Dealing with QED at B Factories:
Caveats and Lessons

23.6.2022

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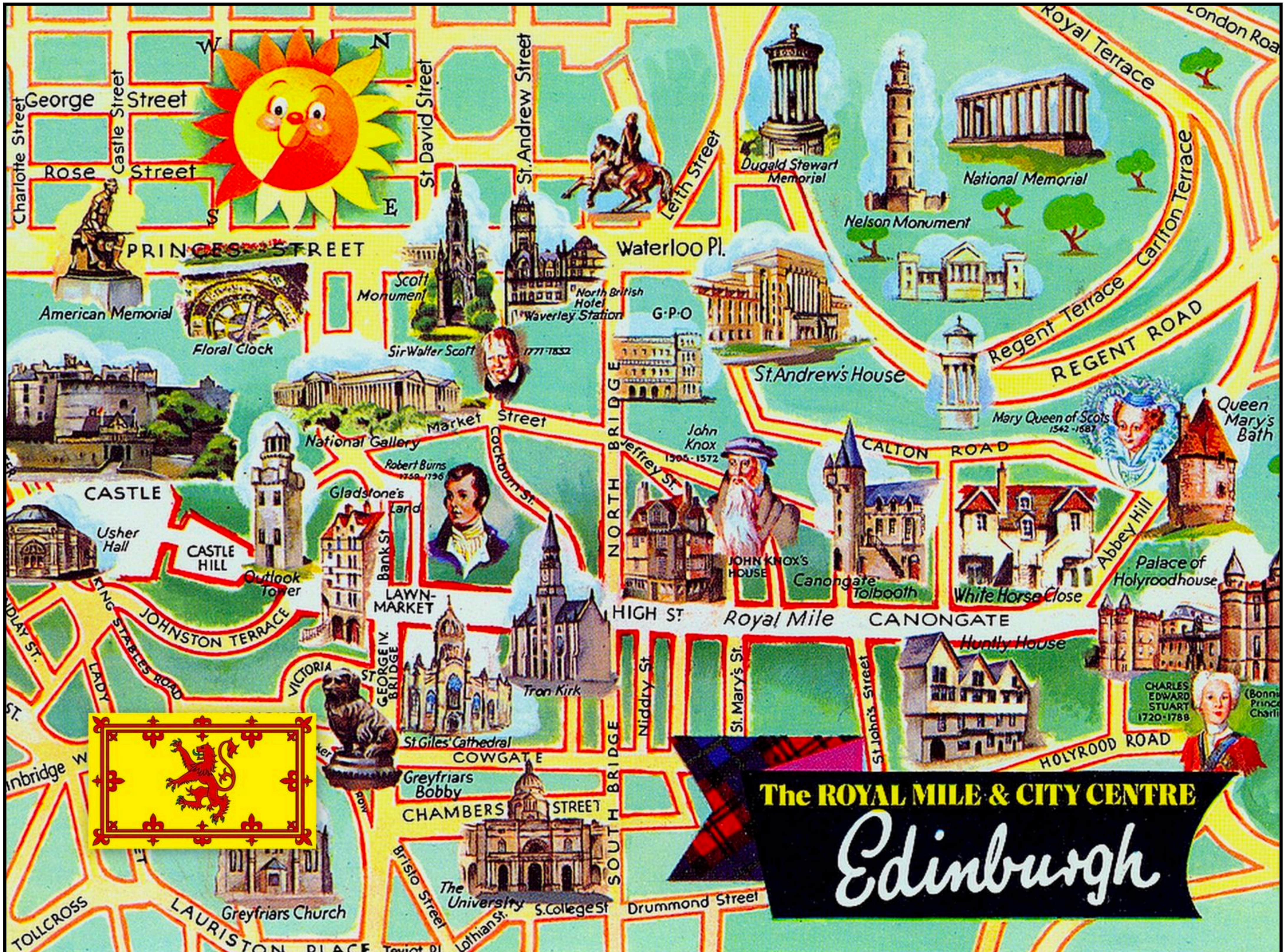
Talk Outline



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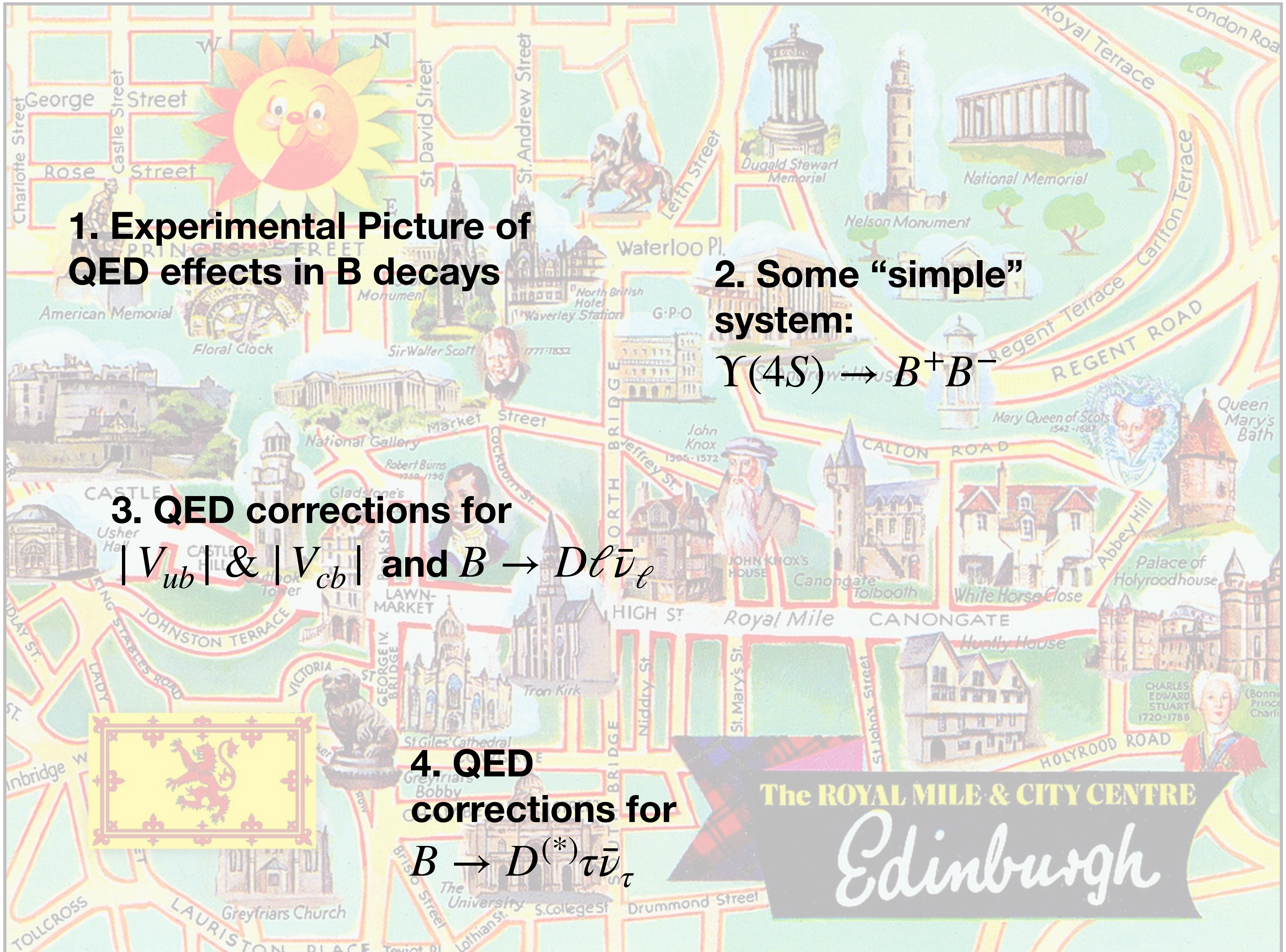


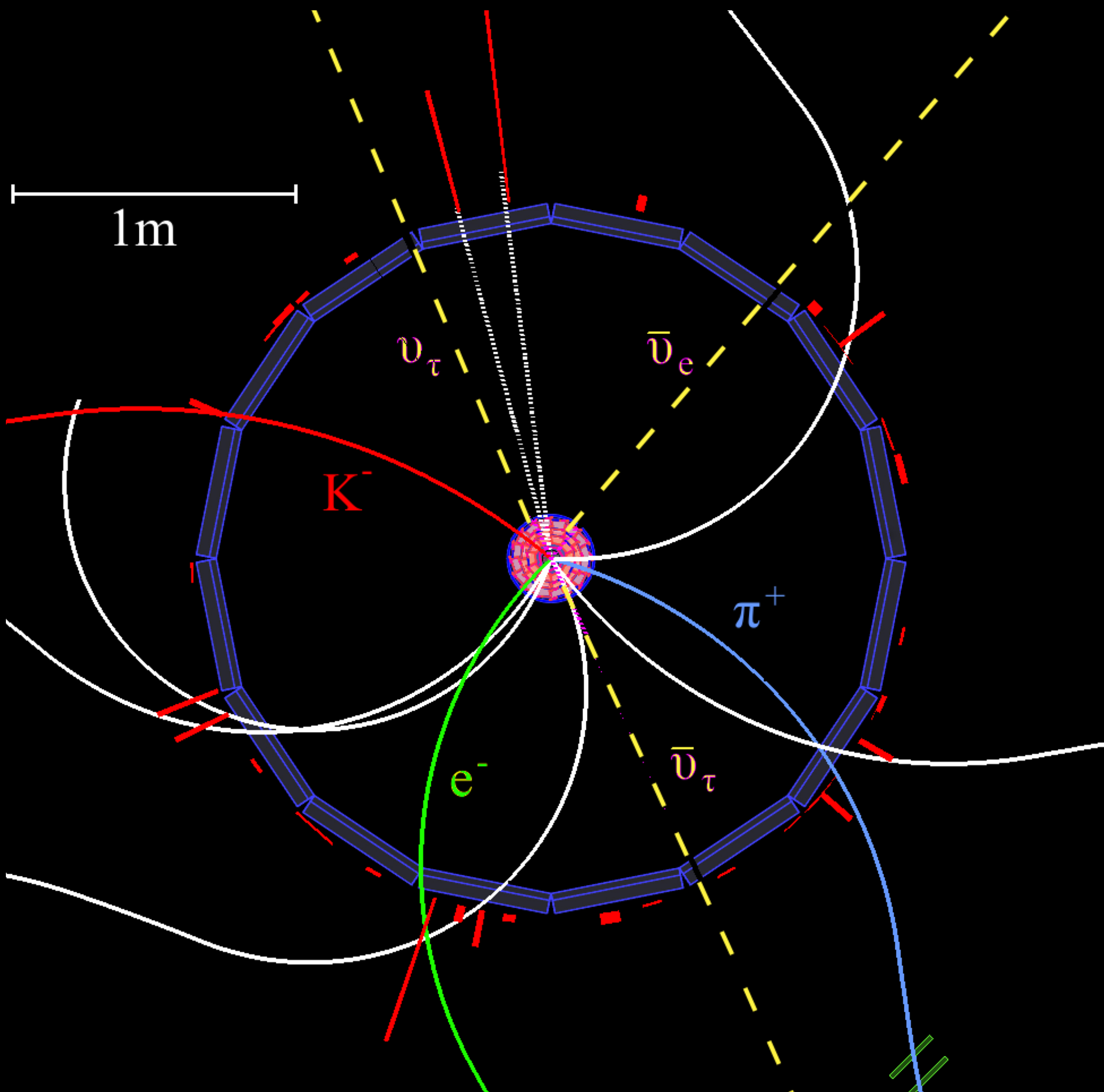
1. Experimental Picture of QED effects in B decays

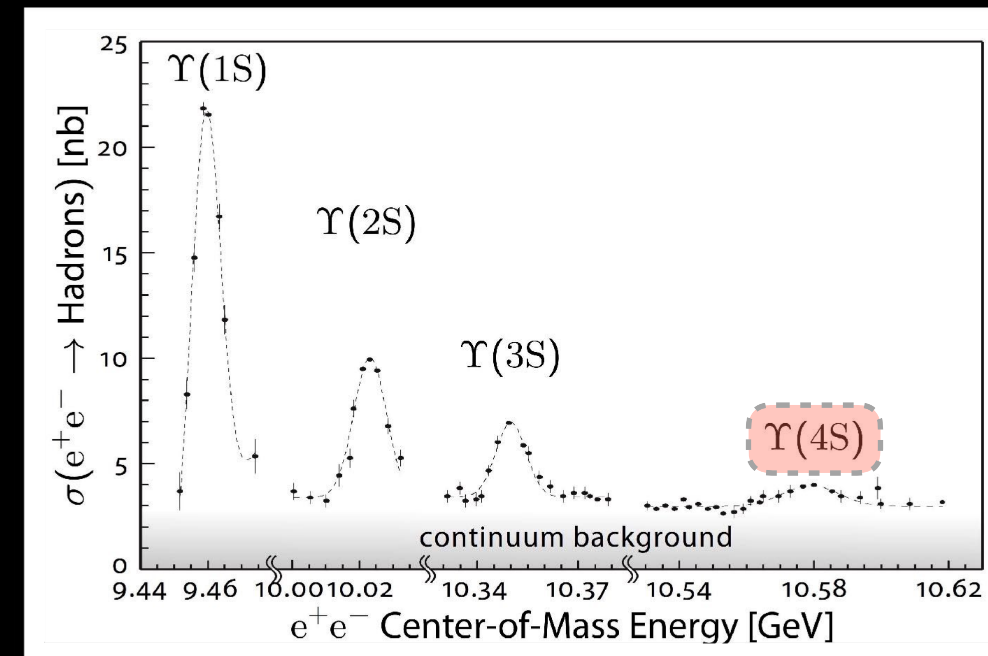
2. Some "simple" system: $\Upsilon(4S) \to B^+B^-$

