the ratio R=data/theory, as reported by Happacher *et al.* (PRD 73, 014026), who performed a consistent evaluation of all existing data as of 2006 using a common theory benchmark
- Data consistently above simulation
- Agreement improves slightly at large p_T
- Problem even in D0 μ+jet that should be less sensitive to the exact features of the b fragmentation

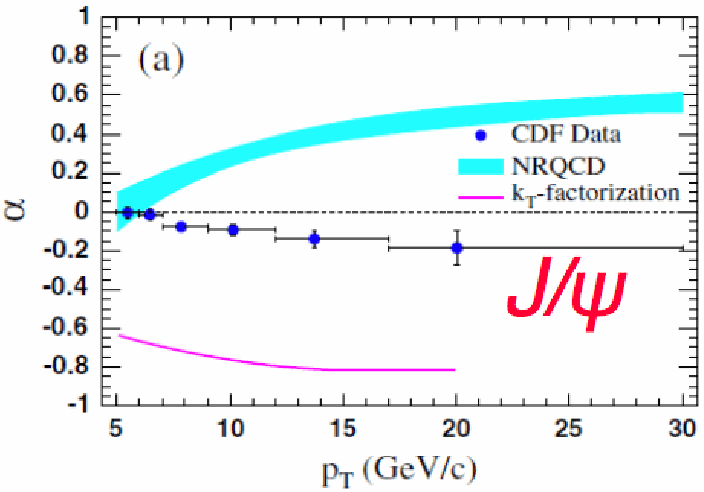


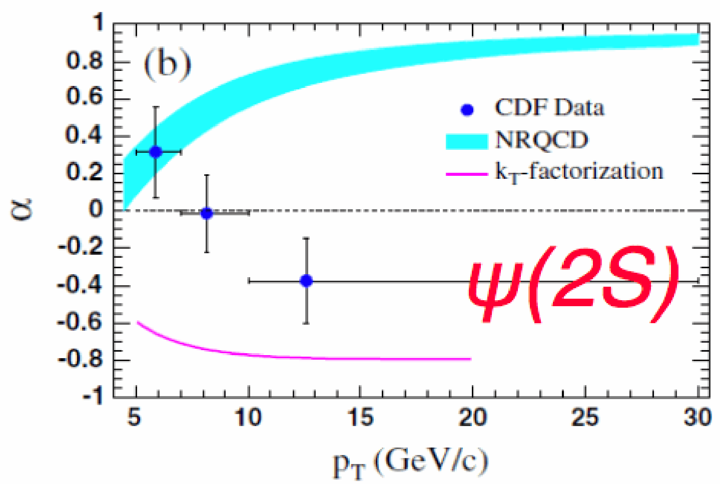
The Quarkonia Puzzle

- Direct J/Ψ production not understood:
  No model explains cross-section and polarization simultaneously.
- Many models on the market:
  CSM (Color Singlet Model): LO,NLO,NNLO
  COM (Color Octet Mechanism): NRQCD
  ...many more



Measurement of J/Ψ and ϒ cross-sections and polarization at the LHC desirable





Heavy Flavor Physics @ ATLAS and CMS

Analysis Examples:

- Cross-section for bottom, charm and quarkonia
  Inclusive J/Ψ, Exclusive B decays ($J/\Psi K^{(*)}$)
- Quarkonia studies: polarization, production mechanisms
- bb correlations:
  - $J/\Psi+\mu$
  - μ + jet
  - jet + jet
- Lifetime and properties of b hadrons: $B_u, B_d, B_s, B_c, \Lambda_b$
- B_s oscillations, CP violation
- FCNC rare decays: $B \to K^{(*)}\mu\mu$, $B_s \to \Phi\mu\mu$
- FCNC very rare decays: $B_{s/d} \to \mu\mu$
- $\tau \to 3\mu$ LFV

$O(10\ pb^{-1})$

$O(100\ pb^{-1})$

$O(1\ fb^{-1})$

$O(10\ fb^{-1})$

$\int \mathcal{L} dt$

Trigger @ CMS

Level 1 Triggers:
Hardware based
Muons and Calorimeters
40 MHz → 200 kHz

High Level Triggers (L2,L3):
Software based
Fast (local) reconstruction in the tracker included
200 kHz → 100 Hz

- Different trigger menu under study, depending on the luminosity (e.g. 8E29, 1E31...)

Relevant Triggers for heavy flavor physics:

- Dimuon triggers

  L1: 2 muons p_T > 3 GeV/c (2μ3)

  HLT:Normal dimuon trigger: 2 muons p_T>3 GeV/c

  Displaced dimuon vertex trigger

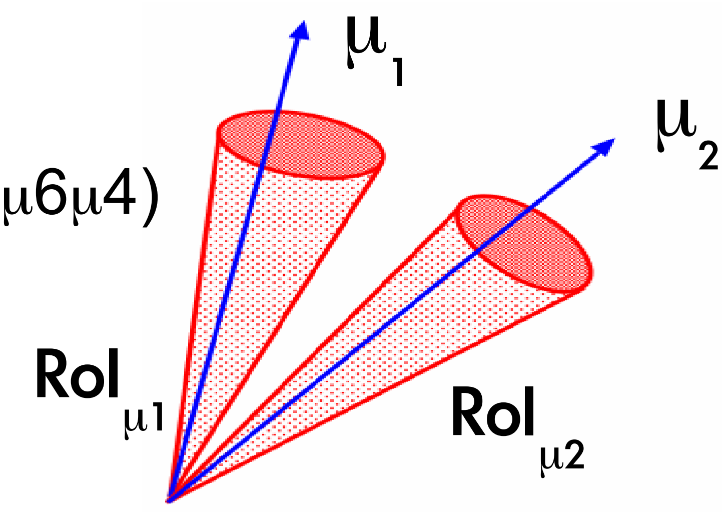
- Single muon triggers

  L1 & HLT: 1 muon with p_T> 9 GeV/c (lower thresholds available, with varying pre-scaling factors)

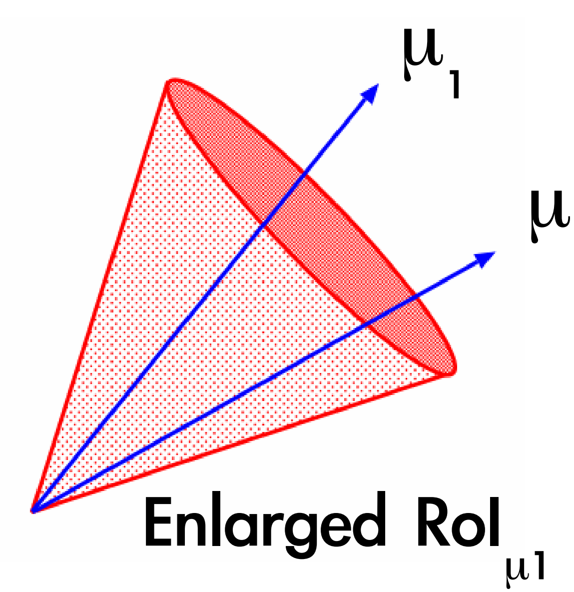
Trigger @ ATLAS

Relevant Triggers for heavy flavor physics:

- TrigDimuon Trigger
  L1: 2 muons $p_{T\mu 1}$ > 6 GeV/c, $p_{T\mu 2}$ > 4 GeV/c (μ6μ4)
  Startup: also μ4μ4
  L2: 2 muons confirmed in small Region of Interest (RoI) around L1 muons



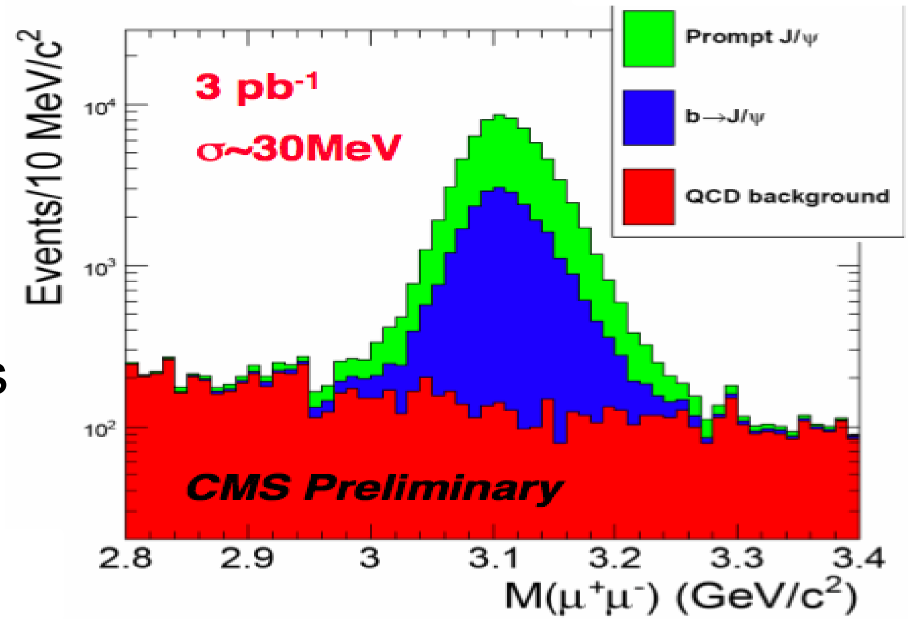
- Topological Trigger
  L1: 1 muon $p_{T\mu 1}$ > 10 GeV/c: (1μ10)
  Startup: also lower
  L2: different possibilities
  2nd muon at L2 found in enlarged RoI around L1 muon
- Tracks/e/gamma reconstructed in RoI around L1 for hadronic final states

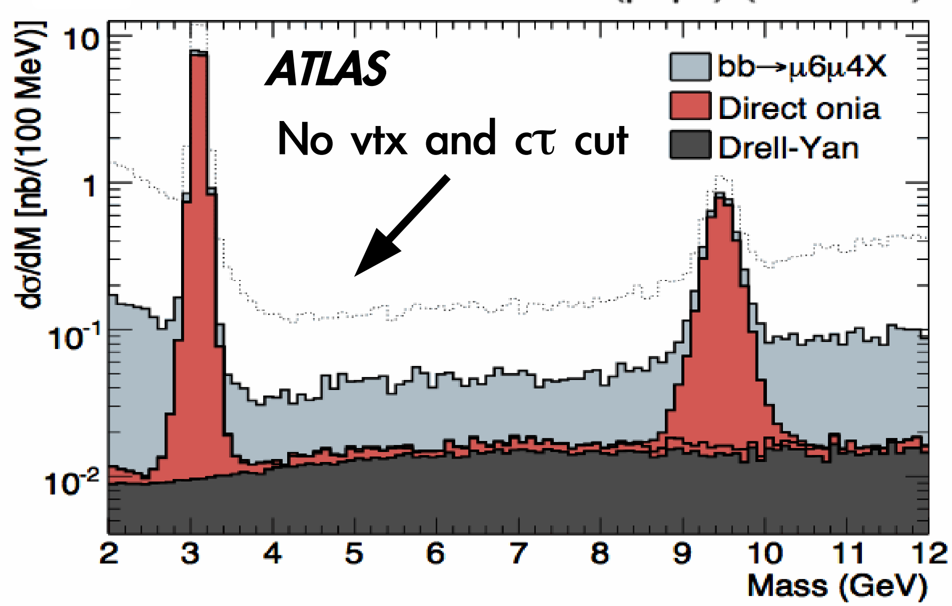


Quarkonium Studies @ Start-up

- Large J/Ψ and ϒ yields with 𝒪(pb^{-1}) data
  Inclusive J/Ψ approach:
- Trigger @ CMS:
  L1: 2μ3, no sensitivity to p_T(J/Ψ) < 5 GeV/c
  HLT: fast J/Ψ reconstruction, invariant mass cut
  Offline: vertex and invariant mass cuts
  Total Eff up to 65% at high p_T
- Trigger @ ATLAS:
  Dimuon trigger: μ6μ4, startup: μ4μ4
  Offline: vertex and invariant mass cuts
  Acceptance up to 80% at high p_T

J/Ψ	CMS	ATLAS
Yield/pb^{-1}	~25000	~15000
Mass Resol.	~30 MeV	~54 MeV
Trigger	2μ3	μ6μ4





J/Ψ Differential Cross-Section

- J/Ψ Production:
  Prompt: direct
  From prompt $\chi_{c0,1,2}$
  Non-prompt: from b-hadron decay

