Experimental status and near-term perspectives of flavour physics in CMS

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The landscape of Flavour Physics towards the high intensity era

9-10 December 2014 /Scuola Normale Superiore (Pisa)

Motivation to study Heavy Flavour @ CMS

- Great impact of LHC experiments in the heavy flavour sector :
  - The large production cross-sections for heavy flavoured particles in *pp* collisions at LHC energies provides opportunities for testing the Standard Model picture of flavour dynamics.
  - Besides LHCb which is a dedicated experiment, CMS & ATLAS are giving significant contributions to beauty and quarkonium sectors, mainly using final states containing muon pairs (trigger constraints)
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  - Precision measurements of rare decays & CP violation are sensitive to effects of particles beyond SM that may contribute to quantum loops (even with masses too large to be produced/detected @ LHC) : look for indirect evidence or constraints to NP [*B* meson decays mediated by FCNC transitions suitable].
  - Production xsection and polarization measurements of *S*- & *P*-wave states of conventional quarkonium allow to study the hadron formation within the NRQCD framework.
  - Test of perturbative & non-perturbative QCD models for B hadrons production/fragmentation. Study dynamics of heavy quarks inside hadrons, decay models and spectroscopy. Also possible to study/search for some quarkonium-like exotic states.

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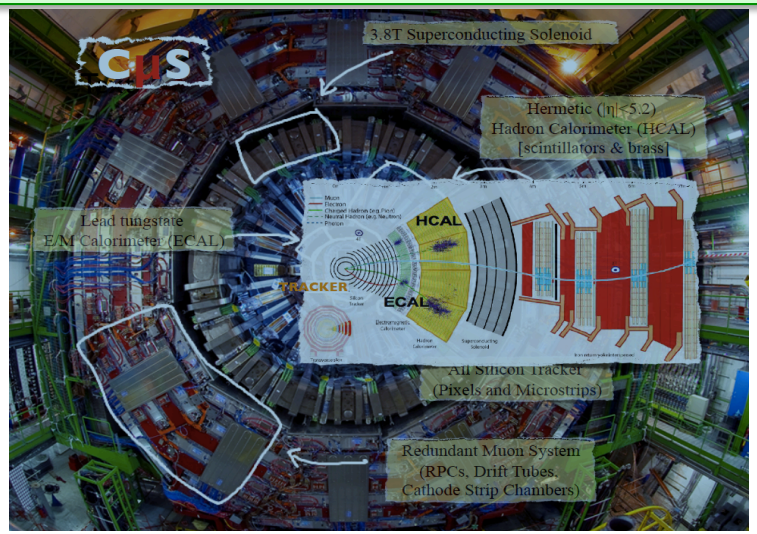
- All that is possible thanks to the excellent tracking and muon identification performance, combined with a flexible trigger system.

Compact Di-Muon Solenoid – μ reconstruction



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 identification : $\begin{cases} \varepsilon(\mu \mid \pi) \leq (0.05 \div 0.13)\% \ , \ \varepsilon(\mu \mid K) \leq (0.08 \div 0.22)\% \\ \varepsilon(\mu \mid p) \leq (0.04 \div 0.15)\% \end{cases}$
  [fake rates estimated in MC and data (K_s, D^*, Λ)]

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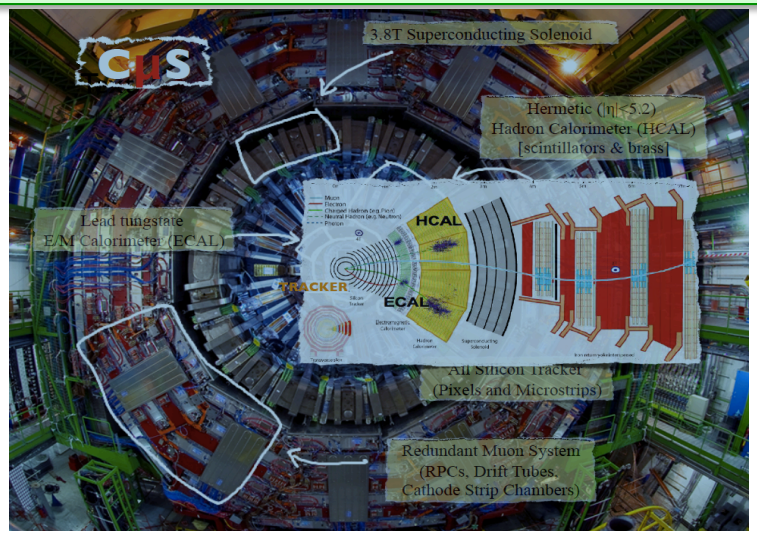

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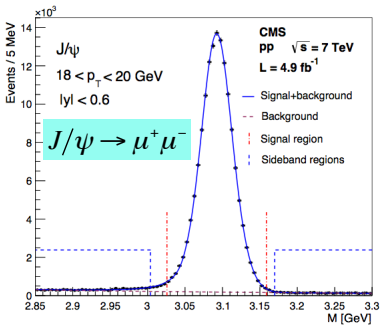
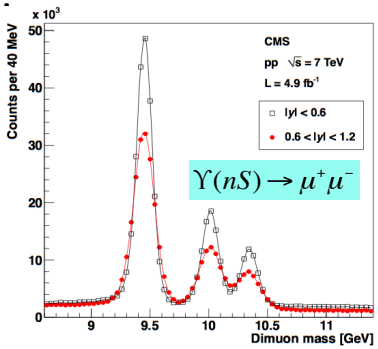
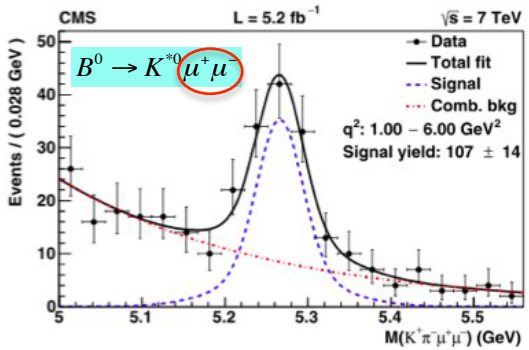
- **Di-muons provide a clean signature & are easier to be reconstructed and triggered on !**
  All shown results here involve dimuons …

… with definite invariant mass





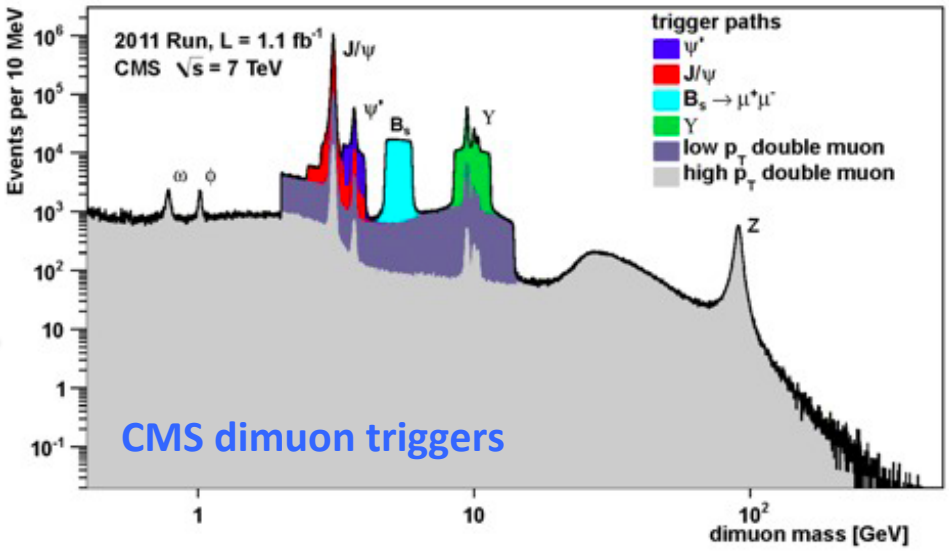
… or not



Compact Di-Muon Solenoid - triggers

Trigger system

Flexible triggers are essential to collect data @ increasing luminosity (and pile-up).
Flavour physics analyses rely on displaced (or inclusive) quarkonium (J/ψ, ψ', $\Upsilon(nS)$), $B_{(s)}$ & non-resonant dimuon triggers:



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

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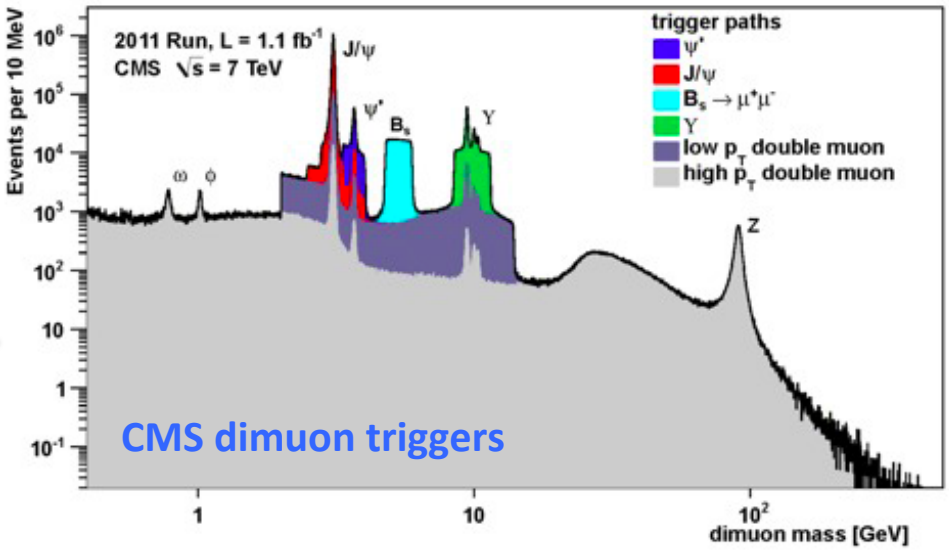

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Data samples:
- $\sqrt{s} = 7$ TeV , $\mathcal{L} = 5$ fb^{-1} (2011 run)
- $\sqrt{s} = 8$ TeV , $\mathcal{L} = 20$ fb^{-1} (2012 run)

Trigger strategy for Run-II being defined in view of higher luminosities and pile-up: work-in-progress (to stay within 100Hz of bandwidth @ $L_{int}=1.4\ 10^{34} cm^{-2}s^{-1}$) is crucial for the capability of carrying out flavour physics in Run-II !
The possibility of Data Parking (delayed reconstruction) is under discussion.

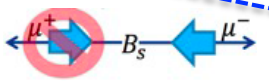
Outline

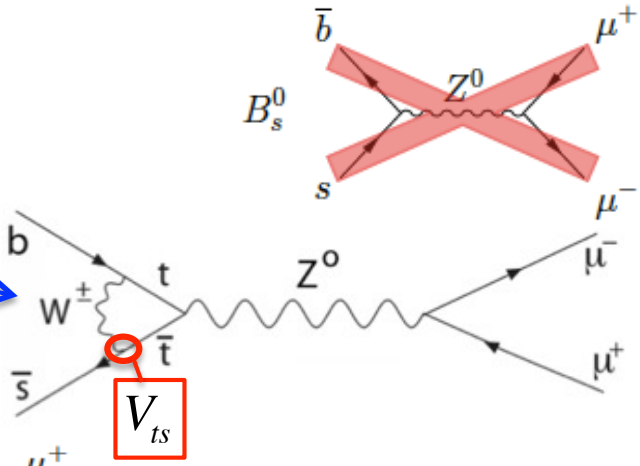
- Here the following analyses will be reviewed :
  - $B_{s(d)} \to \mu^+\mu^-$
  - $B^0 \to K^{*0}\mu^+\mu^-$
  - $B_s^0 \to J/\psi\,\phi$
  - $J/\psi,\ \psi(2S),\ \Upsilon(nS)_{n=1,2,3}$ production Xsections & polarizations
  - Exotic quarkonia : *X(3872), Y(4140)*

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

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 $|V_{ts(td)}|^2$





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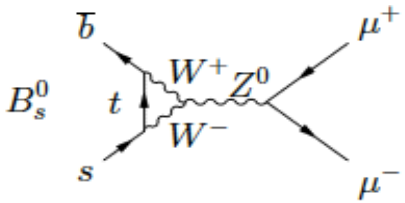

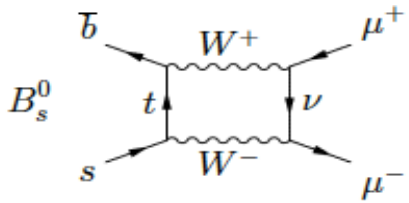

... and BF are reliably calculated [**Bobeth et al., PRL 112 (2014) 101801**] to be:
(suppression of B_d over B_s in SM given by $\sim(|V_{td}|/|V_{ts}|)^2$)

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

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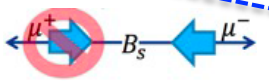

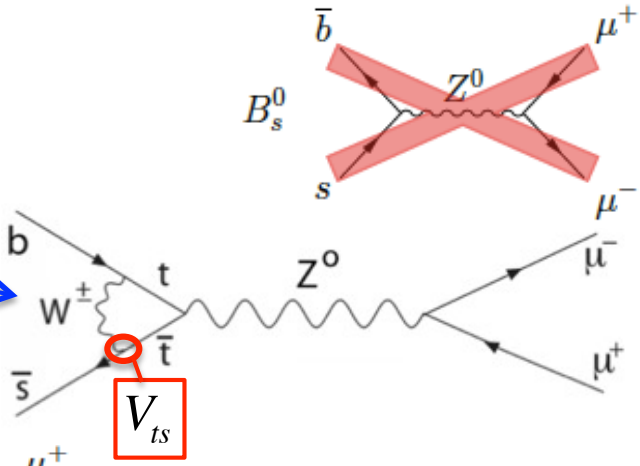

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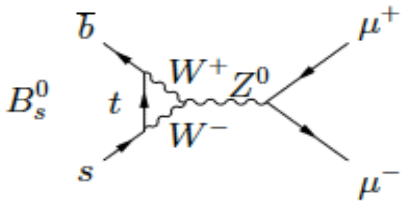

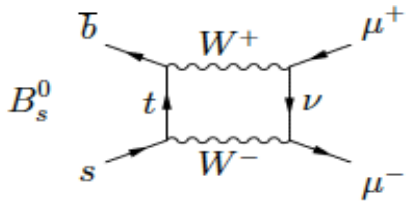

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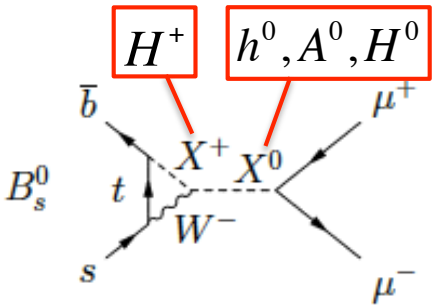
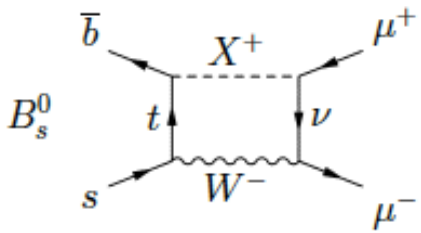
  NP scenarios in the extended Higgs sector may enhance or suppress decay rates w.r.t SM (and would show different *tanβ* dependence).





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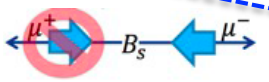

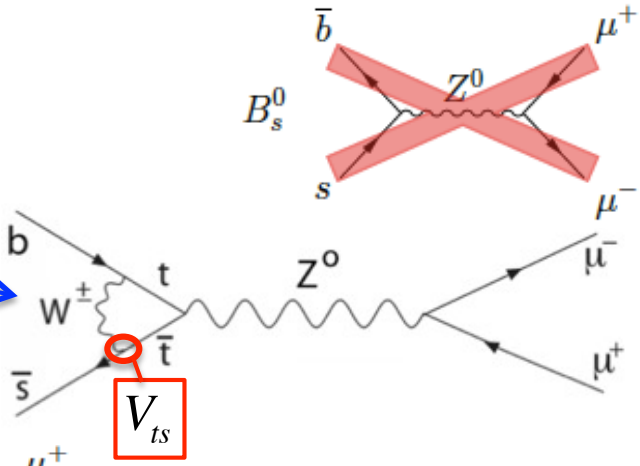

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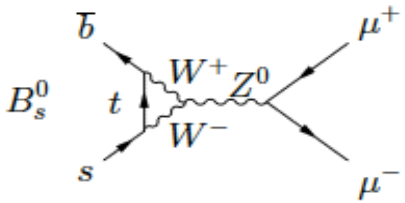

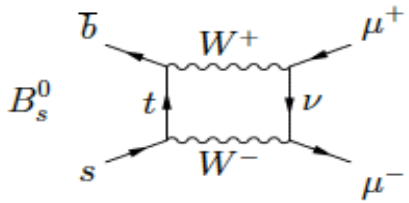

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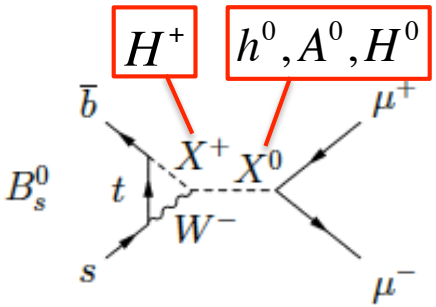
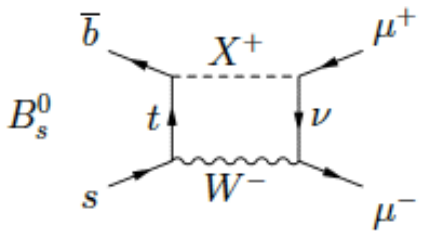




- The ratio of BF provides powerful discrimination among BSM theories.
  Those with the property of Minimal Flavour Violation predict the same value as the SM.

