B physics at CMS

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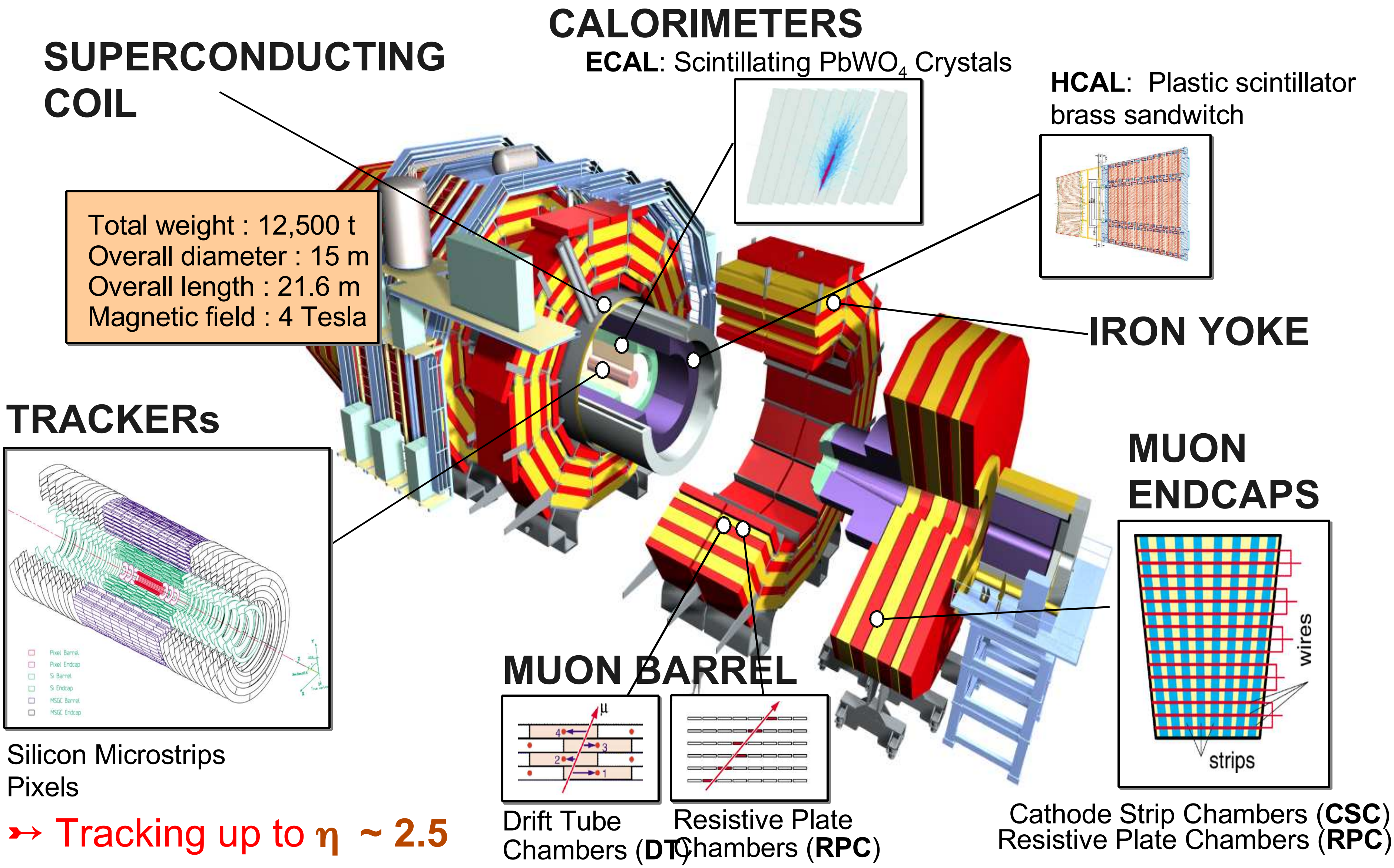
B-physics at the LHC

- LHC: proton-proton collisions at $\sqrt{s}$ = 14 TeV
- High *bb* production cross section: σ_{bb} ~500 μb
- High luminosity:
  - low-luminosity: up to $2\cdot10^{33}$ cm^{-2} s^{-1} (~10 fb^{-1} per year)
  - high-luminosity: 10^{34} cm^{-2} s^{-1} (~100 fb^{-1} per year)
- CMS: multi-purpose experiments, with emphasis in high-p_T physics
  - Special interest in the initial low-luminosity period
  - Many B decays channels yield J/ψ and μ that are useful for understanding the detectors – calibration, alignment, *B*-field, etc.
- *B*-physics performance is strongly dependent by trigger menu
  - Only limited trigger bandwidth is available for *B*-physics
- Most of the *B*-physics program based on dimuon Level-1 trigger, with some use of single muons trigger.
- Most *B*-physics measurements to be done at low-luminosity
  - Search for rare decays may also be continued at high-luminosity
- CMS *B*-physics capabilities studied in benchmark channels:
  - $B_s \rightarrow J/\psi\, \varphi$, $B_s^0 \rightarrow \mu^+\mu^-$, B_C, (*b*-production)

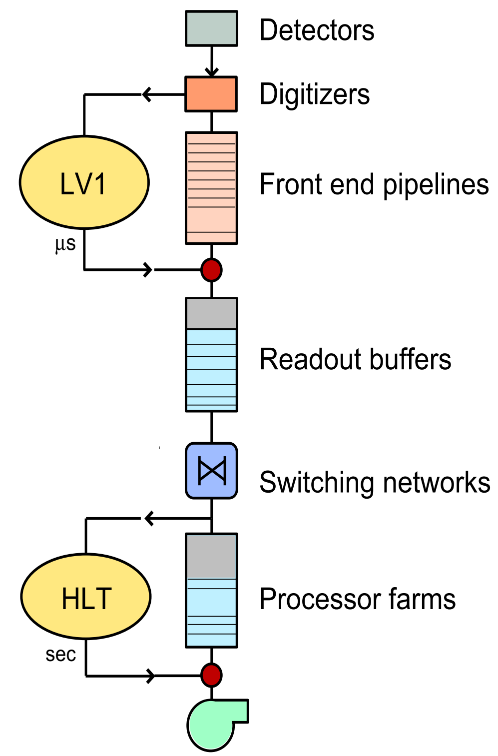
The CMS experiment



➳ Tracking up to η ~ 2.5

Trigger and DAQ

- Two level trigger architecture:
  - Level 1 trigger based on muon & calorimeters
    (40 MHz → ~100 kHz)
  - High Level trigger (HLT) using similar reconstruction algorithms as offline
    (100 kHz → ~150 Hz)



Triggers for *B* physics:

- Level 1: Single-muon or dimuon trigger:
  - Single muon: $p_T > 14$ GeV/*c*
  - Dimuon: $p_T > 3$ GeV/*c*
- HLT:
  - Inclusive *b*, *c* trigger through *b*-tagging: ~ 5 Hz (L1: high E_T jet)
  - Exclusive *B* decays – under study : consider partial reconstruction of decay products in the tracker in Region of Interest around the muons

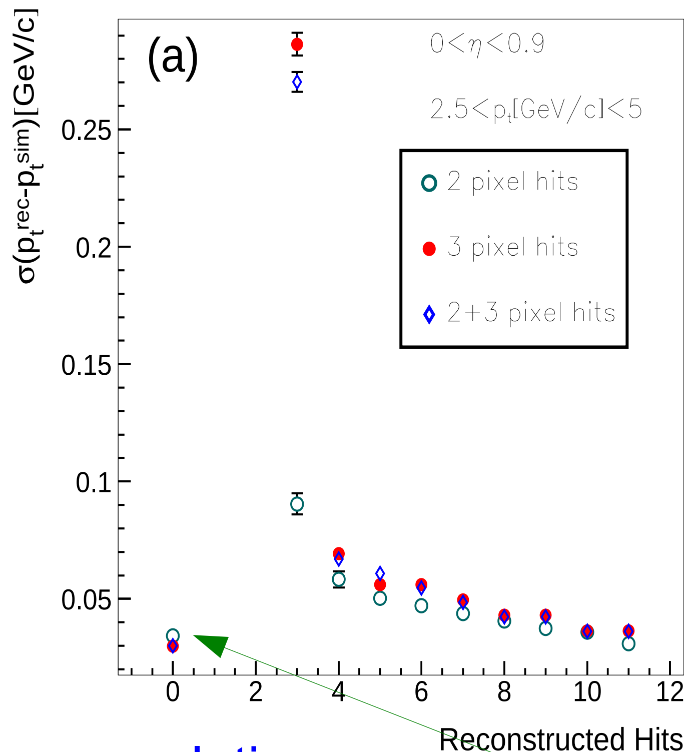
    Special interest in the initial low-luminosity period.

Partial reconstruction

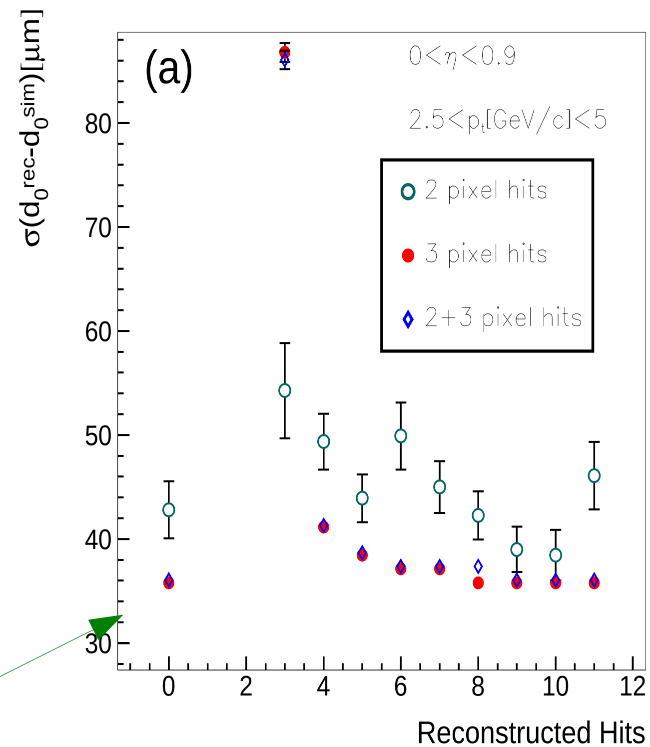
Partial reconstruction: stop track reconstruction once enough information is available to answer a specific question

- Track parameter resolutions reach asymptotic value after using only first 5/6 hits

Resolutions as a function of the number of hits used: (*b*-jets, $2.5<p_T<5$, $|\eta|<0.9$)



p_T resolution



Transverse impact parameter resolution

("0 hits" indicates full track reconstruction!)

The decay $B_s \to J/\psi\ \varphi$

- Study of the decay: $B_s \to J/\psi\ \varphi$, $J/\psi \to \mu^+\mu^-$, $\varphi \to K^+K^-$
  - Fully reconstructed decay: Branching fraction= $(5.4 \pm 1.9) \cdot 10^{-5}$
  - Selection and reconstruction
  - Untagged analysis: unbinned maximum likelihood fit (flavour tagging tools not yet available)
- Measurements:
  - Without tagging:
    - Width difference $\Delta\Gamma_s/\Gamma_s$ - SM: $\Delta\Gamma_s/\Gamma_s \sim 10\%$
    - (Weak phase φ)
  - With tagging:
    - Mass difference: Δm_s
    - Weak phase – SM: $\varphi = -2\lambda^2\eta \sim 0.04$
- First measurements from CDF & D0:
    - CDF: $\Delta\Gamma_s/\Gamma_s = (65^{+25}_{-33} \pm 1)\%$
    - D0: $\Delta\Gamma_s = 0.13 \pm 0.09\ \mathrm{ps}^{-1}$
    - D0: $\varphi = -0.70^{+0.47}_{-0.39}$

The decay $B_s \to J/\psi\ \varphi$

- B_s signal: Fully reconstructed decay: $B_s \to J/\psi\ \varphi$, $J/\psi \to \mu^+\mu^-$, $\varphi \to K^+K^-$
- Backgrounds:
  - Prompt $J/\psi \to \mu\mu$: Important background in trigger
  - Inclusive $b \to J/\psi\ X$
  - Misidentified $B_d^0 \to J/\psi\ K^{*0} \to \mu^+\mu^- K^+\pi^-$ decays: similar angular distribution, distorted due to misidentified pion, kinematic requirements

Data sample	$B_s^0 \to J/\psi\phi$	Direct J/ψ	$b \to J/\psi X$	(filt)	$B^0 \to J/\psi K^{*0}$
Cross section	42.87 ± 1.07 nb	141 μb	682 ± 64 nb	682 ± 64 nb	$20.4 \pm 1.7nb$
w. kine.sel.	74 ± 27 pb	176 ± 2 nb	27.9 ± 2.4 nb	3.20 ± 0.3 nb	366 ± 22 pb

