$B^0 \rightarrow K^* \mu\mu$ at CMS: status and perspective

KMI, Nagoya

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About myself

- PhD in physics in Padova
  - Development of High Level Trigger algorithm for the CMS experiment for events with muons in the final state (2002)
- Currently Staff Researcher at INFN Padova, Italy
  - Gruppo 1 coordinator for Padova (physics at accelerator)
- Member of CMS 1999-now (phasing out, currently 10%)
  - Muon reconstruction responsible
  - EWK conveener
  - Workload management
  - Computing technical coordinator
  - B-physics: Rare decay and angular analysis coordinator
- Member of BelleII 2015- now
  - Data processing manager
  - TDCPV working group conveener

Outline

- Introduction
    - Physics motivation
- B^0->K^* $\mu\mu$ measurement
- B^+->K^+ $\mu\mu$ measurement
- Perspective
    - Other b->sll angular measurements
    - Parking
        - R(K*)
- Conclusion

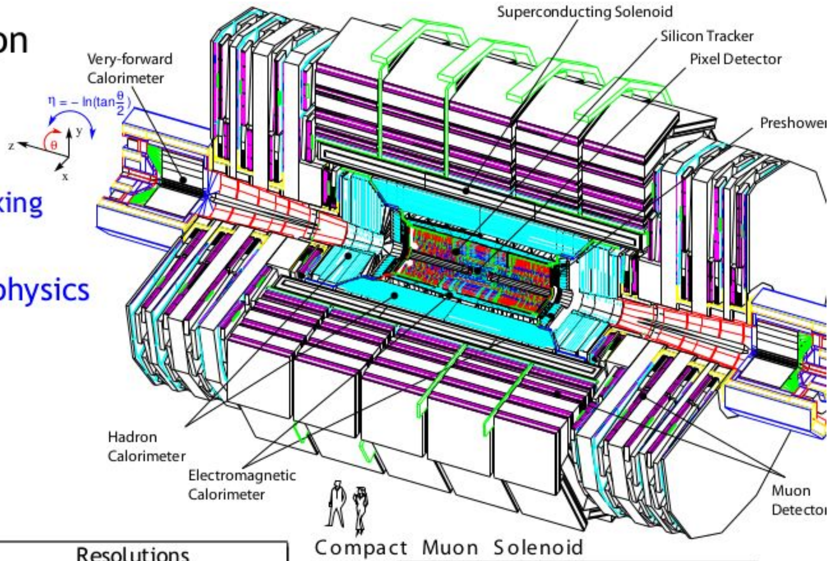
B-physics at CMS

- In addition to high pT physics (SM, Higgs, searches) CMS can give significant contribution to beauty and heavy flavour physics
    - in some field able to compete with a dedicated experiment as LHCb
- Key elements:
    - Large production x-section at LHC
    - Excellent tracking and muon id performances
    - Flexible trigger system able to collect data at high luminosity and large pile up
- Trigger for B-physics:
    - **L1**: hardware trigger based on muons
    - **HLT**: full tracking and vertexing, specific trigger paths for each analysis
        - "displaced" J/ψ, ψ'
        - "displaced" $\mu^+\mu^-$
        - $B^0_s \to \mu^+\mu^-$: no displacement, but strict inv mass cut
        - ...

CMS detector in a nutshell

- Design prioritization
  - ▷ lepton ID
    - → muons
  - ▷ b/τ tagging
    - → tracking/vertexing
  - ▷ jets and $\not{E}_T$
- → well suited for B physics

Weight	12’500 t
Length	21.6 m
Diameter	15 m
Magnetic field	3.8 T



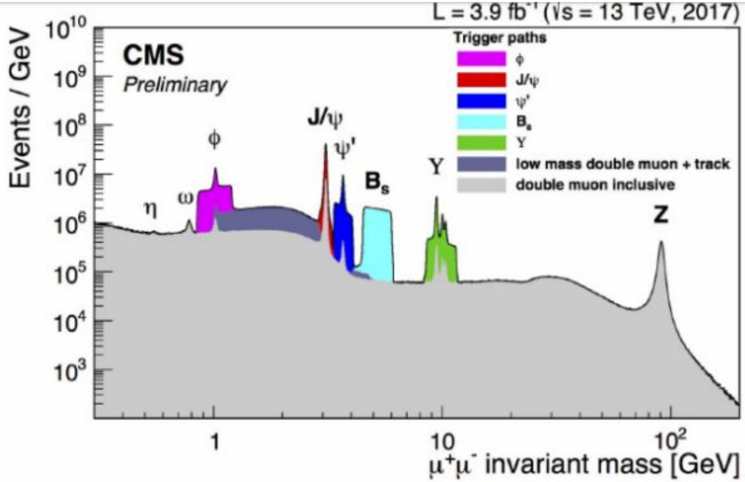
Component	Characteristics	Resolutions
Pixel	3/2 Si layers	$\delta_z \approx 20\,\mu$m, $\delta_\phi \approx 10\,\mu$m
Tracker	10/12 Si strips	$\delta(p_\perp)/p_\perp \approx 1\%$
ECAL	$PbWO_4$	$\delta E/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
HCAL (B)	Brass/Sc, $> 7.2\lambda$	$\delta E/E \approx 100\sqrt{E}\%$
HCAL (F)	Fe/Quartz	$\delta(\not{E}_T) \approx 0.98\sqrt{\sum E_T}$
Magnet	3.8 T solenoid	
Muons	DT/CSC + RPC	$\delta(p_\perp)/p_\perp \approx 10\%$ (STA)

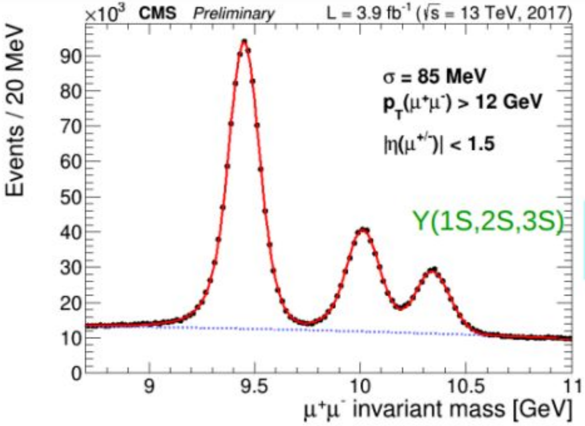
Tracking resolution:
impact parameter $\approx 15\,\mu$m

Primary vertex resolution:
$\Delta z \approx 20 - 80\,\mu$m

- Excellent muon-ID capability
  - Low fake rate
- All silicon tracker
  - high granularity, low occupancy
  - well described by MC simulation
- Pixel detector
  - 100 × 150 µm^2 pixel size
  - substantial charge sharing (low V_{bias})
  - excellent resolution in rφ and z
- Essential in high-pileup environment!

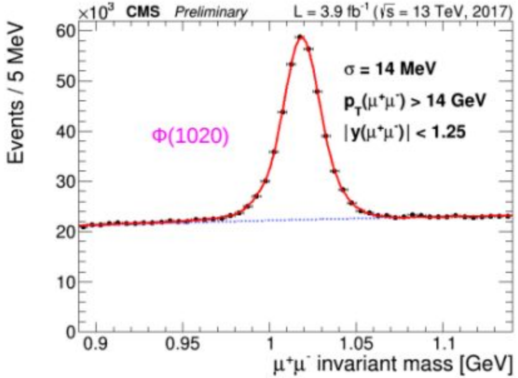
CMS trigger for B physics

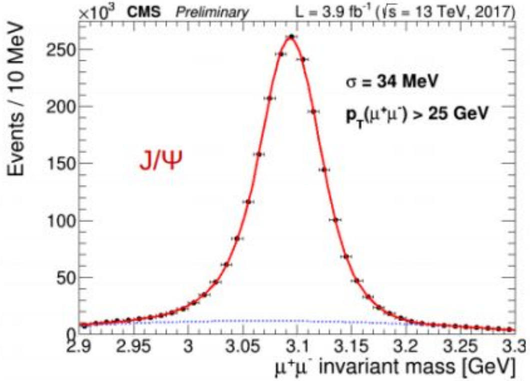


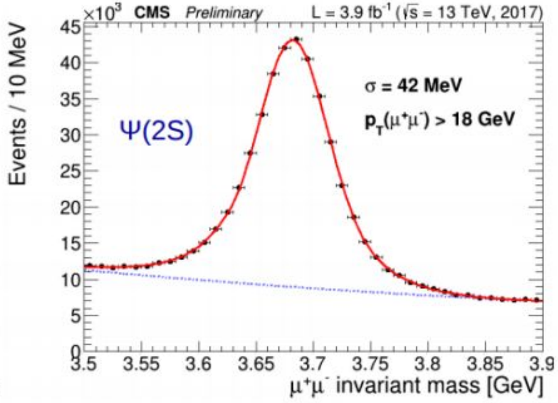


Experimental setup: dedicated HF triggers

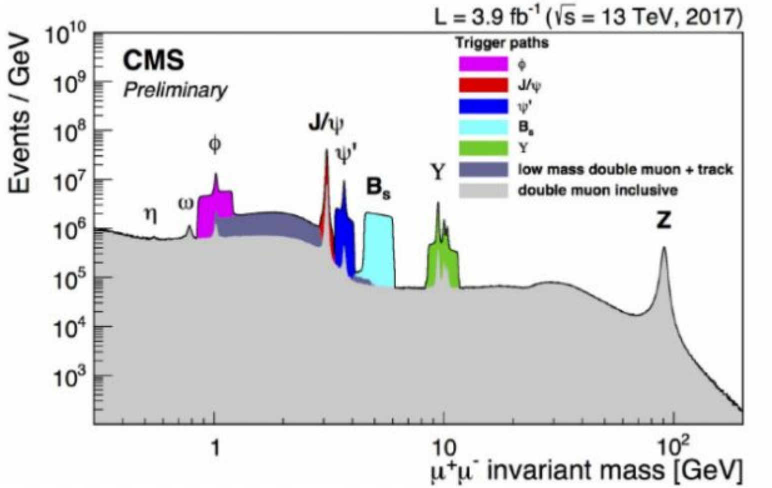
Using 2017 data:
CMS-DP-2017-029

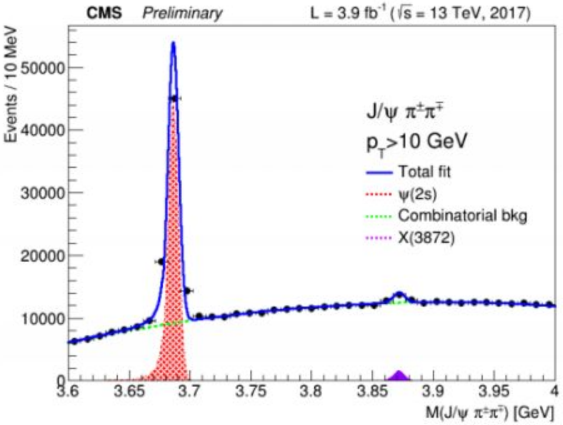






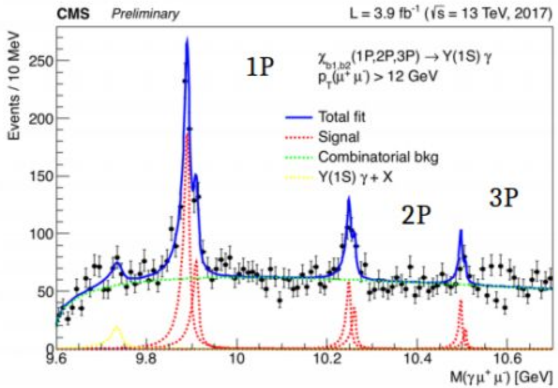
Results using 2017 13 TeV data

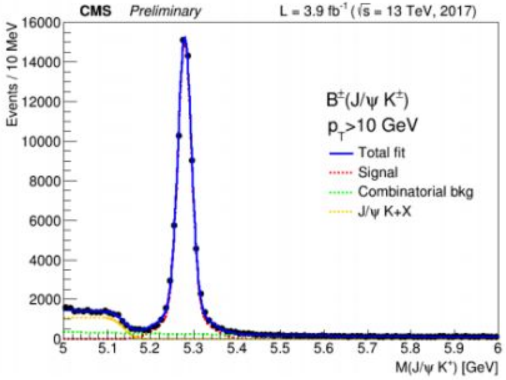


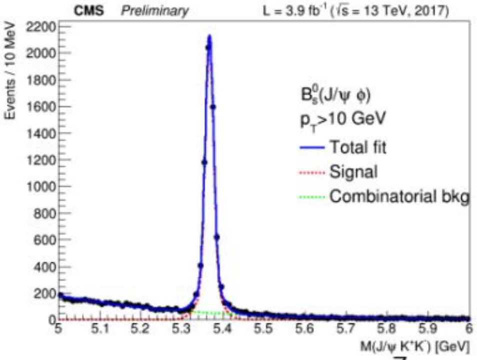


Experimental setup: trigger optimised for different analysis

Using 2017 data: CMS-DP-2017-029

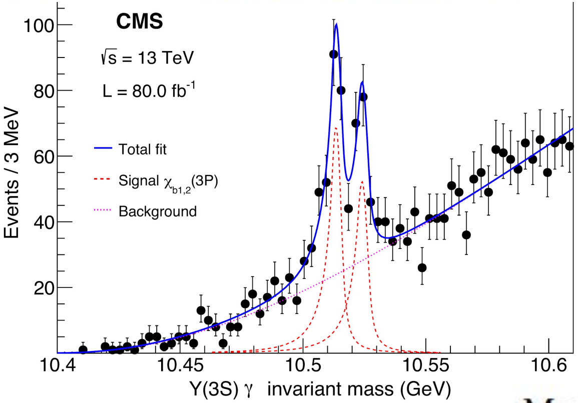






Some recent examples (not covered today)

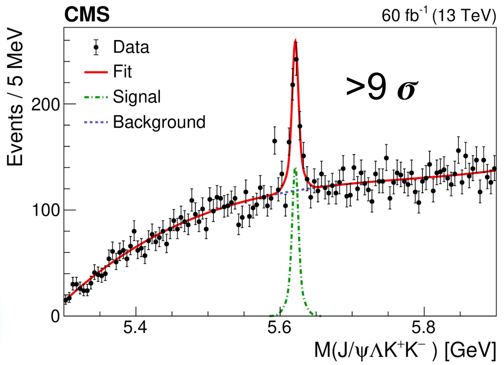
Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ and Measurement of their Masses



Phys. Rev. Lett. 121, 092002

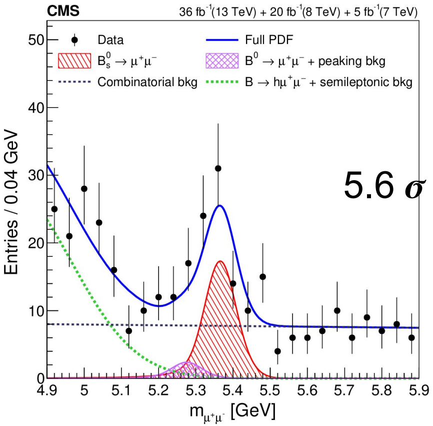
->Y(3S)γ

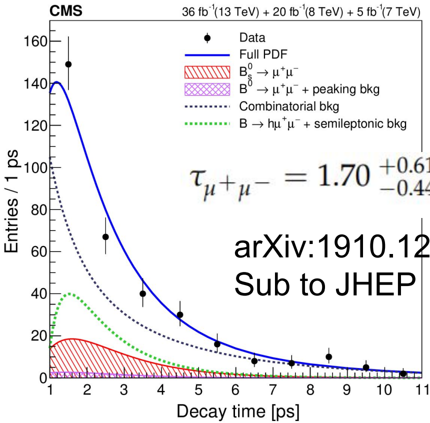
Observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$



>9 σ

Measurement of properties of $B_s^0 \to \mu^+\mu^-$ decays and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment





$\tau_{\mu^+\mu^-} = 1.70\,^{+0.61}_{-0.44}\,\mathrm{ps}$

arXiv:1910.12127
Sub to JHEP

$\Lambda_b^0 \to J/\psi\,\phi\Lambda$

is baryonic equivalent to

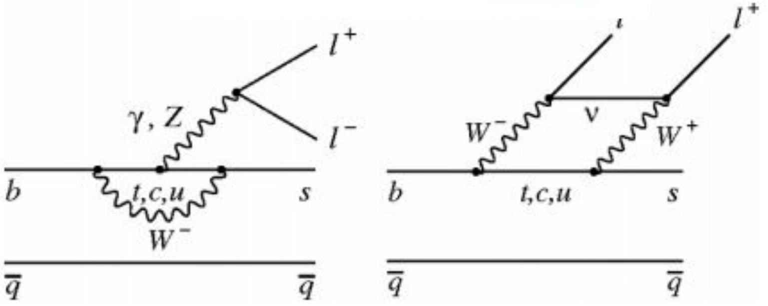
$B^+ \to J/\psi\,\phi K^+$

arXiv:1911.03789
Accepted by PLB

$B^0 \rightarrow K^* \mu\mu$ angular analysis

Physics case

- $b \to s l^+ l^-$ is a FCNC decays, doubly suppressed in SM.
  - Penguin and box mediated
- Good test to probe new physics via angular analysis and BR measurement
  - New physics can enter in the loop



- $B^0 \to K^{*0}\mu\mu$ decay
  - Trigger possible via the μμ pair: no peak in invariant mass but displaced tracks
  - Fully charged final state: can be reconstructed at CMS
  - Flavour eigenstate identified via $K^{*0} \to K^- \pi^+$decay
    - No PID (K/π separation) at CMS
  - Statistics not very high O(1000) events in whole q^2 range
    - Need some smart way to perform fit in q^2 bins in spite of low stat.

Effective operator expansion

Rare b decays are a multi-scale problem: $\Lambda^2_{\mathrm{NP}} \gg m_W \gg m_b > \Lambda_{QCD}$

FCNC effective hamiltonian described as operator product expansion

Wilson coefficients
("effective coupling")

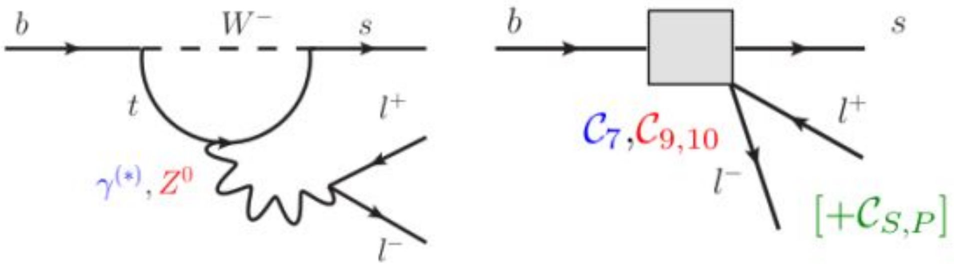
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts} \sum_i \boxed{\mathcal{C}_i}\,\boxed{\mathcal{O}_i}$$

Local operator

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

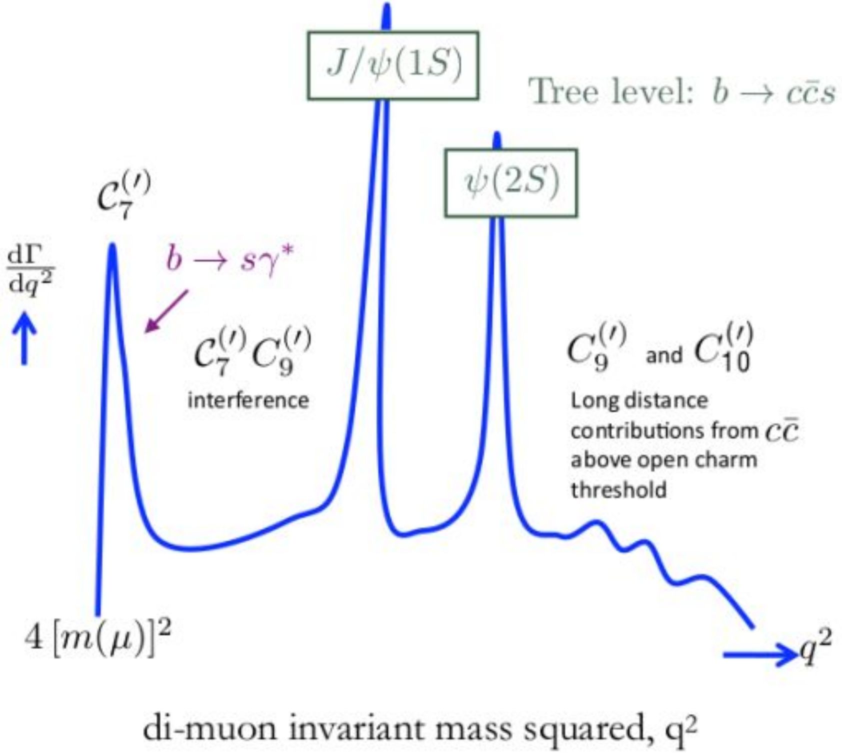
- The Wilson coefficients encode short-distance contributions and possible NP effects
- SM prediction for Wilson coefficients available
- Different processes sensitive to different Wilson coefficients

Sensitivity to Wilson coefficients



- $B^0_{(s)} \to l^+l^-$
  $[\mathcal{C}_{10}, \mathcal{C}_S, \mathcal{C}_P]$
- $b \to sl^+l^-$
  $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

