Measurement of the weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ using the $B_s \rightarrow J/\psi\phi$ decay channel

Beauty2014, July 14 – 18, 2014

Edinburgh, Scotland

NEW CMS RESULTS
PAS BPH-13-012

Paula Eerola for the CMS collaboration

Outline

- Introduction
- $B_s \rightarrow J/\psi\phi$
  - Reconstruction, selections
  - Efficiencies, resolutions
- Flavour tagging
- Data fit, systematic uncertainties and results
- CMS prospects
- Summary

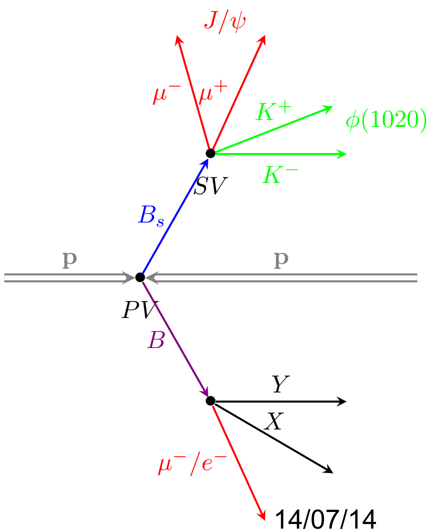
$B_s \rightarrow J/\psi\phi$: probe the weak decay phase ϕ_s

GENERAL:

- B_s and $B_s$bar decay to the same final state: **weak phase ϕ_s** arises from interference between direct decays and decays via mixing
- $\phi_s \approx -2\beta_s$, where $\beta_s = \arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb})$
- Weak phase accurately predicted in the Standard Model (SM): $2\beta_s = (0.0363\ ^{+0.0016}_{-0.0015})$ rad
- Sensitivity to New Physics beyond the SM
- Experimentally clean, fully reconstructed final state, small background

CMS ANALYSIS

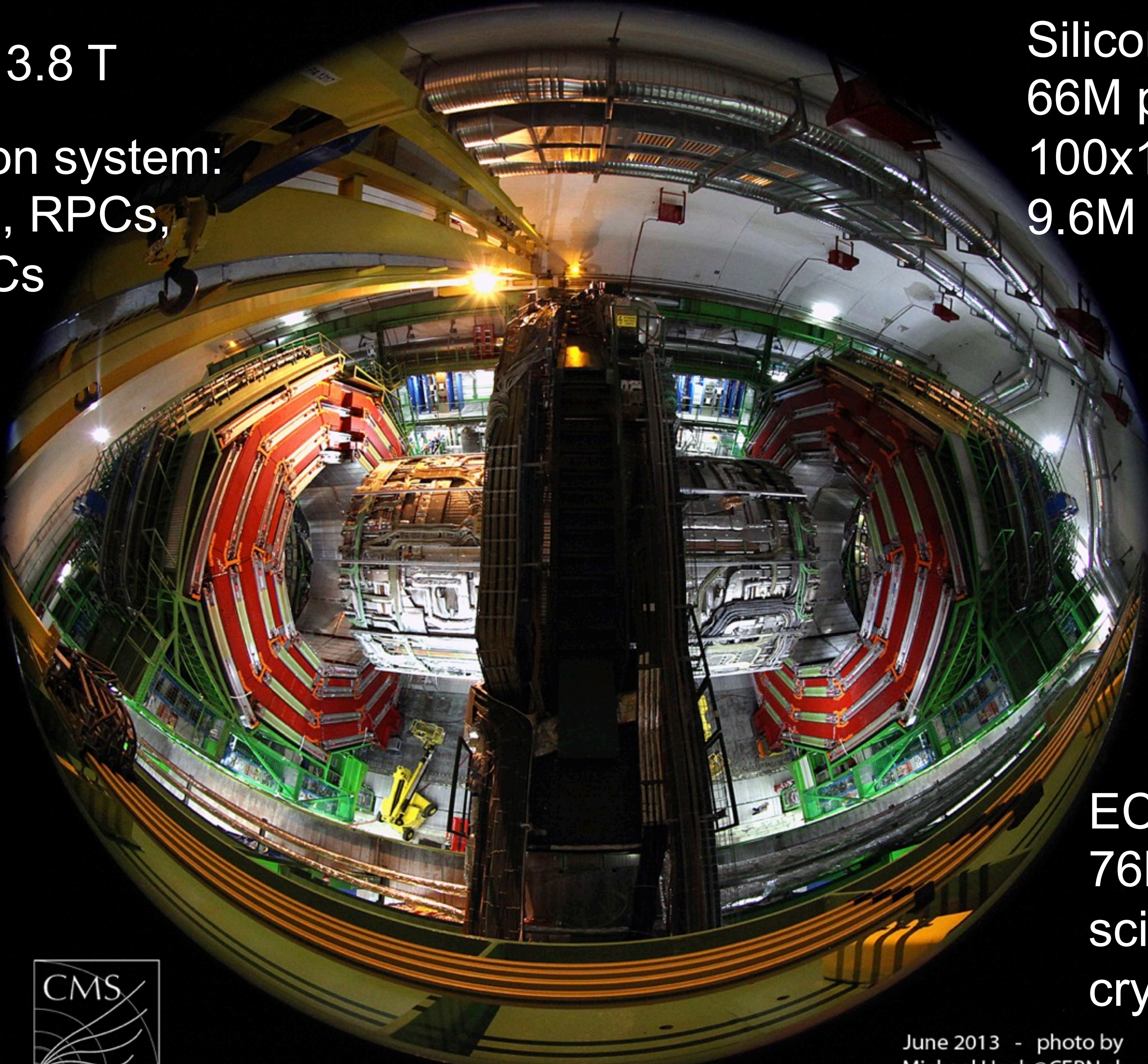
- 2012 data, 20 fb^{-1}
- Dimuon trigger (with decay length cut)



B = 3.8 T

Muon system:
DTs, RPCs,
CSCs

Silicon tracker
66M pixels
100x150 μm^2
9.6M Si strips



ECAL
76k $PbWO_2$
scintillating
crystals

CMS

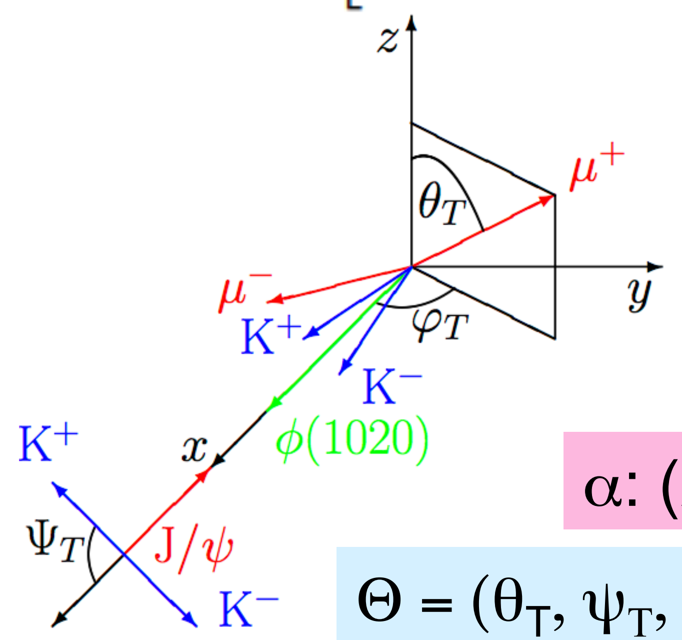
June 2013 - photo by
Michael.Hoch@CERN.ch

$B_s \rightarrow J/\psi\phi$: angular analysis

- **Time-dependent angular analysis to disentangle CP-odd and CP-even components of the final state**

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = f(\Theta,\alpha,t) = \sum_{i=1}^{10} O_i(\alpha,t).g_i(\Theta),$$

$$O_i(\alpha,t) = N_i e^{-\Gamma_s t}\left[a_i \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_i \sinh(\frac{1}{2}\Delta\Gamma_s t) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t)\right]$$



