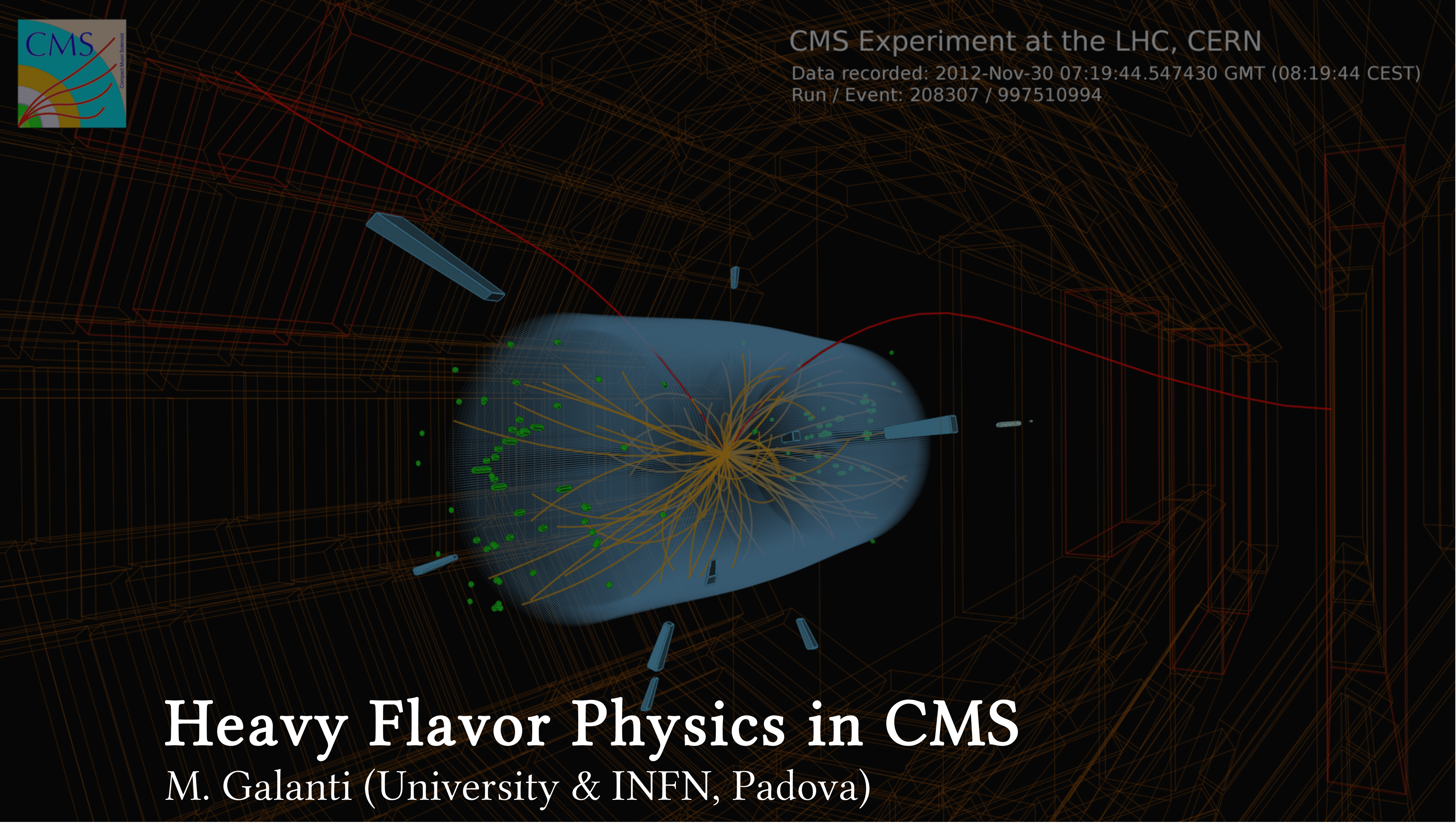


# Heavy Flavor Physics in CMS

M. Galanti (University & INFN, Padova)

CP3, Université Catholique de Louvain, Louvain-la-Neuve, 14/5/2014

Università degli Studi di Padova

INFN
Istituto Nazionale
di Fisica Nucleare

# Summary

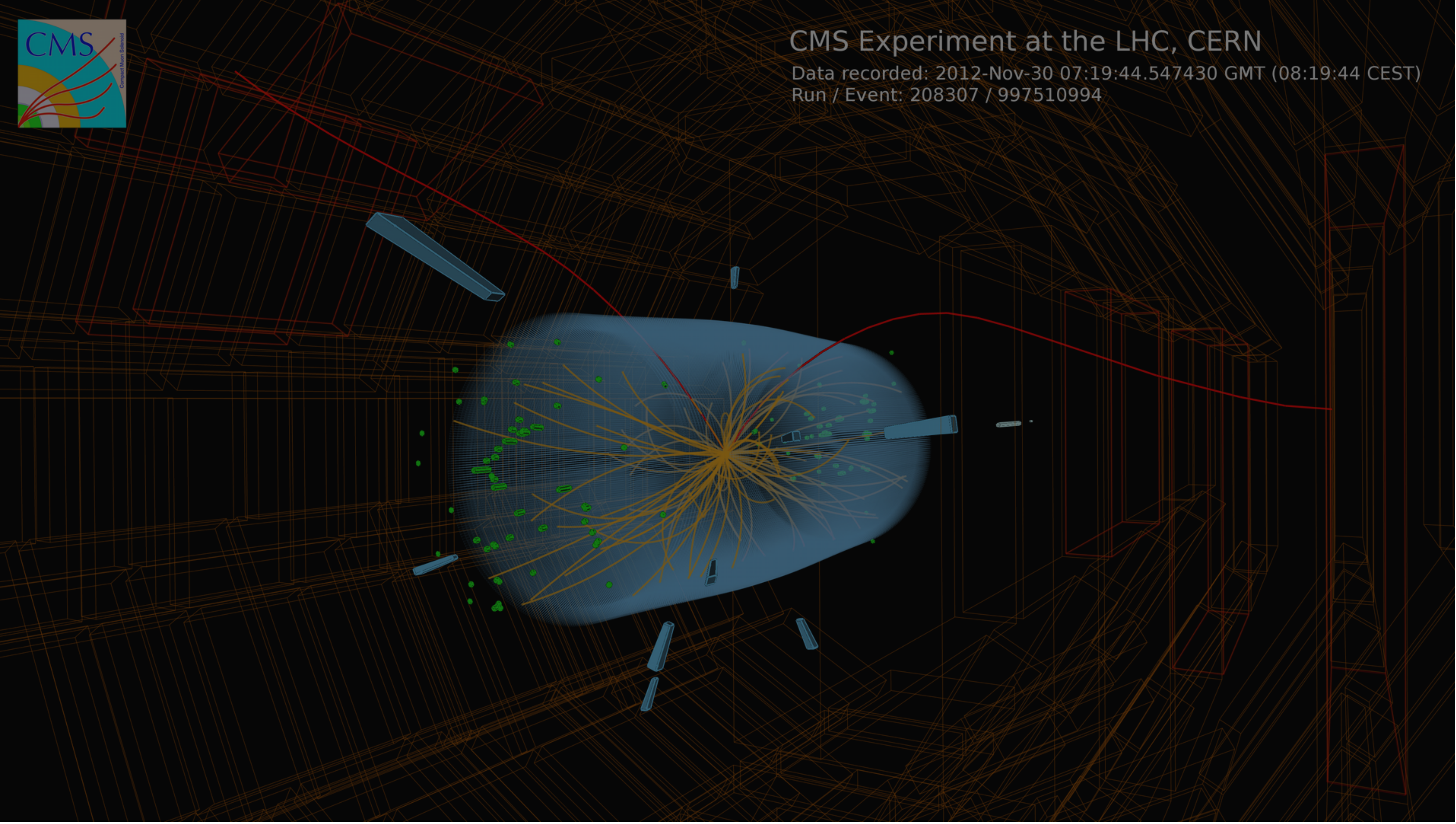
## Why HF physics in CMS?

- Heavy flavor physics at hadron colliders
- CMS performance for heavy flavors

## What HF physics in CMS?

- Rare decays: $B^0_{(s)} \rightarrow \mu\mu$
- Quarkonium physics
- Exotic hadrons

- **Conclusions**



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    - Origin of the 3 fermion generations and of the fermion mass hierarchies
    - Origin of CP violation and of the matter-antimatter asymmetry in the universe

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    - Origin of the 3 fermion generations and of the fermion mass hierarchies
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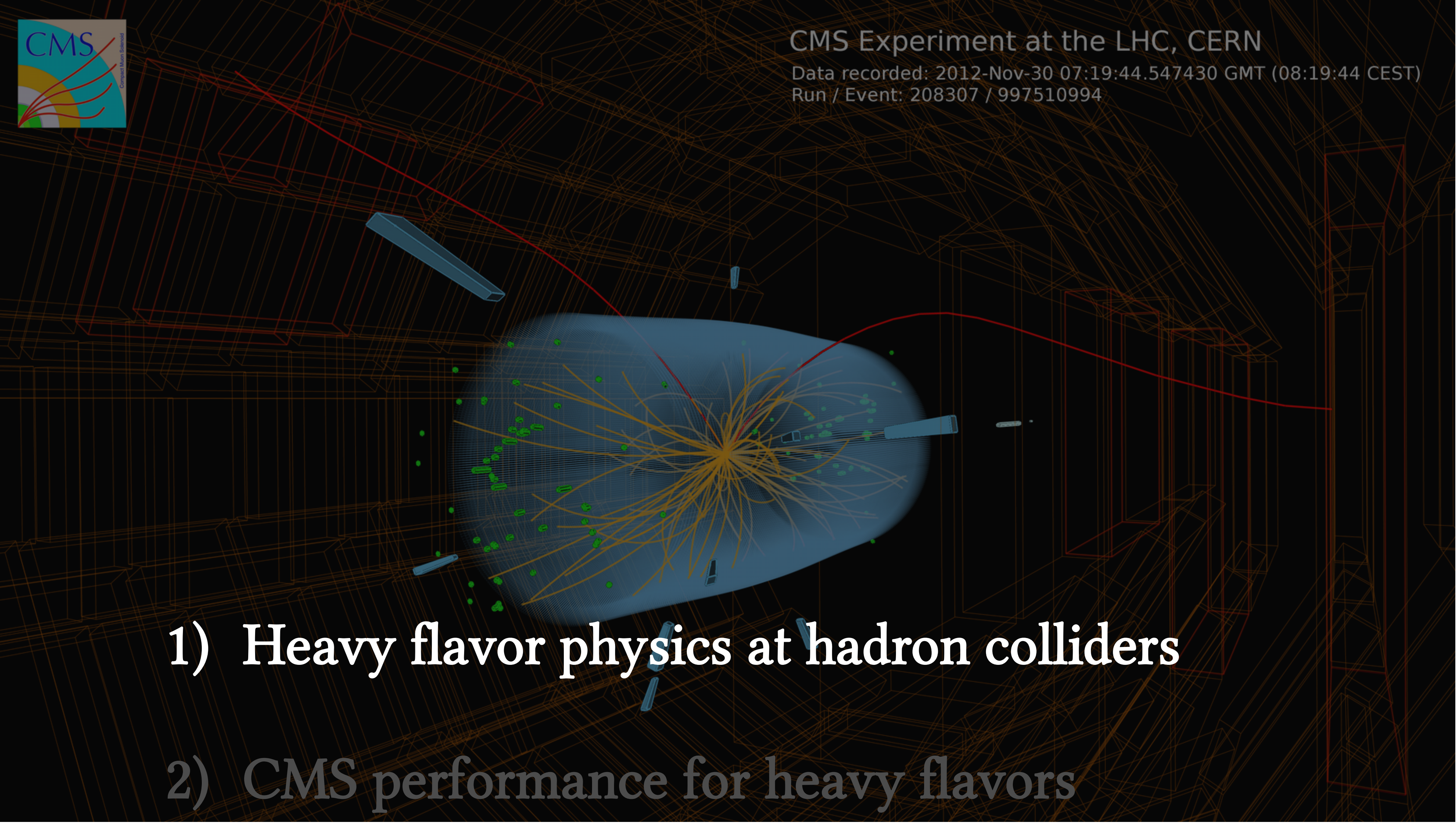
- There are already **dedicated facilities (b- and c-factories)** and **a dedicated LHC experiment (LHCb)** that try to answer these questions – **and perform very well at that!**

- **Why bother doing heavy flavor physics with a (non-dedicated) hadron collider experiment?**



1) Heavy flavor physics at hadron colliders

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# B physics at hadron colliders

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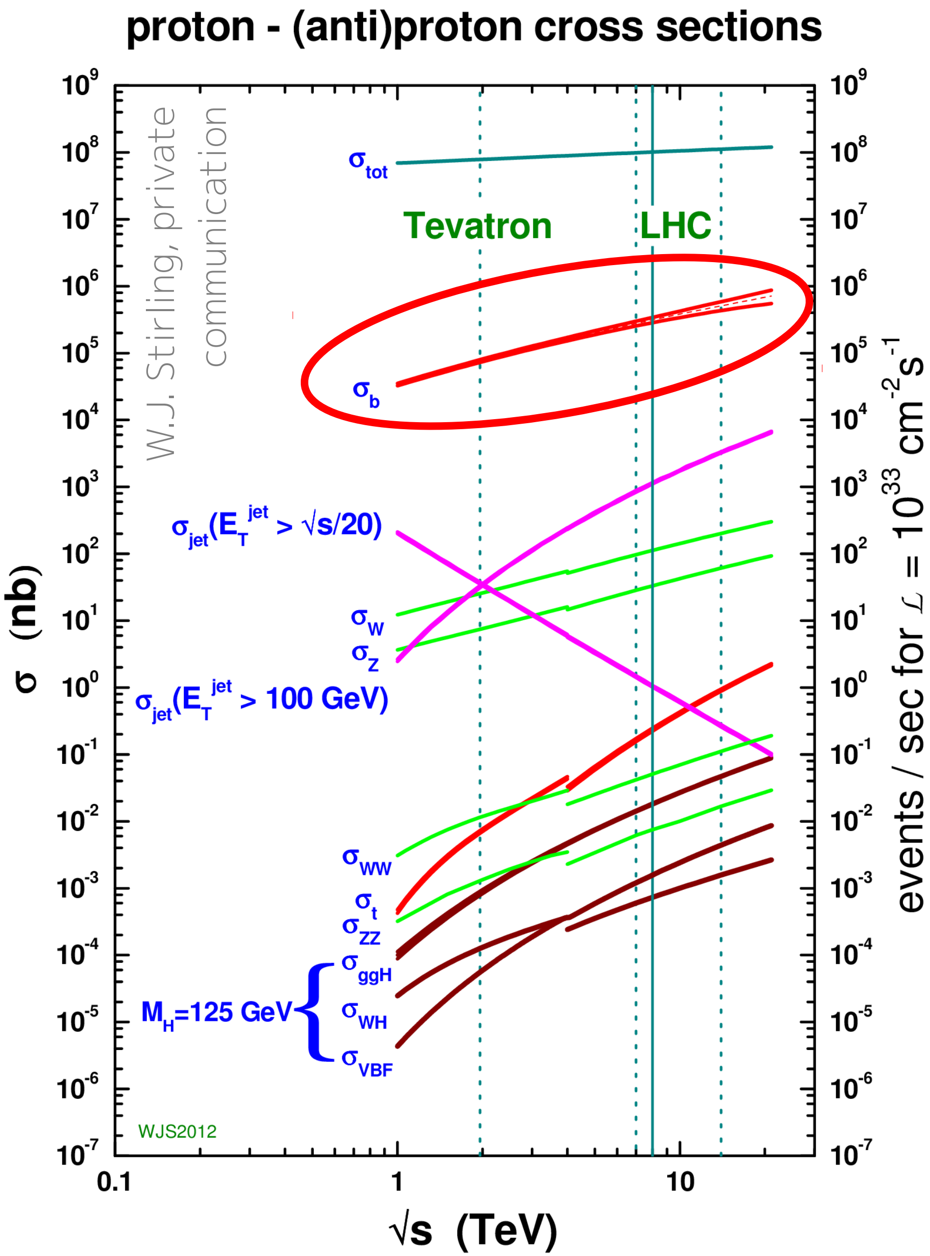

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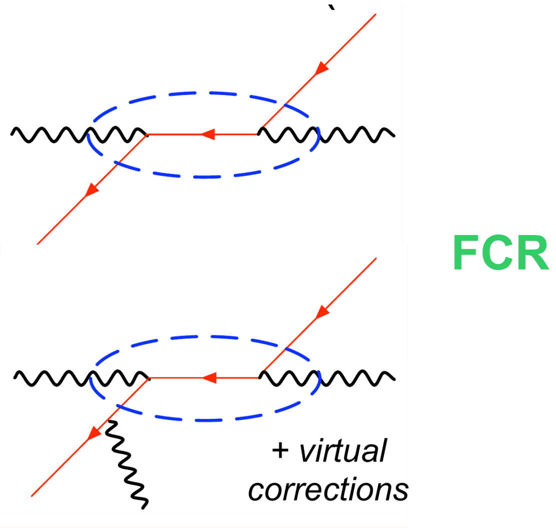

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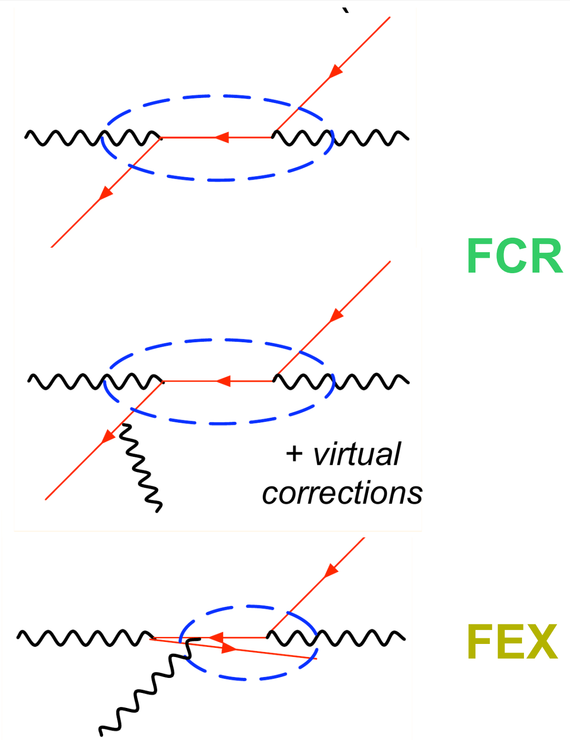

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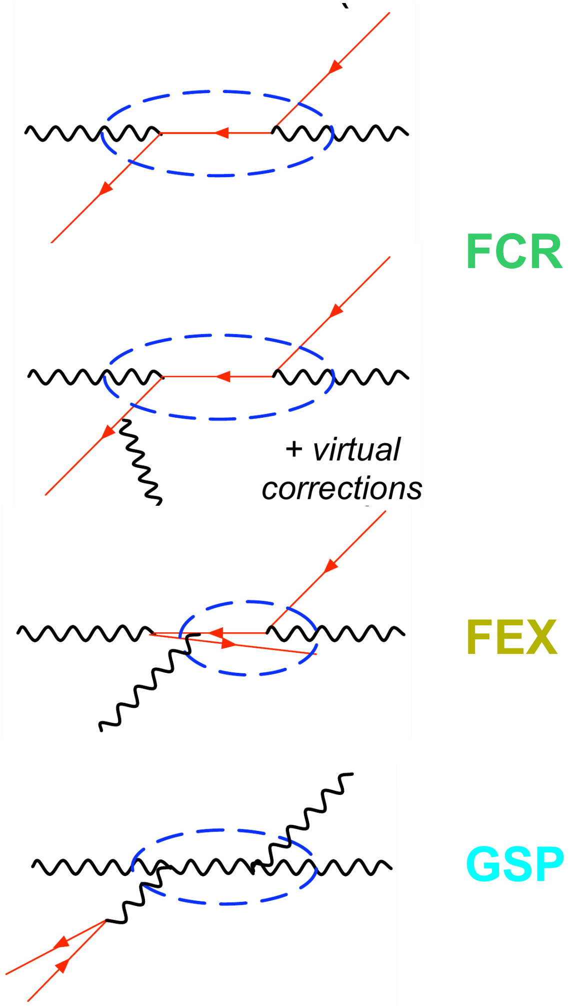

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  - **Gluon splitting**: g⟶$b\bar{b}$ in initial or final state
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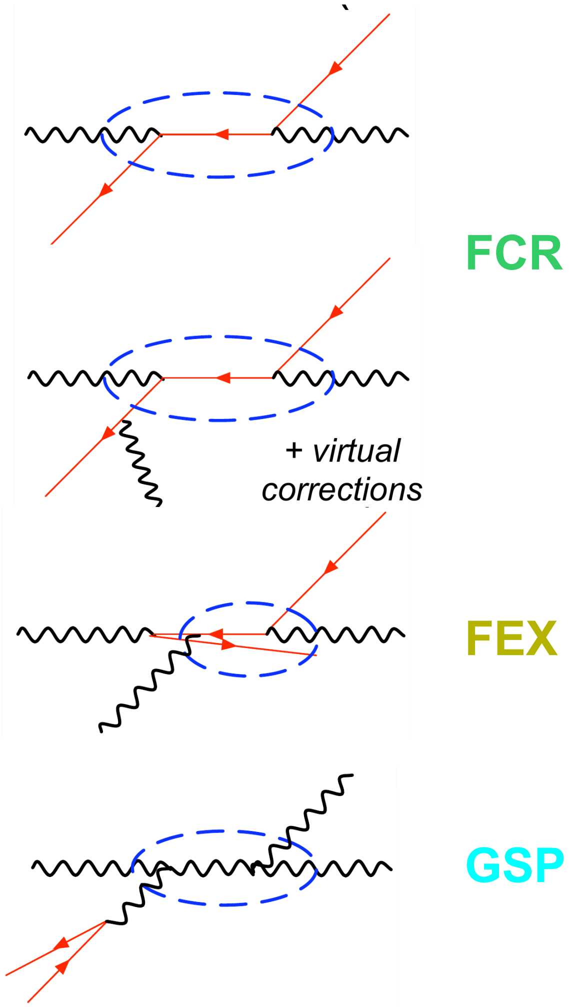
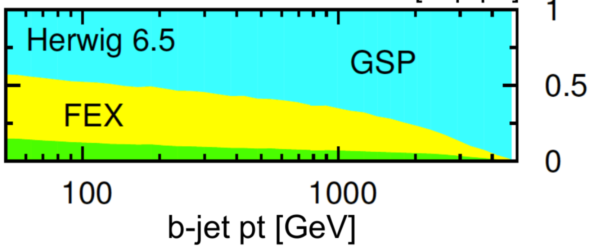
- **FEX and GSP processes dominating** the production
  - Challenge for experiments (b produced at low $p_T$ or collinear) and theory (pQCD)



arXiv:0705.1937 [hep-ph]



# Signatures of b production and decay

- Once produced, b quarks quickly hadronize

| | $B^0$ and $B^{\pm}$ | $B_s$ | $\Lambda_b^0$ |
|---|---|---|---|
| **Fragmentation fraction** | ~40% each | ~10% | ~9% |

  - Some hadrons (e.g. $B_s$) normally not produced at b-factories

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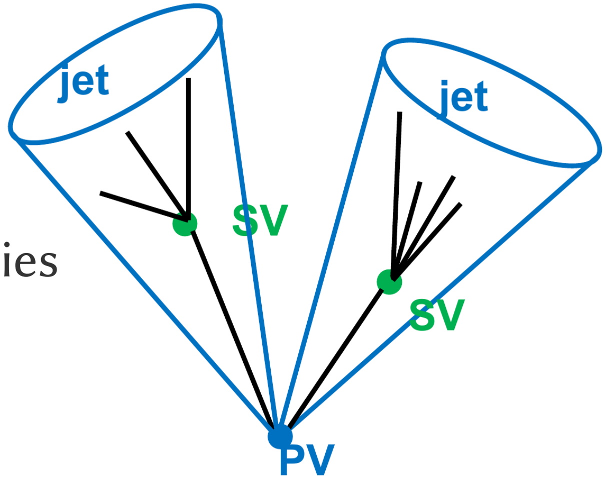

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  - E.g. $c\tau(B^\pm) \approx 490$ μm; $c\tau(B^0) \approx 460$ μm
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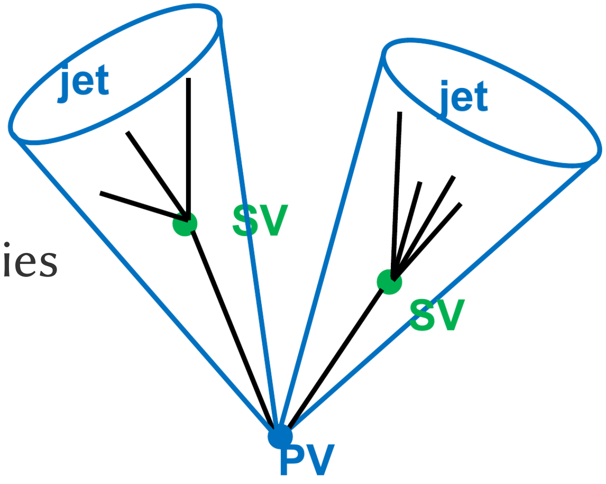

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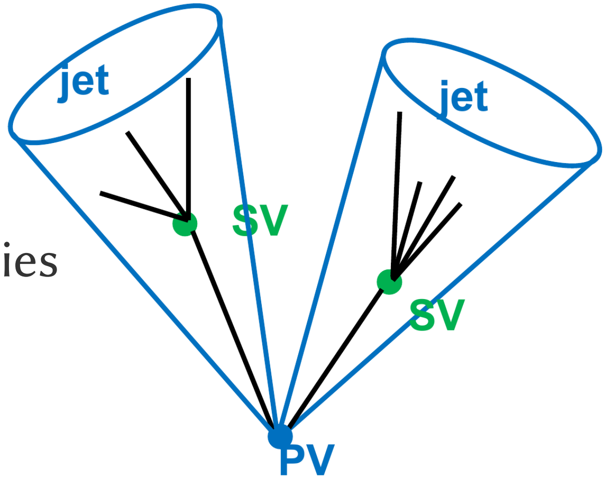

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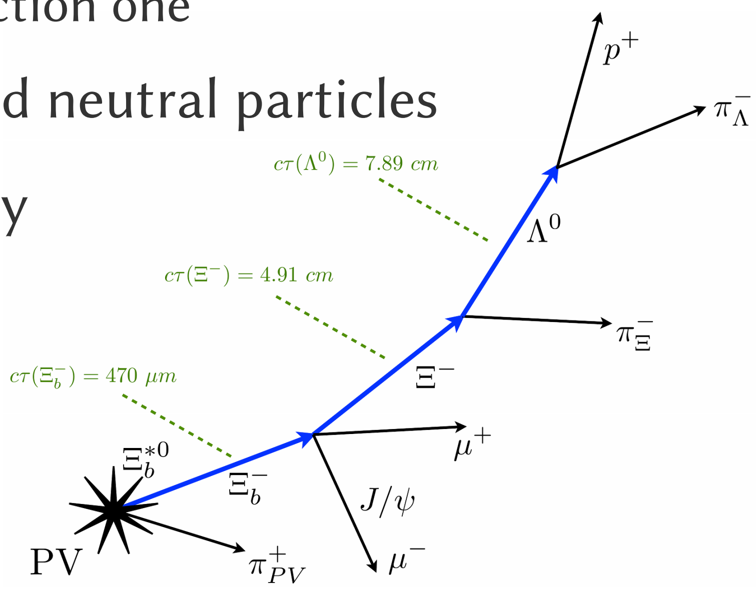

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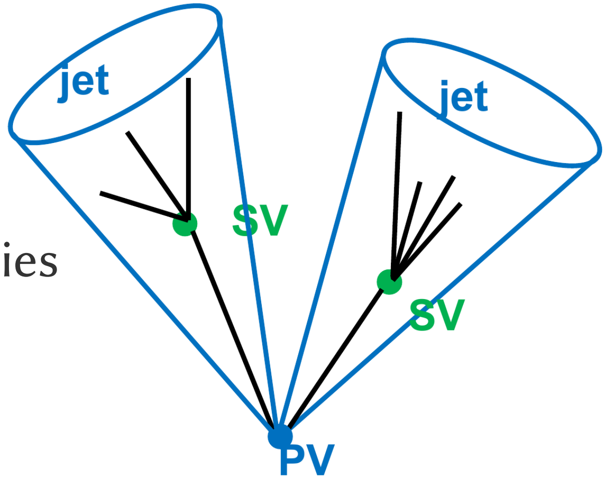
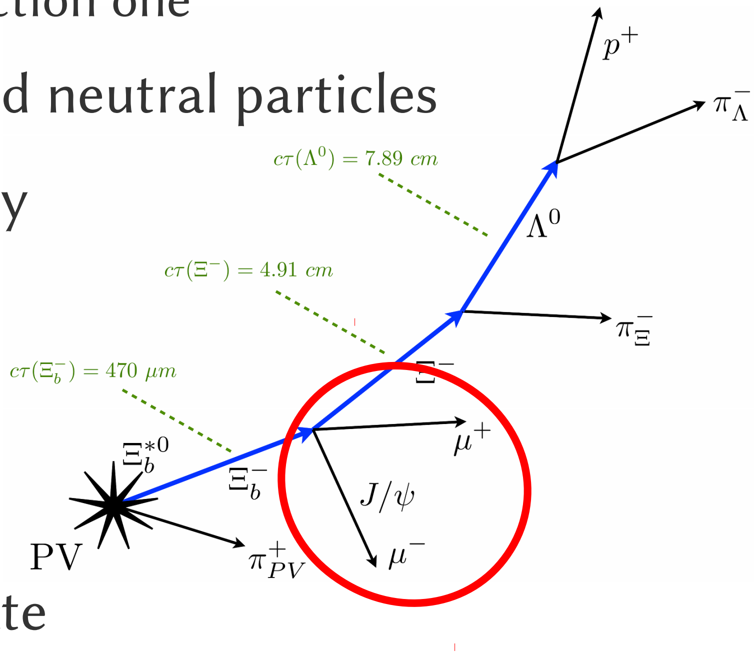
- At CMS, often looking at **$J/\psi \to \mu\mu$** in the final state





# Inclusive vs. exclusive signatures

- **Inclusive signatures**
  - Do not reconstruct a specific decay or hadron species, but look for generic production and decay of b (or $b\bar{b}$) quarks
  - **Main signatures**: b-jets, secondary vertices, impact parameter, muon $p_T$ with respect to jet axis, etc.
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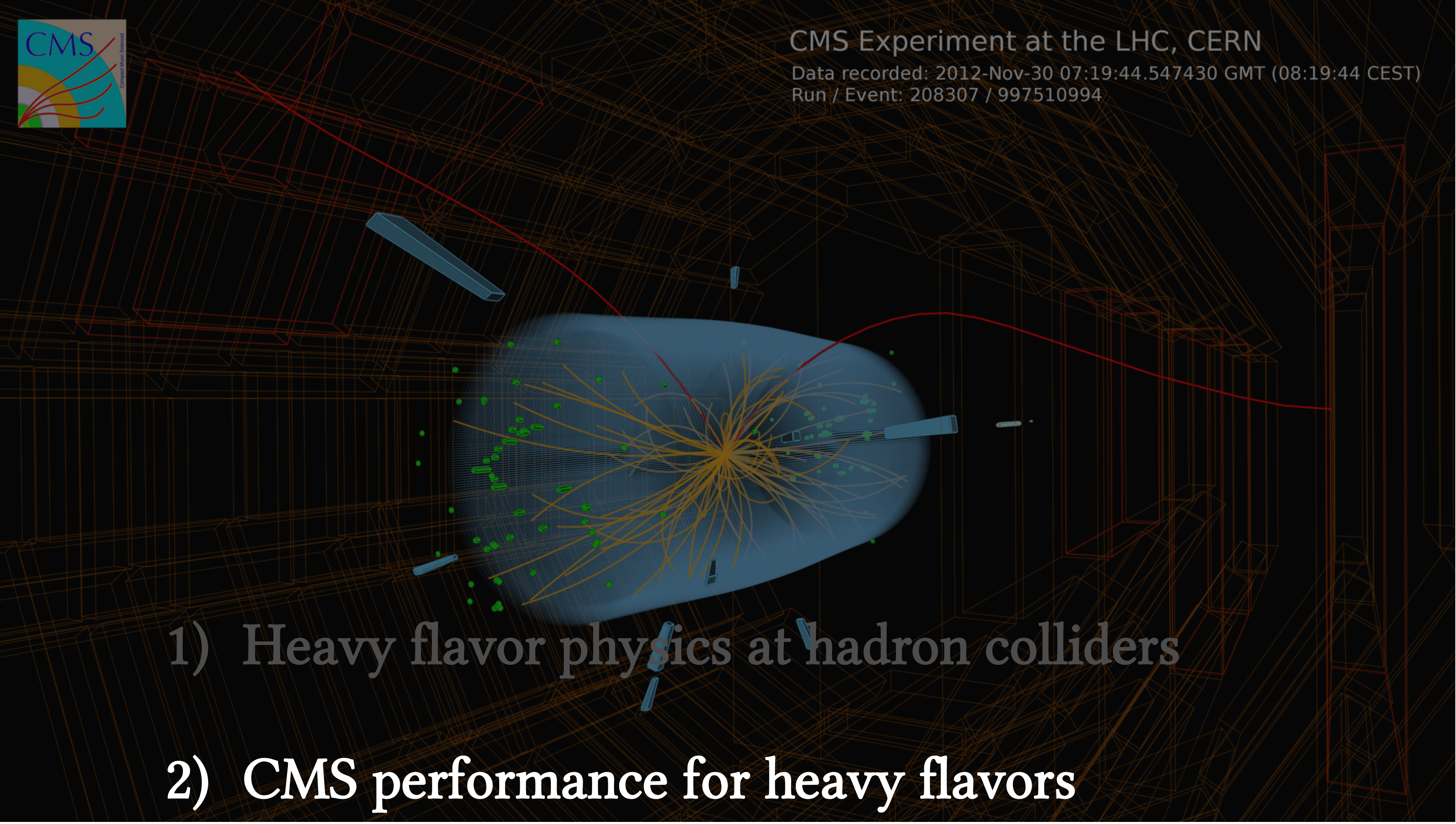
- **Exclusive signatures**
  - Look for a specific hadron and/or a specific decay chain, in order to study the properties of a single process
  - **Main signatures**: tracks of charged leptons and hadrons, secondary vertices, impact parameter, candidate invariant mass, proper decay length, pointing angle, etc.
  - **Possible measurements**: spectroscopy, polarization, branching fractions, CP violation, etc.