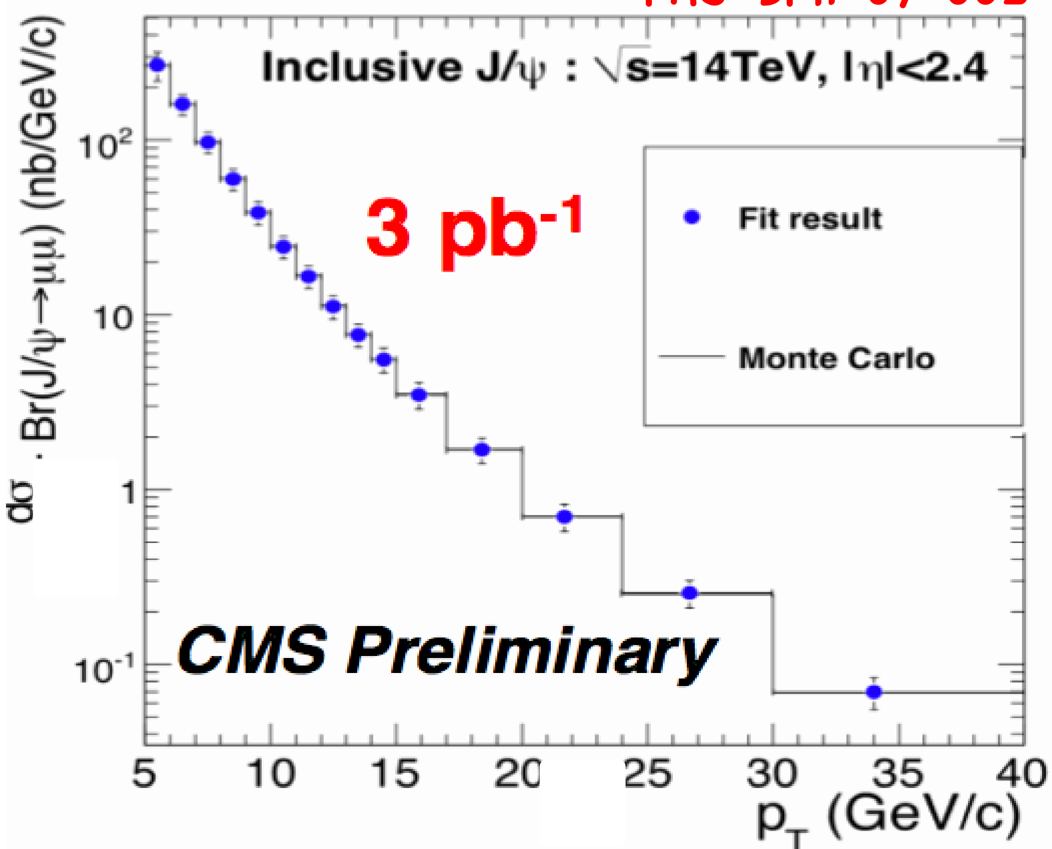
- Inclusive cross-section with 1-d fit to J/Ψ invariant mass

- Dominant systematic uncertainties: Luminosity, J/Ψ polarization, fit technique

- Data-driven approach to validate μ reco at low p_T (Tag And Probe)

With $\mathcal{O}(pb^{-1})$ competitive with the Tevatron, probe new p_T regime!

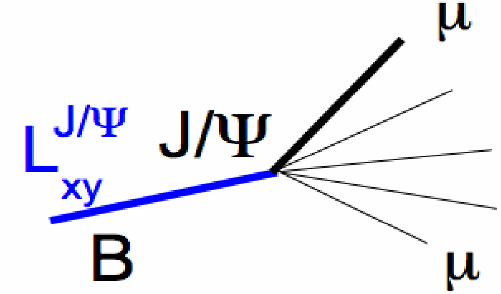
PAS BPH-07-002



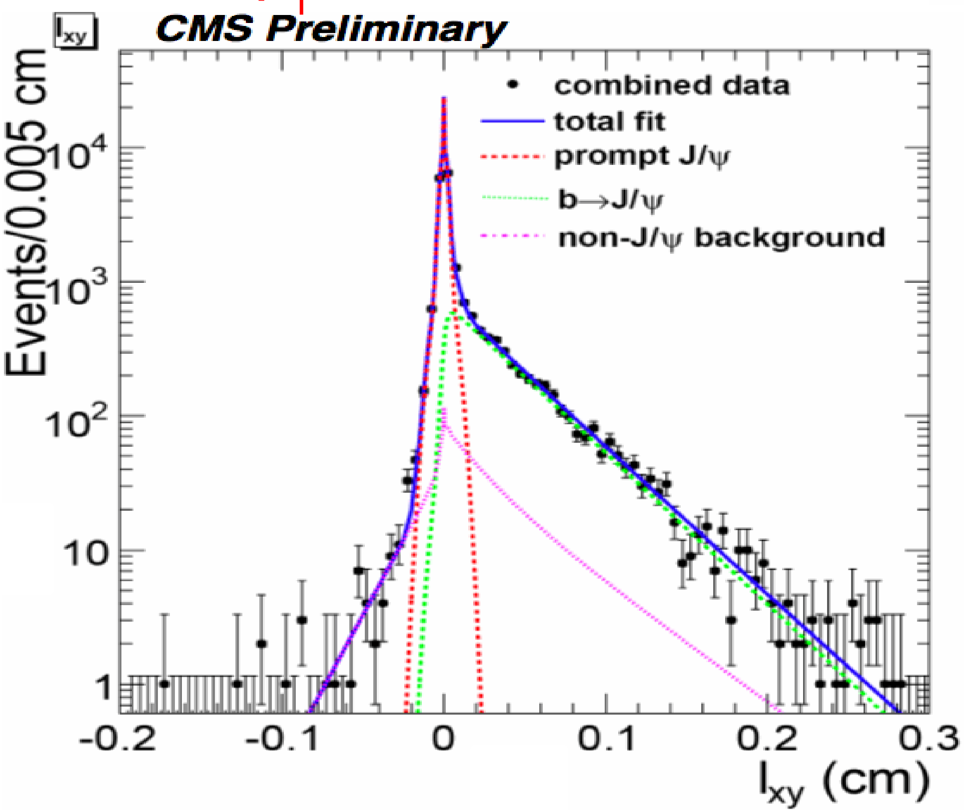
Prompt J/Ψ and b → J/ΨX

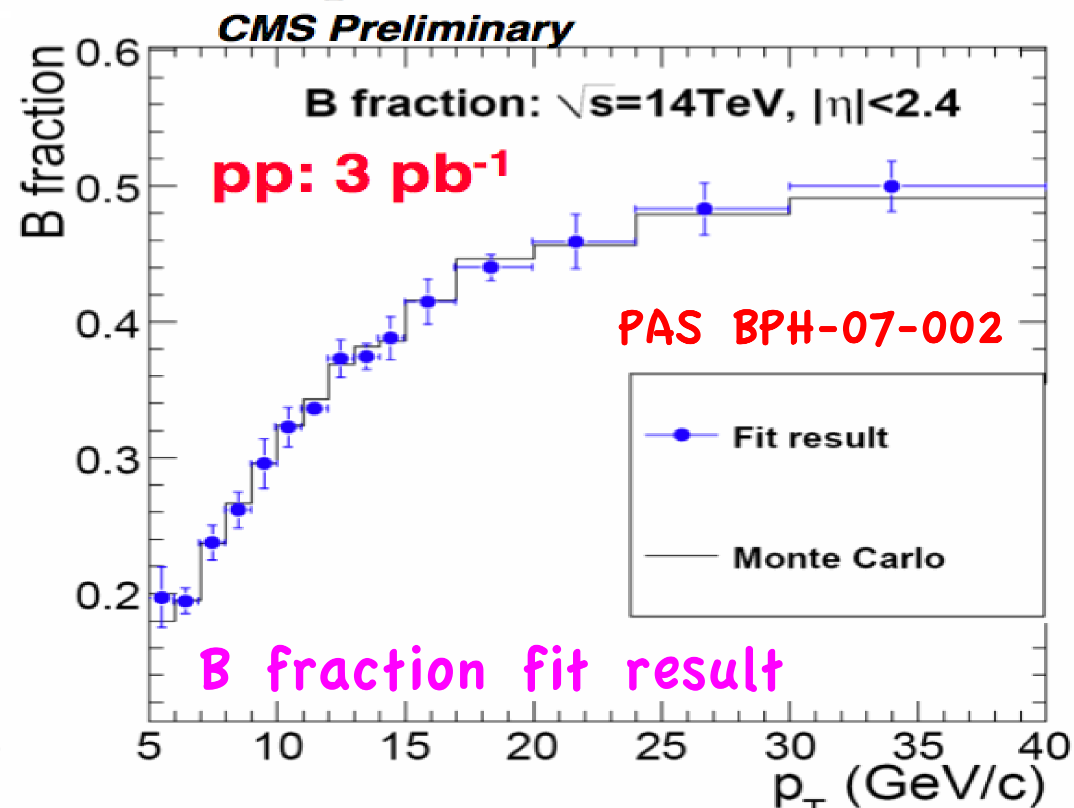
- Measure prompt and non-prompt contributions by 2-d unbinned LH fit to mass and pseudo proper-decay length
- Sensitive to alignment

$$\ell_{xy} = \frac{L_{xy}^{J/\Psi} \cdot M^{J/\Psi}}{p_T^{J/\Psi}}$$



Example of decay-length fit in J/Ψ p_T bin 9-10 GeV/c



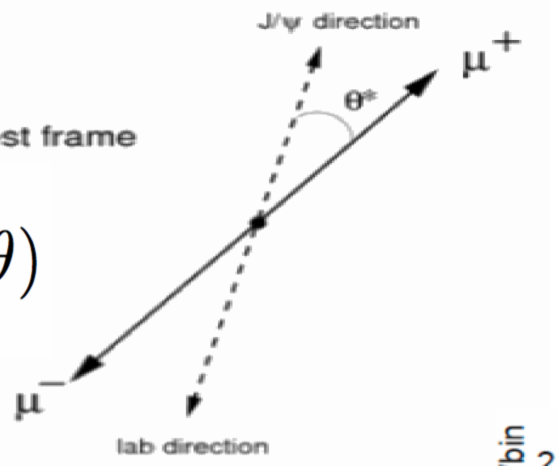


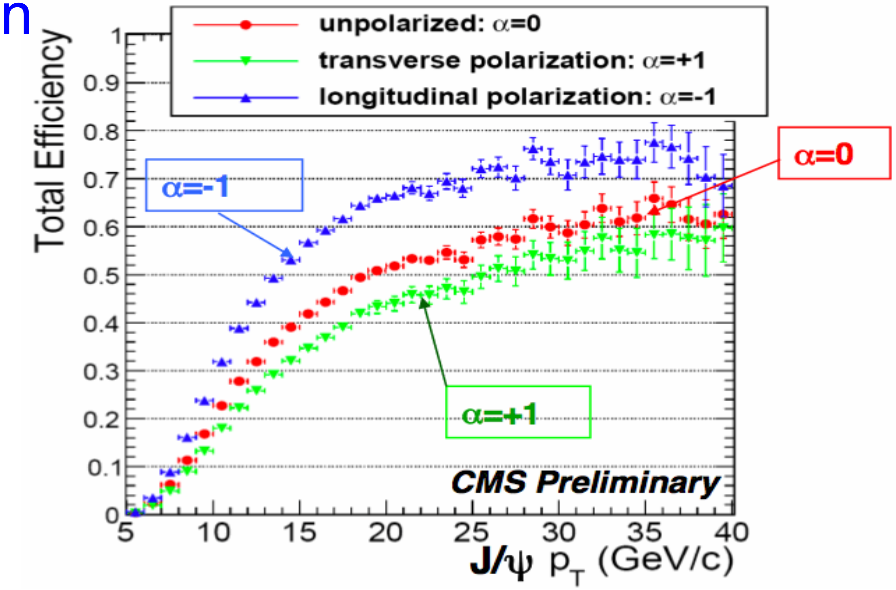
J/Ψ Polarization

Total efficiency depends on J/Ψ polarization

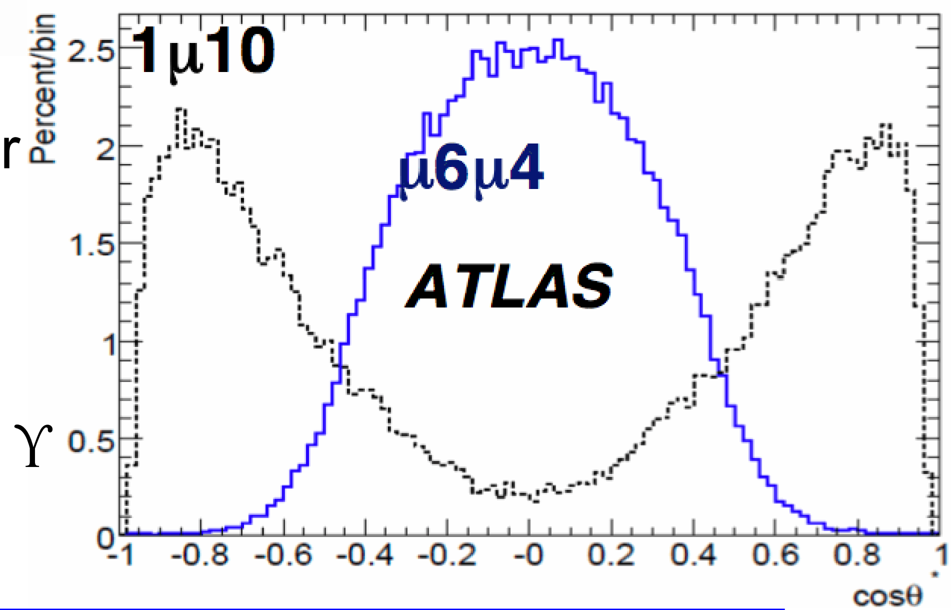
- Polarization measurements puzzling
  Tevatron data in disagreement with Color-Octet models

