Testing lepton flavor universality at CMS

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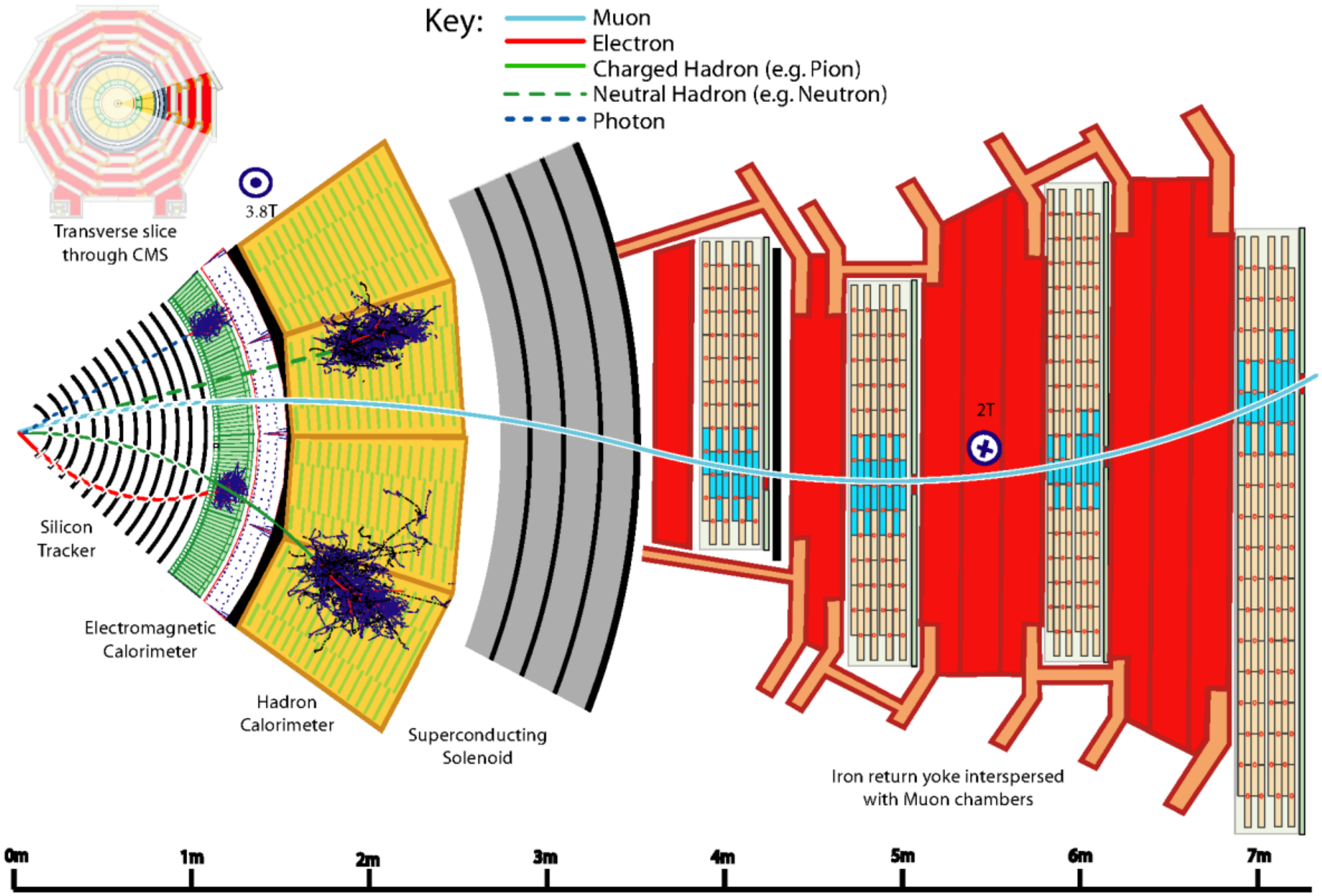
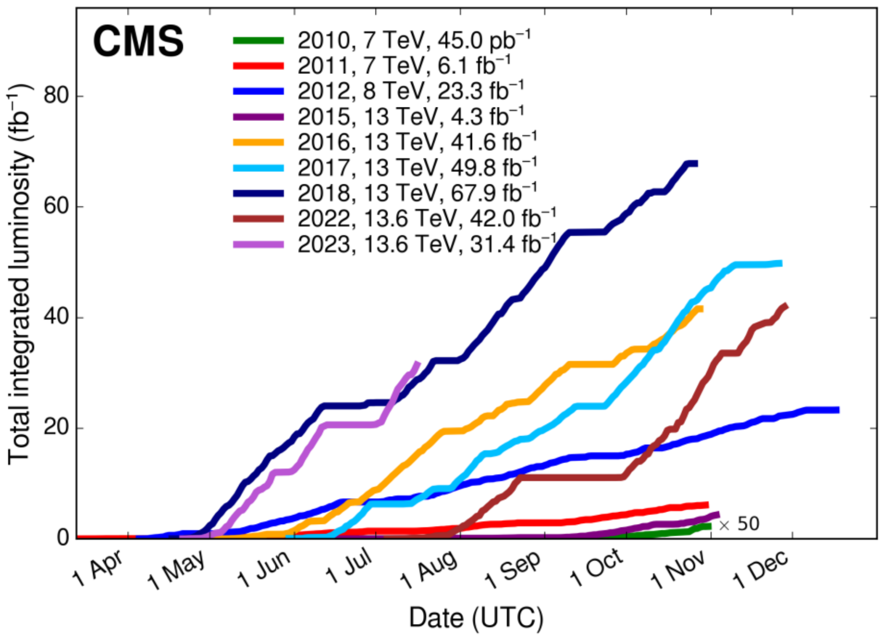
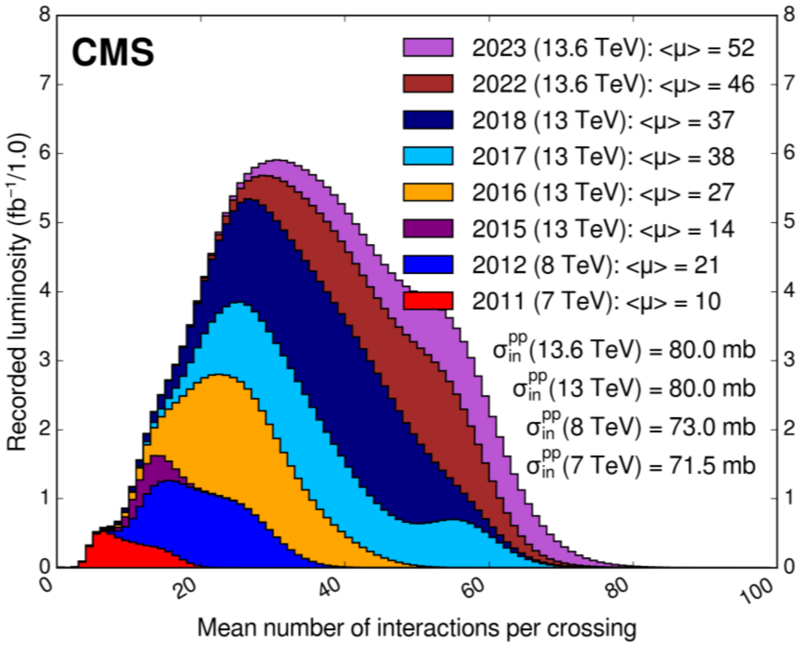
CMS Detector