Sensitivity to Wilson coefficient vs q^2



$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})\;(\bar{\ell}\gamma^\mu \ell)$$

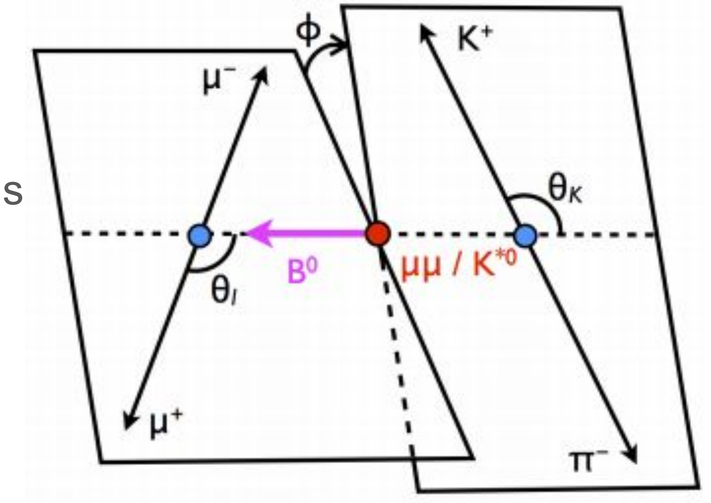
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})\;(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- And different regions of $q^2=M^2_{\mu\mu}$ are sensitive to different current type
- Eg: new vector or axial-vector currents (C_9 and C_{10}) and virtual photon polarization (C_7)
- No reliable prediction for the region between the two resonances
- Optimized **parameters**, **$P^{(\prime)}_i$**
  - combination of Wilson coeff.:
  - less dependent on hadronic form factor.
- **Robust SM prediction available**

$B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$ angular analysis

Phys. Lett. B 781 (2018) 517-541
Phys. Lett. B 753 (2016) 424-448
Phys. Lett. B 727 (2013) 77

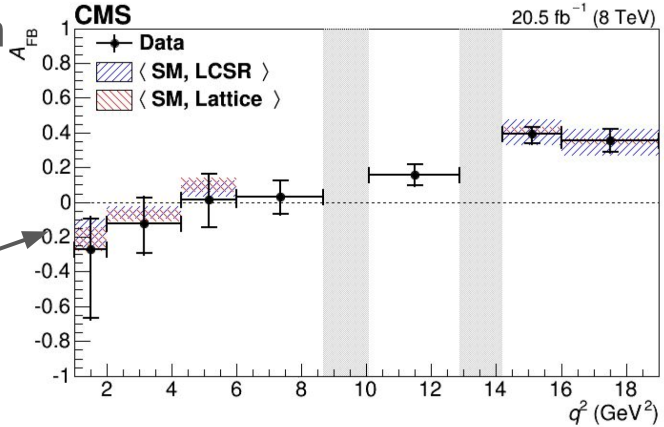
- Decay is fully described by three angles: $\boldsymbol{\theta_l}$, $\boldsymbol{\theta_K}$, $\boldsymbol{\varphi}$, and $\mathbf{q^2 = M^2_{\mu\mu}}$
  - θ_l , the decay angle of the dimuon system
  - θ_K , the decay angle of the K^{*0}
  - φ, the angle between the two decay planes
- The q^2 range has been divided in 9 bins
  - **7 signal bins**, in each of them the angular analysis is performed independently
  - **2 control-region bins**, covering the two resonant decays
    - $B^0 \to J/\psi K^{*0}$
    - $B^0 \to \psi(2S)K^{*0}$

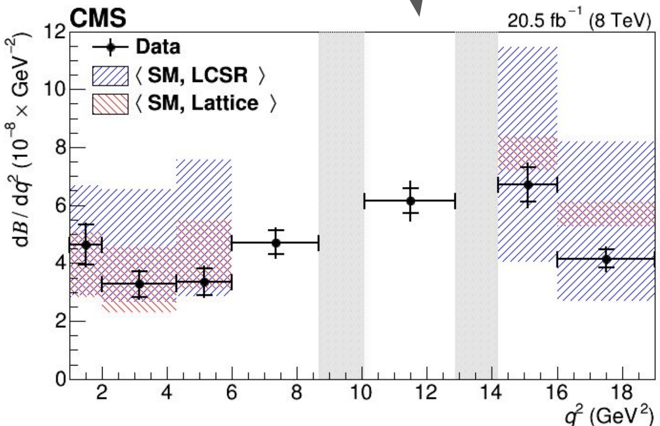


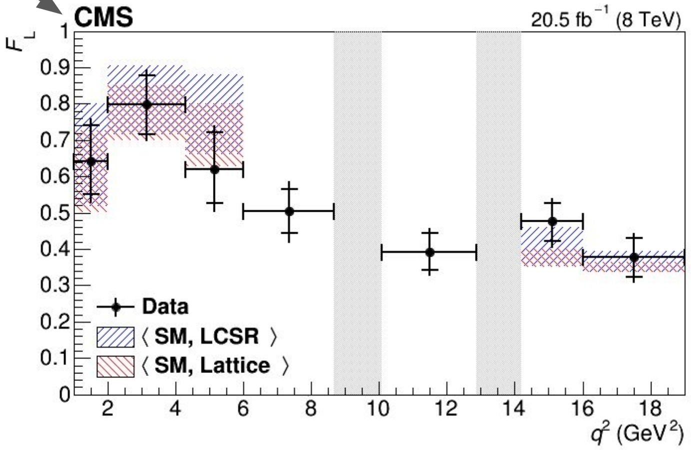
Old CMS analyses

Phys. Lett. B 727 (2013) 77
Phys. Lett. B 753 (2016) 424-448

- Two angular analyses were published by CMS with 2011 (7 TeV) and 2012 (8 TeV) data
- The parameters space was reduced by integrating over the φ angular variable
  - A_{FB} (**forward-backward asymmetry** of the muons)
  - F_L (**longitudinal polarisation** fraction of the K*)
  - **dB/dq^2** differential branching fraction
- No deviations from SM prediction

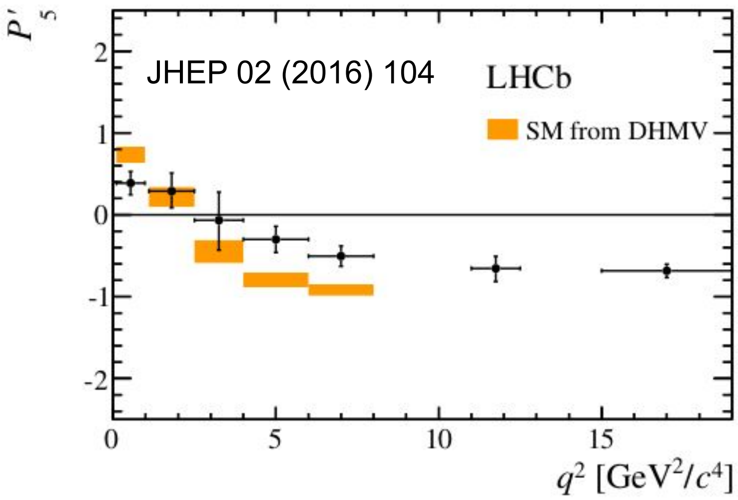


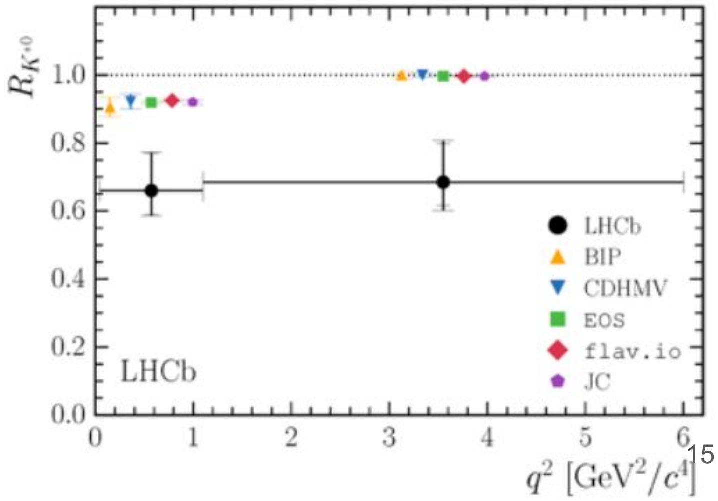




LHCb measurement of **P’$_5$**

- In 2016 LHCb measured for the first time the complete set of angular parameters
    - Tension with SM prediction for P’$_5$ parameter,
    - Both in 2011 and 2012 data
- φ angular distribution is sensitive to P’$_5$
    - Our integration of that variable makes our old analysis not sensitive to P’$_5$
- Setup a task force to repeat the analysis including the φ dependency with focus on independent measurement of P’$_5$ parameter.
    - **Same dataset, same selection, different fit**
- Since then interesting measurement on **R(K$^{(*)}$)** by LHCb have switched a bit the focus on LFV
    - More on R(K*) in CMS later


JHEP 02 (2016) 104



Angular decay rate

Full angular analysis very hard with low statistics: **focus on P'$_5$**

- Final state $K^+\pi^-\mu^+\mu^-$ has contribution from P-wave (K^*), S-wave, and interference
- in total, it has 14 parameters: fold around $\varphi = 0$ and $\theta_\ell = \pi/2$ to reduce them

$$\begin{aligned}\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_\mathrm{K}\mathrm{d}\phi} = \frac{9}{8\pi}\Bigg\{&\frac{2}{3}\left[(F_\mathrm{S} + A_\mathrm{S}\cos\theta_\mathrm{K})\left(1-\cos^2\theta_l\right) + A_\mathrm{S}^5\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\\ &+(1-F_\mathrm{S})\Bigg[2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right)\\ &+\frac{1}{2}P_1(1-F_\mathrm{L})(1-\cos^2\theta_\mathrm{K})(1-\cos^2\theta_l)\cos 2\phi\\ &+2P_5'\cos\theta_\mathrm{K}\sqrt{F_\mathrm{L}\left(1-F_\mathrm{L}\right)}\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\Bigg]\Bigg\}\end{aligned}$$

- 6 angular parameters left: fit with all of them free to float shows convergence issues

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& + (1-F_\mathrm{S})\Bigg[2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right) \\
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\end{aligned}
$$

- 6 angular parameters left: fit with all of them free to float shows convergence issues
- F_L, F_S, and A_s fixed from previous CMS measurement

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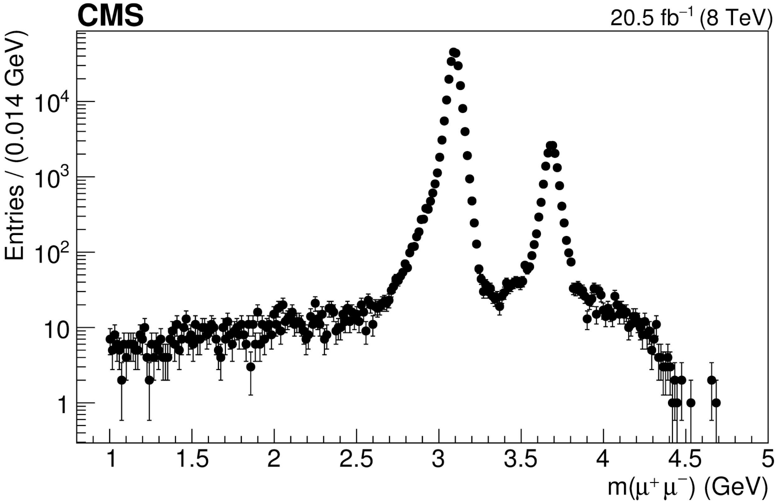
& +(1-F_\mathrm{S})\left[2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right)+\frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right)\right.\\
& +\frac{1}{2}P_1(1-F_\mathrm{L})(1-\cos^2\theta_\mathrm{K})(1-\cos^2\theta_l)\cos 2\phi\\
& \left.\left.+2P_5'\cos\theta_\mathrm{K}\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}
\end{aligned}
$$

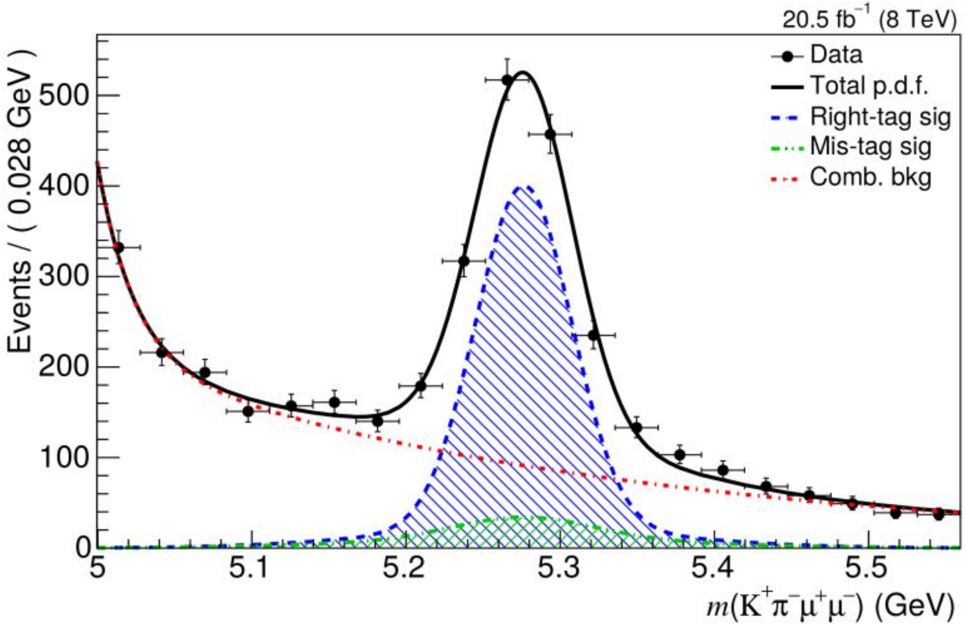
- 6 angular parameters left: fit with all of them free to float shows convergence issues
- F_L, F_S, and A_s fixed from previous CMS measurement
- P_1 and P_5' measured, A_s^5 nuisance parameter

Signal selection



- Trigger selections
  - L1: dimuon low p_T
  - dedicated High-Level Trigger path:
  - Low p_T dimuon, displaced, low invariant mass
- Offline selections
  - **μ**: $p_T^{\mu} > 3.5$ GeV, $p_T^{\mu\mu} > 6.9$ GeV,
    - with high-quality displaced vertex
  - **h:** $p_T^{h} > 0.8$ GeV, $|M(K\pi) - M_{K*}| < 90$ MeV,
    - $M_{KK} > 1.035$ (φ veto), displaced from the primary vertex
  - **B⁰**: $p_T > 8$ GeV, $|\eta| < 2.2$, with four-body displaced vertex requirement and global momentum alignment
- both B^0 and B^0-bar considered
- J/ψ and ψ’ resonances used as control regions and treated in the same way.
  - anti radiation cut against feed-down of J/ψ and ψ’

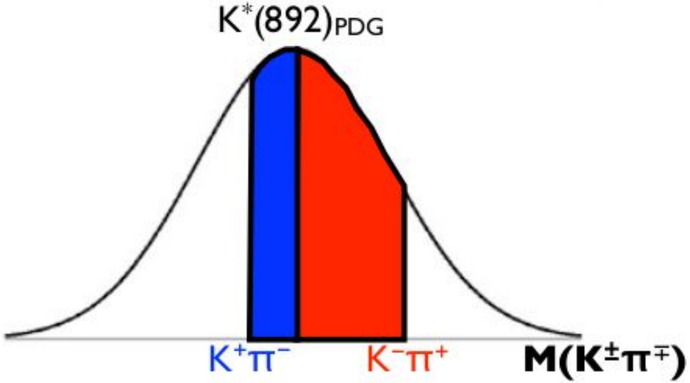
Signal sample and B Tagging



Dataset: 2012 8 TeV Data: 20.5 fb^{-1}

Signal sample: ~1400 events in all q^2 regions

- No **K/*π*** PID at CMS
- The CP-state is assigned based on the closest mass hypothesis to K^{*0}_{PDG} mass.



- This is a B^0 not a B^0-bar event
- mistag rate **14%**, measured on MC

Full pdf description

$$
\begin{aligned}
\mathrm{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = {} & Y_S^C \cdot \Big(S^R(m) \cdot S^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \\
& + \frac{f^M}{1 - f^M} \cdot S^M(m) \cdot S^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon^M(\cos\theta_l, \cos\theta_{\mathrm{K}}, \phi) \Big) \\
& + Y_B \cdot B^m(m) \cdot B^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B^{\cos\theta_l}(\cos\theta_l) \cdot B^{\phi}(\phi).
\end{aligned}
$$

Full pdf description

$$\begin{aligned}\mathrm{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = Y_S^C \cdot & \boxed{\Big(S^R(m) \cdot S^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi)} \\ & + \frac{f^M}{1 - f^M} \cdot \boxed{S^M(m) \cdot S^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon^M(\cos\theta_l, \cos\theta_{\mathrm{K}}, \phi)} \Big) \\ & + Y_B \cdot B^m(m) \cdot B^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B^{\cos\theta_l}(\cos\theta_l) \cdot B^{\phi}(\phi).\end{aligned}$$

Signal components for correctly-tagged and mis-tagged events, each composed by:

- double-Gaussian mass shape
- angular decay rate
- 3D efficiency function

Full pdf description

$$\begin{aligned}\text{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = Y_S^C \cdot \Big(& S^R(m) \cdot S^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \\ & + \frac{f^M}{1-f^M} \cdot S^M(m) \cdot S^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon^M(\cos\theta_l, \cos\theta_{\mathrm{K}}, \phi) \Big) \\ & + Y_B \cdot \boxed{B^m(m) \cdot B^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B^{\cos\theta_l}(\cos\theta_l) \cdot B^{\phi}(\phi).}\end{aligned}$$

Signal components for correctly-tagged and mis-tagged events, each composed by:

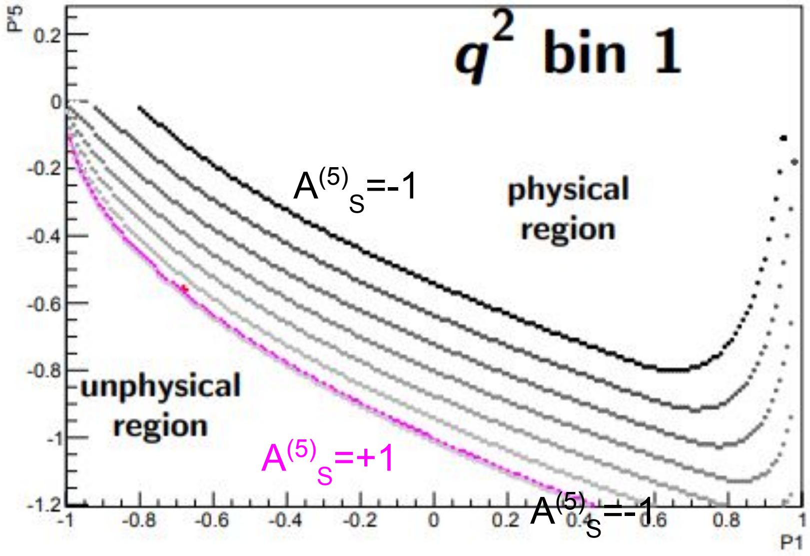
- double-Gaussian mass shape
- angular decay rate
- 3D efficiency function

Background component

- exponential mass shape
- polynomial shape for each angular variable
- factorisable angular component tested

Validity range

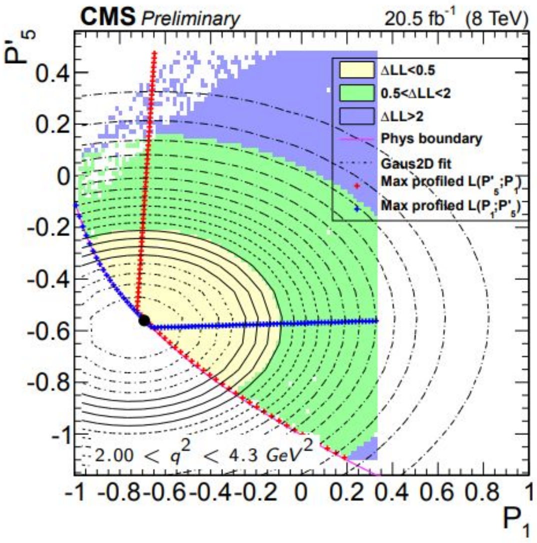
- Final fit performed with 6 parameters: P'_5,P_1, F_L, F_S, A_s, $A^{(5)}_S$ (interference P-S wave)
- Not all phase space is allowed:
  - Positive pdf for P-wave: **$(P'_5)^2 - 1 < P_1 < 1$**
- Interference term complex
  - Boundary depends on all other parameters
  - In particular P'_5,P_1
- This caused a lot of fit convergence issue
- Required dedicated fit algorithm