  - In all samples : $p_T(\mu) > 3$ GeV/c ($|\eta|<1.2$), $p_T(\mu) > 2$ GeV/c
  - In signal + B_d bkg : $p_T(\pi/K) > 0.8$ GeV/c
  - Low luminosity PU (2×10^{33} cm^{-2}s^{-1}) included in all samples

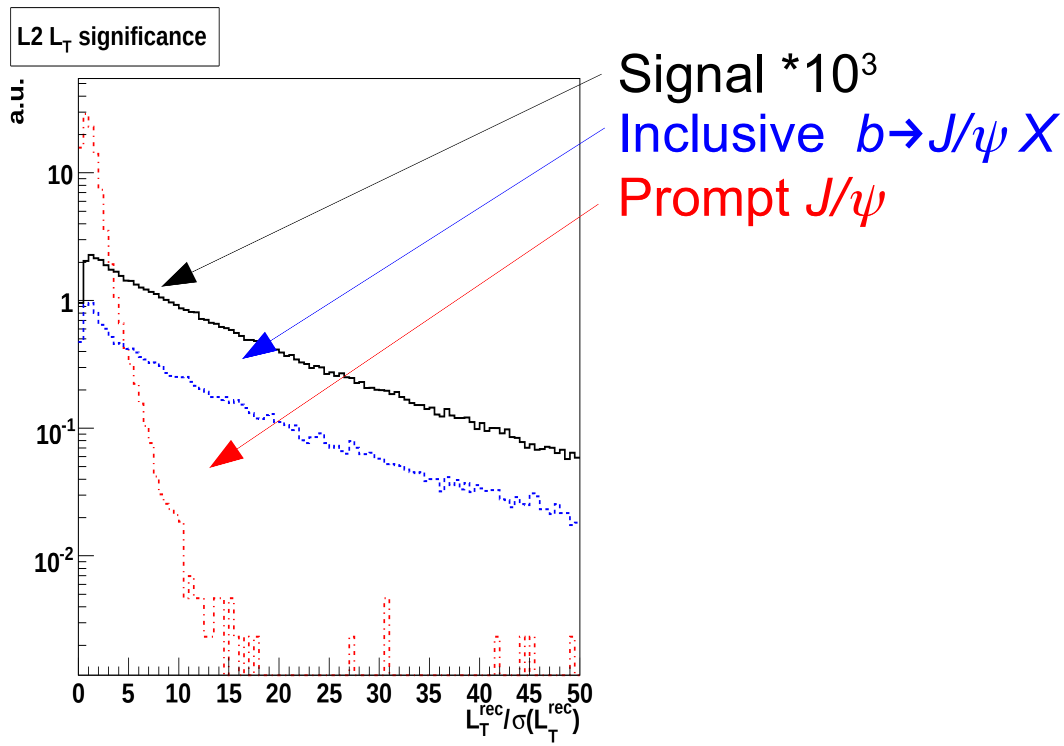
Large uncertainties in *bb*, prompt J/ψ cross-section, p_T distribution, fragmentation

The decay $B_s \to J/\psi\ \varphi$: High-Level Trigger selection

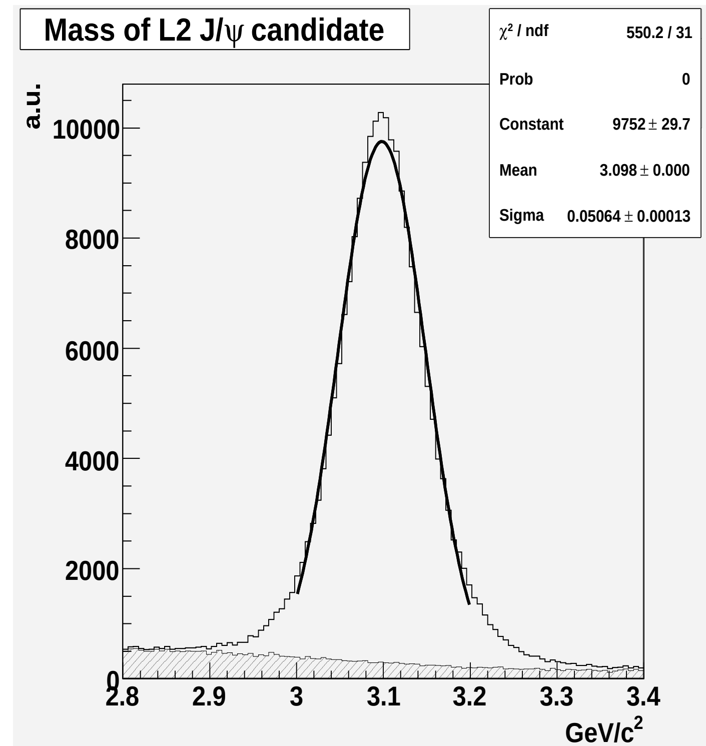
Level 2: J/ψ search – Prototype for inclusive $B \to J/\psi$ selection

- Primary Vertex Reconstruction using only the pixel detector
- Regional, partial track reconstruction in cones around L1 muon candidates
  - Partial reconstruction up to 5 hits maximum
  - $p_T^{\mu} > 2.5$ GeV/c ($|\eta|<1.2$) , $p_T^{\mu} > 2$ GeV/c
  - $p_T^{J/\psi} > 4$ GeV/c
- Track pairs with opposite charge: $|M(\mu\mu) - M(J/\psi)| < 150$ MeV/c^2
- Vertex Fit of track pairs:
  - $\chi^2 < 20$
  - Transverse decay length significance > 3
  - Cosine of angle (momentum/decay length) > 0.9
- Accept rate reduced to ~ 15 Hz
- 80% of J/ψ from B decays
- Main challenge: Timing due to track reconstruction

The decay $B_s \rightarrow J/\psi\, \varphi$: HLT selection



Transverse decay length significance



J/ψ mass distribution (HLT)

Mean = 3.098 GeV/c^2 – σ = 51 MeV/c^2

Data sample	$B_s^0 \rightarrow J/\psi\phi$	Direct J/ψ	$b \rightarrow J/\psi X$	$B^0 \rightarrow J/\psi\, K^{*0}$
Cross section (nb)	0.074	176	28.7	0.366
L2 ϵ	28.69(7)%	0.65(2)%	21.27(11)%	30.28(12)%
L2 R (Hz)	0.042463(9)	2.287(7)	12.21(6)	0.2434(1)

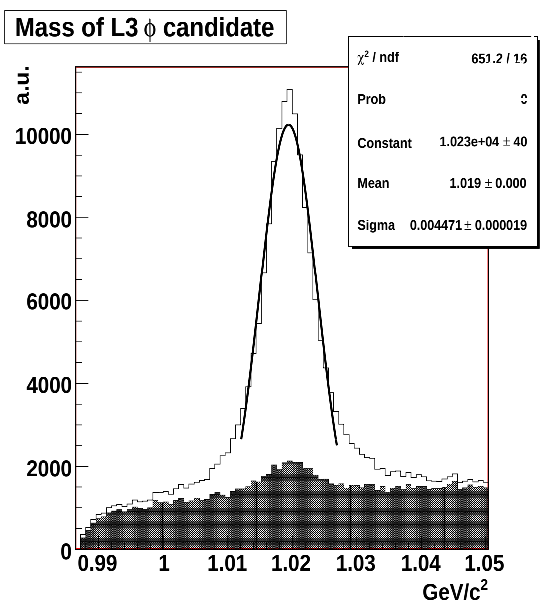
The decay $B_s \to J/\psi\ \varphi$: HLT selection

Level 3: Further reduction through full reconstruction – φ search

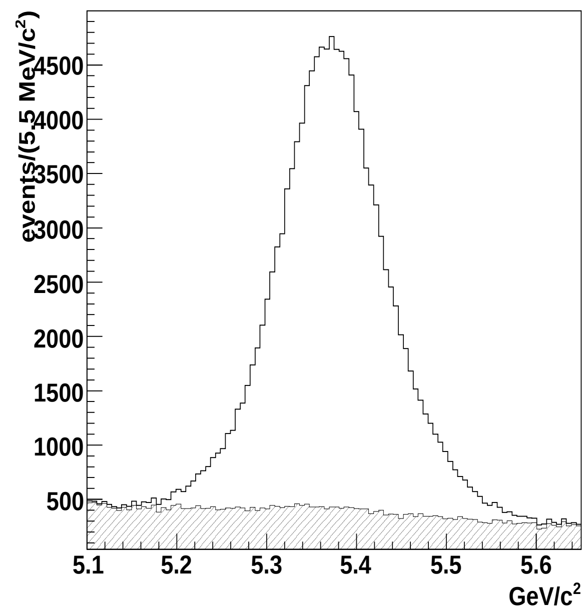
- Regional, partial track reconstruction in cones around J/ψ candidates

Data sample	$B_s^0 \to J/\psi\phi$	Direct J/ψ	$b \to J/\psi X$	$B^0 \to J/\psi K^{*0}$
Cross section (nb)	0.074	176	28.7	0.266
L3 ϵ	20.50(6)%	0.0007(7)%	0.15(1)%	0.961(26)%
L3 R (Hz)	0.03034(8)	0.002(2)	0.083(6)	0.0077(2)

Events/10fb^{-1}: ~150'000 - HLT accept rate < 0.1 Hz



φ mass distribution
Mean = 1.019 GeV/c^2
σ = 4.5 MeV/c^2



B_s mass distribution
Mean = 5.372 GeV/c^2
σ = 65.4 MeV/c^2

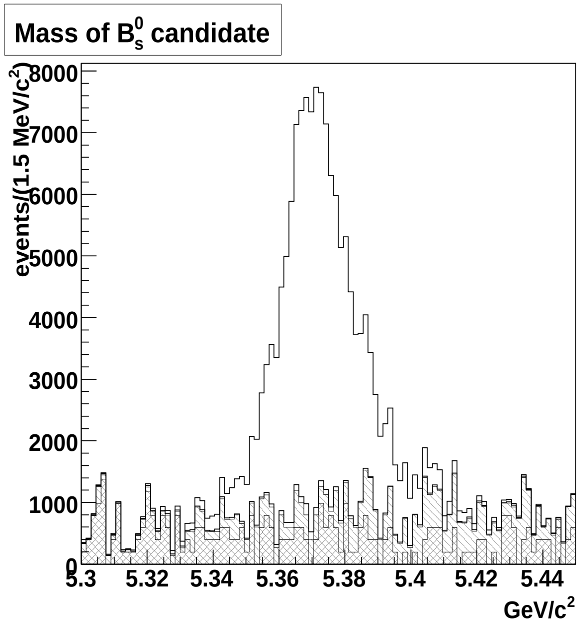
The decay $B_s \to J/\psi\ \varphi$: Offline selection

- Muon reconstruction:
  - Full reconstruction using tracker and muon chambers or MuonID on Tracker-only tracks
  - p_T^{μ} > 3 GeV/c ($|\eta|<1.2$) , p_T^{μ} > 2 GeV/c
- Track reconstruction: Combinatorial TF, with p_T > 0.8 GeV/c
- Kinematic Fit (vertex and J/ψ mass constraint)
  - Prob(χ^2) > $1 \cdot 10^{-3}$ (6 dof)
  - Cosine of angle (momentum/decay length 2D) > 0.98
  - $|M(KK) - M(\varphi)| < 8$ MeV/c^2
  - p_T^{φ} > 1.0 GeV/c, p_T^{Bs} > 5.0 GeV/c
- Number of events per 10 fb^{-1}:

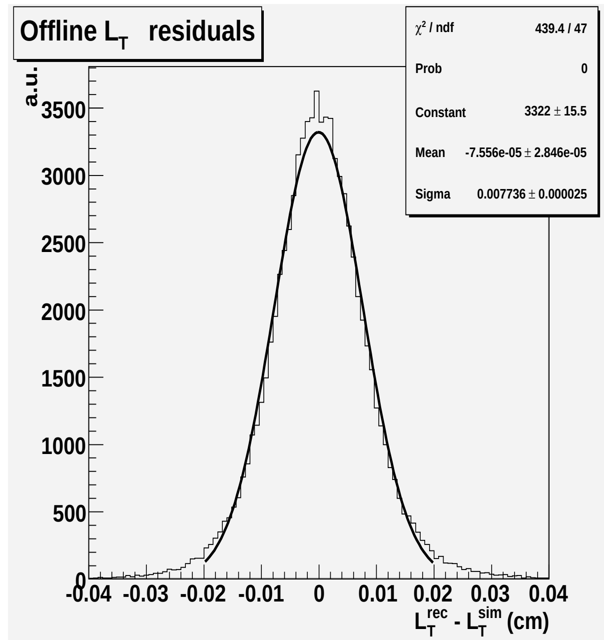
	$B_s^0 \to J/\psi\ \phi$	$b \to J/\psi$ incl.	$B_d \to J/\psi K^*$
$\sigma \cdot Br$ (nb)	0.074	28.7	0.322
ϵ (%)	14.7	.113	0.202
Events per 10 fb^{-1}	109'000	32'400	6'500