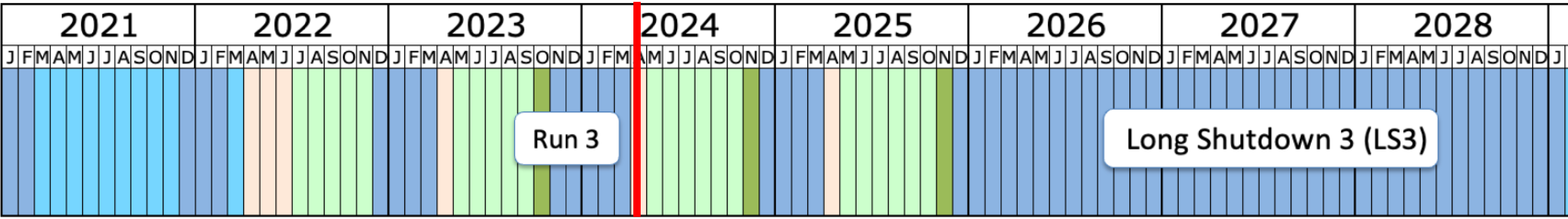
- General purpose detector
- Collection of subdetectors that are successively layered around an interaction point
- Core feature is the 4 Tesla solenoid that bends the paths of moving charged particles
- Comprised of tracker, ECAL, HCAL, muon chambers
- Subdetectors work together with software to reconstruct P-P collision decays.



CMS Programme



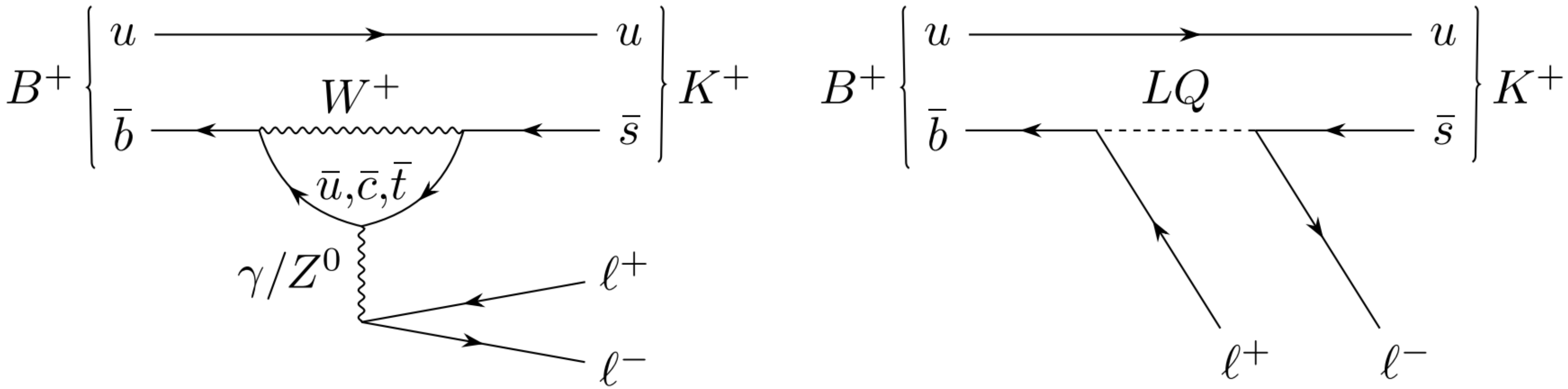




Lepton Flavour Universality (LFU)

LFU

- LFU is an accidental symmetry of the Standard Model
- Couplings between EW gauge bosons and leptons are equal across all generations
- Has been tested extensively in W, Z, Tau, Pion and Kaon decays, all consistent with SM
- LFU violation may occur measurably through processes which include the $b \to s\ell\ell$ transition due to its heavy suppression in SM