Fit algorithm

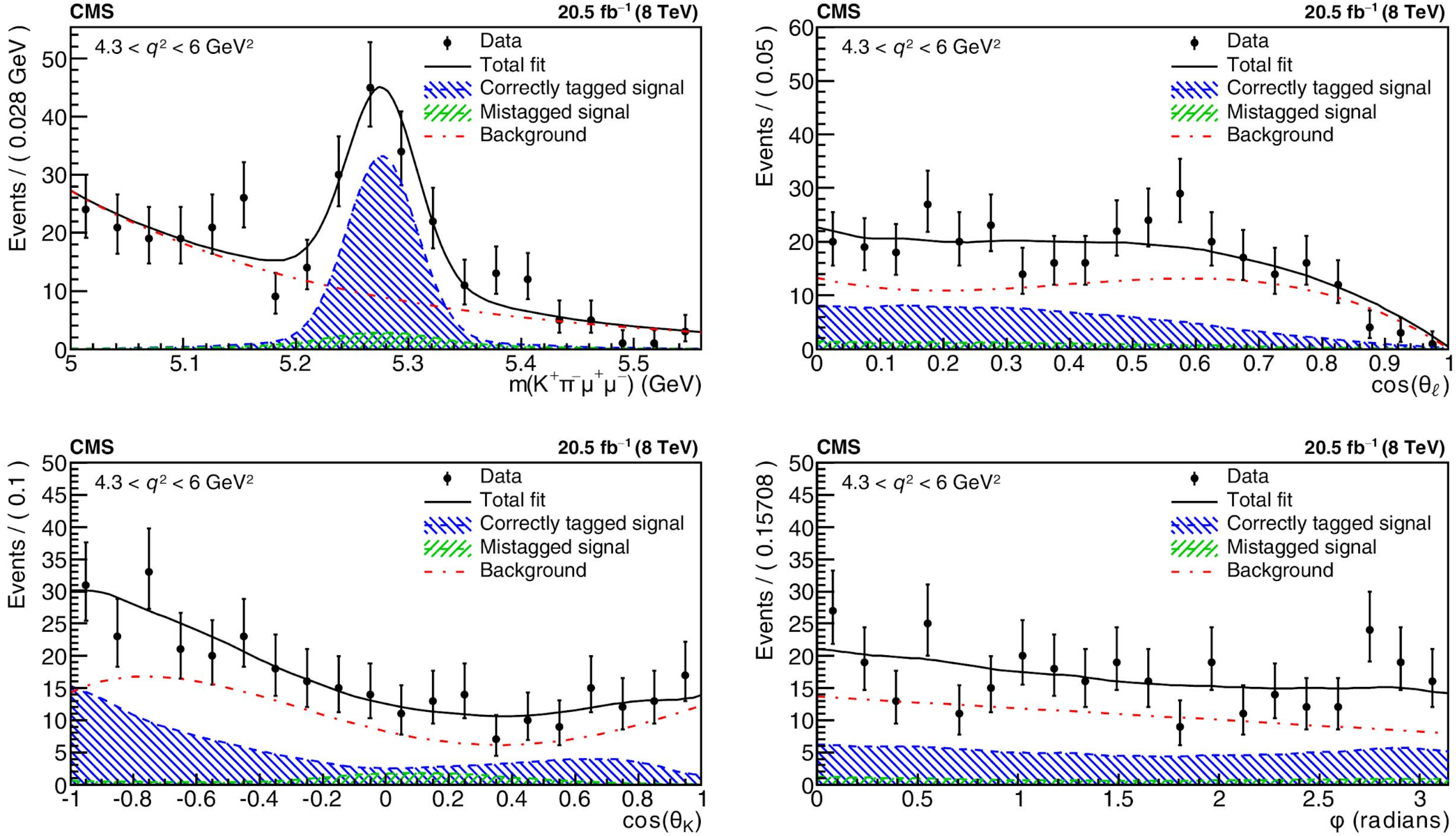
$$
\begin{aligned}
\text{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = {} & Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \\
& + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \Big) \\
& + Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).
\end{aligned}
$$

- Fit performed for 7 (+2 CR) different q^2 bins
- Fit m side bands to determine the background shape;
- Fit whole mass spectrum with 5 floating parameters;
- used unbinned extended maximum likelihood estimator
  - discretize P_1, P_5' space
  - maximize $\mathcal{L}(Y_S, Y_B, A_s^5)$
  - fit $\mathcal{L}$ with 2D-gaussian
  - find abs max of $\mathcal{L}$ inside the physically allowed region
- stat uncert using FC construction along the 1D profiled $\mathcal{L}$

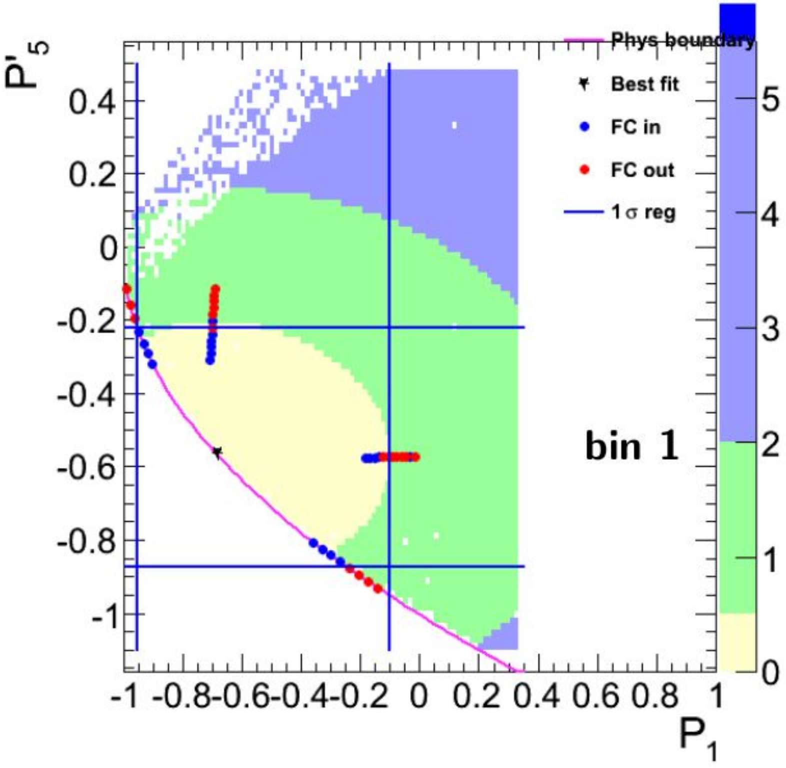


Blind procedure: fit data on signal region once fit procedure fully validated and tested on MC and CR

Fit results for bin $4.3<q^2<6$ GeV^2



Statistical uncert: Feldman-Cousins estimation

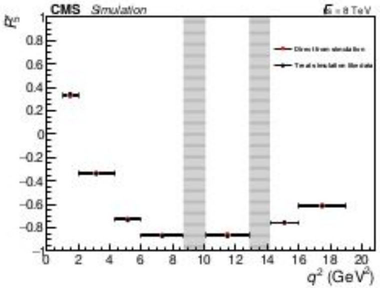


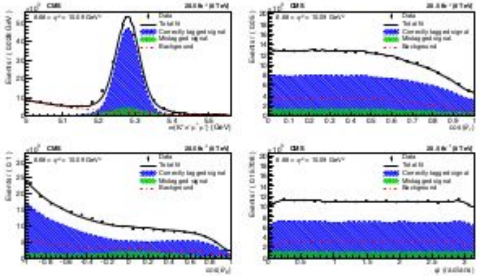
- Feldman-Cousins method used to estimate the confidence interval
- Produce a robust uncertainty estimation even in proximity of the physical boundary
- Approximation used to limit the computing usage:
  - Parameter space probed only along the profiles of the likelihood distribution in data

Fit validation

extensive fit validation with MC: used as **systematics**

- compare fit results with MC input values (**sim mismodeling**)
- compare with data-like MC (**fit bias**)
  - signal only correct tag
  - signal correct+wrong tag
  - signal + background
- Data control channel (J/ψ and $\psi(2S)$), comparing fit results with PDG (F_L) (**efficiency**)
- compare P_1 and P_5' on J/ψ and $\psi(2S)$ w/ and w/o F_L fixed: no bias

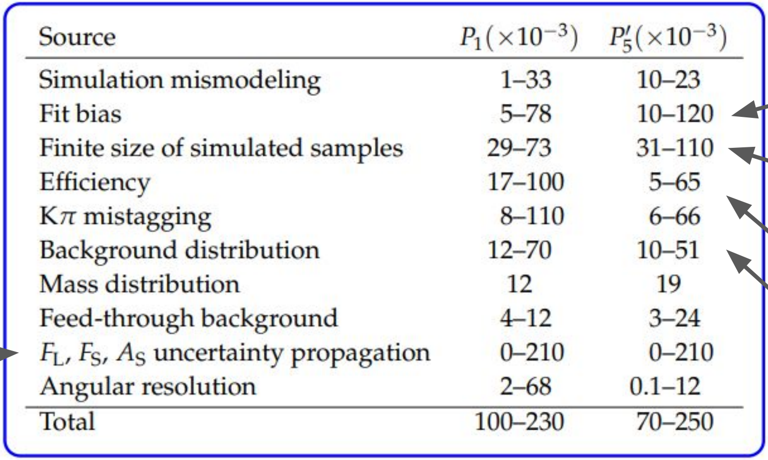




$$\frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S))}{\mathcal{B}(B^0 \to K^{*0}J/\psi)} == \frac{Y_{\psi(2S)}}{\epsilon_{\psi(2S)}}\frac{\epsilon_{J/\psi}}{Y_{J/\psi}}\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)} = 0.480 \pm 0.008(\mathrm{stat}) \pm 0.055(\mathrm{R}_{\psi}^{\mu\mu})$$

vs PDG $0.484 \pm 0.018(\mathrm{stat}) \pm 0.011(\mathrm{syst}) \pm 0.012(\mathrm{R}_{\psi}^{ee})$

Systematics



Source	$P_1 (\times 10^{-3})$	$P'_5 (\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
Background distribution	12–70	10–51
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

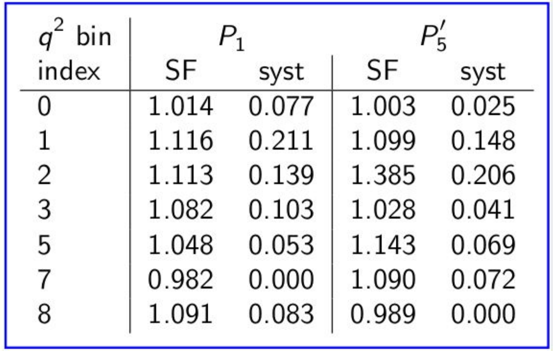
- **Fit bias** with cocktail signal MC + toy background from data side-bands
- **MC stat** due to limited statistics in efficiency shape evaluation
- **Efficiency**: comparing F_L on CR wrt PDG
- **Kπ mistag** evaluated in J/ψ control region and propagated to all bins

Propagation of F_L, F_S, and A_s uncertainties:

- Generate pseudo experiments, with x100 events, for each q^2 bin
- Fit with F_L, F_S, A_s free to float and with F_L, F_S, A_s fixed
- Ratio of stat. uncert. on P_1 and P'_5 with free and fixed fit used to estimate syst uncertainties

Propagation of Fl, Fs, and As uncert

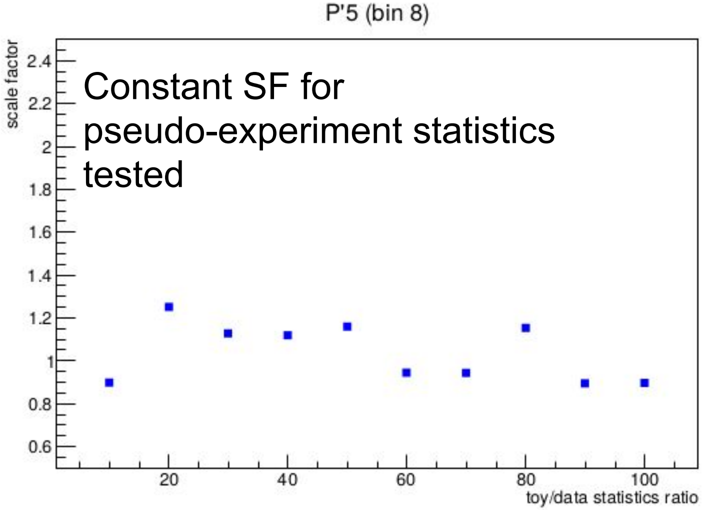
- Generate pseudo-experiments, with x100 events, for each q^2 bin
- Fit with F_L, F_S, A_s free to float and with F_L , F_S , A_s fixed
- Ratio of stat. uncert. on P_1 and P'_5 with free and fixed fit used to estimate syst uncertainties



q^2 bin index	P_1 SF	P_1 syst	P'_5 SF	P'_5 syst
0	1.014	0.077	1.003	0.025
1	1.116	0.211	1.099	0.148
2	1.113	0.139	1.385	0.206
3	1.082	0.103	1.028	0.041
5	1.048	0.053	1.143	0.069
7	0.982	0.000	1.090	0.072
8	1.091	0.083	0.989	0.000

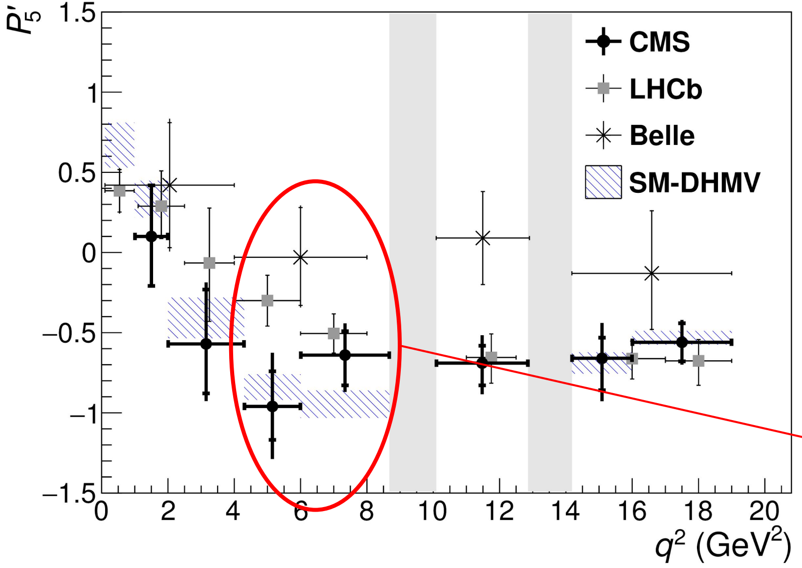
$$\mathrm{SF} = \frac{\sigma_{float}}{\sigma_{fix}}$$

$$\mathrm{Syst} = \sigma_{data}\sqrt{\mathrm{SF}^2 - 1}$$

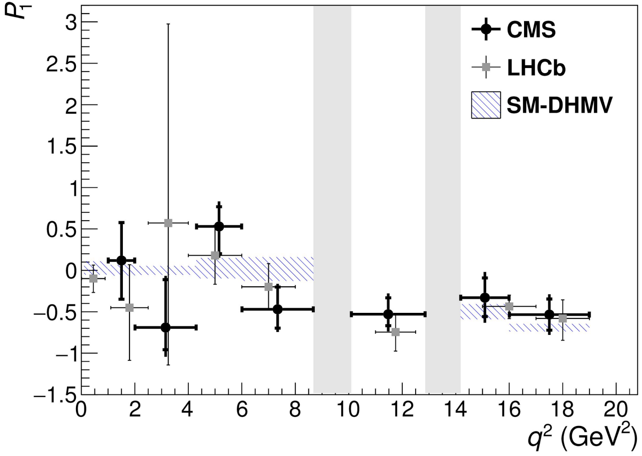


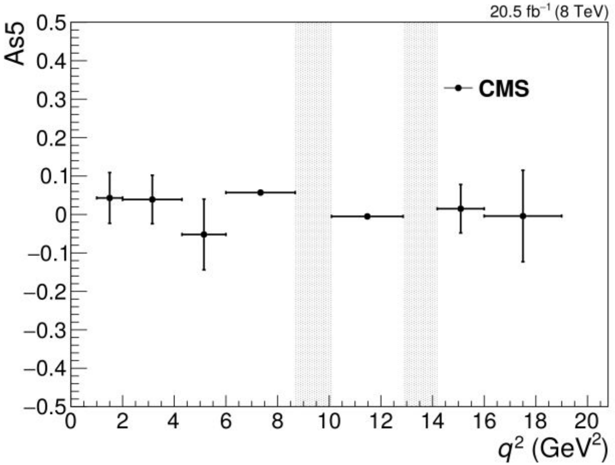
Constant SF for pseudo-experiment statistics tested

Results



q^2 bins with LHCb largest tension wrt SM



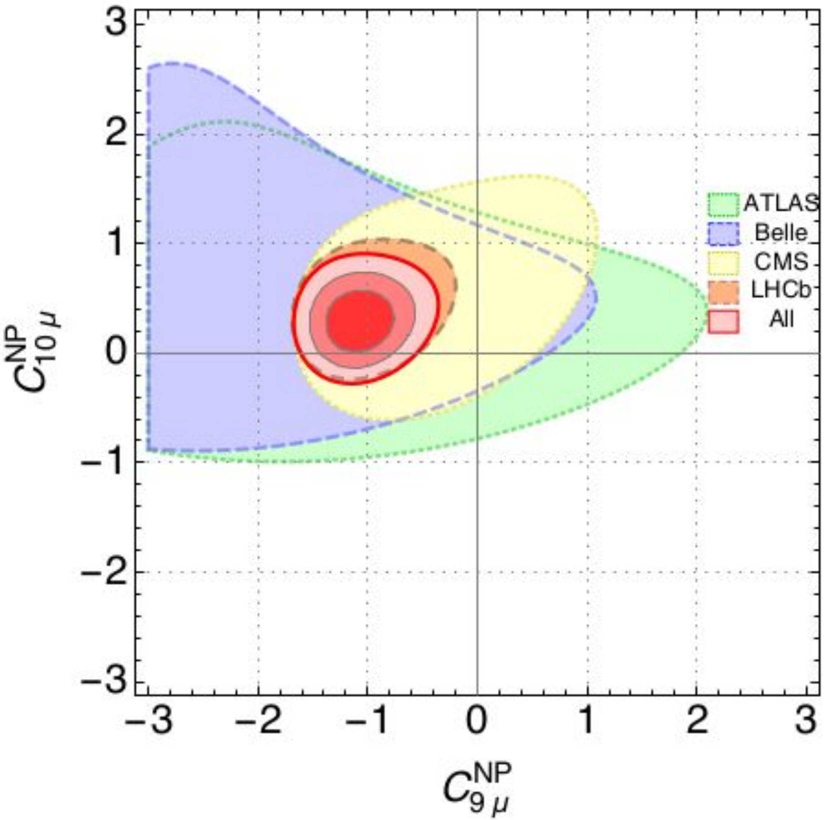


- **SM-DHMV** prediction computed using
  - soft form factors + parametrized power corrections
  - hadronic charm-loop contribution derived from calculations
- **Results compatible with SM predictions**
- No significant deviations with other experimental results

Global fit

Capdevila, B.. *et al.* Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data. *J. High Energ. Phys.* 2018, 93 (2018) doi:10.1007/JHEP01(2018)093

- global fit to all available $b \to s l^+ l^-$ data
  - l = μ, e [Belle]
  - $C_{9\mu}^{NP} = C_9 - C_9^{SM}$
  - 3σ constraint for each experiment
- constraints from b → sγ, $B(B \to X_s \mu\mu)$ and $B(B_s \to \mu\mu)$ included
- 3σ constraint for each experiment
- CMS is consistent with (0,0)
  - As Belle and ATLAS
- LHCb is not
- And it drives the global fit
  - 1,2,3σ contours shown
  - 5σ effect (?)

