Search for new physics in rare hadron decays

INFN Pisa

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on behalf of the LHCb collaboration
with results from ATLAS, Belle (II), BES III, CMS, KOTO, LHCb, NA62

17 July 2023

31st Lepton Photon Conference 2023
MELBOURNE CONVENTION
& EXHIBITION CENTRE
17 - 21 JULY

Physics beyond the Standard Model

- SM as an effective theory at low energy
- New degrees of freedom expected above the electroweak scale

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}$$

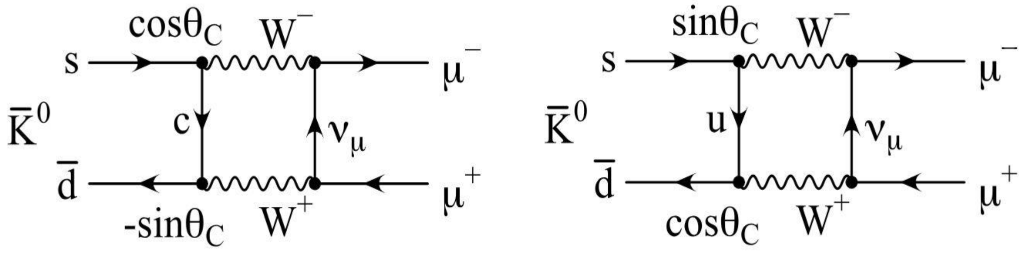
- Two complementary approaches:
  - High-energy frontier: Direct search of non-SM particles above the EW scale
  - High-intensity frontier: Search for deviations of SM predictions in low energy processes (“indirect searches”)

- Historically, indirect searches have unveiled new fundamental particles

➔ prediction of charm quark (1970) (to explain the $K_s \rightarrow \mu\mu$ rate)

➔ Prediction of 3rd generation of quarks (1973) (to explain CP violation)

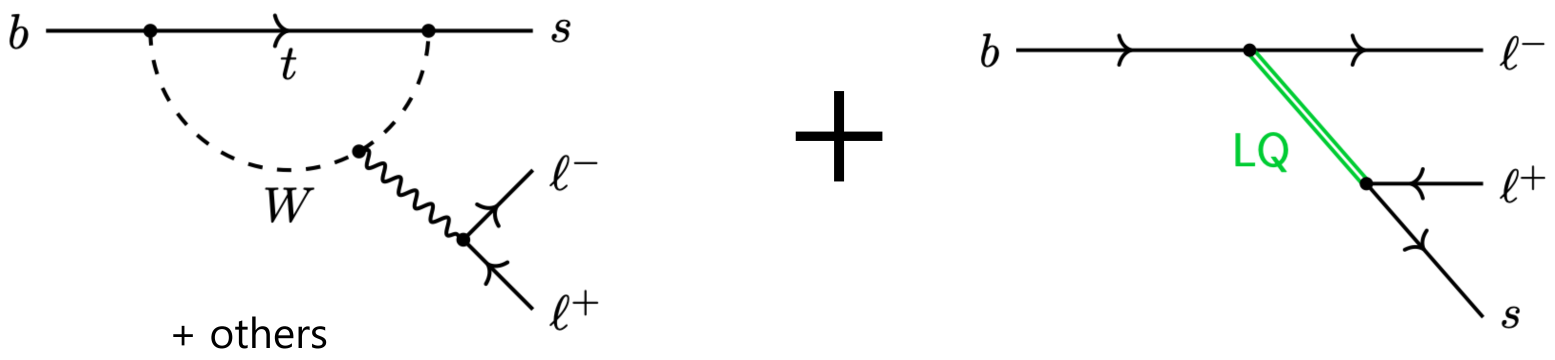
➔ Top quark mass > 50 GeV (1987) (from $B^0\overline{B^0}$ mixing)



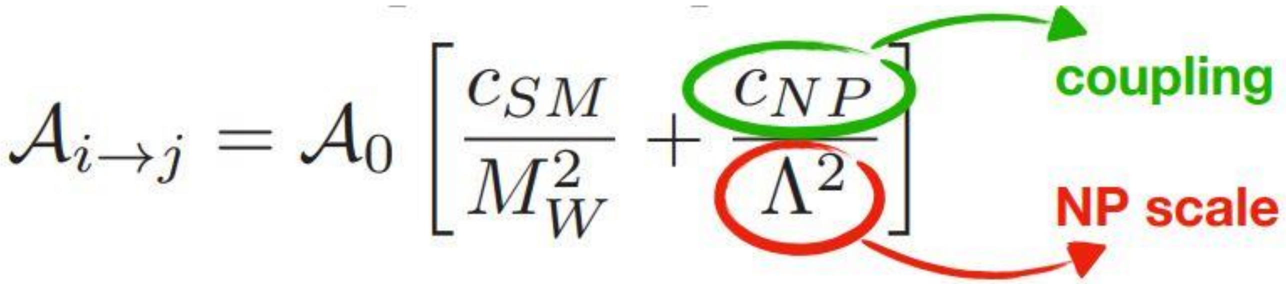
GIM mechanism to explain $K_s \rightarrow \mu^+\mu^-$ rate

Requirements for indirect searches

- Example of new physics contribution in FCNC process $b \to s\ell^+\ell^-$



observables are altered by new (virtual) particles



$$\mathcal{A}_{i\to j} = \mathcal{A}_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

- Conditions to optimize the sensitivity to new physics

1. Very large statistics – the mass reach scales as $\left(\int Ldt\right)^{1/4}$
2. Low systematic uncertainty – which implies optimised detectors
3. Precise and reliable SM predictions - clean observables (eg LFU ratios), hadronic contributions calculable with small uncertainty (lattice QCD, ...), null tests (LFV,...)
4. Multiple independent measurements – ideally, same measurement from different experiments

Main players

from M. Palutan, LP21

LHCb, Belle II, BES III

Dedicated heavy-flavour experiments with wide range of measurements

ATLAS, CMS

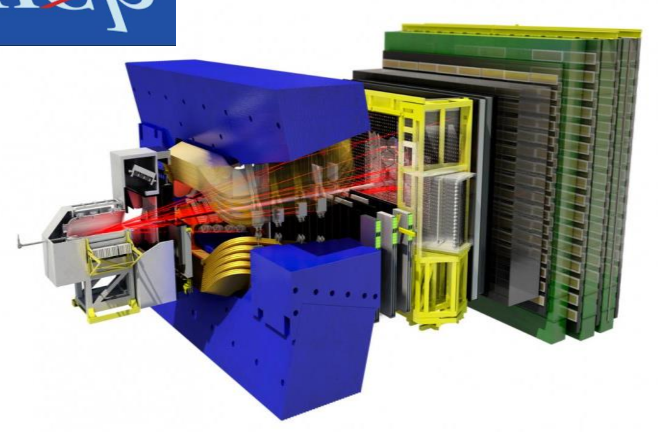
General-purpose detectors, suitable for b-physics studies mainly with muons in final states

NA62, KOTO

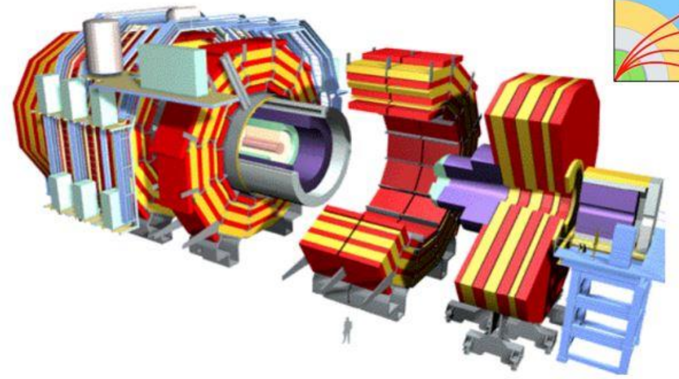
Dedicated to ultra-rare kaon decays

pp colliders

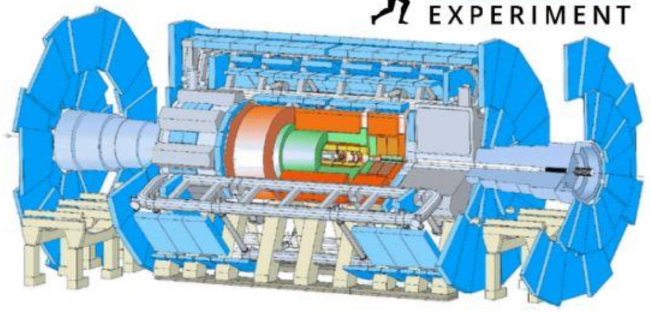
LHCb



CMS

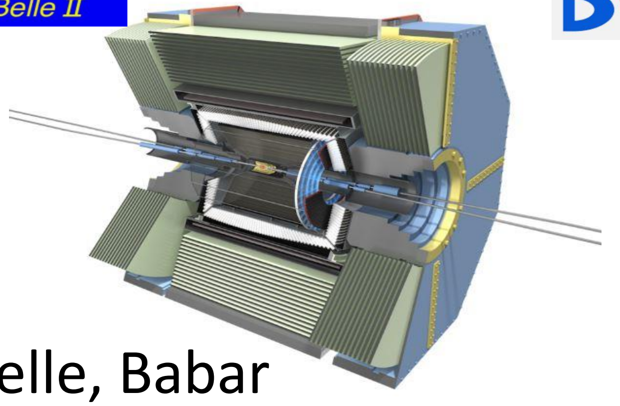


ATLAS EXPERIMENT



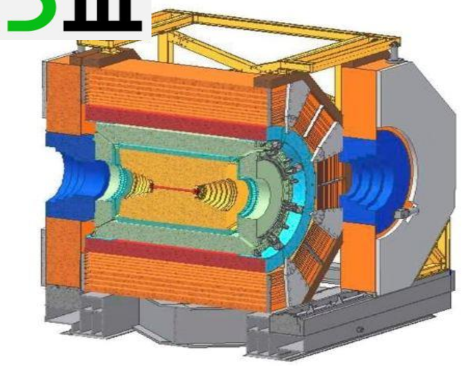
e^+e^- colliders

Belle II



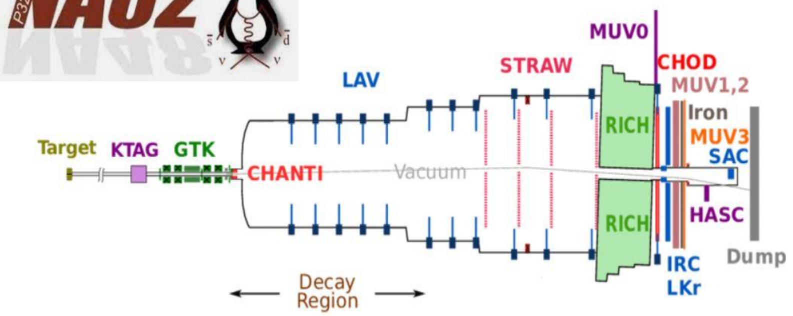
+ Belle, Babar

BESIII

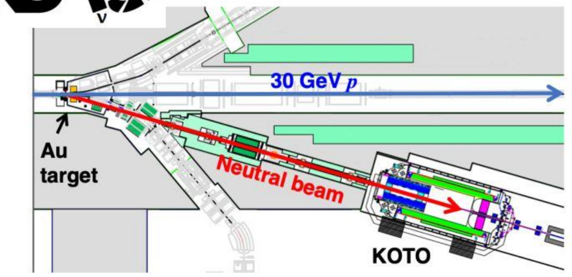


kaon beams

NA62



KOTO



Environments and datasets

pp collider (ATLAS, CMS, LHCb)

- 😐 Crowded event (O(100) tracks). Signal rates limited by trigger efficiency.
- 🙂 Large p ➔ large vertex separation
- 🙂 $b\bar{b}, c\bar{c}$ production cross sections O(100) μb

e^+e^- collider (B-factories)

- 🙂 Clean event (~10 tracks) ➔ Easier reconstruction of final states with neutrinos
- 🙂 Good π^0, γ and $e^\pm$ reconstruction
- 😐 $B\bar{B}, c\bar{c}$ production cross sections O(1) nb

➔ Complementarity

Number of particles in detector acceptance*

ATLAS/CMS: 3×10^{13} $b\bar{b}$ pairs

LHCb: 1×10^{12} $b\bar{b}$ pairs

BES III: 1×10^{7} $D^0\overline{D^0}$ pairs

Belle II: 2×10^{8} $B\bar{B}$ pairs (Babar+Belle: 1.2×10^{9} $B\bar{B}$ pairs)

NA62: 4×10^{12} K^+ decays in fiducial region

KOTO: 6×10^{12} K_L flux

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* Max number on which the measurements presented in next pages are based on. Trigger/sel efficiencies not included. More data have been collected and are being analysed.

Outline

Main focus on FCNC-mediated decays

Covered in this talk:

- $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
- $B^+ \to K^+ \nu\bar{\nu}$
- $D^0 \to \pi^0 \nu\bar{\nu}$
- $B \to X_s \gamma$
- $b \to s l^+ l^-$
- $\eta \to 4\mu$
- LFV decays
- Future

Related experimental talks:

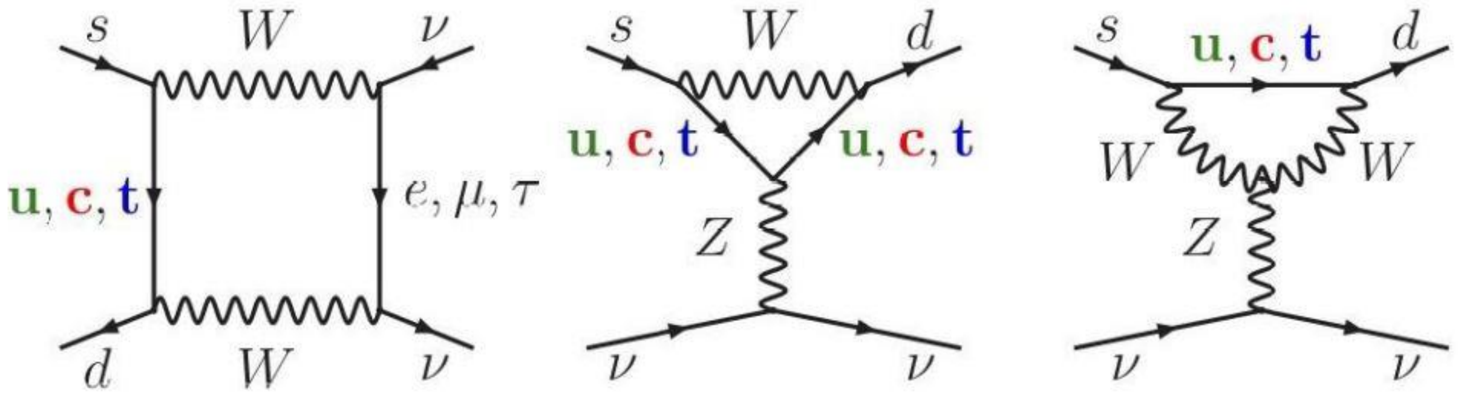
With more measurements and details

Flavour parallel, Tue 18/7 @ 13:30

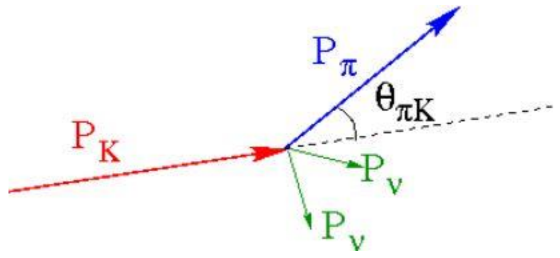
Dark Matter parallel, Tue 18/7 @ 15:45

Flavour parallel, Wed 19/7 @ 9:00

$K^+ \to \pi^+ \nu\bar{\nu}$



- FCNC process, strong GIM and CKM suppression
- Theoretically very clean: short-distance dominated, hadronic matrix element from $BF(K^+ \to \pi^0 e^+ \nu)$

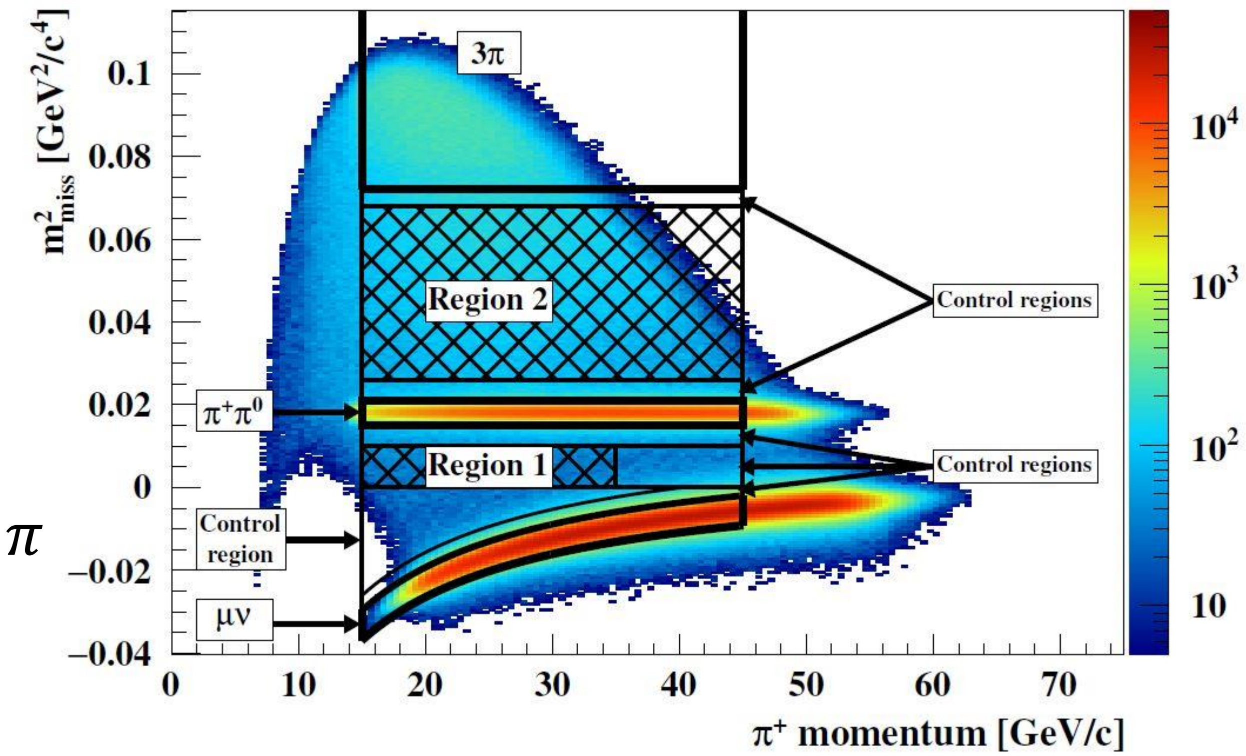


- SM prediction: $BF(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$

Buras et al, JHEP11(2015)033
see also Buras, 2205.01118

- Very sensitive to new physics: $O(50\%)$ BF variations in several NP models (Z', leptoquarks, non-MFV MSSM, …).
- Signal signature: matched kaon and pion tracks + a number of vetoes to reject background events
- Backgrounds: Accidental single π^+ + $K^+ \to \pi^+\pi^0,\ \mu^+\nu,\ \pi^+\pi^-e^+\nu,\ 3\pi$
- Counting experiment in regions of $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$ vs p_{π^+}

JHEP 06(2021) 093]



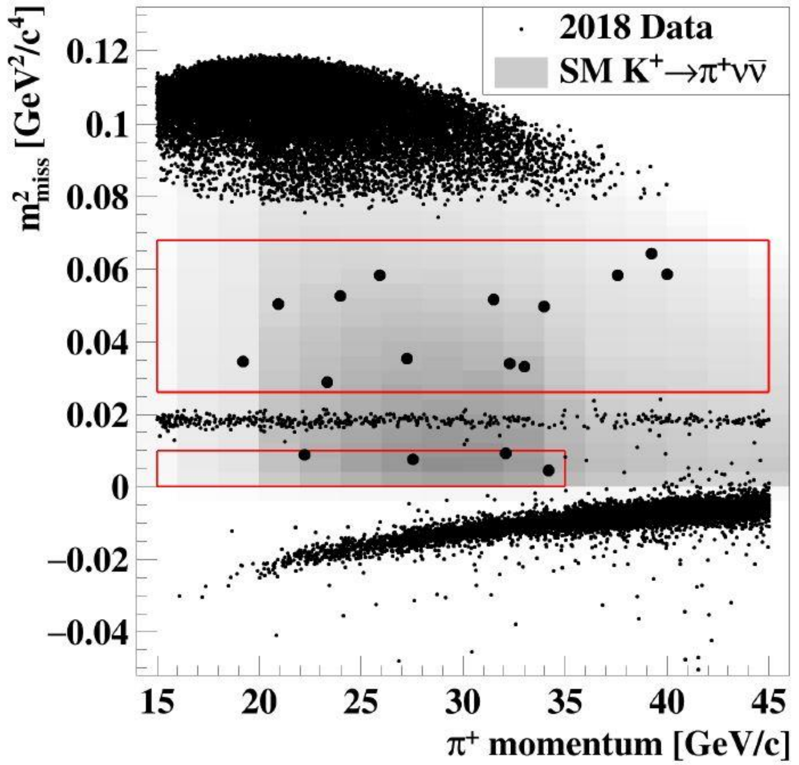
$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

- 2018 data combined with previously-analysed 2016+2017 data
- $N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}$ $N^{\text{exp}}_{\text{background}} = 7.03^{+1.05}_{-0.82}$ $N_{obs} = 20$

$BF(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ at 68% CL

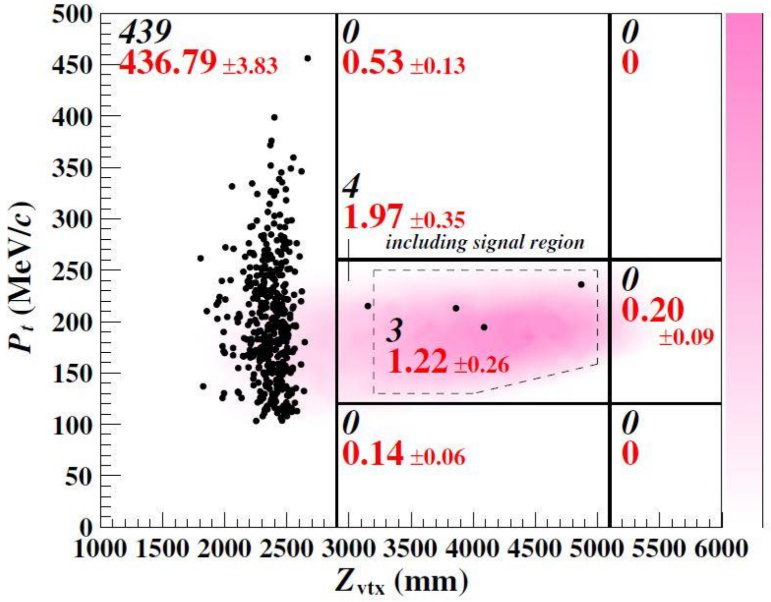
3.4σ evidence

JHEP 06(2021)093]



Search for $K_L \to \pi^0\nu\bar{\nu}$

PRL 126(2021),121801



Black: observed; Red: expected bkg

- Theoretically very clean and sensitive to new physics, similarly to $K^+ \to \pi^+\nu\bar{\nu}$
- SM prediction:

$BF(K_L \to \pi^0\nu\bar{\nu}) = (2.94 \pm 0.15) \cdot 10^{-11}$

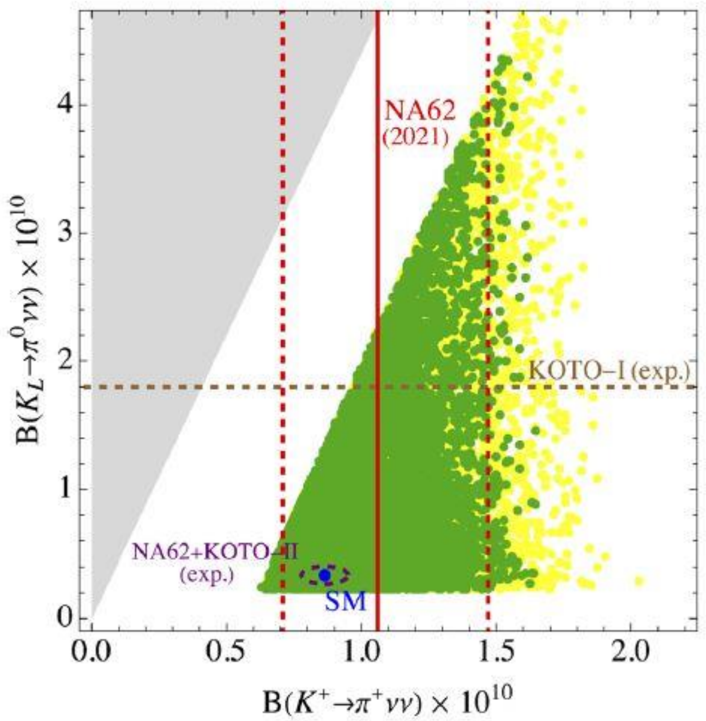
Buras, 2205.01118

Using 2016-2018 data:

$BF(K_L \to \pi^0\nu\bar{\nu}) < 4.9 \times 10^{-9}$ @90% CL

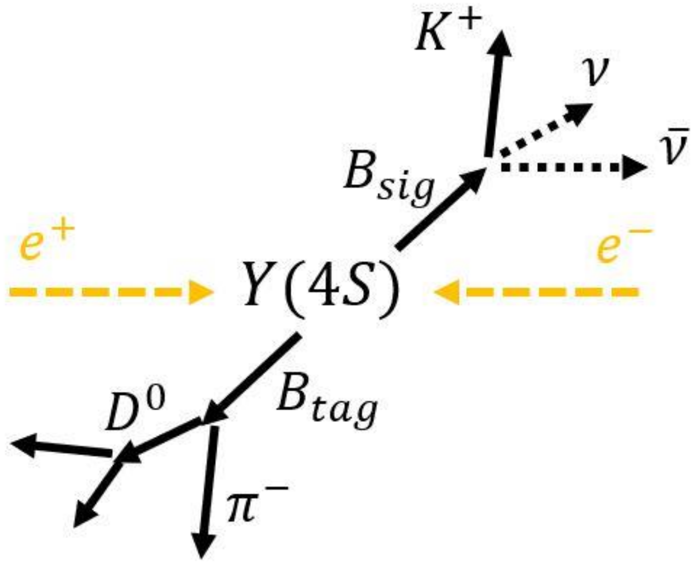
cf. $BF < 3.0 \times 10^{-9}$ @ 90%CL using 2015 data PRL122(2019)021802

Marzocca et al, Eur Phys J C 82, 320 (2022)



Rare decays with missing energy at e^+e^- colliders

Selection of rare decays with missing energy at e^+e^- *B*-factories



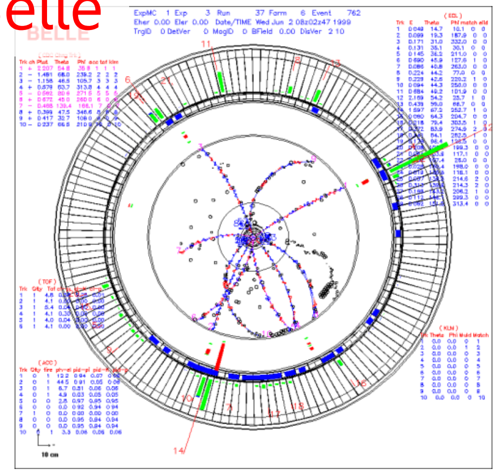
- 100% B mesons produced from $Y(4S) \rightarrow B\bar{B}$
- **p** of $Y(4S)$ is known

➔ reconstruct B_{tag} to:

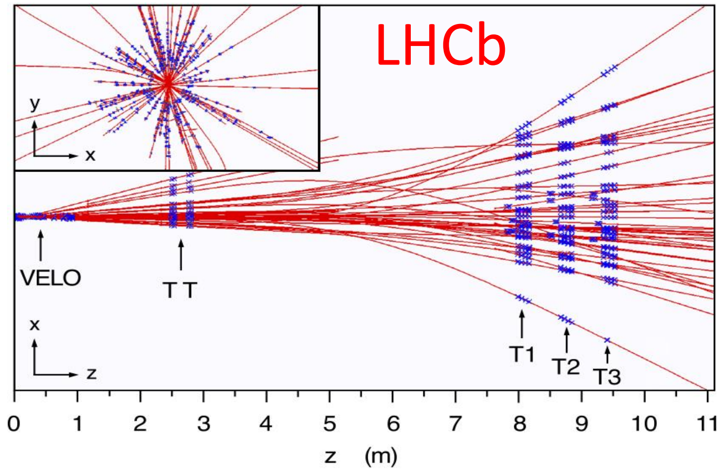
  - Infer properties of B_{sig}
  - Suppress $B\bar{B}$ and continuum backgrounds

B_{tag} technique NOT applicable at *pp* colliders

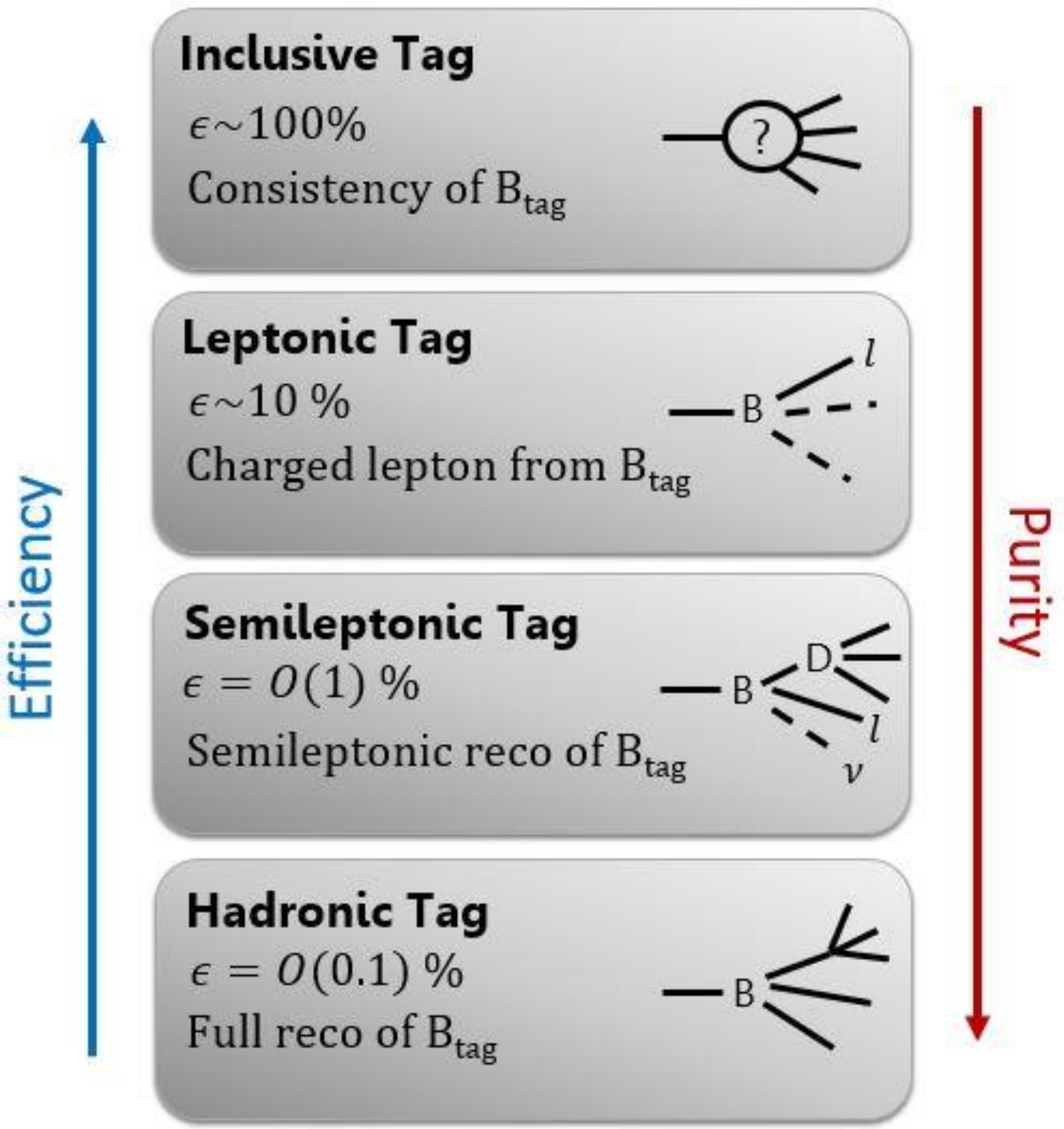
Belle



vs



Many techniques to reconstruct B_{tag}



Inclusive Tag
$\epsilon \sim 100\%$
Consistency of B_{tag}

Leptonic Tag
$\epsilon \sim 10\ \%$
Charged lepton from B_{tag}

Semileptonic Tag
$\epsilon = O(1)\ \%$
Semileptonic reco of B_{tag}

Hadronic Tag
$\epsilon = O(0.1)\ \%$
Full reco of B_{tag}

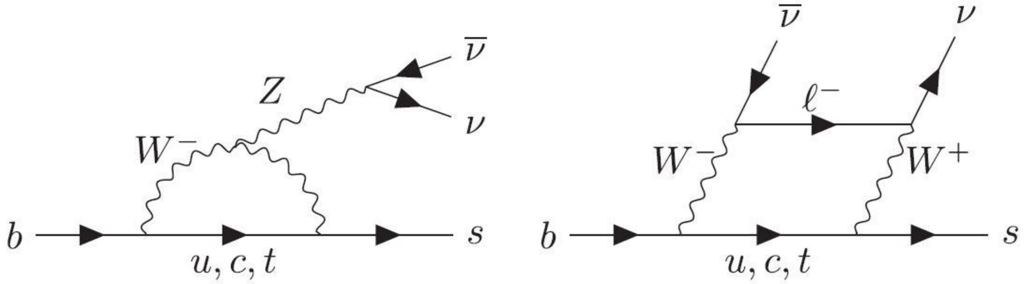
The measurements in the next three slides are unique at e^+e^- $B/charm$-factories

Search for $B^+ \to K^+ \nu\bar{\nu}$

- Theoretically clean FCNC transition. Only hadronic uncertainty is from FF.

- SM $BF = (4.6 \pm 0.5) \times 10^{-6}$

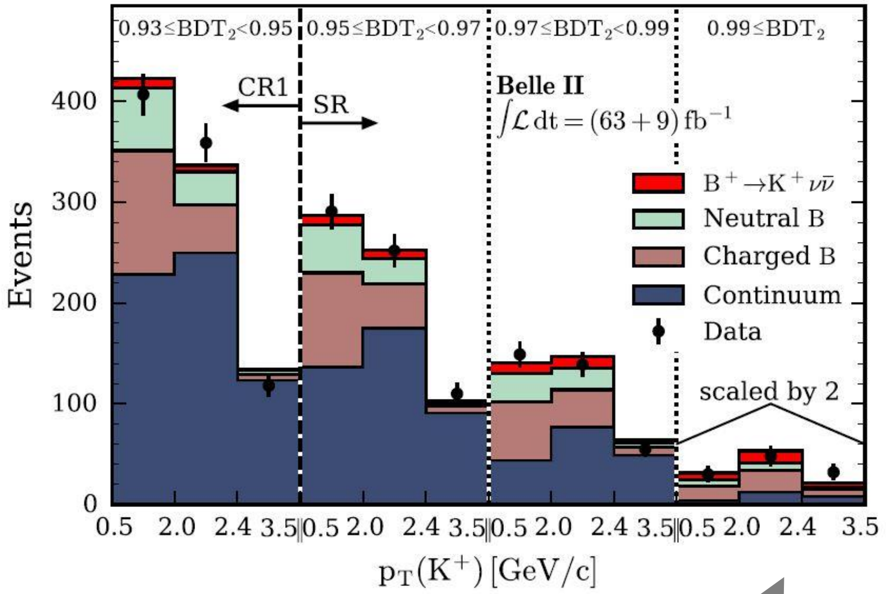
Buras et al, JHEP02(2015)184
Blake et al, PPNP(2017)92



- Inclusive B_{tag} reconstruction

- Selection and yield measurement based on BDT vs $p_T(K)$. BDT uses properties of kaon candidate, event topology and B_{tag}

PRL127(2021)181802



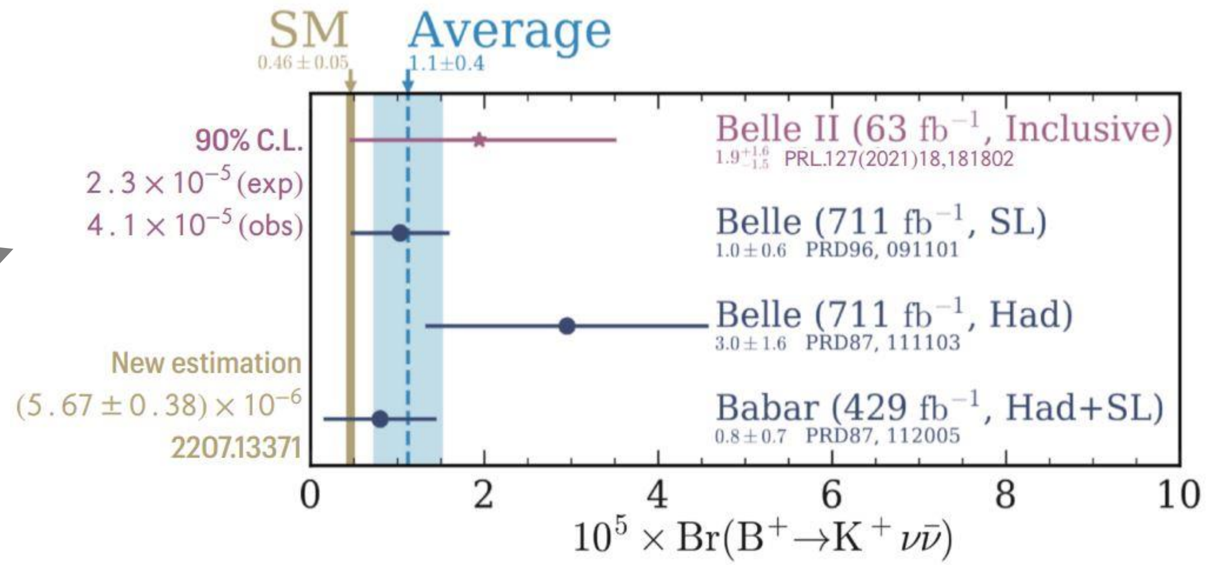
22% signal purity in this region

$BF = (1.9^{+1.3}_{-1.3}{}^{+0.8}_{-0.7}) \times 10^{-5}$ (63 fb^{-1})

➔ $BF(B^+ \to K^+ \nu\bar{\nu}) < 4.1 \times 10^{-5}$ @90%CL

→ Sensitivity/lumi 20% better than SL tag from Belle

NB: measurement considered ''impossible'' at LHCb



Search for $D^0 \to \pi^0 \nu\bar{\nu}$

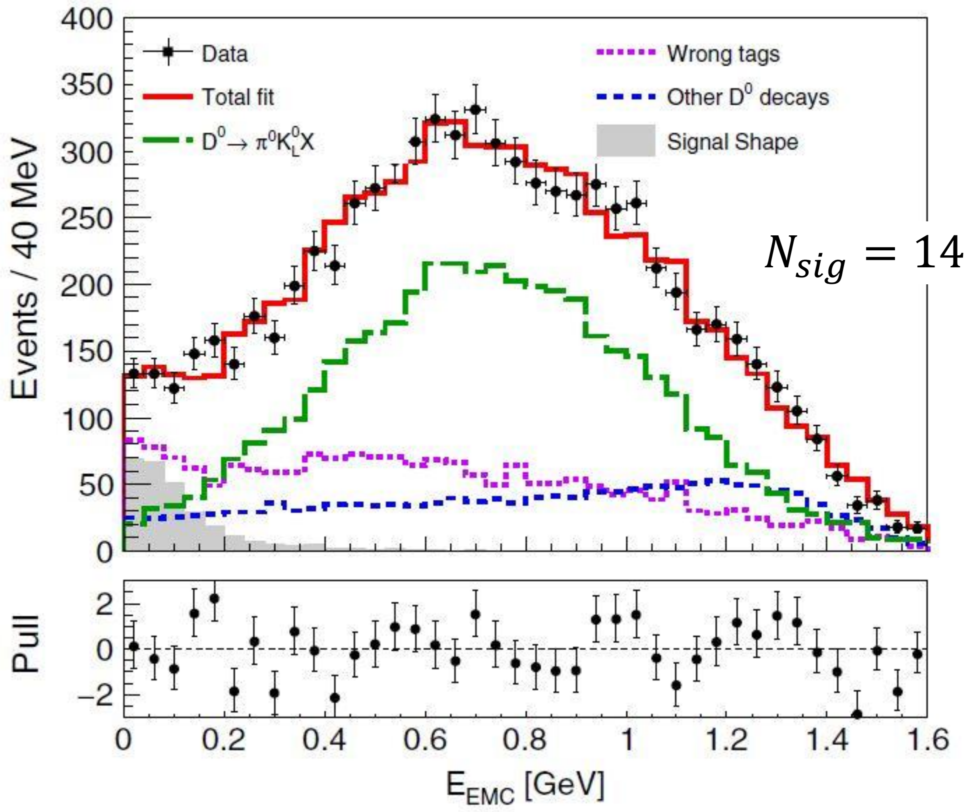
- $c \to u\nu\bar{\nu}$, analogous to $b \to s\nu\bar{\nu}$. Theoretically very clean, SM BF $\sim 10^{-15}$ (strong GIM and CKM suppression)
- 2.93 fb^{-1} of $\Psi(3770) \to D^0\overline{\mathrm{D}^0}$ decays with tagged-$\overline{D^0}$
- Concept analogous to measurement of $B^+ \to K^+\nu\bar{\nu}$
  - Reconstruct the tag-D to suppress backgrounds

    ➔ NB: hadronic D-tag BF very high, as opposed to B-tag
    $BF(D^0 \to K\pi + K\pi\pi^0 + K3\pi)$ ~27%
  - 1 reconstructed π^0 besides D-tag, no other charged tracks
  - Signal signature: unassigned calo energy peaking at 0

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm sig}}{\mathcal{B}_{\pi^0\to\gamma\gamma}\sum_\alpha N^\alpha_{\rm tag}\epsilon^\alpha_{\rm tag,sig}/\epsilon^\alpha_{\rm tag}}$$

α= tag channel

PRD105(2022),L071102



$N_{sig} = 14 \pm 30$

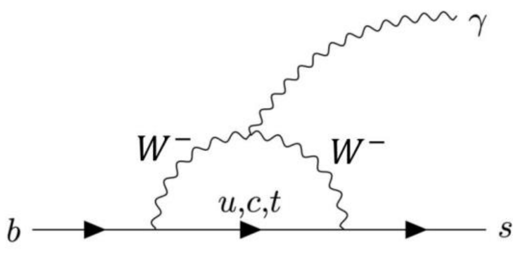
E_{EMC} = unassigned energy in the calorimeter

no signal ➔ $BF(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \times 10^{-4}$ @90%CL

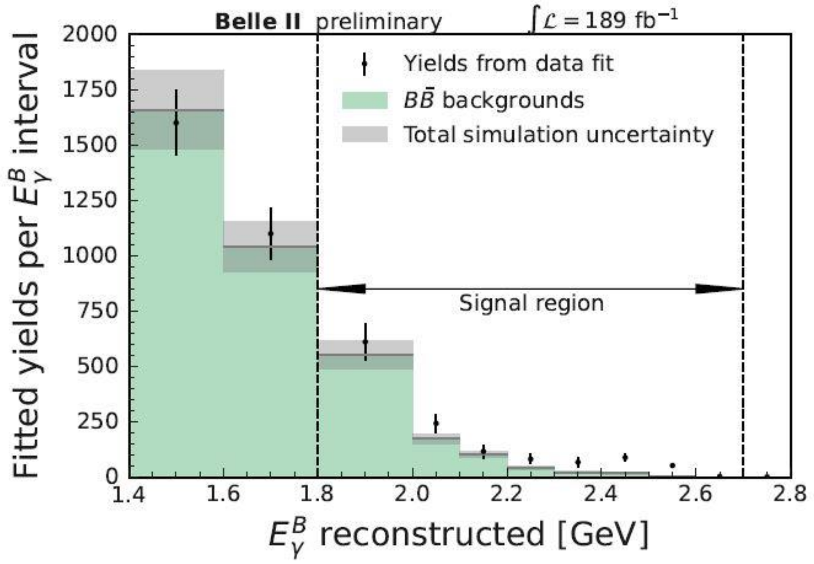
First limit for this decay

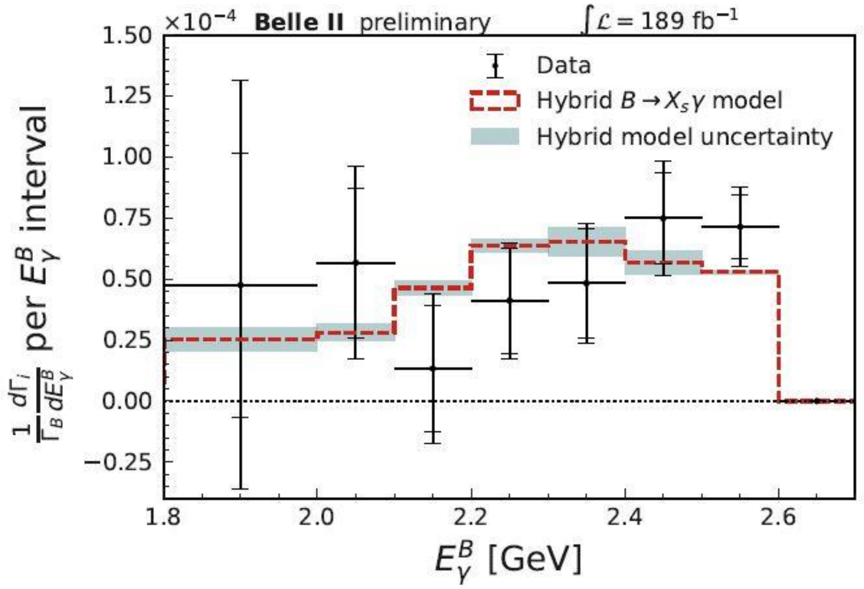
$B \to X_s \gamma$

- FCNC, theoretically clean, BF sensitive to NP
- E_γ spectrum gives insights of mass and p of b quark in B meson, used in $|V_{ub}|$ and $|V_{cb}|$ extraction
- X_s inclusive: all final states with net strangeness