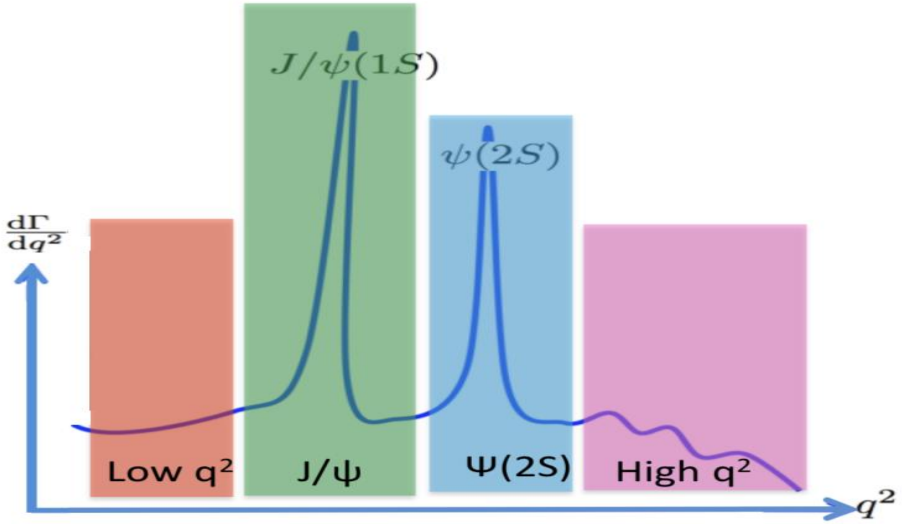


R_K observable

R_K

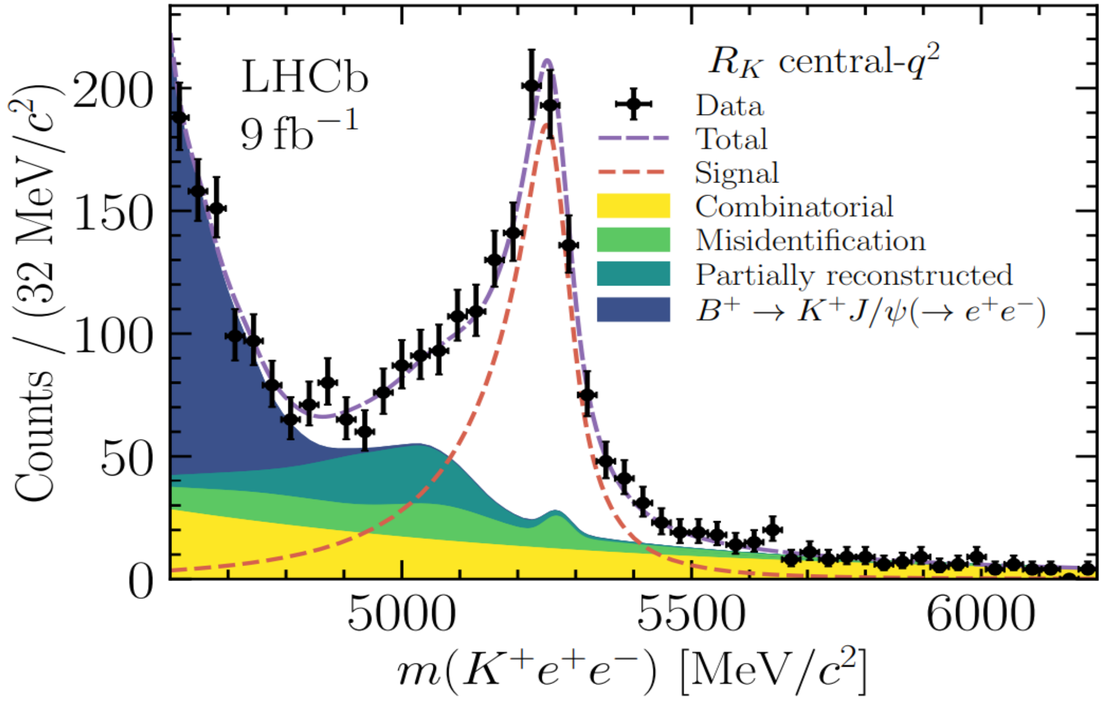
- Ratio of charged B decays to kaons and leptons (muons & electrons)
- Ratio great as hadronic form factor uncertainties largely cancel
- R_K is measured in bins of q^2 of the di-lepton system to avoid charmonium resonances
- Low-q^2 bin is $1.1 < q^2 < 6.0$ GeV^2
- SM prediction R_K $(1.1 < q^2 < 6.0) = 1.00 \pm 0.01$
- This ratio is then further divided by its corresponding J/Psi resonance decay, to cancel out most systematics

$$R_K = \frac{\dfrac{\int_{q^2_{min}}^{q^2_{max}} \mathcal{B}(B^+ \to K^+ \mu^+ \mu^- (q^2)) dq^2}{\mathcal{B}(B^+ \to K^+ J/\Psi(\mu^+ \mu^-))}}{\dfrac{\int_{q^2_{min}}^{q^2_{max}} \mathcal{B}(B^+ \to K^+ e^+ e^- (q^2)) dq^2}{\mathcal{B}(B^+ \to K^+ J/\Psi(e^+ e^-))}}$$



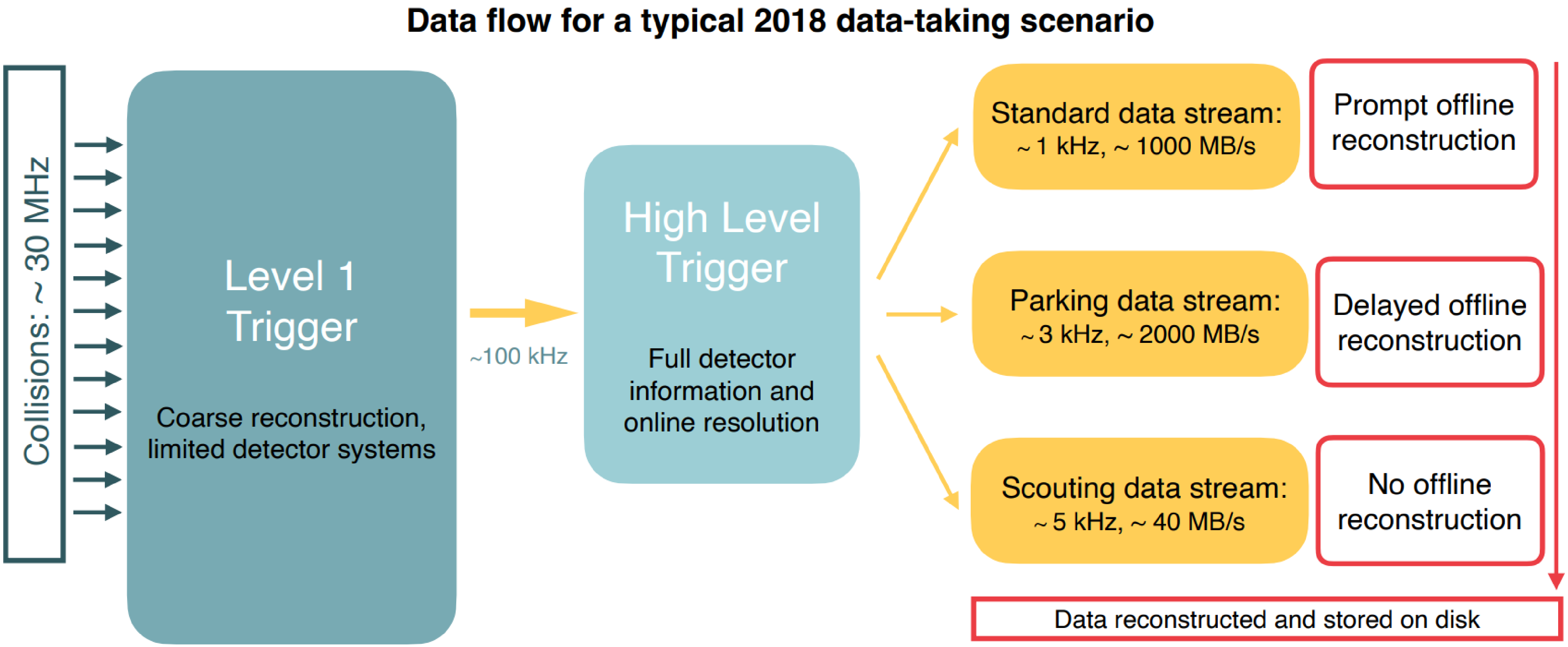
Latest R_K Results (LHCb results)