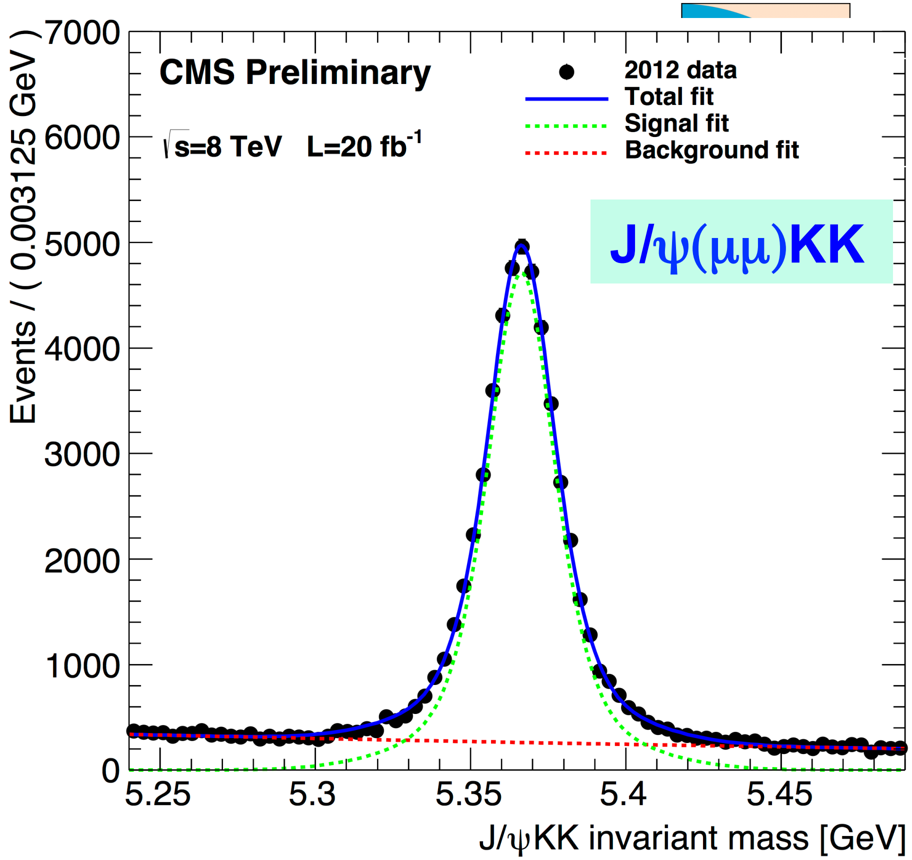
Depend on ϕ_s

α: ($\Delta\Gamma_s$, ϕ_s, $c\tau$, $|A_0|^2$, $|A_S|^2$, $|A_T|^2$, $\delta_{||}$, δ_{ST}, δ_T)

$\Theta = (\theta_T, \psi_T, \varphi_T)$ transversity basis

$B_s \to J/\psi\phi$: reconstruction and selections

- **Trigger: displaced J/ψ from B**
  - $p_T(\mu\mu)$>6.9 GeV, $p_T(\mu)$>4 GeV, $|\eta|$<2.1,
  - L_{xy}/σ_{xy} > 3, $DCA_{3D}(\mu\mu)$>0.5 cm,
  - 2.9 < M($\mu\mu$) < 3.3 GeV,
  - χ^2 vertex fit prob > 15%, $\cos\Delta\alpha$>0.9
- **$|m(J/\psi) - m(J/\psi)_{PDG}|$ <150 MeV**
- **p_T(K)>0.7 GeV, >5 tracker hits**
- **$|m(KK) - m(\phi)|$ < 10 MeV**
- **B_s kinematic and vertex fit:**
  - J/ψ mass constraint,
  - χ^2 vertex fit prob > 2%,
  - mass 5.24-5.49 GeV, *ct* 0.02-0.3 cm
- **PV: closest to B_s (min angle $\Delta\alpha$ between L_{xyz} and p)**



