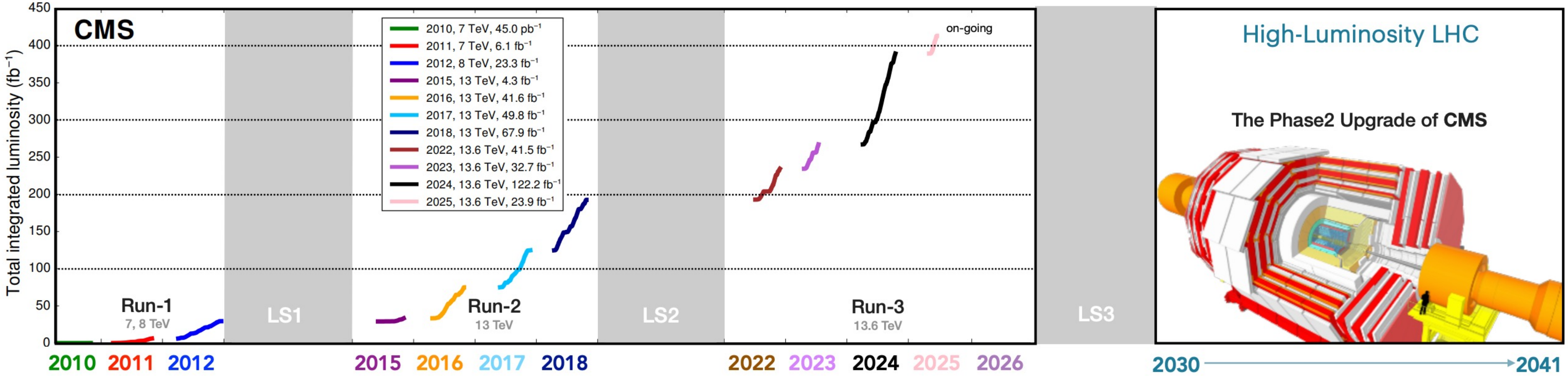
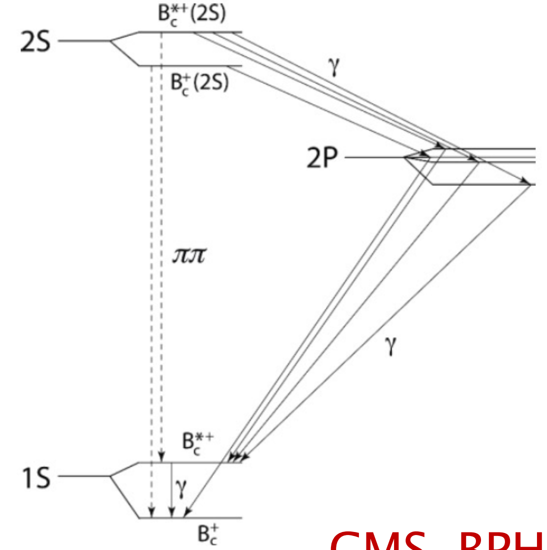
CMS Heavy Meson FCNC results

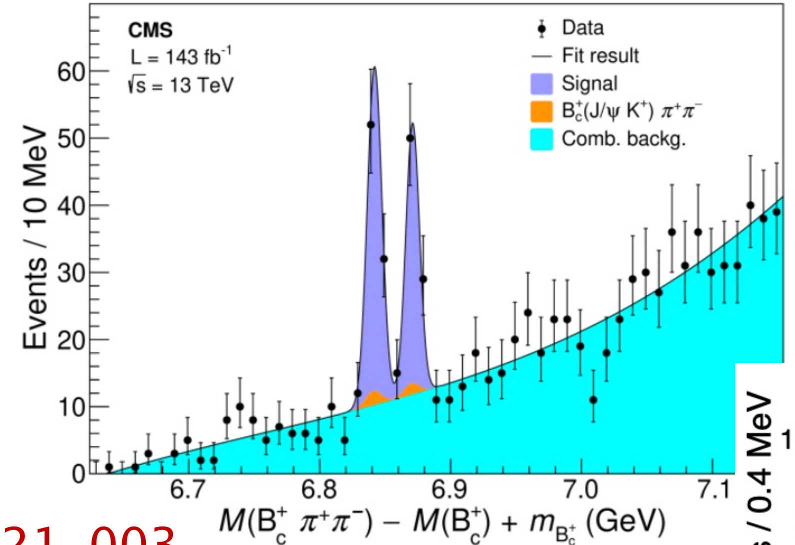


Dayong Wang
Peking University

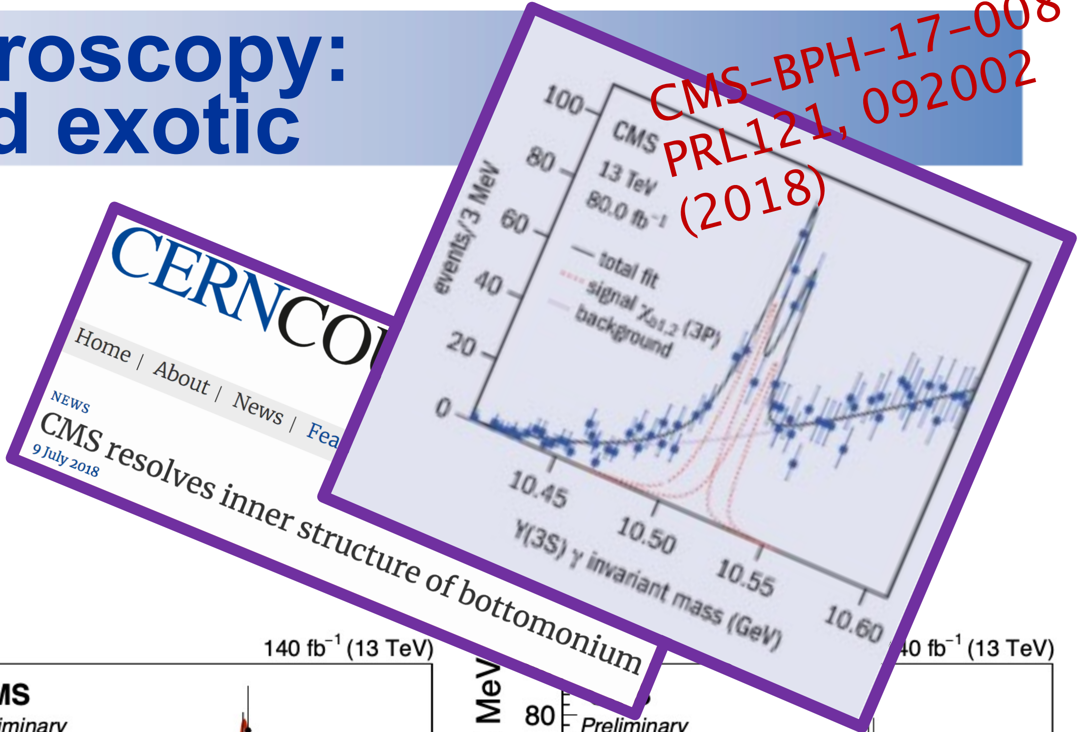
CMS Heavy spectroscopy: conventional and exotic

CMS-BPH-18-007
PRL122, 132001 (2019)

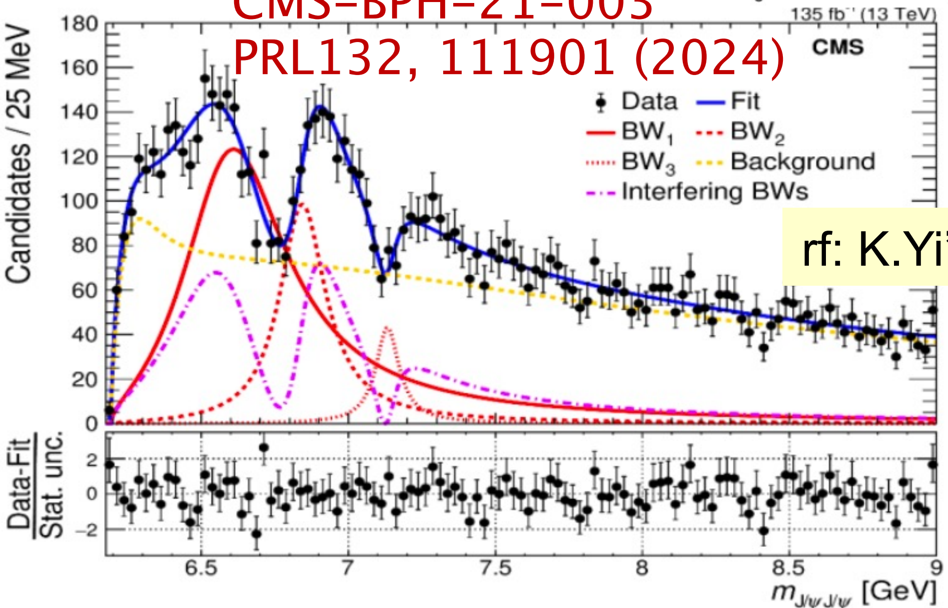




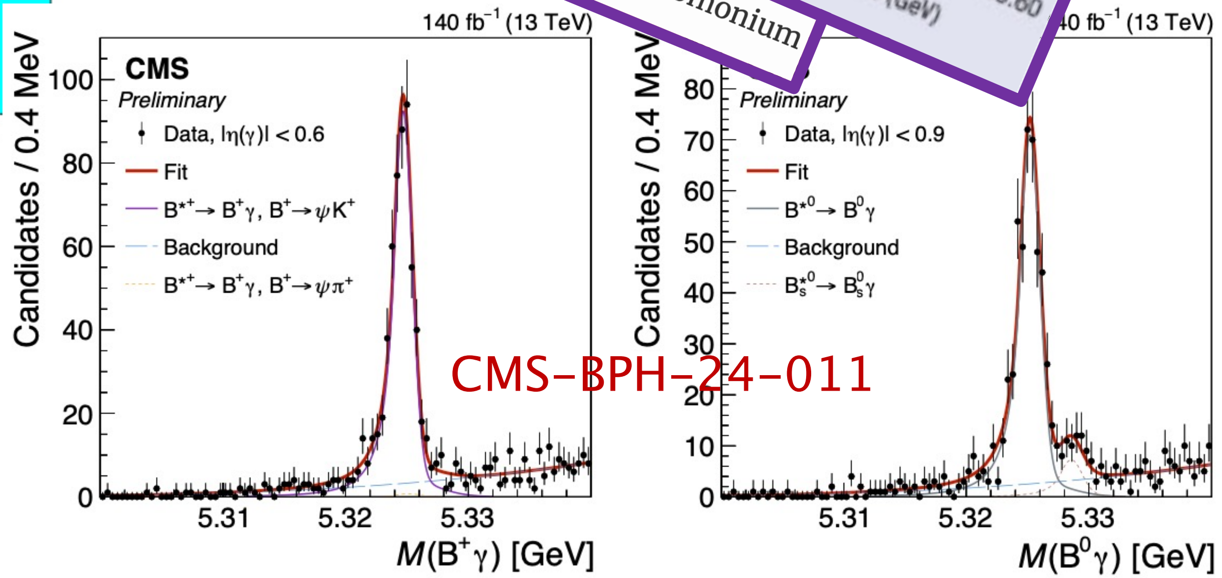
CMS-BPH-17-008
PRL121, 092002 (2018)



CMS-BPH-21-003
PRL132, 111901 (2024)



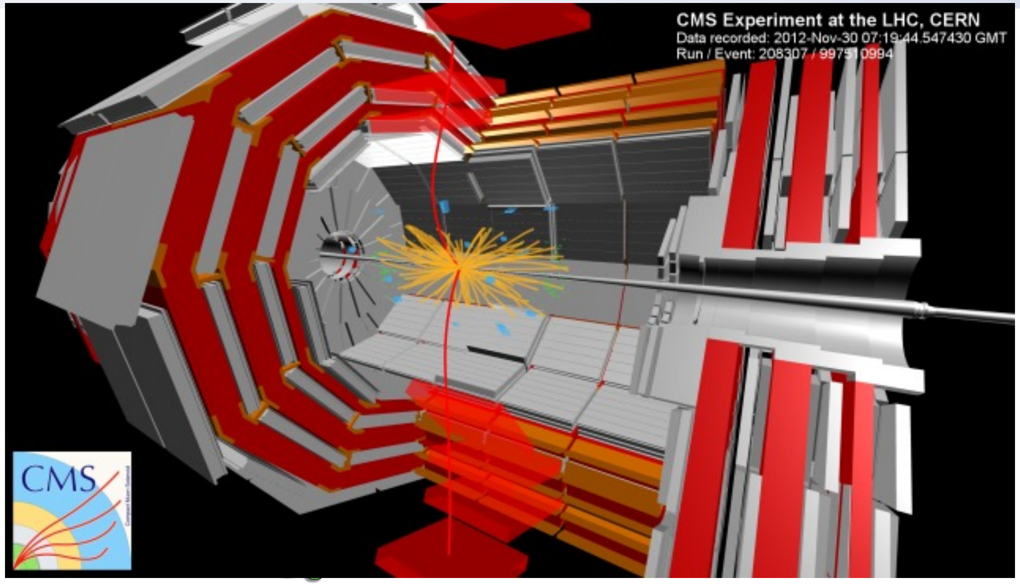
rf: K.Yi’s talk



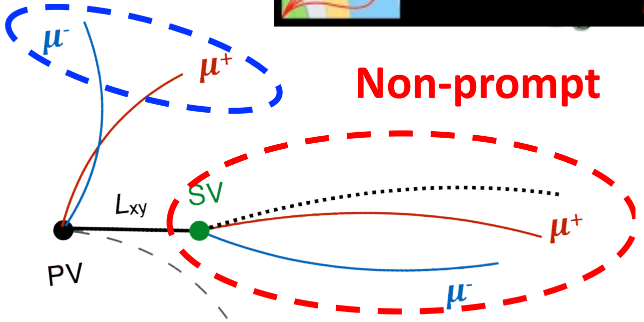
CMS-BPH-24-011

$$\Delta m(B^{*+}) \equiv m(B^{*+}) - m(B^+) \quad 45.277 \pm 0.039 \pm 0.021\,\text{MeV}$$
$$\Delta m(B^{*0}) \equiv m(B^{*0}) - m(B^0) \quad 45.471 \pm 0.056 \pm 0.024\,\text{MeV}$$
$$\Delta m(B_s^{*0}) \equiv m(B_s^{*0}) - m(B_s^0) \quad 49.407 \pm 0.132 \pm 0.034\,\text{MeV}$$

Why CMS is marvelous for heavy hadron studies



- Large silicon tracker
- Strong magnetic field
- Broad acceptance
- Superb muon systems
  - Three different devices, coverage up to |η|<2.4
  - Dimuon mass resolution ~0.6-1.5% (depending on |y|).
  - General fake rate ≤1%
    - ≤0.1% for pi,K; ≤0.05% for proton with a tight muon ID