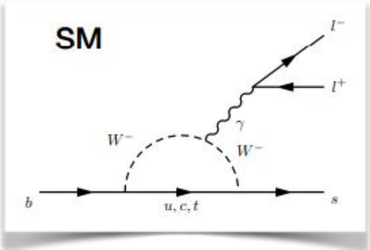


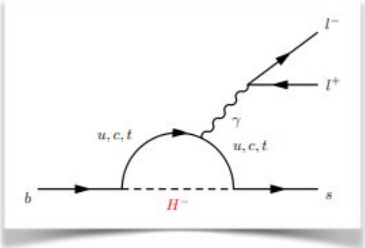
B^+->K^+ $\mu\mu$

Phys. Rev. D 98 (2018) 112011 - arXiv:1806.00636

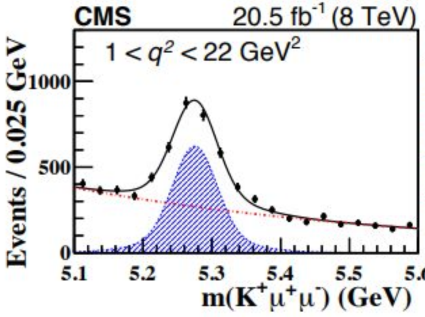
$B^+ \to K^+ \mu\mu$ decay: overview

- The decay $B^+ \to K^+ \mu\mu$ is a FCNC process of the type b → sll
    - forbidden at tree level in the SM (BR ~ 4.4 x 10-7)
- New heavy particles from NP can appear in competing diagrams, affecting the differential angular distributions
- Previously studied by BABAR , Belle, CDF, and LHCb
    - no hints of beyond SM physics
- CMS analysis is based on Run 1 data at 8 TeV (20.5 fb-1)
    - events selected by a displaced dimuon trigger
    - cut-based selection determined to optimise signal significance
    - **2286 ± 73** signal events with $1 < q^2 < 22\ \mathrm{GeV}^2$





Phys. Rev. D 98 (2018) 112011 - arXiv:1806.00636

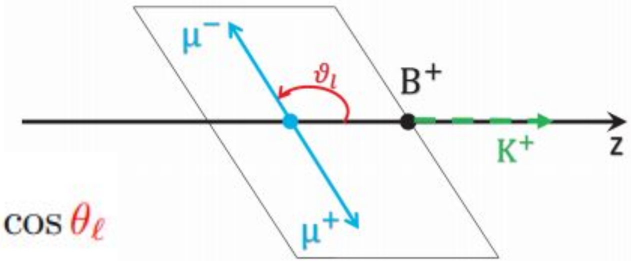


Phys. Rev. D 98 (2018) 112011

Angular analysis of the $B^+ \to K^+ \mu\mu$ decay

- Fully described by the angle θ_l and $q^2 = M^2_{\mu\mu}$;
  - θ_l angle between μ^- and K^+ in the dimuon rest frame
- Angular decay rate:

$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell} = \frac{3}{4}(1 - F_H)(1 - \cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell$$

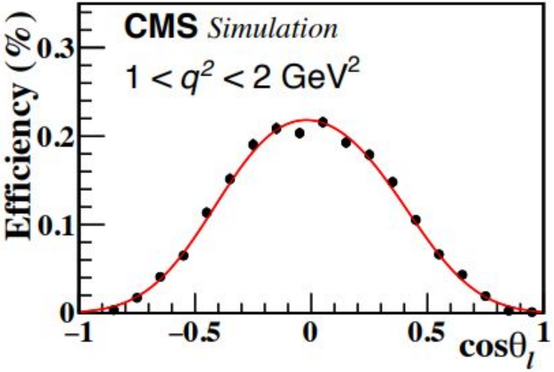


- A_{FB}: forward-backward asymmetry of dimuon system
  - Expected to be zero in SM (up to small correction)
- F_H: contribution from the (pseudo)scalar and tensor amplitudes to the decay width
  - Predicted to be small as well in SM
- Range of q^2 divided in 9 bins:
  - 7 signal bins
    - Plus 2 resonant decays $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$ used as control channel
  - 2 additional special bins:
    - [1-6] GeV^2 (clean predictions) and [1-22] GeV^2 (full signal)

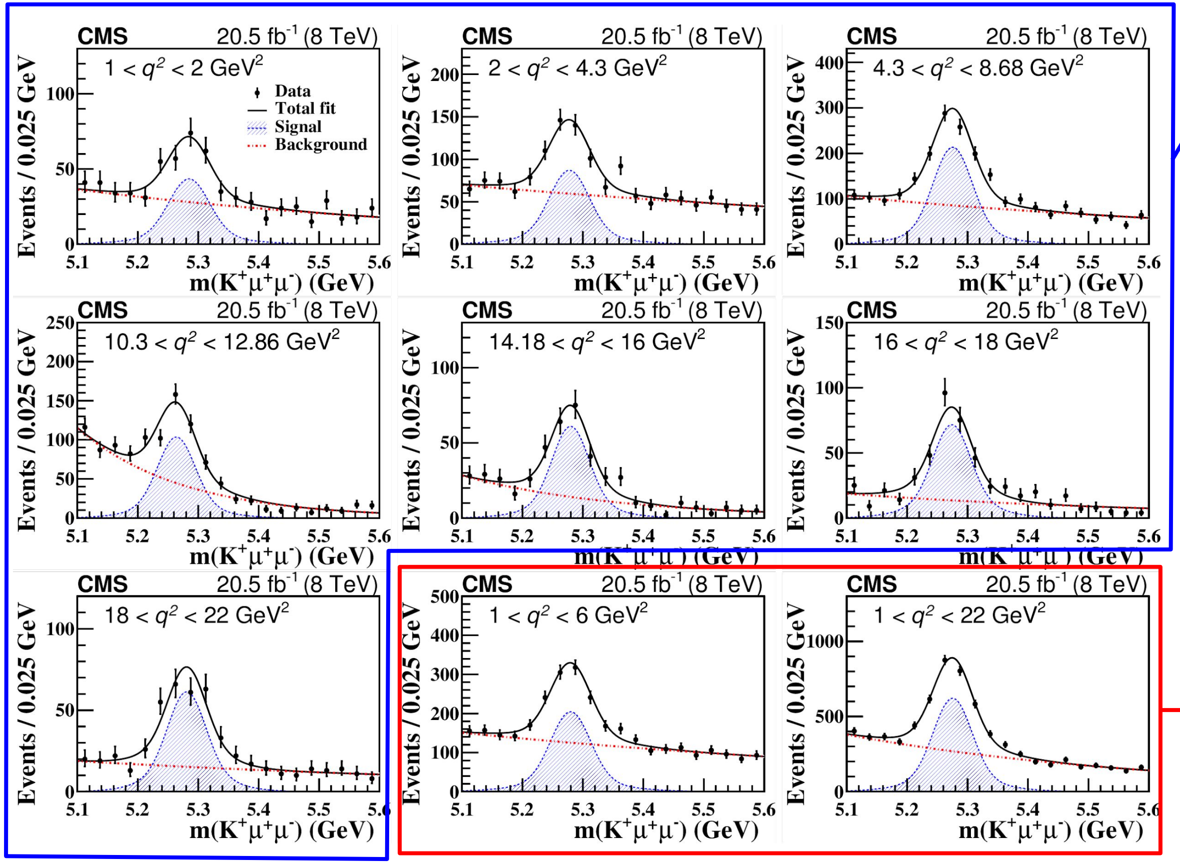
Parameter extraction

$$\begin{aligned}\text{p.d.f.}(m, \cos\theta_l) &= Y_S \cdot S_i(m) \cdot S_i^a(\cos\theta_l) \cdot \epsilon_i(\cos\theta_l) \\ &+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_l}(\cos\theta_l)\end{aligned}$$

- Extended 2D UML fit
- Signal:
  - Double gaussian mass shape
  - Angular decay rate
- Efficiency:
  - From MC, parametrized with 6th-order polynomial
  - Validated on control region $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$
- Background extracted from data side-bands
- Two-step fit:
  - fit m side bands to determine the background shape (fixed in second step)
  - fit whole mass spectrum with 4 floating parameters (2 yields + 2 angular param)
- Statistical uncertainty using profiled Feldman-Cousins method



B^+ mass distribution and signal yield

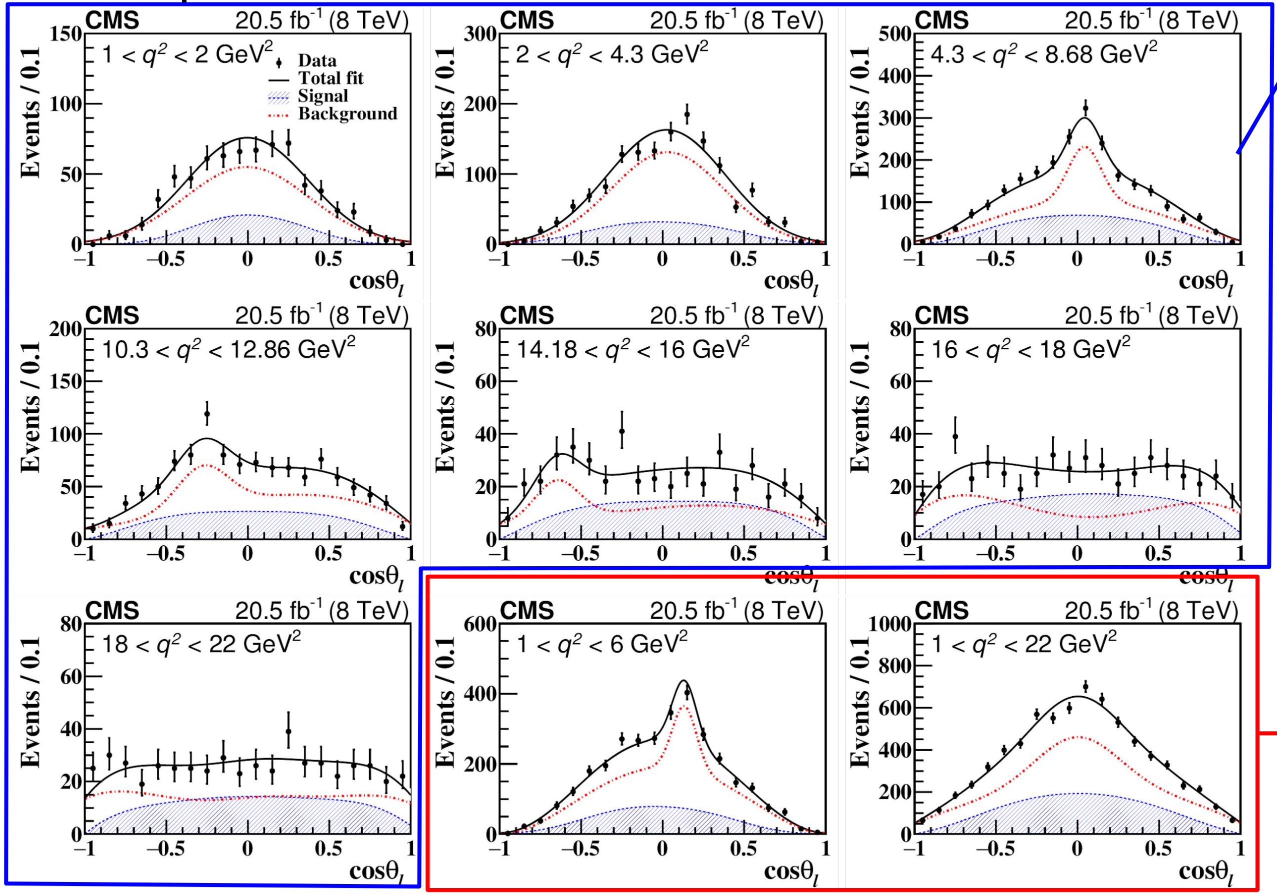


7 signal bins

q^2 (GeV^2)	Y_S
1.00–2.00	169 ± 22
2.00–4.30	331 ± 32
4.30–8.68	785 ± 42
10.09–12.86	365 ± 29
14.18–16.00	215 ± 19
16.00–18.00	262 ± 21
18.00–22.00	226 ± 20
1.00–6.00	778 ± 47
1.00–22.00	2286 ± 73

2 inclusive bins

$\cos(\theta_l)$ fit results



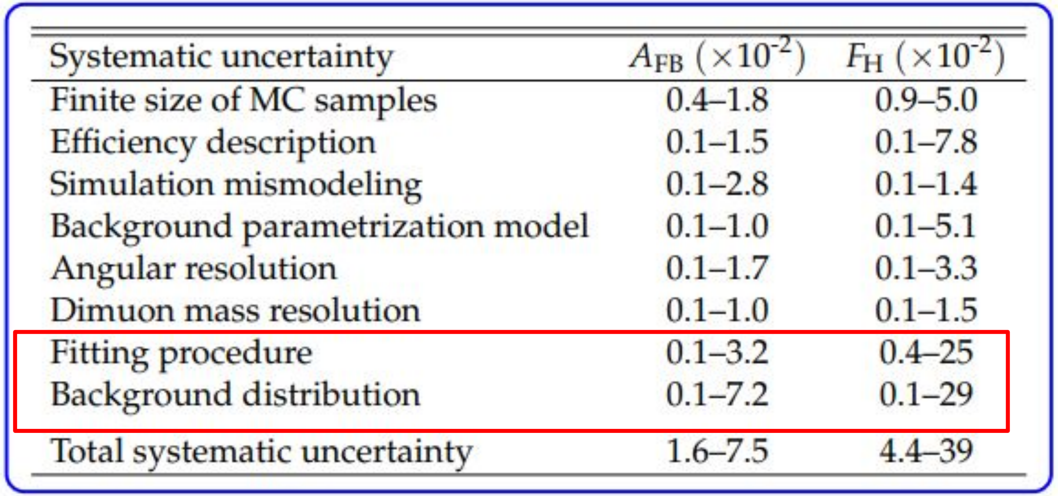
7 signal bins

2 inclusive bins

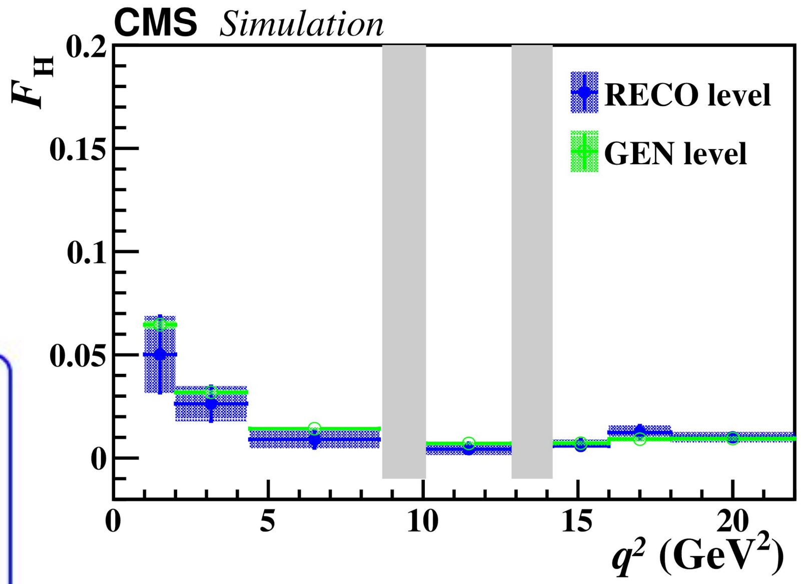
- Peak structure in $\cos(\theta_l)$ presents in side bands
    - Modelled from SB
- Origin not understood,
- systematics included.

Validation and systematic

- Efficiency, fit procedure validated:
  - High statistics MC
  - Data-like statistics MC
  - Toys
  - Control regions (resonant)

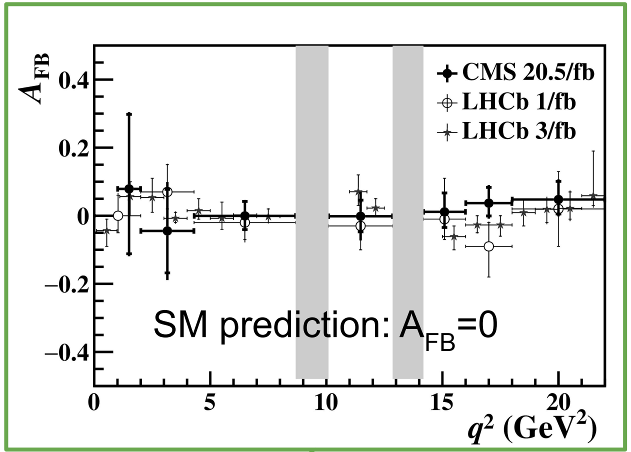


Systematic uncertainty	A_{FB} ($\times 10^{-2}$)	F_H ($\times 10^{-2}$)
Finite size of MC samples	0.4–1.8	0.9–5.0
Efficiency description	0.1–1.5	0.1–7.8
Simulation mismodeling	0.1–2.8	0.1–1.4
Background parametrization model	0.1–1.0	0.1–5.1
Angular resolution	0.1–1.7	0.1–3.3
Dimuon mass resolution	0.1–1.0	0.1–1.5
Fitting procedure	0.1–3.2	0.4–25
Background distribution	0.1–7.2	0.1–29
Total systematic uncertainty	1.6–7.5	4.4–39



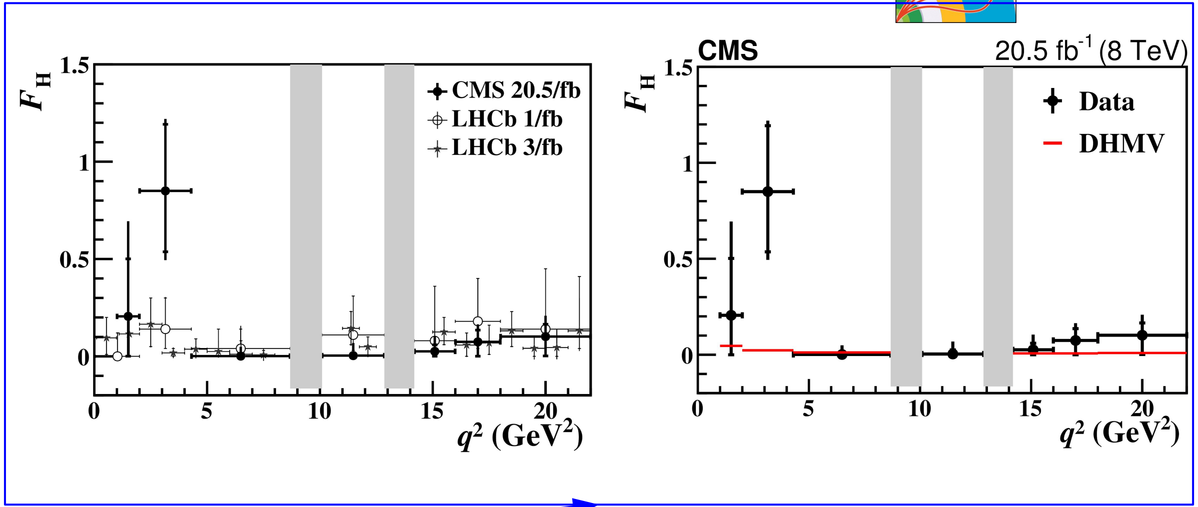
Systematic dominated by
- **Fit procedure**
- **Background description**

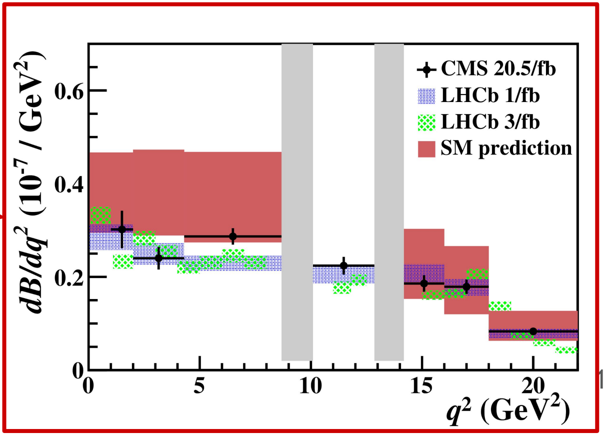
Results



SM prediction: A_{FB}=0

F_H





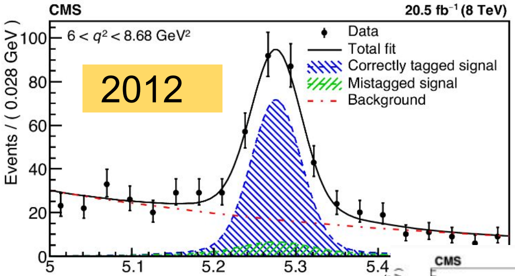
- **A_{FB}** and **F_H**:
  - Good agreement with SM and LHCb measurement
- Measured also differential **branching fraction** vs q^2:
  - Good agreement with LHCb
  - Confirm lower values than SM predictions

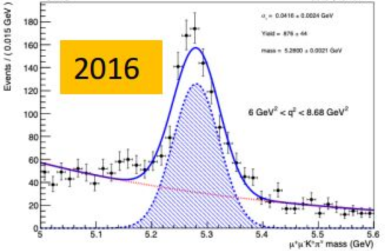
Perspective:

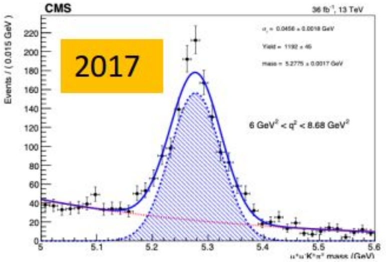
- Run 2: 13 TeV
- Other channels for angular analysis
- Parking data

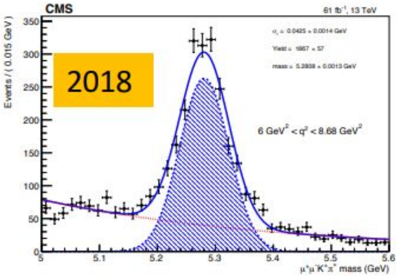
$B^0 \rightarrow K^*\mu\mu$ at 13 TeV

- So far, CMS used 7+8 TeV data (5+20 fb^{-1})
  - **Other 140 fb^{-1} collected at 13 TeV**
  - **σ(pp->bX) increase 2x between 8->13 TeV**
- Di-muon displaced trigger was active
  - harder threshold at L1 but still effective
- Foreseen improvements:
  - Optimized signal selection (BDT vs cut): higher eff, same background
  - Larger statistical sample: **O(15’000) candidates (was 1400 at 8 TeV)**
    - Expected O(13000 for Belle2 at 50 ab^{-1}) per lepton channel
  - Full angular fit: all parameters and correlations
    - Possibly a finer binning
  - Alternative analysis using moments method
    - Exploit orthogonality of terms of decay rate (3D spherical harmonics)
    - Robust for low signal yield (more bins)
- Timescale: goal is summer 2020 (we will see)