BELLE2-CONF-PH-2022-018





- First measurement from Belle II, based on hadronic tag and 189fb^{-1}

$$BF(B \to X_s\gamma) = (3.54 \pm 0.78 \pm 0.83) \times 10^{-4} \qquad E_\gamma > 1.8\ \text{GeV}$$

Experimental status

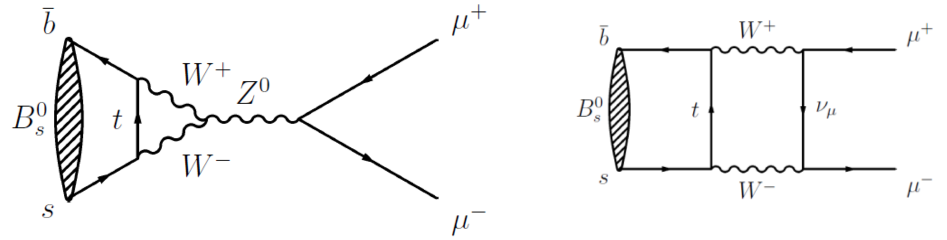
[HFLAV, PRD107(2022)052008]

$\mathcal{B}(B \to X_s\gamma)$ (10^{-6})	Belle [550]	$347 \pm 15 \pm 40$ [2]	605 fb^{-1}, fully inclusive, inclusive+lepton tag
	BaBar [1102]	$332 \pm 16 \pm 31$ [2]	347 fb^{-1}, fully inclusive, lepton tag
	Belle [1103]	$375 \pm 18 \pm 35$ [2]	711 fb^{-1}, Xs sum of exclusive modes
	BaBar [1104]	$352 \pm 20 \pm 51$ [2]	429 fb^{-1}, Xs sum of exclusive modes
	CLEO [551]	$329 \pm 44 \pm 29$ [2]	9 fb^{-1}, fully inclusive, inclusive+lepton+semi-excl tag
	BaBar [1105]	$390 \pm 91 \pm 64$ [2]	210 fb^{-1}, fully inclusive, hadronic tag

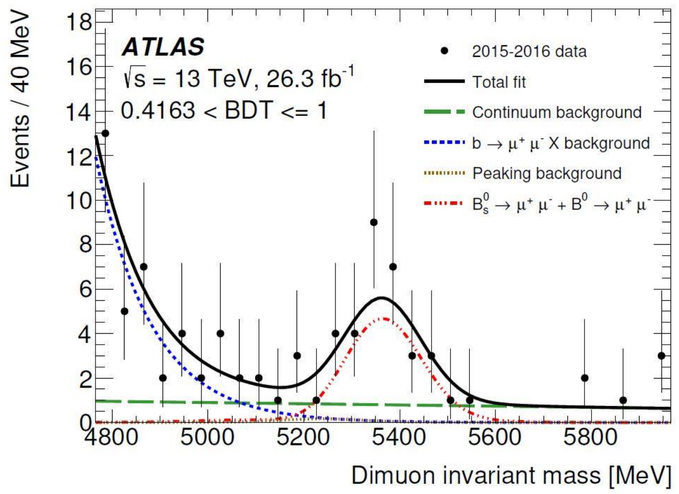
[2] Measurement extrapolated to $E_\gamma > 1.6$ GeV

HFLAV average: $(349 \pm 19) \times 10^{-6}$

$B_{s,d} \to \mu^+\mu^-$



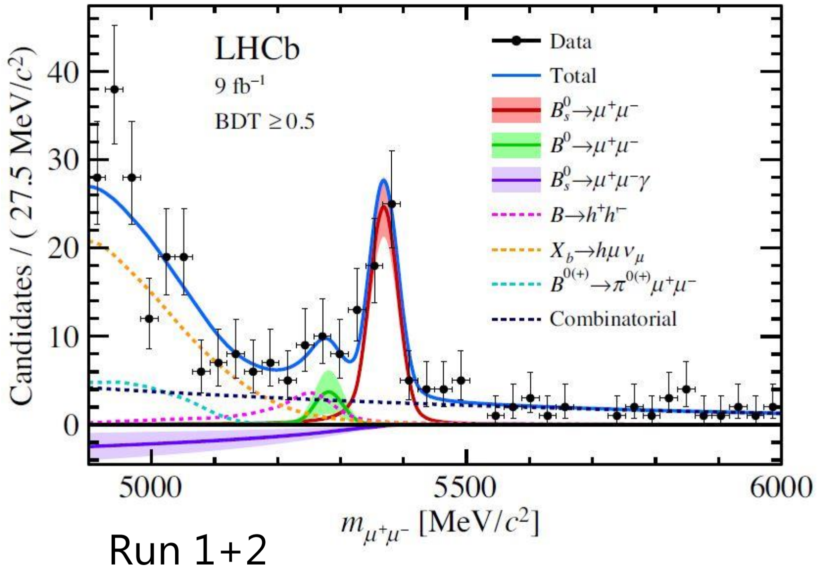
JHEP04(2019)098



2015+16 data

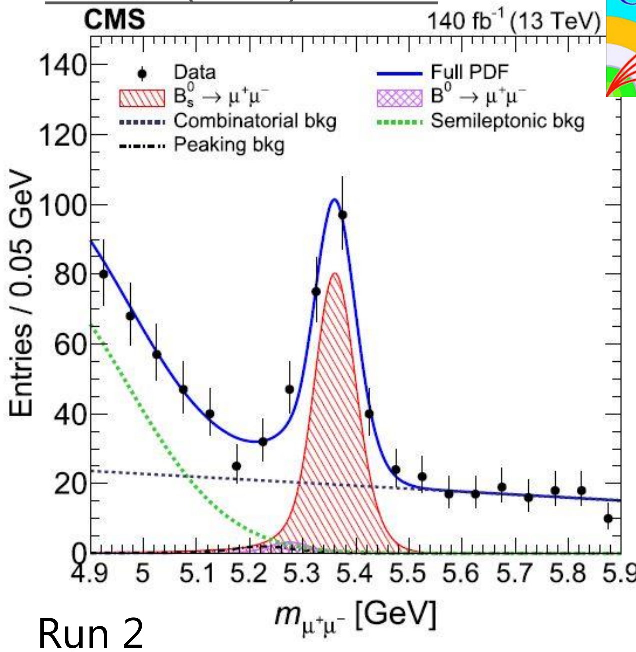
PRL128(2022)041801

PRD105(2022)012010



Run 1+2

PLB842(2023)137955



Run 2

- FCNC, helicity and CKM suppressed, theoretically very clean, BF sensitive to NP

$$BF(B_s \to \mu\mu)_{SM} = \left(3.78^{+0.15}_{-0.10}\right) \times 10^{-9}$$

$$BF(B^0 \to \mu\mu)_{SM} = \left(1.02^{+0.05}_{-0.03}\right) \times 10^{-10}$$

Buras, 2205.01118

Bobeth et al, PRL112(2014)101801

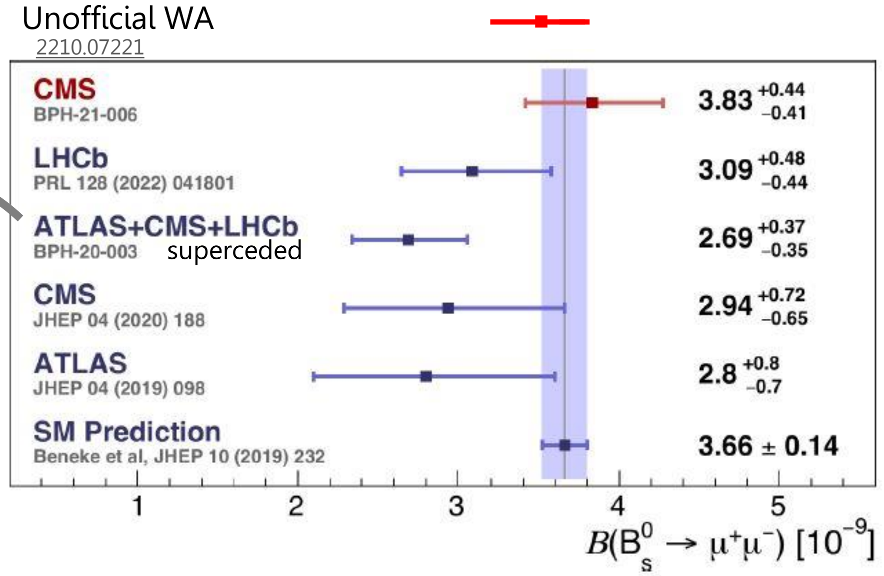
- ATLAS and CMS key players thanks to muon trigger and large integrated luminosity

$$BF(B_s \to \mu\mu) = \left(3.21^{+0.96}_{-0.91}{}^{+0.49}_{-0.30}\right) \times 10^{-9} \qquad \text{ATLAS}$$

$$BF(B_s \to \mu\mu) = \left(3.83^{+0.38}_{-0.36}{}^{+0.19}_{-0.16}{}^{+0.14}_{-0.13}\right) \times 10^{-9} \qquad \text{CMS}$$

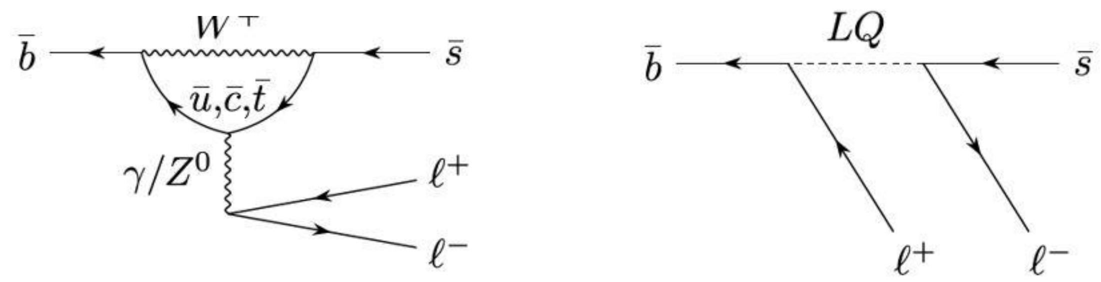
$$BF(B_s \to \mu\mu) = \left(3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}\right) \times 10^{-9} \qquad \text{LHCb}$$

- 2σ tension washed out following latest LHCb and CMS results
- $BF(B_s \to \mu\mu)$ becoming precision measurement. Still room for 15% NP
- No evidence of $B^0 \to \mu\mu$ yet (UL~ $O(1) \times 10^{-10}$)

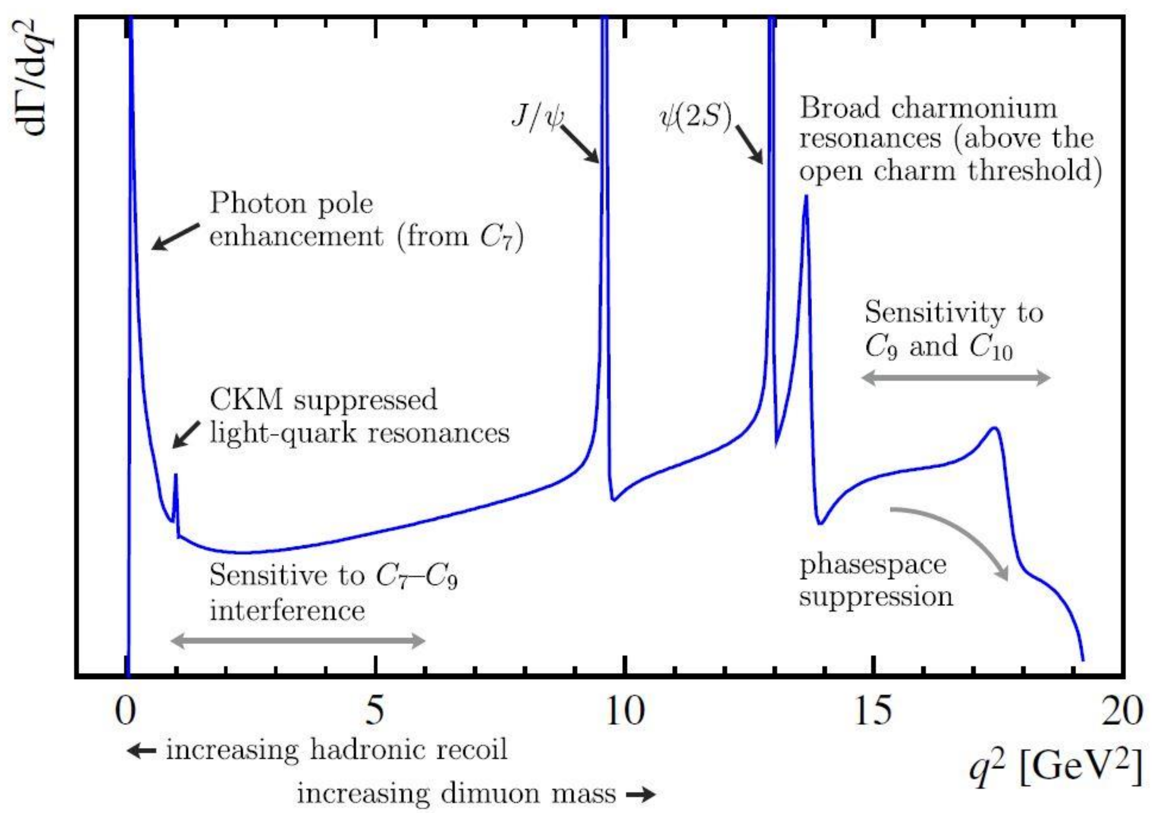


Still benchmark channels to search for signs of NP

The $b \to sl^+l^-$ decays



Blake et al, PPNP(2017)92



$q^2 = m(l^+l^-)^2$

- Unlike $B_s^0 \to \mu\mu$, there is a hadron in the final state
  - Multitude of observables complementary to $B \to \mu\mu$ measurement
  - Observables not always as theoretically clean

Branching fractions

$B \to K^{(*)}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-$

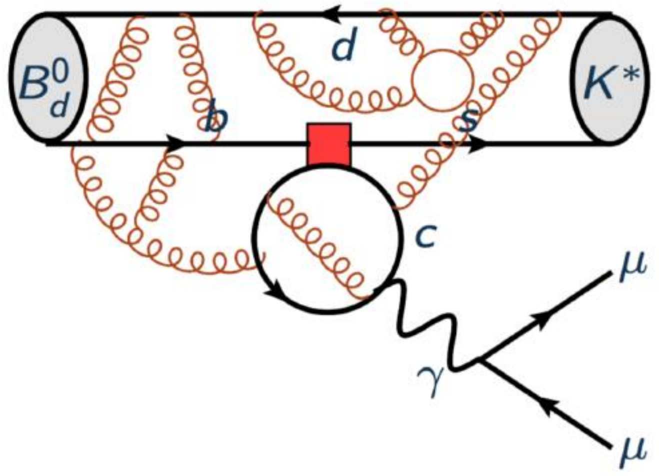
Angular analyses

$B \to K^{(*)}\mu^+\mu^-$ $\Lambda_b \to \Lambda\mu^+\mu^-$

Lepton flavour universality tests

$B^0 \to K^{(*)0}l^+l^-$ $B^+ \to K^+l^+l^-$

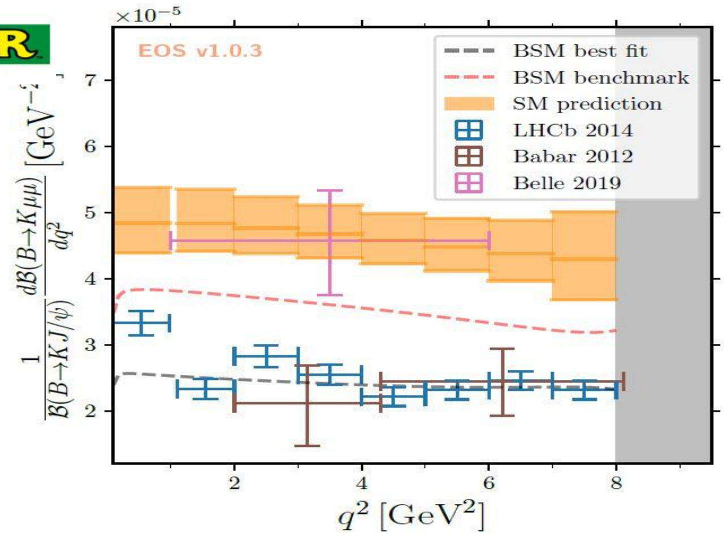
Increasing SM precision



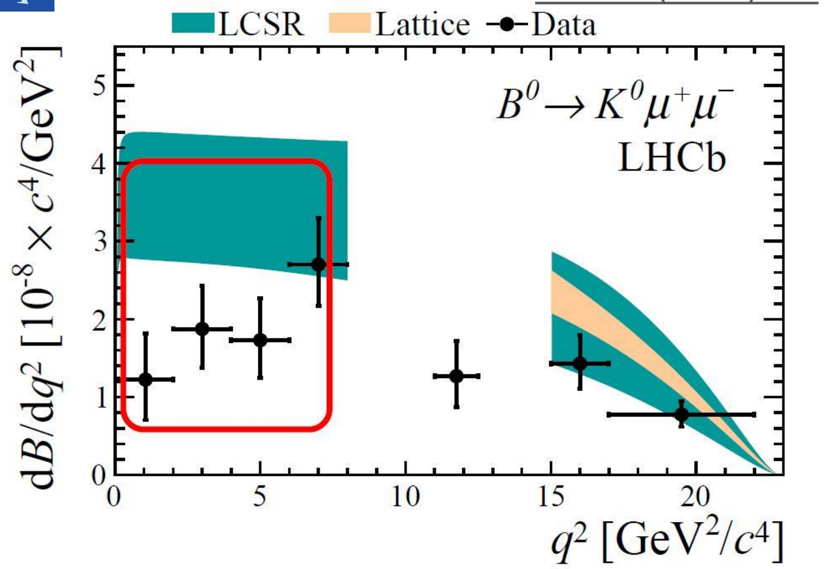
SM $c\bar{c}$ loop affecting the amplitude

$b \to s\mu^+\mu^-$ BF

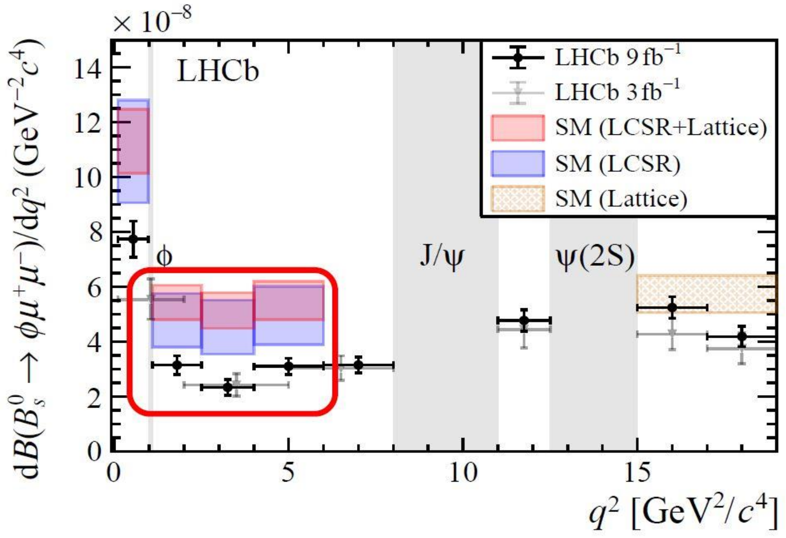
$B^+ \to K^+\mu^+\mu^-$ JHEP09(2022)133



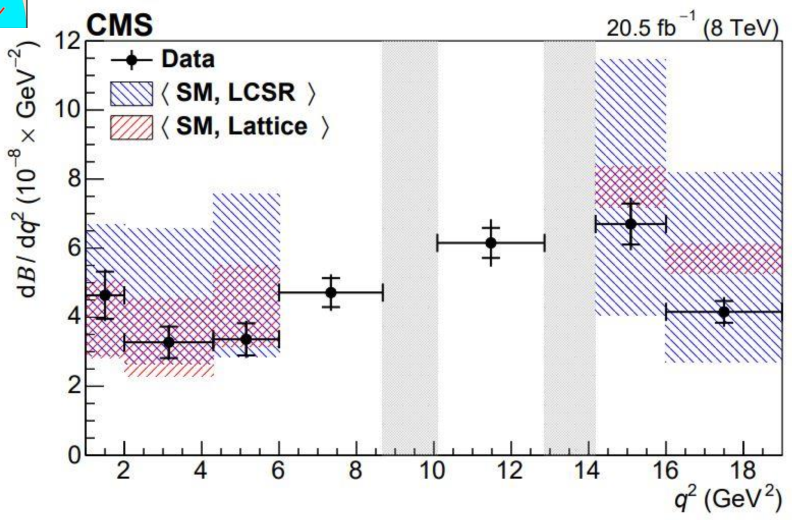
$B^0 \to K^0\mu^+\mu^-$ JHEP06(2014)133



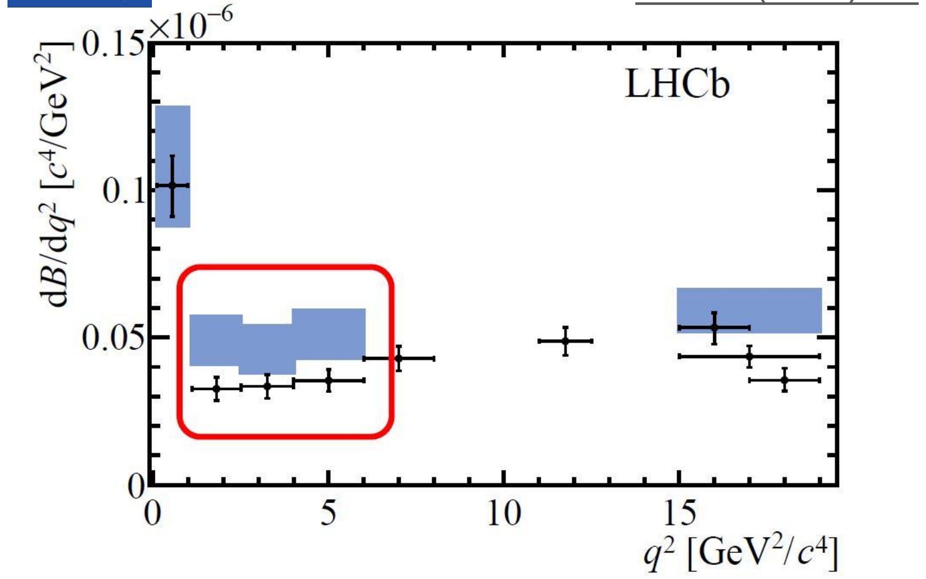
$B_s \to \phi\mu^+\mu^-$ PRL127(2021)151801



