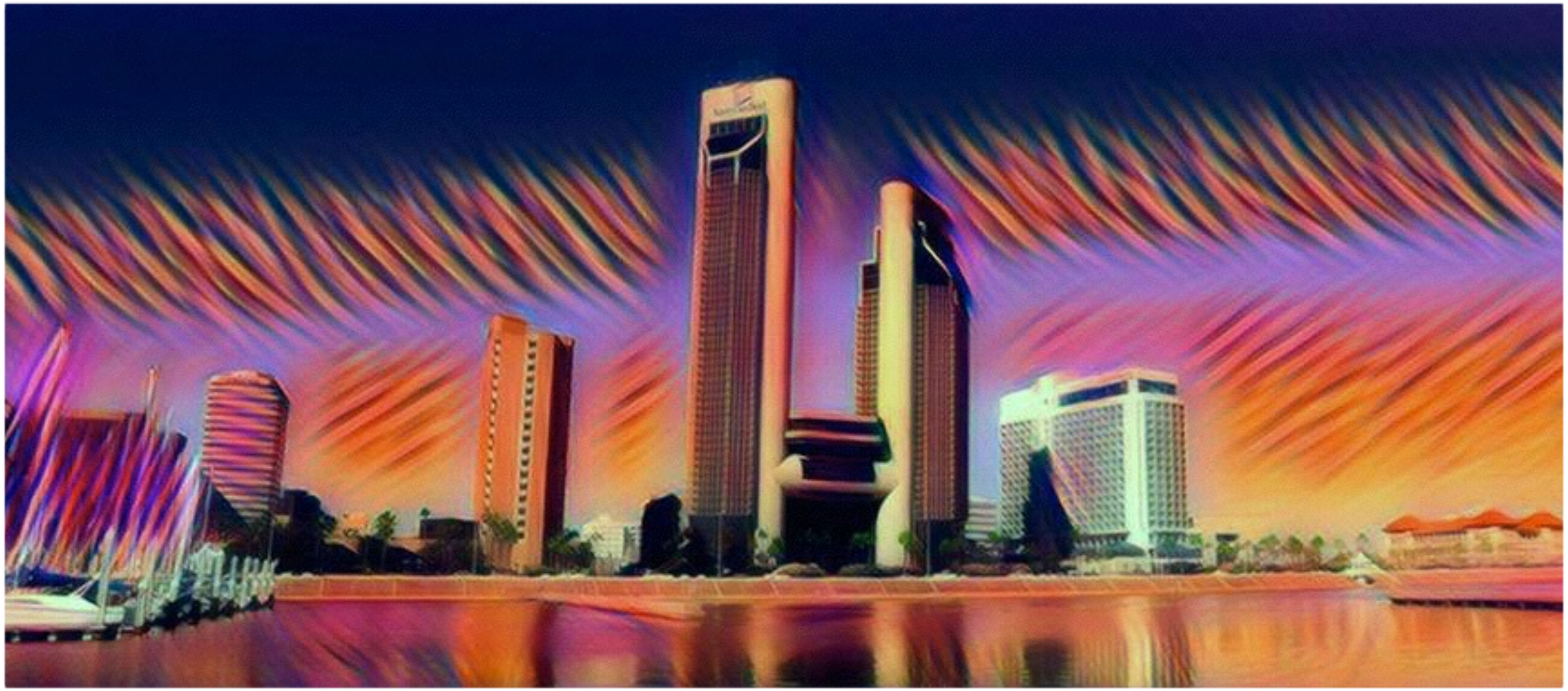


SUSY 2019, May 20, 2019, Corpus Christi, Texas, USA

RECENT FLAVOR PHYSICS RESULTS FROM CMS

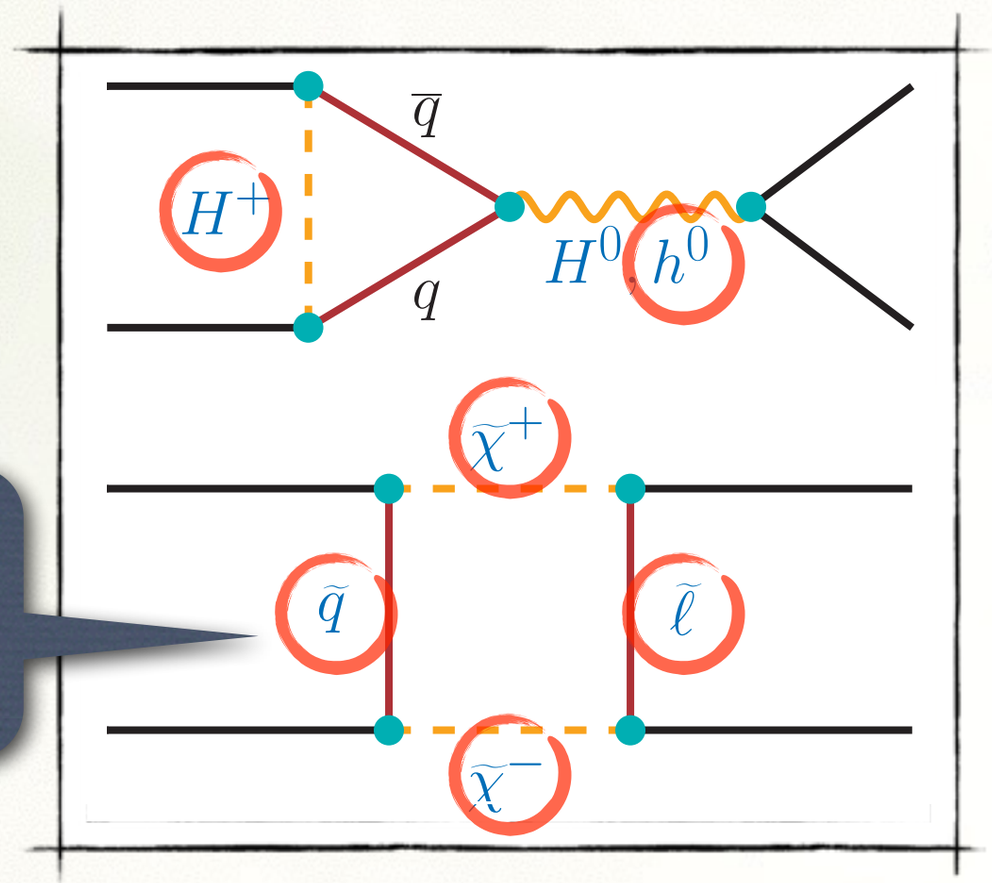
Kai-Feng Chen

National Taiwan University

On behalf of the CMS Collaboration

CMS Objective in Flavor Physics

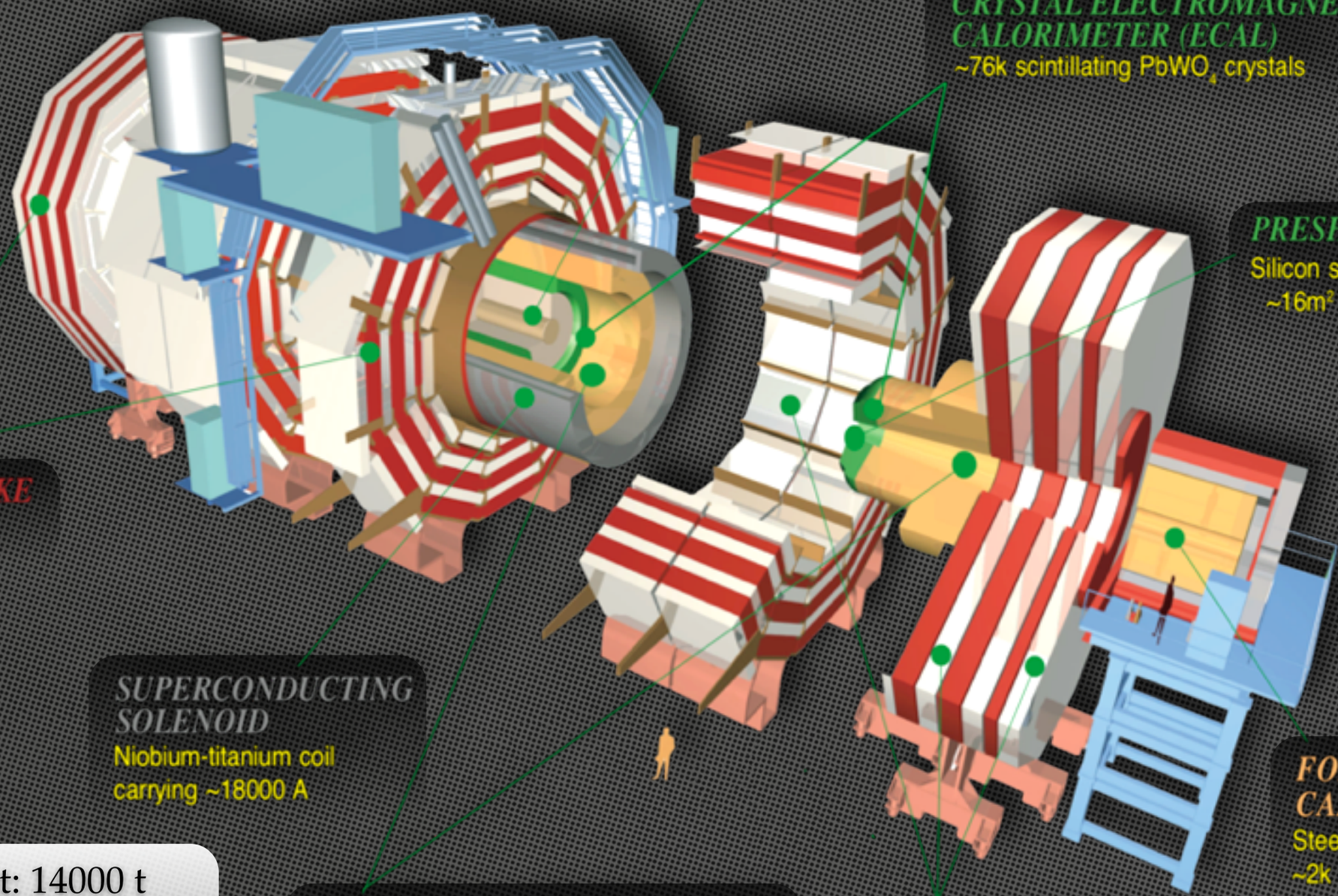
- **Understand the underlying QCD processes**
  - Measure the spectrum of standard quarkonia production, polarization, and heavy flavor productions.
  - Look for new exotic quarkonia states and new heavy baryons.
- **Test the Standard Model with high precision measurements**
  - Measurement of decay rates, lifetime, and CP phases of B hadrons.
- **Look for new physics in the loop**
  - Study of rare decays: $B_{s,d} \to \mu\mu$, $B \to K^*\mu\mu$, $\tau \to 3\mu$, etc.