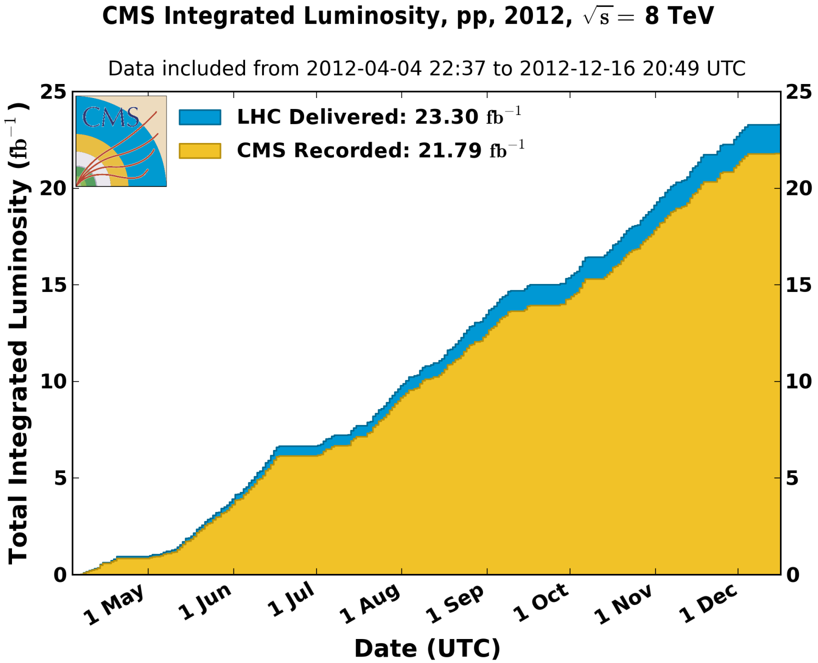
1) Heavy flavor physics at hadron colliders

2) CMS performance for heavy flavors

# Introduction:
# why HF physics in CMS?

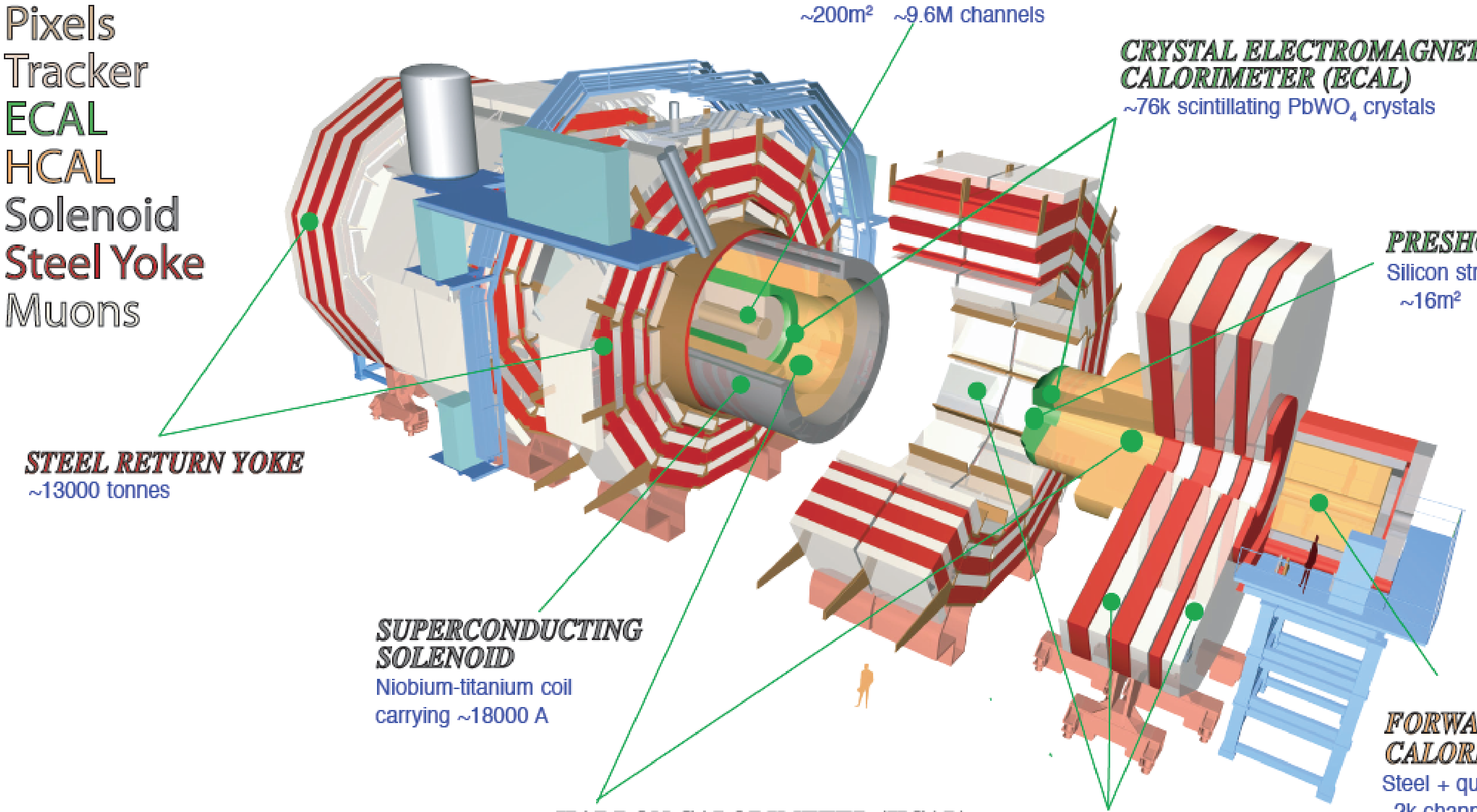
# LHC Run 1

- During Run 1 LHC has collided two proton beams with $\sqrt{s}$ = 7 TeV (2010, 2011) and 8 TeV (2012)
- The total luminosity delivered to CMS was **~29 fb**$^{-1}$ (6 fb$^{-1}$ in 2011 and 23 fb$^{-1}$ in 2012)
- CMS recorded **~27 fb**$^{-1}$ of data (~93% data taking efficiency)



# CMS detector

JINST 3 (2008) S08004



**SILICON TRACKER**
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
~76k scintillating $PbWO_4$ crystals

**PRESHOWER**
Silicon strips
~16m² ~137k channels

**STEEL RETURN YOKE**
~13000 tonnes

**SUPERCONDUCTING SOLENOID**
Niobium-titanium coil
carrying ~18000 A

**HADRON CALORIMETER (HCAL)**
Brass + plastic scintillator
~7k channels

**FORWARD CALORIMETER**
Steel + quartz fibres
~2k channels

**MUON CHAMBERS**
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

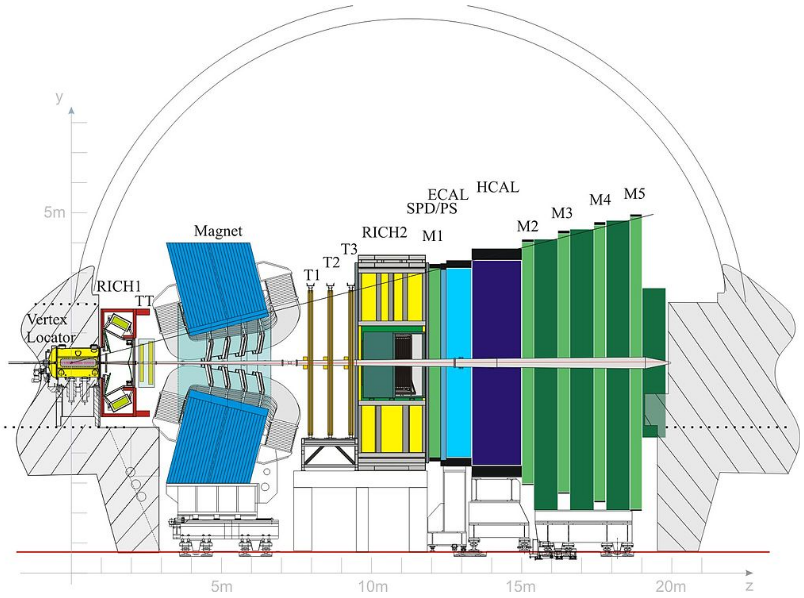
**Total weight : 14000 tonnes**
**Overall diameter : 15.0 m**
**Overall length : 28.7 m**
**Magnetic field : 3.8 T**

**~93%** of proton-proton collisions recorded by CMS are **good for physics**
(**~5 fb$^{-1}$** in 2011 + **~20 fb$^{-1}$** in 2012)

# CMS vs. LHCb

JINST 3 (2008) S08005

- A dedicated detector for b and c physics (**LHCb**) is also active at LHC
  - Been carrying out a wide heavy flavor physics program

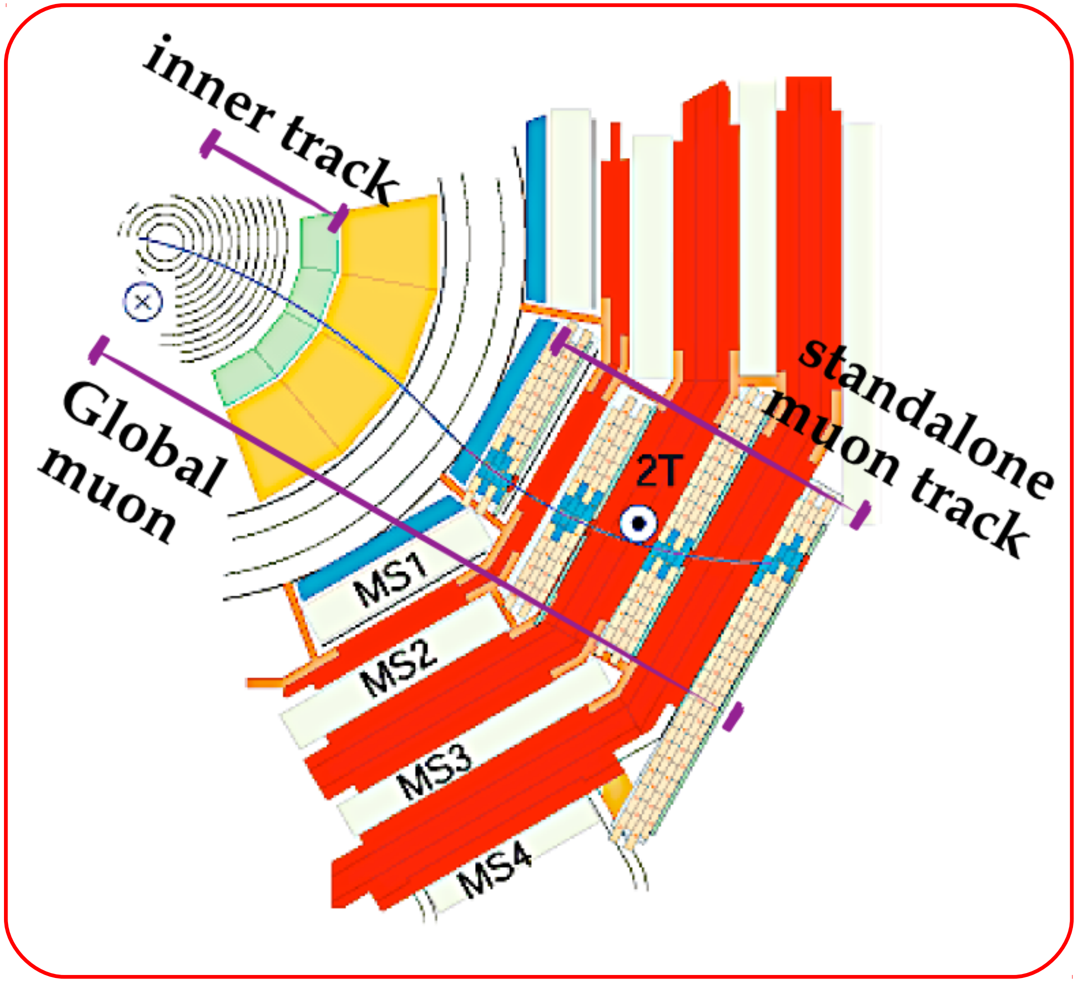


**How does CMS compare to it?**

| CMS | LHCb |
|---|---|
| **$\eta$ acceptance** | $\eta = -\log[\tan(\theta/2)]$ |
| Tracking in the central region ($-2.4 < \eta < 2.4$), calorimetry up to $\|\eta\| < 5$ | Forward region ($2 < \eta < 5$), where most b production occurs (cfr. FEX process) |
| **Collected luminosity** | |
| Full LHC luminosity (25 $fb^{-1}$ of data) | Leveled luminosity (3 $fb^{-1}$ of data) |
| **Particle ID capabilities** | |
| Limited hadronic PID capability, need to rely on **muons for HF trigger/reconstruction** | Powerful hadronic PID, can perform analyses using fully-hadronic final states |

# CMS muon reconstruction

- At CMS, **muons** are the most popular signature of HF production and decay
- Their reconstruction depends on the **inner silicon tracker** and **muon detectors**
- Muons are reconstructed
  - **Locally** in the muon detectors (standalone muons)
  - **Inside-out** (tracker muons)
  - **Outside-in** (global muons)
- Normally, HF physics analyses use a **tight muon** definition, requiring a μ to be reconstructed as both tracker and global muon
  - Other requirements include a low $\chi^2$ of the track fit, minimum number of hits, etc.



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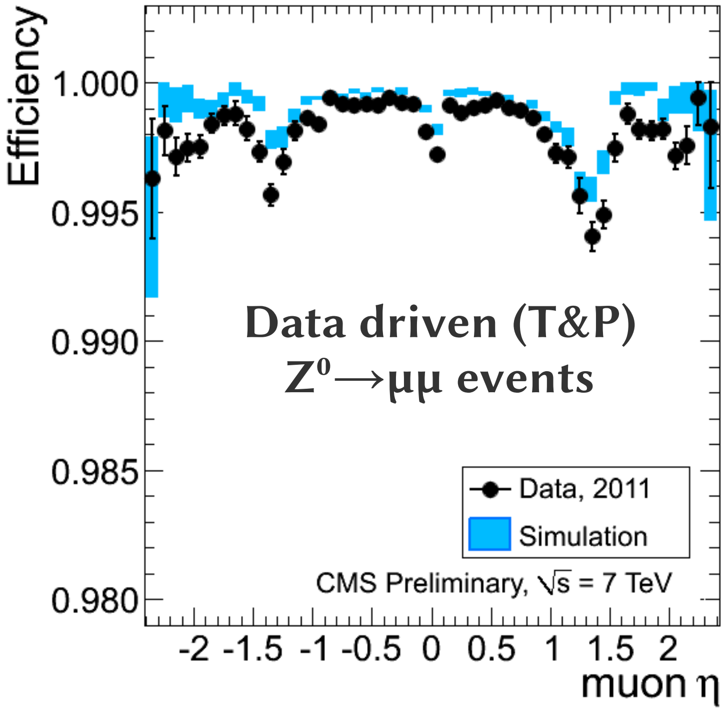
**Data driven (T&P)**
**$Z^0 \rightarrow \mu\mu$ events**

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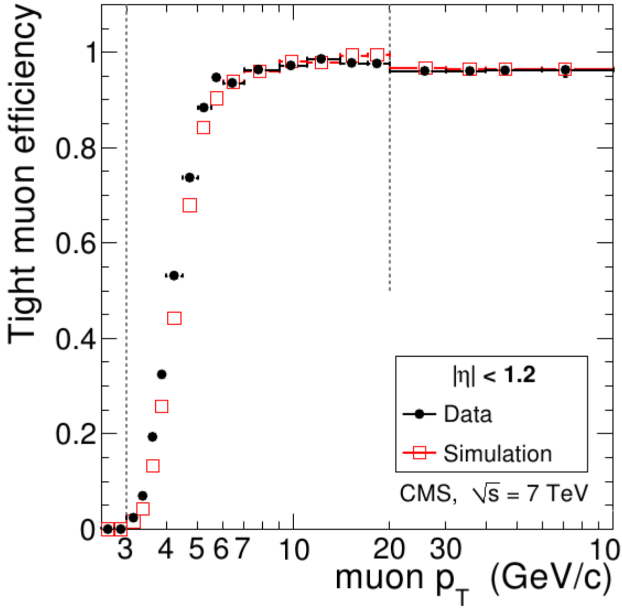

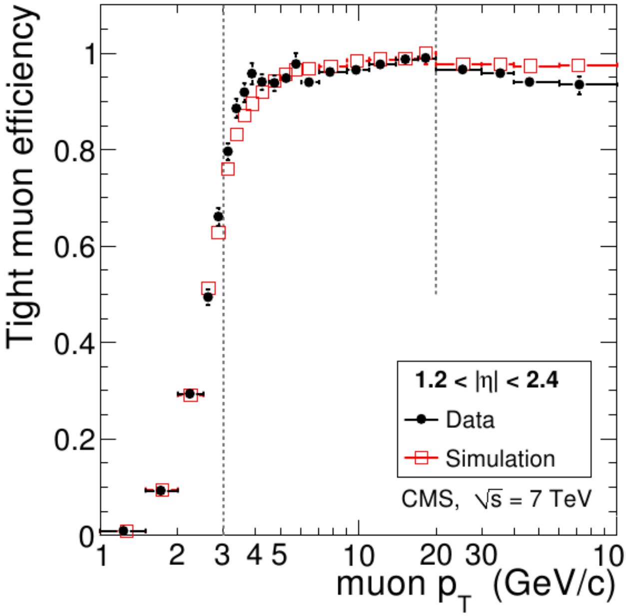

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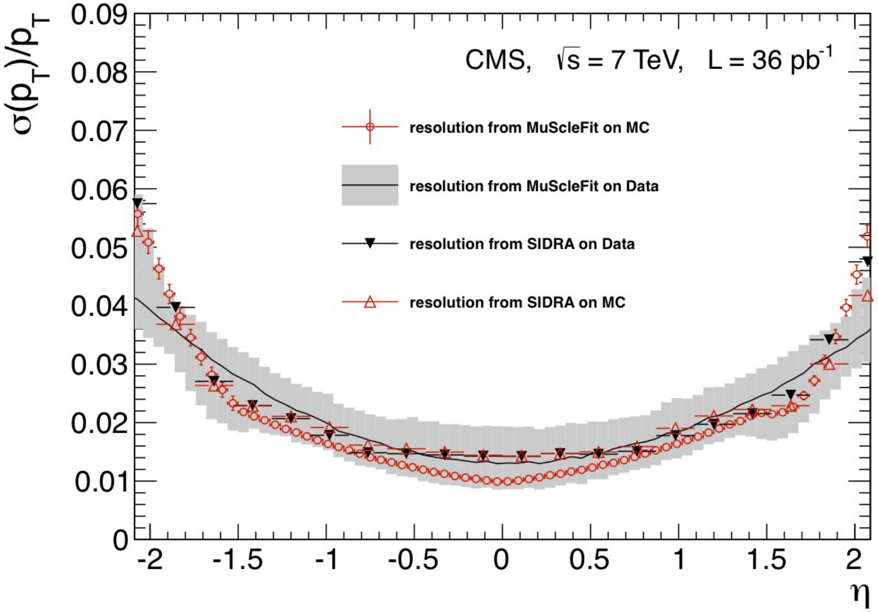

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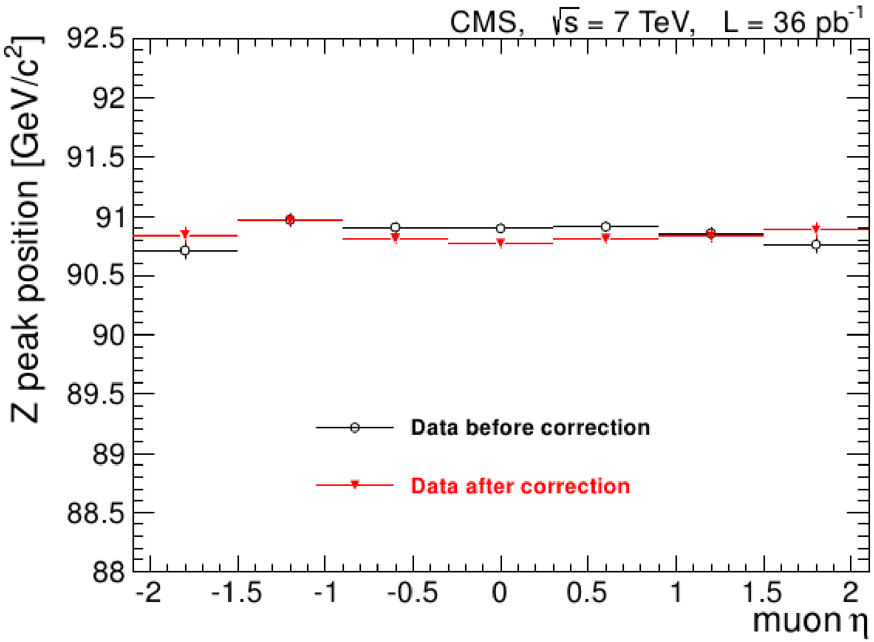

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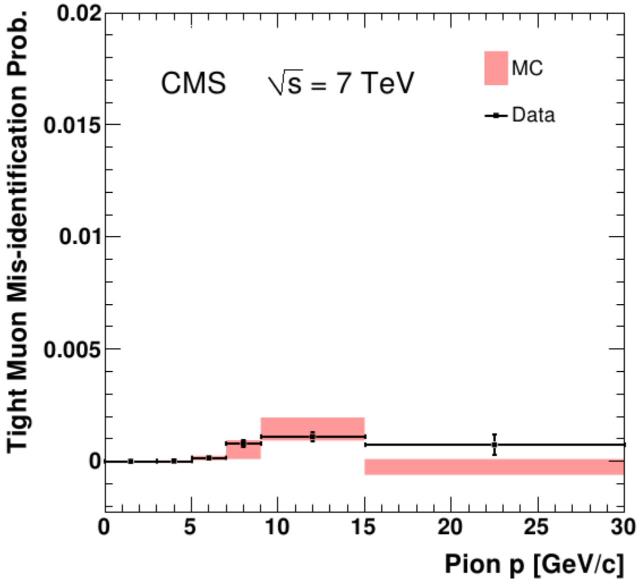

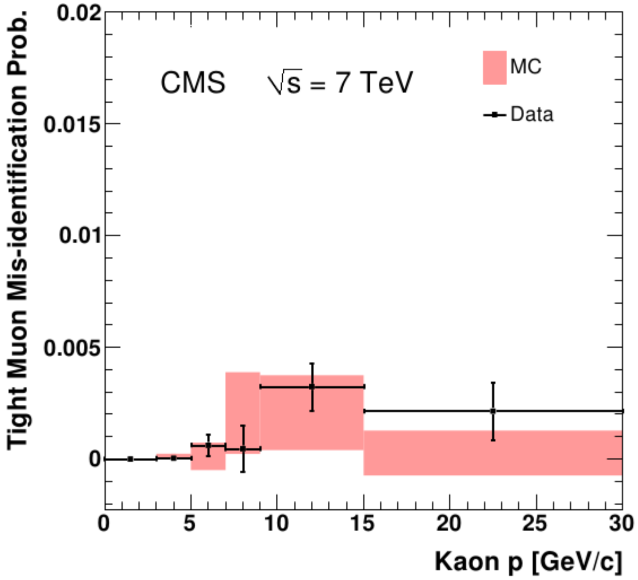

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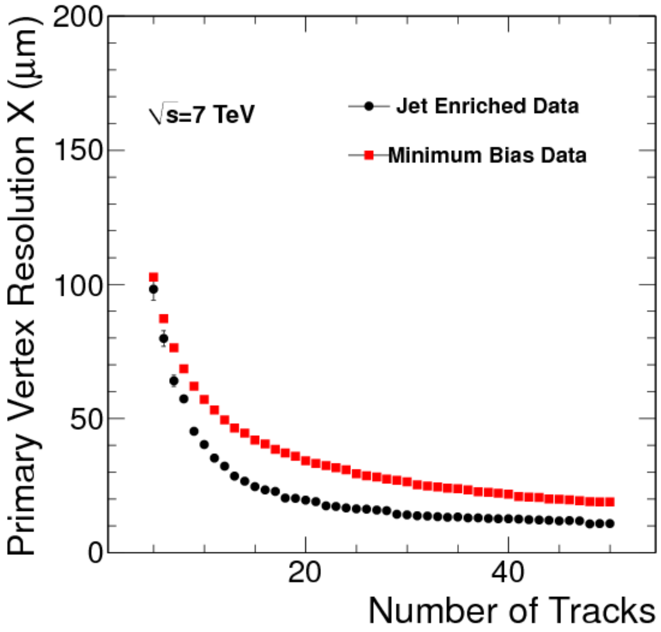
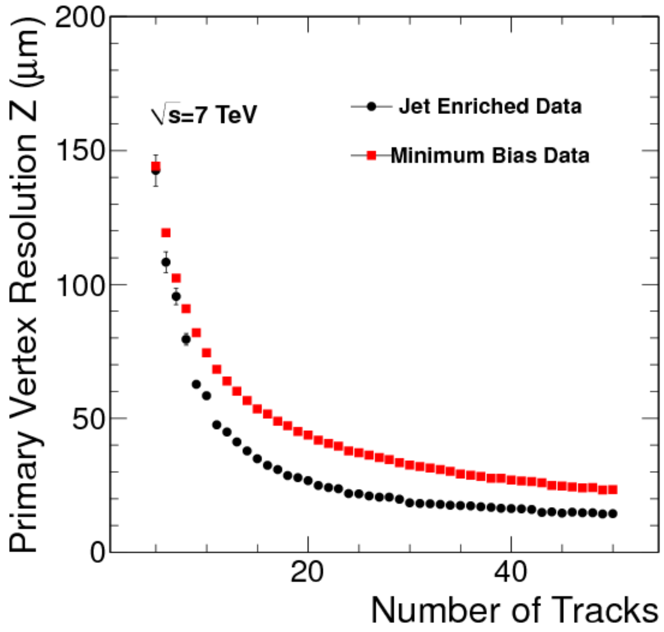
- **Vertex resolution of ~10÷20μm**

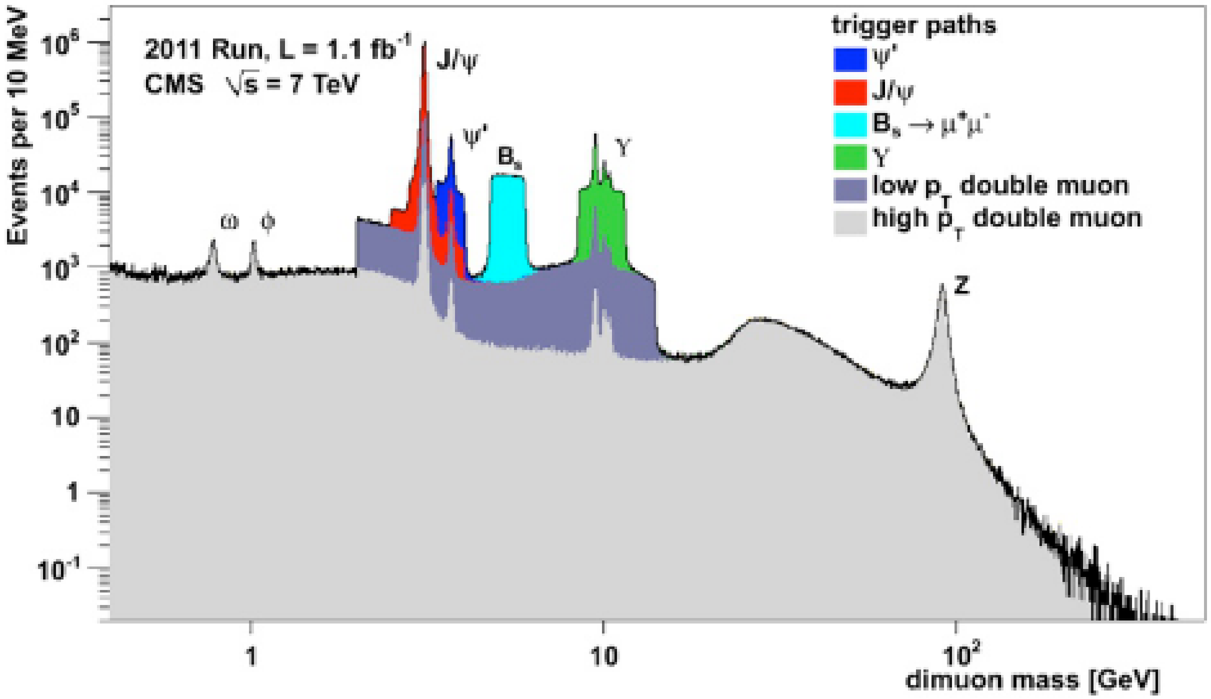




# CMS triggers for heavy flavors

- CMS has a **3-level trigger system** that allows to apply complex selections already in the very early stages of the event processing
- Crucial to select the **~50/s** pp interactions interesting for HF physics out of the **~5×10$^8$/s** produced by LHC (in 2012)
- Most HF triggers based on the presence of **di-μ in the final state**

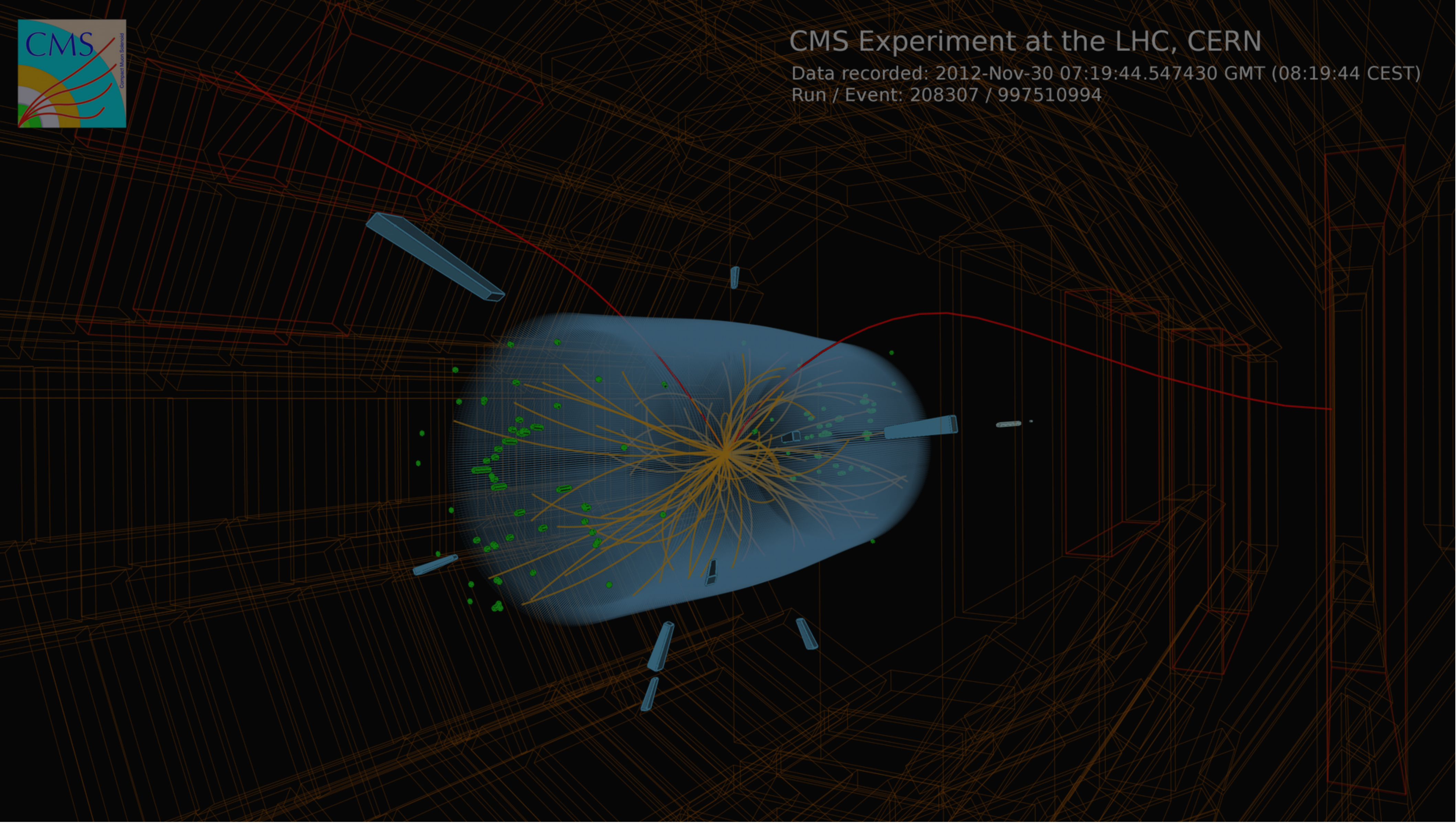
**"Out-of-the-box" invariant mass distribution of the di-μ selected by the CMS HF triggers (no further cleaning applied)**



# Why HF physics in CMS?

1) **Hadron colliders complementary to B factories for HF studies**
   - Very high b and c production cross sections
   - Can study hadron species not produced at B factories
   - Can study production mechanisms not occurring at B factories
2) **Though not a dedicated detector, CMS can compete with LHCb on several fronts**
   - Covers a different phase space and gets more luminosity from LHC
   - Excellent tracking and vertexing performance
   - Excellent muon reconstruction and identification
   - Powerful trigger system

- **These points show the CMS potential to be a leading heavy flavor experiment**
- **We can now see more in detail what it has done to realize this potential!**



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- Many measurements covering several different fields
  - Inclusive cross sections and correlations
  - Exclusive B hadron production cross sections
  - B hadron properties (lifetimes, masses, etc.)
  - Rare B decays
  - CP violation
  - Conventional quarkonia properties
  - Exotic hadrons and quarkonia properties

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- **Programme too vast to be summarized in this seminar**

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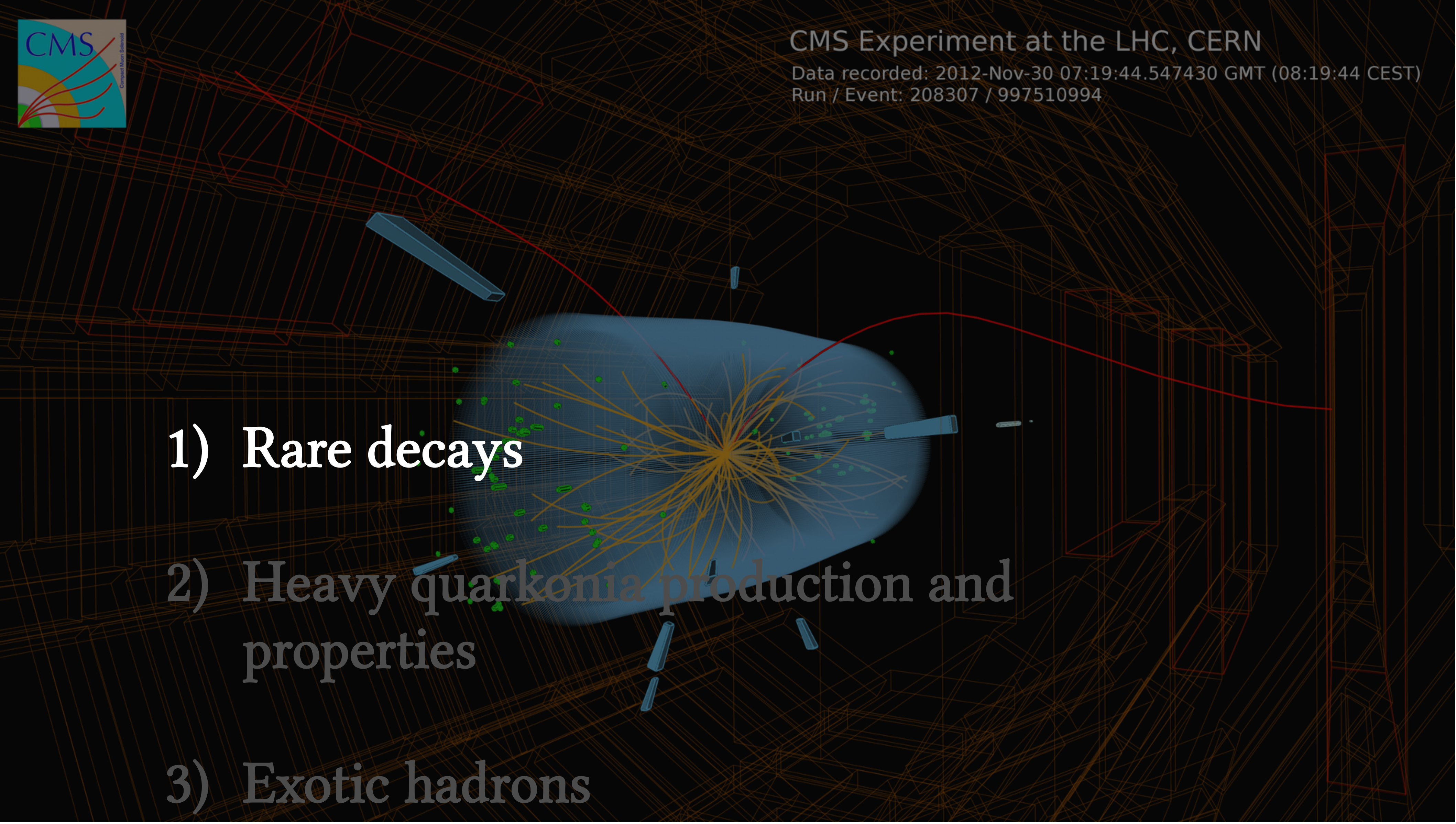
  - B hadron properties (lifetimes, masses, etc.)
  - **Rare B decays**
  - CP violation
  - **Conventional quarkonia properties**
  - **Exotic hadrons and quarkonia properties**
- **Programme too vast to be summarized in this seminar**
- I picked **a few topics** that cover some of the most recent results (**based also on my taste**) and will concentrate on them