- Without B_s mass cut! (sidebands to be used in analysis)

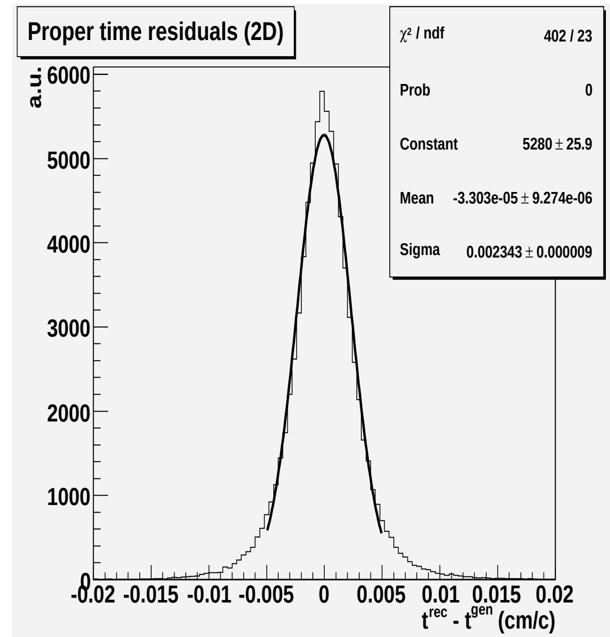
The decay $B_s \to J/\psi\ \varphi$: Offline selection



B_s mass residuals
using Kinematic Fit
Mean = 5.373 GeV/c^2
σ = 13 MeV/c^2



Decay length residuals L_T
σ = 77 μm



Proper decay length residuals
σ = 23 μm (77 fs)

Use of transverse coordinates only

The decay $B_s \to J/\psi\,\varphi$: The Analysis

- Measurement of $\Delta\Gamma_s/\Gamma_s$ on untagged sample
- Final state: admixture of CP-even / CP-odd eigenstates
- The CP-even/CP-odd components have different angular dependences
- Unbinned maximum likelihood fit on observed time evolution of the angular distribution (3 angles + proper decay length):

$$P = \varepsilon(t, \Theta) \cdot \mathrm{f}(\Theta, \alpha, t)$$

- Distortion due to acceptance, selection: $\varepsilon(t, \Theta) = \varepsilon(t) \cdot \varepsilon(\Theta)$
  - $\varepsilon(\Theta)$: Distortion of the angular distributions due to kinematic requirements
  - $\varepsilon(t)$: Time-dependent efficiency due to HLT requirements
- Resolution on proper decay length:
  - *pdf* convolved with Gaussian resolution function
  - Resolution on angles negligible

The decay $B_s \to J/\psi\ \varphi$: The Analysis

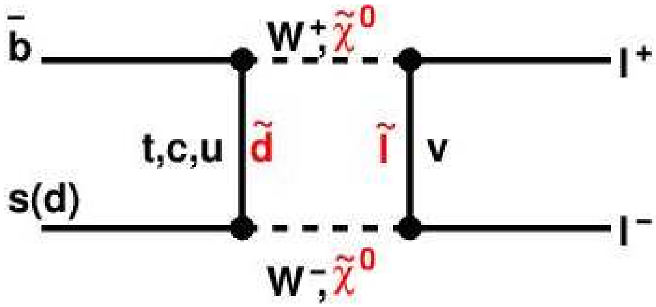
- Dataset of 1.3 fb^{-1} with expected B_s/B_d signal-to-background ratio
  - Low number of background events, to to few include background distribution in *pdf*
  - Invariant mass requirement: $|M(\mu\mu KK) - M(B_s)| < 36$ MeV/c^2
    - $\varepsilon(B_d) = 41\%$
    - $\varepsilon(B_s) = 97.1\%$
- Fit Result on selected signal and background events:

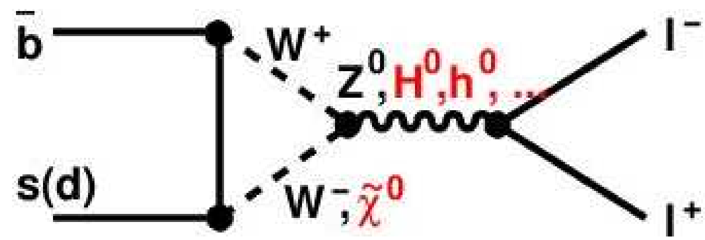
Parameter	Input value	Result	Stat. error	Sys. error	Total error	Rel. error
$\lvert A_0(0)\rvert^2$	0.57	0.5823	0.0061	0.0152	0.0163	2.8%
$\lvert A_{\Vert}(0)\rvert^2$	0.217	0.2130	0.0077	0.0063	0.0099	4.6%
$\lvert A_{\perp}(0)\rvert^2$	0.213	0.2047	0.0065	0.0099	0.0118	5.8%
$\bar{\Gamma}_s$	0.712 ps^{-1}	0.7060 ps^{-1}	0.0080 ps^{-1}	0.0227 ps^{-1}	0.0240 ps^{-1}	3.4%
$\Delta\Gamma_s$	0.142 ps^{-1}	0.1437 ps^{-1}	0.0255 ps^{-1}	0.0113 ps^{-1}	0.0279 ps^{-1}	19%
$\Delta\Gamma_s/\Gamma_s$	0.2	0.2036	0.0374	0.0173	0.0412	20%

- For 10 fb^{-1}, expect to measure $\Delta\Gamma/\Gamma$ with stat.error of 0.011

FCNC Decays $B^0 \to \mu^+\mu^-$

- FCNC forbidden at first order → higher orders





Helicity suppression: width proportional to m_l^2

- $B_d^{\,0}$: suppression $(|V_{td}|\,/\,|V_{ts}|)^2$

Decay	SM prediction	Upper Limit	Exp.
$B_d^{\,0} \to e^+e^-$	$2.4 \cdot 10^{-15}$	$6.1 \cdot 10^{-8}$	Babar
$B_s^{\,0} \to e^+e^-$	$8.0 \cdot 10^{-14}$	$5.4 \cdot 10^{-5}$	CDF
$B_d^{\,0} \to \mu^+\mu^-$	$1.0 \cdot 10^{-10}$	$3.0 \cdot 10^{-8}$	CDF
$B_s^{\,0} \to \mu^+\mu^-$	$3.5 \cdot 10^{-9}$	$7.5 \cdot 10^{-8}$	D0
$B_d^{\,0} \to \tau^+\tau^-$	$3.1 \cdot 10^{-8}$	$3.2 \cdot 10^{-3}$	Babar
$B_s^{\,0} \to \tau^+\tau^-$	$7.4 \cdot 10^{-7}$	5.0%	Aleph

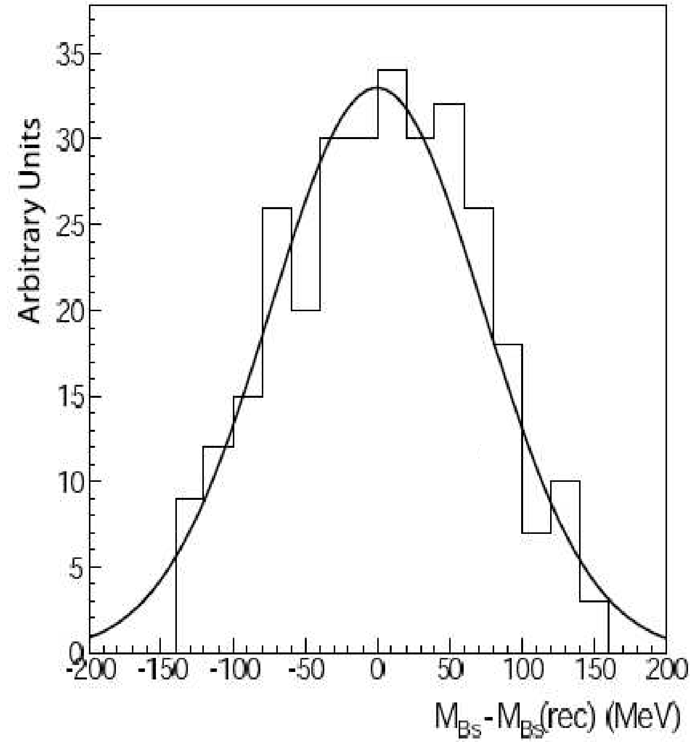
- Contributions from non-Standard Model processes can be important

FCNC Decays $B^0 \to \mu^+\mu^-$: Backgrouds

Sample	Decay channel/Generator cuts	N_{Gen}	σ_{vis}[fb]	N_{exp} in 10 fb^{-1}
$B_s \to \mu^+\mu^-$	$p_\perp{}^\mu > 3\,\mathrm{GeV}, \lvert\eta^\mu\rvert < 2.4$	8000	3.90E + 01	390
$b\bar{b} \to \mu^+\mu^- + X$	$p_\perp{}^{\mu\mu} > 5\,\mathrm{GeV}, p_\perp{}^\mu > 3\,\mathrm{GeV}$ $\lvert\eta^\mu\rvert < 2.4, 5 < m_{\mu\mu} < 6\,\mathrm{GeV}$ $0.3 < \Delta R(\mu\mu) < 1.8$	14472	1.74E + 07	1.67×10^8
QCD hadrons	$5 < m_{hh} < 6\,\mathrm{GeV}$	4875	2.24E + 11	1.12×10^8
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^+ decays	$B_u \to \mu^+\mu^-\mu^+\nu$	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

- Muons from independent semi-leptonic B decays (mostly gluon splitting)
- Non-resonant QCD background (hadron misidentification)
- Hadronic B decays (hadron misidentification)
- Rare B decays
- Hadron misidentification: $\varepsilon_{mis}(\pi) = 0.5\%$ - $\varepsilon_{mis}(K) = 1.0\%$ - $\varepsilon_{mis}(p) = 0.1\%$

Search for the decay $B_s \to \mu^+\mu^-$: HLT selection



B_s mass residual,using 6 hits
σ = 74 MeV/c^2

Similar HLT selection as for $B_s \to J/\psi\ \varphi$ search:

- Primary Vertex Reconstruction (Pixel only)
- Regional, partial track reconstruction in cones around L1 muon candidates
  - Partial reconstruction up to 6 hits maximum
  - $p_T^\mu > 4$ GeV/c
- Track pairs with opposite charge:
  $|M(\mu\mu) - M(B_s)| < 150$ MeV/c^2
- Vertex Fit of track pairs (χ^2<20)
  - Transverse decay length > 150 μm
- Efficiency: 41 % (w.r.t to decays with $p_T(\mu) > 3$ GeV/c, $|\eta|< 2.4$)
  - Level 1 efficiency: 69 %
  - HLT efficiency: 60 %
- Events / 10fb^{-1}: 150
- HLT accept rate: < 1.7 Hz

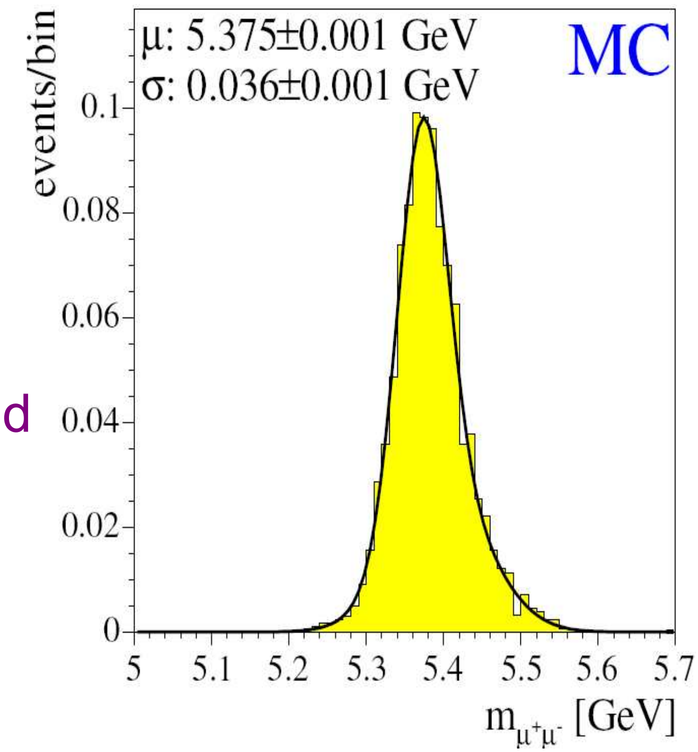
Search for the decay $B_s \to \mu^+\mu^-$: Offline selection

