QED-effects in B—>Kll moments

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OVERVIEW

Theory

I. Brief overview QED frontier & summary of B->Kll results so far [2]

II. QED moments in B->Kll [5]
- 2015 perspective
- 2020/21 perspective & new opportunities

III. Experimental perspective [5]

Experiment

IV. Conclusions [1]

Backup including other work QED-corrections

Workshop: Beyond Flavour Anomalies II - Duham IPPP 20-22 April 2021

I) QED-corrections in Flavour Physics

"….. becoming an active field and a precision frontier"

- Overview of Methods in increasing structure dependence (resolving the Mesons)

Meson a point particle → Meson with partons!

"Scalar QED"
PHOTOS MC
Bordone,Pattori, Isidori '16 B->Kll

Meson EFT B->Kll
Isidori Nabeebaccus, RZ '20

Chiral Perturbation Theory
K->πlv '00 Cirigliano, Knecht, Neufeld,…
K-> πll, '10 Kubis et al

Inclusive b-> ell
Huber, Lunghi, Misiak, Wyler '05
Huber, Hurth, Lunghi '15

Lattice -
proposed '15 - Sachrajda and Rome group
K->l v fist results
more to come other groups Portelli, Guelpers

SCET-
$B_s \to \mu\mu$ Beneke, Bobeth, Szafron'17'19
$B \to K\pi$ Beneke, de Boer, Teolstede,Vos'20

Analytic approaches (SCET & more to come):

- Good α_{QED}-**convergence** (attention to large logs) ✅
- (Soft)-collinear **Factorisation,** absorbing unphysical IR-divergences) more **complicated** than in **QCD**! ⚡ ⚡ ⚡

Overview of rare mode B-> Kll

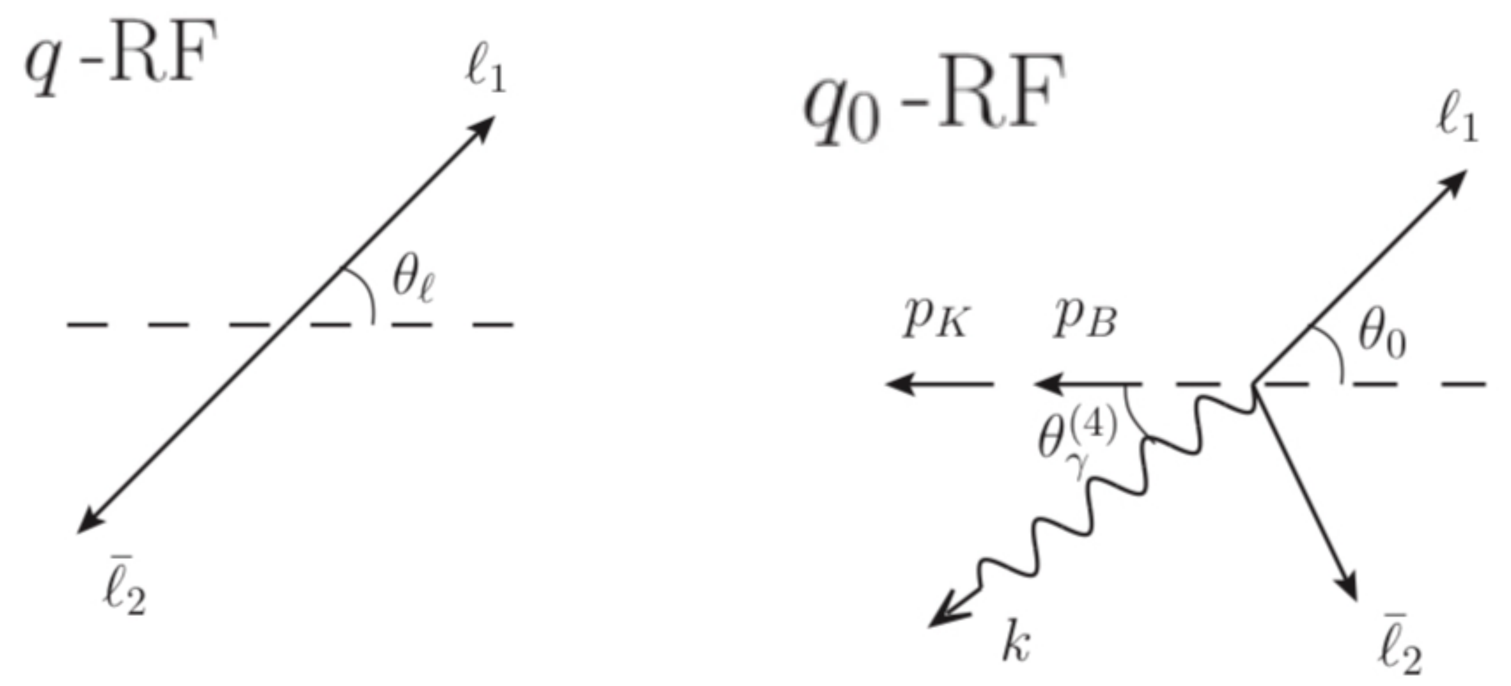
- **scalar QED:** B,K= point particle - PHOTOS & Bordone, Pattori, Isidori'16
  - compute real and infer virtual logs from cancellation in rate (good variables)
  - check $m_{B_{rec}}$ -histogram against PHOTOS and it looks good
- **meson EFT:** B,K partially resolved form factor expansion Isidori Nabeebaccus, RZ '20
  - compute real,virtual ("partial finite terms"), $\ln m_K/m_b$-logs O(2%) in rate & establish (non)-cancellations of logs
  - fully double differential (no need to resort to kinematic approximations for mirgation)
  (cf. app A.2.or backups for BIP'16 -comparison) R_K

1) Proof (by gauge invariance) no further dangerous logs by structure dependance !
2) Cancellation depends collinear logs depends on kinematic variables

Results

Do collinear logs cancel at differential level (photon inclusive case)?

$q_\ell^2 = (\ell_1 + \ell_2)^2,$	["Hadron collider" variables] ,	no
$q_0^2 = (p_B - p_K)^2$	["B-factory" variables] ,	yes



→ R_K **theoretically** clean observable, (more) solid ground

- **structure depend approach:** in progress in collinear factorisation
  get finite terms & improved $\ln m_K/m_b$ ….