S/B ≈ 6.8 in 5.33-5.40 GeV

49 000 signal events

Main background: displaced J/ψ's from B with combinatorial tracks

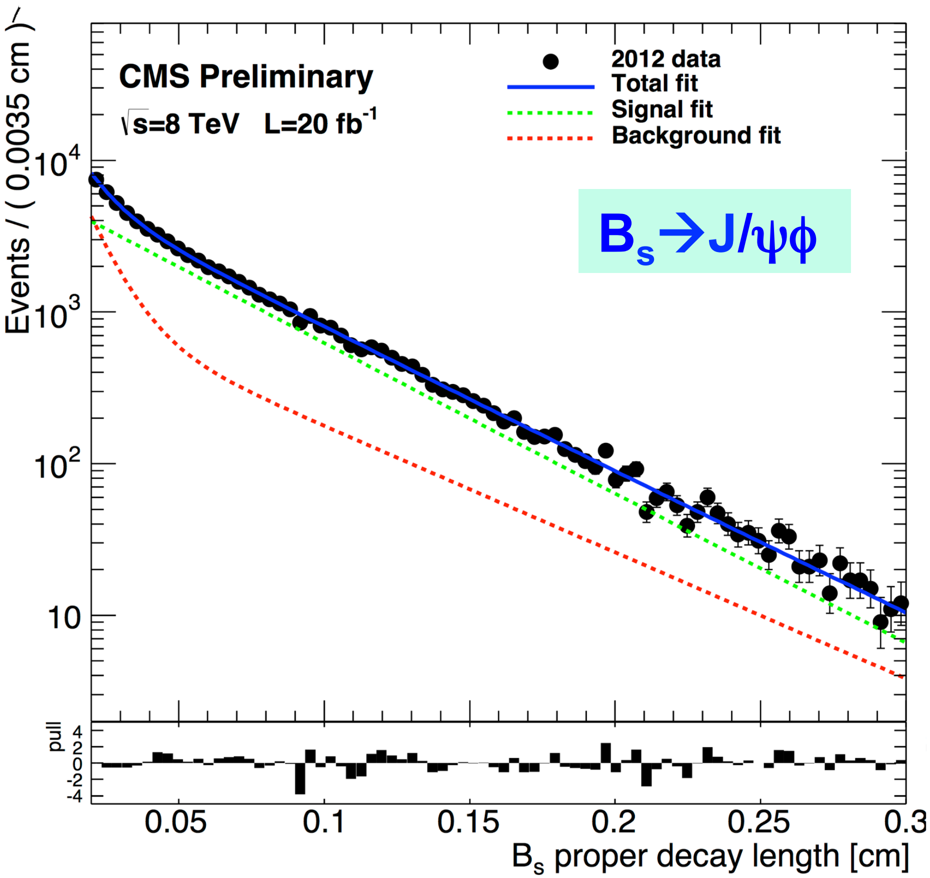
Efficiencies and resolutions

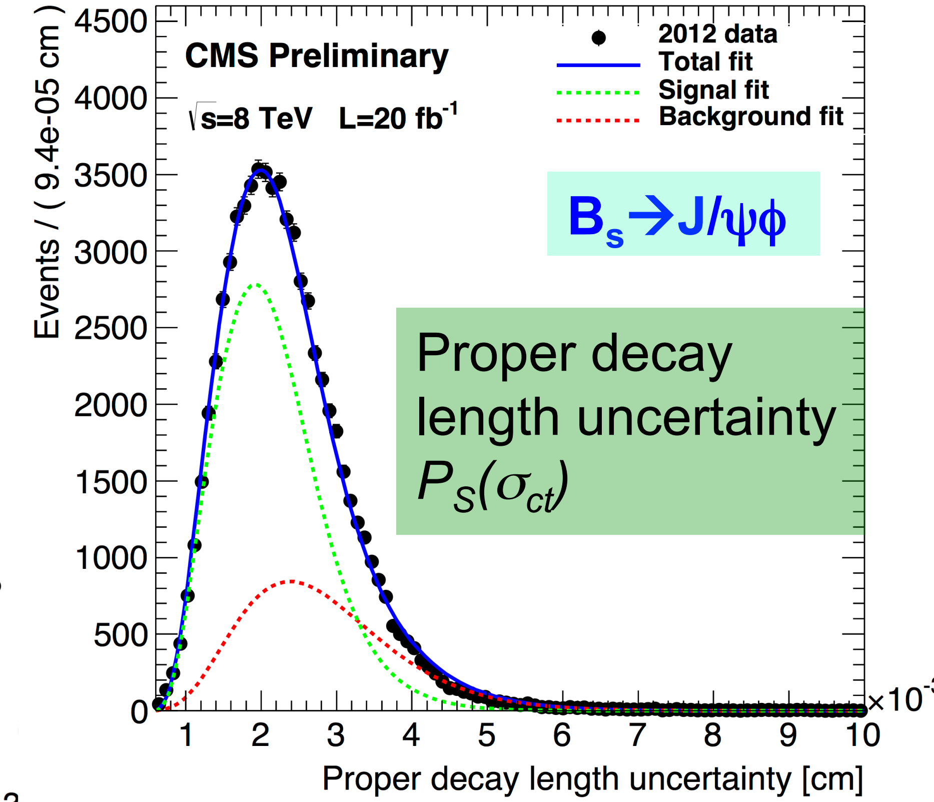
- **Most important: angular and time efficiencies and resolutions**

- **Angular efficiency** $\varepsilon(\Theta) = \varepsilon(\cos\theta_T, \cos\psi_T, \varphi_T)$
  - **MC, parametrized as a 3D-function**
- **Angular resolution**
  - **MC, not included in the fit, considered as systematic uncertainty**

- **Proper decay time efficiency: MC and cross-checked with data**
  - **Flat in the fit range *ct* = [0.02 - 0.3] cm → not included in the fit**
  - **Variation from flat considered as systematic uncertainty**

- Proper decay time resolution: ≈ 70 fs, included in the fit per-event
  - taken from the proper decay time uncertainty and scaled with $\kappa(ct)$, cross-checked with prompt J/ψ

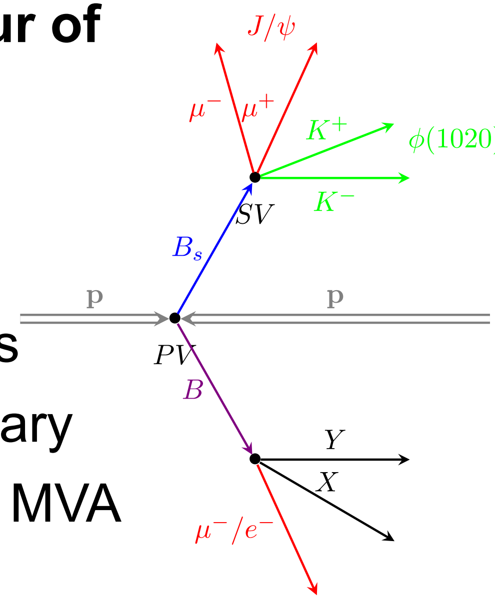




Decay length resolution appr. 21 μm (≈ 70 fs)

Opposite side flavour tagging

- Opposite side leptons (μ, e) used to tag the flavour of the B_s at the production time
- Tagging performance optimized by maximizing $P = \varepsilon_{tag}(1-2\omega)^2$
  - Particle-flow muons, Gaussian-sum filter electrons
  - Selections: p_T>2.2 GeV, IP_{3D}< 1 mm w.r.t. B_s primary vertex, ΔR(lepton, B_s) > 0.2 (0.3) for e (μ), and an MVA discriminator for e

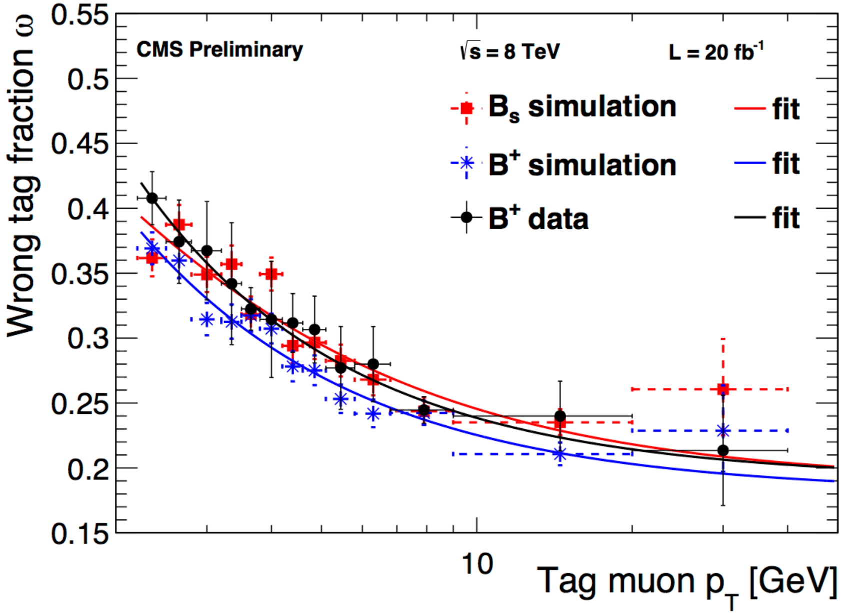


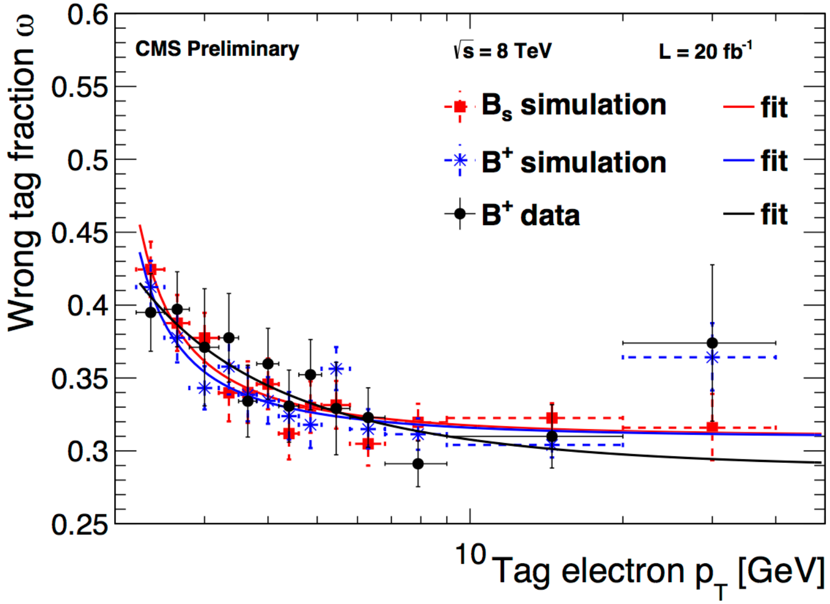
- Tagging performance measured with $B^+ \rightarrow J/\psi K^+$ data, and validated with $B^+ \rightarrow J/\psi K^+$ and $B_s \rightarrow J/\psi\phi$ simulations
- Average tagging performance, combined e, μ

ω = 32.2 ± 0.3%, ε_{tag} = 7.67 ± 0.04 %, P_{tag} = 0.97 ± 0.04%

- Tagging parametrized as a function of p_T for e and μ
- Tag decision $P_S(\xi)$ (histograms)

	Muons	Electrons
Mistag fraction ω [%]	$30.7 \pm 0.4 \pm 0.7$	$34.8 \pm 0.3 \pm 1.0$
Tagging efficiency ϵ_{tag} [%]	$4.55 \pm 0.03 \pm 0.08$	$3.26 \pm 0.02 \pm 0.01$
Tagging power P_{tag} [%]	$0.68 \pm 0.03 \pm 0.05$	$0.30 \pm 0.02 \pm 0.04$