If these particles cannot be observed in the direct searches, this is the place one shall still look for!

THE CMS DETECTOR

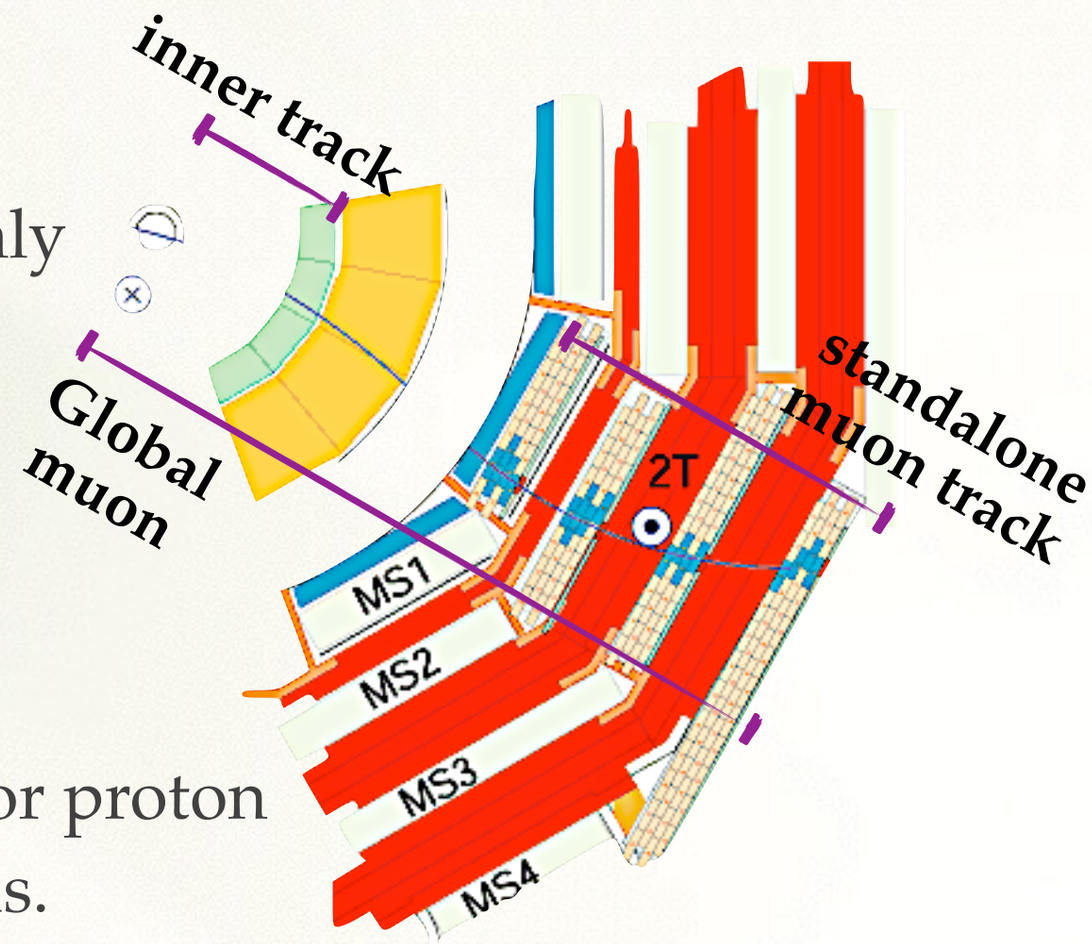
The CMS experiment at the CERN LHC,
J. Instrum. 3 (2008)



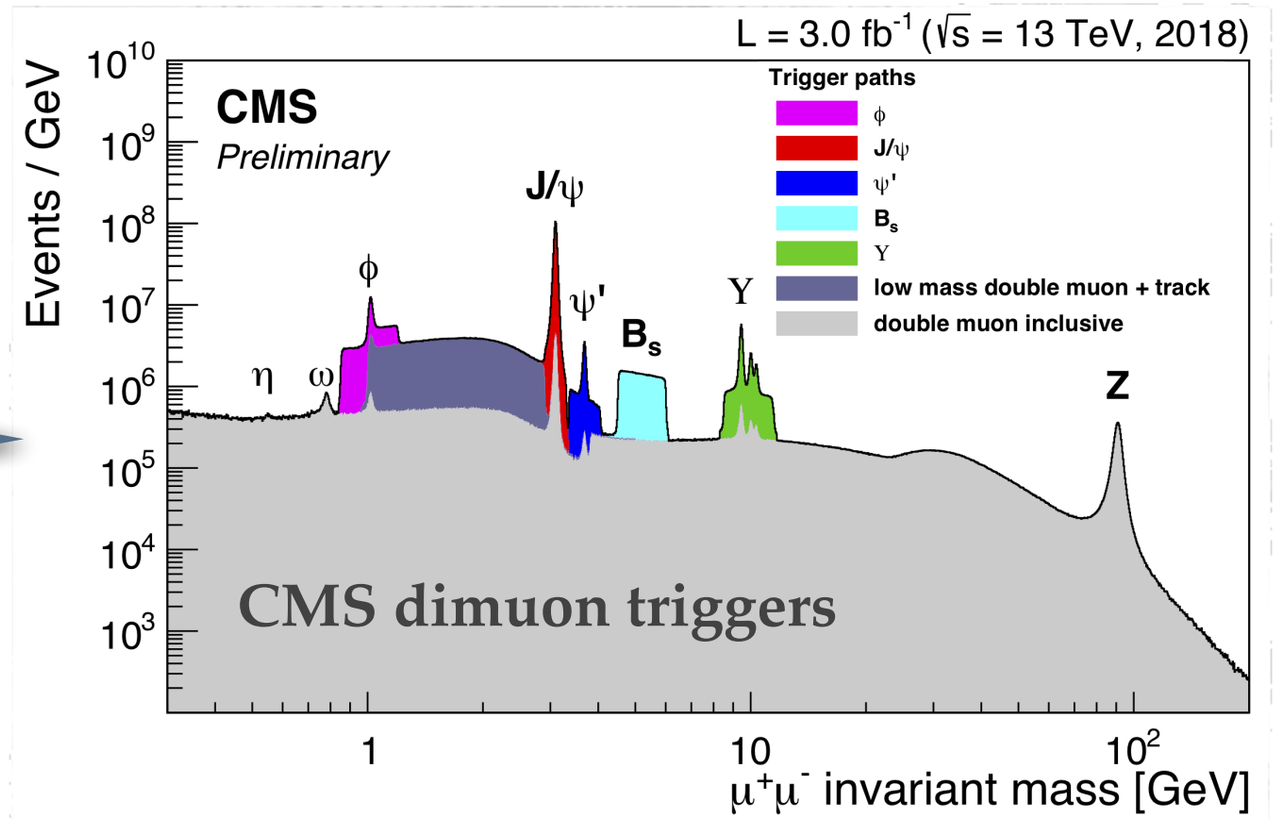
Total weight: 14000 t
Overall diameter: 15 m
Overall length: 28.7 m
Magnetic field: 3.8 Tesla

CMS Muon Reconstruction

- **CMS muon system:**
  - 3 different devices installed, with a large coverage up to $|\eta|<2.4$.
  - Good dimuon mass resolution
    ~0.6-1.5% (depending on $|y|$).
- **Reconstruction algorithms:**
  - **standalone muon:**
    reconstructed in muon system only
  - **global muon:**
    standalone muon ⇒ inner track
  - **tracker muon:**
    inner track ⇒ muon system
- **Excellent muon identification**
  - Fake rate ≤0.1% for π,K; ≤0.05%for proton
  - MVA-based ID for B→μμ analysis.

