Recent results of flavour physics in CMS

Leonardo Cristella (on behalf of the CMS Collaboration)

UNIVERSITA' DEGLI STUDI DI BARI "ALDO MORO" & I.N.F.N. SEZIONE DI BARI

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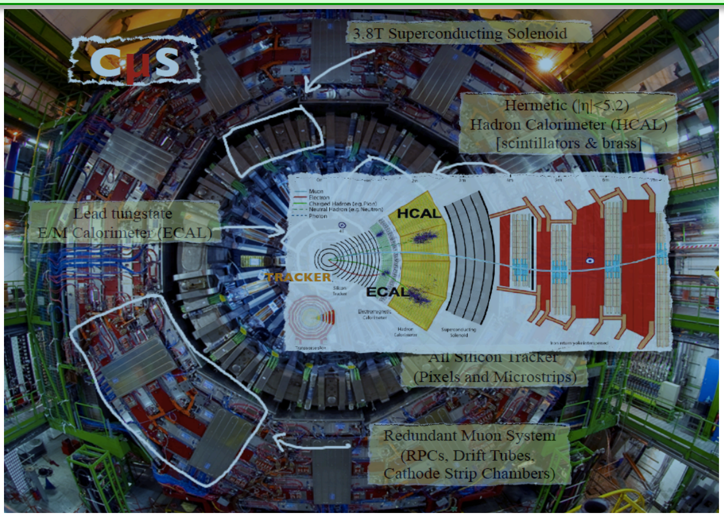
Compact Di-Muon Solenoid – μ reconstruction & triggers

Tracking system

- Good p_T resolution (down to $\Delta p_T / p_T \approx 1\%$ in barrel)
- Tracking efficiency >99% for central muons
- Good vertex reconstruction & impact parameter resolution down to $\approx 15 \mu m$



Muon system

- Muon candidates by matching muon segments and a silicon track in a large rapidity coverage ($|\eta| < 2.4$)
- Good dimuon mass resolution (depending on $|y|$): $\Delta M / M \approx 0.6 \div 1.5\%$ (⇨ $J/\psi : \approx (20 \div 70) MeV$)
- Excellent (high-purity) muon-ID: $\varepsilon(\mu \mid \pi, K, p) \leq (0.1 \div 0.2)\%$ [fake rates estimated in MC and data]

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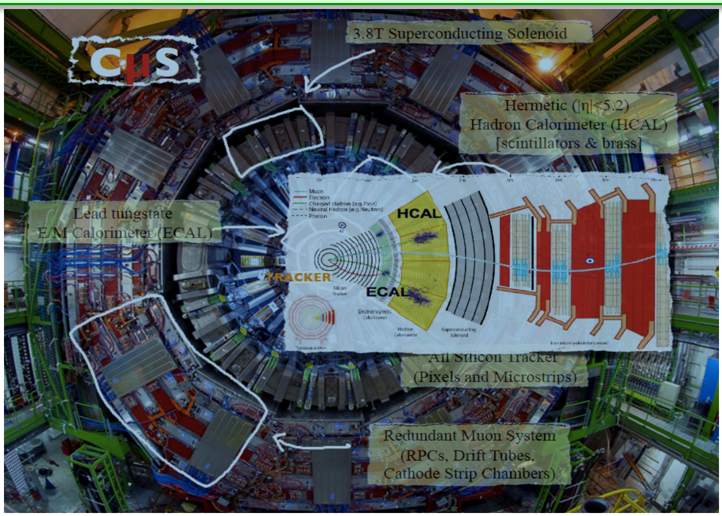

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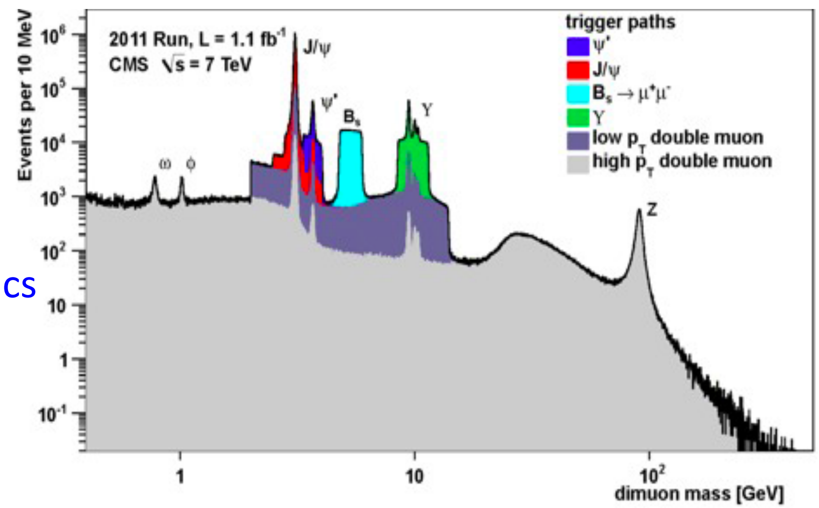
Trigger system

- fast HW (Muon Detector based) triggers (L1)
  SW triggers with full tracking & vtx recon. (HLT)
- rare decays/quarkonia almost 100% BKG/Signal paths
- ~10% of CMS bandwidth (~10*kHz* @L1) to flavour physics
  Data Parking in 2012: clear benefits having ~120*Hz* on top of the 25-30*Hz* on prompt stream (@HLT)



Data samples:

- $\sqrt{s} = 7$ TeV , $\mathcal{L} = 5$ fb^{-1} (2011 run)
- $\sqrt{s} = 8$ TeV , $\mathcal{L} = 20$ fb^{-1} (2012 run)

Outline

- The following analyses with recent results will be reviewed:

  - $B_{s(d)} \to \mu^+\mu^-$
  - $B_s^0 \to J/\psi\,\phi$
  - $B_s^0 \to J/\psi\, f_0(980)$
  - $J/\psi,\ \psi(2S),\ \Upsilon(nS)_{n=1,2,3}$ production cross-sections

$B_{s(d)} \to \mu^+\mu^-$

arXiv: 1411.4413 (submitted to *Nature*)

CMS-BPH-13-007
LHCb-PAPER-2014-220

$B^0_{s(d)} \to \mu^+\mu^-$: CMS + LHCb combination

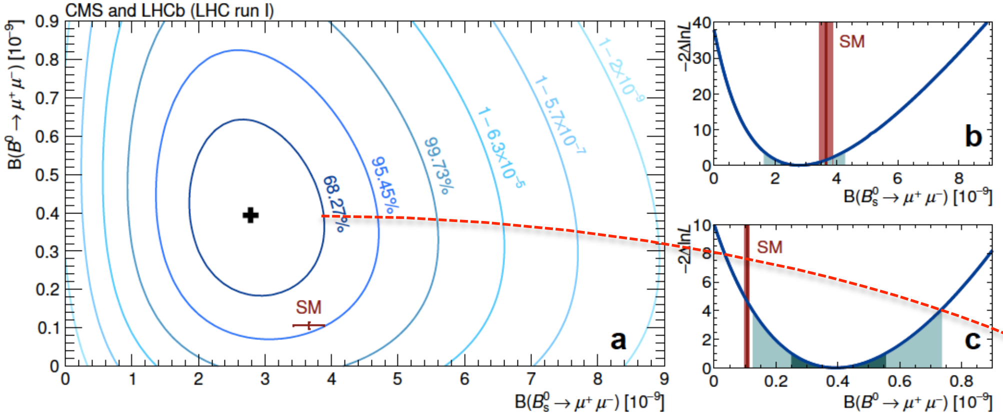
- CMS+LHCb ext. UML fit provides BF (taking into account correlation from f_s/f_u) :

$$\mathbf{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \text{ (stat+syst)}$$ **(6.2σ significance)**

$$\mathbf{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \text{ (stat+syst)}$$ **(3.0σ significance)**

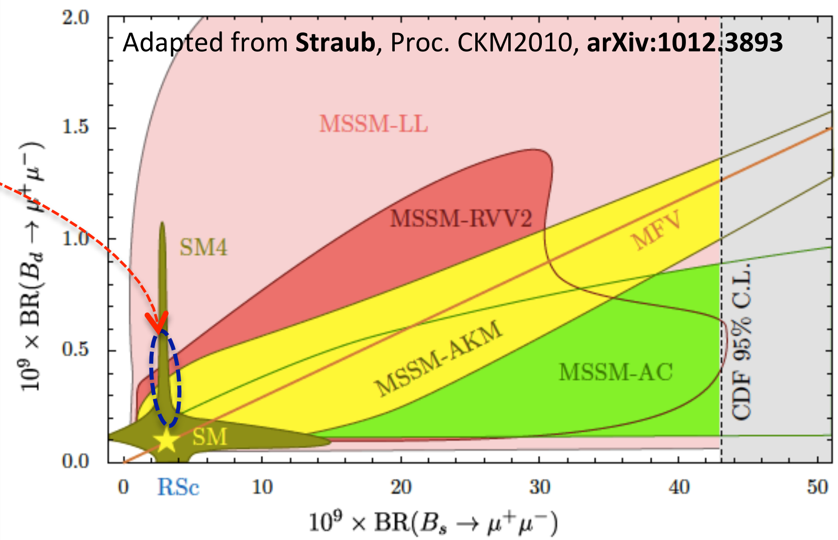
[Feldman-Cousins]

Likelihood contours in the $\mathbf{B}(B^0_s \to \mu\mu)$ vs $\mathbf{B}(B^0 \to \mu\mu)$ plane:



Compare with SM, MFV & 4 SUSY flavor models

- MFV assumes:
  1) no CPV beyond the CKM phase
  2) flavour independence of Wilson coefficients



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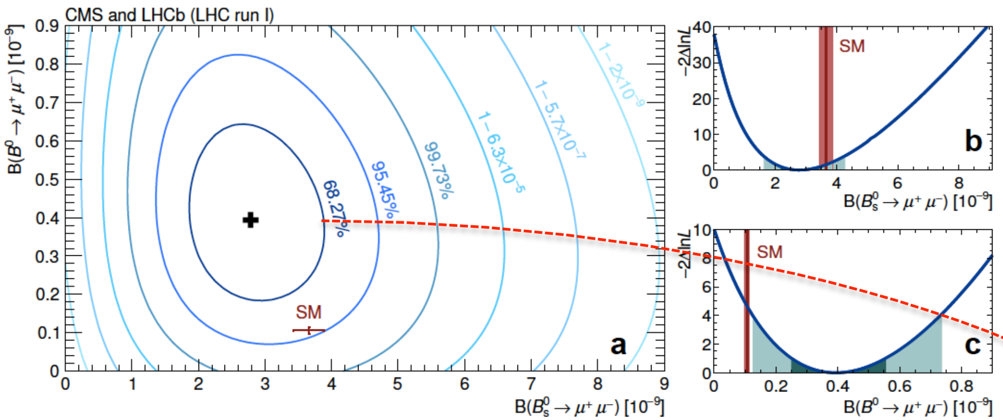

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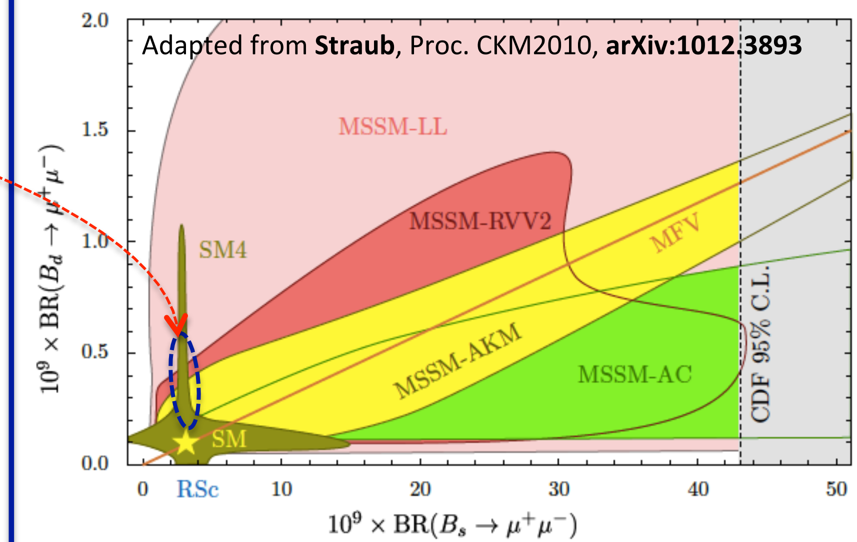
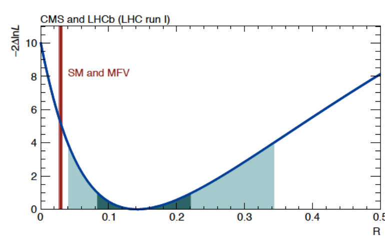


- The ratio of BF is very sensitive probe of NP:

$$R \equiv \frac{\mathbf{B}(B^0 \to \mu^+\mu^-)}{\mathbf{B}(B^0_s \to \mu^+\mu^-)} = (0.14^{+0.08}_{-0.06})$$

compatible with SM @ 2.3σ level

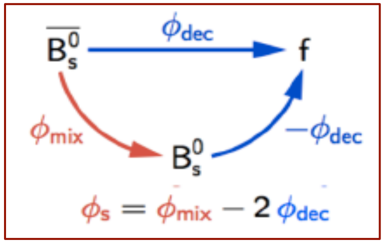


- The focus now will be on BF $\mathbf{B}(B^0 \to \mu^+\mu^-)$ and on the ratio R for Run-II (100 fb^{-1})

$B_s^0 \to J/\psi\,\phi$ CMS-PAS-BPH-13-012

CPV in $B_s^0 \to J/\psi\phi$: a tiny effect sensitive to NP

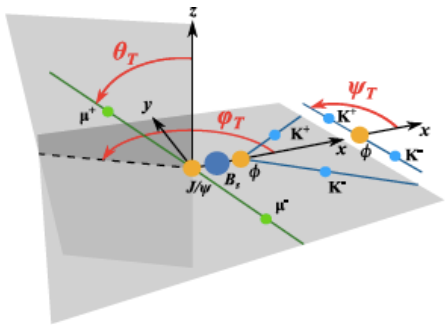
- When B_s^0 & $\overline{B}_s^0$ decay to a *CP* eigenstate (as in flavor-blind $B_s^0 \to J/\psi\phi\ (f_0)$) the weak phase ϕ_s arises from the interference between direct decays & decays with mixing (B mesons mix via box diagrams)



Theoretically clean decay mode: tiny CPV ruled by $\phi_S^{SM} \approx -2\beta_S = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \cong -0.0363^{+0.0016}_{-0.0015}\,rad$

[PRD 84 (2011) 033005]

⇨ Sensitivity to NP in mixing: many NP scenarios predict enhanced values of ϕ_S

- 

$J/\psi\phi$ final state: admixture of CP-odd and CP-even eigenstates
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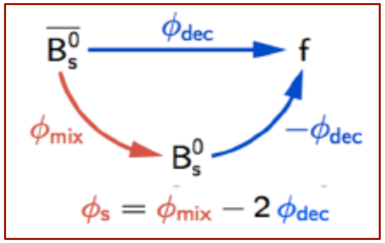