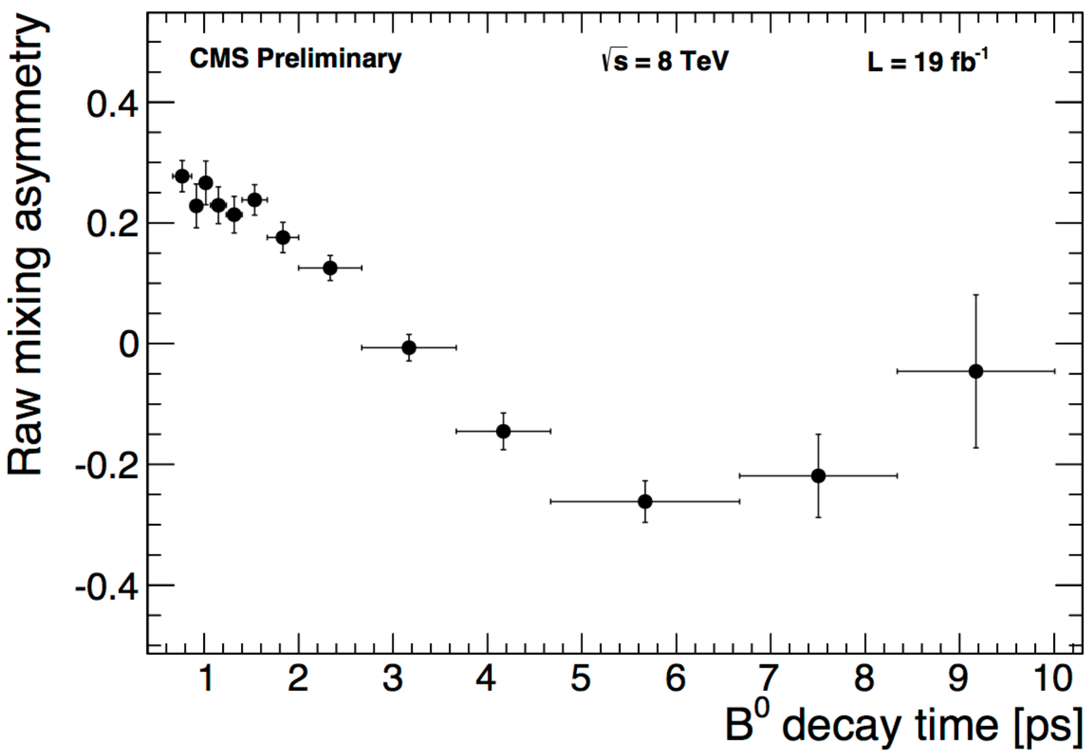
Test: $B^0 \rightarrow J/\psi\ K^{*0}$ asymmetry

- **Measure raw mixing asymmetry**

  $$A(t) = (N_{unmixed}(t) - N_{mixed}(t))/(N_{unmixed}(t) + N_{mixed}(t)) \sim \cos(\Delta m_d t)$$

- **Similar trigger and selection cuts as for B_s**

$B^0 \rightarrow J/\psi\ K^{*0}$

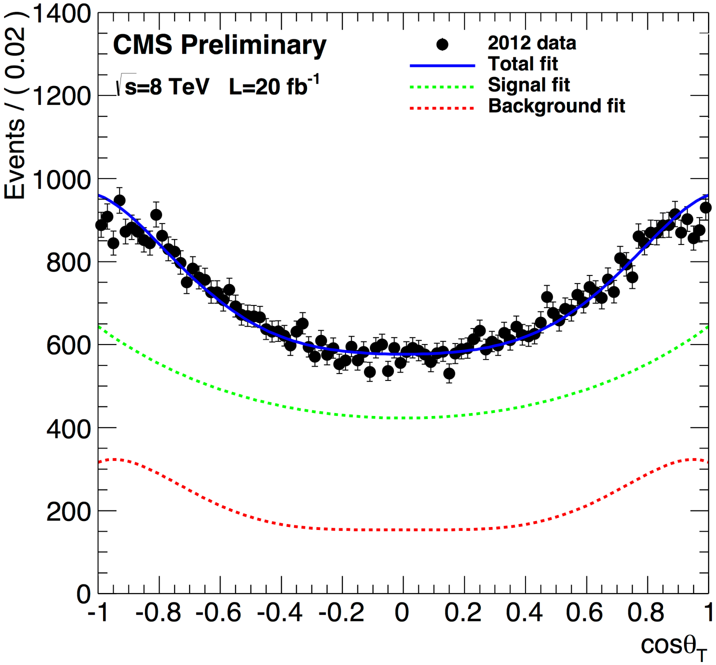


Data fit

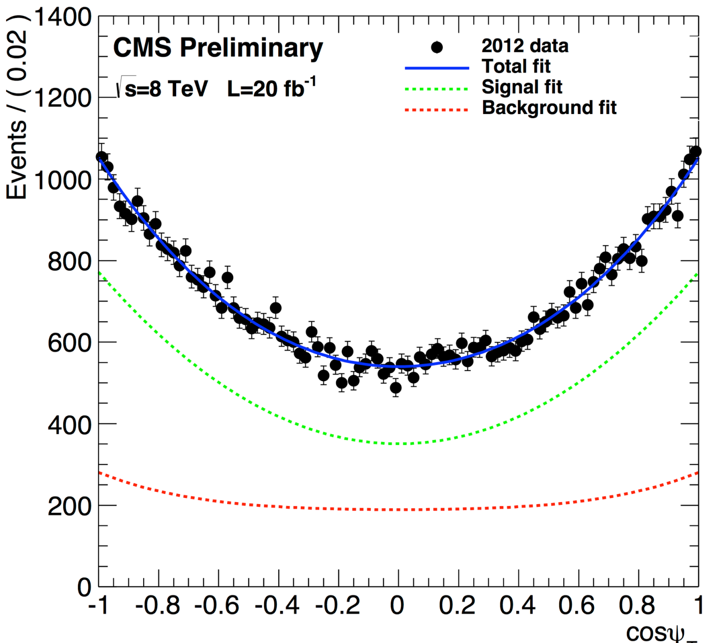
- Extended maximum likelihood fit of the tagged model, with a Gaussian constraint on Δm_s
- Fit range B_s mass [5.24-5.49] GeV, *ct* [0.02-0.3] cm

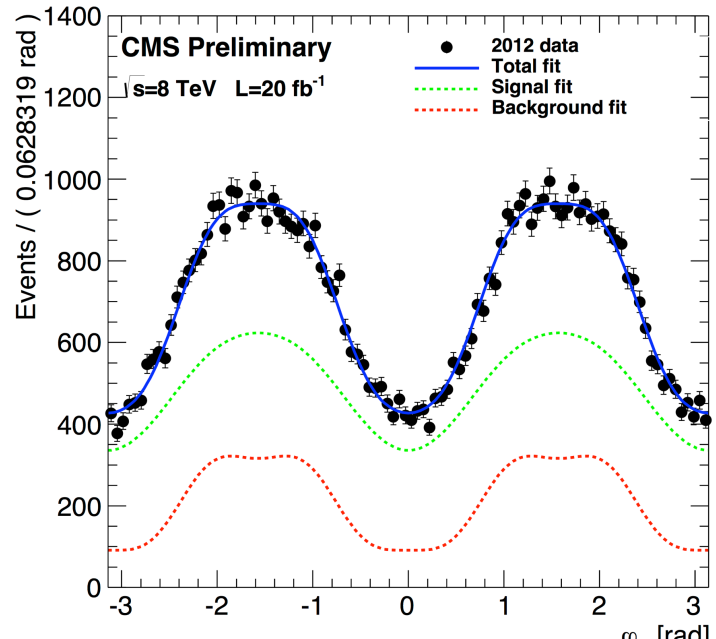
$$\mathcal{L} = L_{\text{signal}} + L_{\text{background}} ,$$
$$L_{\text{signal}} = N_S \cdot \left(\tilde{f}(\Theta,\alpha,ct) \otimes G(ct,\sigma_{ct}) \cdot \epsilon(\Theta)\right) \cdot P_S(m_{B_s}) \cdot P_S(\sigma_{ct}) \cdot P_S(\xi) ,$$
$$L_{\text{background}} = N_{BG} \cdot P_{BG}(\cos\theta_T,\phi_T) \cdot P_{BG}(\cos\psi_T) \cdot P_{BG}(ct) \cdot P_{BG}(m_{B_s}) \cdot P_{BG}(\sigma_{ct}) \cdot P_{BG}(\xi)$$