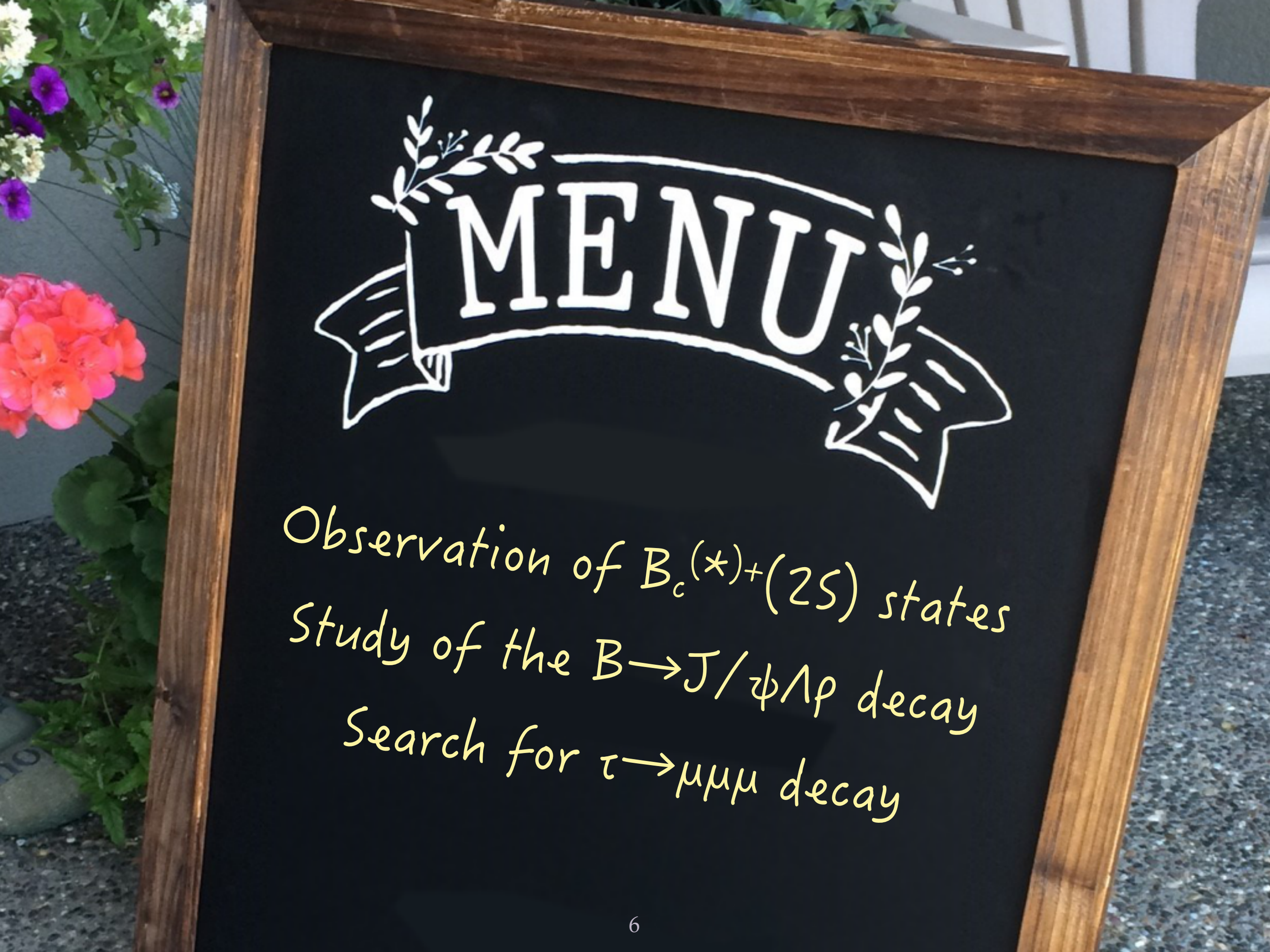


CMS Dimuon Triggers



Most flavour physics analyses rely on displaced/non-displaced quarkonia (J/ψ, ψ' & Υ), $B_{(s)}$, and non-resonant **DIMUON** triggers.

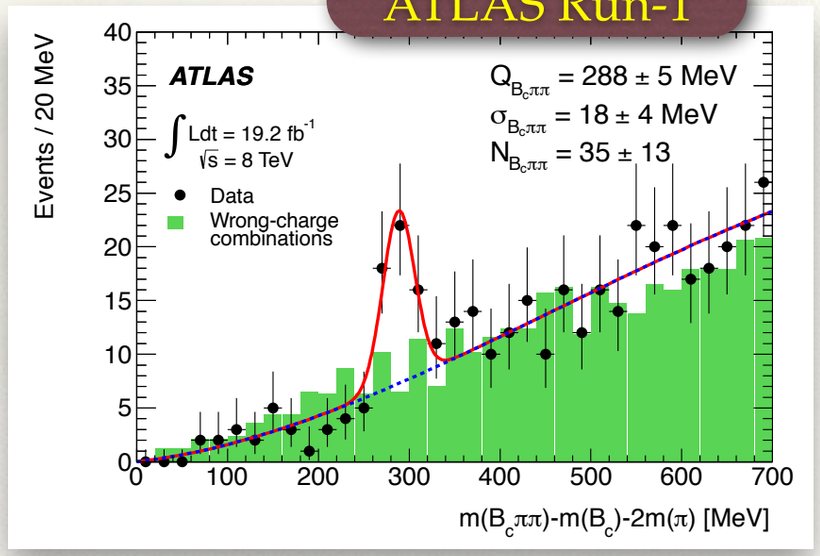
- **CMS trigger system:**
  - **Fast hardware trigger (L1)**
  - **Software trigger with full tracking & vertex reconstruction (HLT).**
  - Specific triggers were developed for various analyses.
  - Trigger requirements tightened with the increased luminosity.
  - ~15% of CMS bandwidth is given to flavour physics.


MENU
Observation of $B_c^{(*)+}(2S)$ states
Study of the $B \to J/\psi \Lambda p$ decay
Search for $\tau \to \mu\mu\mu$ decay

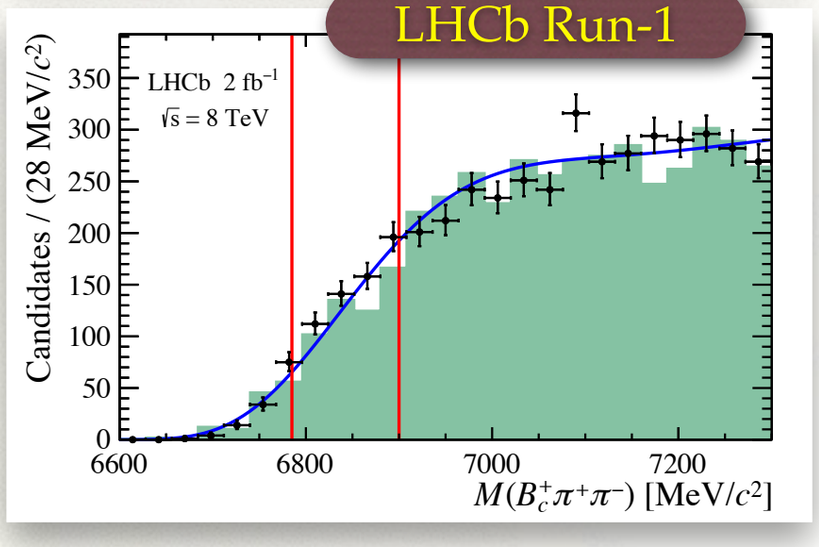
Excited B_c States: Introduction

- The known B_c^+ meson is the lowest state of bottom+charm bound state family.
- Experimental studies are limited by its lower production rate, which is only ~1/1000 comparing to other B mesons.
- As an analogy to ψ/Υ system, **ATLAS has observed an excited state $B_c^+(2S)$ decaying in $B_c^+\pi^+\pi^-$** with full Run-1 data **[PRL 113 (2014) 212004]**:
  - LHCb did not confirm this state with the analysis of Run-1 data **[JHEP 01 (2018) 138]**.
  - Suspects of different rapidity coverage; **has to be checked by CMS**.

ATLAS Run-1



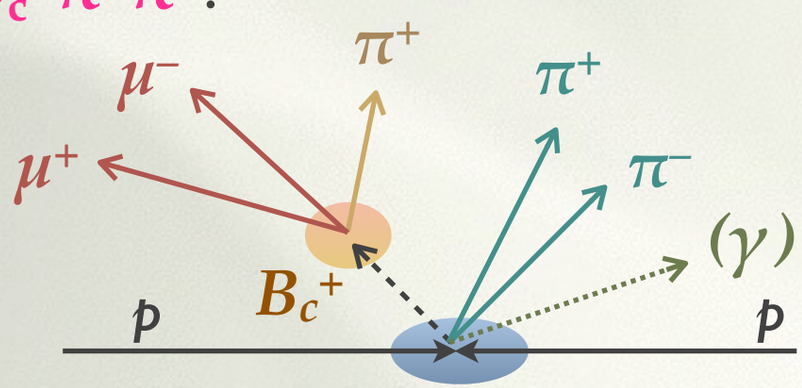
LHCb Run-1



CMS carried out the searches for excited Bc states, using the data collected in full Run-2 period of 140 fb^{-1}.