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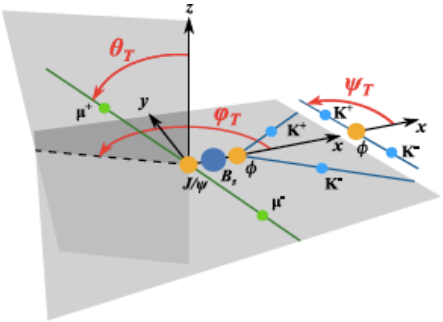


- $J/\psi\phi$ final state: admixture of CP-odd and CP-even eigenstates … to be disentangled by angular analysis (3 angles)

- The differential decay rate for $B_s^0 \to J/\psi\phi$ can be expressed as:

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

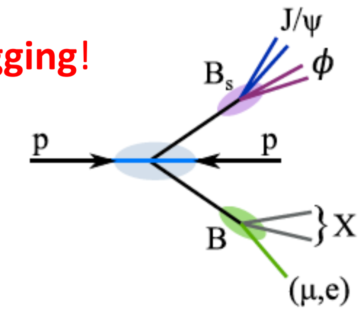
Time-dependent functions | **Angular-dependent functions**

where:
- $\Theta,\ t$: measured angles & B_s^0 proper decay time
- α : physics param. of interest: $\phi_S, \Delta\Gamma_S, c\tau; |A_0|^2, |A_S|^2, |A_\perp|^2; \delta_\parallel, \delta_\perp, \delta_{S\perp}$
- $O_i(\alpha,t) = N_i e^{-t/\tau}[a_i \cdot \cosh\left(\frac{\Delta\Gamma_S ct}{2}\right) + b_i \cdot \sinh\left(\frac{\Delta\Gamma_S ct}{2}\right) + c_i \cdot \cos(\Delta m_S t) + d_i \cdot \sin(\Delta m_S t)]$

» ***b_i*** & ***d_i*** proportional to *$\sin\phi_s$* & *$\cos\phi_s$*

$B_s^0 \to J/\psi\,\phi$: analysis strategy

- How to tell B_s^0 flavour at production? Use Opposite-Side Lepton ($\mu + e$) **Flavour Tagging**!



  - Search for a second B-hadron in the OS of the event decaying semi-leptonically:
  - Lepton charge-flavour correlation is diluted (⇨ mistag) by:
    - sequential cascade: $b \to cX \to \ell X'$ decays
    - oscillations: opposite side *B*-meson mixing
    - leptons from other sources (DIF, charmed mesons)

- Tagging performance measured by self-tagging $B^+ \to J/\psi K^+$ and validated with MC $(B^+ \to J/\psi K^+,\ B_s^0 \to J/\psi\phi)$

[%]	Muons	Electrons	**Combined**
ε_{tag}	$4.55 \pm 0.03 \pm 0.08$	$3.26 \pm 0.02 \pm 0.01$	7.67 ± 0.04
ω	$30.7 \pm 0.4 \pm 0.7$	$34.8 \pm 0.3 \pm 1.0$	32.2 ± 0.3
$\mathcal{P}_{tag}$	$0.68 \pm 0.03 \pm 0.05$	$0.30 \pm 0.02 \pm 0.04$	0.97 ± 0.03

$$[P_{tag} = \varepsilon_{tag} \cdot D^2 = \varepsilon_{tag} \cdot (1-2\omega)^2]$$

- PDF modified to include tagging info in c_i & d_i

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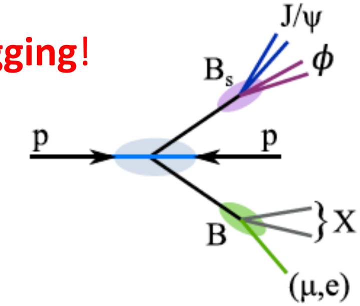

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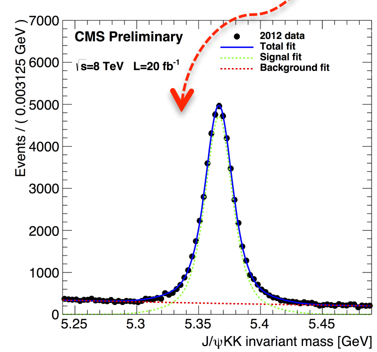
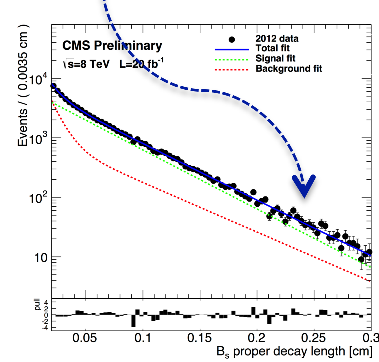
- Ext. UML fit used to extract the physics param. α by including: { 3 angles Θ, invariant mass, proper decay length ct } ... of B_s^0 candidate
  - Δm_S with a gaussian constrained to world average
  - $\Delta\Gamma_S > 0$ by using previous LHCb result
  - Uncertainty on proper decay time computed on event basis & included in the fit together with its resolution (~70fs)
  - $|\lambda|$ includes eventual contribution from CPV in direct decay; assumed =1 in the fit & left free to assign a systematic



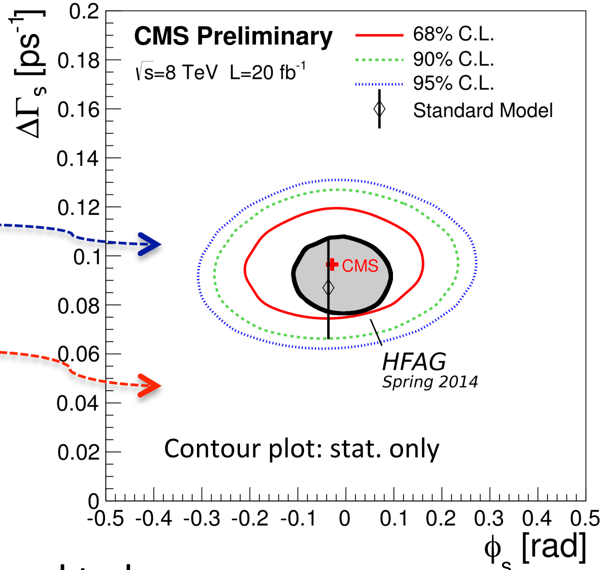


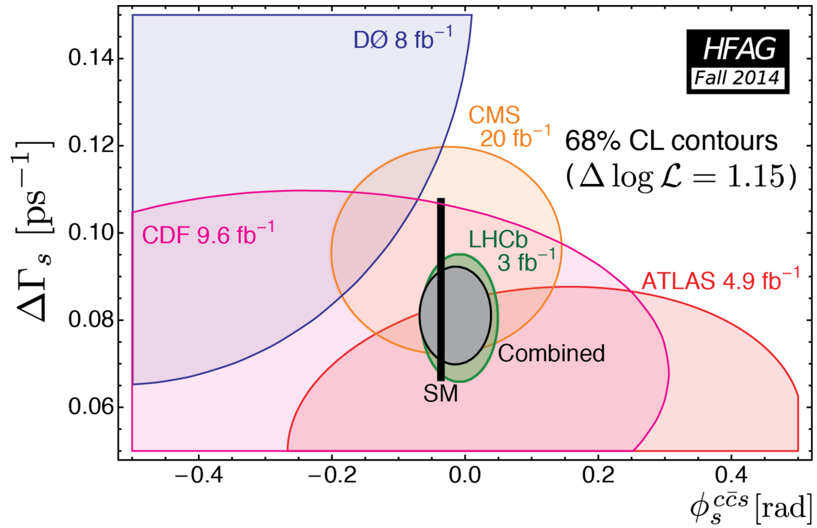
$B_s^0 \to J/\psi\phi$: angular analysis results ($\sqrt{s} = 8TeV$)

- Prelim. Results (2012 data) with 49k ***B_s*** signal events:

$$\phi_S = (-0.03 \pm 0.11 \pm 0.03)rad$$
$$\Delta\Gamma_S = (0.096 \pm 0.014 \pm 0.07)ps^{-1}$$

Parameter	Fit result
$\lvert A_0 \rvert^2$	0.511 ± 0.006
$\lvert A_S \rvert^2$	0.015 ± 0.016
$\lvert A_\perp \rvert^2$	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





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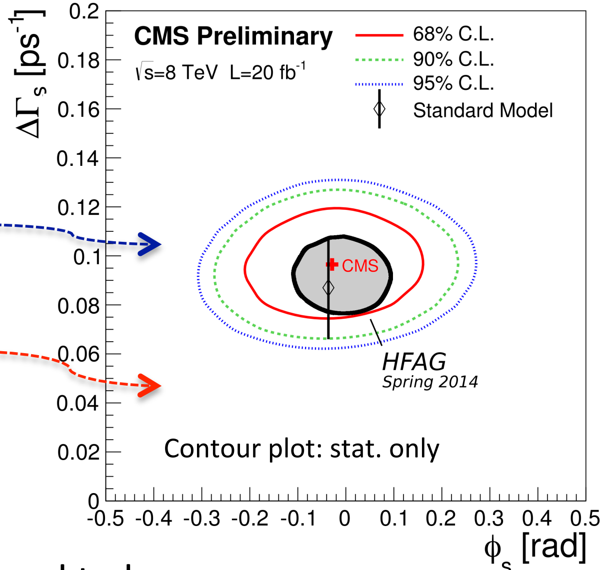

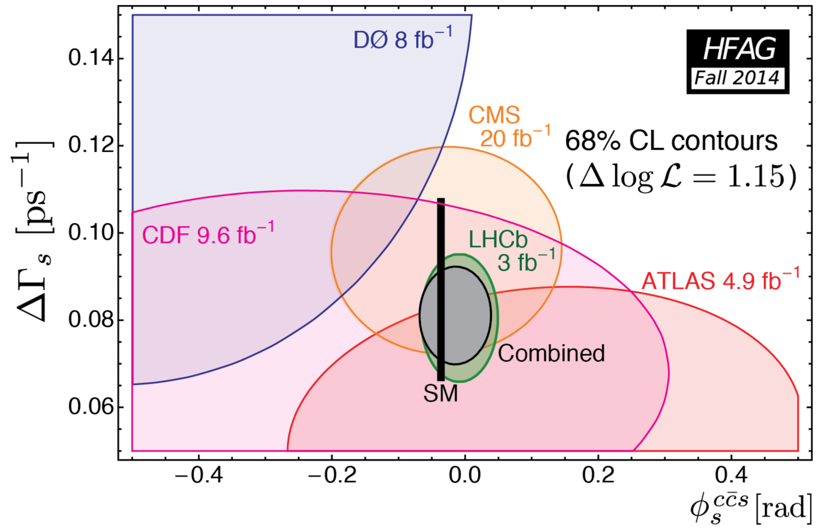

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- Final results will be released soon and will include:
  - usage of an improved lepton tagger (MVA tool)
  - study of the bkg channel $\Lambda_b \to J/\psi Kp$
  - better description/treatment of *S*-wave component

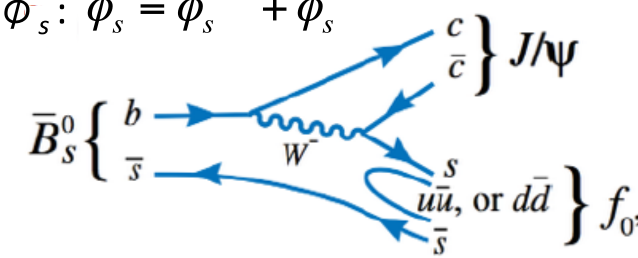
- Next analysis with $B_s^0 \to J/\psi f_0$ decays: CP-odd final state
  - ⇨ no need for angular analysis

- The uncertainties of the measurements are still dominated by statistical one (especially ϕ_S) and can be reduced further with Run-II data!

$B_s^0 \to J/\psi\, f_0(980)$ arXiv: 1501.06089

$B_s^0 \to J/\psi\, f_0(980)$: analysis strategy

- The decay $B_s^0 \to J/\psi(\to \mu^+\mu^-) f_0(\to \pi^+\pi^-)$ is:
  - useful to study the CPV phase ϕ_s by measuring the lifetime of the CP-odd part of B_s^0 meson
  - **sensitive to NP**: many NP scenarios predict enhanced values of ϕ_s: $\phi_s = \phi_s^{SM} + \phi_s^{NP}$
  - useful to study f_0(980) structure (tetraquark system?)



- **Analysis target:**

$$R_{f_0/\phi} \equiv \frac{BF(B_s^0 \to J/\psi\, f_0(980); f_0(980) \to \pi^+\pi^-)}{BF(B_s^0 \to J/\psi\,\phi; \phi \to K^+K^-)}$$

where many uncertainties cancel out:
- *b* quark production Xsection
- $BF(J/\psi \to \mu^+\mu^-)$
- integrated luminosity
- tracking efficiency and muon ID

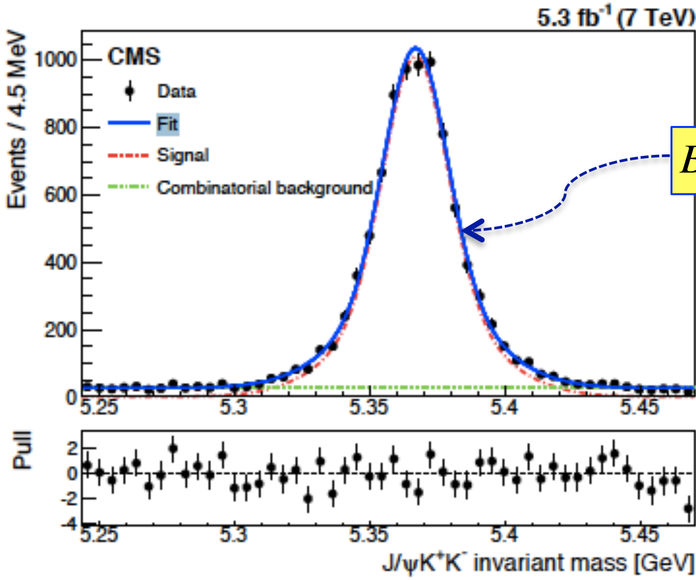
- $B_s^0 \to J/\psi\, f_0$ **lifetime** needed to measure the lifetime of the B_s^0 CP-odd part (useful input in the fit for ϕ_s) → future analysis

- **Experimentally:** $R_{f_0/\phi} = \dfrac{N_{f_0}}{N_\phi} \times \dfrac{\varepsilon_\phi}{\varepsilon_{f_0}}$ where

$$N_{(f_0,\phi)} = \text{observed yield of } B_s^0 \to J/\psi(f_0,\phi)$$
$$\varepsilon_{(f_0,\phi)} = \text{detection efficiency of } B_s^0 \to J/\psi(f_0,\phi)$$