# What HF physics in CMS?



1) Rare decays
2) Heavy quarkonia production and properties
3) Exotic hadrons

# Rare decays: a complement to direct searches

- **Rare B decays** (i.e. **decays that are forbidden to happen at tree level**) are among the key tests of the Standard Model within flavor physics

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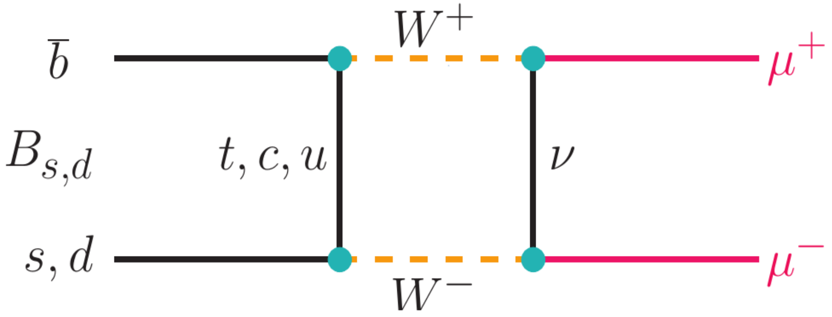
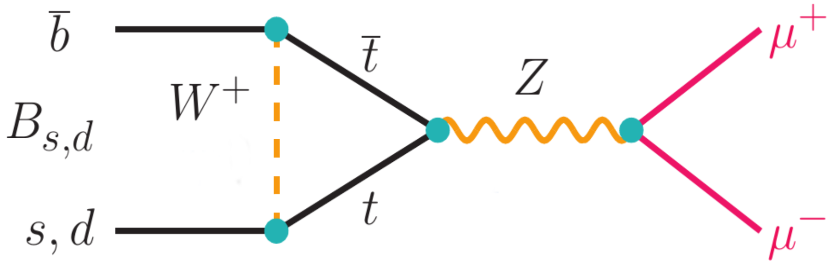
- **The "golden" example: $B_s \longrightarrow \mu\mu$**
  - Involves a FCNC ⟶ forbidden at tree level
  - Can happen through **1-loop diagrams**
  - Additional helicity suppression factor $(m_\mu^2/m_B^2)$





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  - Can happen through **1-loop diagrams**
  - Additional helicity suppression factor $(m_\mu^2/m_B^2)$
- **Sensitive to new physics contributions to the loop!**
  - NP particles in the loop can significantly affect the branching fractions
  - Measuring $\mathcal{B}(B_s \to \mu\mu)$ constrains NP models

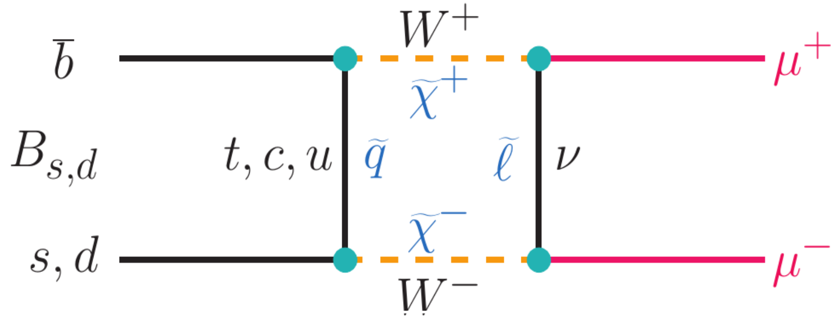
**A few examples**

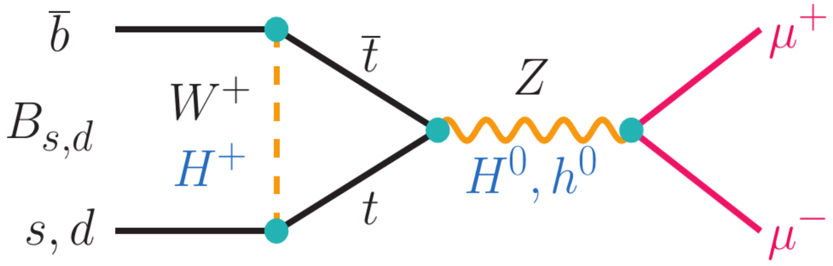
- **2HDM**: $\mathcal{B} \sim \tan^4\beta$

  JHEP 05 (2006) 063
- **MSSM**: $\mathcal{B} \sim \tan^6\beta$

  Nucl. Phys. B 760 (2007) 38
- **Leptoquarks**

  JHEP 11 (2010) 073





# $\mathcal{B}(B^0_{(s)} \rightarrow \mu^+\mu^-)$ in the Standard Model

Theoretical expression of the branching fraction

$$\mathcal{B}^{(0)}_{s,\mathrm{SM}} = \underbrace{\frac{G_F^2}{\pi}\left[\frac{\alpha_{\mathrm{em}}(M_Z)}{4\pi \sin^2\theta_W}\right]^2}_{\text{Gauge couplings}} \tau_{B_s} f_{B_s}^2 m_{B_s} m_\mu^2 \times \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}\,|V_{\mathrm{tb}}^* V_{\mathrm{ts}}|^2 \underbrace{Y^2(x_{tW}, x_{ht}; \alpha_s)}_{\textbf{Short-distance coefficient}}$$

CKM matrix

**Long-distance matrix element**

$$x_{tW} = (m_t / m_W)^2$$

$$x_{ht} = (m_h / m_t)^2$$

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Phenomenological expression of the branching fraction:

Eur. Phys. J. C 72 (2012) 2172
JHEP 07 (2013) 077

$$\mathcal{B}^{(0)}_{s,\mathrm{SM}} = 3.2348 \times 10^{-9} \times \left(\frac{M_t}{173.2\ \mathrm{GeV}}\right)^{3.07}\left(\frac{f_{B_s}}{227\ \mathrm{MeV}}\right)^2 \times \left(\frac{\tau_{B_s}}{1.466\ \mathrm{ps}}\right)\left|\frac{V_{\mathrm{tb}}^* V_{\mathrm{ts}}}{4.05 \times 10^{-2}}\right|^2$$

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- Makes evident the external inputs needed for the theoretical prediction
  - The SM value precision strongly depends on these inputs: **~6.4%(8.5%) for $B_s(B^0)$**

C. Bobeth, Moriond 2014

| Error budget | $M_t$ | $f_{Bs}$ | $\tau_{Bq}$ | CKM | Non-param. | Total error |
|---|---|---|---|---|---|---|
| $B_s$ | **1.6%** | **4.0%** | **1.3%** | **4.3%** | 1.5% | **6.4%** |
| $B^0$ | **1.6%** | **4.5%** | **0.5%** | **6.9%** | 1.5% | **8.5%** |

**Latest $M_t$ Tevatron-LHC average not considered yet**

**Biggest contributions to the error budget**
**Respectively from lattice QCD and UTFit averages**

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  - **Soft γ emission**: due to finite $M(B^0_{(s)})$ experimental resolution
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**Latest SM predictions for the two branching fractions**

$$\mathcal{B}(B_s\to\mu\mu) = (3.65 \pm 0.23)\times10^{-9}$$

$$\mathcal{B}(B^0\to\mu\mu) = (1.06 \pm 0.09)\times10^{-10}$$

PRD 89 (2014) 034023, PRL 112 (2014) 101801

# $B^0_{(s)}$→μμ in CMS: general strategy

PRL 111 (2013) 101804

- **Blind analysis**: look at the signal region only after having frozen the method and the selections
  - Use simulation to estimate the effect on the signal and the expected sensitivity
- **$B^+$→J/ψ$K^+$** as **normalization channel** to reduce the systematic uncertainties:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_S}{N^{B^+}_{\text{obs}}} \frac{f_u}{f_s} \frac{\varepsilon^{B^+}_{\text{tot}}}{\varepsilon_{\text{tot}}} \mathcal{B}(B^+)$$

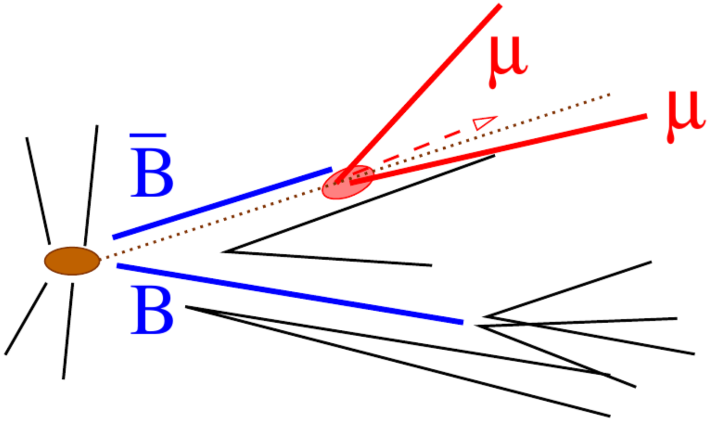
- **$B_s$→J/ψϕ** as a **control channel** to validate the signal simulation

- **$\mathcal{B}$($B_s$→μμ) measured** with an unbinned maximum likelihood fit to the invariant mass distribution
- **Upper limit to $\mathcal{B}$($B^0$→μμ)** extracted with the $CL_s$ method

# Signal and main backgrounds

PRL 111 (2013) 101804

- **Signal**: two muons from the same displaced vertex, momentum aligned with flight direction, mass peaking at $M(B_{s,d})$



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PRL 111 (2013) 101804

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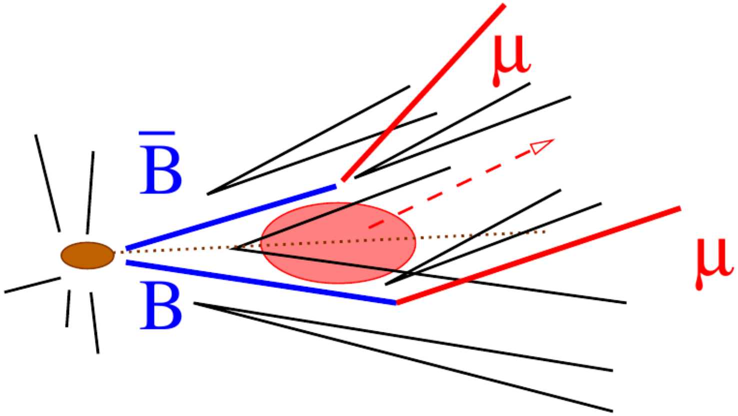
- **Combinatorial background**: mainly real di-μ coming from uncorrelated processes
  - Flat around the signal region
  - Estimated from mass sidebands in data



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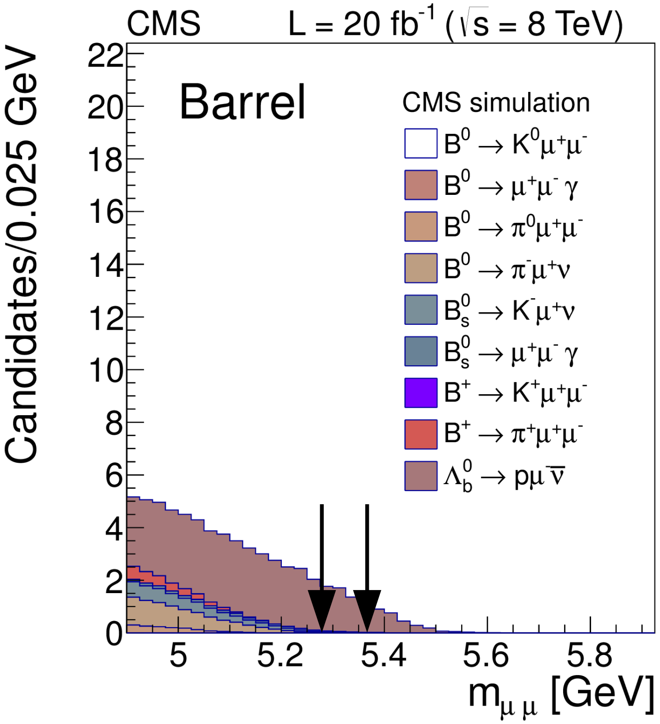

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PRL 111 (2013) 101804

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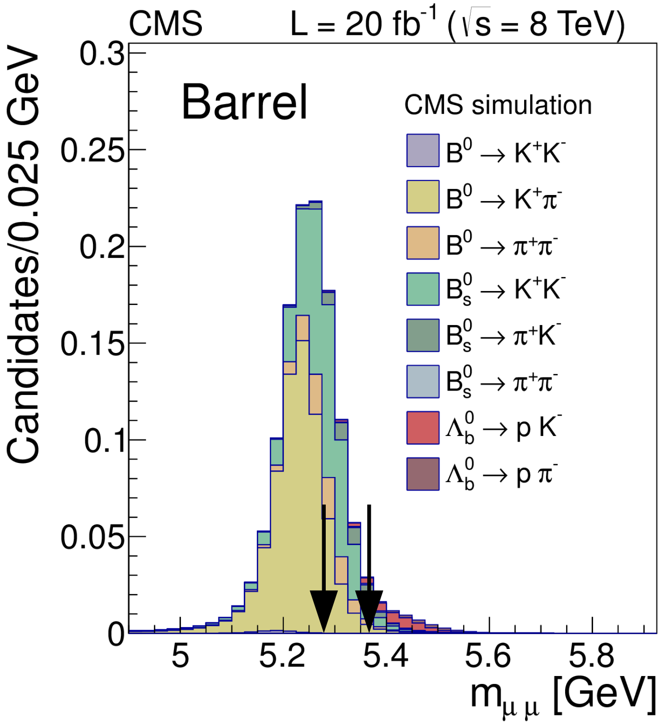
- **Peaking backgrounds**: B⟶hh′ (h, h′ = π, K, p) decays, with both light hadrons misidentified as μ
  - Both semileptonic and peaking backgrounds studied from simulations



# Background rejection

PRL 111 (2013) 101804

**1) Muon selection based on boosted decision tree (BDT)**

- Developed specifically for this analysis
  - Applied on top of standard tight muon selection
  - Necessary to reduce the peaking and semileptonic backgrounds
- Performance with respect to standard tight muons
  - **Hadron misidentification** rate reduced by **~50%**
  - **Real muon efficiency ~90%**

| **Probability to reconstruct a hadron as μ(%)** | | | |
|---|---|---|---|
| | **$\pi^{\pm}$** | **$K^{\pm}$** | **p** |
| **BDT μ** | 0.05-0.13 | 0.08-0.22 | 0.04-0.15 |

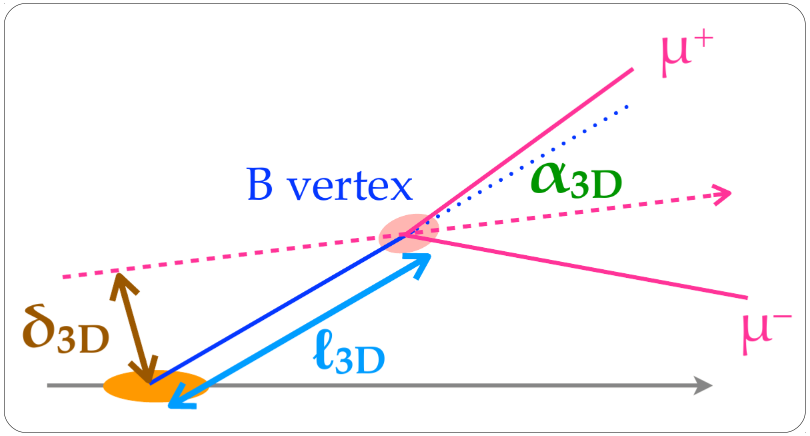
# Background rejection

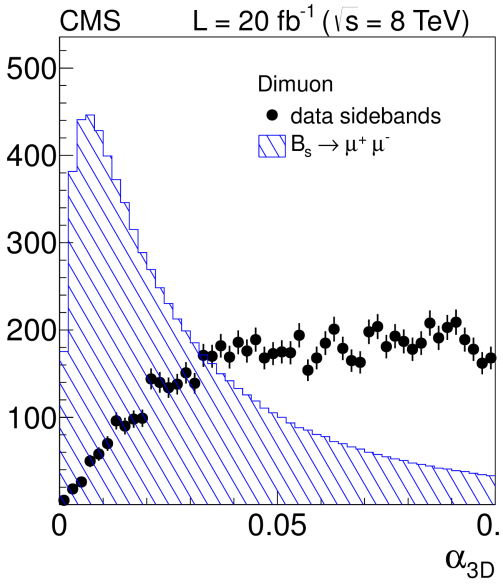
PRL 111 (2013) 101804

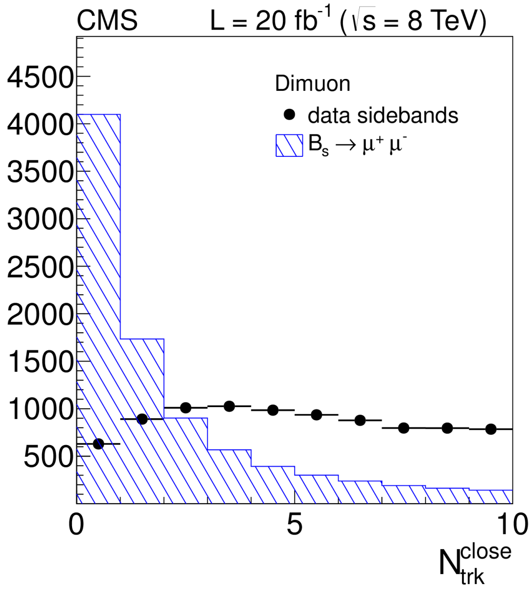
## 1) Muon selection based on boosted decision tree (BDT)

## 2) Signal selection based on BDT

- Trained with signal from MC and background from data sidebands (no assumptions made on background model)
    - **Isolation**
    - **Trajectory and vertexing**





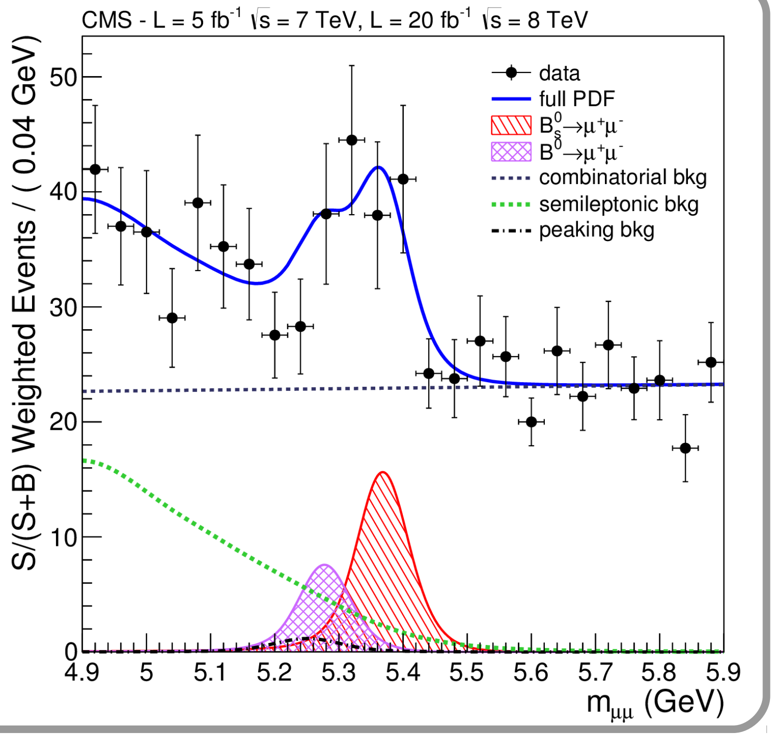


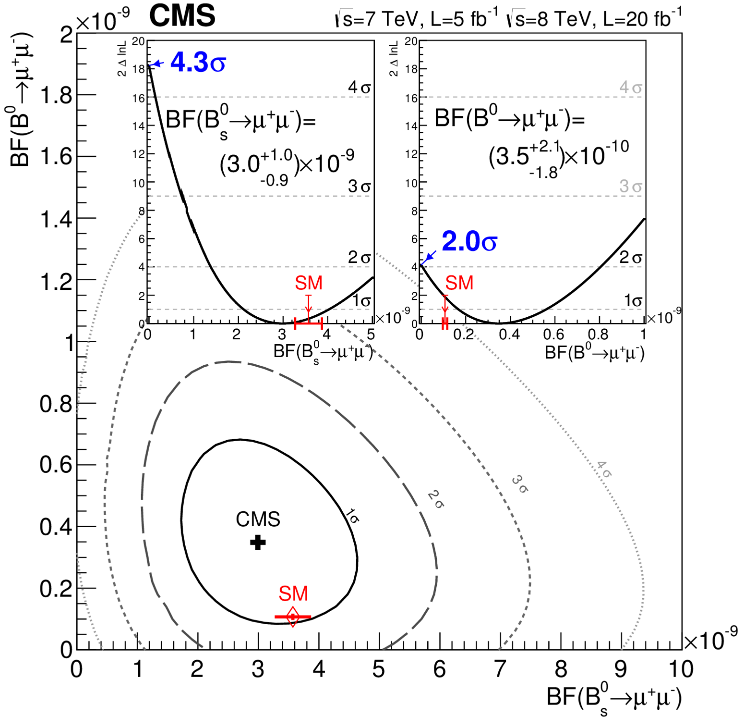
- – $\alpha_{3D}$: angle (in 3D) between the B candidate momentum and flight direction
- – $\delta_{3D}$ and $\ell_{3D}$: B candidate impact parameter and flight distance from primary vertex
- – $N_{trk}^{close}$: number of tracks in the vicinity of the B candidate decay vertex

# Results

PRL 111 (2013) 101804

**S/(S+B) weighted invariant mass distribution with fit results**





**2D likelihood** nσ contours in the $\mathcal{B}(B^0\to\mu\mu)$ vs. $\mathcal{B}(B_s\to\mu\mu)$ plane

**Inserts showing 1D likelihood contours**

- $\mathcal{B}(B_s\to\mu\mu) = 3.0^{+1.0}_{-0.9}\times10^{-9}$
  - Observed significance **4.3 σ** (expected 4.8σ)
- $\mathcal{B}(B^0\to\mu\mu) = 3.5^{+2.1}_{-1.8}\times10^{-10}$
  - Observed significance **2.0 σ**
- **Upper limit:** $\mathcal{B}(B^0\to\mu\mu) < 1.1\times10^{-9}$ **@ 95% CL**
  - Results **compatible with the Standard Model predictions** within 1 σ

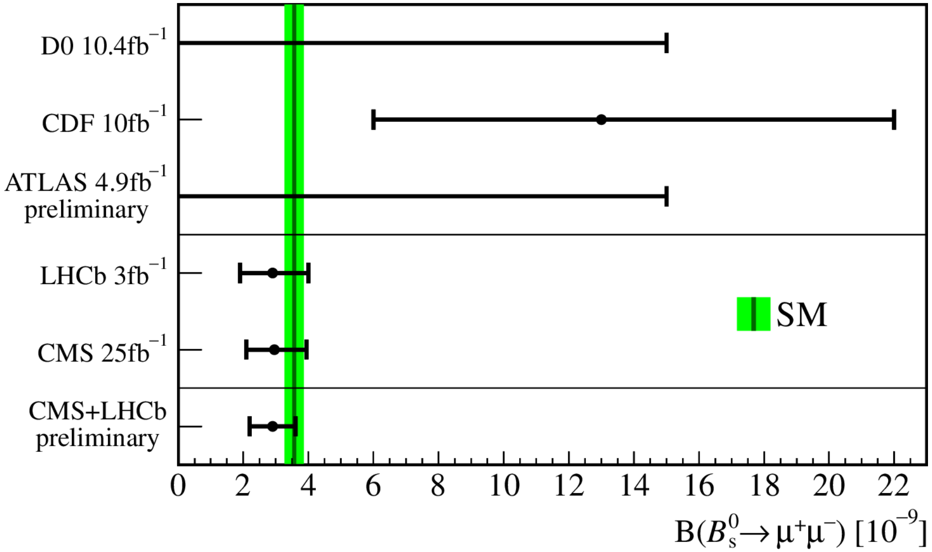
# CMS-LHCb combination

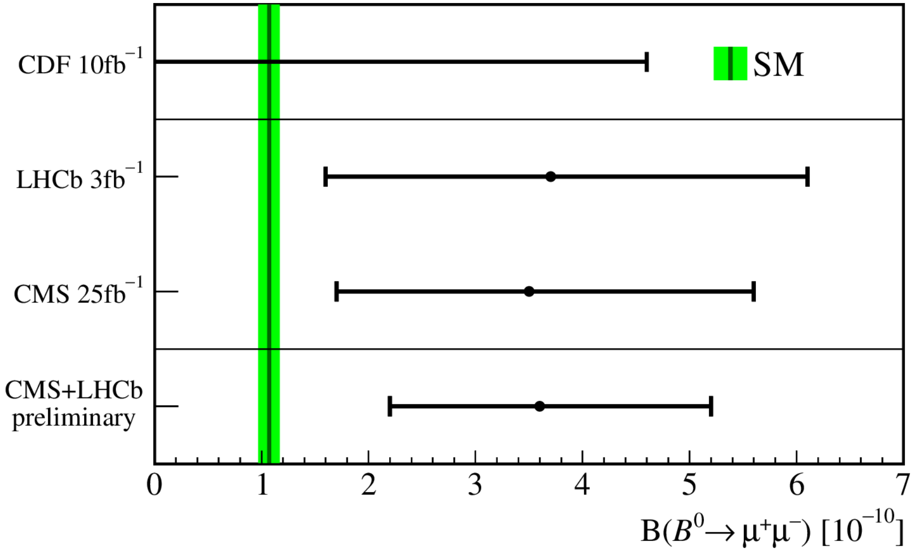
**CMS:** CMS-PAS-BPH-13-007
**LHCb:** LHCb-CONF-2013-012

- **Preliminary combination** of the CMS and LHCb results based on the whole Run 1 statistics
  - Known correlation between the uncertainties on $f_s/f_u$ taken into account
  - Work in progress in both experiments to get the final combination results
- Preliminary result:

$$\mathcal{B}(B_s \rightarrow \mu\mu) = (2.9 \pm 0.7) \times 10^{-9} \text{ (combined significance > 5}\sigma\text{)}$$

$$\mathcal{B}(B^0 \rightarrow \mu\mu) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10} \text{ (combined significance < 3}\sigma\text{)}$$

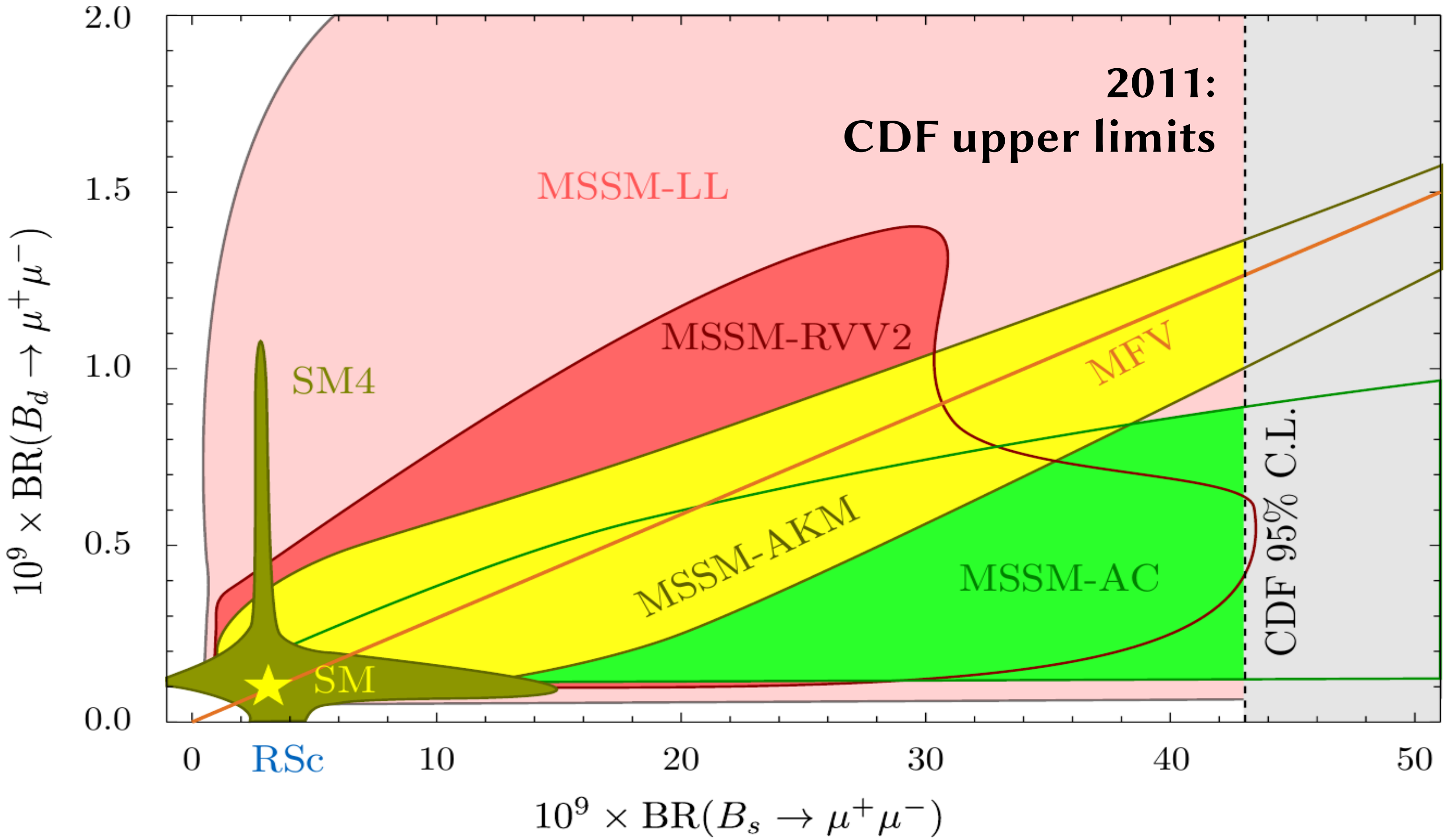




# $B^0_{(s)}$→μμ constraints to new physics

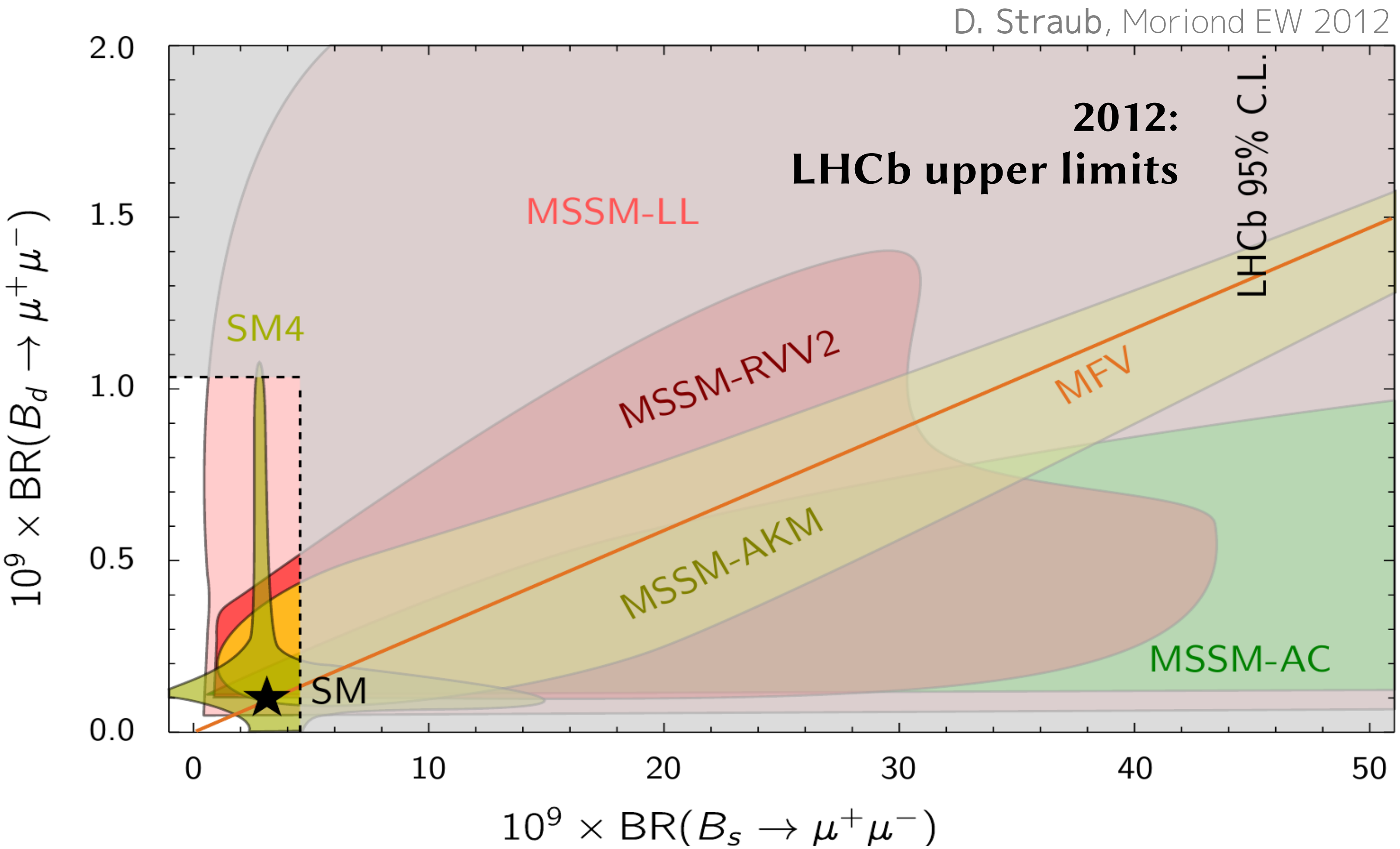
- Constraints on several new physics models:
  - Minimal Supersymmetric Standard Model (MSSM)
  - Minimal Flavor Violation (MFV)
  - Standard Model + 4th generation (SM4)