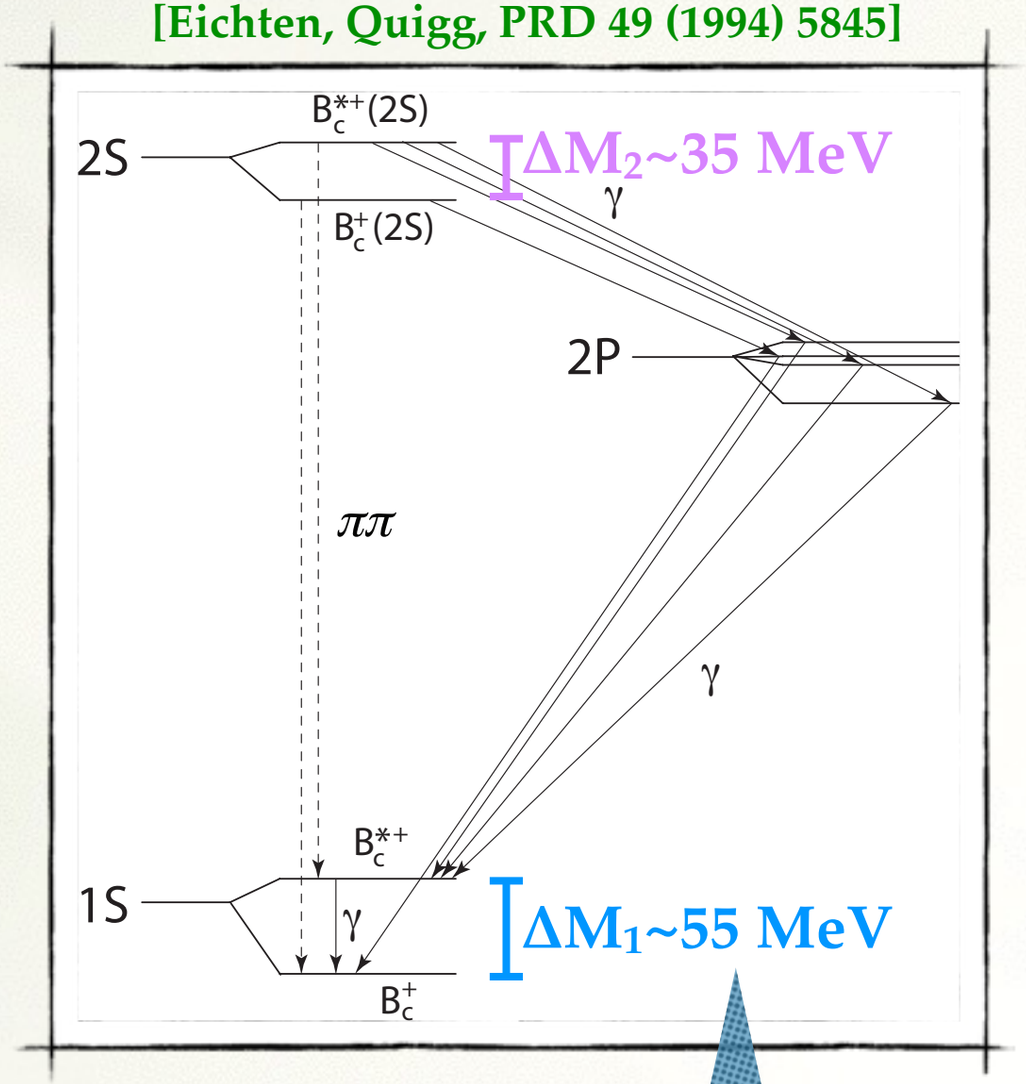
Excited B_c States: Decays

- Multiple excited B_c states might be accessible by
  $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^- \to Bc^+\pi^+\pi^- + \gamma$
  $B_c^{+}(2S) \to B_c^{+}\pi^+\pi^-$
- Since the soft photon is not detected, both decays can end up with the same final state of $B_c^{+}\pi^+\pi^-$.



- A mass splitting is expected to be $\Delta M = \Delta M_1 - \Delta M_2 \sim 20$ MeV.

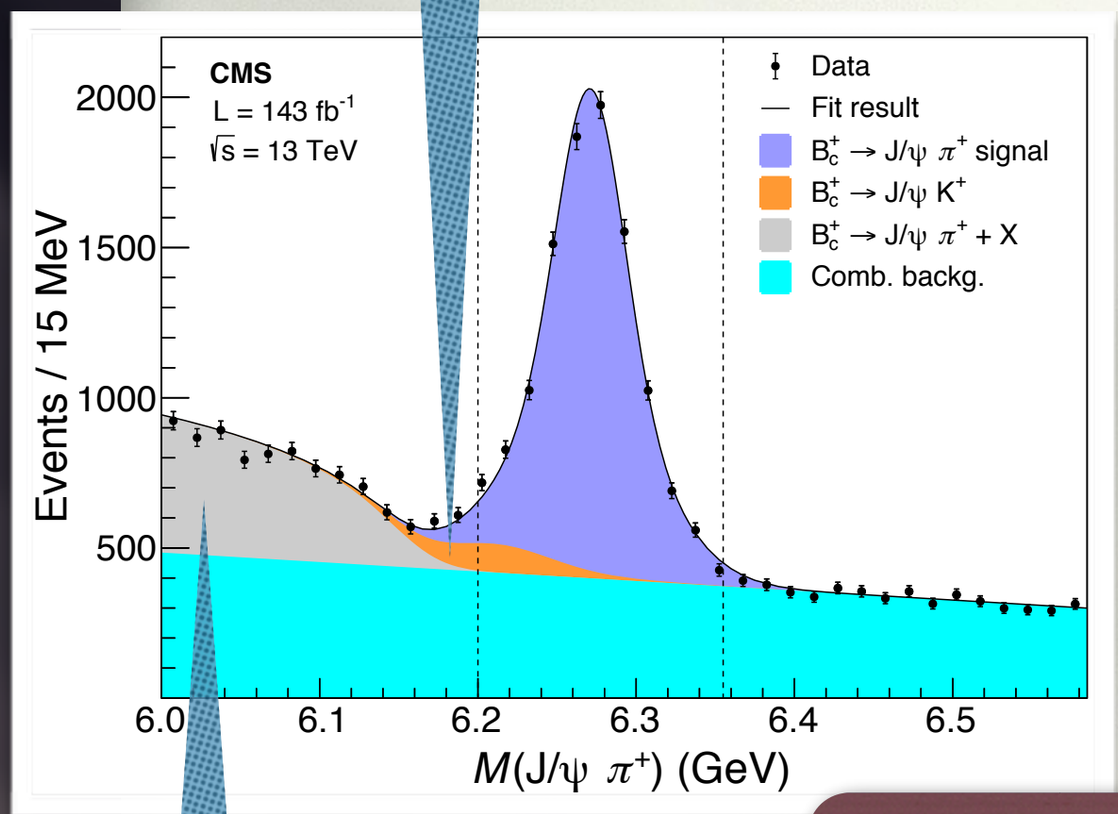
[Eichten, Quigg, PRD 49 (1994) 5845]



Note the mass splitting of 1S states (ΔM_1) is larger than of 2S states (ΔM_2).

Event Reconstruction & Selection

Peaking background from $B_c^+ \to J/\psi K^+$ decay, modelled with simulated sample



$N(B_c^+) = 7629 \pm 225$

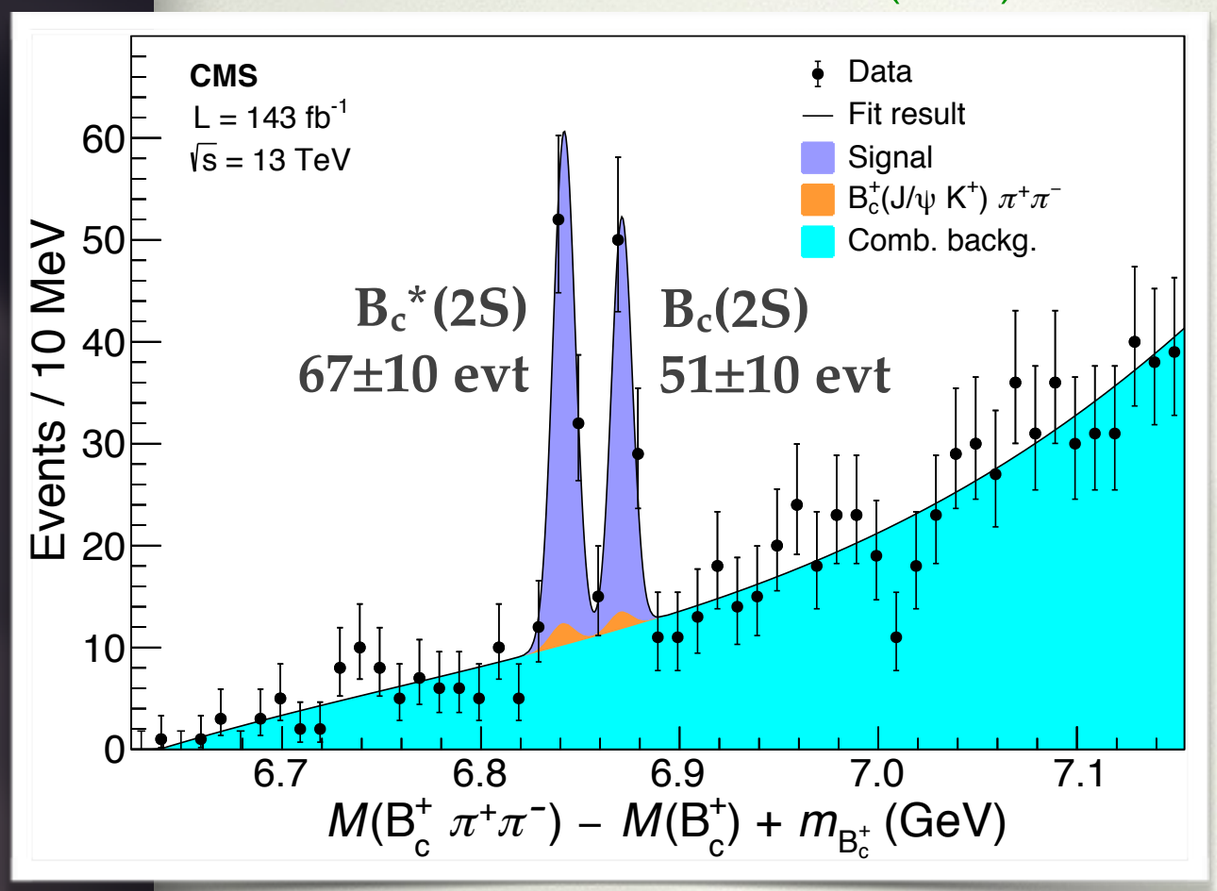
Partially reconstructed background, from $B_c^+ \to J/\psi\pi^+ + X$ processes.

- **Reconstruction of B_c^+:**
  - Triggering with two muons from J/ψ plus a track, with a common vertex displaced from the interaction point;
  - Muons $p_T > 4$ GeV, track $p_T > 3.5$ GeV; B_c^+ transverse momentum > 15 GeV;
  - Common vertex with displacement > 100 μm;
- **Reconstruction of $B_c^{*+}(2S)$:**
  - Adding two tracks with opposite charges from primary vertex to a B_c^+ candidate;
  - B_c^+ & $\pi^+\pi^-$ common vertex is required;
  - If multiple candidates in an event — the one with largest p_T is selected.