- LHCb's Run 2 analysis results displayed a 3.1 σ deviation from SM
- Deviation was due to electron misidentification
- Misidentifying one or more hadrons as electrons can create peaking structures which impact invariant mass fits
- Reducing R_K away from unity
- Latest LHCb Run 2 results shows R_K to be compatible with the SM



$$R_K = 0.949^{+0.047}_{-0.046}$$

Trigger System

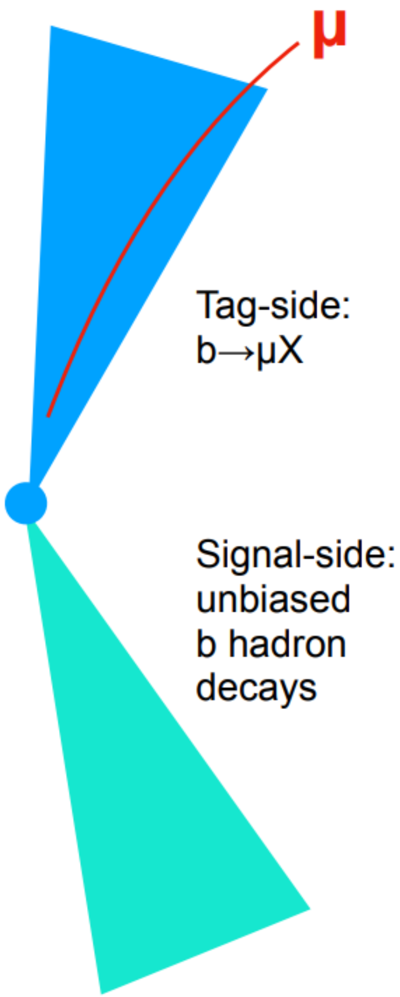


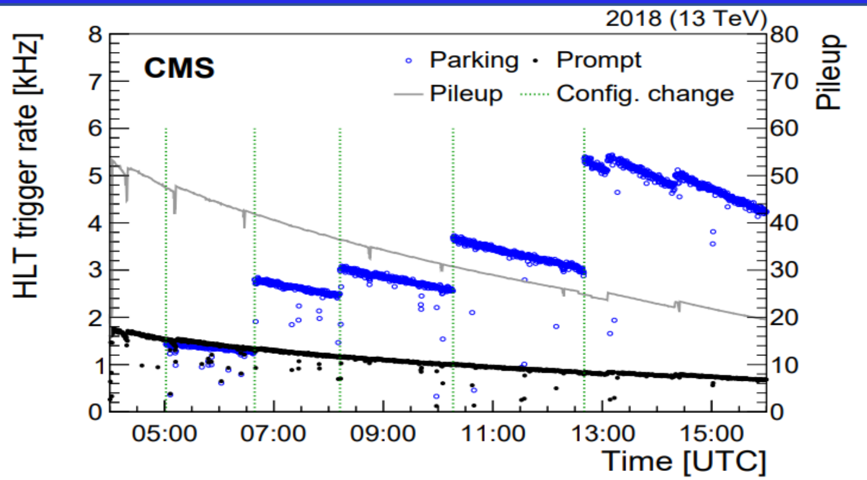
For detailed explanation look at https://arxiv.org/abs/2403.16134

BParking Strategy

Strategy

- Suite of muon triggers
- Utilize 20% Branching fraction
- Tag side is the muon and probe side is unbiased B decays
- Variable trigger threshold strategy to utilise spare L1 bandwidth and park data.
- Muon channel used tag-side of the BParking trigger
- Electron channel is done on the probe side.





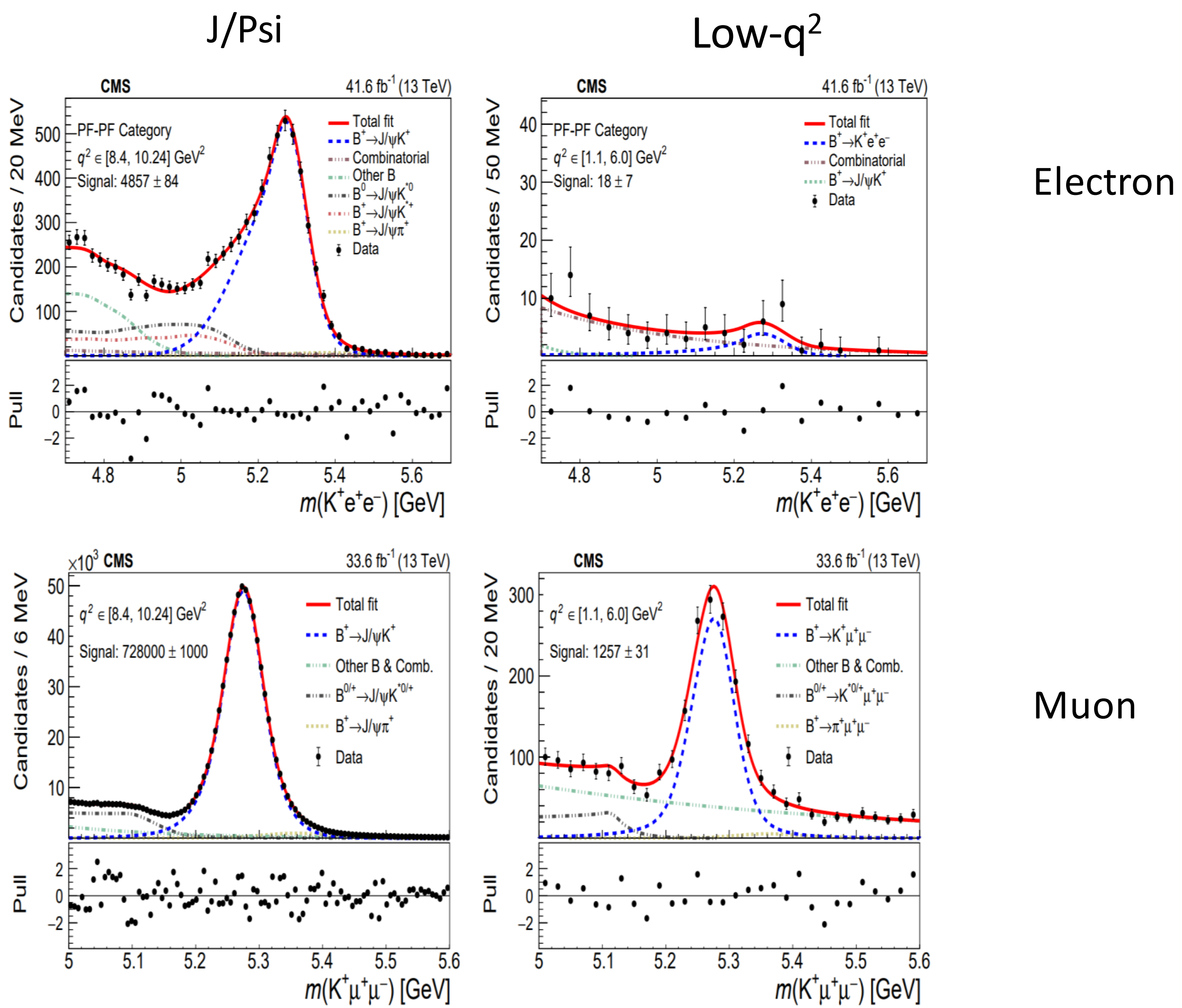
L1 p_T [GeV]	HLT p_T [GeV]	HLT IP_{sig}	$\mathcal{L}_{int}$ [fb^{-1}]	Mean PU	Events [$\times 10^9$]
12	12	6	8.1	37.7	0.72
10	9	6	8.4	32.9	1.67
10	9	5	1.6	33.9	0.37
9	9	6	1.6	28.2	0.34
9	9	5	5.2	28.3	1.30
9	8	5	1.6	29.2	0.52
8	9	6	1.8	24.2	0.40
8	9	5	3.8	23.9	1.00
8	8	5	1.7	24.2	0.60
8	7	4	1.5	24.5	0.84
7	8	3	0.8	19.1	0.45
7	7	4	5.5	18.6	3.56
Other combinations			0.3	—	0.12
Total			41.9	22.7	11.9