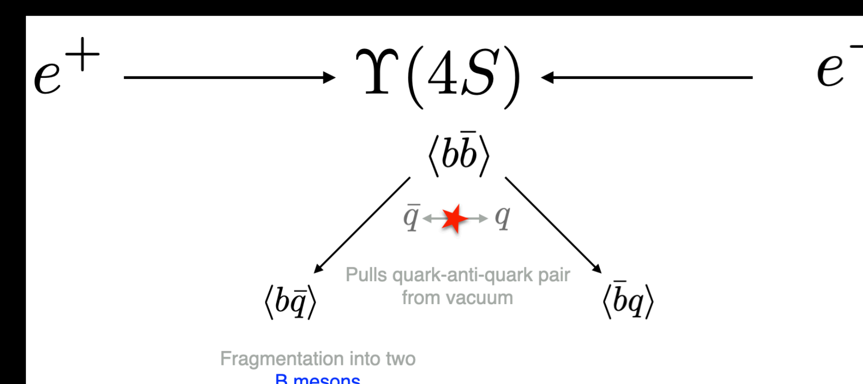
3. QED corrections for $|V_{ub}|$ & $|V_{cb}|$ **and** $B \to D\ell\bar{\nu}_\ell$

4. QED corrections for $B \to D^{(*)}\tau\bar{\nu}_\tau$

FSR & Bremsstrahlung



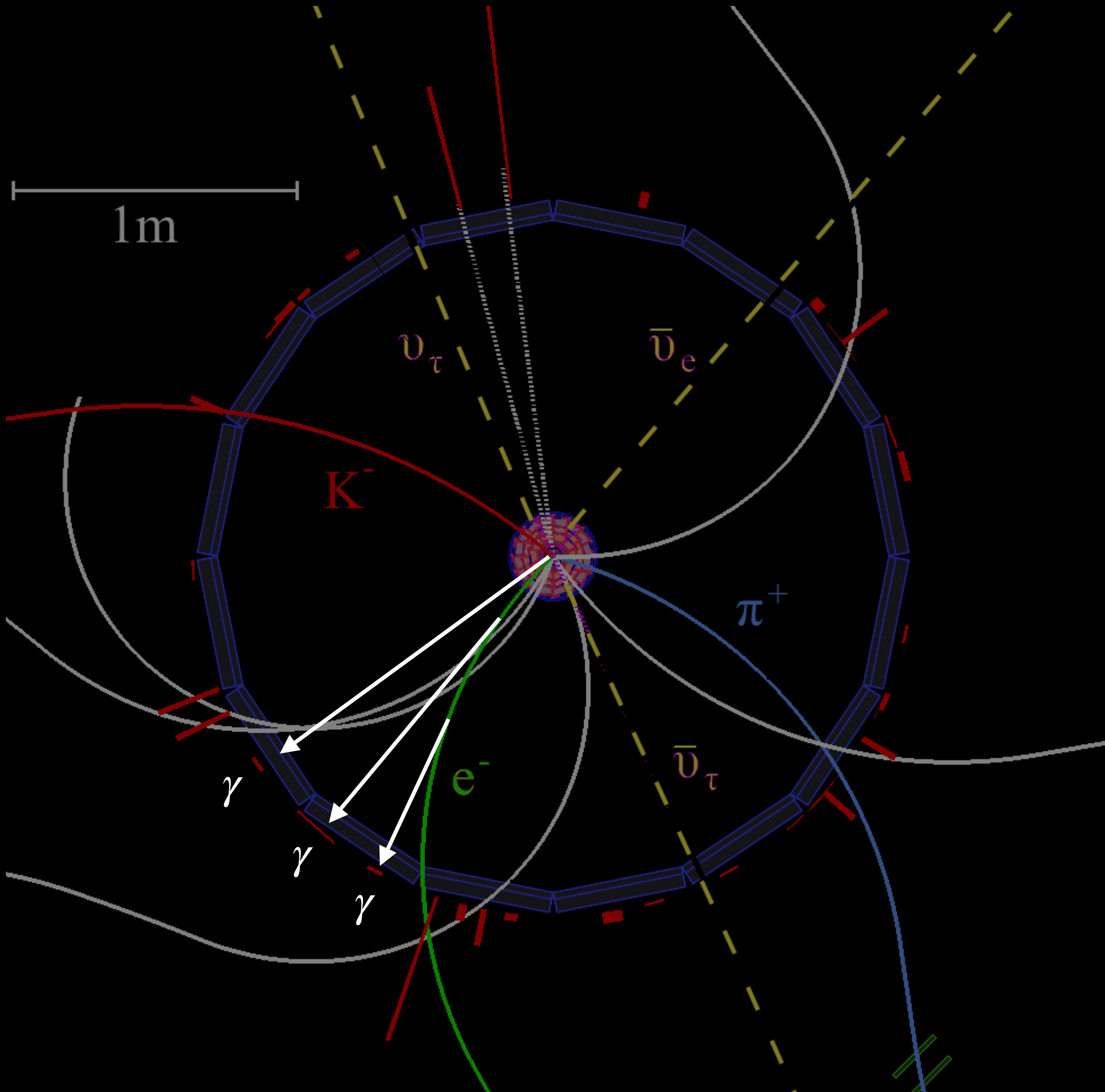




* About 5 charged tracks per B meson decay

* Electrons radiate a fair bit while traversing the detector

FSR & Bremsstrahlung



Example Trajectory:

First layer of material a particle encounters is the beam-pipe

Then layer of tracking detectors

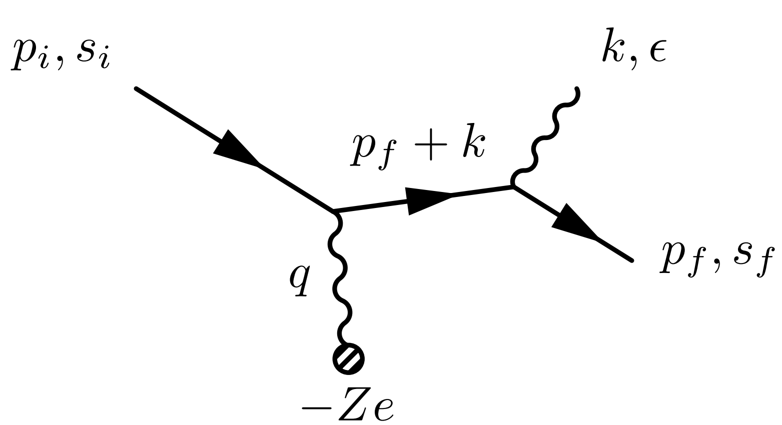
Then a drift chamber

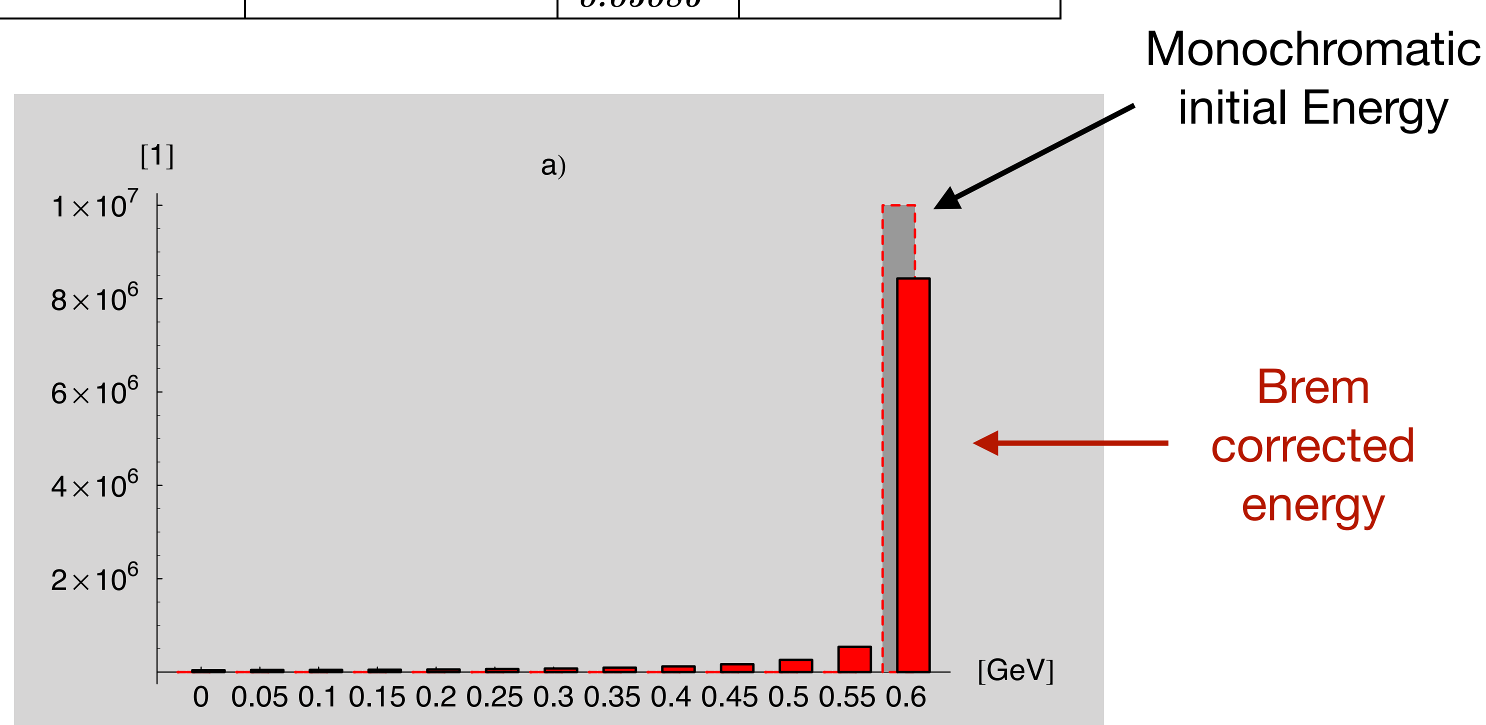
Emissions from the **beam-pipe** look a lot like **FSR**

Example material Budget of a detector (here *BaBar*):

		material	thickness l (mm)	density ρ (g/cm^3)	mean path $<l>$ (mm)	radiation length X_0 (mm)	$<l>/X_0$	plasma frequency k_p (Gev)
Beam-pipe	PEP II tube	Au	0.004	19.3	0.005	3.347	0.00153	$8.0168 \cdot 10^{-8}$
		Be	0.830	1.85	1.064	346.416	0.00307	$2.6113 \cdot 10^{-8}$
		H_20	1.48	0.998	1.896	370 [17]	0.00513	$2.1476 \cdot 10^{-8}$
		Be	0.530	1.85	0.679	346.416	0.00196	$2.6113 \cdot 10^{-8}$
		total					*0.01169*	
Tracking Detector	SVT 1-3	Si	0.300	2.33	0.404	93.344	0.00433	$3.1099 \cdot 10^{-8}$
		Cu	0.0089	8.96	0.0119	14.350	0.00084	$5.8267 \cdot 10^{-8}$
		Kapton	0.0254	1.42	0.0342	324.948	0.00011	$2.3311 \cdot 10^{-8}$
	SST	Kevlar (C)	-	2.27	0.0911	188.109	0.00048	$3.0677 \cdot 10^{-8}$
	SVT 4	Si	0.300	2.33	0.387	93.344	0.00415	$3.1099 \cdot 10^{-8}$
		Cu	0.0089	8.96	0.0115	14.350	0.00080	$5.8267 \cdot 10^{-8}$
		Kapton	0.0254	1.42	0.0328	324.948	0.00010	$2.3311 \cdot 10^{-8}$
	SST	Kevlar (C)	-	2.27	0.0911	188.109	0.00048	$3.0677 \cdot 10^{-8}$
	SVT 5	Si	0.300	2.33	0.386	93.344	0.00414	$3.1099 \cdot 10^{-8}$
		Cu	0.0089	8.96	0.0115	14.350	0.00080	$5.8267 \cdot 10^{-8}$
		Kapton	0.0254	1.42	0.0327	324.948	0.00010	$2.3311 \cdot 10^{-8}$
	SST	Kevlar (C)	-	2.27	0.0911	188.109	0.00048	$3.0677 \cdot 10^{-8}$
		total					*0.03331*	
Drift chamber	ST	Kevlar (C)	0.97	2.27	1.25	249 [14]	0.005 [13]	$3.0677 \cdot 10^{-8}$
	DCH	Be	1.00	1.85	1.28	346.416	0.00370	$2.6113 \cdot 10^{-8}$
		He : C_4H_{10} + wires	573.0	0.000624	734.2	340000 [14]	0.00216	$5.0067 \cdot 10^{-10}$
		total					*0.00586*	
		overall total					***0.05086***	