[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 :

$$\mathbf{B}(B^0_s \to \mu^+\mu^-) = \frac{Y_S}{Y_N} \cdot \frac{\varepsilon_N}{\varepsilon_S} \cdot \frac{f_u}{f_s} \cdot \underbrace{\mathbf{B}(B^+ \to K^+ J/\psi \to K^+\mu^+\mu^-)}_{=(6.0\pm0.2)\cdot10^{-5}} \quad \text{where} \quad \frac{\varepsilon_N}{\varepsilon_S} = \frac{\varepsilon^{sel}_{B^+}}{\varepsilon^{sel}_{B^0_s}} \cdot \frac{\varepsilon^{\mu ID}_{B^+}}{\varepsilon^{\mu ID}_{B^0_s}} \cdot \frac{\varepsilon^{trig}_{B^+}}{\varepsilon^{trig}_{B^0_s}}$$

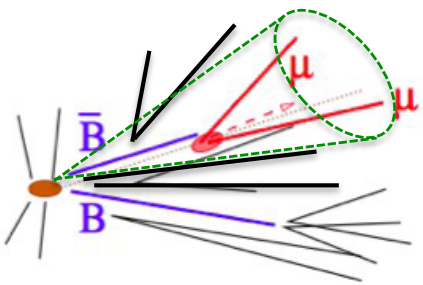
Ratio of Signal & Normalization Yields

Ratio of Normalization & Signal Efficiencies

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

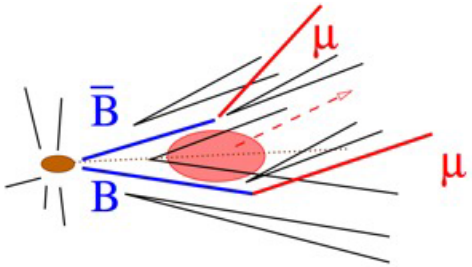
- This normalization sample allows: 1) to avoid uncertainties from b production xsection and luminosity
  2) to set nearly identical selections to reduce efficiency systematics
- Choose $B^0_s \to J/\psi\phi$ as control channel to calibrate and validate simulation
- SIGNAL characteristics

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]

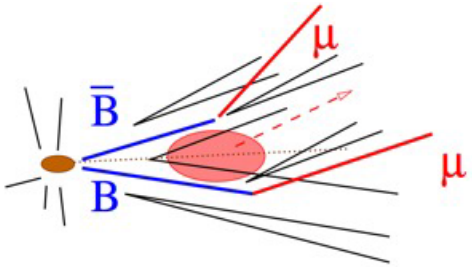
- Two semileptonic B/D decays
- One semileptonic B decay & one mis-identified hadron

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

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

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

- **BKG characteristics**



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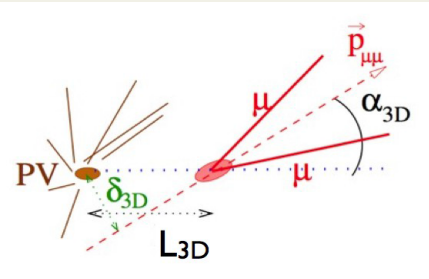
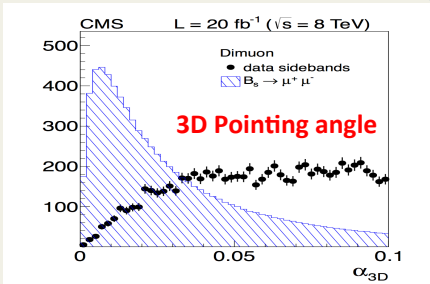
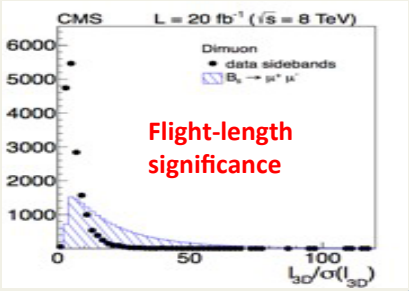
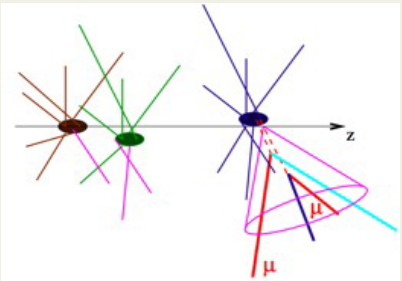
- Events selected by means of a BDT (Root TMVA) exploiting kinematic, vertexing & isolation variables (12)

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



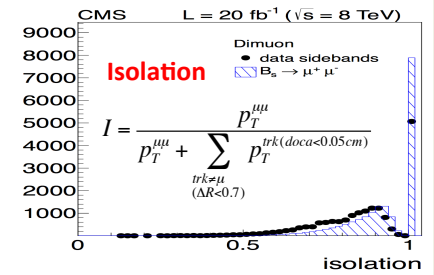


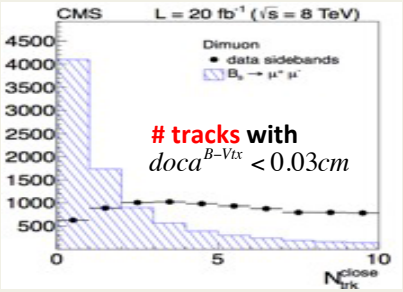




$p_T(\vec{B}) \Rightarrow$ **cone's axis**

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





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

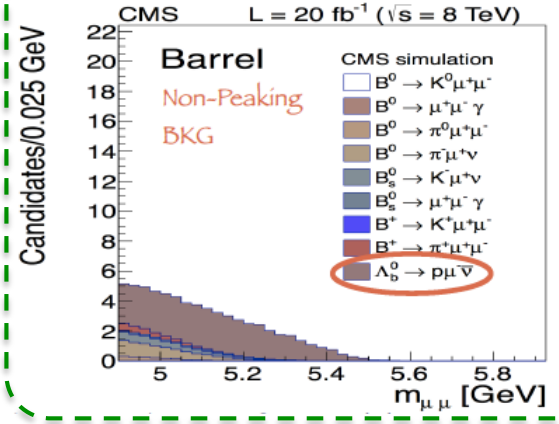
- Extract signal/BKG yields from an UML fit to $m(\mu\mu)$ simultaneously for the 12 BDT categories

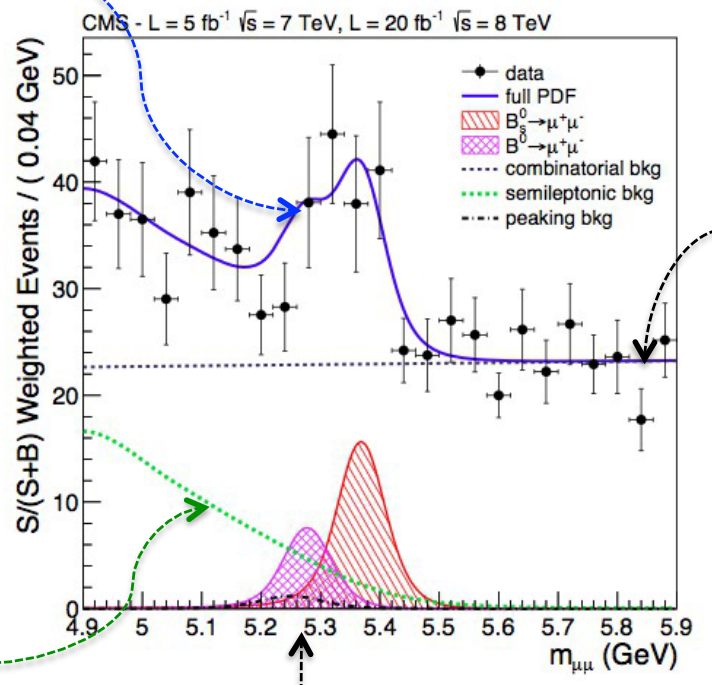
B_s & B_d signals

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

Rare non-peaking BKG

[fixed shape, constrained normalization]



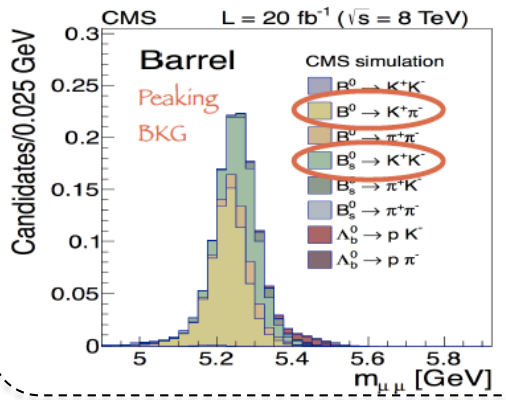


Combinatorial BKG

[first-degree polynomial]

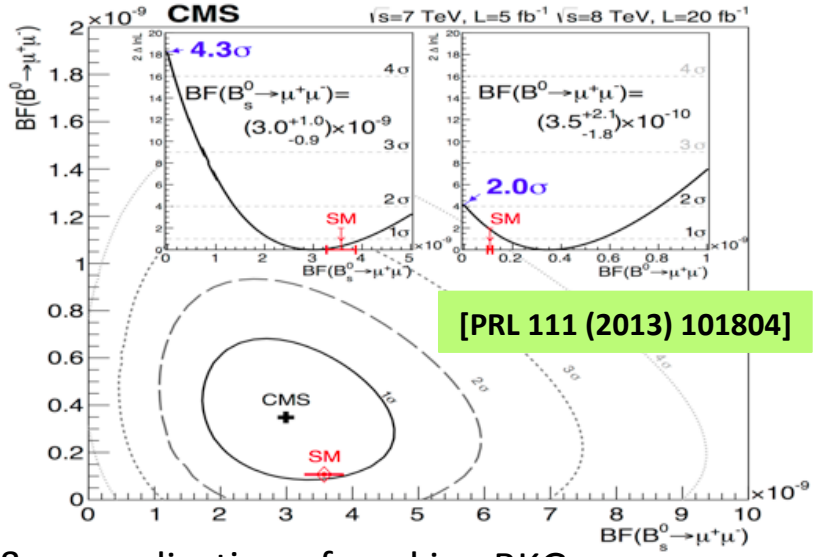
Rare peaking BKG

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



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

- CMS results with full Run-I dataset (25 fb^{-1}) are:
  - statistically dominated
  - consistent with SM expectations
  - $\mathbf{B}(B^0_s \to \mu^+\mu^-) = \left(3.0^{+0.9}_{-0.8}(\text{stat})\ ^{+0.6}_{-0.4}(\text{syst})\right)\cdot 10^{-9}\,(4.3\sigma\ \text{signif.})$ **[UML fit – categ.BDT]**
  - $\mathbf{B}(B^0 \to \mu^+\mu^-) = \left(3.5^{+2.1}_{-1.8}(\text{stat+syst})\right)\cdot 10^{-10}\,(2.0\sigma\ \text{signif.})$
  - $\mathbf{B}(B^0 \to \mu^+\mu^-) < 1.1\cdot 10^{-9}\ @95\%\text{CL}$ **[CLs method – 1D BDT]**



[PRL 111 (2013) 101804]

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

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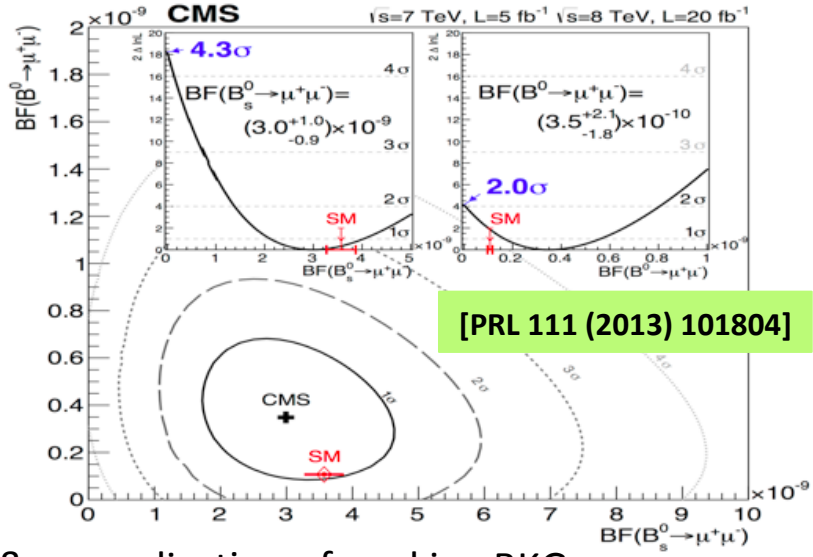

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Main systematics μ-misID, BF of rare BKG decays ($\Lambda^0_b \to p\mu\bar{\nu}$) & normalization of peaking BKG

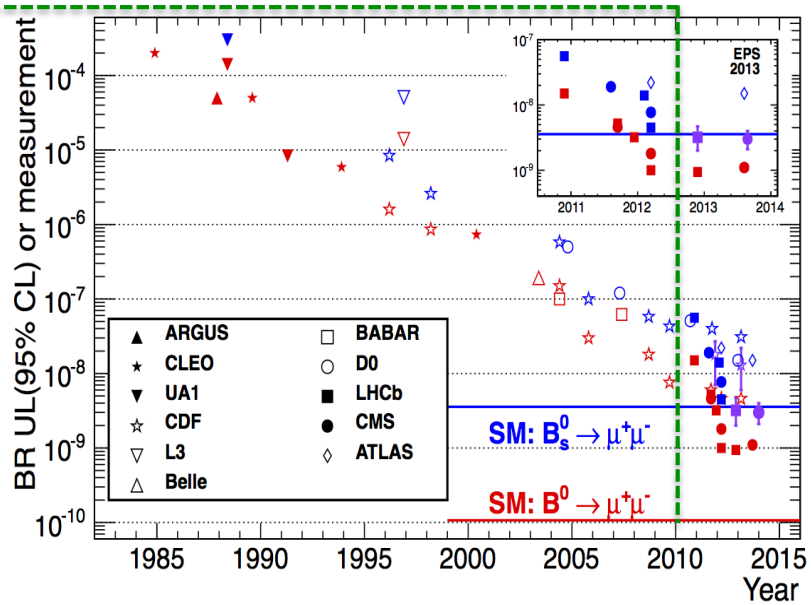
- A long journey ... (only upper limits in pre-LHC era)

Other LHC experiments :

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

  [PRL 111 (2013) 101805]

Combination with CMS to get observation !



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

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

[CMS-BPH-13-007, LHCb-PAPER-2014-220]

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

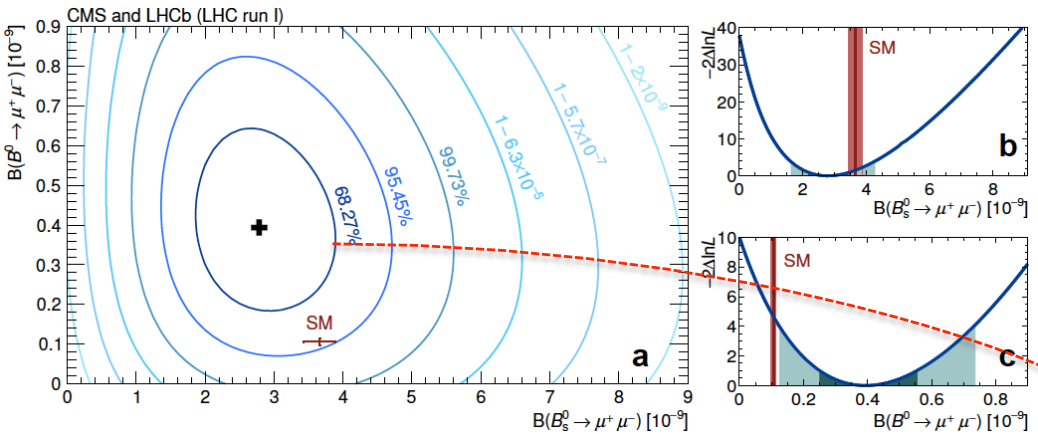
(6.2σ significance)

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

(3.0σ significance)

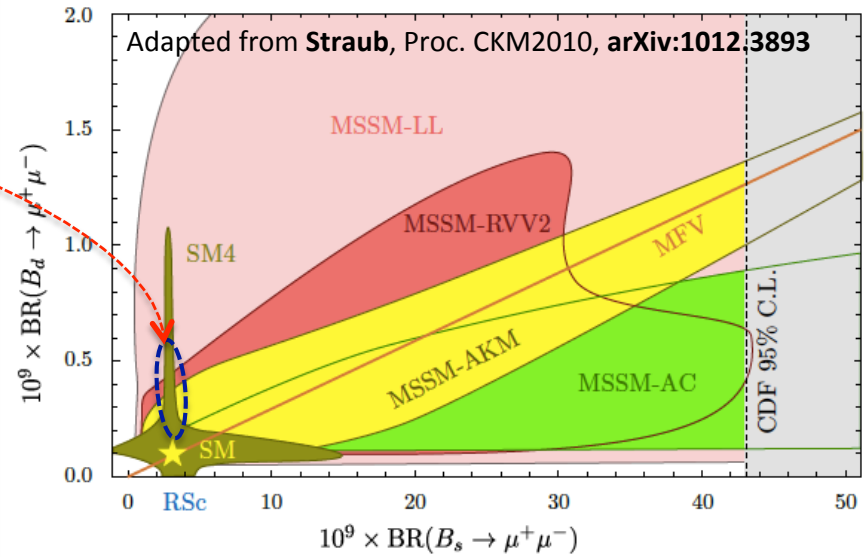
[Feldman-Cousins]

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 coeff.



