B PHYSICS PARKING PROGRAM AT CMS

Greg Landsberg - RDMS 2018 Meeting - 9/12/18

Introduction

- The B physics parking proposal was submitted to the CMS management in February 2018, with the main goal to make CMS competitive with LHCb in the R(K)/R(K*) measurements, which attracted a lot of attention in the last couple of years
- It also has potential to enable a number of new measurements in B physics sector, which were not possible before
- The proposal was enthusiastically endorsed by the management and implemented in early May
- The goal is "simple": record $\sim 10^{10}$ unbiased B hadron events this year using the flexibility of the CMS data taking model

Documentation

- The proposal can be found here (April 4 XC meeting):
  - https://indico.cern.ch/event/718742/contributions/2954094/attachments/1626805/2590890/B_Parking_Proposal_V2.pdf

Proposal to collect a generic sample of $\mathrm{O}(10^{10})$ B hadron decays designed to measure $\mathrm{R_K}$ and $\mathrm{R_{K^*}}$ in CMS using data parking in 2018

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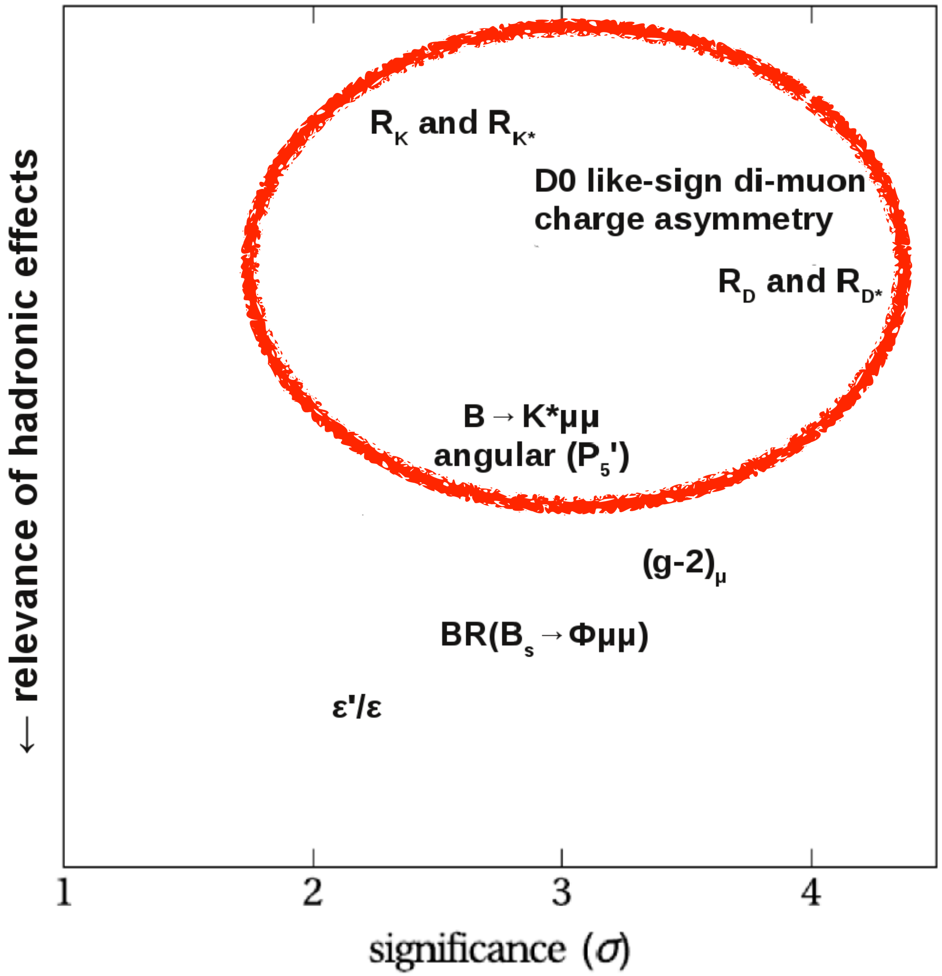
The Case for 10^{10} B's

- The original case for a sample of 10^{10} B's was to offer a unique test of the B physics flavor anomalies:
  - R(K)
  - R(K*)
  - Possibly R(D)/R(D*)
- Soon realized that the sample offers significantly more broad program with a potential to revolutionize the way we do B physics in CMS
- The number of B's we propose to put on tape rivals the full Run 1 event count of LHCb and offers a possibility of opposite-side tagging for time-dependent/CP-violation analyses
- Could profit from the key features of the CMS detector (excellent tracking, muon system, ECAL, τ ID) to compete with (or beat!) LHCb on a number of important measurements of rare decays and searches for new states (e.g., via radiative decays)

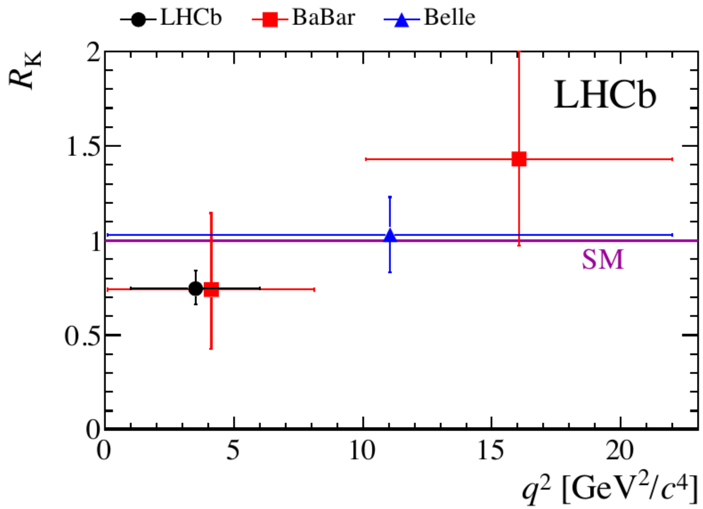
Status of Flavor Anomalies

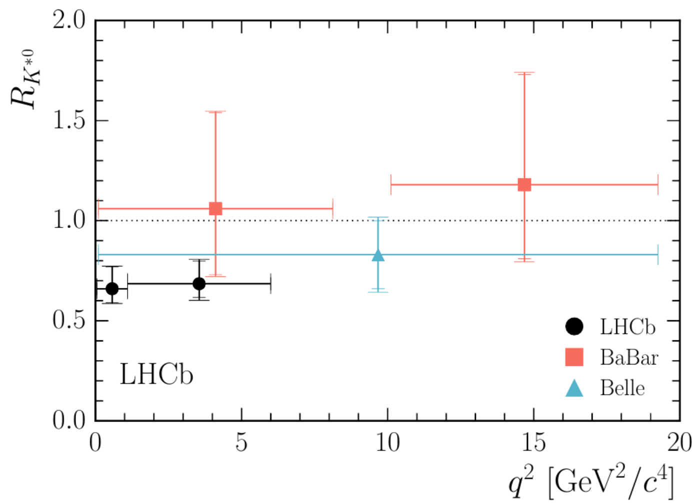
- From Wolfgang Altmannshofer's talk at the Aspen 2018 Winter Conference:
  - https://indico.cern.ch/event/660187/contributions/2888216/attachments/1625622/2588612/talk_Aspen.pdf



- Angular observables in $B^0 \to K^{*0}\mu\mu$ decay
- Br of several of $b \to sll$ processes
- Lepton-flavor universality tests in $b \to sll$ and $b \to cl\nu$