2018 R_K Analysis

- The electron side (probe) decays were extremely soft because there was no kinematic requirement for the decay
- low-pt electron algorithm was created to aid in electron reconstruction
- Increased signal-yield by ~ 50%
- R_K measurement is statistically limited due to electron side

$$R_K = 0.78^{+0.47}_{-0.23}$$

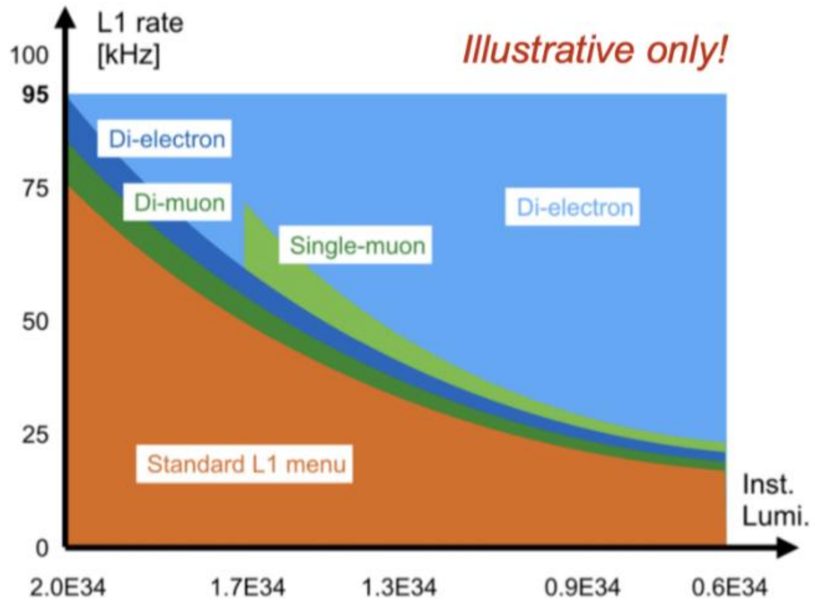
Public Result Paper: https://arxiv.org/abs/2401.07090



Run 3 Approach (2022)

Strategy

- New strategy needed to gather more electron side events
- Now trigger directly on the B Decay to di-electron final state
- Utilize spare L1 bandwidth during the end of fills and the ramp up period
- Should be able to improve number of candidates by a factor 10 w.r.t. Run 2

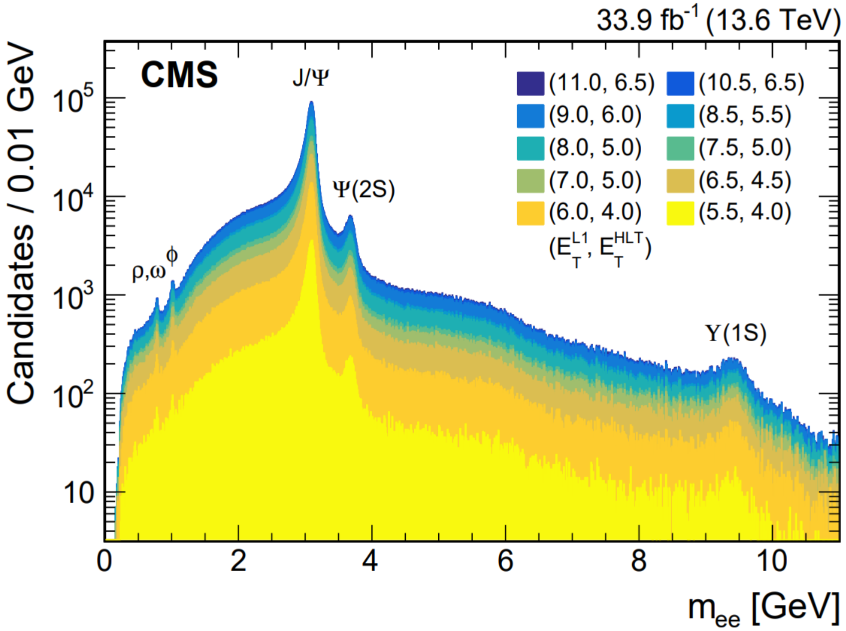


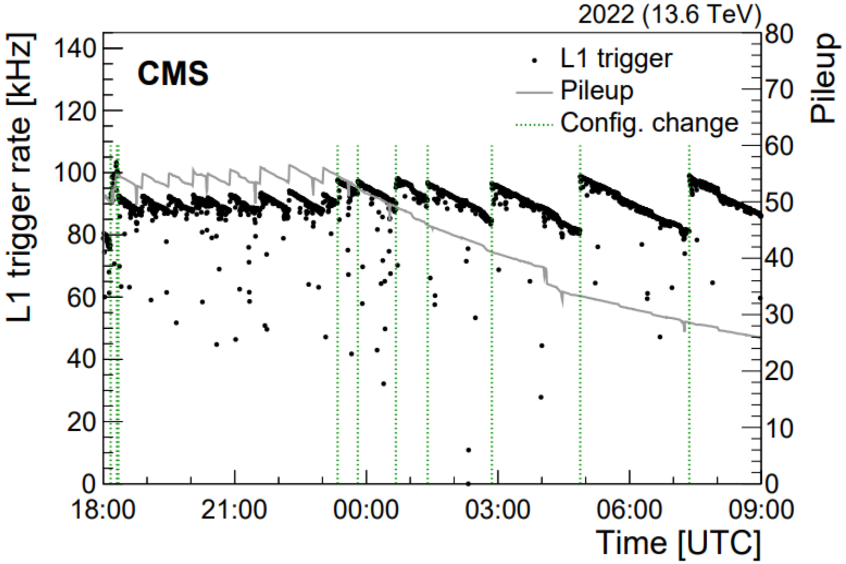
CMS motivation

- LHCb is currently the only experiment to have measured R_K with good precision and independent measurements are needed to corroborate their results
- Belle II will only be able to support/falsify by late 2020's (20/ab required for 5% stat)
- CMS may be able to have a precision measurement by the end of Run 3