- $f(\Theta, \alpha, ct)$ signal PDF
- $G(ct, \sigma_{ct})$ Gaussian proper decay time resolution, per-event
- $\varepsilon(\Theta) = \varepsilon(\cos\theta_T, \cos\psi_T, \varphi_T)$ angular efficiencies
- $P_S(m_{Bs})$ signal mass PDF, triple-Gaussian with a common mean
- $P_S(\sigma_{ct})$ proper time uncertainty (Γ functions)
- $P_S(\xi)$ tag decision (histograms)
- P_{BG} background PDFs



Parameter	Fit result
$\|A_0\|^2$	0.511 ± 0.006
$\|A_S\|^2$	0.015 ± 0.016
$\|A_\perp\|^2$	0.242 ± 0.008
$\Delta\Gamma_s$ [ps^{-1}]	0.096 ± 0.014
$\delta_\parallel$ [rad]	3.48 ± 0.09
$\delta_{S\perp}$ [rad]	0.34 ± 0.24
$\delta_\perp$ [rad]	2.73 ± 0.36
ϕ_s [rad]	-0.03 ± 0.11
$c\tau$ [μm]	447 ± 3





Systematic uncertainties

Source of uncertainty	$\|A_0\|^2$	$\|A_S\|^2$	$\|A_\perp\|^2$	$\Delta\Gamma_s$ [ps^{-1}]	$\delta_\parallel$ [rad]	$\delta_{S\perp}$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$c\tau$ [μm]
Statistical uncertainty	0.0058	0.016	0.0077	0.0138	0.092	0.24	0.36	0.109	3.0
Proper time efficiency	0.0015	-	0.0023	0.0057	-	-	-	0.002	1.0
Angular efficiency	0.0060	0.008	0.0104	0.0021	0.674	0.14	0.66	0.016	0.8
Model bias	0.0008	-	-	0.0012	0.025	0.03	-	0.015	0.4
Proper decay time resolution	0.0009	-	0.0008	0.0021	0.004	-	0.02	0.006	2.9
Background mistag modelling	0.0021	-	0.0013	0.0018	0.074	1.10	0.02	0.002	0.7
Flavour tagging	-	-	-	-	-	-	0.02	0.005	-
PDF modelling assumptions	0.0016	0.002	0.0021	0.0021	0.010	0.03	0.04	0.006	0.2
$\|\lambda\|$ as a free parameter	0.0001	0.005	0.0001	0.0003	0.002	0.01	0.03	0.015	-
Kaon p_T re-weighting	0.0094	0.020	0.0041	0.0015	0.085	0.11	0.02	0.014	1.1
Total systematics	0.0116	0.022	0.0117	0.0073	0.685	1.12	0.66	0.032	3.5

Results

- ϕ_s = -0.03 ± 0.11 (stat.) ± 0.03 (syst.) rad
- $\Delta\Gamma_s$ = 0.096 ± 0.014 (stat.) ± 0.007 (syst.) ps^{-1}

  constraining $\Delta\Gamma_s > 0$

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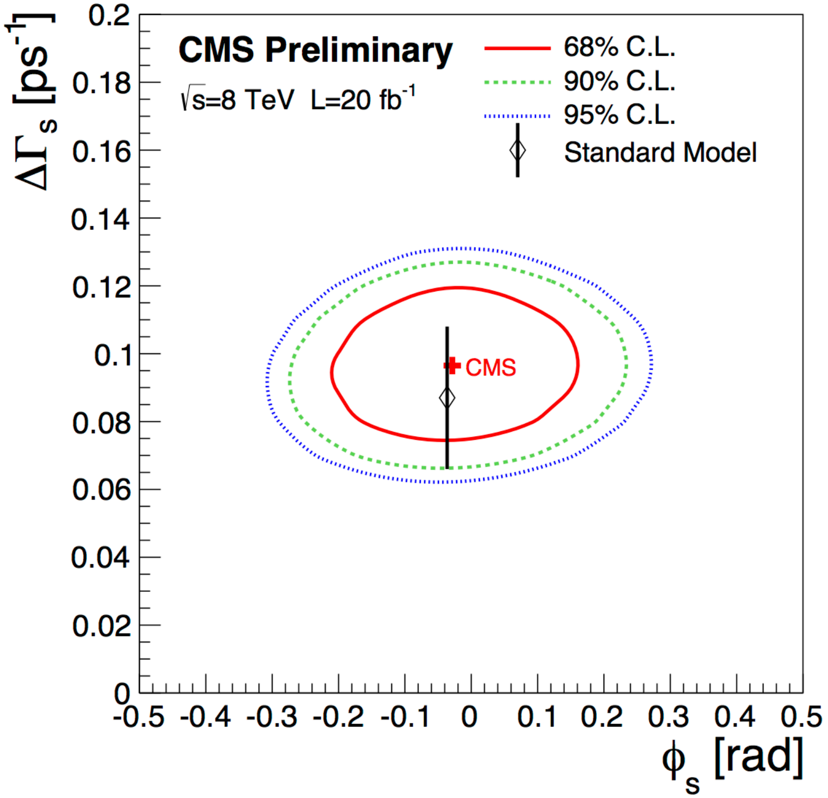
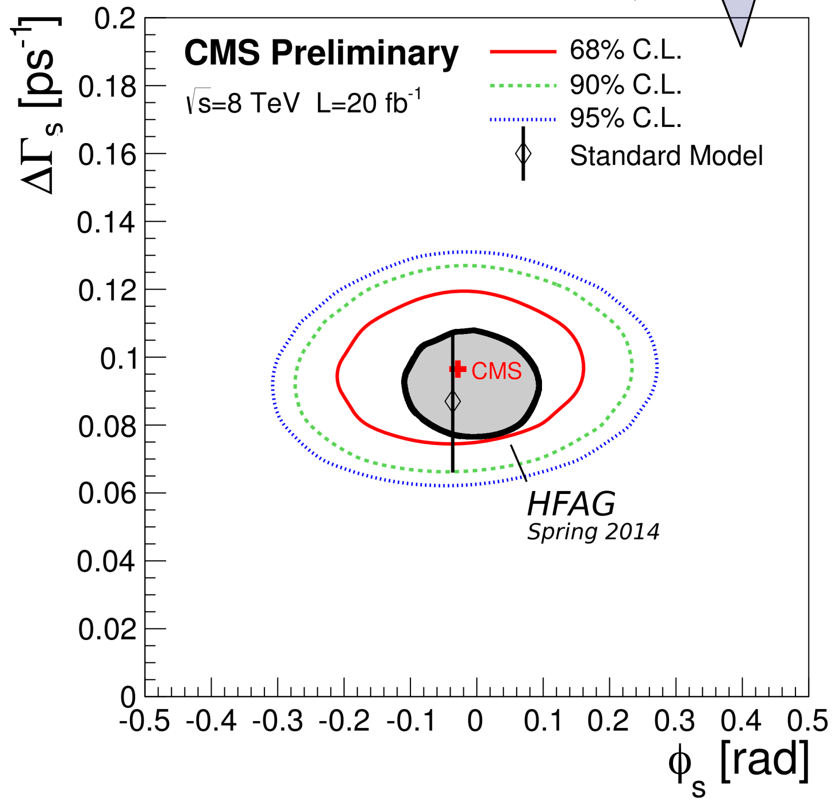
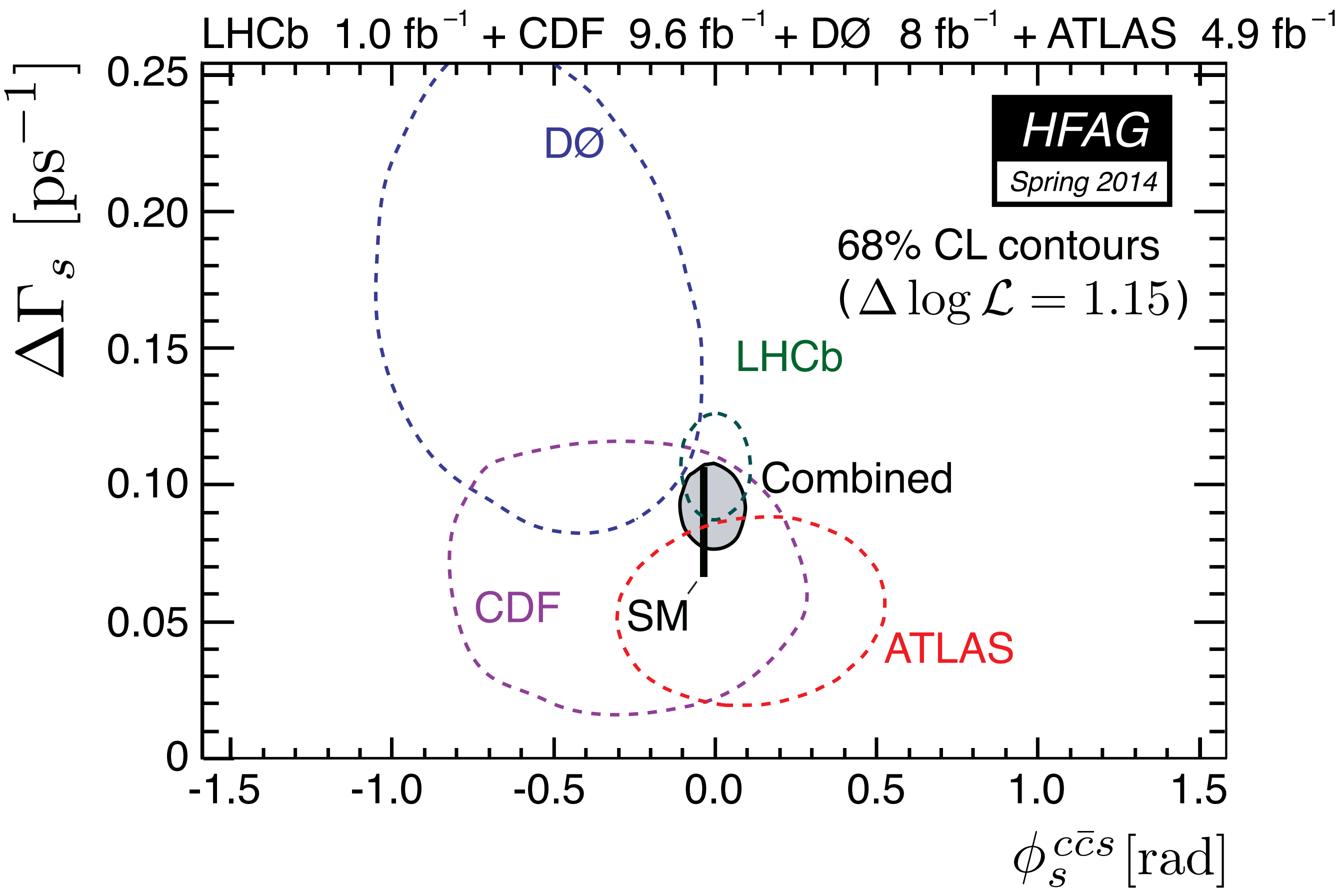