$B_s^0 \to J/\psi\, f_0(980)$: signal extraction

- Apply same kinematics selection criteria to both signal & normalization modes determined by maximizing the significance $\left(S/\sqrt{S+B}\right)$ of the B_s signal.
  - UML fit used to extract yields; single/double gaussian for signal $(J/\psi) f_0 / \phi$ candidates:



$B_s^0 \to J/\psi\, \phi$

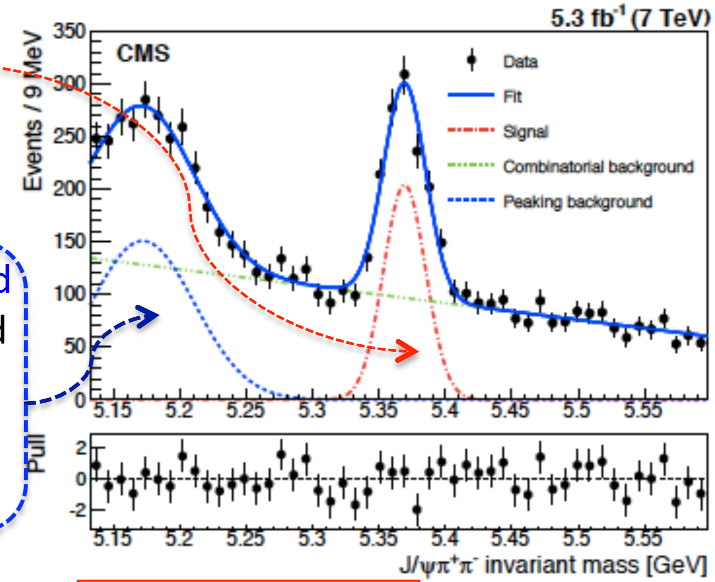
8377 signal events

$B_s^0 \to J/\psi\, f_0$

peaking background due to K considered as π in …

$B^0 \to J/\psi\, K^*(K\pi)$

$B_s^0 \to J/\psi\, K^+K^-$



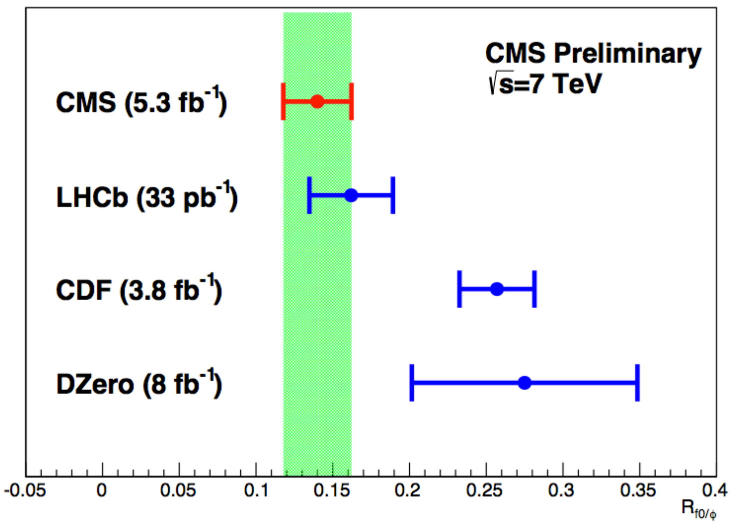
873 signal events

- Detection efficiency $\varepsilon = \dfrac{\text{reco yield in MC}}{\text{generated events}}$ measured to be $1.344 \pm 0.095(\text{stat})$
  The uncertainty is included in the final statistical uncertainty of the ratio measurement.
- Relevant kinematic and geometric variables' distributions in simulation agree with bkg-subtracted data

$B_s^0 \to J/\psi\, f_0$: results ($\sqrt{s} = 7TeV$)

- **Result** (using 2011 data) with **873 ±49** signal events: $R_{f_0/\phi} = 0.140 \pm 0.013(\text{stat}) \pm 0.018(\text{syst})$

Systematics' source	Uncertainty (%)
Fit model	2.1
f_0 mass window width	6.4
MC simulation (f_0 natural width)	8.6
Decay model in MC generation	6.2



- This measurement is consistent with
  - theoretical prediction [PRD 79 (2009) 074024]
  - previous measurements
- It is the most precise measurement of the ratio to date!

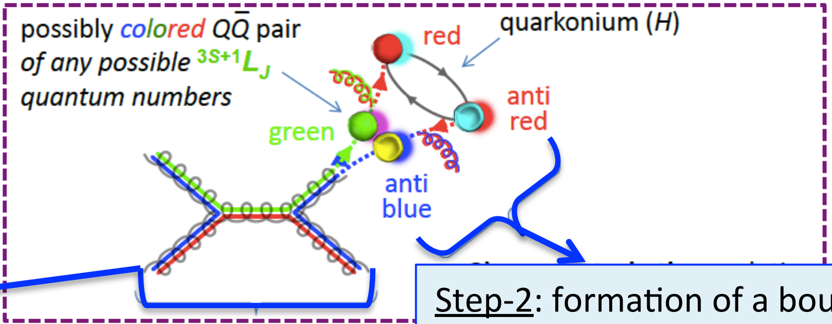
arXiv:1502.04155

arXiv:1501.07750

$J/\psi,\ \psi(2S),\ \Upsilon(nS)_{n=1,2,3}$ production cross-sections

Reference theory of production & polarization of quarkonia

- **NRQCD**: effective field theory that treats heavy quarkonia as non-relativistic systems. Inclusive quarkonium production can be factorized in two distinct steps:



Step-1: $Q\bar{Q}$ production in the regime of perturbative QCD

Step-2: formation of a bound state driven by non-pert. QCD

Inclusive Xsection for producing quarkonium (***H***) with enough large momentum transfer p_T:

$$\sigma(A+B \to H+X) = \sum_n \sigma\left(A+B \to [Q\bar{Q}]_n + X\right) \otimes P\left([Q\bar{Q}]_n \to H\right), \quad n = {}^{2S+1}L_J^{[C]}$$

Short-distance coefficients (SDCs)

calculated by perturbative QCD (expansions in α_S)

Long-distance matrix elements (LDMEs)

determined from fits to experimental data

relative relevance given by $v = \upsilon/c << 1$ **(scaling rules)**

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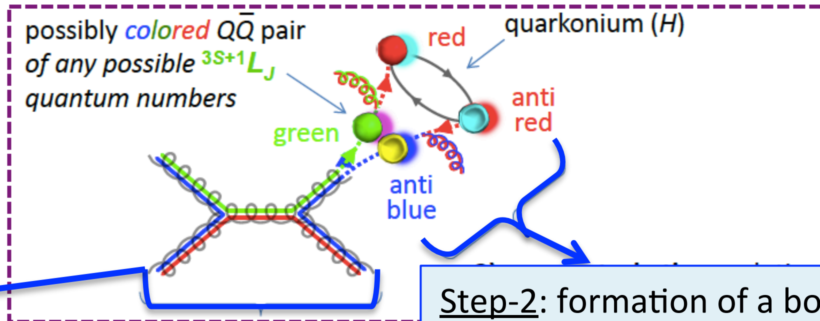

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<u>Step-2</u>: formation of a bound state driven by non-pert. QCD

Inclusive Xsection for producing quarkonium (*H*) with enough large momentum transfer p_T:

$$\sigma(A+B\to H+X)=\sum_n \sigma\left(A+B\to[Q\bar{Q}]_n+X\right)\otimes P\left([Q\bar{Q}]_n\to H\right)\quad ,\quad n={}^{2S+1}L_J^{[C]}$$

Short-distance coefficients (SDCs): **calculated** by perturbative QCD (expansions in α_S)

Long-distance matrix elements (LDMEs): **determined from fits** to experimental data; relative relevance given by $v = \upsilon/c << 1$ **(scaling rules)**

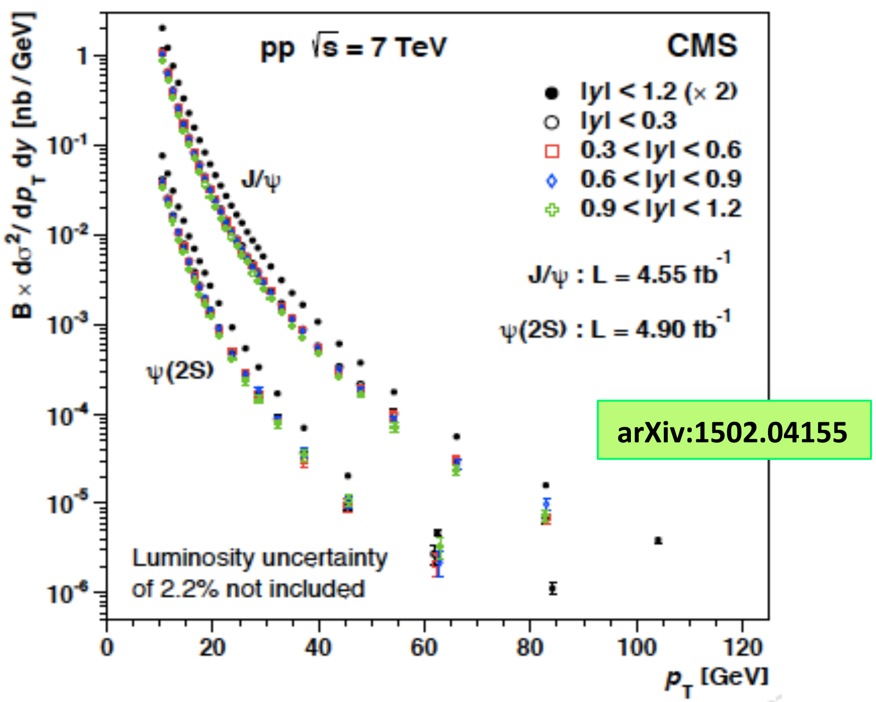
- Theoretical predictions are organized as double expansions in α_S and v. Truncation of *v-expansion* for *S-wave* states in NRQCD includes 4 terms:
  - Color Singlet (CS) term
  - 3 Color Octet (CO) terms

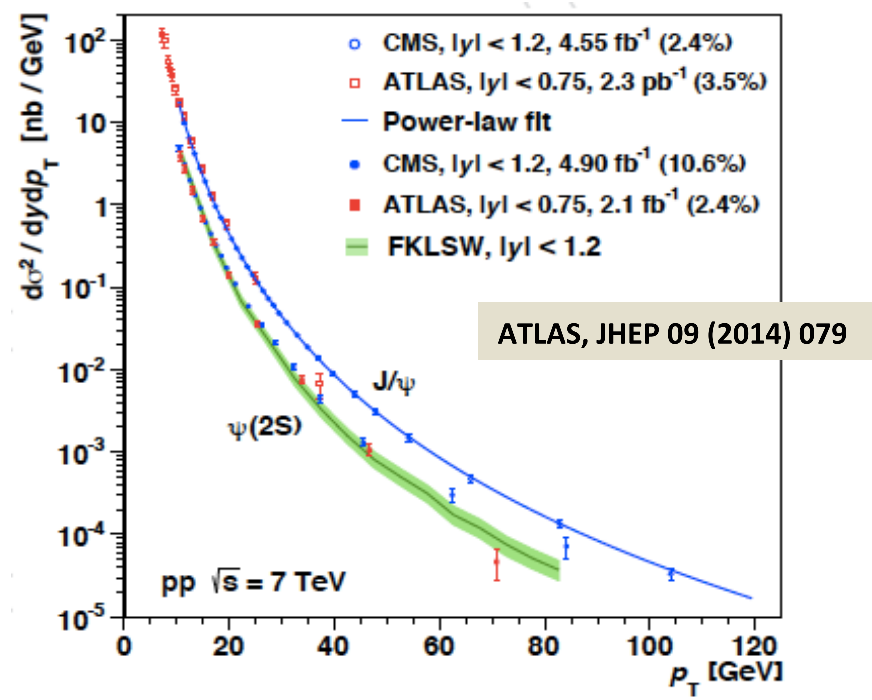
- NRQCD predicts the existence of intermediate CO states in nature, that subsequently evolve into physical color-singlet quarkonia by non-perturbative emission of soft gluons.

- Recent developments to explain production Xsections & polarization get reasonable agreement with data excluding data at low p_T: **unpolarized CO contribution dominates the production**
[PLB 737 (2014) 98 (data-driven approach)] [PRL 113 (2014) 022001 (leading-power fragm. formalism)]

Prompt production Xsections of charmonium S-wave states

- **Double differential prompt prod. Xsections times the dimuon branching fractions for** $J/\psi,\ \psi(2S)$ **as a function of** p_T **in 4 rapidity bins & integrated over the range** $|y|<1.2$ **(assuming unpolarized scenario)** **[**uncertainties from int. luminosity and branching fractions not included (% in the legend)**]:**

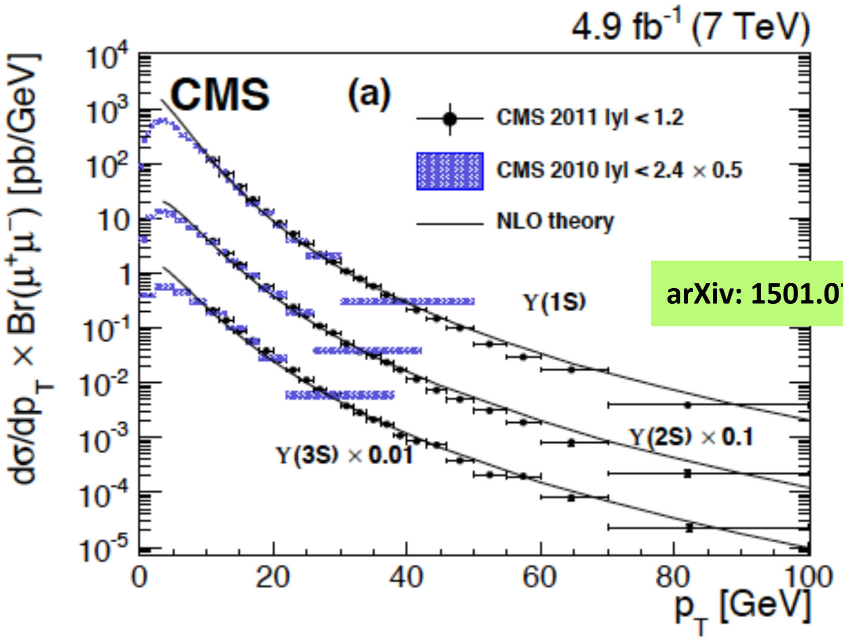




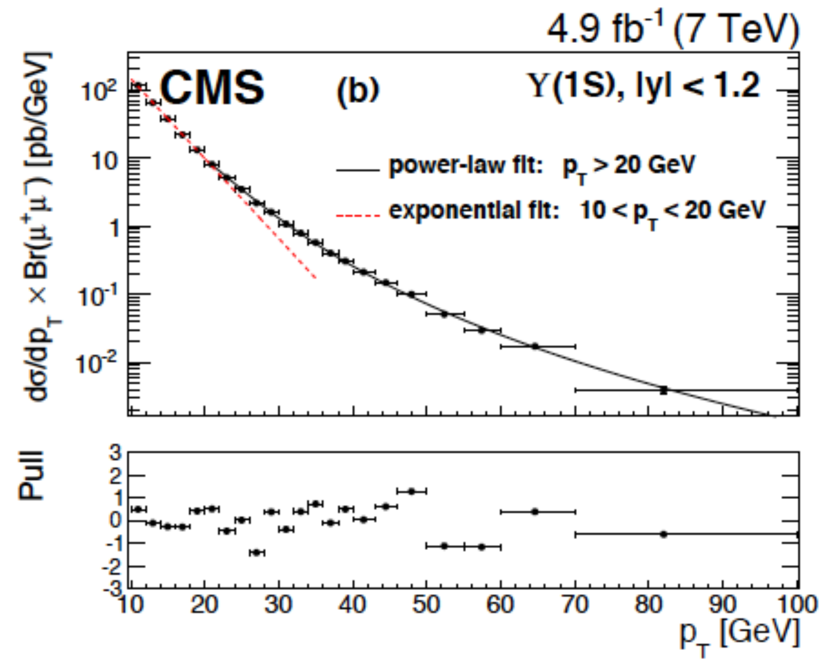
- Significant improvement in terms of precision and $\boldsymbol{p_T}$ reach ($p_T \approx 100 GeV$)
- Blue curve shows a **power-law fit** to J/ψ cross section
- Green band labelled FKLSW represents a calculation of the $\psi(2S)$ cross section using LDMEs determined in a global fit of Xsections and polarizations [PLB 736 (2014) 98]. According to that fit $\psi(2S)$ mesons are **produced predominantly unpolarized**.