- Flexible trigger and data-taking schemes


Physics Reports 1115 (2025) 678–772

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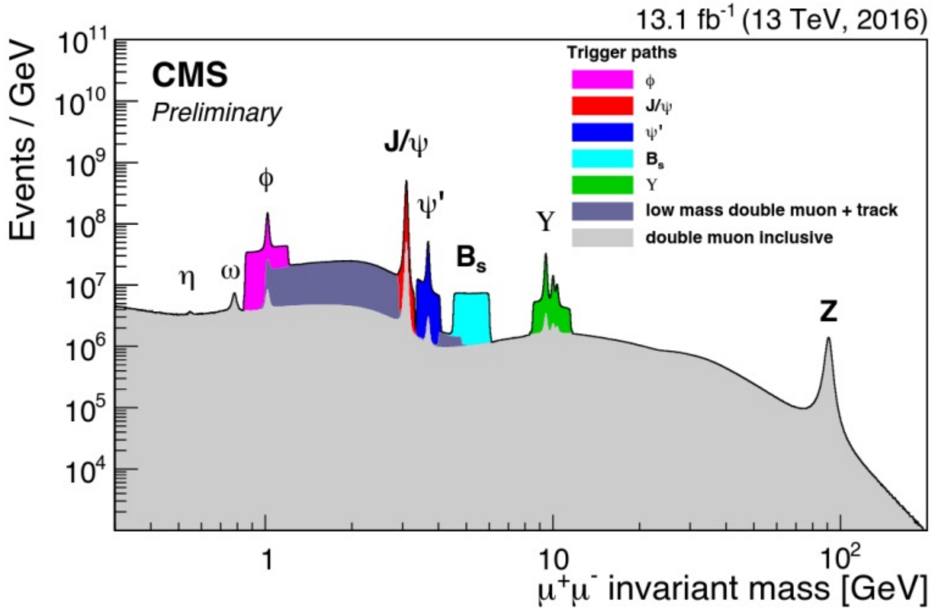
ELSEVIER

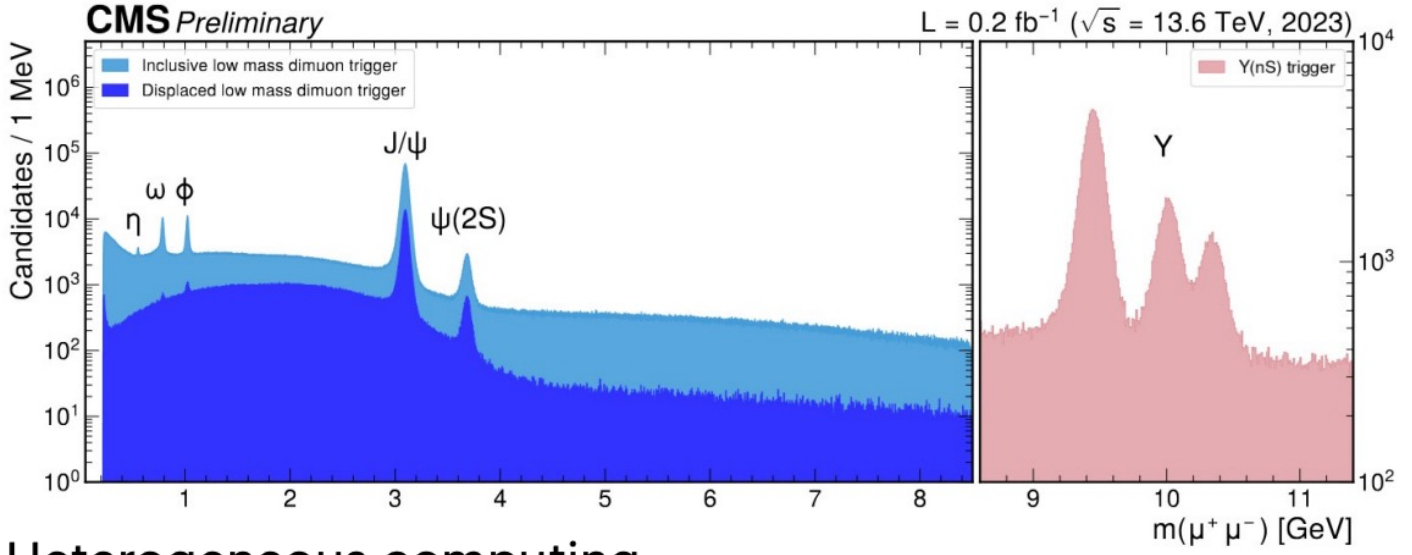
Enriching the physics program of the CMS experiment via data scouting and data parking

The CMS Collaboration

Physics Reports 1115 (2025) 678–77

Evolution of BPH triggers

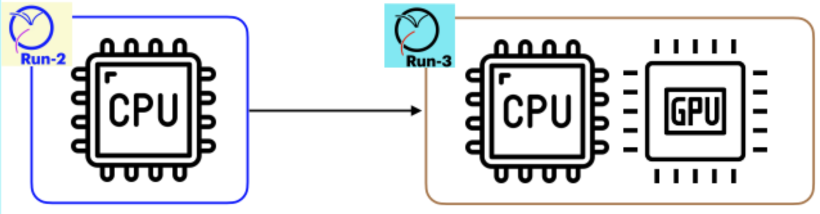




- **Many heavy-hadron analyses in CMS rely on dimuon triggers**
- **we moved from a set of triggers dedicated to specific dimuon mass regions or topologies, to an inclusive dimuon trigger with loose requirements on the momenta**

Heterogeneous computing

Successful R&D effort to run the High-Level Trigger reconstruction on heterogeneous hardware in production since the start of Run-3



Faster and more power-efficient HLT reconstruction

+50% event processing throughput
+15-25% performance per kW

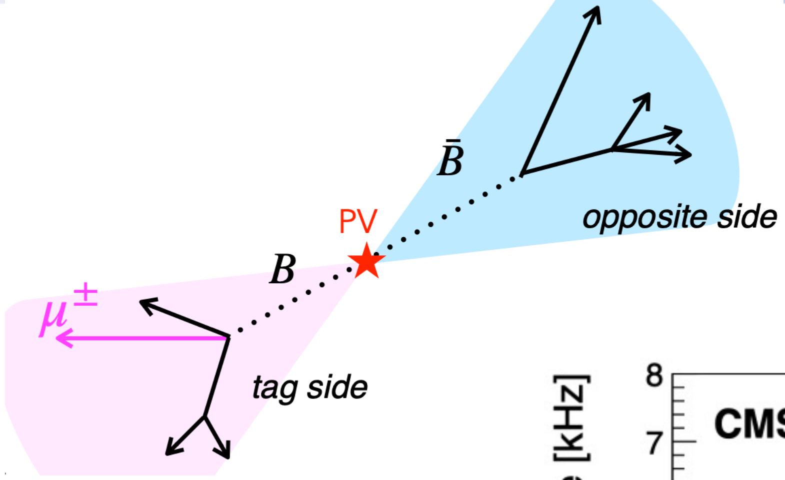
Portable heterogeneous software (Alpaka) deployed

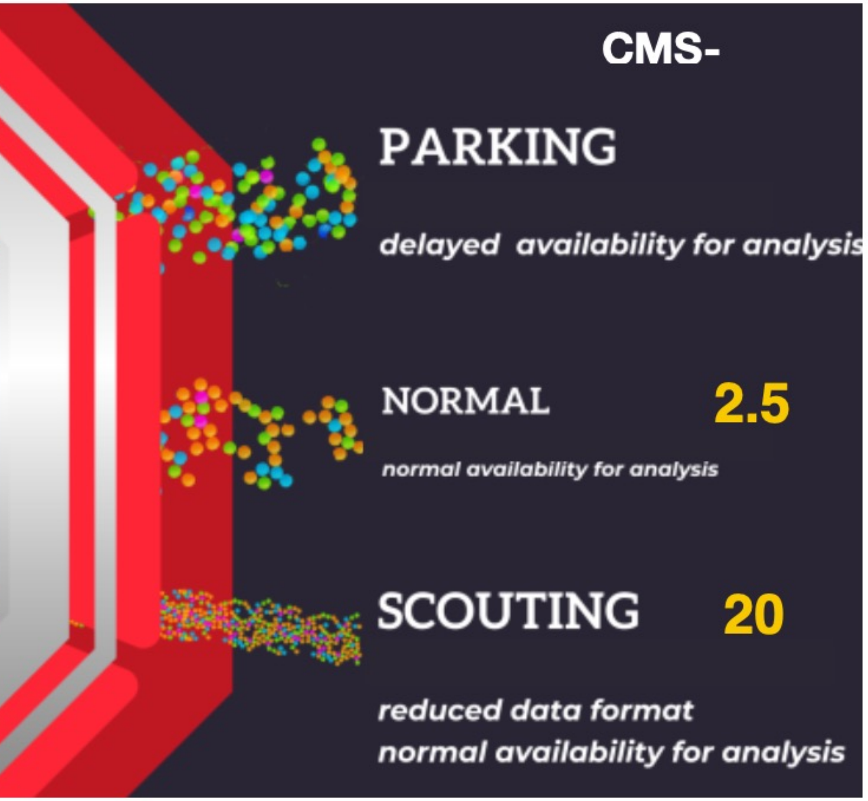
same code base can run seamlessly on CPUs and GPUs

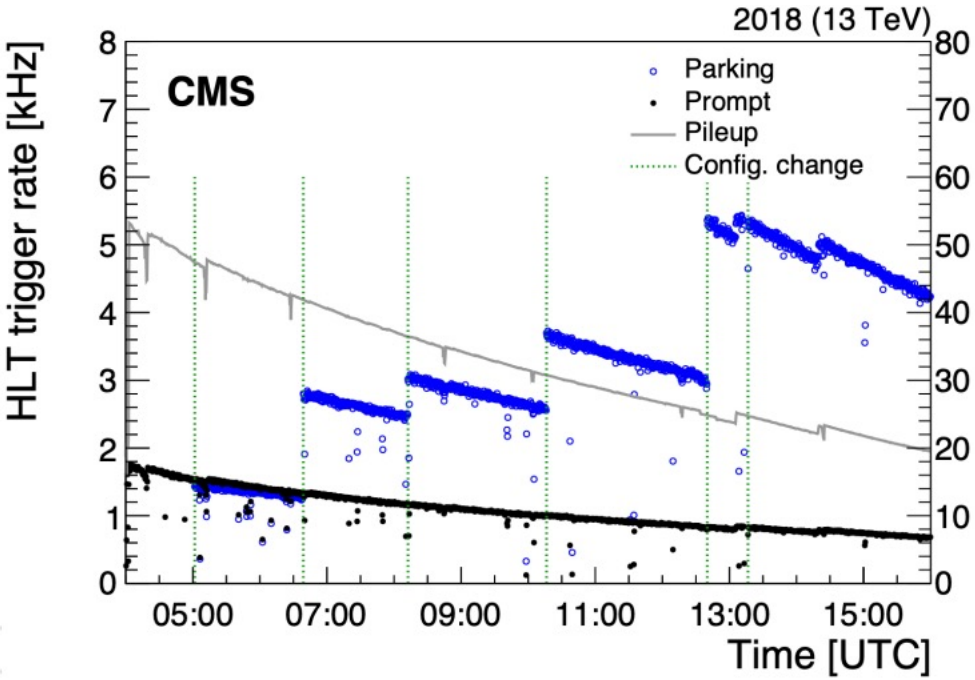
NexTGen
Next Generation Triggers

w/ Eric and Wendy Schmidt Fund for Strategic Innovation

Data Parking and scouting





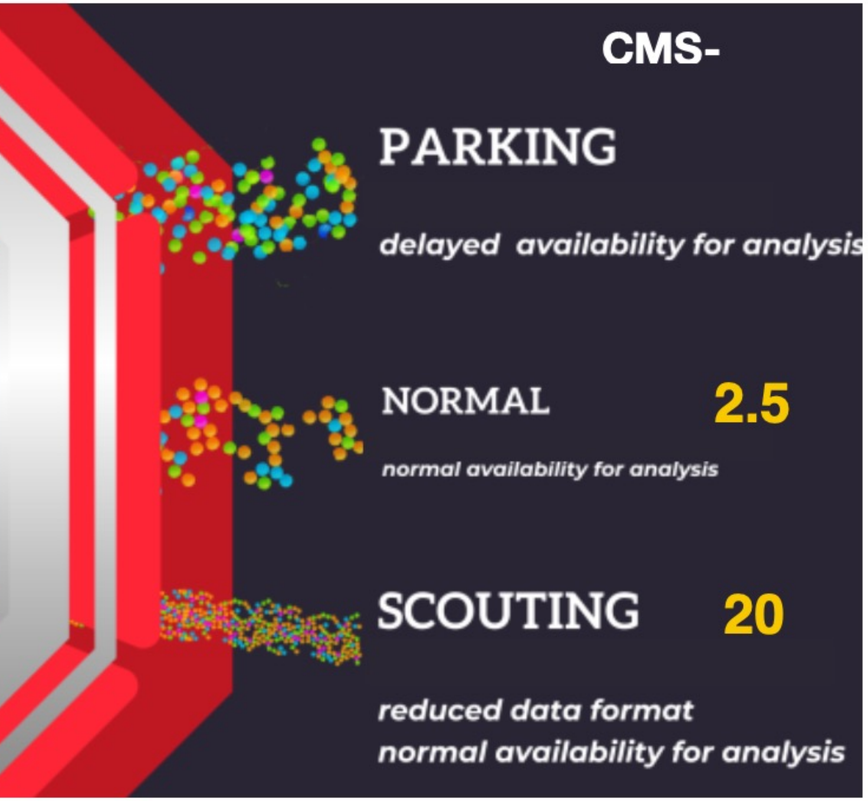


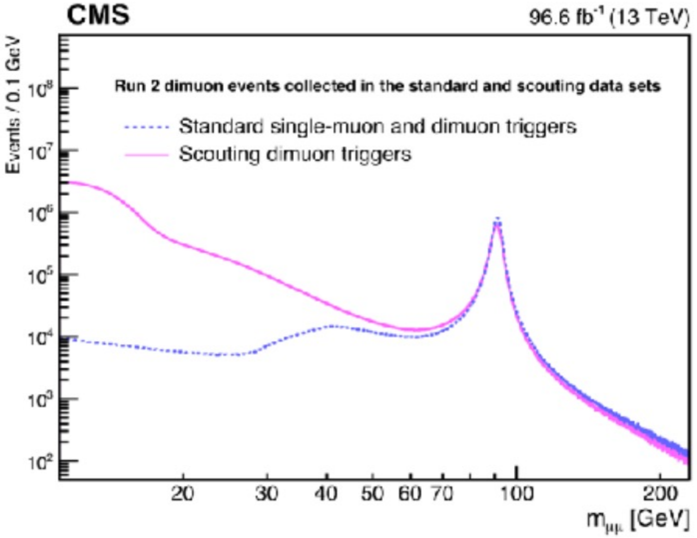
Greatly increase the event rate we can take and used in analysis

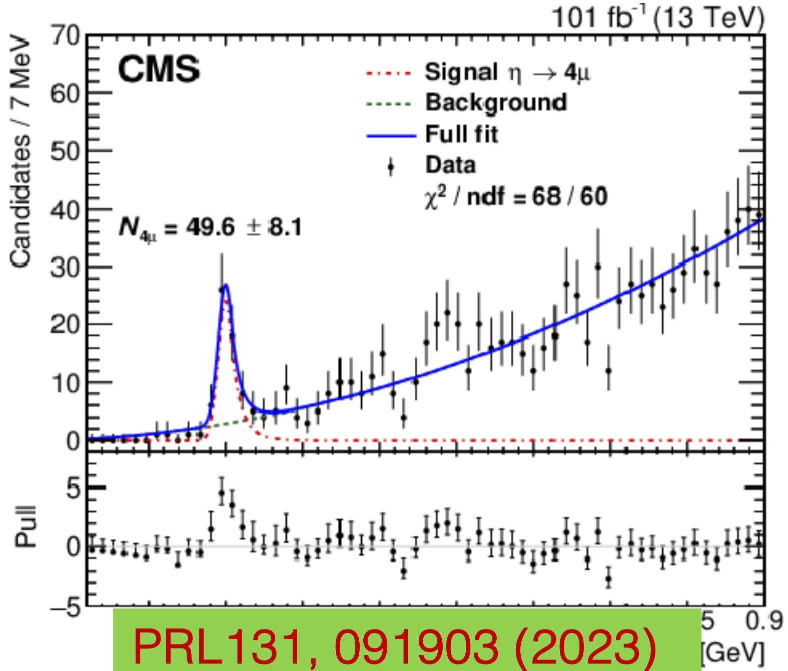
Run2018 Displaced Single Muon Dataset
12B events useful events were collected