Di-electron triggers

- ~ 2 billion events (33.9 /fb) have been collected by triggers
- Several resonances observed in di-electron mass spectra after loose offline selections applied
- Lower-threshold triggers crucial for low-q^2 region ($1.1 < q^2 < 6.0$ GeV^2)



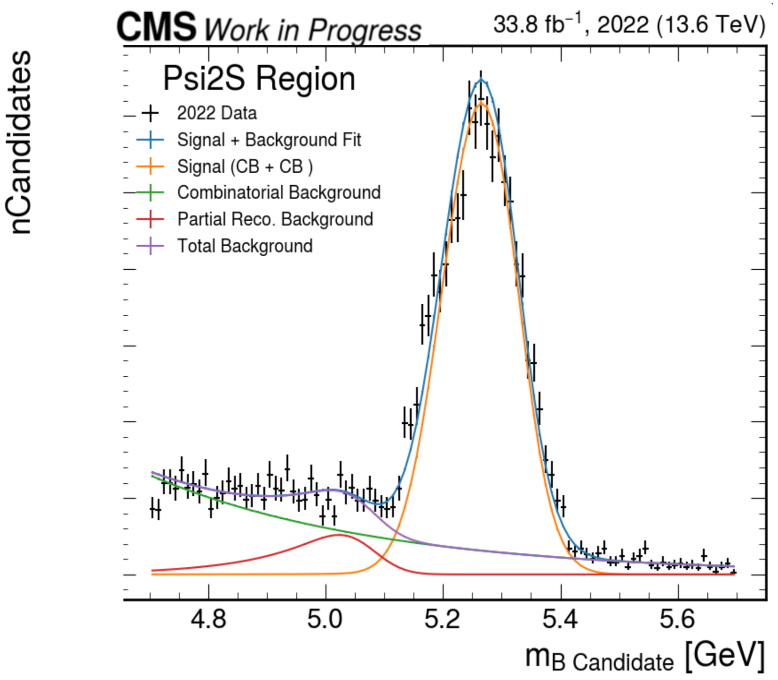


Analysis strategy

1. Collect Data Using Di-Electron triggers
2. Build Di-electron candidates
3. Build eeK candidates
4. Corrections for efficiency and acceptance
5. Apply Analysis level BDT
6. Extract Signal yields
7. Combine with 2018 Muon channel measurement

Run 3 Analysis (On going)

- Analysed the full 2022 data set and validated the Run 3 trigger strategy
- MC modelling, Trigger reweighting, Trigger Scale factors, Control Region checks, Analysis BDT, fitting procedure etc.
- Preliminary Blind Analysis has been conducted
- Initial results look very promising



From fit to data → $N(B \to J/\psi(ee)K)$

From MC → $\alpha \times \varepsilon$ terms

$$N(B\to eeK)_{low\,q2} = N(B\to J/\psi(ee)K) \times \frac{Br(B\to eeK)}{Br(B\to J/\psi(\to ee)K)} \times \frac{\alpha \times \varepsilon\,(B\to eeK)_{low\,q2}}{\alpha \times \varepsilon\,(B\to J/\psi(\to ee)K)}$$

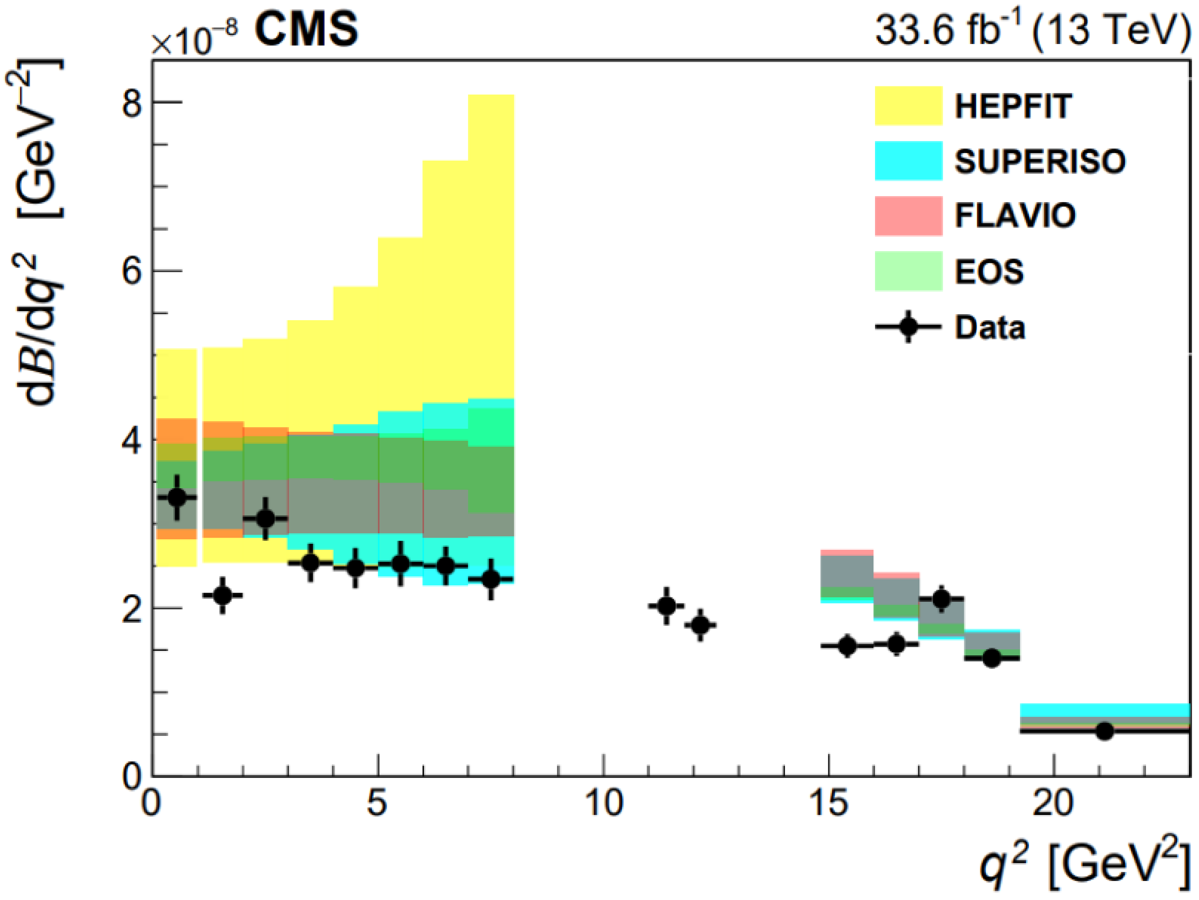
Current/Future work

- Finalisation of Run 3 R_K analysis BDT
- Developing a more sophisticated fitting strategy
- 2023 dataset
  - 2023 Di-electron triggers collected 22.6 /fb of data
  - This data was collected at a higher PU and differing conditions
  - The previous studies and checks must be conducted on the 2023 data
- Impact of using Low-pt electron algorithm