Ref. CMS PRL 122 (2019) 132001

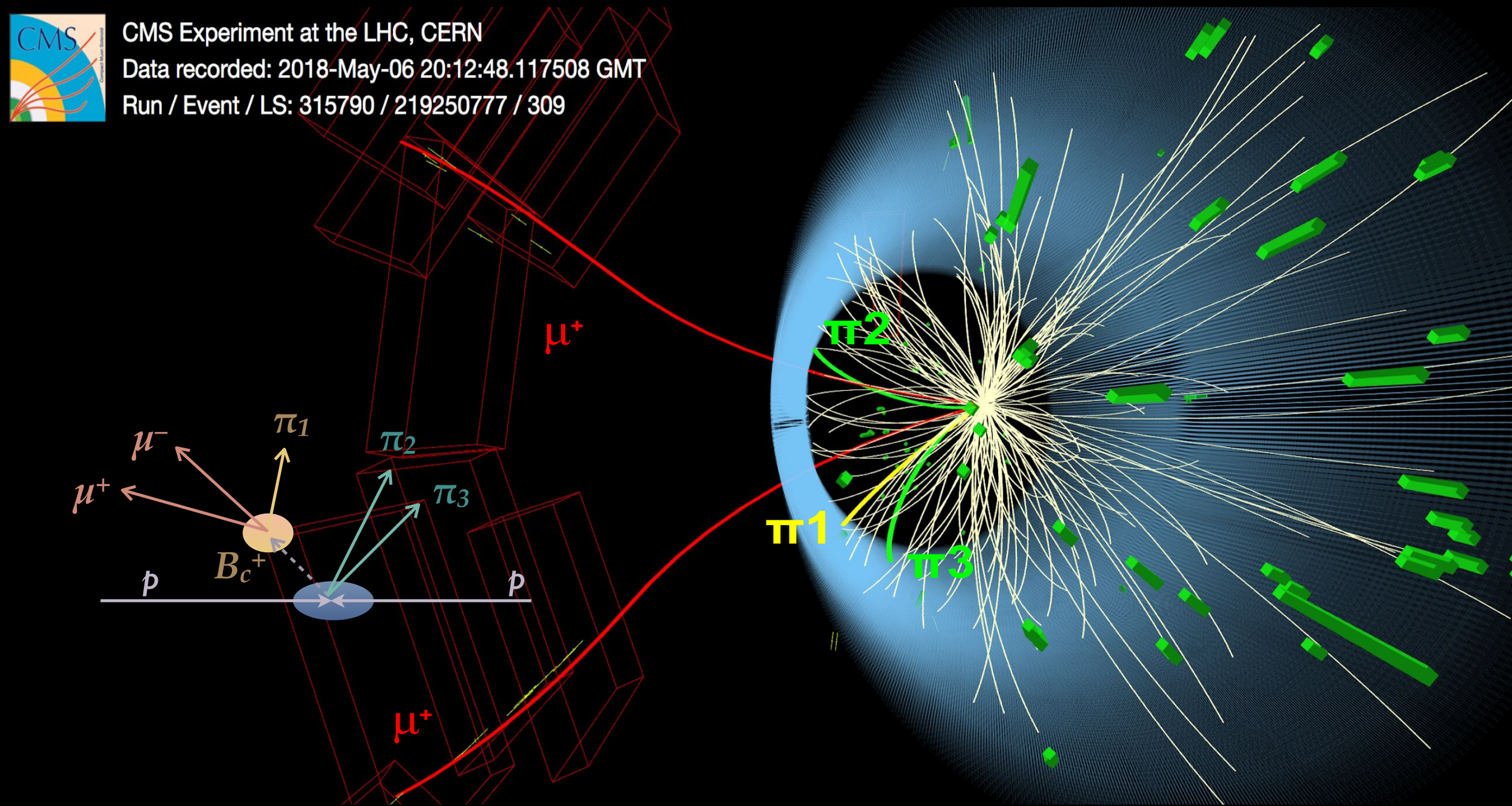
Observation of Excited B_c States

Ref. CMS PRL 122 (2019) 132001



Measured mass difference:
$\Delta M = 29.1 \pm 1.5_{(stat)} \pm 0.7_{(sysy)}$ MeV
Measured $B_c^+(2S)$ mass:
$6871.0 \pm 1.2_{(stat)} \pm 0.8_{(stat)} \pm 0.8_{(B_c^+)}$ MeV

- **Clear two-peak structure seen!**
- Fits to the mass distribution with
  - Gaussians for signal and $B_c^+ \to J/\psi K^+$ peaking background;
  - 3rd order polynomial for the combinatorial background.
- Exceeding 6σ for observing two peaks rather than just one; **each peak has a significance >5σ**.
- Results are consistent with predicted narrow widths [50-90 keV], smaller than the detector resolution.
- **Also confirmed by new LHCb analysis with Run1+Run2** [arXiv:1904.00081].

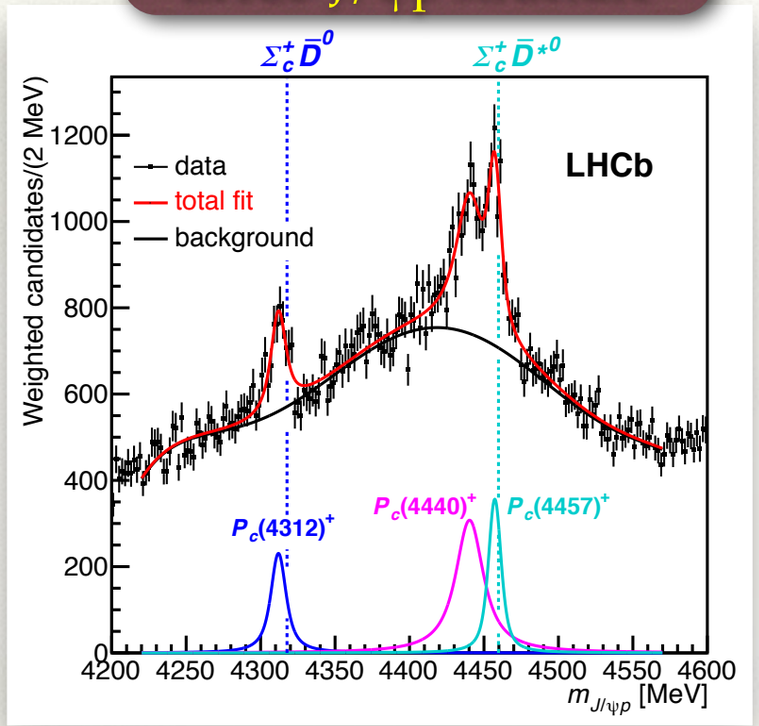


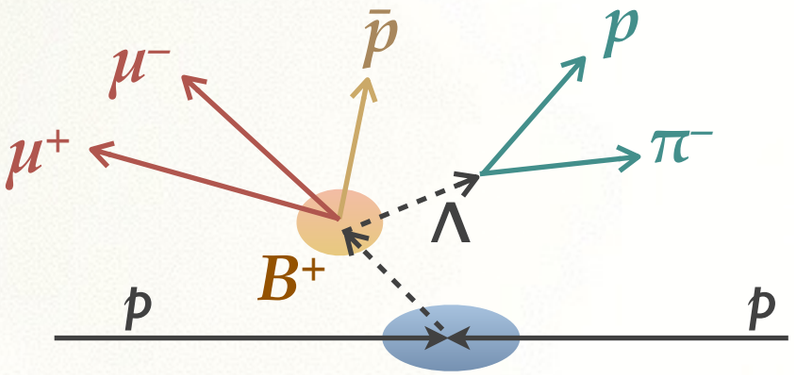
A nice $B_c^+(2S) \rightarrow B_c^+\pi^+\pi^-$ candidate event!

Measurement of $B^+ \to J/\psi \Lambda p$

- First example of B meson decaying into a charmonium state and baryons, first seen by B factories; world average in PDG: $(11.8 \pm 3.1)\times 10^{-6}$.
- Additional motivation to search for possible new intermediate resonances in the **$J/\psi\Lambda$**, **J/ψ p** and **Λp** systems.
- Several similar decays have been probed by LHCb recently: $B_c^+ \to J/\psi\, p\bar{p}\pi^+$ **[PRL 113 (2014) 152003]**, B^0, $B_s \to J/\psi\, p\bar{p}$ **[JHEP 09 (2013) 006]**, and $\Lambda_b \to J/\psi\, pK^-$ **[PRL 115 (2015) 072001; arXiv:1904.03947]**.
  - In Λ_b decays new multiquark states found in $J/\psi p$ distribution, and are consistent with pentaquark.
- CMS analysis is performed with data collected at 8 TeV, corresponding to 19.6 fb^{-1}.