Data Parking and scouting

- Selected L1 Triggers feed into stream with higher HLT rate and reduced content events for specific signatures
- Two streams: jets and muons





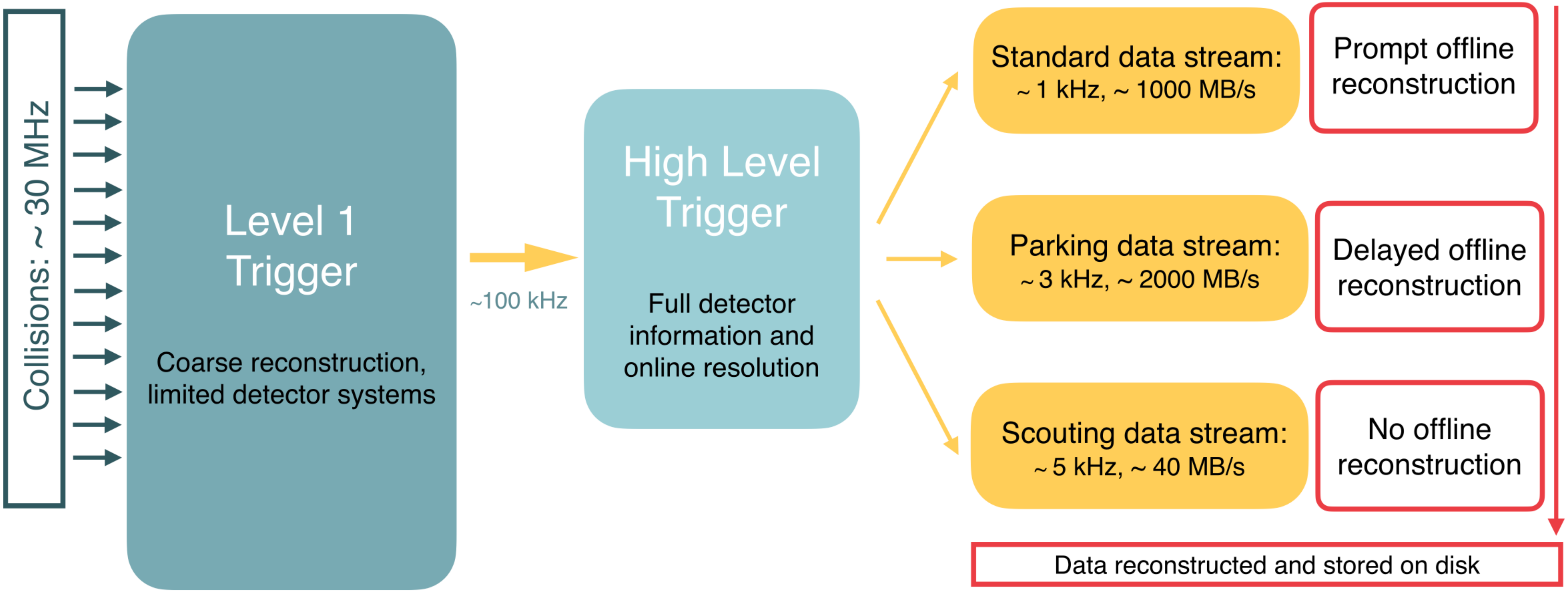


PRL131, 091903 (2023)

opening up otherwise inaccessible low-mass phase space

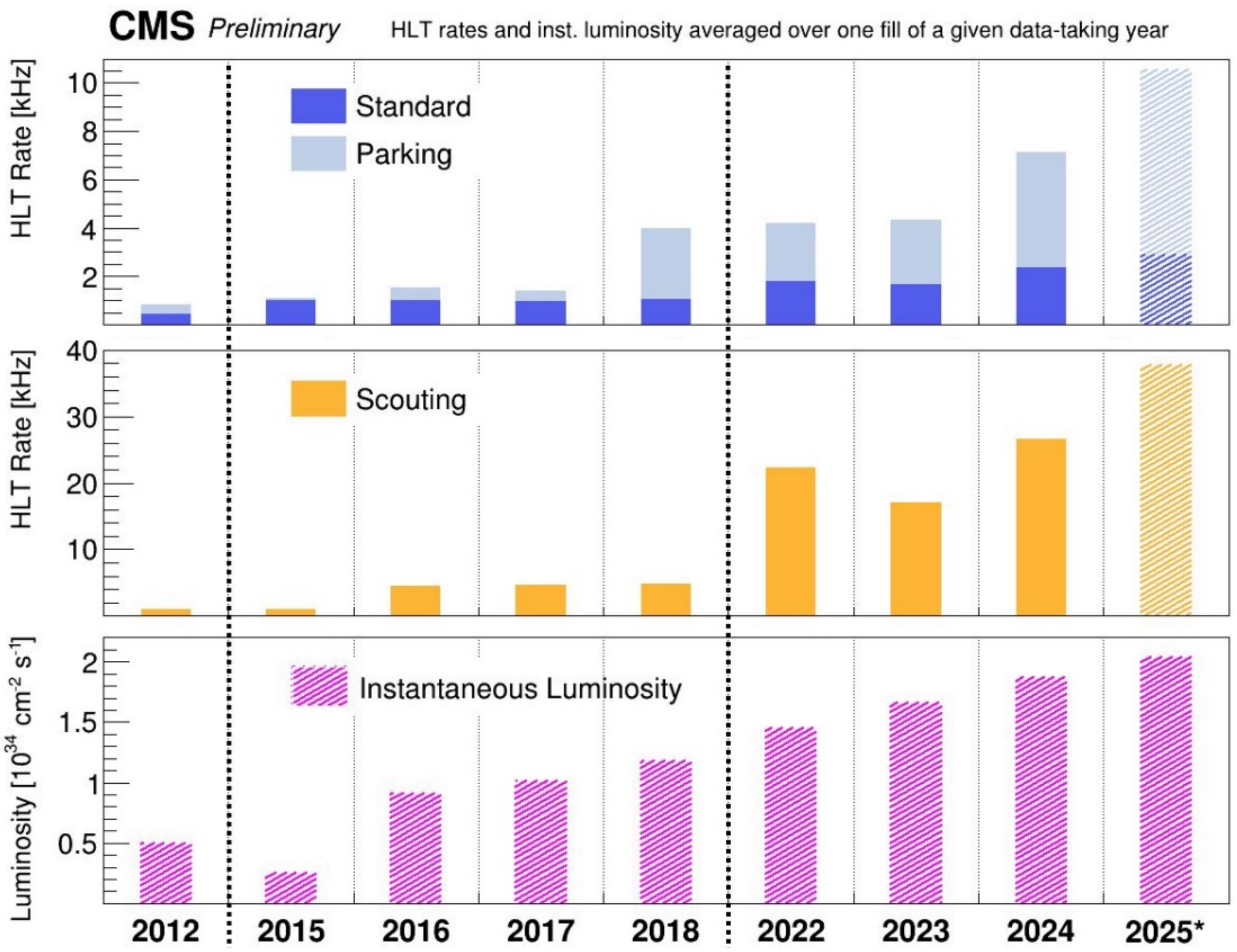
$$\mathcal{B}(\eta \to \mu^+\mu^-\mu^+\mu^-) =$$
$$(5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$

CMS data taking scheme(RunII)



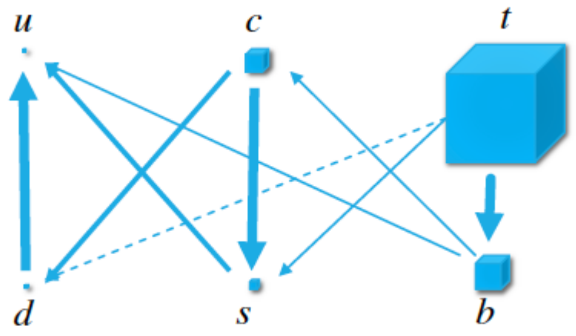
CMS coverage far beyond design values

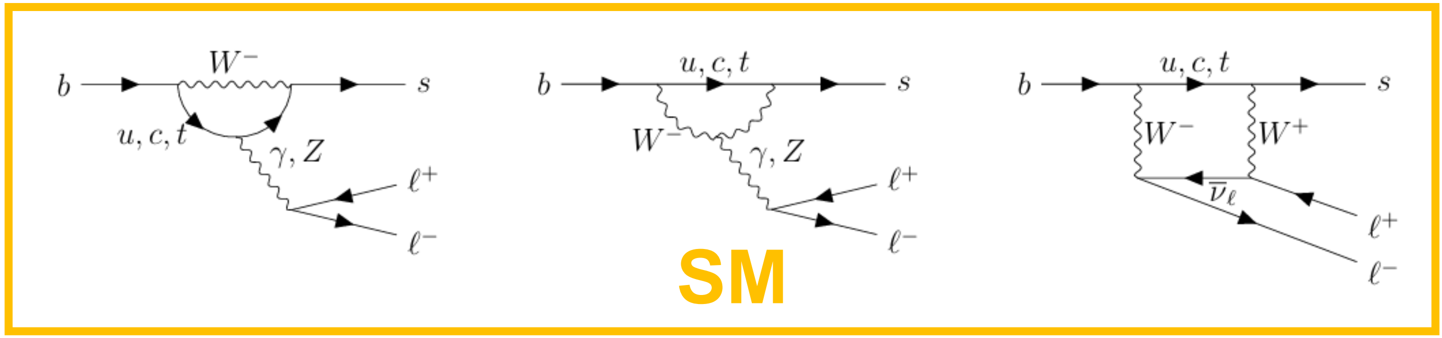
- **Parking** is now integral to the core physics program (Higgs, searches, etc.), and opens large phase space for flavour physics
- **HLT scouting** runs at ~30 kHz (1/3 of accepted L1T events)
  - Using HLT objects for physics analyses in an even wider phase space

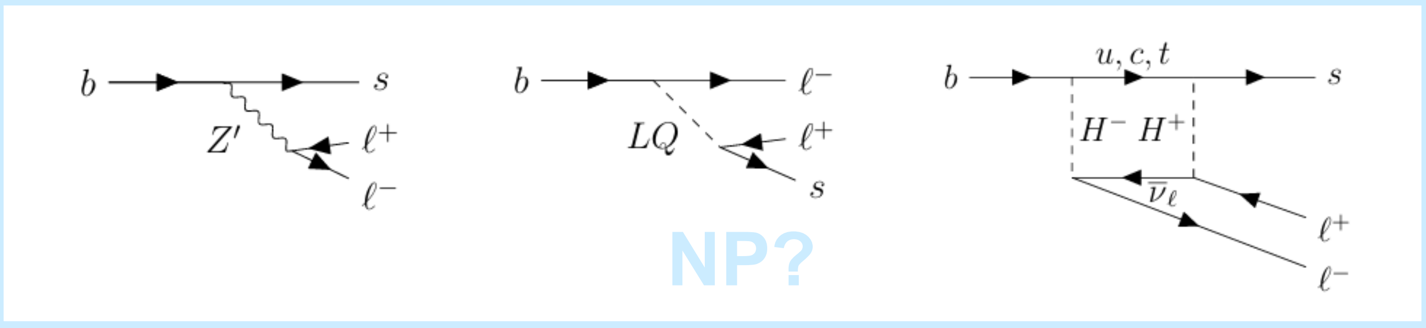


味改变的中性流过程

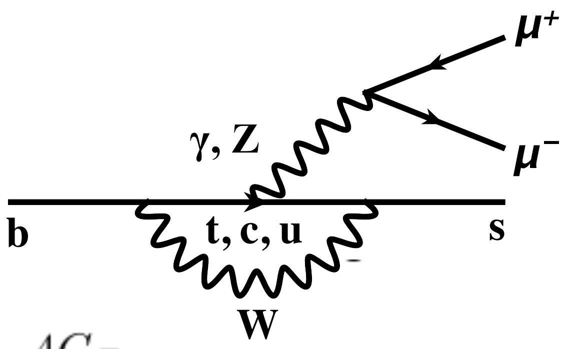
- Flavour-changing-neutral-current (FCNC) transition: transitions between quarks of the same electric charge
- SM: forbidden at tree level, need more complex diagrams to achieve
- Enhanced in many BSM theories: new particles can contribute at the loop or tree level
- NP can modify angular parameters, decay rates …

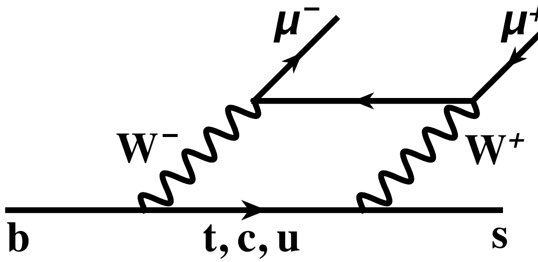






FCNC processes $b \to s\mu^+\mu^-$: golden indirect probes of NP





$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V^*_{\rm tq} \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suspressed}} + \sum \frac{c}{\Lambda^2_{\rm NP}} \mathcal{O}_{\rm NP}$$

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

Effective theory:Different processes are sensitive to different operators

Operator $\mathcal{O}_i$	$B_{s,d} \to X_{s,d}\mu^+\mu^-$	$B_{s,d} \to \mu^+\mu^-$	$B_{s,d} \to X_{s,d}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma^{\mu\nu} b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu \ell)$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$	(✓)	✓	

clean exp signature;
robust theory calc;
high sensitivity

$B^0 \rightarrow K^{*0}\mu\mu$ 过程的角分析

Angular analysis

- **measure the rate of a decay process as a function of the angles of the final decay products**
- **Compared to measuring the branching fractions: give access to large range of observables with reduced theory uncertainties**
- **Can help deduce nature of new physics models**

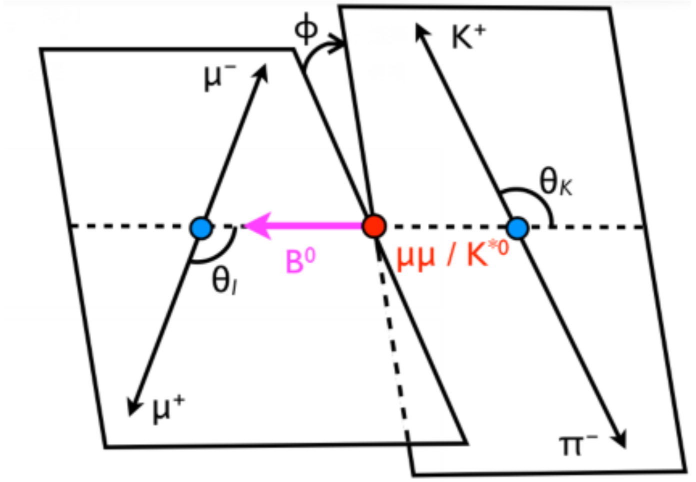
$B^0 \rightarrow K^{*0}\mu\mu$ can be fully described by **the three angles (θ_l, θ_k, ϕ)** and **the dimuon invariant mass squared q^2**

$$\cos\theta_l = (\hat{p}_{\mu^+}^{(\mu^+\mu^-)}) \cdot (-\hat{p}_{B^0}^{(\mu^+\mu^-)})$$

$$\cos\theta_K = (\hat{p}_{K^+}^{(K^{*0})}) \cdot (-\hat{p}_{B^0}^{(K^{*0})})$$

$$cos\phi = (\hat{p}_{\mu^+}^{(B^0)} \times \hat{p}_{\mu^-}^{(B^0)}) \cdot (\hat{p}_{K^+}^{(B^0)} \times \hat{p}_{\pi^-}^{(B^0)})$$

$$sin\phi = [(\hat{p}_{\mu^+}^{(B^0)} \times \hat{p}_{\mu^-}^{(B^0)}) \times (\hat{p}_{K^+}^{(B^0)} \times \hat{p}_{\pi^-}^{(B^0)})] \cdot \hat{p}_{K^{*0}}^{(B^0)}$$



bin index	q^2 range [GeV ^{2}]
0	1.1 - 2
1	2 - 4.3
2	4.3 - 6
3	6 - 8.68
4	8.68 - 10.09 (J/ψ region)
5	10.09 - 12.86
6	12.86 - 14.18 ($\psi(2S)$ region)
7	14.18 - 16
8	16 - 19