Prompt production Xsections of bottomonium S-wave states

- **Differential prompt prod. Xsections times the dimuon branching fractions for $\Upsilon(nS)$ as a function of p_T over the range $|y| < 1.2$** [uncertainty from int. luminosity not included]



arXiv: 1501.07750



- All 3 Υ(nS) states show similar trends
- Measured Xsections show a transition from exponential to power-law behaviour at $p_T \sim 20$ GeV (fit holds for all the 3 states)

Prompt production Xsections of bottomonium S-wave states

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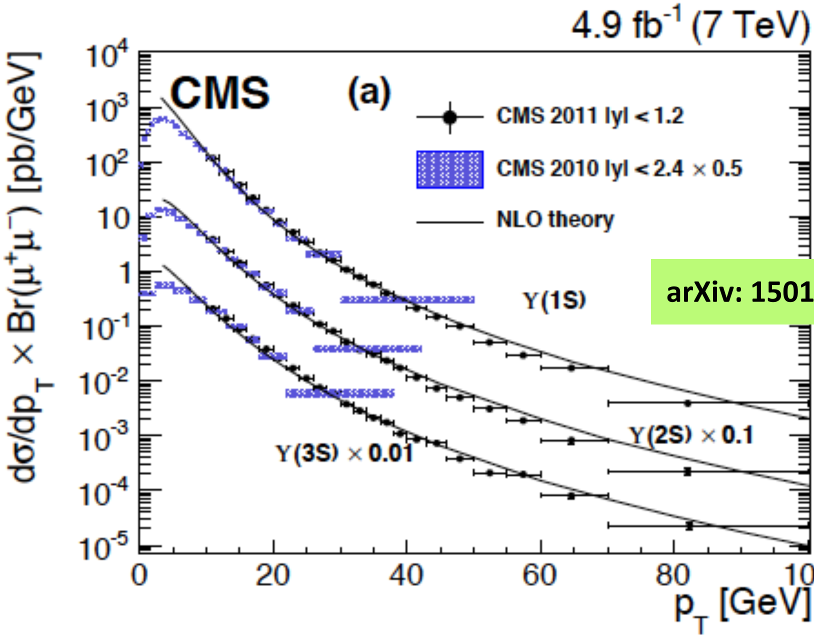

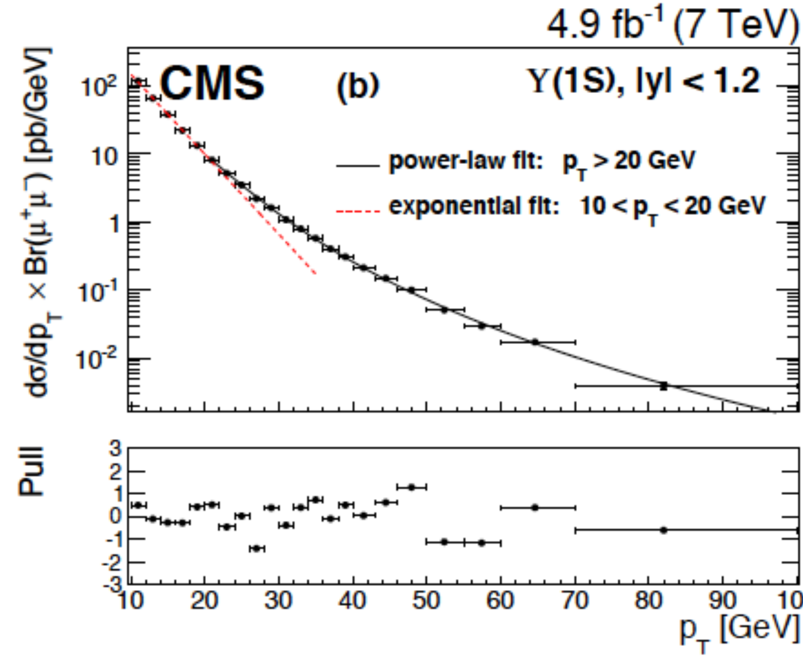

- All 3 Υ(*n*S) states show similar trends
- Measured Xsections show a transition from exponential to power-law behaviour at ***p_T ~ 20 GeV*** (fit holds for all the 3 states)

- **NLO calculations** from [Gong et al., **PRL 112, 032001**, for p_T < *50 GeV*] have been extended to cover the range **p_T < 100 GeV** and describe data trend for all 3 Y(nS) states!

- More details in the poster by B. T. Carlson

Summary

- Although designed for high-p_T physics …
  … CMS is an exceptional apparatus for dealing with flavour physics topics!

  - CMS results on golden channels ($B^0_{s,d} \to \mu\mu,\ B^0 \to K^*\mu\mu,\ B^0_s \to J/\psi\,\phi$) to look for indirect evidence of NP are competitive with those from other experiments and consistent with the SM predictions.

    Nevertheless we still have chances to "see" NP in CKM with more data (Run-II), together with upgraded LHCb and complementing future Belle-II results.

    Propedeutic analysis on $B^0_s \to J/\psi\, f_0$ has been released.
    The aim is to use this mode to help in the determination of mixing-induced CPV phase.

Summary

- Although designed for high-p_T physics …
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    Propedeutic analysis on $B^0_s \to J/\psi\, f_0$ has been released.
    The aim is to use this mode to help in the determination of mixing-induced CPV phase.

  - Being LHC a "quarkonium factory" it will be possible to further test the validity domain of NRQCD.

    CMS will provide S-wave production Xsections & polarizations with 2012 data (only 2011 so far).
    Considering Run-II integrated luminosity, a factor 2 in Xsections & improved triggers we expect a sample of quarkonia few hundreds times larger than in 2011, crucial to extend considerably the p_T- reach of quarkonium studies with very small uncertainties.

Backup slides / Additional material

$$B_{s(d)} \to \mu^{+}\mu^{-}$$ [CMS-BPH-13-007]

Weak Decay Amplitude & NP

- Weak decay of hadron M into final state F described via an Effective Hamiltonian expressed by means of Operator Product Expansion:

$$A(M \to F) = \langle F | H_{eff} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$C_i(\mu)$: Wilson Coefficients (perturbative short distance couplings)
$Q_i(\mu)$: Hadronic Matrix Elements (non -perturbative long distance effects)

- NP could modify Wilson Coefficients $C_i(\mu)$ and/or add new operators $Q_i(\mu)$

Penguin decays

In penguin decays, non-SM particles might give their contribution in loop diagrams. These decays are conventionally split in three classes:

(i) radiative penguins, with a single photon accompanying the hadronic system,
(ii) electroweak (EW) penguins, where two leptons are emitted instead of a photon, and
(iii) *Higgs penguins, which are the s-channel version of the previous ones.*

The branching ratios for radiative penguin decays are typically 10^{-4} or less. One might expect EW penguins to be suppressed in the SM about a factor $\alpha_{em} \approx 1/100$ with respect to radiative ones, resulting in typical BRs of 10^{-6}. Higgs penguins are further helicity suppressed, with predicted BRs at the 10^{-9} level. The effective hamiltonian describing these processes can be written by means of the Operator Product Expansion technique, with Wilson coefficients calculable from perturbation theory and matrix elements of operators which need to be computed non perturbatively. A parametrization in terms of the Lorentz structure of the operators can be written as

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [C_i(\mu) O_i(\mu) + C_i'(\mu) O_i'(\mu)] \quad (1)$$

where C_i are Wilson coefficients and O_i Lorentz-Invariant operators. Primed and unprimed quantities refer to right- and left-handed couplings, the former being suppressed in the SM. The relevant operator for radiative penguins is $O_7 \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$. The operators $O_9 \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \ell$ and $O_{10} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \gamma_5 \ell$ dominate EW penguis, while the scalar and pseudoscalar $O_S \sim \bar{s}_L b_R \bar{\ell} \ell$, $O_P \sim \bar{s}_L b_R \bar{\ell} \gamma_5 \ell$ contribute to Higgs penguins.

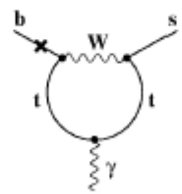
[Bozzi, Int.J.Mod.Phys. Conf.Ser. 201431]

Effective approach to b→s transitions

Effective approach to radiative decays

- $b \to s\gamma$ and $b \to s\ell^+\ell^-$ Flavour-Changing Neutral Currents
- enhanced sensitivity to New Physics effects
- analysed in model-independent approach effective Hamiltonian
- integrating out all heavy degrees of freedom

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} C_i Q_i + \dots$$



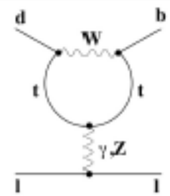
- $Q_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma_\mu\ell$ [$b \to s\mu\mu$ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma_\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

NP changes short-distance C_i and/or add new long-distance ops Q_i'

- Chirally flipped ($W \to W_R$) $Q_7 \to Q_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) $Q_9, Q_{10} \to Q_S \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, Q_P$
- Tensor operators ($\gamma \to T$) $Q_9 \to Q_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\ \bar{\ell}\sigma_{\mu\nu}\ell$

S. Descotes-Genon (LPT-Orsay) | Global fits to radiative $b \to s$ | 16/03/14 | 2

Wilson Coefficients and processes



Matching SM at high-energy scale $\mu_0 = m_t$ and evolving down at $\mu_{\rm ref} = 4.8$ GeV

$$C_7^{SM} = -0.29, C_9^{SM} = 4.1, C_{10}^{SM} = -4.3,$$

(formulae known up to NNLO + e.m. corrections)

C_i	Observables	SM values
$C_7^{\rm eff}$	$\mathcal{B}(B \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, B \to K^*\ell\ell$	-0.29
C_9	$\mathcal{B}(B \to X_s\ell\ell), B \to K(^*)\ell\ell$	4.1
C_{10}	$\mathcal{B}(B_s \to \mu^+\mu^-), \mathcal{B}(B \to X_s\ell\ell), B \to K(^*)\ell\ell$	-4.3
C_7'	$\mathcal{B}(B \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, B \to K(^*)\ell\ell$	0
C_9'	$\mathcal{B}(B \to X_s\ell\ell), B \to K(^*)\ell\ell$	0
C_{10}'	$\mathcal{B}(B_s \to \mu^+\mu^-), B \to K(^*)\ell\ell$	0

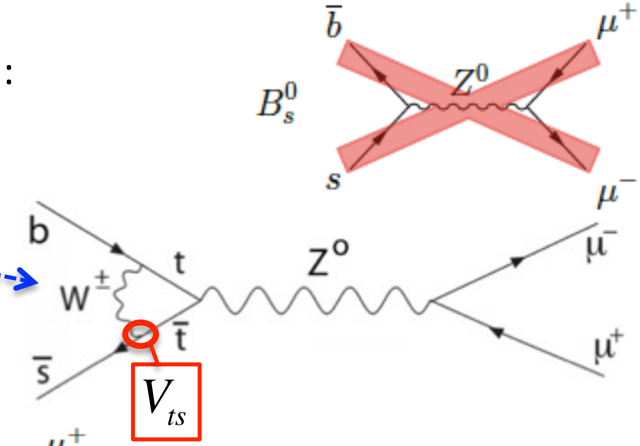
- $B \to X_s\gamma$: strong constraints on $C_7, C_{7'}$ [Misiak, Gambino, Steinhauser...]
- $B \to X_s\ell\ell$: not accurate enough expt [Misiak, Bobeth, Gorbahn, Haisch, Huber, Lunghi...]
- $B_s \to \mu\mu$: recent th. and exp. progress [talks from C. Bobeth and M. Gorbahn]
- $B \to K(^*)\ell\ell$: recent th. and exp. progress

S. Descotes-Genon (LPT-Orsay) | Global fits to radiative $b \to s$ | 16/03/14 | 3

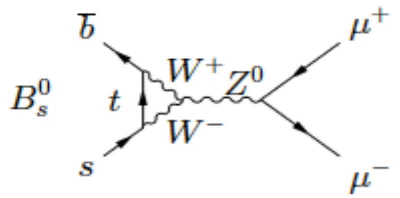
[Descotes-Genon, @Moriond EW. 2014]

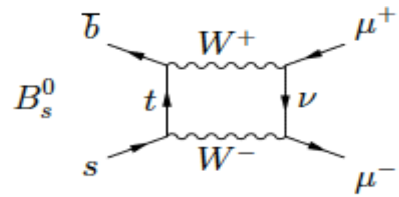
Rare *B* decays as New Physics probes : $B_{s(d)} \to \mu^+\mu^-$

- The rare decays $B_{s(d)} \to \mu^+\mu^-$ are FCNC highly suppressed in SM: effective FCNC transitions (forbidden @ tree-level) can only proceed through high-order loop diagrams
  - helicity-suppressed by $(m_\mu / m_B)^2$ 
  - CKM-suppressed by $|V_{ts(td)}|^2$



Thus SM allowed processes are:

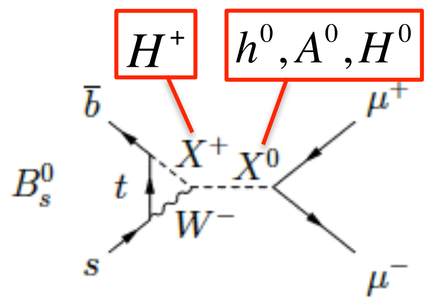


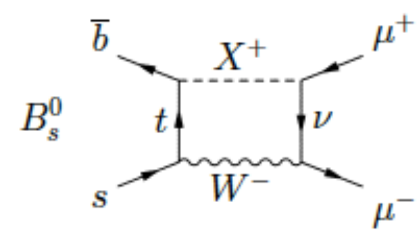


… and BF are reliably calculated [**Bobeth et al., PRL 112 (2014) 101801**] to be:
(suppression of B_d over B_s in SM given by $\sim (|V_{td}|/|V_{ts}|)^2$)

$$\mathbf{B}_{SM}(B_s^0 \to \mu^+\mu^-) \approx 3.7 \cdot 10^{-9}$$
$$\mathbf{B}_{SM}(B_d^0 \to \mu^+\mu^-) \approx 1.1 \cdot 10^{-10}$$

- High sensitivity to NP contributions in the loops: new particles can alter decay !
  NP scenarios in the extended Higgs sector may enhance or suppress decay rates w.r.t SM (and would show different *tan*β dependence).