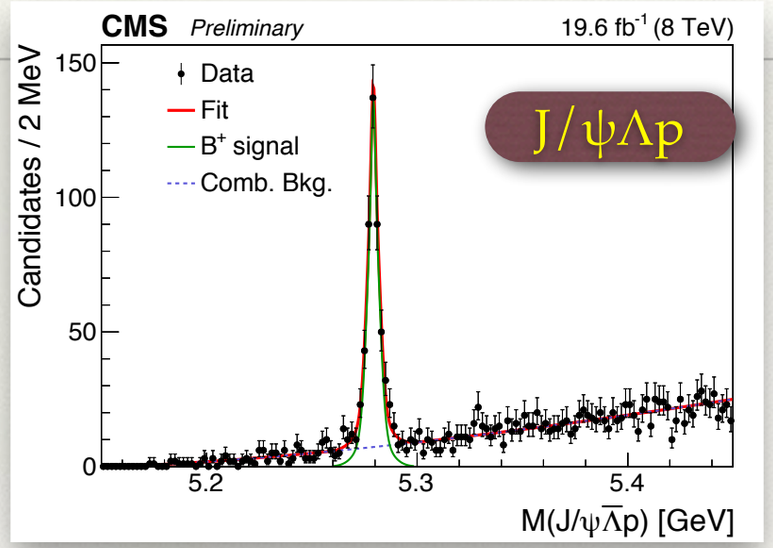
LHCb J/ψp structure

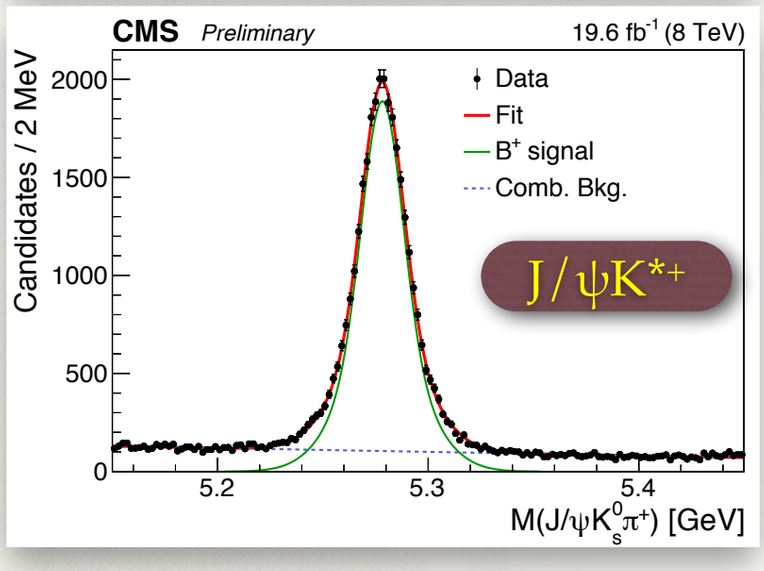




Selection & Reconstruction

- Triggering by a $J/\psi \to \mu\mu$ candidate and the vertex is displaced from the interaction point.
- Offline selections:
  - Muons $p_T > 4$ GeV, J/ψ $p_T > 7$ GeV, p_T of Λ and $p > 1$ GeV.
  - Pointing angle of B^+; vertex with displacement significance $> 3\sigma$;
  - Λ candidates originate from K_S are rejected.
- Branching fraction is calculated by **normalizing to $B^+ \to J/\psi K^{*+} (\to K_S \pi^+)$**:





$$\frac{\mathcal{B}(B^+ \to J/\psi \Lambda p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = 1.054 \pm 0.057_{(\text{stat.})} \pm 0.028_{(\text{syst.})} \pm 0.011_{(\mathcal{B})}\%$$

$$\mathcal{B}(B^+ \to J/\psi \Lambda p) = 15.07 \pm 0.81_{(\text{stat.})} \pm 0.40_{(\text{syst.})} \pm 0.86_{(\mathcal{B})} \times 10^{-6}$$

(w/ world average value of $J/\psi K^{*+}$ branching fraction)

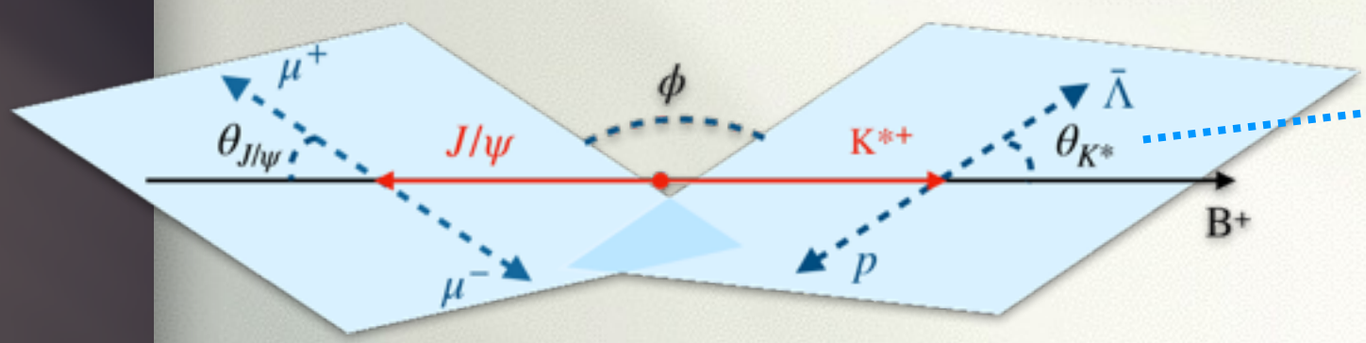
Study of Two-body Mass Spectra

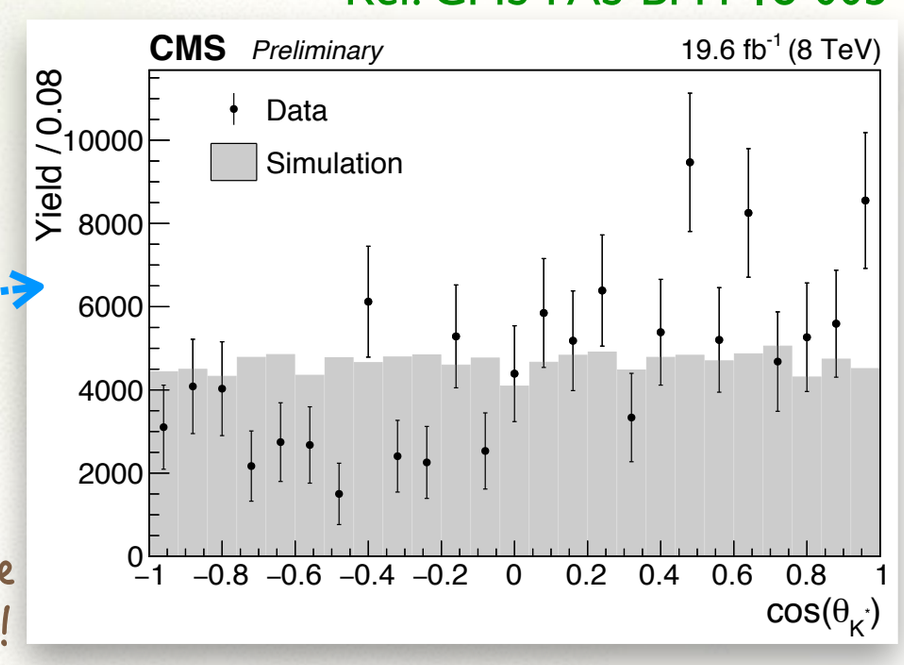
- A model independent approach / moment analysis has been introduced.
- There are at least three known K* resonances that can decay to Λp; these broad excited kaon states can contribute to the two-body invariant mass distributions.
- The formulation — in each **M(Λp) bin**, the **cos(θ_{K^*})** distribution can be expressed as an expansion with Legendre polynomials:

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{L_{\max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

- L_{max} = 8 is twice of the maximum spin [K_4*(2045), J=4] state in the consideration; $\langle P_j^U \rangle$ are the unnormalized Legendre moments.
- Then re-weight the sample according to the observed angular structure.