D. Straub, arXiv:1107.0266



# $B^0_{(s)} \longrightarrow \mu\mu$ constraints to new physics

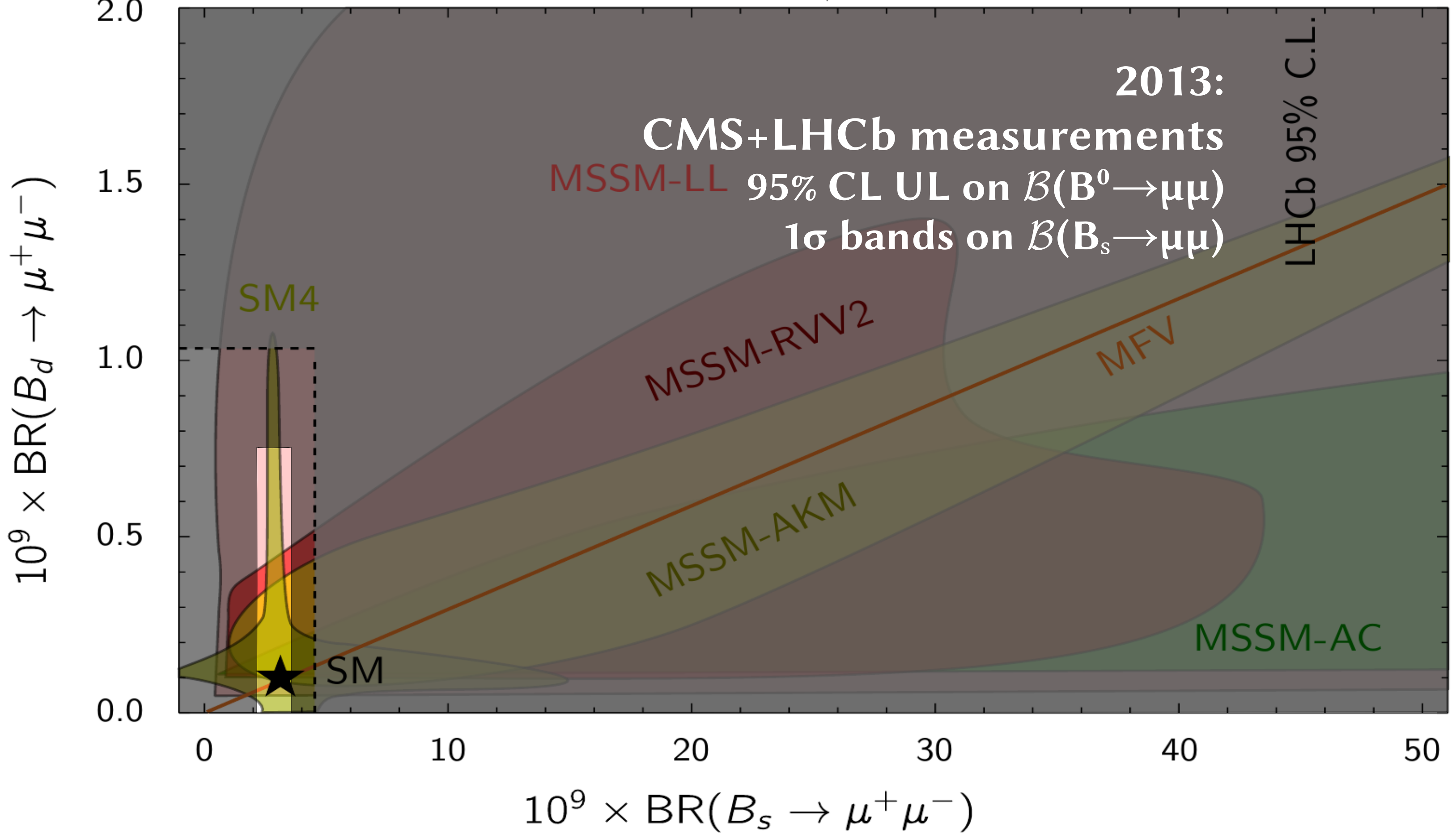
- 2012 LHCb upper limits on the two branching fractions

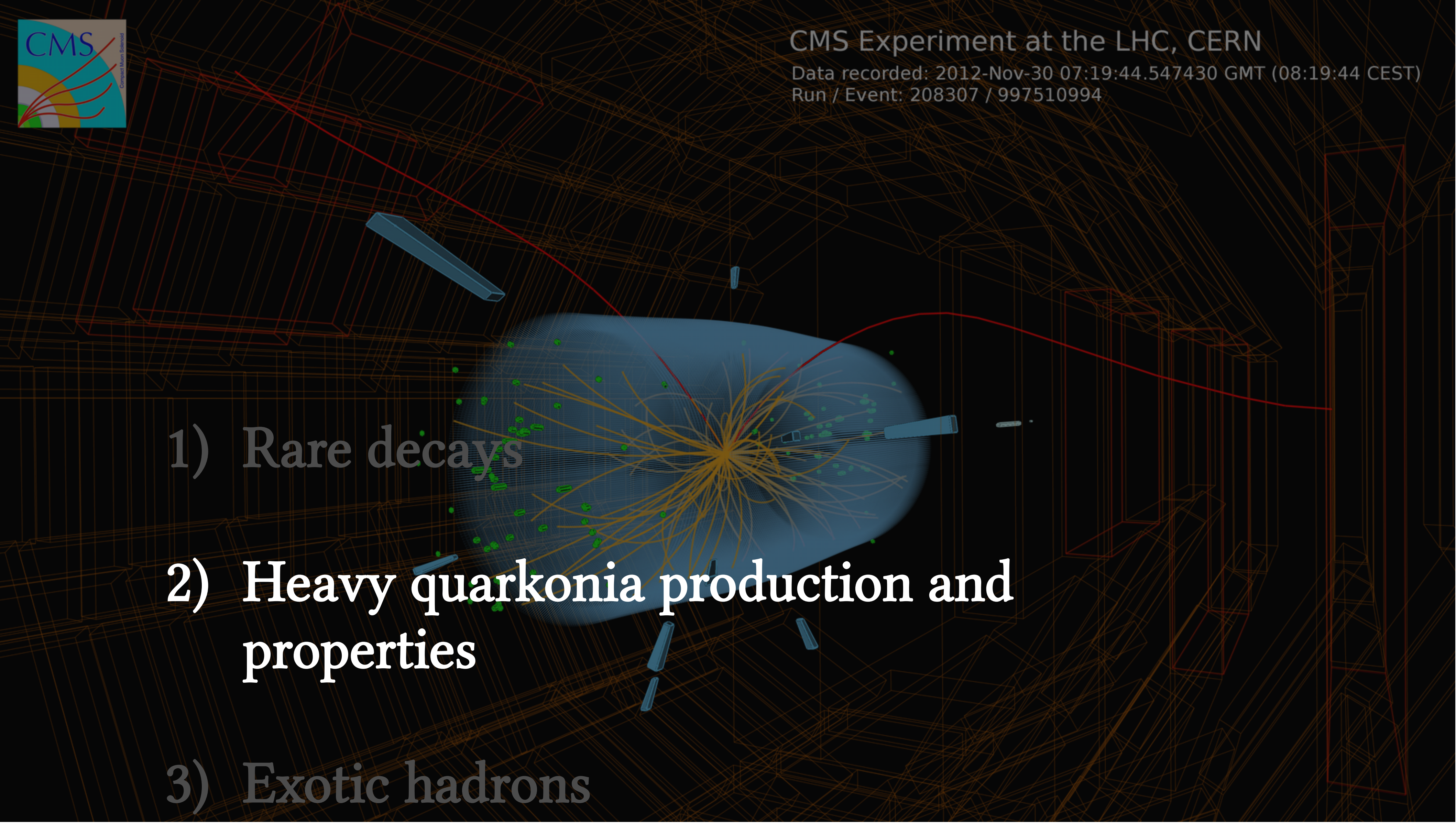


# Constraints from new CMS+LHCb results

- The new results significantly constrain the parameter space of several NP models
  - **New physics needs to look more and more like the Standard Model!**

Adapted from D. Straub, Moriond EW 2012





1) Rare decays

2) Heavy quarkonia production and properties

3) Exotic hadrons

# What HF physics in CMS?

# Quarkonium production at LHC

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  in the decays of heavier states (i.e. $B \longrightarrow \psi(nS)+X$)
    - Prompt production still not understood!

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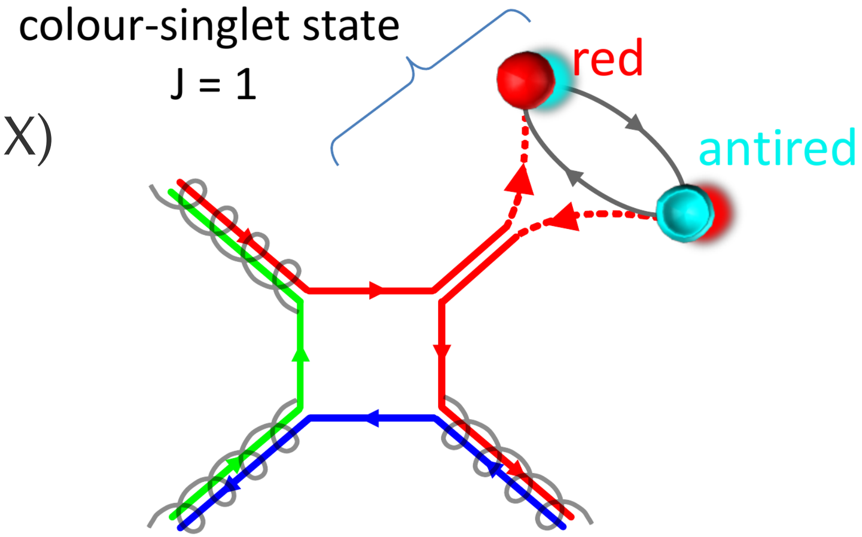
- **Color Singlet Model** (CSM)
  - Quarkonia directly produced as observable color-neutral states
  - The only model till Tevatron showed that σ(J/ψ) was higher by a factor ~30 than predictions



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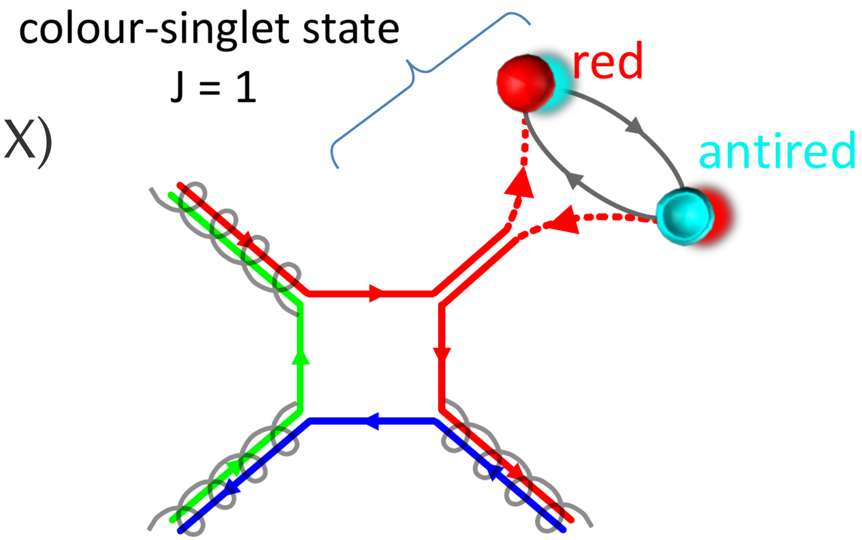

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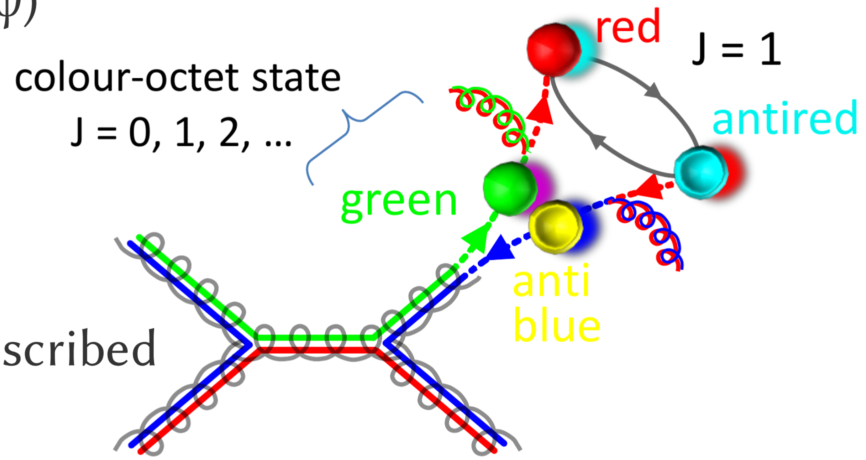
    - Quarkonia directly produced as observable color-neutral states
    - The only model till Tevatron showed that $\sigma(J/\psi)$ was higher by a factor ~30 than predictions
- **Non-relativistic QCD** (NRQCD)
    - $q\bar{q}$ produced as colored states
    - Non-perturbative decays to colorless states described by long-distance matrix elements (LDME) fitted from data or found from lattice QCD



# Experimental signatures

- The CSM and NRQCD frameworks make several predictions that can be compared with the experiments
- Large number of observables to test the two models
- **At CMS, studied only processes involving ψ(nS)[Υ(nS)]→μμ decays**

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- Production cross sections
  - $d\sigma(\psi(nS))/dp_T$, $d\sigma(\Upsilon(nS))/dp_T$
- Polarizations
  - $\lambda_\theta$, $\lambda_\varphi$, $\lambda_{\theta\varphi}$

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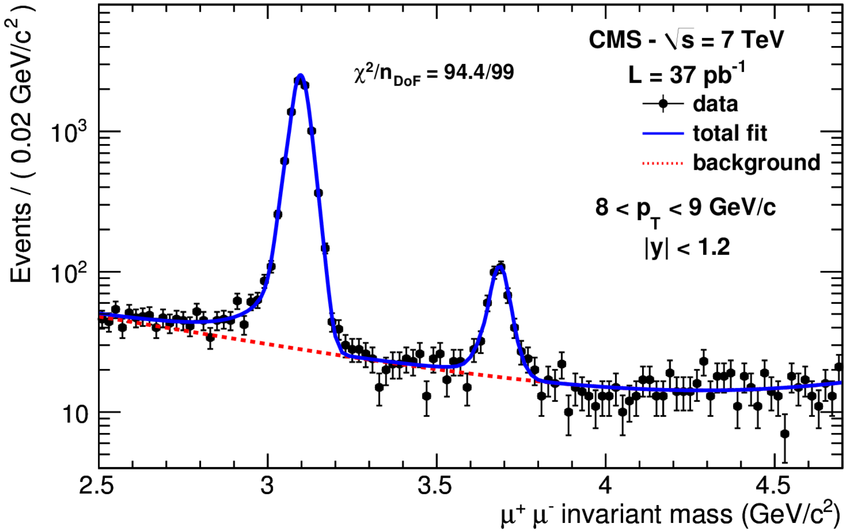
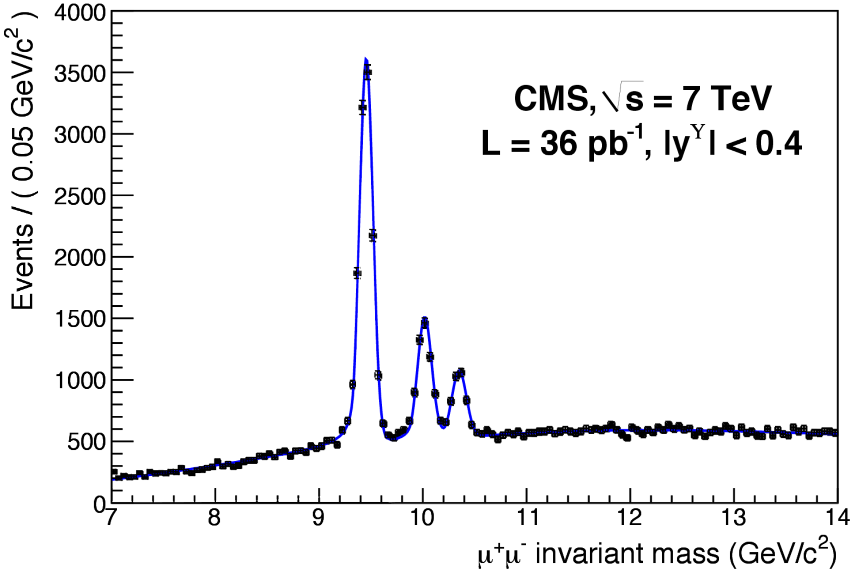
- **Production cross sections**
    - **$d\sigma(\psi(nS))/dp_T$, $d\sigma(Y(nS))/dp_T$**
- Polarizations
    - $\lambda_\theta$, $\lambda_\varphi$, $\lambda_{\theta\varphi}$

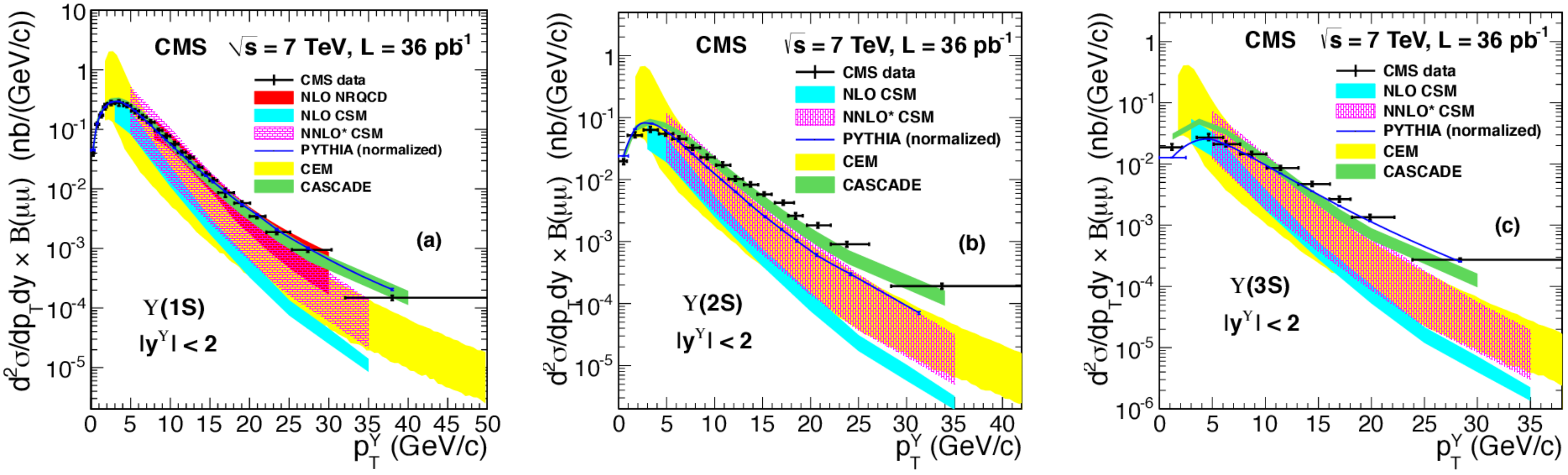




# Y(nS) production cross sections

PLB 727 (2013) 101

- Production cross sections of Υ(1S, 2S, 3S) states measured in 2010 data and compared with the predictions of several models and generators
- In particular
  - **NLO NRQCD in good agreement** with Υ(1S) data
  - **CSM** **not describing data at NLO** but **in better agreement** (within the higher uncertainty) **at NNLO***

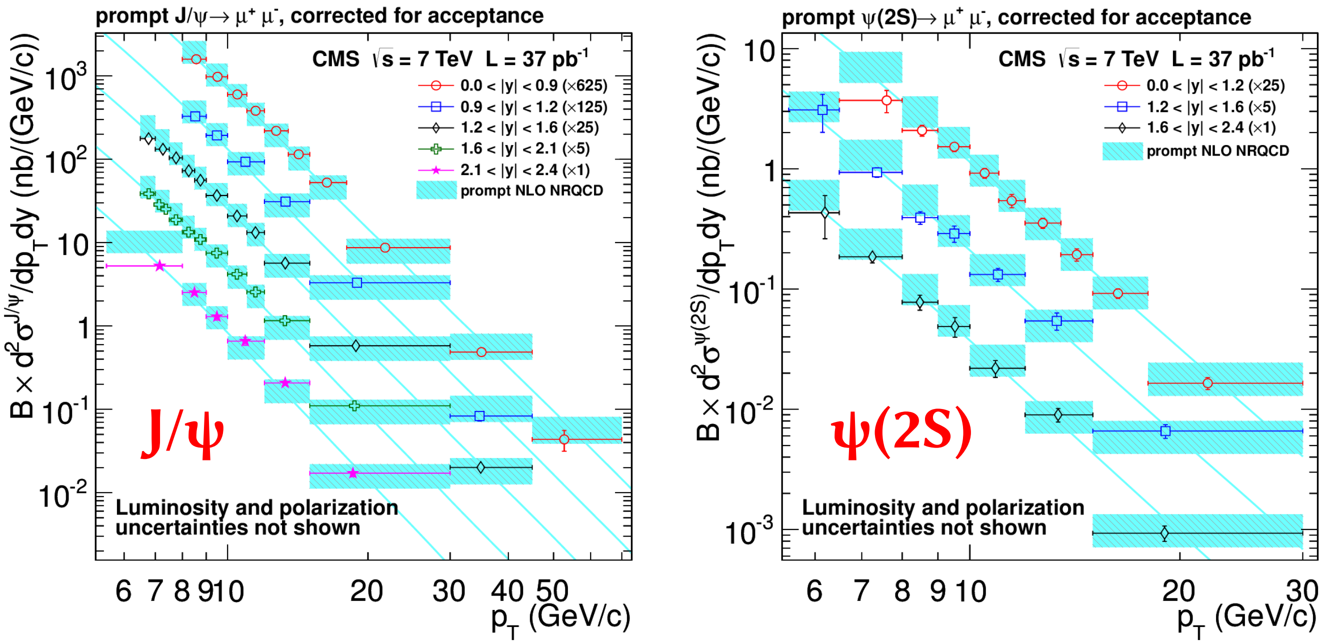


# J/ψ and ψ(2S) cross sections

JHEP 02 (2012) 011

- Prompt component **well described by NLO NRQCD** in the full $p_T$ and rapidity range

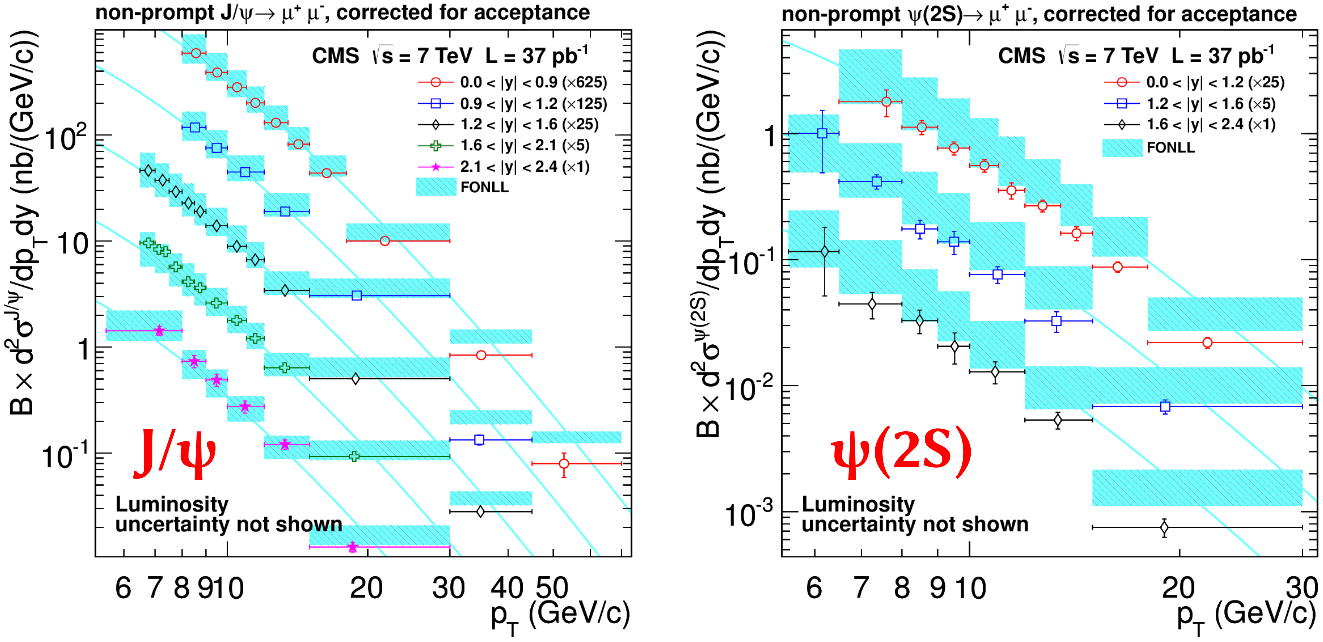
**PROMPT**


prompt J/ψ→ μ⁺ μ⁻, corrected for acceptance

prompt ψ(2S)→ μ⁺ μ⁻, corrected for acceptance

- Nonprompt component compared with **perturbative FONLL calculations**
- Model well describing data for J/ψ, slightly higher for ψ(2S)

**NONPROMPT**


non-prompt J/ψ→ μ⁺ μ⁻, corrected for acceptance

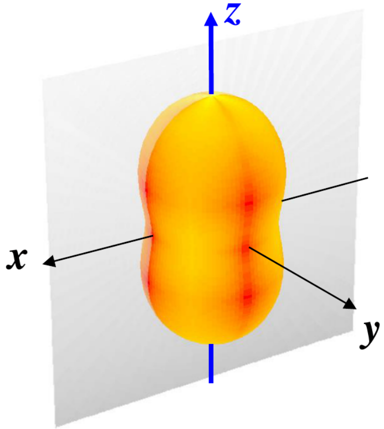
non-prompt ψ(2S)→ μ⁺ μ⁻, corrected for acceptance

# Experimental signatures: polarizations

- The CSM and NRQCD frameworks make several predictions that can be compared with the experiments
- Large number of observables to test the two models
- At CMS, studied only processes involving **$\psi(nS)[\Upsilon(nS)]\rightarrow\mu\mu$** decays
- Production cross sections
  - $d\sigma(\psi(nS))/dp_T$, $d\sigma(\Upsilon(nS))/dp_T$
- **Polarizations**
  - $\lambda_\theta$, $\lambda_\varphi$, $\lambda_{\theta\varphi}$

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

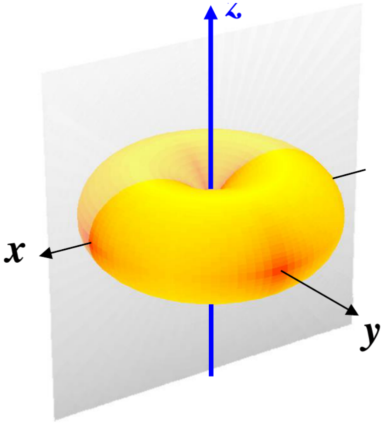
**Muon angular distributions**



**Transverse polarization**

$| J/\psi \rangle = | 1, +1 \rangle$
or $| 1, -1 \rangle$

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\vartheta$$



**Longitudinal polarization**

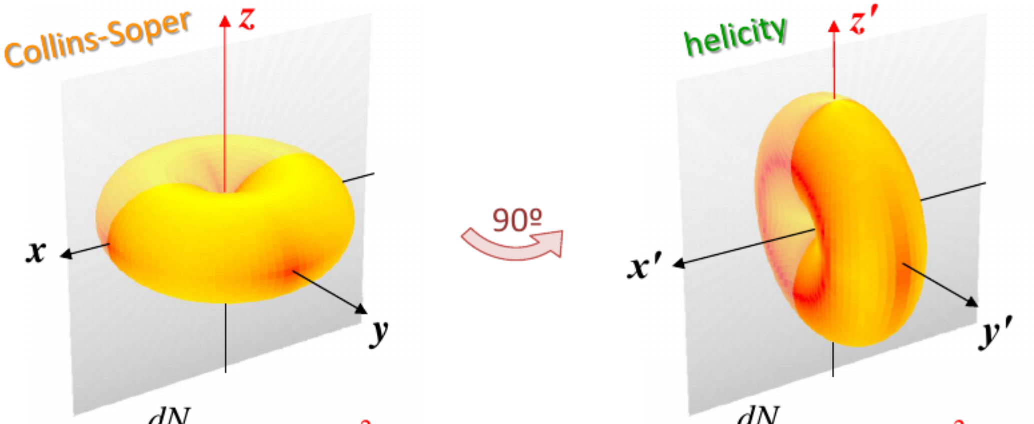
$| J/\psi \rangle = | 1, 0 \rangle$

$$\frac{dN}{d\Omega} \propto 1 - \cos^2\vartheta$$

# Quarkonium polarization in CMS

- Values of polarization constants depend on the **reference frame** used to measure them
  - Different possible **orientations** of the frame's axes with respect to the quarkonium direction

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$



$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta$$

longitudinal

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta - \sin^2\theta \cos 2\varphi$$

“transverse”

- Results given in **three reference frames:**
  - Collins-Soper **(CS)**
  - Center-of-mass helicity **(HX)**
  - Perpendicular helicity **(PX)**

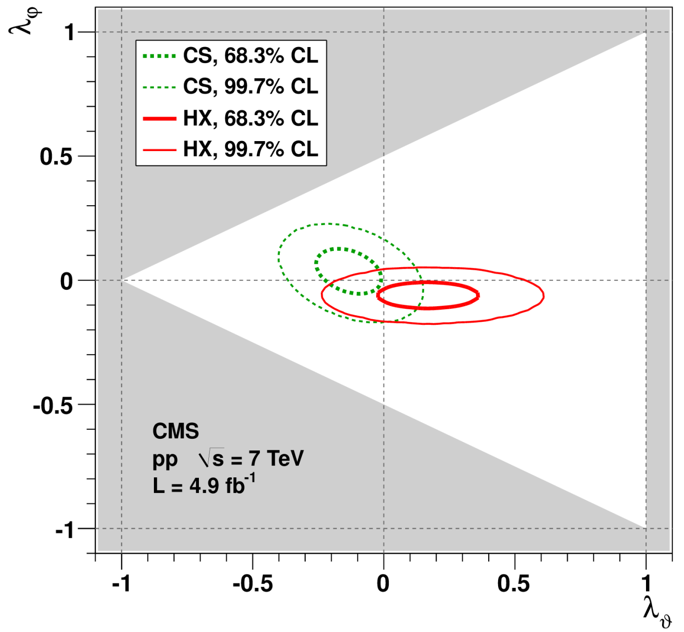
- Extracted also a **frame-invariant** quantity only sensitive to the **shape** of the muon angular distribution

$$\boxed{\tilde{\lambda} = (\lambda_\theta + 3\,\lambda_\varphi)/(1 - \lambda_\varphi)}$$

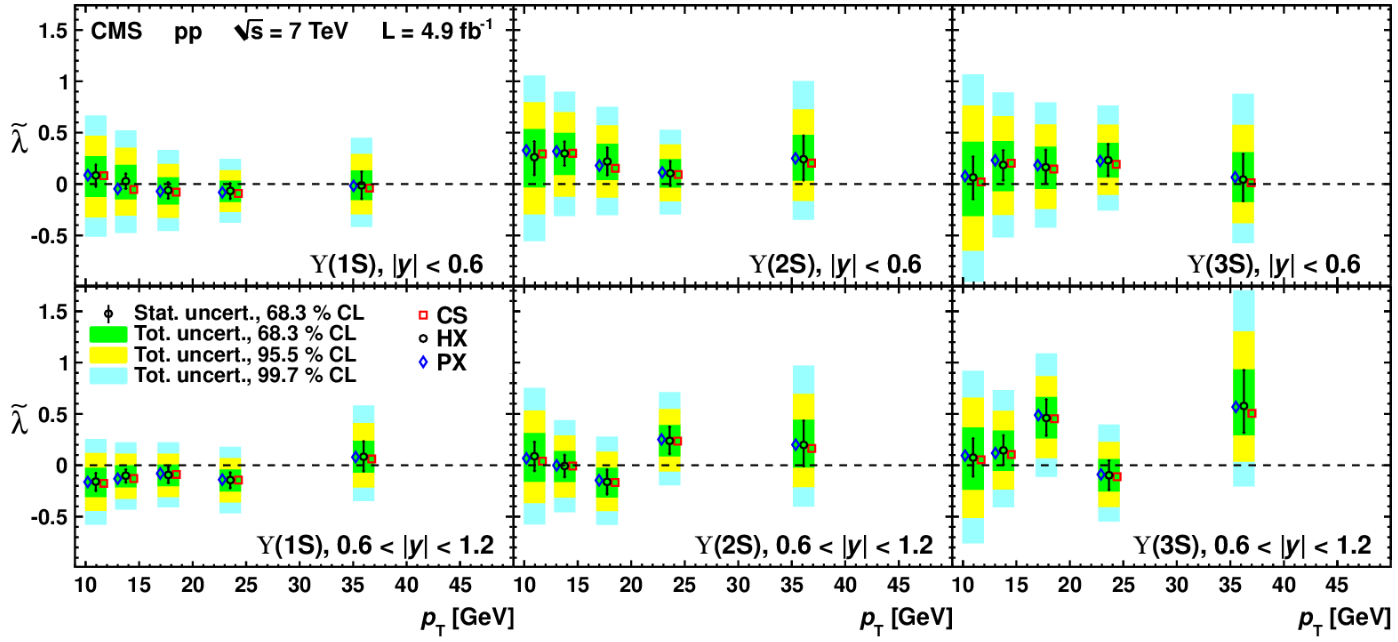
# Υ(nS) polarizations

PRL 110 (2013) 081802

- Results given in terms of posterior probability densities
- In general, **all the 3 frame-dependent observables found very close to 0**
- Also the frame-independent quantity $\tilde{\lambda}$ found close to 0
- No $p_T$ dependence of the results observed



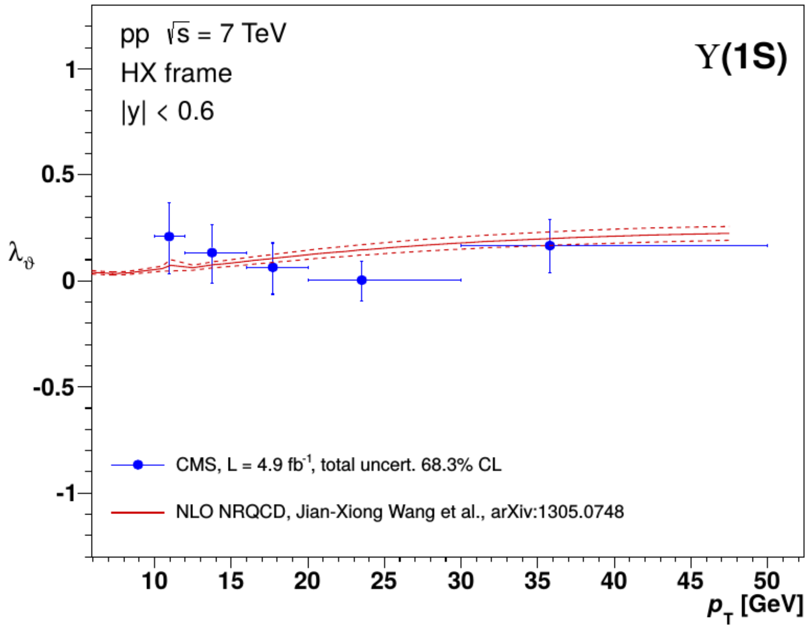
**No hints of strong Υ(nS) polarization in CMS data!**