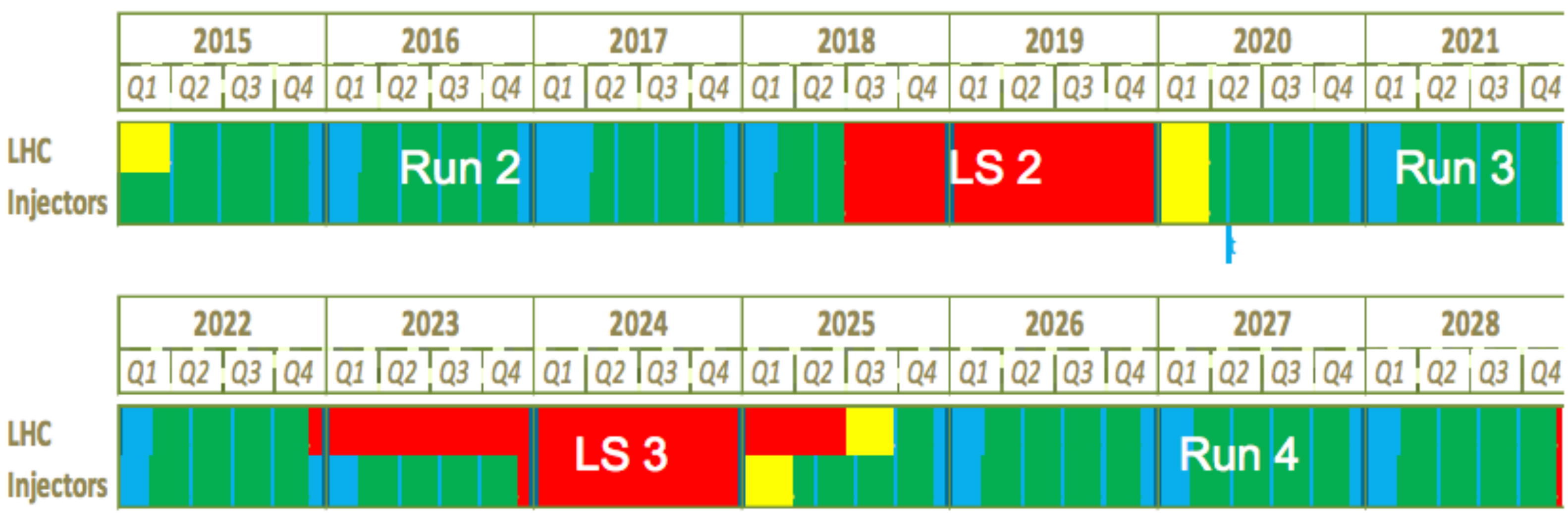


HFAG combination spring 2014



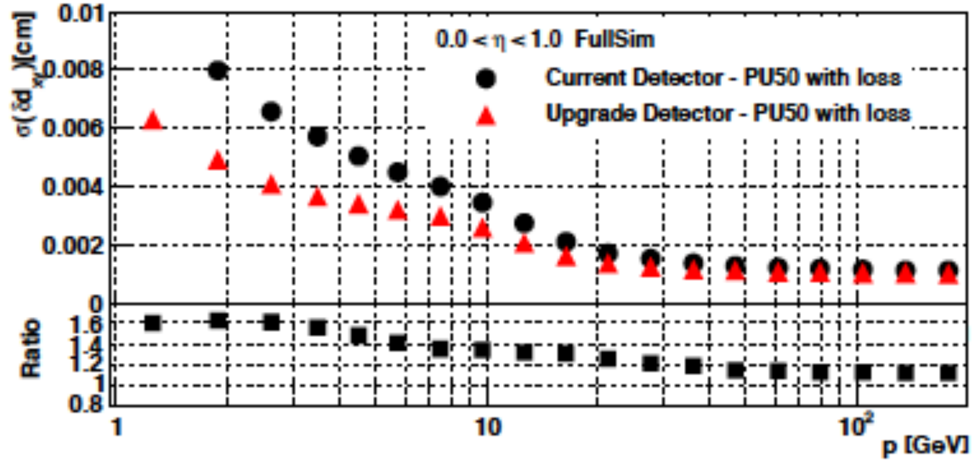
CMS prospects

- Run 2 starting 2015: goal to collect ~100 fb^{-1} by LS2
- Forward muon trigger acceptance slightly improved
- New beampipe
- B physics challenge: maintain trigger (mainly displaced dimuons plus additional constraints)
- Pixel detector upgrade during extended year-end technical stop 2016-2017
- New tracker LS3