Note: $\hat{p}_x^y$ refers to the unit vector giving the direction of x in the rest frame

微分衰变率公式

Differential distribution:

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}F_T\sin^2\theta_K + \boxed{F_L}\cos^2\theta_K$$
$$+ (\frac{1}{4}F_T\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l$$
$$+ \frac{1}{2}\boxed{P_1}F_T\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+ \sqrt{F_TF_L}(\frac{1}{2}\boxed{P_4'}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{P_5'}\sin 2\theta_K\sin\theta_l\cos\phi)$$
$$- \sqrt{F_TF_L}(\boxed{P_6'}\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\boxed{P_8'}\sin 2\theta_K\sin 2\theta_l\sin\phi)$$
$$+2P_2F_T\sin^2\theta_K\cos\theta_l - P_3F_T\sin^2\theta_K\sin^2\theta_l\sin 2\phi)\Big]$$

$$(1-F_S)\Gamma_P + 2./3.(\boxed{F_S}\sin^2\theta_l + \boxed{A_S}\sin^2\theta_l\cos\theta_K$$
$$+ \boxed{A_S^4}\sin\theta_K\sin 2\theta_l\cos\phi + \boxed{A_S^5}\sin\theta_K\sin\theta_l\cos\phi$$
$$+ \boxed{A_S^7}\sin\theta_K\sin\theta_l\sin\phi + \boxed{A_S^8}\sin\theta_K\sin 2\theta_l\sin\phi)$$

Additional terms account for contaminations from **S-wave component and the interference** for the system of B⁰→Kπμμ

P_i' basis: form factor uncertainties cancel at first order

$$F_L$$
$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$
$$P_3 = \frac{-S_9}{1-F_L}$$
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$
$$P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}$$

- 8 angular parameters
- Sensitive to the Wilson coefficients
- $F_L, A_{FB}, S_i = \mathrm{f}(C_7, C_9, C_{10})$
- $\mathrm{F}_T = 1 - F_L$

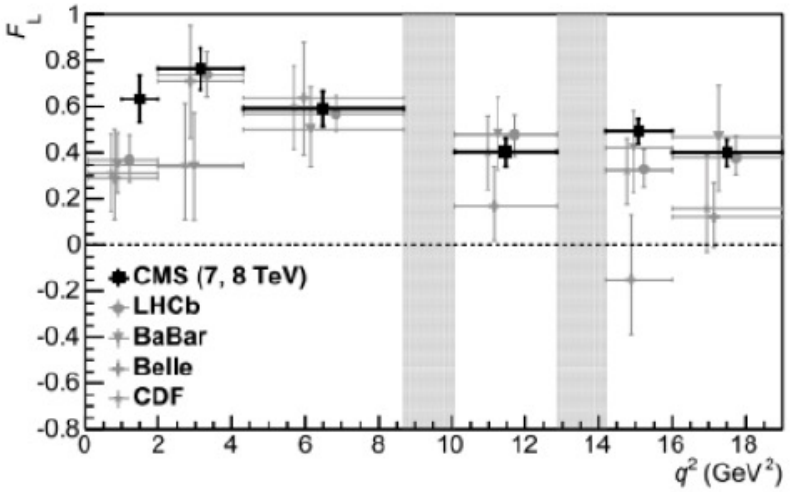
实验测量的意义与历史: F_L and A_{FB}

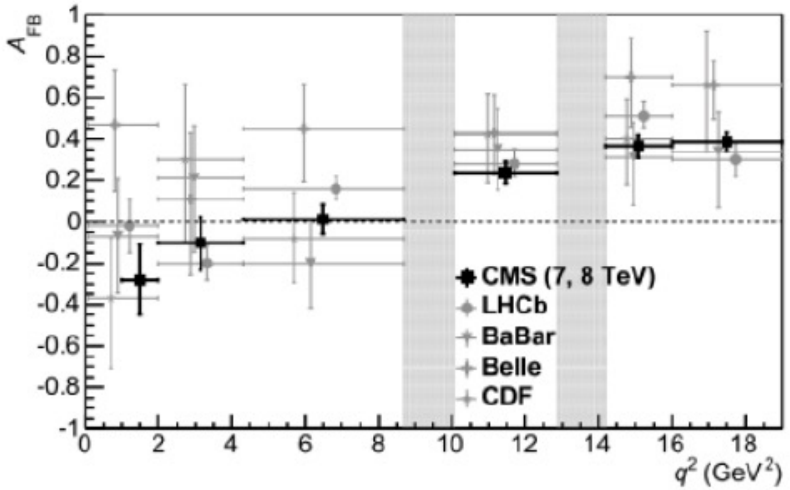
FCNC processes b→sl+ l - are not ultra rare, but provide an exceedingly rich set of observables to probe for NP effects, sensitive to non-SM helicity structures (and more).

- **Long history of measurement at B-factories and hadron colliders**

- **Angular analysis with ATLAS, BaBar, Belle, CDF, CMS and LHCb**

- **No deviation from SM for F_L and A_{FB}**

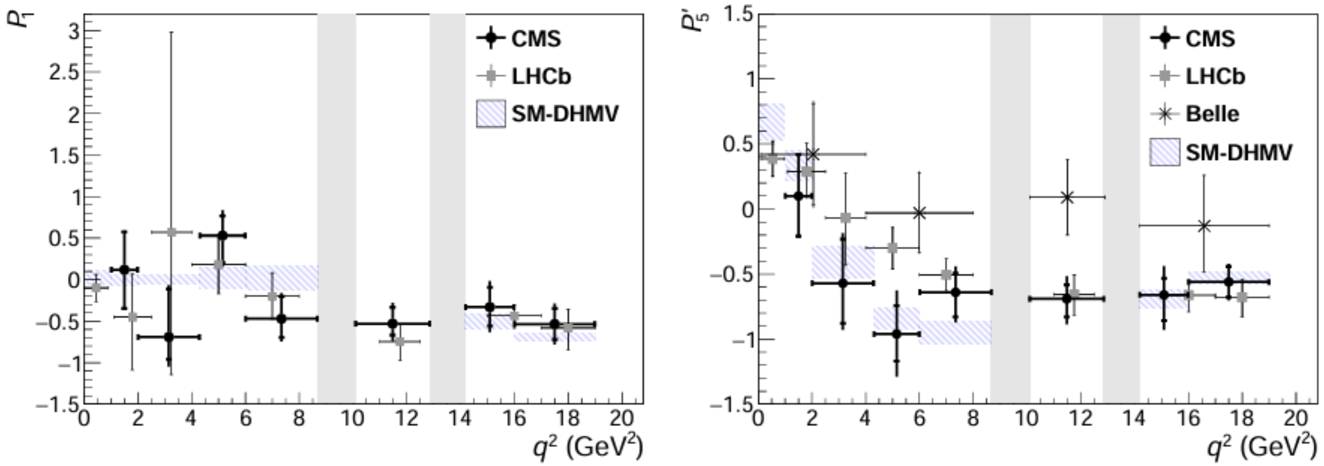




BaBar: PRD 86,032012
Belle: PRL 88,021801
PRL 103,171801
CDF: PRD 79,031102
PRL 108,081807
CMS: PLB 727 (2013) 77
PLB 753 (2016) 424
LHCb: JHEP 08 (2013) 131

CMS Run-I results

- **CMS performed partial angular analyses with Run-1 data, to measure F_L, A_{FB} and P_1, P_5' separately**
  - **Parameter space was reduced by integrating or folding the angular variable**



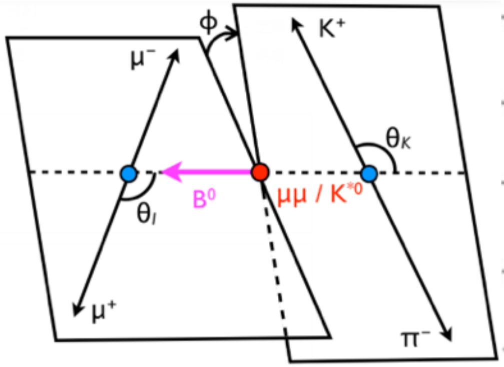
CMS: PLB 781 (2018) 517541
LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017)
SM: JHEP 01 (2013) 048, JHEP 05 (2013) 137

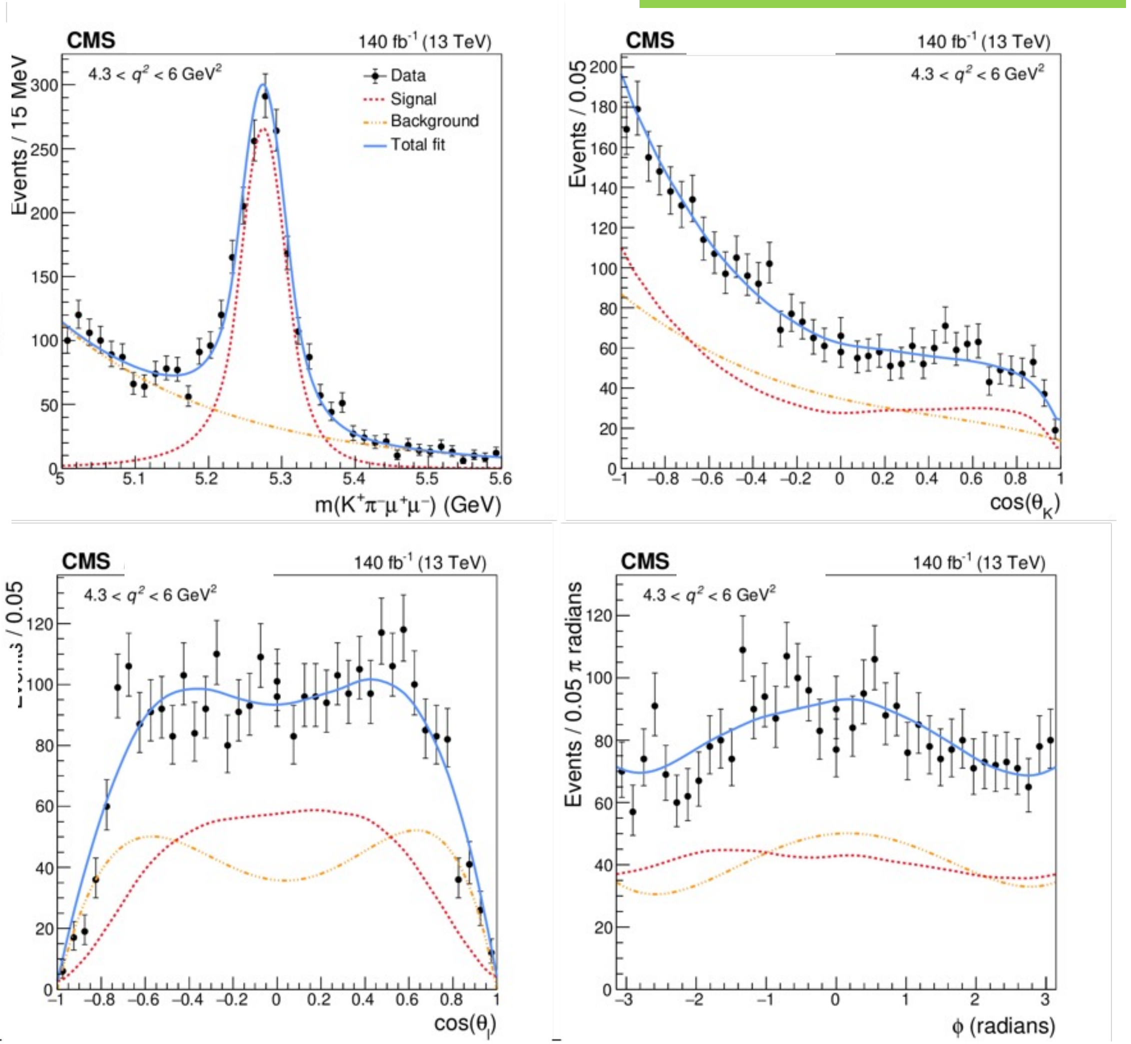
- **P_5' anomaly: ~3σ discrepancy in some q^2 bin in LHCb results**
- **CMS Run2 collected 140 fb^{-1} of 13 TeV p-p data -> make it possible to perform a full angular analysis**

Run2: Full angular analysis of $B^0 \to K^{*0}\mu\mu$

CMS-BPH-21-002
PLB 864 (2025) 139406

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\left[\frac{3}{4}(1-\boxed{F_L})\sin^2\theta_K + \boxed{F_L}\cos^2\theta_K \right.$$
$$+\left(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right)\cos 2\theta_l$$
$$+\frac{1}{2}\boxed{P_1}(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\sqrt{(1-F_L)F_L}\left(\frac{1}{2}\boxed{P_4'}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{P_5'}\sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{(1-F_L)F_L}\left(\boxed{P_6'}\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\boxed{P_8'}\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$
$$\left.+2\boxed{P_2}(1-F_L)\sin^2\theta_K\cos\theta_l - \boxed{P_3}(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\right],$$





$$\mathrm{pdf}(m,\cos\theta_K,\cos\theta_l,\phi) = Y_S\left[S^C(m)S^a(\cos\theta_K,\cos\theta_l,\phi)\epsilon^C(\cos\theta_K,\cos\theta_l,\phi)\right.$$
$$\left.+R\cdot S^M(m)S^a(-\cos\theta_K,-\cos\theta_l,-\phi)\epsilon^M(\cos\theta_K,\cos\theta_l,\phi)\right]$$
$$+Y_B B^m(m)B^a(\cos\theta_K,\cos\theta_l,\phi)$$