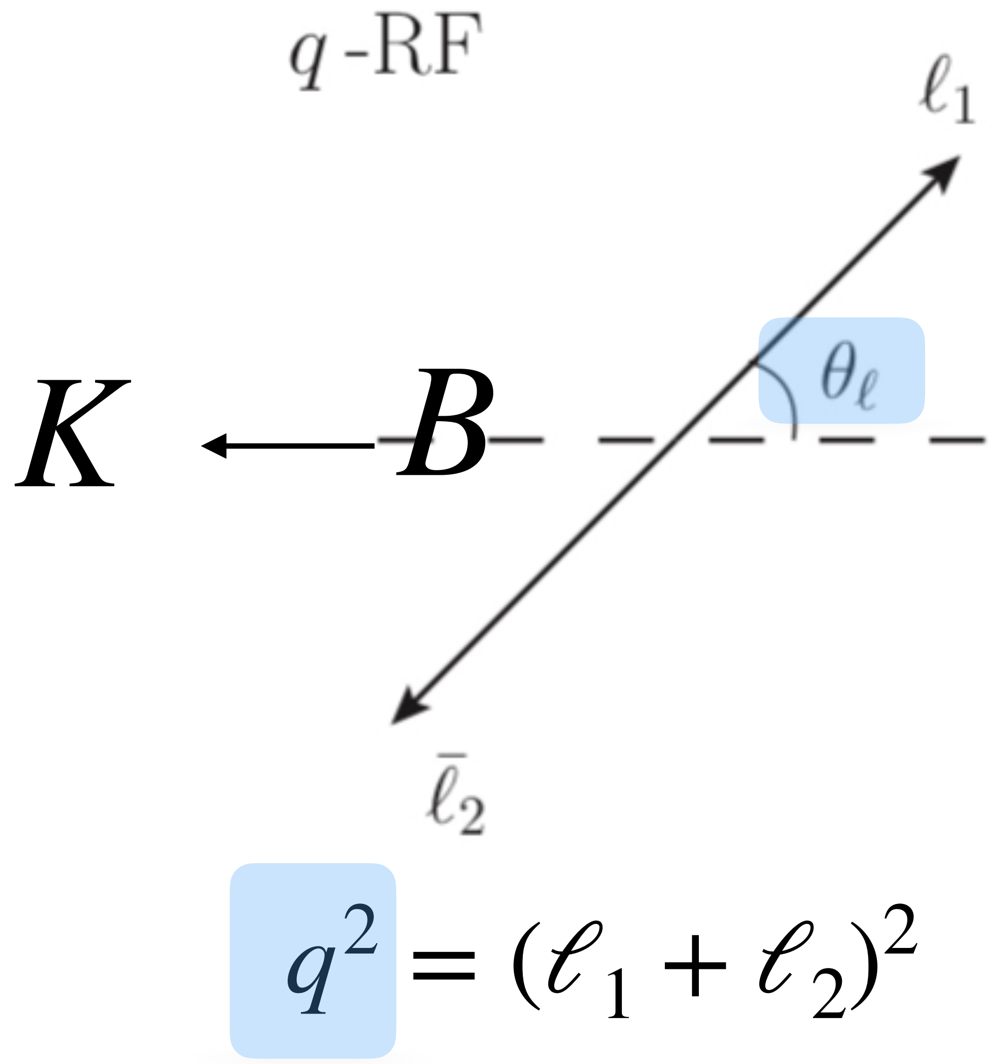
hopefully next time …..

After summary - main talk starts

Moments in B-> Kll

$$\frac{d^2}{dq^2 dc_{\theta_\ell}}\Gamma = \sum_{l=0}^{l_{\max}} \sum_{m=-l}^{l} M_{lm}(q^2, c_{\theta_\ell}) P_\ell^m(c_{\theta_\ell})$$

$$M_{lm} \propto \int_{-1}^{1} dc_{\theta_\ell} P_l^m(c_{\theta_\ell}) \frac{d^2}{dq^2 dc_{\theta_\ell}}\Gamma$$



Kinematics

- Hypothesis: (a) no QED-corrections
  (b) dim=6 Heff (standard one)

Then it's well understood that $l_{max} = 2$ as only S- & P-wave in amplitude

QED-corrections in B->Kll

$$\Gamma(B \to K\ell\ell) + \Gamma(B \to K\ell\ell\gamma) = \Gamma^{(0)}(1 + \frac{\alpha}{\pi}O(1))$$

small in photon inclusive rate
(no logs by unitarity e.g. Bloch-Nordsiek, KLN)

- However, sizeable (logs)
  1) differential in (q^2, θ_ℓ)
  2) differential in photon e.g. photon energy cut-off ΔE

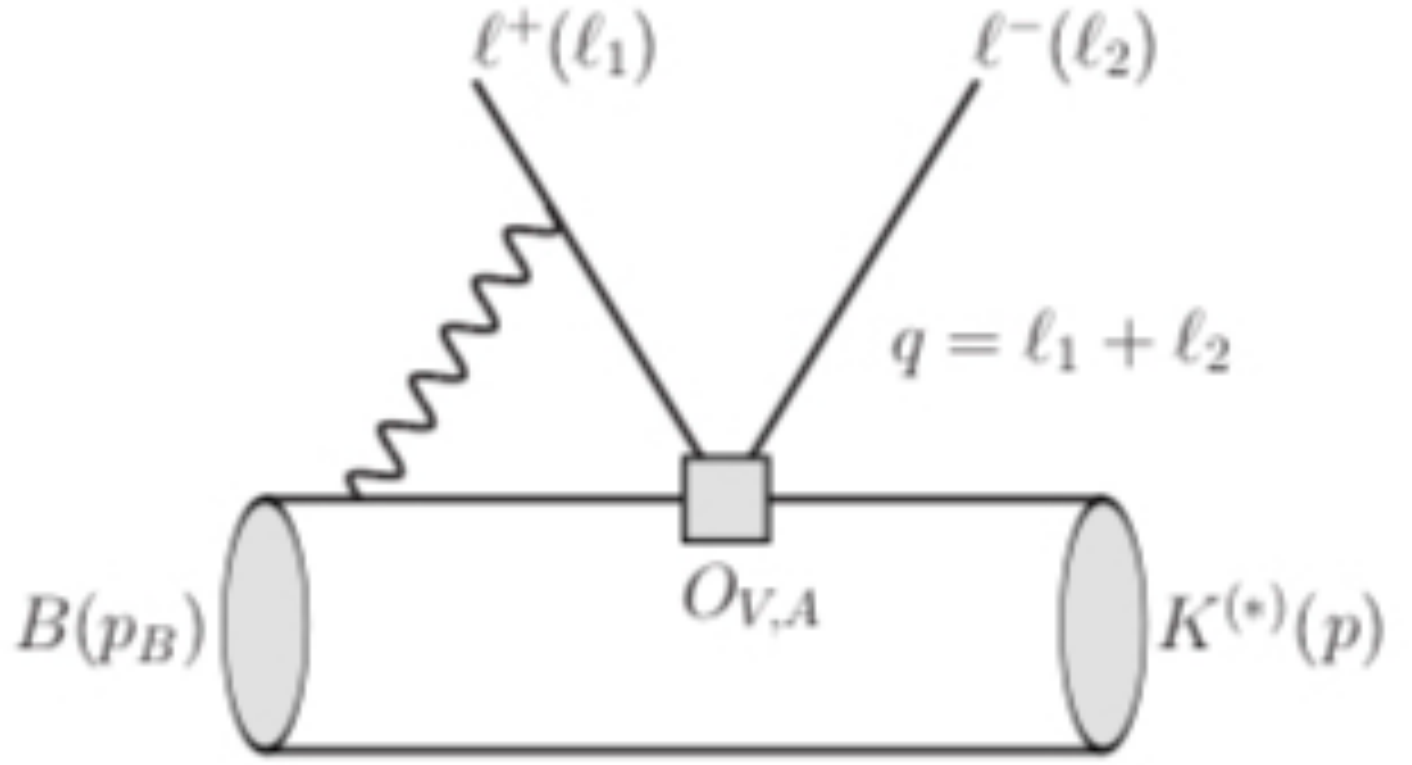
$$\frac{\alpha}{\pi}O(1) \to \frac{\alpha}{\pi}O(1)\ln\frac{m_\ell}{m_b}\ln\frac{\Delta E}{m_b}$$