- Track reconstruction: Combinatorial KF, with p_T > 0.9 GeV/c
- Muon pairs with opposite charge
- Muon separation in $\eta\phi$: $0.3 < \Delta R(\mu\mu) < 1.2$

$$\Delta R(\mu\mu) = \sqrt{(\eta_{\mu 1} - \eta_{\mu 2})^2 + (\phi_{\mu 1} - \phi_{\mu 2})^2}$$

- Tracker Isolation of muon pair: $I > 0.85$
  - Tracks in cone of $\Delta R < 1$ around reconstructed dimuon momentum

$$I = \frac{p_T(B_s)}{p_T(B_s) + \sum_{tracks} p_T}$$

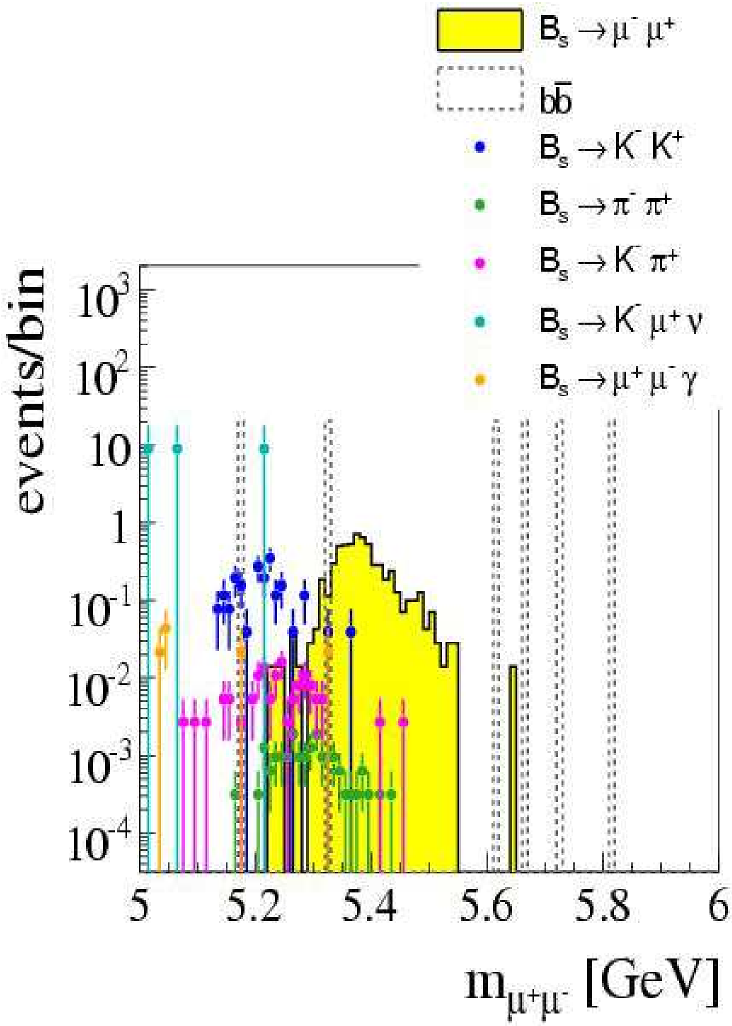


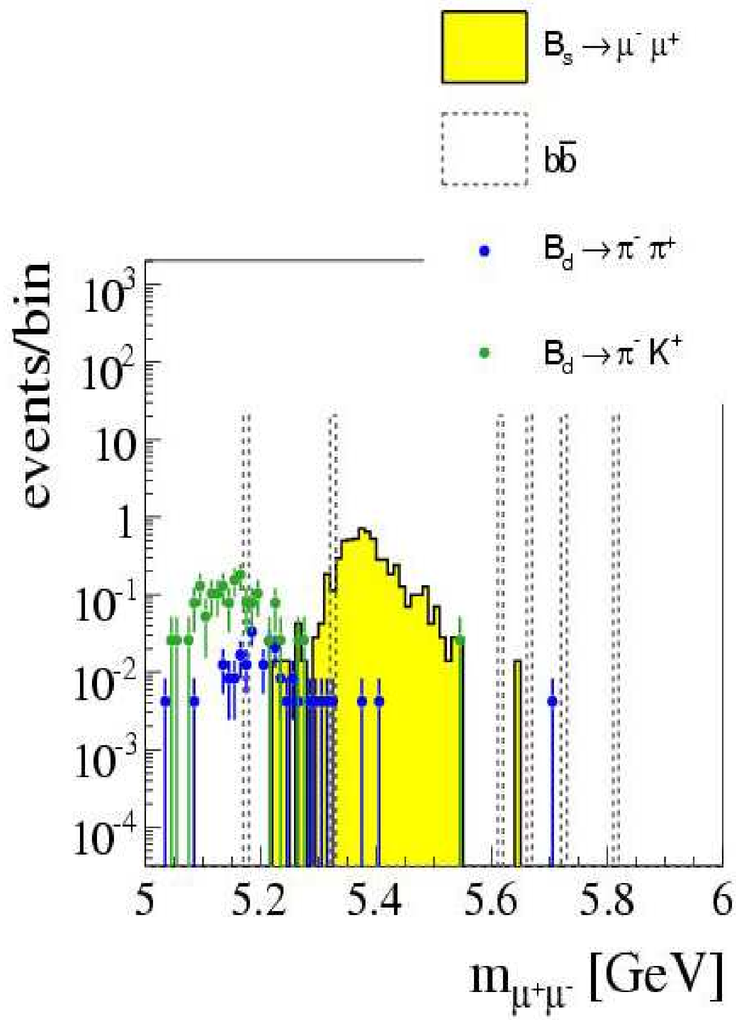
Reconstructed B_s mass(signal)[GeV/c^2]
Mean = 5.375 GeV/c^2
σ(core) = 32 MeV/c^2
σ(tail) = 60 MeV/c^2

- Vertex Fit of dimuon pairs (χ^2<1)
  - Transverse decay length significance : $L_{xy}/\sigma(L_{xy}) > 18$
  - Cosine of angle (momentum/decay length) > 0.995
- Mass window: $|M(\mu\mu) - M(B_s)| < 100$ MeV/c^2

Search for the decay $B_s \to \mu^+\mu^-$: Result

Rare background after cuts (10 fb^{-1})





Search for the decay $B_s \to \mu^+\mu^-$: Result

- Mass window: $|M(\mu\mu) - M(B_s)| < 100$ MeV/c^2
- Study limited by sizes of MC samples!
  - No background events remain when applying all cuts!
  - Factorize isolation and χ^2 cuts
- Selection efficiency: (w. factorization)
  - Signal: $\varepsilon_s = 0.019 \pm 0.002$
  - Background: $\varepsilon_b = 2.6 \times 10^{-7}$
- Events after all offline requirements (10 fb^{-1})
  - Signal: $n_S = 6.1 \pm 0.6(stat) \pm 1.5(syst)$
  - Background: $n_B = (13.8 + 0.3)\,^{+22.3}_{-14.1}$
- Upper limit (90% CL, including statistical and systematic error):

$$Br\,(B_s \to \mu^+\mu^-) \leq 1.4 \cdot 10^{-8}$$

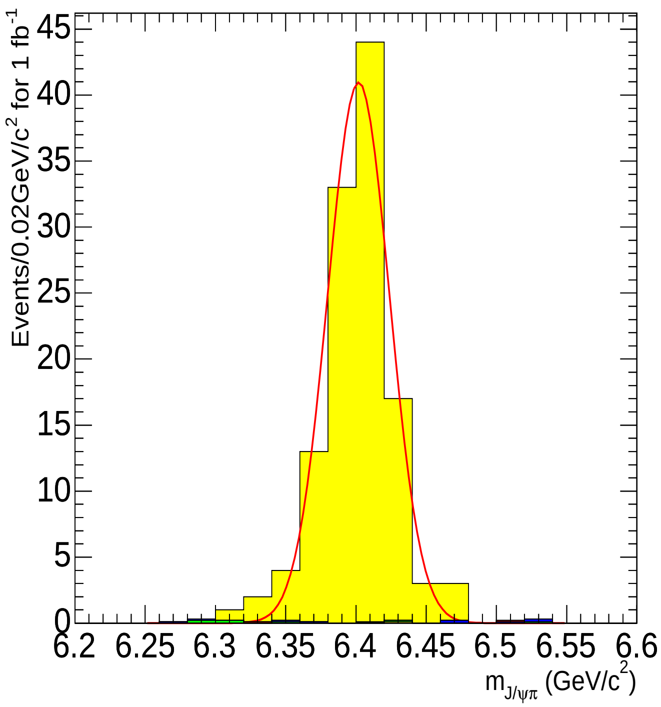
$$Br(B_s \to \mu^- \mu^+) \leqslant \frac{N(n_{obs}, nb, ns)}{L \cdot \sigma_{Bs} \cdot \epsilon_{gen} \cdot \epsilon_{sel}}$$

Expected SM Branching fraction: $Br\,(B_s \to \mu^+\mu^-) = 3.5 \cdot 10^{-9}$

Study of the B_c

Study of the B_c in decay $B_c \rightarrow J/\psi\ \pi$

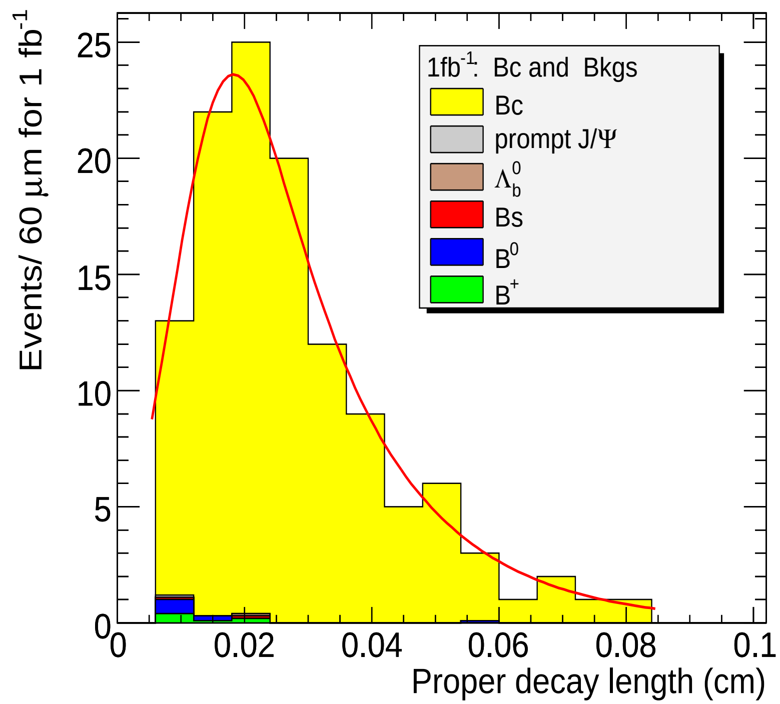
- ~120 candidates in first fb^{-1} of data



B_c mass distribution

$M(B_c)$ = 6406 ± 2 (stat) ± 14.9 (syst) MeV/c^2

Simulation input: $M(B_c)$ = 6.4 GeV/c^2



Proper decay length distribution

$c\tau$: 148.8 ± 13.1 (stat) ± 3.0 (syst) μm

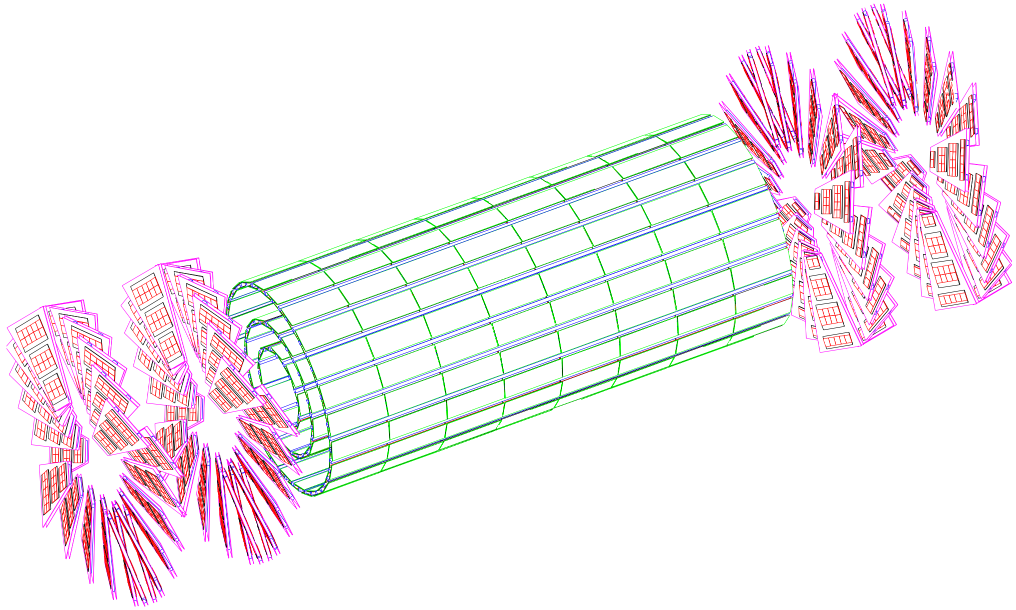
Simulation input: $c\tau$ = 150 μm

Conclusion

- CMS well suited for *B* physics
  - Large *b* production cross section
  - High luminosity (even at the initial "low luminosity"!)
- Powerful Muon system, used also for Level-1 Trigger
- Robust and versatile tracker and track reconstruction algorithms
  - Good performance at HLT
- Most *B*-physics measurements to be done at low-luminosity
  - Search for rare decays may also be continued at high-luminosity
- Trigger strategies and trigger-menus are being prepared to be ready for first collisions and first measurements!
- First *B*-physics measurements with early data!
  - New Physics ?
  - Constraints on models beyond SM
  - Can expect high yield of rare decays ($B_s \to \mu^+\mu^-$, $B_s \to \mu^+\mu^-\varphi$, $B \to \mu^+\mu^- K$, $B \to \mu^+\mu^- K^*$, $B_s \to \mu^+\mu^-\gamma$)

