

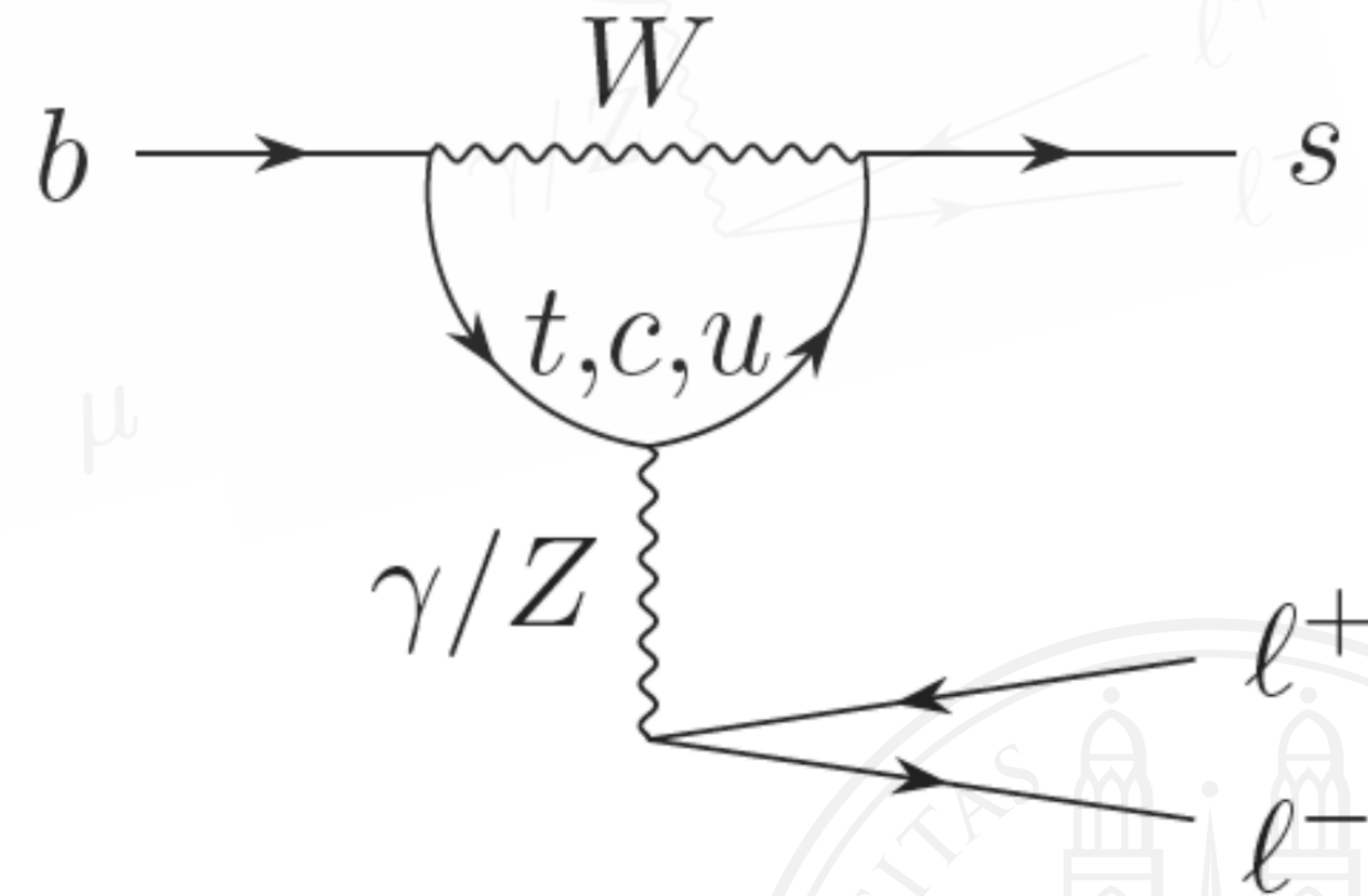
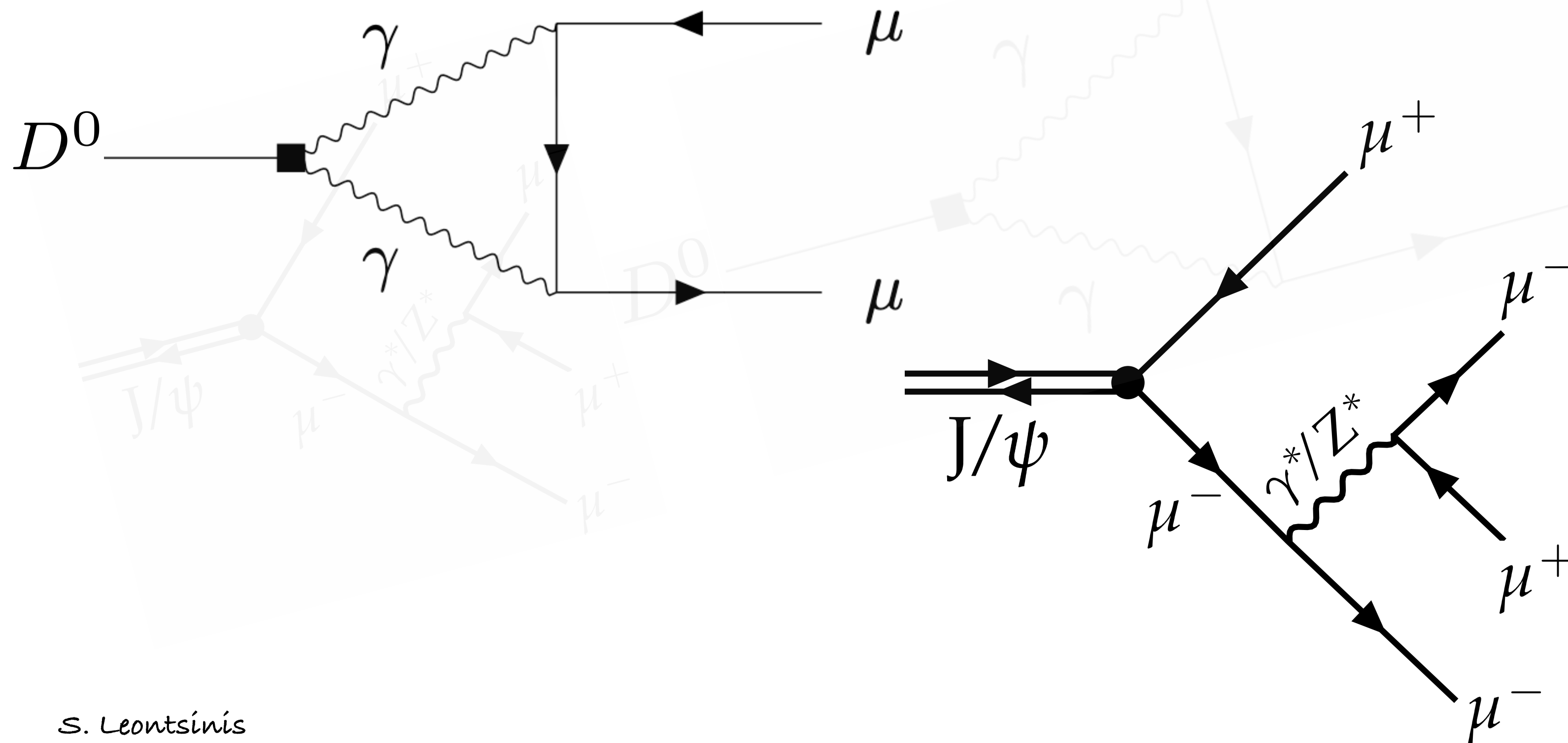
Rare and forbidden decays at CMS



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ICHEP 2024
19th July 2024

- Discovering rare and unusual processes is inherently interesting
- Investigating new physics via direct or indirect methods:
 - new beyond the standard model particles can take part in the loops, altering the decay rates
 - flavour changing neutral current decays suppressed in the standard model
 - in general these rare decays allow for model independent searches
- Observing deviations from expected outcomes will indicate how the standard model needs to be extended



- Angular analysis of the rare decay $B^0 \rightarrow K^{*0}(892)\mu^+\mu^-$ in the $K^{*0}(892) \rightarrow K\pi$

- rate can be written as a function of the angular variables θ_K, θ_l, ϕ

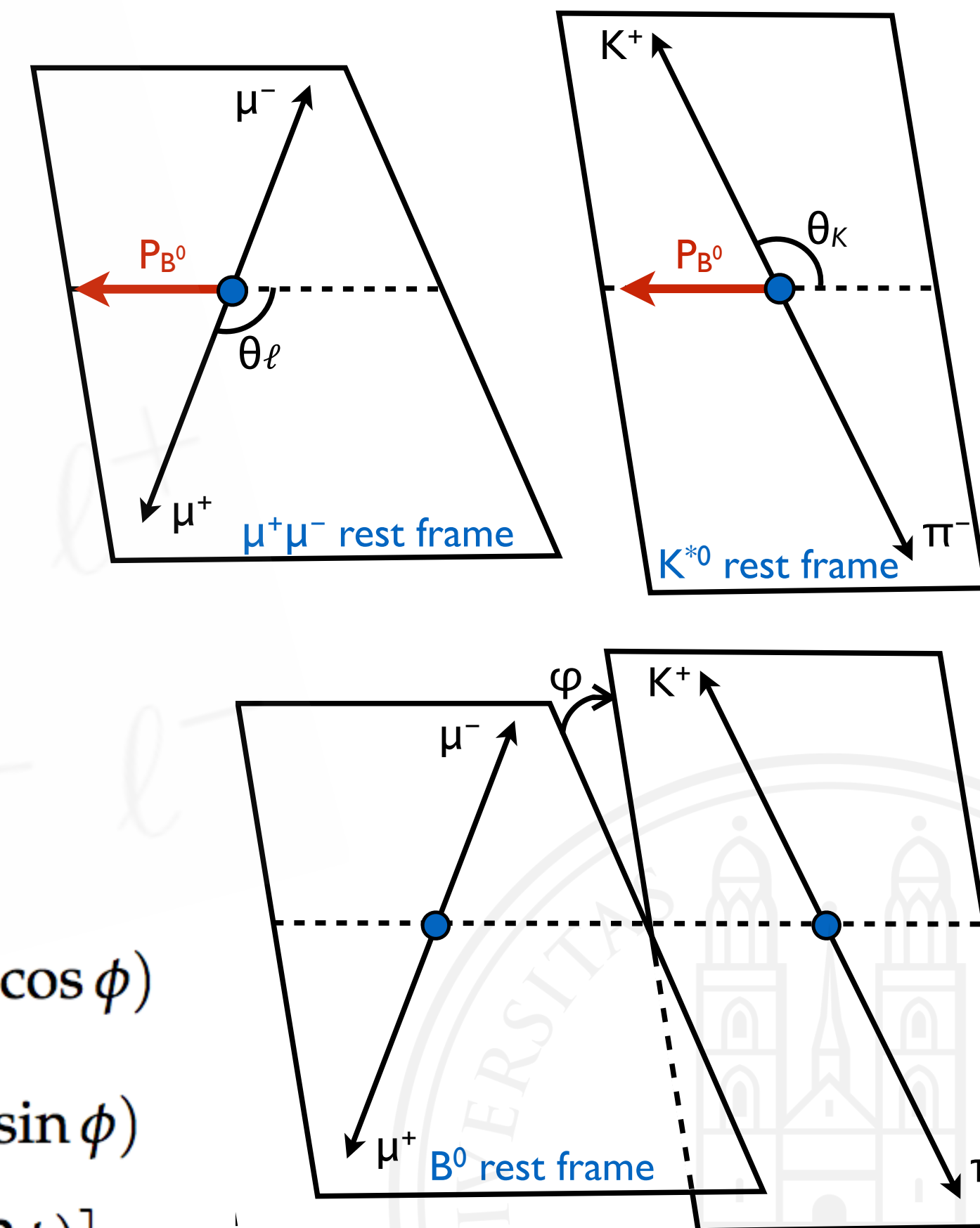
- expressed by a set of clean observables related to the Wilson coefficients [JHEP 01 (2013) 048]