Ref. CMS-PAS-BPH-18-005

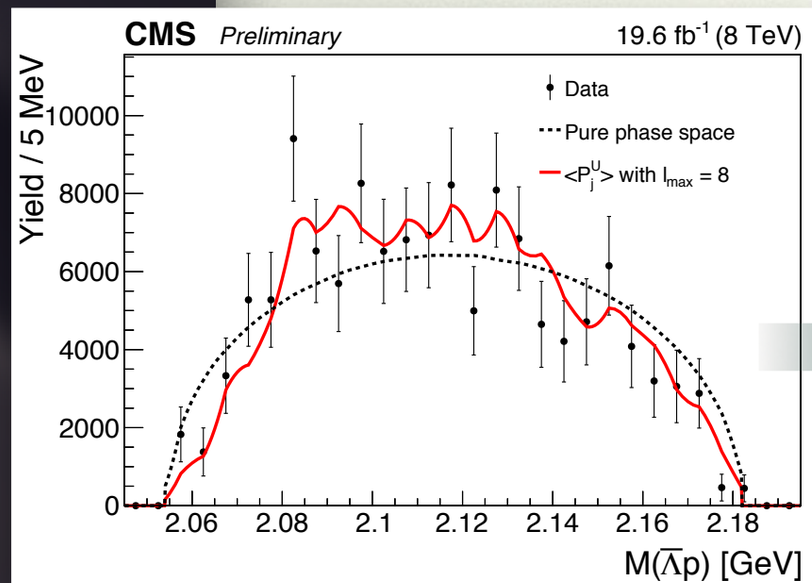


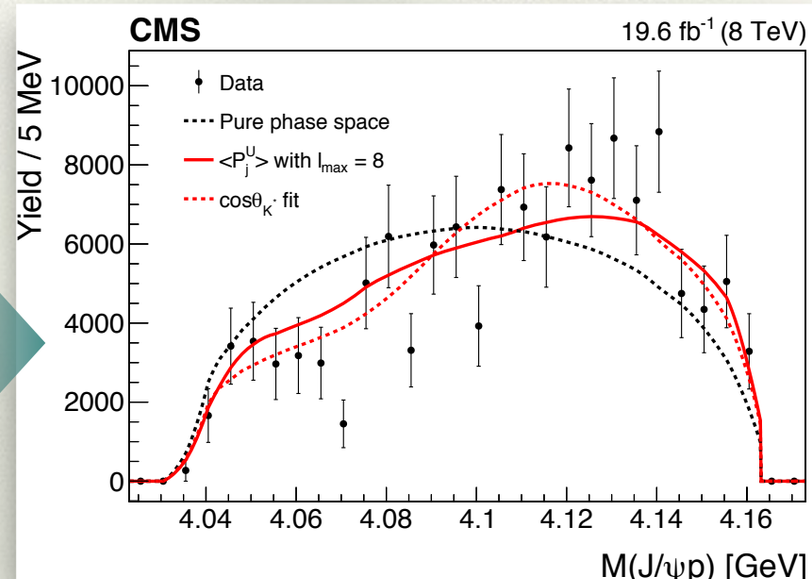


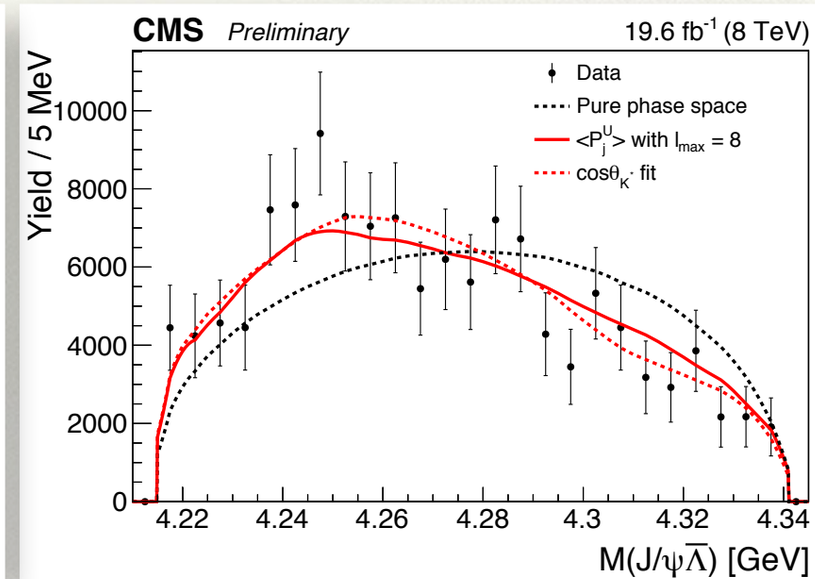
Not flat, could affect the two-body invariant mass!

Two-body Mass Spectra (cont.)

Ref. CMS-PAS-BPH-18-005





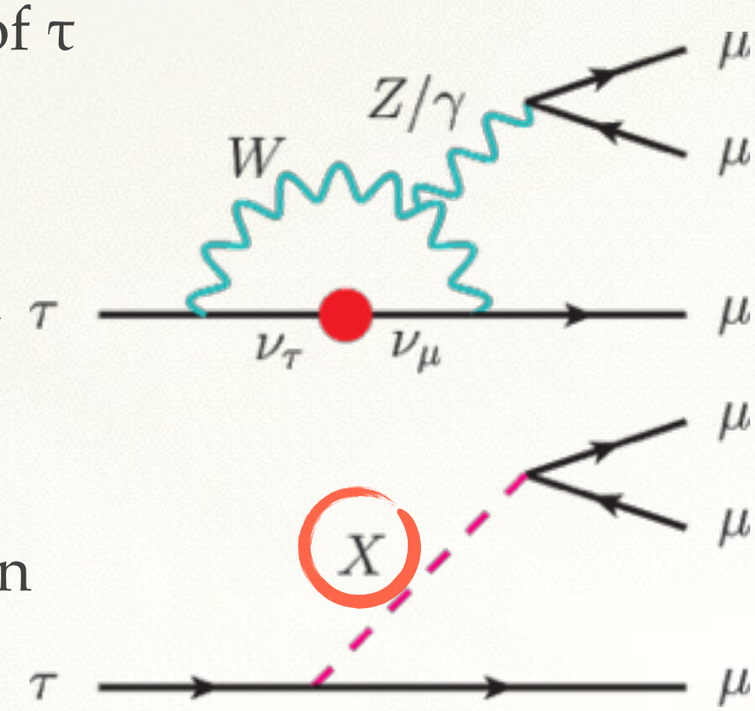


- Compare efficiency corrected sPlot from data, with **pure phase-space**, simulation **corrected by the moments in pΛ system**, and **reweighting with 1D $\cos(\theta_{K^*})$**.
  - *The spectra can not be modeled with a phase space distribution satisfactory.*
- Description of the M(J/ψΛ) and M(J/ψp) has been improved after accounting for considering the angular and invariant mass structure in the Λp system.

The model with moments sufficiently described the data (*within 3σ*), no clear sign of new resonance yet.

Search for τ→3μ: Introduction

- A charged lepton flavor violating (CLFV) decay of τ to 3 muons, no missing neutrinos.
- Allowed by neutrino oscillations, but with extraordinarily small branching fractions beyond experimental accessibility.
- The rate can be **strongly enhanced with New Physics scenarios**; experimentally the three-muon final state is accessible and clean.
- Searches have been performed by Belle, BaBar, LHCb, ATLAS, no hint of signal yet.
- Best limit from Belle: $< 2.1\times10^{-8}$ (@ 90% C.L.)
  [PLB 687 (2010) 139143]



Good for probing NP!

CMS performed a search for the τ → 3μ, where τ leptons produced in D and B hadron decays, using the data collected in 2016 of 33 fb^{-1}.

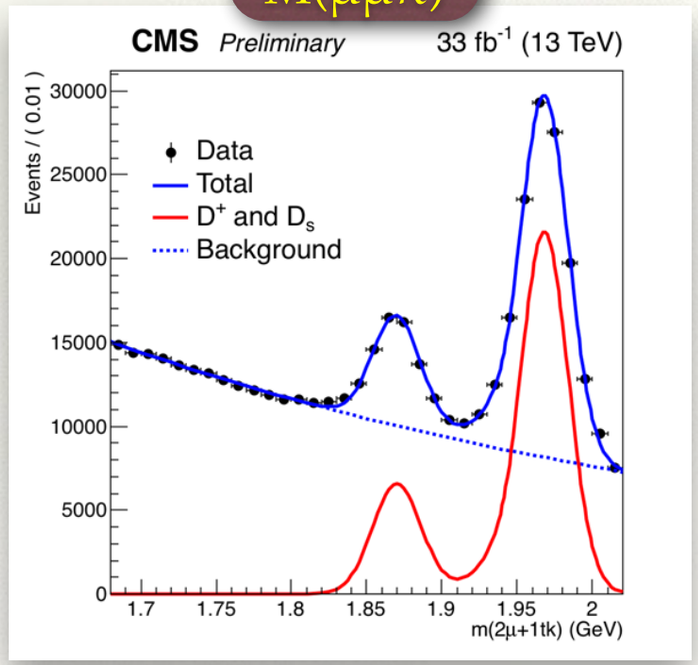
Event Selection

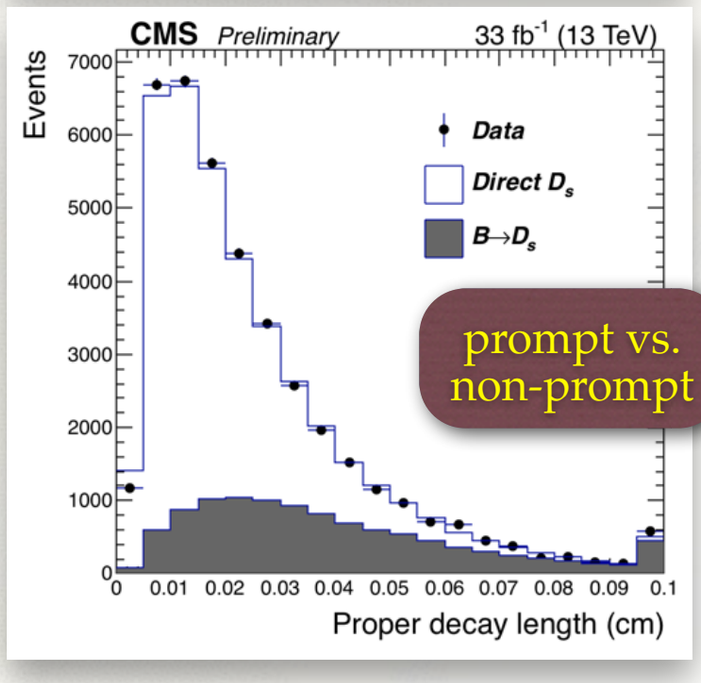
- **For τ candidate:**
  - Triggering with two muons plus a track, with vertex and mass requirement;
  - Requiring 3 global muons offline and sum of charges should be ±1.
- **For normalization:**
  - Select $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ with the same trigger and very similar momentum thresholds.
  - The fraction of (non-)prompt D_s estimated from a fit to the proper decay length distribution.