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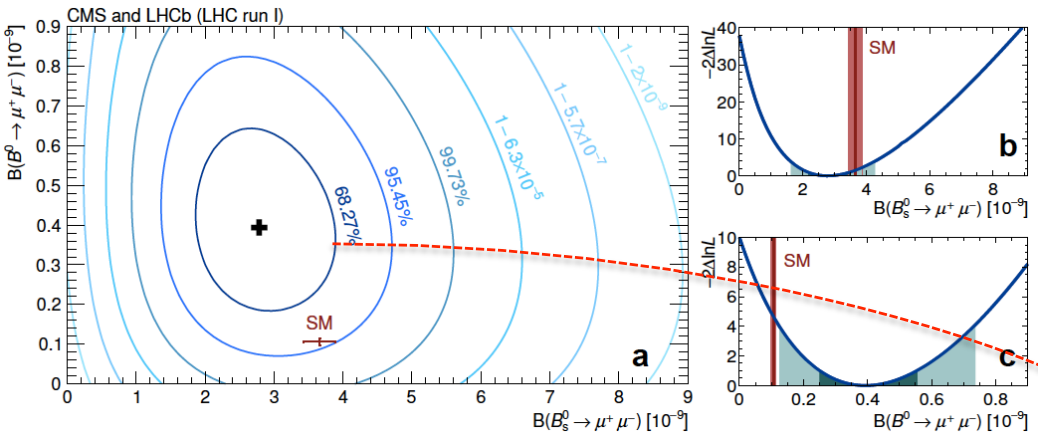

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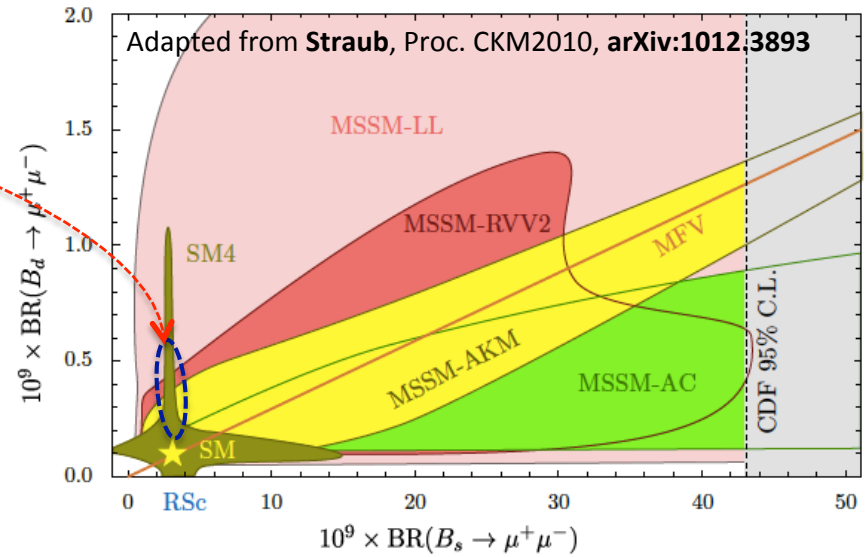
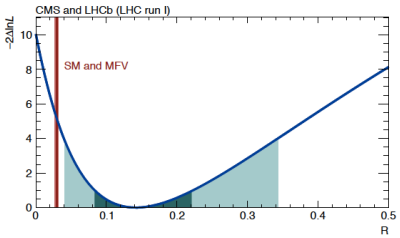


The ratio of BF is very sensitive probe of NP:

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

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}) :

the relative error on R will go from 100% to 70% still statistically limited (TH error already at 5% !)

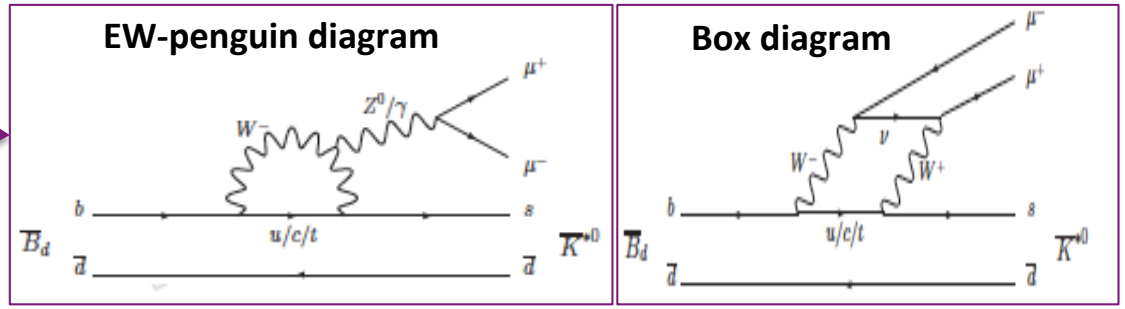
More projections @ talk by M.Galanti

[Isidori @ ECFA-2014]

$B^0 \to K^{*0}\mu^+\mu^-$

Rare *B* decays as New Physics probes : $B^0 \to K^{*0}\mu^+\mu^-$

- The $B^0 \to K^{*0}\mu^+\mu^-$ quasi-rare decay proceeds via FCNC process (forbidden @ tree-level: $BR_{SM} \sim 10^{-6}$); it is sensitive to NP effects in photon, vector & axial-vector couplings.



Its sensitivity to NP is complementary to that of $B_{s(d)} \to \mu^+\mu^-$
[for which NP could enter the observables via the Wilson coefficients of the (pseudo-)scalar & axial-vector operators in the effective Hamiltonian]

Operator $\mathcal{O}_i^{(\prime)}$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$
$\mathcal{O}_7$: Photon	✓	
$\mathcal{O}_9$: Vector	✓	
$\mathcal{O}_{10}$: Axial-Vector	✓	✓
$\mathcal{O}_{S,P}$: (Pseudo)-Scalar	(✓)	✓

Petridis, talk @ Moriond QCD-2014

- Amplitudes expressed using OPE in terms of:
  - Hadronic Form Factors (long-distance) [accuracy ~20%] [**Barucha *et al.*, arXiv:1004.3249**]
  - Wilson coefficients C_7^{eff}, C_9^{eff}, C_{10}^{eff} (short-distance) [**Ali *et al.*, PRD 61, 074024; Z.Phys.C67, 417**]

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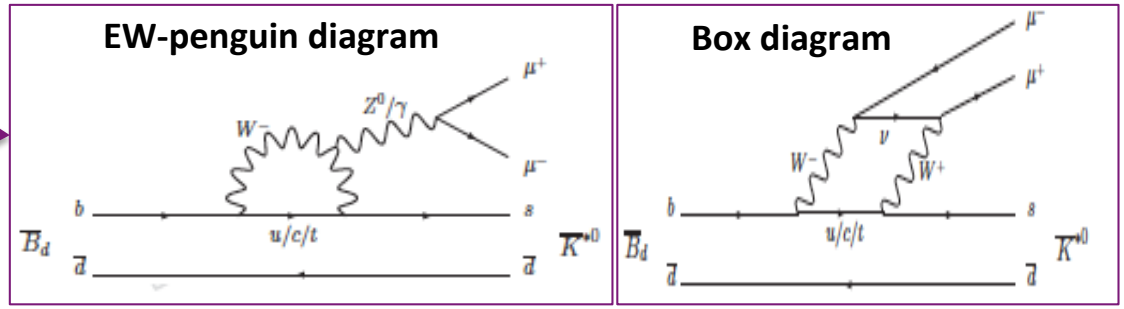

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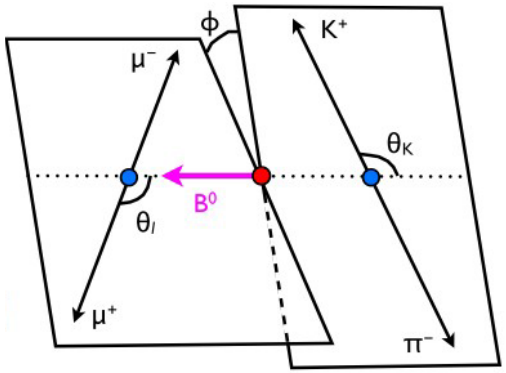
  (robust theoretical calculations)

- Decay kinematics determined by 3 angular observables :

  θ_K : helicity angle of the K^{*0} candidate

  θ_ℓ : helicity angle for the dimuon system

  ϕ : angle between two decay planes (integrated out in current analysis)



$B^0 \to K^{*0}\mu^+\mu^-$: analysis strategy

F_S, A_S are for S-wave contribution

- Differential amplitude (angular distribution): $\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K\, d\cos\theta_L\, dq^2} = \frac{9}{16}\left\{\left[\frac{2}{3}F_S + \frac{4}{3}A_S\cos\theta_K\right](1-\cos^2\theta_L) + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_L) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_L) + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_L\right]\right\}$

  - physics parameters:
    - A_{FB} : forward-backward muons asymmetry
    - F_L : fraction of longitudinally polarized K^{*0}
    - F_S : fraction of spinless $K\pi$ (S-wave) [not from K^{*0} (P-wave)];
    - A_S : interference amplitude between S- and P-wave decays

    from fit using $B^0 \to K^{*0} J/\psi$

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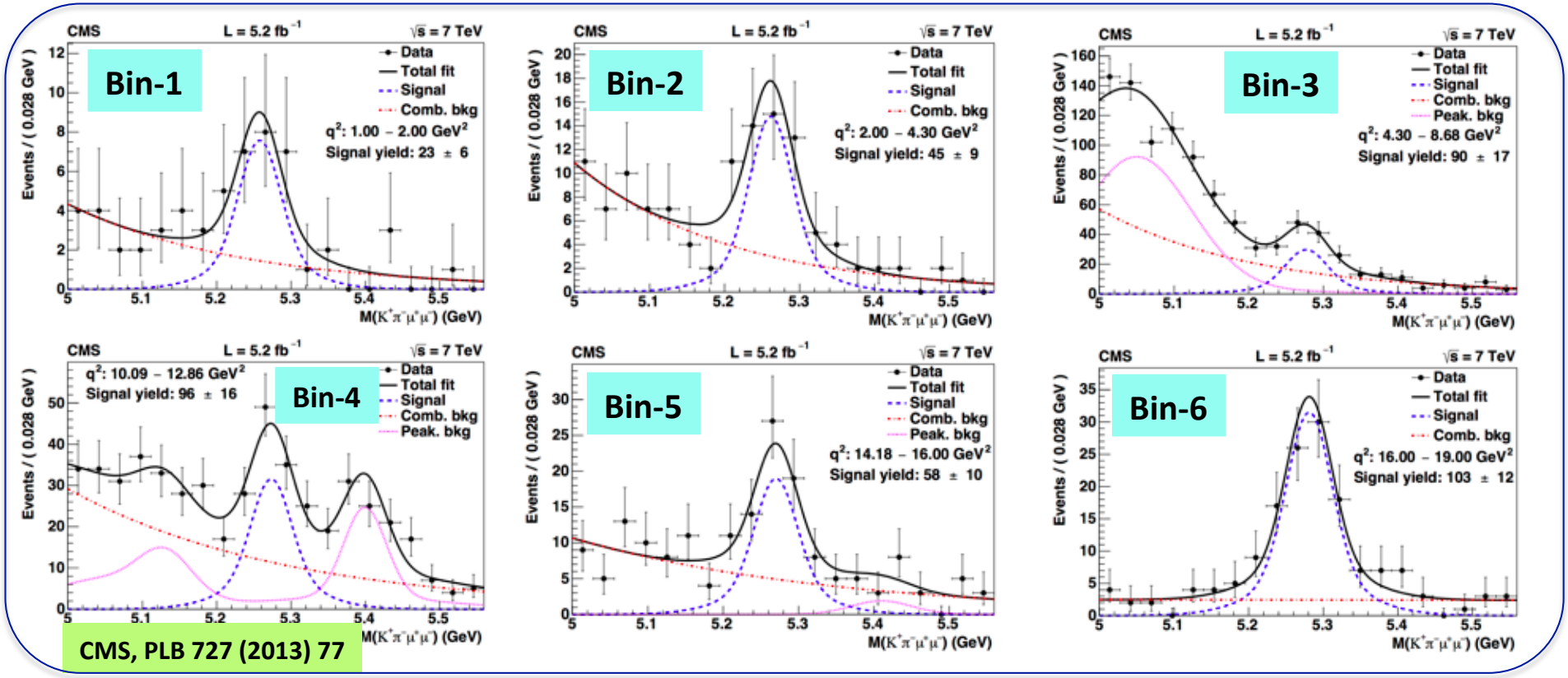
- Strategy: 1) B flavour assignment from $K\pi$ charge (charge comb. with closest $m(K\pi)$ to K^{*0}) [8% mistag]
  (why? angular observables behave oppositely for each CP-state)
  2) candidates yields divided in q^2 bins [$q^2 \equiv m^2(\mu^+\mu^-)$](removing $B^0 \to K^{*0}(J/\psi, \psi')$ regions)
  3) measure candidates yield Y_S , A_{FB} and F_L from an UML simultaneous fit to $m(K\pi\mu\mu)$, $\cos(\theta_K)$, $\cos(\theta_\ell)$
  3a) BKG parametrized from MC: combinatorial +peaking ($B^0 \to K^{*0}(J/\psi, \psi')$)]

$B^0 \to K^{*0}\mu^+\mu^-$: angular analysis



- Differential branching fraction (obtained relatively to the normalization mode $B^0 \to K^{*0} J/\psi$):

$$\frac{d\mathbf{B}(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{Y_S}{Y_N} \cdot \frac{\varepsilon_N}{\varepsilon_S} \cdot \mathbf{B}(B^0 \to K^{*0} J/\psi) \quad \text{where} \left\{ \begin{array}{l} Y_S,\ Y_N \\ \varepsilon_S,\ \varepsilon_N \end{array} \right. \quad \text{Signal \& Normalization} \left\{ \begin{array}{l} \text{yields} \\ \text{efficiencies} \end{array} \right.$$

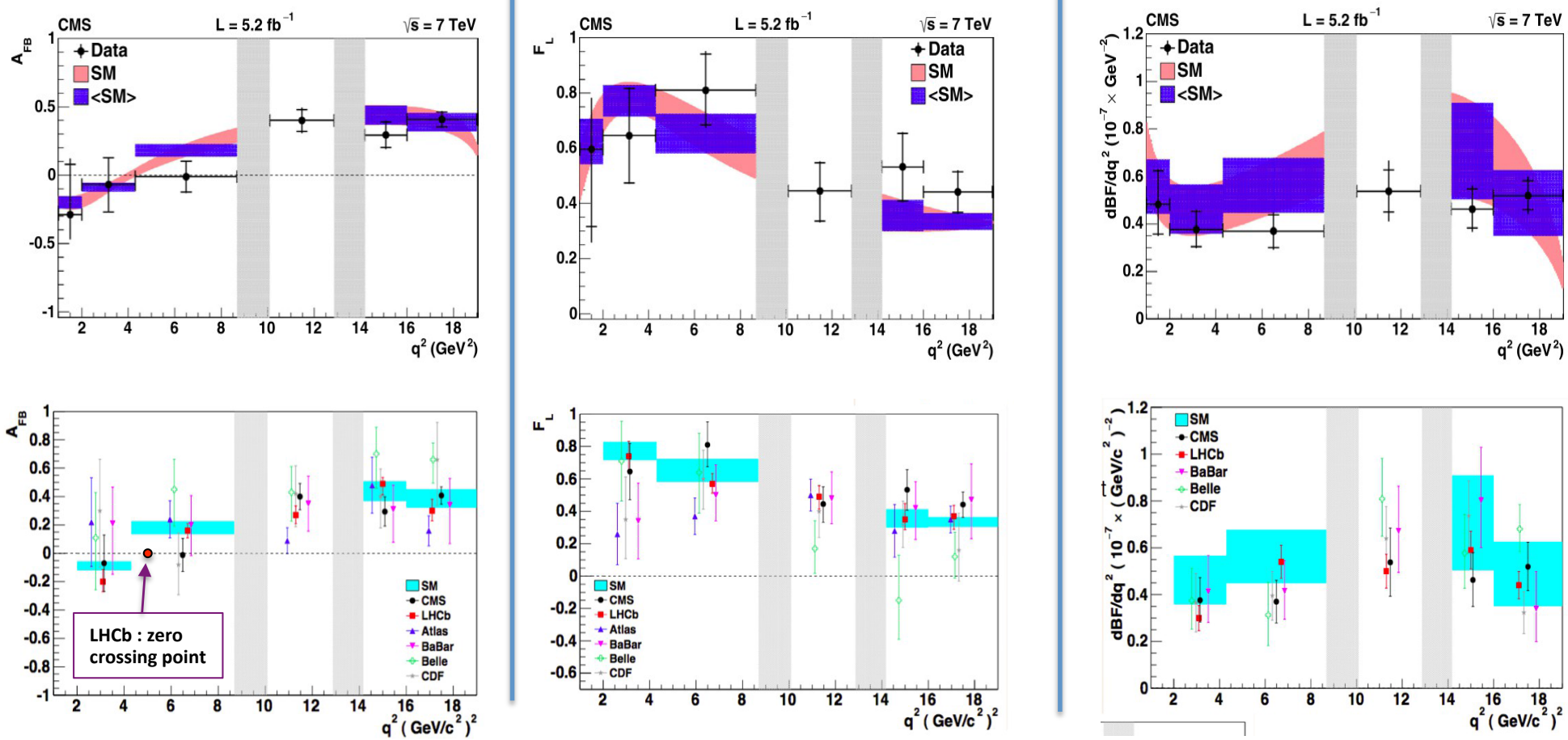
- Systematics' sources: fit strategy, efficiencies, BKG shapes, S-wave contribution

$B^0 \to K^{*0}\mu^+\mu^-$: angular analysis results ($\sqrt{s} = 7TeV$)

- Results consistent with SM predictions (theor. & exp. errors comparable size) and other measurements

- Measurement of A_{FB} and F_L with good/competitive precision at high q^2
  (validation: they are compatible with world averages for $B^0 \to K^{*0}(J/\psi, \psi')$ decays)

A_{FB} | F_L | dBF/dq^2



$B^0 \to K^{*0}\mu^+\mu^-$: what next from CMS ?