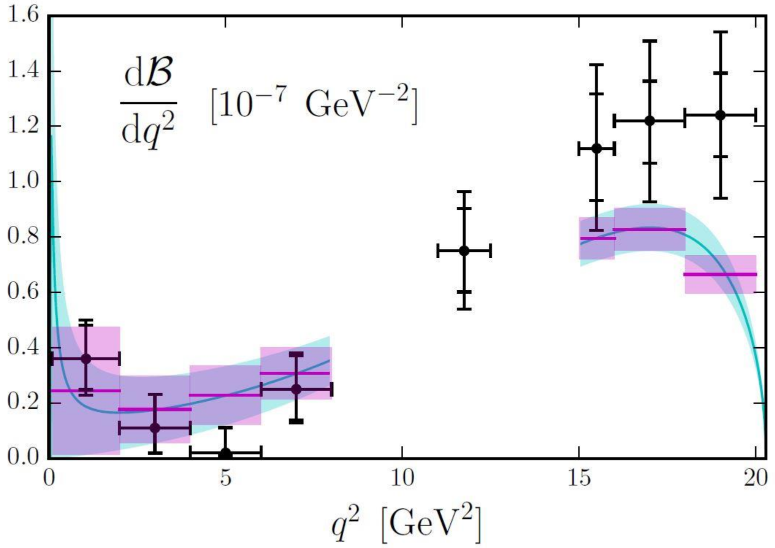
$B^0 \to K^{*0}\mu^+\mu^-$ PLB753(2016)424



$B^0 \to K^{*0}\mu^+\mu^-$ JHEP04(2017)142



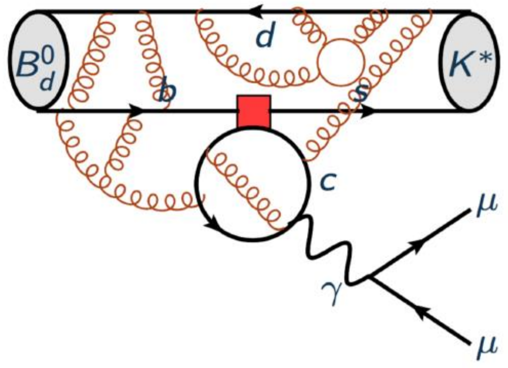
$\Lambda_b \to \Lambda\mu^+\mu^-$ JHEP06(2015)115



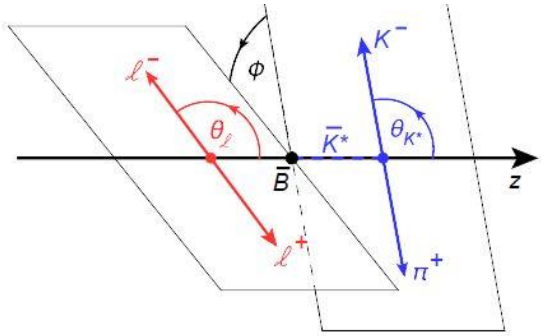
- Data often below SM predictions especially at low q^2 values
- Non-local hadronic uncertainties difficult to estimate ➔ Area of active theory development

$b \to s\mu^+\mu^-$ angular analysis

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



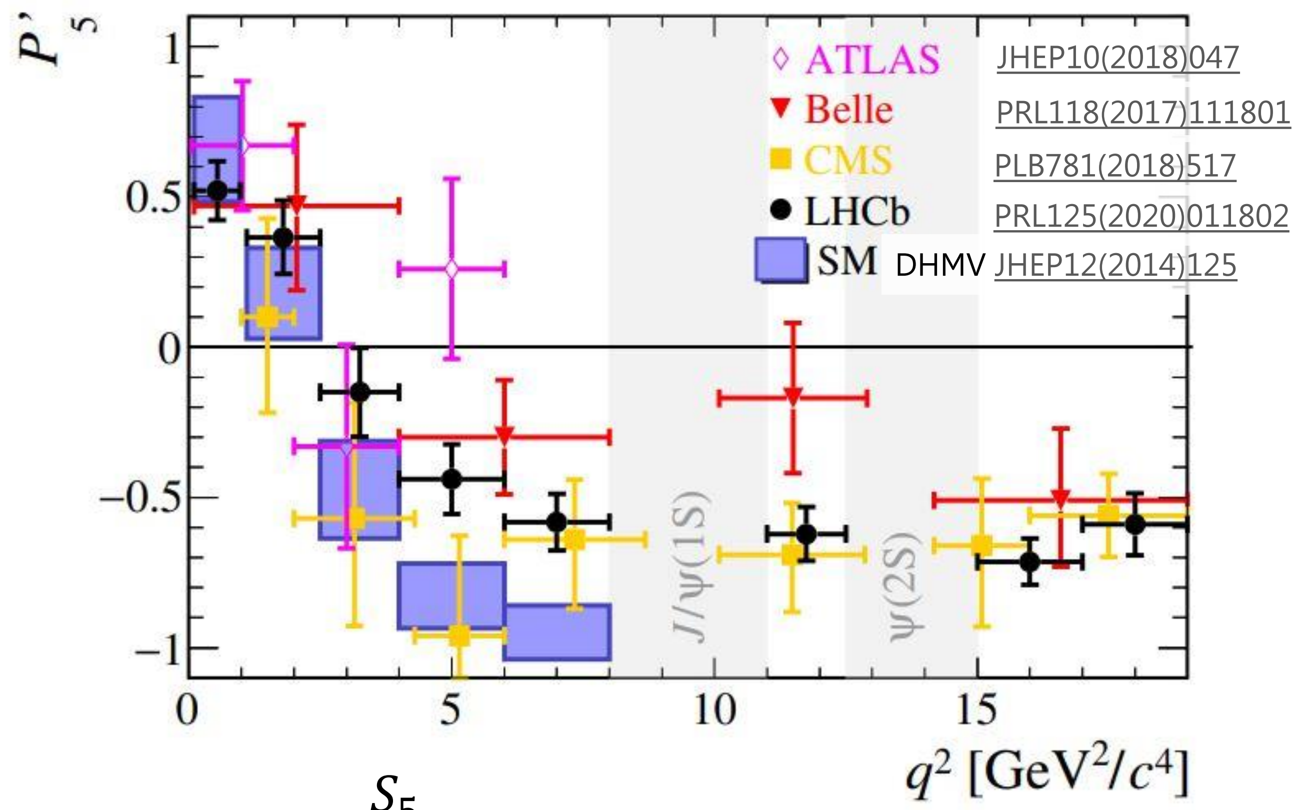
$\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$



Decay rate:

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

PPNP120(2021)103885



$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

- Angular observables (vs q^2) sensitive to new physics
- Possible to choose parameterisations less sensitive to $B \to K^{*0}$ form factors uncertainties (eg P'_5 in the plot)
- Still, dependency on other hadronic uncertainties remains ($c\bar{c}$ loop)

- Tensions of data vs SM in regions around $q^2 = 6$ GeV^2
- Ongoing efforts to update the q^2-binned measurements and to explore additional unbinned methods

$b \to s l^+ l^-$ lepton flavour universality tests ($l = e, \mu$)

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour ("lepton universality")

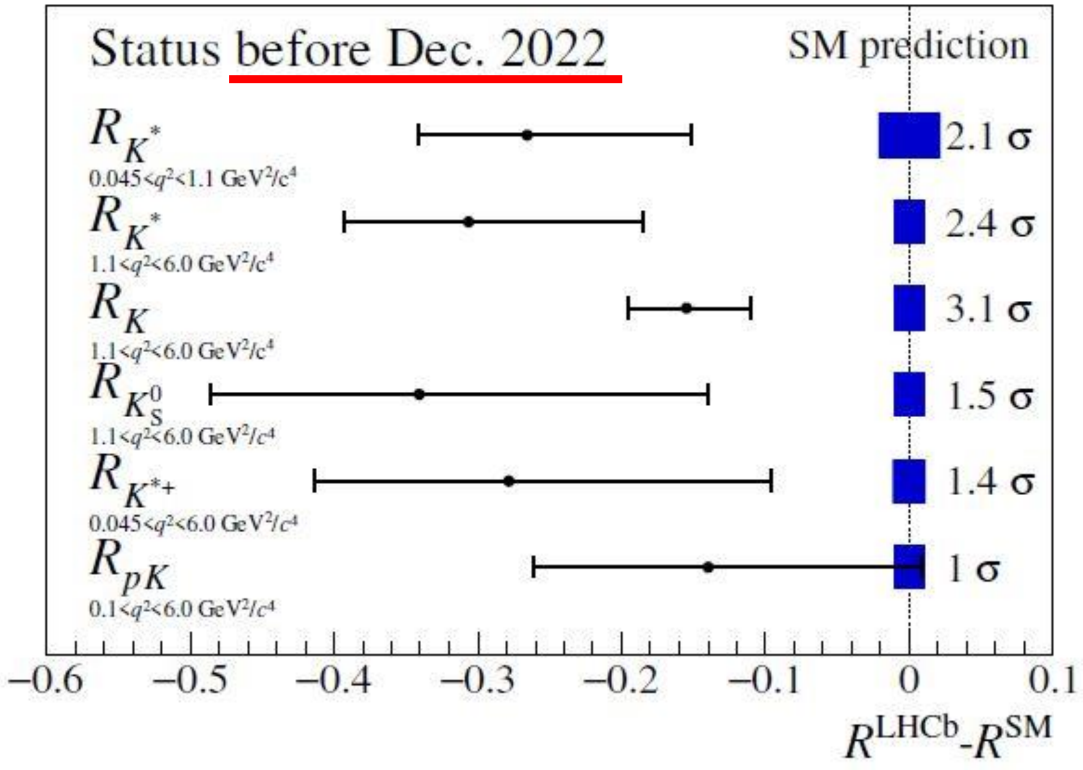
- Ratios of the form

$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$

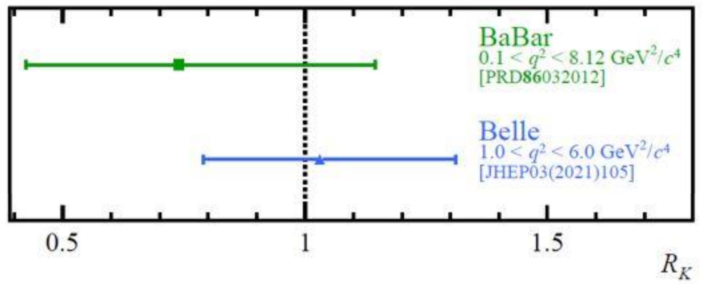
in SM are essentially free of QCD uncertainties.
Reliable e.m. 1% uncertainties.

[Bordone et al, EPJC76(2016)440
Isidori et al, JHEP12(2020)104
Isidori et al, JHEP10(2022)14]

C. Langenbruch@Recontres de Blois 2023



- $R_{K^{(*)}}$ sensitive to contributions beyond SM up to >10% (eg models with Z' or leptoquarks)

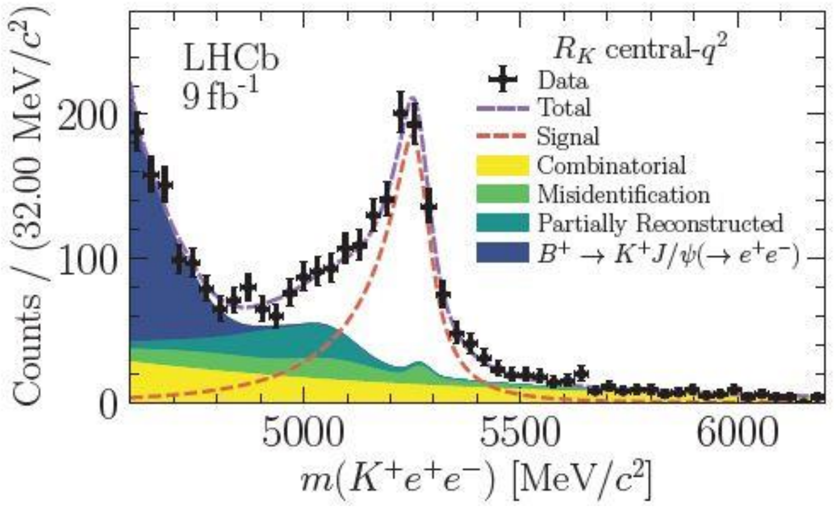


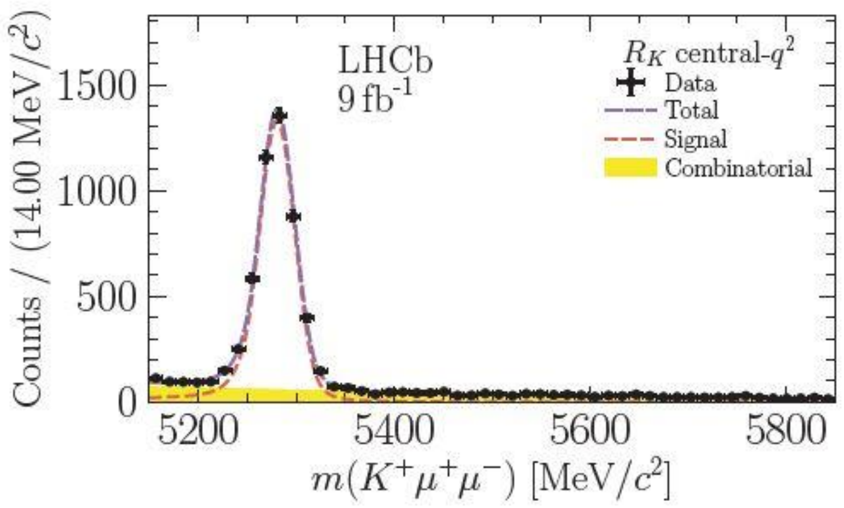
- Experimentally convenient to measure:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\text{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\text{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\text{rare}}_{e^+e^-}}{N^{\text{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

Measurement of $R_{K^{(*)}}$

- Channel with e^+e^- experimentally much more challenging at LHCb due to brem. γ emission
  - Bremsstrahlung recovery. Worse p resolution. Lower selection efficiency
  - Larger and ‘trickier’ backgrounds



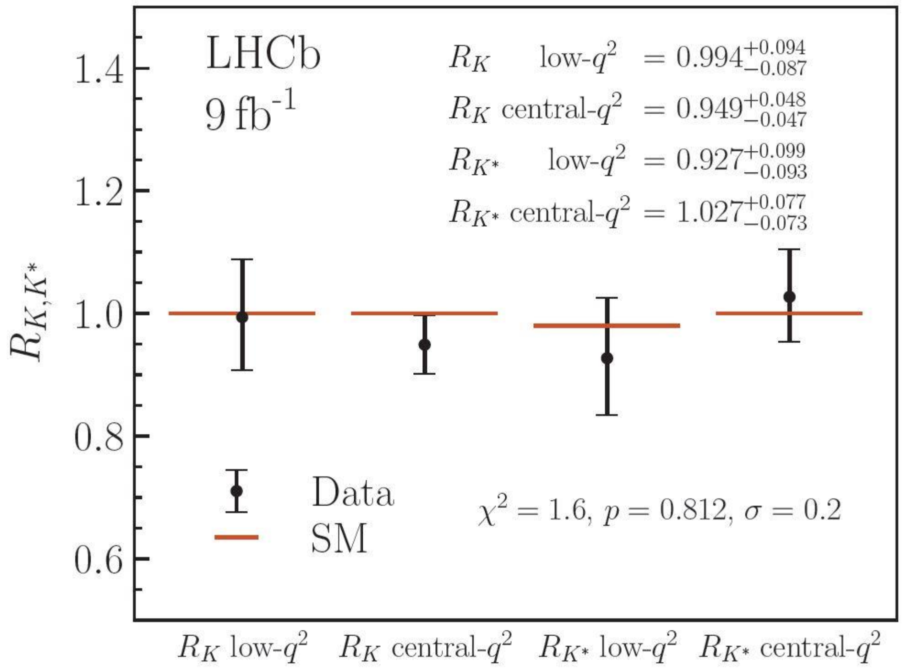


2212.09152 accepted by PRL
2212.09153 accepted by PRD

- LHCb measurement of R_K and $R_{K^{*0}}$ using the full Run 1+2 dataset
  - Better understanding of mis-identified backgrounds in the e^+e^- channel
  - Added low-q^2 measurement for R_K, more data for $R_{K^{*0}}$

Results consistent with SM predictions. Still room for NP effects at 5-10% level

- Measurements driven by LHCb, but CMS, ATLAS and Belle II are expected to contribute



See:
R_K Belle, 711fb^{-1}, JHEP 03 (2021) 105
$BF(B \to K^*l^+l^-)$ Belle II, 189 fb^{-1}, 2206.05946
$R_K(J/\psi)$ Belle II, 189 fb^{-1}, 2207.11275

Interpretation of results

- Possible interpretations using effective Hamiltonian approach

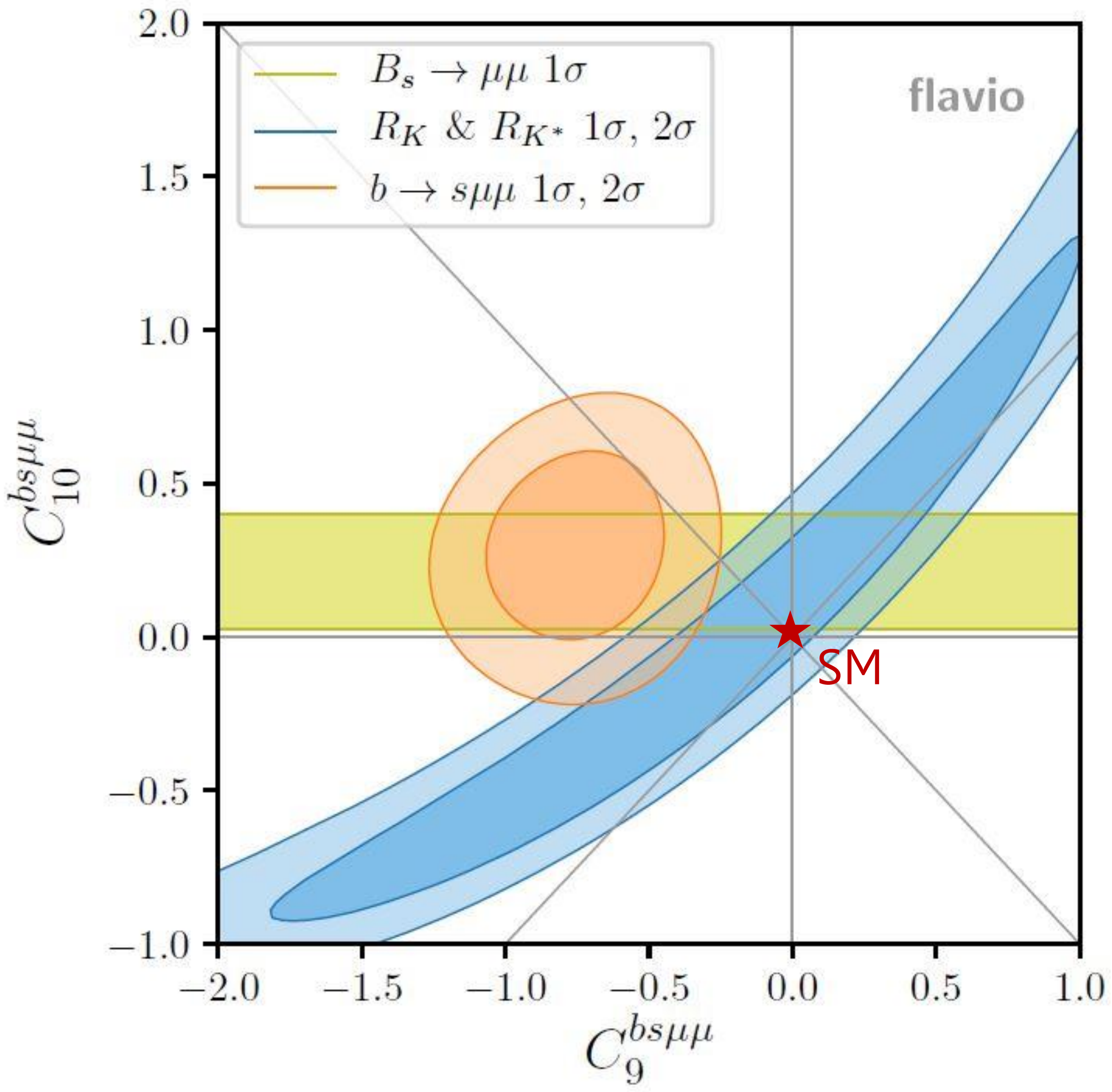
$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}\sum_{q=s,d}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P} V_{tb}V_{tq}^*(C_i^{bq\ell\ell}O_i^{bq\ell\ell} + C_i^{\prime bq\ell\ell}O_i^{\prime bq\ell\ell}) + \text{h.c.}$$

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9^{\prime bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}^{\prime bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$
$$O_S^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\ell)\,, \qquad O_S^{\prime bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\ell)\,,$$
$$O_P^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P^{\prime bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$

- In the example, NP C$_9$ and C$_{10}$ of $b \to s\mu^+\mu^-$ free to vary, SM assumed for $b \to se^+e^-$

- Useful to test different NP scenarios in mod-indep way, provided that theory uncertainties of input parameters are under control

Greljo et al, JHEP05(2023)087



$b \to s\tau^+\tau^-$ transitions

- FCNC process involving 3° generation of leptons
- SM BF predictions are $O(10^{-7})$
- At least 2 neutrinos in final state ➔ Experimentally much more challenging than $b \to sl^+l^-$ with $l = e, \mu$

Babar: $BF(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3}$ @90% CL   424 fb^{-1} PRL118(2017)031802

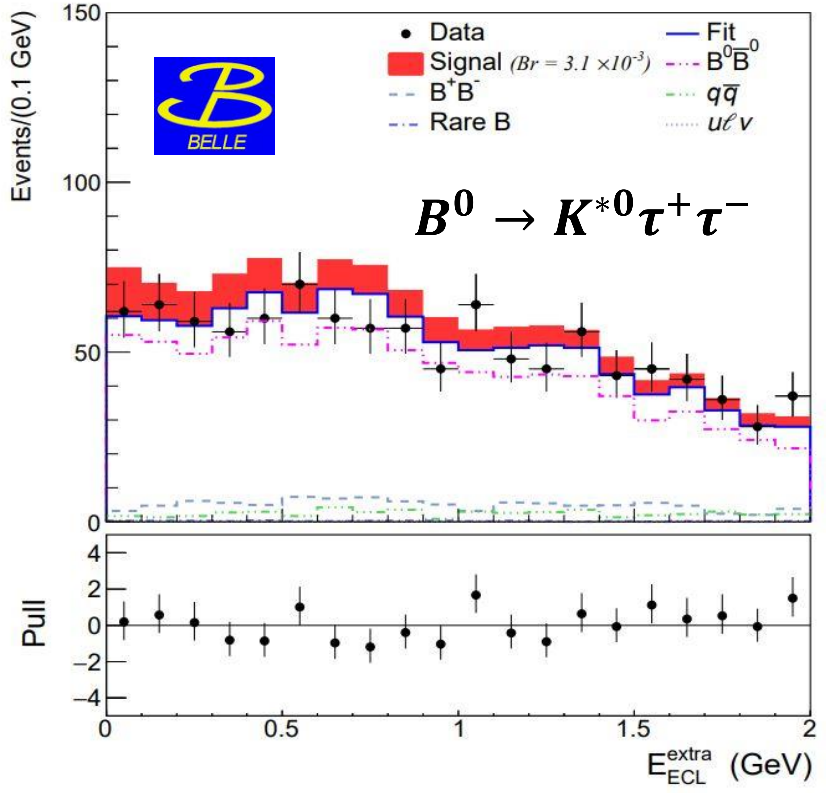
Belle: $BF(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$ @90% CL   711 fb^{-1}