Flavor Anomalies: $R(K^{(*)})$





Bordone, Isidori, Pattori 1605.07633

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

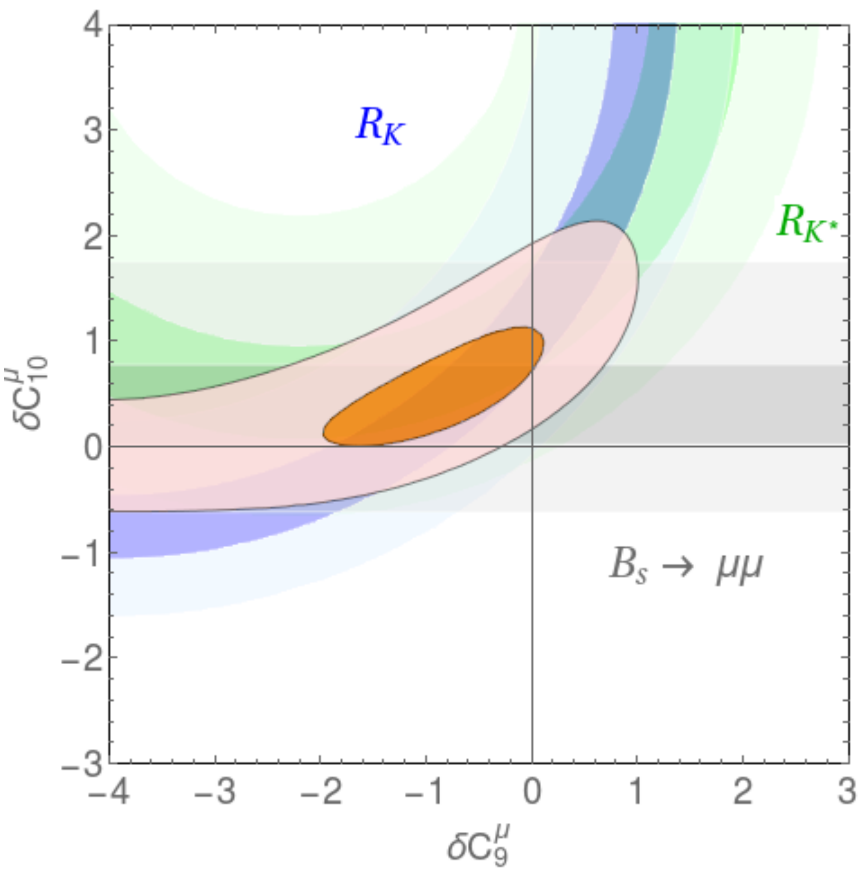
$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

3 observables
deviating by $\sim 2\sigma - 2.5\sigma$
from the SM predictions

$$R_K^{[1,6]} = 1.00 \pm 0.01 \quad , \quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \quad , \quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

$R(K^{(*)})$ Implications

- **If correct, undoubtedly means new physics**
- Main contributions are expected from C_9 and C_{10} Wilson coefficients (or C_7 at low q^2 for $R(K^*)$, but there are severe constraints from $b \to s\gamma$ transitions)

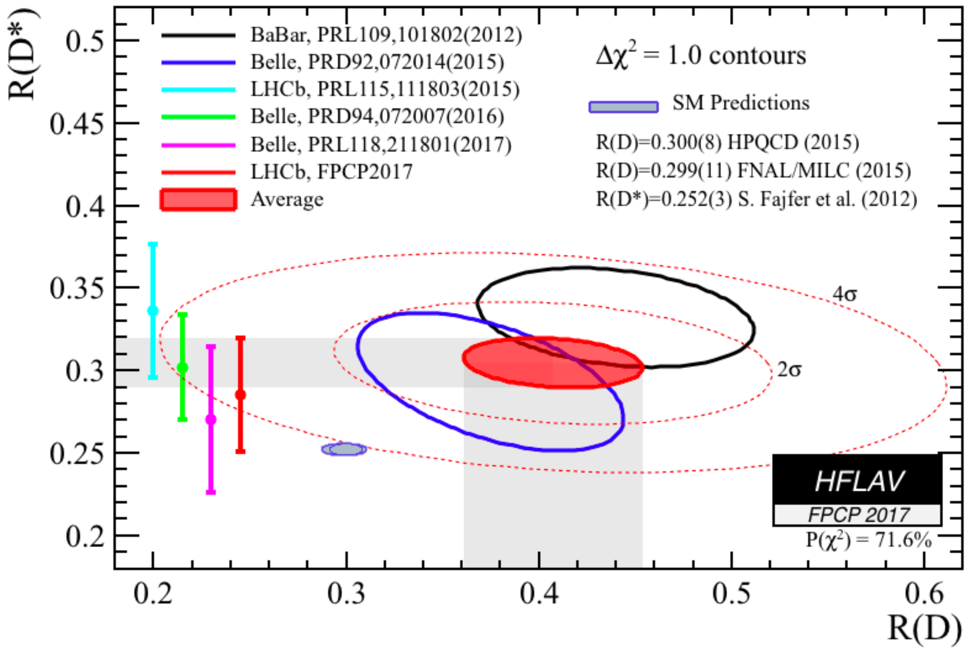


Geng et al., arXiv:1704.05446

Potential connection to the $B_s(\mu\mu)$ branching fraction, which is presently ~1σ low

Flavor Anomalies R(D$^{(*)}$)

world average from the heavy flavor averaging group



$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

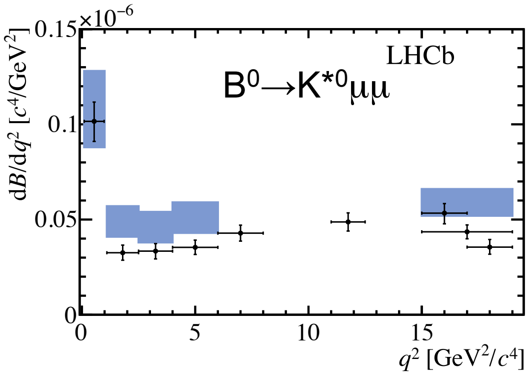
$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

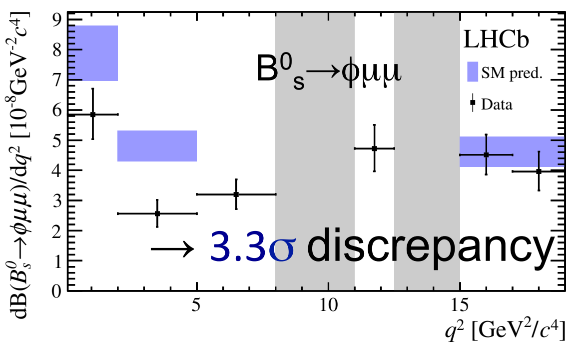
$$R_D^{\text{exp}} = 0.407 \pm 0.039 \pm 0.024 \quad , \qquad R_{D^*}^{\text{exp}} = 0.304 \pm 0.013 \pm 0.007$$

discrepancies with the SM by 2.3σ and 3.4σ, respectively

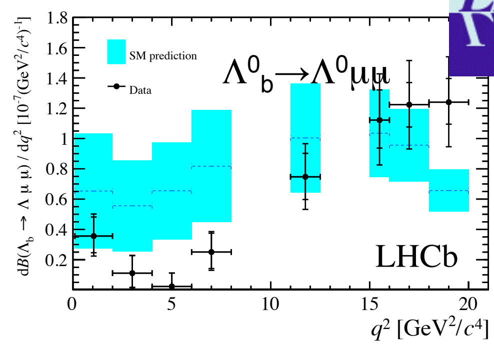
Flavor Anomalies: Br



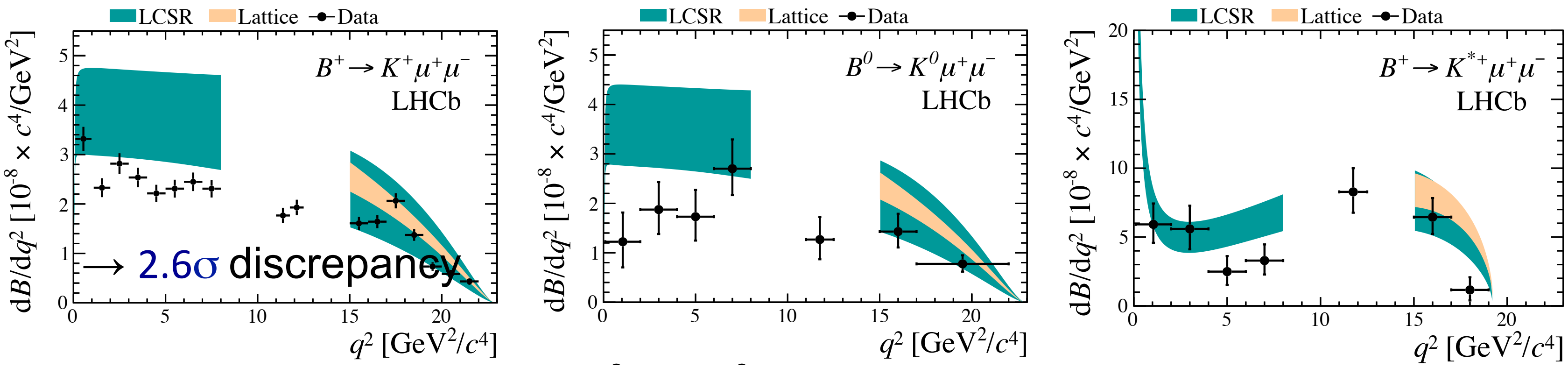
[JHEP 11 (2016) 047,
JHEP 04 (2017) 142]