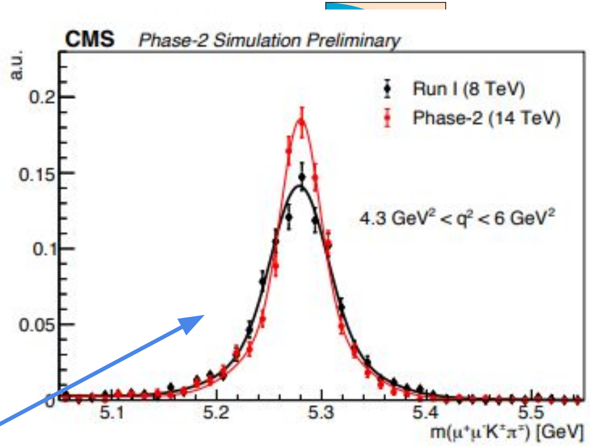


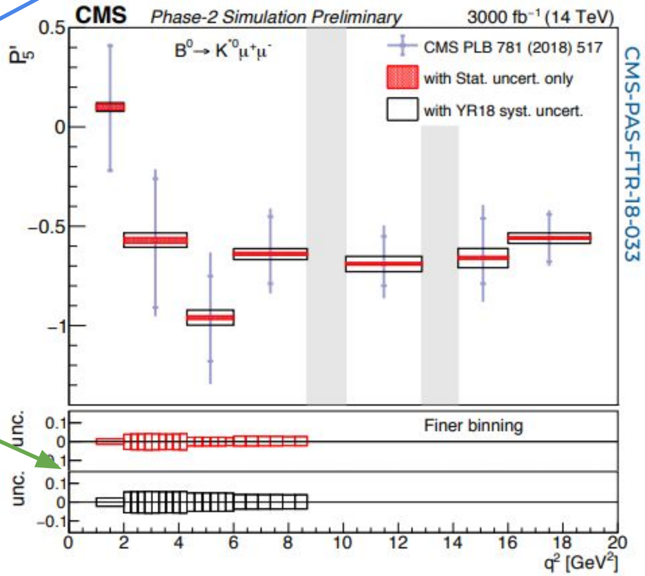


$B^0 \rightarrow K^*\mu\mu$ at High Lumi

CMS-PAS-FTR-18-033

- Extrapolated sensitivity to P'_5 with 3000 fb^{-1}
    - Expected 200 Pile Up
    - Same analysis strategy and trigger
    - Statistical improvement: expected ~700 k events in full q^2 range
        - Systematics scaled by factor 2: more control sample
    - Mass resolution will be better with new tracker
- Uncertainties are estimated to improve up to a factor of 15 compared to the Run-1 result
    - Much finer binnig will be possible





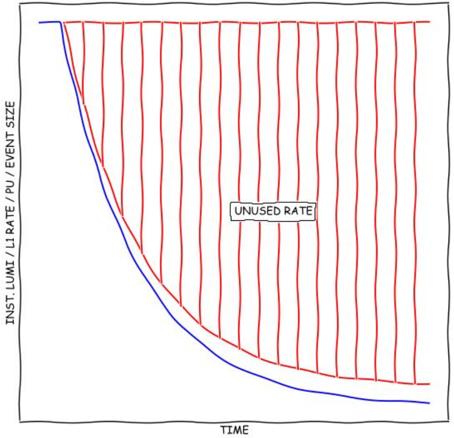
Other possible measurement in CMS

- **$B_d^0 \rightarrow K^{*0} \mu\mu$**
  - Published for Run1: BR and partial angular analisis
  - At Run2: BR and full angular analysis.
    - Yield O(15.5k) events (was 1.4 at Run1): Summer ?
- **$B_s^0 \rightarrow \phi\mu\mu$**
  - Not done at Run1, being done at Run2
    - Extrapolated yield O(800) events in full q^2 range
  - Expect BR and partial angular analysis. No self tagging final status
- **$B^+ \rightarrow K^+ \mu\mu$**
  - Run1: full angular analysis, no BR
    - Yield O(2300) ev: extrapolated to Run2: O(25k) events
- **$B^+ \rightarrow K^{*+} \mu\mu$**
  - Run1: partial angular analysis, no BR, not published yet
  - Currently in approval process: Spring?
    - Yield very low O(100) events: extrapolated O(1000) events at Run2

Can CMS do more?

The issue is the trigger

Parking concept



- Used with success for Run1 2012
- **DAQ bandwidth exceed computing capacity for experiment**
    - Can write ~1kHz on tape, cannot prompt process all of them
    - Park some of the data, to be processed later during LHC downtime
    - In particular LHC long shutdown
- On 2012, recorded ~1kHz extra data (7-18 fb^{-1} at 8 TeV) with VBF, single photon, and B-physics trigger
    - It worked: published several paper with that data
        - "Search for exotic decays of a Higgs boson into undetectable particles and photons", Phys. Lett. B 753 (2016) 363
        - "Search for the standard model Higgs boson produced through vector boson fusion and decaying to bb", Phys. Rev. D 92 (2015) 032008
- 2018: devote all extra capacity to B-physics program

Motivation and goal

- Lepton Flavour Universality seriously challenged by R(K$^{(*)}$) measurement
  - Mostly LHCb but also Belle [also charged] (and BaBar)

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

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

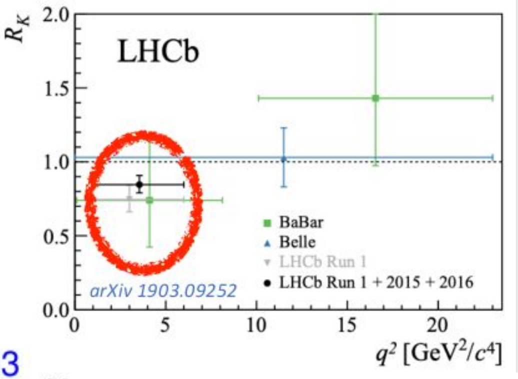
$$\text{Theory:} \quad R_K^{[1,6]} = 1.00 \pm 0.01$$

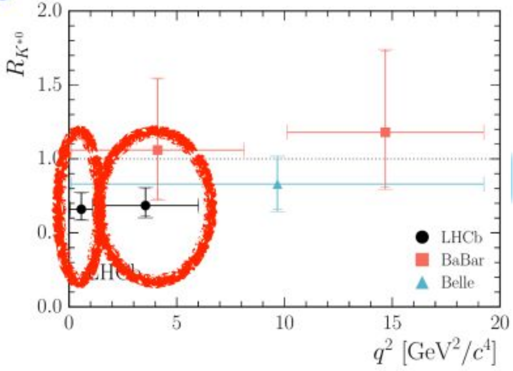
$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

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

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

$$R_K = 0.846 \, {}^{+0.060}_{-0.054} \, {}^{+0.016}_{-0.014}$$

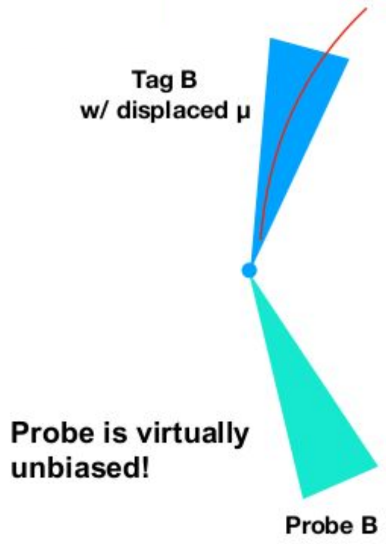




- Can CMS enter the game?
  - “Easy” for muon channel, hard for electron one: trigger is the problem
- **Goal: to record ~10^{10} unbiased B hadron decays in 2018, using the flexibility of the CMS data taking model**

B parking trigger strategy

- **Trigger on Tag side:** look at unbiased probe side
- **L1** seed: single μ, $|\eta|$-restricted
  - L1 is the limiting factor
- **HLT**: non isolated, displaced μ in the TAG side
  - As lumi drops during LHC fill, enable lower single μ, $|\eta|$-restricted, L1 threshold and increase HLT rate

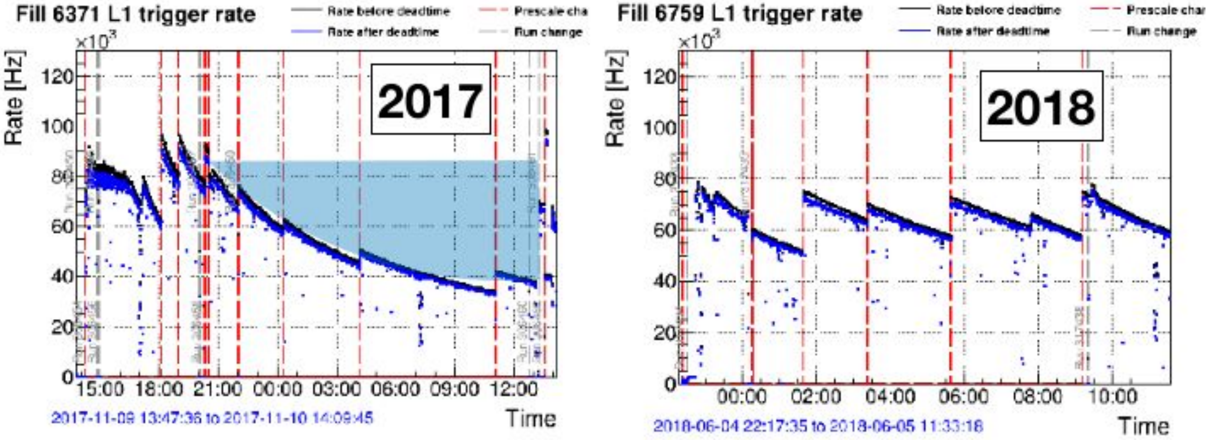


Tag B w/ displaced μ

Probe is virtually unbiased!

Probe B

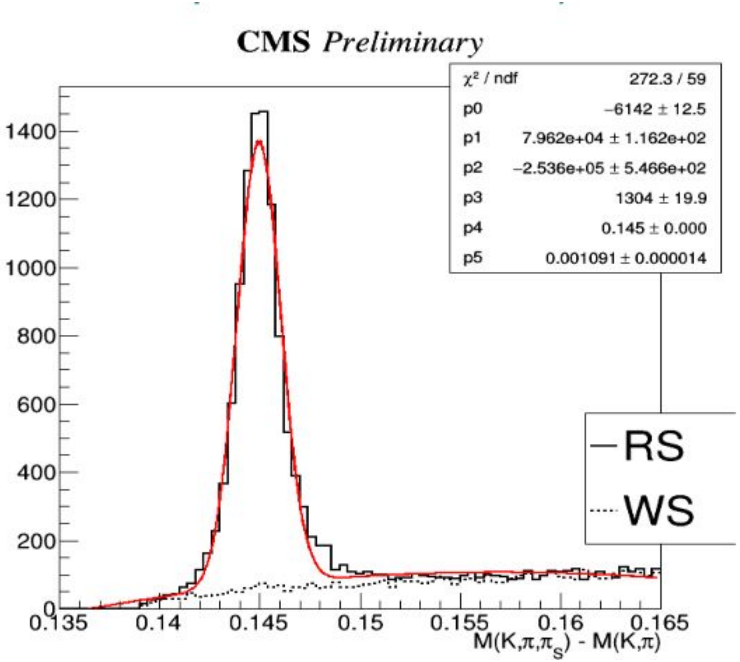
Trigger strategy — L1

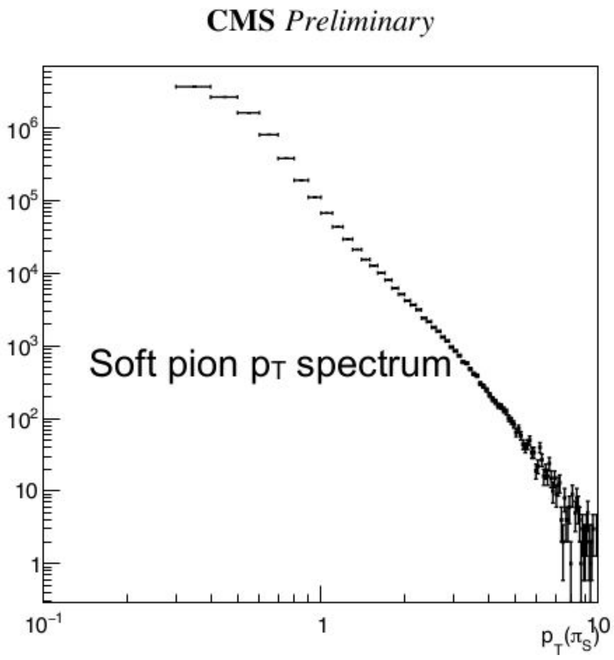


Lumi (E34)	L1 seed	HLT	rate	purity	#B
1.7	Mu12er1p5	Mu12_IP6	1585	0.92	10.5M
1.5	Mu10er1p5	Mu9_IP5	3656	0.80	21M
1.3	Mu8er1p5	Mu9_IP5	3350	0.80	20M
1.1	Mu8er1p5	Mu7_IP4	6153	0.59	33M
0.9	Mu7er1p5	Mu7_IP4	5524	0.59	29M

Purity

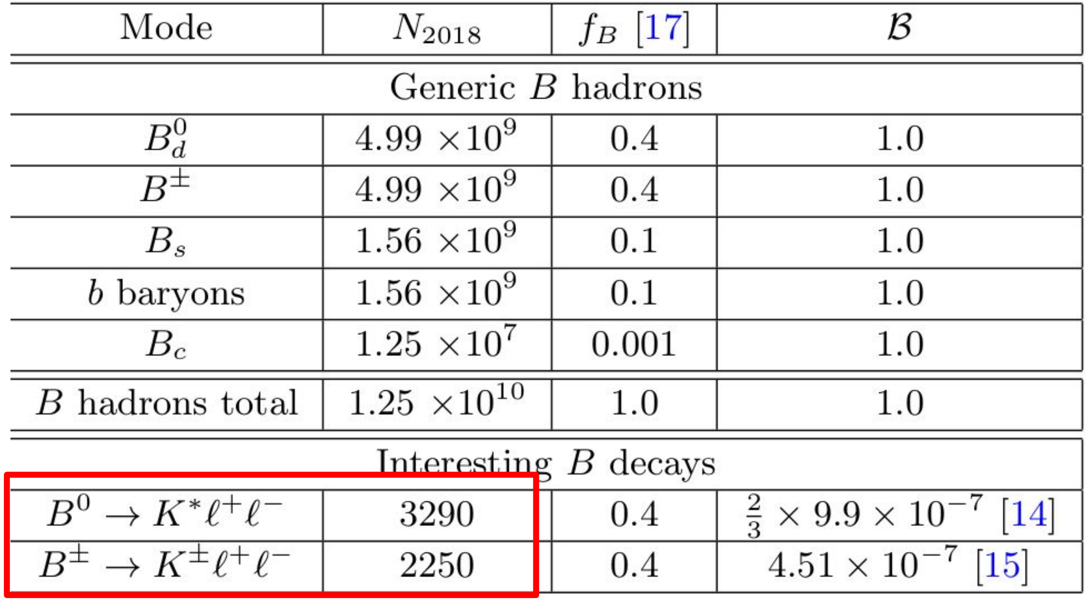
- Fraction of triggers from b->μ decays, using B^0->D*$\mu\nu$->$K\pi\pi_s\,\mu\nu$
- Average purity probe side: ~73% (using 5% of the full parked dataset)





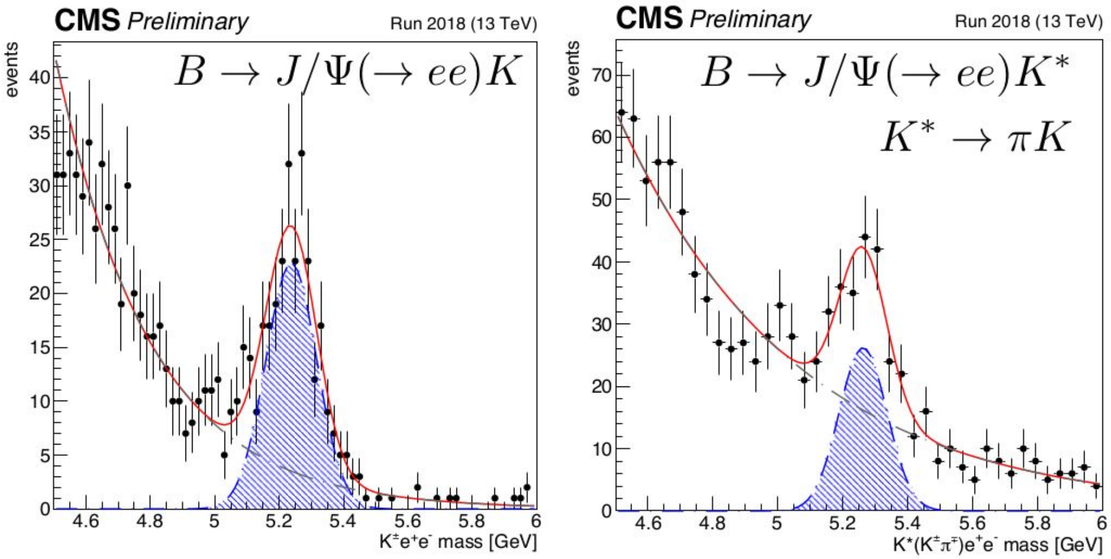
Data collected

- An impressive success! No incident (eg saturation of DAQ/Tier0)
- Collected ~1.2 x 10^{10} triggers, or ~10^{10} B, 40 fb^{-1}
  - Full reconstruction finished december last year

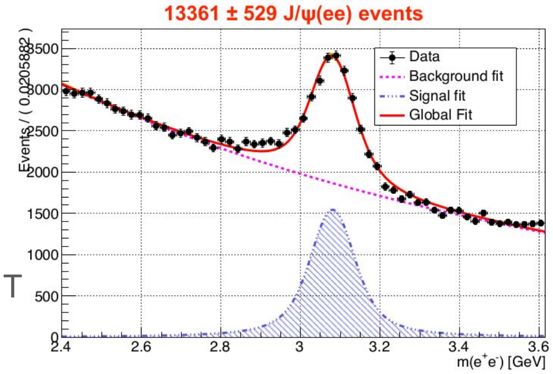


Mode	N_{2018}	f_B [17]	$\mathcal{B}$
Generic B hadrons			
B_d^0	4.99×10^9	0.4	1.0
$B^\pm$	4.99×10^9	0.4	1.0
B_s	1.56×10^9	0.1	1.0
b baryons	1.56×10^9	0.1	1.0
B_c	1.25×10^7	0.001	1.0
B hadrons total	1.25×10^{10}	1.0	1.0
Interesting B decays			
$B^0 \to K^* \ell^+ \ell^-$	3290	0.4	$\frac{2}{3} \times 9.9 \times 10^{-7}$ [14]
$B^\pm \to K^\pm \ell^+ \ell^-$	2250	0.4	4.51×10^{-7} [15]

Electron reco



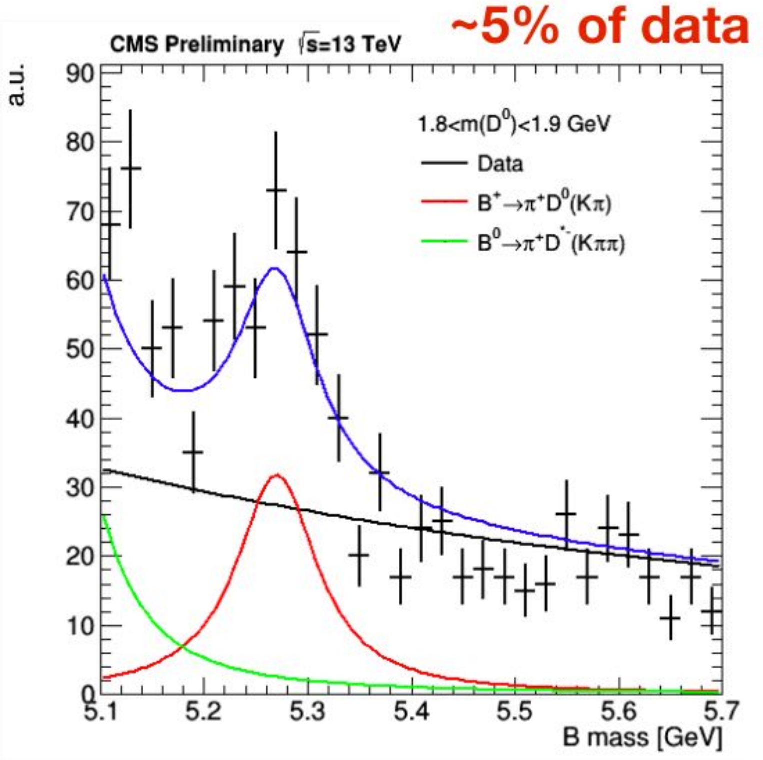
- First observation of these decays K, in CMS
- **5% of parked data**
- Out of the box reconstruction,
  - optimized for high pT electrons