Angular rate

Signal and bkg mass shapes

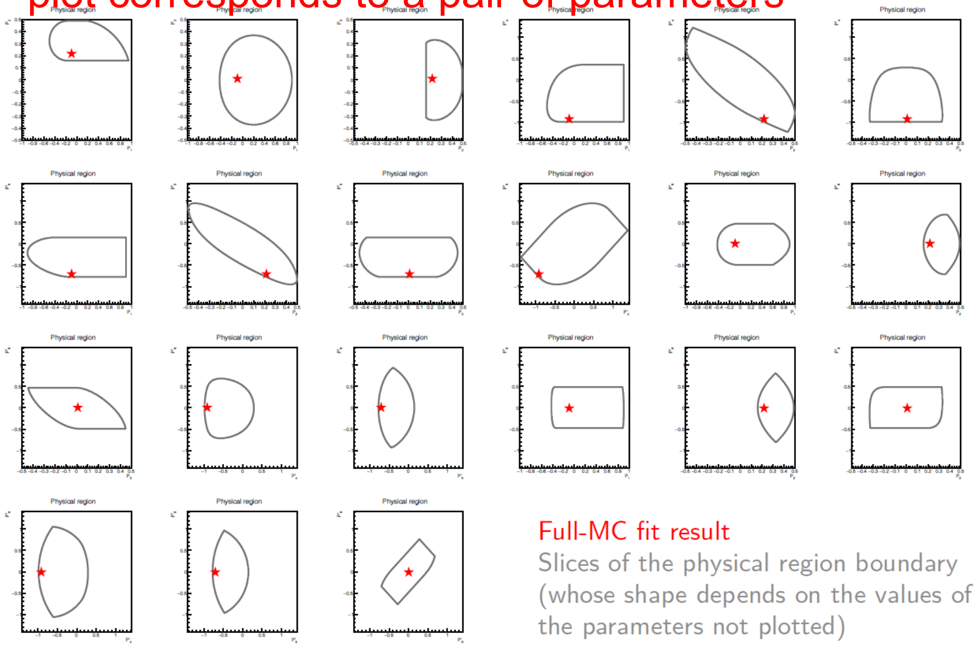
KDE efficiency

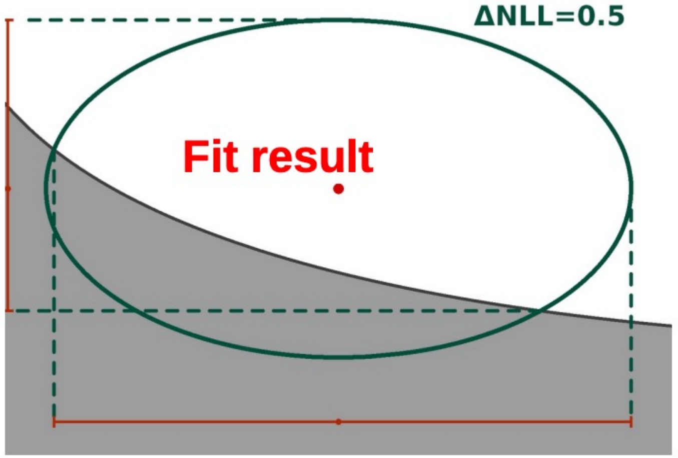
Bkg angular shape

物理边界和统计误差

- **Physical region: the decay rate is guaranteed to be positive for any values of three angles, a 7-dimensional requirements on P_i' parameters**
  - For full MC sample: fit results are always physical
  - For data-like statistics MC subsamples: only a fraction of the fit converges to a physical result, a penalized likelihood is used to obtain a physical result from the rest of the samples
- **Statistical uncertainty extracted with likelihood profile on each parameter**
  - ΔNLL=0.5 contour of the fit likelihood profile on each parameter
  - Method accounts for limits of physical region in parameter space

2D slice of the physical region for q^2 bin 2, each plot corresponds to a pair of parameters





效率描述

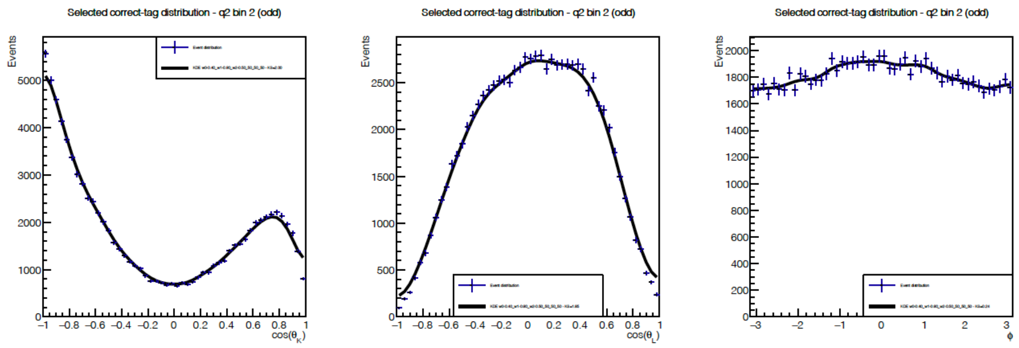
- **Evaluated from MC for CT and WT separately**

$$\epsilon_c(\cos\theta_K,\cos\theta_l,\phi)=\frac{N_{\mathrm{acc}}(\cos\theta_K,\cos\theta_l,\phi)_{\mathrm{GEN}}}{D_{\mathrm{acc}}(\cos\theta_K,\cos\theta_l,\phi)_{\mathrm{GEN}}}\cdot\frac{N_{\mathrm{sel}}^{\mathrm{corr}}(\cos\theta_K,\cos\theta_l,\phi)_{\mathrm{RECO}}}{D_{\mathrm{sel}}(\cos\theta_K,\cos\theta_l,\phi)_{\mathrm{GEN}}}$$

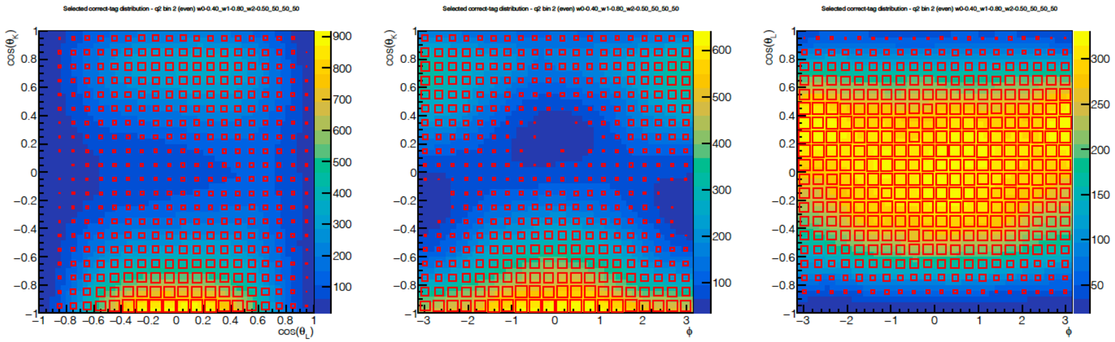
- $$\epsilon_w(\cos\theta_K,\cos\theta_l,\phi)=\frac{N_{\mathrm{acc}}(-\cos\theta_K,-\cos\theta_l,-\phi)_{\mathrm{GEN}}}{D_{\mathrm{acc}}(-\cos\theta_K,-\cos\theta_l,-\phi)_{\mathrm{GEN}}}\cdot\frac{N_{\mathrm{sel}}^{\mathrm{wrong}}(\cos\theta_K,\cos\theta_l,\phi)_{\mathrm{RECO}}}{D_{\mathrm{sel}}(-\cos\theta_K,-\cos\theta_l,-\phi)_{\mathrm{GEN}}}$$
  - **Method to describe distributions as sum of multi-variate Gaussians**
  - **Applied on numerators and denominators, then ratio is performed on the functions**

q^2 bin 2 2016

1D and 2D projections of KDE function for correct tag



cosθ$_K$ cosθ$_l$ ϕ



cosθ$_K$ vs cosθ$_l$ cosθ$_K$ vs ϕ cosθ$_l$ vs ϕ

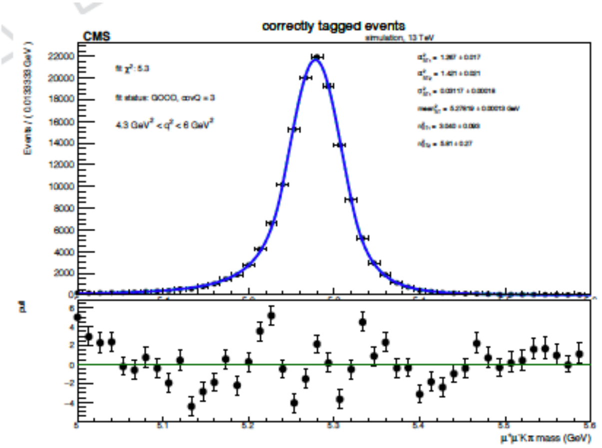
拟合策略总结

	Params	2016	2017	2018
Signal angular pdf	F_L		$[0, 1]$	
	P_1		$[-1, 1]$	
	P_2		$[-0.5, 0.5]$	
	P_3		$[-0.5, 0.5]$	
	P'_4		$[-\sqrt{2}, \sqrt{2}]$	
	P'_5		$[-\sqrt{2}, \sqrt{2}]$	
	P'_6		$[-\sqrt{2}, \sqrt{2}]$	
	P'_8		$[-\sqrt{2}, \sqrt{2}]$	
Signal mass pdf RT	$\sigma_{RT1}, \sigma_{RT2}, \alpha_{RT1}, \alpha_{RT2}, n_{RT1}, n_{RT2}, f^{RT}$	constr. to MC	constr. to MC	constr. to MC
	m_{RT}	free	free	free
Signal mass pdf WT	$(m_{WT} - m_{RT}), \sigma_{WT}, \alpha_{WT1}, \alpha_{WT2}, n_{WT1}, n_{WT2}, f^{WT}$	constr. to MC	constr. to MC	constr. to MC
Mistag corr. factor	R	constr. to MC	constr. to MC	constr. to MC
Bkg mass shape	slope	free	free	free
Bkg angular shape	various c_i	fixed from sb	fixed from sb	fixed from sb
Yields	Y_S, Y_B	free	free	free

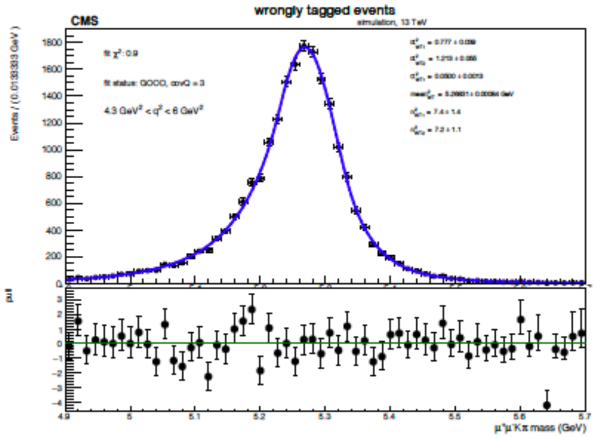
$K\pi\mu\mu$不变质量谱的描述

- **Mass model for each signal component (CT and WT) are modeled on MC**
  - **parametrized by a Double Crystal-ball function or combination of Gaussian and Crystal-ball functions used (according to q^2bin)**

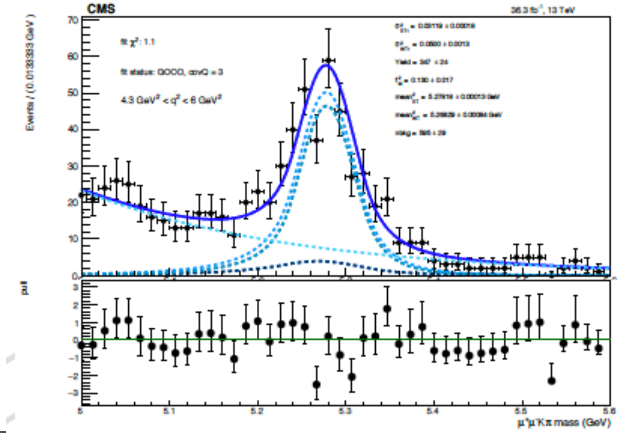
- **The data mass distribution is then fit with the model defined on the MC**
  - **means, widths, mistag fraction have gaussian constraints to values fitted on signal MC**
  - **The background is parametrized using an exponential function**



MC



MC
WT



Data

2016 q2Bin2 1D mass fit

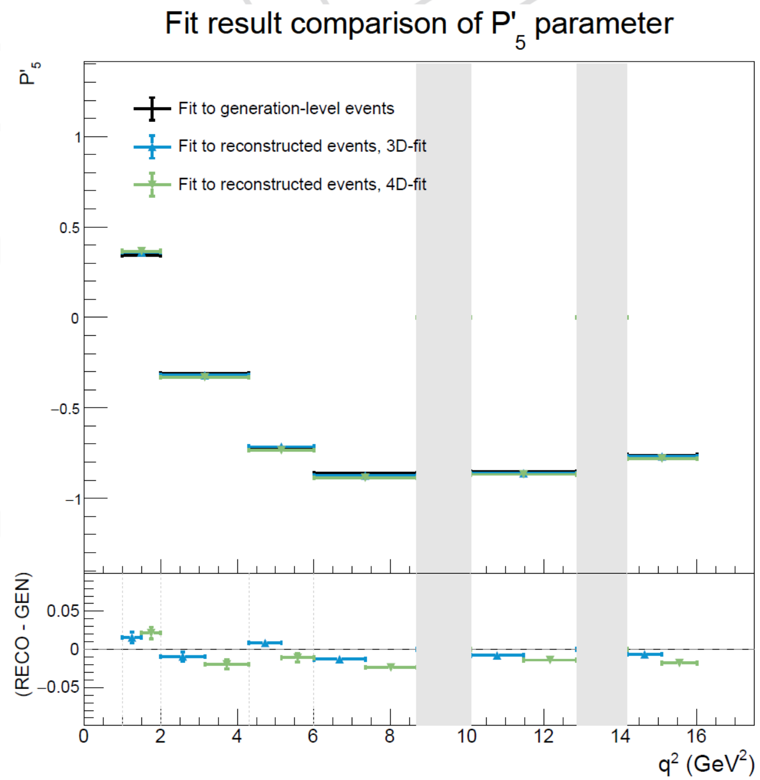
基于模拟样本的封闭性检验

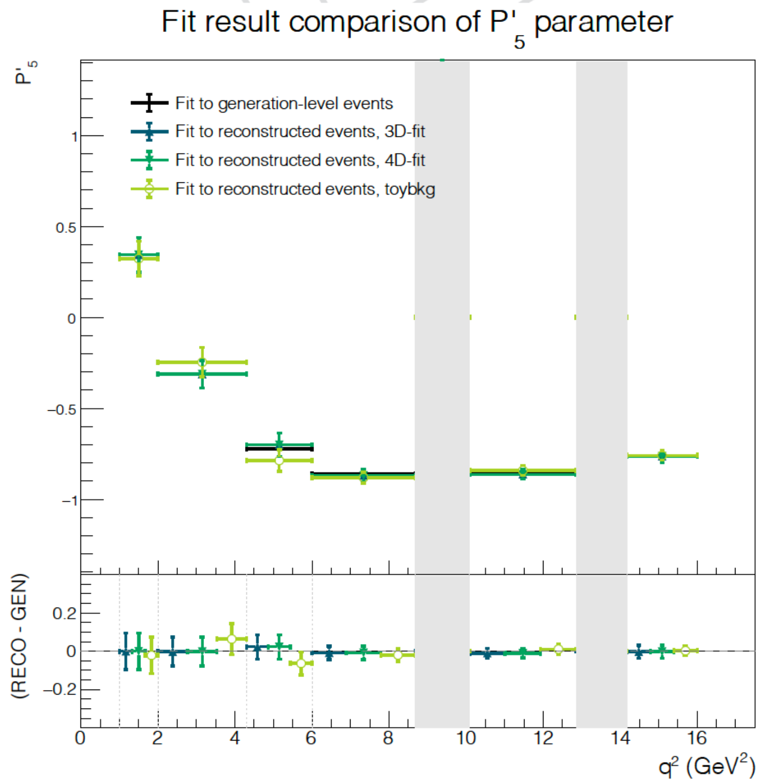
全蒙卡样本

- 3D Fit to Gen-level MC
  - Use pure decay rate as pdf, reference values in the following validation steps
- Fit to Reco-level MC
  - angular decay rate times efficiency, add signal mass shape when perform 4D fit