[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]



[JHEP 06 (2014) 133]

Summary of Flavor Anomalies

Observable	SM prediction	Measurement	Discrepancy
$R_{K^{(*)}}(q^2 = m^2_{\ell\ell}) = \Gamma(B^{\pm(0)} \to K^{(*)}\mu\mu)/\Gamma(B^{\pm(0)} \to K^{(*)}ee)$			
$R_K([1,6]\ \mathrm{GeV}^2)$	1.00 ± 0.01 [11, 12]	$0.745^{+0.090}_{-0.074}$ [2]	$\approx 2.5\sigma$
$R_{K^*}([0.045, 1.1]\ \mathrm{GeV}^2)$	0.92 ± 0.01[13]	$0.660^{+0.110}_{-0.024} \pm 0.036$ [1]	$\approx 2.3\sigma$
$R_{K^*}([1.1, 6.0]\ \mathrm{GeV}^2)$	1.00 ± 0.01 [11, 12]	$0.685^{+0.113}_{-0.069} \pm 0.047$ [1]	$\approx 2.4\sigma$
$B^0 \to K^*\mu\mu$ angular distribution			
P'_5	see text	see Refs. [4, 5]	$\approx$ 2 to 4σ
$R_{\mu\mu} = \Gamma(B \to \mu\mu)/\Gamma_{\mathrm{SM}}(B \to \mu\mu)$			
$R_{\mu\mu}$	1	$0.75^{+0.14}_{-0.13}$ [9]	$\approx 1.7\sigma$
$R_{D^{(*)}} = \Gamma(B \to D^{(*)}\tau\nu)/\Gamma(B \to D^{(*)}\ell\nu)\ (\ell = e, \mu)$			
$R_{D^{(*)}}$	see Ref. [10]	see Ref. [10]	$\approx 4\sigma$

[1] R. Aaij, et al. (LHCb), JHEP **08**, 055 (2017), 1705.05802

[2] R. Aaij, et al. (LHCb), Phys. Rev. Lett. **113**, 151601 (2014), 1406.6482

[4] R. Aaij, et al. (LHCb), Phys. Rev. Lett. **111**, 191801 (2013), 1308.1707

[5] R. Aaij, et al. (LHCb), JHEP **02**, 104 (2016), 1512.04442

[9] http://mastercode.web.cern.ch/mastercode/

[10] http://www.slac.stanford.edu/xorg/hfag/semi/fpcp17/RDRDs.html

[11] S. Descotes-Genon, L. Hofer, J. Matias, et al., JHEP **06**, 092 (2016), 1510.04239

[12] M. Bordone, G. Isidori, A. Pattori, Eur. Phys. J. **C76**, 8, 440 (2016), 1605.07633

[13] B. Capdevila, A. Crivellin, S. Descotes-Genon, et al., JHEP **01**, 093 (2018), 1704.05340

Competing on R(K(*))

- LHCb measurements are based on ~100 ee events each
- By now should have doubled the data set
- Given the branching fraction ~10^{-7} and reconstruction efficiency ~10% we hope to achieve, requires ~1000 recorded events to start getting competitive

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi(\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285\,^{+18}_{-18}$	$353\,^{+21}_{-21}$	$274416\,^{+602}_{-654}$
e^+e^- (L0[illegible])	$55\,^{+9}_{-8}$	$67\,^{+10}_{-10}$	$43468\,^{+222}_{-221}$
e^+e^- (L0[illegible])	$13\,^{+5}_{-5}$	$19\,^{+6}_{-5}$	$3388\,^{+62}_{-61}$
e^+e^- (L0[illegible])	$21\,^{+5}_{-4}$	$25\,^{+7}_{-6}$	$11505\,^{+115}_{-114}$

- Need to use a L1 seed with high B rate and purity and park it after simple HLT refinement:

$$N^{L1}_{2018}(K^{(*)}) = f_B \times BR(K^{(*)}) \times R_{L1seed} \times P_{L1seed} \times sec_{LHC}$$

with

- f_B being the fraction of B hadrons (e.g. B^0 or $B^\pm$),
- $BR(K^{(*)})$ the branching fraction for $B^0 \to K^* l^+ l^-$ or $B^\pm \to K^\pm l^+ l^-$,
- R_{L1seed} the rate in Hz of the L1 seed that is considered,
- P_{L1seed} the purity of the L1 seed, which is defined to be the number of B's selected wrt to the total number of events triggered, and
- sec_{LHC} is the number of seconds that the LHC will take date in 2018.

Putting it all Together

L3-μ p_T [GeV]	Rate [Hz]	Rate (B only) [Hz]	B Purity	Rate Red.	ϵ (signal)
5	2118.9	1603.0	75.7%	3.0	66.9%
6	2069.7	1588.9	76.8%	3.0	66.3%
12	1644.1	1353.2	82.3%	3.8	56.5%
22	703.0	390.7	55.6%	18.9	16.3 %

- N.B. to make the parked data maximally useful for other analyses, we DO NOT WANT to bias the probe side
  - The HLT requirements are only applied to the tag, creating truly minimal bias on the probe side
- With these numbers, assuming 2 kHz of parking rate to tape and 1 MB/event (i.e. 2GB/s parking rate), we expect to write ~3300 K*ll and 2200 Kll events to tape