- The ratio of BF provides powerful discrimination among BSM theories.
  Those with the property of Minimal Flavour Violation predict the same value as the SM.

[Straub (CKM2010), arXiv:1012.3893]

[MFV: general structure of SM FCNC is preserved & flavour violation depends only on CKM]

$B^0_{s(d)} \to \mu^+\mu^-$: analysis strategy - BF

- Full Run-I datasets [2011 & 2012] split in 2 regions: { Barrel (better sensitivity) / Endcap (more events) } ⇨ 4 analysis 'channels'
- Dedicated 2μ-trigger path & BDT-based μ-ID [kinematic variables + tracker/μ-chambers fit info (alone or not)]
- Define BF choosing $B^+ \to J/\psi K^+$ as Normalization channel :

$$\mathbf{B}(B^0_s \to \mu^+\mu^-) = \frac{Y_S}{Y_N} \cdot \frac{\varepsilon_N}{\varepsilon_S} \cdot \frac{f_u}{f_s} \cdot \underbrace{\mathbf{B}(B^+ \to K^+ J/\psi \to K^+\mu^+\mu^-)}_{=(6.0\pm0.2)\cdot 10^{-5}}$$

where

$$\frac{\varepsilon_N}{\varepsilon_S} = \frac{\varepsilon^{sel}_{B^+}}{\varepsilon^{sel}_{B^0_s}} \cdot \frac{\varepsilon^{\mu ID}_{B^+}}{\varepsilon^{\mu ID}_{B^0_s}} \cdot \frac{\varepsilon^{trig}_{B^+}}{\varepsilon^{trig}_{B^0_s}}$$

Ratio of Signal & Normalization Yields

Ratio of Normalization & Signal Efficiencies

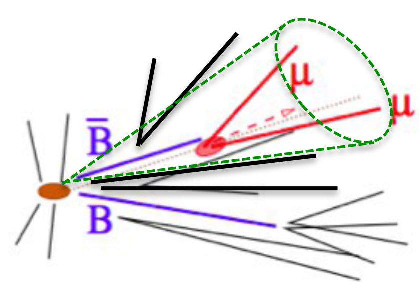
Ratio between B^+ & B^0_s fragmentation functions [$= 0.256 \pm 0.020$ measured by LHCb, JHEP04 (2013) 001]

- This normalization sample allows: 1) to avoid uncertainties from b production xsection and luminosity
  2) to set nearly identical selections to reduce efficiency systematics

- Choose $B^0_s \to J/\psi\phi$ as control channel to calibrate and validate simulation

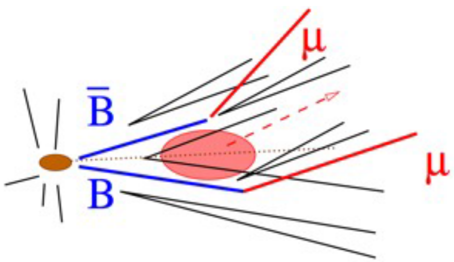
- SIGNAL characteristics

Two isolated muons from a secondary vertex, dimuon momentum aligned to flight direction and invariant mass around $m(B^0_{d/s})$



$B^0_{s(d)} \to \mu^+\mu^-$: analysis strategy - BDT

BKG characteristics



a) combinatorial BKG [from uncorrelated semileptonic decays] (from sidebands)

[estimated by extrapolation]

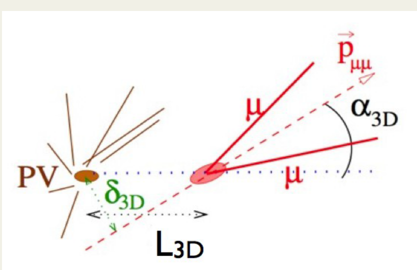
- Two semileptonic B/D decays
- One semileptonic B decay & one mis-identified hadron

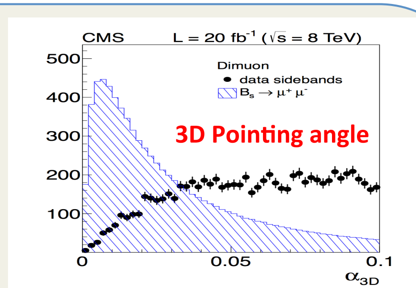
b) single B decays BKG (from simulation) [estimated normalizing to $B^+ \to J/\psi K^+$ yield]

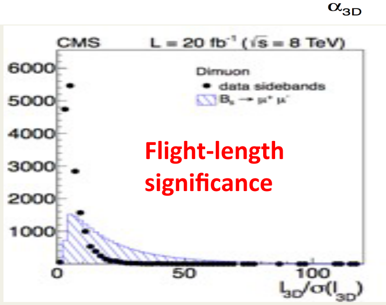
- peaking: $\begin{cases} B^0_{s/d} \to h^+ h'^- \\ \Lambda^0_b \to p h'^- \end{cases}$ [with double mis-ID] (*h*, *h'* = mis-identified *K* or π)
- non-peaking : $B^0_{s/d} \to h\mu\nu, \mu\mu\gamma,\ B^+ \to h\mu\mu,\ \Lambda^0_b \to p\mu\bar{\nu}$

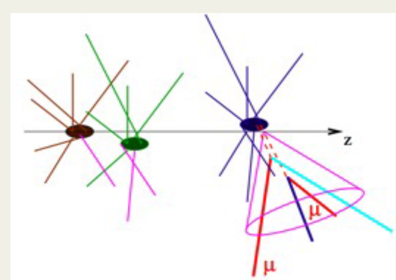
Events selected by means of a BDT (Root TMVA) exploiting kinematic, vertexing & isolation variables (12)

[Training: use MC for signal & data mass sidebands for BKG]



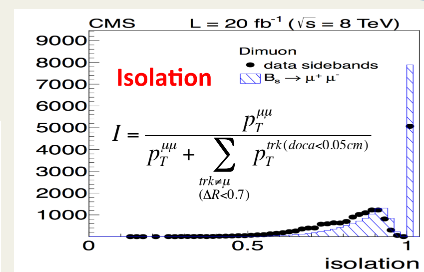


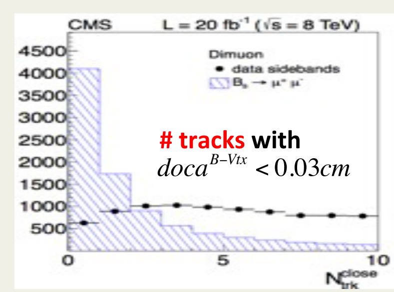




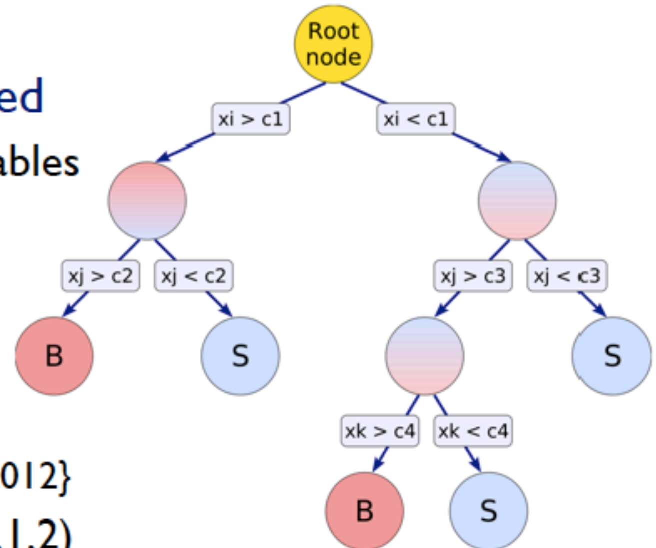
$p_T(\vec{B}) \Rightarrow$ cone's axis

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





$B_{s(d)} \to \mu^+\mu^-$ Multivariate Selection



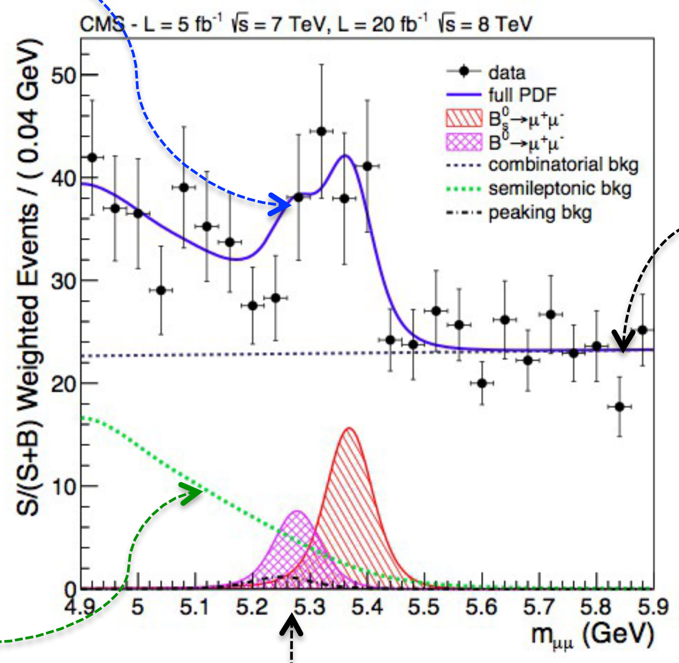
- a Boosted Decision Tree (BDT) is employed
  - combining the various (12) discriminating variables
  - TMVA Root framework implementation used
- BDT training
  - signal: $B_s \to \mu\mu$ MC simulation
  - background: dimuon data mass sidebands
- multiple BDTs: 12 = 3 x {barrel, endcap} x {2011, 2012}
  - per channel, split data samples in 3 subsets (0,1,2)
  - 1st BDT: is trained on 0, tested on 1, applied on 2; etc
- verifications
  - BDT output independent of mass (eg low- vs high- mass sidebands, mass shifts)
  - BDT output insensitive to pileup (including isolation variables)
- selection application approaches
  - 1D: use single cut (optimized per channel) on BDT discriminator (cross check)
  - categorized: use instead different (2-4) BDT bins (default for B_s selection)

$B^0_{s(d)} \to \mu^+\mu^-$: analysis strategy – UML fit

- The BDT output discriminant is used in two ways:
  a) Categorized-BDT: used to define 12 categories with different S/B ratio
  b) 1D-BDT: use single cut (optimized for the 4 channels) on discriminator [for cross-check purposes and UL on $\mathcal{B}(B^0 \to \mu^+\mu^-)$]
- Extract signal/BKG yields from an UML fit to $m(\mu\mu)$ simultaneously for the 12 BDT categories

B_s & B_d signals

2 Crystal Ball (fixed shape, width=resolution on per-event basis floating normalization)

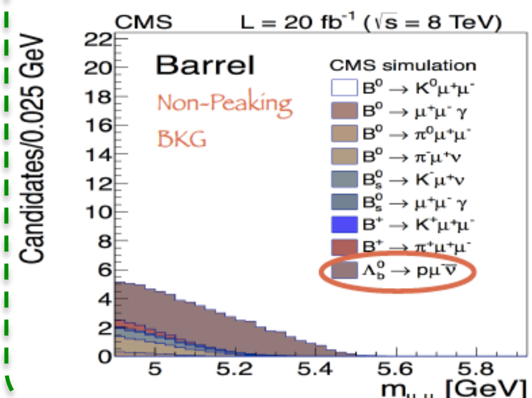


Combinatorial BKG

[first-degree polynomial]

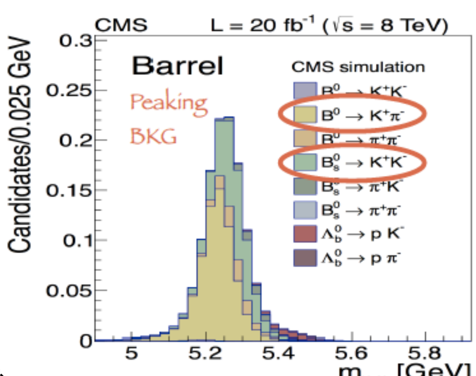
Rare non-peaking BKG

[fixed shape, constrained normalization]



Rare peaking BKG

[constrained to expectation (Gaussian+CB, common mean)]



$B_{s(d)} \to \mu^+\mu^-$ Systematics

- Implemented as Gaussian PDF constraints in UML fit
- Hadron to muon misidentification probability
  - studied with $D^* \to D^0 \pi$ ($D^0 \to K\pi$); $K_S \to \pi\pi$; $\Lambda \to p\pi$
  - 50% uncertainty (conservatively assumed to be uncorrelated)
- Branching fractions uncertainties
  - dominated by $\Lambda_b \to p\mu\nu$ (6.5×10^{-4}), with 100% uncertainty
- $f_s/f_u = 0.256 \pm 0.020$ from LHCb
  - additional 5% to account for possible p_T and η dependencies
  - in situ studies show no p_T dependence from ratios $B^+ \to J/\psi K^+$ vs $B_s \to J/\psi \Phi$
- Normalization channel
  - yields: 5%
  - $BR(B^+ \to J/\psi K^+) \times BR(J/\psi \to \mu\mu) = (6.0 \pm 0.2) \times 10^{-5}$

$B_d \to \mu^+\mu^-$ Limits

- No significant excess is observed for $B_d \to \mu\mu$
- Upper limit is computed using CLs method, based on observed number of events in the signal and sideband regions with 1D-BDT approach