Backup

The Pixel system



Active area ~ 1m^2 - 66·10^6 pixels

Geometry:

- 3 Barrel layers
  r = 4.4 cm, 7.3 cm, 10.2 cm
- 2 Pairs of Forward/Backward Disks
  r = 6 cm-15 cm ; *z* = 34.5cm, 46.5cm

Pixel-size: 100 μm x 150 μm

Hit-resolution:

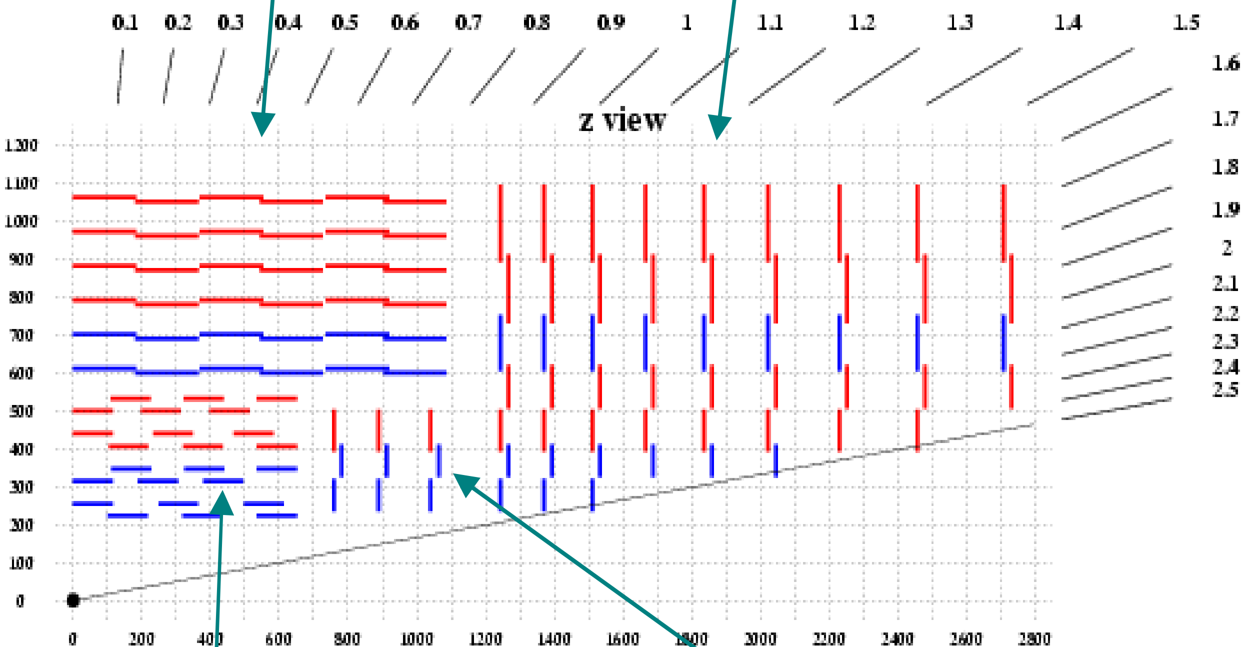
- *r-φ* : σ ~ 10 μm
  (Lorentz angle 23° in 4 T field)
- *r-z* : σ ~ 20 μm

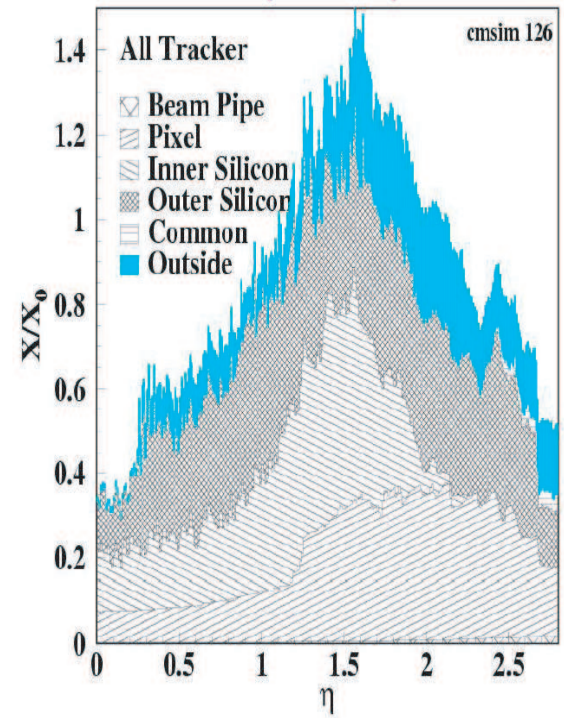
➣ 3 high resolution measurement points for **|η| < 2.2**

The Silicon Strip Tracker

Outer Barrel (TOB): 6 layers
- Thick (500 µm) sensors
- Long Strips

Endcap (TEC): 9 disks pairs
- r<60cm: Thin sensors
- r>60cm: Thick sensors





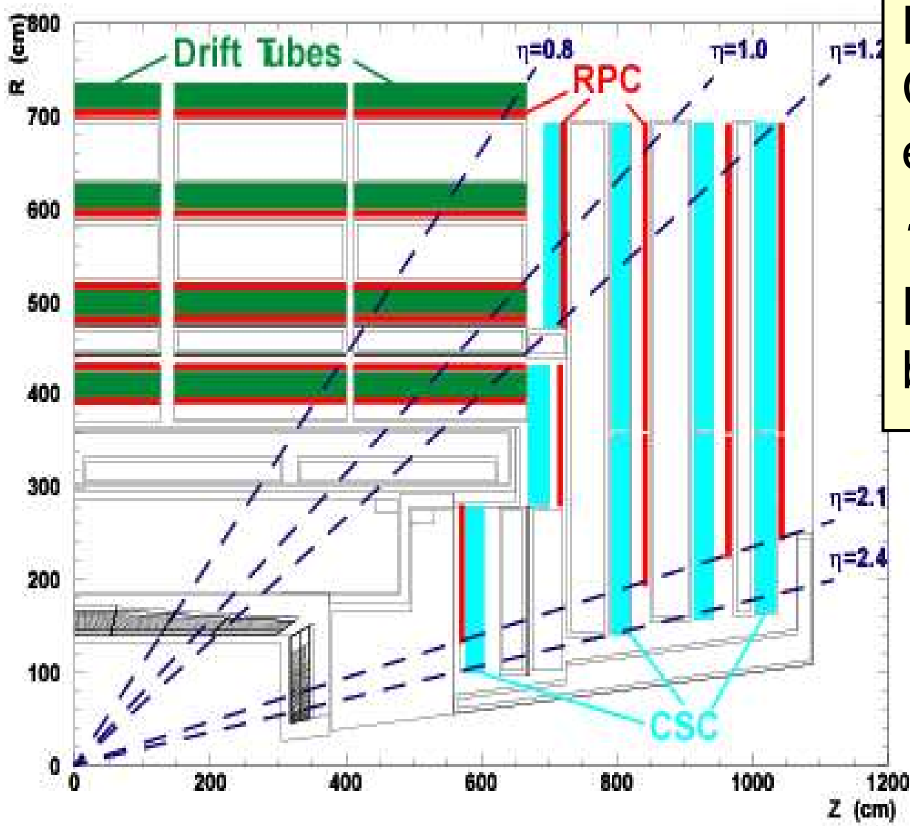
Material budget of the tracker

Inner Disks (TID): 3 disks pairs
- Thin sensors

Inner Barrel (TIB): 4 layers
- Thin (320 µm)sensors
- Short Strips

blue: double-sided detectors
red: single-sided detectors

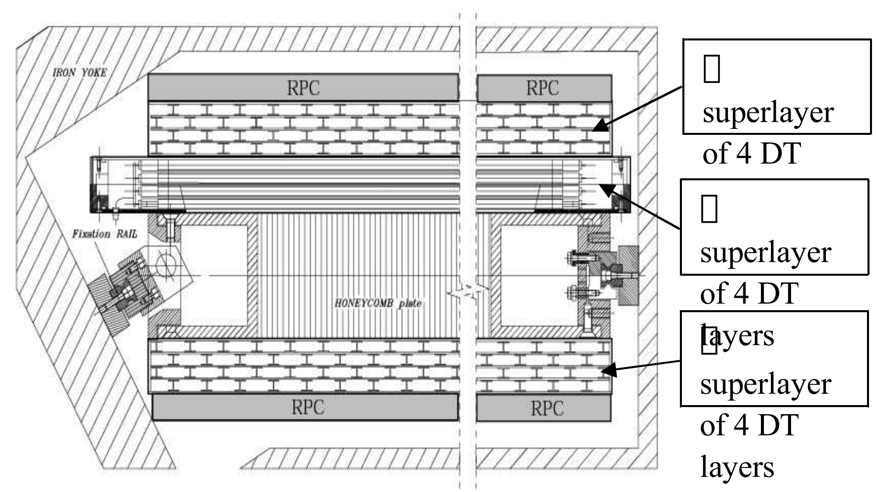
The Muon detectors



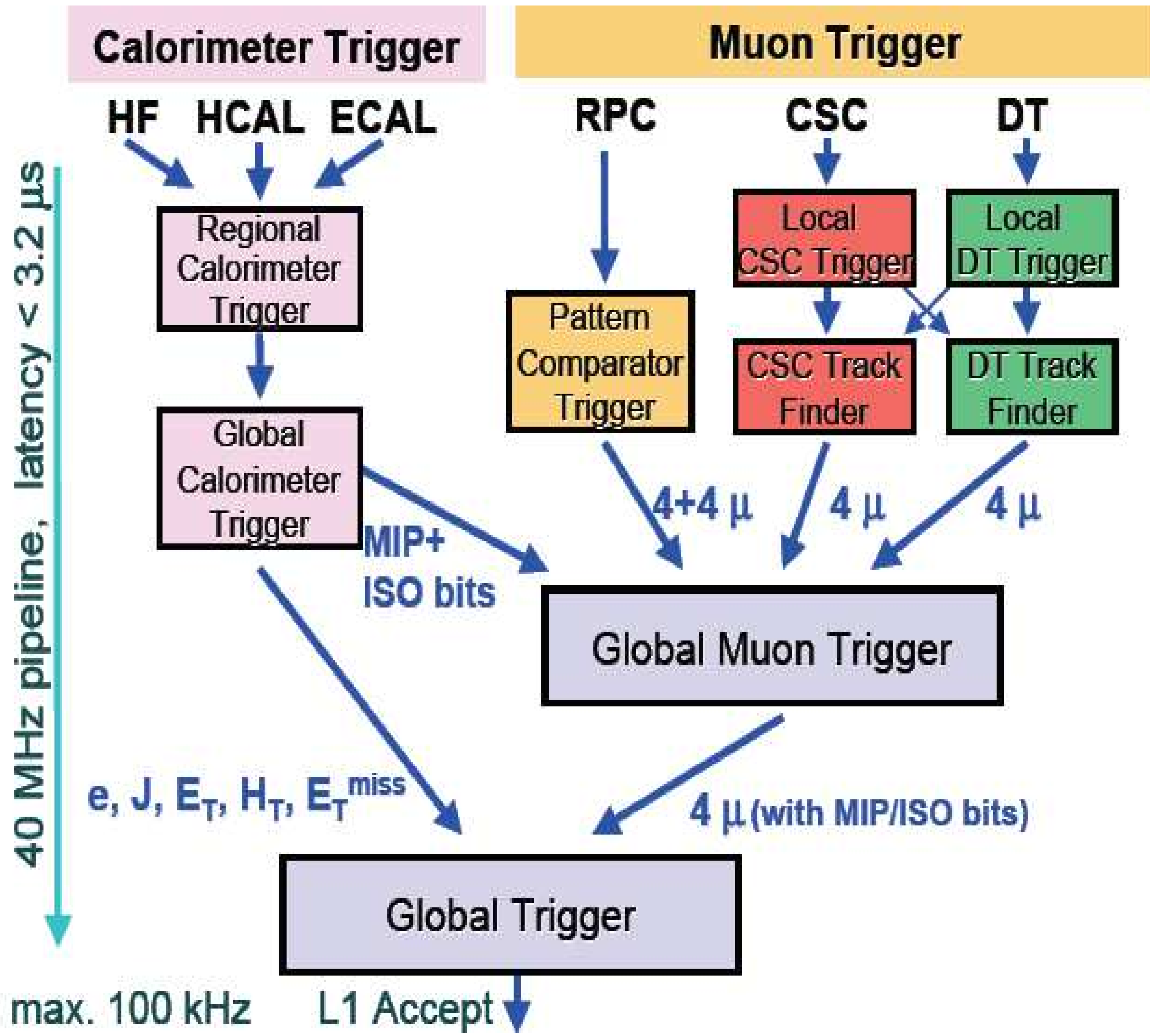
Position measurement:
Drift Tubes (DT) in barrel
Cathode Strip Chambers (CSC) in endcaps