类数据统计量模拟样本

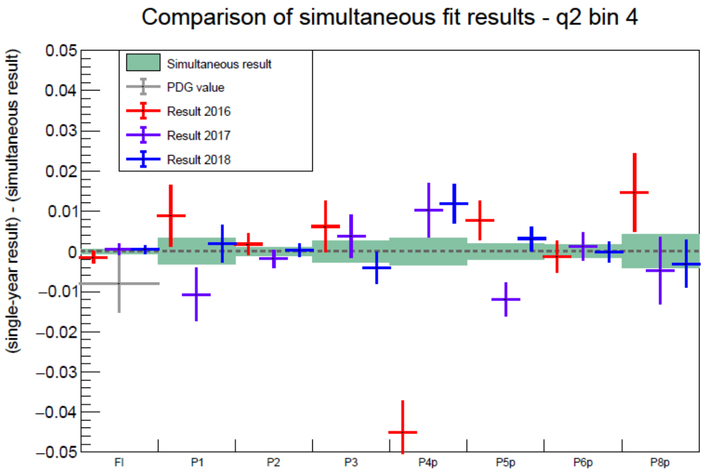
- validation on toy samples are performed in 3 steps
  - 3D fit to data-like statistics signal only
  - 4D fit to data-like statistics signal only
  - 4D fit to cocktail toy samples
- Validate the fit procedure with data-like statistics and background

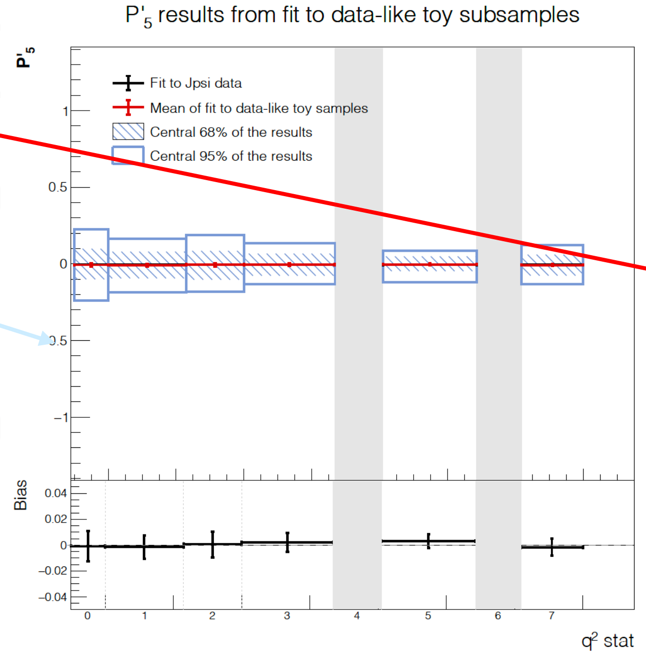


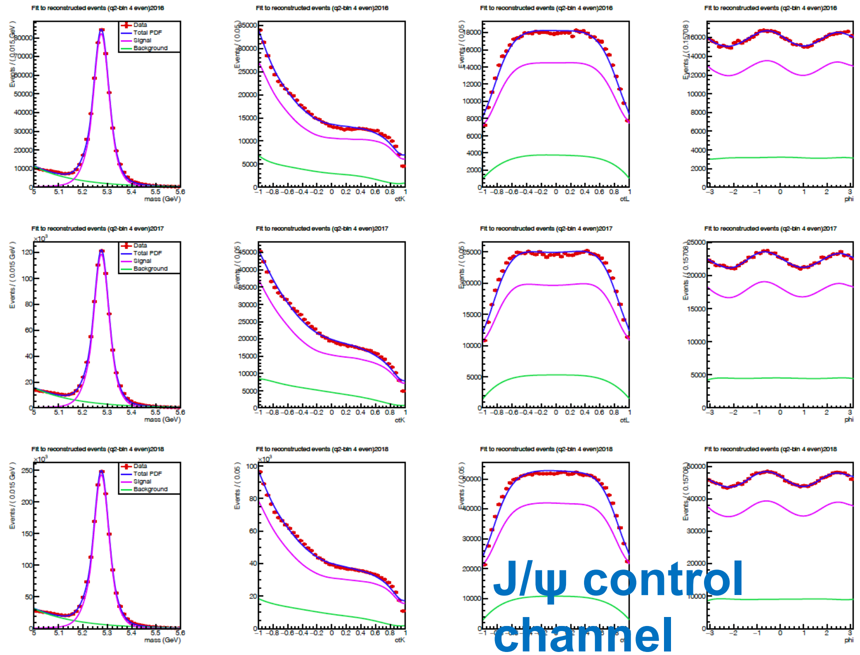


封闭性检验—控制道

- Full fit procedure validated on control channels data samples (adding the S-wave component to the pdf)
- Fit validation also perform on data-like samples
  - ➢ Subsamples of J/ψ channel dataset
  - ➢ Toy samples generated from J/ψ channel fit model
- Validate the fit method in realistic signal q^2 bin





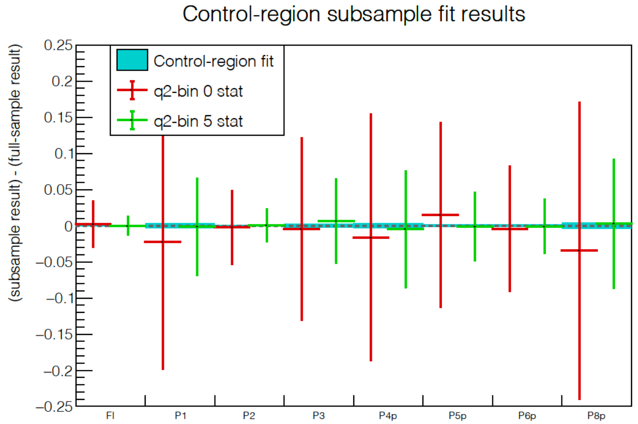


2016

2017

2018

mass cosθ$_K$ cosθ$_l$ ϕ

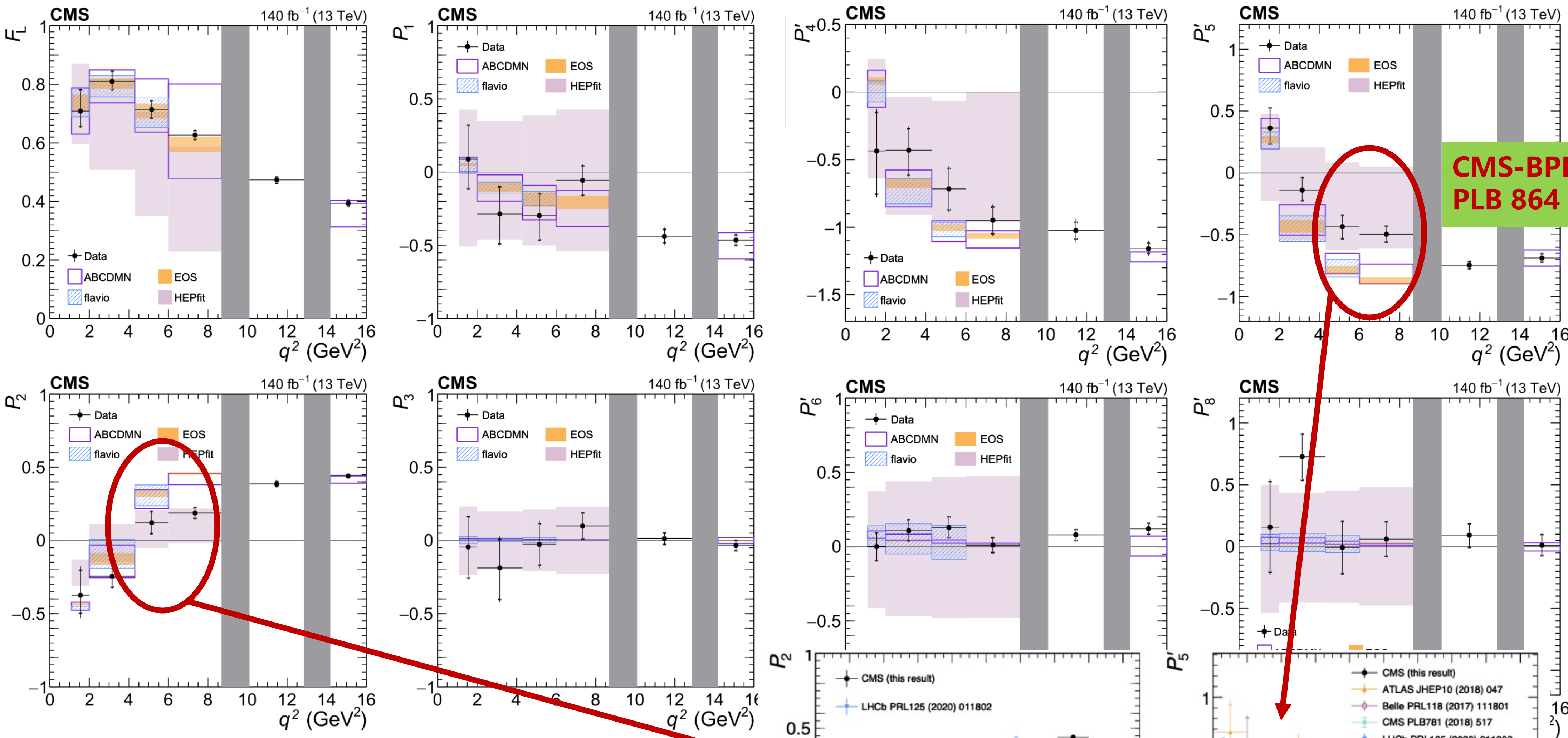


系统误差

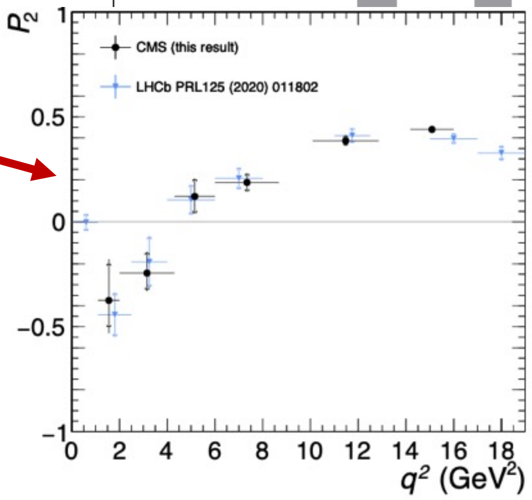
- **MC statistics:** propagation of the statistical fluctuation of the distribution of MC events
- **Sideband statistical uncertainty:** statistical fluctuation on the angular distribution of the data sideband
- **Partially-reconstructed background:** remove a fraction of the low mass sideband from the fit procedure, and use the difference of the results as systematic uncertainty
- **Resonant background:** add a MC-based component to describe the leaking contribution of resonant channels

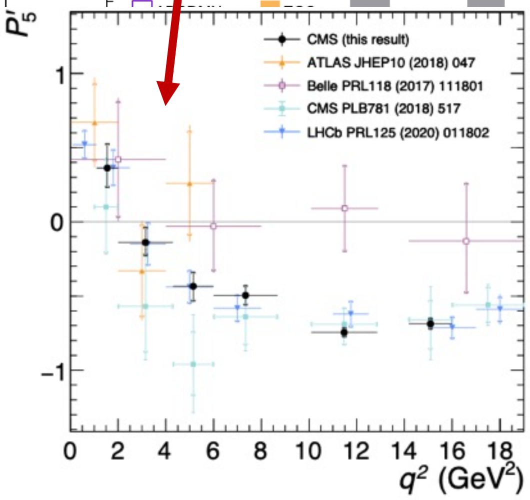
Source	F_L ($\times 10^{-3}$)	P_1 ($\times 10^{-3}$)	P_2 ($\times 10^{-3}$)	P_3 ($\times 10^{-3}$)
Efficiency modeling	1-9	7-44	3-11	0-46
Fit bias	1-2	0-6	2-62	1-12
Mistag fraction	0-2	1-4	1-3	0-14
Signal mass resolution	1-10	1-12	2-11	1-21
Signal mass shape	0-9	1-22	0-10	3-70
Background mass shape	0-5	1-16	1-13	0-8
MC statistics	1-10	5-31	1-64	4-45
Background statistics	2-6	4-20	1-21	2-16
Data/MC differences	8-8	0-23	0-16	0-13
Partially reco bkg	1-1	1-1	0-0	1-1
Resonant bkg	0-1	0-6	0-5	0-2

Source	P'_4 ($\times 10^{-3}$)	P'_5 ($\times 10^{-3}$)	P'_6 ($\times 10^{-3}$)	P'_8 ($\times 10^{-3}$)
Efficiency modeling	3-87	2-13	5-16	6-28
Fit bias	9-54	0-8	0-3	0-24
Mistag fraction	1-5	1-10	0-4	0-12
Signal mass resolution	4-23	0-12	0-5	0-16
Signal mass shape	2-16	1-15	0-7	0-91
Background mass shape	6-30	1-13	0-7	1-10
MC statistics	5-47	4-22	4-13	10-59
Background statistics	6-37	4-24	3-9	5-23
Data/MC differences	0-11	0-13	0-3	0-30
Partially reco bkg	25-25	0-0	0-0	2-2
Resonant bkg	0-30	0-11	0-5	0-12



CMS-BPH-21-002
PLB 864 (2025) 139406





- ✓ among the most precise measurements of the angular observables of this decay
- ✓ valuable contribution to the understanding of the $b \to s l^+ l^-$

CMS $B^0 \to K^{*0}\mu\mu$: HL-LHC projections

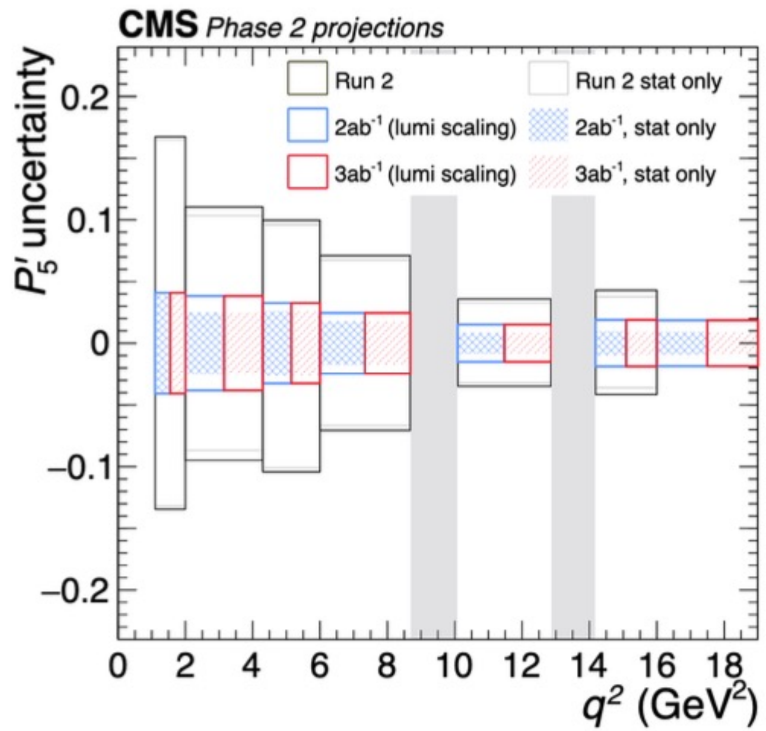
CMS-BPH-25-004
arXiv:2503.24346

Flavour inputs to ESPPU

New projection. For each q^2 bin:

- Yields scaled for $\int L$ and bb-cross section (14/13 TeV) ratio
- Stat. error obtained scaling the Run2 uncertainty by $\sqrt{L}$ ratio
- Syst. error related to N(B) in the sideband scaled by $\sqrt{L}$ ratio
- No syst. related to MC statistics
- For other systematics 2 scenarios: same as Run2 or reduced by a factor 2 wrt Run2

q^2 bin [GeV^2]	P'_4 (x10^{-3}) σ_{st}	σ_{sy}	σ^l_{sy}	P'_5 (x10^{-3}) σ_{st}	σ_{sy}	σ^l_{sy}	P'_6 (x10^{-3}) σ_{st}	σ_{sy}	σ^l_{sy}	P'_8 (x10^{-3}) σ_{st}	σ_{sy}	σ^l_{sy}
1.1 – 2	64	47	94	31	5	11	20	8	16	77	48	95
2 – 4.3	36	31	60	20	15	29	15	7	13	39	20	39
4.3 – 6	32	31	62	21	10	19	15	4	7	45	7	13
6 – 8.68	21	25	49	14	9	17	11	7	13	30	18	35
10.09 – 12.86	14	28	57	7	6	12	8	5	10	21	11	22
14.18 – 16	8	20	40	8	8	16	8	4	9	18	8	17
16 – 19	8	20	40	7	8	16	8	4	9	17	8	17



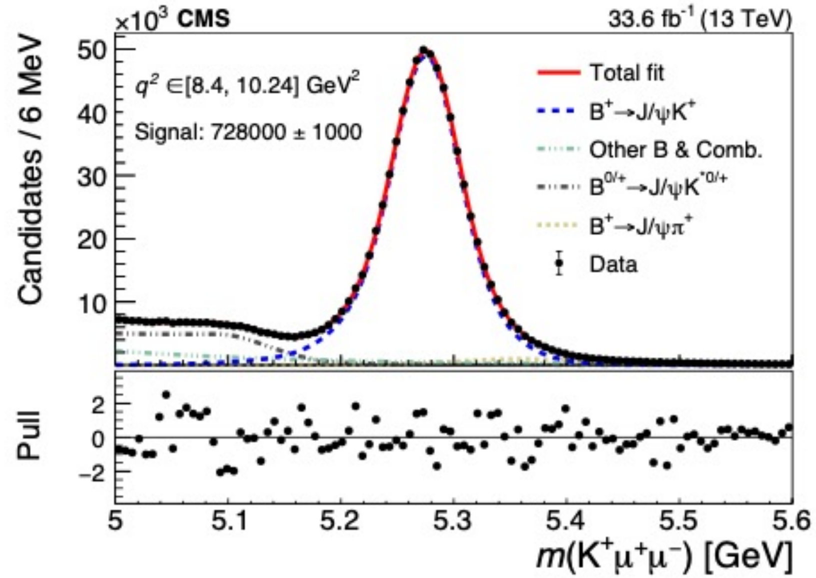
Statistical error still dominant

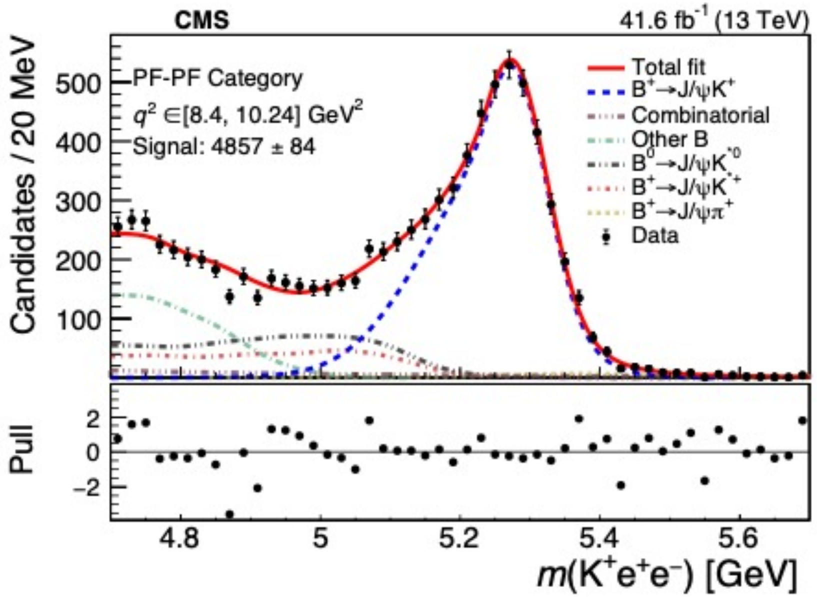
Measurements of $B^+ \to K^+ l\, l$ with B parking data

$$\mathcal{R}(K) = \frac{\mathcal{B}(B \to \mu\mu K)}{\mathcal{B}(B \to J/\psi(\to \mu\mu)K)} \Big/ \frac{\mathcal{B}(B \to eeK)}{\mathcal{B}\big(B \to (B \to J/\psi(\to ee)K)\big)}$$

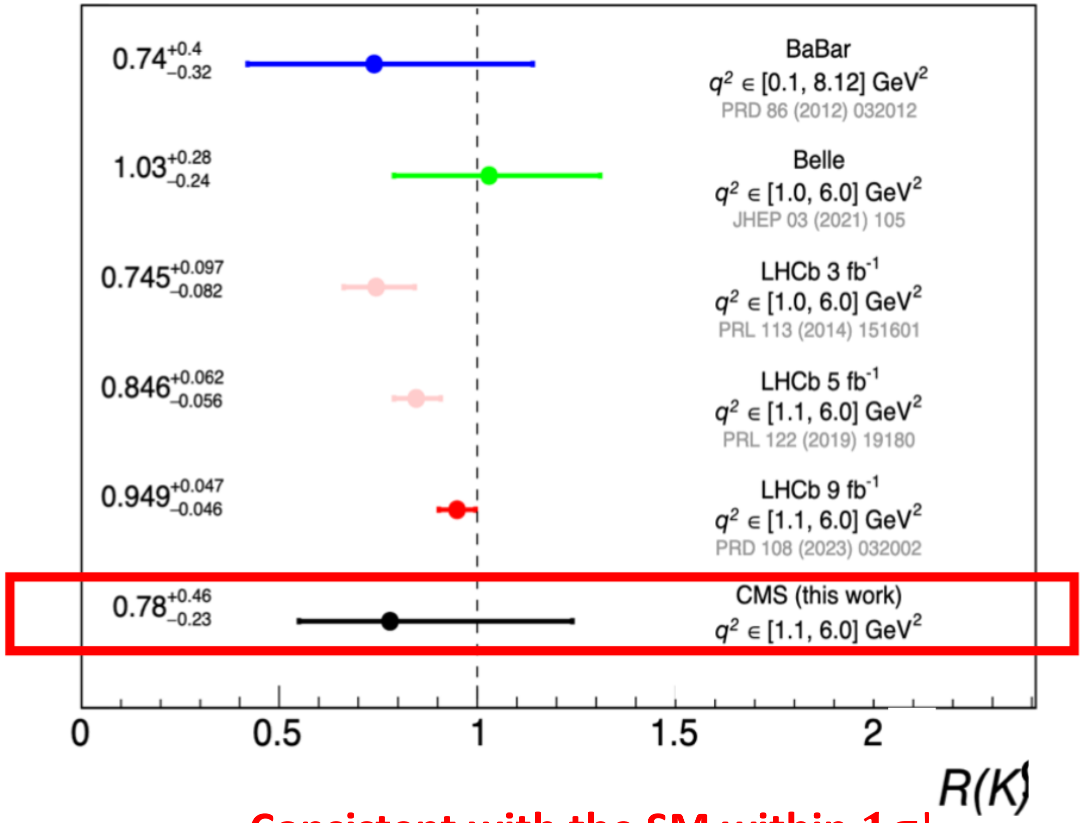
- Theoretical precision:1.00±0.01
- New data-acquisition technique: 2018 B-Parking
- Fit to Kll invariant mass in 3 q^2 regions,
  - SR: (1.1, 6.0) GeV, J/ψ CR: (8.41, 10.24)GeV $\psi(2S)$CR: (12.6,14.4) GeV
- Dedicated low-pT ID for electrons
- Main Backgrounds suppressed mostly through ID BDTs:
  - Partially reconstructed $B \to K^*(892)$ll
  - J/ψ leakage and any other B decays
  - Combinatorial
- Ratio extracted from profile likelihood

$$R(\mathrm{K}) = 0.78^{+0.46}_{-0.23}\,(\mathrm{stat})^{+0.09}_{-0.05}\,(\mathrm{syst}) = 0.78^{+0.47}_{-0.23},$$



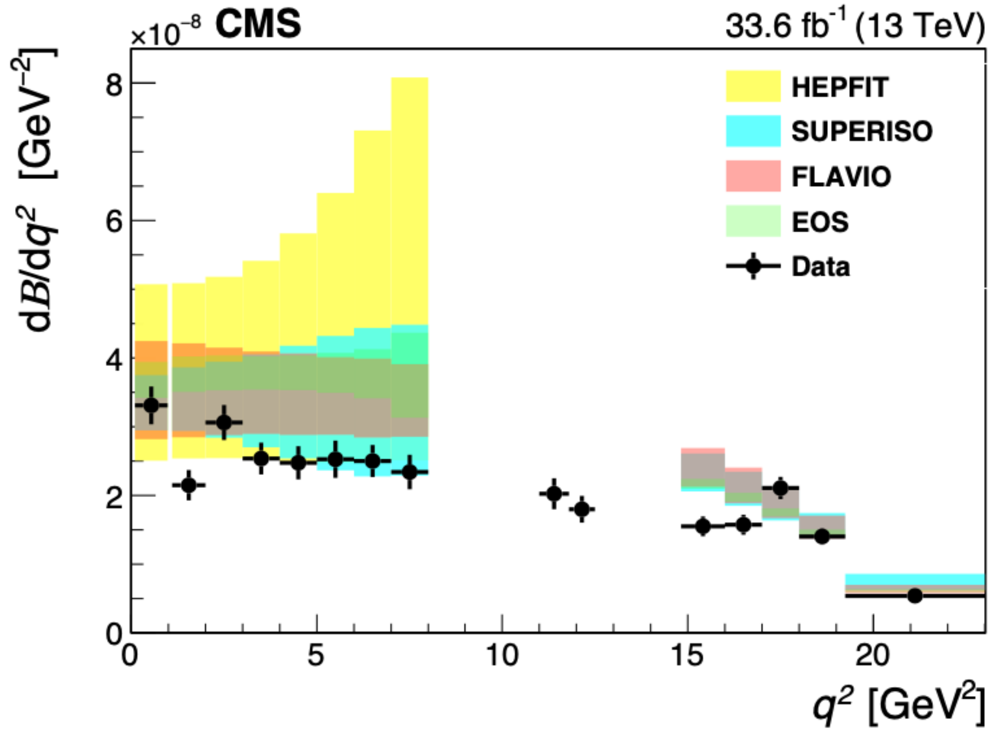


Source	Impact on the $R(\mathrm{K})$ ratio [%]	
	PF-PF	PF-LP
Signal and background description	5	5
J/ψ event leakage to the low-q^2 bin	4	9
BDT efficiency stability	2	5
BDT cross validation	2	3
Trigger efficiency	1	4
BDT data/simulation difference	1	2
J/ψ meson radiative tail description	1	1
Total systematic uncertainty	7	13
Statistical and total uncertainty	40	200



Consistent with the SM within 1σ!

Electron channel limiting precision



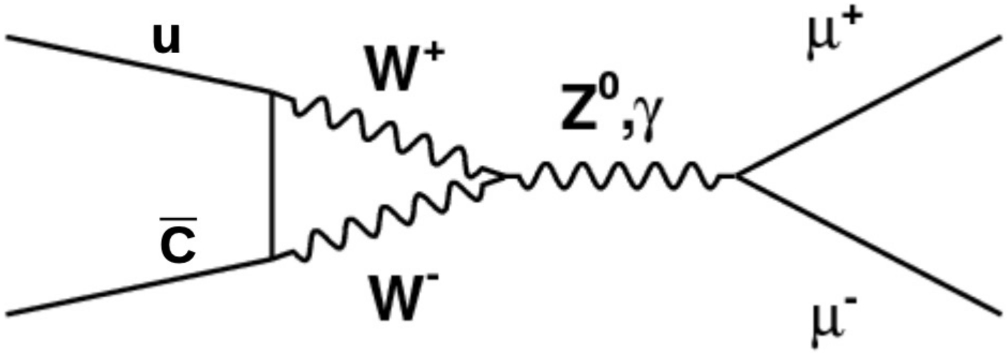
$$\mathcal{B}(\mathrm{B}^{\pm} \to \mathrm{K}^{\pm}\mu^{+}\mu^{-}) = (12.42 \pm 0.68) \times 10^{-8}$$

consistent with and has a comparable precision to the present world average

CMS-BPH-22-005
Rep. Prog. Phys. 87 (2024) 077802

Search for $D^0 \rightarrow \mu\mu$ decay

- **Heavily suppressed in the SM (loop diagram + helicity)**
  - BR prediction ~ 10^{-13}
  - High sensitivity to new-physics phenomena
  - Previous best limit at: $BR(D^0 \rightarrow \mu\mu) < 3.5 \times 10^{-9}$ (95% CL) by LHCb
- **This analysis uses 2022+2023 CMS data with new low-momentum dimuon trigger**
  - a newly developed inclusive dimuon trigger, expanding the scope of the CMS flavor physics program.



Key points of the search

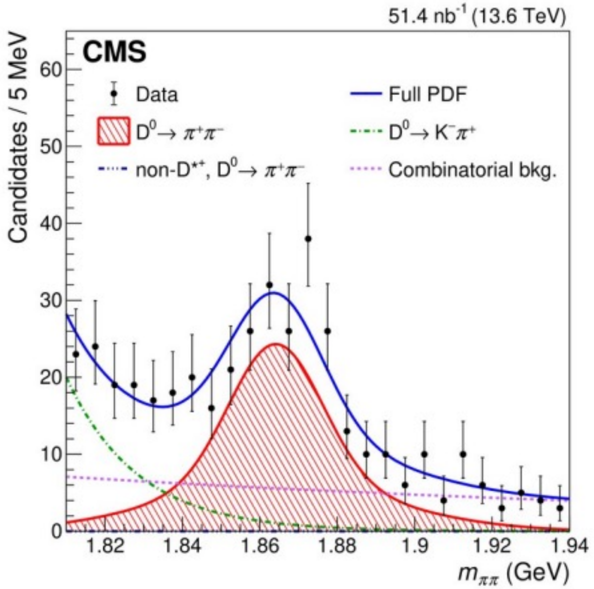
- **Analysis Strategy**
  - uses D0 from cascade decays: $D^{*+} \to D^0 \pi^+$
  - Exploits mass difference $\Delta m = m(D^{*+}) - m(D^0)$ to strongly suppress combinatorial
  - D^{*+} produced promptly or from B-hadron decays
  - Final state: opposite charged muons + track
- **$D0 \to \pi^+\pi^-$ used as normalization channel:**

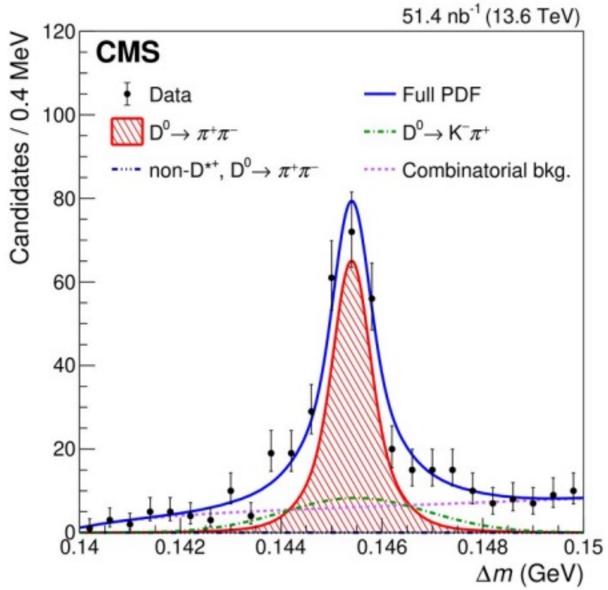
$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-) \frac{N_{\mathrm{D}0 \to \mu\mu}}{N_{\mathrm{D}0 \to \pi\pi}} \frac{\varepsilon_{\mathrm{D}0 \to \pi\pi}}{\varepsilon_{\mathrm{D}0 \to \mu\mu}}$$