$O(1\%)$ $\quad$ $O(10+\%)$

QED-Moments in B-> Kll the 2015 perspective

Hopfer, Gratrex, RZ'15

Generalised helicity formalism for EFT



- with (no) QED B->Kll 1-> 3(2) process}

  no: (ll)-pair = "1-particle" : $l_{max} = 2$

  with: richer: $l_{max} = \infty$

relax condition a)

⇒ Proposed to assess QED in higher moments (i.e. l>2)
(soft)-collinear logs would lead to sizeable moments

$$M^{ee}_{l>2} \gg M^{\mu\mu}_{l>2}$$

QED-Moments in B-> Kll the 2020 perspective

- A splendid **formula (hard-collinear logs)** from LO-differential rate

$$\frac{d\Gamma}{dq^2}\Big|_{hard-col.} \propto Q_{\ell_1}^2 \frac{\alpha}{\pi} \frac{1}{\Gamma^{\rm LO}} \left(\int_{\hat{q}^2}^1 \frac{dz}{z} P_{f\to f\gamma}(z) \frac{d\Gamma^{\rm LO}(\hat{q}^2/z)}{d\hat{q}^2/z} \right) \ln \frac{\Lambda_b}{m_\ell}$$

also holds when double differential

$$P_{f\to f\gamma}(z) = \frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)$$

universal splitting function for fermion to photons

$$\int_0^1 dz P_{f\to f\gamma}(z) = 0.$$

cancellation of logs in photon inclusive rate

⇒ No sizeable QED in higher moments (i.e. l>2) as no higher moments @LO !!

$$M^{ee}_{l>2} \approx M^{\mu\mu}_{l>2}$$

QED-Moments in B-> Kll the 2021 chase of perspective

What is the new bottom line?

1.Test experimentally $M^{ee}_{l>2} \approx M^{\mu\mu}_{l>2}$ (hard for electrons)

2.Predict $M^{\ell\ell}_{l>2}$ from theory $\Rightarrow$ **need structure dependent approach**

Meson EFT QED-moment paper makes limited sense

(A) Compare $M^{\mu\mu}_{l>2}$ to experiment.

(B) Test for New Physics (NP) relax assumptions b) ithen **dim= 8,10 Heff**

$$H_{eff} \supset \frac{C_8}{\Lambda^2_{NP}} \bar{b}\gamma_{\{\mu}\overleftrightarrow{D}_{\nu\}}s \; \bar{\ell}\gamma_{\{\mu}\overleftrightarrow{D}_{\nu\}}\ell$$

$$\Delta_{C_8} = \begin{cases} \frac{m_b^2}{\Lambda^2_{NP}} \approx O(10^{-5})? & \text{UV-NP} \\ O(\text{not-so-small}) & \text{light-NP} \end{cases}$$

- Can we test for light NP using higher muon moments?

If new physics really light then what $\Delta_{C_{10,12}}$? (which we can also predict)

- Theorists wish: $M^{\ell\ell}_{l>2}(q^2)\,|_{photon-cuts}$ & $M^{\ell\ell}_{l>2}(q_0^2)\,|_{photon-cuts}$ from experiment (Bresmstrahlung removed)

⇒ A lot of useful information can be extracted

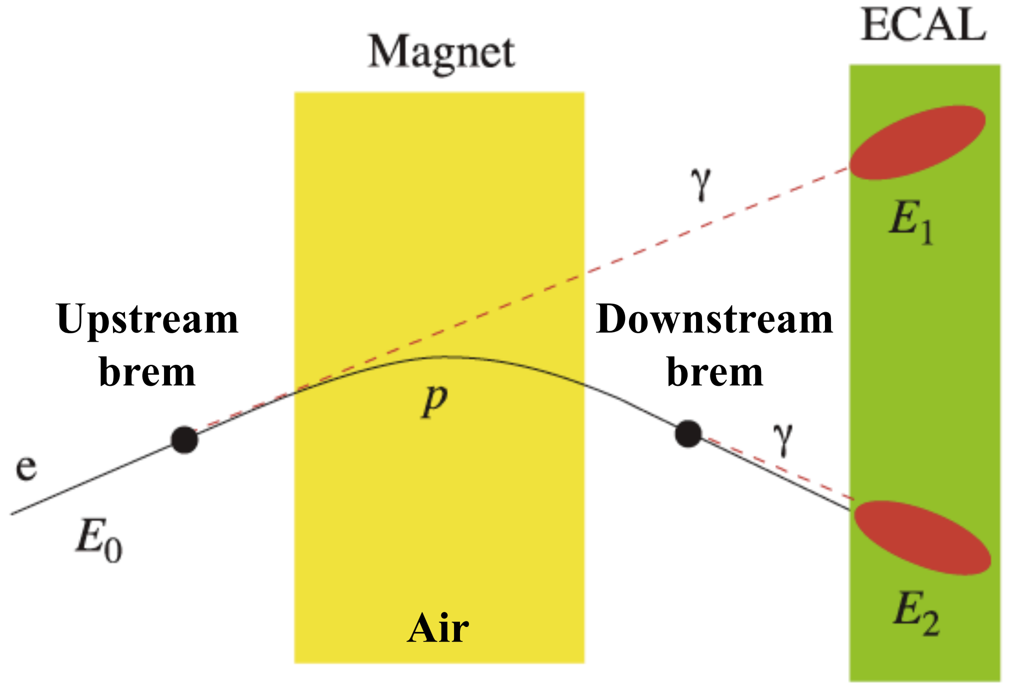
Now, Patrick will give you an idea why this is not traighforward….