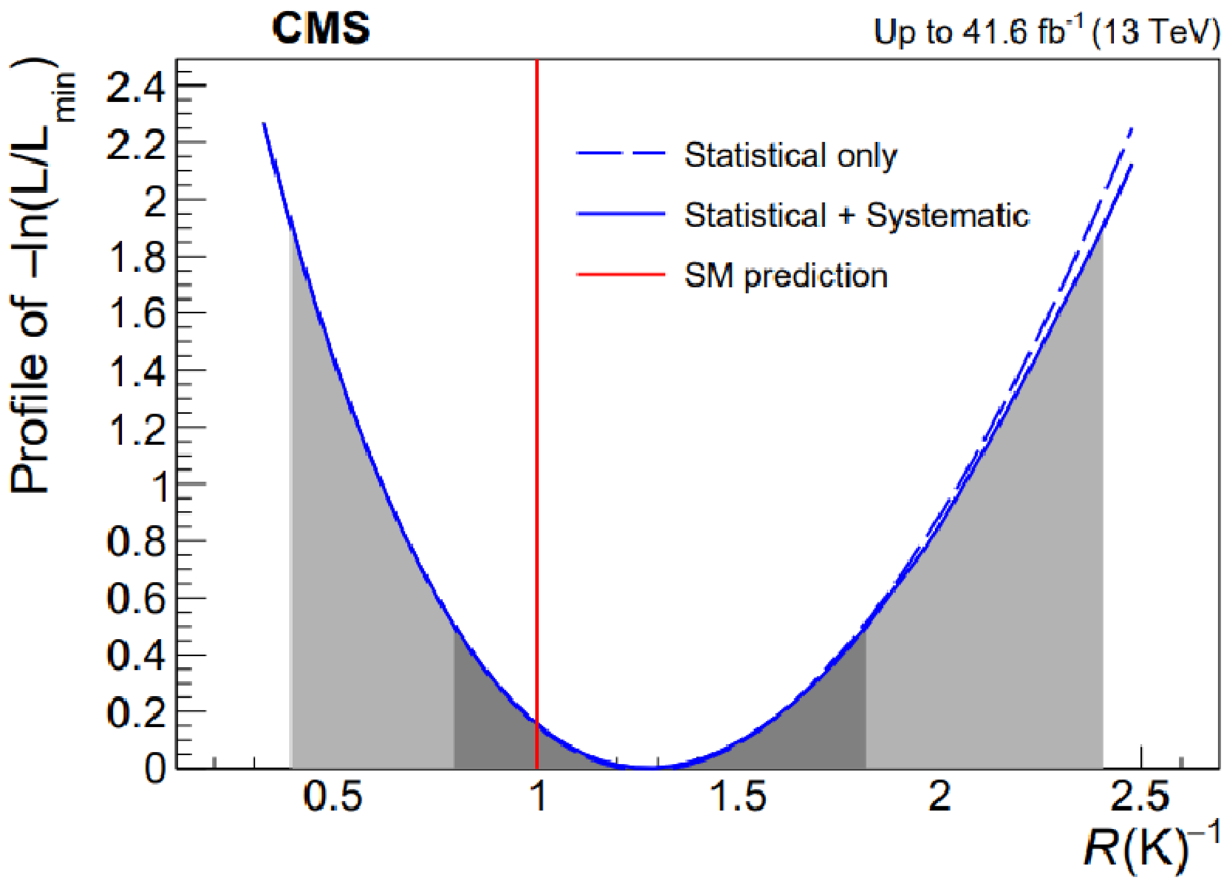
Conclusions

- Successfully implemented new trigger strategy in Run 3
- Trigger studies and data set validation very mature
- First steps of R_K analysis complete, estimates of low-q2 suggest a successful outcome
- Preliminary analysis of 2022 complete, now tackling 2023
- Full R_K analysis well underway