$$\frac{d\Gamma}{d\cos\theta} \propto (1 + \alpha\cos^2\theta)$$



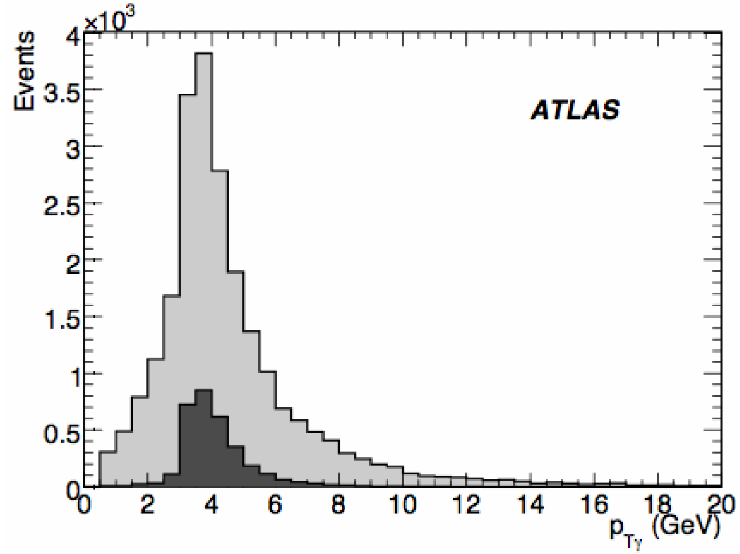


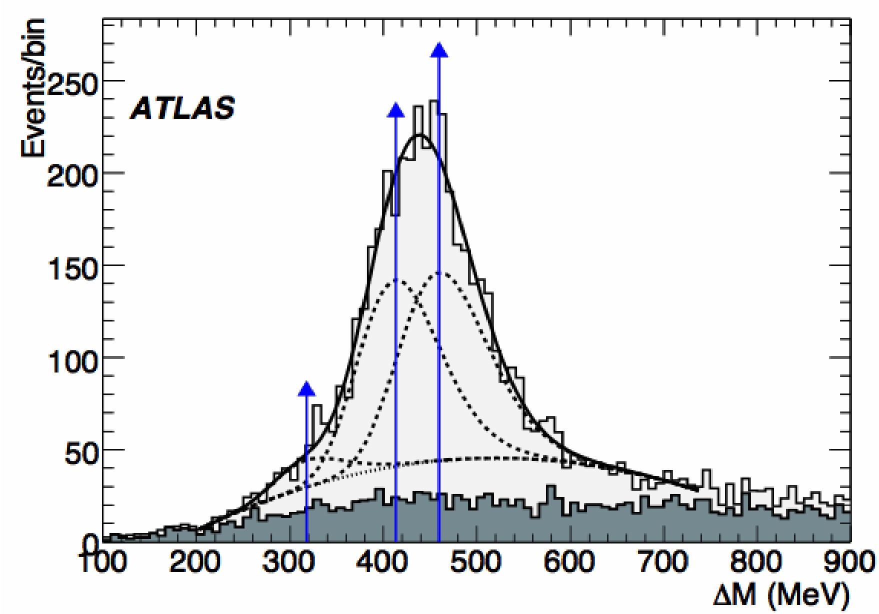
- Measure polarization with first data
  Problem with 2μ trigger: no sensitivity for |cos θ| =1 (asymmetric p_T)
  ATLAS propose to use μ6μ4 +1μ10
  Use track for second leg of J/Ψ
  Increase in bkg manageable for J/Ψ, for Υ use only 2μ trigger



χ_c Reconstruction @ATLAS

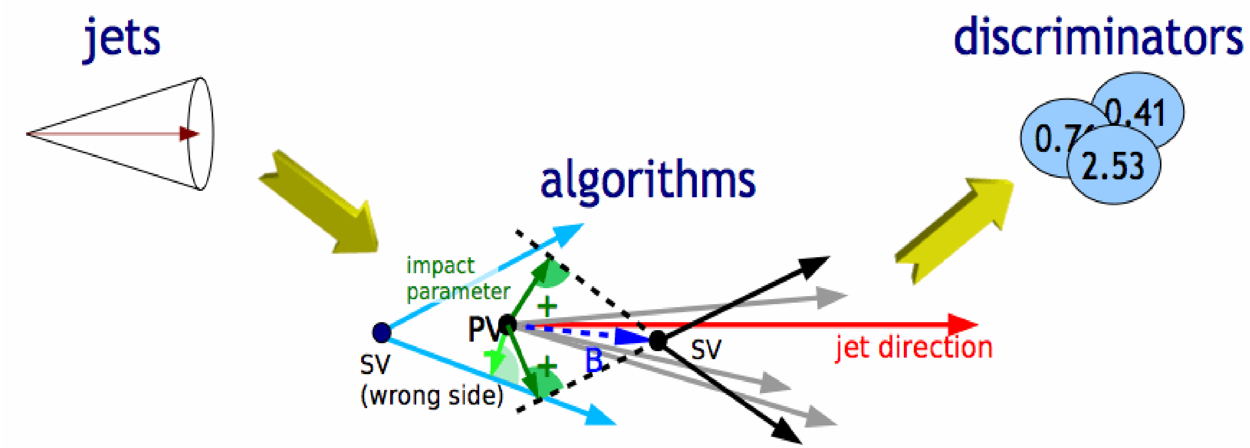
- About 30%(50%) of J/Ψ(ϒ) cross-section comes from χ_c (χ_b) feed-down
- For a complete understanding of production mechanism important to disentangle direct quarkonia production from $\chi_c \rightarrow J/\Psi\,\gamma$ feed-down
- Look for photon in narrow cone around J/Ψ direction (cos θ >0.97)
- Use μμγ-μμ invariant mass difference to measure χ_{c0},χ_{c1},χ_{c2} yields (fix mass differences to nominal value)
- More statistics (~1fb^{-1}) needed for $\chi_b \rightarrow \Upsilon\gamma$
- χ_b also studied in J/Ψ J/Ψ mode

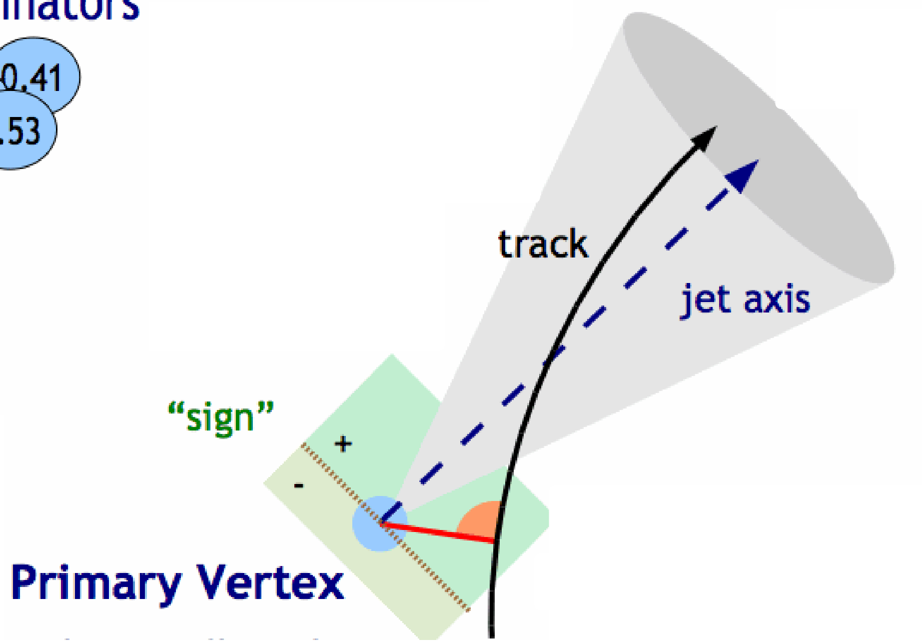




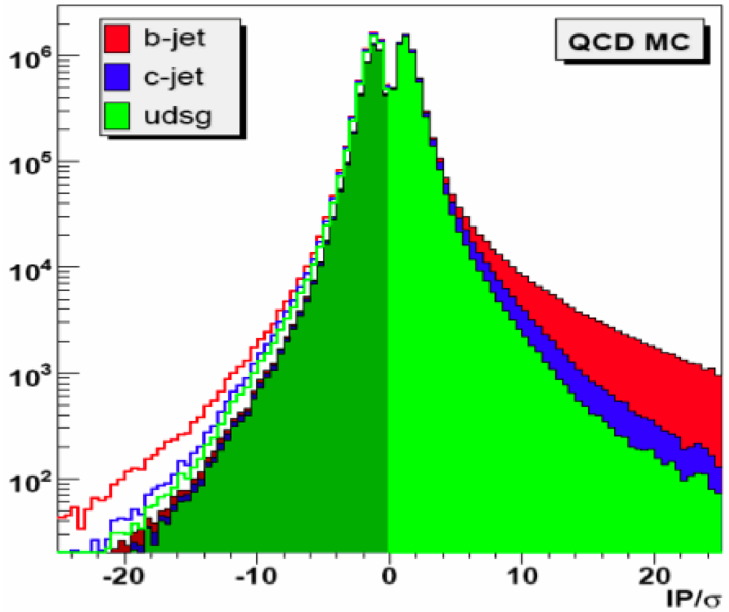
b Tagging with Early Data

Goal: identify b-decay in jet with high efficiency and low misidentification





CMS PAS BTV-07-002



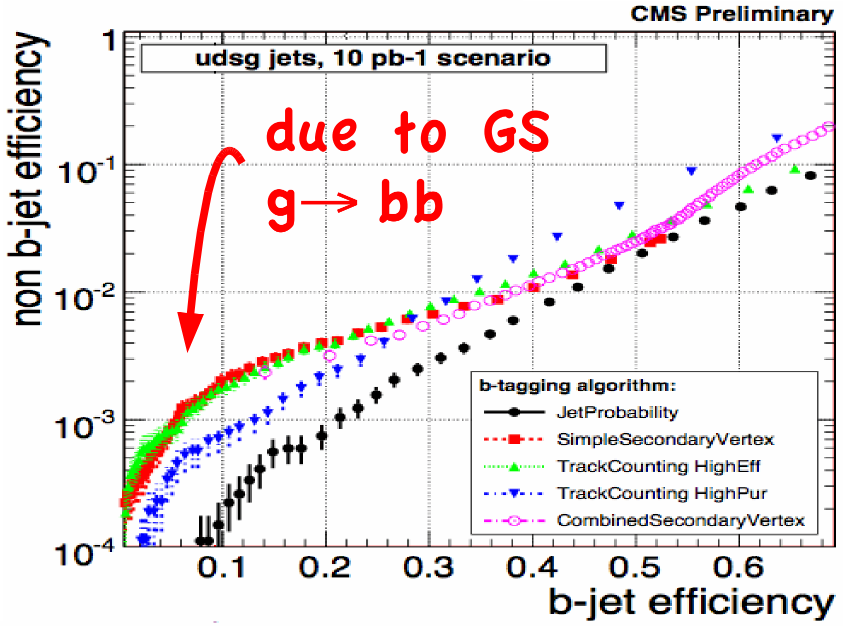
- Use Impact Parameter Significance (IP/σ) as discriminator
- Compute and sort IP/σ for all tracks in jet
- Use IP/σ of 2nd (3rd) track (higher efficiency/purity)
- Simple and fast, ok for HLT

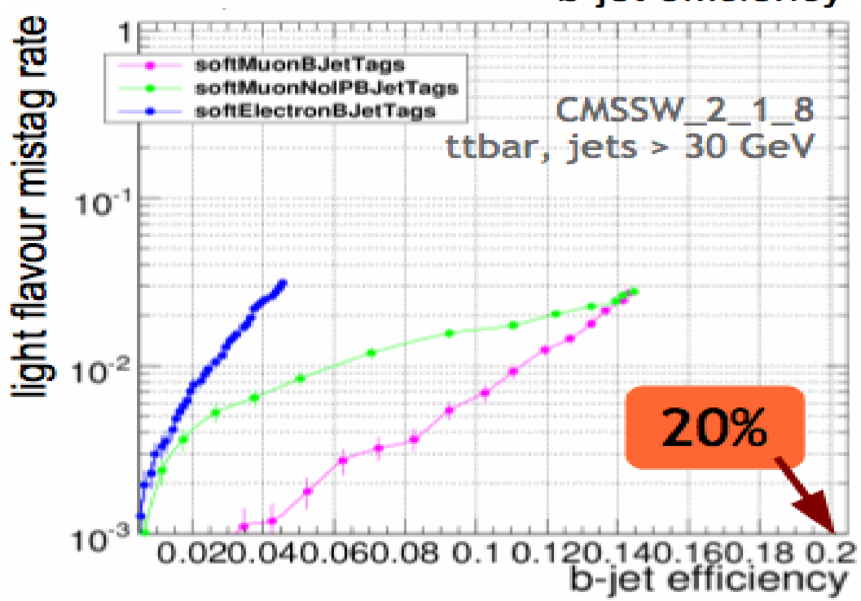
b Tagging

Other algorithms suitable for early data:

- Use presence of reconstructed Secondary Vertex as b-tag
- Use flight length measurement as discriminator
- Allows to define “negative vertex tag” for mis-tag measurements

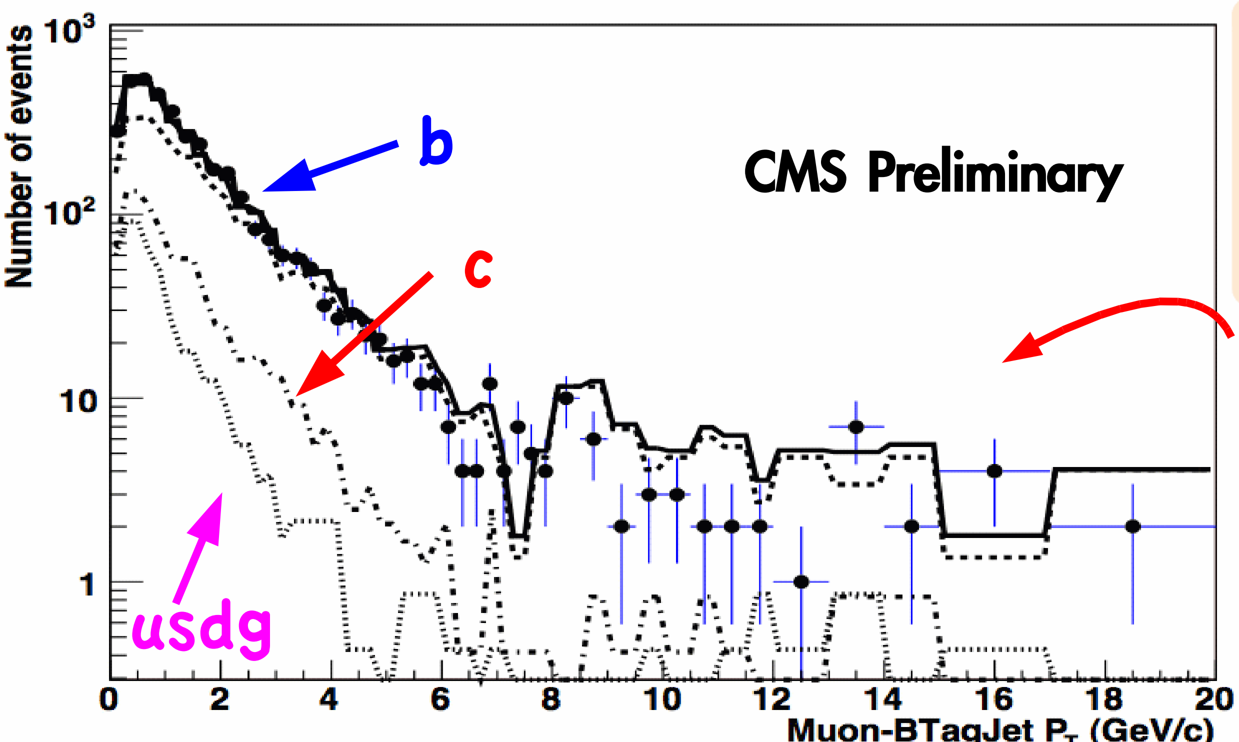
- Use leptons to tag b-jets
- 20% of B decays into lepton final states
- Needs leptons in jets, not isolated

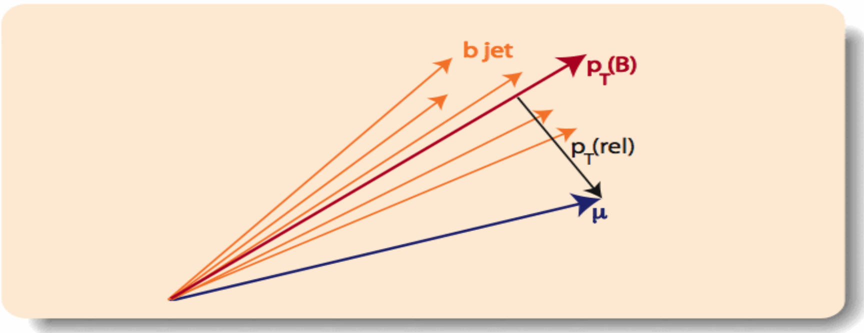




Inclusive b production (μ+Jet)

- Measure inclusive differential b cross-section: $d\sigma/d\eta$, $d\sigma/dp_T$
- CMS AN-2006-120: Study performed at 14 TeV collisions and high lumi
  HLT: μ + b-jet: 1 non isolated μ (with p_T>19 GeV/c) plus a b-tagging requirement on a jet (E_T>50 GeV and $|\eta|$<2.4, Track counting from pixel tracks)
- Select events with at least one b-tagged jet and one μ
  Select b-tagged jet with highest p_T, μ associated to jet (ΔR)





Use p_T(Rel) to distinguish between b,c,and light quark events

b purity between 55 and 70%

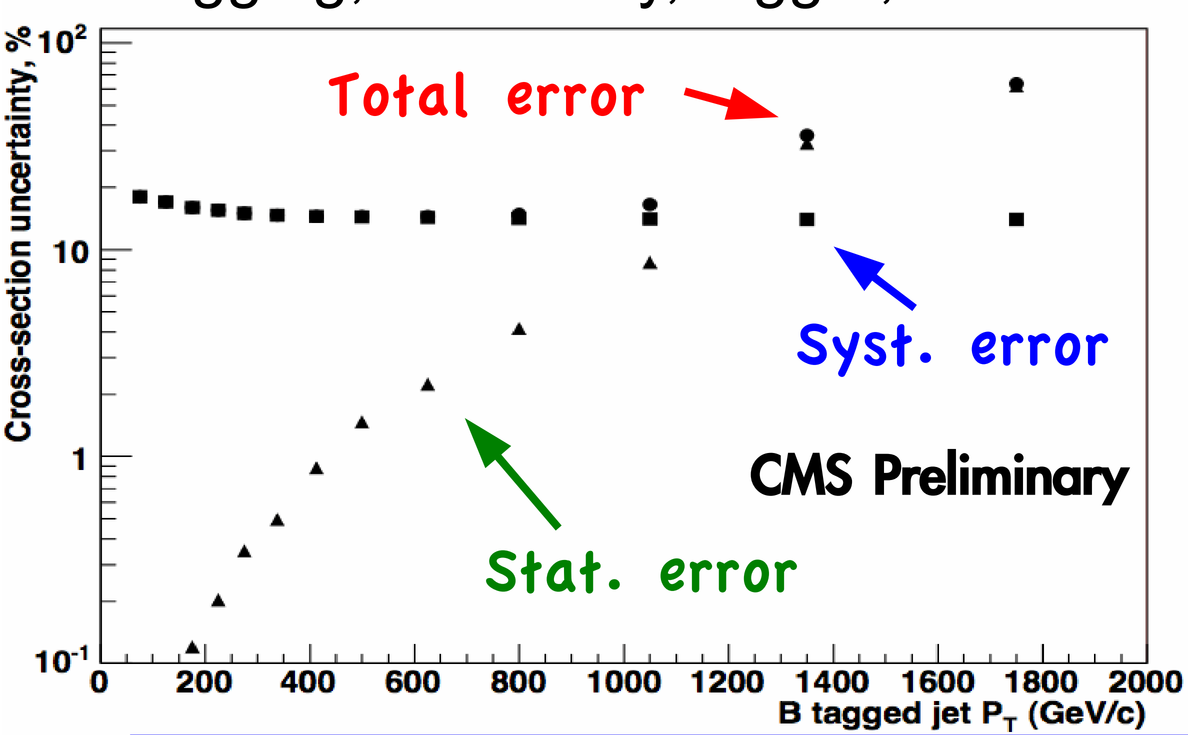
b-hadron p_T range up to 1.5 TeV/c

tt contamination <1%

Inclusive b production (μ+Jet)

- Systematics uncertainties for an integrated luminosity of 10 fb^{-1} at 14 TeV dominated by:
  - Jet Energy Scale uncertainty
  - b-quark fragmentation
  - MC modeling
  - B-tagging, luminosity, trigger, etc.

Source	uncertainty, %
jet energy scale	12
event selection	6
B tagging	5
luminosity	5
trigger	3
muon Br	2.6
misalignment	2
muon efficiency	1
$t\bar{t}$ background	0.7
fragmentation	9
total	18

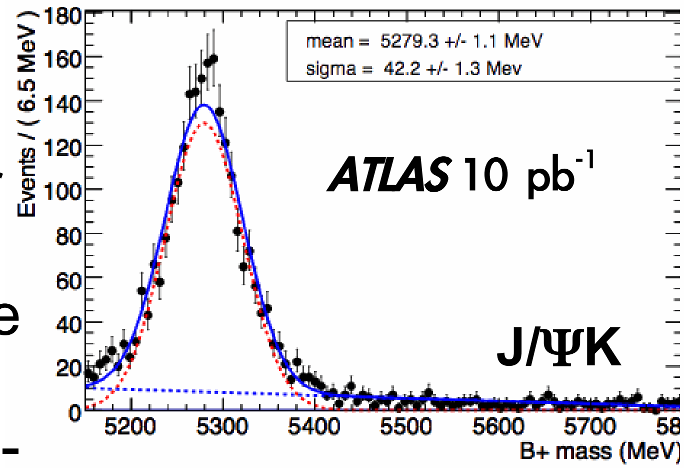


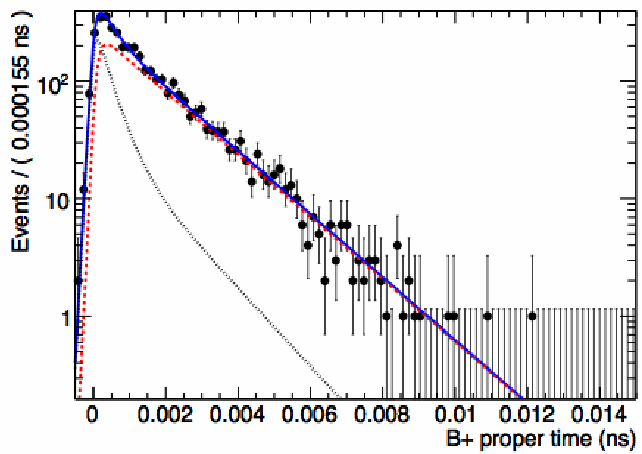
Large statistics, systematic dominated from JES
Calorimeter calibration crucial

Prospects:
$\int\mathcal{L}dt$ 1fb^{-1} 1.6 M

Exclusive B Decays @ ATLAS

- Large $b\bar{b}$ cross-section and clear event topology make exclusive B decays ideal for startup
- Allows detector performance studies
- Measure b production cross-section





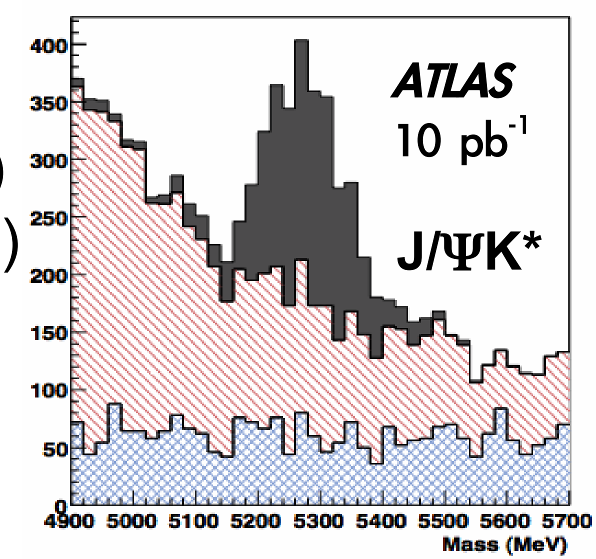
- B → J/Ψ$K^{(*)}$ @ ATLAS

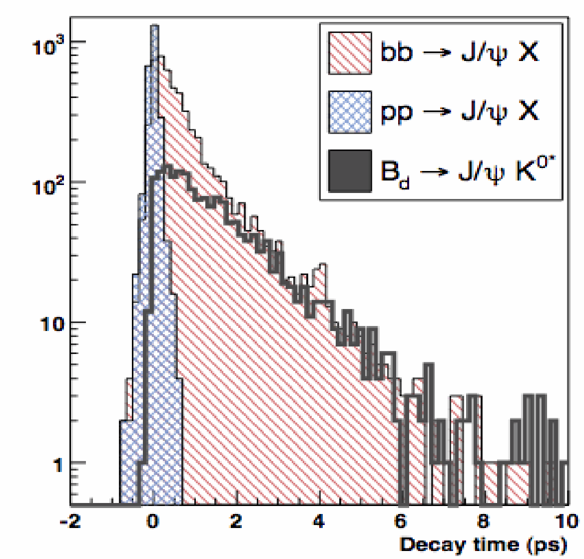
  1μ6 (μ6μ4) trigger forJ/ΨK(K*)

  Select J/Ψ and additional trk(s) (m(Kπ)~m(K*))