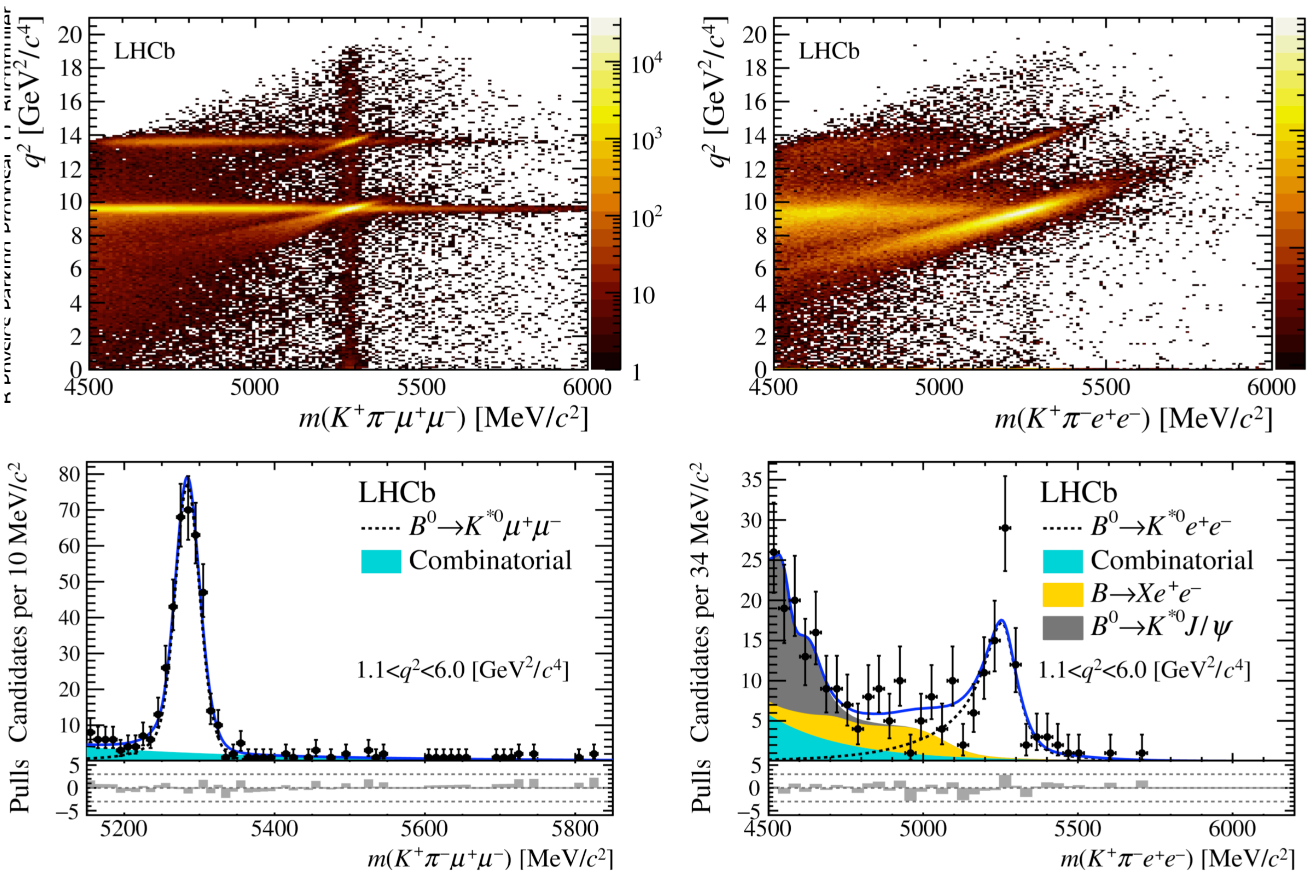
Summary of the Proposal

Mode	N_{2018}	f_B [17]	$\mathcal{B}$
Generic B hadrons			
B_d^0	4.99×10^9	0.4	1.0
$B^\pm$	4.99×10^9	0.4	1.0
B_s	1.56×10^9	0.1	1.0
b baryons	1.56×10^9	0.1	1.0
B_c	1.25×10^7	0.001	1.0
B hadrons total	1.25×10^{10}	1.0	1.0
Interesting B decays			
$B^0\to K^*\ell^+\ell^-$	3290	0.4	$\frac{2}{3}\times9.9\times10^{-7}$ [14]
$B^\pm\to K^\pm\ell^+\ell^-$	2250	0.4	4.51×10^{-7} [15]

More than 20x the entire BaBar B sample in 6 months!

R(K(*)): Tough Experimentally

- LHCb has poor electron energy resolution and there is significant radiative tail, leading to potential J/ψK(*) leakage - very hard to control experimentally



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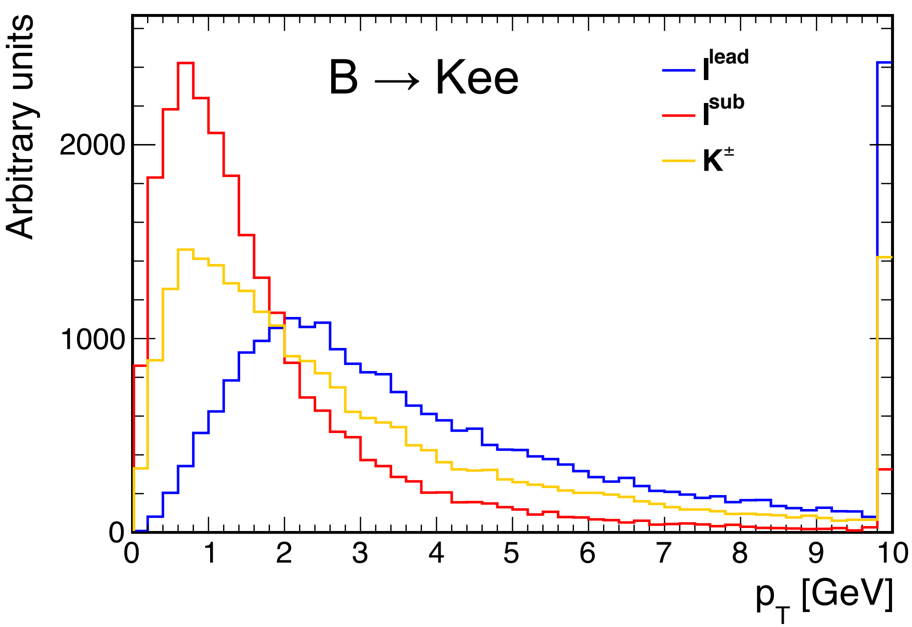
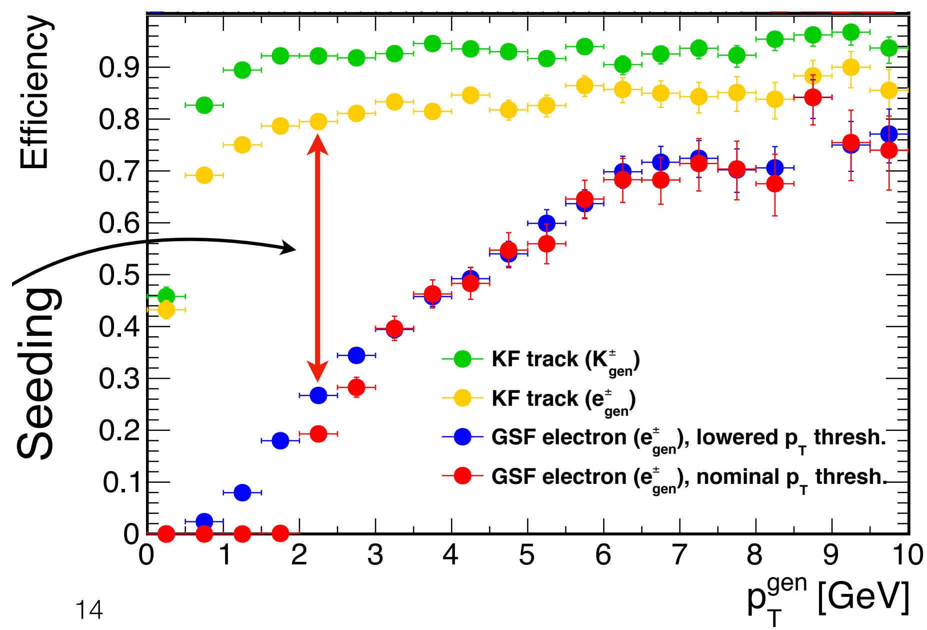
Challenges for CMS

- Main challenges: Br ~ 10^{-7}
  - This is why need ~10^{10} B's!
- Low-energy electron reconstruction
  - Need significant investment to improve it down to ~1 GeV
  - A bit less challenging with R(K)

Rob Bainbridge





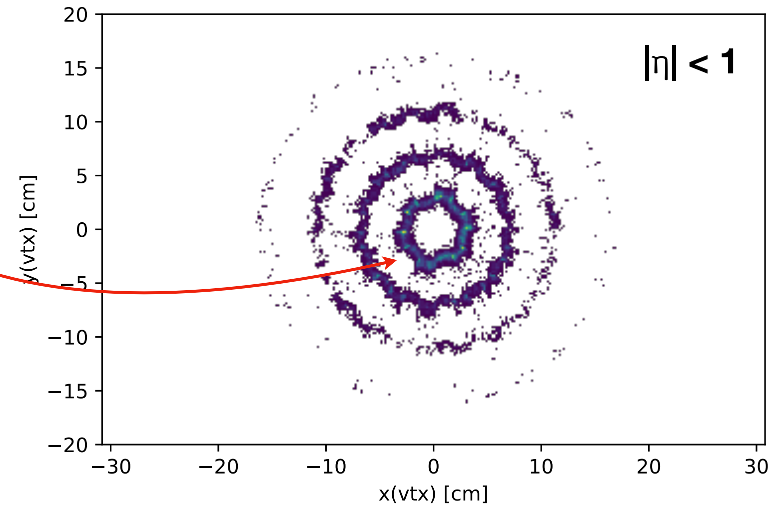
Conversions to Rescue

Nancy Marinelli
Mauro Verzotti

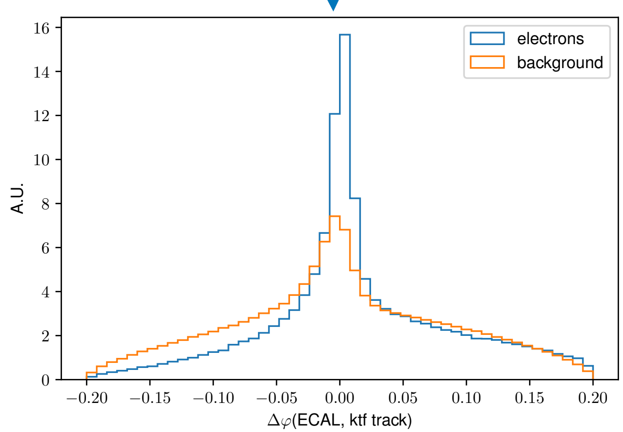
- Use conversions to study low-p_T electrons