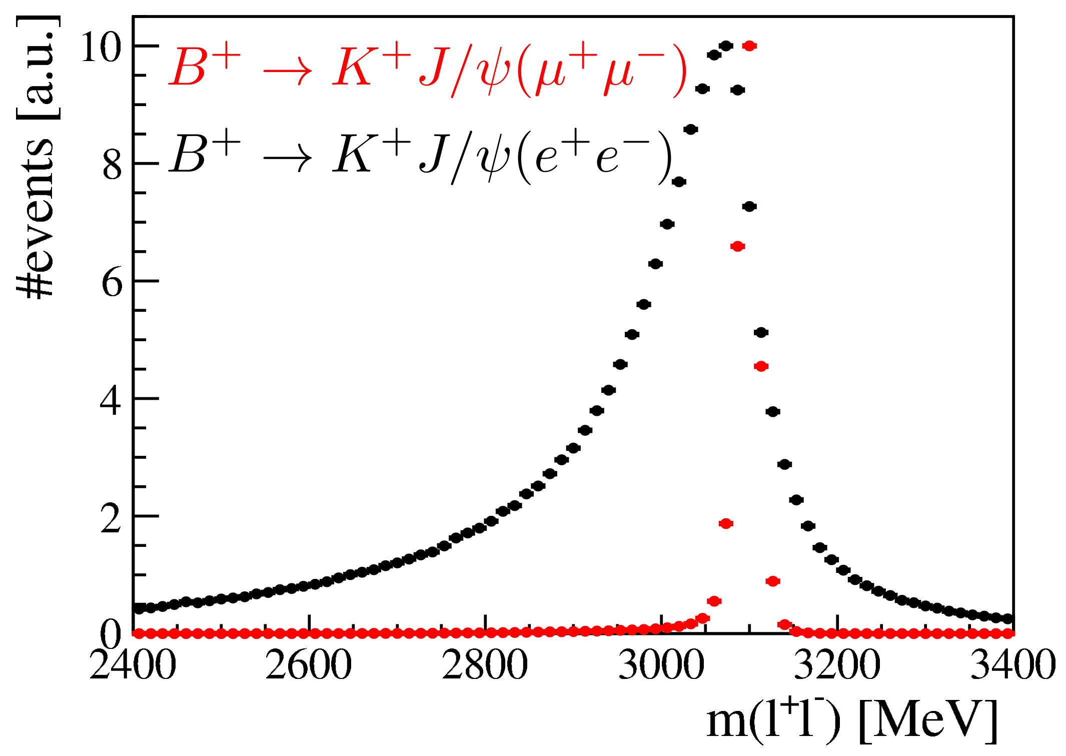
Electrons at LHCb

Many plots have been taken from Thibaud Humair's thesis: CERN-THESIS-2019-044

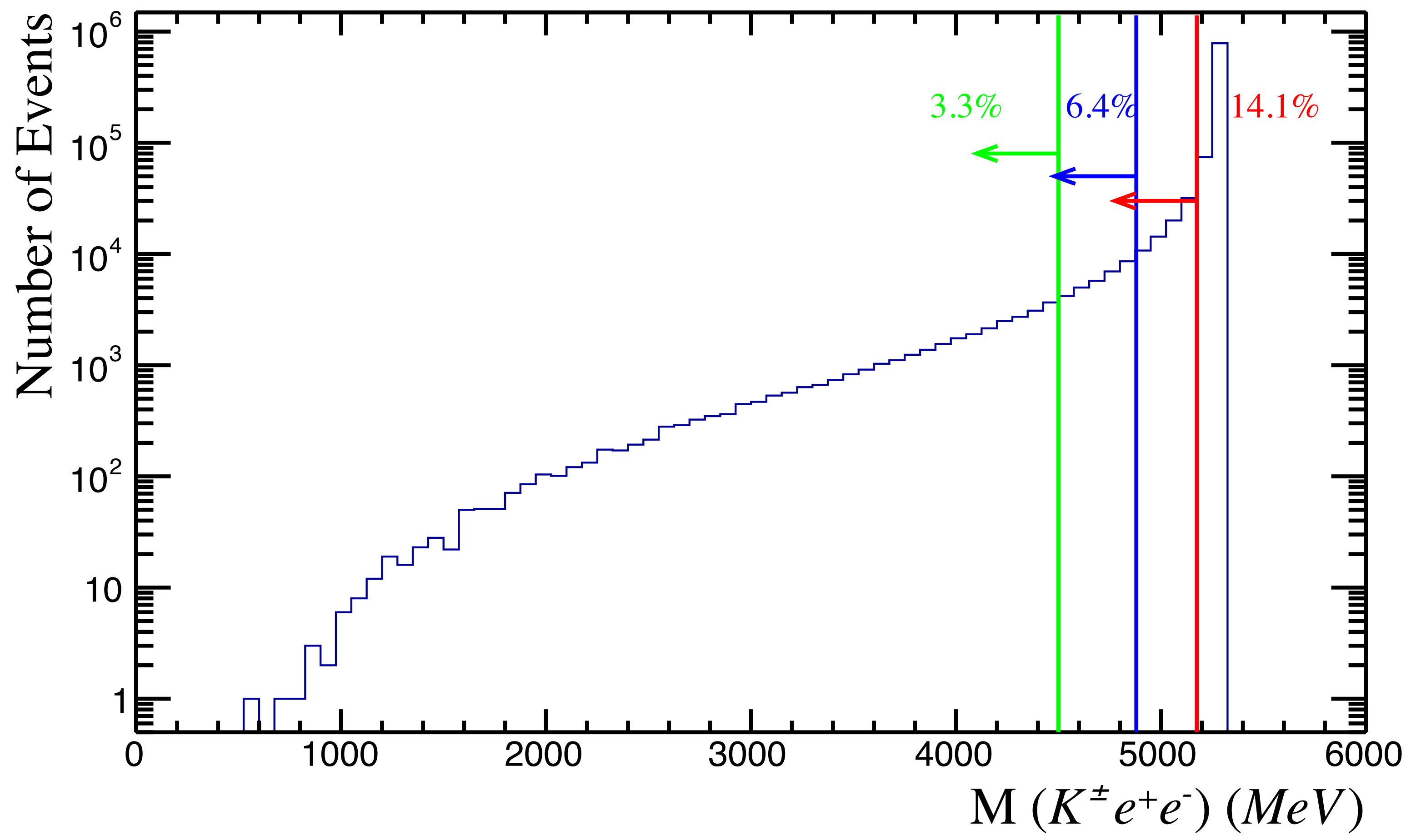
Electrons lose energy from two ways in LHCb:

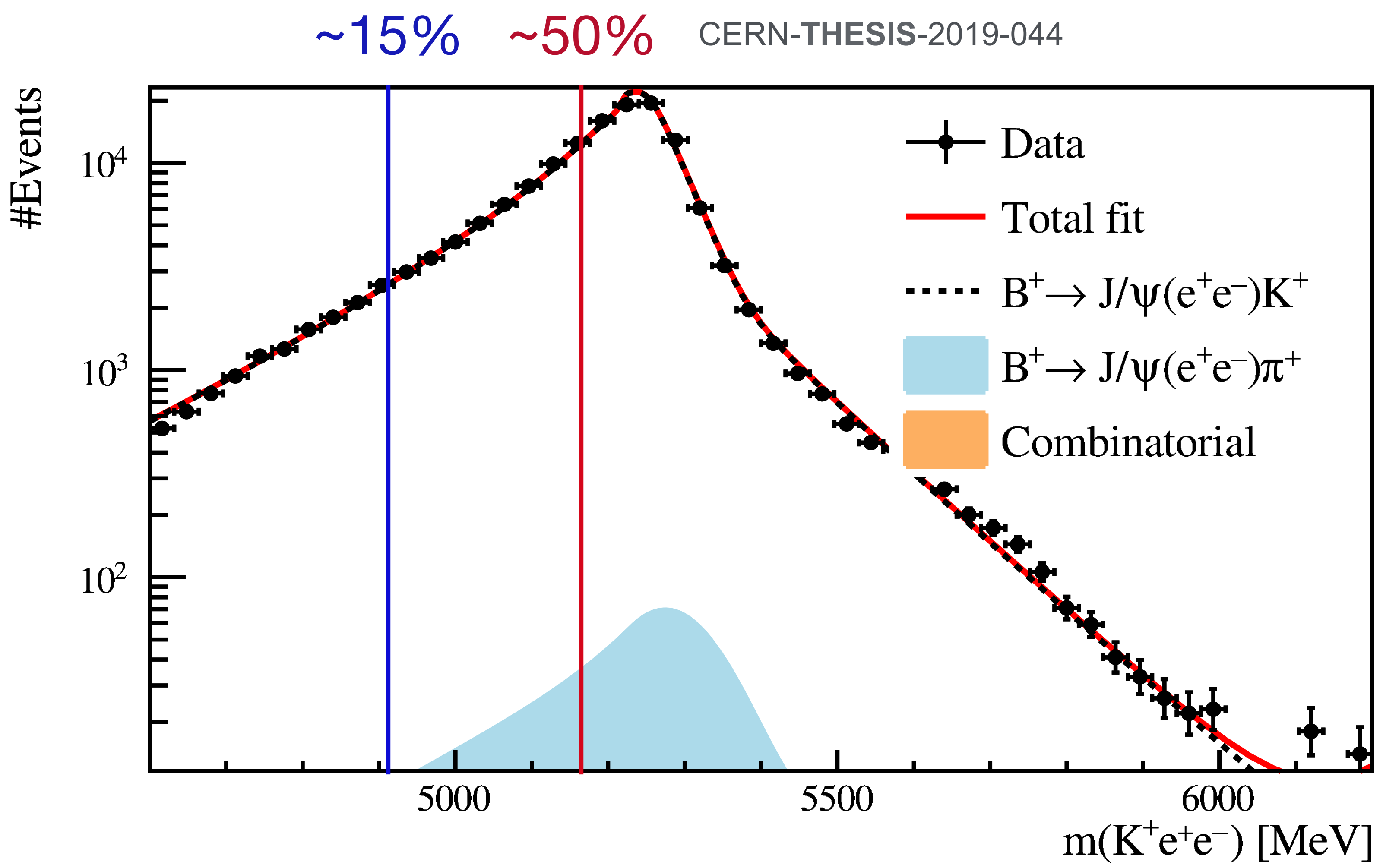
- Bremsstrahlung
- FSR - modelled with PHOTOS