- LHCb [**JHEP 1308, 131 (201?)**] measured the position [$q_0^2 = 4.9 \pm 0.9\ GeV^2$] of the A_{FB} zero-crossing point (theoretically clean) in agreement with SM [**Ali *et al.*, EPJ C47 (2006) 625**]

- Additional variables rather free from Form-Factor contributions proposed [**Descotes-Genon *et al.*, JHEP 05,137 (2013)**]

- CMS analysis updated with 2012 data is expected soon :

  - will contain: A_{FB} , F_L , dB/dq^2 & A_{FB} zero crossing point

  Instead CMS will use new angular variables with small Form-Factor dependence (like LHCb) only in a later re-analysis. Analysis to be repeated with Run-II data.

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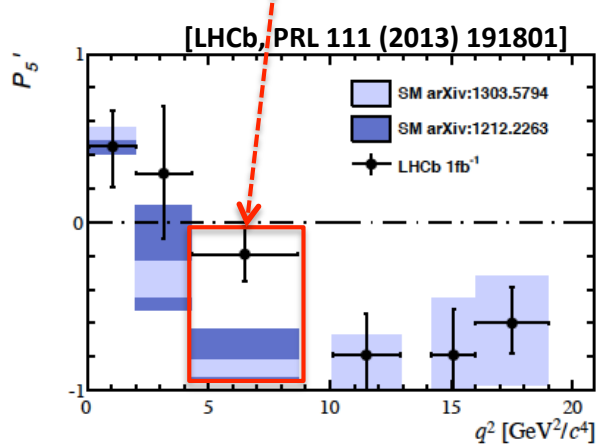
- CMS can make an effort to study similar differential BFs: $B^0 \to K^0\mu^+\mu^-$ (likely $B^+ \to K^+\mu^+\mu^-$) [already studied by LHCb, motivated by a tension (3.7σ discrepancy) in P'_5 in a specific q^2 bin, possibly interpretable as a NP contribution to Wilson coeff. C_9].

  This tension needs to be confirmed by LHCb with the full Run-I data; it would also imply a suppression of inclusive BR($B \to X_S \ell^+\ell^-$) recently not confirmed by BaBar [**PRL 112 (2014) 211802**]

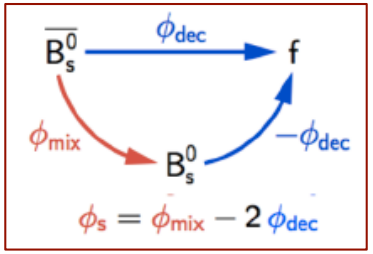


- The analysis $B^0 \to \phi\mu^+\mu^-$ is likely to be carried out in the future (likely on Run-II data).

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

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

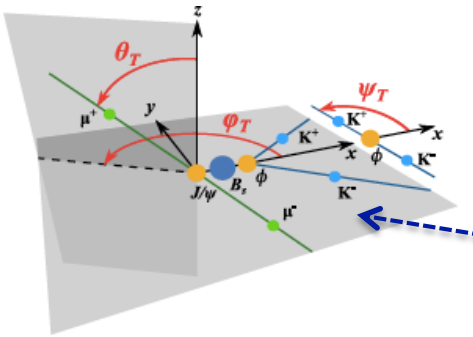
- B_s mesons mix via box diagrams [with relatively large decay width difference $\Delta\Gamma_S$ between the mass eigenstates]



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

Theoretically clean decay mode: tiny CPV ruled by $\phi_S^{SM} \approx -2\beta_S = -0.0363^{+0.0016}_{-0.0015} rad$ $[\beta_S = \arg(-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*)]$ **[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 eigenstate
… to be disentangled by angular analysis

Angular distribution is defined in the transversity base
Definition of the set of 3 angles $\Theta = (\theta_T, \psi_T, \varphi_T)$

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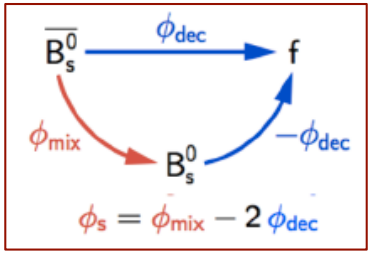

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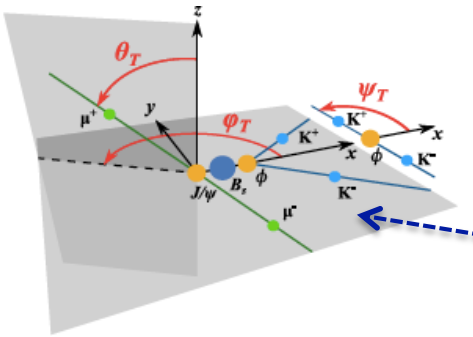
- 

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

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

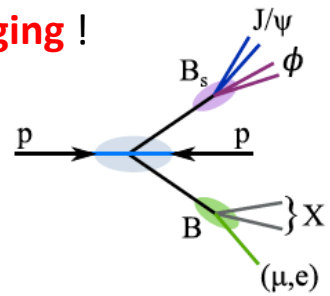
Time-dependent functions | Angular-dependent functions

where:
- $\Theta,\ t$: measured angles & B_s^0 proper decay time
- α : physics param. of interest: $\phi_S, \Delta\Gamma_S, c\tau; |A_0|^2, |A_S|^2, |A_\perp|^2; \delta_\parallel, \delta_\perp, \delta_{S\perp}$
- $O_i(\alpha,t) = N_i e^{-t/\tau}[a_i \cdot \cosh(1/2\Delta\Gamma_S ct) + b_i \cdot \sinh(1/2\Delta\Gamma_S ct) + c_i \cdot \cos(\Delta m_S t) + d_i \cdot \sin(\Delta m_S t)]$

  - the parameters b_i & d_i contain the contribution from ϕ_S
  - $\overline{B}_s^0$ decay described by switching sign of c_i & d_i

$B_s^0 \to J/\psi\phi$: 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 ± 0.2
$\mathcal{P}_{tag}$	$0.68 \pm 0.03 \pm 0.05$	$0.30 \pm 0.02 \pm 0.04$	0.97 ± 0.04

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

  - PDF modified to include tagging info in $\boldsymbol{c_i}$ & $\boldsymbol{d_i}$

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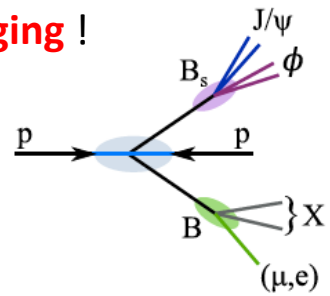

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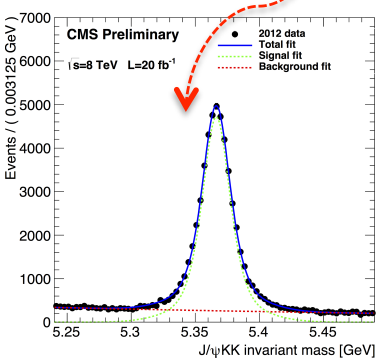
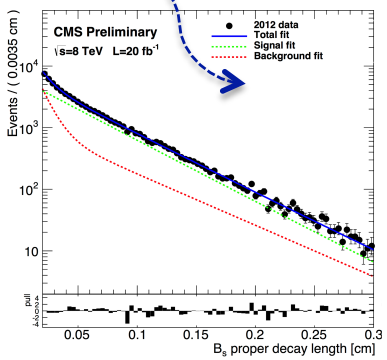
- Ext. UML fit used to extract the physics param. α by including :
  - 3 angles Θ
  - invariant mass ... of B_s^0 candidate
  - proper decay length *ct*

  - 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)
  - $|\lambda|$ include 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: $\begin{cases} \phi_S = (-0.03 \pm 0.11 \pm 0.03)rad \\ \Delta\Gamma_S = (0.096 \pm 0.014 \pm 0.07)ps^{-1} \end{cases}$

CMS-PAS-BPH-13-012

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
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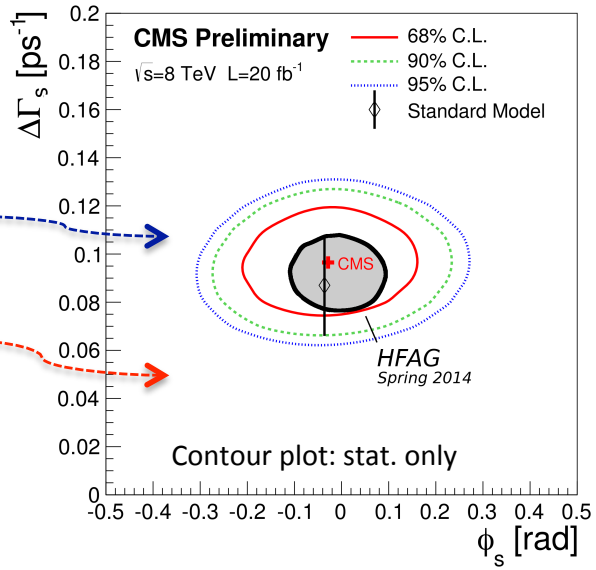

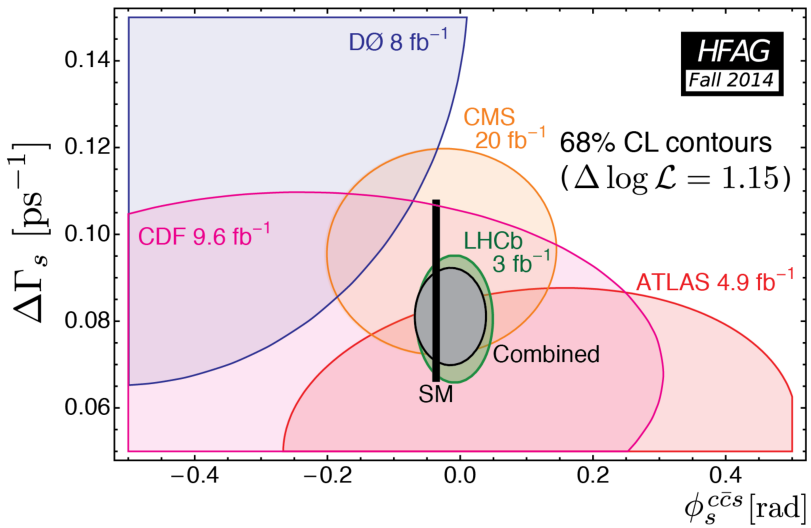

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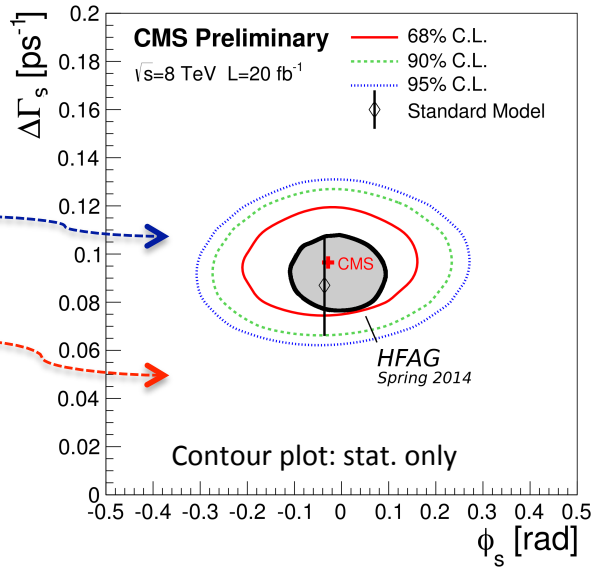

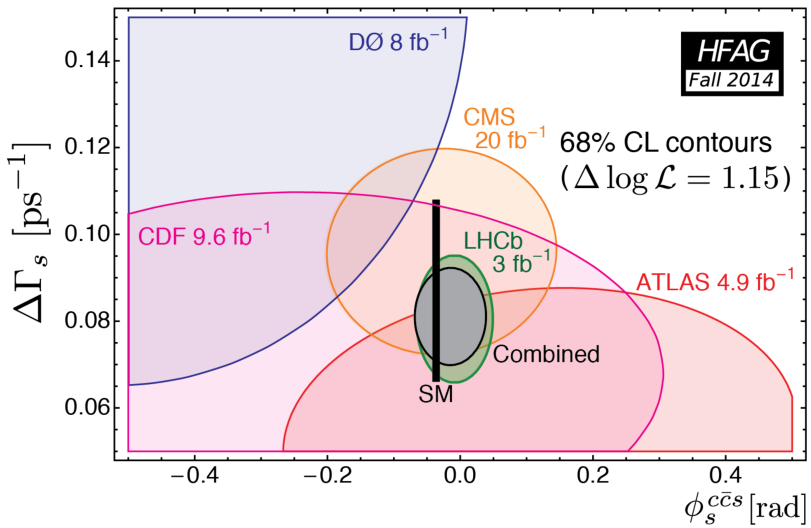

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- Final results will be released soon and will include:
  - usage of an improved lepton tagger (MVA tool)
  - study of the bkg channel $\Lambda_b \to J/\psi Kp$
  - better description/treatment of *S*-wave component

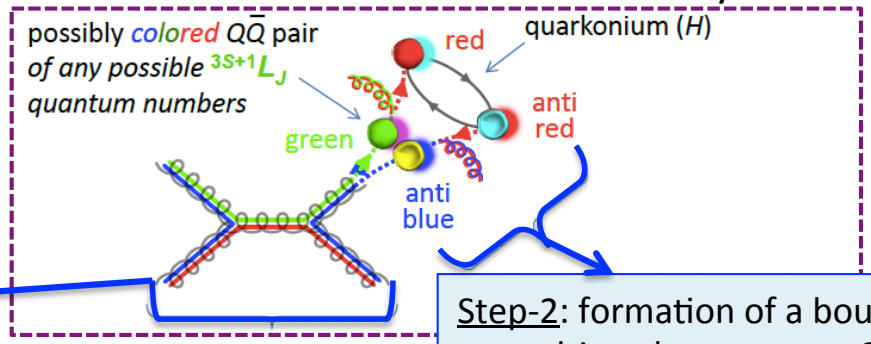
- Possible future analysis with $B_s^0 \to J/\psi f_0$ decays: CP-odd final state
  ⇨ no need for angular analysis

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

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

NRQCD factorization framework

Sketch by P.Faccioli



- **NRQCD** : effective field theory that treats heavy quarkonia as non-relativistic systems

The heavy-Q mass >> Λ_{QCD} ⇨ 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 :

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

Short-distance coefficients (SDCs)

Long-distance matrix elements (LDMEs)

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

calculated perturbatively as expansions in α_S

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

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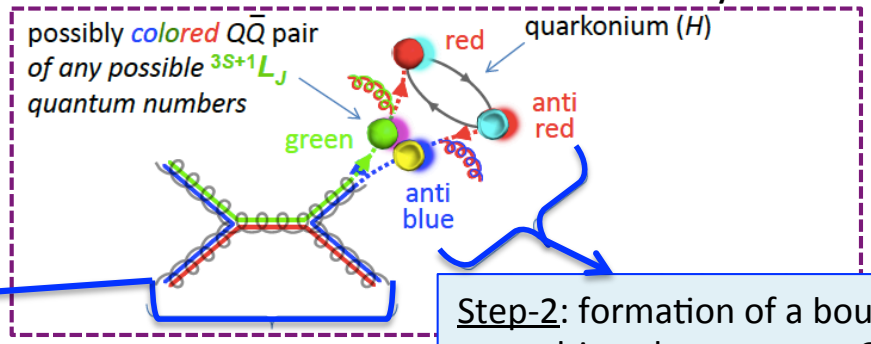

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- Theoretical predictions are organized as double expansions in α_S and v.
  Truncation of v-expansion for *S-wave* states in NRQCD includes 4 terms:
  - the Color Singlet (CS) term: ${}^3S_1^{[1]}$
  - 3 Color Octet (CO) terms: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_{J=0,1,2}^{[8]}$