Expected and observed no. of events in signal regions

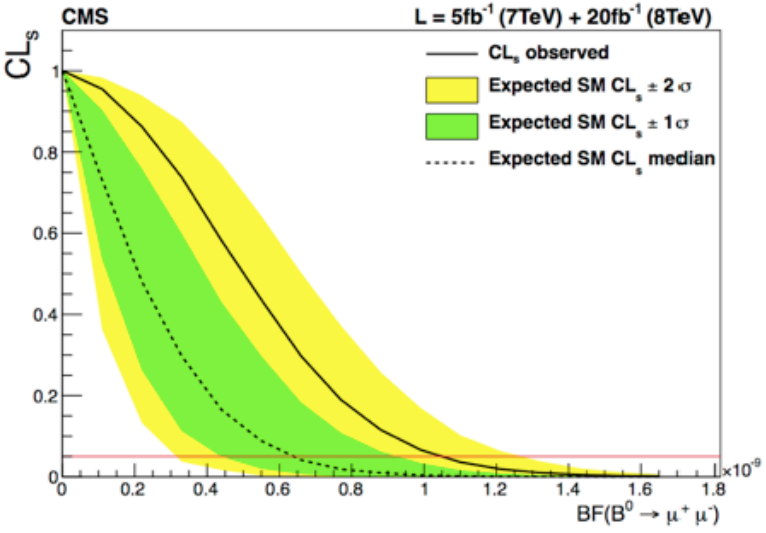
	2011 barrel		2012 barrel	
	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
$\varepsilon_{tot}[\%]$	0.33 ± 0.03	0.30 ± 0.04	0.24 ± 0.02	0.23 ± 0.03
N^{exp}_{signal}	0.27 ± 0.03	2.97 ± 0.44	1.00 ± 0.10	11.46 ± 1.72
N^{exp}_{total}	1.3 ± 0.8	3.6 ± 0.6	7.9 ± 3.0	17.9 ± 2.8
N_{obs}	3	4	11	16

	2011 endcap		2012 endcap	
	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_s \to \mu^+\mu^-$
$\varepsilon_{tot}[\%]$	0.20 ± 0.02	0.20 ± 0.02	0.10 ± 0.01	0.09 ± 0.01
N^{exp}_{signal}	0.11 ± 0.01	1.28 ± 0.19	0.30 ± 0.03	3.56 ± 0.53
N^{exp}_{total}	1.5 ± 0.6	2.6 ± 0.5	2.2 ± 0.8	5.1 ± 0.7
N_{obs}	1	4	3	4

$$\mathrm{BR}(B_d \to \mu\mu) < 1.1 \times 10^{-9} \text{ @95\% CL}$$

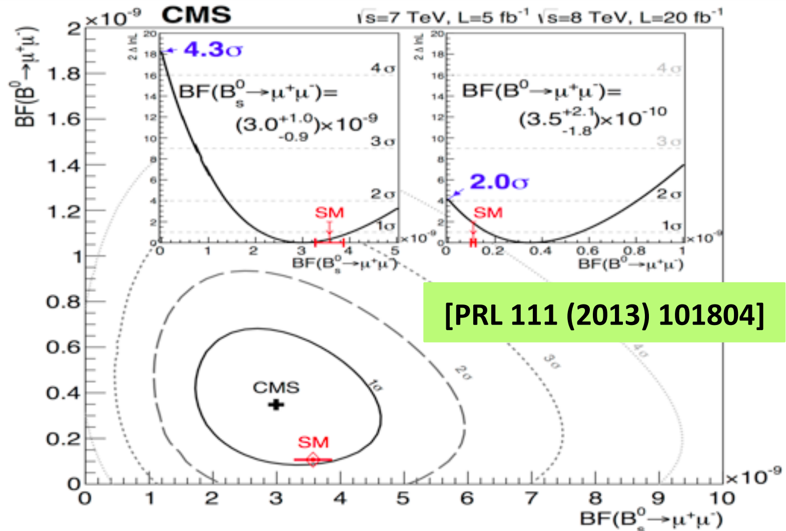
(expected 6.3×10^{-10} in presence of SM+background)

$$\mathrm{BR}(B_d \to \mu\mu) < 9.2 \times 10^{-10} \text{ @90\% CL}$$



$B^0_{s(d)} \to \mu^+\mu^-$: results

- CMS results with full Run-I dataset (25 fb^{-1}) are:
  - statistically dominated
  - consistent with SM expectations

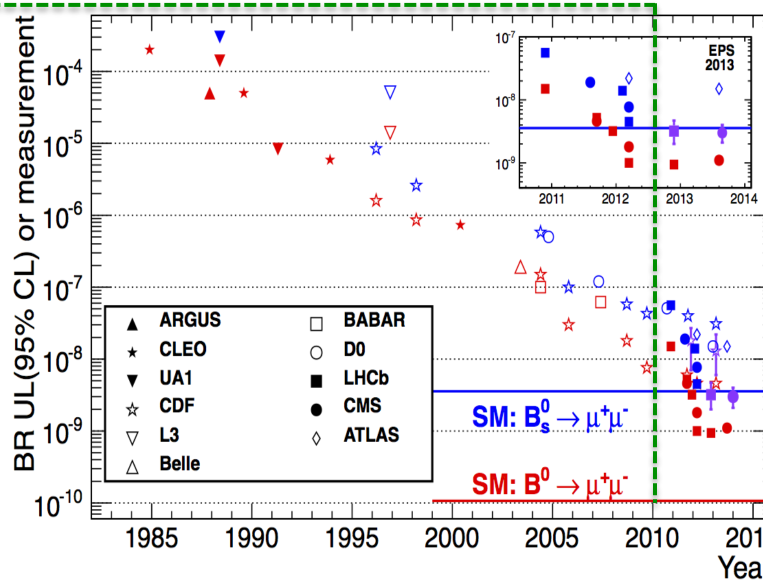


[PRL 111 (2013) 101804]

- $\mathbf{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0^{+0.9}_{-0.8}(\text{stat})\ ^{+0.6}_{-0.4}(\text{syst})\right)\cdot 10^{-9}(4.3\sigma \text{ signif.})$ [UML fit – categ.BDT]
- $\mathbf{B}(B^0 \to \mu^+\mu^-) = \left(3.5^{+2.1}_{-1.8}(\text{stat+syst})\right)\cdot 10^{-10}(2.0\sigma \text{ signif.})$
- $\mathbf{B}(B^0 \to \mu^+\mu^-) < 1.1\cdot 10^{-9}$ @95%CL [CLs method – 1D BDT]

Main systematics μ-misID, BF of rare BKG decays ($\Lambda_b^0 \to p\mu\bar{\nu}$) & normalization of peaking BKG

- A long journey ... (only upper limits in pre-LHC era)



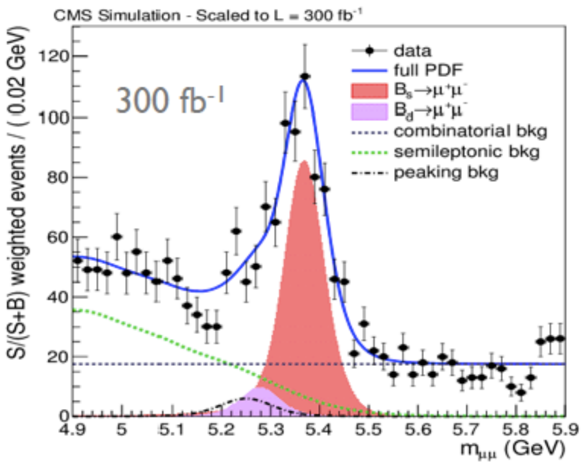
Other LHC experiments :

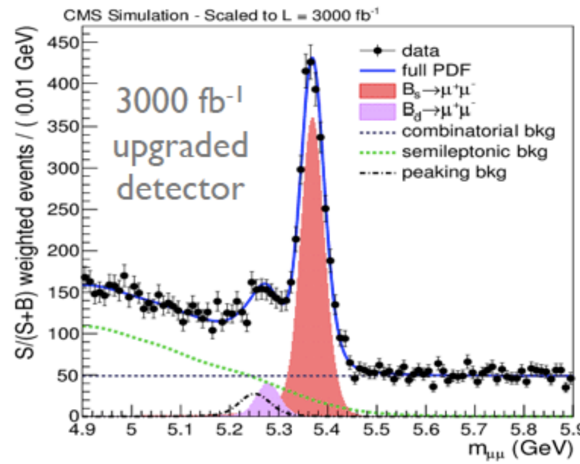
- ATLAS: $\mathbf{B}(B_s^0 \to \mu^+\mu^-) < 1.5\cdot 10^{-8}$ @95%CL [ATLAS-CONF-2013- 076]
- LHCb:
  - $\mathbf{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0})\cdot 10^{-9}$ (4.0σ signif.)
  - $\mathbf{B}(B^0 \to \mu^+\mu^-) < 7.4\cdot 10^{-10}$ @95%CL

[PRL 111 (2013) 101805]

Combination with CMS to get observation!

$B_{s(d)} \to \mu^+\mu^-$ Projections





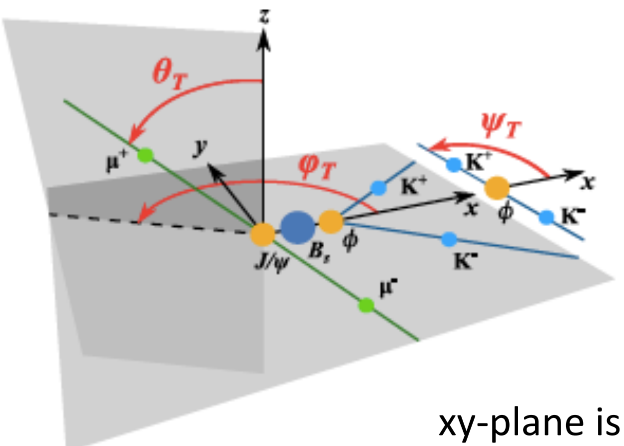
Year	L (fb^{-1})	No. of B_s^0	No. of B^0	$\delta\mathcal{B}/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$
now	20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
2018	100	144	18	15%	66%	0.5–2.4 σ	71%
2021	300	433	54	12%	45%	1.3–3.3 σ	47%
2023	3000	2096	256	12%	18%	5.4–7.6 σ	21%

- expectations assuming SM BRs, and planned detector upgrades
- HI-LHC: inner tracker with improved granularity & muon detector with extended coverage

With $100fb^{-1}$ the relative error on R will go to 70% still statistically limited (TH error already at 5% !)

$B_s^0 \to J/\psi\,\phi$ CMS-PAS-BPH-13-012

$B_s^0 \to J/\psi\phi$ decay angles



Angular distribution is defined in the transversity base

The set of three angles $\Theta = (\theta_T, \psi_T, \varphi_T)$ is defined as follows:

θ_T : polar angle of the μ^+ in the J/ψ rest frame w.r.t. z-axis

φ_T : azimuthal angle of the μ^+ in the J/ψ rest frame w.r.t x-axis

xy-plane is the ϕ decay plane; x-axis given by ϕ momentum in J/ψ rest frame

ψ_T : elicity angle of the K^+ in the ϕ rest frame w.r.t. the negative J/ψ flight direction

$B_s^0 \to J/\psi\phi$ Signal model & Flavour tagging

We use the same notations as LHCb [arXiv:1304.2600]:

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

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

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

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

$|\lambda|$ includes possible contribution from CP violation in direct decay, we assume $|\lambda| = 1$ and we assign a systematics.
$\Delta\Gamma_s > 0$: we use previous LHCb results. α physics parameters ($\Delta\Gamma_s$, ϕ_s, $c\tau$, $|A_0|^2$, $|A_S|^2$, $|A_\perp^2|$, $\delta_\parallel$, $\delta_{S\perp}$, $\delta_\perp$)

- The c_i and d_i terms of the O_i time dependent functions are modified according to the flavour tagging response

$$O_i(\alpha, ct) = N_i e^{-ct/c\tau}[a_i \cosh(\frac{1}{2}\Delta\Gamma_s ct) + b_i \sinh(\frac{1}{2}\Delta\Gamma_s ct) + c_i\xi(1-2\omega)\cos(\Delta m_s ct) + d_i\xi(1-2\omega)\sin(\Delta m_s ct)]$$

- ξ is the tag decision, based on the charge of the lepton:
  - $0 \to$ untagged
  - $+1 \to B_s$ tagged
  - $-1 \to \overline{B}_s$ tagged
- ω is the mistag fraction evaluated as a function of the lepton tranverse momentum: $\omega = \omega\left(p_T^\ell\right)$

$B_s^0 \to J/\psi\phi$ PDFs of UML fit

$$\mathcal{L} = L_{sig} + L_{bkg}$$
$$L_{sig} = N_{sig} \cdot [X(\Theta, \mathrm{ct}; \alpha) \otimes G(\mathrm{ct}, \sigma_{\mathrm{ct}}) \cdot \varepsilon(\Theta)] \cdot P_{sig}(m_{B_s}) \cdot P_{sig}(\sigma_{\mathrm{ct}}) \cdot P_{sig}(\xi)$$
$$L_{bkg} = N_{bkg} \cdot P_{bkg}(\cos\theta_T, \varphi_T) \cdot P_{bkg}(\cos\psi_T) \cdot P_{bkg}(\mathrm{ct}) \cdot P_{bkg}(m_{B_s}) \cdot P_{bkg}(\sigma_{\mathrm{ct}}) \cdot P_{bkg}(\xi)$$

- $G(\mathrm{ct}, \sigma_{\mathrm{ct}})$: gaussian resolution function, which makes use of the per-event proper decay length uncertainty $\sigma(\mathrm{ct})$ scaled by a factor $\kappa(\mathrm{ct})$
- $\varepsilon(\Theta) = \varepsilon(\cos\theta_T, \cos\psi_T, \varphi_T)$: 3-dimensional angular efficiency
- $P_{sig}(m_{B_s})$: B_s mass signal PDF $\to$ triple gaussian with common mean
- $P_{sig}(\sigma_{\mathrm{ct}})$: proper decay length uncertainty signal PDF $\to$ sum of two Gamma functions
- $P_{sig}(\xi)$: signal tag decision obtained from data

- $P_{bkg}(\cos\theta_T, \varphi_T)$ and $P_{bkg}(\cos\psi_T)$: angular background PDFs $\to$ Legendre polynomials for $\cos\theta_T$ and $\cos\psi_T$ and sinusoidal functions for φ_T. A 2-dimensional PDF is used for $\cos\theta_T$ and φ_T to take into account the correlations
- $P_{bkg}(\mathrm{ct})$: proper decay length background PDF $\to$ sum of two exponential functions
- $P_{bkg}(m_{B_s})$: B_s mass background PDF $\to$ single exponential
- $P_{bkg}(\sigma_{\mathrm{ct}})$: proper decay length uncertainty background PDF $\to$ single Gamma function
- $P_{bkg}(\xi)$: background tag decision obtained from data

$B_s^0 \to J/\psi\phi$ Systematics

Key elements for the measurement: resolution & efficency modelling for proper decay time and decay angles

	Angular	Proper decay time
efficiency	MC, included in the fit	MC, systematics only
resolution	MC, systematics only	per event uncertainty × scale κ

Source	$\|A_0\|^2$	$\|A_S\|^2$	$\|A_\perp\|^2$	$\Delta\Gamma_s$ [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 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	0.0016	0.002	0.0021	**0.0021**	0.010	0.03	0.04	**0.006**	0.2
Free $\|\lambda\|$ fit (***)	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	0.684	1.12	0.66	0.032	3.5