R. Coutinho's talk at Munich



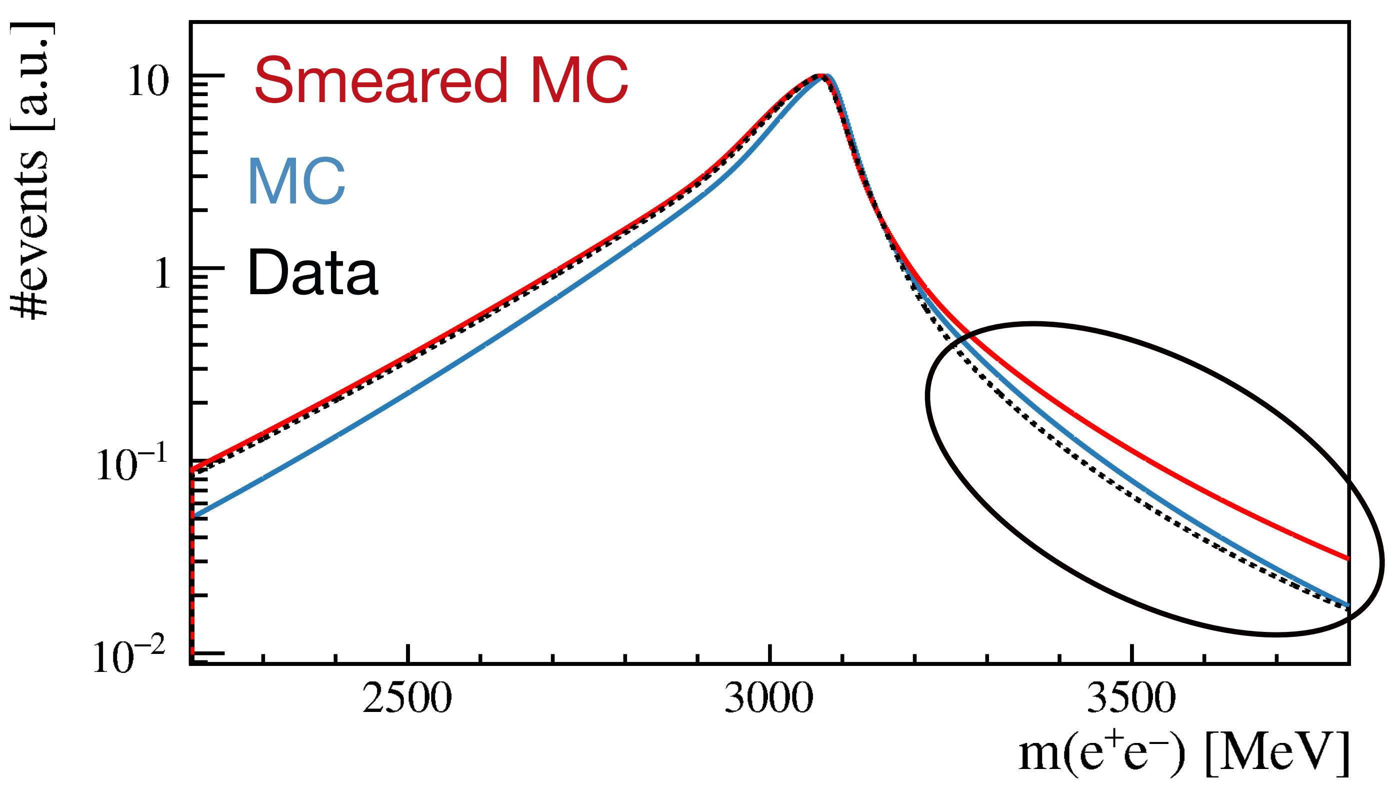


Effect of QED is sub-dominant with respect to bremsstrahlung - but that doesn't mean it doesn't matter!

How is it controlled

- Shape difference between data/MC obtained from J/psi mode. This difference is assumed to translate to rare mode.
  - Simulation shows that the correction is nicely portable.
  - What would happen if QED effects are vastly different between the two modes?

CERN-THESIS-2019-044



Imperfection here leads to negligible systematic.

- Migration in and out of q^2 bin very small, unlikely to be an issue in any case.

CERN-THESIS-2019-044

	up→in [%]	down→in [%]	in→in [%]	in→up [%]	in→down [%]
Run 1					
No smearing	8.00 ± 0.23	0.34 ± 0.05	96.94 ± 0.14	1.31 ± 0.10	1.75 ± 0.11
smearing	7.90 ± 0.23	0.43 ± 0.06	96.83 ± 0.15	1.53 ± 0.10	1.65 ± 0.11

- Only possible problem would be in the B mass shape. This was checked for rare mode*. Should we also check the J/psi?

*Bordone, Isidori, Pattori, arXiv:1605.07633

Why it's probably fine

PHOTOS cross-checked with independent calculation, things look under control.

Bordone, Isidori, Pattori
arXiv:1605.07633

Only impact would be on Mass shape (bin migration barely affected).

Shapes between J/ψ and rare mode very similar in simulation.

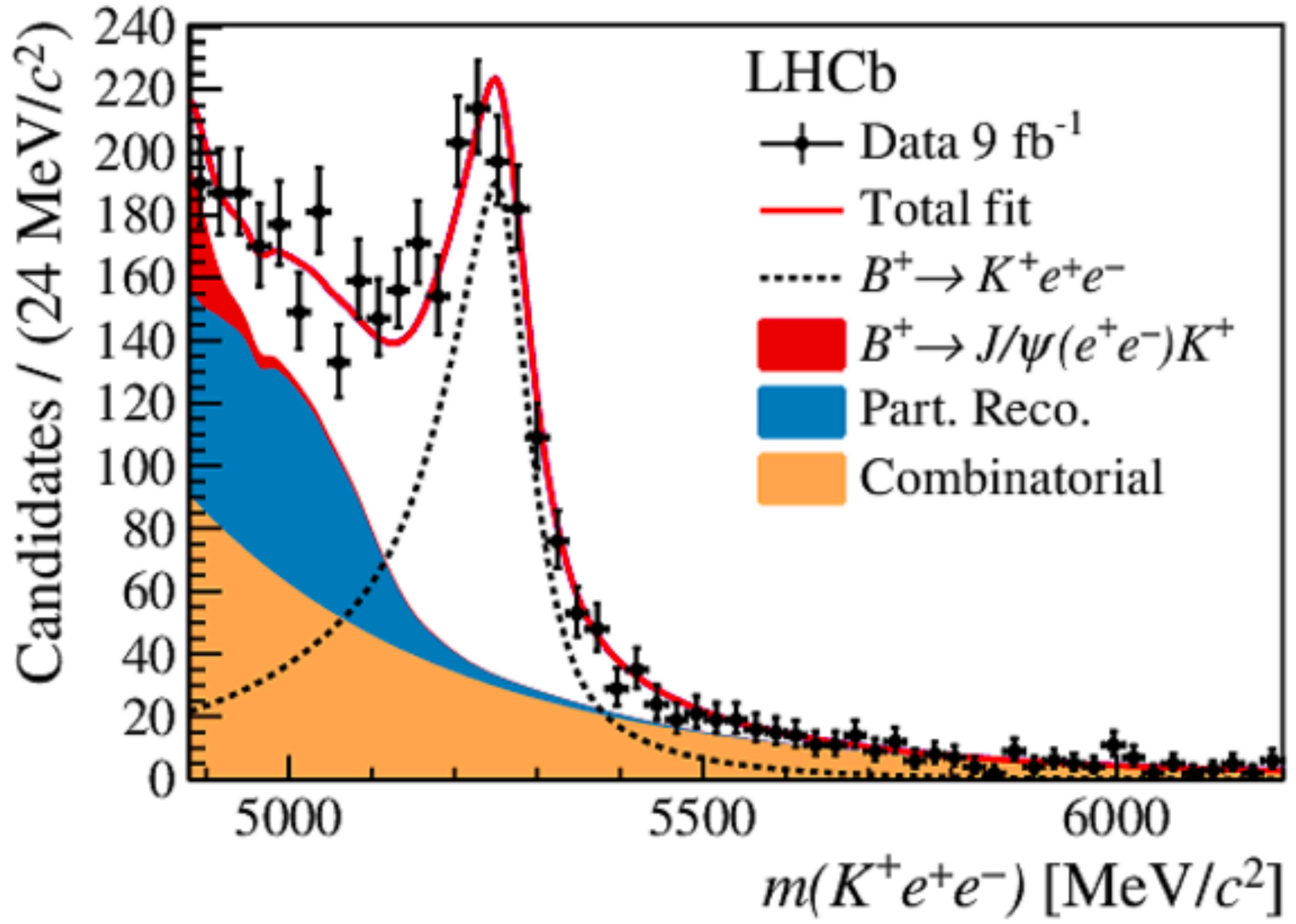
After correction J/ψ shape looks good.