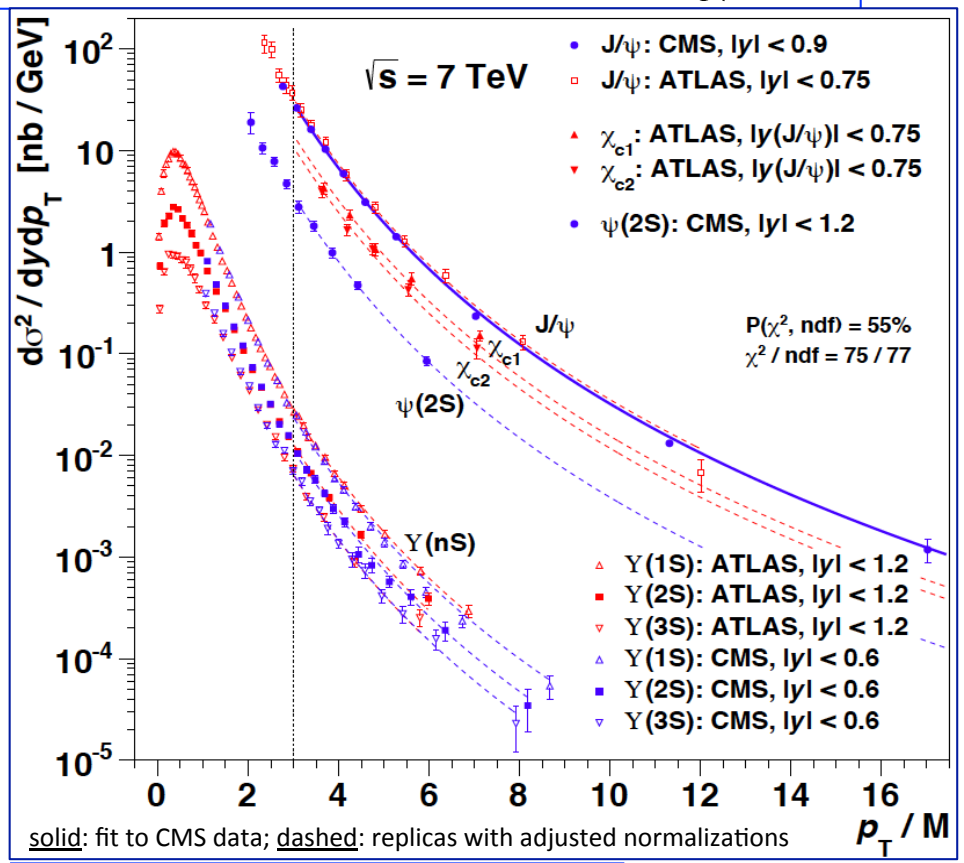
- Color singlet assumption: initial $Q\bar{Q}$ & final ***H*** (${}^3S_1$) have same quantum numbers!

- 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.

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.



solid: fit to CMS data; dashed: replicas with adjusted normalizations

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

CMS, JHEP 02, 011 (2012)

CMS, PLB 727, 101 (2013)

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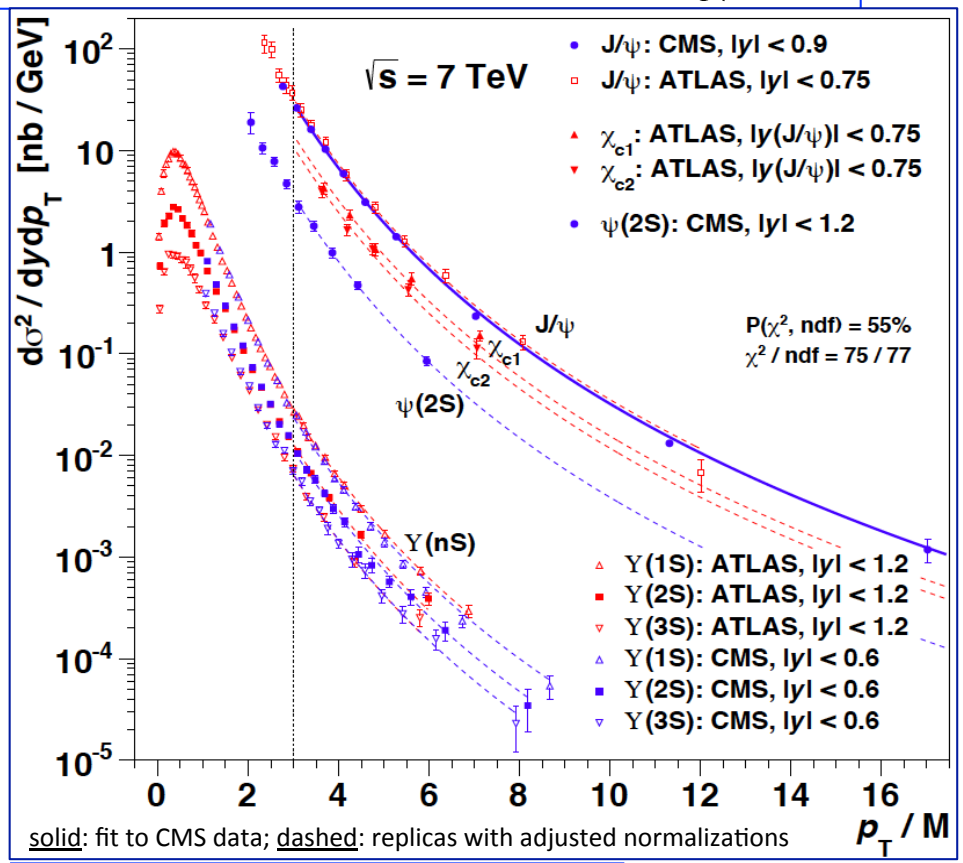
CS processes must be negligible!
A single CO term dominates production!
It could be $^1S_0^{[8]}$ **IF** the NRQCD fit would start @ 10-15*GeV* **[Faccioli et al.,PLB 736 (2014) 98]**



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Scaling behaviour must be confirmed with:

- more accurate data up to higher p_T
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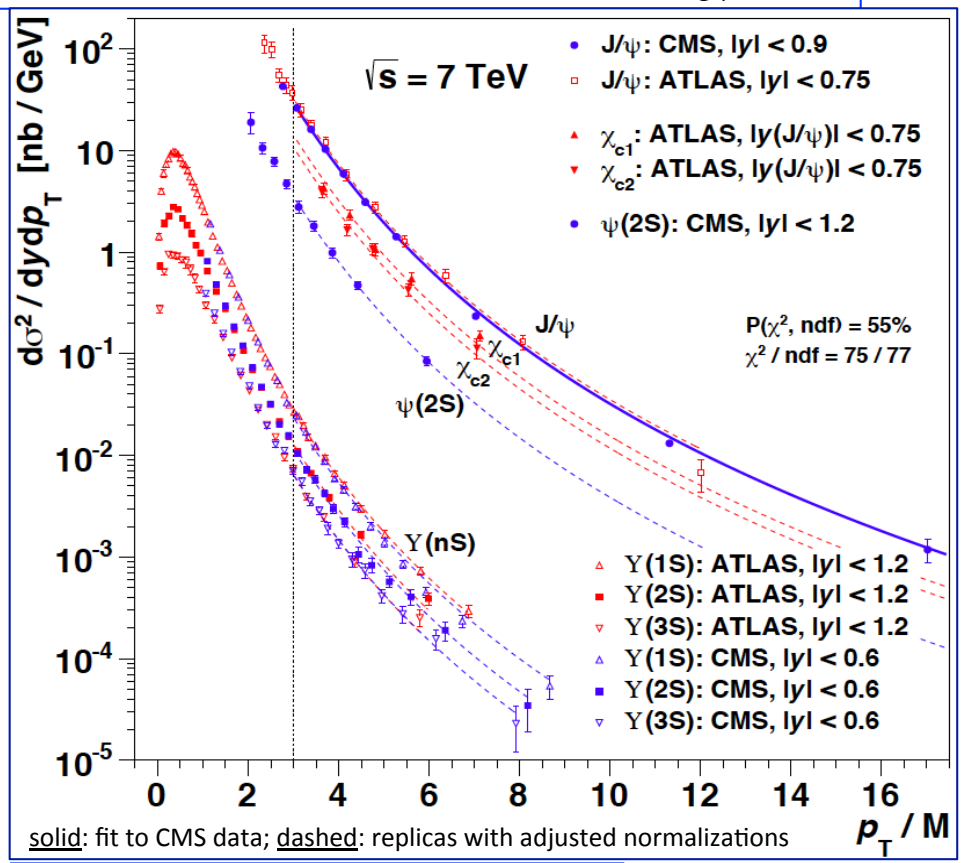

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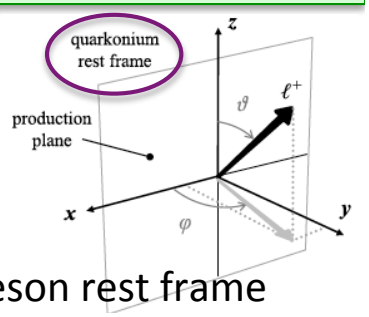
- Run-II can be a great opportunity to explore higher p_T regions with better accuracy. Right now CMS has not used 2012 data yet! Very soon new prod. xsections results - with full 2011 data - will be released extending p_T-range to 120*GeV* for J/ψ and 100*GeV* for $\psi(2S)$ and $\Upsilon(nS)_{n=1,2,3}$.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

Polarization of S-wave states

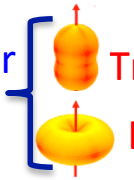


- The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions. The most general 2D angular distribution W for the dileptons is specified by 3 polarization parameters $\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}$:

$$W \equiv \frac{d^2\mathrm{N}}{d(\cos\theta)d\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$ 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]
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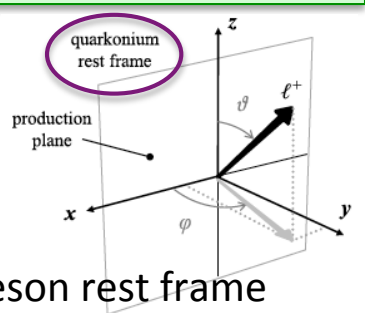

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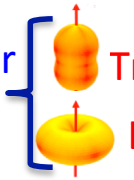

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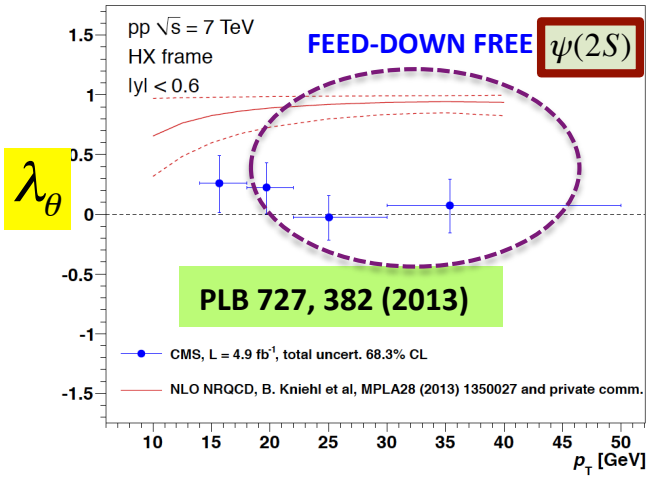
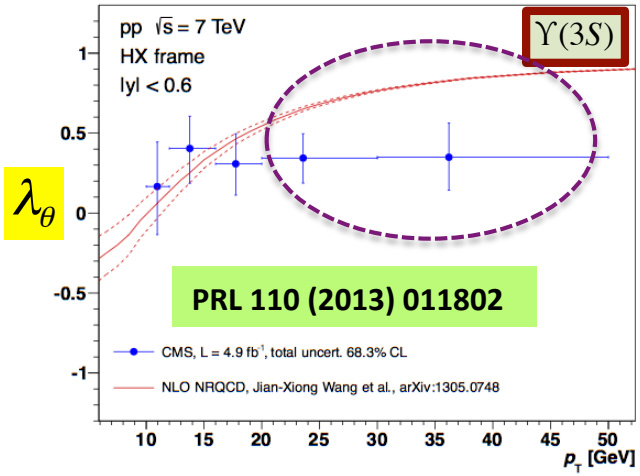
- All LHC results compatible with each other: the polarizations cluster around the unpolarized limit
Thus the dominant production mechanism must be CO ${}^1S_0^{[8]}$ $(\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0)$

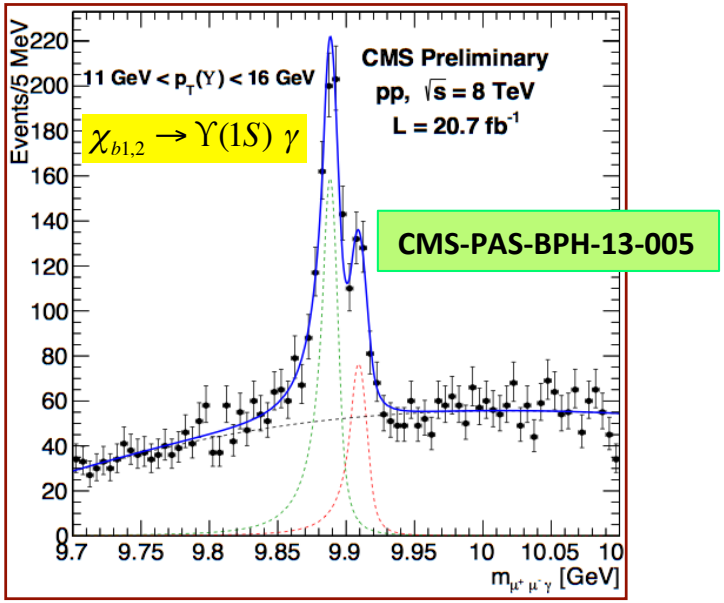




If the ${}^3S_1^{[8]}$ term becomes dominant @higher p_T/M, the quarkonia @ high p_T should be transversely polarized: need analysis with 2012 data and with Run-II data ! Test if this hierarchy among CO contributions holds also for P-wave states !

Relative production rate of $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$

- P-wave states measurements are crucial to understand quarkonium production. They also help to …
  - … study feed-down effects into S-wave states
  - … constrain CO LDMEs of the χ_c and χ_b states in NRQCD fits to S-wave production/polarization data
- Reconstruction of photons by conversions into e^-e^+ pairs provides enough mass resolution to resolve the two peaks (with 19*MeV* separation)



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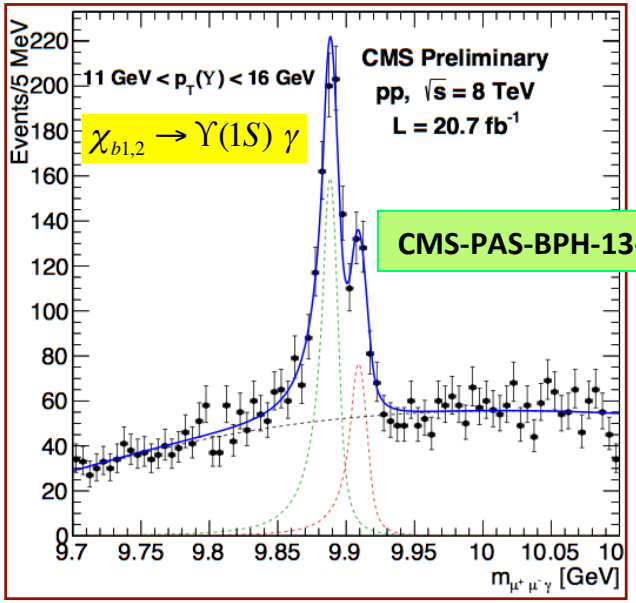
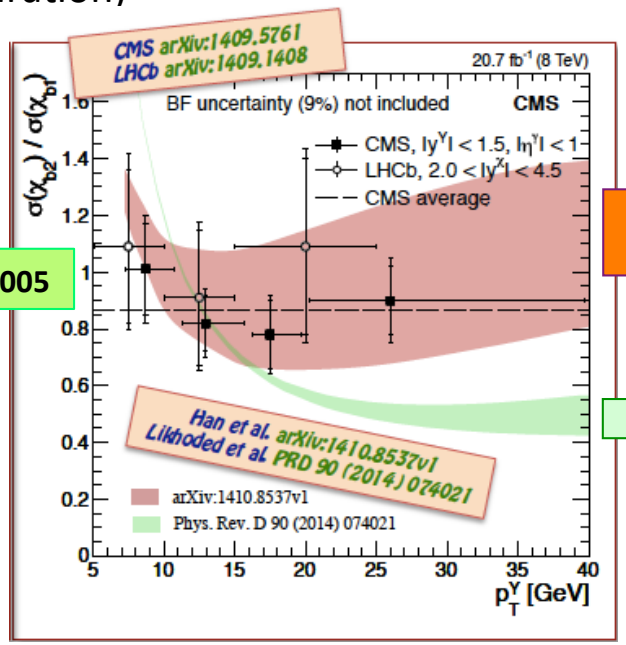


CMS-PAS-BPH-13-005



CMS & LHCb data consistent & compared with two different NLO NRQCD calculations (and fits based on different experimental data)

Improve p_T reach & accuracy with Run-II data !