- F_L is the fraction of longitudinally polarised K^*

- P_2 is related to A_{FB} , the muon forward backward asymmetry

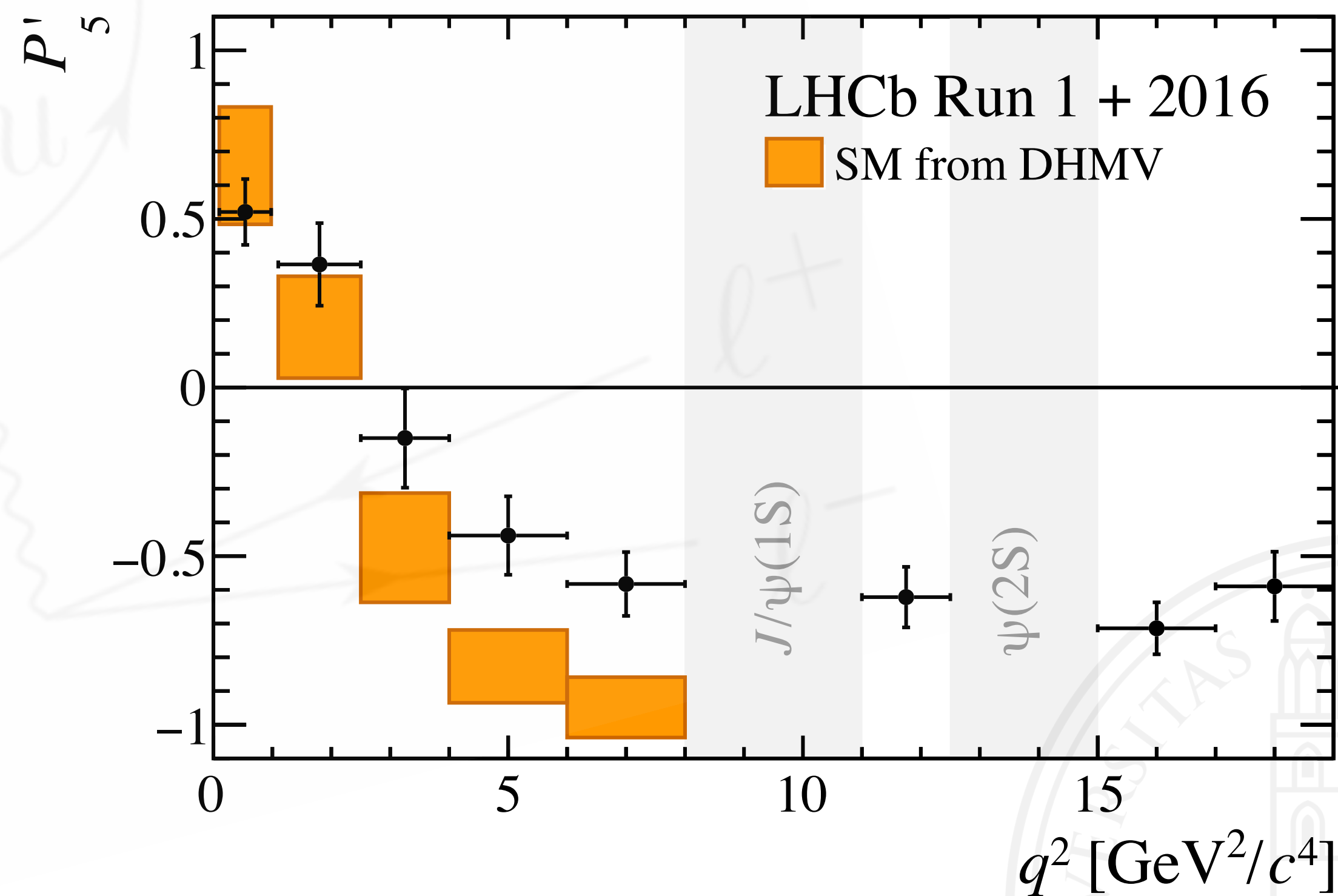
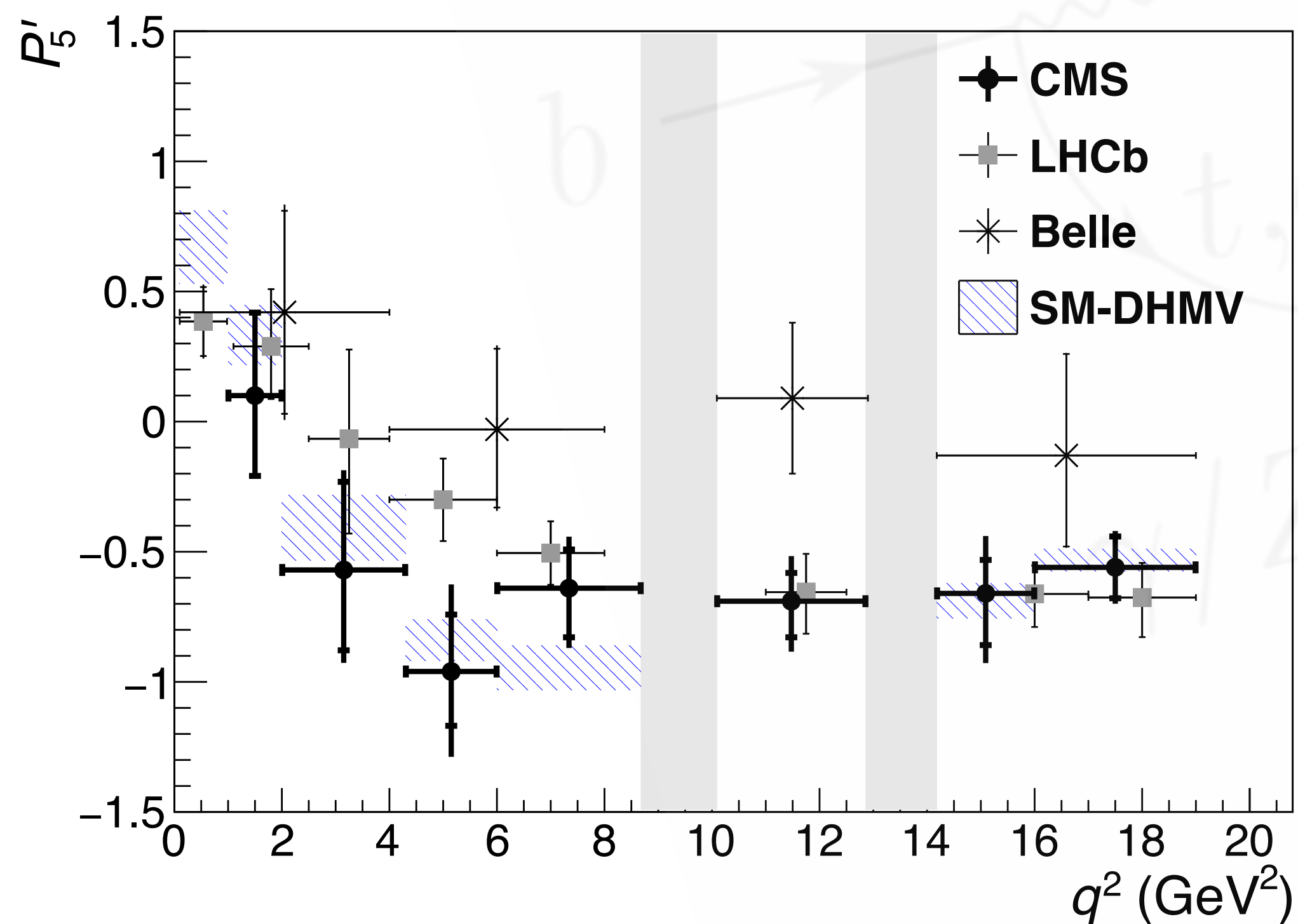
- P'_i is the base of optimised observables

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ + \left(\frac{1}{4}(1 - F_L) \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_l \\ + \frac{1}{2}P_1(1 - F_L) \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\ + \sqrt{(1 - F_L)F_L} \left(\frac{1}{2}P'_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + P'_5 \sin 2\theta_K \sin \theta_l \cos \phi \right) \\ - \sqrt{(1 - F_L)F_L} \left(P'_6 \sin 2\theta_K \sin \theta_l \sin \phi - \frac{1}{2}P'_8 \sin 2\theta_K \sin 2\theta_l \sin \phi \right) \\ \left. + 2P_2(1 - F_L) \sin^2 \theta_K \cos \theta_l - P_3(1 - F_L) \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$



- Current status

- CMS Run-1 - measure partial angular observables, including P'_5 [[Phys. Lett. B 753 \(2016\) 424](#), [Phys. Lett. B 781 \(2018\) 517](#)]
- ATLAS Run-1 - different foldings used to measure the various parameters [[JHEP 10 \(2018\) 047](#)]
- LHCb - angular analysis, discrepancy in both Run-1 and Run-2 data measurement [[Phys. Rev. Lett. 125 \(2020\) 1](#)]



- In order to describe a system of $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ decaying events, in which the $K^+\pi^-$ system can also be in an S-wave configuration, the following extension of the angular decay rate is used:

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = (1 - F_S)\Gamma_P + \frac{3}{16\pi} (F_S \sin^2\theta_l + A_S \sin^2\theta_l \cos\theta_K + A_S^4 \sin\theta_K \sin 2\theta_l \cos\phi + A_S^5 \sin\theta_K \sin\theta_l \cos\phi + A_S^7 \sin\theta_K \sin\theta_l \sin\phi + A_S^8 \sin\theta_K \sin 2\theta_l \sin\phi)$$

- Unbinned maximum likelihood fits performed in q^2 bins

signal component

$$P(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S \left[S^C(m) S^a(\cos\theta_K, \cos\theta_l, \phi) \epsilon^C(\cos\theta_K, \cos\theta_l, \phi) \right.$$

$$\left. + R \cdot S^M(m) S^a(-\cos\theta_K, -\cos\theta_l, -\phi) \epsilon^M(\cos\theta_K, \cos\theta_l, \phi) \right]$$