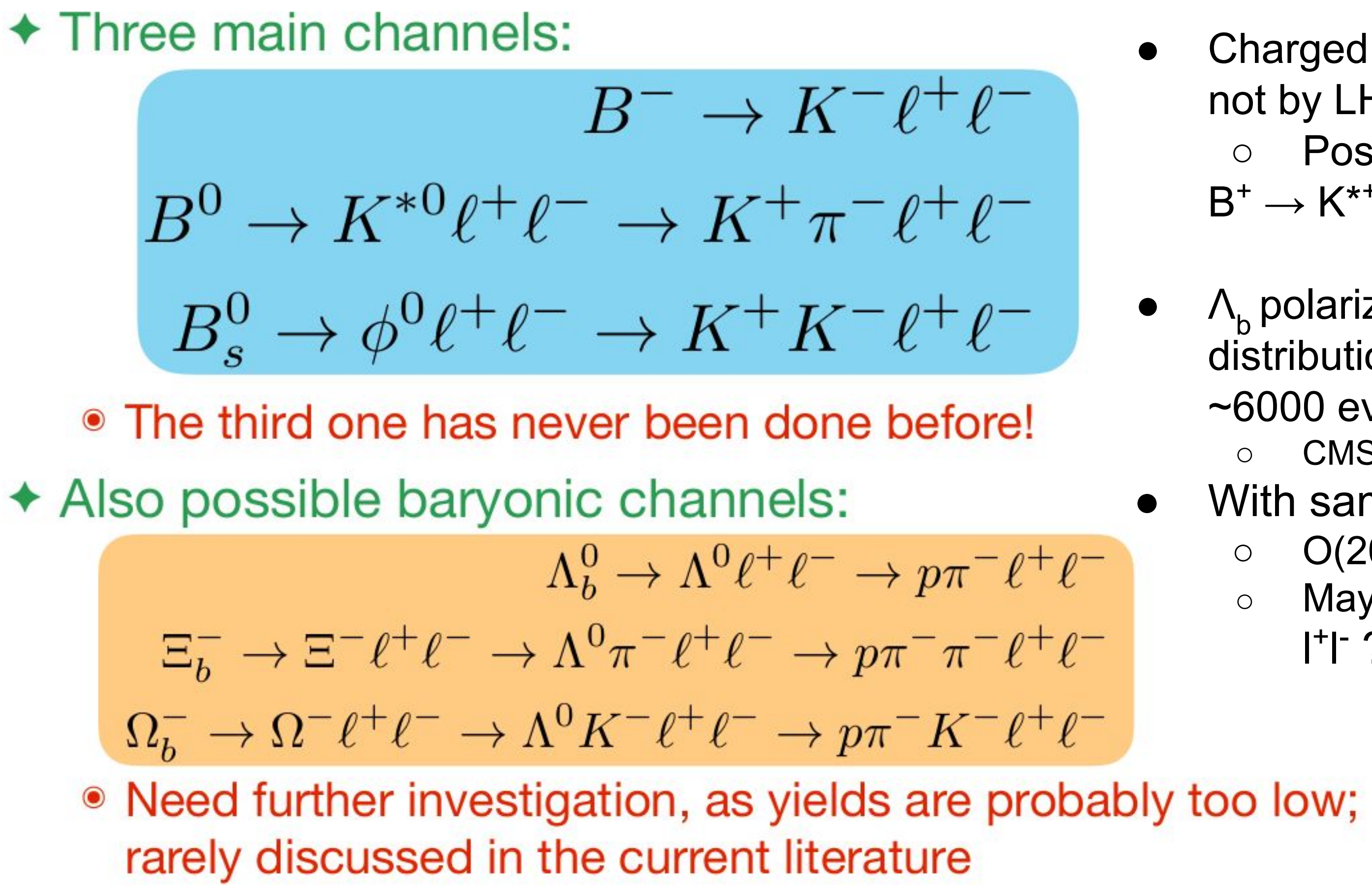
- significant effort to improve electron reconstruction at low p_T
  - Combination of ECAL cluster-seeding and track-based seeding
  - x3 eff increase achieved, still some more room for improvement

First All-Hadronic Decay in CMS

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



LFV program



- Three main channels:

$$B^- \to K^- \ell^+ \ell^-$$
$$B^0 \to K^{*0} \ell^+ \ell^- \to K^+ \pi^- \ell^+ \ell^-$$
$$B_s^0 \to \phi^0 \ell^+ \ell^- \to K^+ K^- \ell^+ \ell^-$$

  - The third one has never been done before!

- Also possible baryonic channels:

$$\Lambda_b^0 \to \Lambda^0 \ell^+ \ell^- \to p \pi^- \ell^+ \ell^-$$
$$\Xi_b^- \to \Xi^- \ell^+ \ell^- \to \Lambda^0 \pi^- \ell^+ \ell^- \to p \pi^- \pi^- \ell^+ \ell^-$$
$$\Omega_b^- \to \Omega^- \ell^+ \ell^- \to \Lambda^0 K^- \ell^+ \ell^- \to p \pi^- K^- \ell^+ \ell^-$$

  - Need further investigation, as yields are probably too low; rarely discussed in the current literature

- Charged channel (done by Belle, not by LHCb) can be interesting
  - Possibly also
$B^+ \to K^{*+} l^+ l^- \to K^0_S \pi^+ l^+ l^-$

- Λ_b polarization and angular distribution studied at CMS with ~6000 ev (Run1 7+8 TeV)
  - CMS, arXiv:1802.04867
- With same cuts:
  - O(20k) events in parked DS
  - Maybe O(100) non resonant l^+l^- ?

Other B Physics Topics

- So far, we only brainstormed other potential physics cases
- Some (rough) ideas:
    - Rare B_s decays: ττ, φφ, KK, Kπ, K*K* , K τ τ, K* τ τ
    - R($D^{(*)}$) measurement
    - Flavor violating decays: B (s) → τμ, τe
    - CP-violation in various decays, using opposite-side tagging
    - Perhaps even probe τ → 3μ via $3x10^8$ $D^{(*)}$τν decays →$D^{(*)}$ μμμ ν
    - Explore CMS strengths over LHCb: K^0_s , Λ reconstruction, and use of narrow resonances (e.g., ϕ, D*) to reduce backgrounds given the lack of particle ID in CMS
- Your favorite topic here

Conclusion

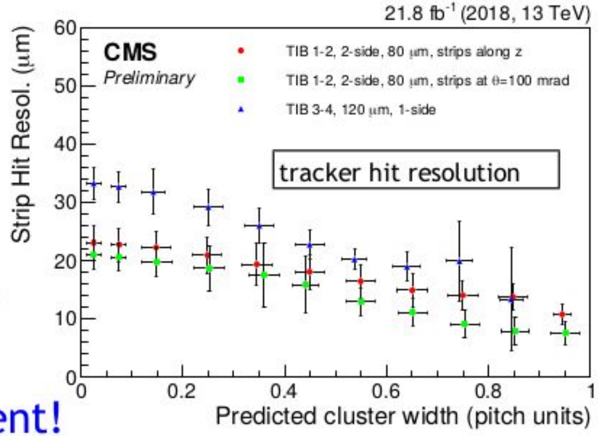
- B^0->K*μμ partial angular analysis performed at CMS with Run 1, 8 TeV Data
    - With 1400 signal event, no significant deviation from SM prediction for P'_5 found
    - Will perform a full angular analysis on run2: 15'000 signal events
- B^+->K+μμ full angular analysis performed
    - no deviation as well
- 10^{10} unbiased B events collected in 2018 via parking which are being analyzed
    - Expect competitive results on $R(K^{(*)})$ and many more channels
- **Exciting time for B-physics in CMS**

Backup

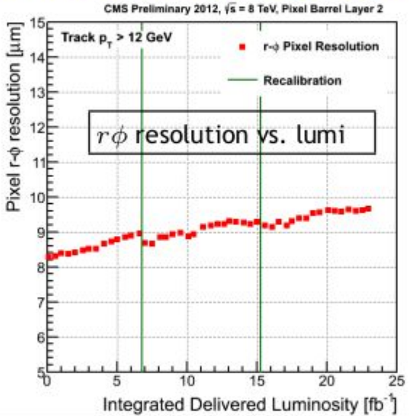
3D tracking and vertexing

- All silicon tracker
  - ▷ high granularity, low occupancy
  - → well described by MC simulation
- Pixel detector
  - ▷ $100 \times 150\,\mu\text{m}^2$ pixel size
  - ▷ substantial charge sharing (low V_{bias})
  - → excellent resolution in $r\phi$ and z

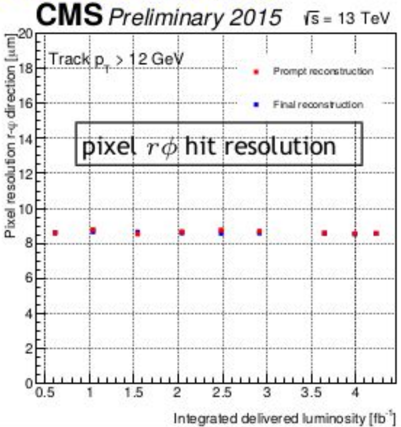
⇒ Essential in high-pileup environment!



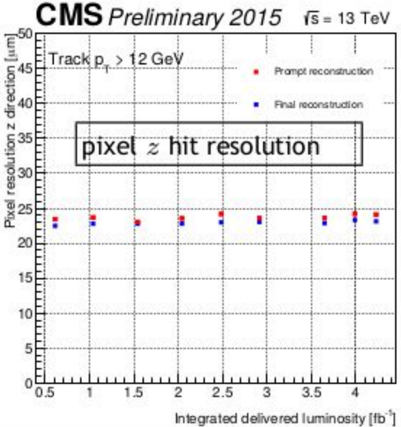
tracker hit resolution



$r\phi$ resolution vs. lumi



pixel $r\phi$ hit resolution



pixel z hit resolution

Muon reconstruction

JINST,13,P06015
JINST,7,P10002

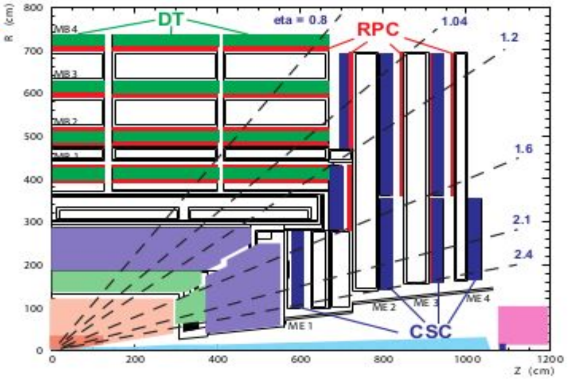
- Large muon acceptance $|\eta| < 2.4$
  - ▷ drift tubes
  - ▷ cathode strip chambers
  - ▷ resistive plate chambers
- 3 muon reconstruction algorithms
  - ▷ standalone muon: in muon system (trigger ingredient)
  - ▷ global muon ('GM'): outside-in standalone muon $\rightarrow$ to inner track
  - ▷ 'soft' and 'BDT'

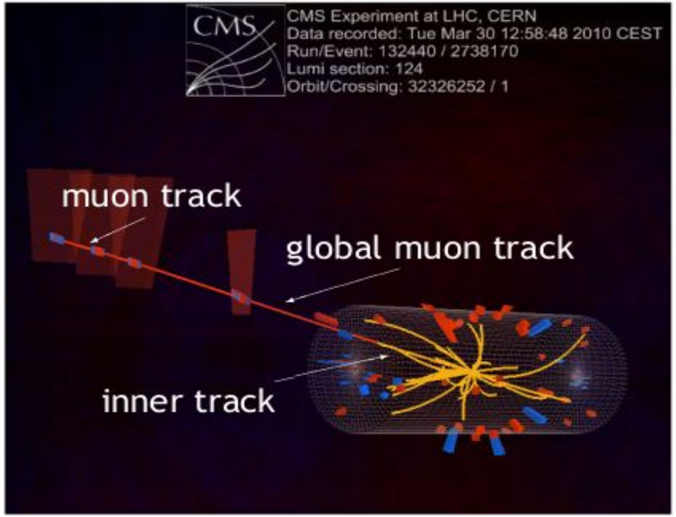
Muon misidentification for BDT muons

$$\varepsilon(\mu|\pi) \approx 0.06\%$$
$$\varepsilon(\mu|K) \approx 0.10\%$$
$$\varepsilon(\mu|p) \leq 0.01\%$$

measured/validated in data:

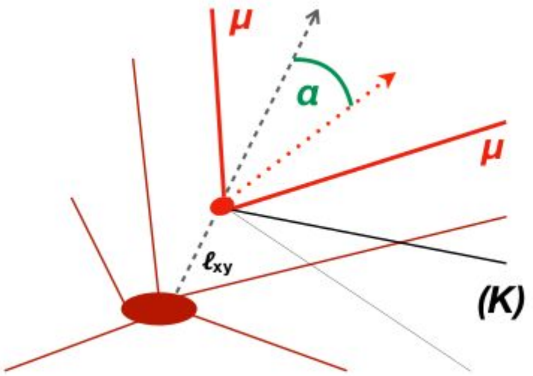
$K^0_S \rightarrow \pi^+\pi^-$, $\phi \rightarrow K^-K^+$, $\Lambda \rightarrow p\pi^-$
$D^{*+} \rightarrow D^0\pi^+_s \rightarrow K^-\pi^+\pi^+_s$

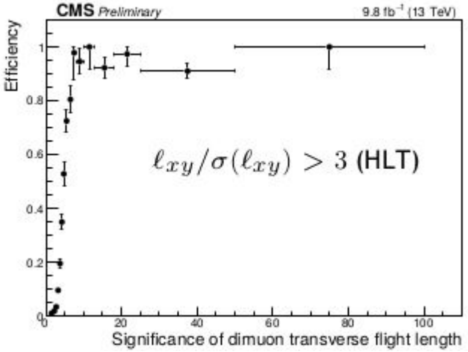




Displaced J/ψ and B_s^0 → μ+μ− triggers

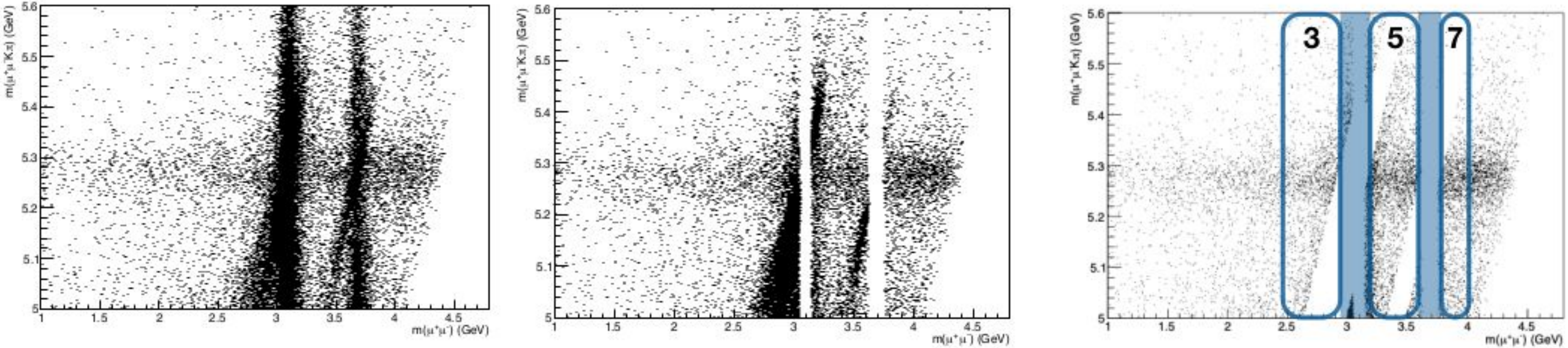
- HLT 'displaced' J/ψ
  - ▷ two muons with opposite charge
    $2.9 < m_{\mu\mu} < 3.3$ GeV
  - ▷ $\cos\alpha > 0.9$, $\mathcal{P}(\chi^2/dof) > 15\%$
- HLT 'displaced' J/ψ + track(s)
  - ▷ two muons with opposite charge
    $2.9 < m_{\mu\mu} < 3.3$ GeV
  - ▷ $\cos\alpha > 0.9$, $\mathcal{P}(\chi^2/dof) > 15\%$
  - ▷ invariant mass requirements on tracks
    (targeted towards $\phi \to K^+K^-$)
- HLT $B_s^0 \to \mu^+\mu^-$
  - ▷ two muons with opposite charge
  - ▷ $p_\perp > 4.0(3.5)$ GeV, $\mathcal{P}(\chi^2/dof) > 0.5\%$
  - ▷ inv. mass $4.8 < m_{\mu\mu} < 6.0$ GeV
  - ▷ no displacement requirement!





Anti radiation cut

- Remove mass window evt by evt : $|m(\mu\mu) - m_{J/\psi}(m_{\psi'})| < 3\sigma_q$ ($\sigma_q \approx 26$ MeV)
- Cuts combining m_{B0}&$m_{\mu\mu}$ applied to further reject feed-through from control channels ($J/\psi(\psi') \rightarrow \mu^+\mu^-\gamma$):
  - Events are rejected if $|(m(K\pi\mu\mu) - m_{B^0_{PDG}}) - (m(\mu\mu) - m_{\phi PDG})| < \Delta m$



Decay rate

$$\frac{\mathrm{d}^4\boxed{\Gamma}[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \boxed{I_i}(q^2)\boxed{f_i}(\vec{\Omega}) \longrightarrow$$

Decay rate involving b quark, *i.e.* B^0_{bar} meson

$$\frac{\mathrm{d}^4\boxed{\bar{\Gamma}}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \boxed{\bar{I}_i}(q^2)\boxed{f_i}(\vec{\Omega}) \longrightarrow$$

Decay rate involving b_{bar} quark, *i.e.* B^0 meson

- **Γ** and **Γ_{bar}**: expression of the decay
- ***$f(\vec{\Omega})$***: combinations of spherical harmonics
- ***I*** and ***I_{bar}***: q^2-dependent angular parameters (combinations of six complex decay amplitudes)

$$\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-\boxed{F_\mathrm{L}})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\
&+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l \\
&-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + \boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\
&+\boxed{S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi \\
&+\frac{4}{3}\boxed{A_\mathrm{FB}}\sin^2\theta_K\cos\theta_l + \boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi \\
&+\boxed{S_8}\sin 2\theta_K\sin 2\theta_l\sin\phi + \boxed{S_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]
\end{aligned}$$

Assumptions / simplifications:

- CP-averaged measurement
- Massless limit, *i.e.* $q^2 \gg 4m^2_\mu$

8 independent angular parameters

Decay rate

Decay rate parameterisation
(*JHEP 01 (2013) 048*)

For example $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}F_L \sin^2\theta_K + F_L\cos^2\theta_K$$

$$+(\frac{1}{4}F_L \sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l + \frac{1}{2}P_1 F_L \sin^2\theta_K \sin^2\theta_l \cos 2\phi$$

$$+\sqrt{F_L F_L}\left(\frac{1}{2}P_4' \sin 2\theta_K \sin 2\theta_l \cos\phi + P_5' \sin 2\theta_K \sin\theta_l \cos\phi\right)$$

$$-\sqrt{F_L F_L}\left(P_6' \sin 2\theta_K \sin\theta_l \sin\phi - \frac{1}{2}P_8' \sin 2\theta_K \sin 2\theta_l \sin\phi\right)$$

$$+2P_2 F_L \sin^2\theta_K \cos\theta_l - P_3 F_L \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big] = \frac{d\Gamma^4_{\text{P-wave}}}{dq^2\, d\Omega}$$

Two channels can contribute to the final state $K^+ \pi^- \mu^+ \mu^-$:

- P-wave channel, $K^+ \pi^-$ from the meson vector resonance K^{*0} decay
- S-wave channel, $K^+ \pi^-$ not coming from any resonance

We have to parametrise both decay rates !

$$\boxed{\frac{d\Gamma^4_{\text{Total}}}{dq^2\, d\Omega} = (1-\boxed{F_S})\frac{d\Gamma^4_{\text{P-wave}}}{dq^2\, d\Omega} + \frac{d\Gamma^4_{\text{S/SP-wave}}}{dq^2\, d\Omega}}$$

Both S-wave and S&P wave interference

$$\frac{d\Gamma^4_{\text{S/SP-wave}}}{dq^2\, d\Omega} = \frac{3}{16\pi}\Big[\boxed{F_S}\sin^2\theta_\ell + \boxed{A_S}\sin^2\theta_\ell\cos\theta_K + \boxed{A_S^4}\sin\theta_K\sin 2\theta_\ell\cos\phi$$

$$+\boxed{A_S^5}\sin\theta_K\sin\theta_\ell\cos\phi + \boxed{A_S^7}\sin\theta_K\sin\theta_\ell\sin\phi + \boxed{A_S^8}\sin\theta_K\sin 2\theta_\ell\sin\phi\Big]$$

6 independent parameters

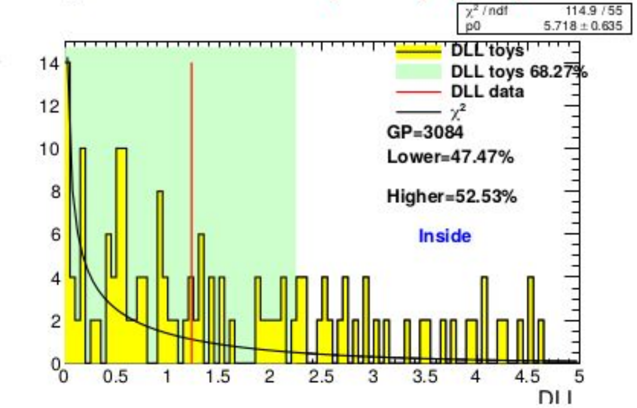
Background considered included:

- Partially reconstructed B^0 decay might pollute left M_{B^0} side bands
  - restrict left s.b. $(5.1 < M < 5.6\,\mathrm{GeV}$, default $5 < M < 5.6\,\mathrm{GeV})$
  - redo fit: change in P_1 and P_5' within the systematic uncertainties.
- $\mathrm{B}^{\pm} \to \mathrm{K}^{\pm}\mu\mu$ plus and additional random $\pi^{\mp}$:
  - distribution ends at $M > 5.4\,\mathrm{GeV}$, further reduced by $\cos\alpha$ cut, and BR similar to $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu\mu$
- $\Lambda_\mathrm{b} \to \mathrm{pK J}/\psi(\mu^+\mu^-)$
  - look at event in the $M_{\mathrm{K}\pi\mu\mu} \approx M_{\mathrm{B}^0}$ peak, reconstruct them using p, K mass hypothesis: no peak seen.
- $\mathrm{B}^0 \to DX$, with $D \to hh$ and h mis-id as μ
  - requires two mis-id: $P_{misId} \sim 1 \cdot 10^{-3}$: given $BR \sim 1 \cdot 10^{-3}$ negligible.
- $\mathrm{B}^0 \to \mathrm{J}/\psi(\mu\mu)\mathrm{K}^{*0}(\mathrm{K}\pi)$, with one h and one μ switched
  - $P_{misId\ \mu} \cdot (1 - \varepsilon_\mu) \sim 1 \cdot 10^{-4}$, $Y_{\mathrm{B}^0 \to \mathrm{J}/\psi\mu\mu} \sim 1.6 \cdot 10^5$: few events in bin close to J/ψ
  - J/ψ feed contamination in close bin included in the fit model

FC statistical uncert determination

- Not fully 2D, only 1D profiling 2D-gaussian description of likelihood inside the physical allowed region
- Generate 100 toys for each point of the path
- Fit the toy and rank according to likelihood-ratio
- Confidence interval is found when data likelihood-ratio exceed the 68.3% of the the toys
    - Statistical fluctuation expected due to limited number of toys
    - Data ranking is plotted along the path explored
    - Intersection with 68.3% found with linear fit

An example of DLL toys distribution compared with DLL(Data) (red)

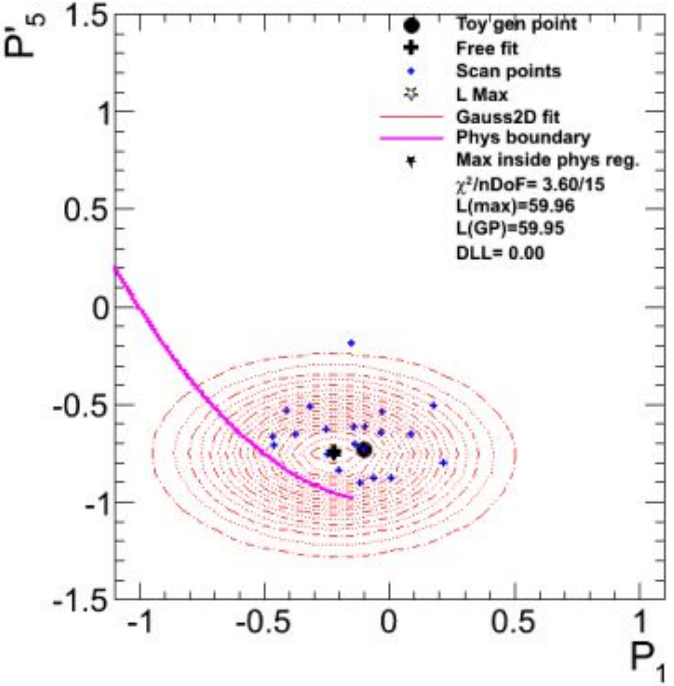


Data DLL does not exceed 68.3% of toys DLL.
Point generated is inside 1σ

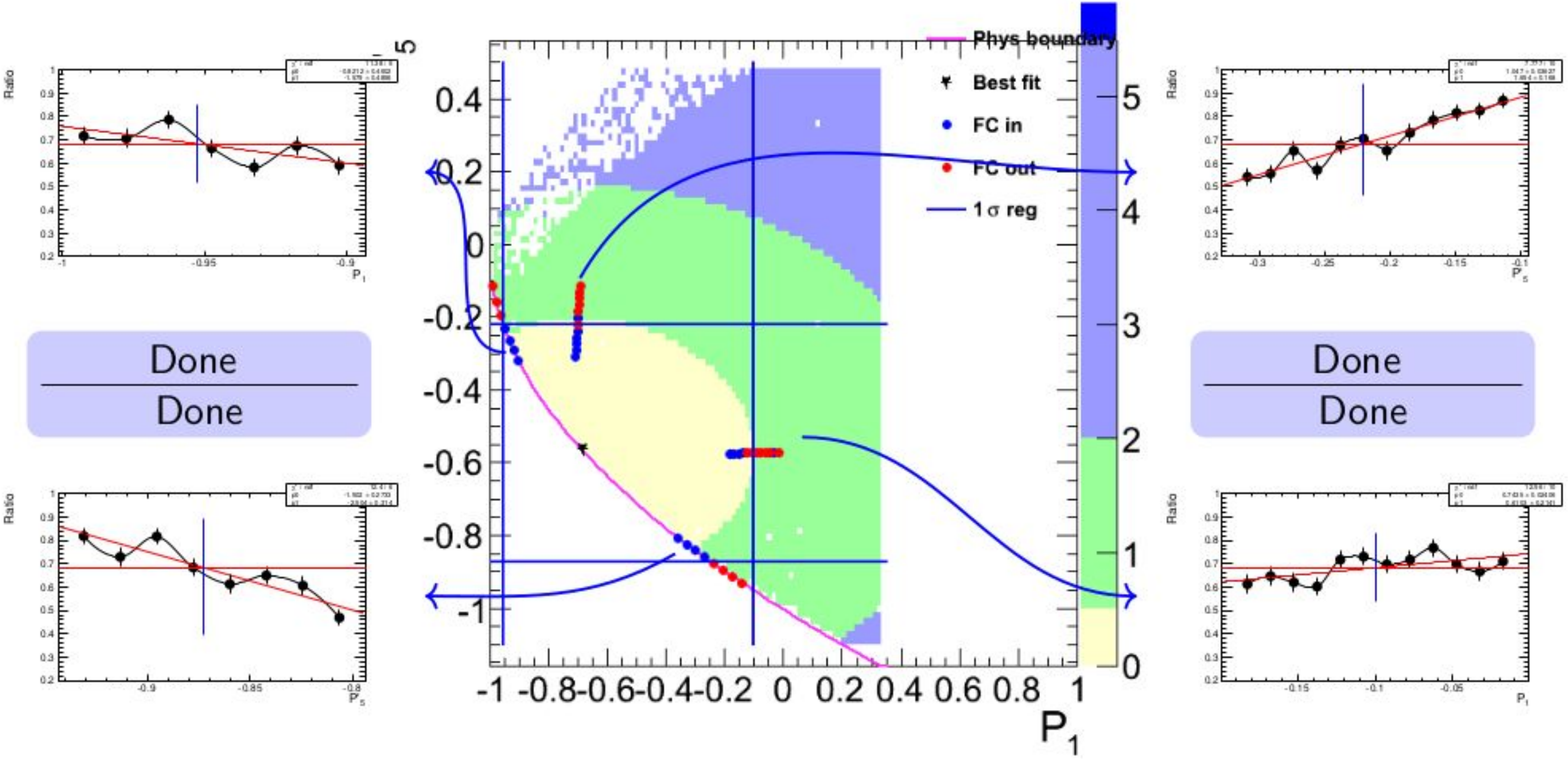
Single Toy fit

Each toy is fitted with the full pdf as done for data

- we repeat the fit with 20 different set of 20 initial values of P_1 and P'_5
  - to find the absolute max, we fit the 20 values with a 2D gauss function
  - the max must be inside the physical region
- Eventually, we have 100 toys, and 100 values for the likelihood.



Example for bin 1



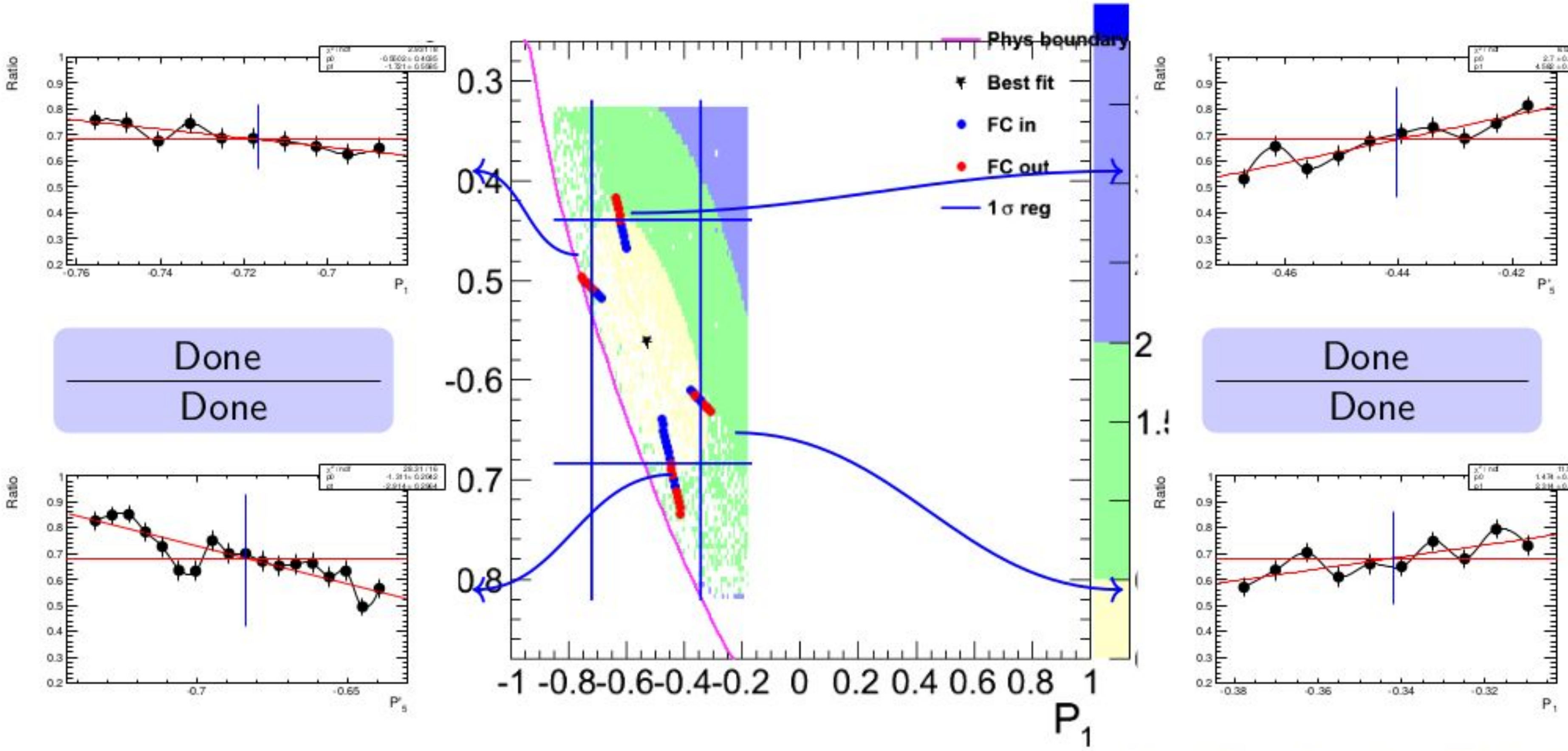
Done

Done

Done

Done

Example for bin 8

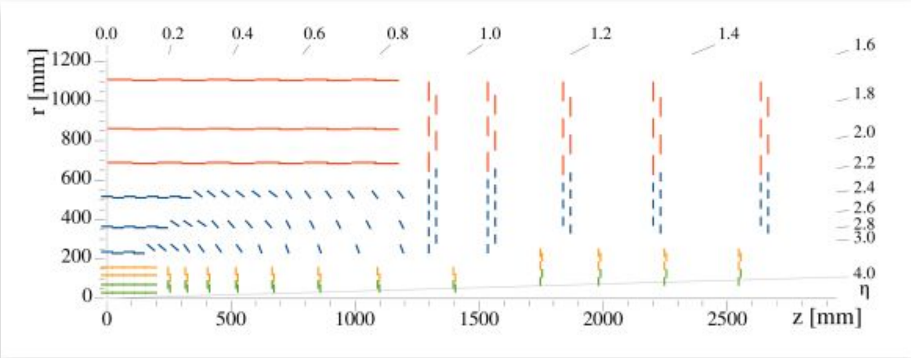


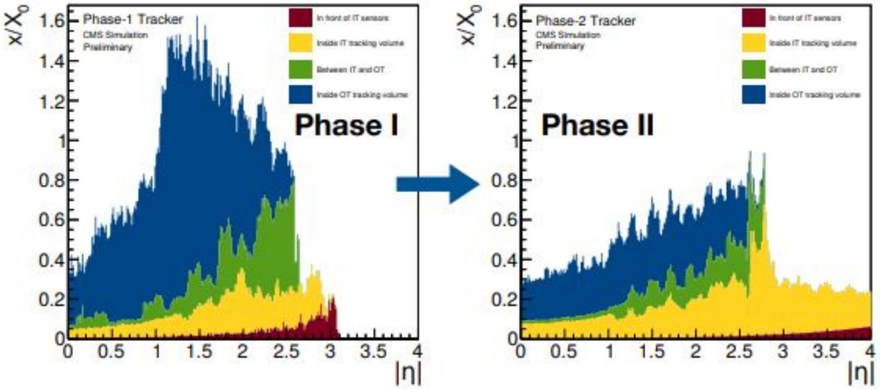
$\frac{\text{Done}}{\text{Done}}$

$\frac{\text{Done}}{\text{Done}}$

Tracker upgrade

- Needed to deal with radiation damage and cope with higher pileup
- **Inner tracker:**
  - pixel sensors
  - narrower pitch than present pixel detector
  - increased granularity to limit the occupancy
  - coverage up to |η|~4
- **Outer tracker:**
  - design driven by addition of hardware track trigger capabilities
  - pixel-strip & 2-strip sensors
  - progressively tilted modules
- Substantial reduction of the material budget with respect to present detector

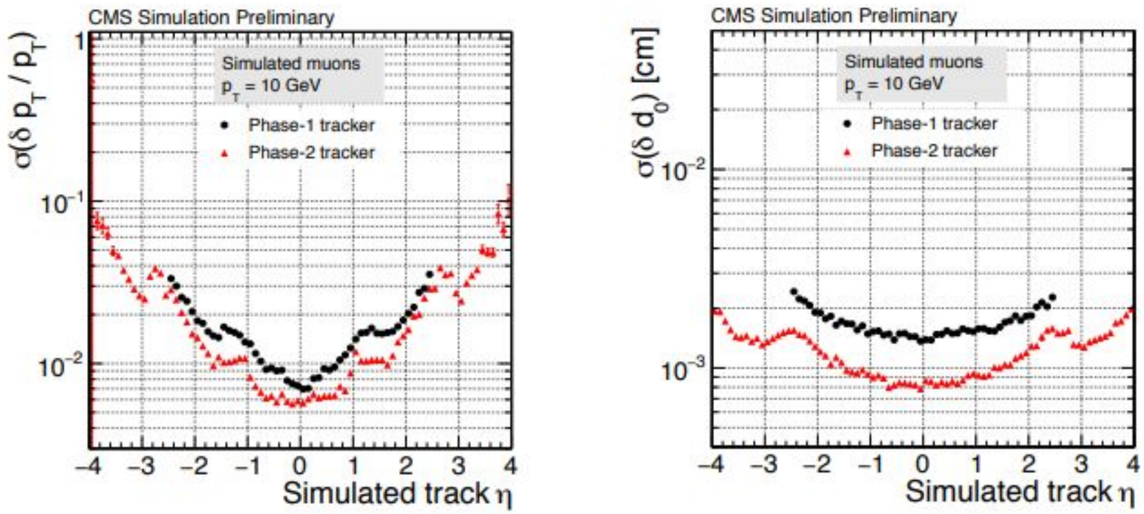




CMS-TDR-014

Tracker performance: resolution

CMS-TDR-014



- Significant improvements in transverse momentum and transverse impact parameter resolution with respect to current detector
  - thanks to better hit resolution and lower material budget

CMS Trigger strategy

L1 Trigger: ~40 MHz → 100 kHz

- Hardware-based
- Only muon stations and calorimeters
  → **No electrons from B's**
- Decision time: ~4 μs

HLT: 100 kHz → 1 kHz(*)

- Software
- Full detector information, but simplified reconstruction
- Decision time: ~300 ms

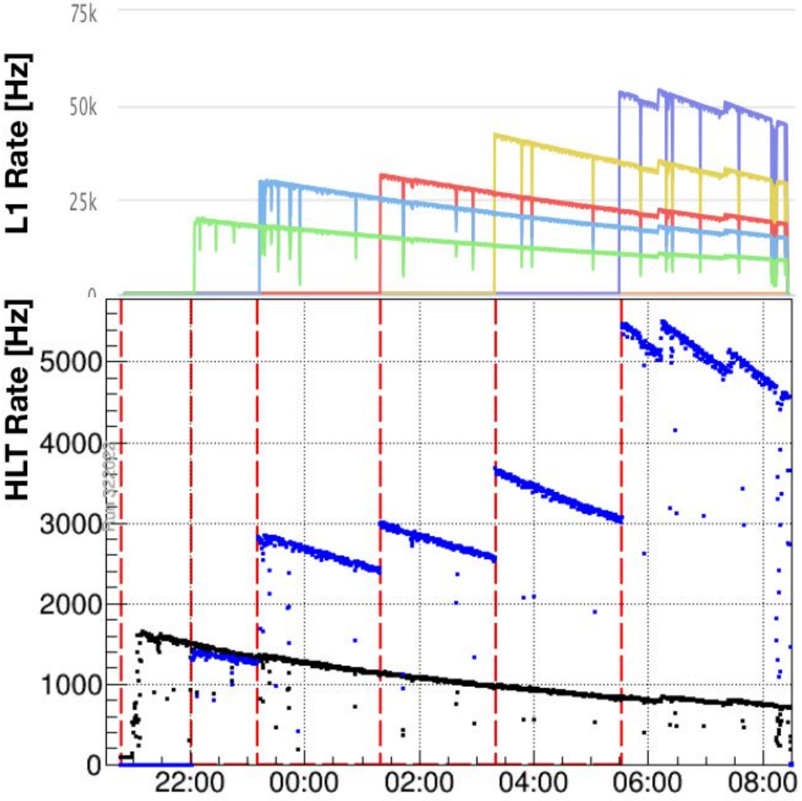
Offline:

- Software
- Reconstruction time O(s)
- Event size ~1MB for standard events

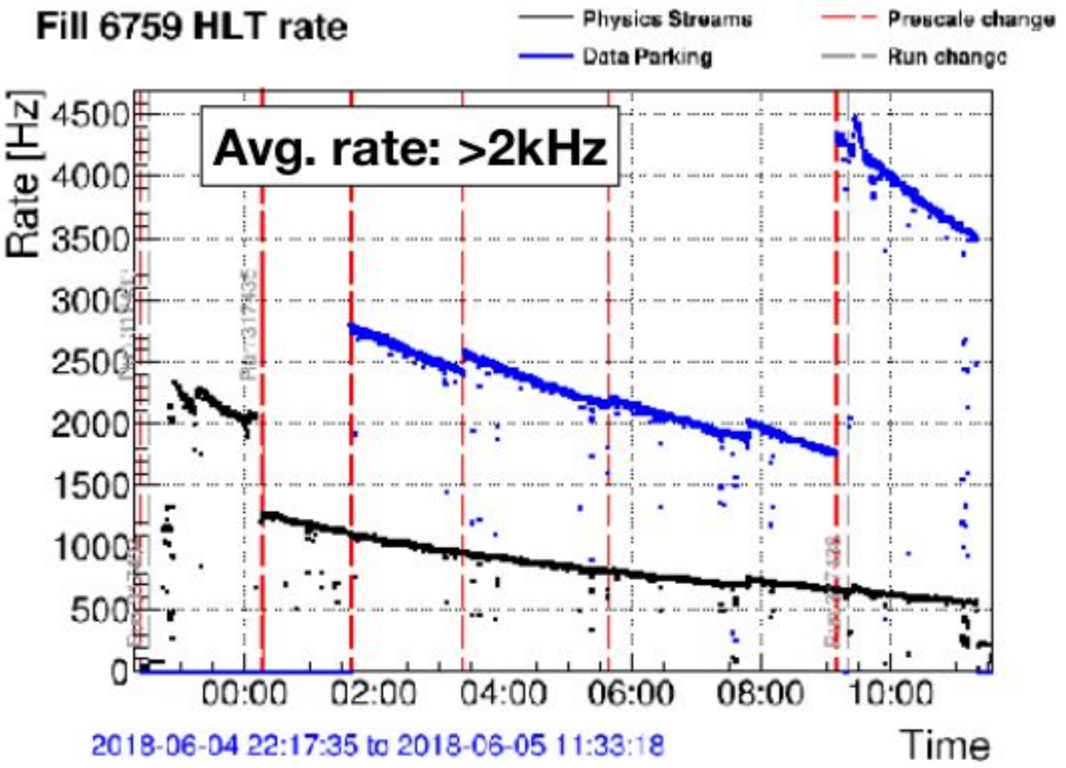
L1 is (and will be) a limiting factor

Only 10% of the L1 rate is kept to achieve good purity.