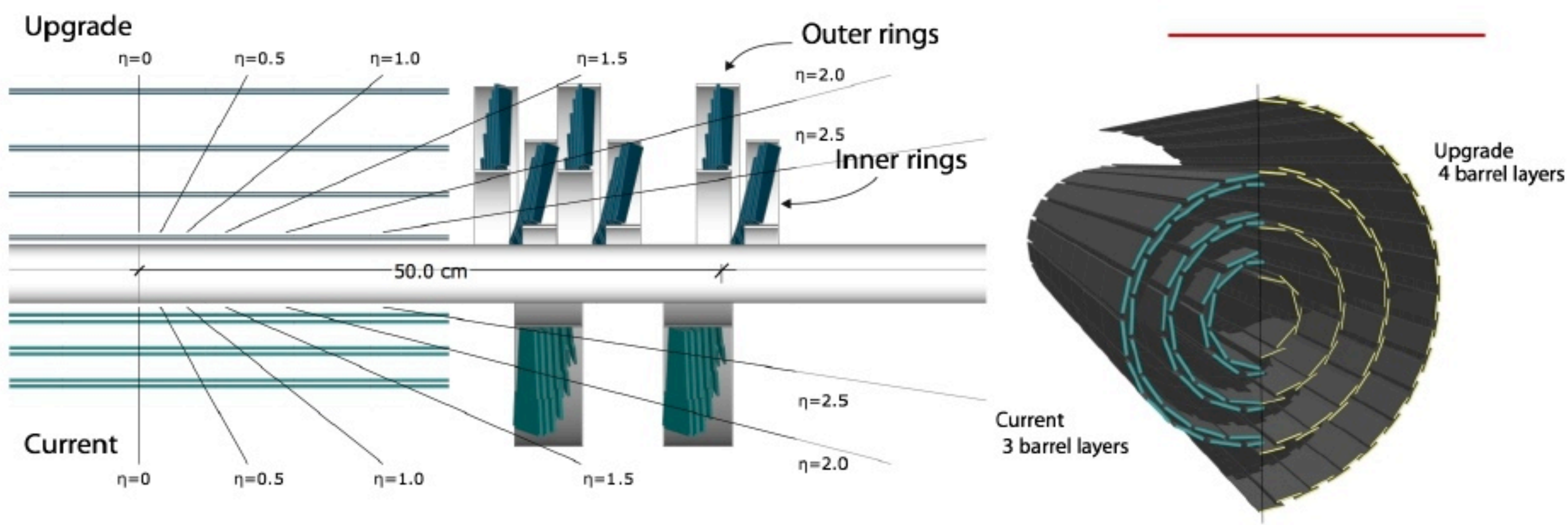


Pixel upgrade

- **4 layers barrel/3 disks forward, smaller inner radius (3 cm)**
- **New readout chip, recovers inefficiency at high rate and PU**
- **Less material, longevity, even better performance at low p_T**



CMS Technical Design Report for the Pixel Detector Upgrade
CERN-LHCC-2012-016 ; CMS-TDR-11



Summary

NEW PAS
BPH-13-012

- **Using 2012 data 20 fb^{-1}, CMS has made accurate and competitive measurements of ϕ_s and $\Delta\Gamma_s$**
- **Well in agreement with the Standard Model**
- **Measurement error dominated by statistical uncertainties**
- **Run 2: much larger statistics, improved tagging**

Backup

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = f(\Theta,\alpha,t) = \sum_{i=1}^{10} O_i(\alpha,t).g_i(\Theta),$$

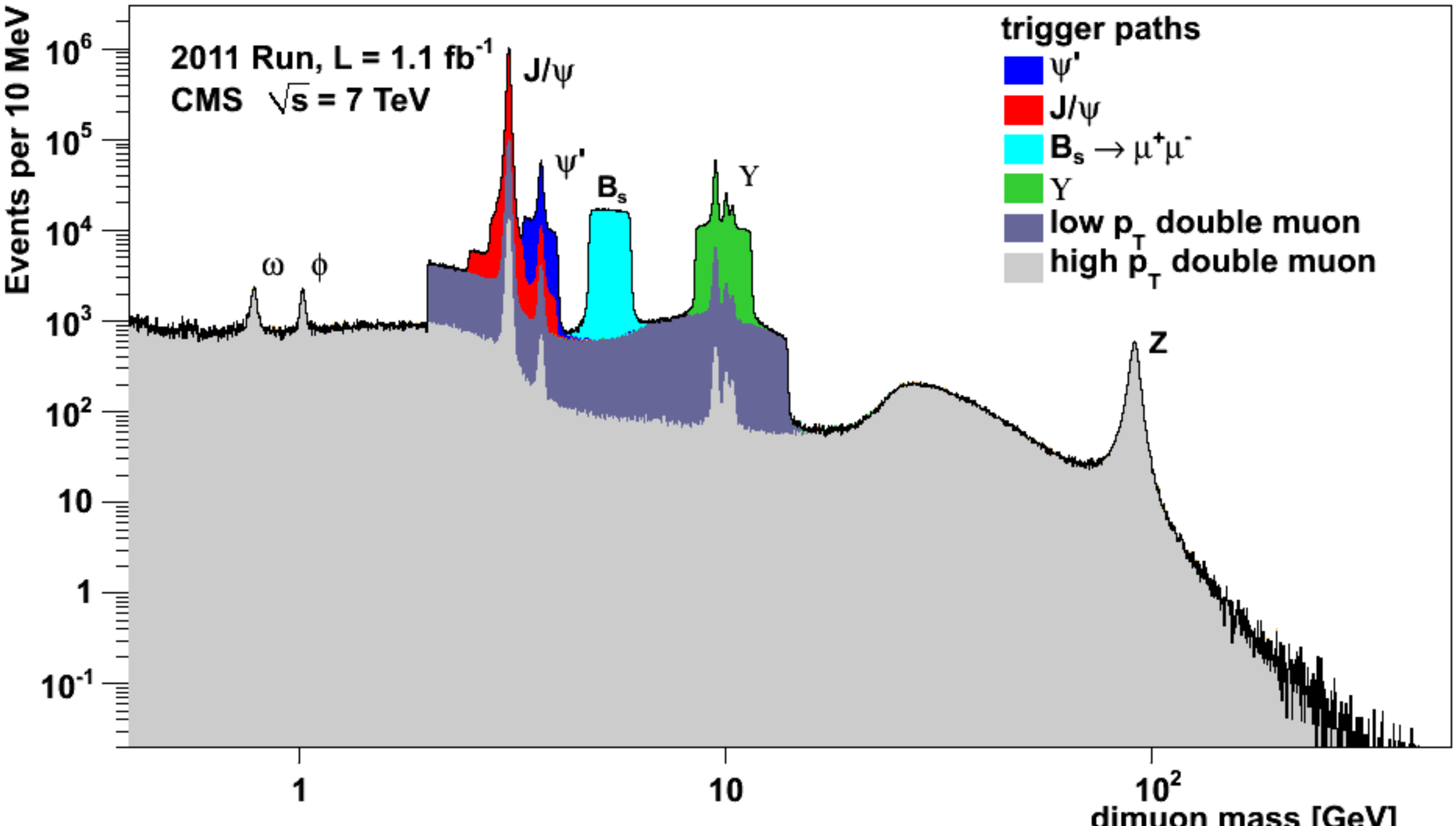
$$O_i(\alpha,t) = N_i e^{-\Gamma_s t}\left[a_i \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_i \sinh(\frac{1}{2}\Delta\Gamma_s t) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t)\right]$$

INSTITUTE OF PHYSICS

i	$g_i(\theta_T,\psi_T,\varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert\lvert A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}$$