(*) evaluated from the statistical uncertainty of the model

(**) determined from toy MC bias tests

(***) let $|\lambda|$ as a free parameter in the fit

(****) propagated from discrepancy between data and simulations

$B_s^0 \to J/\psi\,\phi$ Systematics' details

- **Proper time efficiency:** fitting the data with a proper decay length efficiency which takes into account a small contribution of the decay length significance cut at small ct and a first order polynomial variations at high ct
- **Angular effiecency:** propagated the statistical uncertainty of the angular efficiency parameters to the physics observables
- **Fit model:** reported the bias of the pulls that were measured using toy MC pseudo-experiments
- **Proper decay time resolution (κ factor):** varied the κ (ct) factors within their stat. errors; the difference with respect to the nominal fit is investigated, and one standard deviation of the obtained distribution is taken as the systematic uncertainty
  - Difference of κ (ct) in simulation and a prompt J/ψ data sample is also studied
- **BG mistag modelling:** no background PDF for ω. Systematic estimated by generating simulated pseudo-experiments with different mistag distributions for signal and background and fitting them with the nominal fit
- **Flavour tagging:** systematic and statistical tagging uncertainties propagated to the physics observables uncertainty
- **PDF modelling assumptions:** all the systematics due to the assumption on the PDF model are evaluated with toy MC pseudo-experiments
- **Kaon p_T re-weighting:** small discrepancy in the kaon p_T spectrum between data and simulations $\to$ syst. evaluated by re-weighting the simulated kaon p_T spectrum to agree with the data
- **$|\lambda| = 1$ assumption:** tested by leaving $|\lambda|$ free in the fit $\Rightarrow$ $|\lambda|$ from fit agrees with 1 within one σ. The differences found in the fit results with respect to the nominal fit are used as systematic uncertainties

$B_s^0 \to J/\psi\, f_0(980)$ arXiv: 1501.06089

$B_s^0 \to J/\psi f_0$

Data Selection

- **Trigger selection**

HLT_Dimuon6p5_Jpsi_Displaced_v1
HLT_Dimuon7_Jpsi_Displaced_v1
HLT_Dimuon7_Jpsi_Displaced_v3
HLT_Double3p5_Jpsi_Displaced_v2
HLT_DoubleMu4_Jpsi_Displaced_v1
HLT_DoubleMu4_Jpsi_Displaced_v4
HLT_DoubleMu4_Jpsi_Displaced_v5

Most data included

- **Trigger cuts**

Variable	Cut	Units
μ pT	> 4.0	GeV/c
J/ψ pT	> 7.0	GeV/c
$\eta(\mu)$	< 2.2	
$\cos\alpha$	> 0.9	
L_{xy}/σ_{Lxy}	> 3.0	

Applied in Offline Reconstruction

- **Selection: hard cuts**

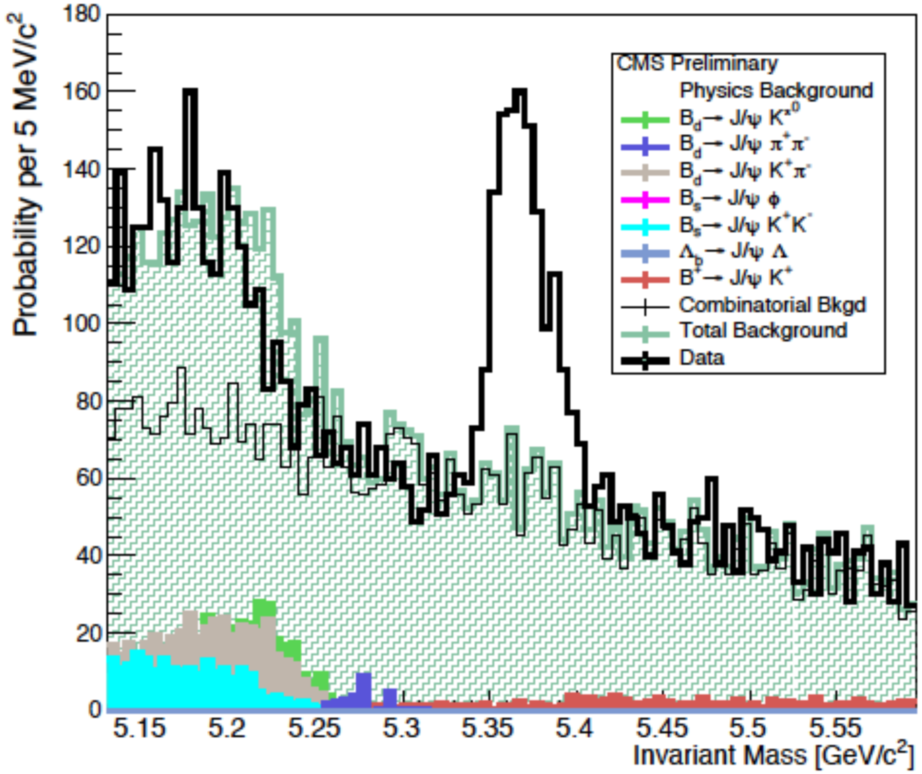
$B_s^0 \to J/\psi\, f_0$

Physics Background

MC study at Truth Level

Most Probably Decays with with similar topology to $B_s^0 \to J/\psi\, f_0(\pi^+\pi-)$

Decay	Probability
$B^0 \to J/\psi\, K^*(K^+\pi^-)$	0.1441
$B^0 \to J/\psi\, K^+\pi^-$	0.0271
$B^0 \to J/\psi\, \pi^+\pi^-$	0.0021
$B_s^0 \to J/\psi\, \phi(K^+K^-)$	0.1547
$B_s^0 \to J/\psi\, K^+K^-$	0.1441
$\Lambda_b \to J/\psi\, \Lambda(p\pi^-)$	0.1680
$B^+ \to J/\psi\, K^+$	0.0972



$$|M_{f_0} - 980| < 35\,\mathrm{MeV}/c^2$$

Smearing in MC of 16 MeV to mimic the detector

Decay removed after Mf0 mass cut:

$B_s^0 \to J/\psi\phi$

No resonant peak bellow signal peak

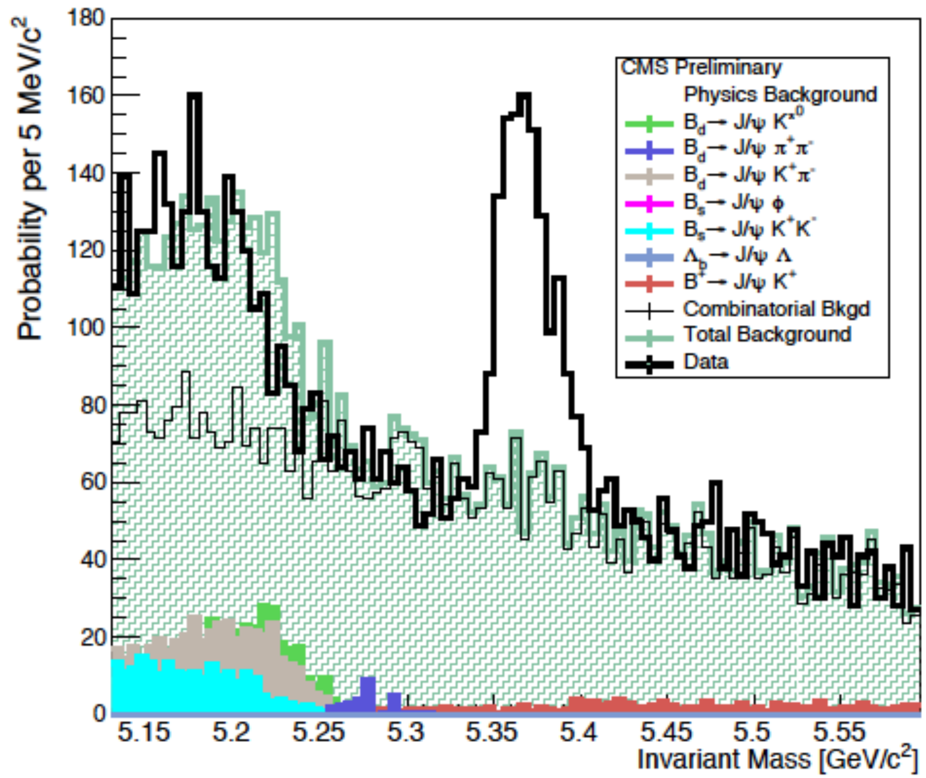
$B_s^0 \to J/\psi\, f_0$

Physics Background

The measurement is in fact restricted to a region where the $\pi^+\pi^-$ invariant mass is requested to be consistent with the $f_0(980)$ mass within ±50 MeV. The efficiency is indeed computed in that mass window.

In this mass region, we made the assumption that the non-resonant components are negligible. This assumption is confirmed by LHCb study (PRD 89 029006), which quotes other components to be 2 to 3 order of magnitude smaller in CMS mass window (mainly Figs. 16 and 17).

Moreover our MC simulation is very good in agreement with the data.



The systematics coming from the above assumption are tested by:

1. varying the assumed width of the f_0 (50 MeV) in the MC simulation by ±20%, which is within the 90% CL of our measured f_0 mass model. This resulted in a systematics of 8.6%, which is our biggest systematics.
2. varying the $f_0(980)$ mass window up to ±100 MeV to account for possible backgrounds (basically $f_0(1500)$ and $f_2(1270)$). That has an effect of 6.4% and is our second biggest systematics.

$B_s^0 \to J/\psi\, f_0$ Systematics' details

Potential systematic uncertainties in the measurement of $R_{f_0/\phi}$ come from sources such as the signal yield extraction procedure, data selection effects caused by the f_0 mass window, and the relative efficiency estimation.

Systematic uncertainties in the signal yield extraction are estimated by changing the modeling of the signal and the background invariant mass distributions in the likelihood fits. For the case of the $J/\psi\, \pi^+\pi^-$ mass distribution the signal shape is changed to a double-Gaussian function and the background to an exponential function, while for the $J/\psi\, K^+K^-$ mass distribution the signal is changed to a Gaussian function and its background is modelled as a first-order polynomial function. These changes lead to a maximum variation of 2.1% in $R_{f_0/\phi}$.

To estimate the possible contribution of unknown background in the f_0 mass region that could affect the $B_s^0 \to J/\psi\, f_0$ yield, the f_0 mass window is widened from 50 to 100 MeV around the f_0 mass, resulting in a variation in $R_{f_0/\phi}$ of 6.4%.

The poorly known f_0 natural width can affect the estimate of $\epsilon_{\mathrm{reco}}^{\phi/f_0}$, an input to the determination of $R_{f_0/\phi}$, as shown in Eq. (1). In the MC simulation used to estimate the ratio of the efficiencies, the f_0 width was set to 50 MeV. This value was varied by $\pm$10 MeV, resulting in a systematic uncertainty of 8.6% in $R_{f_0/\phi}$.

In addition, different decay models used in the signal MC generation could influence the estimated detection efficiency. For both channels the decay models are set to phase space instead of the default decay models, leading to a 6.2% systematic uncertainty in $R_{f_0/\phi}$.

Combining these uncertainties in quadrature leads to a total systematic uncertainty of 12.6%.

$B_s^0 \to J/\psi\, f_0$ Systematics' details

Source	$R_{f_0/\phi}$	R'	$\lvert R_{f_0/\phi} - R'_{max}\rvert / R_{f_0/\phi} (\%)$
Fit Model			
Sig: 1 Gauss, Bkgd: Gauss+Exponential	0.149 ± 0.012		
Sig: 1 Gauss, Bkgd: Exp+Polynomial	0.142 ± 0.012		
Sig: 2 Gauss, Bkgd: Gauss+Polynomial	0.147 ± 0.012		
Nominal	0.146 ± 0.013	0.142 ± 0.012	2.1
$f_0(980)$ mass windows			
$(\lvert M_{f_0} - 980\rvert < N \times 35$ MeV$/c^2)$			
$N = 2$	0.144 ± 0.012		
$N = 3$	0.147 ± 0.012		
$N = 4$	0.161 ± 0.013		
Nominal	0.146 ± 0.013	0.161 ± 0.013	6.4
MC efficiency			
f_0 Width $= 40$ MeV$/c^2$	0.202 ± 0.016		
f_0 Width $= 60$ MeV$/c^2$	0.237 ± 0.019		
f_0 Width $= 100$ MeV$/c^2$	0.309 ± 0.031		
Nominal	0.214 ± 0.017	0.237 ± 0.019	8.6
MC model ($B_s^0 \to J/\psi\phi$)			
PHSP	0.202 ± 0.016		
Nominal	0.214 ± 0.017	0.202 ± 0.016	5.6
Sum (in quadrature)			12.6

CMS-PAS-BPH-14-001

arXiv:1501.07750

$$J/\psi,\ \psi(2S),\ \Upsilon(nS)_{n=1,2,3}$$

production cross sections

NRQCD : color-singlet & color-octet terms

Inclusive xsection for producing quarkonium (***H***) with enough large momentum transfer p_T :

$$\sigma(A+B\to H+X)=\sum_n \sigma\left(A+B\to[Q\bar{Q}]_n+X\right)\otimes P\left([Q\bar{Q}]_n\to H\right)\ ,\quad n={}^{2S+1}L_J^{[C]}$$

$Q\bar{Q}$ can be, at short distances, produced in a state ***n*** with definite: spin ***S***, angular momentum ***L***, and color ***C*** = 1,..,8.