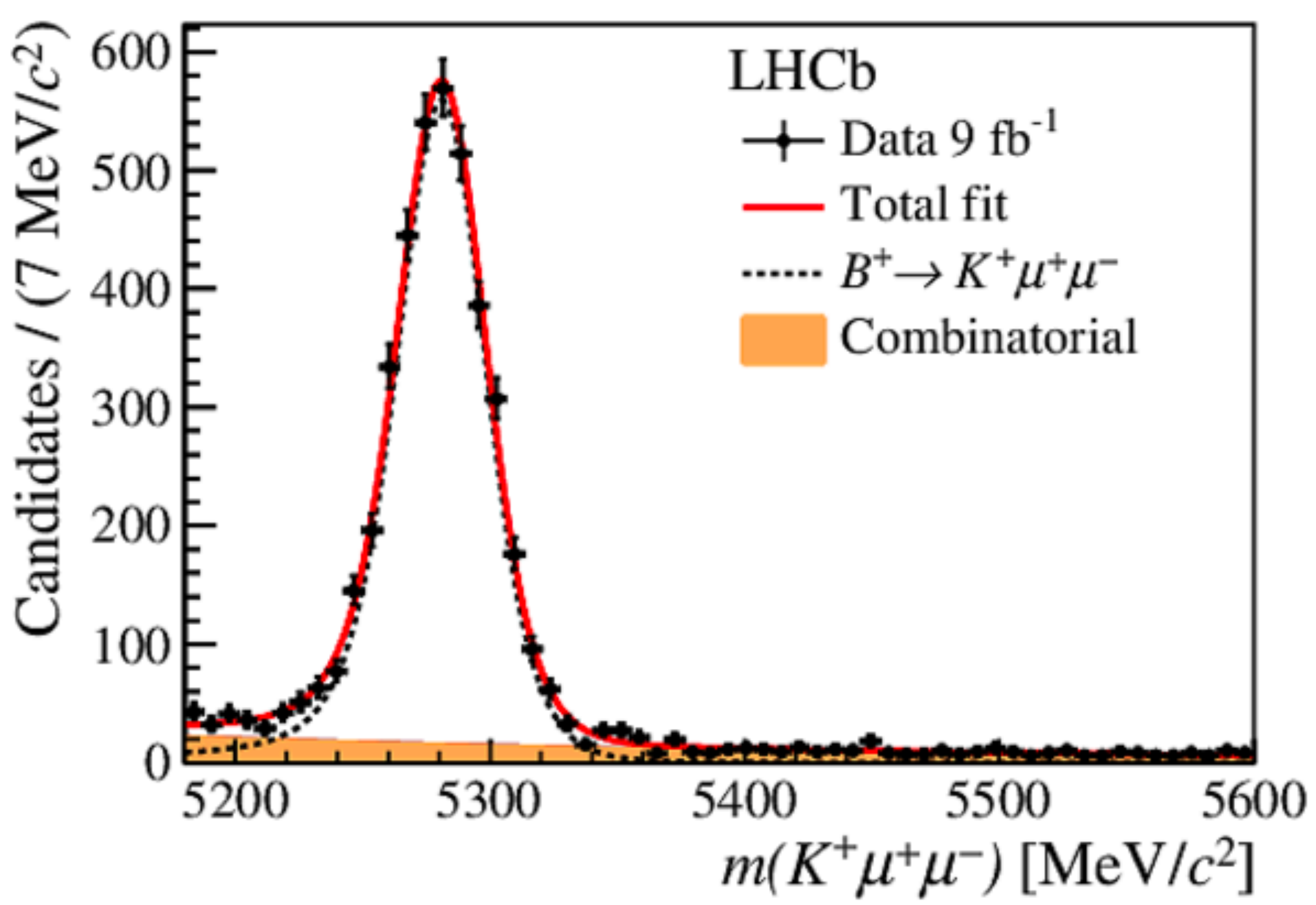
—>Everything should be under control.

Still, can we test it to make sure?

How to test it

- Could we compare $\cos(\theta_l)$ distributions between J/ψ and rare mode?
- Problem: QED effect very correlated with B mass.
  - Can we control this enough to make precise enough test?
  - Another problem: Veto to reject $B \to (X_c \to K^- \ell^+ \nu_\ell X)\ell^- \nu_\ell X$ cuts out $\cos(\theta_l)$ region.