Trigger:
Resistive Plate Chambers (RPCs) in barrel and endcaps

First muon chamber just after solenoid
➣ extend lever arm for p_T measurement



The Level 1 trigger



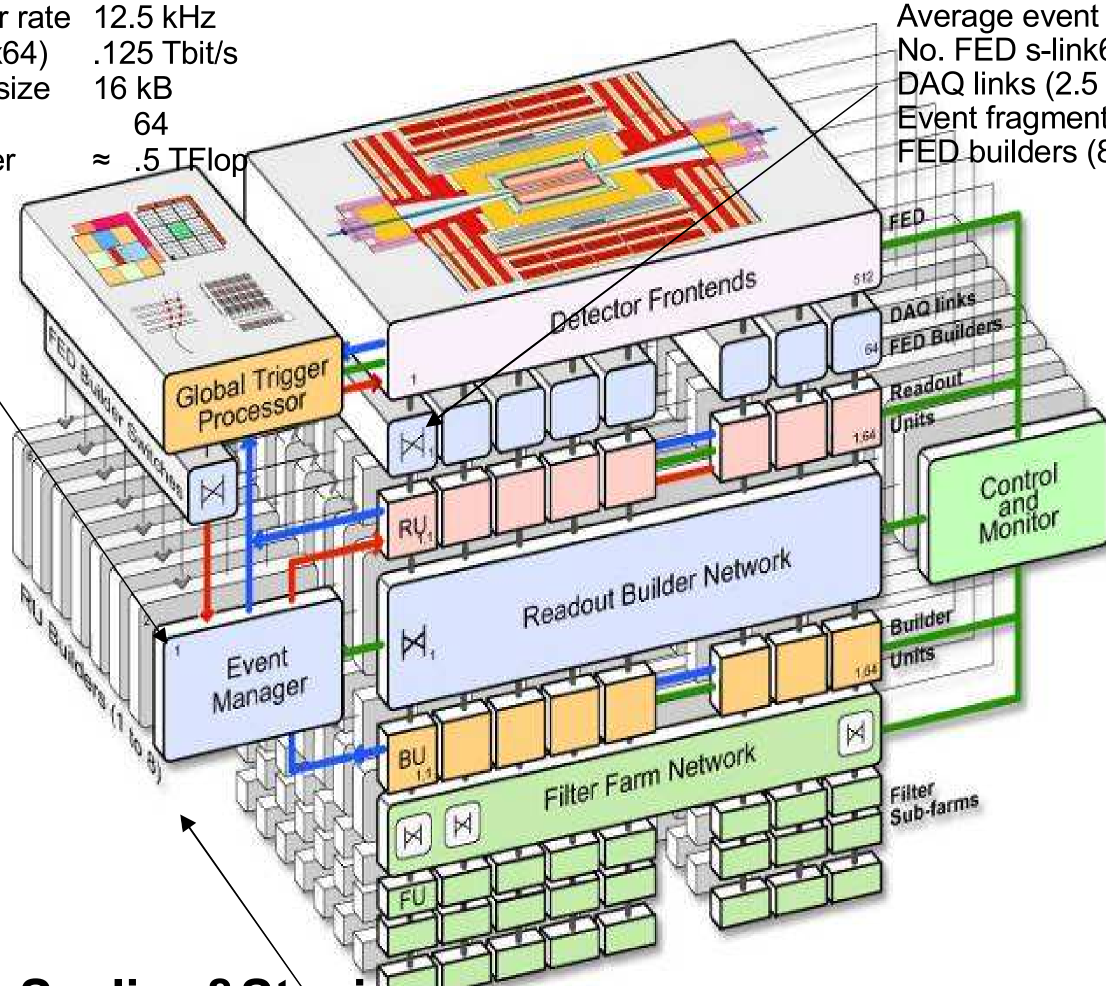
3D-EVB: scalable DAQ

DAQ unit (1/8th full system):

Lv-1 max. trigger rate 12.5 kHz
RU Builder (64x64) .125 Tbit/s
Event fragment size 16 kB
RU/BU systems 64
Event filter power ≈ .5 TFlop

Data to surface:

Average event size 1 Mbyte
No. FED s-link64 ports > 512
DAQ links (2.5 Gb/s) 512+512
Event fragment size 2 kB
FED builders (8x8) ≈ 64+64



DAQ Scaling&Staging

The decay $B_s \rightarrow J/\psi\, \varphi$: The Analysis

- Final state: admixture of CP-even / CP-odd eigenstates
- The CP-even and CP-odd components have different angular dependences!
  - A.Dighe *et al.*, Phys. Lett B 369 (1996) 144-150
  - A.Dighe *et al.*, Eur. Phys. J. C 6, 647-662 (1999)
- Differential decay rate:

$$\frac{d^4\Gamma(B_s(t))}{d^3\Theta\, dt} = f(\Theta, \alpha, t) = \sum_i b^{(i)}(\alpha, t)\, g^{(i)}(\Theta)$$

  - $g^{(i)}(\Theta)$: angular distribution functions
    - Θ: angles describing the kinematics (3 angles: Transversity basis)
  - $b^{(i)}(\alpha,t)$: observables
    - α: kinematics independent parameters (e.g. Γ_H, Γ_L, Δm_s...)
    - can be expressed in terms of bilinear combinations of the linear polarization amplitudes:

$$|A_0(t)|^2 ,\ |A_{//}(t)|^2 ,\ |A_\perp(t)|^2,$$

$$\mathrm{Re}\,[A_0^*(t)A_{//}(t)] ,\ \mathrm{Im}[A_{//}^*(t)A_\perp(t)] ,\ \mathrm{Im}[A_0^*(t)A_\perp(t)]$$

The decay $B_s \to J/\psi\, \varphi$: The Analysis

Observables for an untagged analysis:

$$
\begin{aligned}
|A_0(t)|^2 &= |A_0(0)|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - |\cos\phi_{CKM}| \left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\right] \\
|A_\parallel(t)|^2 &= |A_\parallel(0)|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - |\cos\phi_{CKM}| \left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\right] \\
|A_\perp(t)|^2 &= |A_\perp(0)|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} + |\cos\phi_{CKM}| \left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\right] \\
\Im(A_\parallel^*(t)A_\perp(t)) &= -|A_\parallel(0)||A_\perp(0)| \cos(\delta_1) \sin\phi_{CKM} (e^{-\Gamma_H t} - e^{-\Gamma_L t}) \\
\Re(A_0^*(t)A_\parallel(t)) &= |A_0(0)||A_\parallel(0)| \cos(\delta_2 - \delta_1) \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - |\cos\phi_{CKM}| \left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\right] \\
\Im(A_0^*(t)A_\perp(t)) &= -|A_0(0)||A_\perp(0)| \cos(\delta_2) \sin\phi_{CKM} (e^{-\Gamma_H t} - e^{-\Gamma_L t}) \,.
\end{aligned}
$$

- Decay widths (Γ_H, Γ_L)
- CP-conserving strong phases δ_1, δ_2 (from FSI)
- CP-violating weak phase $\delta\phi$: interference between mixing and decay:

$$
e^{i\delta\phi} = \frac{V_{tb} V_{ts}^*}{V_{ts} V_{tb}^*} \frac{V_{cb} V_{cs}^*}{V_{cs} V_{cb}^*} \quad , \quad \delta\phi \simeq 2\lambda^2 \eta \sim O(0.03)
$$

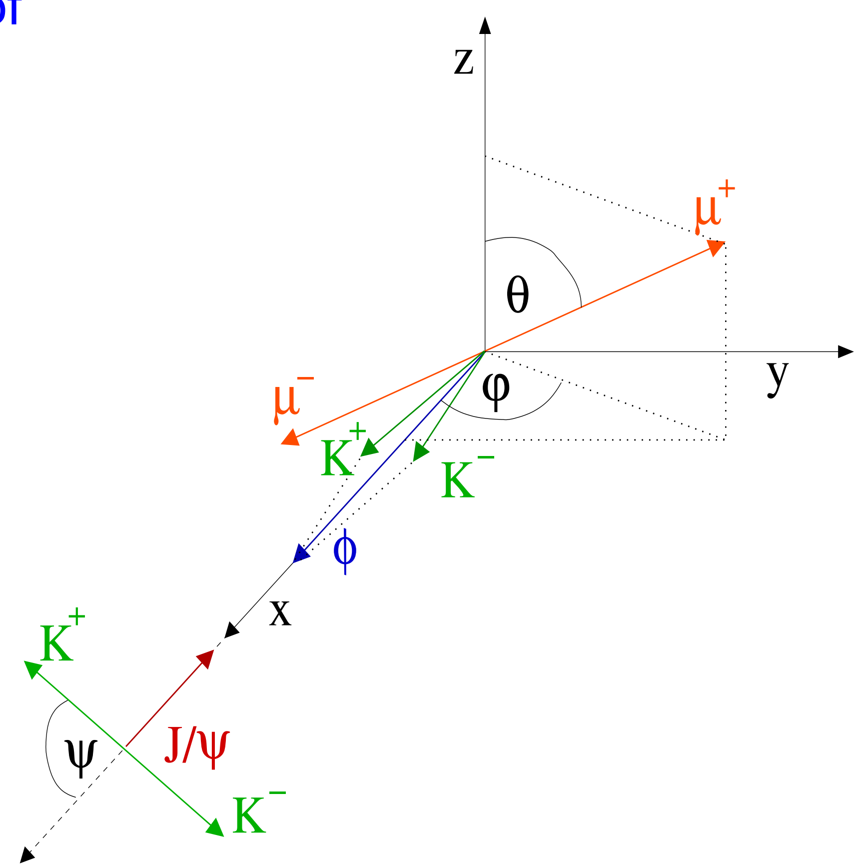
- In tagged analysis, dependence on mass difference ($\Delta m = m_H - m_L > 0$)