  Vertex cuts

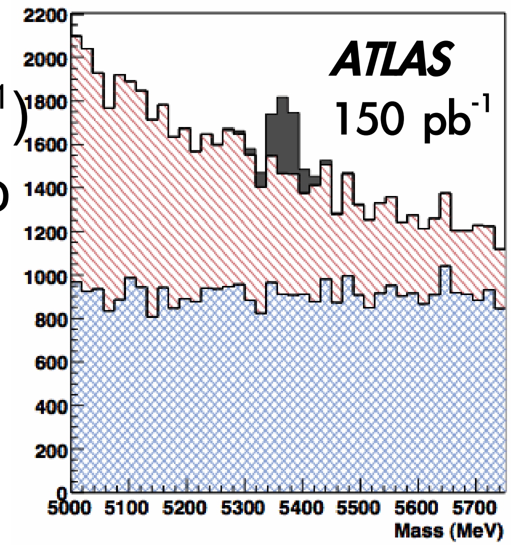
  Lifetime and cross-section measurement in p_T bins

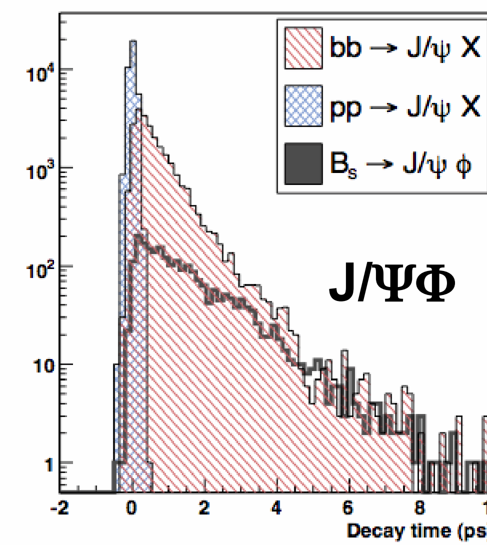




Exclusive B Decays @ ATLAS

- First $B_s \to J/\Psi\phi$ branching fraction measurement doable with $\mathcal{O}(100\ pb^{-1})$
  Similar trigger and offline selection to $J/\Psi K^*$





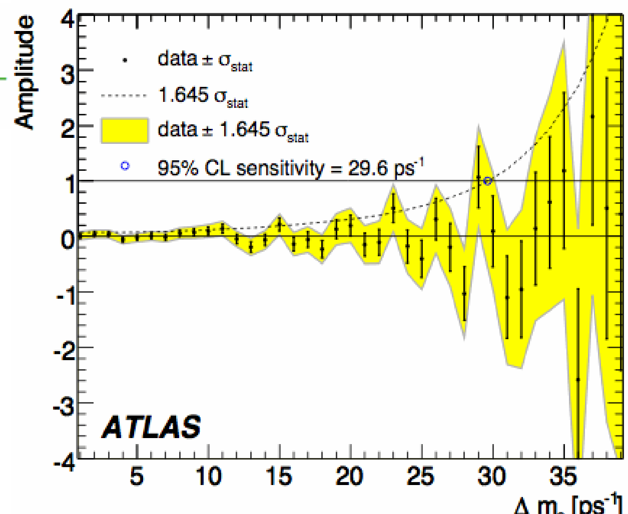
- Δm_s measurement will require $\mathcal{O}(1 fb^{-1})$

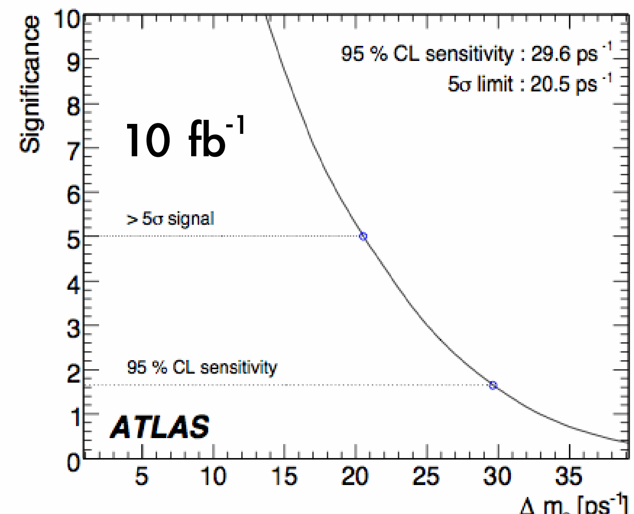
ATLAS:

- Use two fully hadronic decay modes:

$$Bs \to D_s^- \pi^+ \to \phi(K^+K^-)\pi^-\pi^+$$
$$Bs \to D_s^- a_1^+ \to \phi(K^+K^-)\pi^-\rho(\pi^+\pi^-)\pi^+$$

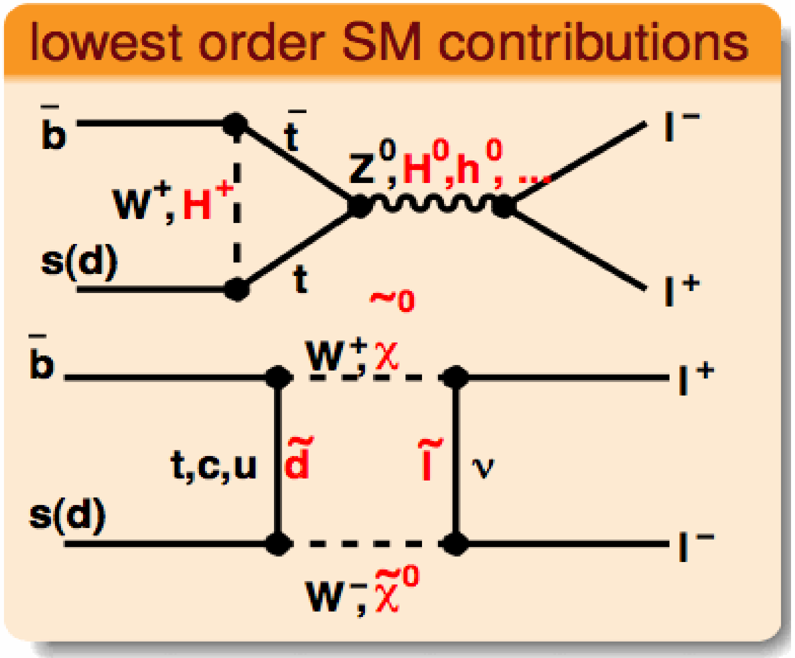
Selection:
Single muon trigger + dedicated trigger for hadronic B_s decays
Opposite side lepton flavor tag
Amplitude scan





Rare Decays: $B_s \to \mu\mu$

- Highly suppressed in the Standard Model
  $\mathcal{B}_{SM}(B_s \to \mu\mu) = (3.42 \pm 0.54) \cdot 10^{-9}$
- Sensitive to New Physics



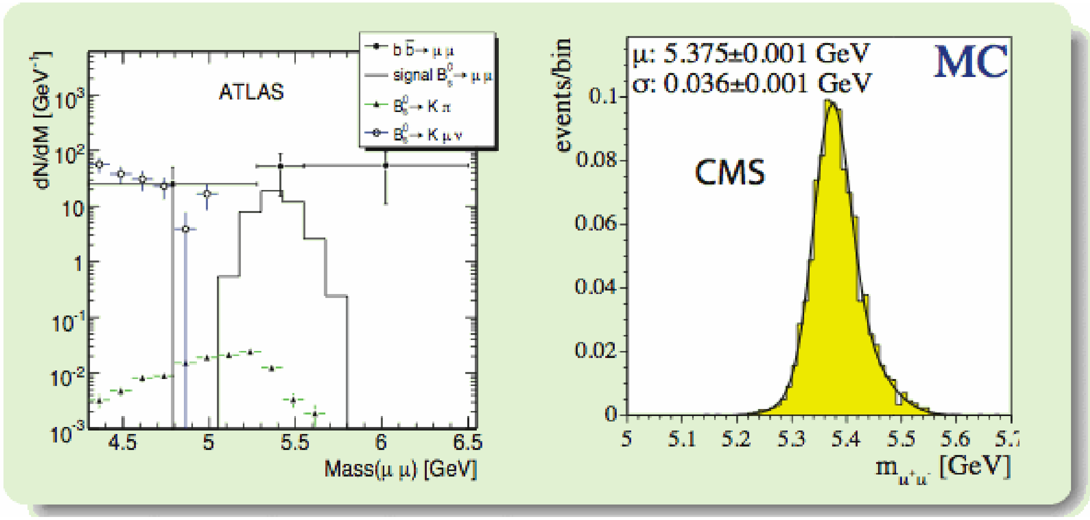
- Selection
  dimuon trigger
  Offline:
  Muon separation and isolation
  Decay Length and Inv. Mass

event yields for 10fb^{-1}:

	signal	BG
ATLAS	5.7	14^{+13}_{-10}
CMS	6.1	$13.8^{+22.0}_{-13.8}$

upper limit at 90% C.L.:

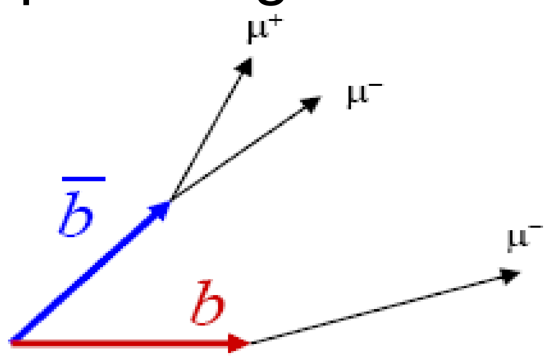
$\mathcal{B}(B_s \to \mu\mu) \leq 1.4 \cdot 10^{-8}$



$b\bar{b}$ Correlations using $J/\Psi + \mu$

- **Strategy**

  Measure $b\bar{b}$ azimuthal correlation using clean leptonic signature in final state



- **Goal**

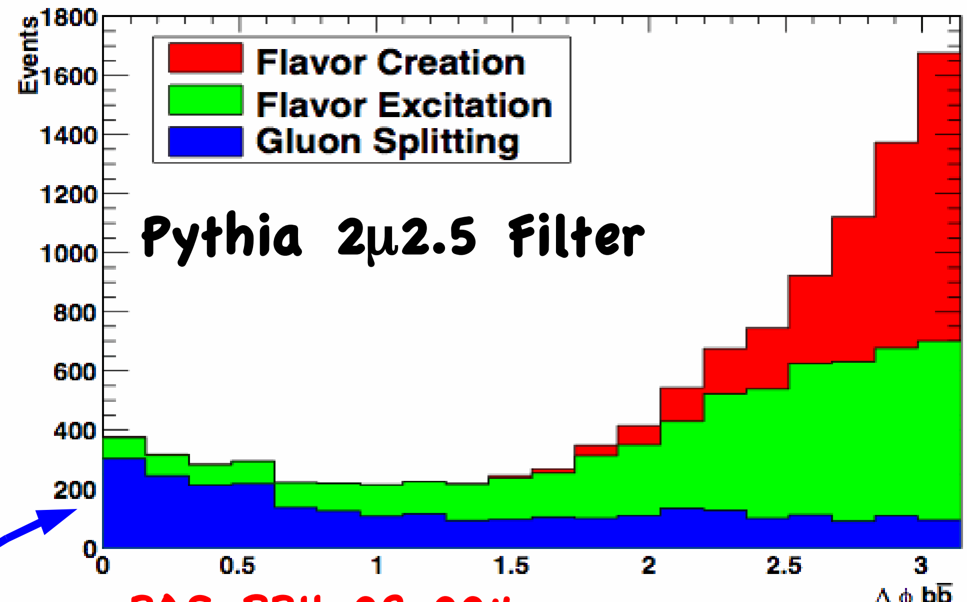
  Measure $b\bar{b}$ cross-section, estimate NLO contribution