tentative legend

C: correctly identified events

M: misidentified events

R is the ratio of the average mistag fraction on data and MC

$$+ Y_B B^m(m) B^a(\cos\theta_K, \cos\theta_l, \phi)$$

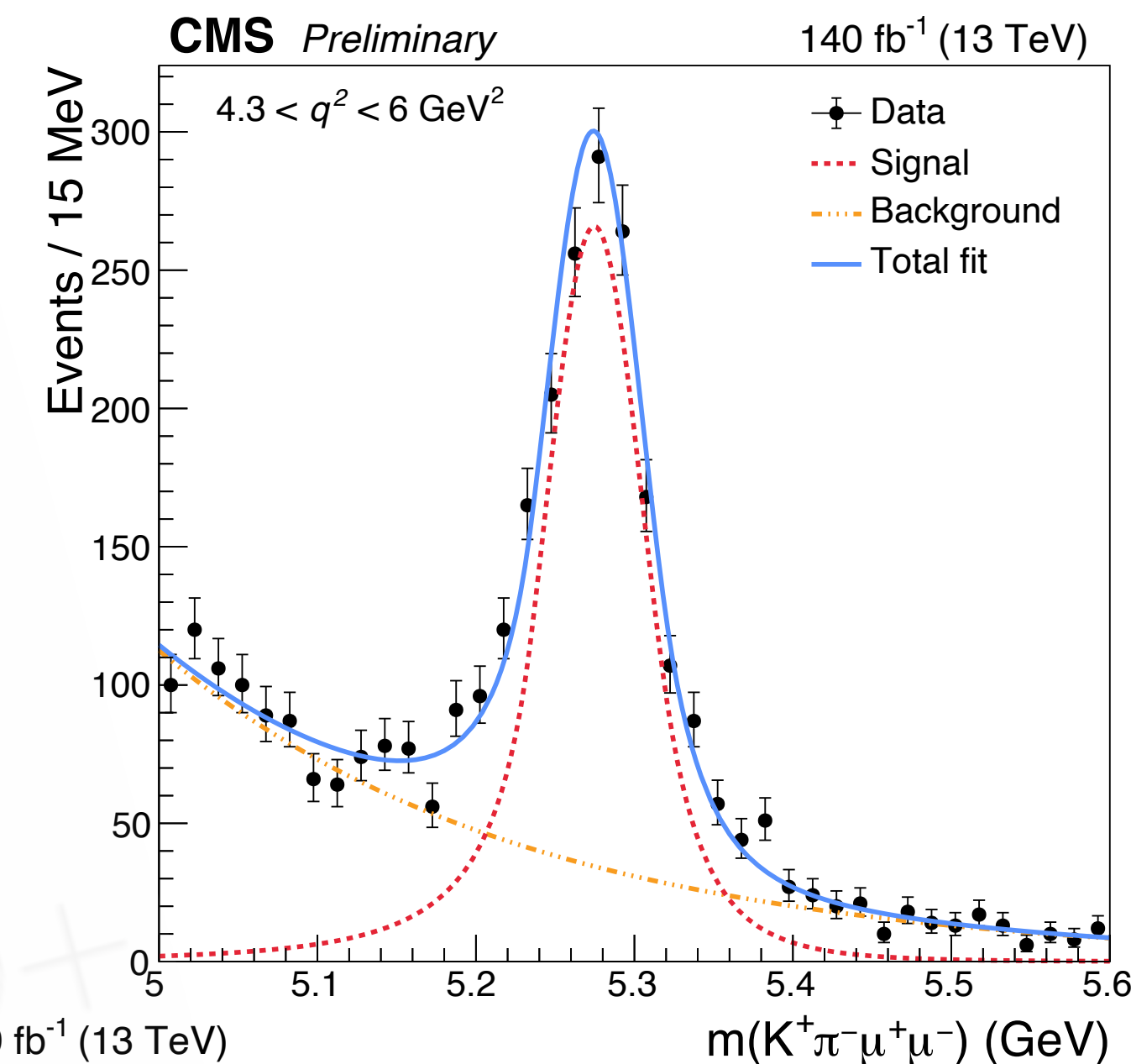
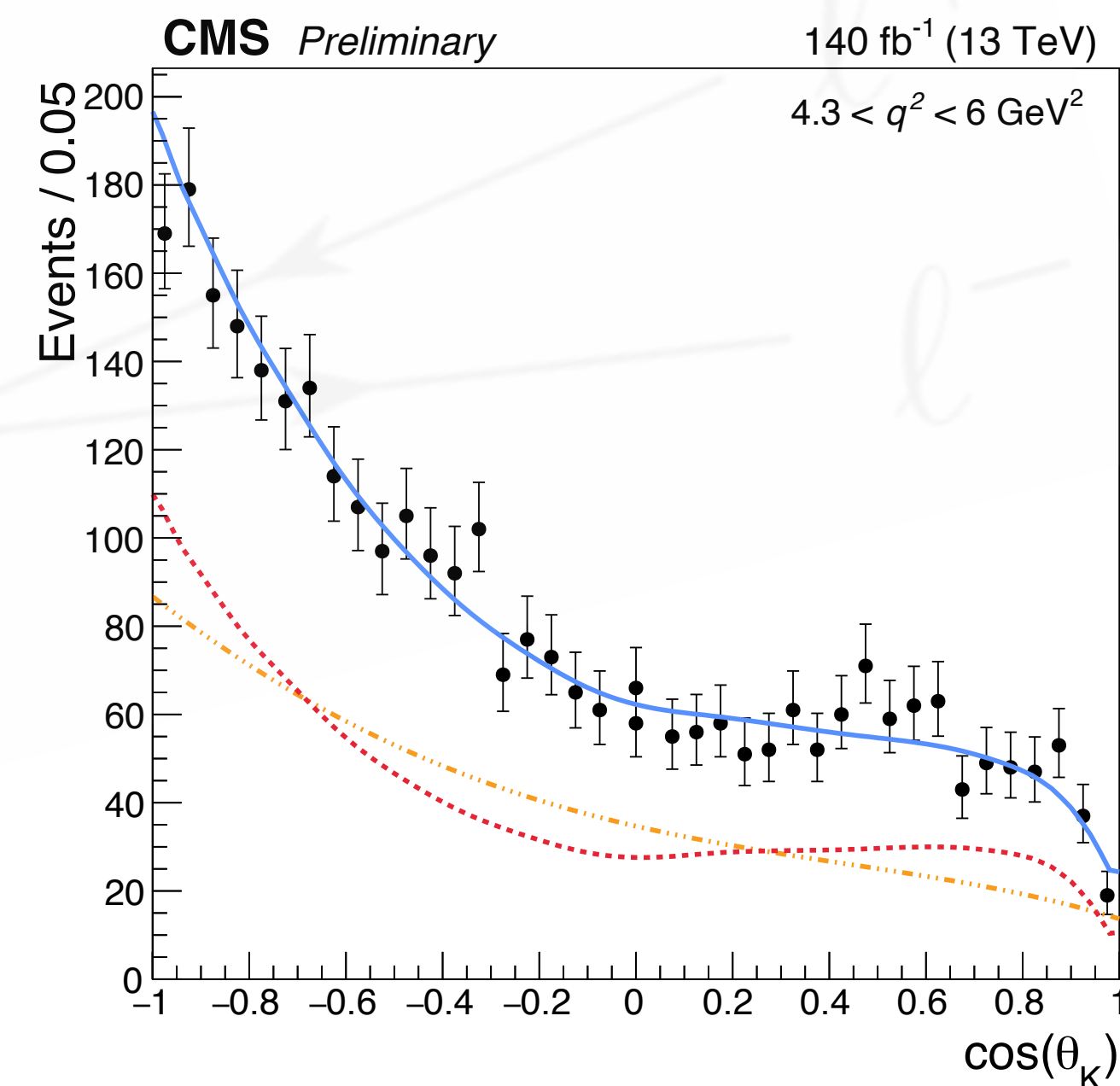
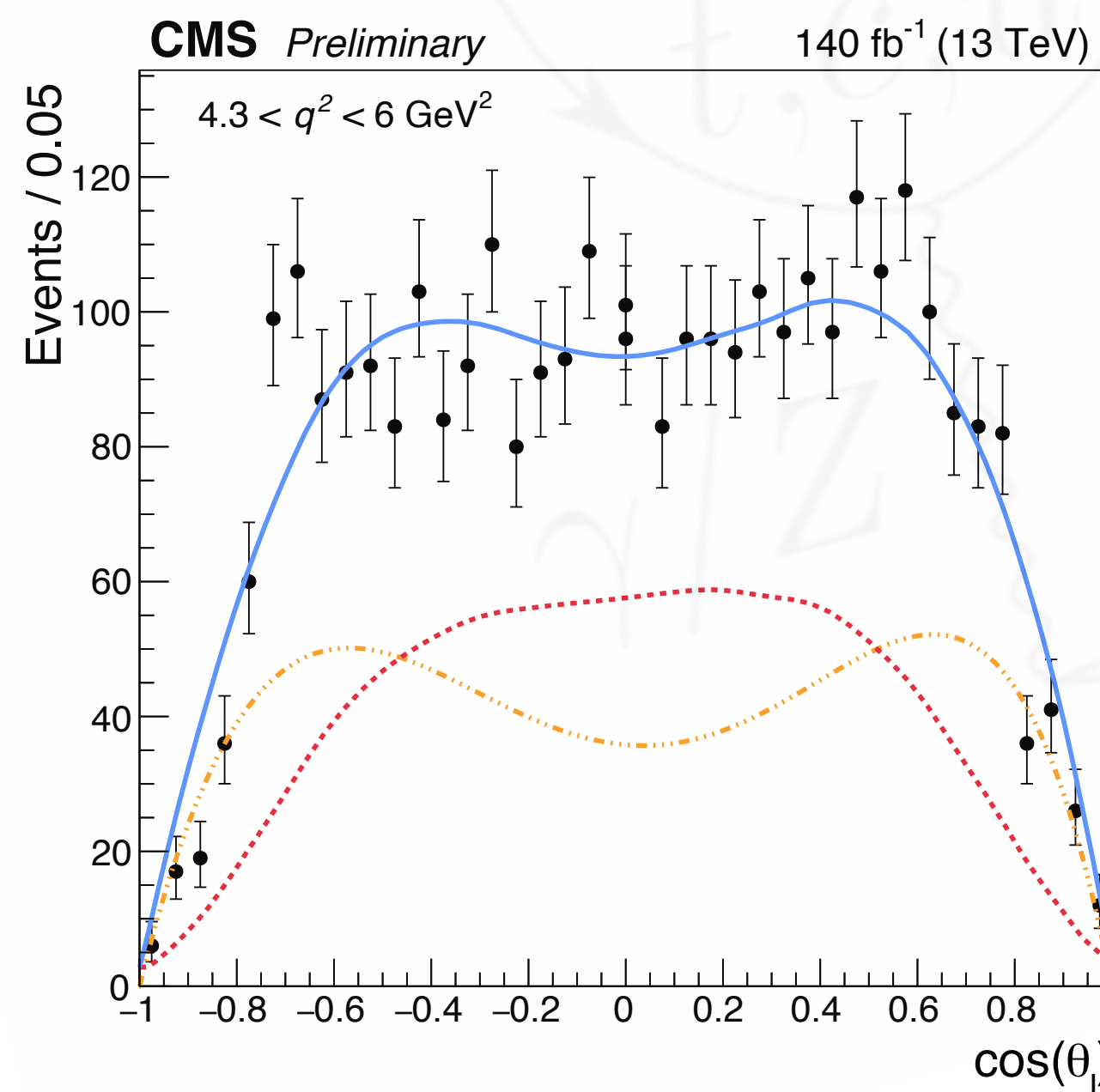
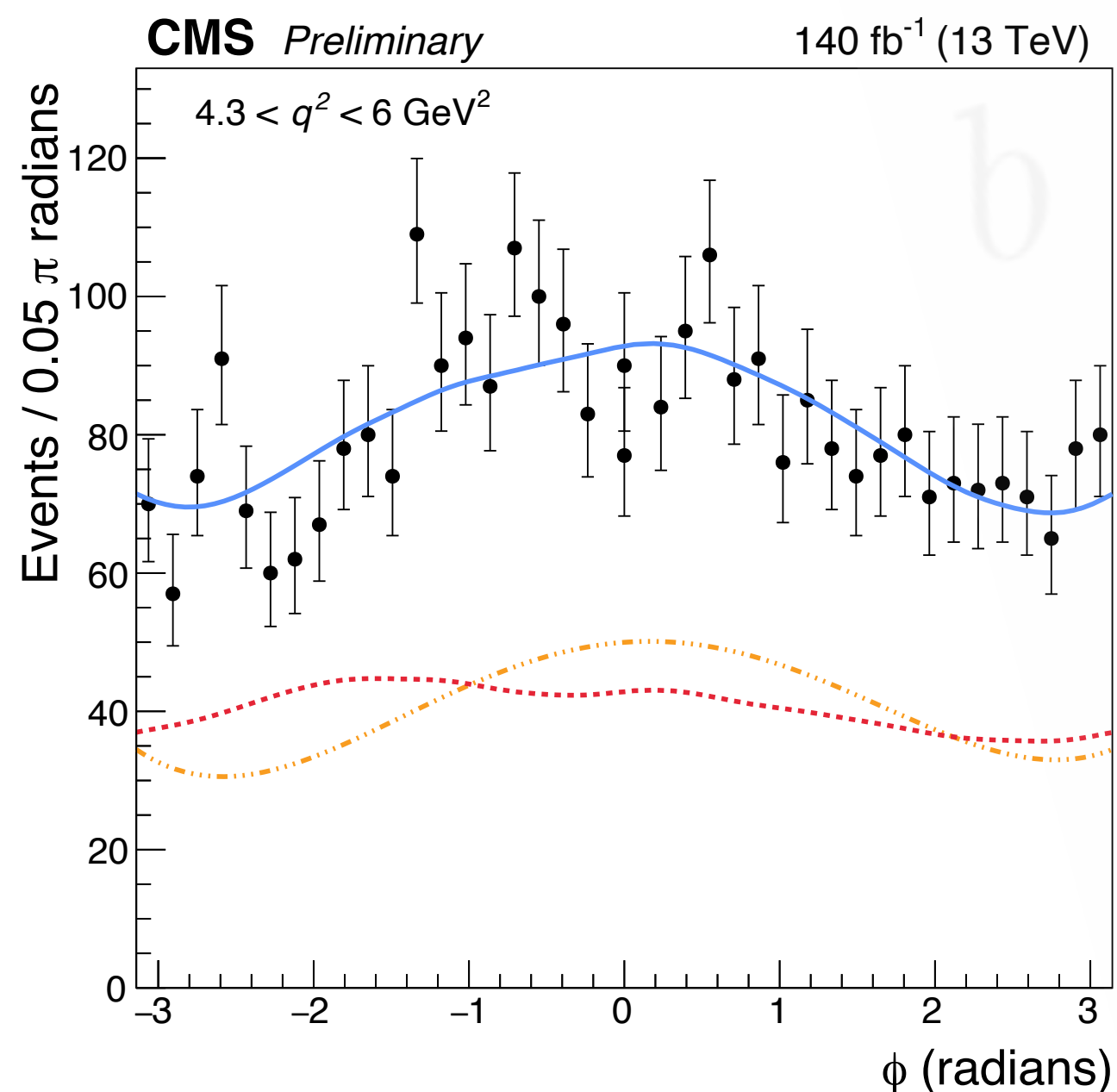
background component