Measurement @ hadron colliders with smaller uncertainties for this production cross section ratio (corrected for the ratio of the BFs):

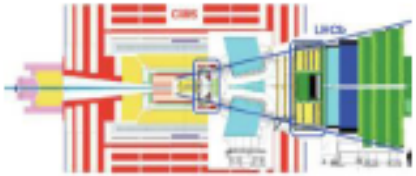
$$< R > \equiv \left\langle \frac{\sigma(pp \to \chi_{b2} + X)}{\sigma(pp \to \chi_{b1} + X)} \right\rangle = 0.85 \pm 0.07(\text{stat+syst}) \pm 0.08\left(BF(\chi_{b1,2} \to \Upsilon(1S) + \gamma)\right)$$

- Before $\frac{\sigma(\chi_{b2}(1P))}{\sigma(\chi_{b1}(1P))}$, CMS already measured $\frac{\sigma(\chi_{c2}(1P))}{\sigma(\chi_{c1}(1P))}$ **[EPJ C72 (2012) 2251]** with the same technique

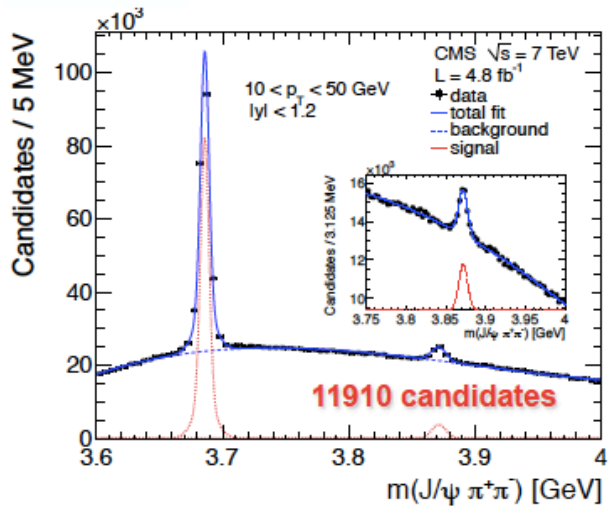
Exotic quarkonia : *X(3872), Y(4140)*

$X(3872)$ production at central rapidities

- Measurements of the prompt production rate at the LHC as a function of p_T provides a test of the NRQCD factorization approach to X(3872) production; CMS does @ central rapidities (kinematic region complementary to that of LHCb)

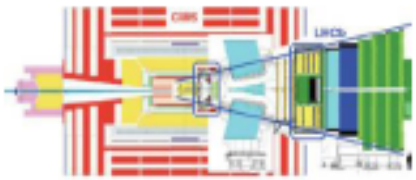


Differential xsection for prompt prod. measured using $J/\psi\ \pi^+\pi^-$ decays and assuming unpolarized *X(3872)* with $J^{PC}=1^{++}$ (later confirmed by LHCb)

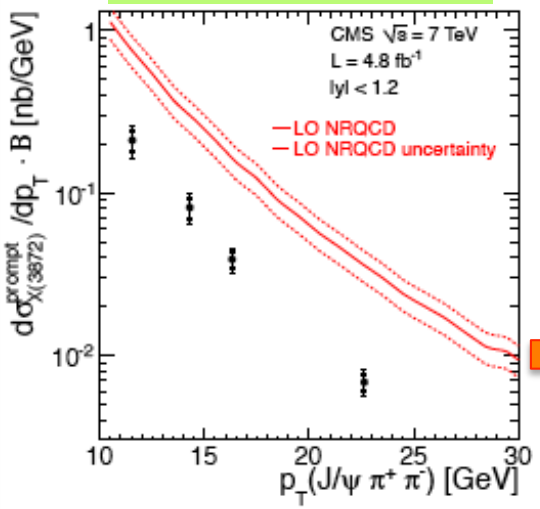


$X(3872)$ production at central rapidities

- Measurements of the prompt production rate at the LHC as a function of p_T provides a test of the NRQCD factorization approach to X(3872) production; CMS does @ central rapidities (kinematic region complementary to that of LHCb)



CMS, JHEP 1304 (2013) 154



Predictions by Artoisenet & Brateen [**PRD 81,(2010),114018**] with calculations normalized using Tevatron results, modified by the authors to match the phase-space of the CMS measurement

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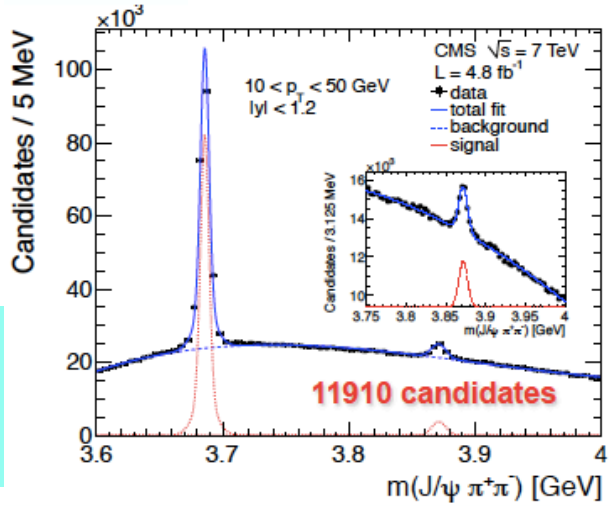
NRQCD predictions rather exceed the measured value, while p_T dependence is reasonably described



- Integrating over p_T (10-30*GeV*) [and $|y|<1.2$] get the integrated cross section times the branching fraction:

$$\sigma^{prompt}_{X(3872)} \times B\left(X(3872) \to J/\psi\ \pi^+\pi^-\right) \cong (1.06 \pm 0.11 \pm 0.15)nb$$

Comparing vs NRQCD prediction $\cong (4.01 \pm 0.88)nb$: **difference >3σ**
[LHCb gets a difference ~2.4σ in its kinematic region]

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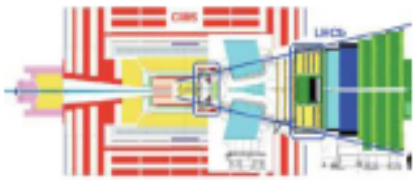

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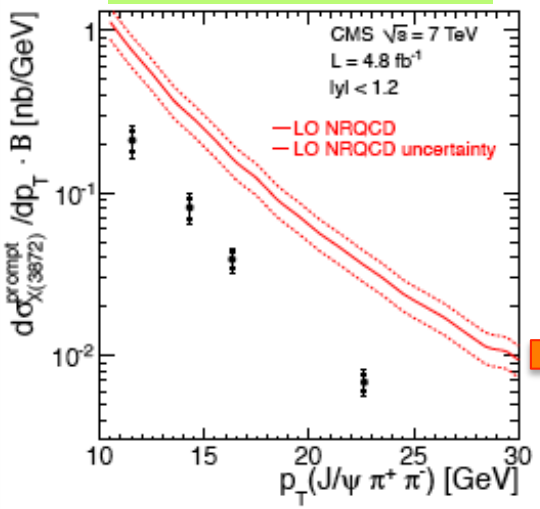

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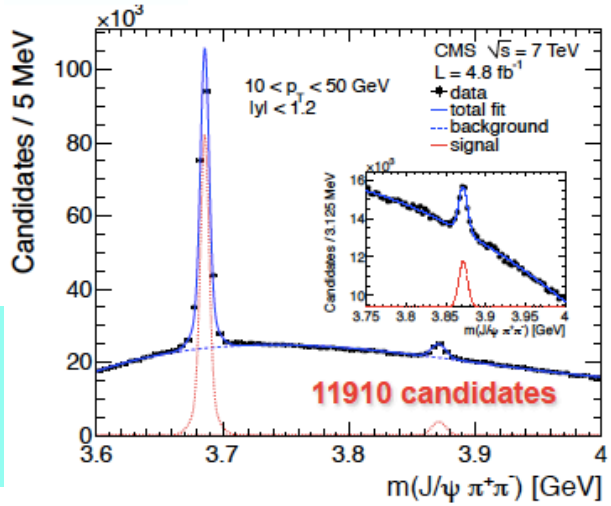

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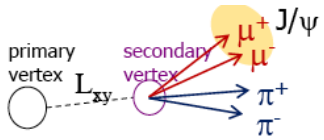
[LHCb gets a difference ~2.4σ in its kinematic region]

- Further results:
  - Dipion invariant mass consistent with intermediate ρ
  - Total xsection largely dominated by prompt production (~75%)
  - Non-prompt fraction ($\cong 0.263 \pm 0.028$) independent on p_T



Peaking structures in the $J/\psi\ \phi$ mass spectrum from $B^+ \to J/\psi\ \phi\ K^+$ decays

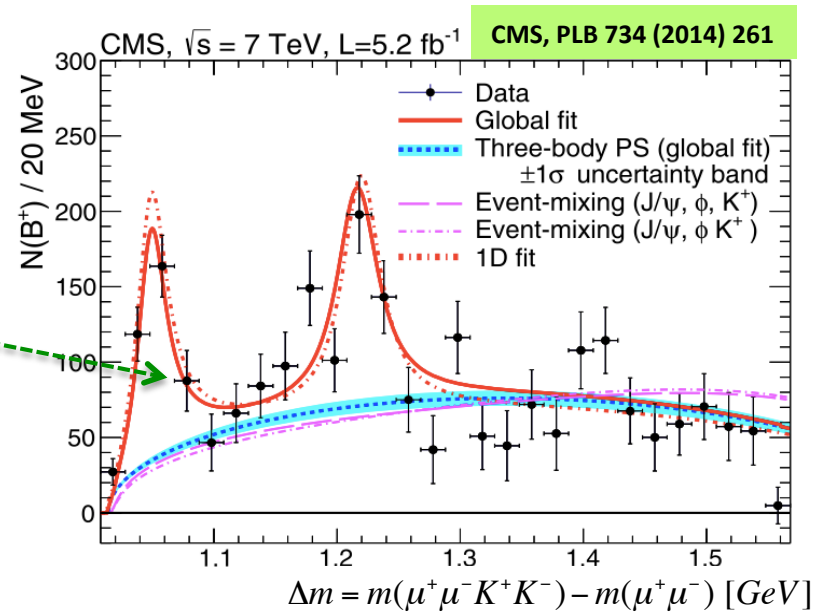
- Observation of two structures in the Δm mass difference spectrum by recostructing the $B^+ \to J/\psi\ \phi\ K^+$ decay (extracted B^+ signal is the largest sample collected so far)

  - Peaking structure @ threshold with:

    $$m = 4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst}) MeV$$

    $$\Gamma = 28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst}) MeV$$

    - observed with $>5\sigma$ stat. significance
    - consistent with the charmonium-like state, possibly exotic, Y(4140) from CDF [PRL 102 (2009) 242002]
    - evidence from DØ while not confirmed by LHCb [PRD 85 (2013) 091103(R)]



- Naïve yields' ratio estimate: $Y_{Y(4140)}/Y_{J/\psi\phi K} \approx 0.11 \pm 0.03\%$ consistent with CDF and with LHCb Upper Limit

- Evidence of additional peak (mass-shifted w.r.t. CDF) that may be affected by possible ϕK^+ resonances

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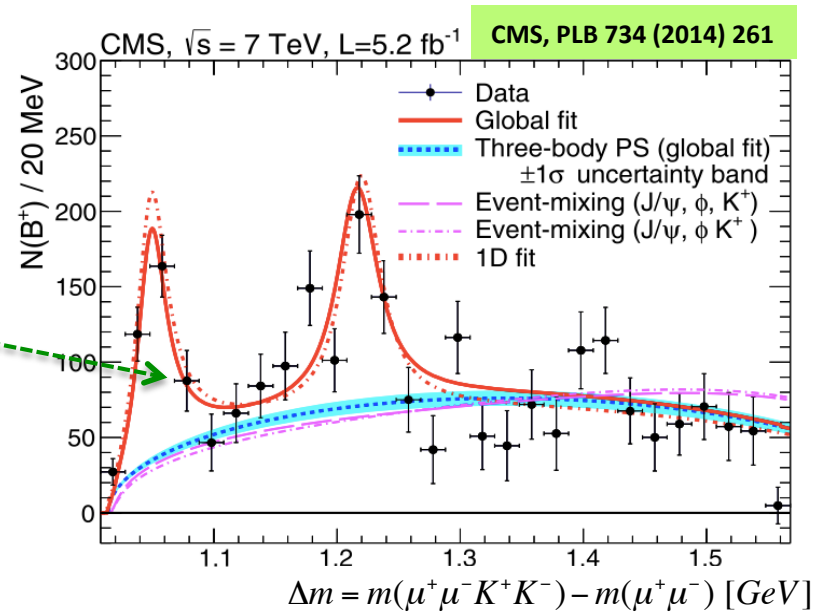

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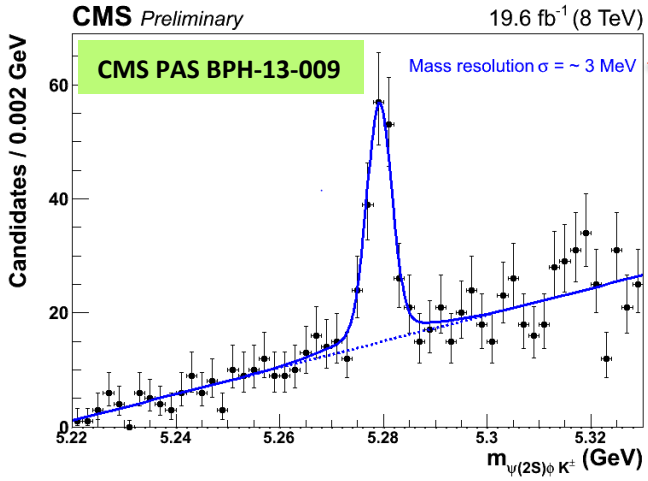
- For the *Y(4140)* decaying into *J/ψ φ* several interpretations have been proposed: $D_s^* \bar{D}_s^*$ molecule, $cs\bar{c}\,\bar{s}$ tetraquark, threshold kinemtaic effect, hybrid charmonium, weak transition with $D_s \bar{D}_s$ rescattering

- Understanding the nature of both structures needs further investigation and requires a full amplitude analysis (after extracting an enough pure B^+ sample). Ongoing analysis adding 2012 data [Run-II might help]

First observation of the decay $B^+ \to \psi(2S)\ \phi\ K^+$

- Result obtained (on 2012 data) as an extension of the previous investigation of the decay $B^+ \to J/\psi\ \phi\ K^+$
  It is a quasi-rare (~10^{-6}) decay mode interesting because of its squeezed phase space:



- Observed yield with a stat. significance well exceeding 5σ

- Absolute BF measurement is ongoing (systematics in progress) and uses $B^+ \to \psi(2S)K^+$ as the normalization channel;

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResutsBPH13009

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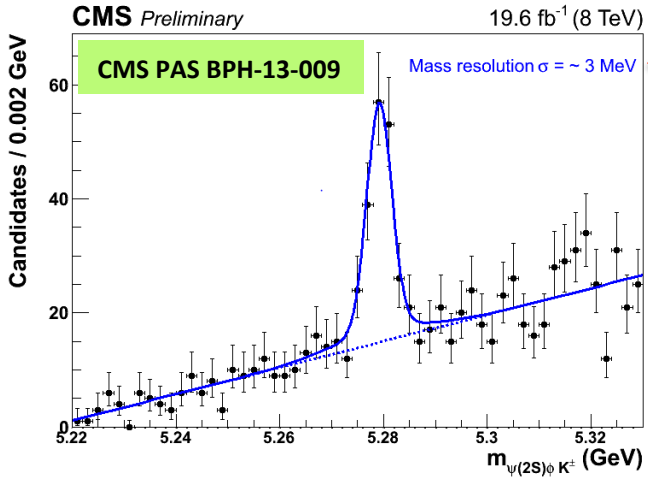

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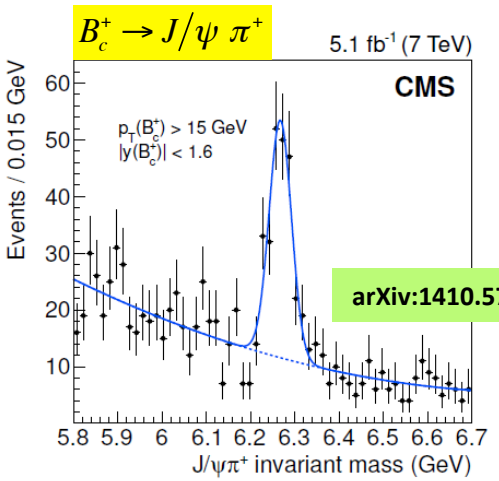
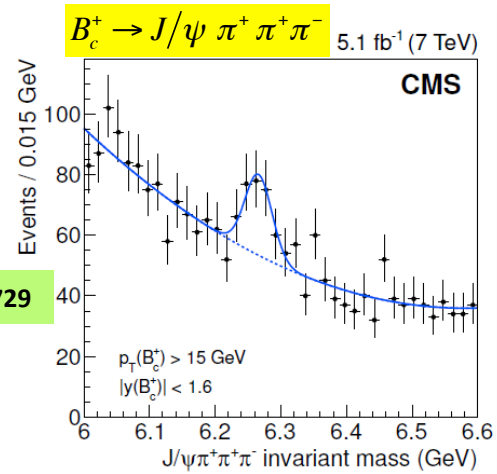
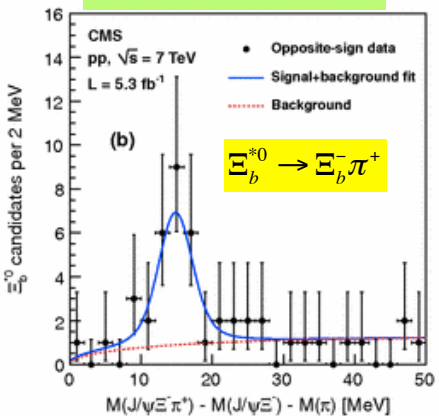
- This is just an example of the capabilities to look for rare decays and, in general, to perform spectroscopic studies (B_c-mesons, baryons, …) with Run-I (and Run-II !) data.