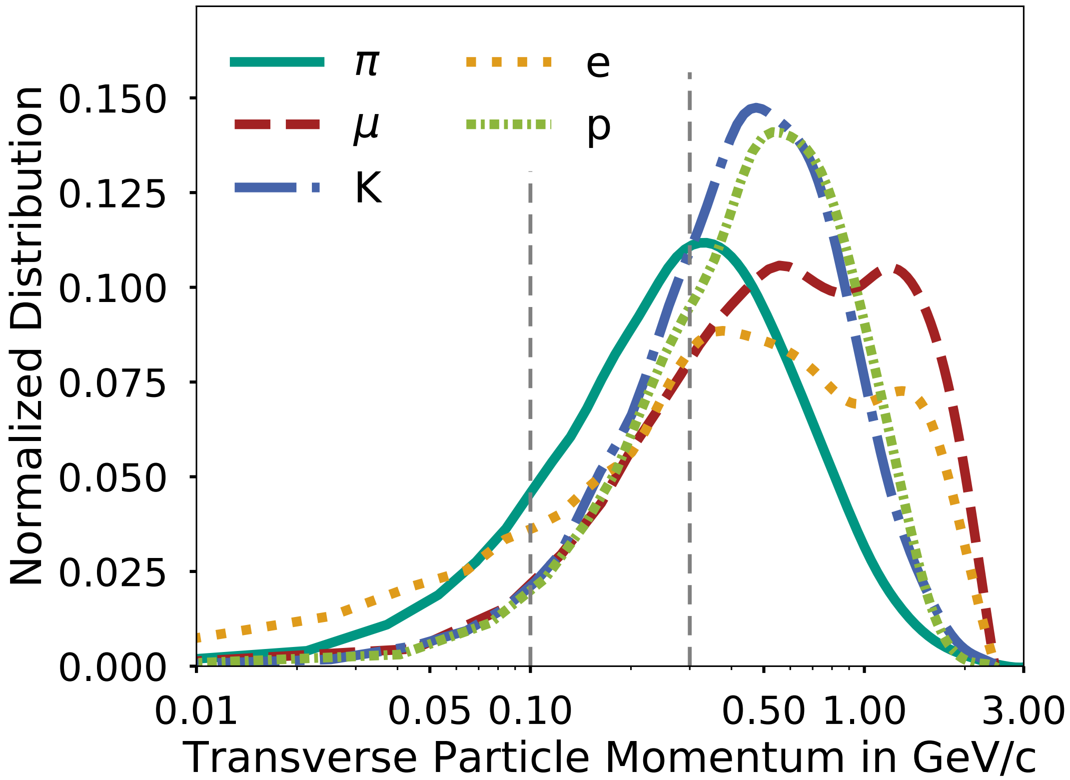
Simulated **energy loss**:

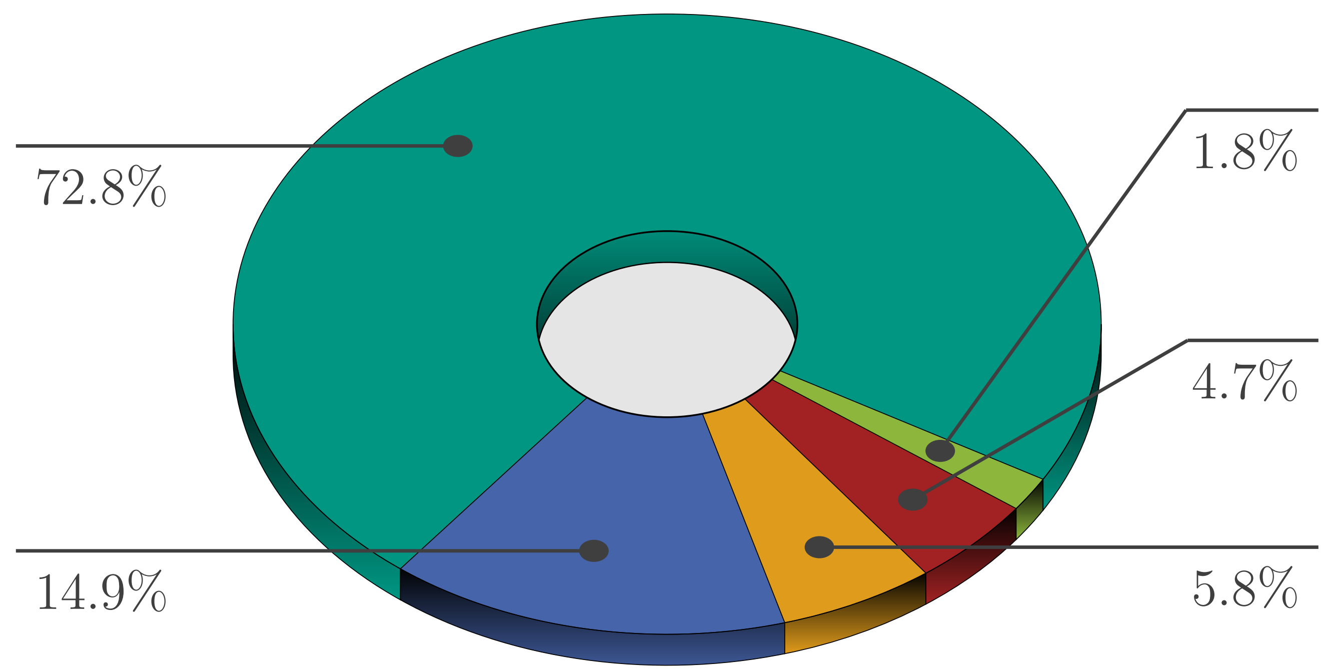




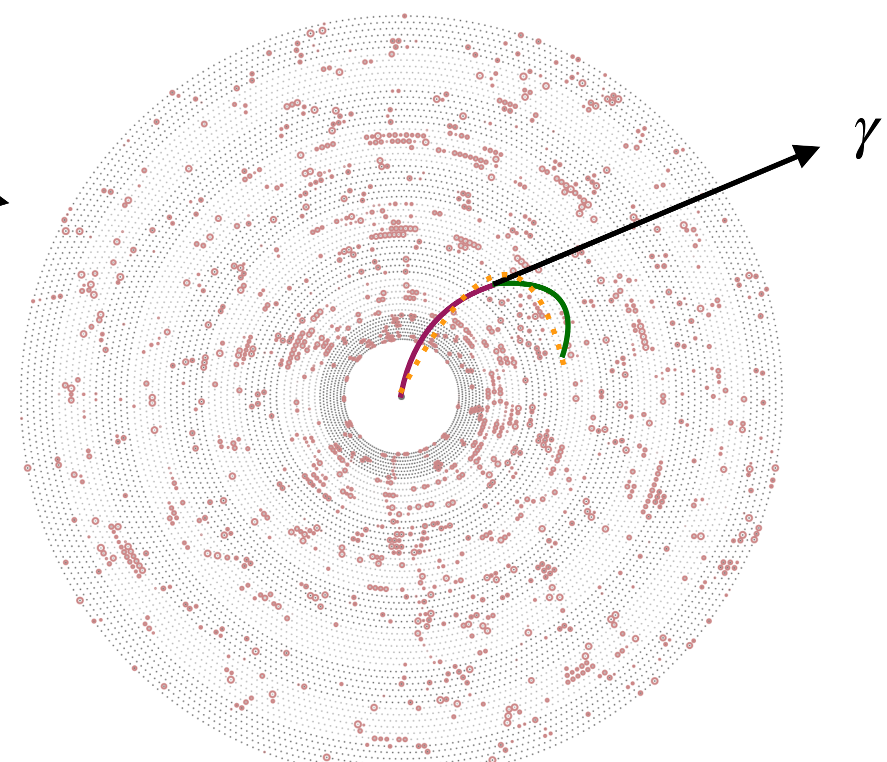
Track fitting

See e.g. Comput.Phys.Commun. 259 (2021) 107610
or





Use Kalman-Filter or global χ^2-fit to find and fit particle tracks



Bremsstrahlung leads to **kinks** in **trajectory**

At Belle II: Reconstructed track has weighted average of **pre-**and **post-emission** momentum