mistagged signal ~13%

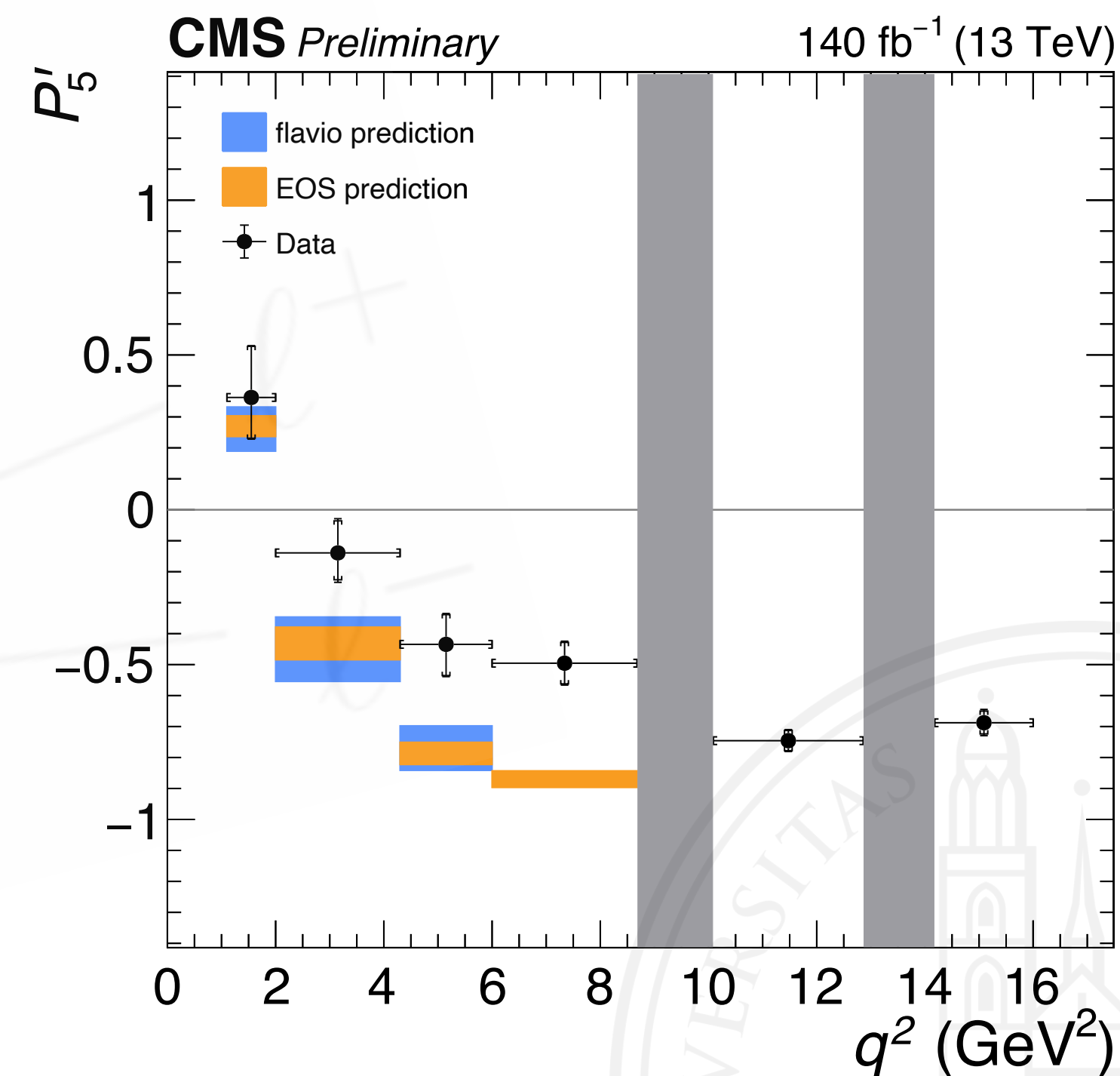
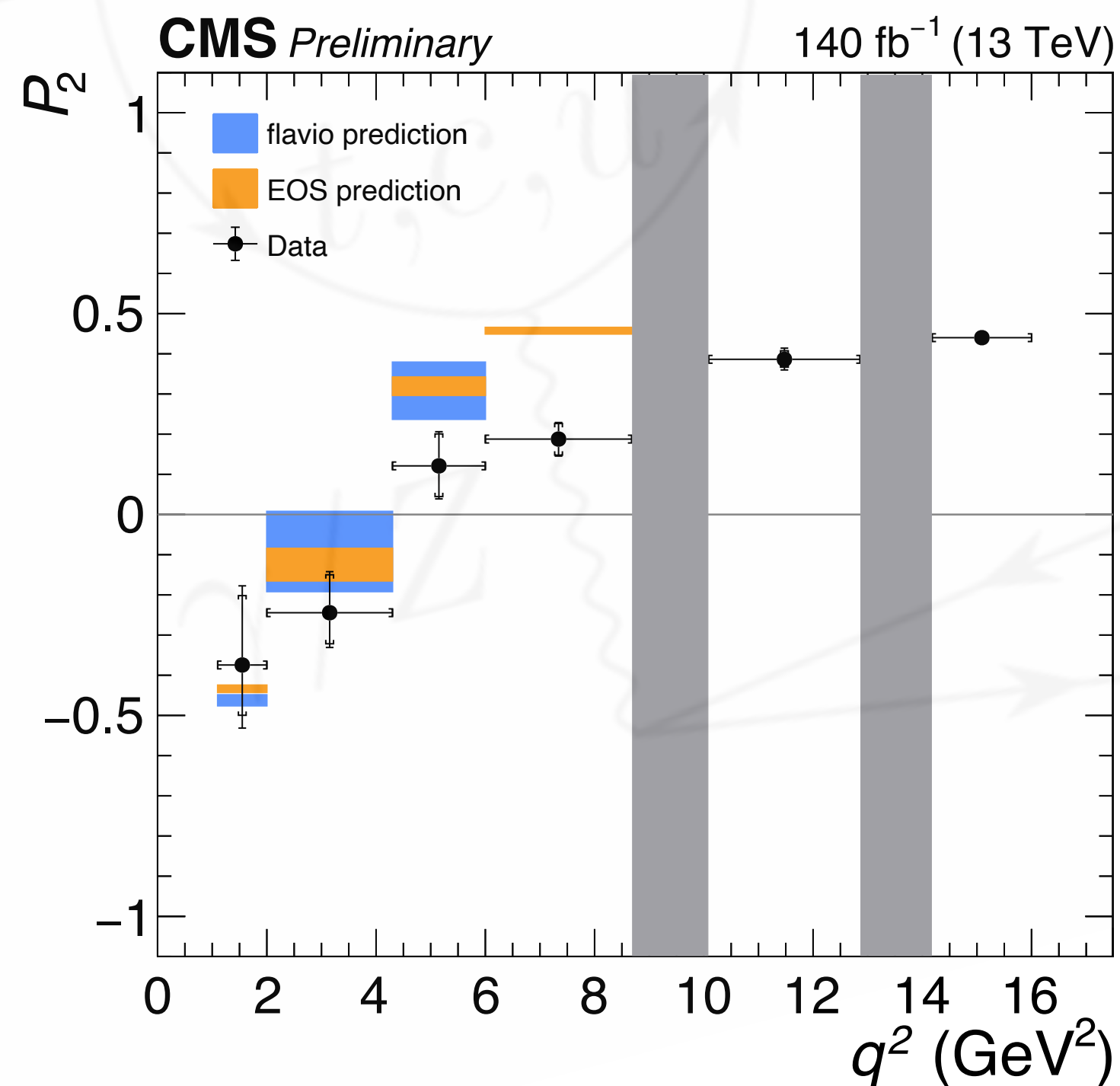
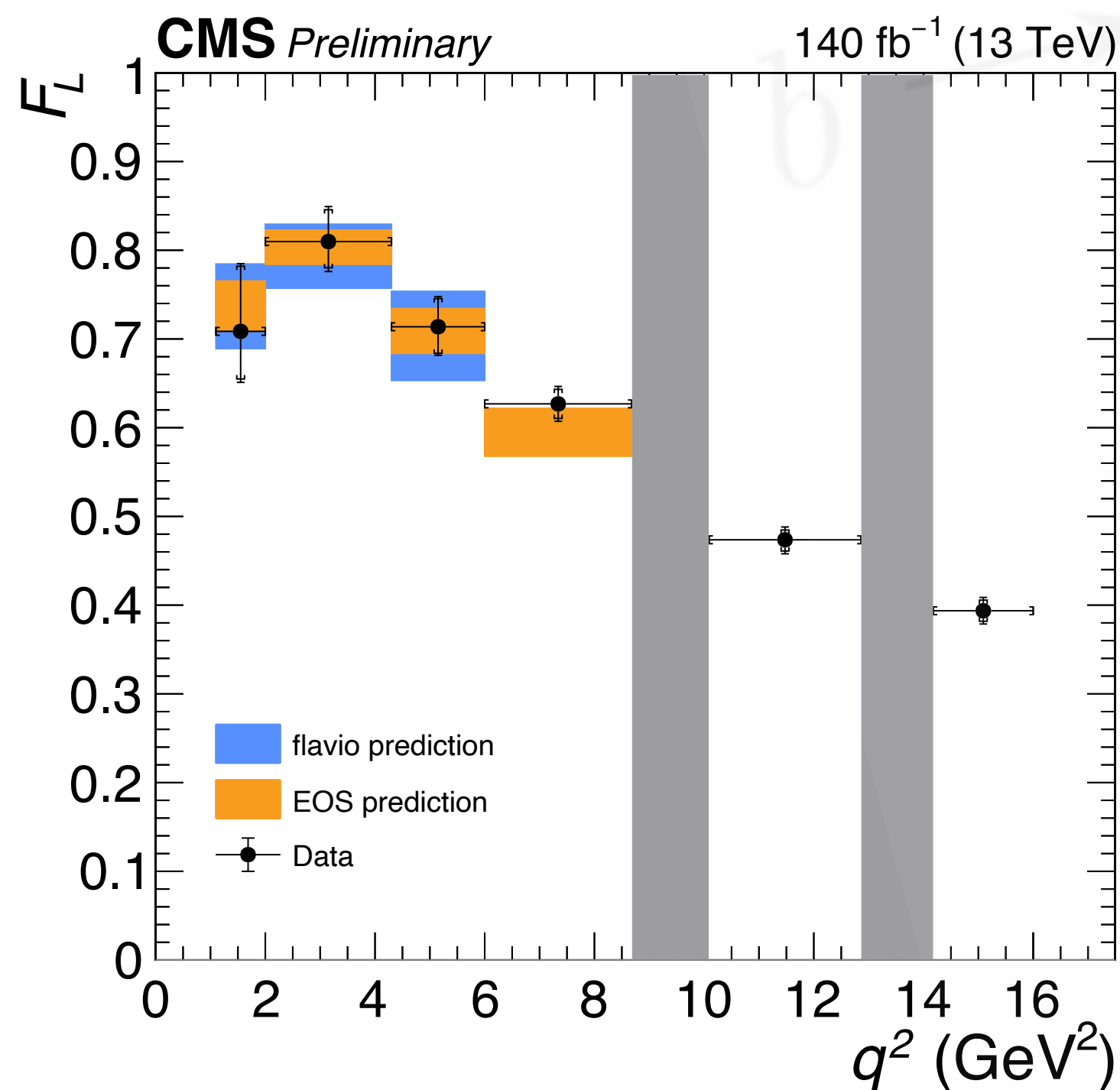
ϵ^C, ϵ^M from simulation

Angular distribution of the background (B^a) determined using sidebands

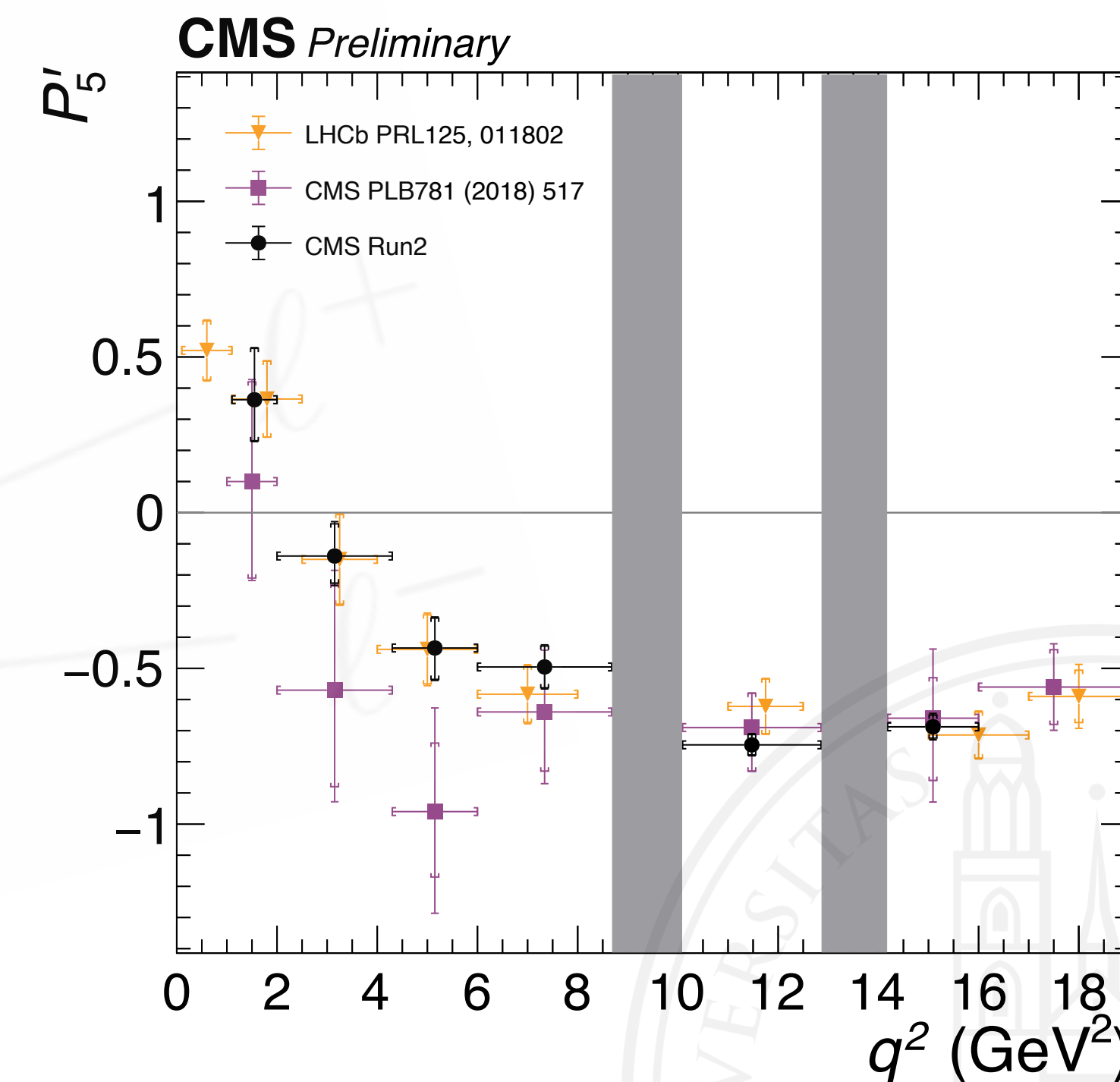
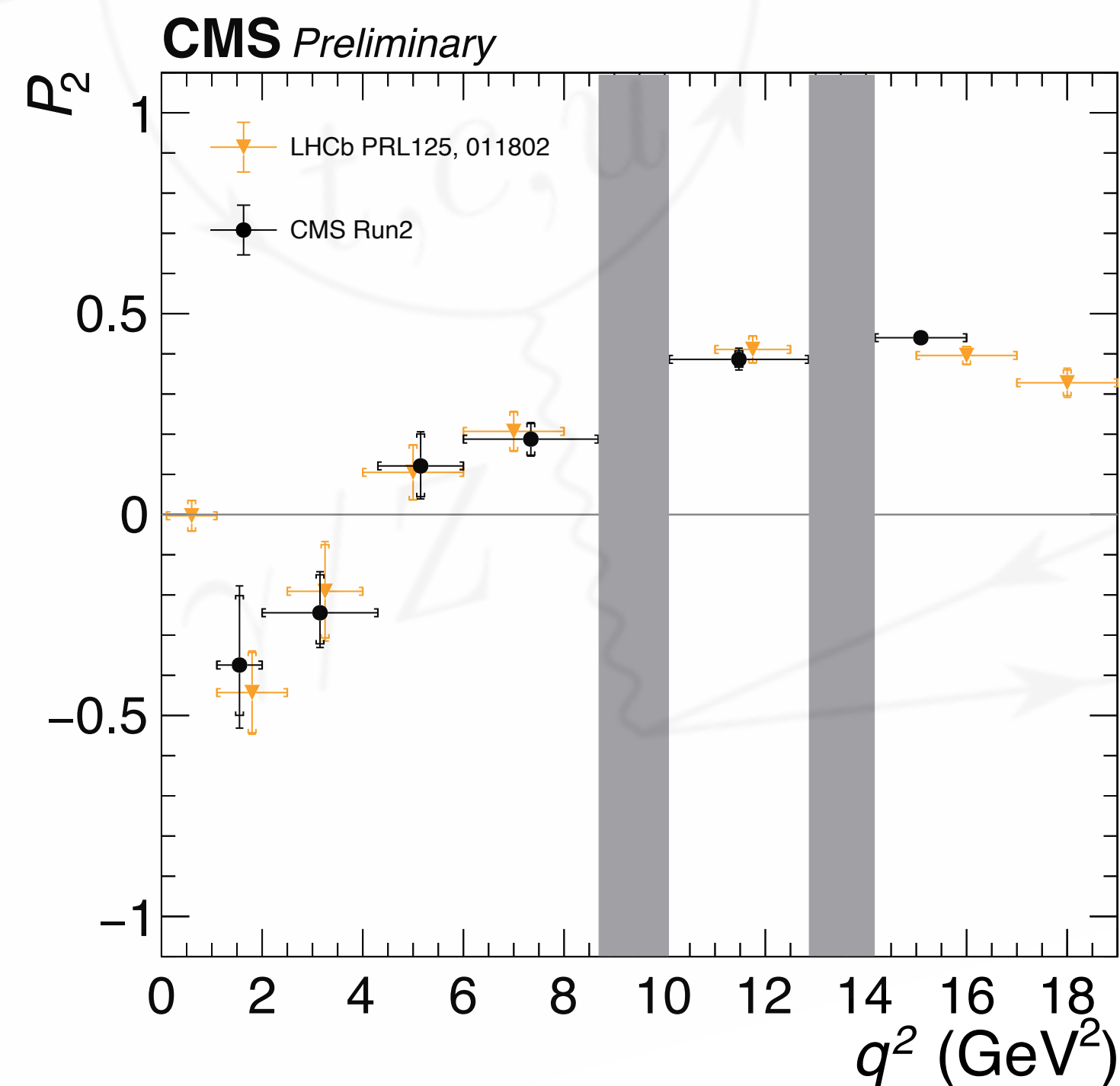
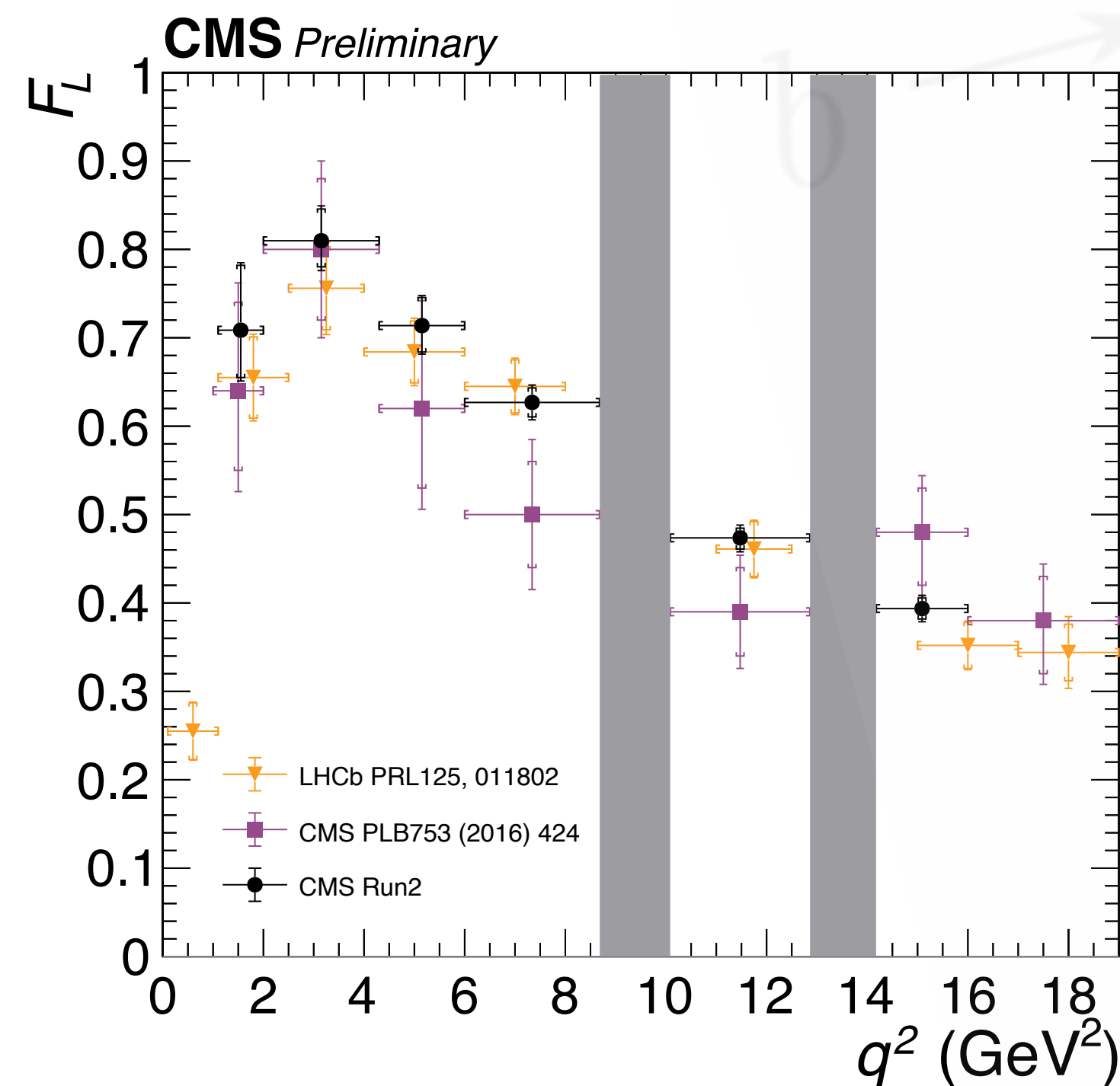
- Angular fit validated in simulation and control regions
- Projections on invariant mass and 3 angle observables
- Good agreement between data and pdf projections
 - an example q^2 bin shown here
 - all fits available [here](#)