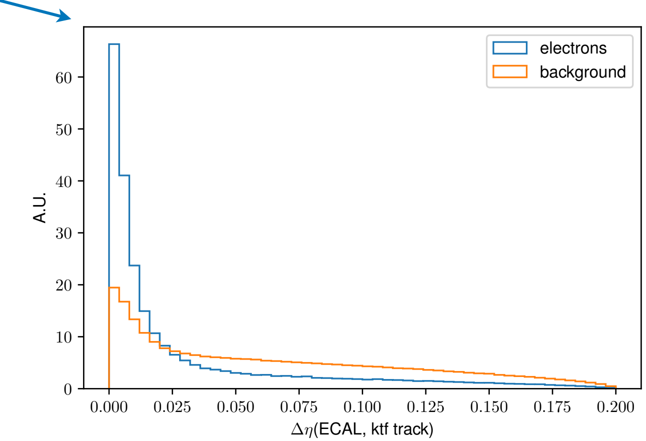
Other datasets are also being considered

Use conversions stemming from the first pixel layer/beampipe



Example of discriminating variables used in the seeding





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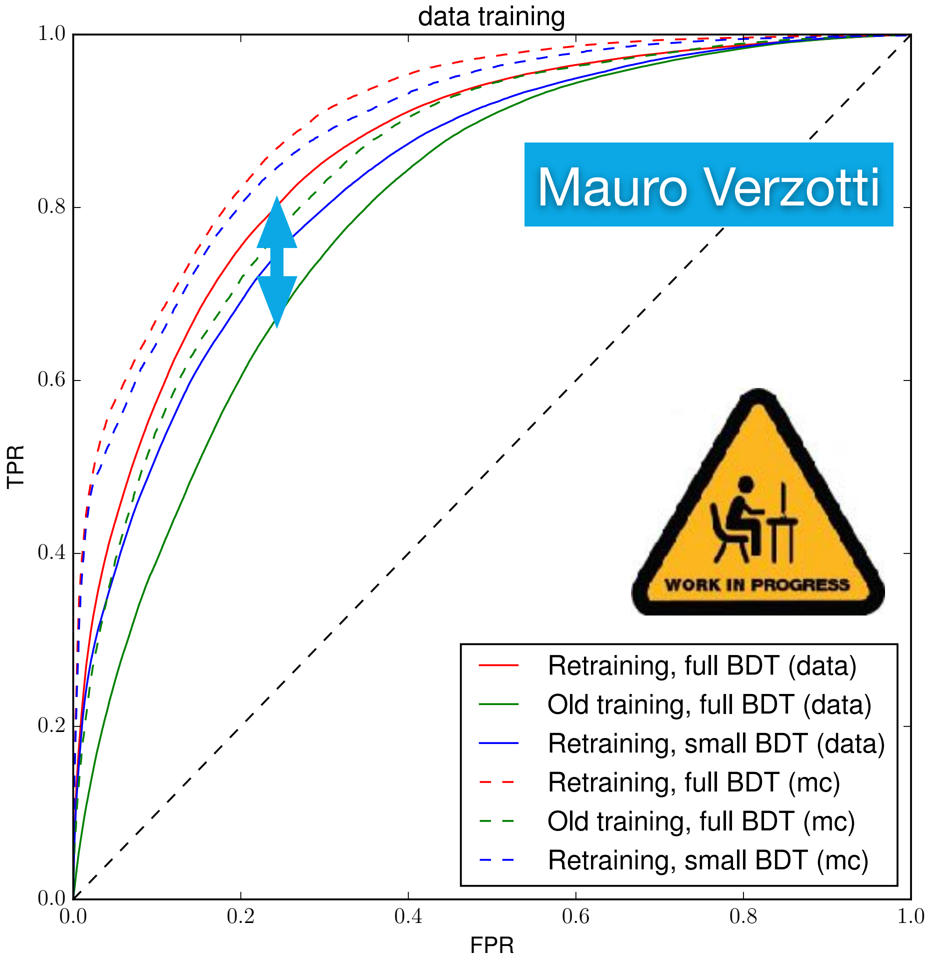
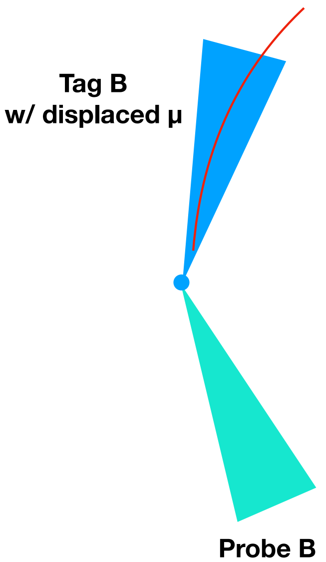
Electron Reconstruction

- First look on improvement of electron reconstruction by retraining the electron ID BDT targeting low-p_T electrons
- Looks very promising!

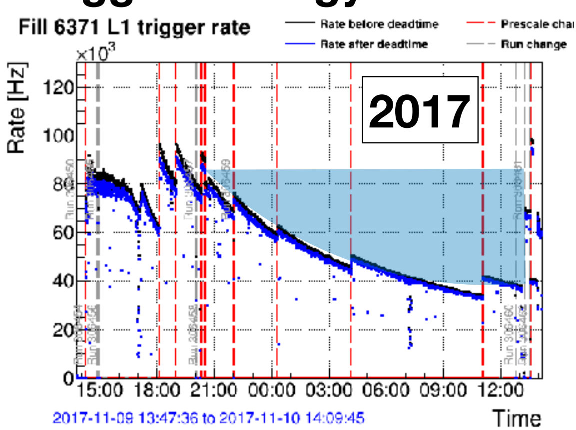


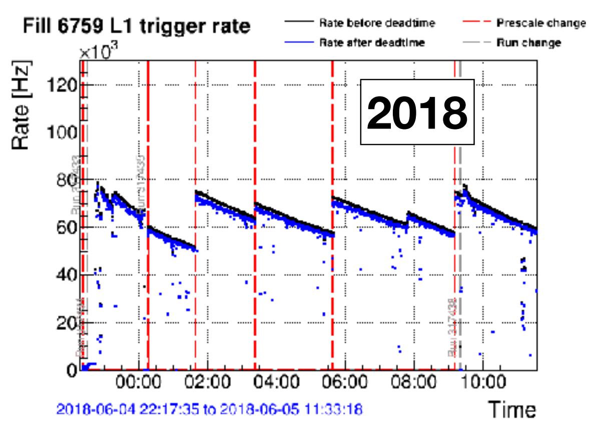
Parking: Trigger Strategy



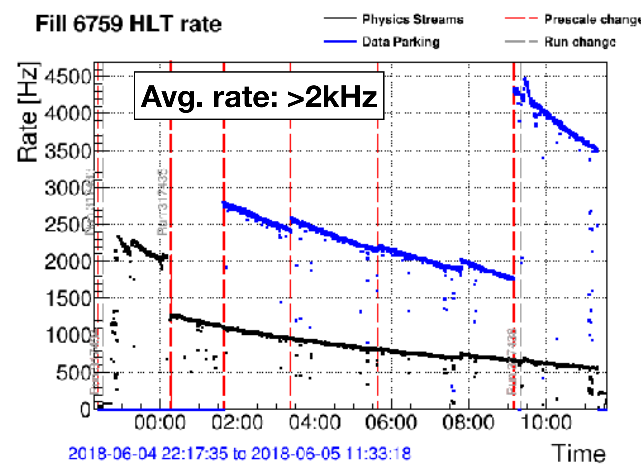
- As the luminosity drops, turn on various single-muon |η|-restricted seeds, which allow to keep L1 rate constant and increase HLT rate toward the end of each fill
- Tuned thresholds, while gaining experience; HLT_Mu9_IP6,5,4 are the main triggers