LHCb: $BF(B_s^0 \to \tau\tau) < 6.8 \times 10^{-3}$ @95% CL   Run 1

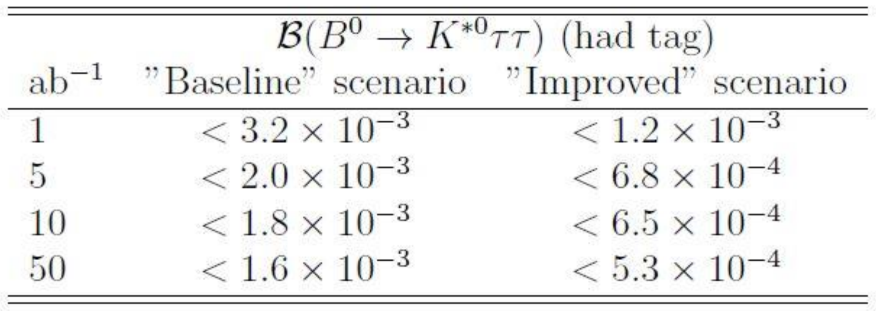
→ far from SM but close to allowed range in some NP scenarios

Capdevila et al, PRL120(2018)181802

2110.03871 accepted by PRD



Belle II projections for $K^{*0}\tau\tau$:

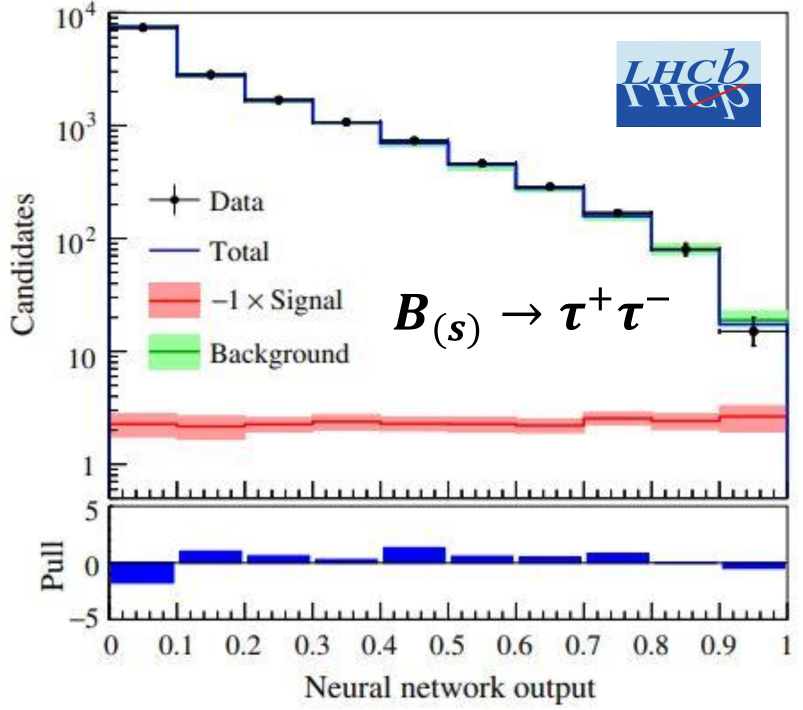


$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)		
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

Snowmass WP, 2207.06307

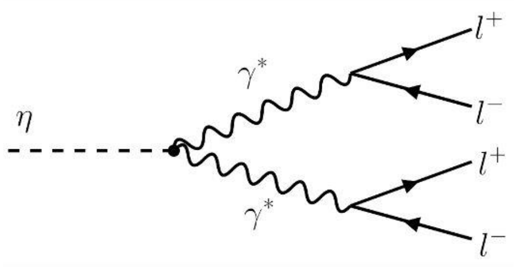
- Hadronic tag assumed: could Belle II do even better with a more inclusive tag?
- K^{*0} vertex can be powerful in suppressing bkg at LHCb compared to $B_s^0 \to \tau\tau$ → LHCb can be competitive with Belle II

PRL118(2017)251802



Observation of $\eta \rightarrow 4\mu$

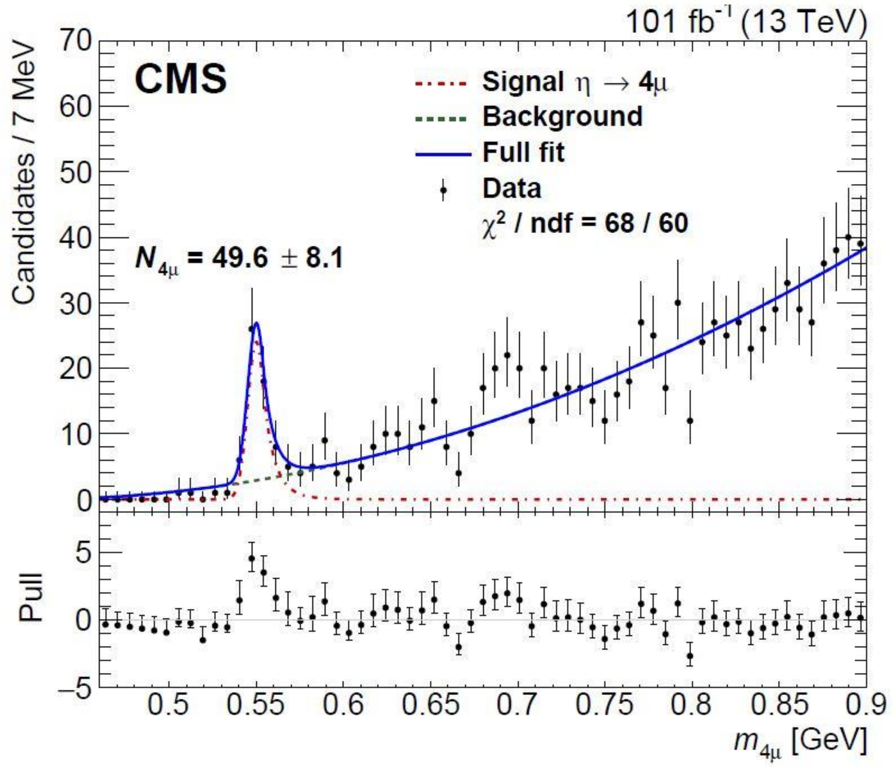
- Decay through e.m. coupling of meson to photons
  - Sensitive to physics beyond SM
  - BF helps quantify had light-by-light component of $(g-2)_\mu$



$$BF(\eta \rightarrow 4\mu)_{SM} = (3.98 \pm 0.15) \times 10^{-9}$$

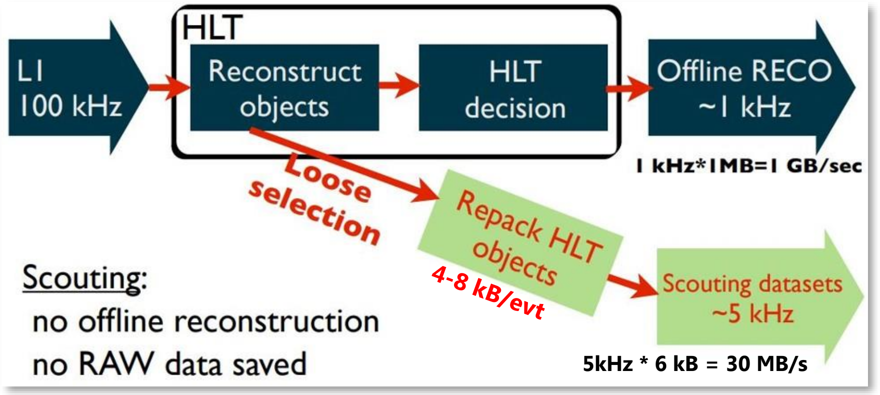
Escribano, Gonzalez-Solis ChinPhysC42(2018)023109

2305.04904 sub to PRL



- Muon p_T threshold of standard CMS trigger too high for $\eta \rightarrow 4\mu$

➔ Data scouting technique:



HLT

L1
100 kHz

Reconstruct objects

HLT decision

Offline RECO
~1 kHz

1 kHz*1MB=1 GB/sec

Loose selection

Repack HLT objects

4-8 kB/evt

Scouting datasets
~5 kHz

Scouting:
no offline reconstruction
no RAW data saved

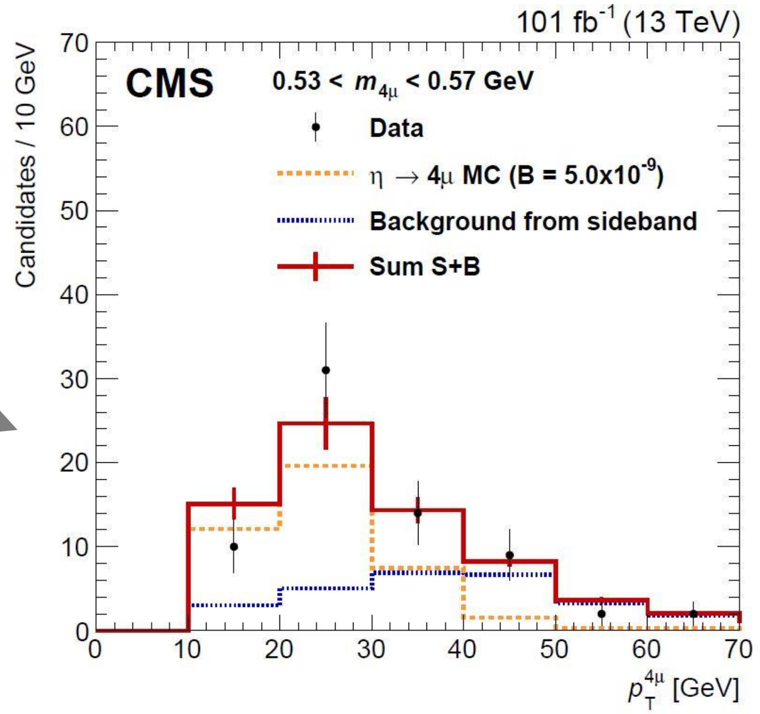
5kHz * 6 kB = 30 MB/s

Adapted from S. Mukherjee@LLP 2018

101 fb^{-1} of 2017,18 data

Estimated 10^{12} η mesons in det acceptance!

p_T of signal consistent with expectation



- BF measured normalizing w.r.t. $\eta \rightarrow \mu^+\mu^-$

$$\mathcal{B}(\eta \rightarrow 4\mu) = (5.0 \pm 0.8\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst}) \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$

First observation > 5σ

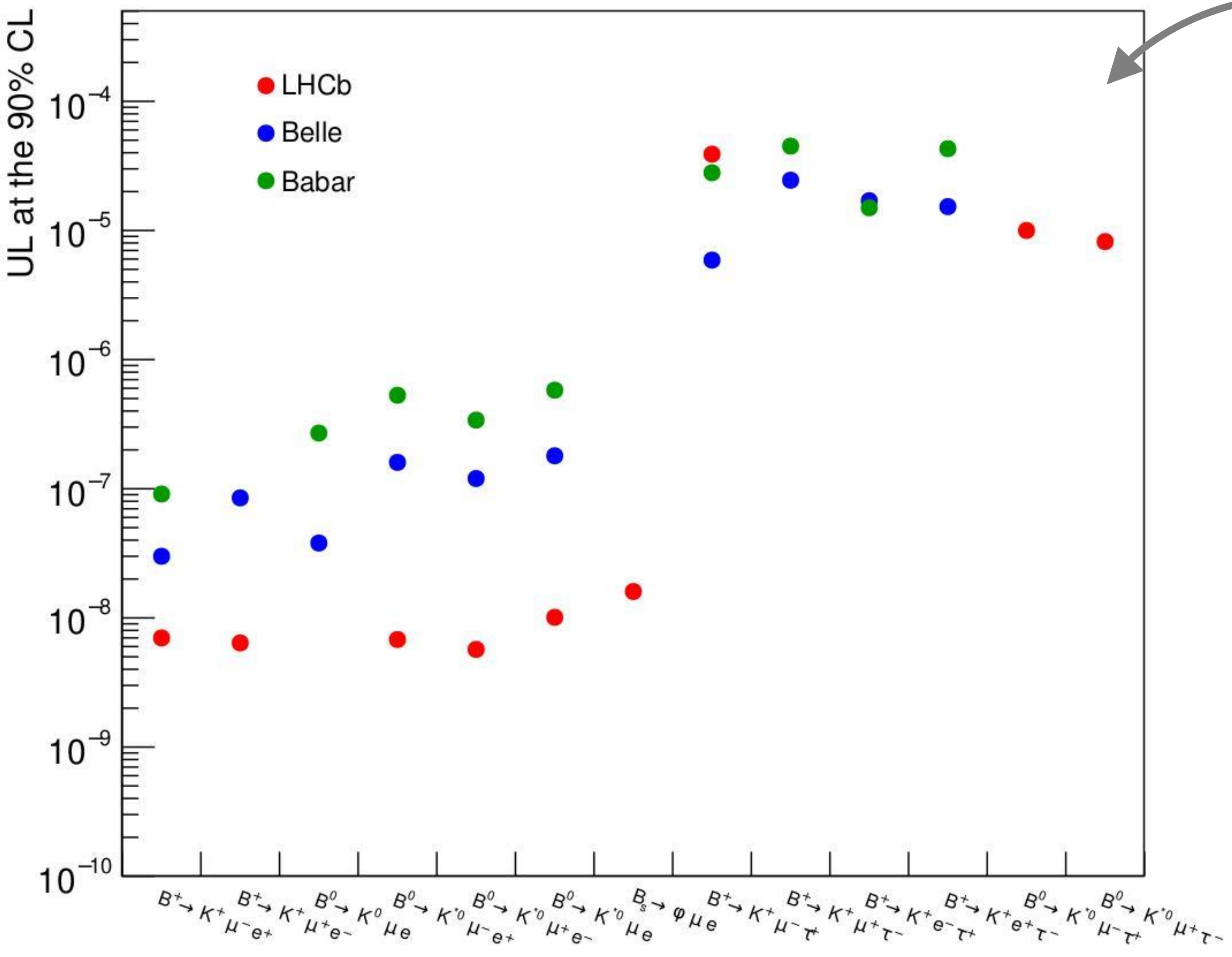
Lepton flavour violation in hadron decays

- Lepton flavour violation (LFV) forbidden in the SM, allowed in several NP scenarios (LQ, Z', …)
- Model parameters constrained already with current datasets

pp vs e^+e^- enviroments

- ○ When τ replaces e or μ, LHCb looses $\geq O(10^3)$ sensitivity; B-factories pay $\sim O(10^2)$
- ○ When no τ, LHCb benefits from very large $b\bar{b}$ prod cross-section

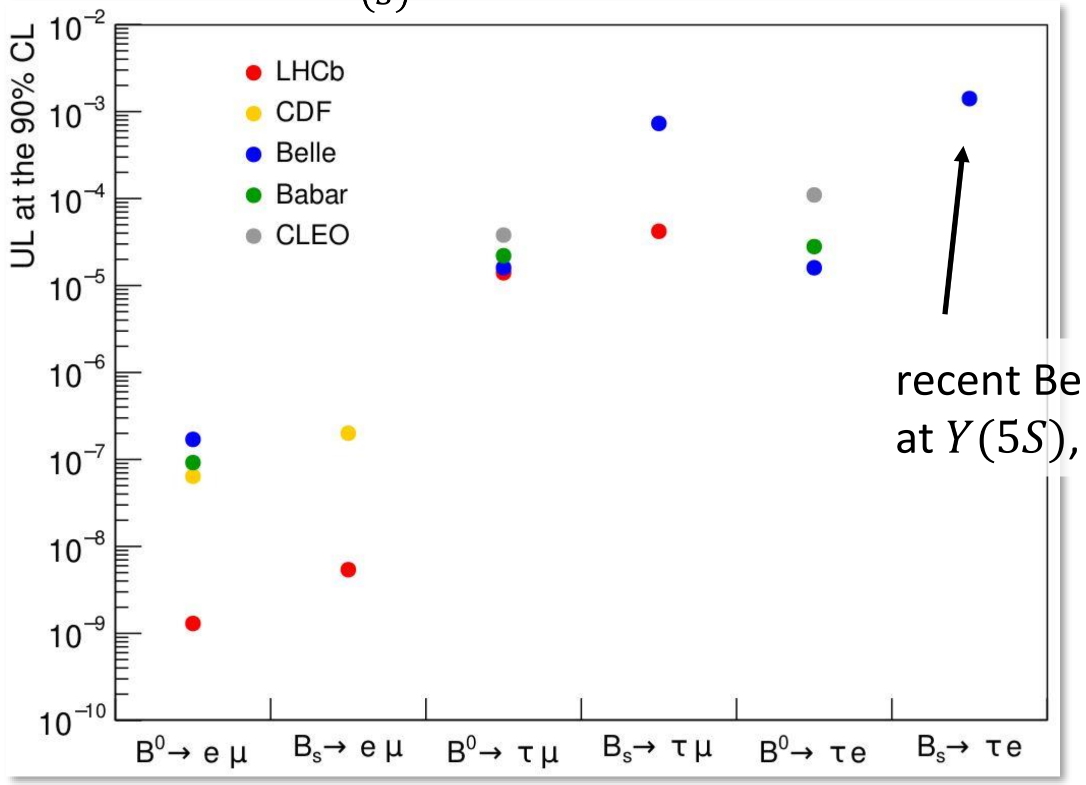
Experimental status of $b \to s\, l\, l'$ searches



no τ in final state

1 τ in final state

$B_{(s)} \to l\, l'$ searches



recent Belle measurement at $\Upsilon(5S)$, 2301.10989

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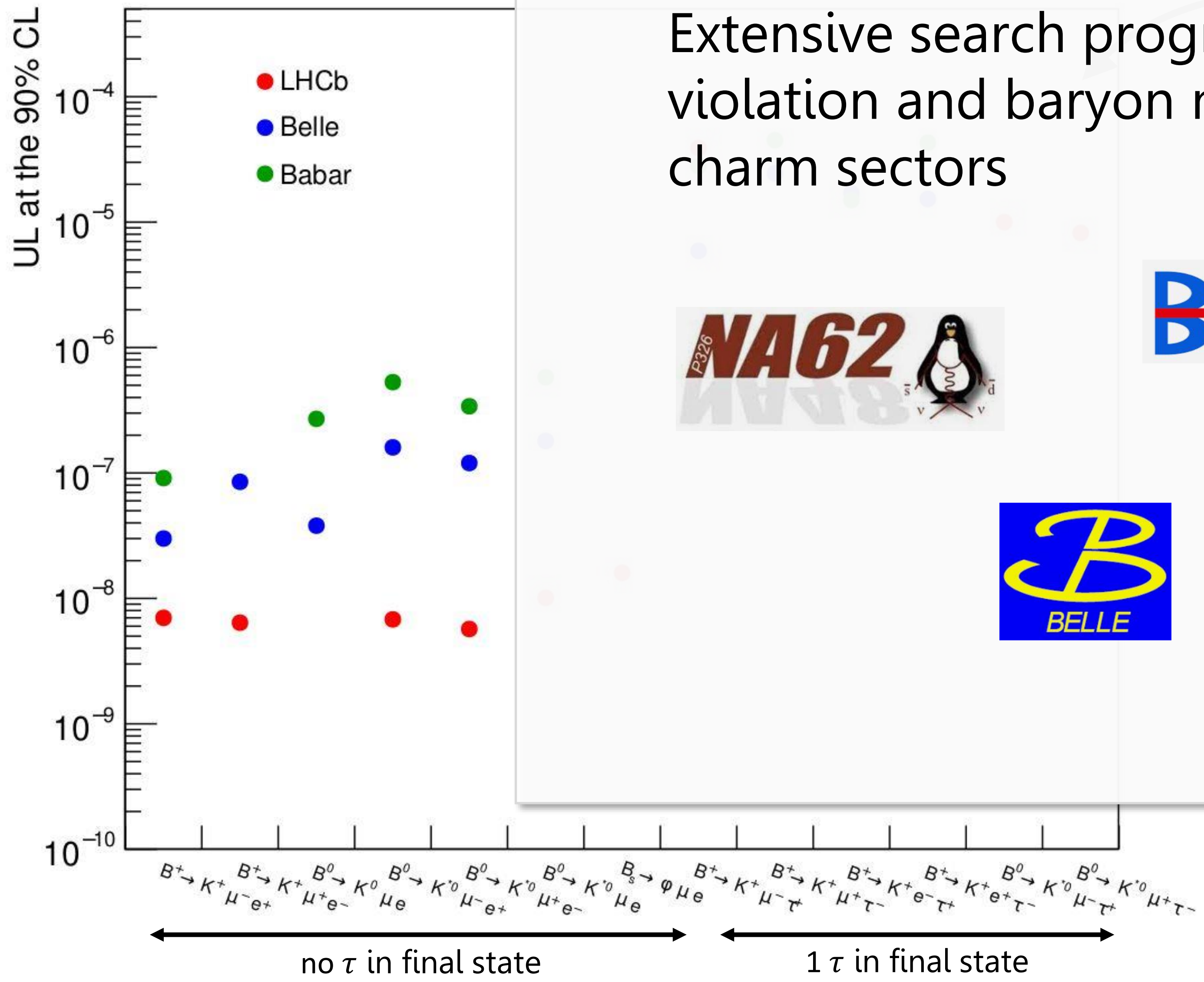
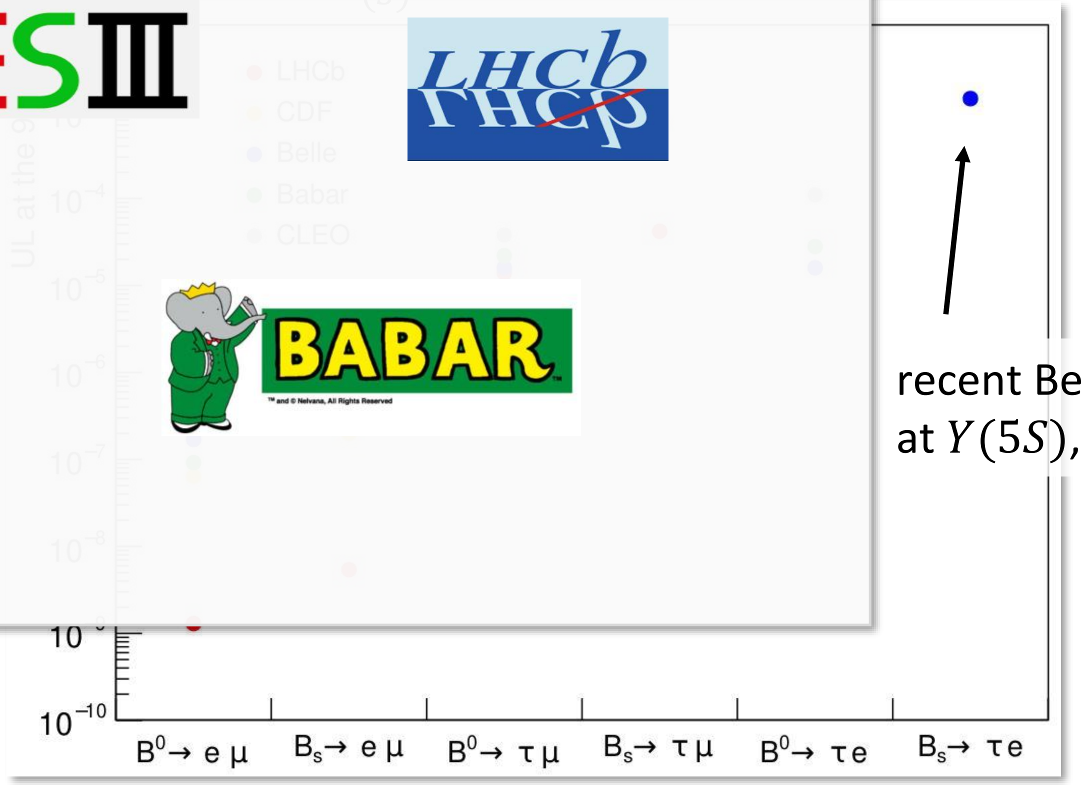