Short-distance coefficients (SDCs)	**Long-distance matrix elements** (LDMEs)
Inclusive pQCD xsection of partonic processes to form $Q\bar{Q}$ in state n (convoluted with PDFs)	Probability of $Q\bar{Q}$ in state n to evolve into the quarkonium final state *H*
process-dependent **functions** of kinematics	universal **constants** (independent of kinematics)
calculated perturbatively as expansions in α_S	**determined by fits** to exp. data
	relative relevance given by v **- scaling rules**

- Theoretical predictions are organized as double expansions in α_S and v.
  Truncation of v-expansion for *S-wave* states in NRQCD includes 4 terms:
  - the Color Singlet (CS) term: ${}^3S_1^{[1]}$ (CS assumption: initial $Q\bar{Q}$ & final ***H*** (${}^3S_1$) have same quantum numbers!
  - 3 Color Octet (CO) terms: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_{J=0,1,2}^{[8]}$ (of relative order $O(v^4)$ w.r.t. CS)

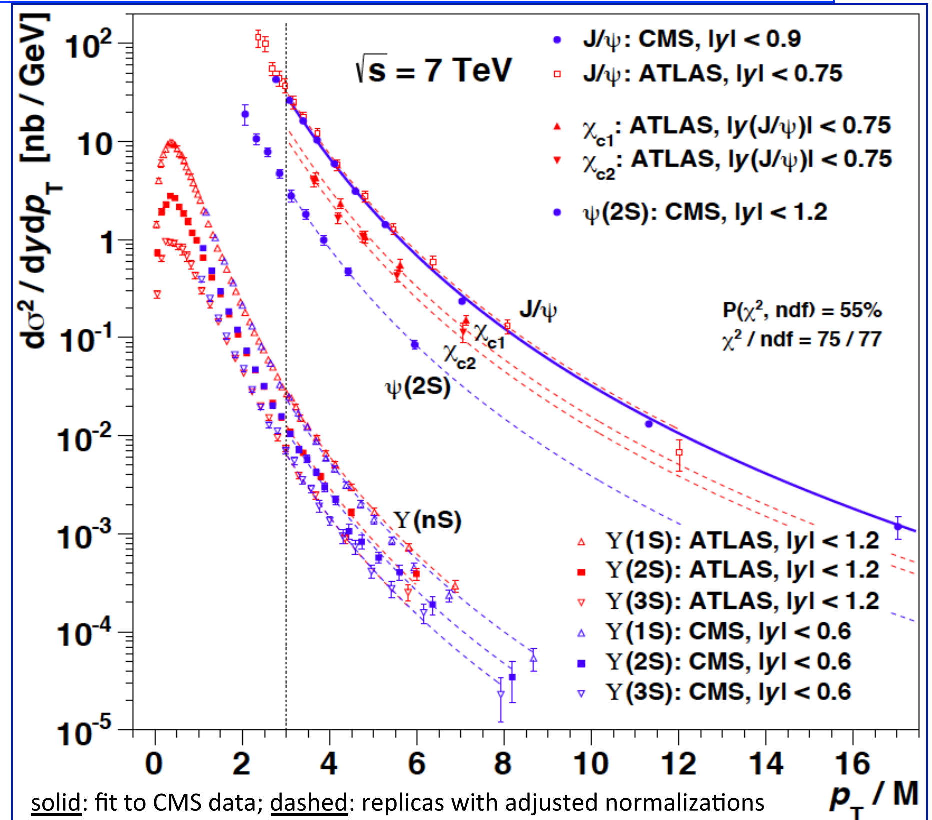
The CS term is characterized by a suppression of powers of α_S thus making important the CO channels despite of their suppression by powers of v !

Prompt production Xsections of S-wave states

- Mid-rapidity double differential prod. xsections for 7 different quarkonia as a function of p_T/M :

Shapes are well described by a single empirical power-law for $p_T/M > 3$.
This p_T/M **scaling behaviour** …
… common to 5 *S-wave* & 2 *P-wave* states
with different feed-down contaminations ,
suggests a simple composition of processes dominated by 1 single mechanism.

CS processes must be negligible!
A single CO term dominates production!
It could be ${}^1S_0^{[8]}$ **IF** the NRQCD fit would start @ 10-15*GeV* **[Faccioli et al.,PLB 736 (2014) 98]**



Compil. by P.Faccioli *et al.*, PLB 736 (2014) 98

CMS, JHEP 02, 011 (2012)
CMS, PLB 727, 101 (2013)

Scaling behaviour must be confirmed with:
- more accurate data up to higher p_T
- polarization data

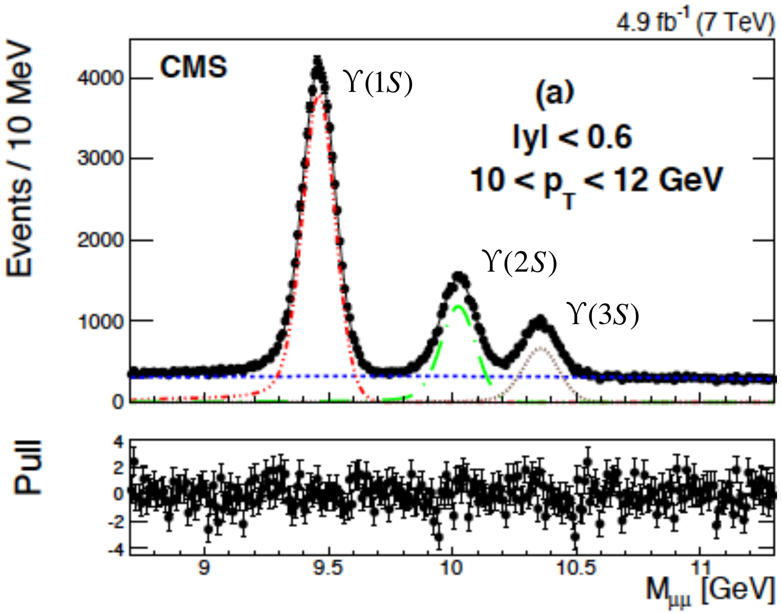
(indeed the ${}^3S_1^{[8]}$ term may become dominant at higher values of p_T/M than currently covered)

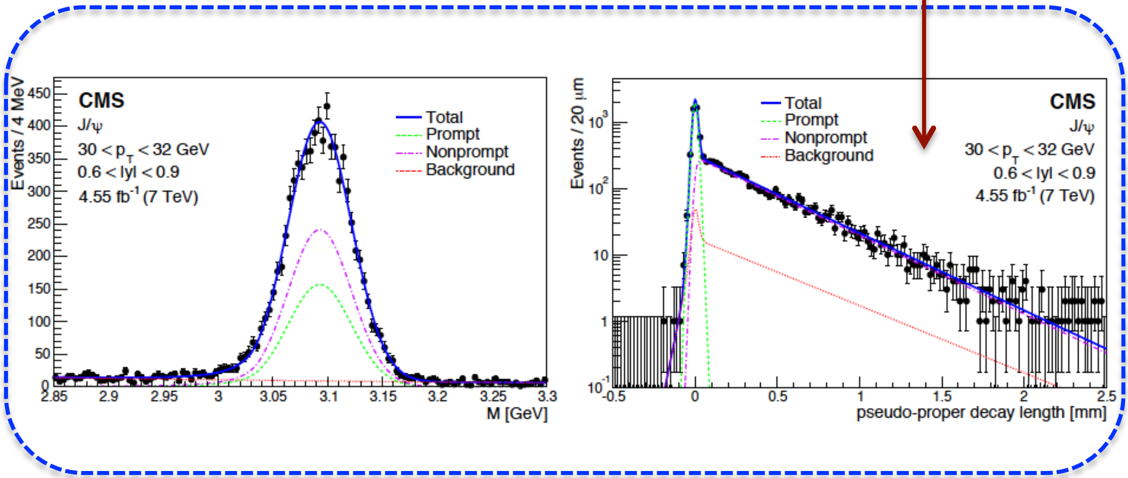
- Run-II can be a great opportunity to explore higher p_T regions with better accuracy. Right now CMS has not used 2012 data yet! Very soon new prod. xsections results - with full 2011 data - will be released extending p_T-range to 120*GeV* for J/ψ and 100*GeV* for $\psi(2S)$ and $\Upsilon(nS)_{n=1,2,3}$. **CMS-PAS-BPH-14-001/12-006**

Polarization measurements

Only dimuon decays are considered :
- they provide a particularly clean signature
- they are easier to be reconstructed and triggered on

An additional non prompt component (decays of *B hadrons* into $J/\psi,\ \psi(2S)$) is taken into account



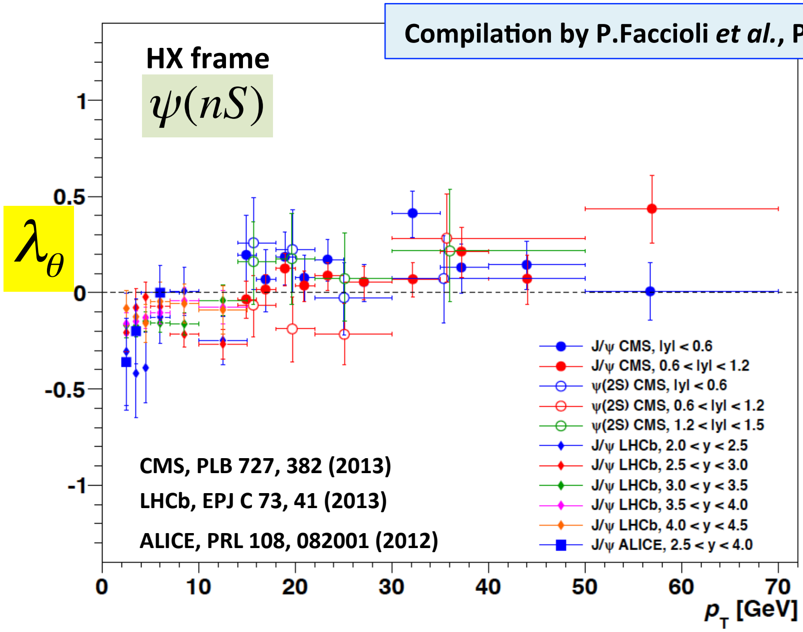


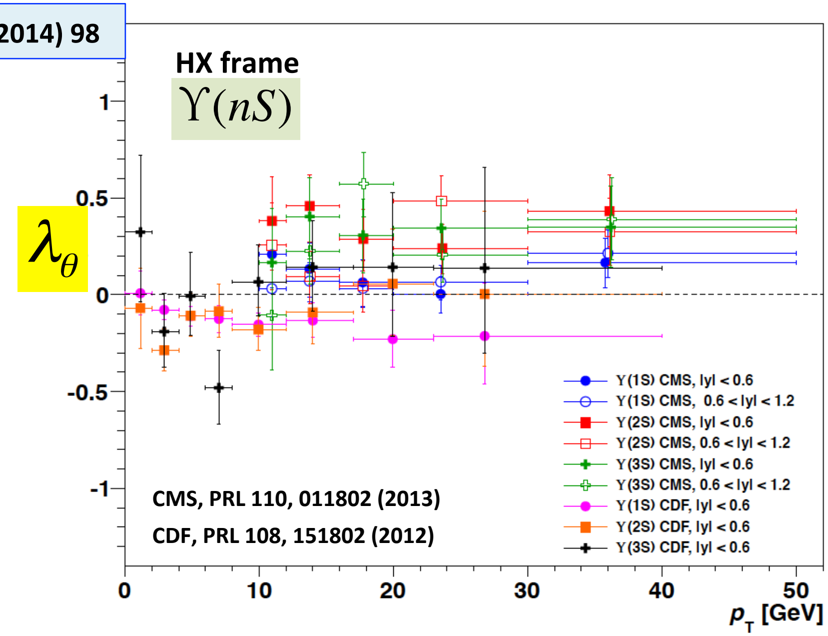
Photons & pions from the feed-down transitions have low energy : difficult to be reconstructed and associated with the dimuon pair in order to separate feed-down and direct production

Precise knowledge of efficiencies are needed to avoid introducing artifical polarization: they are data-driven and accounted on an event-by-event basis

Polarization: comparison with other LHC experiments

Compilation by P.Faccioli *et al.*, PLB 736 (2014) 98

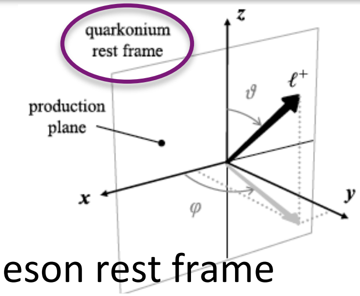




- All LHC results compatible with each other
- The polarizations cluster around the unpolarized limit ($\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0$) with …
  - no significance dependencies on p_T or y
  - no strong changes from full directly-produced states to those affected by *P-wave* feed-down decays
  - no evident differences between $c\bar{c}$ and $b\bar{b}$

Polarization of S-wave states

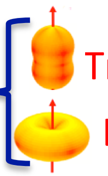
- The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions. The most general 2D angular distribution W for the dileptons is specified by 3 polarization parameters $\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}$:



$$W \equiv \frac{d^2N}{d(\cos\theta)d\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos2\phi+\lambda_{\theta\phi}\sin2\theta\cos\phi\right)$$ where θ & ϕ for $\vec{p}(\ell^+)$ in meson rest frame

The choice of a polarization frame that is not unique: there are 3 conventional frames: HX, CS, PX.

- Two extreme angular decay distributions:



Transverse Pol. $\lambda_\theta = +1$ $(\lambda_\phi = 0,\ \lambda_{\theta\phi} = 0)$

Longitudinal Pol. $\lambda_\theta = -1$

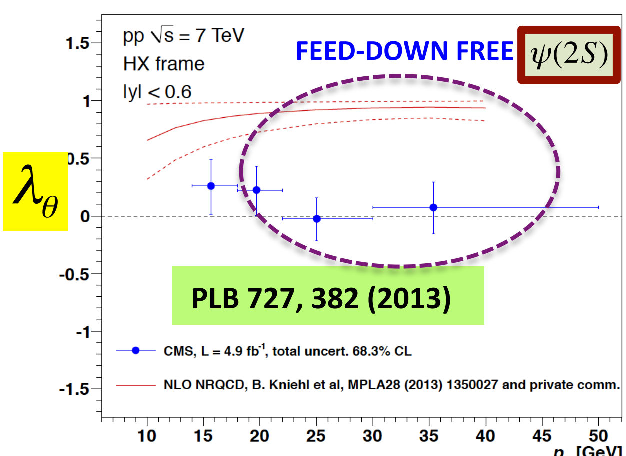
Each CS and CO term has a specific polarization; @NLO, in HX---->

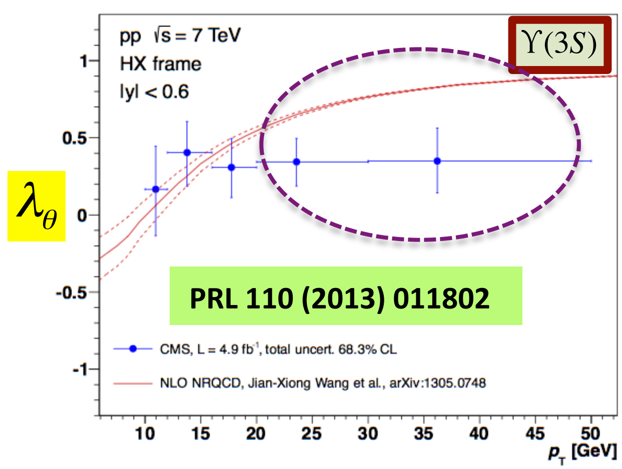
$CS\ \ {}^3S_1^{[1]}:\ \lambda_\theta = -1$ [longitudinal]

$CO\ \ {}^1S_0^{[8]}:\ \lambda_\theta = 0$ [isotropic]

$CO\ \ {}^3S_1^{[8]}:\ \lambda_\theta = +1$ (@ high p_T) [transverse]

- All LHC results compatible with each other: the polarizations cluster around the unpolarized limit $(\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0)$
Thus the dominant production mechanism must be CO ${}^1S_0^{[8]}$





If the ${}^3S_1^{[8]}$ term becomes dominant @higher p_T/M, the quarkonia @ high p_T should be transversely polarized: need analysis with 2012 data and with Run-II data ! Test if this hierarchy among CO contributions holds also for P-wave states !