The decay $B_s \to J/\psi\, \varphi$: The Analysis

"Transversity basis": 3 angles: cos θ, ψ, cos ϕ

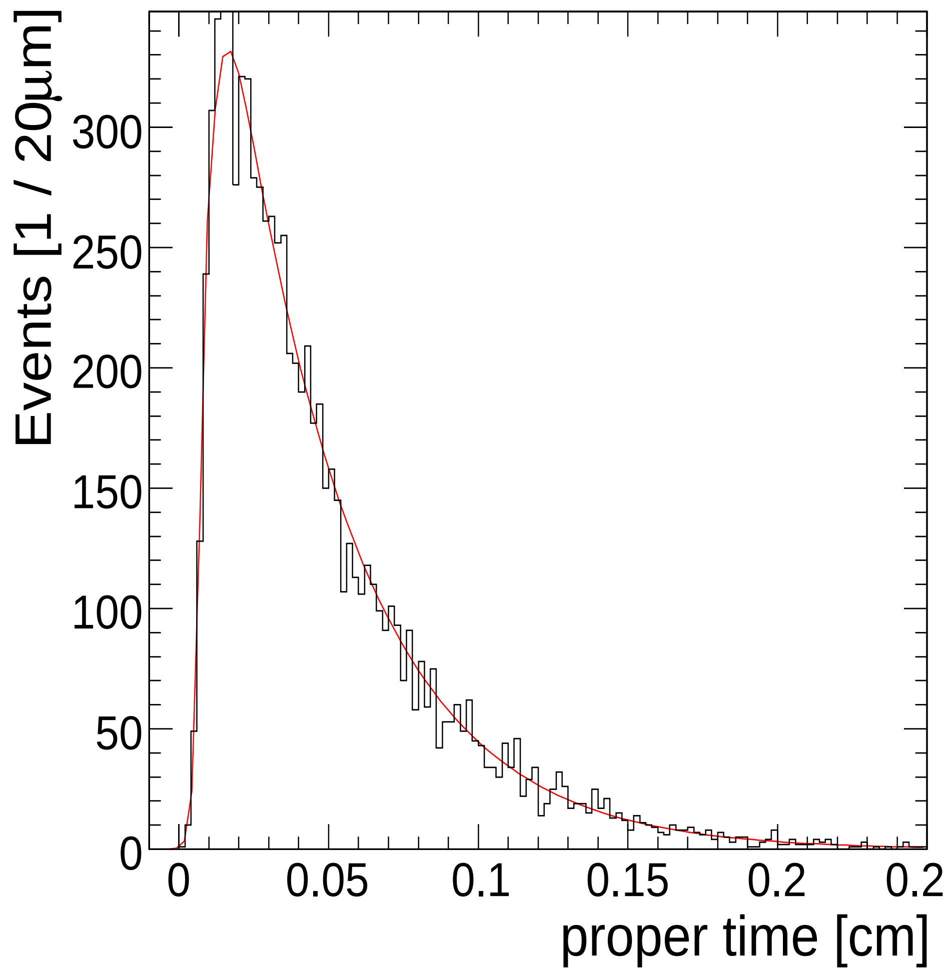
- Right handed coordinate system in the J/ψ rest frame:
  - **x**: direction of flight of the ϕ meson
  - **y**: $\perp$ to **x**, in the direction of flight of the K^+
- (θ, ϕ) : direction of flight of l^+ in the J/ψ rest frame
- ψ : angle between ***x*** and direction of flight of the K^+ in the $\boldsymbol{\phi}$ rest frame
- Angular distribution functions:

$$
\begin{aligned}
g_1 &= 2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)\,, \\
g_2 &= \sin^2\psi(1-\sin^2\theta\sin^2\varphi)\,, \\
g_3 &= \sin^2\psi\sin^2\theta\,, \\
g_4 &= \sin^2\psi\sin 2\theta\sin\varphi\,, \\
g_5 &= 1/\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\varphi\,, \\
g_6 &= 1/\sqrt{2}\sin 2\psi\sin 2\theta\cos\varphi\,.
\end{aligned}
$$



The decay $B_s \rightarrow J/\psi\, \varphi$: The Analysis

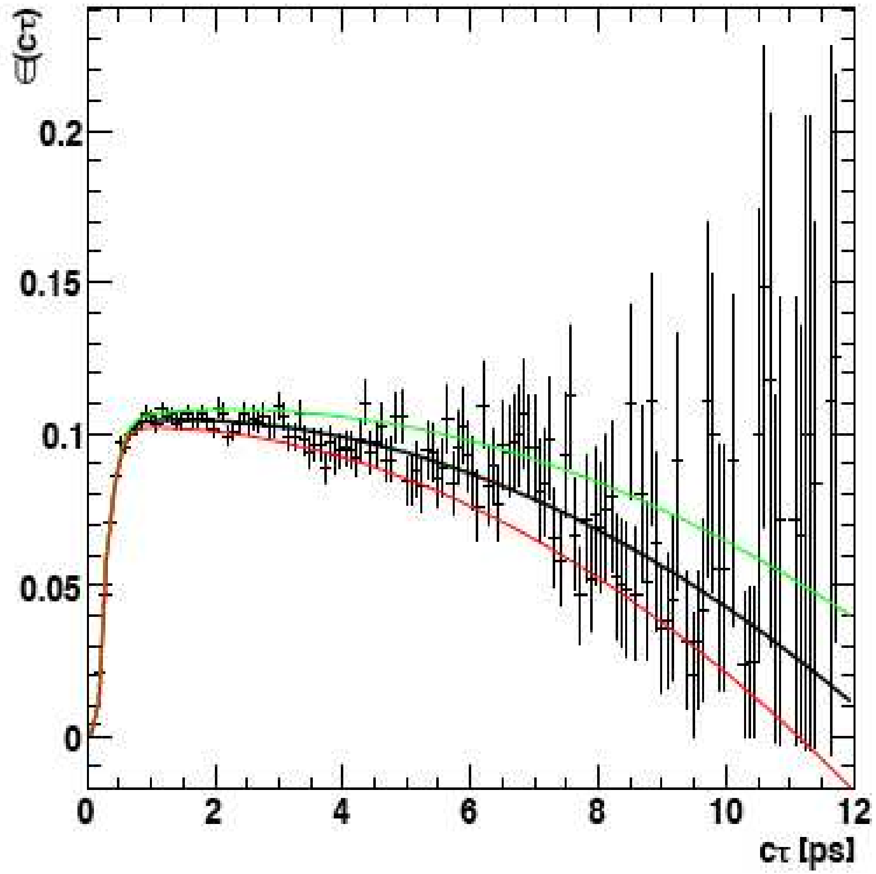
Distributions of the proper decay length of the selected events with fit projection:



Time-dependent efficiency

Time-dependent efficiency due to HLT requirements:

- Cut on decay length significance
- Lower track reconstruction efficiency for tracks from displaced vertices



- Measurement/cross-check for other *B* decays ($B_d^0 \to J/\psi\, K^*$) from data

$$\epsilon(t) = \begin{cases} c \cdot \left(1 + \tanh\left(\frac{t-t_0}{\Delta t}\right)\right) & t < t_0 \\ (a \cdot t^2 + b \cdot t + c) \cdot \left(1 + \tanh\left(\frac{t-t_0}{\Delta t}\right)\right) & t > t_0 \end{cases}$$

Angular efficiency

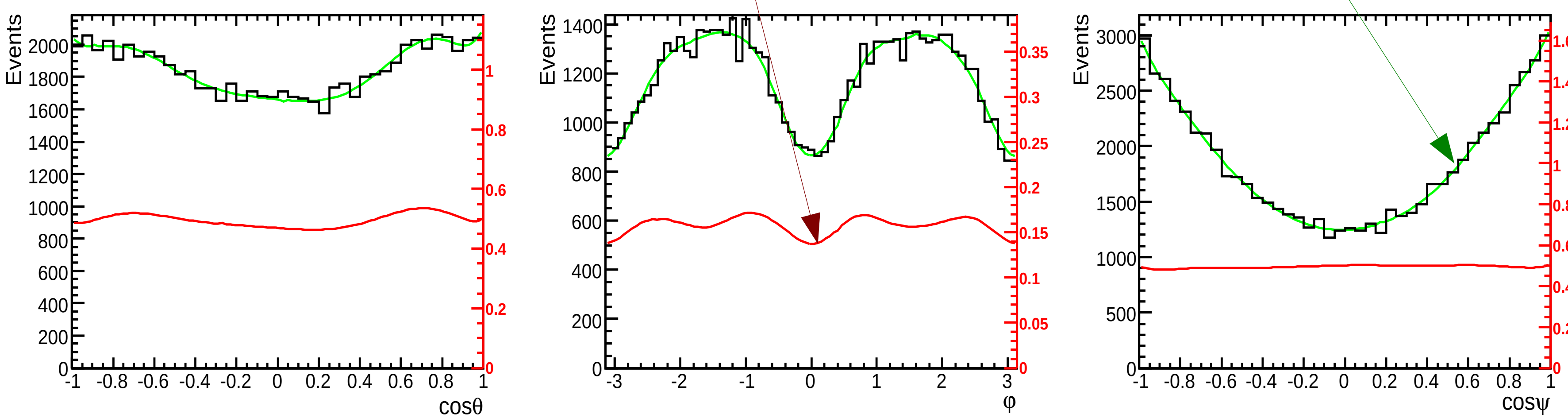
Distortion of the angular distributions due to kinematic requirements:

- ➢ Expansion of products of spherical harmonics

- Angular efficiency (projections)

Angular efficiency

Expected angular distributions
$f(\Theta)\cdot\varepsilon(\Theta)$

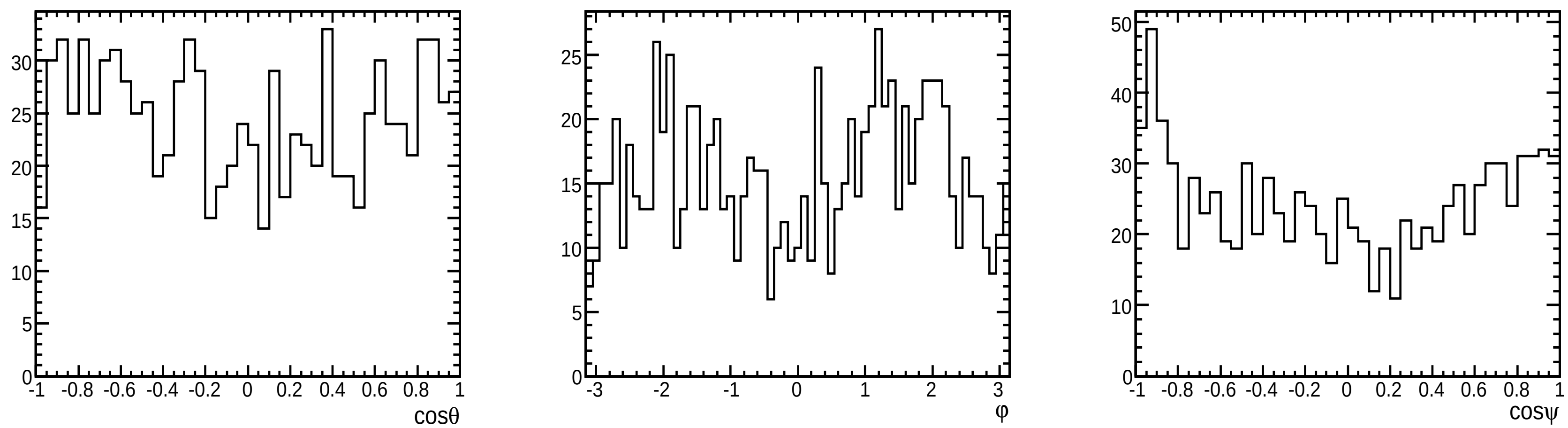


- Method can be tested on similar $B_d^0 \rightarrow J/\psi\, K^*$ decays (data vs. MC)
  - ➢ Efficiency function/moments will be different due to different kinematics

Background distributions

- Observed angular distribution of misidentified $B_d^0 \rightarrow J/\psi\, K^*$ decays:
  - Similar angular distribution, distorted due to misidentified pion, kinematic requirements
  - Expansion of products of spherical harmonics (up to L = R = 8)

  To few events in current data set to estimate the moments
  - Time-dependence: single exponential decay with time-dependent efficiency