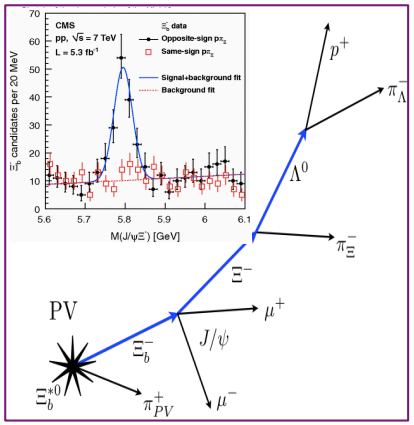


arXiv:1410.5729



PRL 108 (2012) 252002





Summary

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

  - CMS results on golden channels ($B^0 \to \mu\mu,\ B^0 \to K^*\mu\mu,\ B_s^0 \to J/\psi\phi$) 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.

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

  - CMS can be competitive in searches/some measurements of exotic XYZ states even without having an hadronic PID, as well as in spectroscopy (B_c, baryons,…)

Backup slides/Additional material

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

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

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.

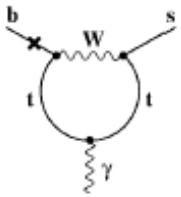
[Bozzi, Int.J.Mod.Phys. Conf.Ser. 201431]

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

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

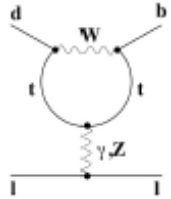


- $Q_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu} b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu \ell$ [$b \to s\mu\mu$ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\gamma_5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

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

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

Wilson Coefficients and processes



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

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

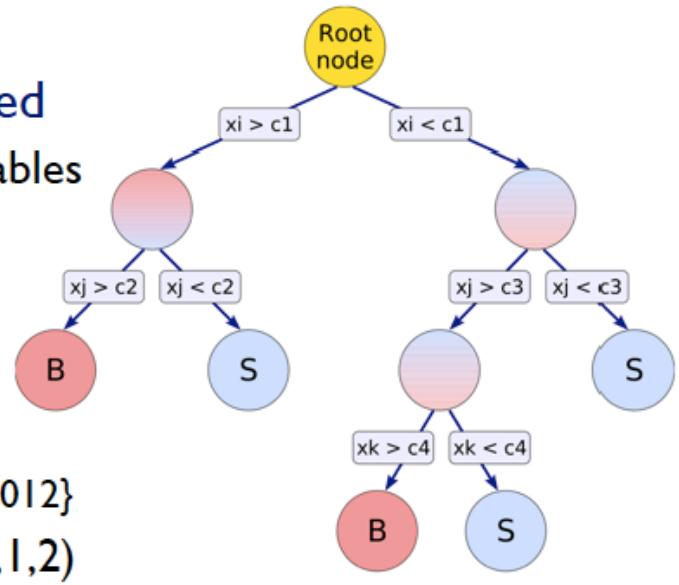
(formulae known up to NNLO + e.m. corrections)

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

[Descotes-Genon, @Moriond EW. 2014]

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

$B_{s(d)} \to \mu^+\mu^-$ 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 $Bs \to J/\psi \Phi$
- 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 CL_S 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

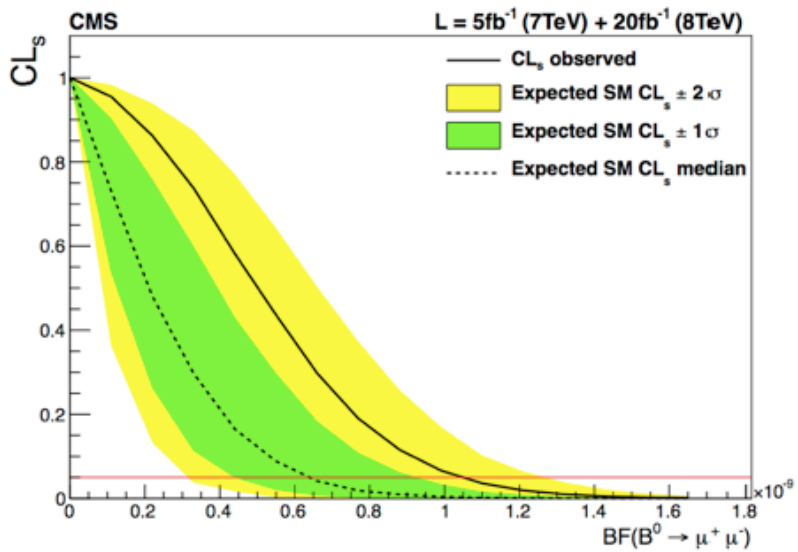
	2011 barrel		2012 barrel	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
$\varepsilon_{tot}[\%]$	0.33 ± 0.03	0.30 ± 0.04	0.24 ± 0.02	0.23 ± 0.03
N^{exp}_{signal}	0.27 ± 0.03	2.97 ± 0.44	1.00 ± 0.10	11.46 ± 1.72
N^{exp}_{total}	1.3 ± 0.8	3.6 ± 0.6	7.9 ± 3.0	17.9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

	2011 endcap		2012 endcap	
	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B_s^0 \to \mu^+\mu^-$
$\varepsilon_{tot}[\%]$	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

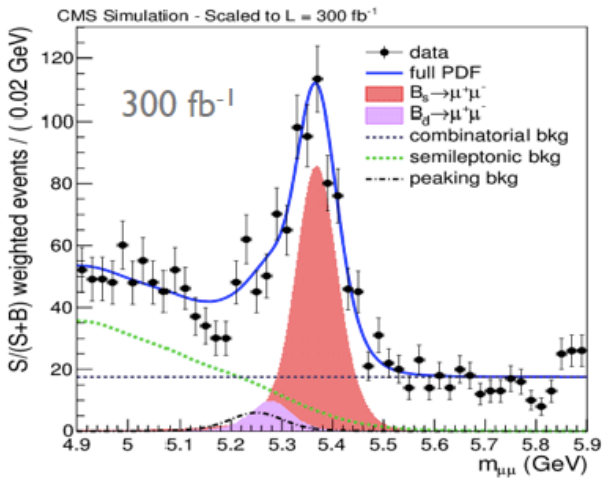
$BR(B_d \to \mu\mu) < 1.1 \times 10^{-9}$ @95% CL

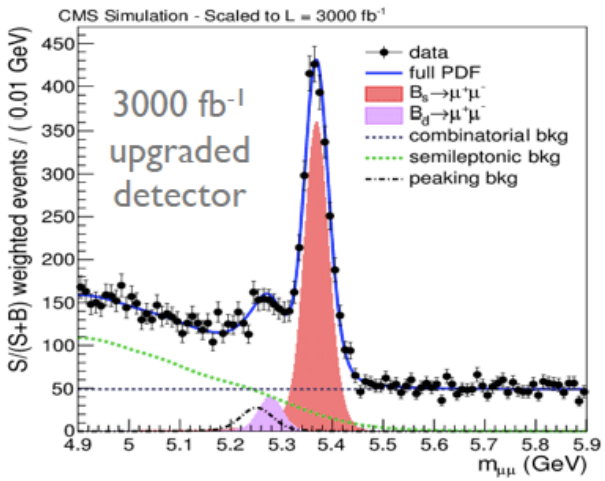
(expected 6.3×10^{-10} in presence of SM+background)

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



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

Projections discussed @ talk by M.Galanti

$B^0 \to K^{*0}\mu^+\mu^-$ PDFs of UML fit

$$PDF(M, \cos\theta_K, \cos\theta_l) = Y_S \cdot S(M) \cdot S(\cos\theta_K, \cos\theta_l) \cdot \epsilon(\cos\theta_K, \cos\theta_l)$$ Signal

$$+ Y_{Bc} \cdot B_C(M) \cdot B_C(\cos\theta_K) \cdot B_C(\cos\theta_l)$$ Combinatorial

$$+ Y_{Bp} \cdot B_P(M) \cdot B_P(\cos\theta_K) \cdot B_P(\cos\theta_l)$$ Peaking BKG from $B^0 \to K^* J/\psi(\psi')$

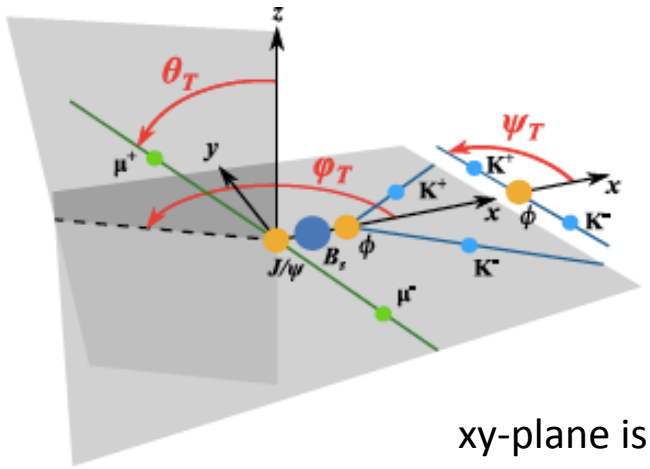
Y_S, Y_{Bc}, Y_{Bp}	Event Yields
$S(\cos\theta_K, \cos\theta_l), \epsilon(\cos\theta_K, \cos\theta_l)$	Signal 2D angular shape and efficiency
$S(M), B_C(M), B_P(M)$	Mass PDFs
$B_C(\cos\theta_{K(l)}), B_P(\cos\theta_{K(l)})$	Angular BKG PDFs

$B^0 \to K^{*0}\mu^+\mu^-$ Systematics

Table 1: Systematic uncertainty contributions for the measurements of F_L, A_{FB}, and $d\mathcal{B}/dq^2$. The F_L and A_{FB} uncertainties are absolute values, while the $d\mathcal{B}/dq^2$ uncertainties are relative to the measured value. The ranges given refer to the variations over the q^2 bins.

Systematic uncertainty	F_L (10^{-3})	A_{FB} (10^{-3})	$d\mathcal{B}/dq^2$(%)
Efficiency statistical uncertainty	5–7	3–5	1
Potential bias from fit algorithm	3–40	12–77	0–2.7
Potential bias from fit ingredients	0	0–17	0–7.1
Incorrect CP assignment of decay	2–6	2–6	0
Effect of $K\pi$ S-wave contribution	5–23	6–14	5
Peaking background mass shape	0–26	0–8	0–15
Background shapes vs. $\cos\theta_{L,K}$	3–180	4–160	0–3.3
Signal mass shape	0	0	0.9
Angular resolution	0–19	0	0
Efficiency shape	16	4	4.3
Normalization to $B^0 \to K^{*0}J/\psi$	—	—	4.6
Total systematic uncertainty	31–190	18–180	8.6–17

$B_s^0 \to J/\psi\,\phi$ 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	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\phi_T$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\sin\phi_T$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\phi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$	$\lvert A_S(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$	$\lvert A_S(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$	$\lvert A_S(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

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

$|\lambda|$ 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

$$
\begin{aligned}
\mathcal{L} &= L_{sig} + L_{bkg} \\
L_{sig} &= N_{sig} \cdot [X(\Theta, \mathrm{ct}; \alpha) \otimes G(\mathrm{ct}, \sigma_{\mathrm{ct}}) \cdot \varepsilon(\Theta)] \cdot P_{sig}(m_{\mathrm{B_s}}) \cdot P_{sig}(\sigma_{\mathrm{ct}}) \cdot P_{sig}(\xi) \\
L_{bkg} &= N_{bkg} \cdot P_{bkg}(\cos\theta_{\mathrm{T}}, \varphi_{\mathrm{T}}) \cdot P_{bkg}(\cos\psi_{\mathrm{T}}) \cdot P_{bkg}(\mathrm{ct}) \cdot P_{bkg}(m_{\mathrm{B_s}}) \cdot P_{bkg}(\sigma_{\mathrm{ct}}) \cdot P_{bkg}(\xi)
\end{aligned}
$$

- $G(\mathrm{ct}, \sigma_{\mathrm{ct}})$: gaussian resolution function, which makes use of the per-event proper decay length uncertainty $\sigma(\mathrm{ct})$ scaled by a factor $\kappa(\mathrm{ct})$
- $\varepsilon(\Theta) = \varepsilon(\cos\theta_{\mathrm{T}}, \cos\psi_{\mathrm{T}}, \varphi_{\mathrm{T}})$: 3-dimensional angular efficiency
- $P_{sig}(m_{\mathrm{B_s}})$: $\mathrm{B_s}$ 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

- $P_{bkg}(\cos\theta_{\mathrm{T}}, \varphi_{\mathrm{T}})$ and $P_{bkg}(\cos\psi_{\mathrm{T}})$: angular background PDFs $\to$ Legendre polynomials for $\cos\theta_{\mathrm{T}}$ and $\cos\psi_{\mathrm{T}}$ and sinusoidal functions for φ_{T}. A 2-dimensional PDF is used for $\cos\theta_{\mathrm{T}}$ and φ_{T} to take into account the correlations
- $P_{bkg}(\mathrm{ct})$: proper decay length background PDF $\to$ sum of two exponential functions
- $P_{bkg}(m_{\mathrm{B_s}})$: $\mathrm{B_s}$ 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	$\lvert A_0\rvert^2$	$\lvert A_S\rvert^2$	$\lvert A_\perp\rvert^2$	$\Delta\Gamma_s$ [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 $\lvert\lambda\rvert$ 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 $\lvert\lambda\rvert$ 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 effieciency:** 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

NRQCD : color-singlet & color-octet terms

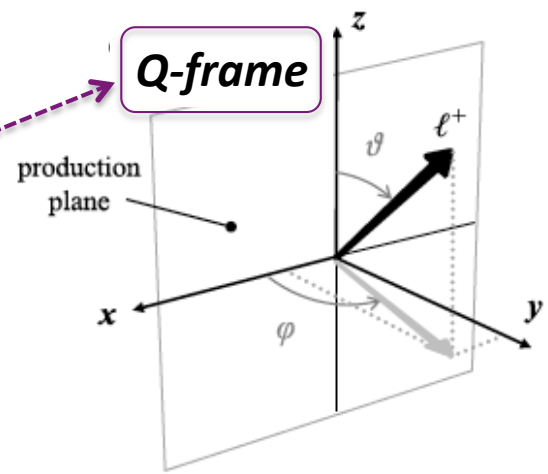
Short-distance coefficients (SDCs)	Long-distance matrix elements (LDMEs)
Inclusive pQCD xsection of partonic processes to form $Q\bar{Q}$ in state n (convoluted with PDFs)	Probability of $Q\bar{Q}$ in state n to evolve into the quarkonium final state *H*
process-dependent **functions** of kinematics	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: $^3S_1^{[1]}$
  - 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 !