Not only LFV and not only in b decays:
Extensive search program of lepton flavour/number violation and baryon number violation in kaon and charm sectors

NA62 BESIII LHCb BELLE BABAR

$B_{(s)} \to l\, l'$ searches



recent Belle measurement at $\Upsilon(5S)$, 2301.10989

Near future

Upgrade

- 9 fb^{-1} collected in Run 1+2
- Taking data with upgraded det
- Expected $L_{peak} = 2 \times 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$
- ~23 fb^{-1} by end of 2025 (x3 stat)

- Current measurements use up to 190 fb^{-1}
- … but collected 370 fb^{-1} @ Y(4S)
- $L_{peak} = 4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- 3 ab^{-1} in 2025, ~7ab^{-1} in 2027

Baudot@FPCP23

- $\sqrt{s}$ =2-4 GeV, $L_{peak} = 1 \times 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$
- Running at $\Psi(3770)$, plan to collect 20 fb^{-1}
- Operate BESIII into 2030's after machine upgrade

- Collected 140fb^{-1} (each) in Run 2
- Run3: $L_{peak} = 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- 450 fb^{-1} by LS3 in 2026

- Ongoing Run 2 data taking, upgraded det to reduce backgrounds
- Expected $BF(K^+ \to \pi^+ \nu\bar{\nu})$ 15% precision by end 2025

- Ongoing analysis of 2021 data with SES~8×10^{-10} similar to 2016-18
- SES <10^{-10} in 3-4 years

Y. B. Hsiung @FPCP23

Farther future

Upgrade

- 9 fb^{-1} collected in Run 1+2
- Taking data with upgraded det
- Expected $L_{peak} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
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- SES <10^{-10} in 3-4 years

Y. B. Hsiung @FPCP23

Upgrade 1b + II

- 50 fb^{-1} by end of Run 4 (2032)
- Then, upgrade II phase:
  - $L_{peak} = 1.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 300 fb^{-1} after Run 5+6 (till end of LHC operation)
  - Ongoing approval process

Framework TDR

Upgrade

- $L_{peak} = 6.5 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ after IR upgrade
- 20-30 ab^{-1} early 2030's, 50ab^{-1} mid 2030

Snowmass WP 2203.11349

Super Charm Tau Factory

- Chinese proposal CDR 2303.15790
  - $\sqrt{s} = 2\text{–}7$ GeV, $L_{peak} \geq 0.5 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ 4 GeV
  - 1 ab^{-1} per year
- Russian proposal with similar features

PAN 83(2020)944

High Lumi LHC

- Starting in 2029 till end of LHC operations
- $L_{peak} = 5 \div 7.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 3000 fb^{-1} (each) and beyond

High Intensity Kaon Experiments

- Proposed K^+, K_L program at CERN SPS after 2025
- Phase 1: $BF(K^+ \to \pi^+ \nu\bar{\nu})$ 5% precision
- Phase 2: $BF(K_L \to \pi^0 \nu\bar{\nu})$ 20% precision

LoI 2211.16586

STEP 2

- Aim at $BF(K_L \to \pi^0 \nu\bar{\nu})$ 20% precision
- Start in 2030's

2110.04462

Summary

- In the search for physics beyond the Standard Model, rare decays of hadrons are one of the key tools
- Joint effort of many experiments operating under different experimental conditions
- Some tensions with SM predictions in a few measurements, but not clear conclusions
    - Importance of having reliable theoretical SM predictions. Great ongoing effort from the theoretical community.
    - Desirable that a measurement can be replicated by independent experiments. In general, good overlap.
- All main players have approved data-taking programs which will allow to significantly increase the datasets in the next 2-3 years
- Exciting next-gen projects, approved or under discussion, aim at further increasing the datasets by order of magnitudes in a time scale of 10-15 years

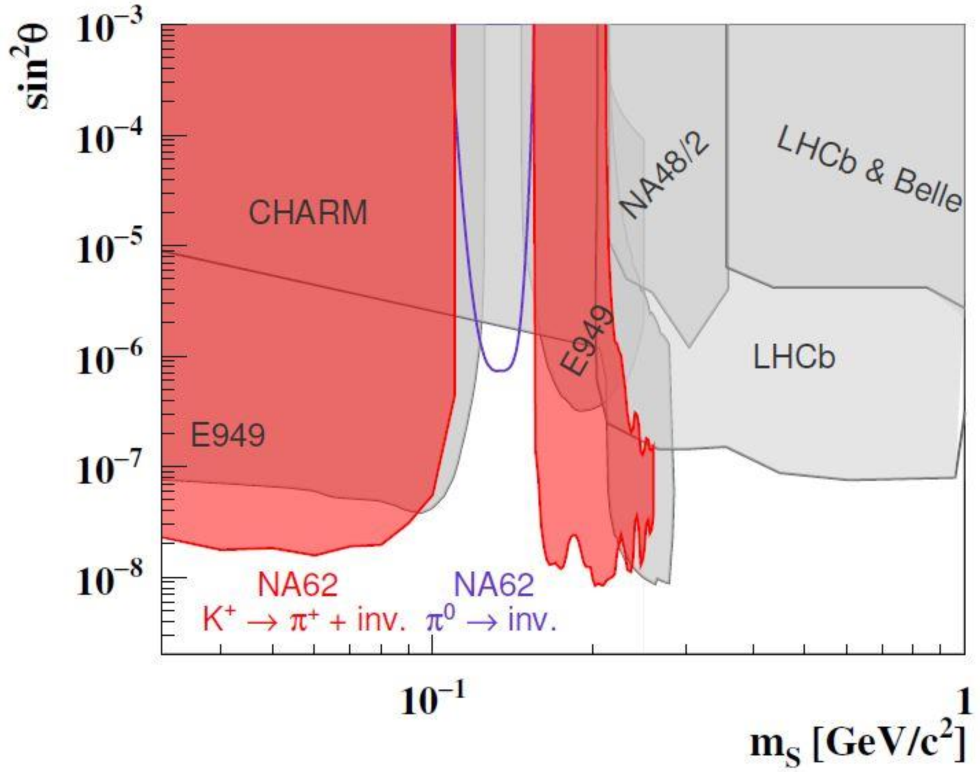
BACKUP

Rare decays as tool to constrain the Dark sector

- Search for $X \rightarrow ''visible''$ or $X \rightarrow'' \ invisible''$ through the decay $A \rightarrow B\ X$, with A and B reconstructed SM particles

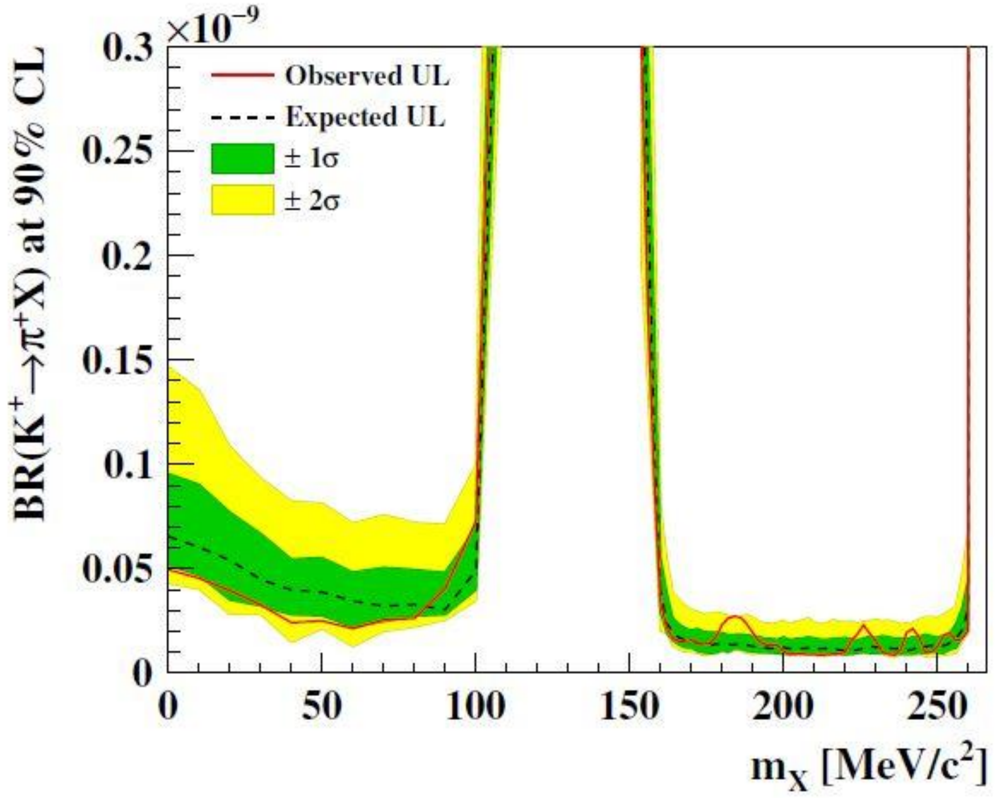
- Example: set UL on $X \rightarrow ''visible''$ through $K^+ \rightarrow \pi^+\ X$ at NA62
  - Assumption: X is dark-sector scalar mixing with SM Higgs (coupling = $\sin\theta$) , with $\tau_X \propto 1/\sin\theta$.
  - From the UL, which depends on τ_X through correlation with signal efficiency, the bound on $\sin\theta - m_X$ is extended

JHEP 06(2021)093]



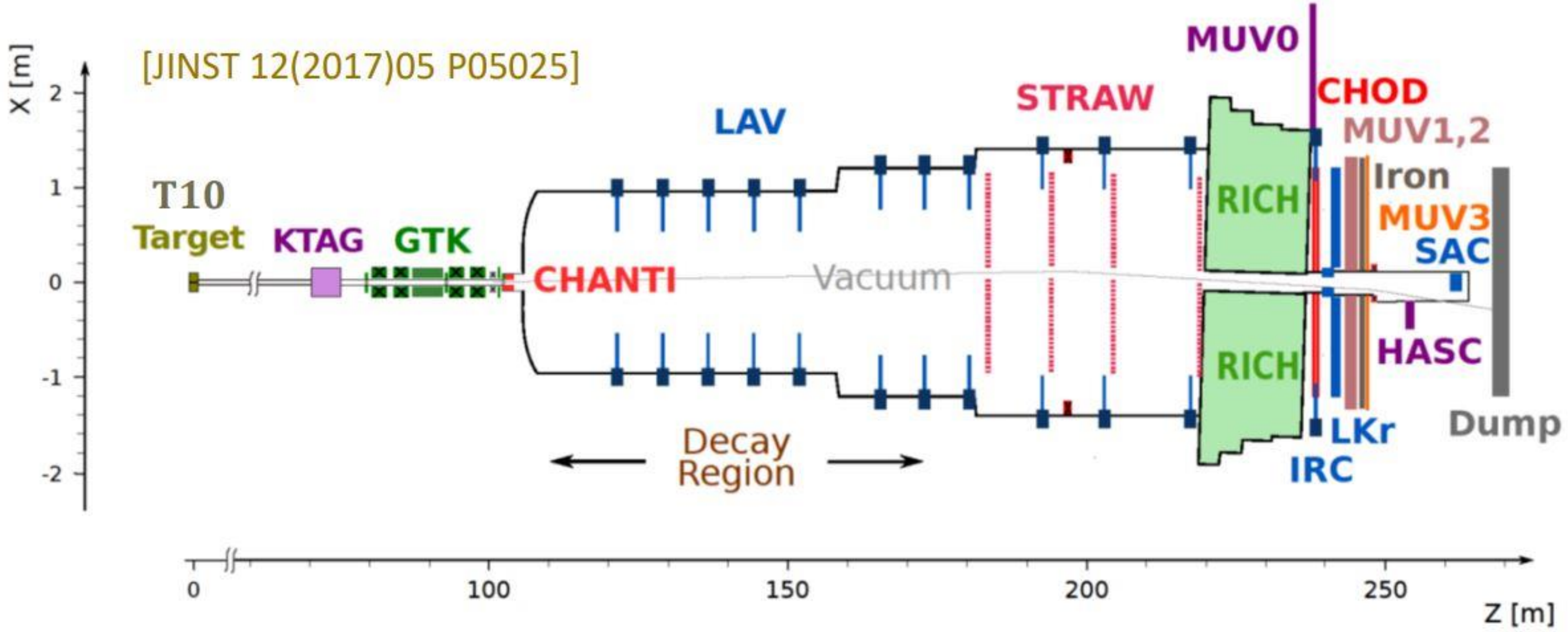
- Assuming $X \rightarrow'' \ invisible''$ in $K^+ \rightarrow \pi^+\ X$, UL vs m_X is set

  NB: SM $K^+\pi^+\nu\bar{\nu}$ is main background in this case!



The NA62 experiment

From G. Ruggiero, FPCP23

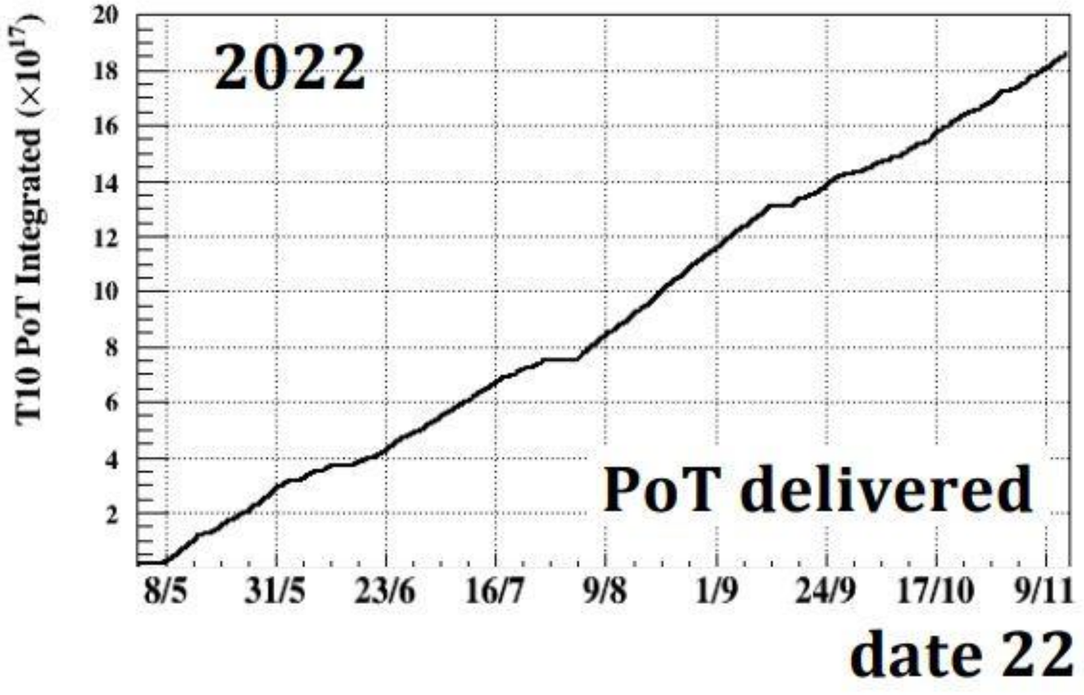


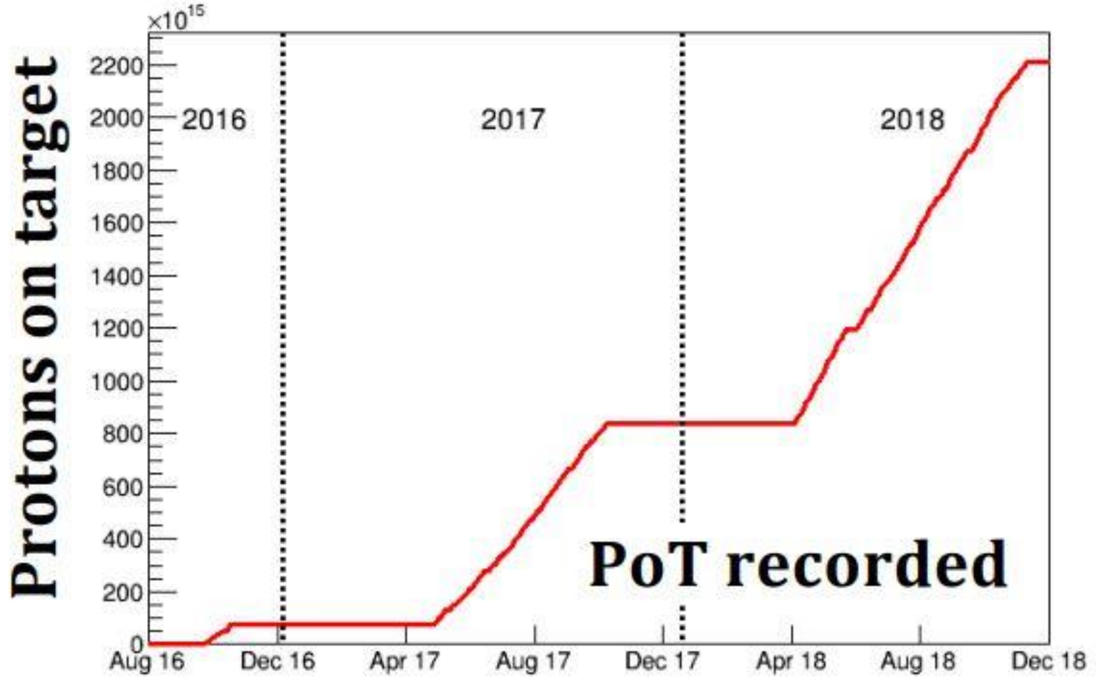
Nominal Intensity	33×10^{11} ppp on T10
Incoming K^+, 75 GeV/c, 1% rms	Timing by KTAG ($\sigma_t \sim 70$ ps); measured by GTK; rate at GTK ~ 600 MHz
Outgoing π^+	Timing by RICH ($\sigma_t \sim 70$ ps); measured by STRAW; rate at Straw ~5 MHz
γ/multitrack veto (LAV, LKr, IRC, SAC, HASC)	$\pi^0 \to \gamma\gamma$ suppression
Particle ID (RICH, LKr, MUV1,2,3)	μ^+ suppression

NA62 data taking periods

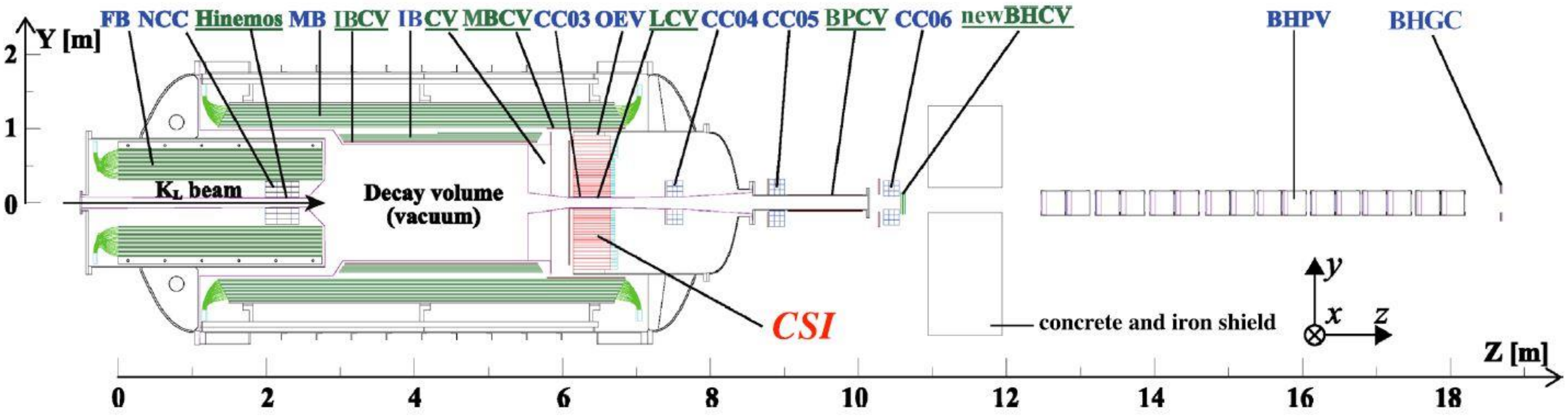
From G. Ruggiero, FPCP23

		Beam intensity	Spills ($\times 10^3$)	
	2025		approved	
	2024		approved	
“RUN2”	**2023**	on - going	on - going	
	2022	nominal	400	
	2021	~ nominal	140	Beam problems
	Long Shutdown 2			
	2018	$O(65)$% nominal	500	
“RUN1”	**2017**	$O(55)$% nominal	300	
	2016	$O(40)$% nominal	80	Commissioning





The KOTO detector



Photon veto counters

Charged-particle veto counters (plastic detectors)

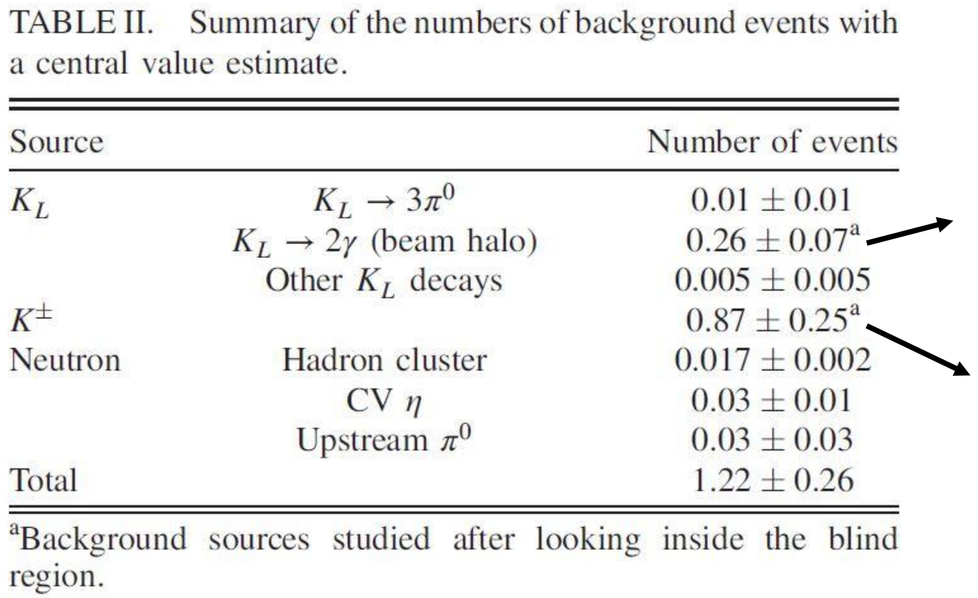


TABLE II. Summary of the numbers of background events with a central value estimate.

Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07^a
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25^a
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

[a] Background sources studied after looking inside the blind region.