Track fitting

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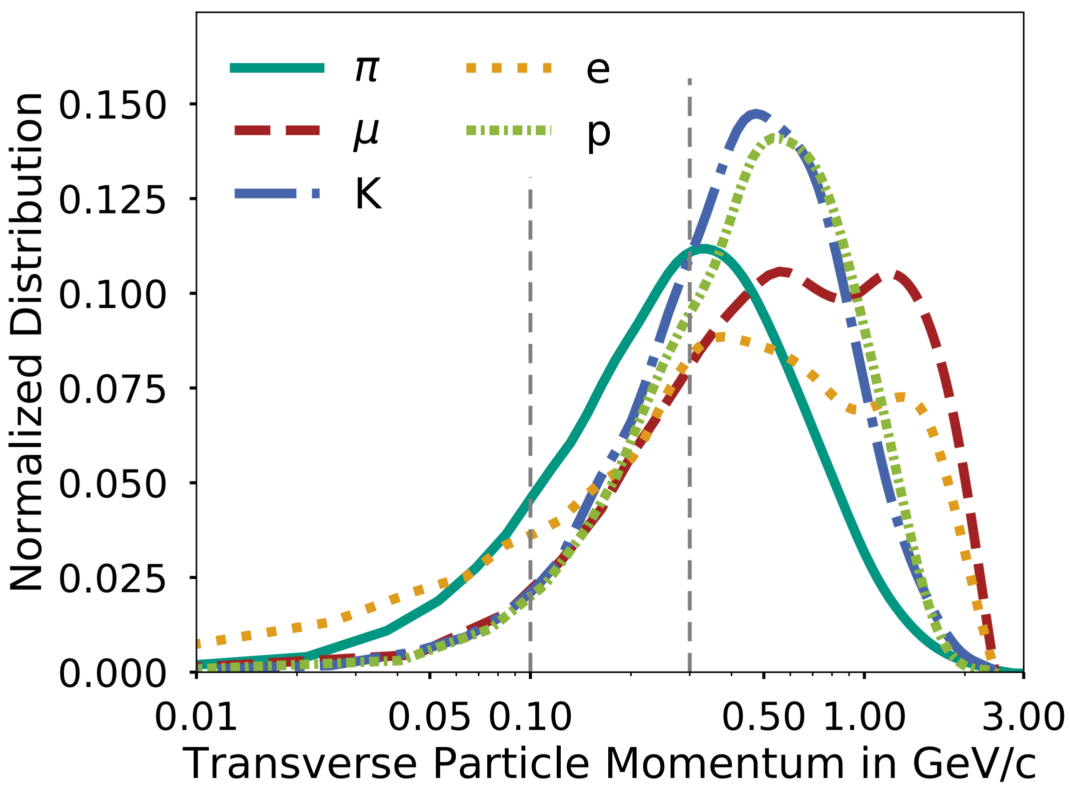
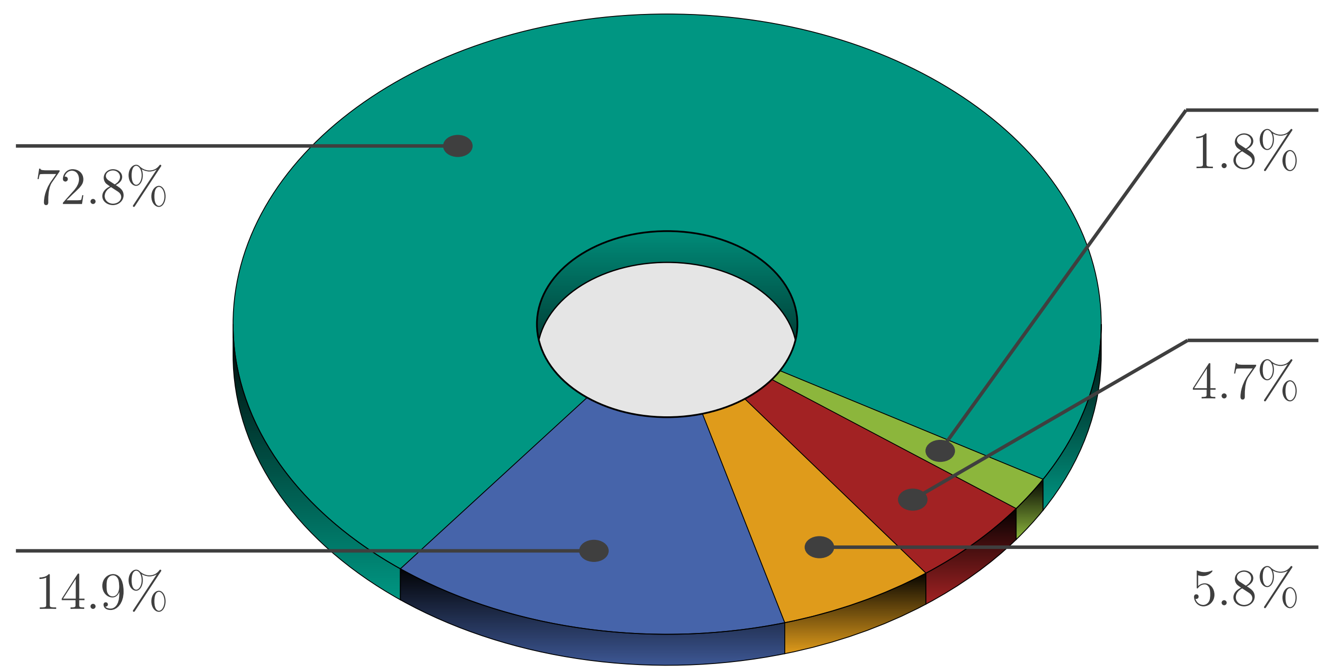
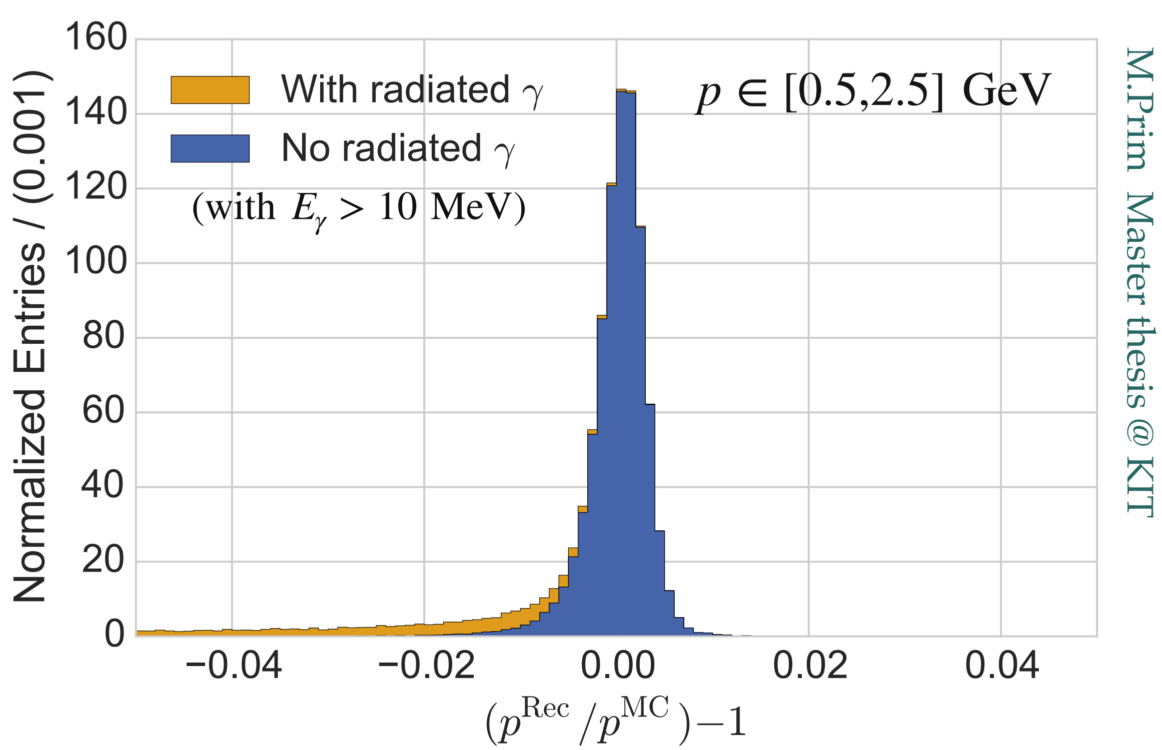
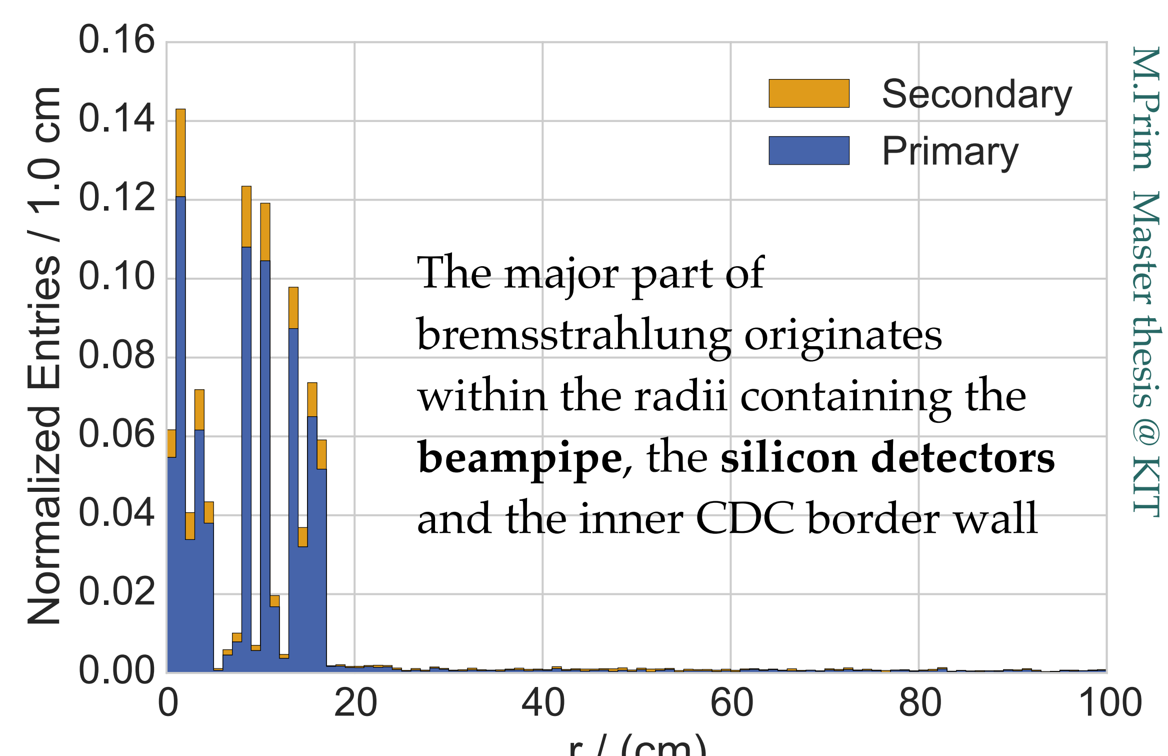








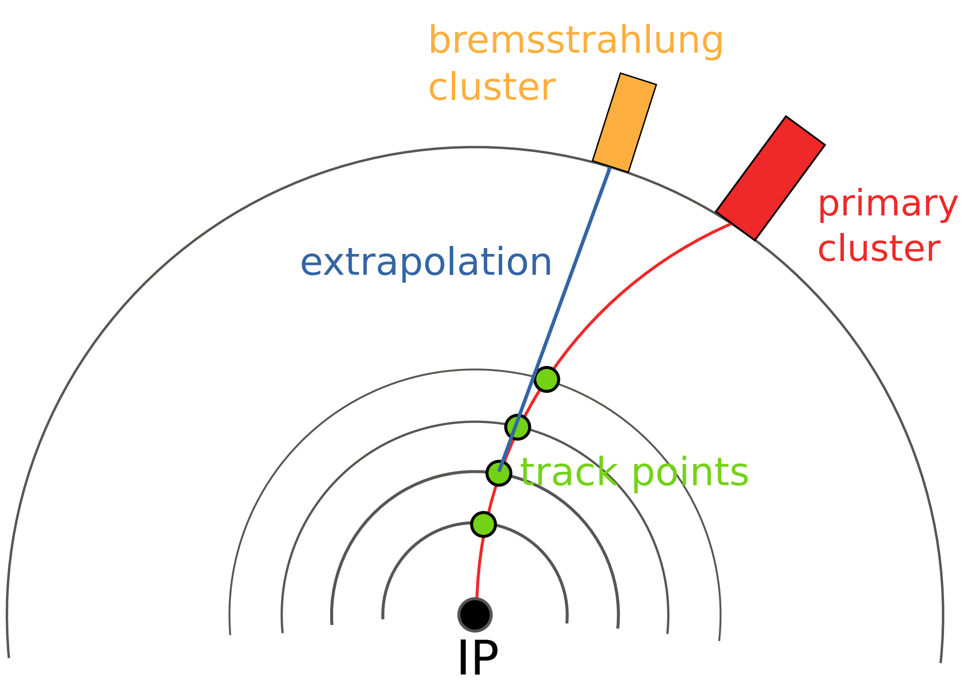
Bremrecovery

Can try to identify and recover Bremsstrahlung & FSR emissions

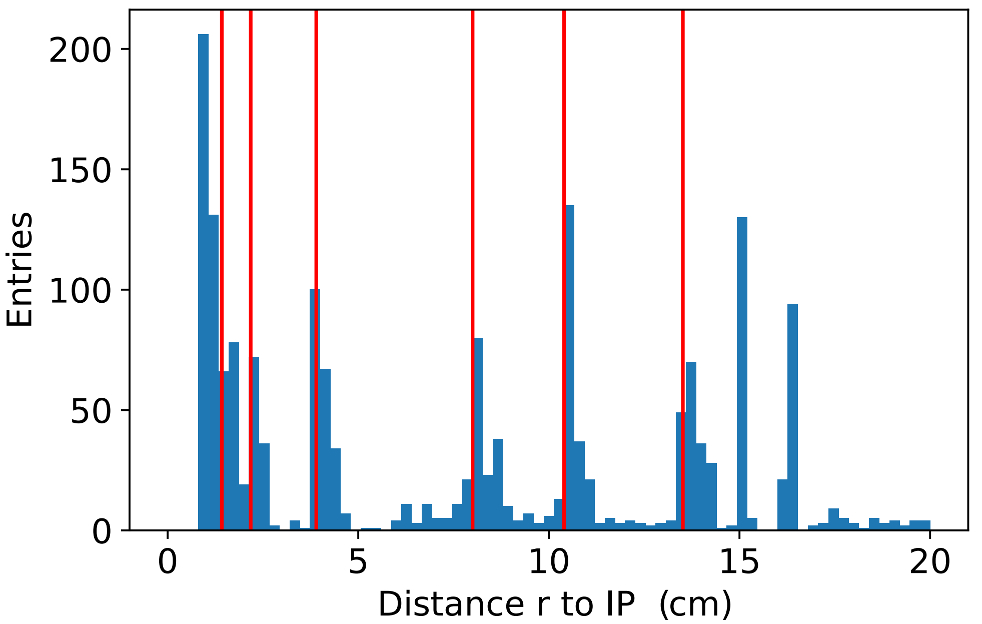
Requires lower energy cut **~ 10 MeV** to identify photon in ECL

Once **identified**, can correct track momentum with identified photons:

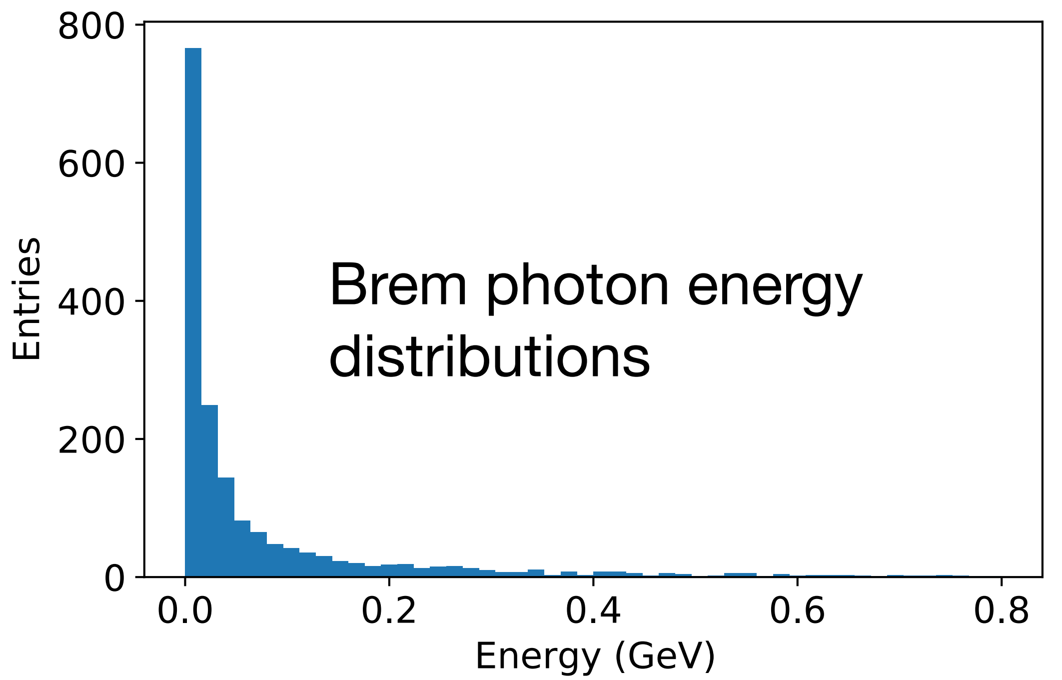
$$p_e = p_e^{tracking} + \Sigma p_\gamma$$