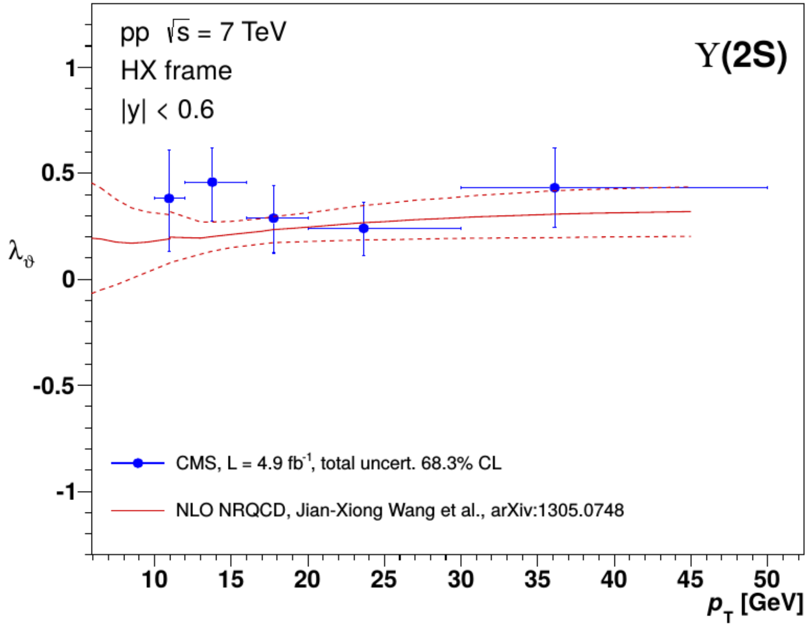


# Υ(nS): comparison with theory

PRL 110 (2013) 081802

- Υ(1S, 2S) predictions agree with data
  - Including P-wave feed-down not known experimentally (must be fitted)
  - NRQCD fit free enough to adapt to data





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PRL 110 (2013) 081802

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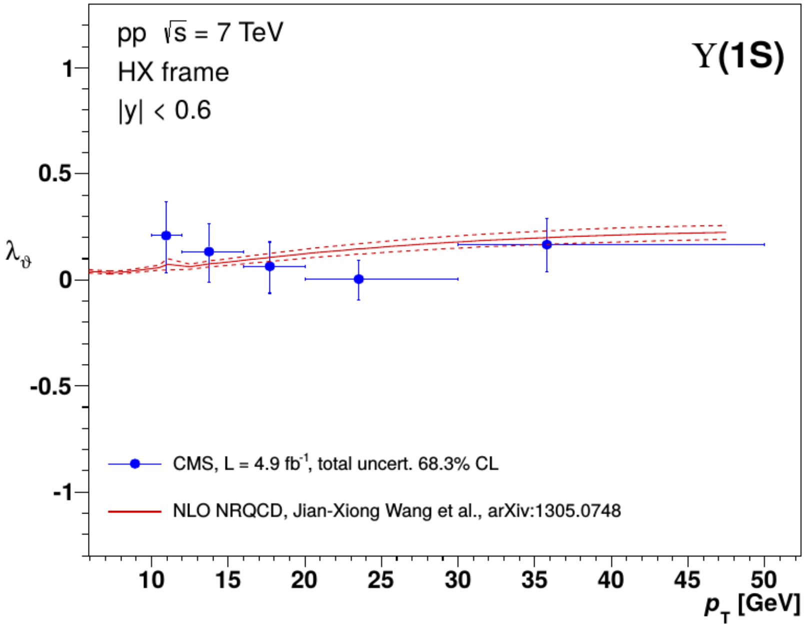
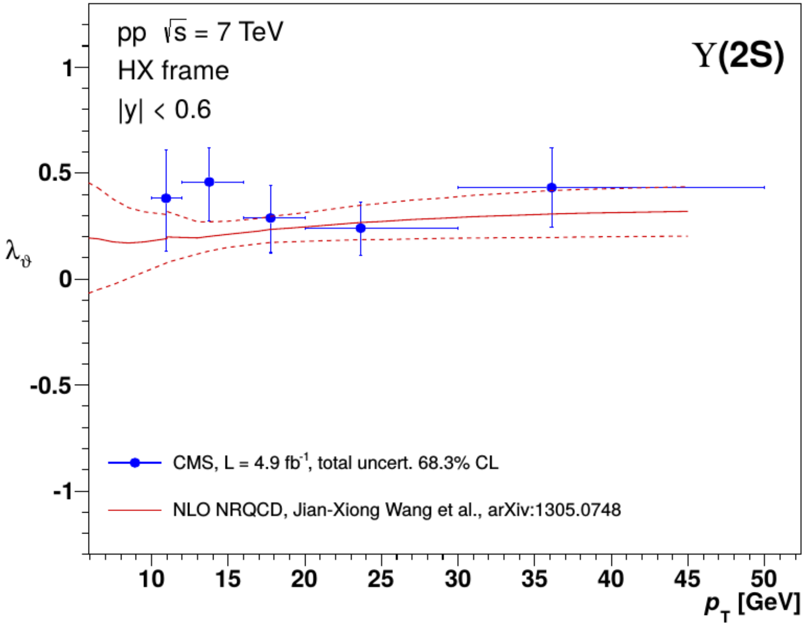
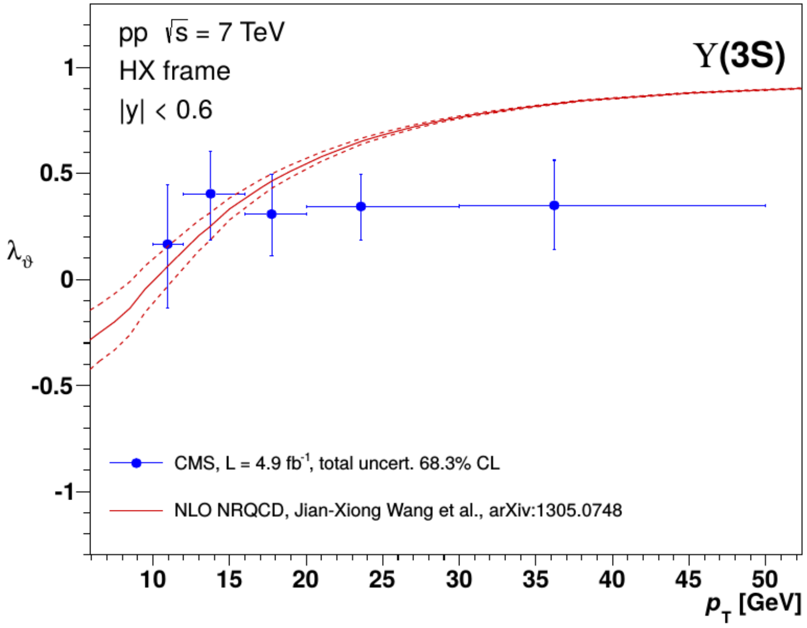
  - Including P-wave feed-down not known experimentally (must be fitted)
  - NRQCD fit free enough to adapt to data
- More precise prediction for Υ(3S) (unaffected from feed-down): increase of transverse polarization with $p_T$
  - **Not observed in CMS data!**







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PRL 110 (2013) 081802

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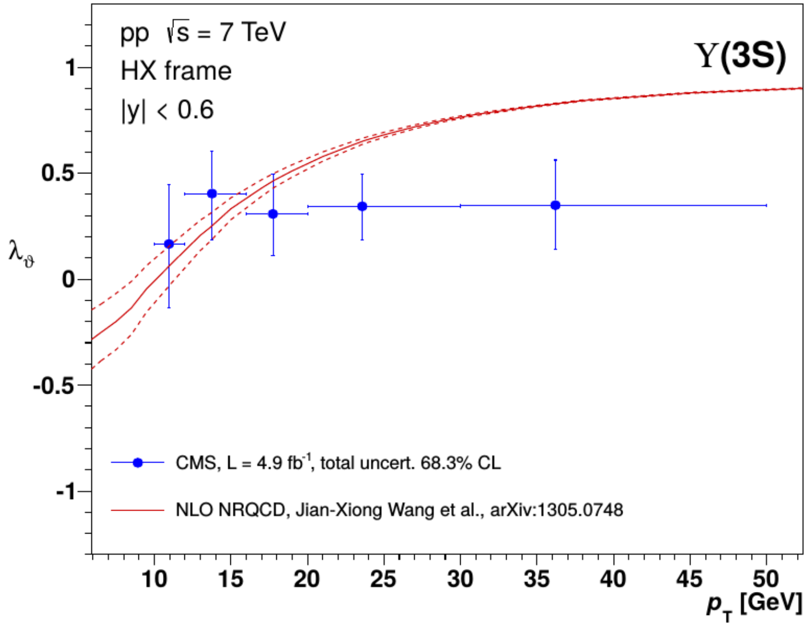
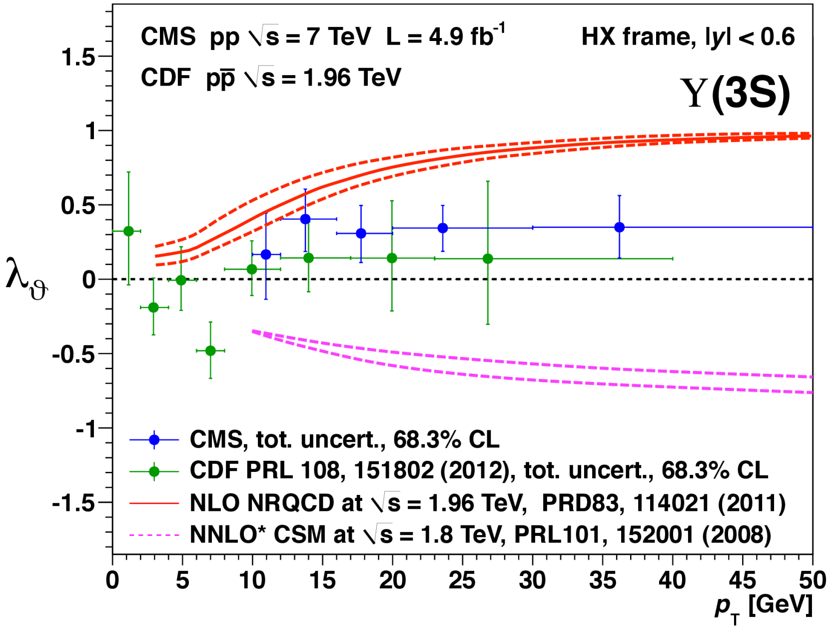


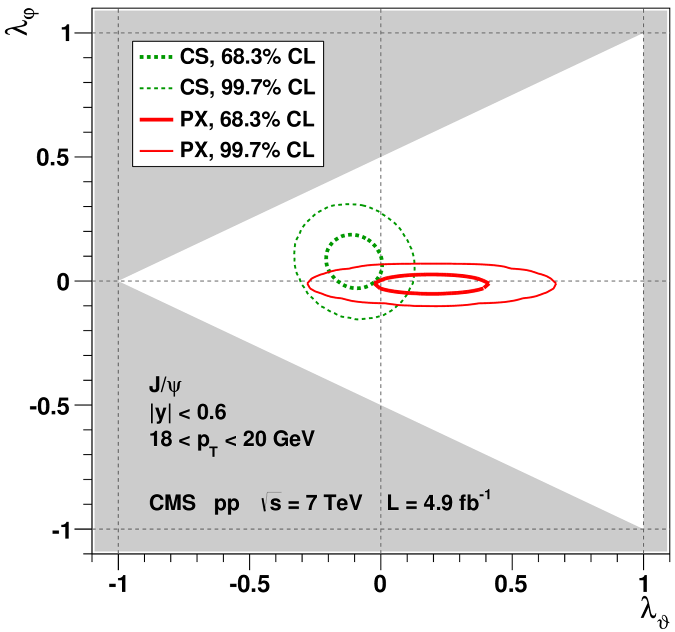
- Similar behavior seen in older NRQCD fits independent from CMS data
- NNLO* CSM calculations predicting smaller but negative $\lambda_\theta$
  - **Also not compatible with CMS (and CDF) results**

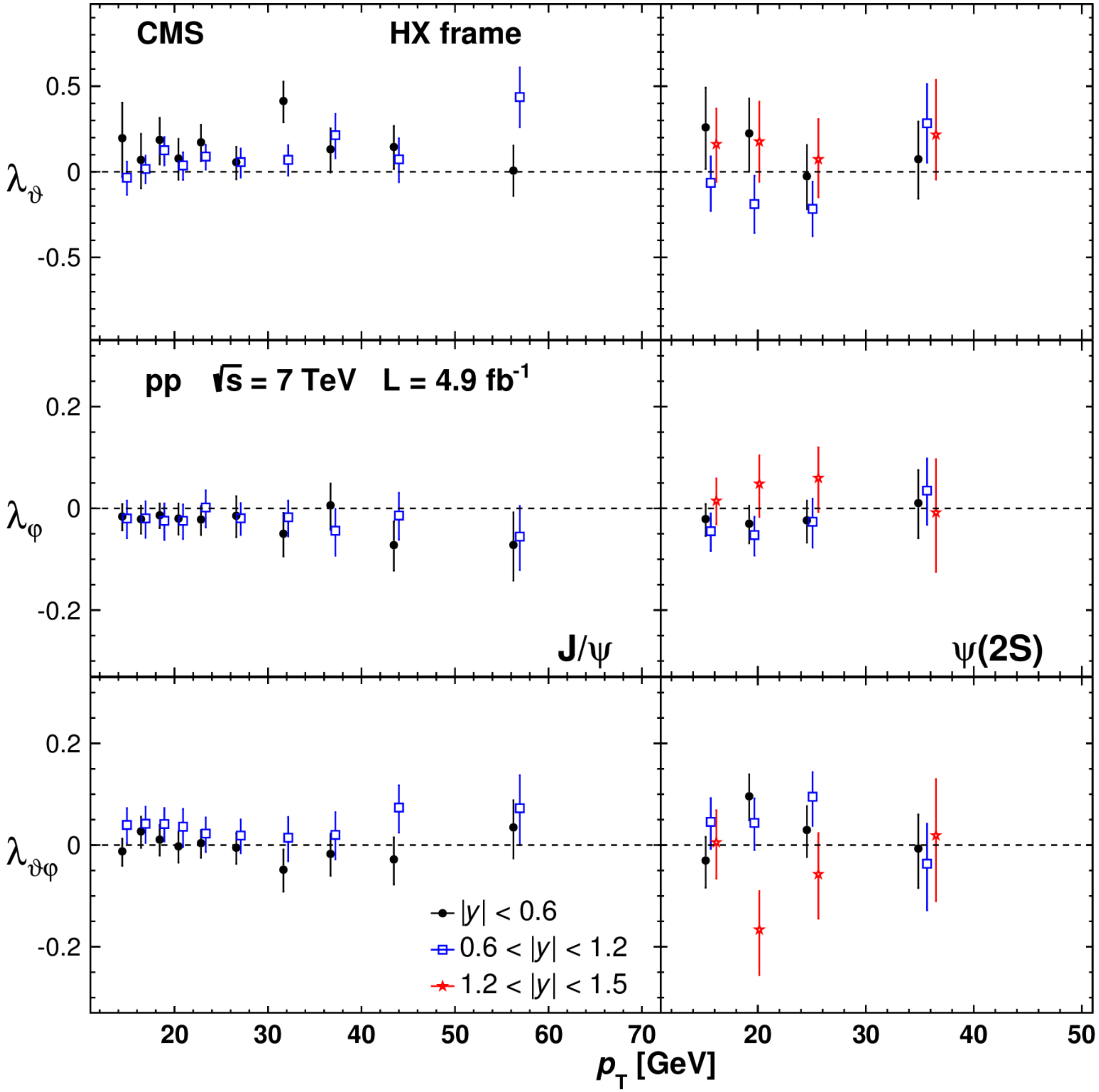


# Prompt ψ(nS): history repeats itself

PLB 727 (2013) 381

- **Also for the prompt ψ(nS) all the measured polarizations (in all frames) are very close to zero…**

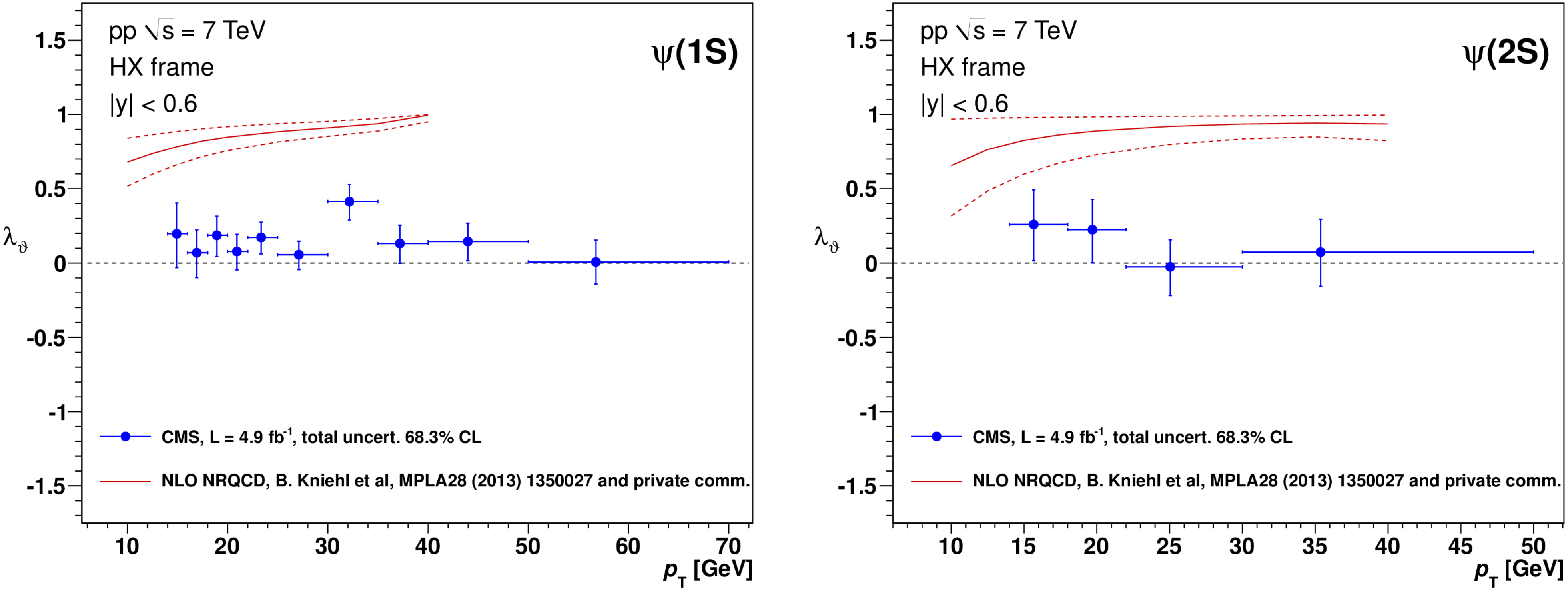


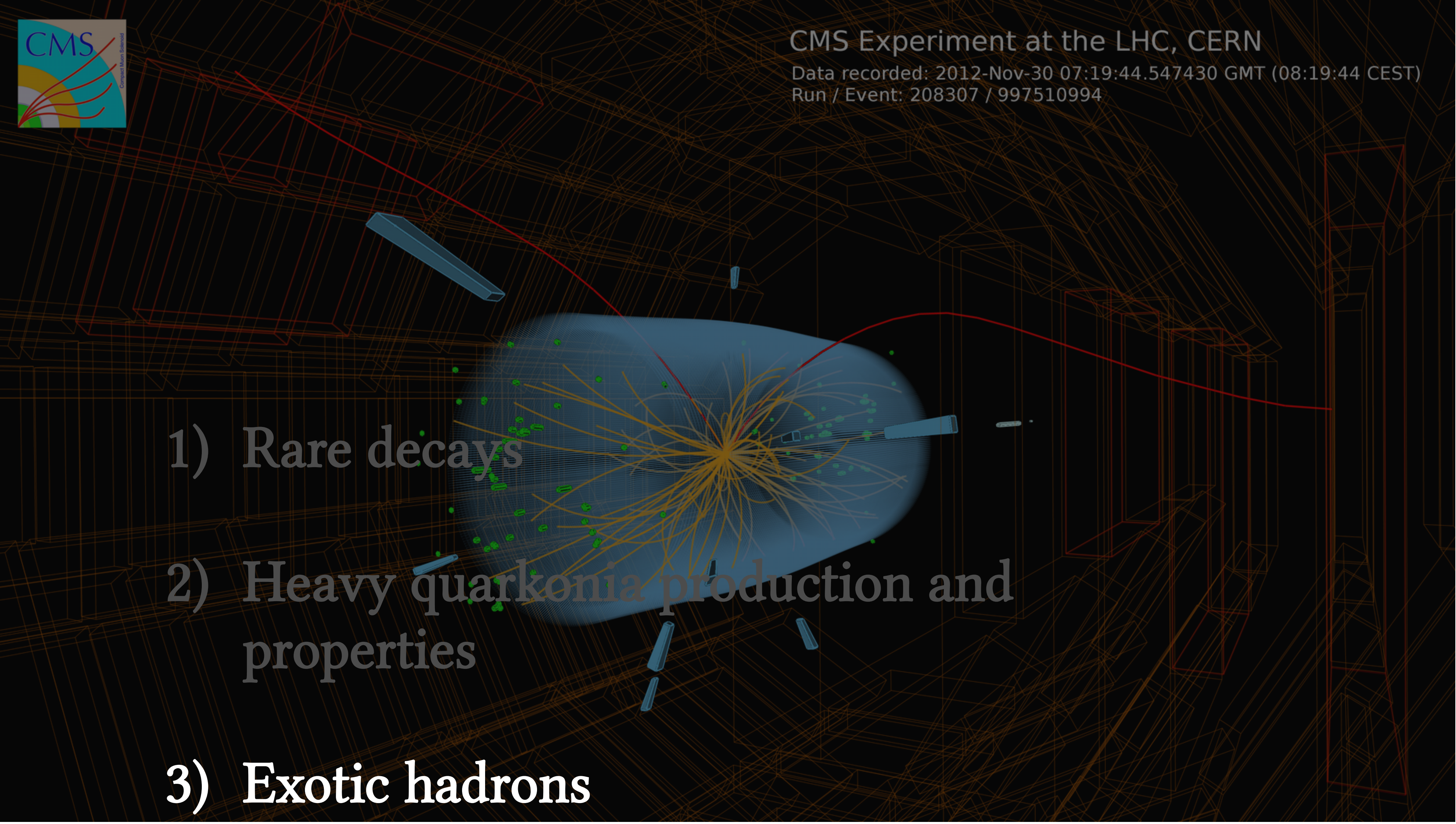


# Prompt ψ(nS): history repeats itself

PLB 727 (2013) 381

- **…and also in this case the polarizations are in stark contrast with NLO NRQCD calculations, predicting $\lambda_\theta \approx 1$**
- So far, CMS measurements have opened more questions than they have solved
    - Maybe the NRQCD calculations are correct in predicting the polarization increase, but they are placing them at the **wrong $p_T$ scale**
    - Need data at higher $p_T$ to see if we will finally observe strong polarizations!





1) Rare decays

2) Heavy quarkonia production and properties

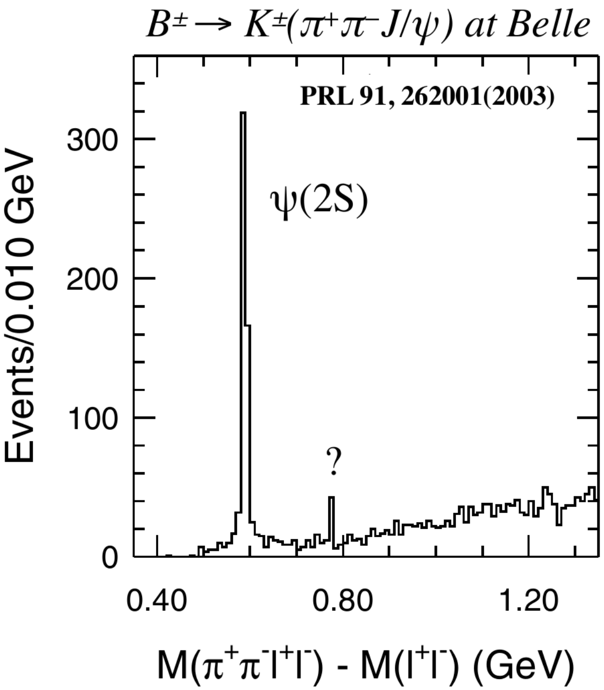
3) Exotic hadrons

# What HF physics in CMS?

# Some uninvited guests in the HF world

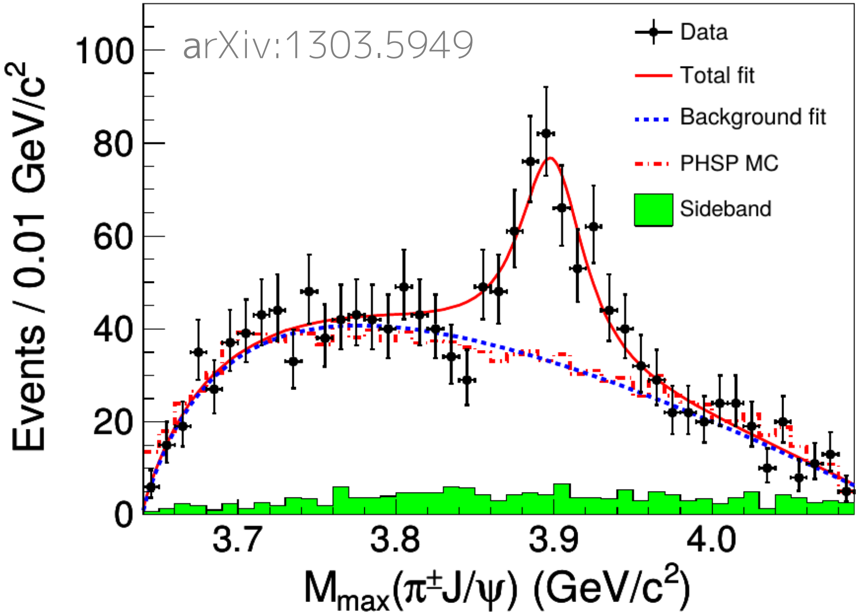
**A plethora of unexpected X, Y, Z bound states discovered in the last years**

**Discovery of X(3872) by Belle (2003)**



**10 years and lots of new particles later…**

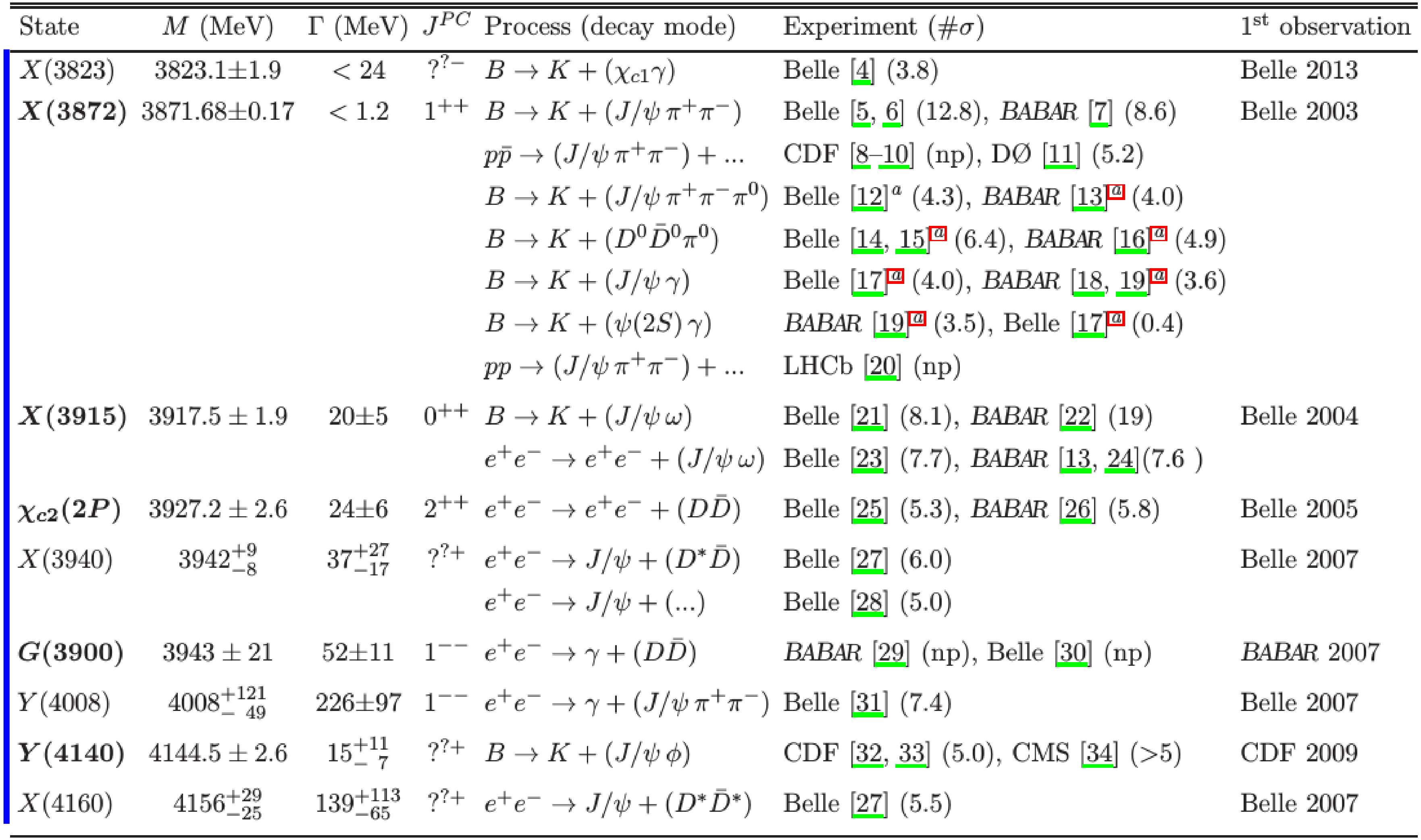
**Discovery of $Z_c^+(3900)$ by BESIII (2013)**



# An “exotic landscape” of new resonances…

## Invariant mass above the $D\bar{D}$ threshold…

arXiv:1307.7425



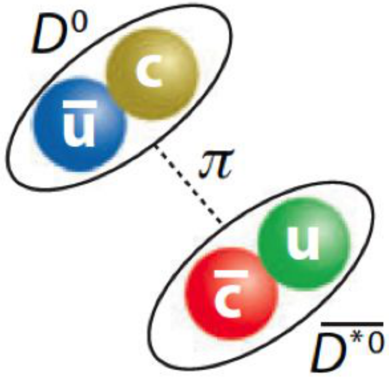
| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (decay mode) | Experiment (#$\sigma$) | 1st observation |
|---|---|---|---|---|---|---|
| $X(3823)$ | 3823.1±1.9 | $< 24$ | $?^{?-}$ | $B \to K + (\chi_{c1}\gamma)$ | Belle [4] (3.8) | Belle 2013 |
| $\boldsymbol{X(3872)}$ | 3871.68±0.17 | $< 1.2$ | $1^{++}$ | $B \to K + (J/\psi\,\pi^+\pi^-)$ | Belle [5, 6] (12.8), *BABAR* [7] (8.6) | Belle 2003 |
| | | | | $p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$ | CDF [8–10] (np), DØ [11] (5.2) | |
| | | | | $B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$ | Belle [12][a] (4.3), *BABAR* [13][a] (4.0) | |
| | | | | $B \to K + (D^0\bar{D}^0\pi^0)$ | Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9) | |
| | | | | $B \to K + (J/\psi\,\gamma)$ | Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6) | |
| | | | | $B \to K + (\psi(2S)\,\gamma)$ | *BABAR* [19][a] (3.5), Belle [17][a] (0.4) | |
| | | | | $pp \to (J/\psi\,\pi^+\pi^-) + \ldots$ | LHCb [20] (np) | |
| $\boldsymbol{X(3915)}$ | $3917.5 \pm 1.9$ | 20±5 | $0^{++}$ | $B \to K + (J/\psi\,\omega)$ | Belle [21] (8.1), *BABAR* [22] (19) | Belle 2004 |
| | | | | $e^+e^- \to e^+e^- + (J/\psi\,\omega)$ | Belle [23] (7.7), *BABAR* [13, 24](7.6 ) | |
| $\boldsymbol{\chi_{c2}(2P)}$ | $3927.2 \pm 2.6$ | 24±6 | $2^{++}$ | $e^+e^- \to e^+e^- + (D\bar{D})$ | Belle [25] (5.3), *BABAR* [26] (5.8) | Belle 2005 |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $e^+e^- \to J/\psi + (D^*\bar{D})$ | Belle [27] (6.0) | Belle 2007 |
| | | | | $e^+e^- \to J/\psi + (\ldots)$ | Belle [28] (5.0) | |
| $\boldsymbol{G(3900)}$ | $3943 \pm 21$ | 52±11 | $1^{--}$ | $e^+e^- \to \gamma + (D\bar{D})$ | *BABAR* [29] (np), Belle [30] (np) | *BABAR* 2007 |
| $Y(4008)$ | $4008^{+121}_{-\ 49}$ | 226±97 | $1^{--}$ | $e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$ | Belle [31] (7.4) | Belle 2007 |
| $\boldsymbol{Y(4140)}$ | $4144.5 \pm 2.6$ | $15^{+11}_{-\ 7}$ | $?^{?+}$ | $B \to K + (J/\psi\,\phi)$ | CDF [32, 33] (5.0), CMS [34] (>5) | CDF 2009 |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $e^+e^- \to J/\psi + (D^*\bar{D}^*)$ | Belle [27] (5.5) | Belle 2007 |