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$K_L \to \gamma\gamma$ with K_L off the beam axis

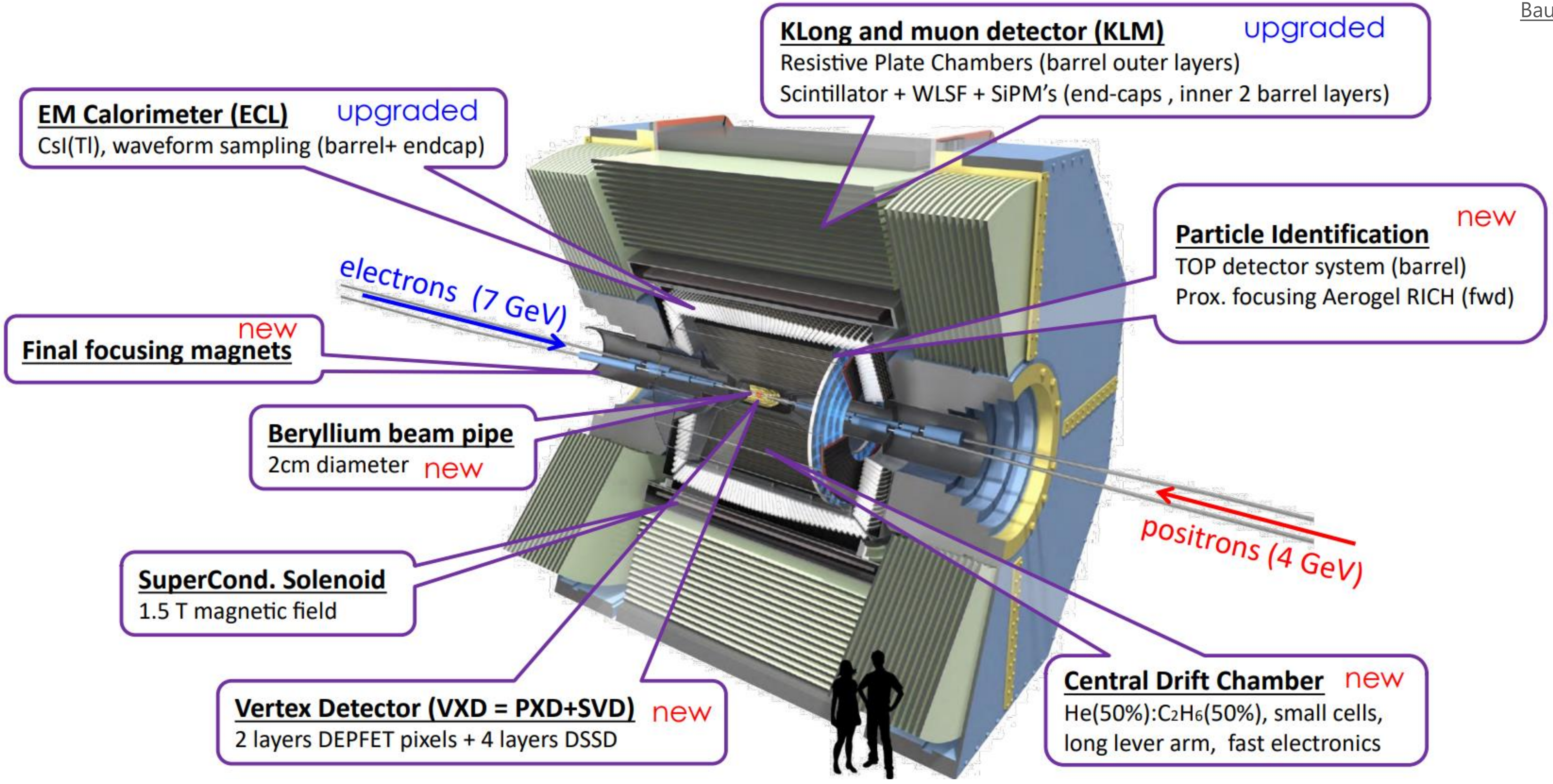
$K^+ \to \pi^0 e^+ \nu$ with K^+ from K_L collision on downstream collimator

Planned actions to increase bkg suppression

- New charged-particle veto counter under preparation to suppress K^+ background
- New sweeping magnet at the detector entrance
- More complex analysis of photon clusters to reduce $K_L \to \gamma\gamma$

Belle II detector

Baudot@FPCP23



KLong and muon detector (KLM) upgraded
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter (ECL) upgraded
CsI(Tl), waveform sampling (barrel+ endcap)

Particle Identification new
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

Final focusing magnets new

Beryllium beam pipe
2cm diameter new

SuperCond. Solenoid
1.5 T magnetic field

Vertex Detector (VXD = PXD+SVD) new
2 layers DEPFET pixels + 4 layers DSSD

Central Drift Chamber new
He(50%):C_2H_6(50%), small cells,
long lever arm, fast electronics

Belle II projections for $B^{(*)} \to K^{(*)}\nu\bar{\nu}$ decays

Snowmass White Paper, 2207.06307

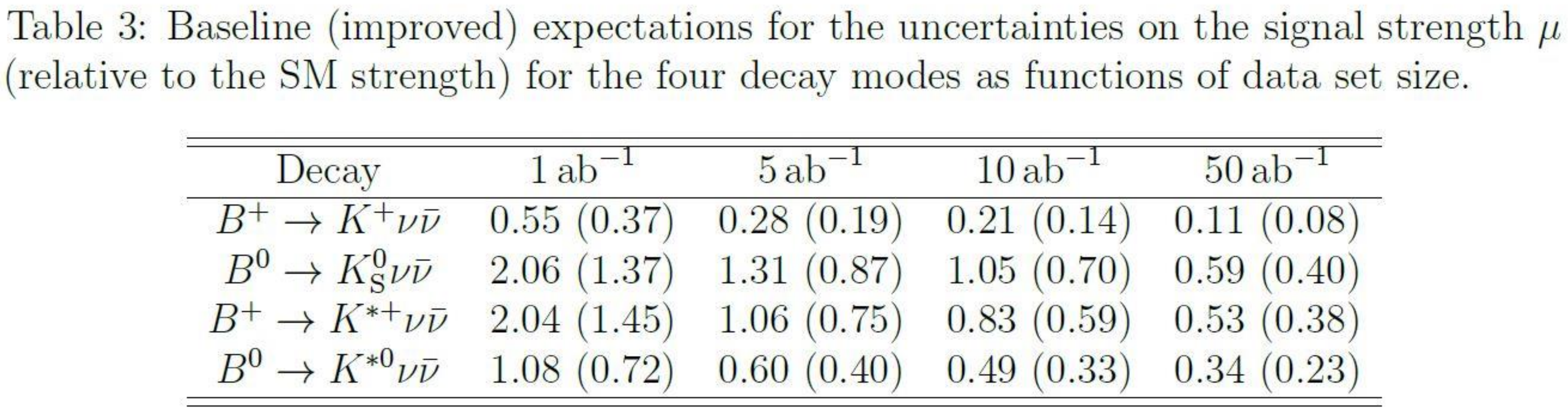


Table 3: Baseline (improved) expectations for the uncertainties on the signal strength μ (relative to the SM strength) for the four decay modes as functions of data set size.

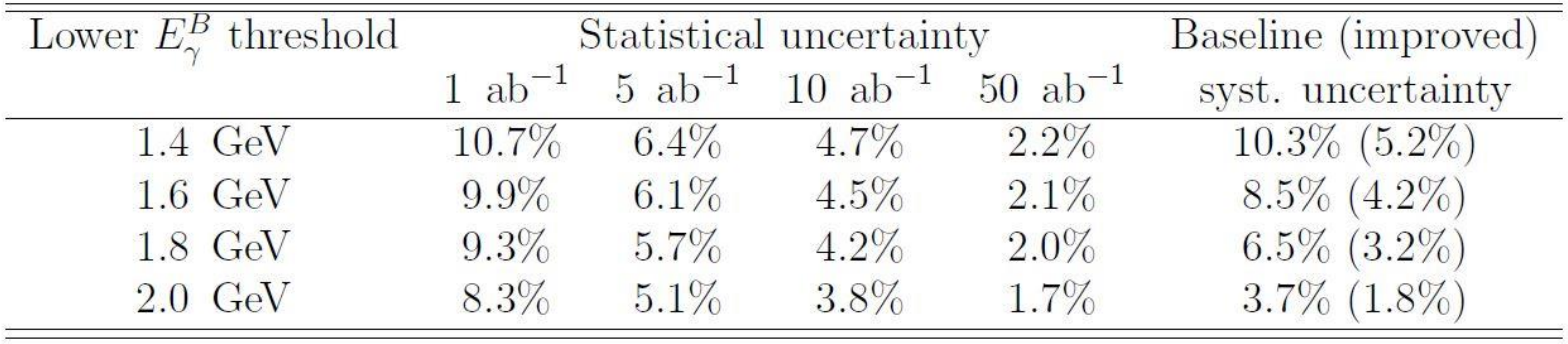
Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_{\mathrm{S}}\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

Baseline scenario: current performance
Improved scenario: assumes 50% signal increase efficiency for same background level

$B^+ \to K^+\nu\bar{\nu}$ analysis sensitive to the SM rate at 3(5) sigma with 5ab^{-1} in the baseline (improved) scenario.

Belle II projections for $B \to X_s\gamma$, hadronic tag

Snowmass White Paper, 2207.06307

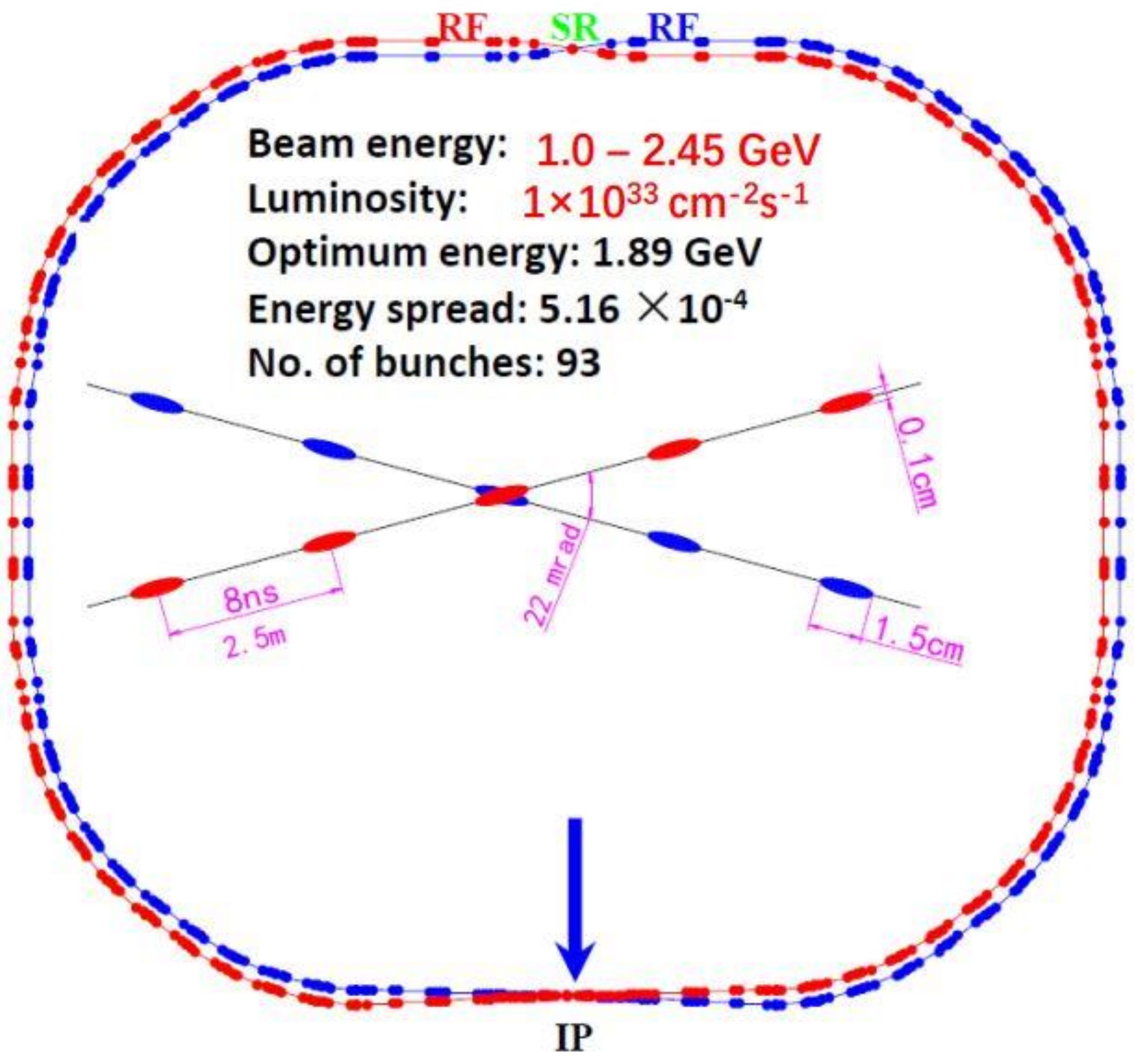


Lower E_γ^B threshold	Statistical uncertainty				Baseline (improved)
	$1\ \text{ab}^{-1}$	$5\ \text{ab}^{-1}$	$10\ \text{ab}^{-1}$	$50\ \text{ab}^{-1}$	syst. uncertainty
1.4 GeV	10.7%	6.4%	4.7%	2.2%	10.3% (5.2%)
1.6 GeV	9.9%	6.1%	4.5%	2.1%	8.5% (4.2%)
1.8 GeV	9.3%	5.7%	4.2%	2.0%	6.5% (3.2%)
2.0 GeV	8.3%	5.1%	3.8%	1.7%	3.7% (1.8%)

Systematic uncertainty driven by knowledge of background
Baseline scenario: background known at 10% level (current Belle II performance)
Improved scenario: background known at 5% level (based on ongoing studies of improved π^0 veto)

BEPCII and BESIII detector

Beijing Electron Positron Collider II



Beam energy: 1.0 – 2.45 GeV

Luminosity: 1×10^{33} cm^{-2}s^{-1}

Optimum energy: 1.89 GeV

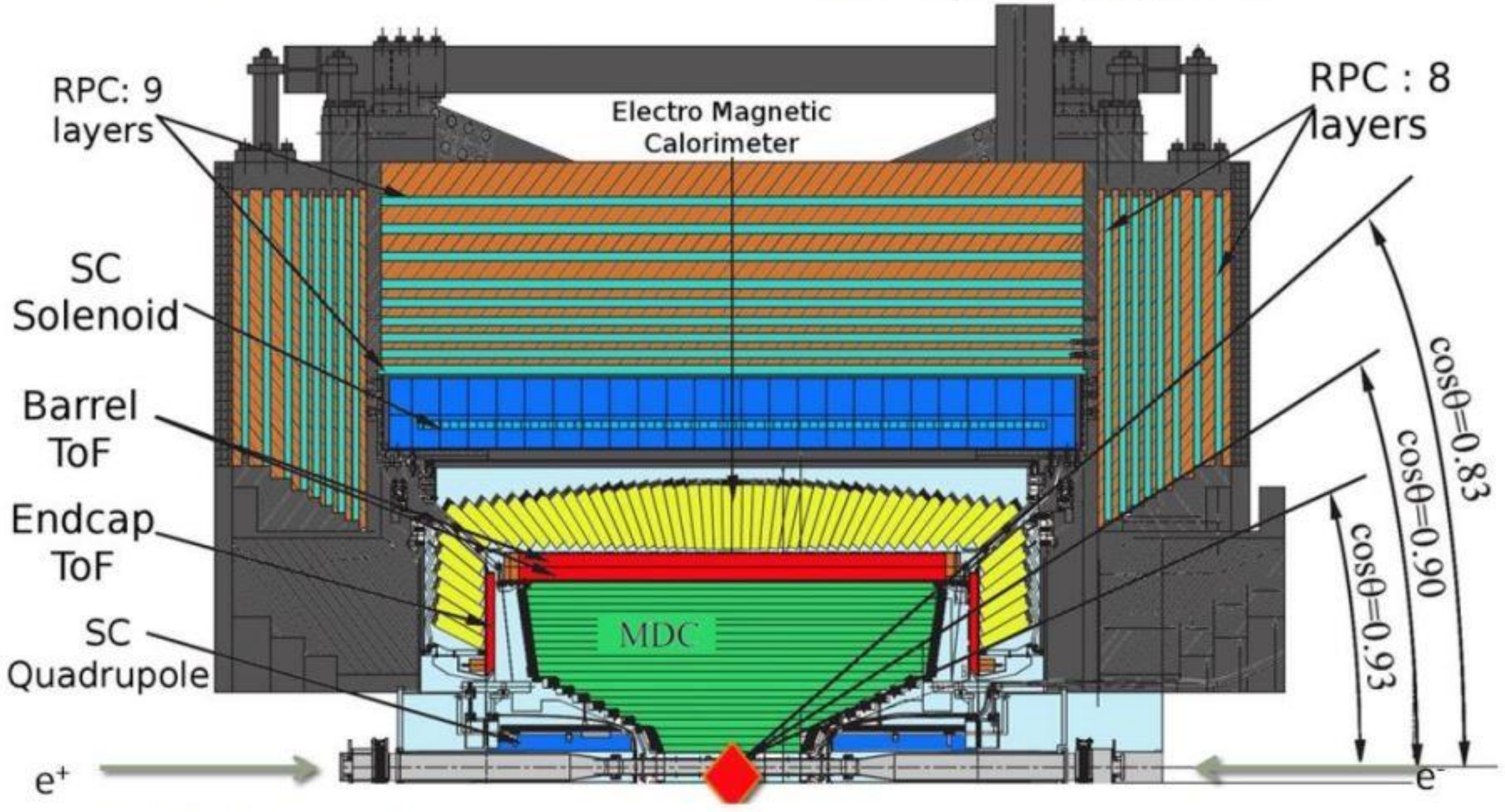
Energy spread: 5.16 $\times10^{-4}$

No. of bunches: 93

BESIII Detector

MDC: σp=0.5% @ 1GeV/c
dE/dx: 6%

EMC: CsI (Tl) 2.5% (5.0%)
barrel (endcap) @ 1GeV

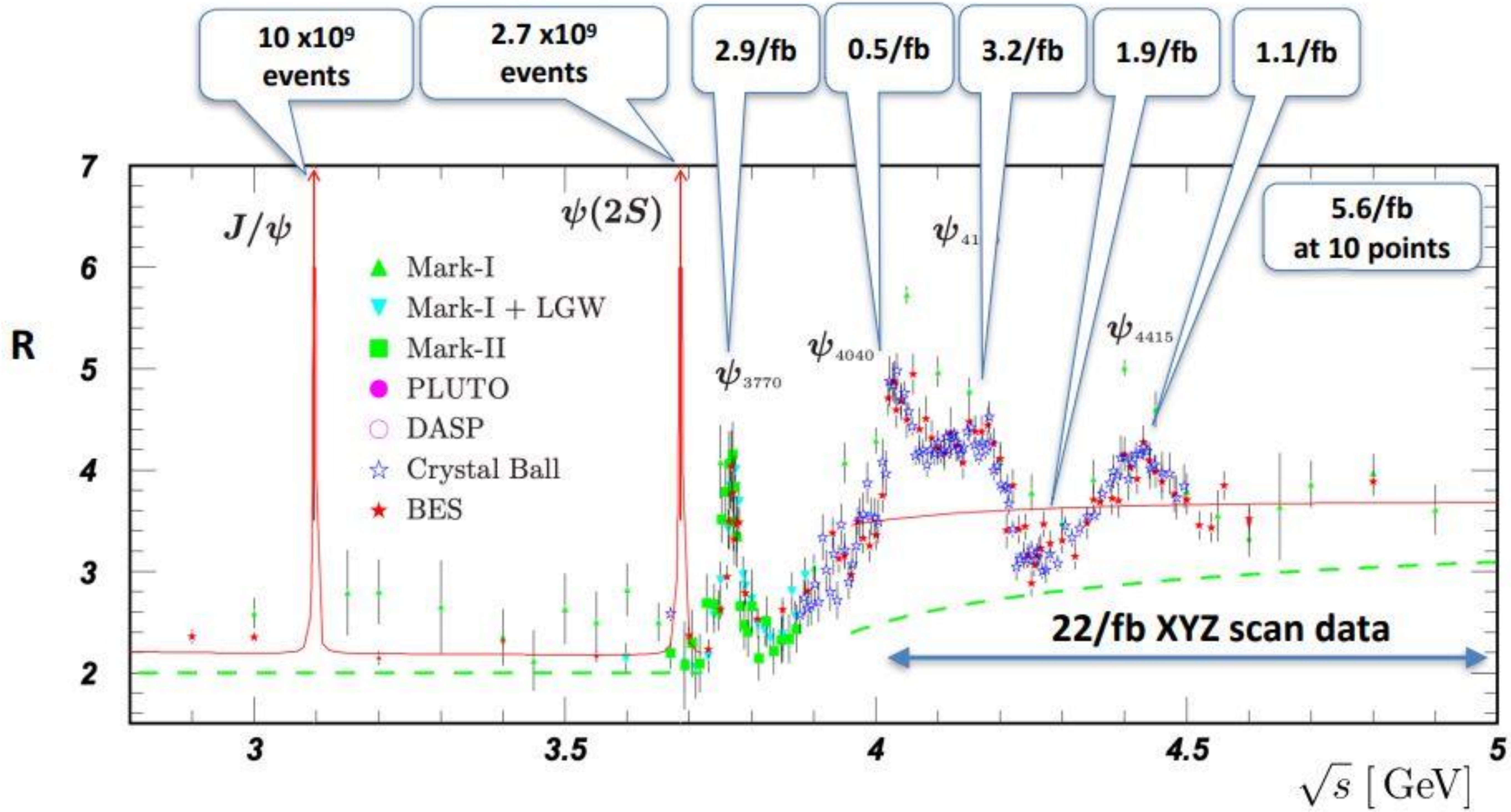


TOF: σT=68 (60) ps
barrel (endcap)

MUC: RPC 9 (8) layers
barrel (endcap)