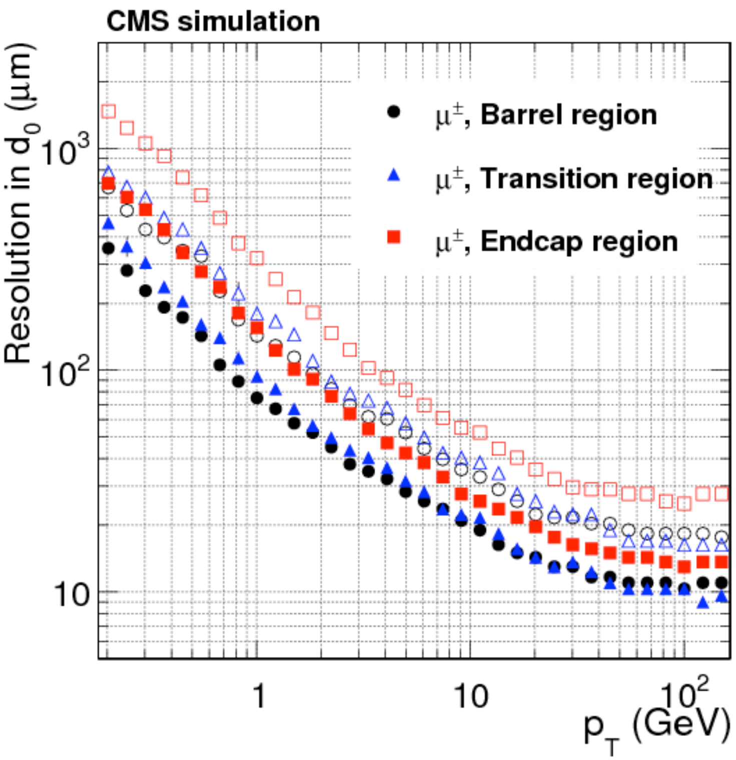
CMS triggers 2011

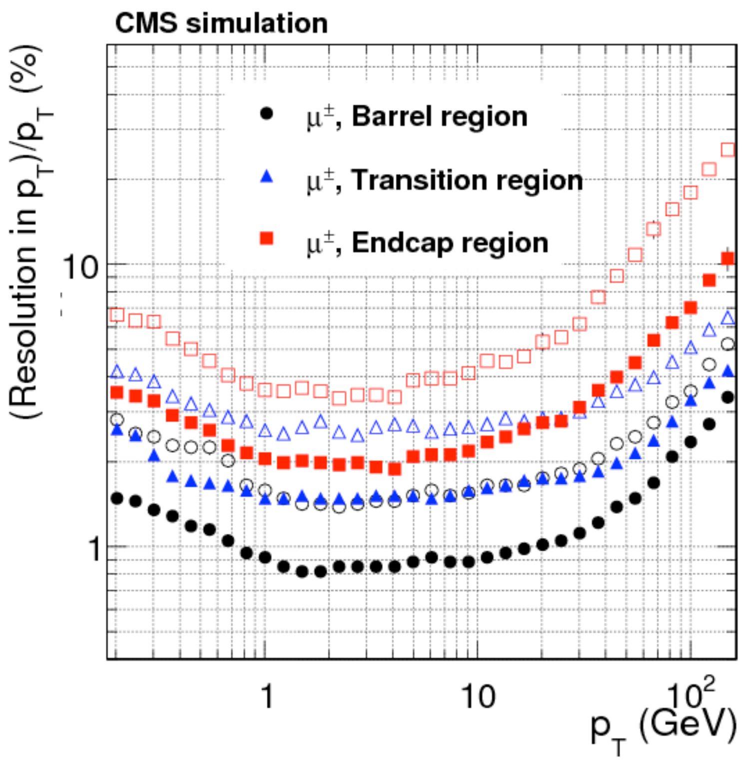


Description and performance of track and primary-vertex reconstruction with the CMS tracker

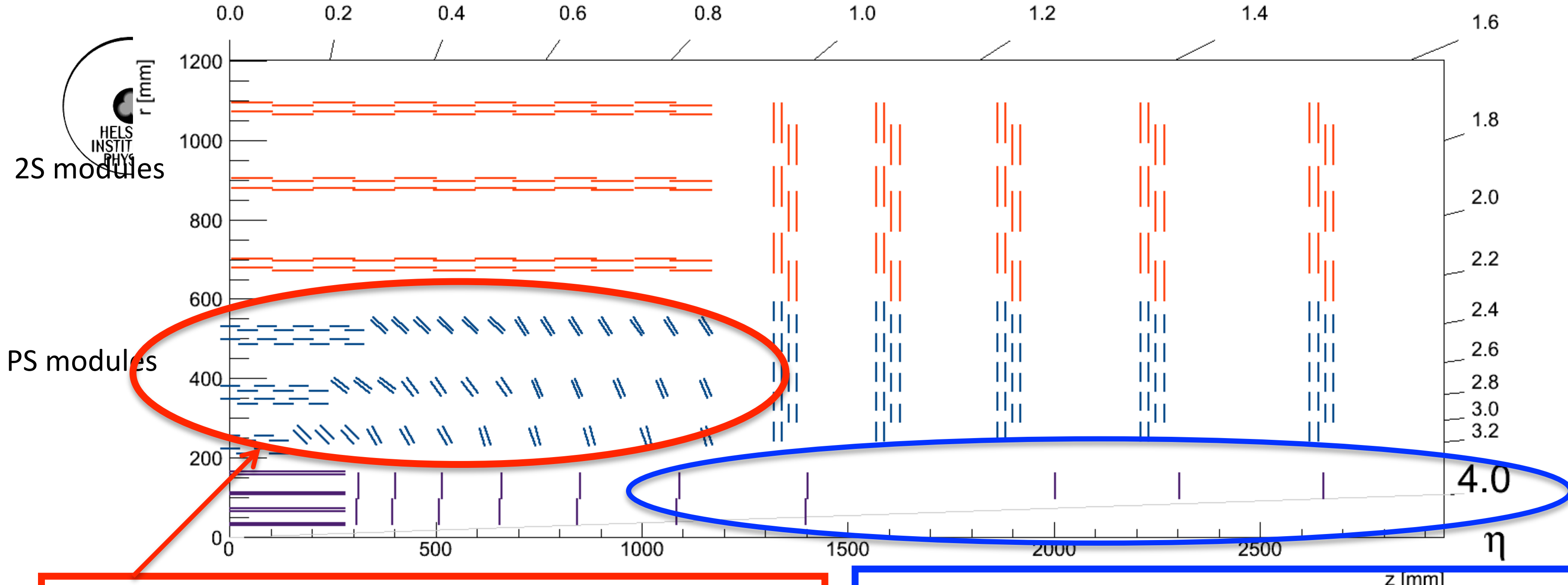
arXiv:1405.6569 [physics.ins-det]

CMS-TRK-11-001, CERN-PH-EP-2014-070



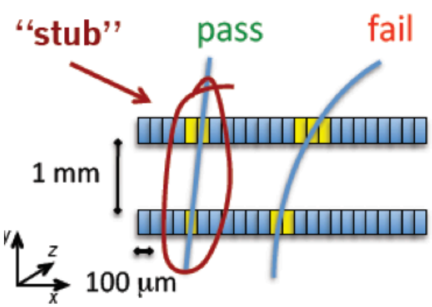


Tracker phase 2

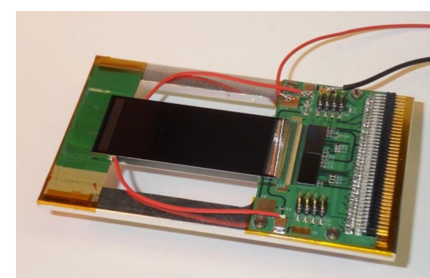


Tilted layout option under study: allows reduction of material and cost savings

Extension of tracking to lower η: allows extension of Pflow paradigm in physics critical area



2 prototypes tested at DESY - 2 CBC chips - FPGA emulation of concentrator and of GBT on GLIB prototype DAQ board – validated trigger concept



All Outer Tracker modules are trigger modules