Trigger strategy — L1





Trigger strategy — HLT

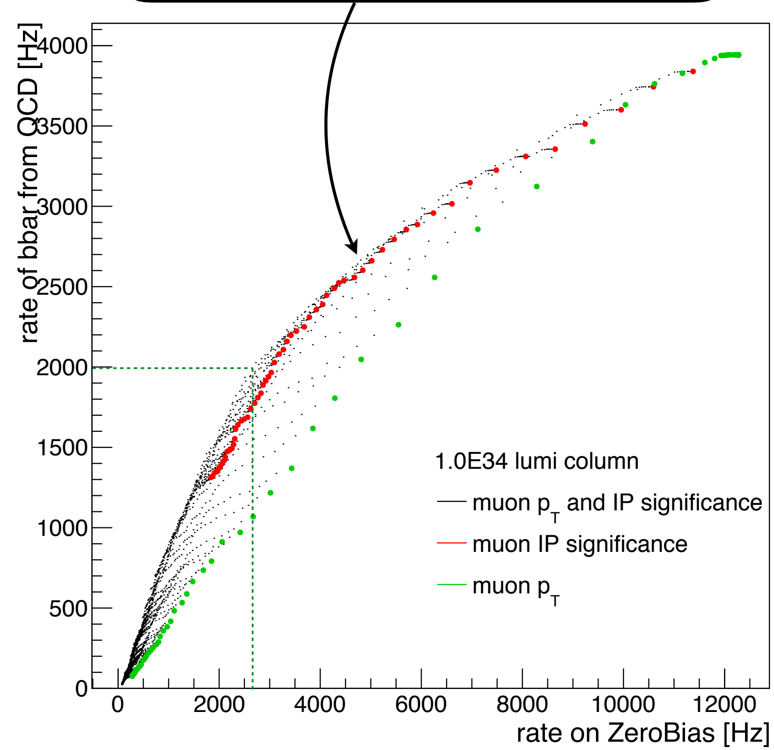


Trigger Tuning

Sara Fiorendi
Riccardo Manzoni
Mauro Verzetti

- Trigger strategy has been carefully optimized to maximize the number of B hadrons to tape, given the fixed bandwidth
- Required calculation of the purity of the triggers in terms of B hadrons
  - Very high purity of 70-80% is achieved
  - Confirmed with the parked data using reconstructed $B \rightarrow D^{*}\mu\nu$ decays on the tag side
  - Makes use of soft pions from D^{*} decays (down to 300 MeV)

Each point in the cloud represent a tentative selection in $p_T(\mu)$ and IP significance

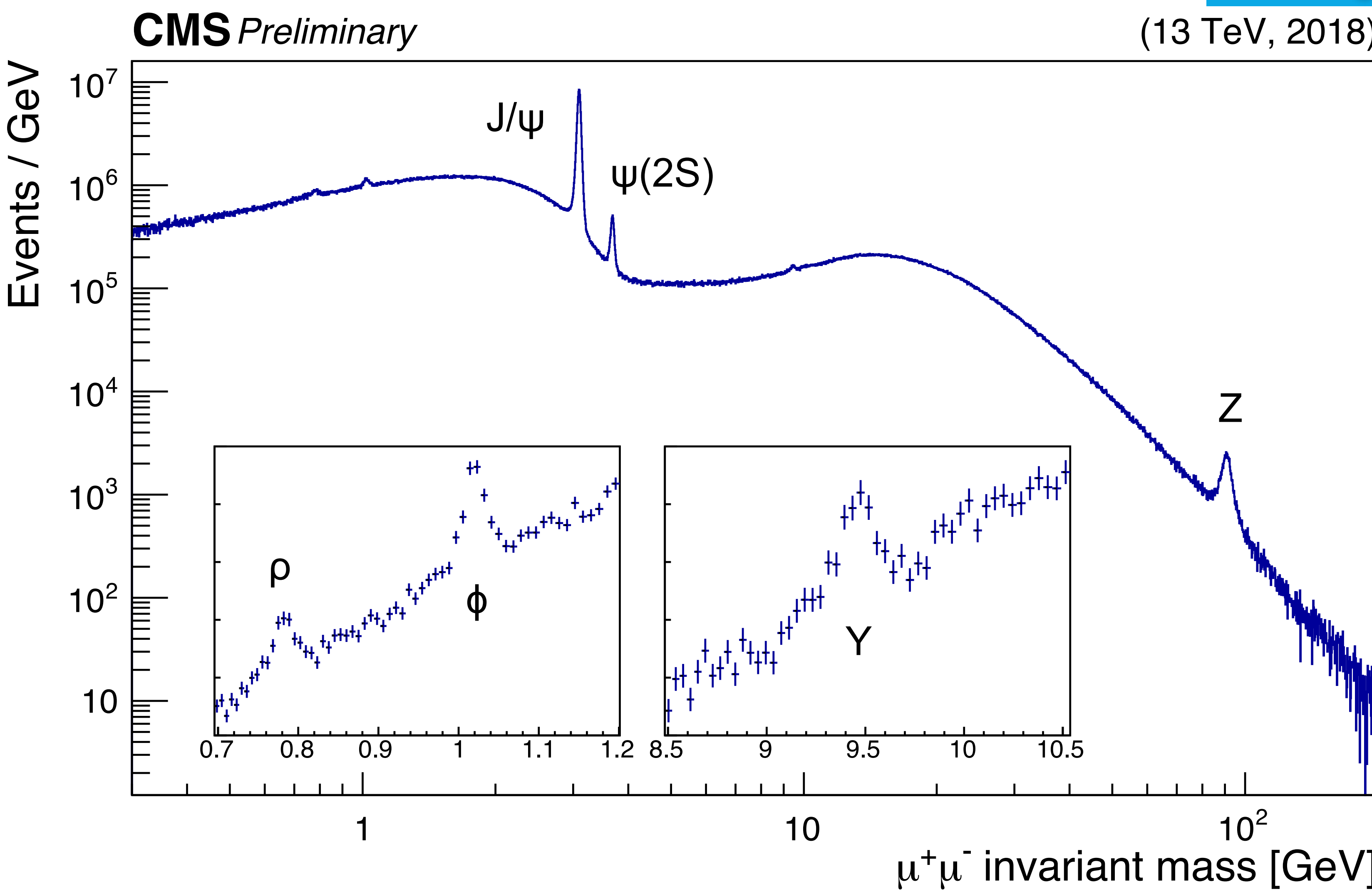


First Look at Parked Data

- As of today, we have written to tape 8.6 x 10^9 events with ~70% purity
  - On track for the design goal of 10^{10} B hadrons to tape
- While the main sample is still only recorded, we have about 500M events already reconstructed, and about as many to be reconstructed soon (O(10%))
- First look at these data is very promising - already see several decays for the first time in CMS
- The next few slides show a collage of some of these results