- **Source of backgrounds**
  - Combinatorial: suppressed via gradient BDT, exploiting topological features
  - Peaking backgrounds for signal:
    - $D^{*+} \to D^0 (\pi\pi)\pi \to \mu\mu + X$
    - $D^{*+} \to D^0 (\pi\mu\nu)\pi$
  - Peaking background for normalization channel:
    - $D^{*+} \to D^0 (K\pi)\pi$

Search results

2D UML fits:
- to [m(ππ), Δm] in normalization sample
- to [m(μμ), Δm] in signal sample

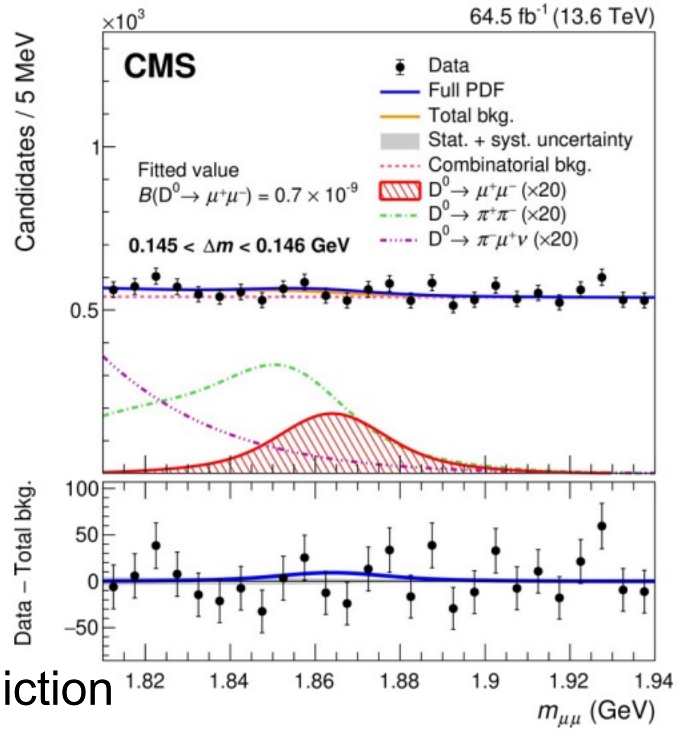


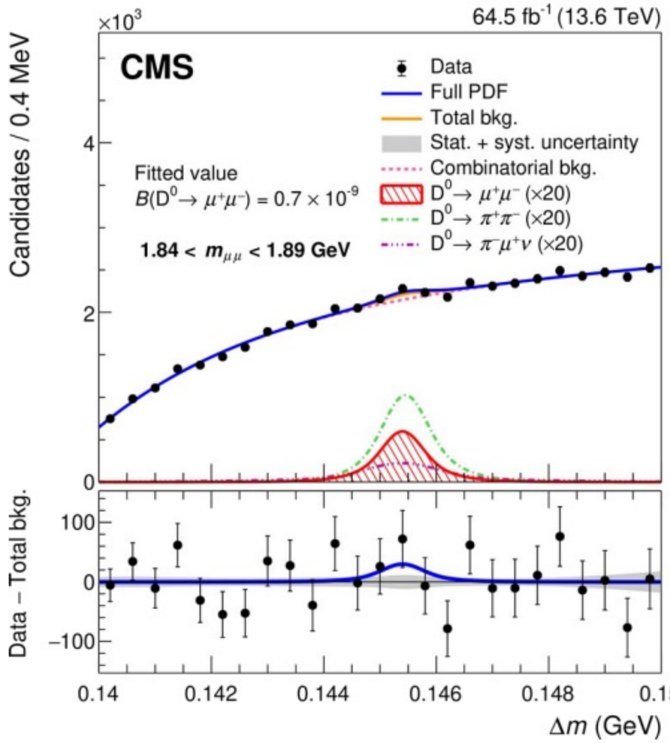


B($D^0 \rightarrow \mu^+\mu^-$) < 2.1(2.4)x$10^{-9}$ at 90(95)% CL, upper limit improved by ~40%

the most stringent upper limit set on any flavor changing neutral current decay in the charm sector

CMS-BPH-23-008
Arxiv:2506.06152



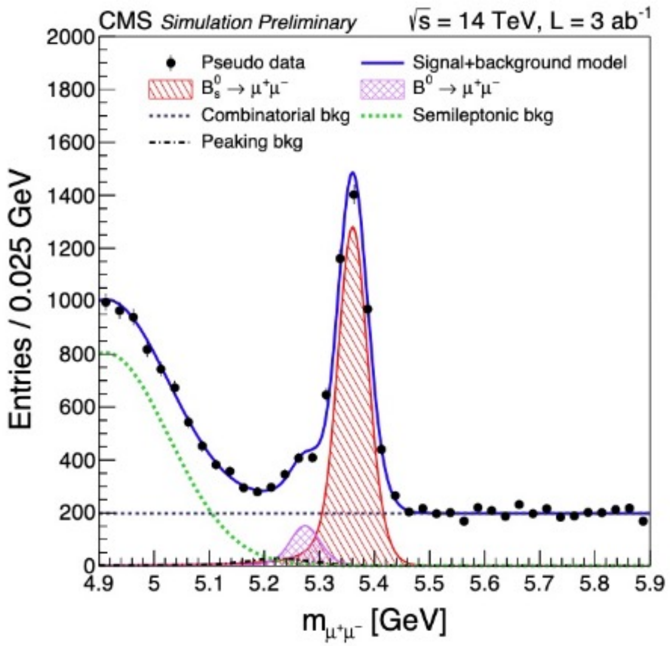


Still 4 order of magnitude above SM prediction

CMS B_s and $B^0 \to \mu\mu$: HL-LHC projections

CMS-BPH-25-004
arXiv:2503.24346

Flavour inputs to ESPPU



New projection:

- Yields scaled for $\int L$ and cross section (14/13 TeV) ratio
- Improved mass resolution included as scaling factor
- Same integrated S/B ratio as in the current analysis
- Stat. uncertainty from fits to pseudo-data
  - with s-plots weights for the lifetime
- Same syst. uncertainty as in Run2. Exceptions:
  - 1.5% instead 2.3% in tracking efficiency
  - 2.4% trigger efficiency uncertainty, uniform across categories
  - *Total: 3.5% from fs/ fu ratio; 4.3% for all other sources*
  - x2 improvement for lifetime fit bias and the mismodeling of the decay time distribution

Systematics becomes relevant for Bs; Clear observation of $B_0 \to \mu\mu$ possible

$\mathcal{L}$	$N(B_s^0)$	$N(B^0)$	$\delta\mathcal{B}(B_s^0 \to \mu\mu)$ stat.+syst.	f_s/f_u	total	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$B^0 \to \mu\mu$ significance	$\delta\tau(B_s^0 \to \mu\mu)$[ps] stat.	syst.	total
2 ab^{-1}	2539	302	5.0%	3.5%	6.1%	14%	7.4–9.7σ	0.044	0.026	0.051
3 ab^{-1}	3808	452	$\boxed{4.8\%}$	$\boxed{3.5\%}$	$\boxed{5.9\%}$	$\boxed{12\%}$	$\boxed{9.1–11.5\sigma}$	0.036	0.026	$\boxed{0.044}$

* Medians of 5k toys

in a $\pm 1\sigma$ range

Summary

- **CMS is probing SM with heavy hadrons extensively**
- **Many new results from heavy hadron studies**
  - **B and D FCNC processes**
    - **Run2: Full angular analysis of $B^0 \to K^{*0}\mu\mu$,** PLB 864 (2025) 139406
    - **BF measurement and LFU test of $B^+ \to K^+ l\, l$:** Rep. Prog. Phys. 87 (2024) 077802
    - **$D^0 \to \mu\mu$:** arxiv:2506.06152
  - **Conventional and exotic hadron spectroscopy**
  - **Heavy hadron production and polarization measurements**
  - **CKM triangle and CP violation**
  - **… …**
- **More Flexible trigger and data-taking schemes implemented in Run3, more sensitive results expected**
  - **HL-LHC coming in ~5 years, projections updated**

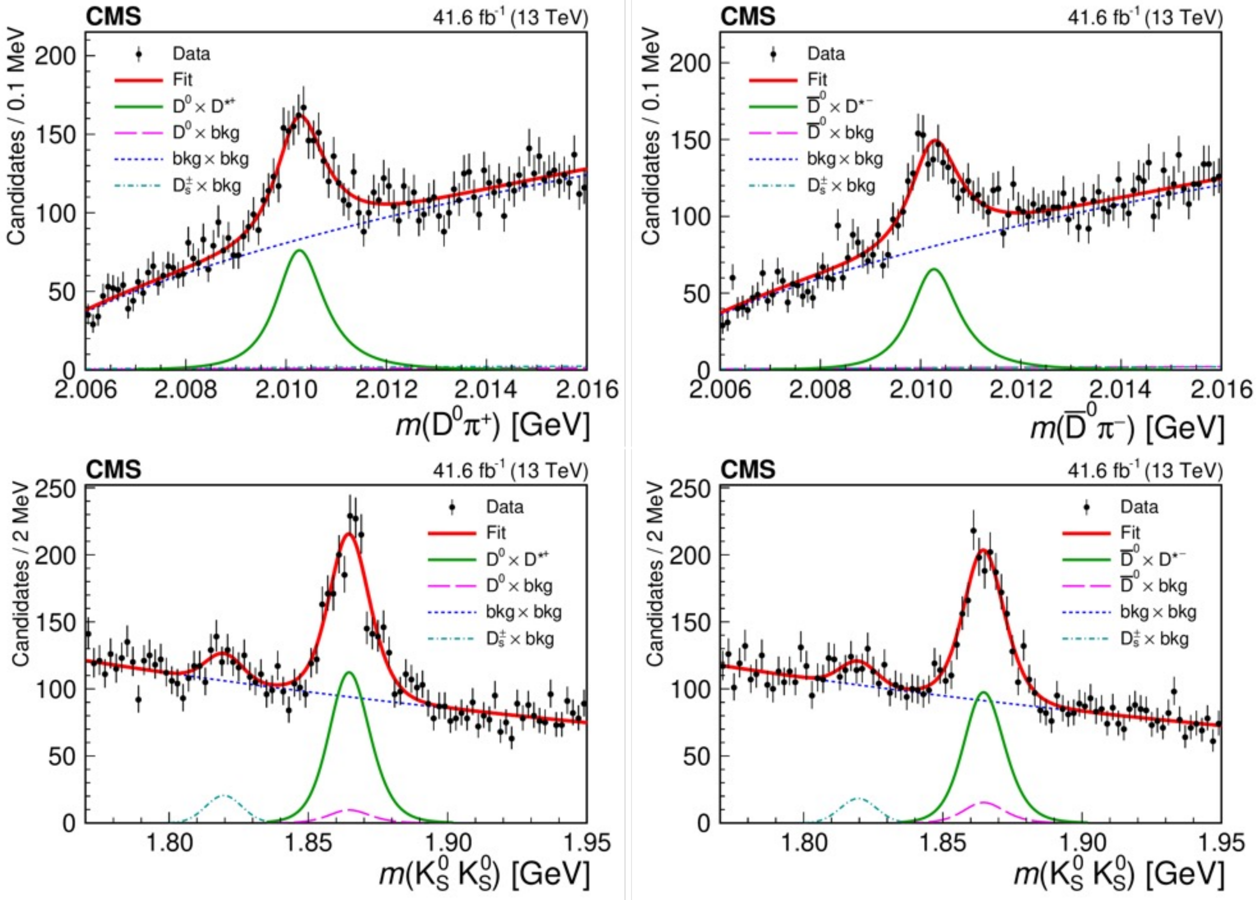
More:
CMS Public Results

Back up

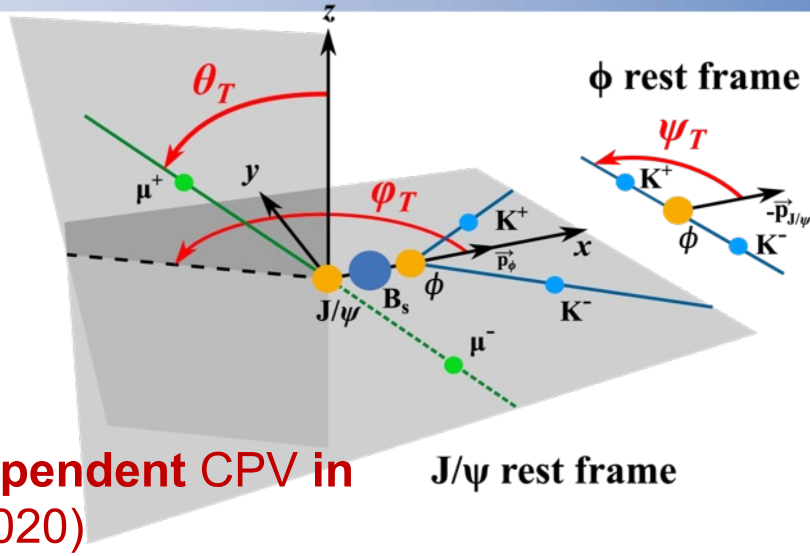
Studies of CP violation in charm and beauty

$D^0 \to K_S^0 K_S^0$

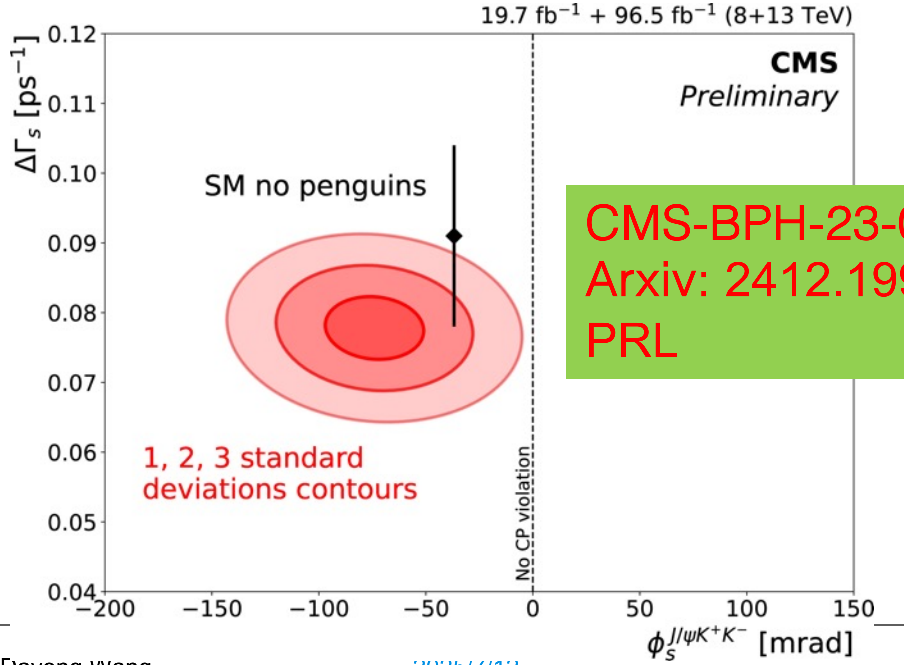
CMS-BPH-23-005
EPJC 84 (2024) 1264



$$A_{CP}(K_S^0 K_S^0) = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%,$$



3.2σ time-dependent CPV **in**
$B_s^0 \to J/\psi\ \phi(1020)$



CMS-BPH-23-004
Arxiv: 2412.19952
PRL