- **Sensitive to $\Delta\phi$ region ~0**

  Allow measurement of GS contribution

- **Commissioning with early data (first $\mathcal{O}(10)$ pb^{-1})**

  Complementary to charmonium inclusive study for lifetime/IP fits



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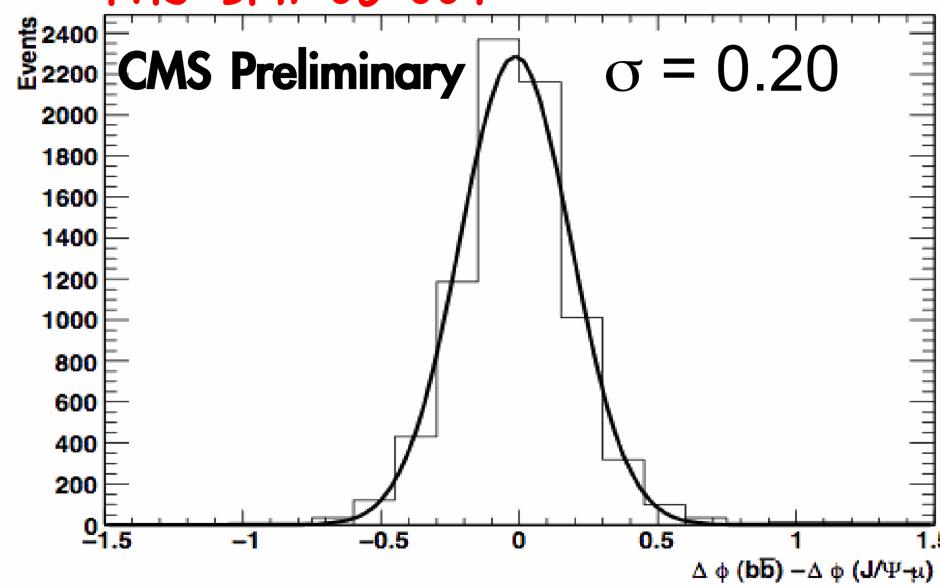
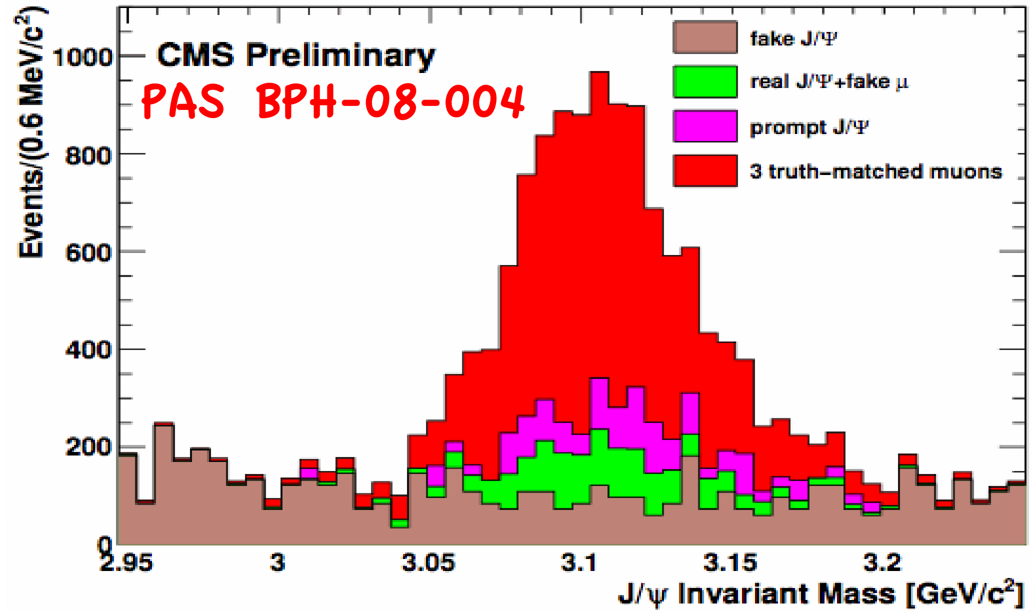
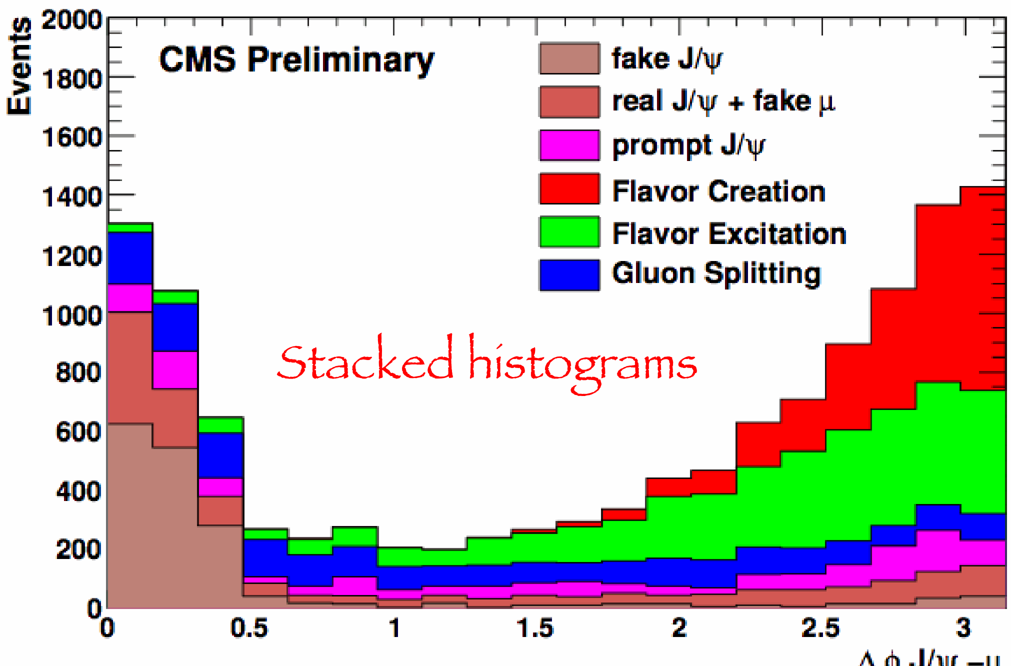


$b\bar{b}$ Correlations using $J/\Psi + \mu$

- Event Selection:
  Trigger: 2μ3
  Vertex μμ pairs to build J/Ψ candidate
  Look for a third μ in the event
  Quality cuts on the third muon track

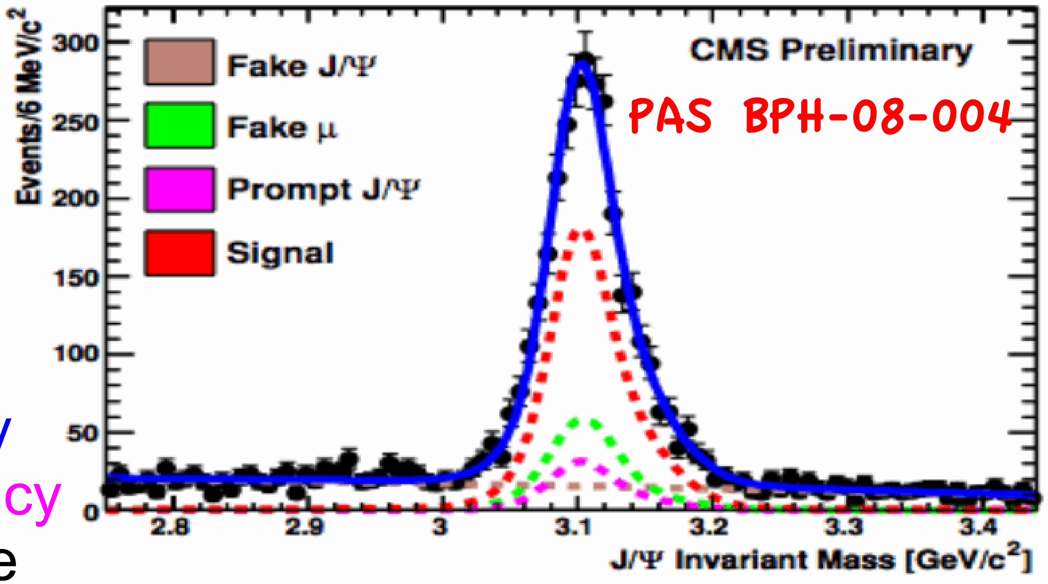




- Backgrounds:
  Misassigned muons
  Real J/Ψ and Fake 3rd muon (hadronic punch-through/Decay in flight),
  Real J/Ψ from prompt decays
  Irreducible background from $B_c \rightarrow J/\Psi X \mu$ decays

$b\bar{b}$ Correlations using $J/\Psi + \mu$

Extract $b\bar{b}$ purity in 8 $\Delta\phi$ bins by simultaneous 3-d unbinned maximum LH fit to J/Ψ invariant mass, L_{xy} transverse flight length, soft μ Impact Parameter



Main Sources of systematic uncertainty

Luminosity, tracking and trigger efficiency

Fraction of muons produced in cascade decays $b \to cX \to \mu X'$

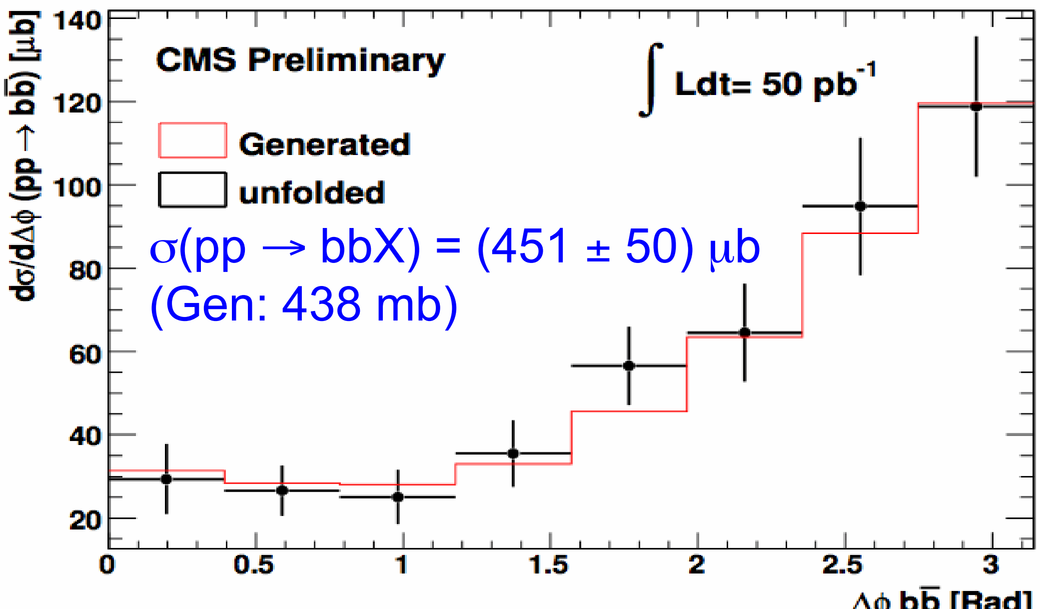
b-quark fragmentation

Uncertainty in the PDF shapes

J/Ψ polarization and misalignment

Total Uncertainty between 15 and 25% in each $\Delta\phi$ bin, for an integrated luminosity of 50 pb^{-1}

Expect an uncertainty of 10% for the integrated $pp \to b\bar{b}X$ cross-section



Conclusions

- b-quark crucial ingredient for LHC goals

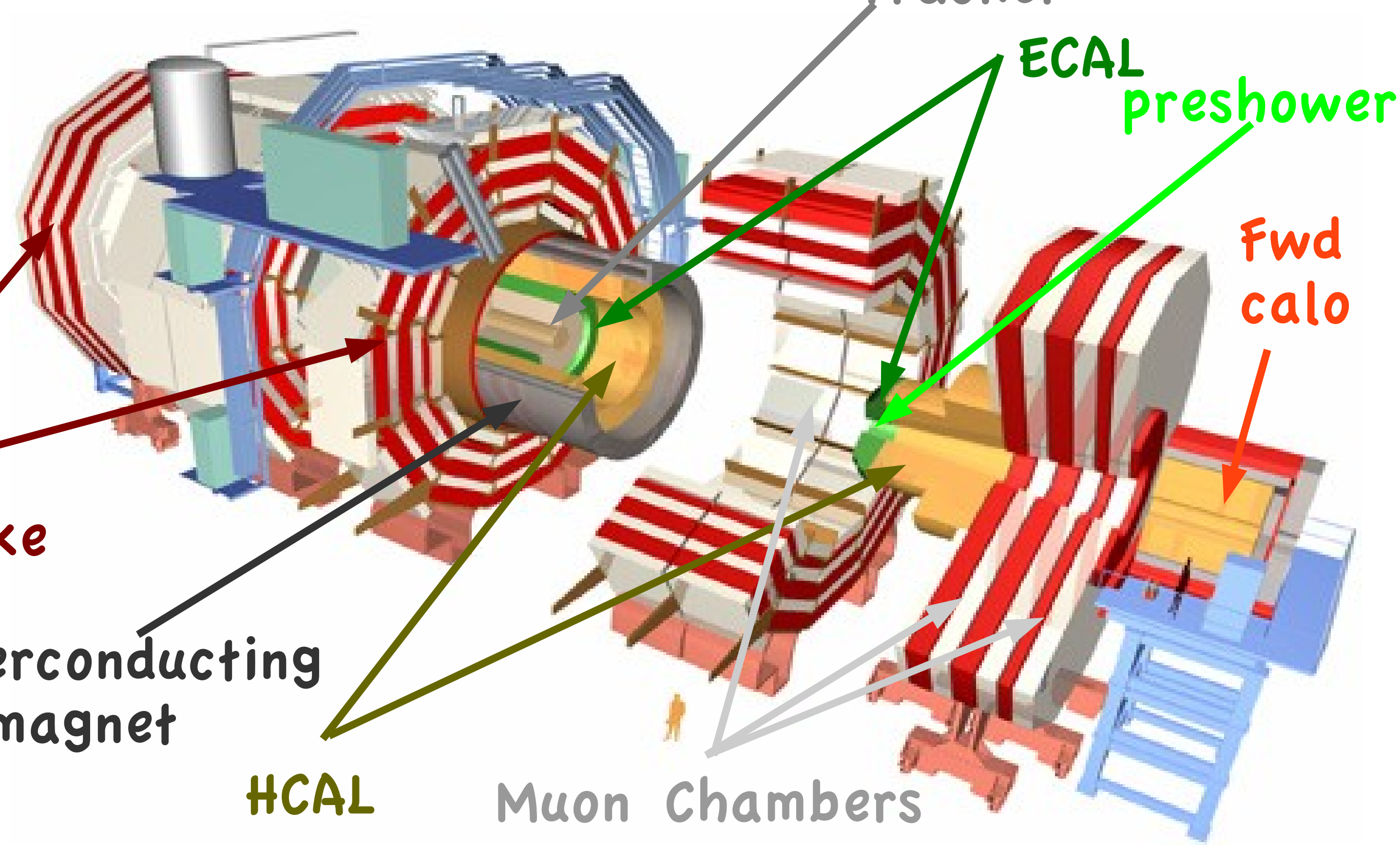
- Large $b\bar{b}$ cross-section makes b production and quarkonium studies Ideal test for LHC first run
  - Better understanding of the detector
  - Competitive results with the Tevatron with $\mathcal{O}(10\ pb^{-1})$ data
- Tevatron data on b production and quarkonium still need to be reconciled with theory

- Measurement of b production and $b\bar{b}$ correlations is an important test of QCD
  - Important to disentangle vanilla QCD effects from real new physics signatures
- We are all waiting for LHC run at the end 2009!