# An “exotic landscape” of new resonances…

## …or the $B\bar{B}$ threshold, and states incompatible with quarkonia interpretation

| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (decay mode) | Experiment (#$\sigma$) | 1st observation |
|---|---|---|---|---|---|---|
| **$Y(4260)$** | $4263^{+8}_{-9}$ | $95\pm14$ | $1^{--}$ | $e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$ | *BABAR* [35, 36] (8.0), CLEO [37] (5.4) | *BABAR* 2005 |
| | | | | | Belle [31] (15) | |
| | | | | $e^+e^- \to (J/\psi\,\pi^+\pi^-)$ | CLEO [38] (11) | |
| | | | | $e^+e^- \to (J/\psi\,\pi^0\pi^0)$ | CLEO [38] (5.1) | |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $??^{+}$ | $B \to K + (J/\psi\,\phi)$ | CDF [33] (3.1) | CDF 2010 |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0/2^{++}$ | $e^+e^- \to e^+e^-\,(J/\psi\,\phi)$ | Belle [39] (3.2) | Belle 2009 |
| **$Y(4360)$** | $4361\pm13$ | $74\pm18$ | $1^{--}$ | $e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$ | *BABAR* [40] (np), Belle [41] (8.0) | *BABAR* 2007 |
| $X(4630)$ | $4634^{+\ 9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$ | Belle [42] (8.2) | Belle 2007 |
| $Y(4660)$ | $4664\pm12$ | $48\pm15$ | $1^{--}$ | $e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$ | Belle [41] (5.8) | Belle 2007 |
| **$Z_c^+(3900)$** | $3898\pm5$ | $51\pm19$ | $1^{?-}$ | $Y(4260) \to \pi^- + (J/\psi\,\pi^+)$ | BESIII [43] (np), Belle [44] (5.2) | BESIII 2013 |
| | | | | $e^+e^- \to \pi^- + (J/\psi\,\pi^+)$ | Xiao *et al.* [45][a] (6.1) | |
| $Z_1^+(4050)$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | ? | $B \to K + (\chi_{c1}(1P)\,\pi^+)$ | Belle [46] (5.0), *BABAR* [47] (1.1) | Belle 2008 |
| $Z_2^+(4250)$ | $4248^{+185}_{-\ 45}$ | $177^{+321}_{-\ 72}$ | ? | $B \to K + (\chi_{c1}(1P)\,\pi^+)$ | Belle [46] (5.0), *BABAR* [47] (2.0) | Belle 2008 |
| $Z^+(4430)$ | $4443^{+24}_{-18}$ | $107^{+113}_{-\ 71}$ | ? | $B \to K + (\psi(2S)\,\pi^+)$ | Belle [48, 49] (6.4), *BABAR* [50] (2.4) | Belle 2007 |
| $Y_b(10888)$ | $10888.4\pm3.0$ | $30.7^{+8.9}_{-7.7}$ | $1^{--}$ | $e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$ | Belle [51, 52] (2.0) | Belle 2010 |
| $Z_b^+(10610)$ | $10607.2\pm2.0$ | $18.4\pm2.4$ | $1^{+-}$ | $\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$ | Belle [53, 54] (16) | Belle 2011 |
| | | | | $\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$ | Belle [53, 54] (16) | |
| $Z_b^+(10650)$ | $10652.2\pm1.5$ | $11.5\pm2.2$ | $1^{+-}$ | $\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$ | Belle [53, 54] (16) | Belle 2011 |
| | | | | $\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$ | Belle [53, 54] (16) | |

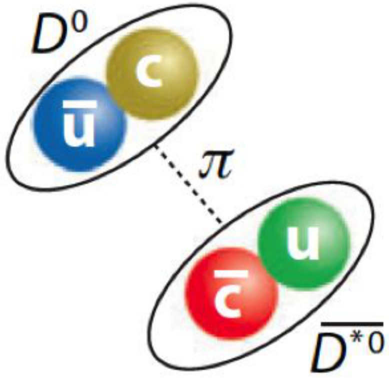
# Contradictory interpretations: X(3872)



**$D^0$–$\overline{D^{*0}}$ “molecule”**

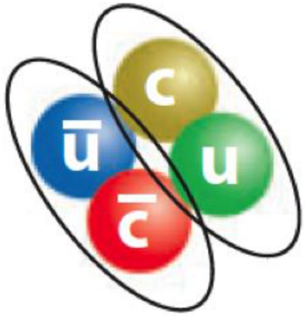
**Loosely bound molecule of hadrons**

# Contradictory interpretations: X(3872)



$D^0$–$\overline{D^{*0}}$ **“molecule”**

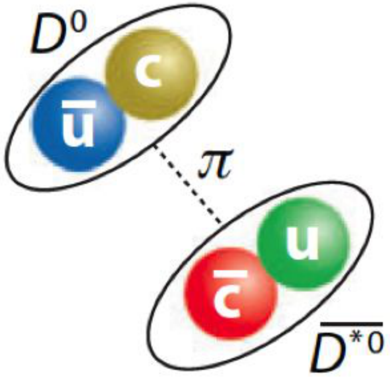
**Loosely bound molecule of hadrons**



**Diquark–diantiquark**

**Tightly bound “tetraquark” state**

# Contradictory interpretations: X(3872)



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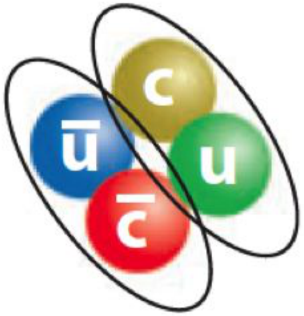


**Diquark–diantiquark**

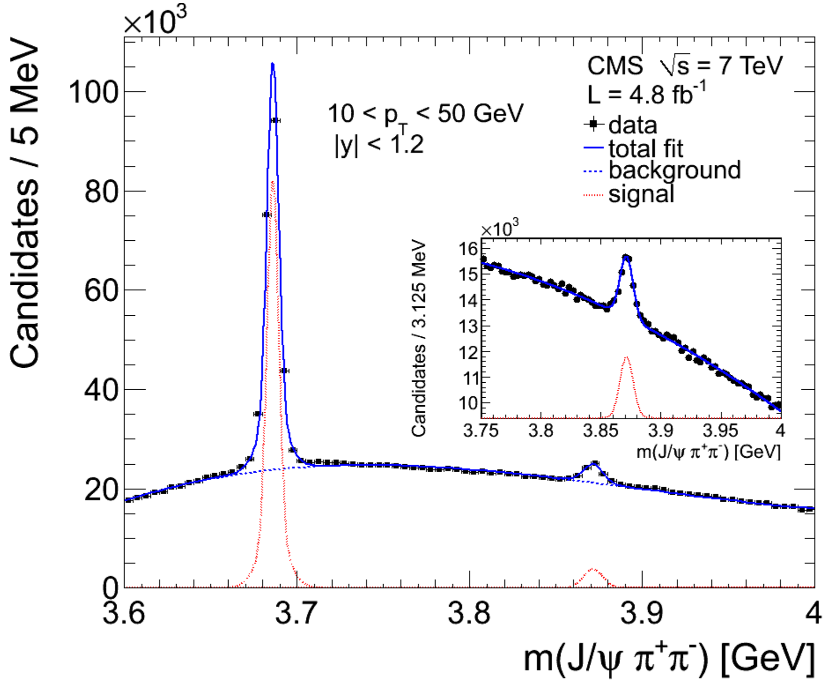
**Tightly bound “tetraquark” state**

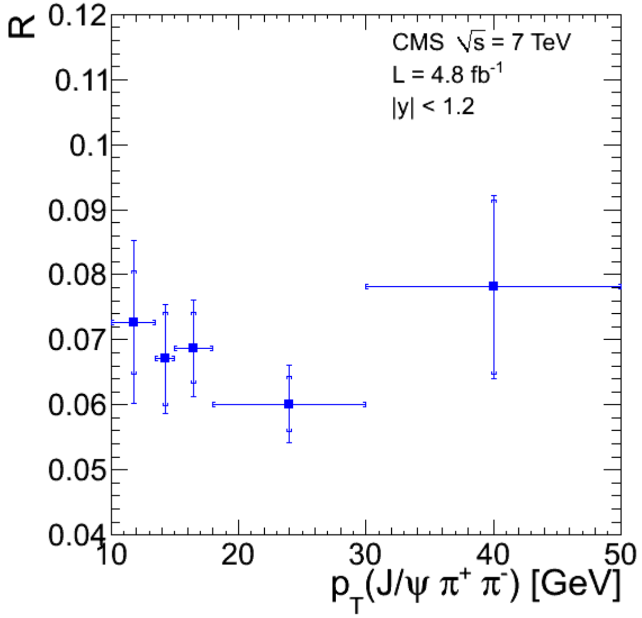
- **And more**
  - “Hybrid” mesons ($q\bar{q}$+g) and glueballs
  - Pentaquarks
  - Hadroquarkonia (Van der Waals forces)
  - …

# Studies of X(3872) properties in CMS

JHEP 04 (2013) 154

- CMS studied the X(3872) in its most common decay **X(3872)→J/ψπ⁺π⁻**, with J/ψ→μμ
- Large sample extracted from 2011 data
- Several properties measured with unprecedented precision





- Measured production × decay rate with respect to ψ(2S)

$$\boxed{R = \frac{\sigma(pp\to X(3872))\times\mathcal{B}(X(3872)\to J/\psi\pi\pi)}{\sigma(pp\to\psi(2S))\times\mathcal{B}(\psi(2S)\to J/\psi\pi\pi)}}$$

- **R = 0.0656 ± 0.0029 ± 0.0065**
  - No significant $p_T$ dependence

# Prompt X(3872) cross section in CMS

JHEP 04 (2013) 154

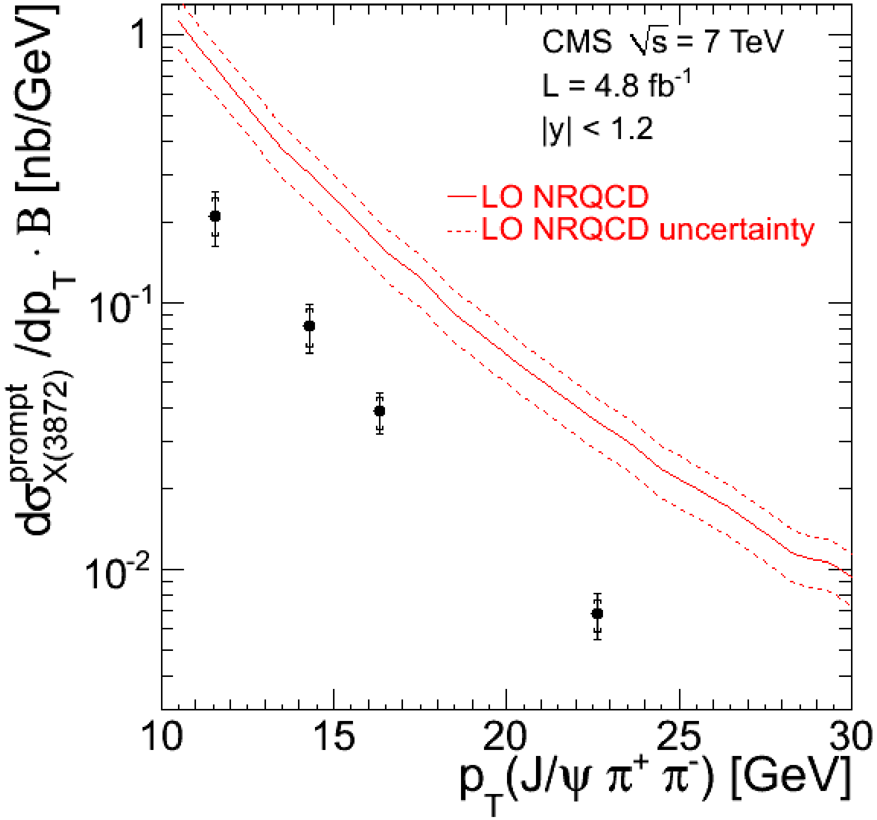
- CMS also measured the prompt production cross section vs. $p_T$

- Results significantly lower than LO NRQCD predictions (which assume that **X(3872) is a $c\bar{c}$ state**)

- **$d\sigma/dp_{T,\,\mathrm{CMS}} = 1.06 \pm 0.11 \pm 0.15$ nb**

- **$d\sigma/dp_{T,\,\mathrm{NRQCD}} = 4.01 \pm 0.88$ nb**

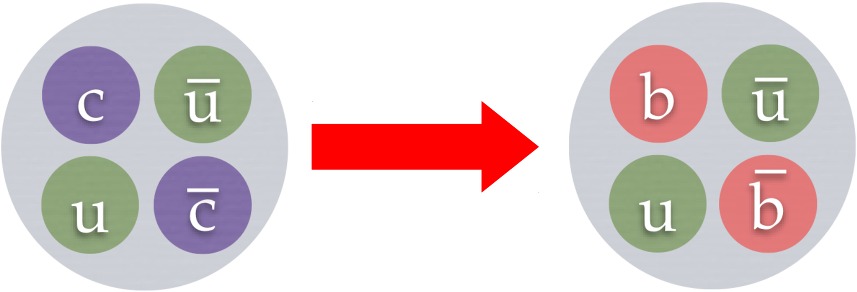
- CMS data **incompatible with the $c\bar{c}$ interpretation** at least within the LO NRQCD framework



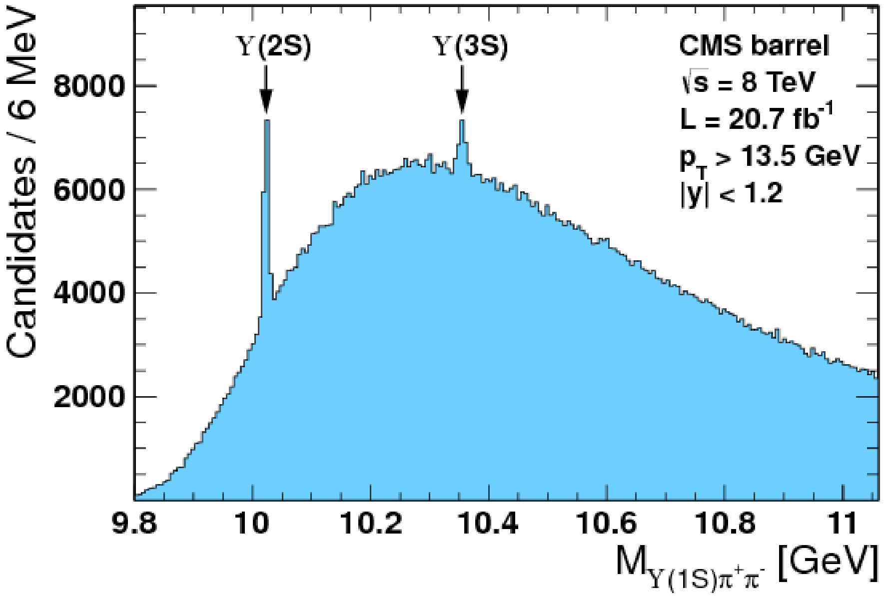
# Search for new $X_b$ states

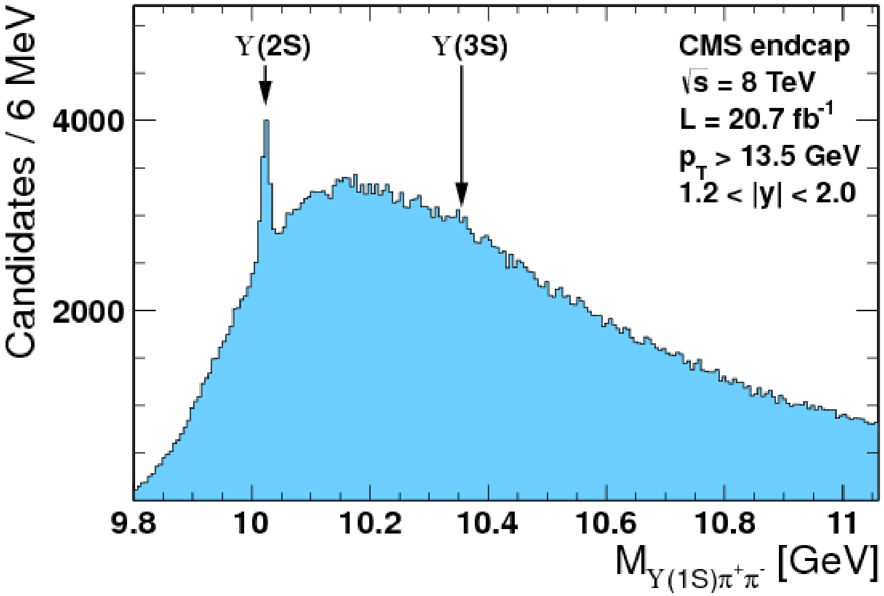
PLB 727 (2013) 57

- CMS also searched for a bottomonium counterpart of the X(3872)
  - Looked at decays $\mathbf{X_b \to Y(1S)\pi^+\pi^-}$
  - Used $\mathbf{Y(2S) \to Y(1S)\pi^+\pi^-}$ decays as normalization channel



- Peaks corresponding to the Y(2S) and Y(3S) states were observed
- **But no hints of other resonant channels were found**





# Search for new $X_b$ states

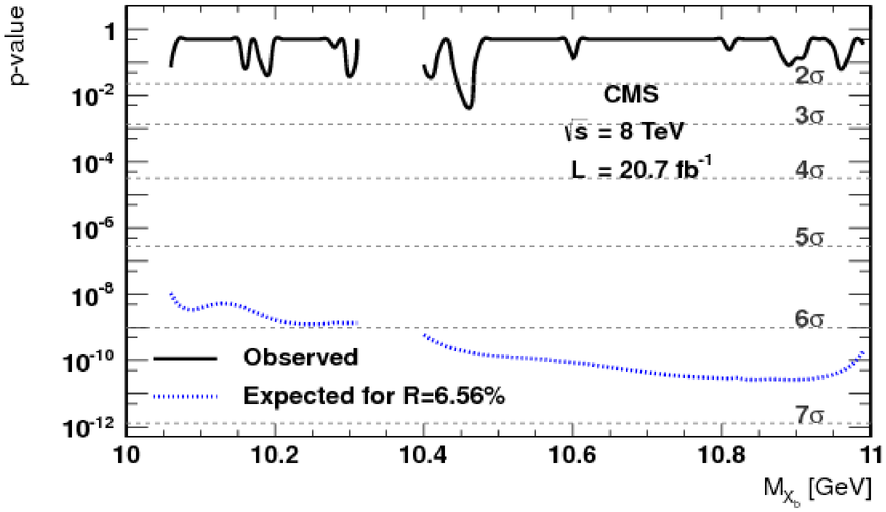
PLB 727 (2013) 57

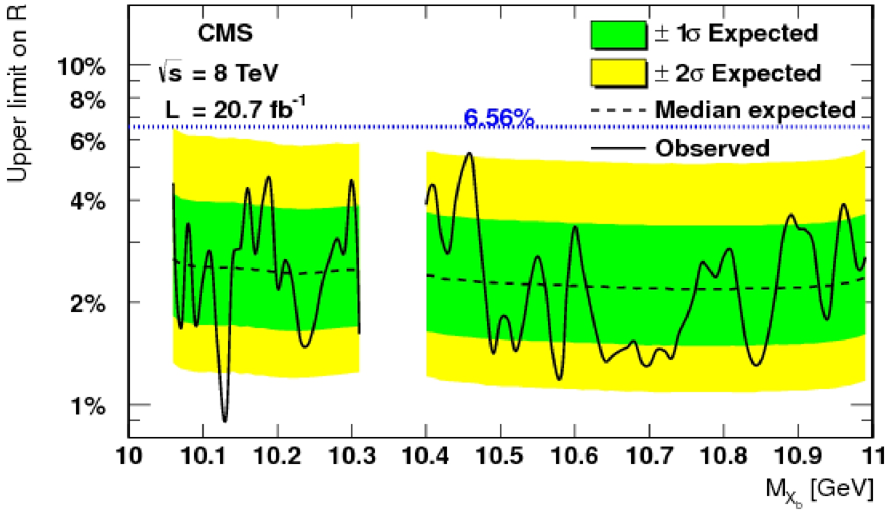
- Extracted a production × decay rate ratio similar to that of X(3872)

$$R = \frac{\sigma(pp\rightarrow X_b)\times\mathcal{B}(X_b\rightarrow Y(1S)\pi\pi)}{\sigma(pp\rightarrow Y(2S))\times\mathcal{B}(Y(2S)\rightarrow Y(1S)\pi\pi)}$$

- **Expected >5σ significance** in the full mass range if R=6.56% (the X(3872) value)

- Observed no excess and set **a limit of 0.9÷5.4% on R** depending on the mass

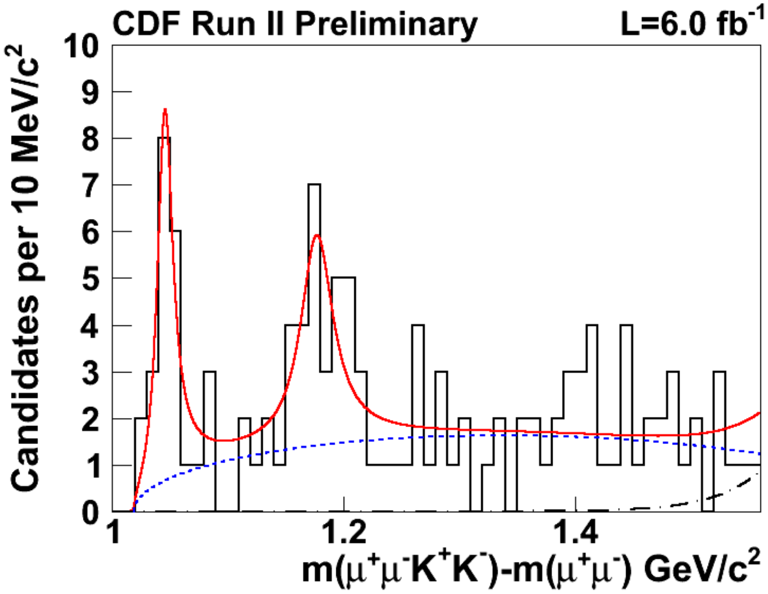




# Y(4140) resonance

**CDF**: PRL 102 (2009) 242002, arXiv:1101.6058 [hep-ex]
**LHCb**: arXiv:1202.5087

- Seen for the first time in 2009 by CDF as a peaking structure in the **J/ψφ mass spectrum** in **$B^+ \to J/\psi\phi K^+$** decays

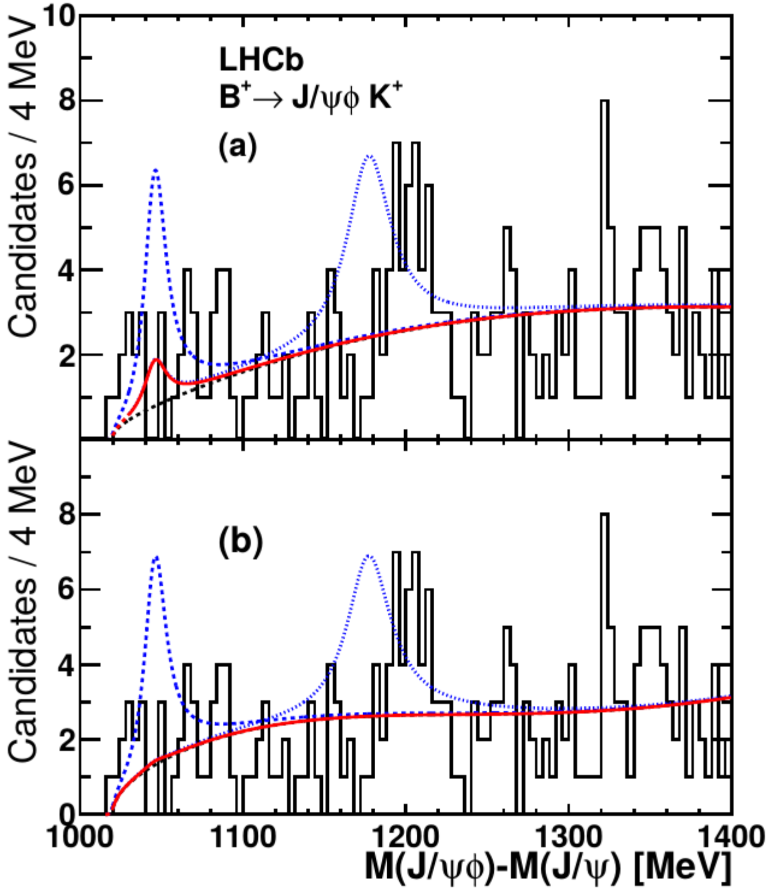


**$M = 4143.4^{+2.9}_{-3.0}$ (st)±0.6(sys) MeV**

**$\Gamma = 15.3^{+10.4}_{-6.1}$ (st)±2.5(sys) MeV**

+ evidence for a second structure with $M_2 \approx 4274$ MeV

- **Not confirmed** by LHCb (2.4σ discrepancy with respect to the CDF result) and Belle in 2012



- **More independent experimental results necessary to solve the puzzle…**

# Observation of Y(4140) at CMS

arXiv:1309.6920,
accepted for publication by PLB

- CMS searched for Y(4140) in the same channel as CDF: $B^+ \longrightarrow J/\psi\phi K^+$
  - $J/\psi \longrightarrow \mu\mu$, $\phi \longrightarrow K^+K^-$
  - Analyzed full 2011 data sample (4/5 of data yet to be analyzed)
- CMS confirmed the presence of the Y(4140) with > 5σ significance

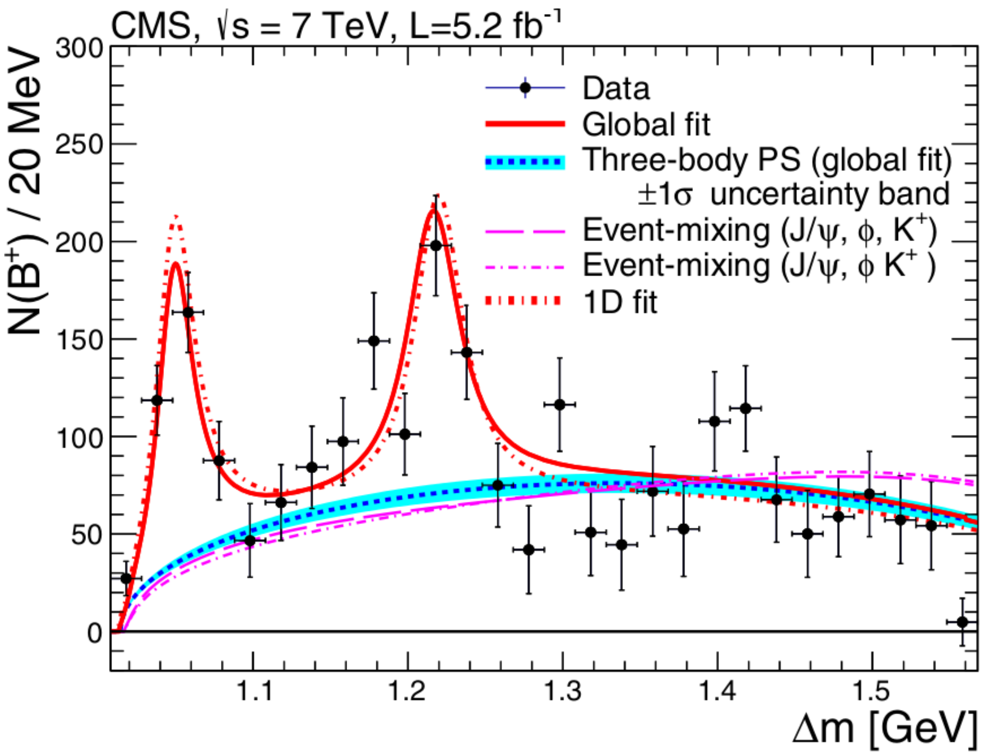
**$M_1$ = 4148.0±2.4(stat)±6.3(syst) MeV**

**$\Gamma_1 = 28^{+15}_{-11}$(stat)±19(syst) MeV**

- And also reported evidence for a second structure

**$M_2$ = 4313.8±5.3(stat)±7.3(syst) MeV**

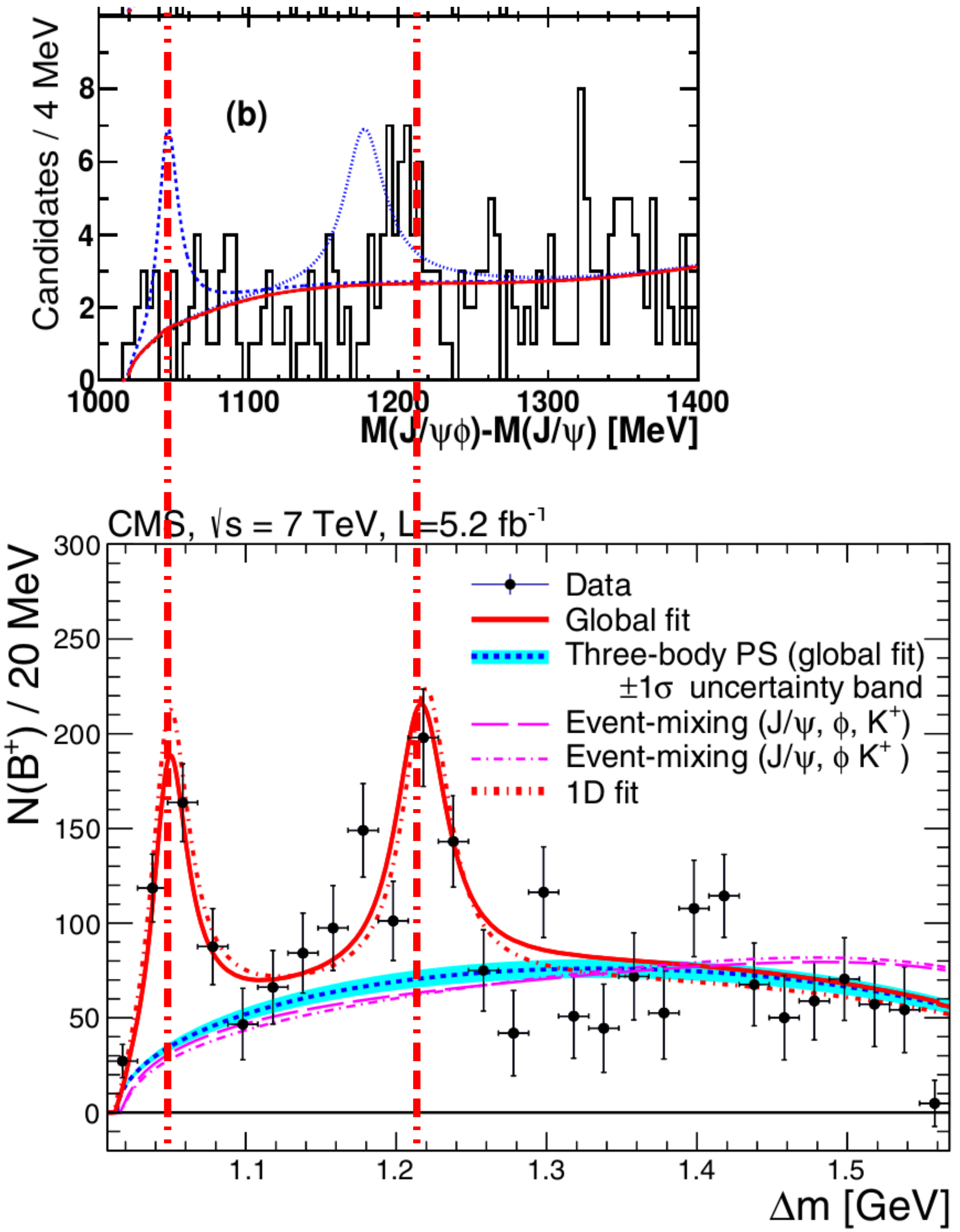
**$\Gamma_2 = 38^{+30}_{-15}$(stat)±16(syst) MeV**



- How do these results compare with those of the other experiments?