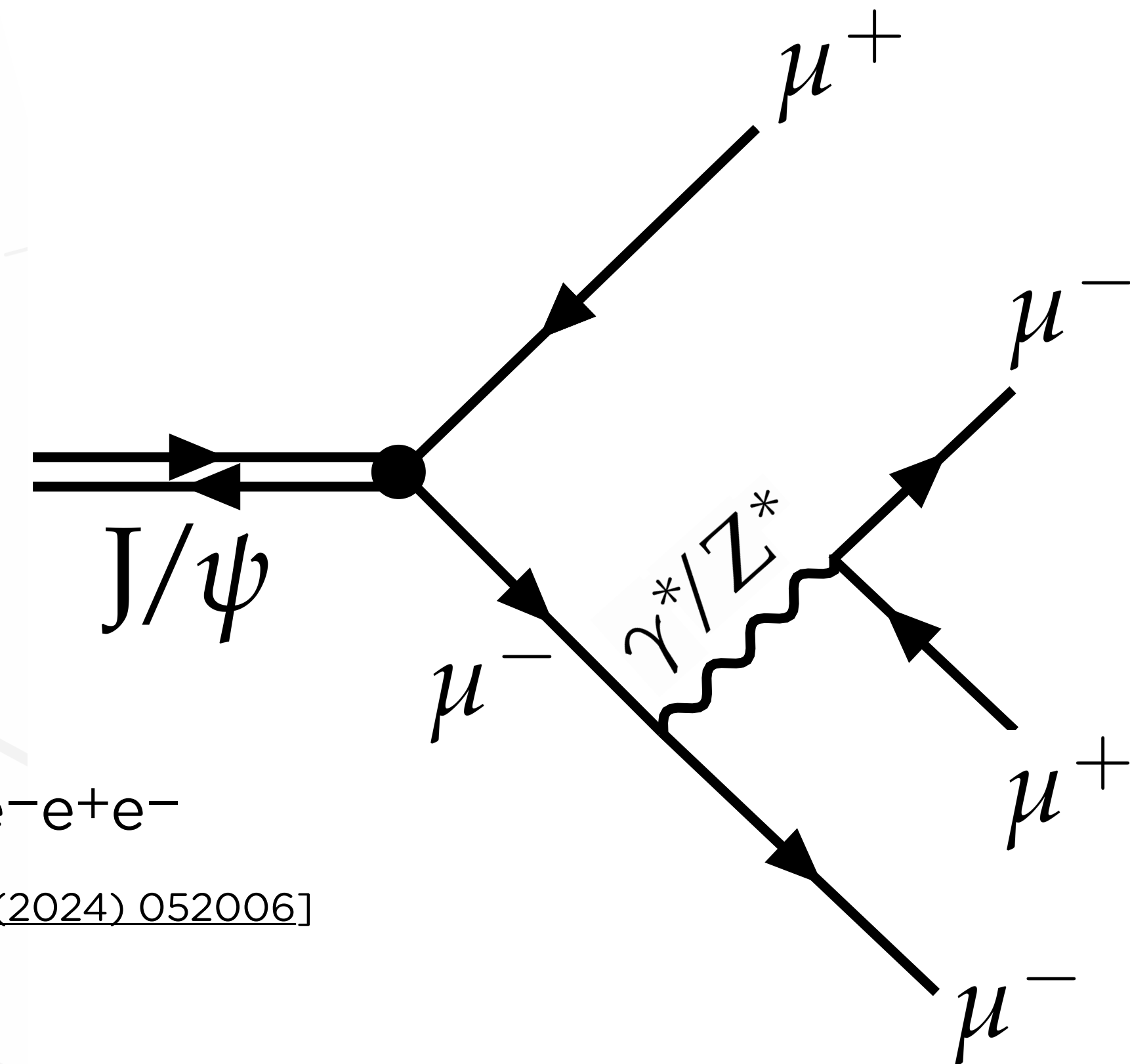
- Two sets of predictions are compared with measurement: flavio and EOS
 - flavio: local form-factors (LQCD and Light-Cone Sum Rule) + non-local form-factors (QCDF)
 - EOS: local form-factors (LQCD and LCSR), novel parametrisation of non-local form-factors
- Clear tensions in the q^2 region below the J/ψ for the P'_5 and P_2 parameters
- The other observables are in agreement with the prediction and available [here](#)



- The results are among the most precise experimental measurements of the angular observables of this decay
- Good agreement with LHCb result. Same tension from the predictions observed in P_2 and P'_5
- The combined tension from the prediction will increase



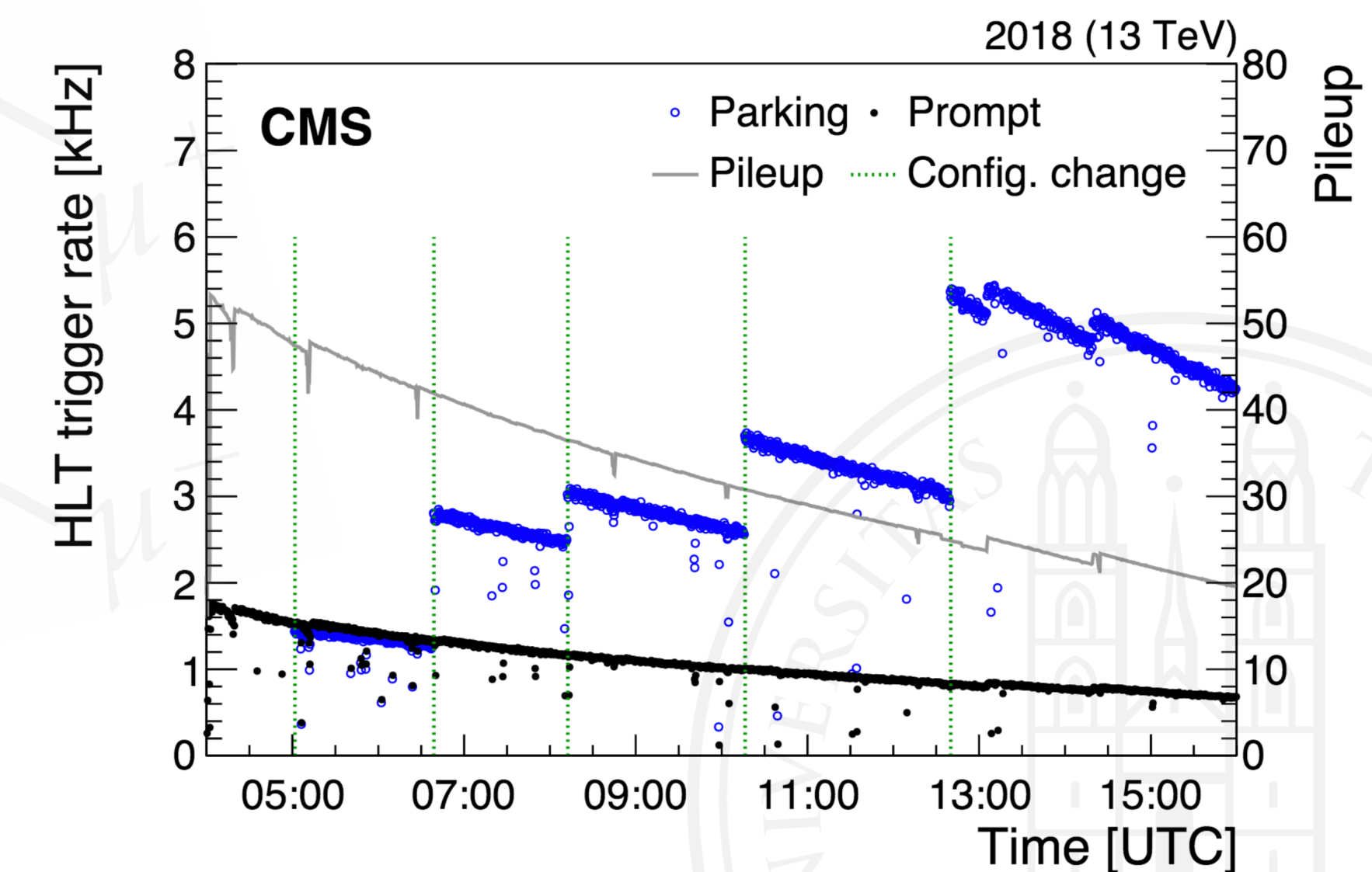
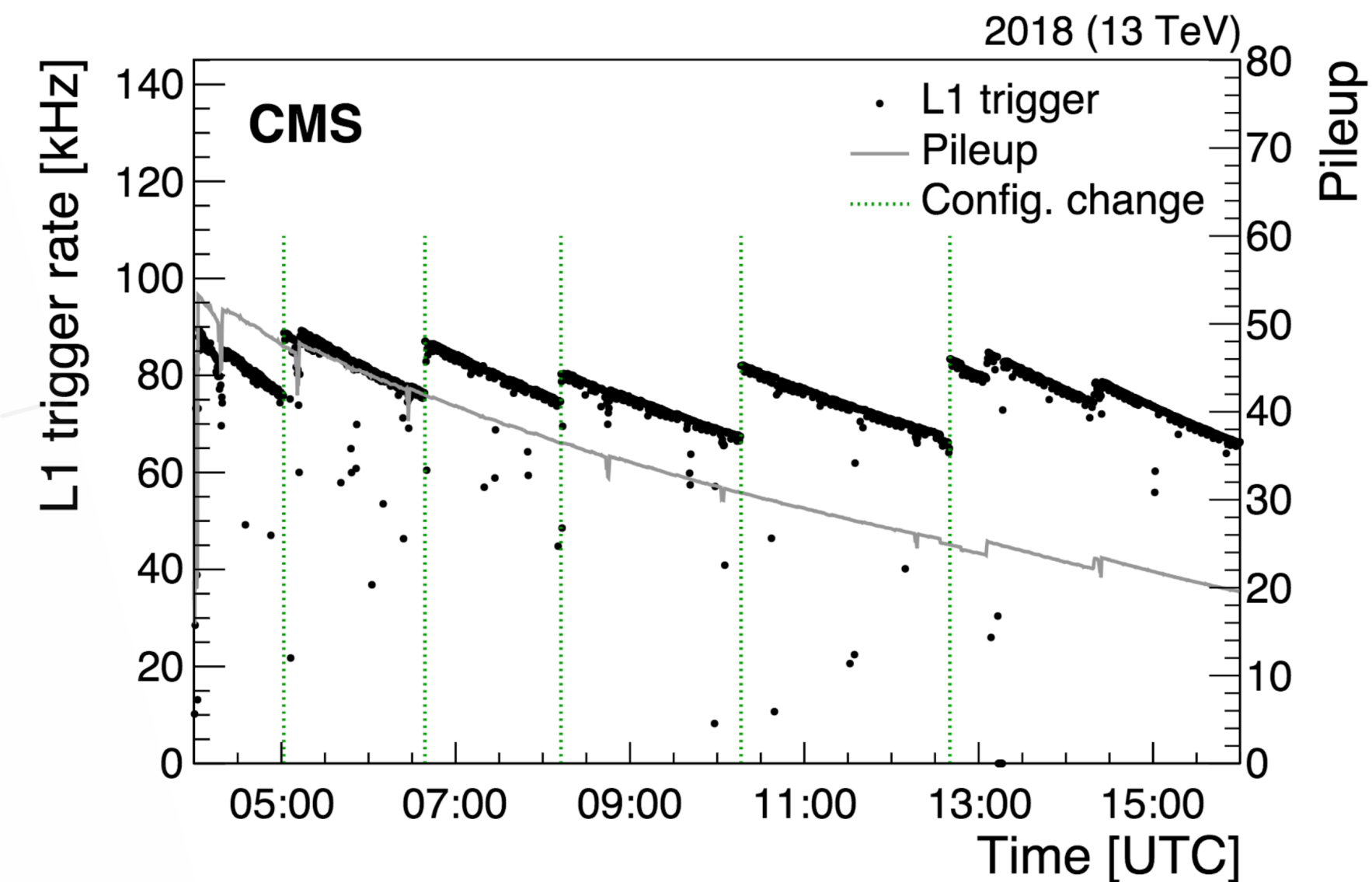
- Muon final states are attractive because they are very clean and in CMS
 - $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ in 2012 [[JHEP 12 \(2012\) 034](#)]
 - $Z \rightarrow J/\psi\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ in 2018 [[Phys. Rev. Lett. 121 \(2018\) 14](#)]
 - $Z \rightarrow \tau^+\tau^-\mu^+\mu^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ in 2022 [[arXiv:2404.18298](#)]
 - $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$ in 2023 [[Phys. Rev. Lett. 131 \(2023\) 9](#)]
- These decay modes involve the $\ell \rightarrow \ell\gamma^*/Z^*$ transition with the subsequent decay of $\gamma^*/Z^* \rightarrow \mu^+\mu^-$
 - probe for 4-lepton Wilson coefficients
- Here we look at the rare decay of the J/ψ meson to $\mu^+\mu^-\mu^+\mu^-$
 - BESIII claimed the observation of $J/\psi \rightarrow \mu^+\mu^-e^+e^-$ and $J/\psi \rightarrow e^+e^-e^+e^-$
 - measured branching fractions in agreement with SM [[Phys.Rev.D 109 \(2024\) 052006](#)]
 - after initial tension with theory
 - theory calculation $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = (9.74 \pm 0.05) \times 10^{-7}$ [[Phys. Rev. D 109 \(2024\) 5](#)]
 - very clean as it's almost free of intermediate vector resonances