Backup

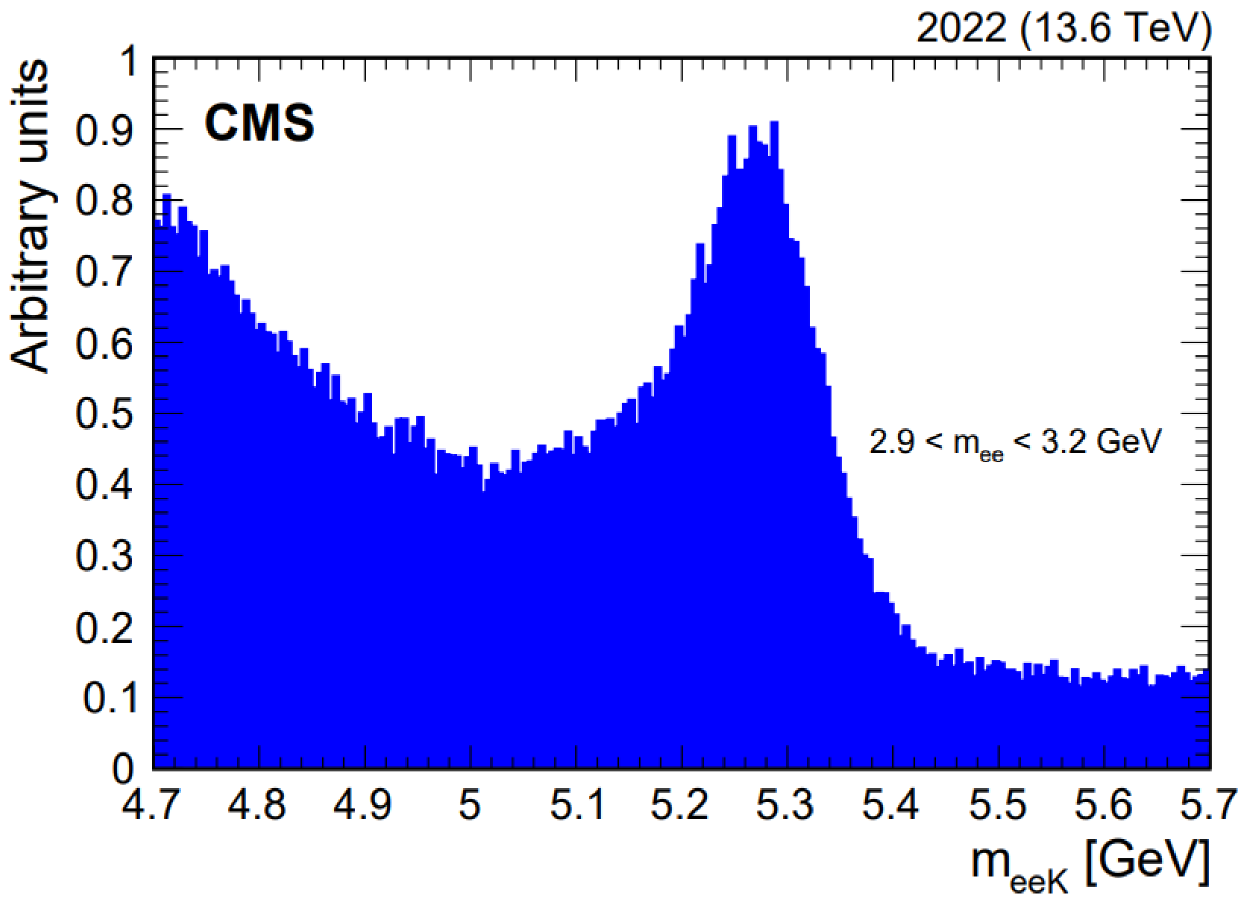


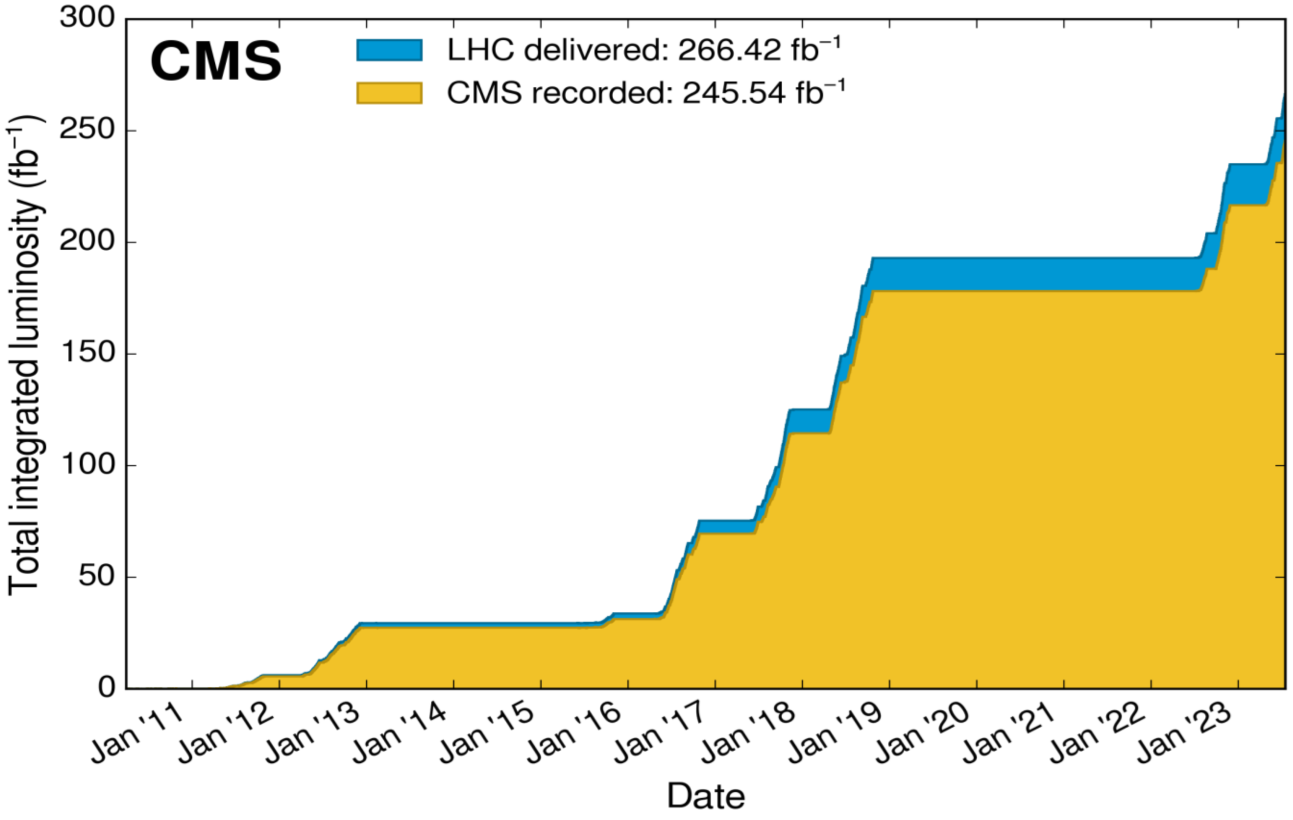
×10^-8 CMS
33.6 fb^-1 (13 TeV)
dB/dq^2 [GeV^-2]
HEPFIT
SUPERISO
FLAVIO
EOS
Data
q^2 [GeV^2]



CMS
Up to 41.6 fb^-1 (13 TeV)
Profile of −ln(L/L_min)
Statistical only
Statistical + Systematic
SM prediction
R(K)^-1

L1 E_T [GeV]	L1 ΔR	HLT E_T [GeV]	$\mathcal{L}_{int}$ [fb^{-1}]	Mean PU	Peak L1 rate [kHz]	Peak HLT rate [kHz]
11.0	0.6	6.5	1.6	45.6	2.2	0.1
10.5	0.6	6.5	1.1	42.2	3.0	0.3
9.0	0.7	6.0	8.8	47.4	9.3	0.6
8.5	0.7	5.5	3.3	46.2	13	0.9
8.0	0.7	5.0	6.9	39.1	16	1.2
7.5	0.7	5.0	1.6	40.3	23	1.4
7.0	0.8	5.0	2.7	36.3	27	1.3
6.5	0.8	4.5	3.6	31.2	35	1.3
6.0	0.8	4.0	2.5	27.4	46	1.4
5.5	0.8	4.0	0.7	23.6	54	1.0
Other combinations			1.0	—	—	—
Total			33.9	34.8	—	—




CMS
LHC delivered: 266.42 fb^{-1}
CMS recorded: 245.54 fb^{-1}
Total integrated luminosity (fb^{-1})
300
250
200
150
100
50
0
Jan '11
Jan '12
Jan '13
Jan '14
Jan '15
Jan '16
Jan '17
Jan '18
Jan '19
Jan '20
Jan '21
Jan '22
Jan '23
Date