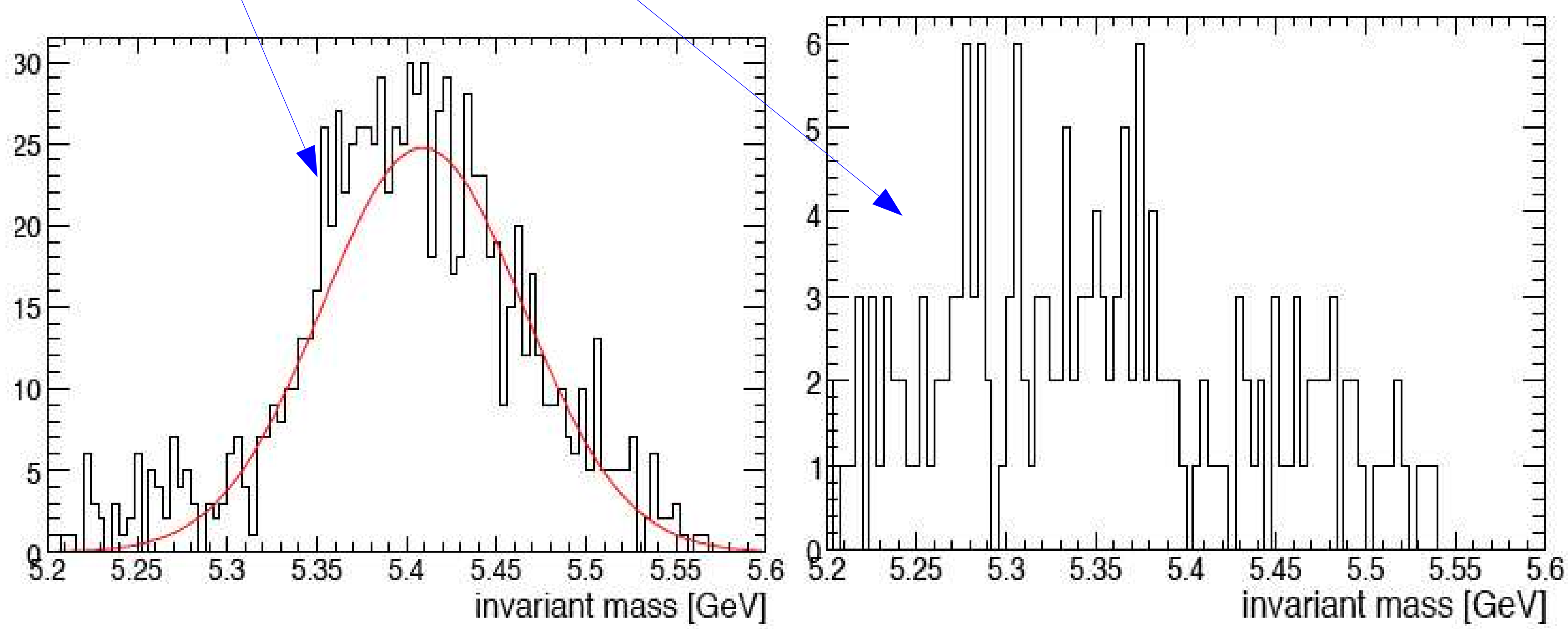


- Other backgrounds (inclusive, combinatorial)
  - Flat angular distribution
  - Time-dependence: two exponential decays with time-dependent efficiency:
    - Short-lived prompt background
    - Long-lived: misidentified heavy-flavoured hadrons

Mass distributions

Better signal/background indentification by use of sidbands and invariant mass distribution in fit

- Use of full region between 5.219 GeV/c^2 and 5.559 GeV/c^2:
- B_s signal: Gaussian distribution $G_s(m; M_s, \sigma_s)$
- B_d background: Gaussian distribution - $G_d(m; M_d, \sigma_d)$
- Other/combinatorial: Linear distribution: $a \cdot m + b$



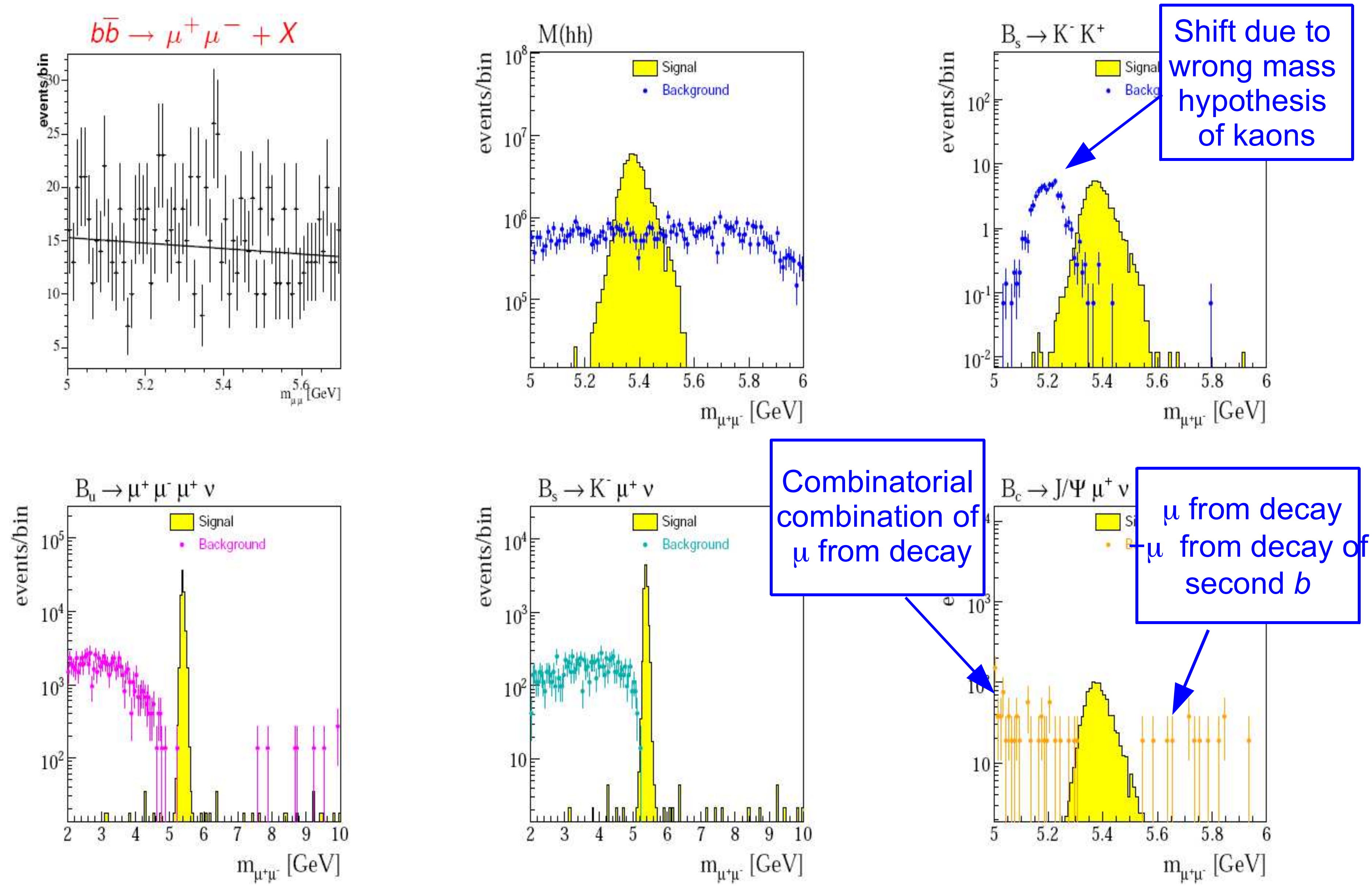
The decay $B_s \rightarrow J/\psi\, \varphi$: Systematic uncertainties

On the measurements:

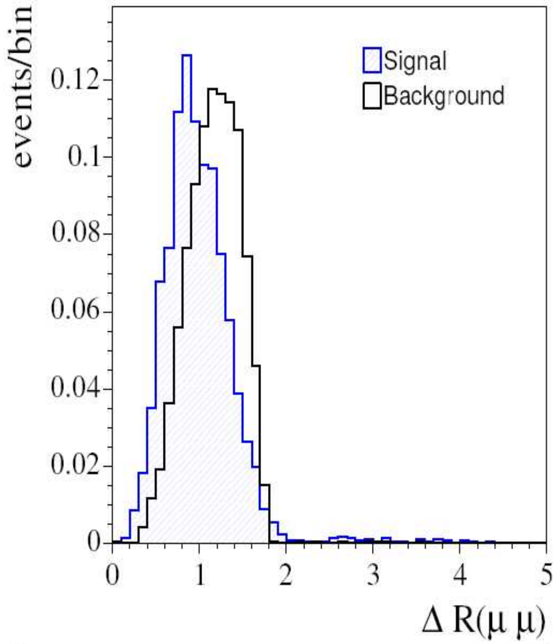
- Background distribution: fits with and without background events
- S/B ratio: Number of B_s events varied to account for uncertainty in S/B
- Resolution on the angles: from validation tests
- Time-dependent efficiency: function varied by 1σ
- Angular efficiency:Fit without ang.efficiency correction, expansion up to L , R ≤ 6, 10
- Misalignment: degradation of proper decay length (23 μm → 32 μm)

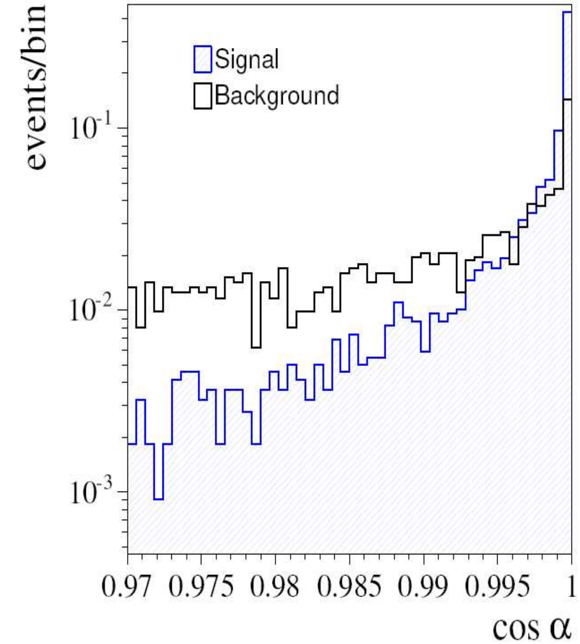
Source	$\lvert A_0(0)\rvert^2$	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_{\perp}(0)\rvert^2$	$\bar{\Gamma}_s$ [ps^{-1}]	$\Delta\Gamma_s/\Gamma_s$
Bckg. distrib.	0.0034	0.0011	0.0045	0.0043	0.0059
S/B ratio	0.0037	0.0001	0.0024	0.0025	0.0055
Resolution	-	-	-	0.00025	0.0040
Ang. distortion	0.0143	0.0061	0.0082	0.00083	0.0010
$c\tau$ distortion	0.0016	0.00073	0.0023	0.0221	0.0146
Alignment	0.00012	0.00042	0.00055	0.00040	0.0014
Total	0.0152	0.0063	0.0099	0.0227	0.0173

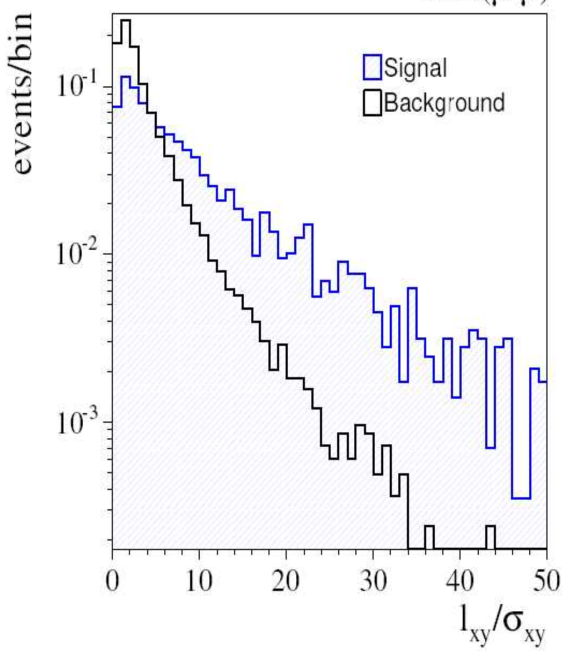
Search for the decay $B_s \to \mu^+\mu^-$: Background distributions

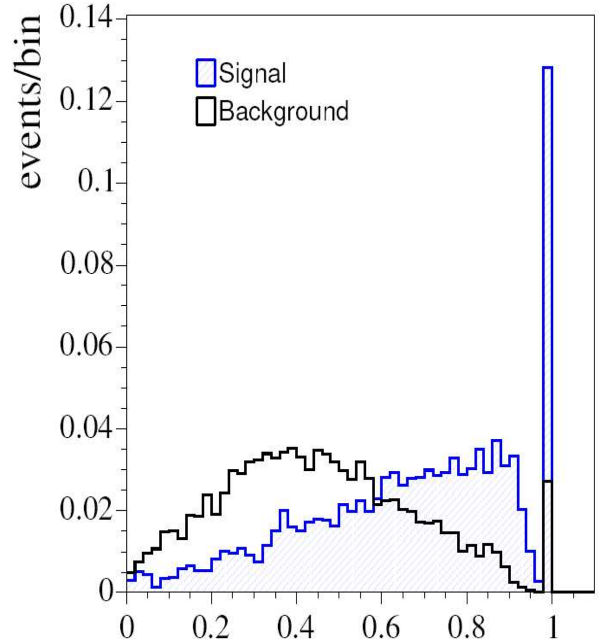


Search for the decay $B_s \to \mu^+\mu^-$: Offline selection









Search for the decay $B_s \to \mu^+\mu^-$: Systematic uncertainties

- Muon identification (1%): < 1%
- Tracking efficiency (1%): < 1%
- Misalignment (mass resolution): < 1%
- Misalignment (degradation of proper decay length): 10% / 50%
- Cut factorization: 15%
- L1 trigger efficiency: 10%
- Normalization: 15%

- Total systematic uncertainty: 25% on signal
- Background uncertainty dominated by statistical uncertainty: 160%