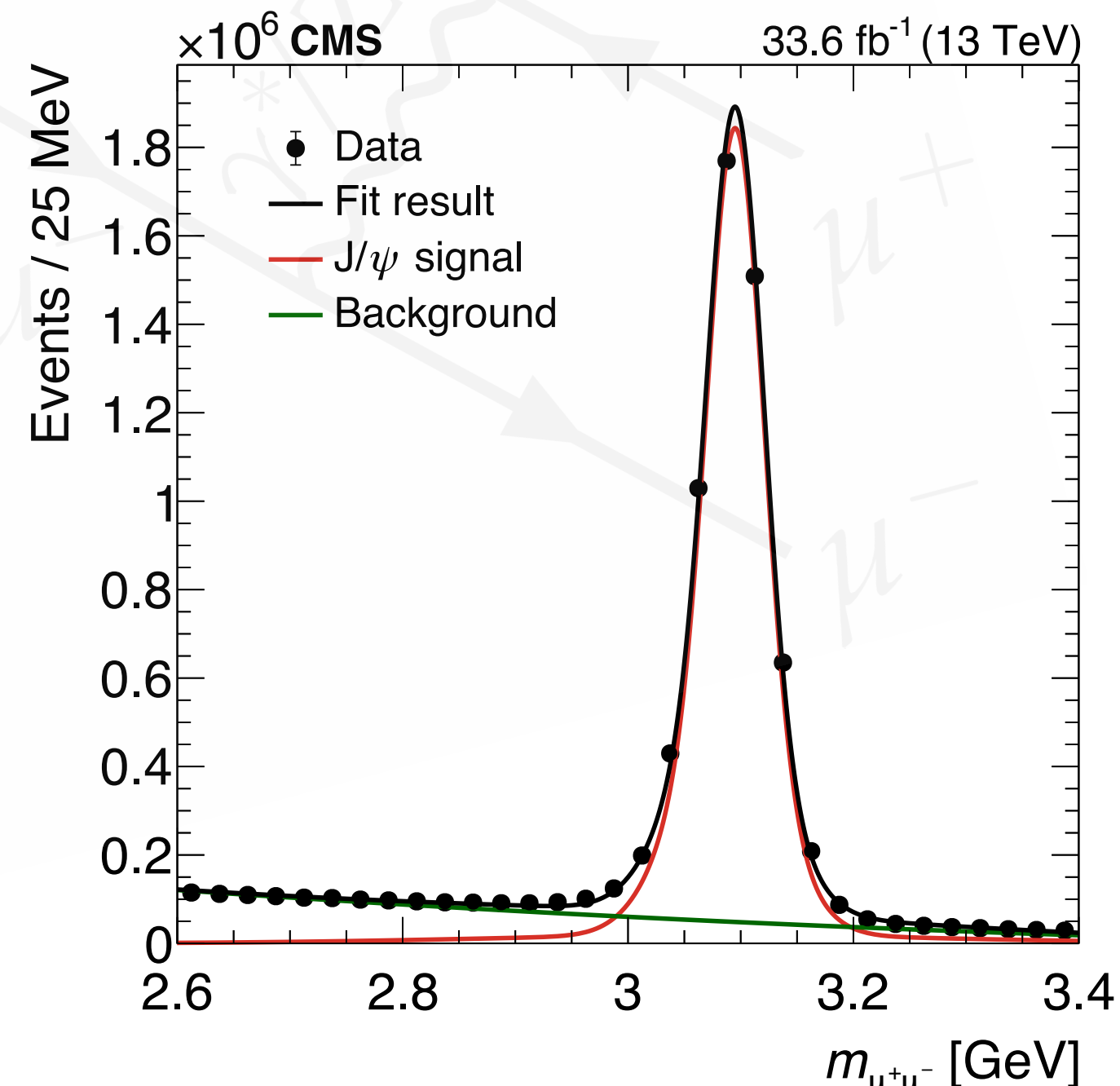
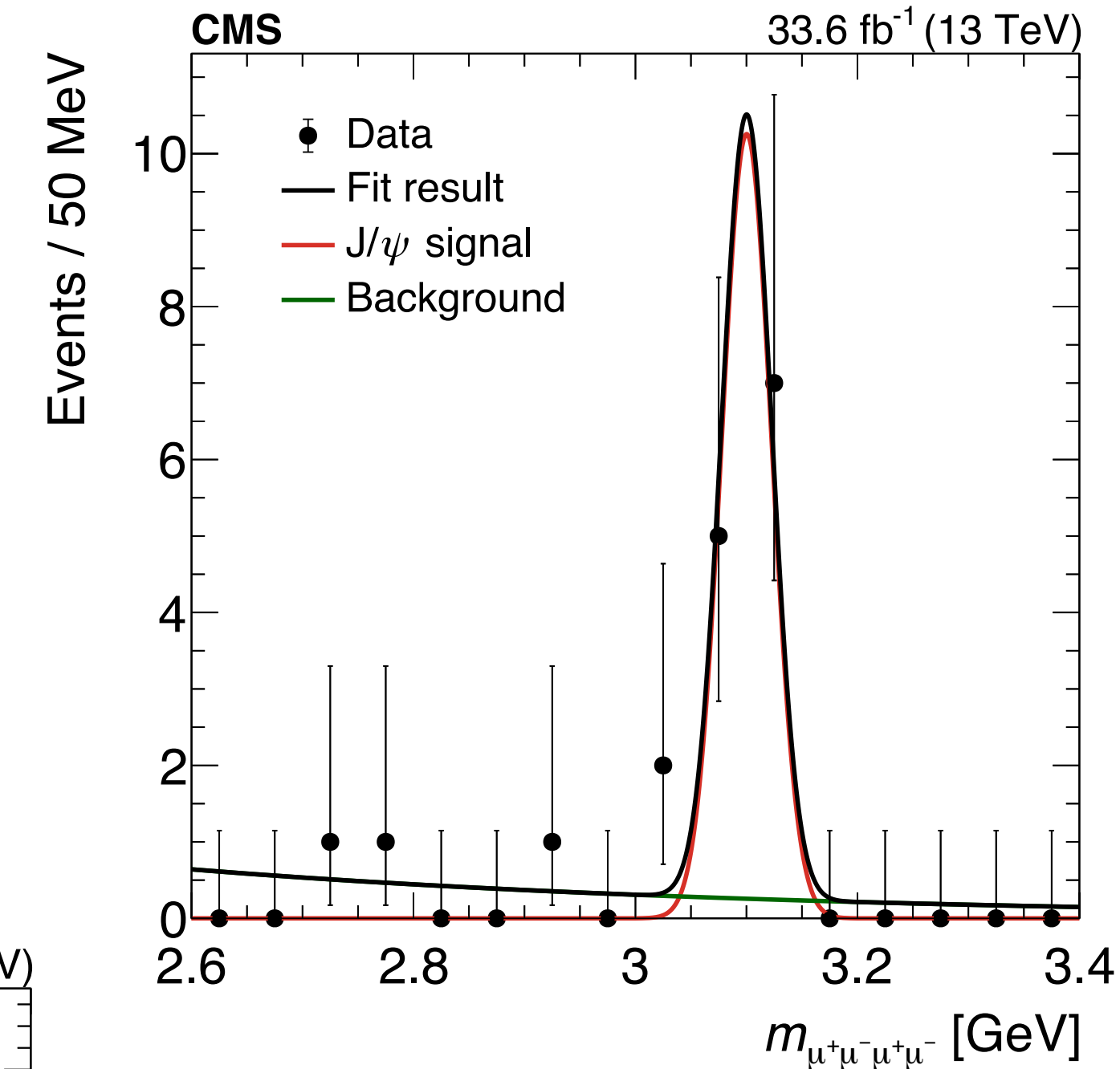
- During Run-2 CMS recorded $O(10^{10})$ B decays
 - low p_T displaced single muon trigger strategy
 - excellent place to look for rare decays
- Analysis strategy
 - exploit this large dataset and measure $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)$ as a function of $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$

$$\frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)} = \frac{N(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)}{N(J/\psi \rightarrow \mu^+\mu^-)} \bigg/ \frac{\epsilon_{J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-}}{\epsilon_{J/\psi \rightarrow \mu^+\mu^-}}$$

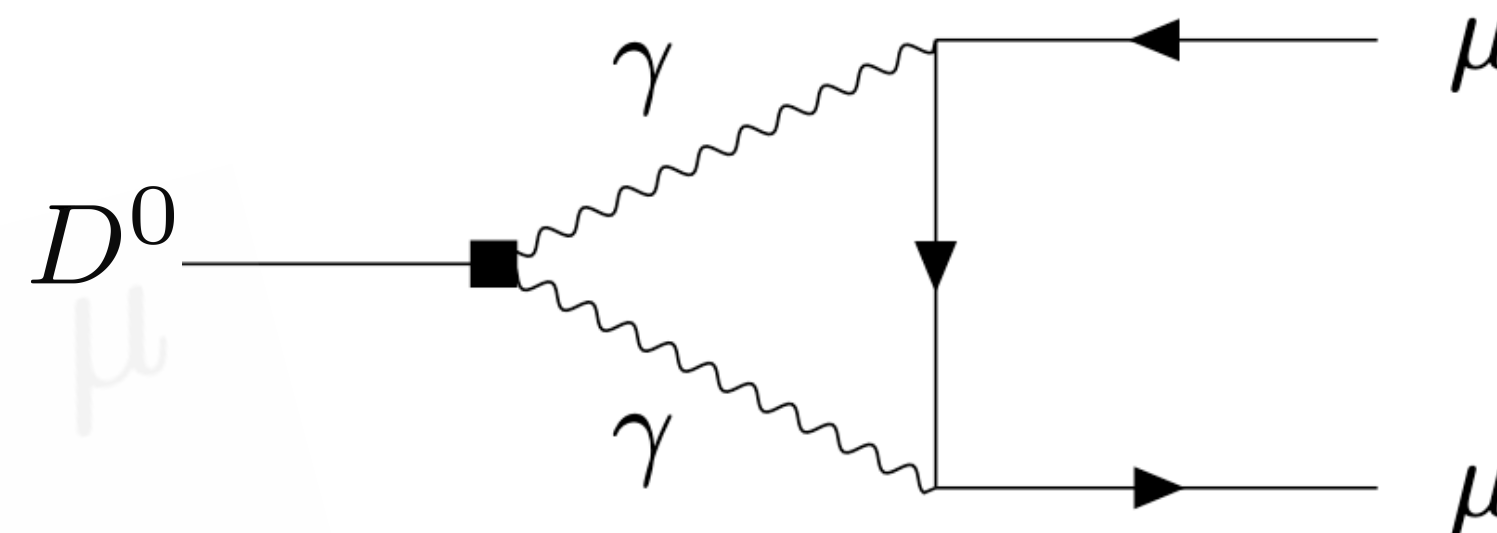
$$\epsilon_{J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-} / \epsilon_{J/\psi \rightarrow \mu^+\mu^-} = (11.92 \pm 0.02) \%$$