Material layers



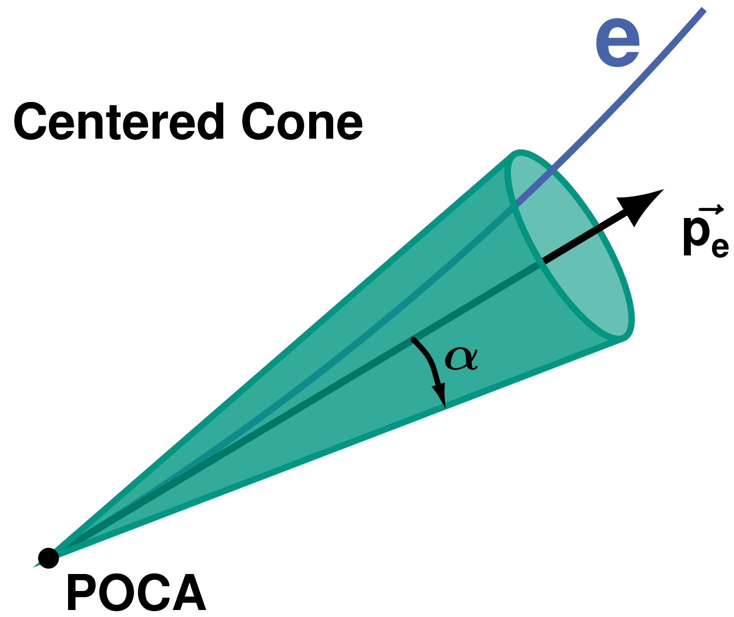
Patrick Ecker, Bachelor Thesis

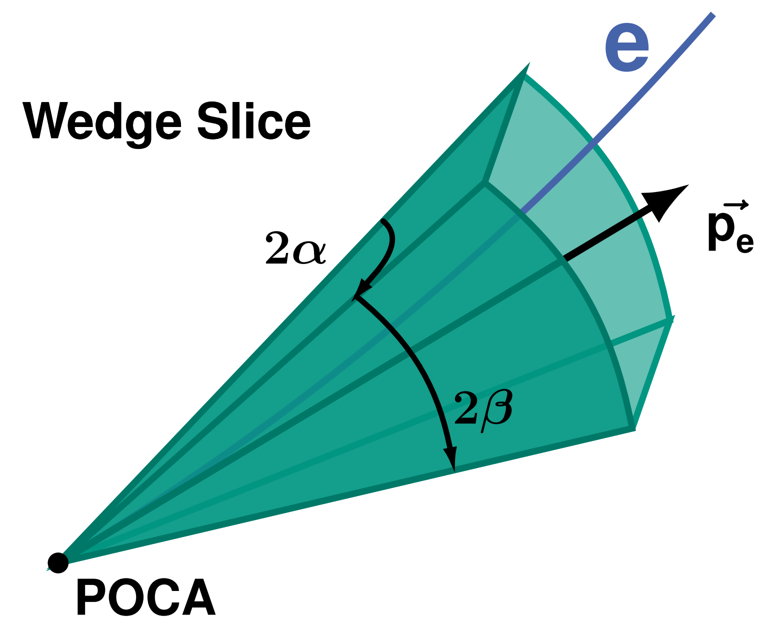


Patrick Ecker, Bachelor Thesis

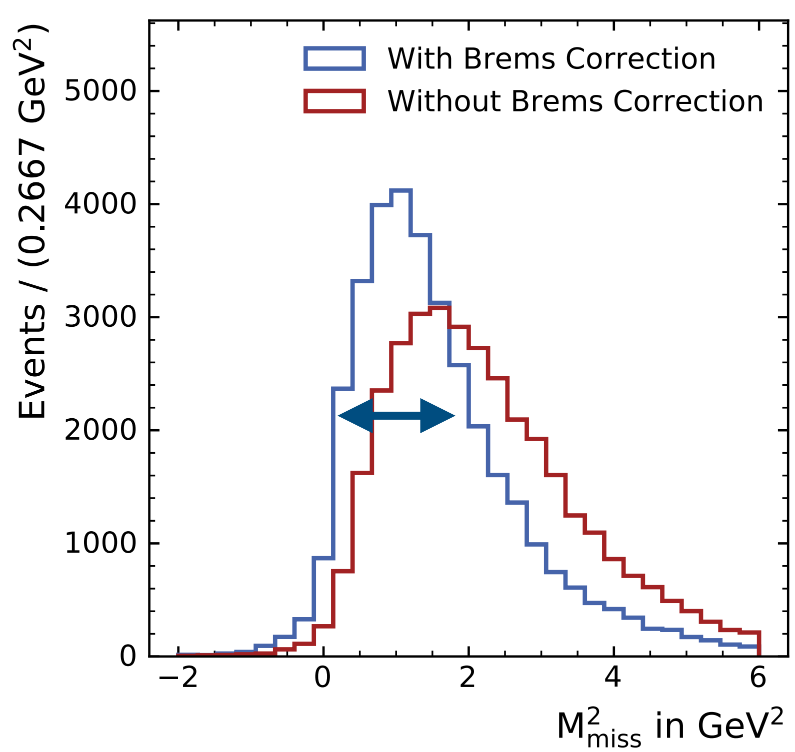
Belle method: use a search cone or wedge around the initial direction to define a search region in the ECL

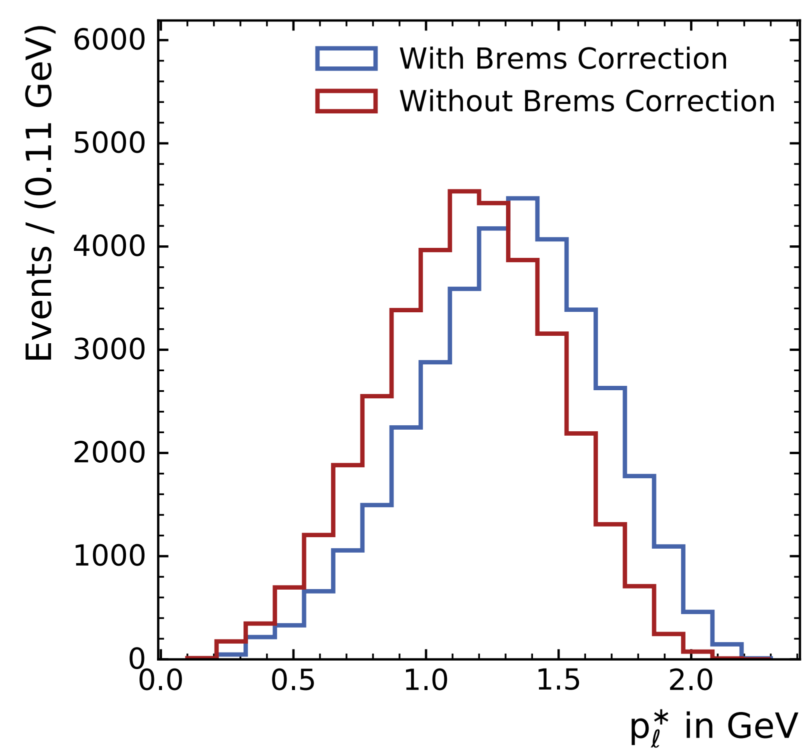
Require
$E_\gamma < 400\,\mathrm{MeV}$
$E_\gamma < 0.4 \times |\vec{p}_e|$





Felix Metzner, PhD Thesis





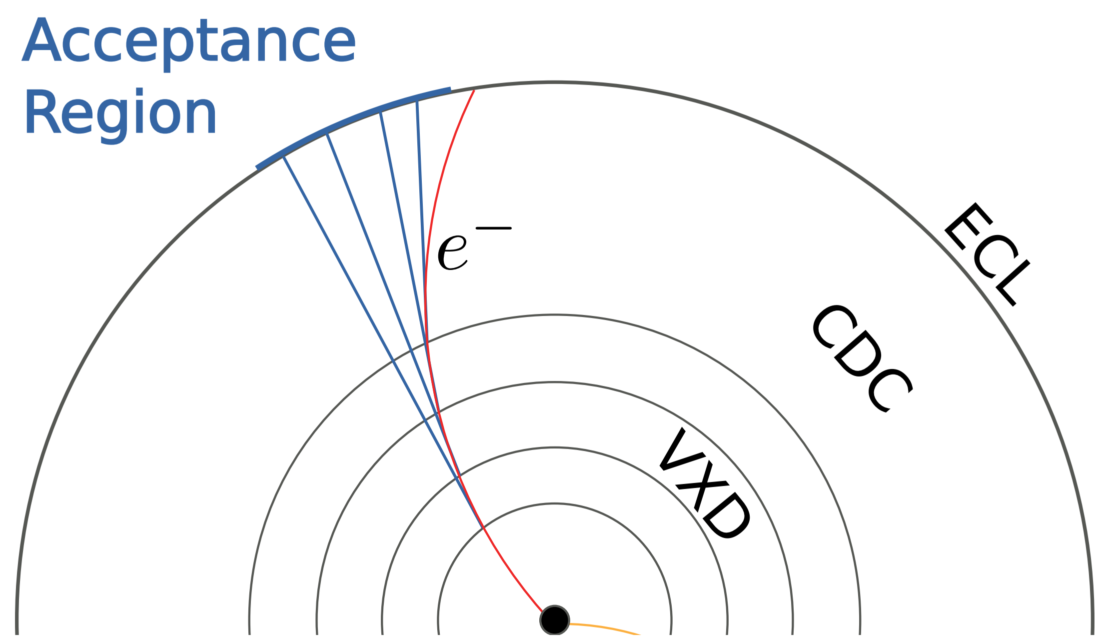
Felix Metzner, PhD Thesis

$$M^2_{\mathrm{miss}} = \left(p_B - p_{D^{(*)}} - p_\ell\right)^2 \sim 0\,\mathrm{GeV}^2 \qquad p_\ell$$

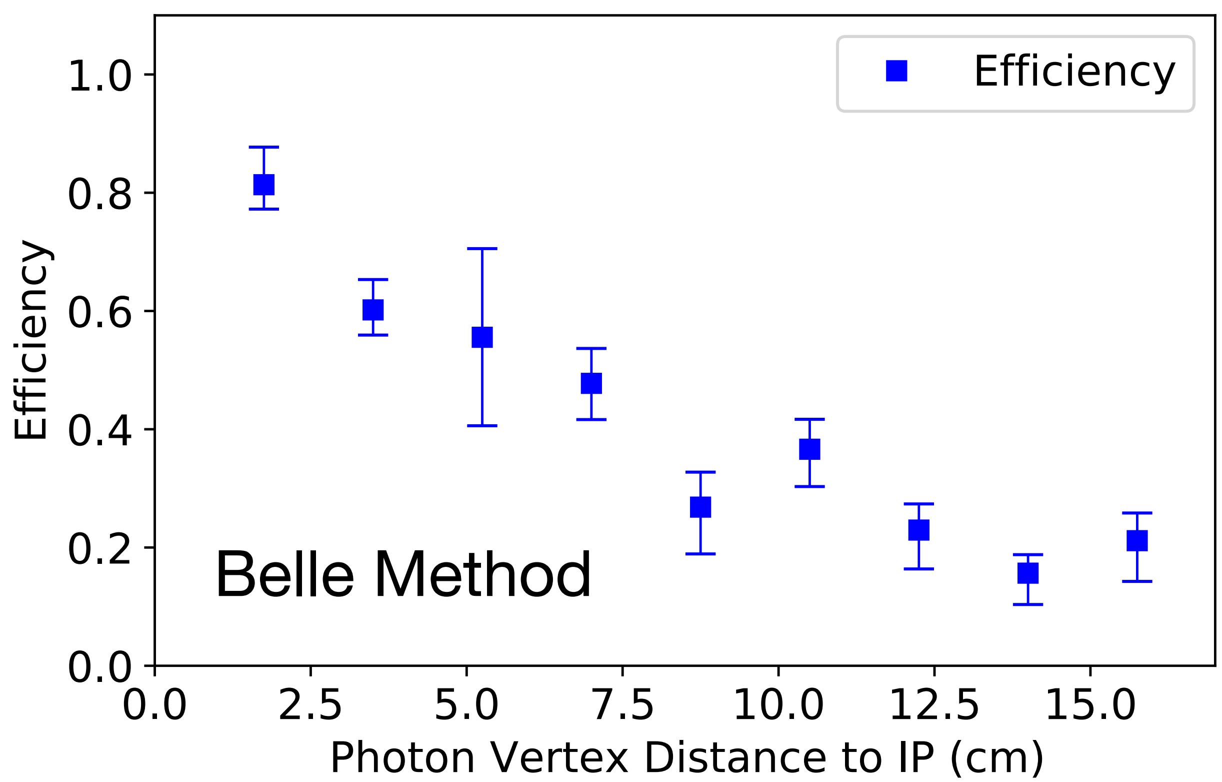
Belle II method:

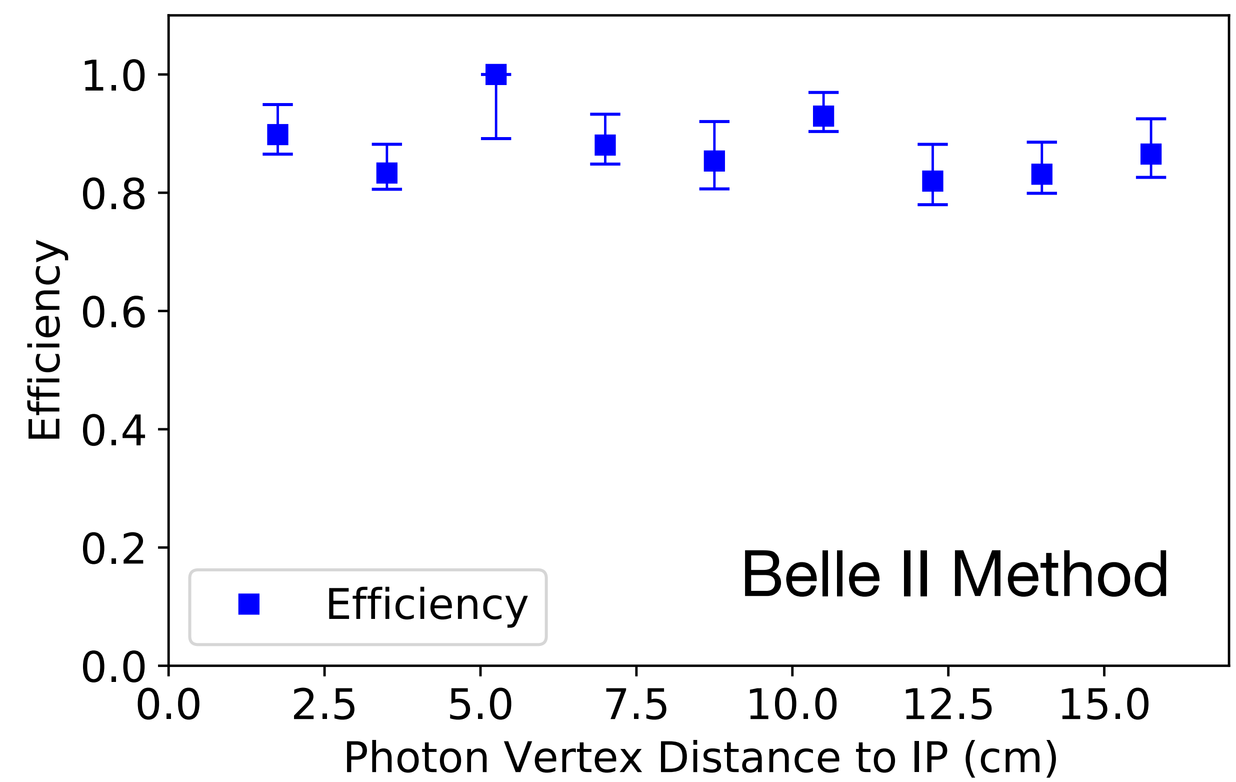
Extrapolate from **all major material** layers plus the transition region

Optimize **Acceptance region** to maximize finding efficiency & minimize fake rate



Finding Efficiency for Brem photons





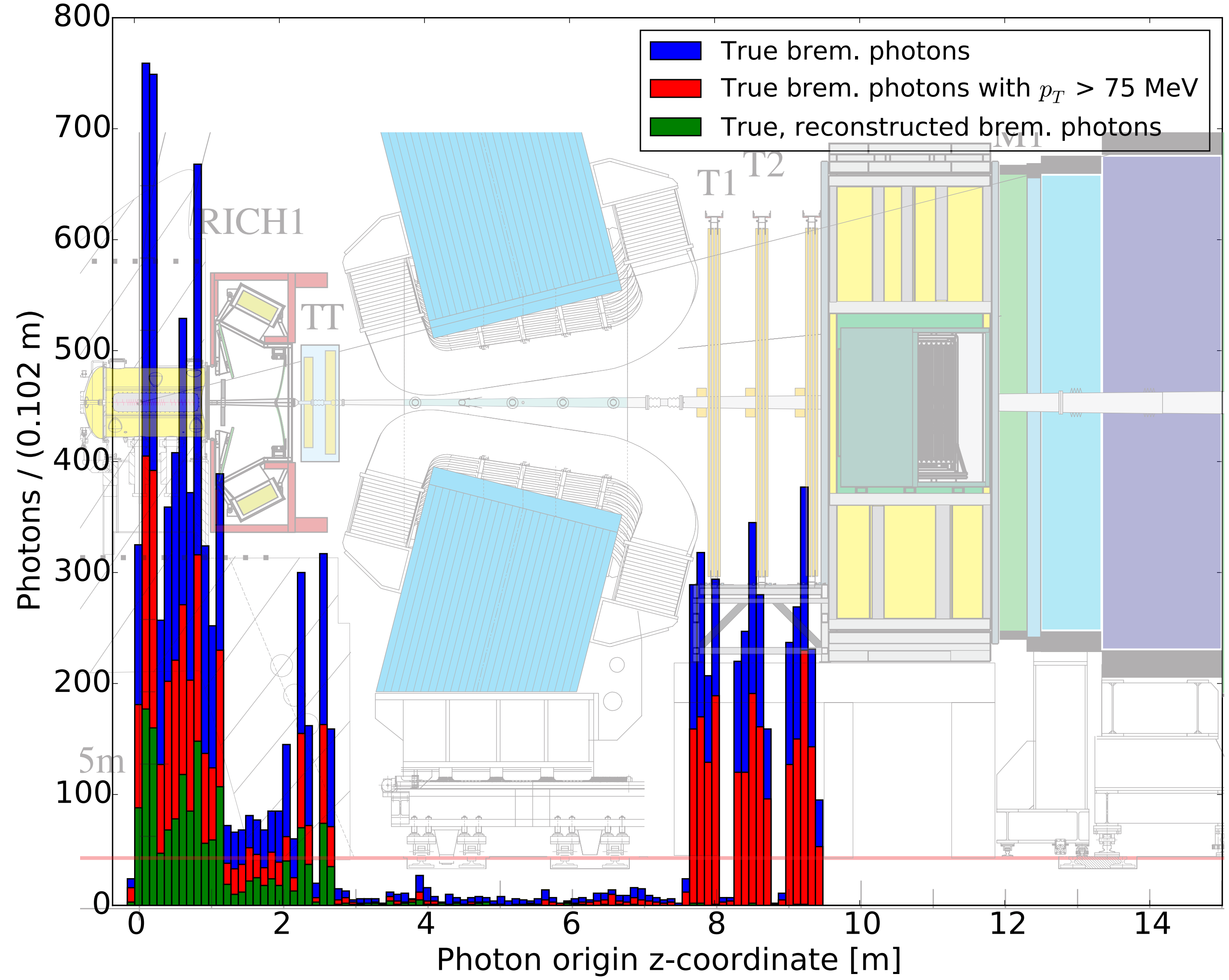
Patrick Ecker, Bachelor Thesis

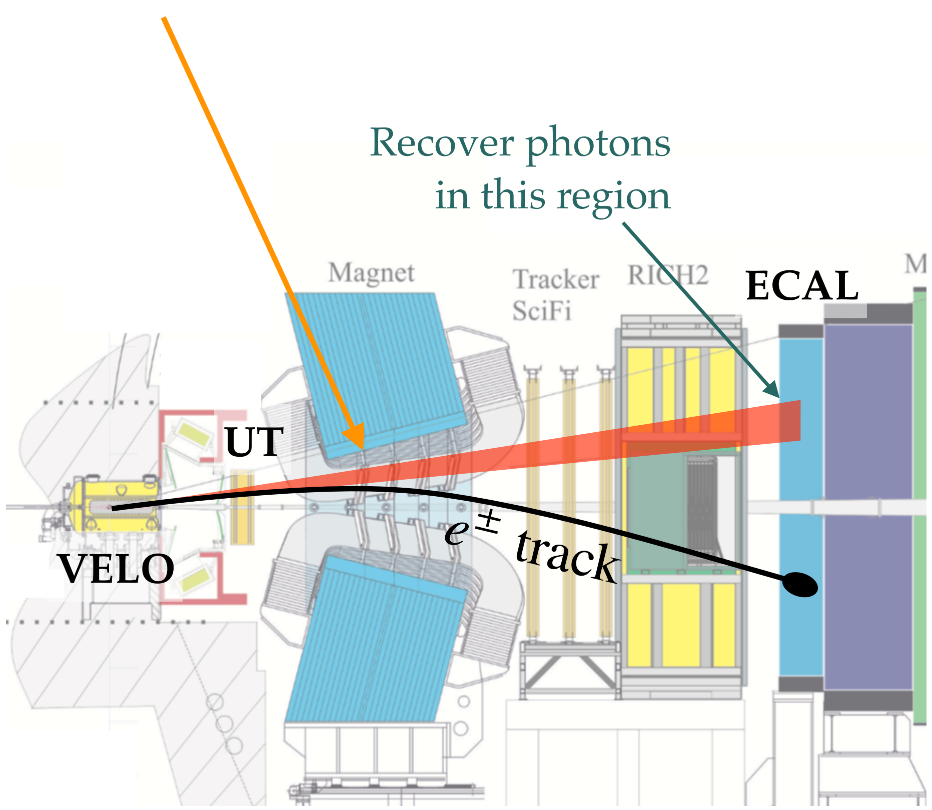
LHCb faces similar challenges:

If emission happens before the magnet impacts momentum measurement

Identify Brem photon and **correct track momentum**

Done by **extrapolating** the upstream $e^{\pm}$ to ECAL





Demand **minimal** $E_T > 75\,\mathrm{MeV}$;

Also helps to identify electrons
(as e.g. pions don't radiate much Brem)

On average one Brem photon per electron:

$$< N_\gamma > = \frac{d}{X_0}\left[\frac{4}{3}\ln\left(\frac{k_{\max}}{k_{\min}}\right) - \frac{4\left(k_{\max}-k_{\min}\right)}{3E} + \frac{k_{\max}^2 - k_{\min}^2}{2E^2}\right] \simeq 1$$