Polarization frames

- The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions, specified in terms of spherical angles θ & ϕ for $\vec{p}(\ell^+)$ in the **meson rest frame**



- To define these angles a *polarization frame* must be chosen:

  θ : polar angle w.r.t. the spin-quantization axis (***z***)

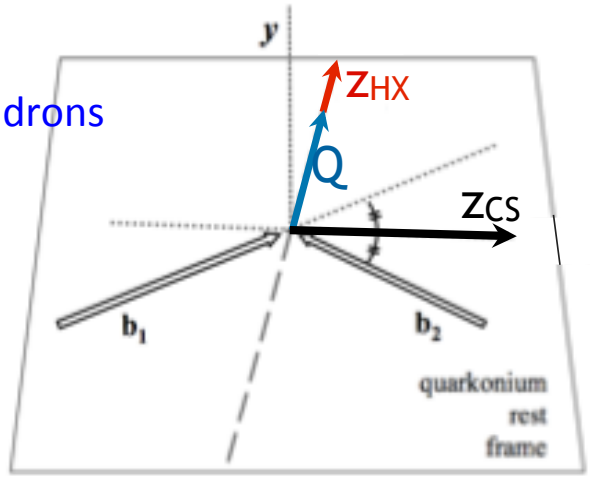
  ϕ : azimuthal angle w.r.t. the ***x***-axis that lies, together with ***z***-axis, in the *collision plane* defined by the momenta of the colliding hadrons boosted in the *Q-frame*

- Not unique choice of polarization ***z***-axis ⇨ 3 conventional reference frames:

  - ***center-of-mass helicity*** axis (**HX**): z_{HX}
    flight direction of the quarkonium in the c.m. frame of colliding hadrons

  - ***Collins-Soper*** axis (**CS**): z_{CS}
    direction of the vectorial difference between the velocity vectors of colliding hadrons in the *Q-frame*

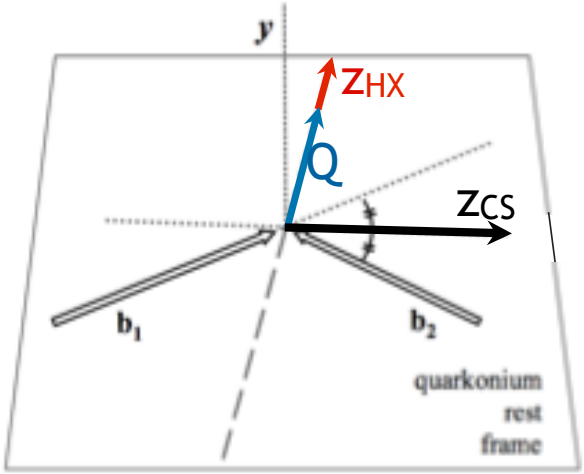
  - ***perpendicular helicity*** axis (**PX**): z_{PX}
    direction of the vectorial sum of the velocity vectors of colliding hadrons in the *Q-frame*



Polarization frames details

Three of the different conventional reference frames are:

- ***center-of-mass helicity*** axis (**HX**): z_{HX}
  flight direction of the quarkonium in the center-of-mass frame of the colliding hadrons
  (= direction of the boost vector required to go from the *Q-frame* to the center-of-momentum frame of the colliding hadrons)



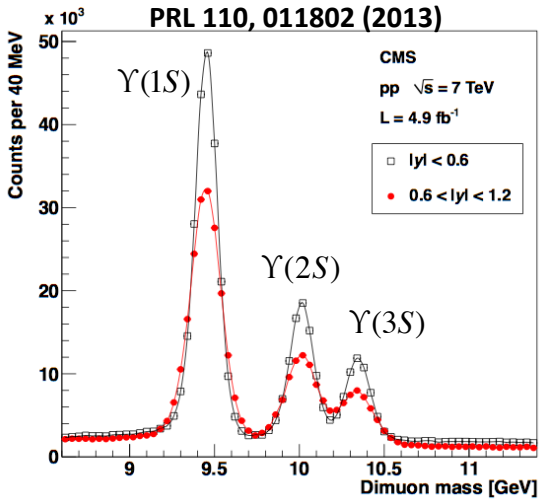
- ***Collins-Soper*** axis (**CS**): z_{CS}
  bisector of the angle between colliding beams (as in figure);
  (≈ direction of the vectorial difference between the velocity vectors of colliding hadrons in the *Q-frame*)

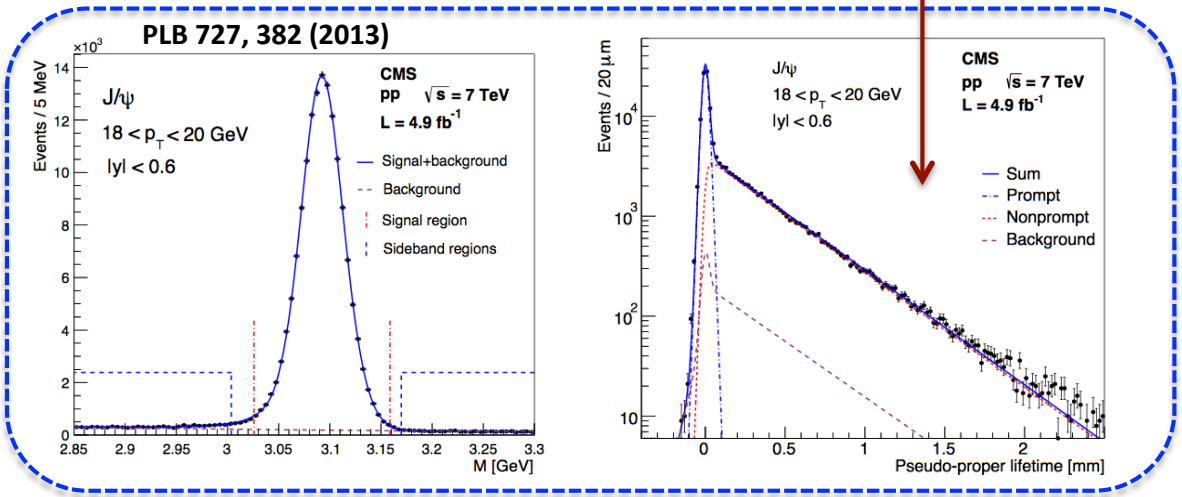
- ***perpendicular helicity*** axis (**PX**): z_{PX}
  direction of the vectorial sum of the velocity vectors of colliding hadrons
  (= direction of the boost required to go from the Q-frame to the frame in which the quarkonium momentum is perpendicular to the axis of the colliding beams)

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

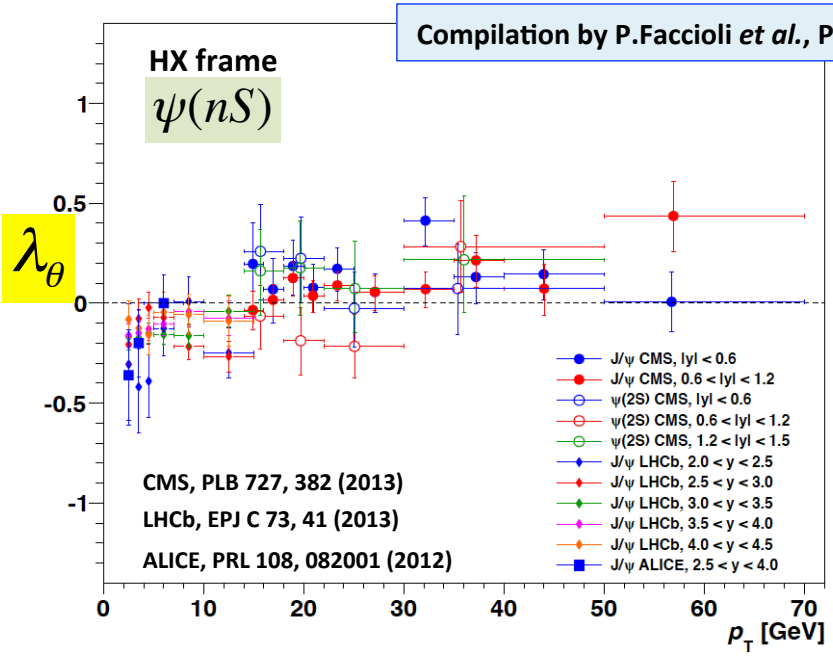


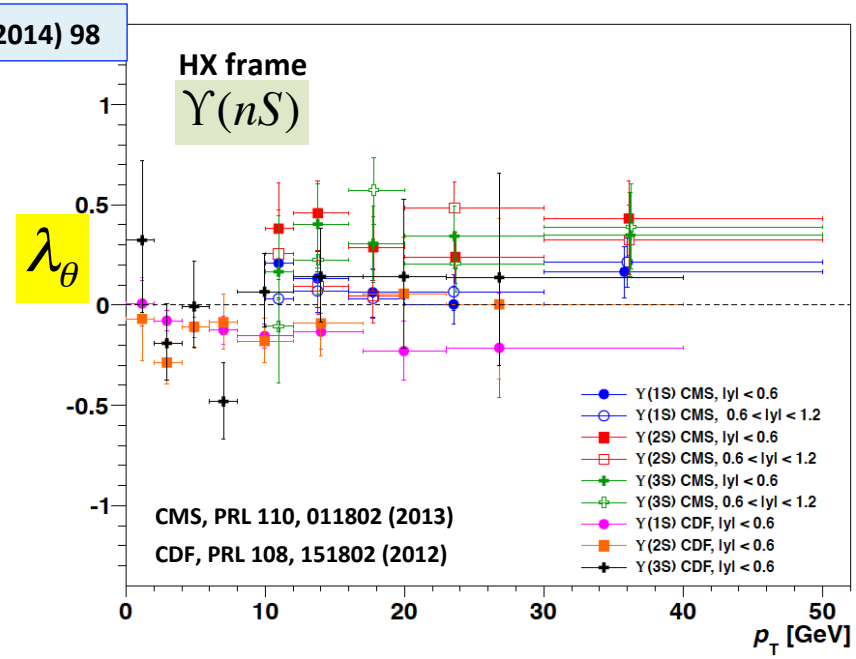


Photons & pions from the feed-down transitions have low energy : difficult to be reconstructed and associated with the dimuon pair in order to separate feed-down and direct production

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

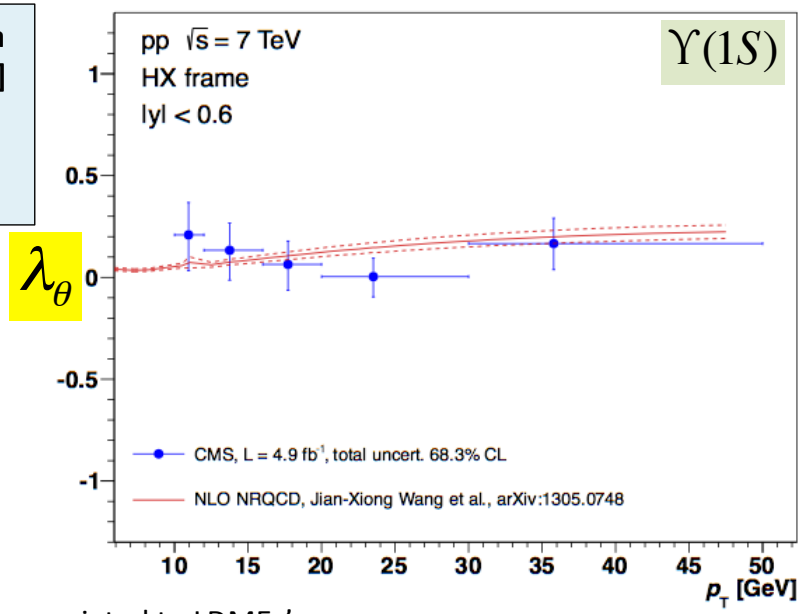


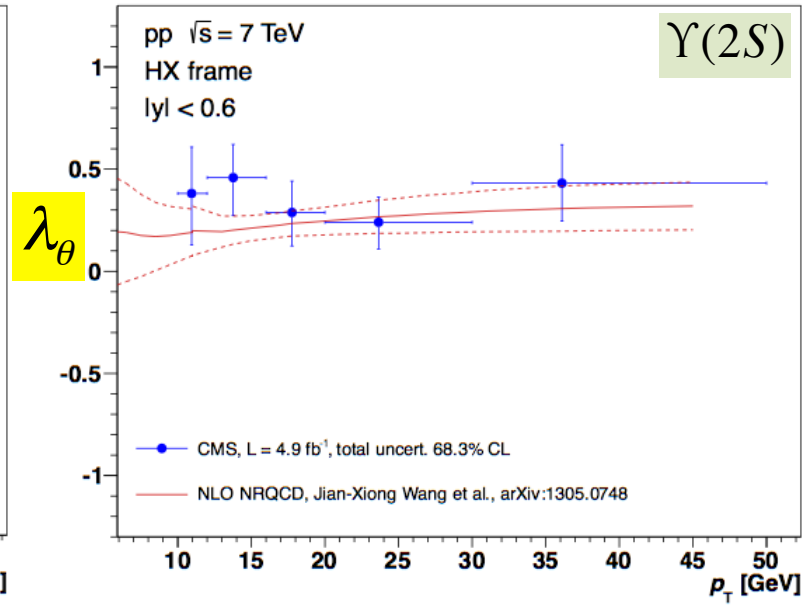


- All LHC results compatible with each other
- The polarizations cluster around the unpolarized limit ($\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0$) with …
  - no significance dependencies on p_T or y
  - no strong changes from full directly-produced states to those affected by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

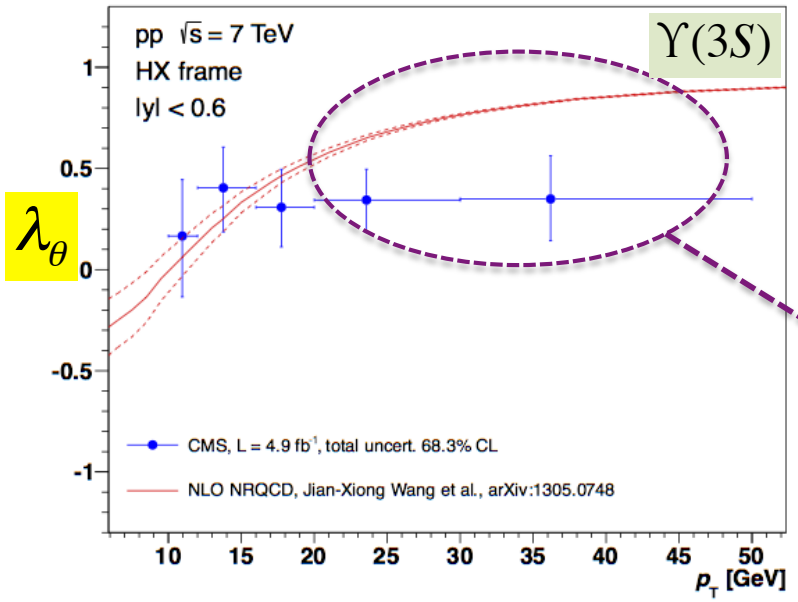
Comparison with NLO NRQCD for $\Upsilon(nS)$ states

Comparison of CMS data [PRL 110, 011802 (2013)] with B.Gong *et al.*, PRL 112, 032001 (2014) [arXiv:1305.0748]





uncertainty bands associated to LDMEs' errors

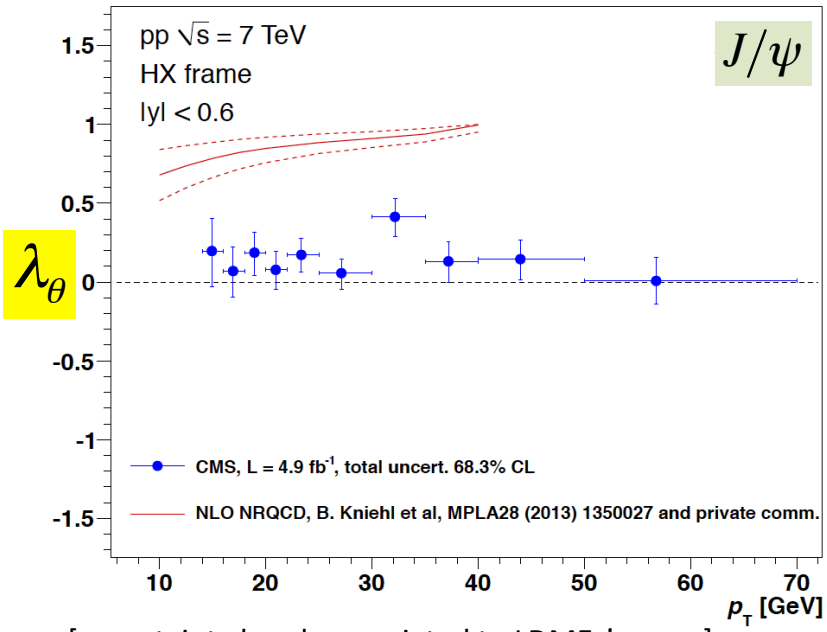


CO LDMEs are fit to hadro-production data (CMS included) combining direct production and feed-down contributions to $\Upsilon(1S)$, $\Upsilon(2S)$. Extra adjustable fit parameters (LDMEs of $\chi_{bJ}(nP)$ states) help compatibility with data!

Assuming that the unknown $\chi_{bJ}(3P)$ feed-down is negligible … the polarization of $\Upsilon(3S)$ can't be explained.

Direct production measurements are needed!

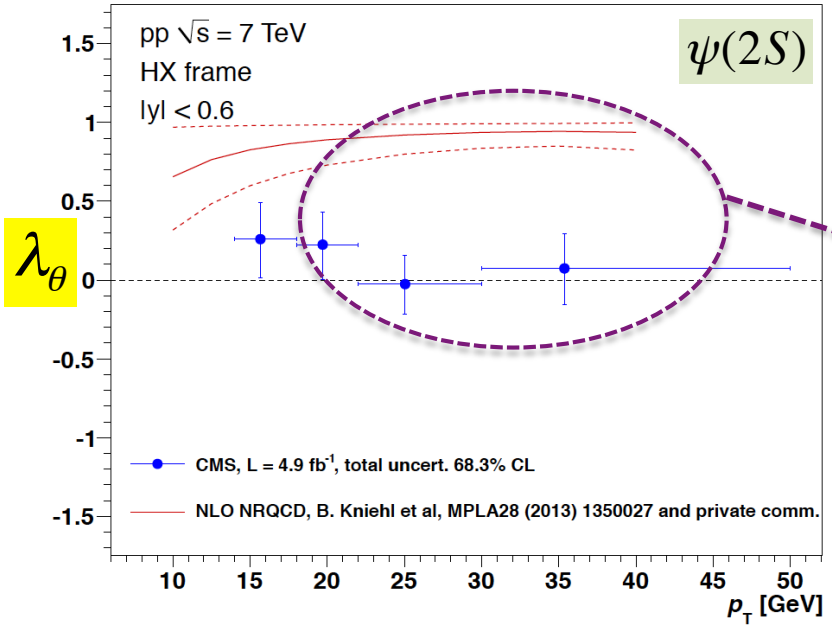
Comparison with NLO NRQCD for $\psi(nS)$ states



[uncertainty bands associated to LDMEs' errors]

Comparison of CMS data [PLB 727, 382 (2013)] with M.Butenschoen & B. Kniehl, PRL 108, 172002 (2012) + Priv. Comm. [later in MPLA28, 1350027 (2013)]

Calculations use global fit of CO LDMEs to photo- as well as hadro-production data (excluding polarization results); predictions only consider direct production



NLO NRQCD predictions fail to describe data for $\psi(2S)$ that shouldn't suffer from feed-down contributions !