- $N(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = 11.6_{-3.1}^{+3.8}$
 - first observation with significance of above 7 sigma
- $N(J/\psi \rightarrow \mu^+\mu^-) = (5770 \pm 3) \times 10^3$
- $\frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)} = [16.9_{-4.6}^{+5.5}(\text{stat}) \pm 0.6(\text{stat})] \times 10^{-6}$
- $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = [10.1_{-2.7}^{+3.3}(\text{stat}) \pm 0.4(\text{stat})] \times 10^{-7}$
 - consistent with the standard model calculation $(9.74 \pm 0.05) \times 10^{-7}$



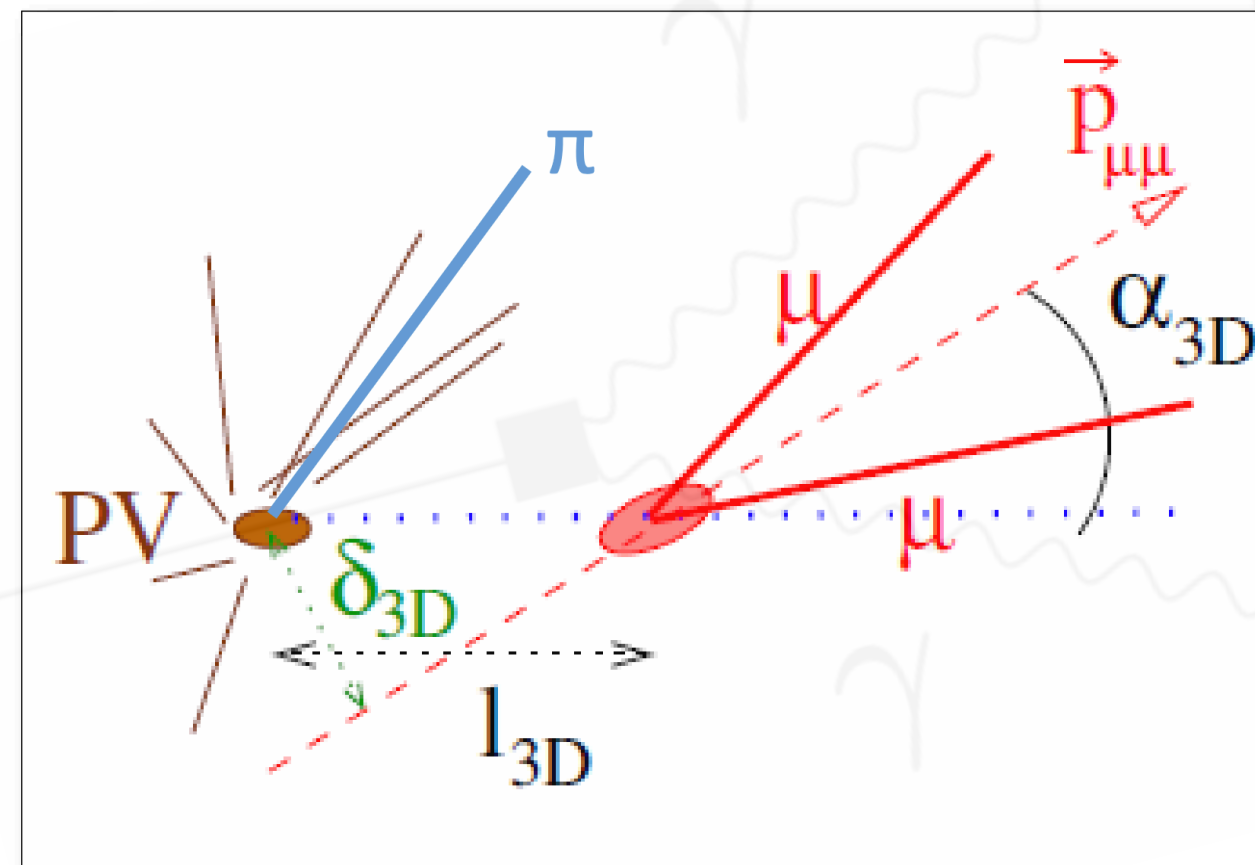
- Search for $D^0 \rightarrow \mu^+\mu^-$ and measure its branching fraction
 - the decay proceeds under FCNC, highly suppressed in SM,
 - sensitive to New Physics
 - SM Prediction: $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) \sim 3 \times 10^{-13}$
- Rare charm decays mediated by “c \rightarrow u” transition, which is less studied, comparing to “b \rightarrow s”
- Most stringent experimental search $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 3.5 \times 10^{-9}$ @ 95 CL (from LHCb), 4 orders of magnitude away from SM
- Instead of search for $D^0 \rightarrow \mu^+\mu^-$, we search for the cascade decay: $D^{*+} \rightarrow D^0\pi^+$ and further on $D^0 \rightarrow \mu^+\mu^-$
 - factor of 4 reduced stats wrt inclusive production
 - orders of magnitude reduction of combinatorial background
- Branching fraction estimated with respect to $D^{*+} \rightarrow D^0\pi^+$, with $D^0 \rightarrow \pi^+\pi^-$
 - close kinematics with signal channel



$$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) = \mathcal{B}(D^0 \rightarrow \pi^+\pi^-) \frac{N_{D^0 \rightarrow \mu^+\mu^-}}{N_{D^0 \rightarrow \pi^+\pi^-}} \frac{\epsilon_{D^0 \rightarrow \pi^+\pi^-}}{\epsilon_{D^0 \rightarrow \mu^+\mu^-}}$$

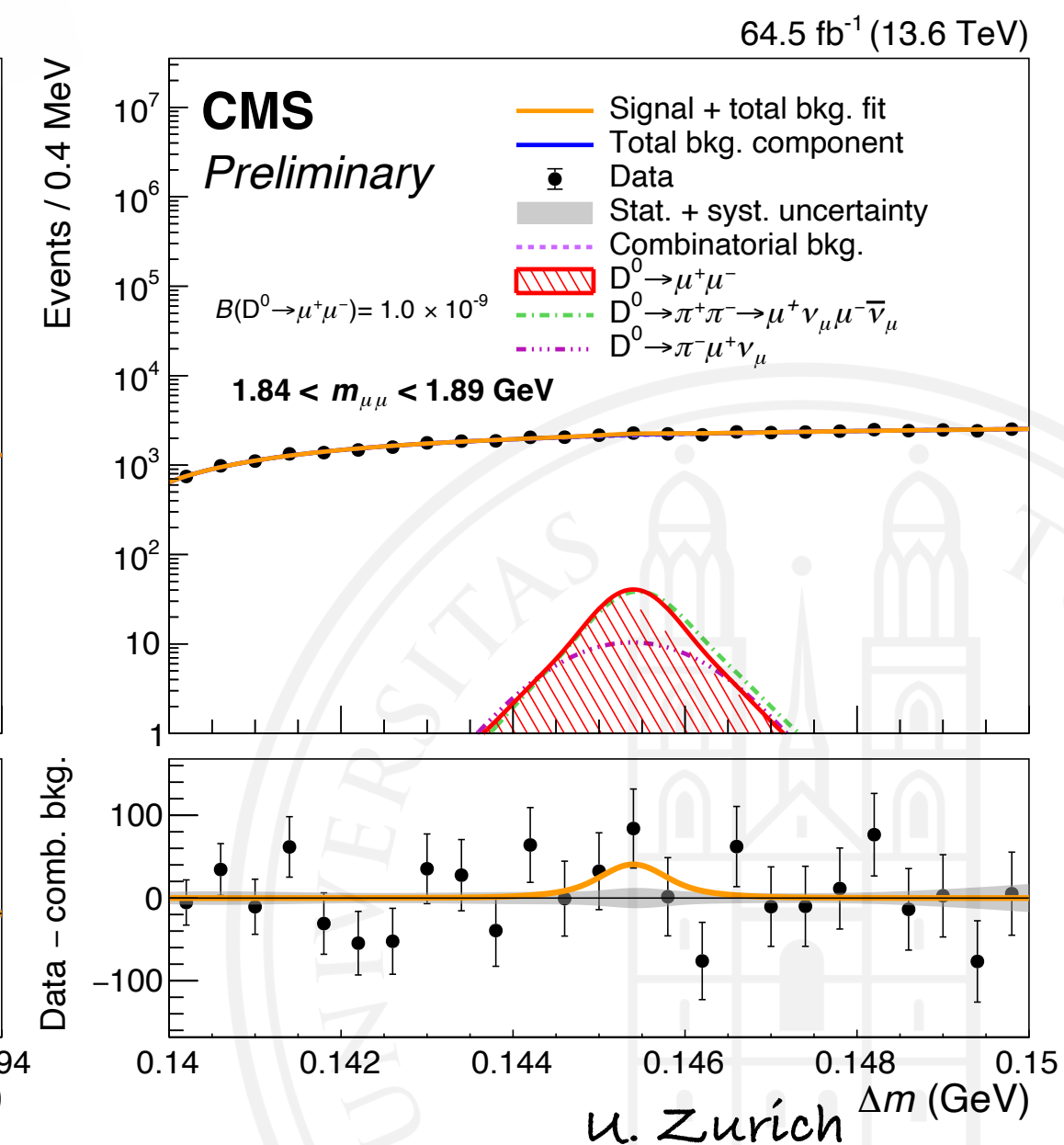
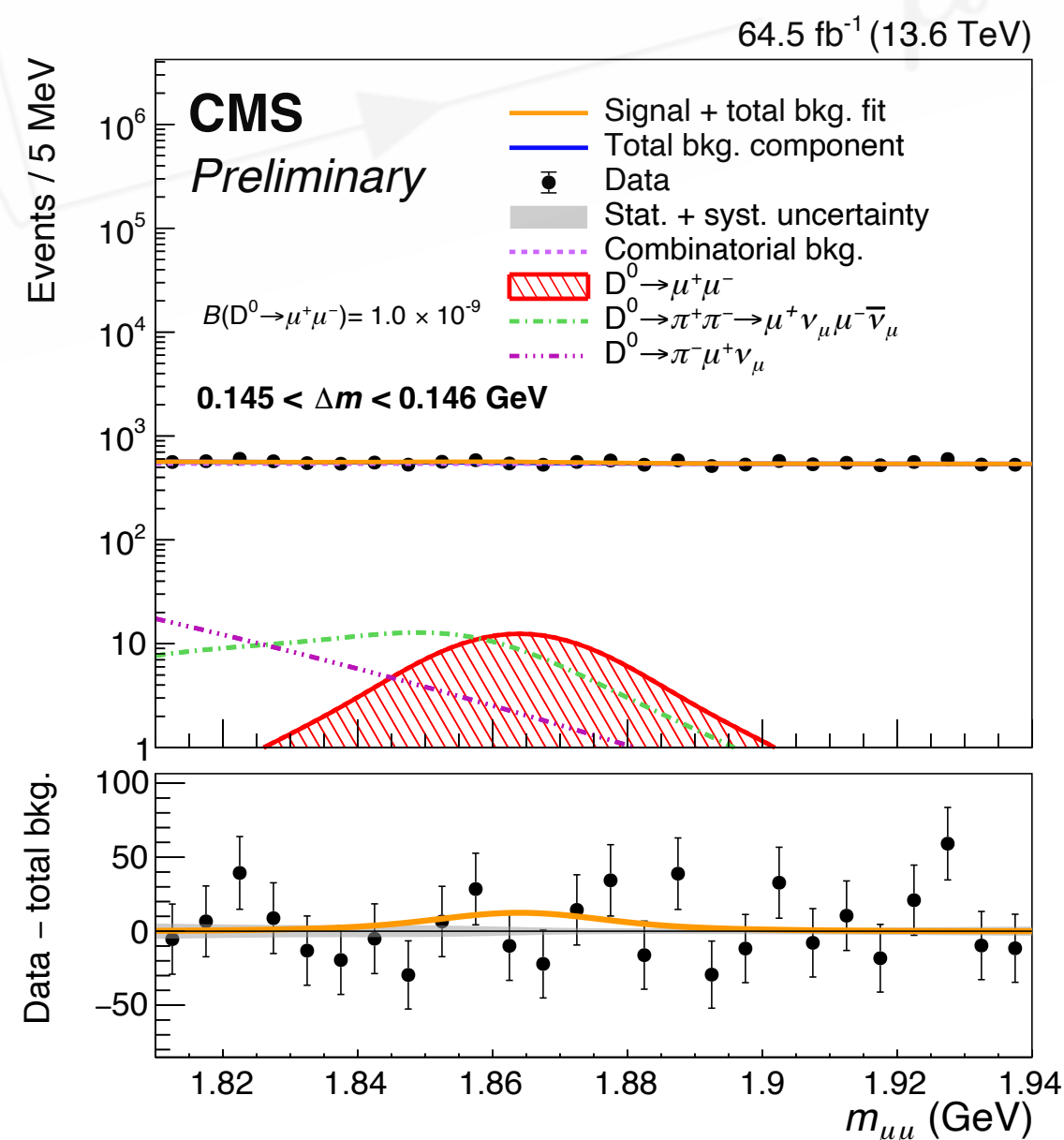
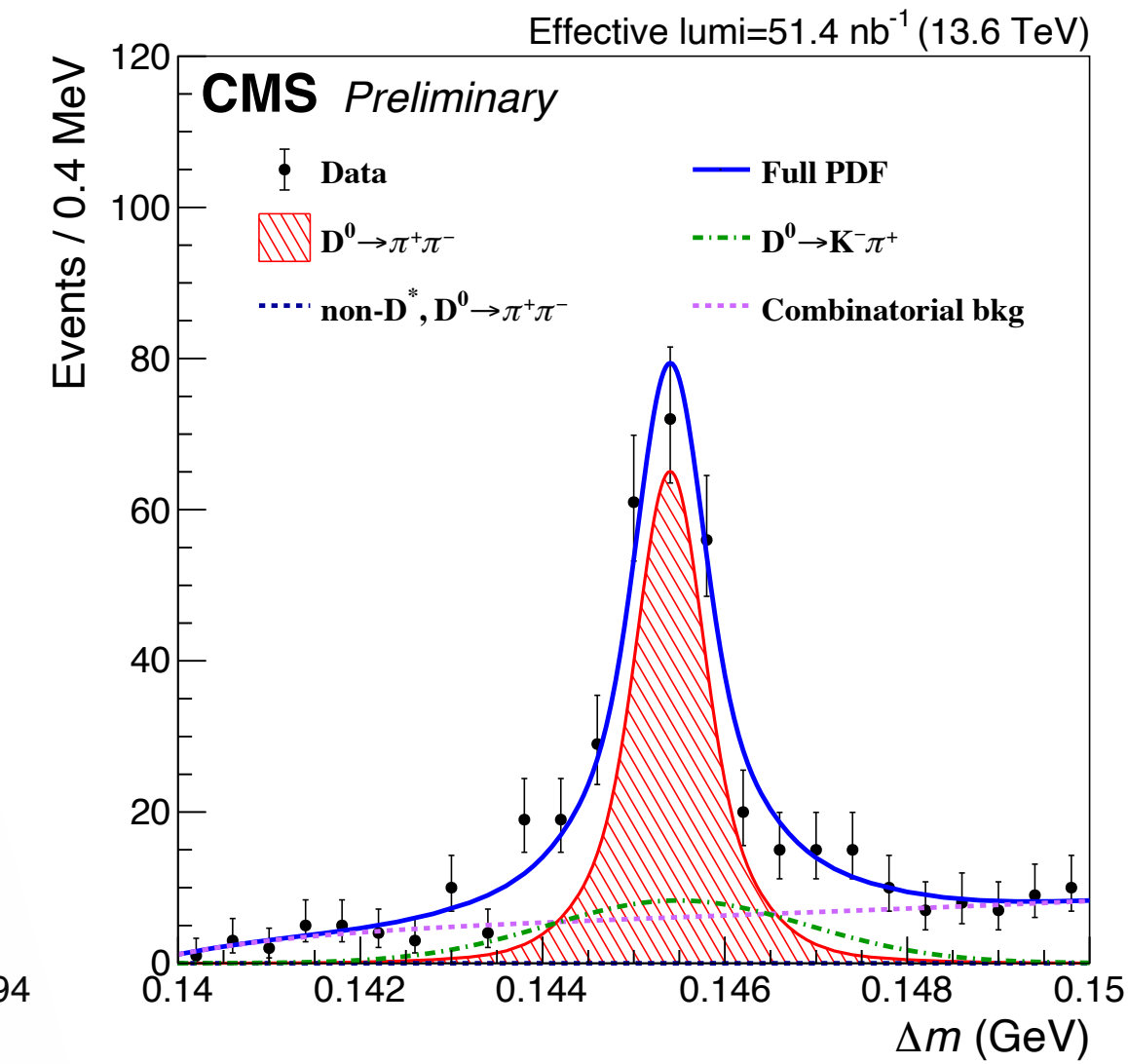
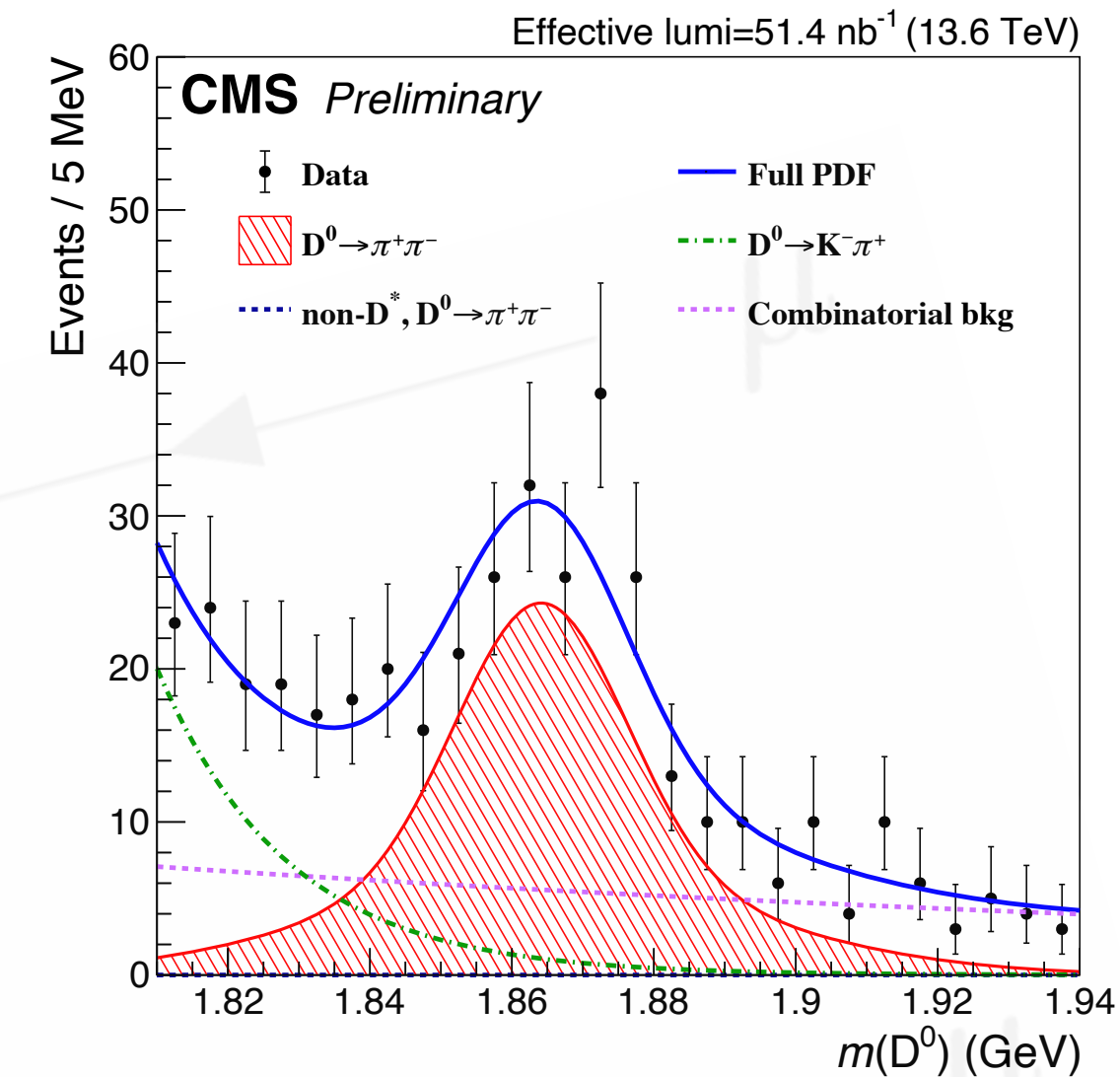
• Final selection employs a multivariate analysis including