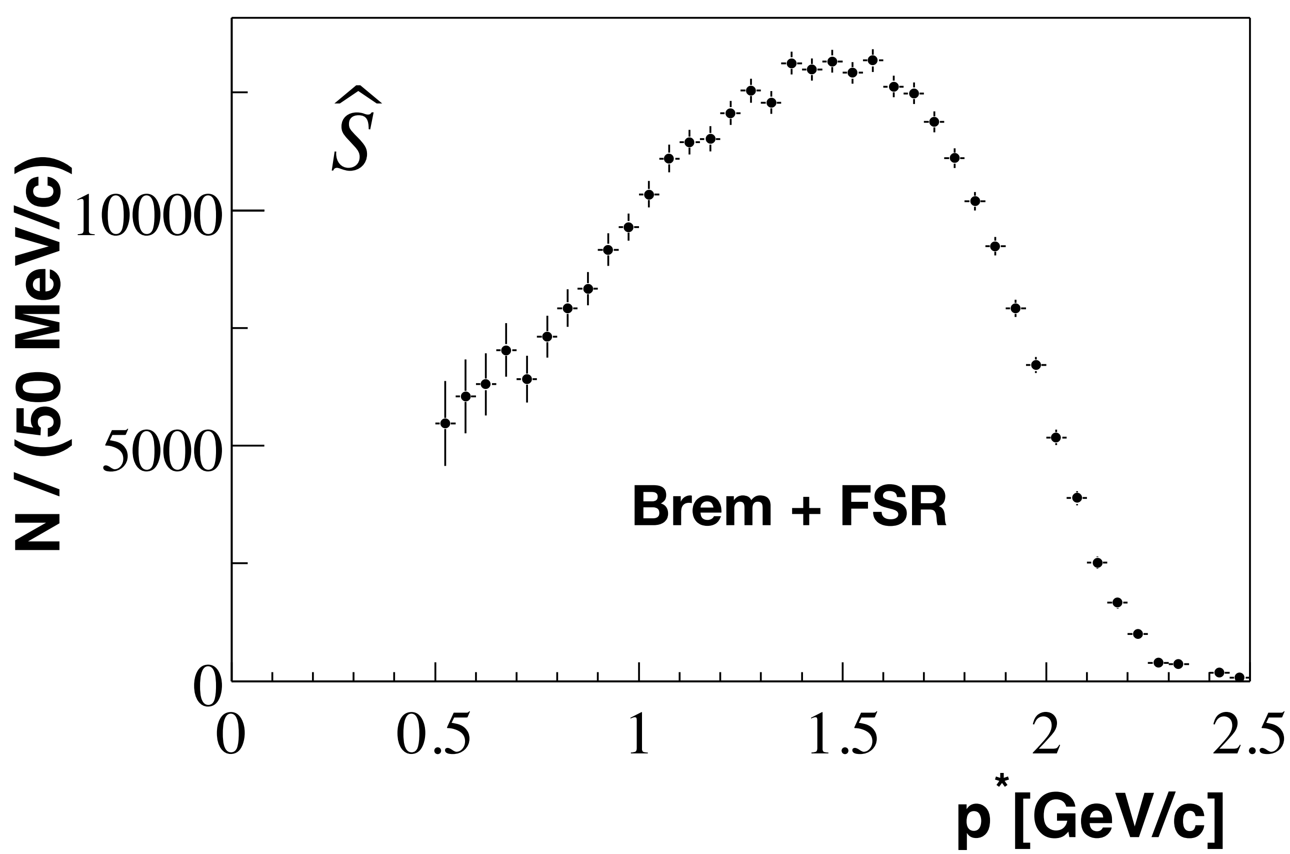
Reversing Bremsstrahlung Effects

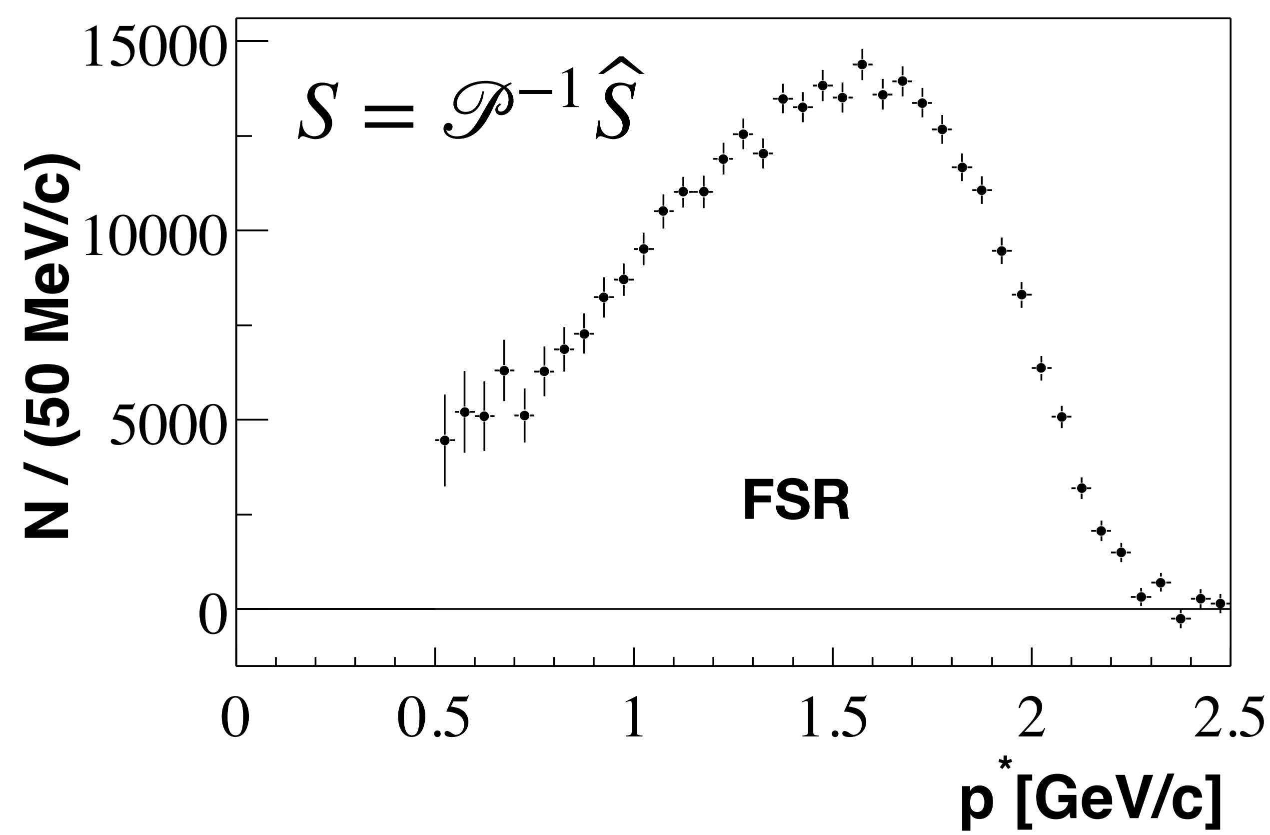
Can use detailed **MC simulations** to **separate Brem & FSR effects** from each other on a statistical basis

Use detailed **Geant4** simulation of material effects of detector

Treat Brem effects as migration problem: $\widehat{S}_i = \sum_j \mathscr{P}(\textbf{in reco bin}\, i \,|\, \textbf{in true bin}\, j)\, S_j$

Example: measured $B \to X_c \ell \bar{\nu}_\ell$ spectrum from BaBar





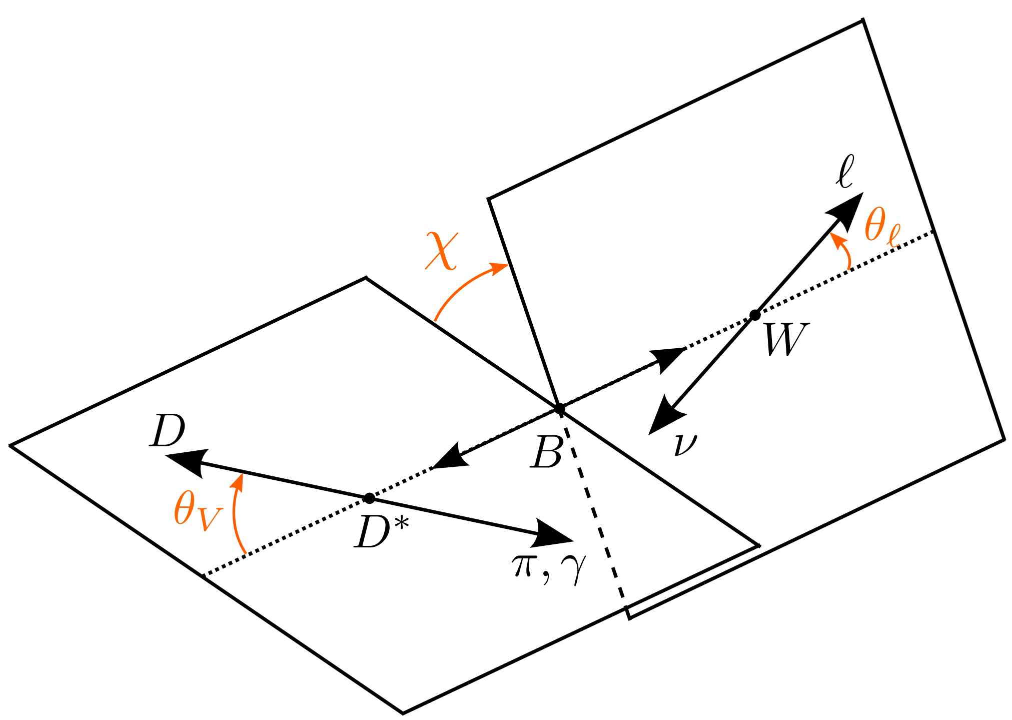
Reversing Brem + FSR Effects

To compare with theory, often also **FSR effects** need to be removed

Method very similar: use PHOTOS and MC simulations to assess migrations between **"bare"** and "**dressed"** leptons

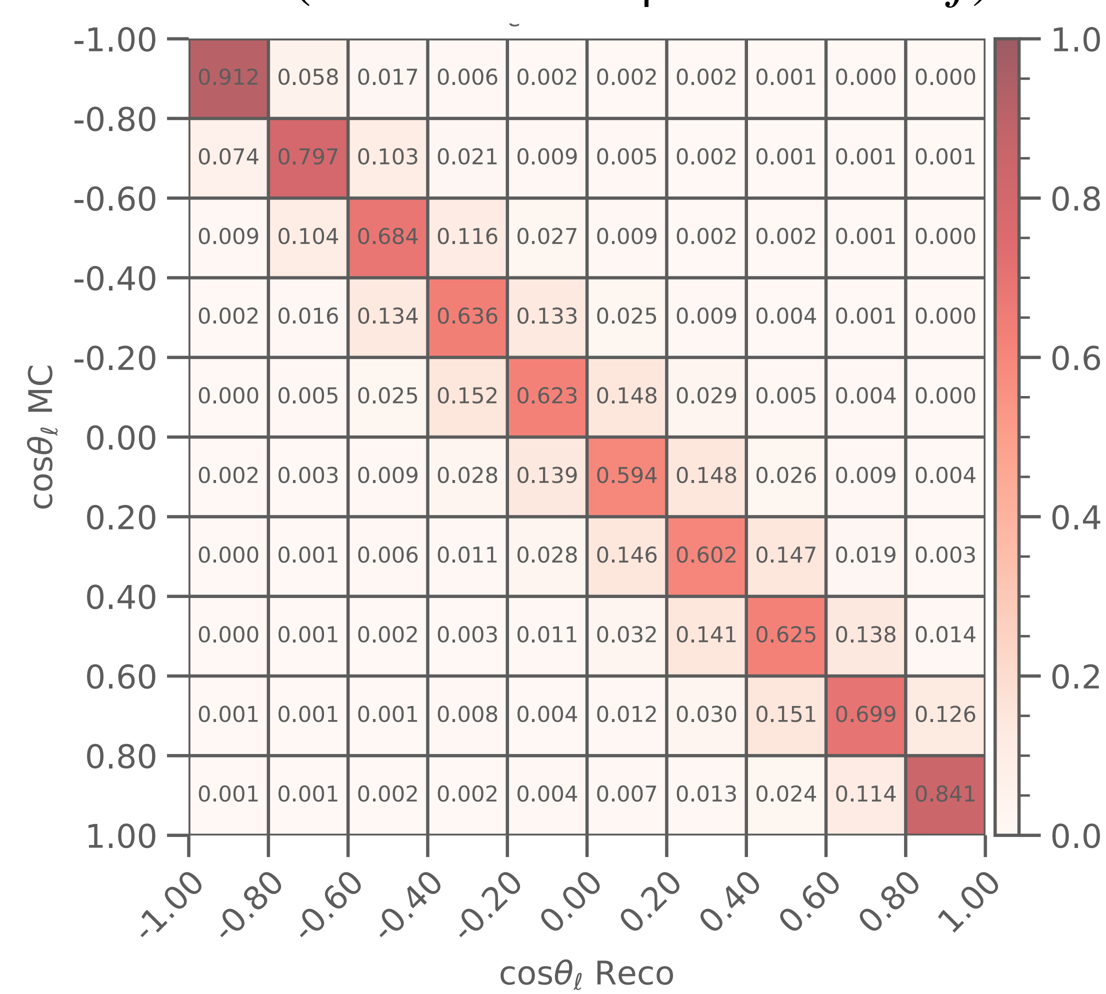
Typically correct for resolution, Bremsstrahlung, FSR effects in **one go:**

Example **decay angles**:



$\mathscr{P}($**in reco bin** $i\,|\,$**in true bin** $j)$

No FSR, Brem, perfect detector



Reconstructed Object

Uncertainties of FSR Effects in measurements

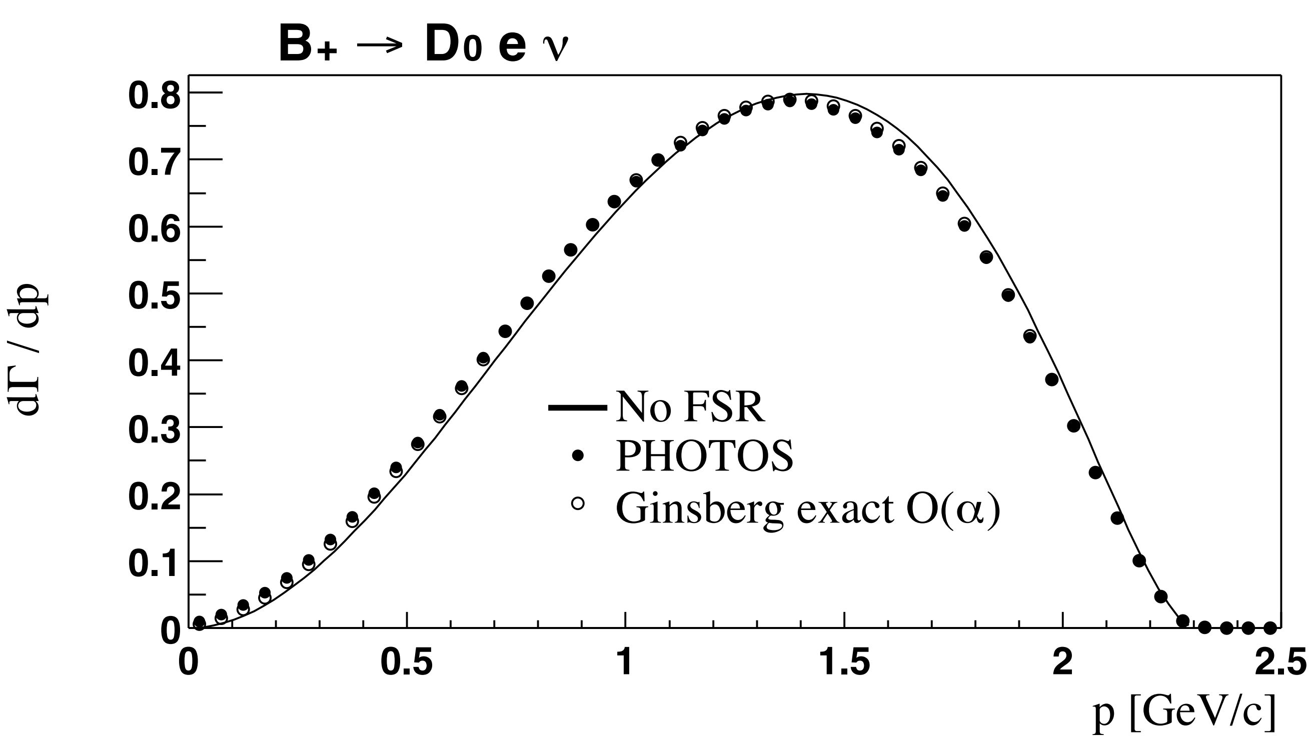
No **consensus** amongst experimentalists how such should be evaluated