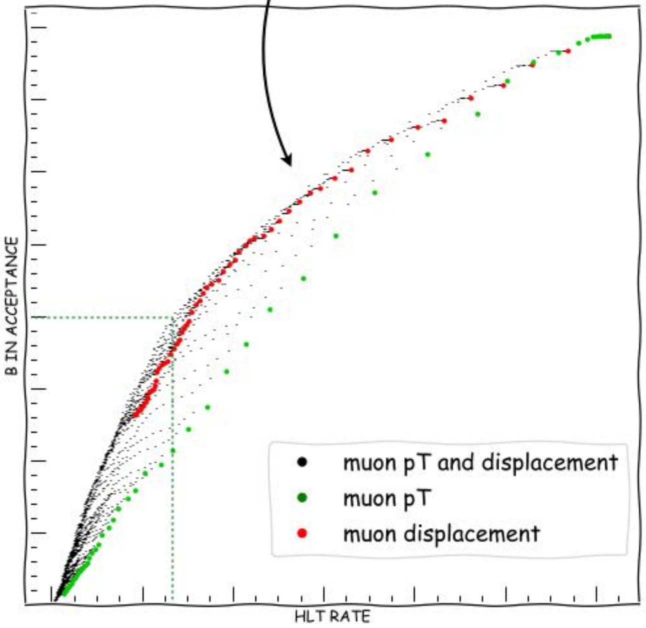
The number further decreases at very low L1 muon p_T threshold



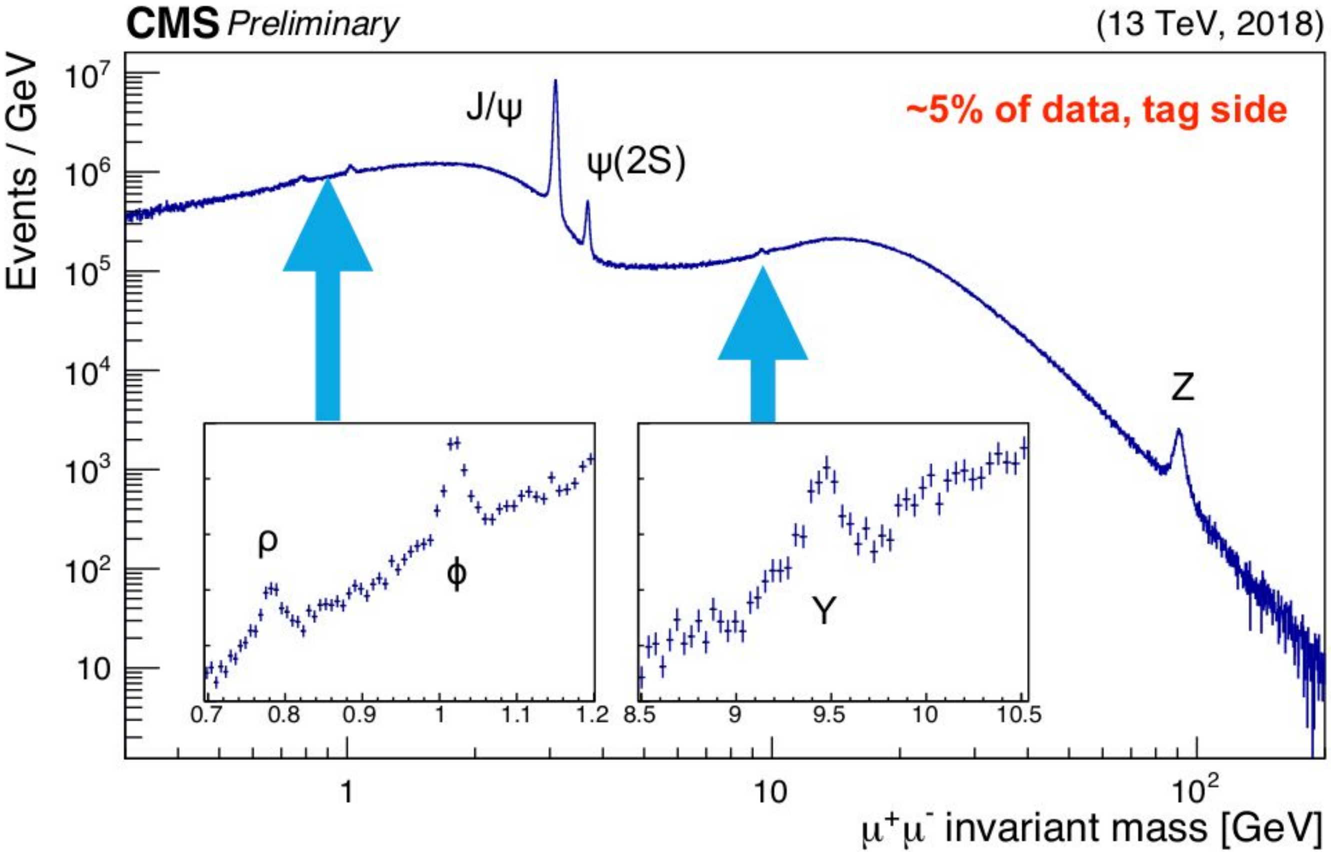
Trigger tuning and HLT



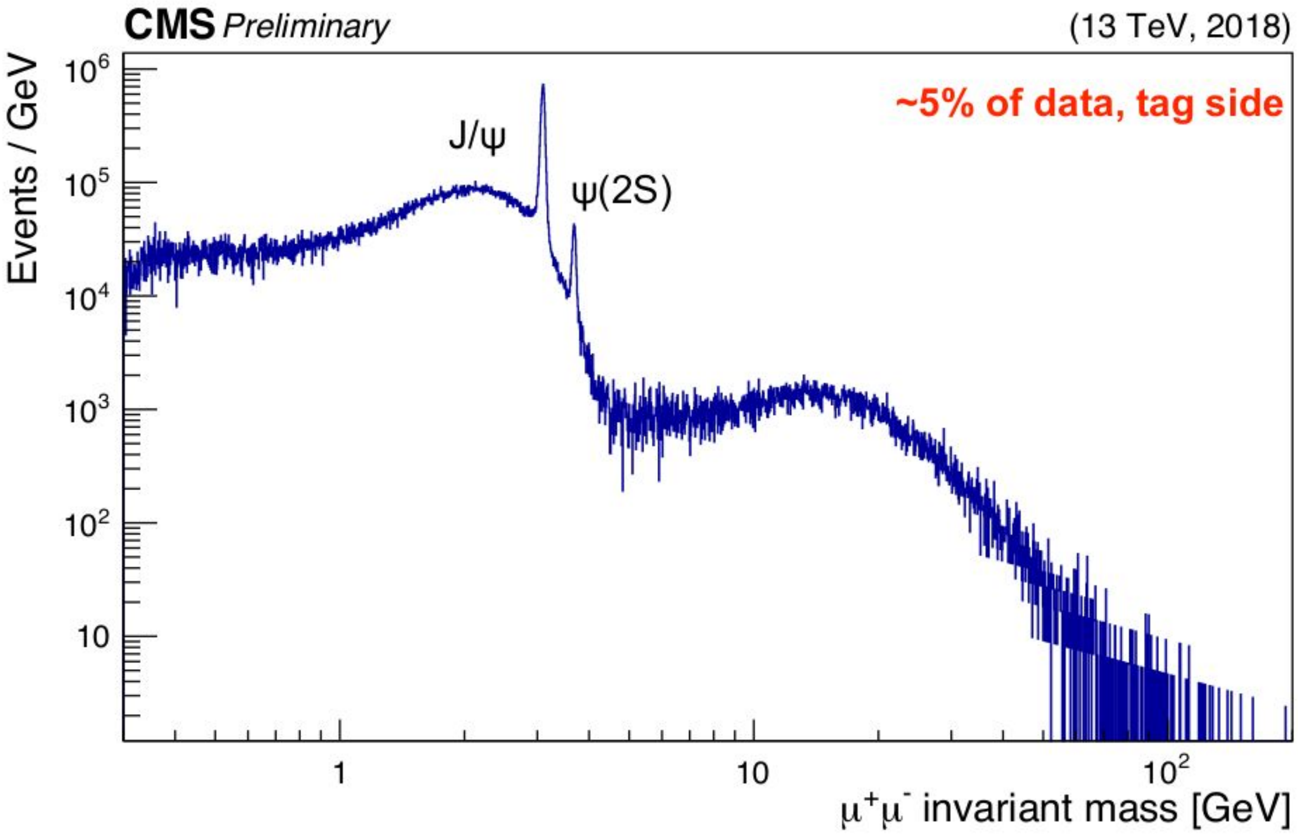
Each point in the cloud represent a tentative selection in $p_T(\mu)$ and IP significance



Trigger level di-muon spectrum

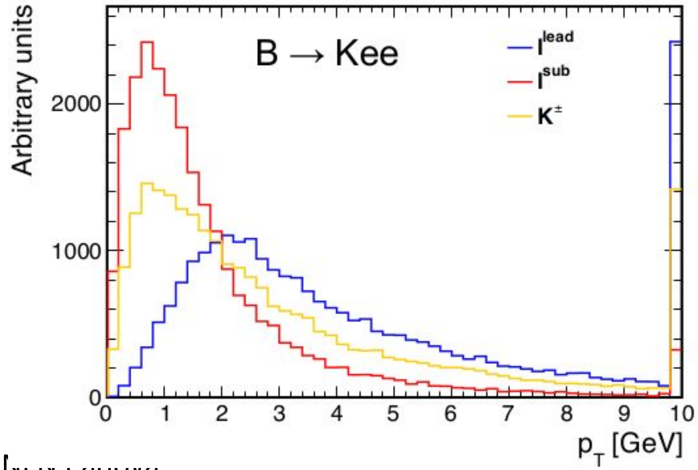


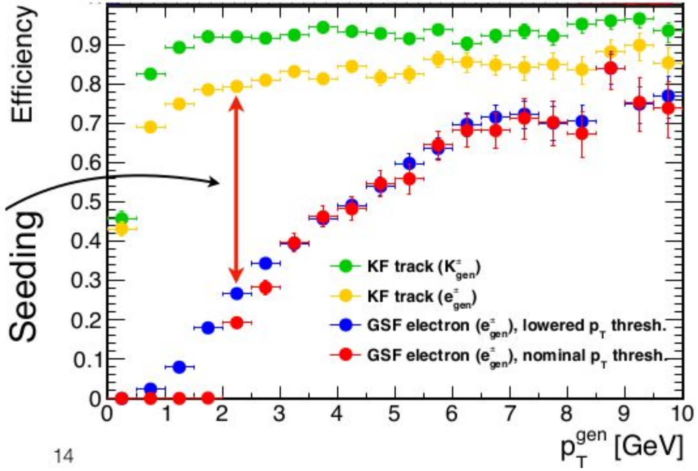
Displaced muons



Challenges for R(K$^{(*)}$)

- Main challenge: Br ~ 10^{-7}
- This is why need ~10^{10} B's!
- Low-energy electron reconstruction
  - Default reconstruction has an (arbitrary) cutoff at 2 GeV
  - Need significant investment to improve it down to ~1 GeV
  - Finalizing the significantly improved electron ID now

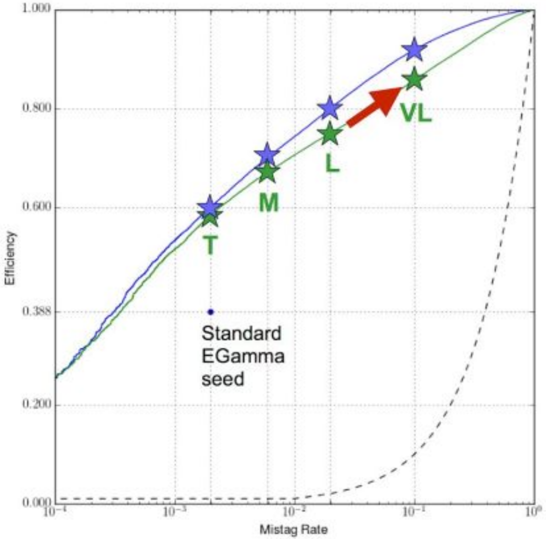




New electron seeding

- Created an alternative reconstruction path for low-p_T electrons
  - Remove limitations of the current seeding without touching the default (particle-flow) electron reconstruction
  - Focus on improving the efficiency for low-p_T electrons by using a combination of ECAL supercluster -based seeding and track-based seeding
  - A factor of three improvement compared to the PF electron case is achieved for the $B \to J/\psi(ee)K$ decay
  - Potentially up to x4 improvement is expected
  - Finalizing the ID to keep fake rate under control

Algo	α	ε	α*ε
PF	0.56	0.14	**0.08**
Low p_T	0.56	0.41	**0.23**



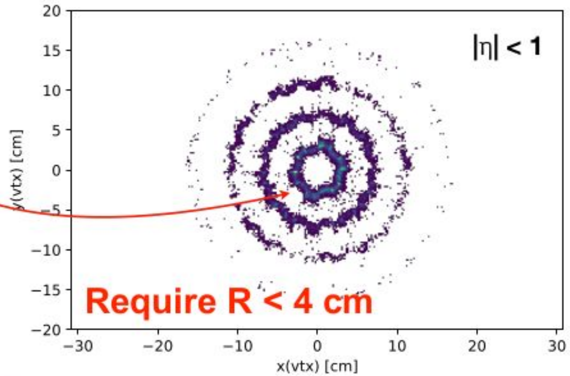
Asymmetric Conversions

- Use asymmetric conversions to study low-p_T electrons

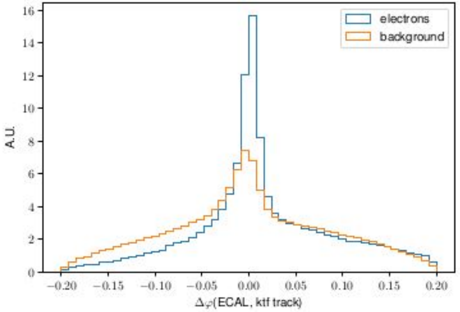
Other datasets are also being considered

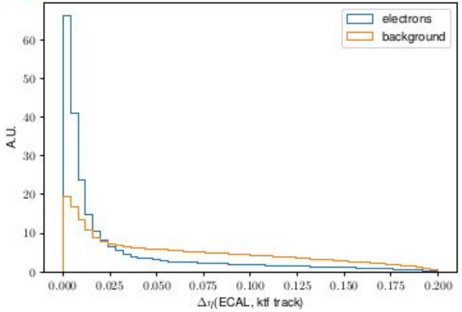
Use conversions stemming from the first pixel layer/beampipe

Example of discriminating variables used in the seeding



Require R < 4 cm





Purity

From data

$$N(b \to \mu X) = \frac{1}{\boxed{F_{corr}}} \, \frac{\boxed{N(B^0 \to D^{*+}\mu\nu)}}{\boxed{\alpha(D^{*+}) \times \varepsilon(D^{*+})} \times \boxed{\mathcal{B}(D^{*+} \to D^0(\to K\pi)\pi)}}$$

$$f_d \frac{\mathcal{B}(B^0 \to D^{*+}\mu\nu)}{\mathcal{B}(b \to \mu X)} \frac{\alpha(B^0 \to D^{*+}\mu\nu)}{\alpha(b \to \mu X)}$$

From MC

Acceptance x efficiency of the D*+ decay chain.

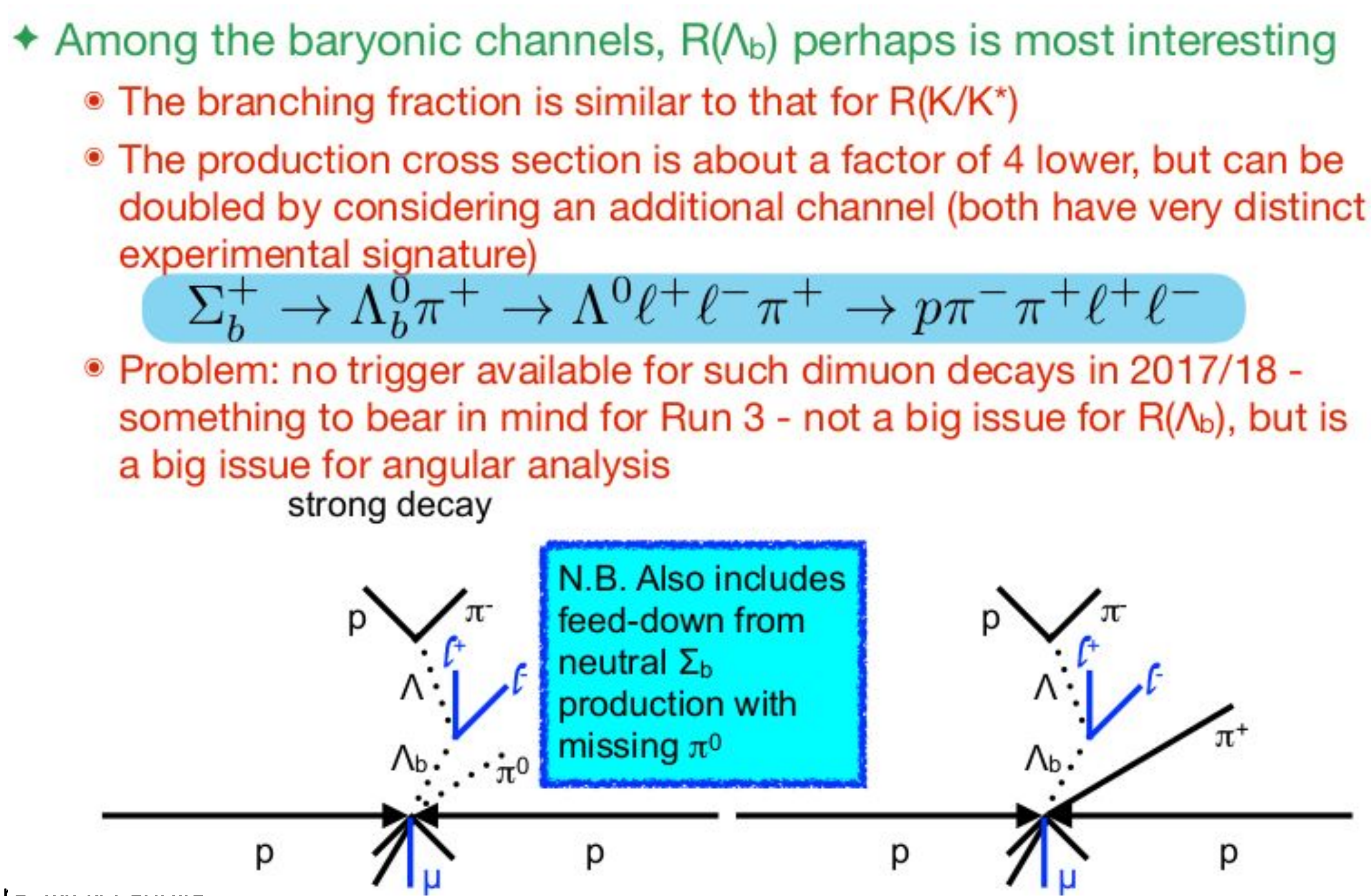
Computed on MC.

From literature: 2.6%

This value does **not** include any acceptance on the probe B

$$P_b = \frac{N(b \to \mu X)}{N(\mu)} \approx 75\,\%$$

Thoughts on R(Λ_b)



- Among the baryonic channels, R(Λ_b) perhaps is most interesting
  - The branching fraction is similar to that for R(K/K*)
  - The production cross section is about a factor of 4 lower, but can be doubled by considering an additional channel (both have very distinct experimental signature)

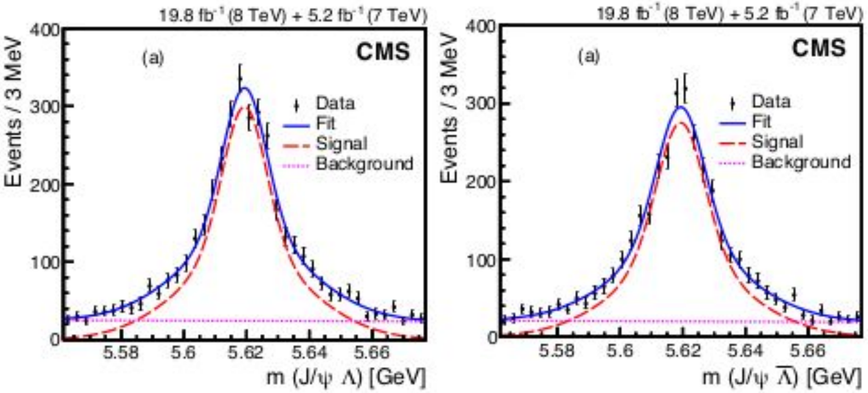
$$\Sigma_b^+ \to \Lambda_b^0\pi^+ \to \Lambda^0\ell^+\ell^-\pi^+ \to p\pi^-\pi^+\ell^+\ell^-$$

  - Problem: no trigger available for such dimuon decays in 2017/18 - something to bear in mind for Run 3 - not a big issue for R(Λ_b), but is a big issue for angular analysis

N.B. Also includes feed-down from neutral Σ_b production with missing π^0

Λ_b in CMS

- We actually published Run 1 paper on Λ_b polarization and angular distributions
  - Signal is extremely clean, so could afford less stringent cuts (such as $p_T(J/\psi)$, $p_T(\Lambda_b)$)
  - Expect about 20K events in the parked data with the same cuts, but could be much more with looser cuts
  - O(100) non-resonant dilepton events is not impossible!



~6000 events in the 7 + 8 TeV data

CMS, arXiv:1802.04867