	D→τ Signal	B→τ Signal	Data
Production	4.4×10^5	1.5×10^5	
3μ in fiducial volume	6.6×10^3	2.3×10^3	
Trigger	214	114	
3μ p_T>2GeV	88	47	1×10^7
3μ candidate	64	29	1×10^5

Yields for BF(τ→3μ) = 10^{-7}

M(μμπ)



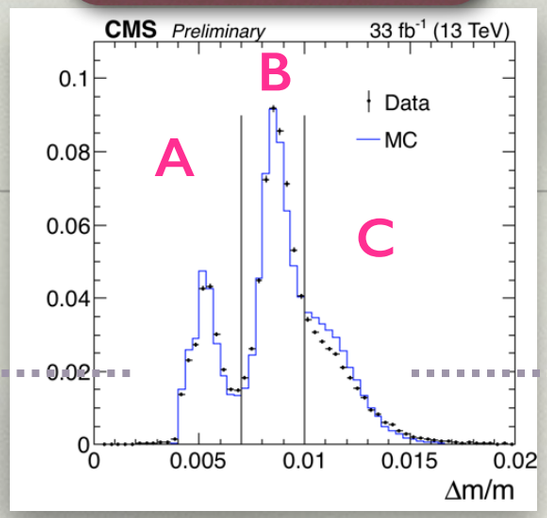


prompt vs. non-prompt

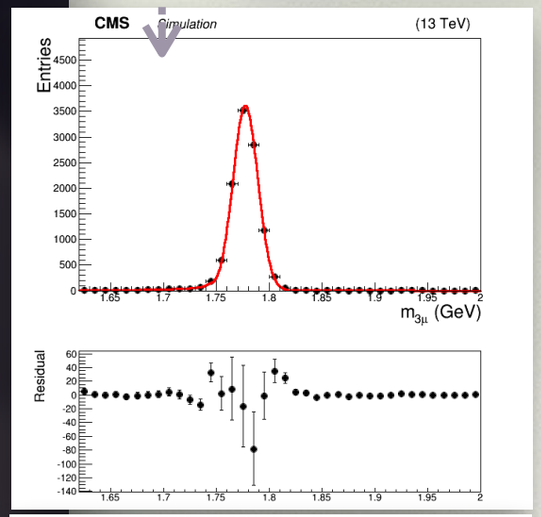
Ref. CMS-PAS-BPH-17-004

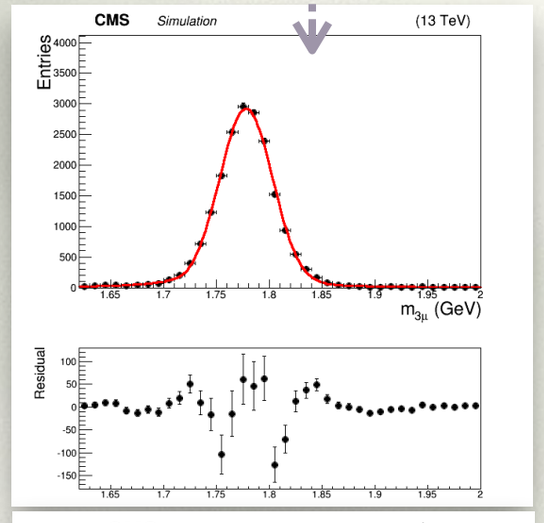
Event Categorizing

Mass resolution

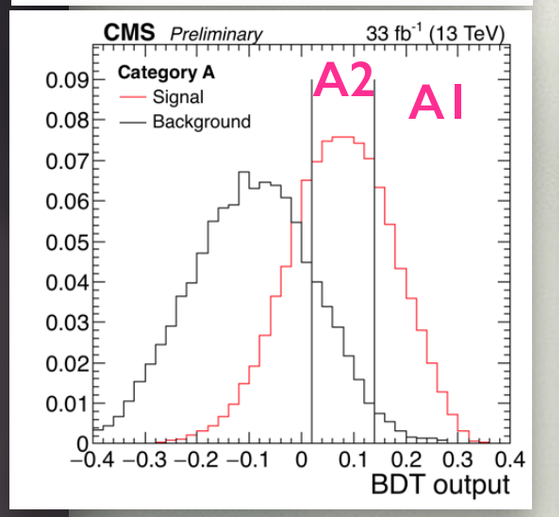


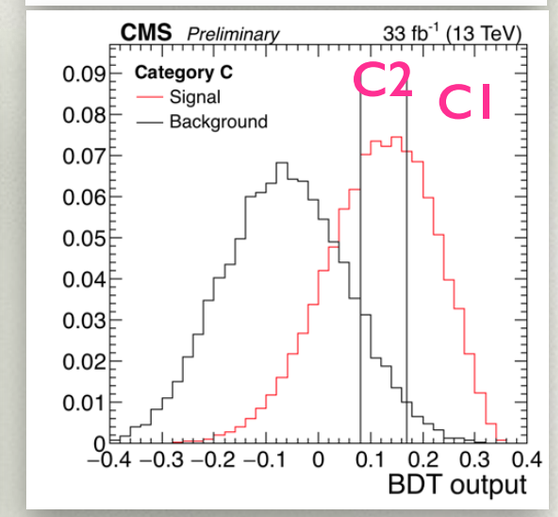
Invariant Mass Model





BDT score





Ref. CMS-PAS-BPH-17-004

- **#1 Categorized by mass resolution:**
  - 3-μ mass resolution has been evaluated event-by-event, ranging from 0.4 to 1.5%, depending on the muon rapidity;
  - Divided into 3 categories: <0.7%, 0.7–1%, >1%.
- **#2 Categorized by BDT score:**
  - BDT trained with vertex/muon quality variables;
  - Further divided into 3 categories, 2 to be included, 1 dropped.
  - **Resulting 6 categories in total.**

⇒ To be included in the fit

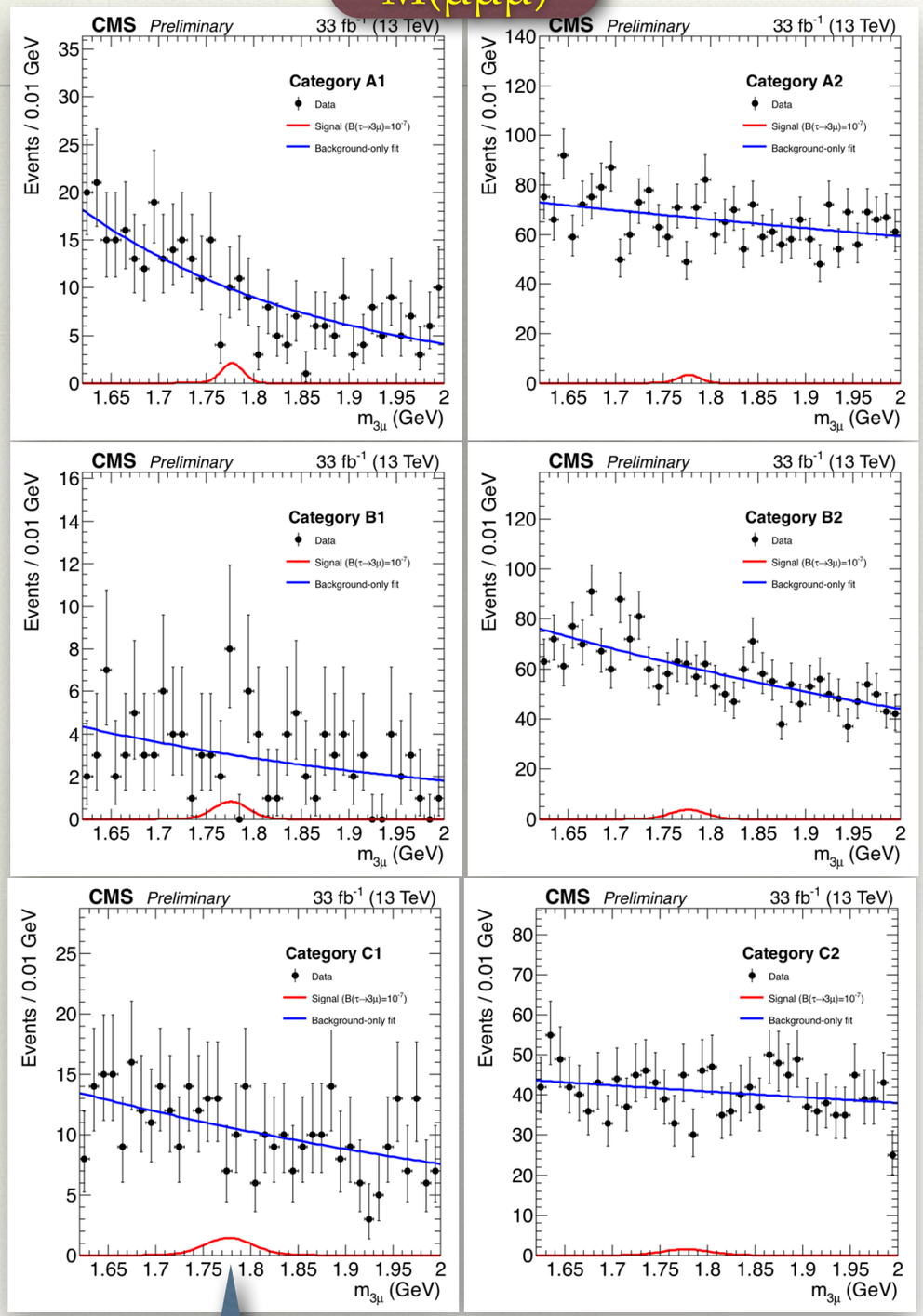
Extraction of Limit

- Simultaneous maximum likelihood fit are performed with 6 resolution-BDT categories.
- Dominant systematic uncertainties: D_s normalization (10%) on, $Ds \to \phi\pi$ branching fraction (8%).
- **No hint of signal found**, observed (expected) limits are evaluated as

$\mathcal{B}(\tau \to 3\mu) < 8.8\ (9.9) \times 10^{-8}$ @ 90% C.L.
$\mathcal{B}(\tau \to 3\mu) < 1.1\ (1.2) \times 10^{-7}$ @ 95% C.L.

Ref. CMS-PAS-BPH-17-004

M(μμμ)



Signal if $BF(\tau \to 3\mu) = 10^{-7}$

Summary

CMS is an unique test bench for flavor physics predictions!

- **Observation of Excited B_c states**
  - **Signals consistent with the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states have been observed** for the first time; the study improves to the understanding of heavy meson spectroscopy and provide information on QCD processes that bind heavy quarks into hadrons.
- **Study of the $B \to J/\psi \Lambda p$ decay**
  - The branching fraction ratio $B \to J/\psi \Lambda p / B \to J/\psi K^{*+}$ has been measured. The **two-body mass spectra can not be modeled with just the phase-space distribution** satisfactory, while a model-independent approach can improve the agreement significantly.
- **Search for $\tau \to \mu\mu\mu$ decay**
  - **Search of CLFV decay $\tau \to 3\mu$ has been conducted** at CMS. Using the τ leptons decaying from D and B mesons, no excess above the expected background is observed. Upper limits have been set.

More results are in the pipeline! Stay tuned!

Backup Slides