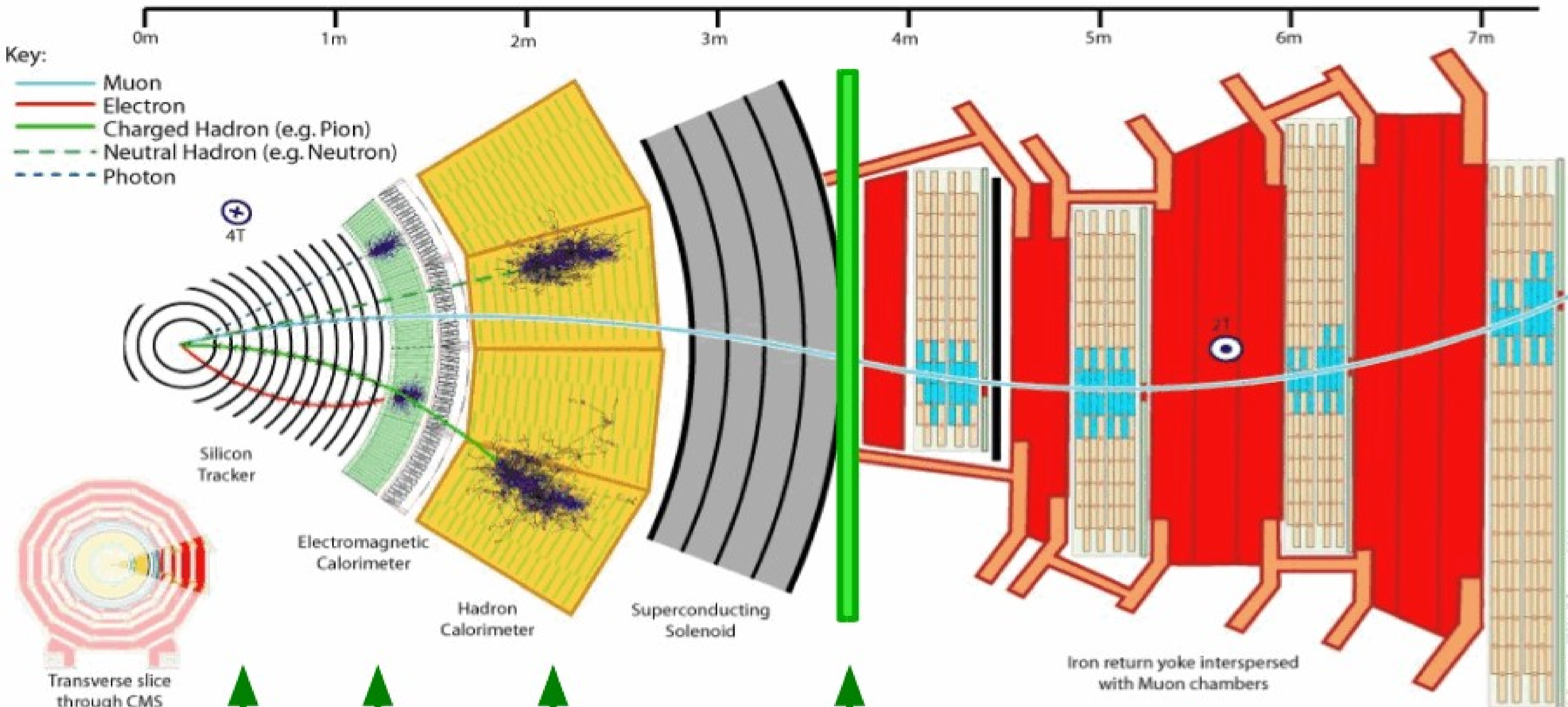
Backup Slides

The CMS Detector

Diameter = 15m, length =21.6 m, Weight = 12000 t
3.8 T solenoidal magnetic field
Steel Return Yoke (2T) instrumented with Muon spectrometer
Tracker, ECAL, HCAL inside coil



CMS Detector Slice



START from Tracker

ECAL

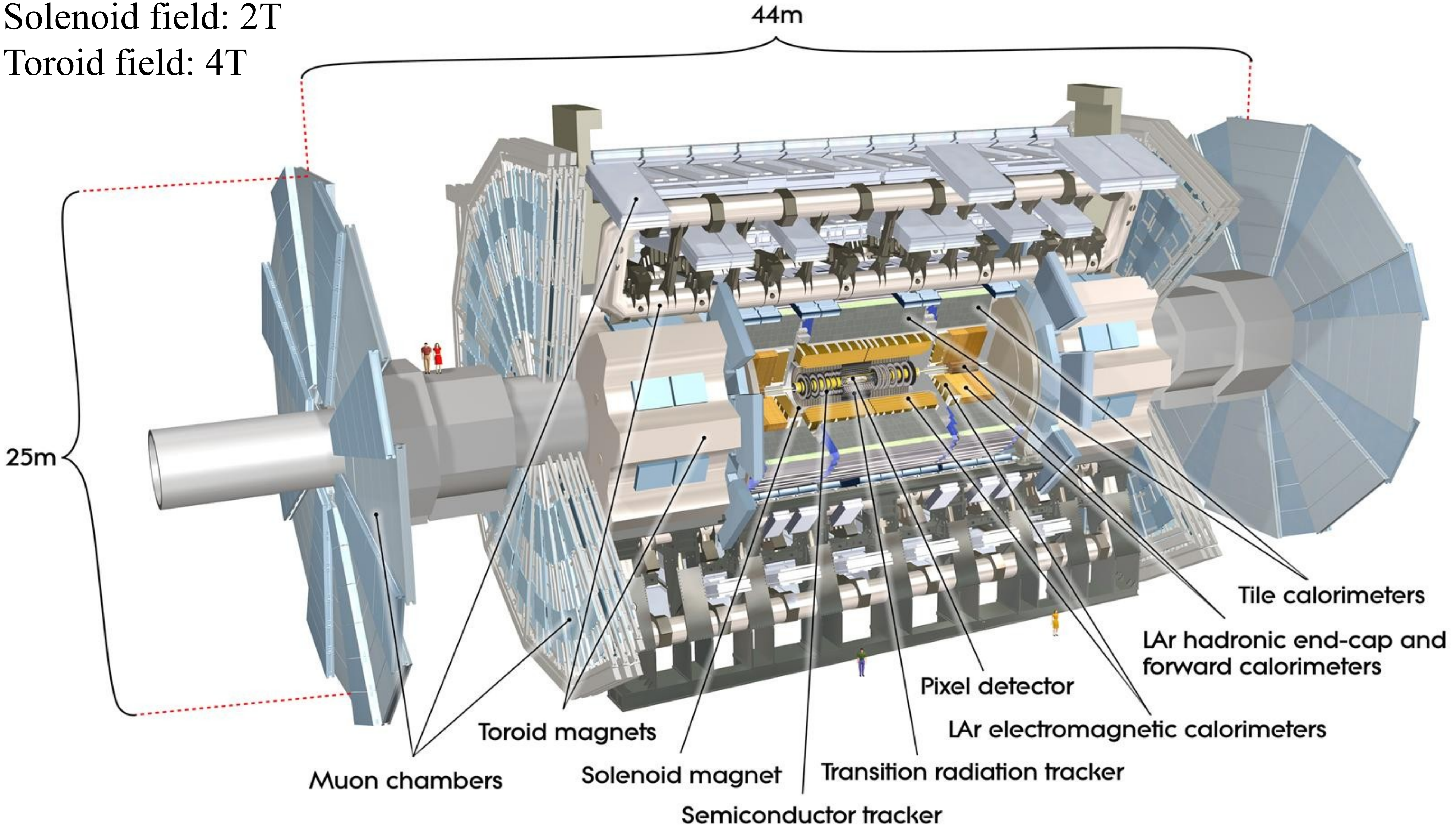
HCAL

HO (barrel only)