LHCb-PAPER-2021-004, arXiv: 2103.11769

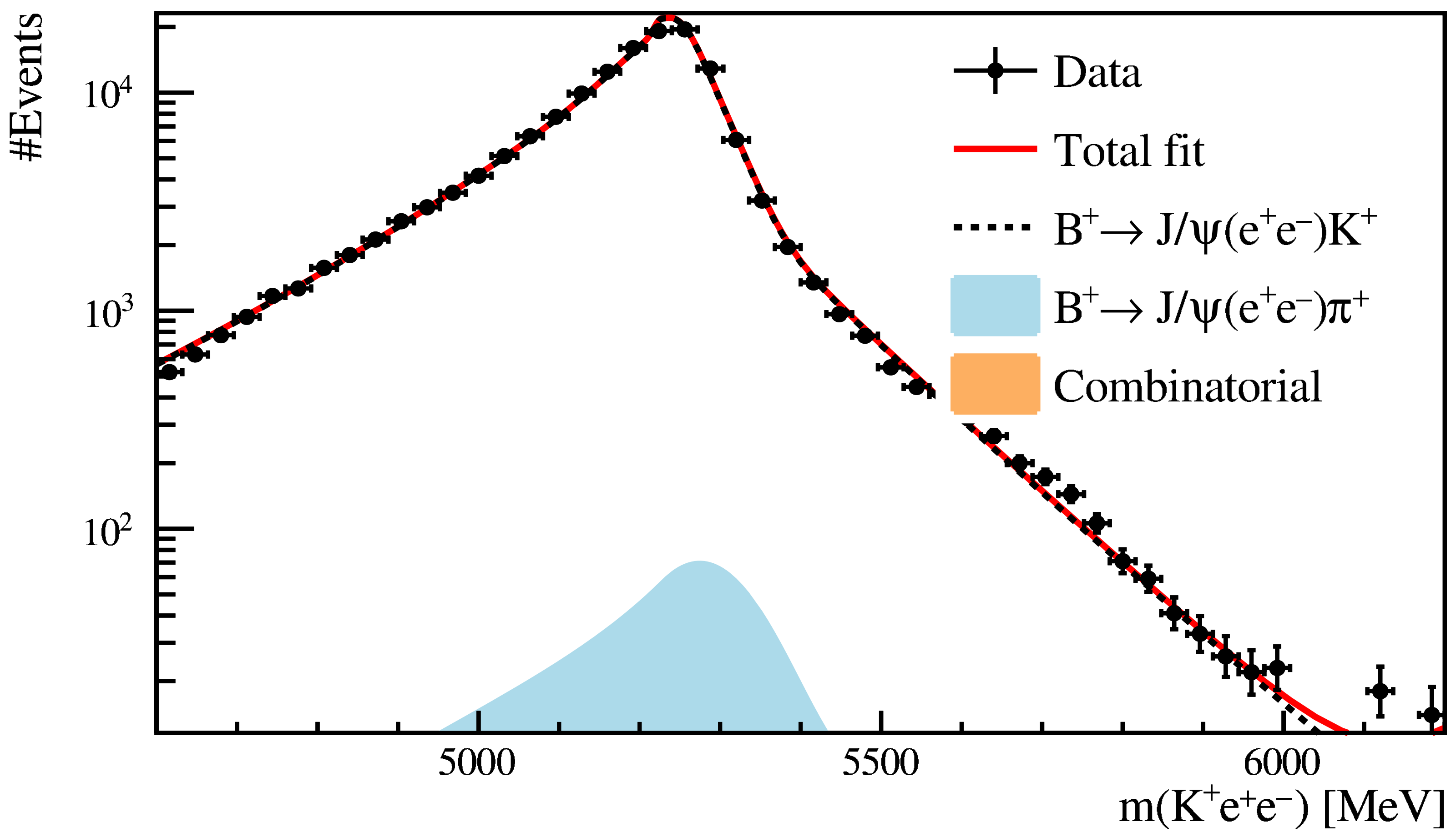
- Would we learn anything from looking at the muon channel?

What about the J/ψ mode?

- J/ψ mode would not suffer from this problem.
- Cannot calculate $\cos(\theta_l)$ after any mass constraint as that would remove sensitivity to it.

- How about:
  - Measure $\cos(\theta_l)$ distribution with no constraints.
  - Turn PHOTOS off and determine migration matrix.
  - Publish unfolded spectrum (and efficiency corrected).

CERN-THESIS-2019-044



- How would one validate the unfolding matrix? Seems difficult without relying on some QED model.
- How do we avoid chasing our tail here? Fold in different QED models?

Conclusions

Understand what we do,
but what exactly does PHOTOS do?

- **Cross checking PHOTOS** against dedicated Monte Carlo using INZ'20 at different q^2 for R_K and $B \to K\ell\ell$ differential rate will be a good sanity check

$$\Delta_{\rm QED} R_K \approx \left.\frac{\Delta\Gamma_{K\mu\mu}}{\Gamma_{K\mu\mu}}\right|^{m_B^{\rm rec}=5.175\,{\rm GeV}}_{q_0^2\in[1,6]\,{\rm GeV}^2} - \left.\frac{\Delta\Gamma_{Kee}}{\Gamma_{Kee}}\right|^{m_B^{\rm rec}=4.88\,{\rm GeV}}_{q_0^2\in[1,6]\,{\rm GeV}^2} = 1.7\,\% \quad vs \quad 3.0\,\%$$

INZ'20 BIP'16

experimental treatment
slight LFU-violation
(needs corrected for)

- 2020-perspective: use **higher moments** to **test light-NP.**
  Theory prediction necessitates structure dependent effects: precision frontier & active field

- The way we correct experimentally means that we implicitly assume no large differences between J/ψ and rare mode.

- Explicitly checking electron mode in data seems difficult, perhaps intractable.

- Muon or J/ψ modes more feasible - would those give us the information we want?

BACKUP THEORY STUFF

Cancellation of logs (photon-inclusive)*

cancel?	$\frac{d^2\Gamma}{dq^2 dc_\ell}$	$\frac{d^2\Gamma}{dq_0^2 dc_0}$
soft	yes	yes
soft-collinear	yes	yes
collinear	no	yes

"main result 1"

- Note: once photon energy cut-off restored (all logs come back)

total rates agree

$$\Gamma(\Delta E) = \int_{\Delta E} \frac{d^2\Gamma}{dq^2 dc_\ell} dq^2 dc_\ell = \int_{\Delta E} \frac{d^2\Gamma}{dq_0^2 dc_0} dq_0^2 dc_0$$

* use photon energy cut-off - all done analytic
(technical aspect: soft energy and angular integral shown to be separately Lorentz-invariant!)

Q: Are the collinear logs universal?

$$C(\Delta E)_{method\,1} \stackrel{?}{=} C(\Delta E)_{method\,2}$$

Or if B, K-meson resolved (structure dependence), further collinear logs?

A: yes, no new col.-logs $\ln m_{\ell_1}$ due to gauge invariance

- Write in meson-EFT: $A^{(1)} = \hat{Q}_{\ell_1} a_{\ell_1} + \delta A^{(1)}$

1) $\hat{Q}^2_{\ell_1} \int_\gamma |a_{\ell_1}|^2 \;=\; O(1)\,\hat{Q}^2_{\ell_1} \ln m_{\ell_1} + \ldots$. whereas $\int_\gamma Rest \xrightarrow{m_{\ell_1} \to 0} finite^*$.

collinear-log **IR-safe**

2) Hence $\delta A \to \delta A + A^{B,K}_{structure}$, no new real collinear logs

3) Since real & virtual cancel (in q_0^2, c_0 variables), no new virtual collinear logs either

"main result 2"

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* by gauge invariance: collinear region: $A = \epsilon^\mu A_\mu \Rightarrow \ell_1^\mu A_\mu = \mathcal{O}(m_{\ell_1})$

Difference between BIP and INZ

sizeable in electron mode at low q^2 ca 8%