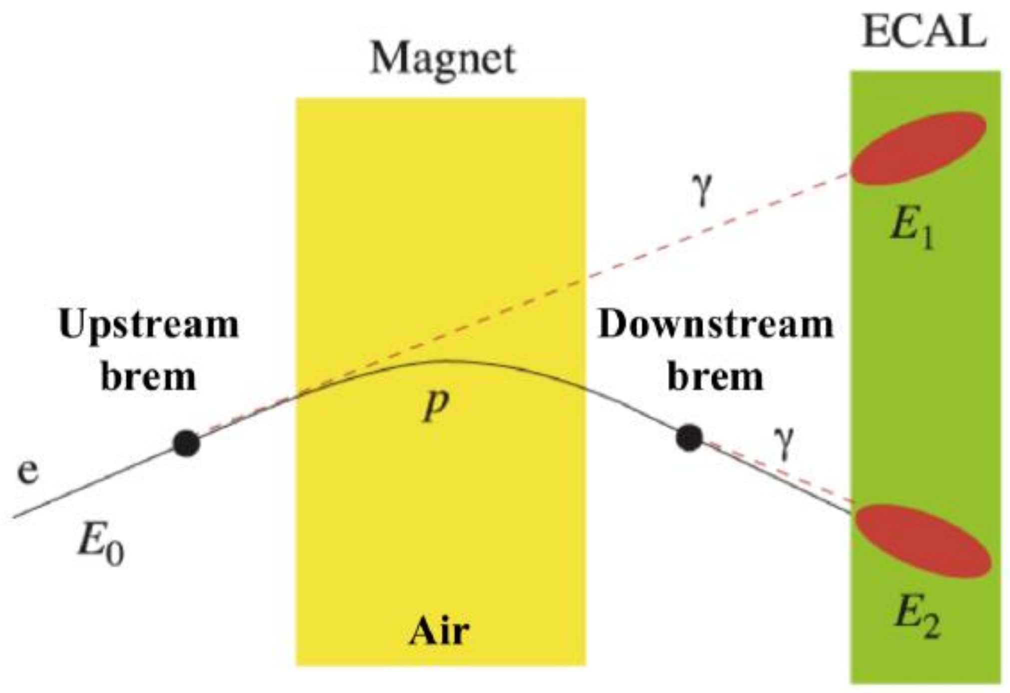
BES III data samples

M. Pelizäus @ Hadron2023



Electrons vs muons at LHCb

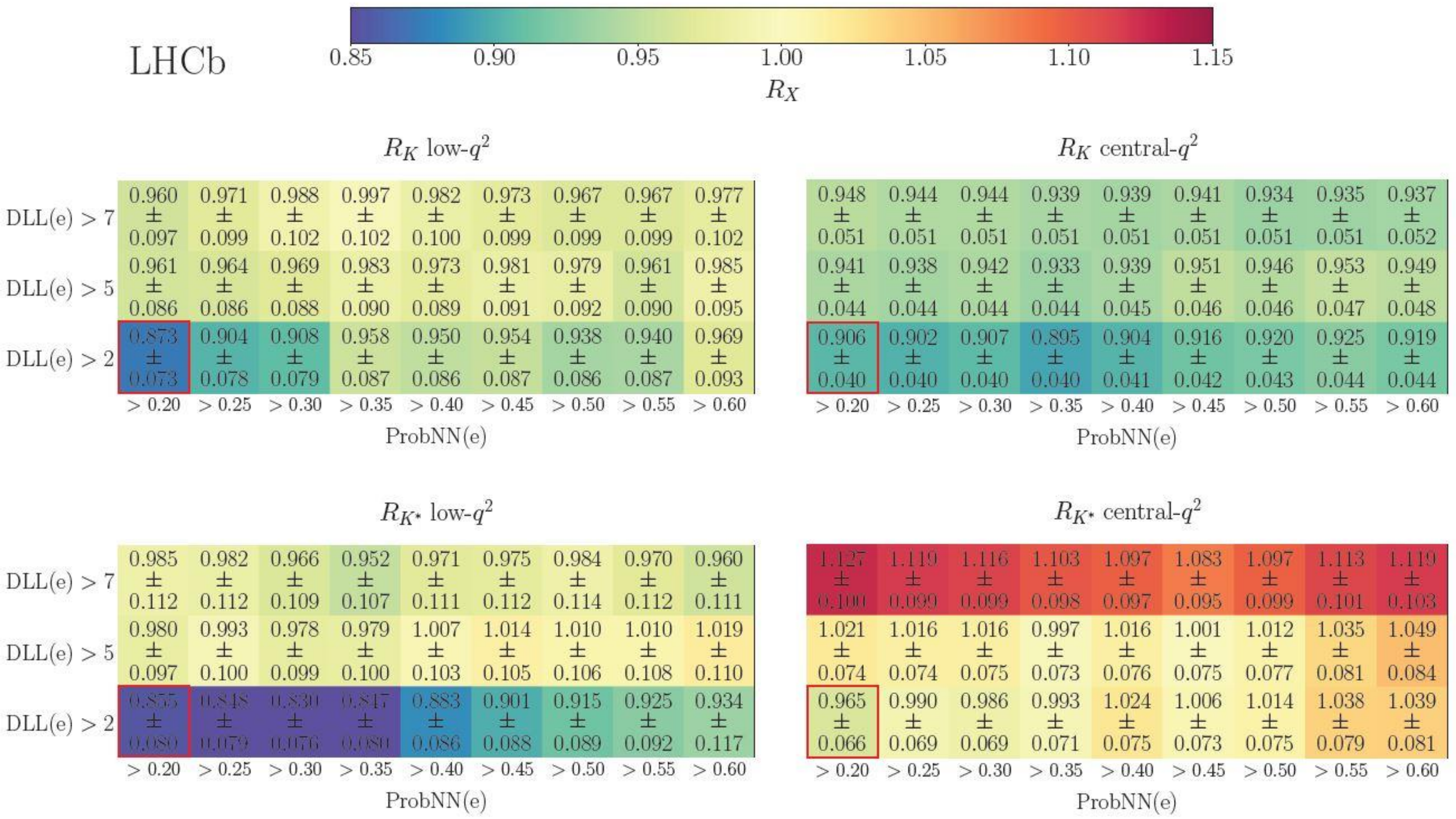
- Electrons lose a large fraction of their energy through Bremsstrahlung in detector material



- Most electrons will emit one energetic photon before the magnet.
  → Look for photon clusters in the calorimeter compatible with electron direction before the magnet.
  → Recover brem energy loss by “adding” the cluster energy back to the electron momentum.

$R_{K^{(*)}}$ vs PID selection without modeling of misID bkg

2212.09153 accepted by PRD



R_K low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.960 ± 0.097	0.971 ± 0.099	0.988 ± 0.102	0.997 ± 0.102	0.982 ± 0.100	0.973 ± 0.099	0.967 ± 0.099	0.967 ± 0.099	0.977 ± 0.102
DLL(e) > 5	0.961 ± 0.086	0.964 ± 0.086	0.969 ± 0.088	0.983 ± 0.090	0.973 ± 0.089	0.981 ± 0.091	0.979 ± 0.092	0.961 ± 0.090	0.985 ± 0.095
DLL(e) > 2	0.873 ± 0.073	0.904 ± 0.078	0.908 ± 0.079	0.958 ± 0.087	0.950 ± 0.086	0.954 ± 0.087	0.938 ± 0.086	0.940 ± 0.087	0.969 ± 0.093

R_K central-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.948 ± 0.051	0.944 ± 0.051	0.944 ± 0.051	0.939 ± 0.051	0.939 ± 0.051	0.941 ± 0.051	0.934 ± 0.051	0.935 ± 0.051	0.937 ± 0.052
DLL(e) > 5	0.941 ± 0.044	0.938 ± 0.044	0.942 ± 0.044	0.933 ± 0.044	0.939 ± 0.045	0.951 ± 0.046	0.946 ± 0.046	0.953 ± 0.047	0.949 ± 0.048
DLL(e) > 2	0.906 ± 0.040	0.902 ± 0.040	0.907 ± 0.040	0.895 ± 0.040	0.904 ± 0.041	0.916 ± 0.042	0.920 ± 0.043	0.925 ± 0.044	0.919 ± 0.044

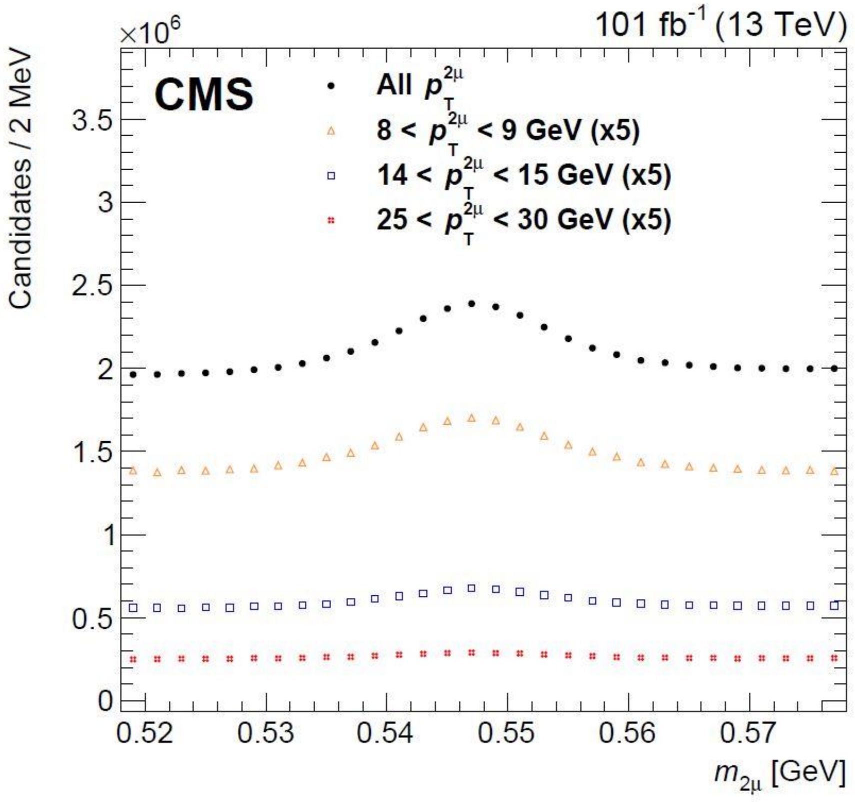
R_{K^*} low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.985 ± 0.112	0.982 ± 0.112	0.966 ± 0.109	0.952 ± 0.107	0.971 ± 0.111	0.975 ± 0.112	0.984 ± 0.114	0.970 ± 0.112	0.960 ± 0.111
DLL(e) > 5	0.980 ± 0.097	0.993 ± 0.100	0.978 ± 0.099	0.979 ± 0.100	1.007 ± 0.103	1.014 ± 0.105	1.010 ± 0.106	1.010 ± 0.108	1.019 ± 0.110
DLL(e) > 2	0.855 ± 0.080	0.848 ± 0.079	0.830 ± 0.076	0.847 ± 0.080	0.883 ± 0.086	0.901 ± 0.088	0.915 ± 0.089	0.925 ± 0.092	0.934 ± 0.117

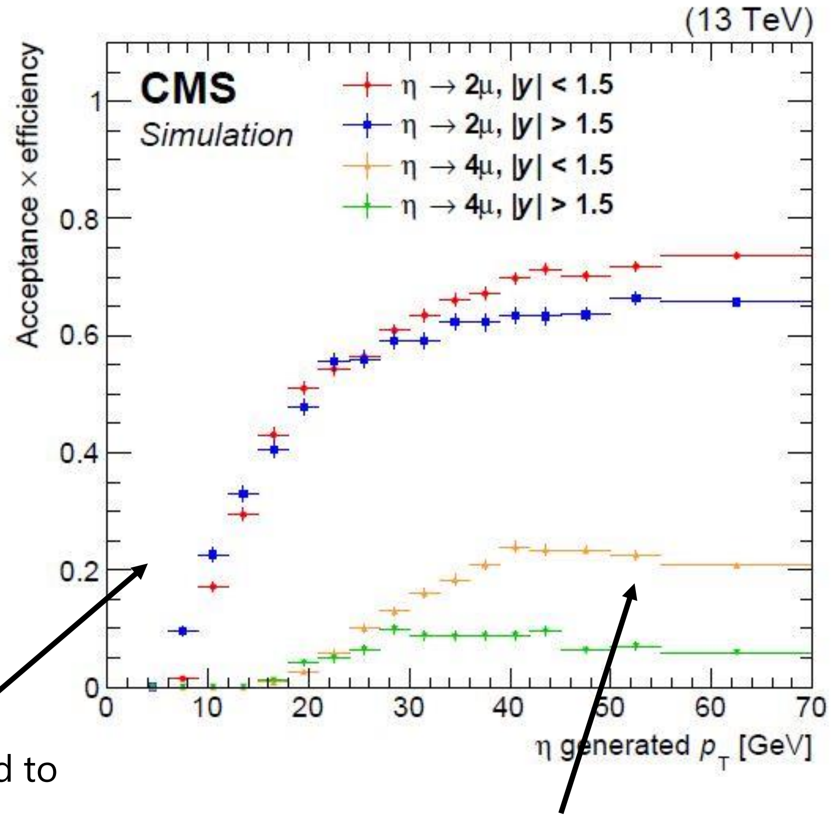
R_{K^*} central-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 5	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075	1.012 ± 0.077	1.035 ± 0.081	1.049 ± 0.084
DLL(e) > 2	0.965 ± 0.066	0.990 ± 0.069	0.986 ± 0.069	0.993 ± 0.071	1.024 ± 0.075	1.006 ± 0.073	1.014 ± 0.075	1.038 ± 0.079	1.039 ± 0.081

Observation of $\eta \to 4\mu$

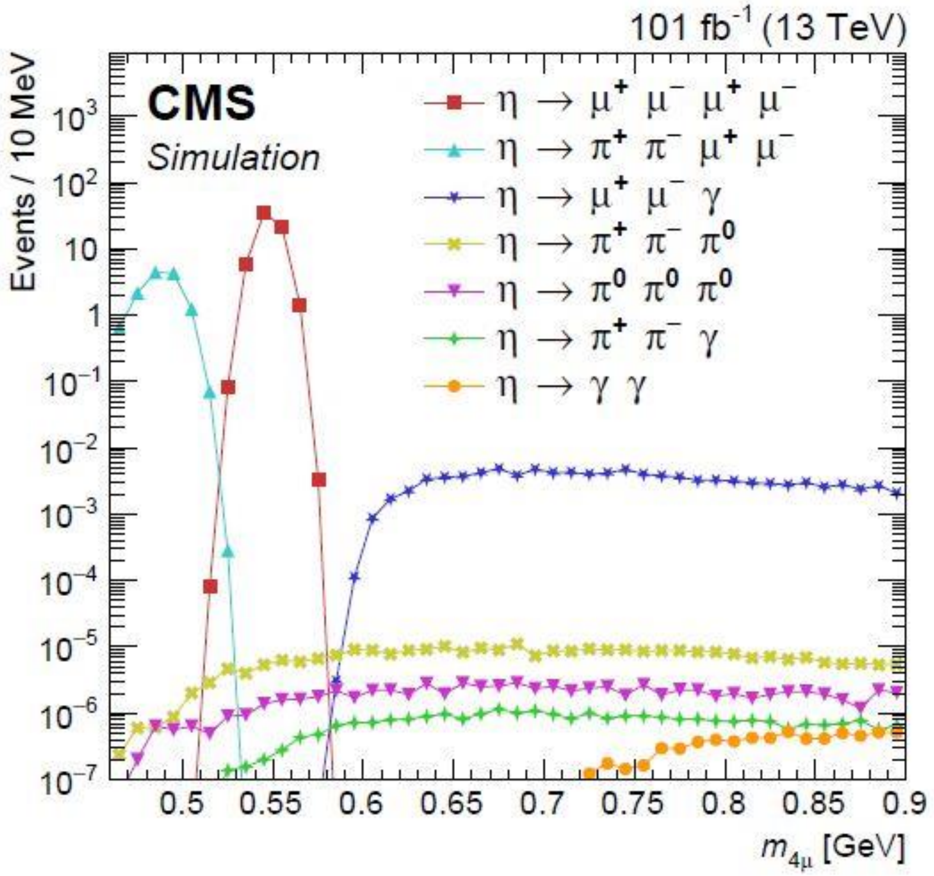


Selected $\eta \to \mu\mu$ sample



pT threshold to reach muon detector

effect of reduced angular separation between muons



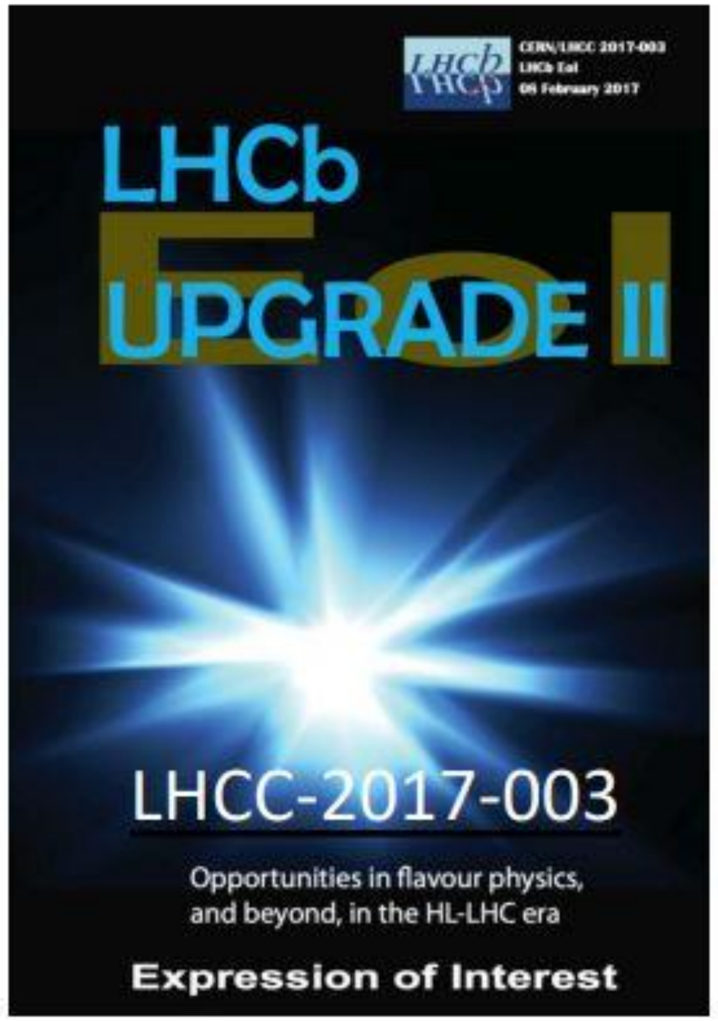
Predicted background contributions estimated with MC, normalized to 101 fb^{-1}

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{\mathrm{i,j}} N^{\mathrm{i,j}}_{2\mu}\,\frac{A^{\mathrm{i,j}}_{4\mu}}{A^{\mathrm{i,j}}_{2\mu}}}$$

i, j are regions of p_T and rapidity (32 regions p_T, 2 regions $|y|$)

LHCb upgrade II

- Expression of Interest (2017), Physics case (2018, Framework TDR (2022)
- To be complemented with more detail plans with scoping scenarios manpower and funds
- Target Scoping document end of 2024



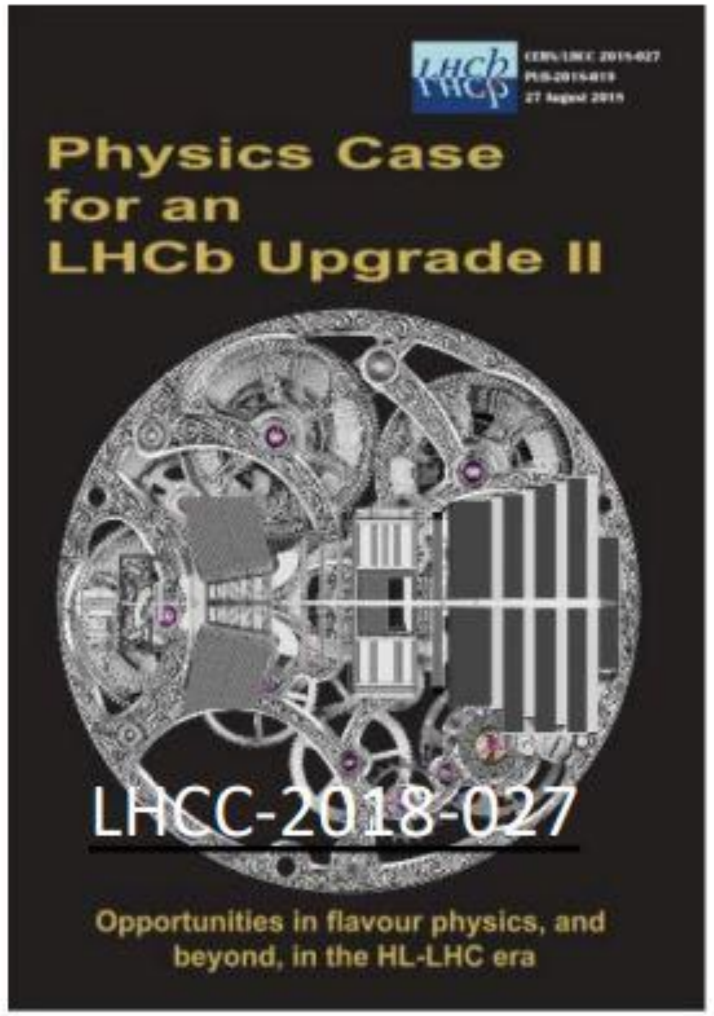
CERN/LHCC 2017-003
LHCb EoI
06 February 2017

LHCb
EoI
UPGRADE II

LHCC-2017-003

Opportunities in flavour physics,
and beyond, in the HL-LHC era

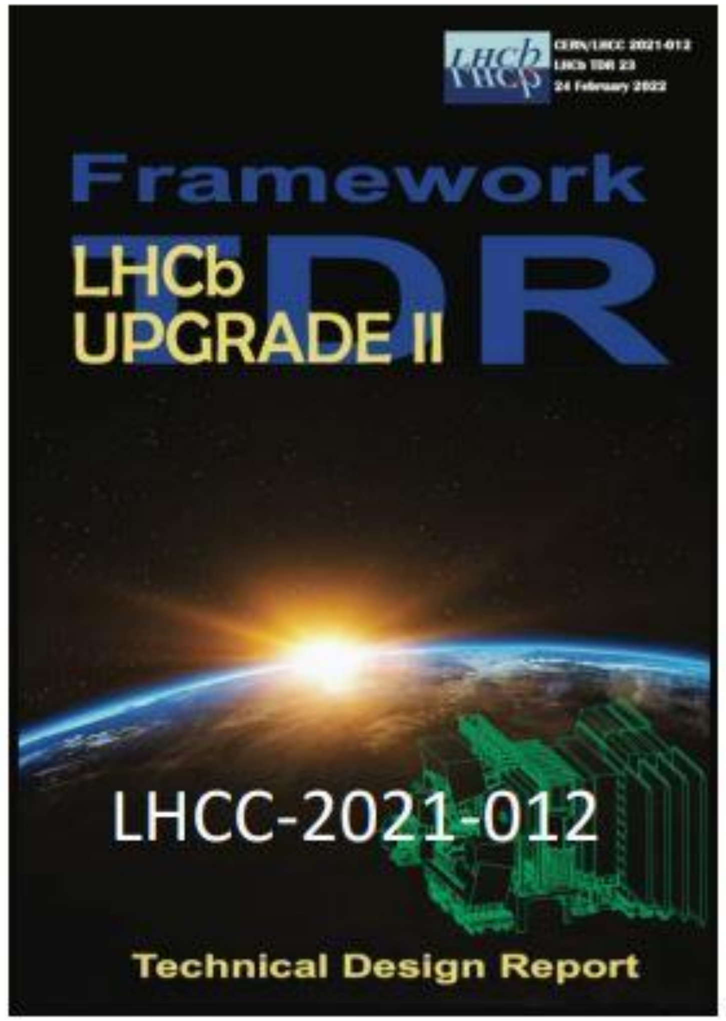
Expression of Interest



**Physics Case
for an
LHCb Upgrade II**

LHCC-2018-027

Opportunities in flavour physics, and
beyond, in the HL-LHC era



CERN/LHCC 2021-012
LHCb TDR 23
24 February 2022

Framework
LHCb
UPGRADE II
TDR

LHCC-2021-012

Technical Design Report

**6th Workshop on LHCb
Upgrade II**

29.03.2023-31.03 2023
Barcelona

CERN-EP Report

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