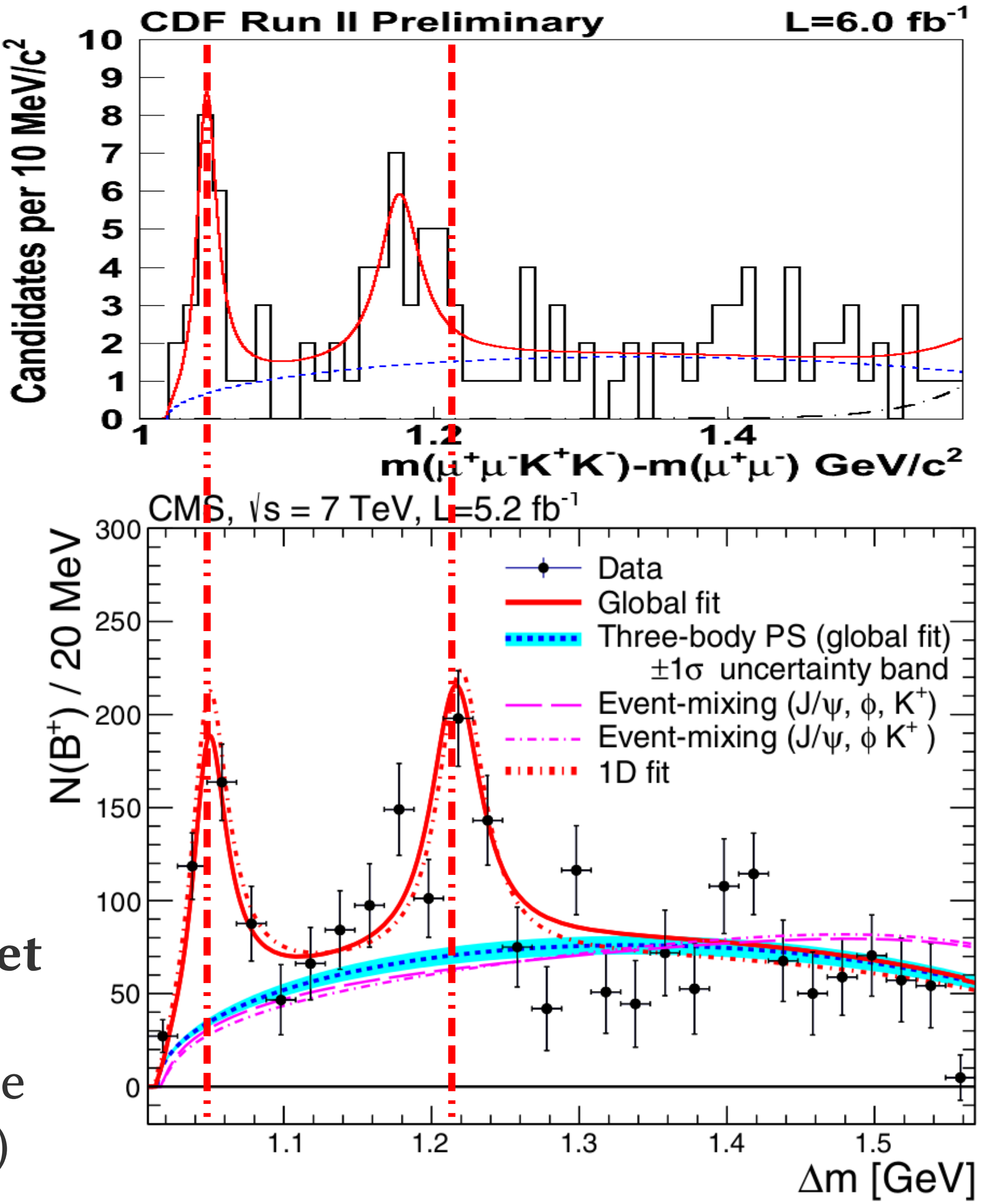
# Comparison of results

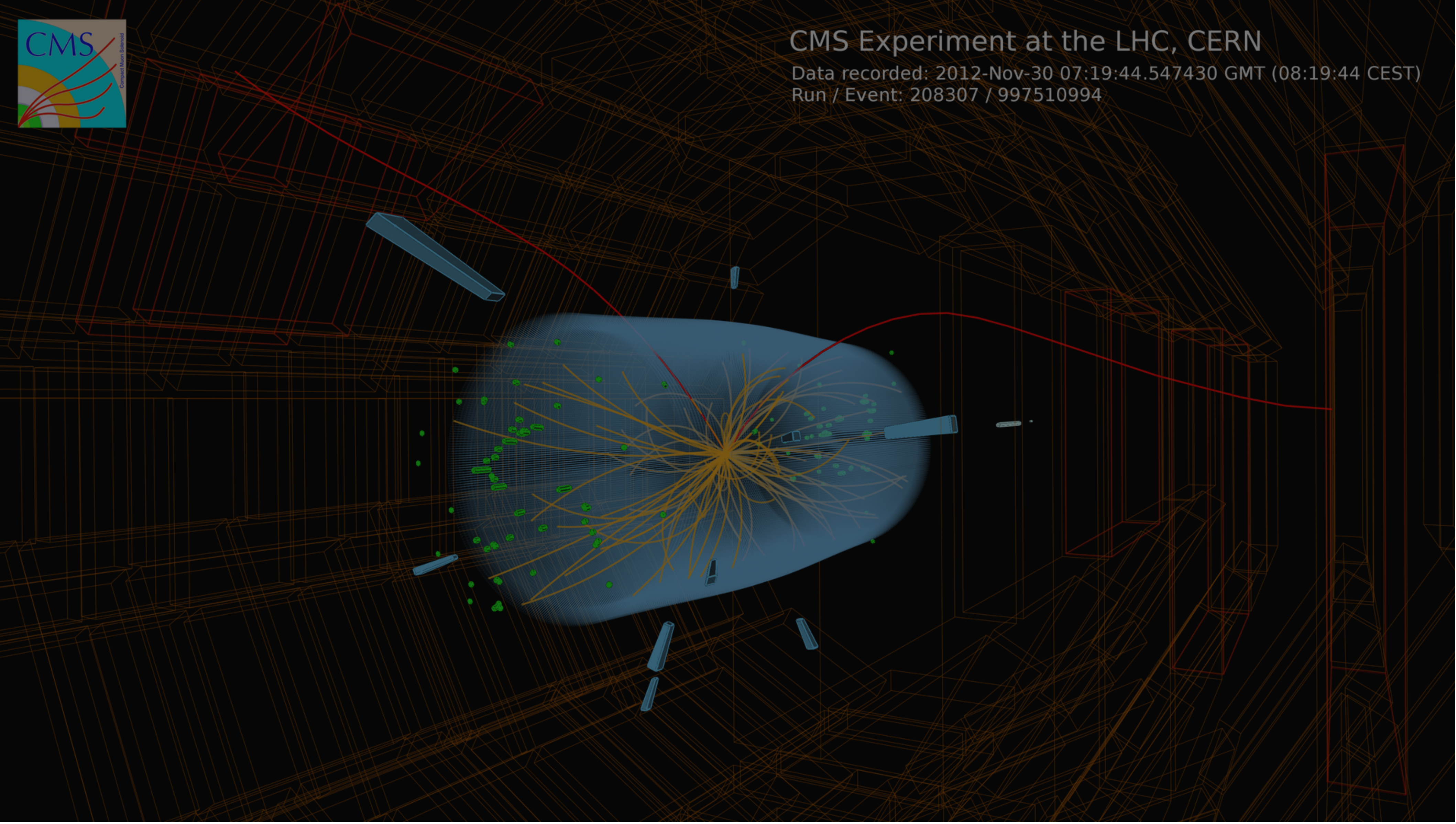
- **LHCb**
  - Does not see a significant enhancement in the Y(4140) region
  - Seems to have an excess corresponding to the second CMS resonance, but it does not try to perform a fit



# Comparison of results

- **LHCb**
  - Does not see a significant enhancement in the Y(4140) region
  - Seems to have an excess corresponding to the second CMS resonance, though it does not try to fit it
- **CDF**
  - Has a narrower Y(4140) peak than CMS
  - Sees the second structure shifted to lower mass with respect to CMS
- **The Y(4140) puzzle is not solved yet** and still more data is needed to understand its nature and confirm the existence of its possible companion(s)



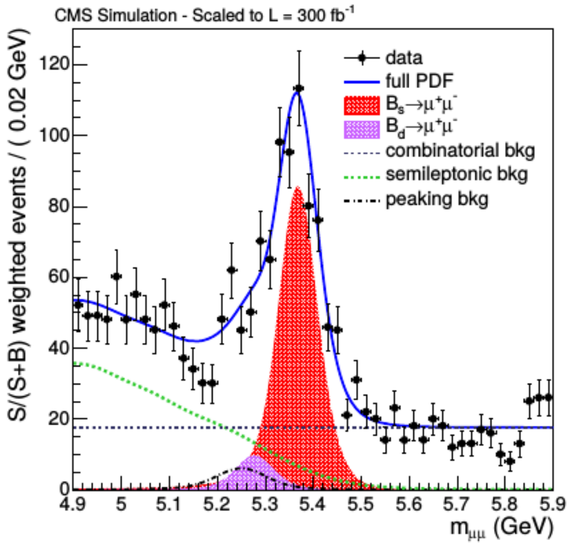


# Conclusions

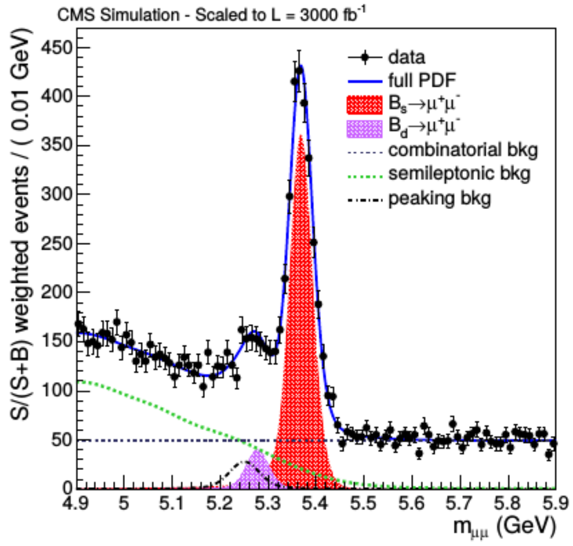
# Conclusions: a glimpse to the future

CMS-PAS-FTR-13-022

- In **LHC run 1**, CMS had an excellent performance, which allowed it to carry out a vast HF program
- With **LHC Run 2** (2015-2018) CMS is expected to collect 100 $fb^{-1}$ of pp data at $s^{½}$ = 13 TeV
  - Repeat all measurements at the new energy
  - Better precision for all rare processes
- CMS is already preparing for the **High Luminosity LHC** (HL-LHC)
  - 3000 $fb^{-1}$ of data will be collected starting from 2024
  - Important detector upgrades (i.e. new tracker)
  - **Simulation studies** show that the upgrades will greatly improve the CMS HF capabilities
- **A promising future paved for CMS HF analyses in LHC run 2 and beyond!**



**Current tracker, 300 $fb^{-1}$**



**New tracker, 3000 $fb^{-1}$**

# Thank you!

# Backup

# Theoretical framework: NRQCD

- Effective field theory featuring the factorization of perturbative short-distance processes and long-distance effects

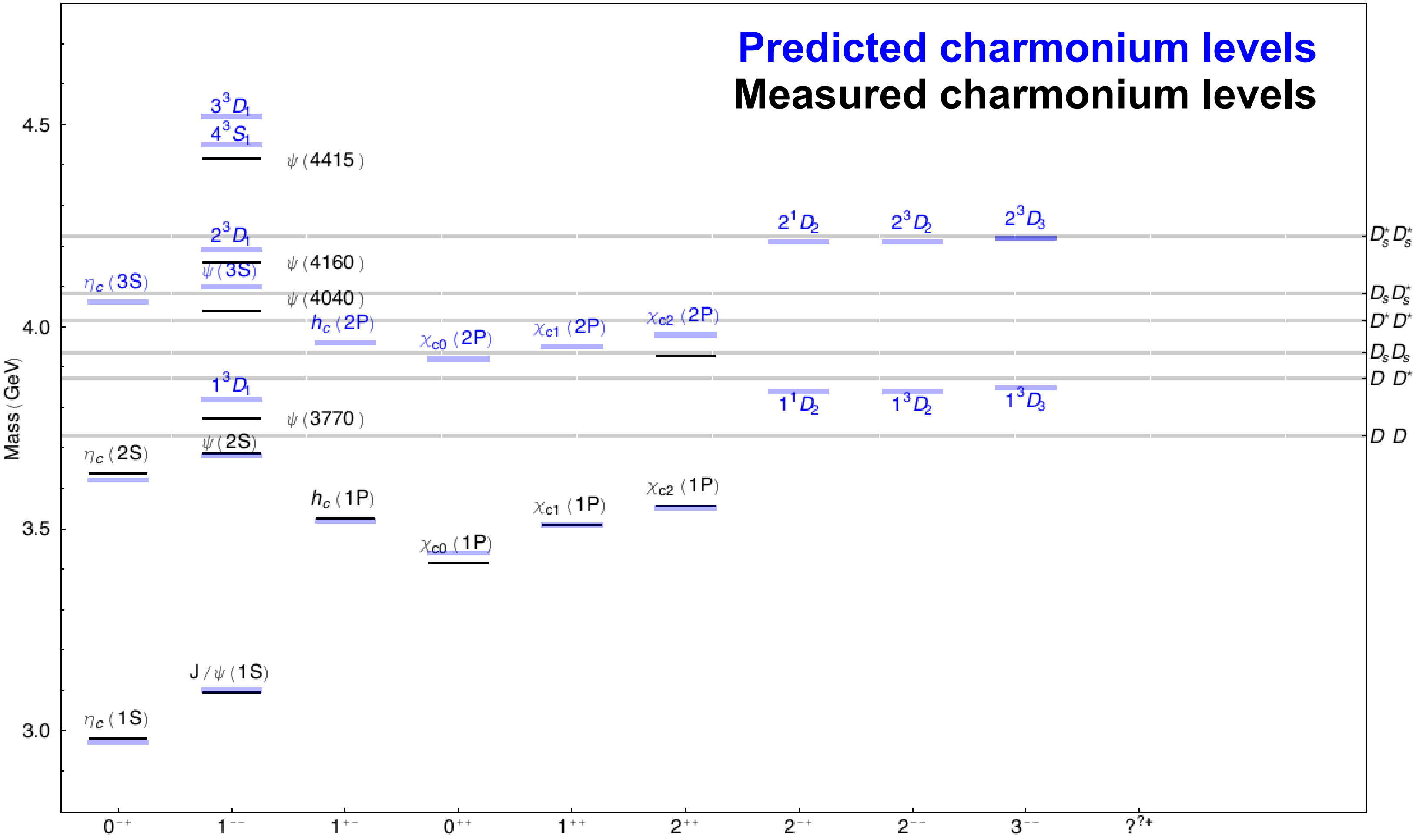
$$d\sigma(H+X) = \sum_{n} d\hat{\sigma}(Q\bar{Q}[n]+X)\,\langle \mathcal{O}^{H}[n] \rangle$$

Short-distance perturbative term
and Parton Distribution Functions

Long-distance matrix elements (LDMEs)
Process independent.
Non-perturbative, extracted phenomenologically or from lattice calculations, with the help of scaling rules

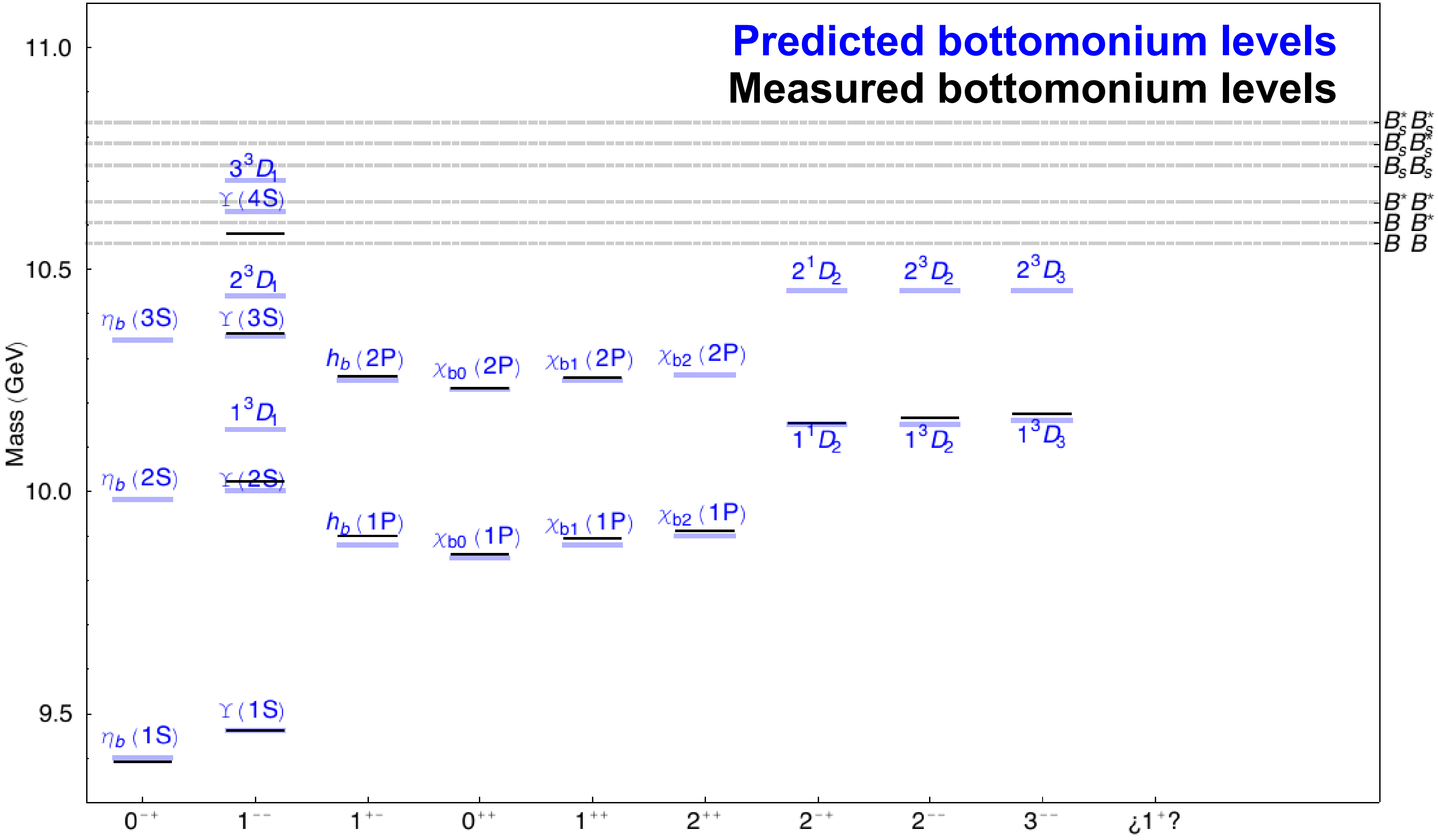
# Heavy quarkonia spectroscopy

- "Conventional" quarkonium spectroscopy well understood



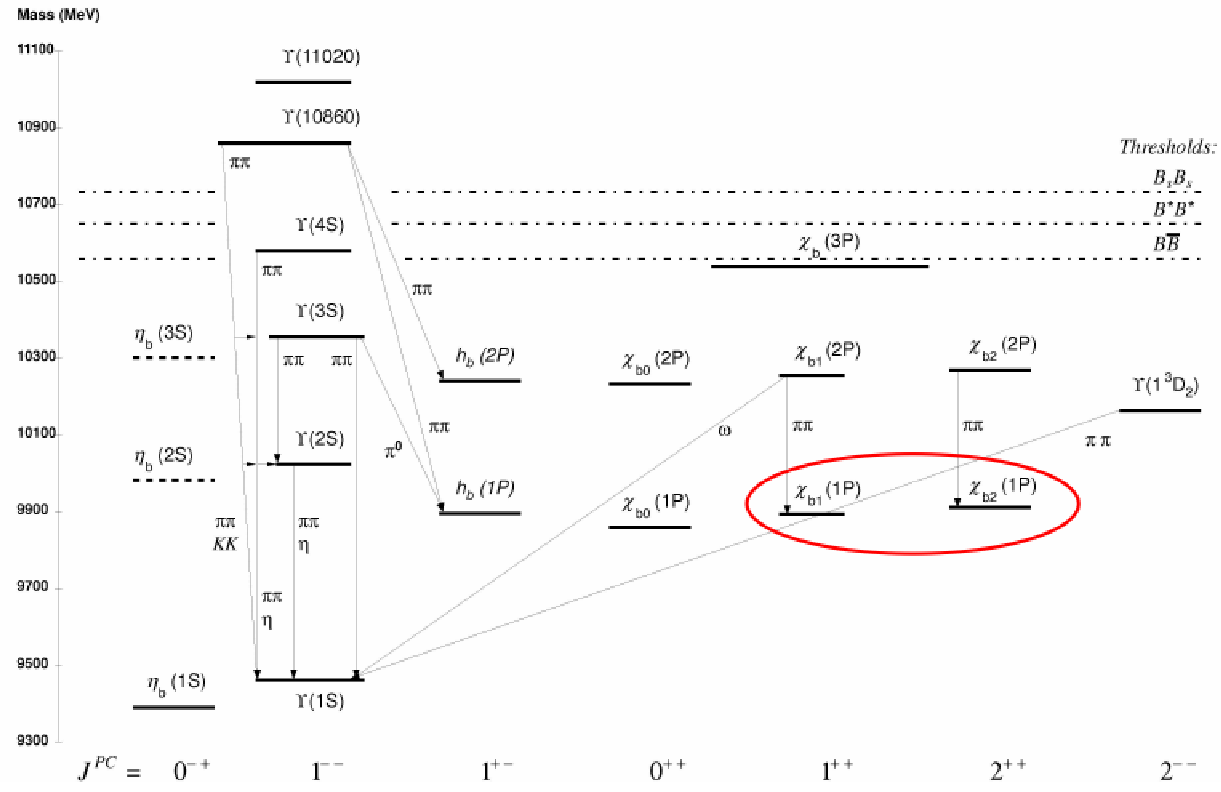
# Heavy quarkonia spectroscopy

- “Conventional” quarkonium spectroscopy well understood



# P-wave quarkonia

- P-Wave states are an essential piece to the quarkonium puzzle
- Feed-down from P-wave states must be taken into account when studying S-wave states.
- Relative production cross section ratios of P-waves are by themselves interesting tests of (NR)QCD. Naïve expectations are challenged (example: suppression of $^3P_1$).



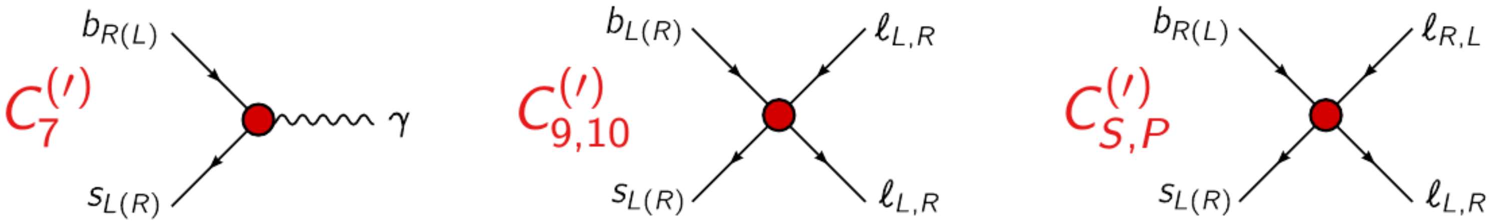
# Effective b⟶s Hamiltonian

D. Straub, Moriond EW 2012

$$\mathscr{H}_{\text{eff}}^{\Delta F=1} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum (C_i \mathscr{O}_i + C_i' \mathscr{O}_i')$$

Wilson coefficient

Dimension-6 operator



| | mag. dipole operator | semileptonic operators | scalar operators | (neglecting: tensor op.s) |
|---|---|---|---|---|
| $B \to (X_s, K^*)\gamma$ | X | | | |
| $B \to (X_s, K^{(*)})\ell^+\ell^-$ | X | X | | |
| $B_s \to \mu^+\mu^-$ | | X | X | |

# A second level of complementarity

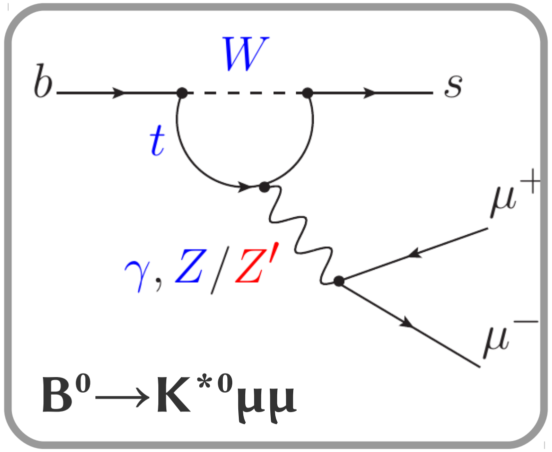
- Model-independent effective Hamiltonian approach to describe new physics in b⟶s transitions

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left( C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

- Different decays probe different operators in the expansion above

| 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 | (✓) | ✓ |

K. Petridis, Moriond 2014



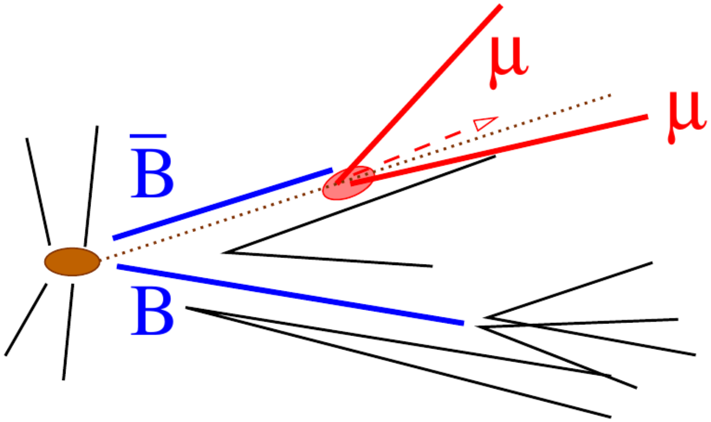
**$B^0$⟶$K^{*0}$μμ**

- **$B_s$⟶μμ** and **$B^0$⟶$K^{*0}$μμ** complementary to each other
  - Necessary to study both in order to have a wider new physics sensitivity
  - **In the following I will only talk about B⟶μμ**

# $B_s \longrightarrow \mu\mu$ signal features

PRL 111 (2013) 101804

- **Two muons** coming from a B decay
  - Presence of a secondary vertex
  - Di-μ momentum aligned to the flight direction
  - Di-μ mass near the nominal $B^0_{(s)}$ value
  - Isolation of the two muons
- **Trigger and signal preselection**
  - Di-μ trigger
  - $p_T^\mu > 4$ GeV, $|\eta^\mu| < 2.4$
  - Preselection on
    - Vertex
    - Flight length
    - Impact parameter
  - $m_{\mu\mu}$ around the $B^0/B_s$ masses ($4.9 < m_{\mu\mu} < 5.9$ GeV)



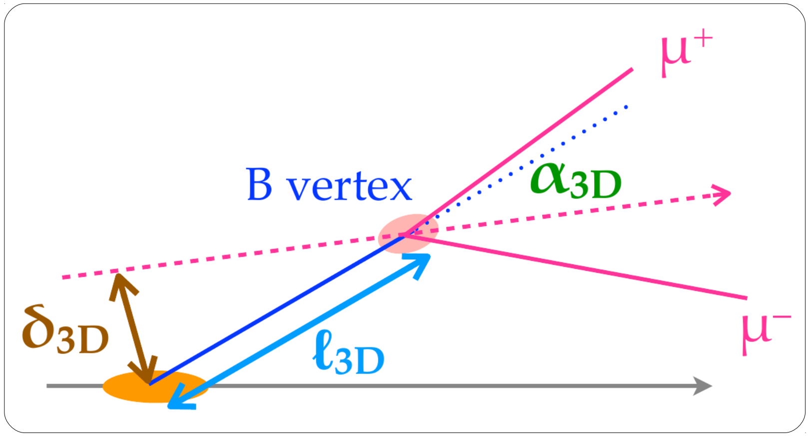
# Background rejection

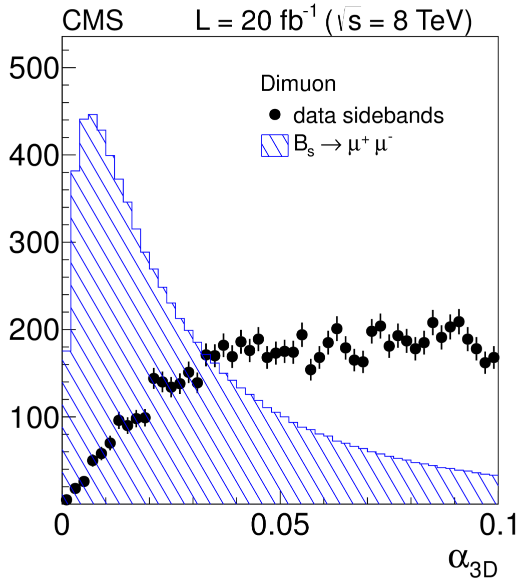
PRL 111 (2013) 101804

**1) Muon selection based on boosted decision tree (BDT)**

**2) Signal selection based on BDT**

- Trained with signal from MC and background from data sidebands (no assumptions made on background model)
  - **Trajectory and vertexing**





- $\ell_{3D}$: B candidate flight distance (distance between primary and decay vertices)
- **$\alpha_{3D}$**: angle (in 3D) between the B candidate momentum and flight direction
- **$\delta_{3D}$**: B candidate impact parameter with respect to primary vertex
- **$\chi^2$/ndof**: vertex fit $\chi^2$ of the B candidate

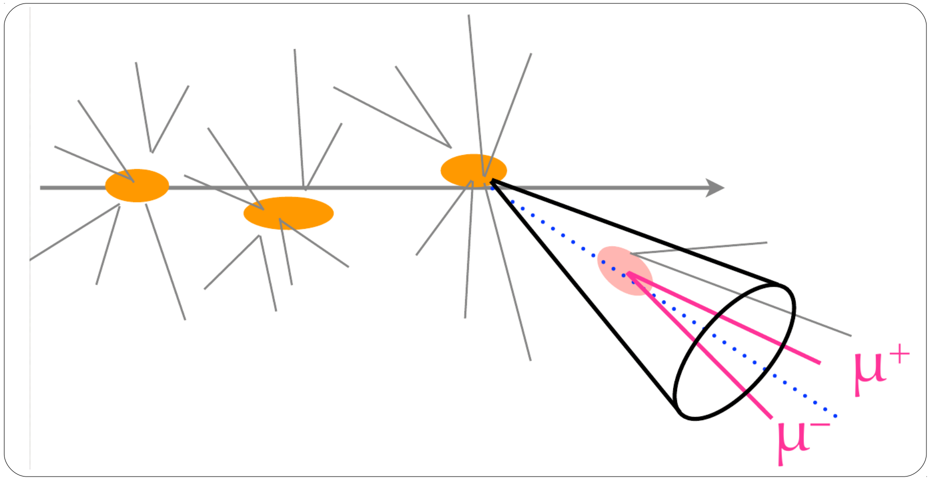
# Background rejection

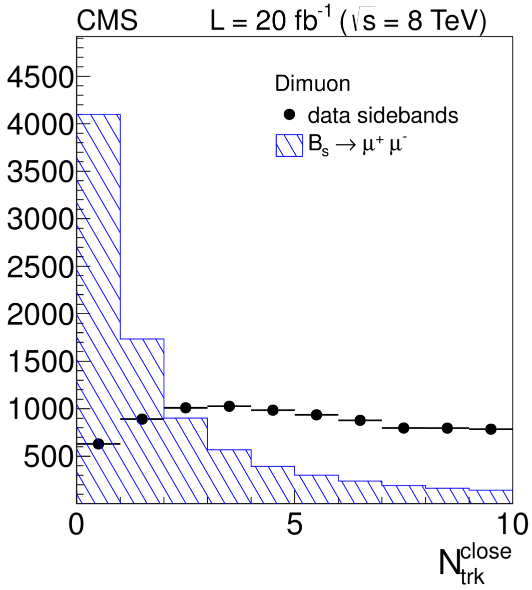
PRL 111 (2013) 101804

**1) Muon selection based on boosted decision tree (BDT)**

**2) Signal selection based on BDT**

- Using several characteristics of the $B^0_{(s)} \to \mu\mu$ decay to discriminate it from the backgrounds
  - **Trajectory and vertexing**
  - **Isolation**



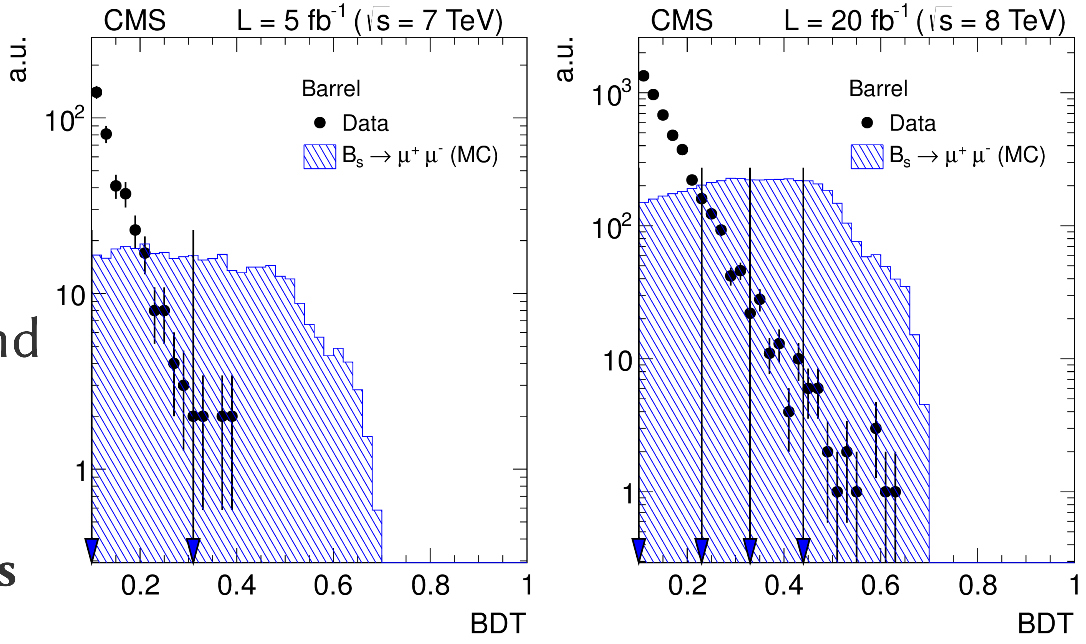


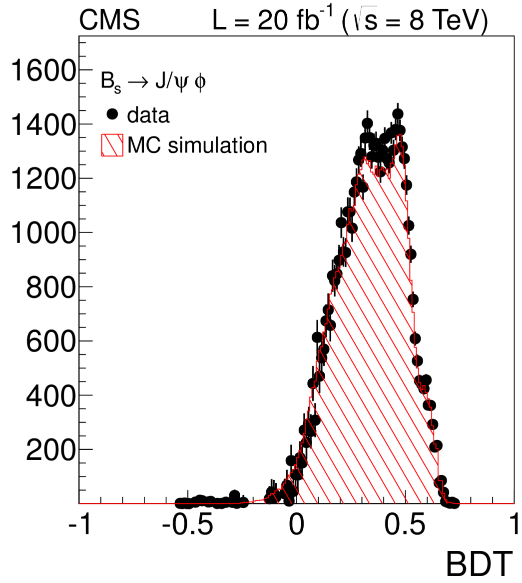
- **Iso:** isolation (w.r.t. charged tracks) of the B candidate in a cone around the μμ momentum
- **$d^0_{ca}$**: distance of closest approach of charged tracks to the B candidate
- **$N_{trk}^{close}$**: number of tracks in the vicinity of the B candidate decay vertex

# $B_s \to \mu\mu$: signal BDT

PRL 111 (2013) 101804

- **4 different event classes**: (2011, 2012) × (barrel, endcap)
  - Barrel if $|\eta^{\mu}| < 1.4$ for both μ, otherwise endcap
- BDT trained with **signal from MC** and **background from data sidebands**
  - Background events in each class randomly split in **3 separate samples**
    - **Training**, **Test**, **Application**
  - Samples **rotated cyclically** to exploit the full statistical power of data
    - **BDT1**: Tr:1 ⟶ Te:2 ⟶ Ap:3
    - **BDT2**: Tr:2 ⟶ Te:3 ⟶ Ap:1
    - **BDT3**: Tr:3 ⟶ Te:1 ⟶ Ap:2
  - **12 different BDTs,** statistically equivalent in groups of 3
- Output tested on the control sample $B_s \to J/\psi\phi$

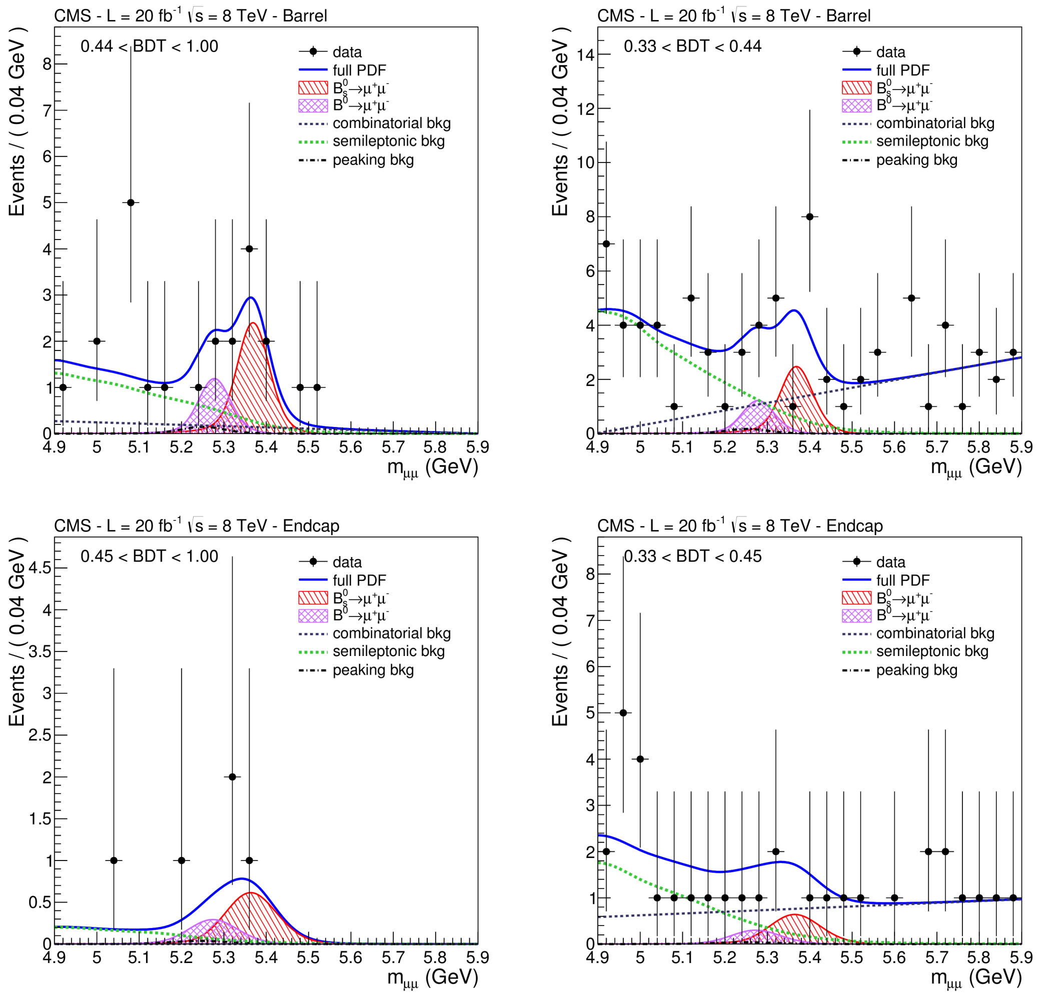




# $B_s \to \mu\mu$: fit

PRL 111 (2013) 101804

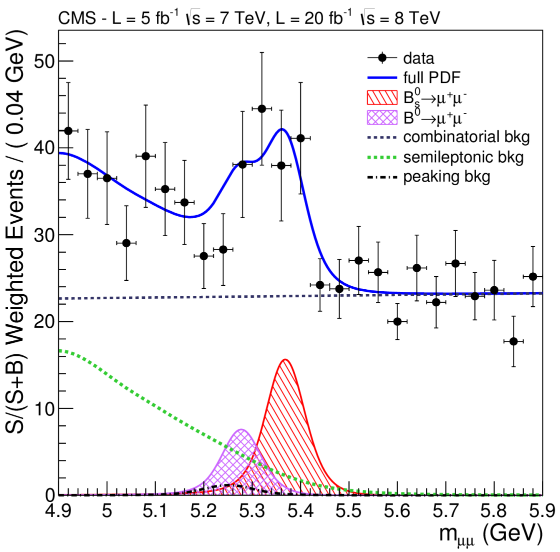
- Split all events in 2(4) **bins** for barrel and endcap 2011(2012) based on the BDT output
    - Same expected $N_{sig}$ in each bin
    - Full signal statistics
    - Simultaneous fit in each bin
- PDF from MC
    - Signal (Crystal Ball)
    - Peaking background (Crystal Ball + Gaussian)
    - Semileptonic background (Gaussian kernels)
    - Combinatorial background ($1^{st}$ degree polinomial)
- Systematics included in the fit as Gaussian constraints