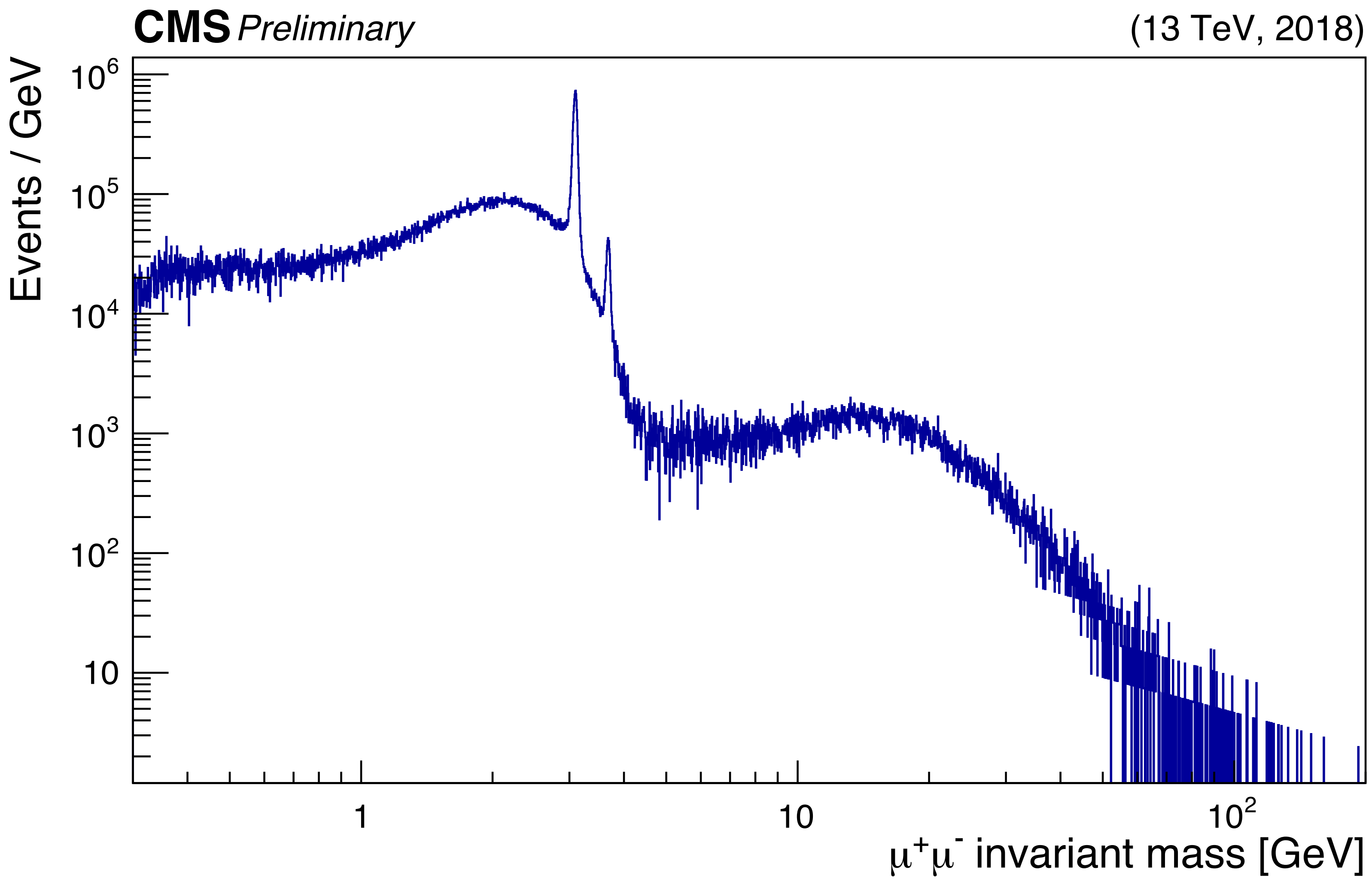
Trigger-Level Dimuon Spectrum

Ka Tung Lau



Displaced Dimuons

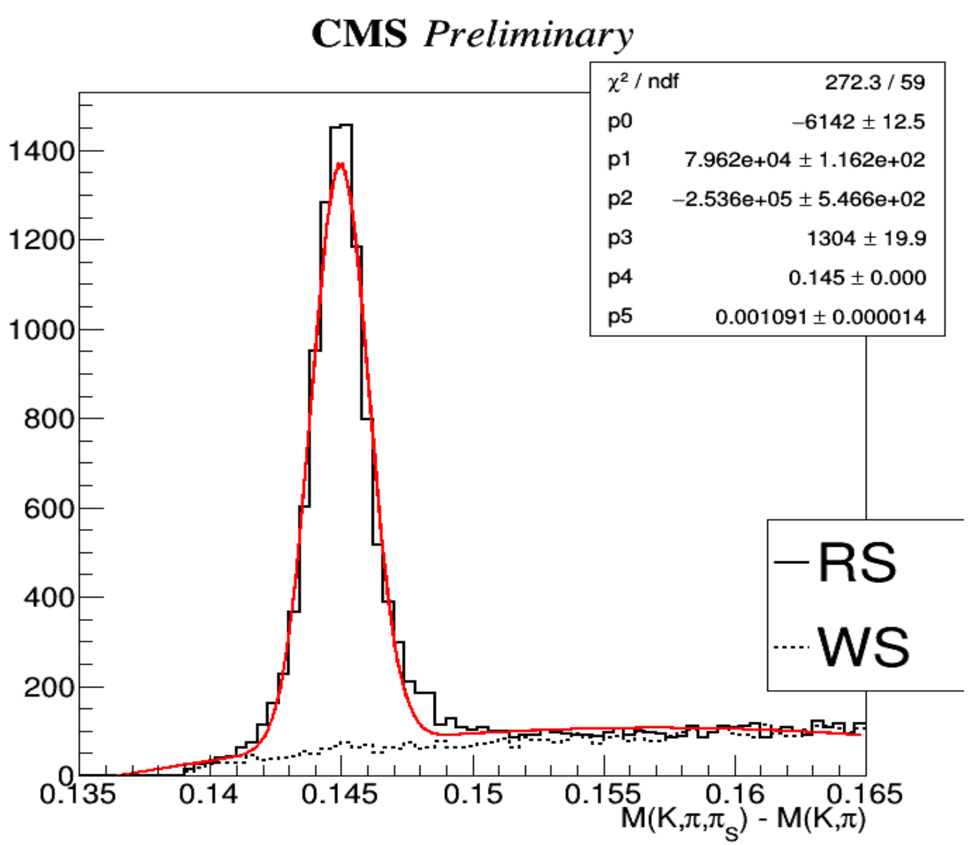
Ka Tung Lau

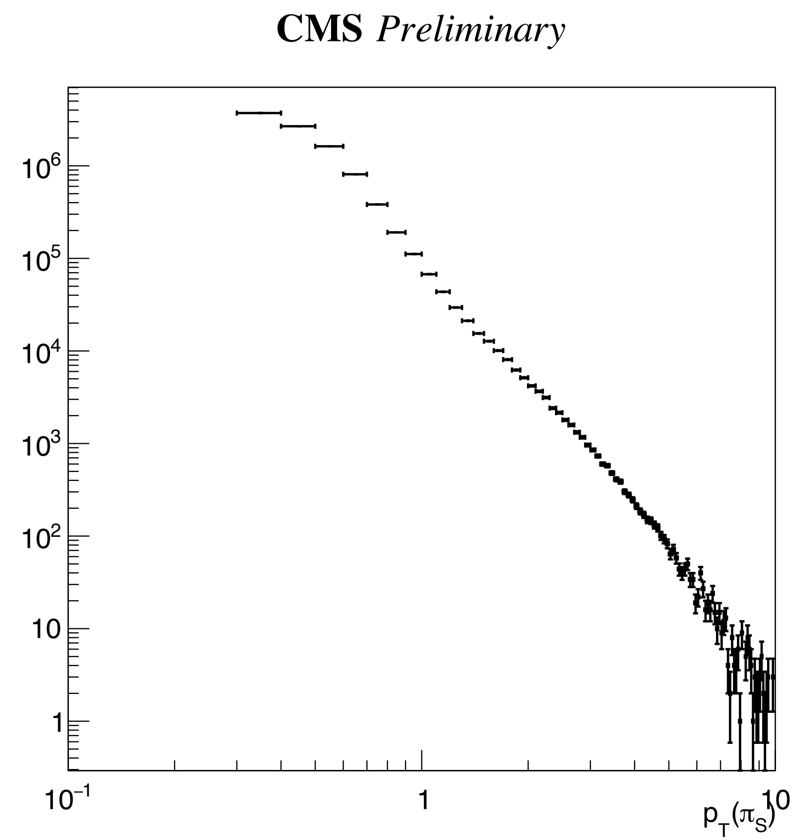


Purity Estimator

George Karathanasis

$$B^0 \to D^* \mu\nu \to \mu K \pi \pi_s \nu$$





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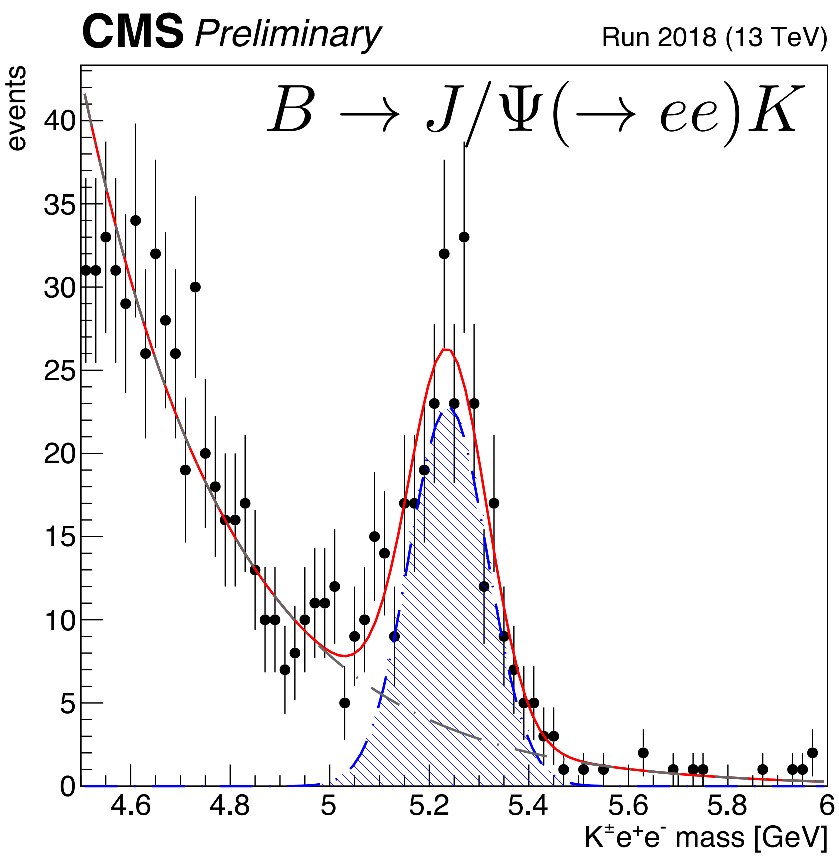
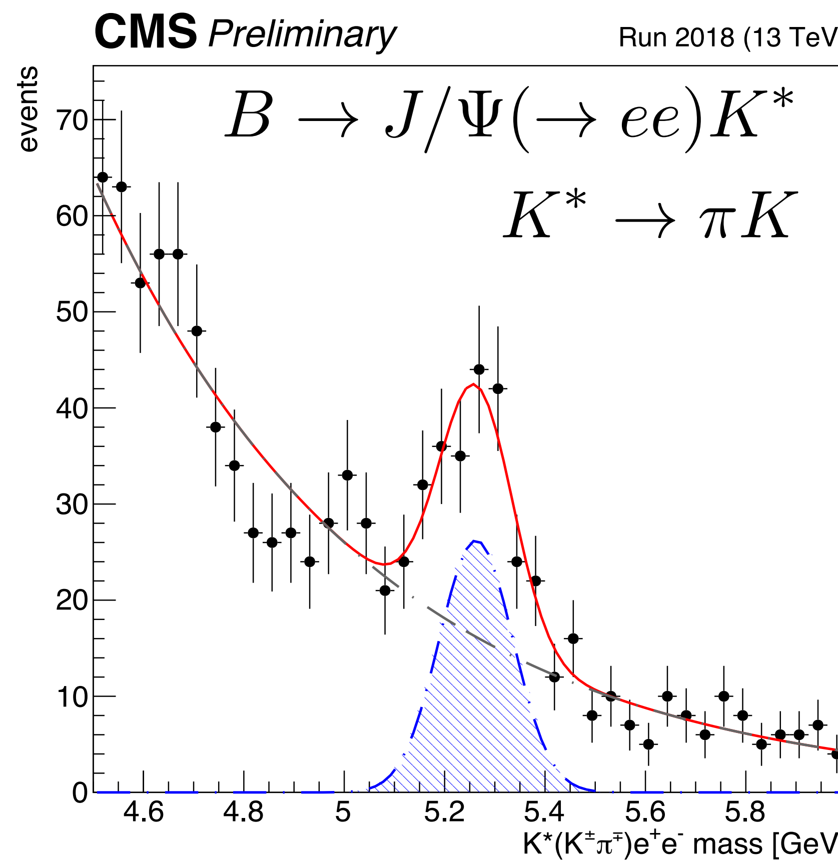
First Electron Results

- First observation of these decays in CMS!
  - Out-of-the-box electron ID

Sara Fiorendi
Riccardo Manzoni

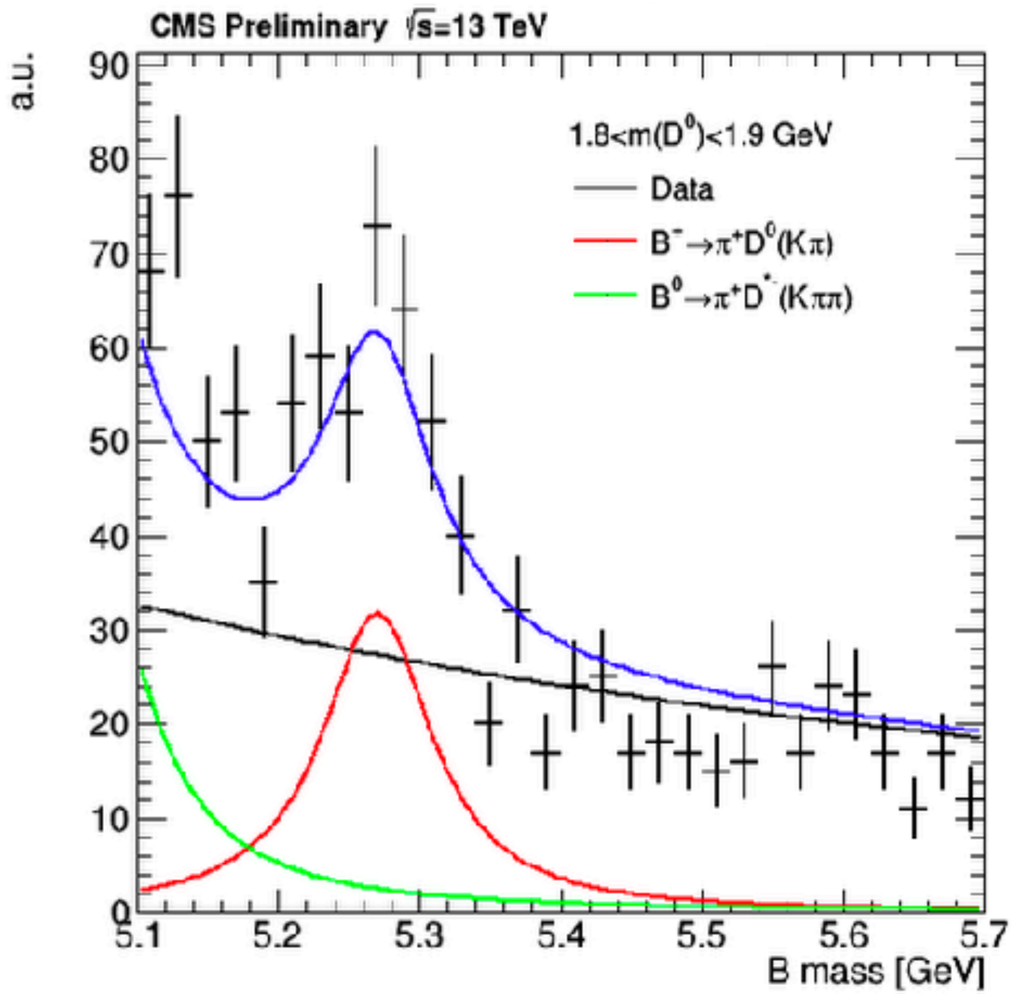




First All-Hadronic Decay

Thomas Strebler

$$B^+ \to D^0(\to K\pi)\pi^+$$



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Other Uses

- So far, we only brainstormed other potential physics cases
- Need significantly more people to start thinking about the potential use and to take ownership of the analyses we could pursue
- Some (rough) ideas:
    - Rare B_s decays: $\tau\tau$, $\phi\phi$, KK, Kπ, K^*K^*, K$\tau\tau$, $K^*\tau\tau$
    - $R(D^{(*)})$ measurement [for the first look, see Oliver's talk]
    - Flavor violating decays: $B_{(s)} \to \tau\mu$, τe
    - CP-violation in various decays, using opposite-side tagging
    - Perhaps even probe $\tau \to 3\mu$ via 3×10^8 $D^{(*)}\tau\nu$ decays $\to$ $D^{(*)}\mu\mu\mu\nu$
    - **Your favorite topic here**

Quintessential CMS!

- This challenging program would not have been possible if not for quintessential CMS strength:
  - Everybody pulled together and were willing to take calculated risks to make this happen!
- Many thanks to Run Coordination, Trigger/TSG, DAQ, Computing & Offline, T0 Operations, PPD, Physics Coordination, EGM for strong support and a lot of help!
- The success of the B Physics Parking initiative is a success of the entire CMS and a demonstration of our strength and flexibility in pursuing novel topics via novel means

Conclusions

- We have succeeded in a bold and aggressive program of putting ~10^{10} B's on tape this year
- Required to push the CMS resources, but offers a very handsome potential for the LS2 years
- Unique opportunity to test several flavor anomalies before Belle II and the LHCb trigger upgrade
  - Significantly enhances the B physics potential in CMS and makes us competitive on a number of measurements that were not possible before
- Looking for many people to join and help with logistic, particle ID, reconstruction, and - of course! - the analysis!
- Open to new ideas and proposals on how to use this wealth of data, which we are about to uncover