- pointing angles: α_{3D}
- flight length significance: $l_{3D}/\sigma(l_{3D})$
- D^0 vertex probability
- impact parameter of D^0 candidate
- p_T of soft pion, muons
- D^* vertex probability



• Signal extraction using 2D unbinned maximum likelihood fit on the D^0 candidate mass and the mass difference between the $D^{*+} \rightarrow D^0 \pi^+$ and the daughter D^0 meson

- $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-9}$ at 95% CL
 - 35% improvement over the current best measurement



- CMS continues to push the boundaries looking for rare processes with several new measurements
- In this talk

- angular analysis of the $B^0 \rightarrow K^{*0}(892)\mu^+\mu^-$ decay

- one of the most precise measurements of the angular observables
- similar effect in P2 and P5' parameters observed as in LHCb measurement

- observation of the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ decay

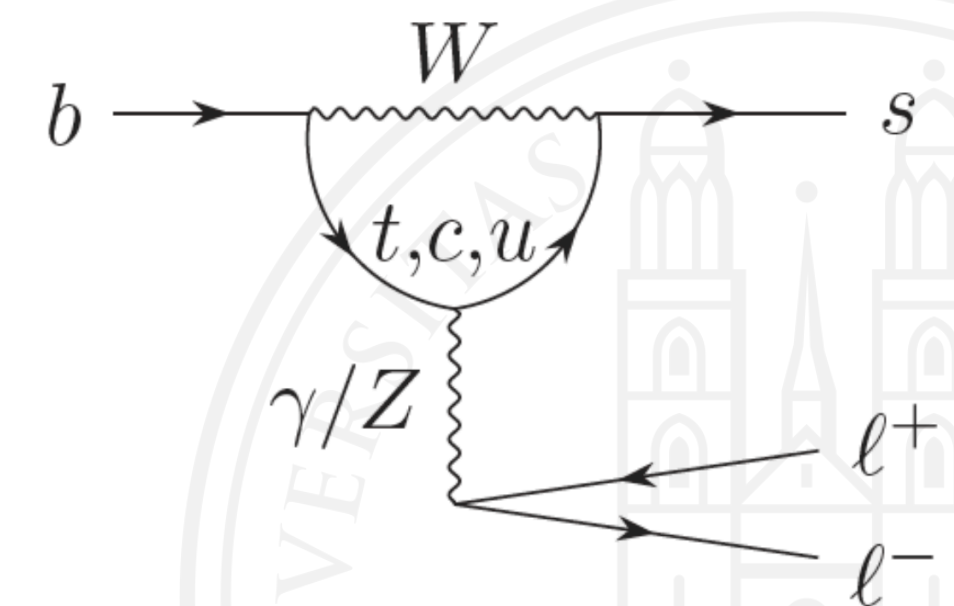
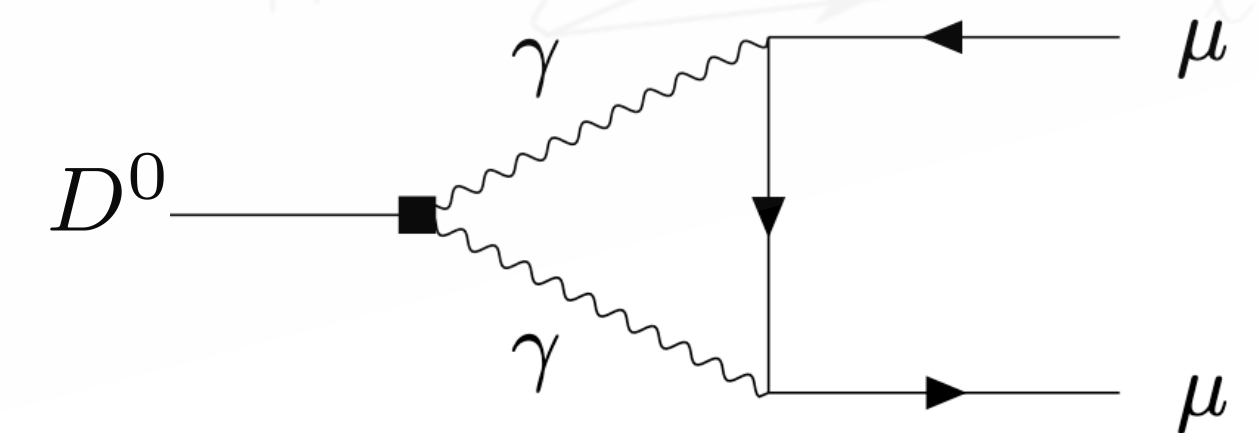
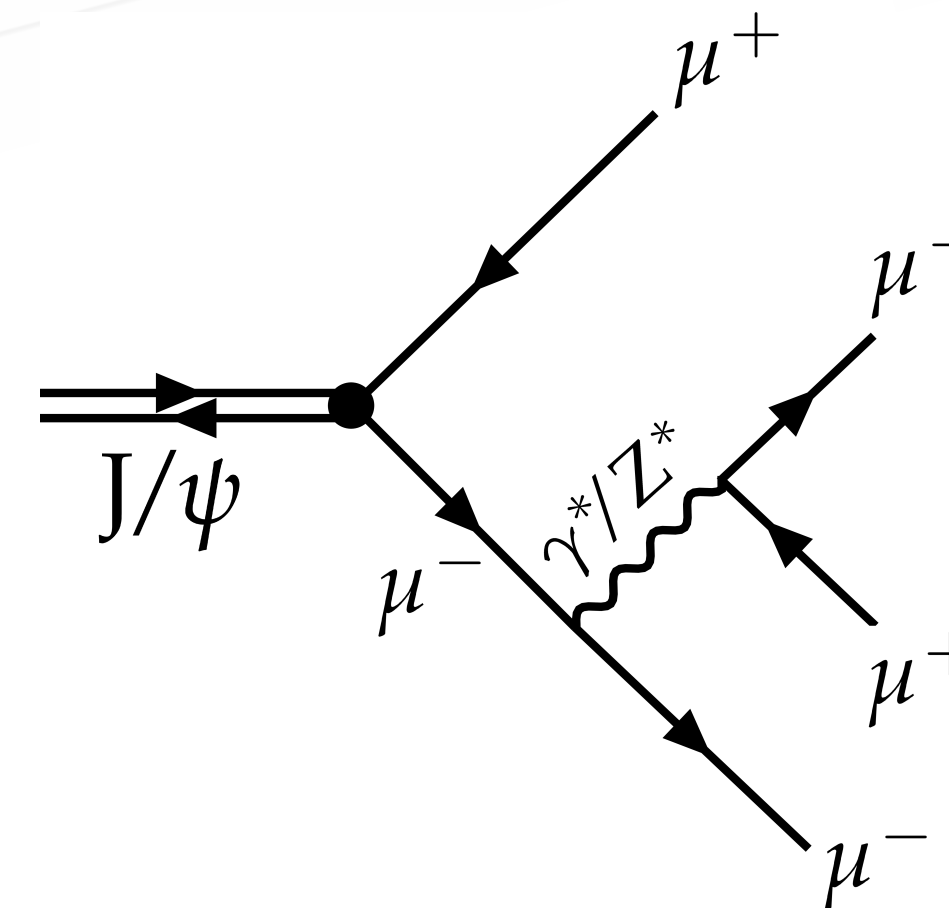
- $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = [10.1_{-2.7}^{+3.3}(\text{stat}) \pm 0.4(\text{stat})] \times 10^{-7}$ consistent with the standard model calculation $(9.74 \pm 0.05) \times 10^{-7}$

- searching for rare charm decays into two muons

- $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-9}$ at 95% CL
- most sensitive measurement to date

- Other new CMS results in other flavour fronts:

- Spectroscopy - Alexis Pompili
- Lepton flavour violation - Chiara Rovelli
- CPV and lifetime - Enrico Lusiani
- Production - Yewon Yang



Rare and forbidden decays at CMS

Backup