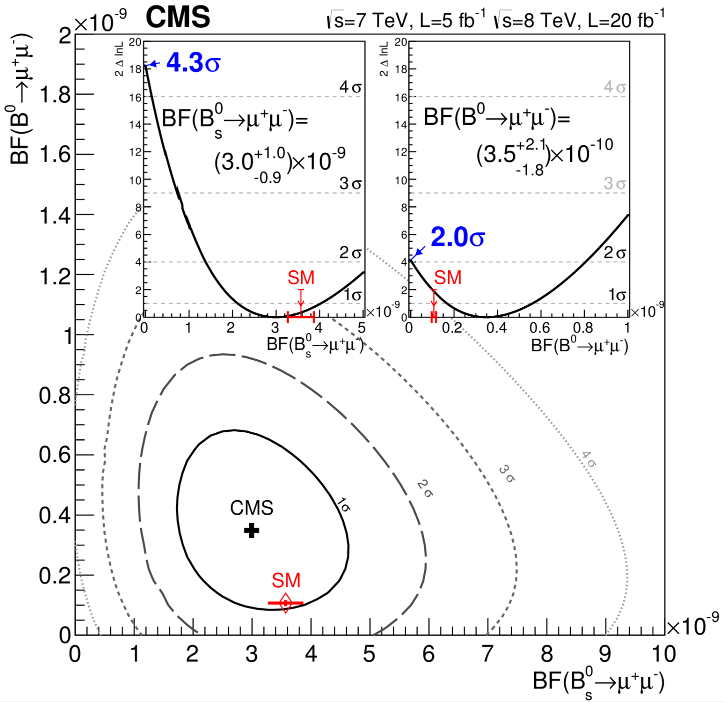
**Fit on 2012 data for the categories with highest S/B in barrel (top) and endcap (bottom)**

# $B_s \to \mu\mu$: results

PRL 111 (2013) 101804

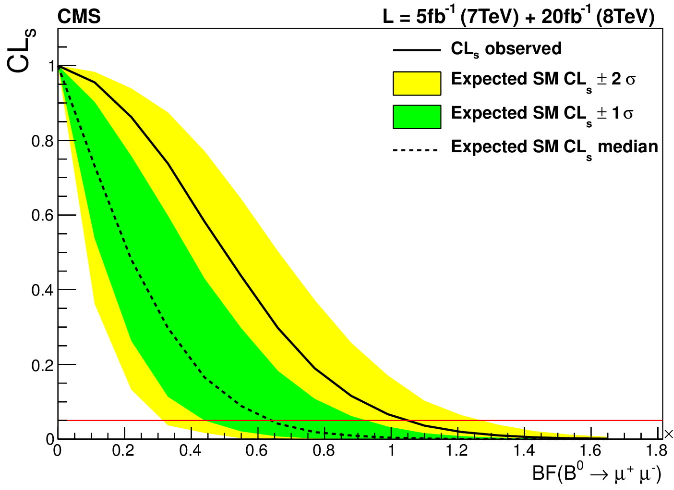


**Categories combination weighted on S/(S+B)**

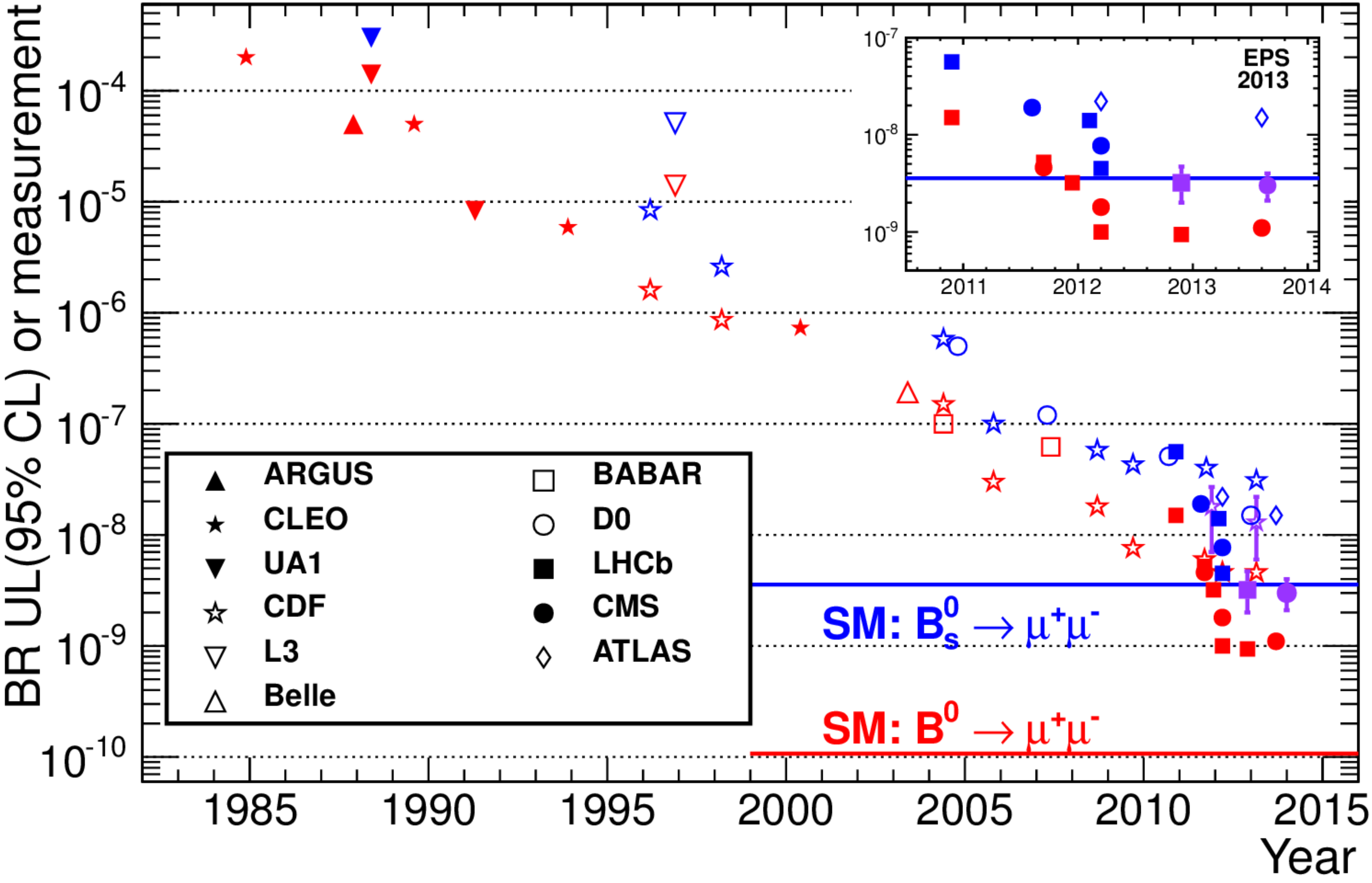


- $\mathcal{B}(B_s \to \mu\mu) = 3.0^{+1.0}_{-0.9} \times 10^{-9}$
  - Significance **4.3 σ**
- $\mathcal{B}(B^0 \to \mu\mu) = 3.5^{+2.1}_{-1.8} \times 10^{-10}$
  - Significance **2.0 σ**
- Results **compatible with the Standard Model predictions** within 1 σ

- **Upper limit to $\mathcal{B}(B^0 \to \mu\mu)$** with the $CL_s$ method
- Used a different strategy with respect to the branching fraction measurement
  - **Cut on the BDT output** depending on period (2011-2012) and pseudorapidity (barrel-endcap)
- $\mathcal{B}(B^0 \to \mu\mu) < 1.1 \times 10^{-9}$ **a 95% CL**



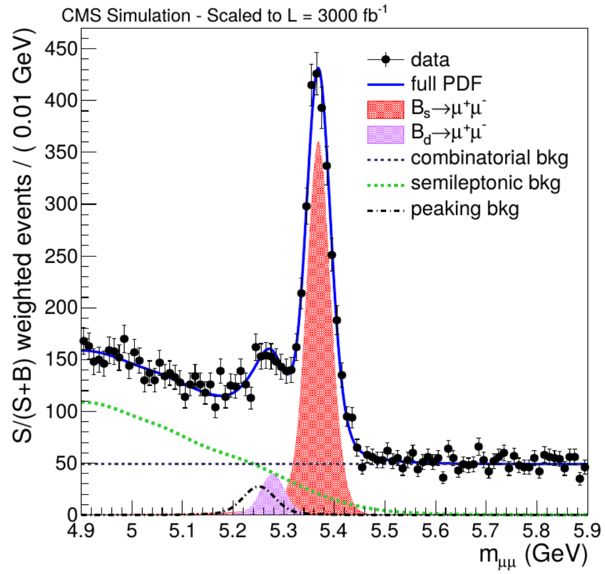
# A 30 year long quest



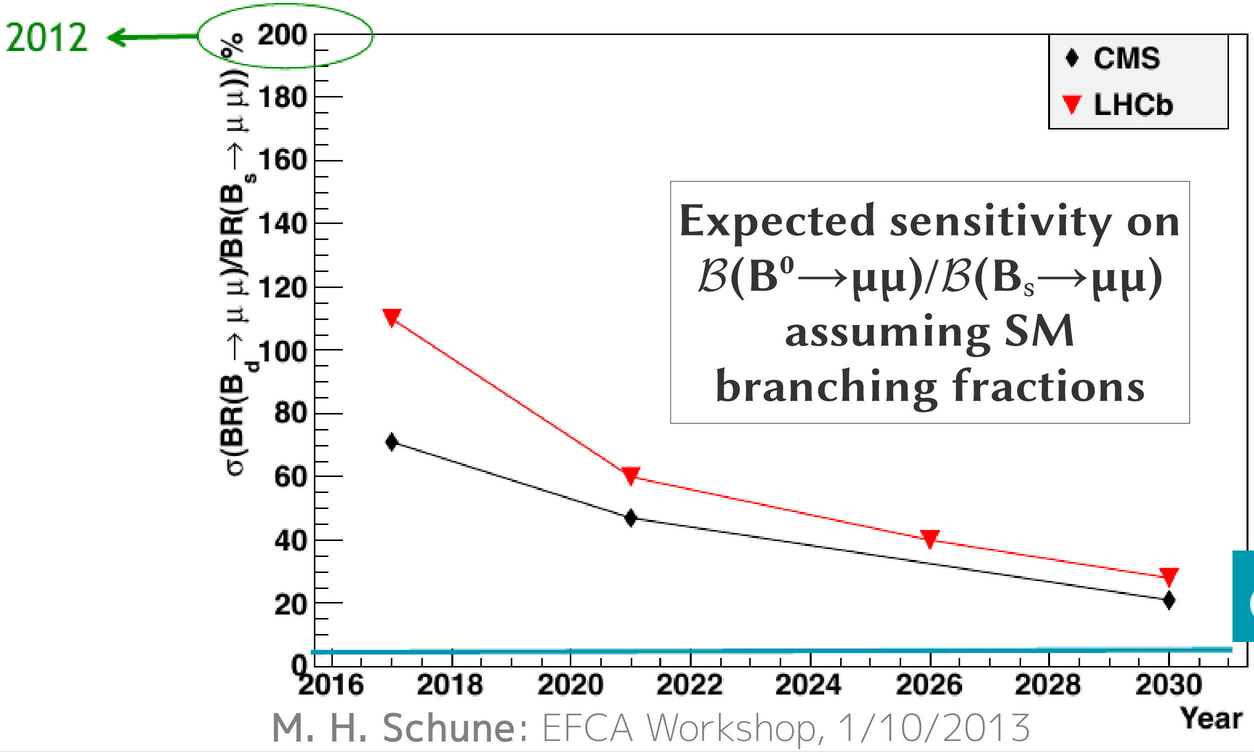
# Future perspectives

CMS-PAS-FTR-13-022

- CMS and LHCb have published **estimates of the sensitivity expected** in the next ~10 years
- Important observables to measure
  - $\mathcal{B}(B^0\to\mu\mu)$
  - $\mathcal{B}(B^0\to\mu\mu)/\mathcal{B}(B_s\to\mu\mu)$
  - Effective average lifetime of $B_s\to\mu\mu$



**CMS projection (3000 fb$^{-1}$)**



**Expected sensitivity on $\mathcal{B}(B^0\to\mu\mu)/\mathcal{B}(B_s\to\mu\mu)$ assuming SM branching fractions**

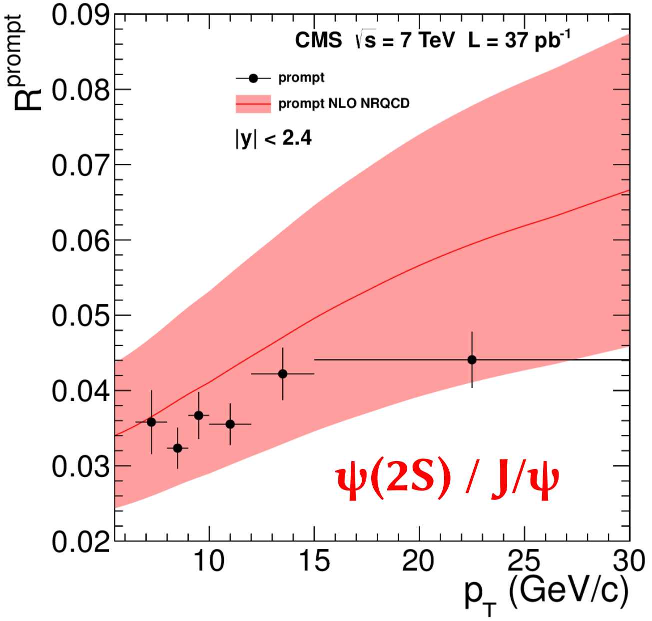
$\sigma_{theory}$ ~5 %

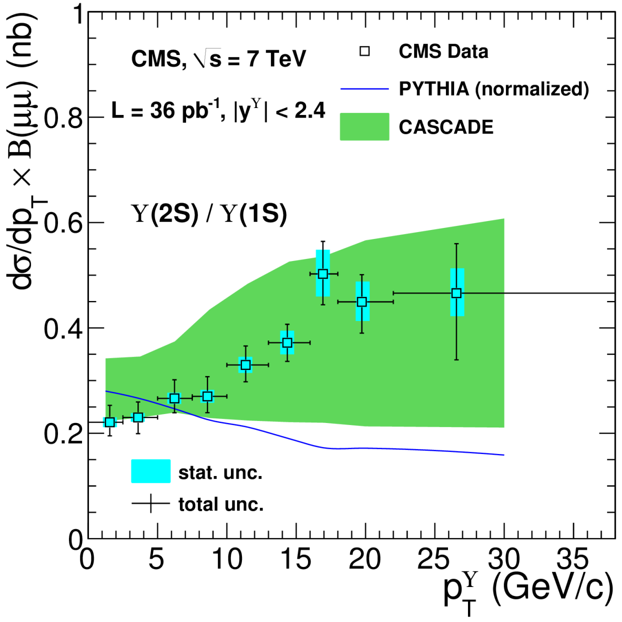
M. H. Schune: EFCA Workshop, 1/10/2013

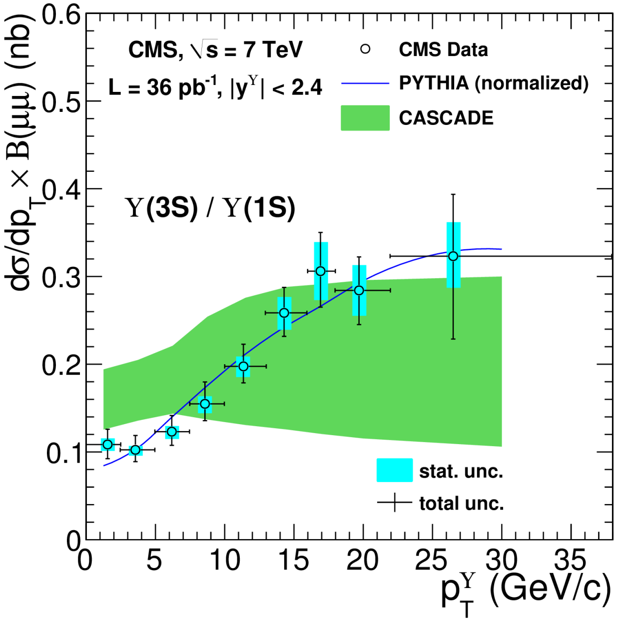
- Necessary high integrated luminosity (**HL-LHC**) and **detector upgrade** in order to measure with precision these three observables

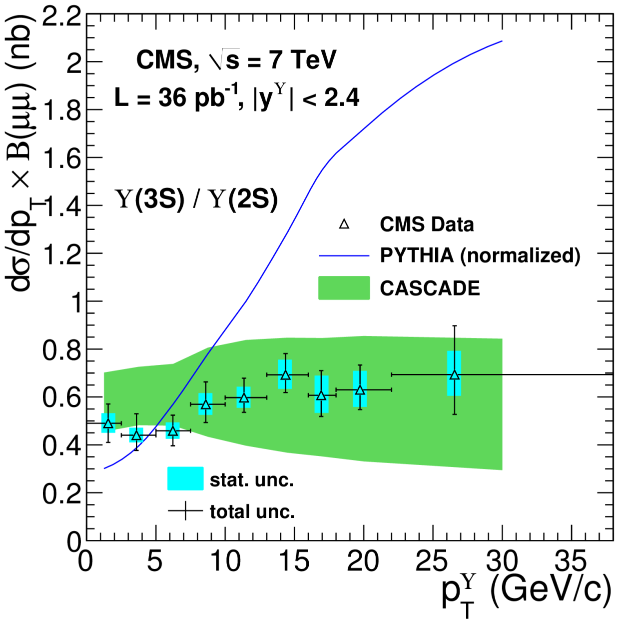
# Cross section ratios

- Found the ratios of prompt cross sections (for J/ψ and ψ(2S) and of total cross sections (for Υ(nS))
- NRQCD compatible with ψ(nS) data within uncertainties
- Υ(nS) data compared with PYTHIA and CASCADE MC generators
  - Fair agreement of the results within uncertainties



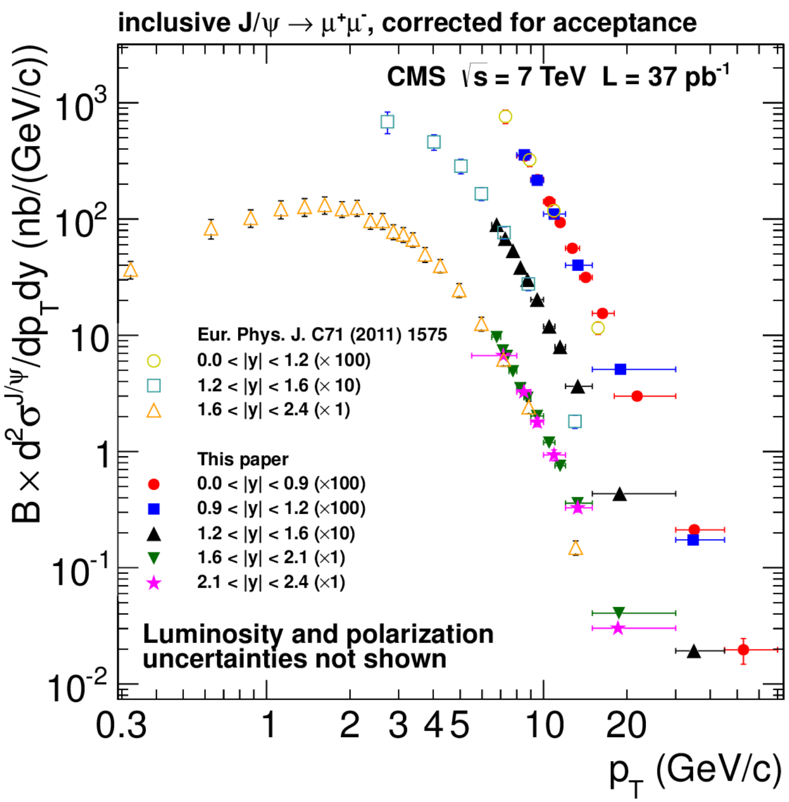


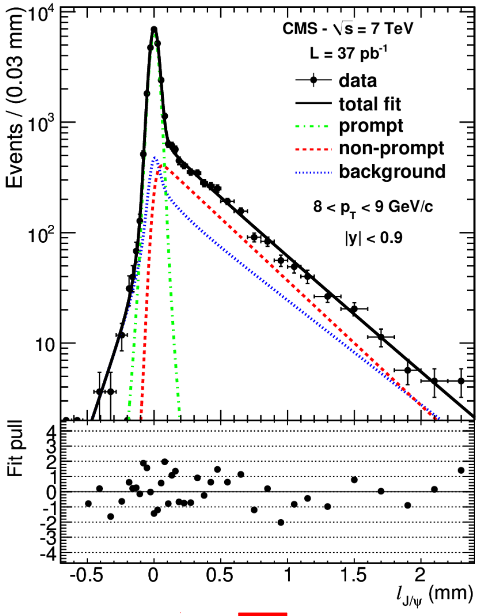




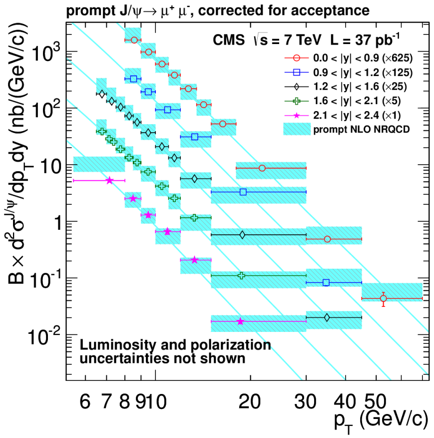
# J/ψ and ψ(2S) cross sections

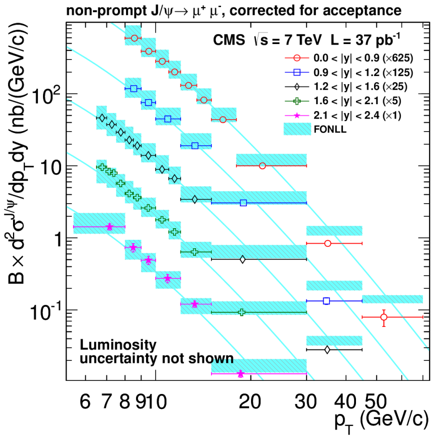
JHEP 02 (2012) 011





$$\ell = \frac{L_{xy} \times m}{p_T}$$

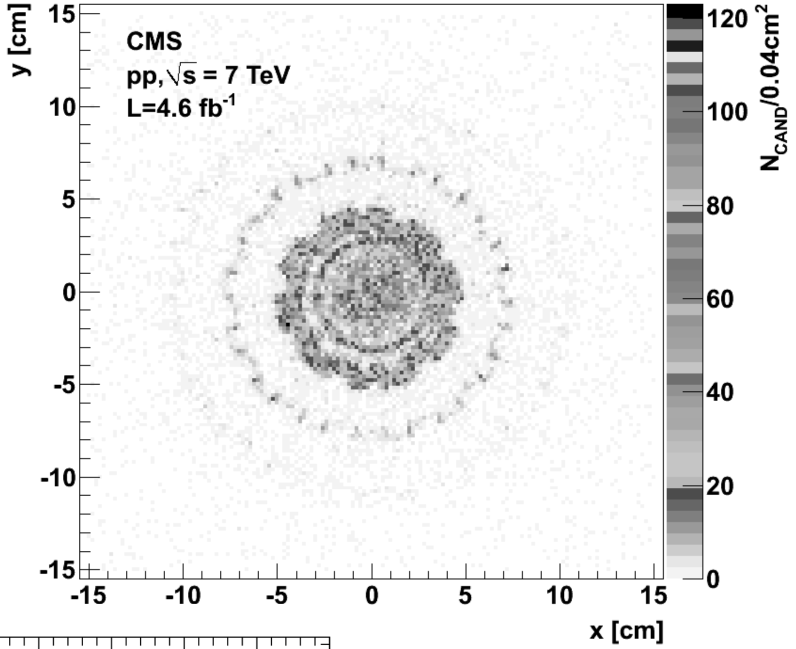




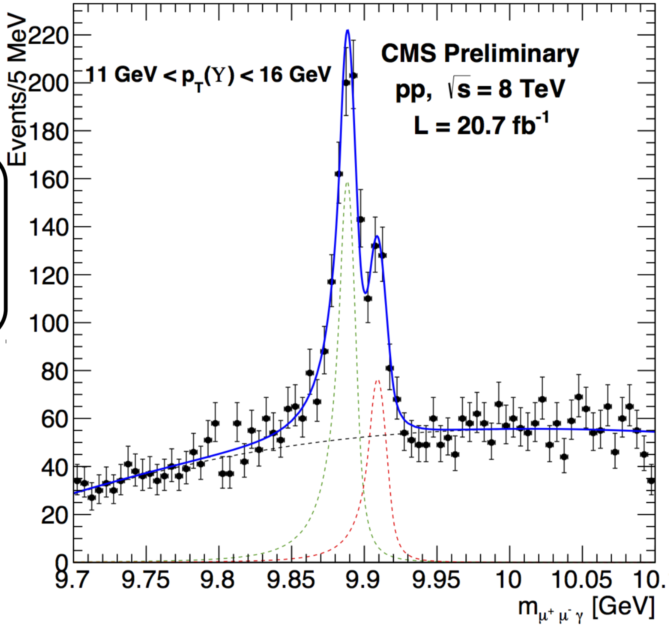
- J/ψ and ψ(2S) have a significant nonprompt fraction
- Use fit to **pseudo-proper lifetime** ℓ to split the prompt and nonprompt components

# Experimental signatures: P-wave cross sections

- The CSM and NRQCD frameworks make several predictions that can be compared with the experiments
- Large number of observables to test the two models
- At CMS, studied only processes involving **$\psi(nS)[\Upsilon(nS)] \rightarrow \mu\mu$** decays



- **Cross sections of P-wave states**
  - $[\sigma(\chi_{b2})\times\mathcal{B}(\chi_{b2})]/[\sigma(\chi_{b1})\times\mathcal{B}(\chi_{b1})]$



**M(χ) resolution of ~5 MeV, reconstructing $\chi_{b1,2}(1P)\rightarrow\Upsilon(1S)+\gamma$ $[\chi_{c1,2}(1P)\rightarrow J/\psi+\gamma]$ using $\gamma\rightarrow e^+e^-$ conversions in the tracker**

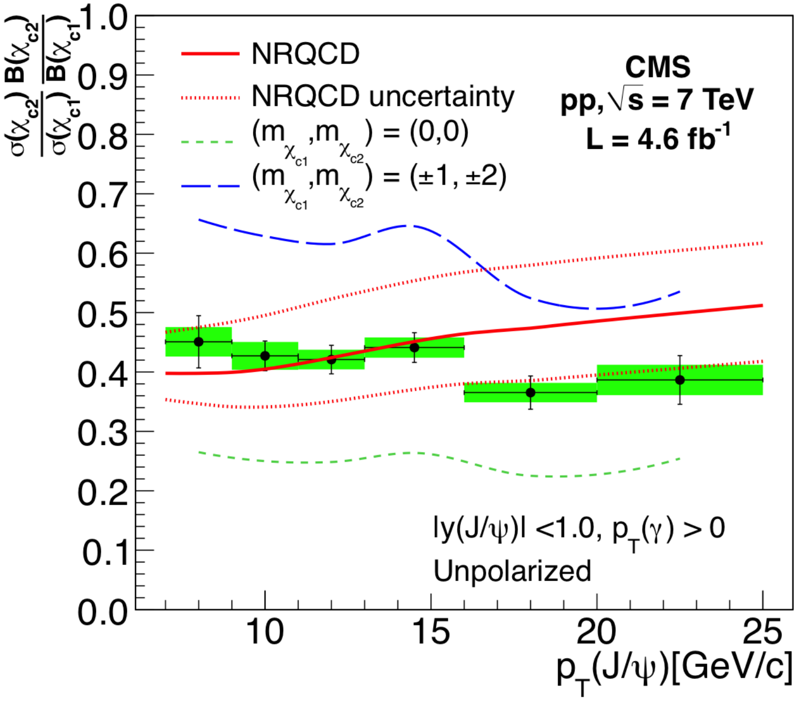
# Prompt P-wave cross sections

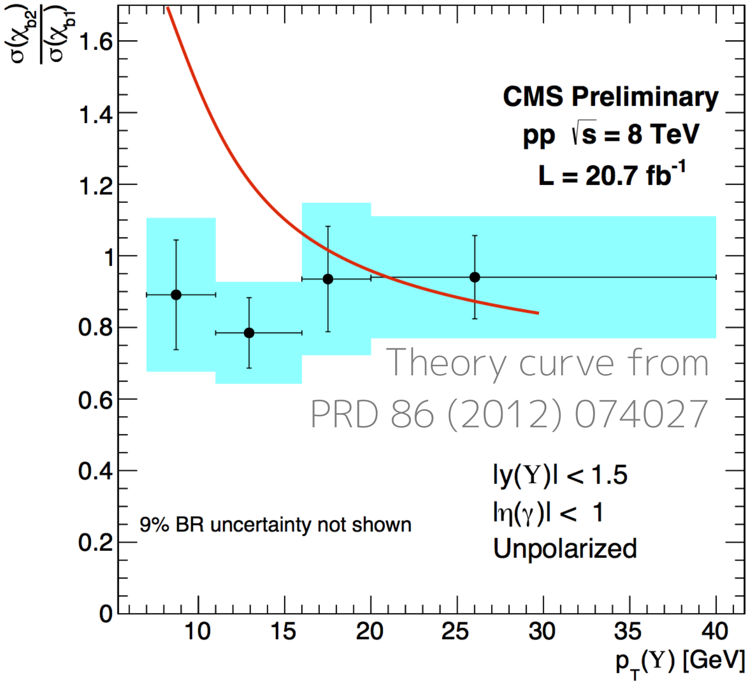
EPJC 72 (2012) 2251
CMS-PAS-BPH-13-005

- For $\chi_{c1}$ and $\chi_{c2}$, NRQCD results compatible with the average prompt cross section × branching fraction ratio
- For $\chi_{b1}$ and $\chi_{b2}$, no increase in the ratio measured at low $p_T$, in significant disagreement with NLO calculation

$$R_c = \frac{\sigma(pp\rightarrow\chi_{c2}+X)\times\mathcal{B}(\chi_{c2}\rightarrow J/\psi+\gamma)}{\sigma(pp\rightarrow\chi_{c1}+X)\times\mathcal{B}(\chi_{c1}\rightarrow J/\psi+\gamma)}$$

$$R_b = \frac{\sigma(pp\rightarrow\chi_{b2}+X)}{\sigma(pp\rightarrow\chi_{b1}+X)}$$



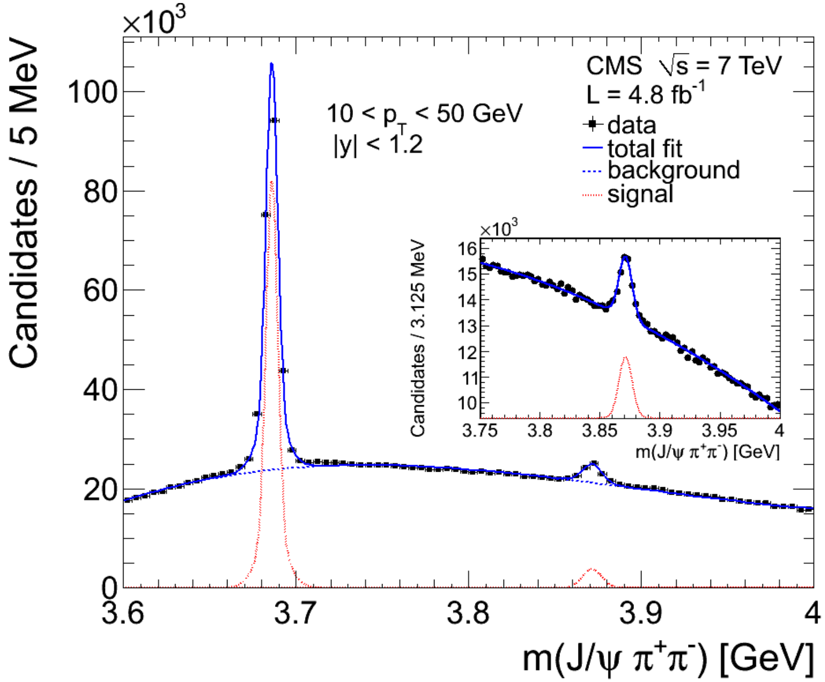


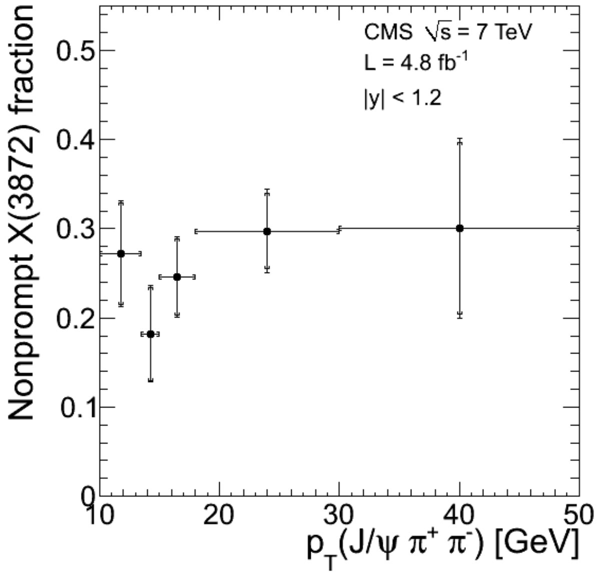
Theory curve from PRD 86 (2012) 074027

# Studies of X(3872) properties in CMS

JHEP 04 (2013) 154

- CMS studied the X(3872) in its most common decay **$X(3872)\rightarrow J/\psi\pi^+\pi^-$**, with $J/\psi\rightarrow\mu\mu$
- Large sample extracted from 2011 data
- Several properties measured with unprecedented precision





- Fraction of prompt vs. nonprompt production extracted
  - Nonprompt = feed-down from B hadron decays
- Most X(3872) are produced in prompt processes
  - **Nonprompt fraction only 0.263±0.023±0.016**
  - No significant $p_T$ dependence