Muon system

The ATLAS Detector

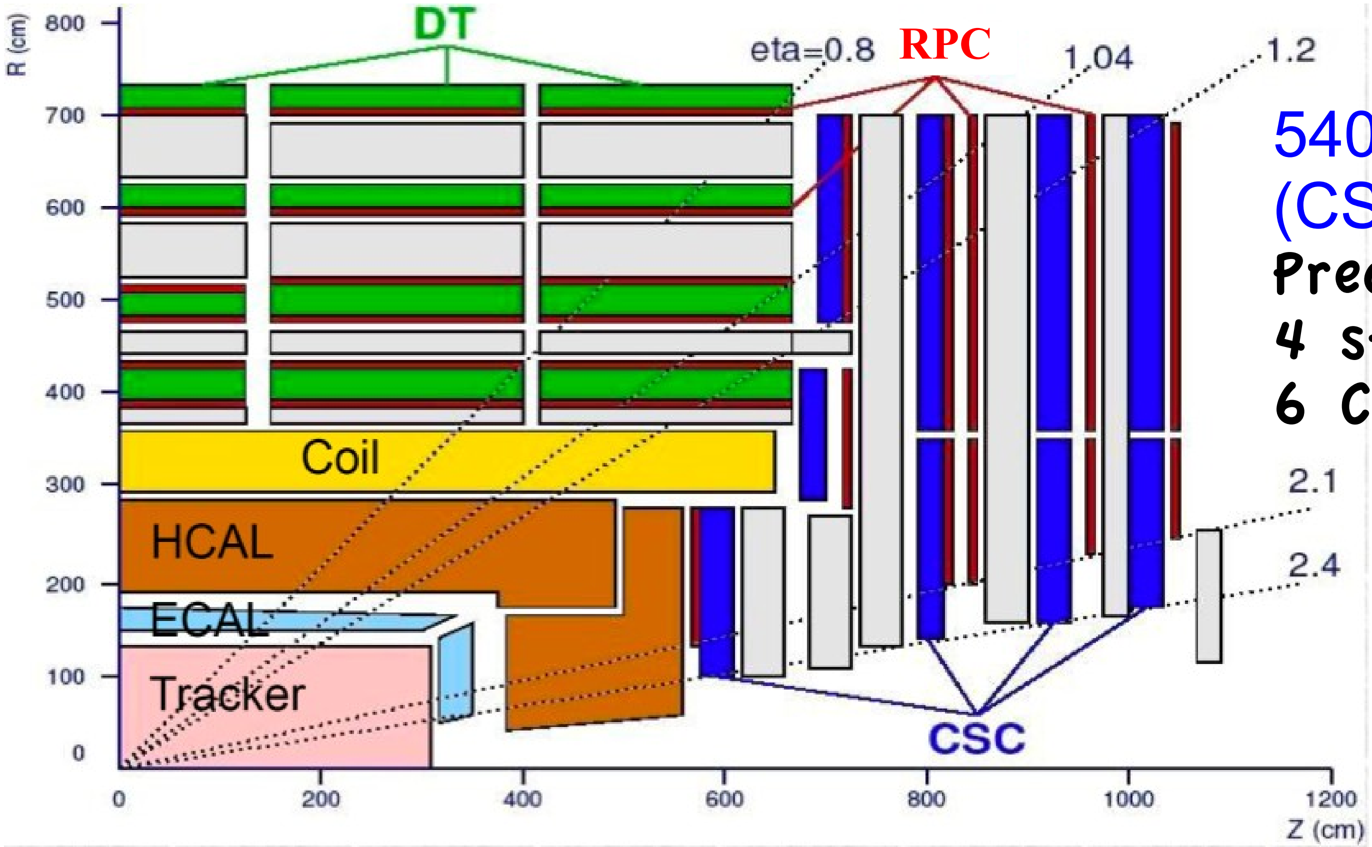
Solenoid field: 2T
Toroid field: 4T



The CMS Muon System

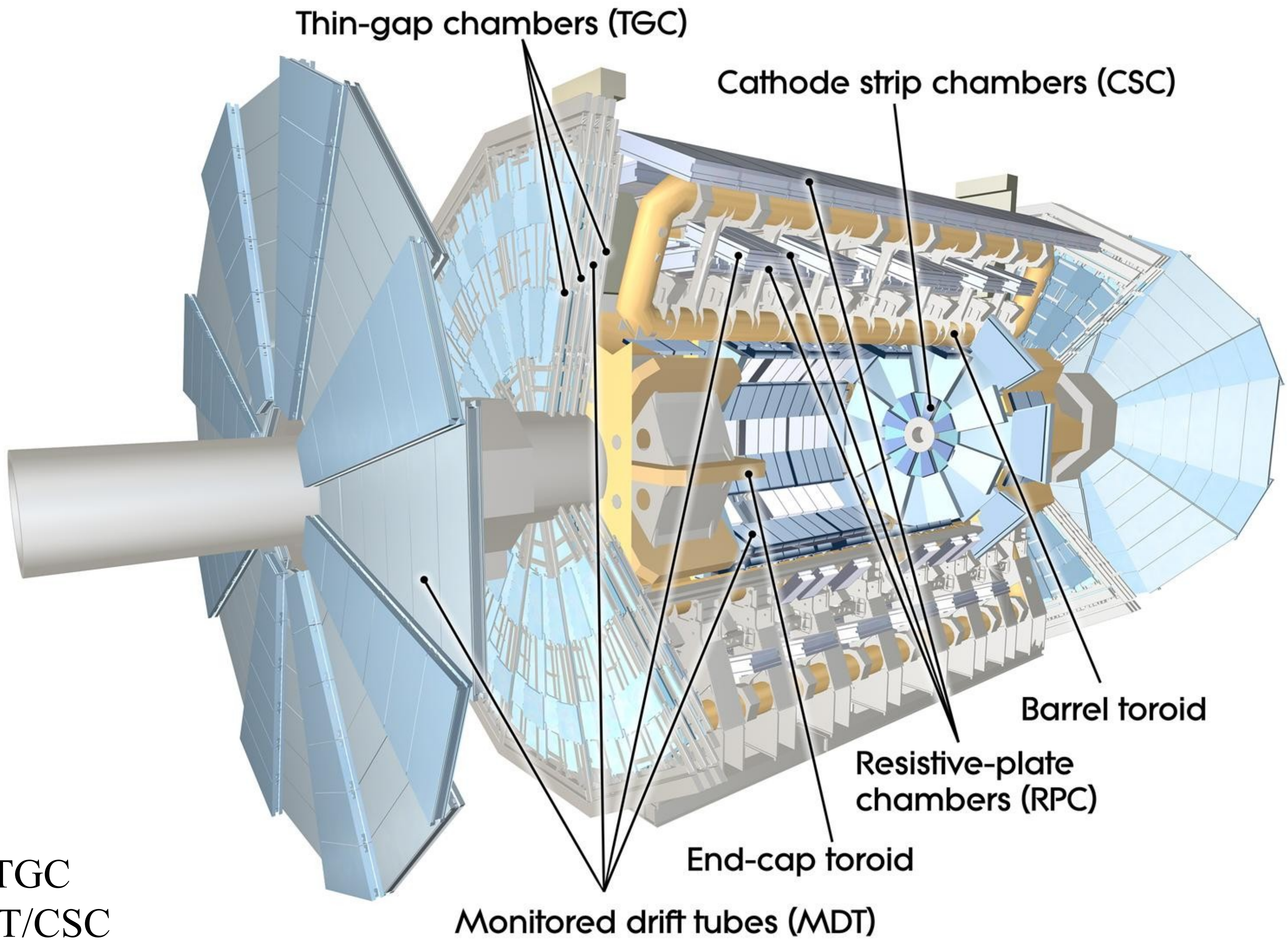
250 Drift Tube Chambers (DT)
Precise tracking
4 stations in the muon barrel
8-12 DT layers/station

Resistive Plate Chambers (RPC)
Fast response < 10 ns
6 layers in muon barrel
4 layers in muon endcap



540 Cathode Strip Chambers (CSC)
Precise tracking
4 stations in muon endcap
6 CSC layers/station

The ATLAS Muon System

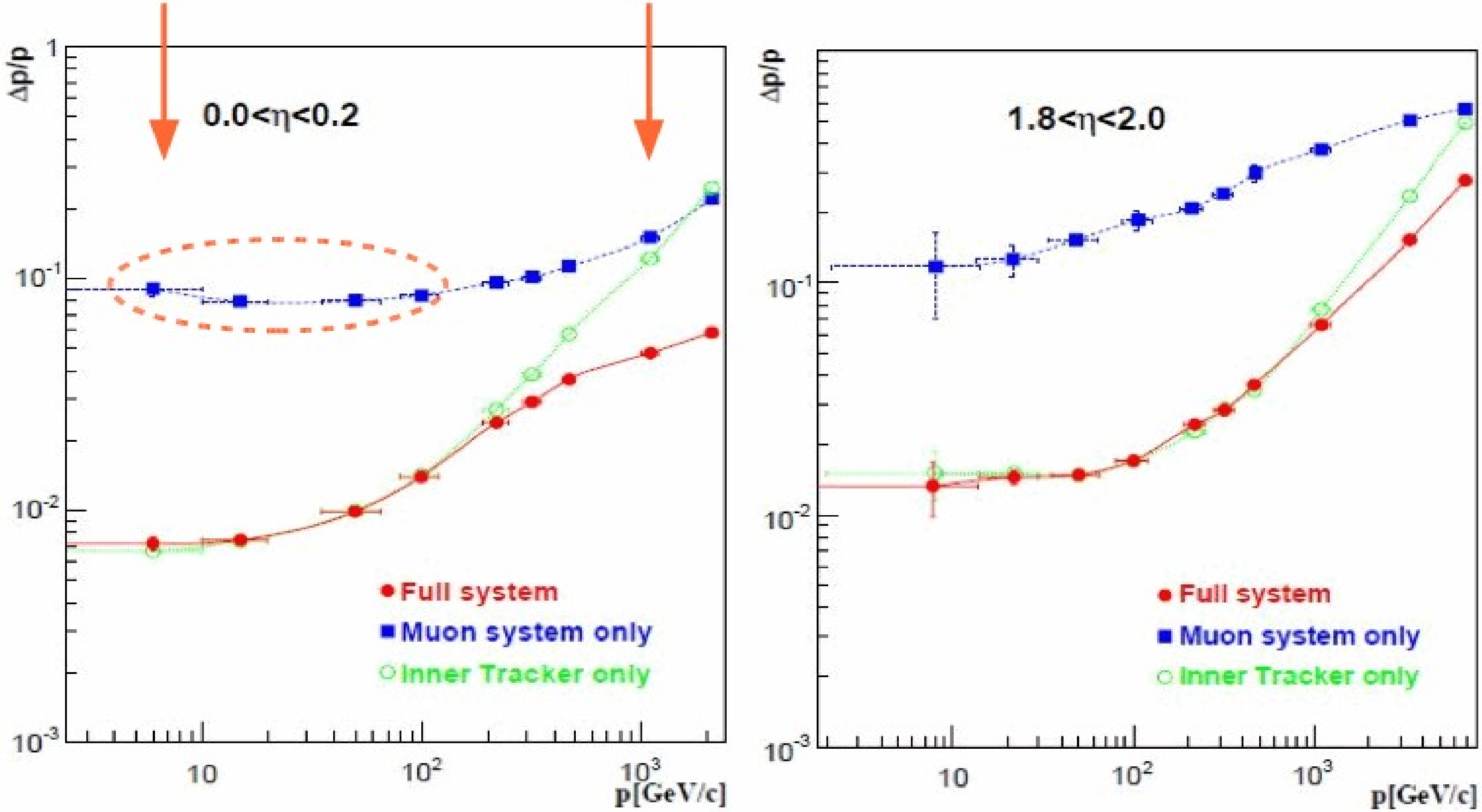


Trigger: RPC/TGC
Precision: MDT/CSC

CMS Muon Reconstruction

Multiple Scattering dominates p <100 GeV/c

Spatial resolution and alignment crucial



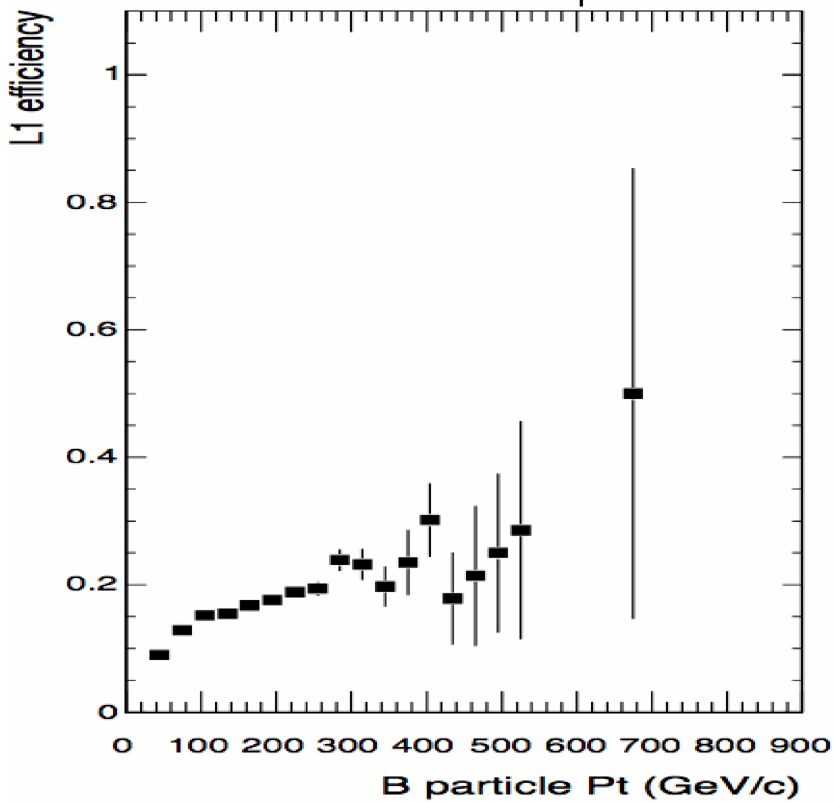
Goal of $\Delta p_T/p_T$ ~10% at 1 TeV seems achievable

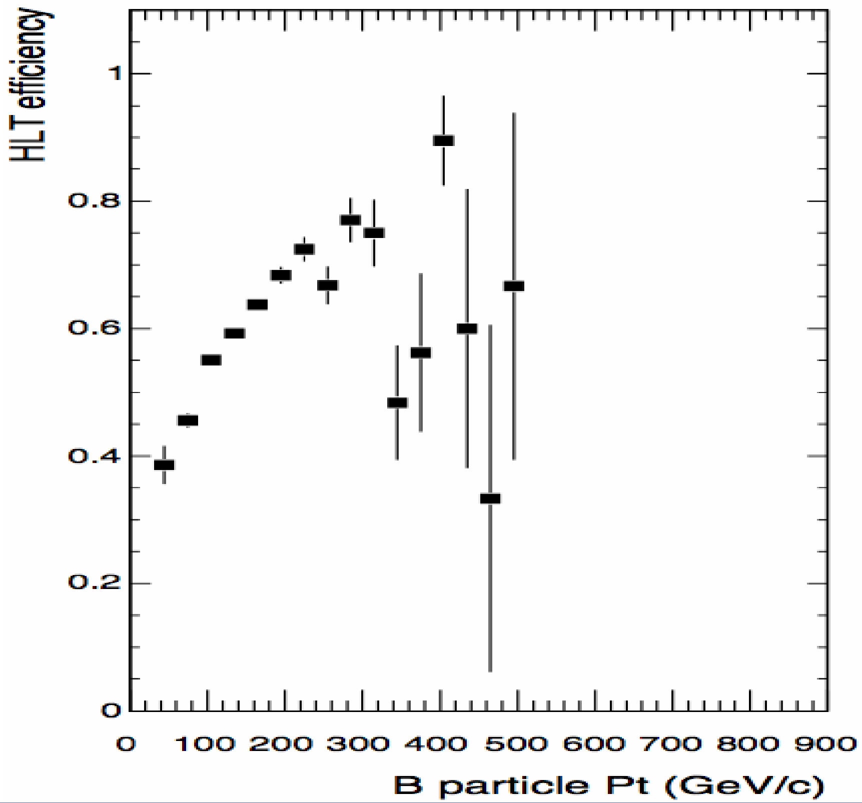
Using silicon tracker improves resolution by a factor 10 at low p_T

Inclusive b production

Measure inclusive differential b cross-section: $d\sigma/d\eta$, $d\sigma/dp_T$

- Study performed at 14 TeV collisions and high lumi
- L1 Trigger: single μ with p_T>14 GeV/c
- HLT: μ + b-jet: 1 non isolated μ (with p_T>19 GeV/c) plus a b-tagging requirement on a jet (E_T>50 GeV and $|\eta|$<2.4, Track counting from pixel tracks)





Unfolding the $\Delta\phi$ Distribution

- Acceptance sculpts reconstructed $\Delta\phi$ distribution

  How to get the true spectrum (a) from the measured spectrum (b)?

  $\hat{A}\vec{a}=\vec{b}$ A:detector/resolution matrix → must be inverted:

  (problems: statistical fluctuations,oscillatory solutions..)

- Use Singular Value Decomposition (SVD) (A.Hocker et al, hep-ph/9509307)

Comparison before and after unfolding