Approaches:

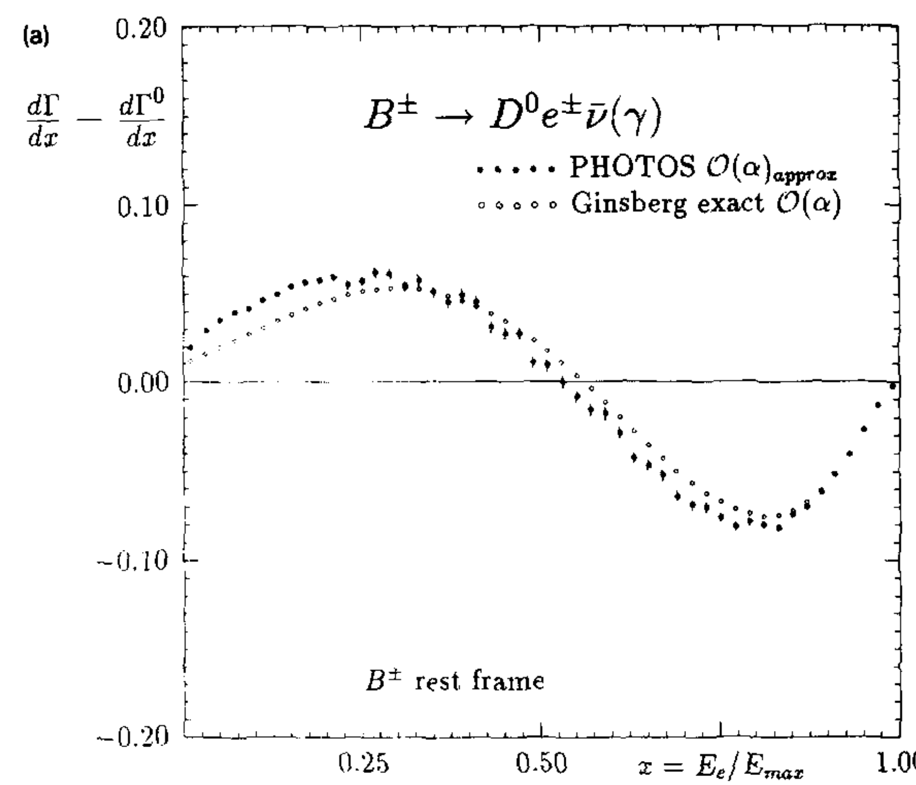
> on dedicated control samples. The uncertainty arising from radiative corrections is studied by comparing the results using PHOTOS [30] to simulate final state radiation (default case) with those obtained with PHOTOS turned off. We take 25 % of the difference as an error. The un-

* **Ignore**
* **Produce samples w/o FSR (PHOTOS), assign** X% difference to nominal result as error **(X = 20-30%)**
* **Compare to Ginsberg calculation;** derive uncertainty from difference

[https://inspirehep.net/literature/50770]

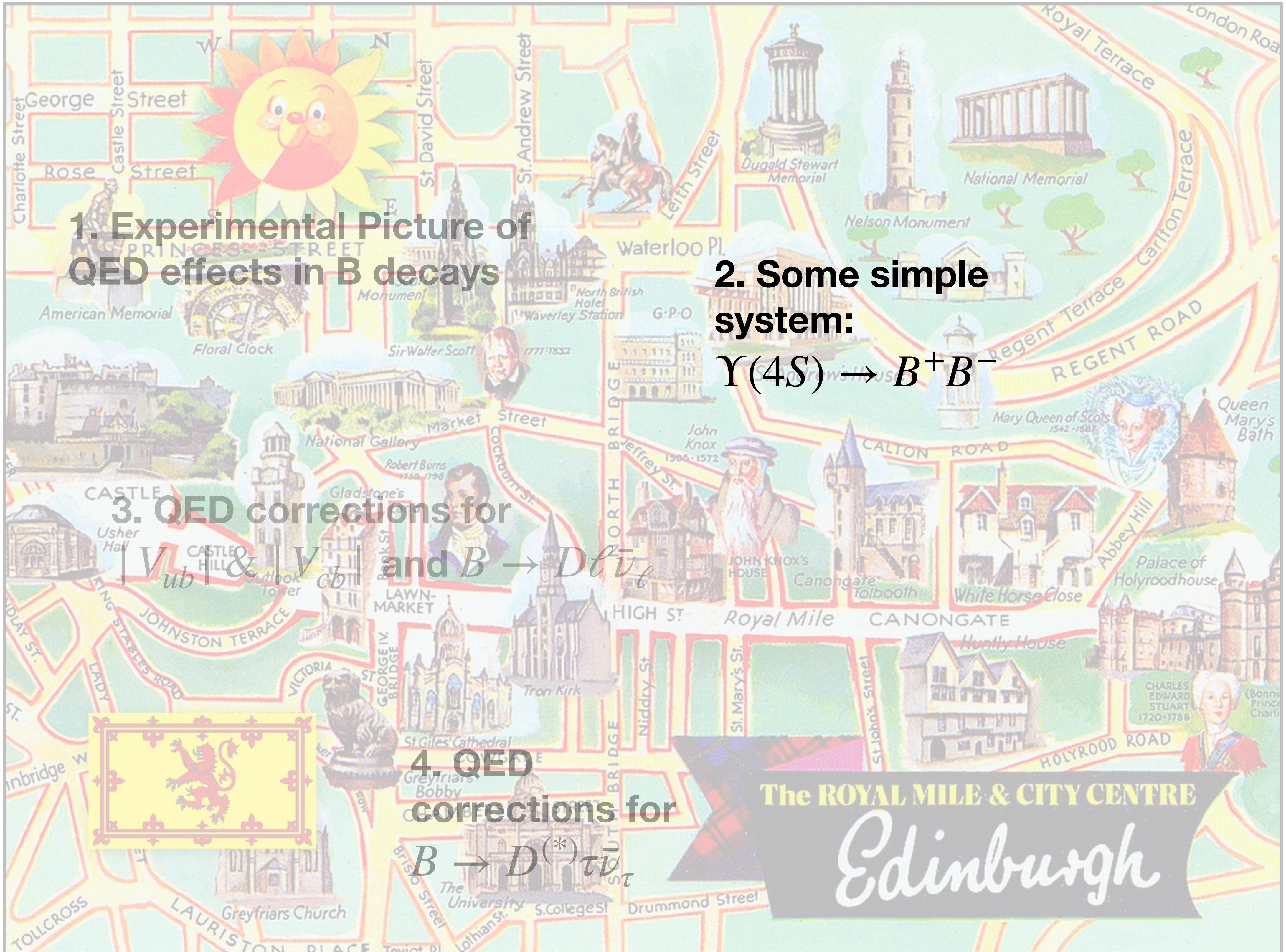


BaBar El Moment meas.



E.Richter-Wąs, Physics Letters B 303 (1993) 163-169

Talk Outline



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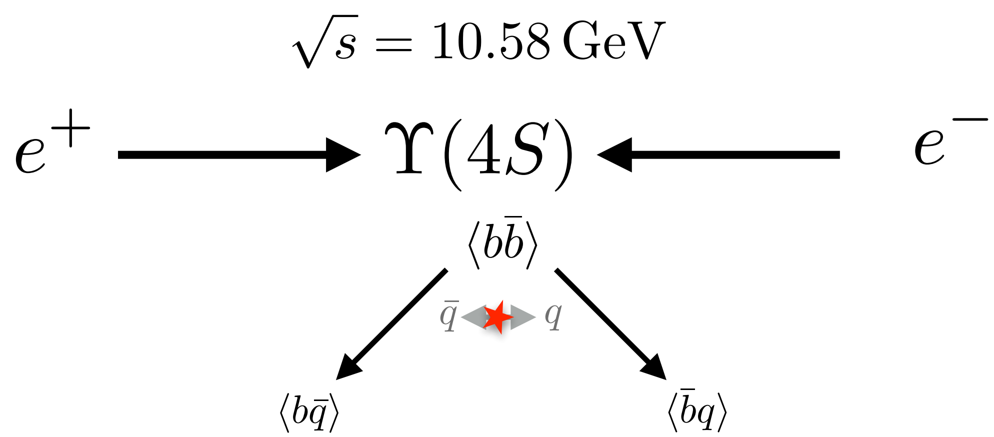
Long-standing problem…



Important observable to measure **branching fractions:**

$$R^{\pm 0} = \frac{\Gamma(\Upsilon(4S) \to B^+B^-)}{\Gamma(\Upsilon(4S) \to B^0\overline{B}^0)}\,,$$

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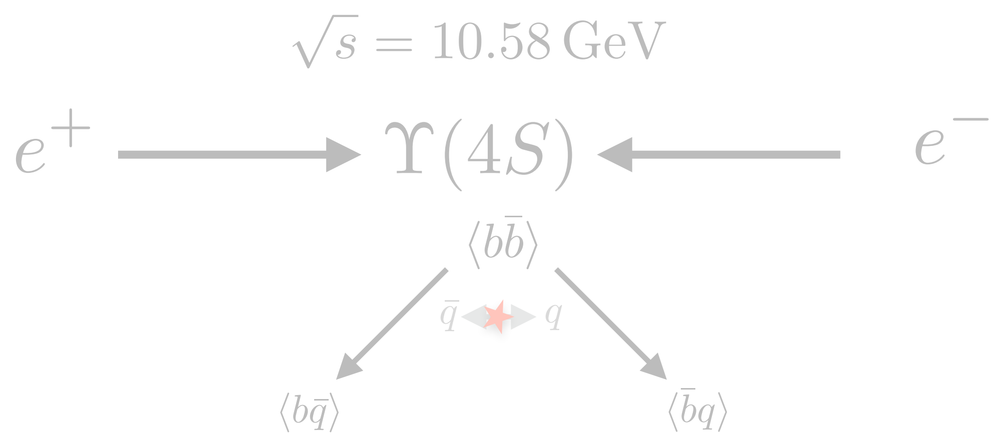

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Restricted phase-space results in small velocities, enhancing EM effects

Expect a **phase-space** & naive **Coulomb enhancement** of

$$R_0^{\pm 0} = \frac{p_\pm^3}{p_0^3} \frac{2\pi\lambda(1+\lambda^2)}{1-\exp(-2\pi\lambda)},$$

$$\lambda = \alpha/(2v_\pm)$$

Velocity $v_\pm = (1 - 4m_{B^\pm}^2/m_\Upsilon)^2$

Decay Mode	$\frac{p_\pm^3}{p_0^3}$	$\frac{2\pi\lambda(1+\lambda^2)}{1-\exp(-2\pi\lambda)}$	$R_0^{\pm 0}$
$\Upsilon(4S) \to B\overline{B}$	1.048	1.20	1.26

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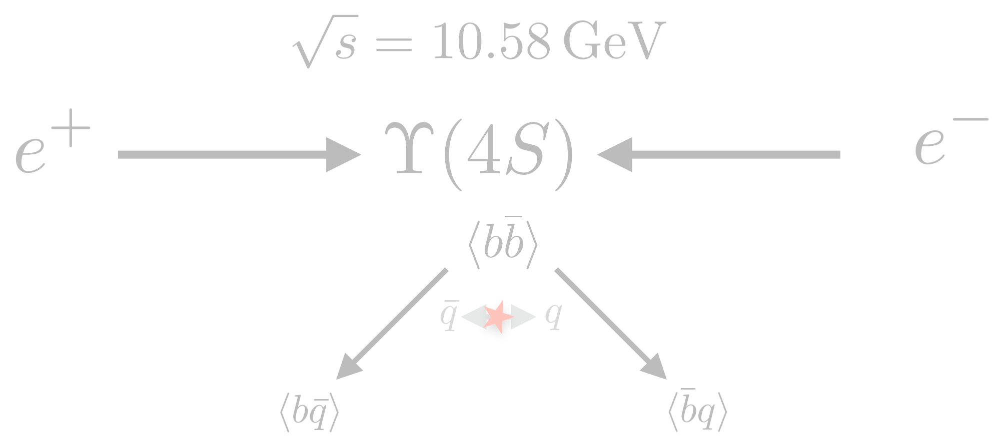

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$\Upsilon(4S) \to B\overline{B}$	1.048	1.20	1.26

Experimentally: $R^{\pm 0} = 1.062 \pm 0.021$

FB, M. Jung, G. Landsberg, Z. Ligeti, to appear

QED effects **suppressed**?

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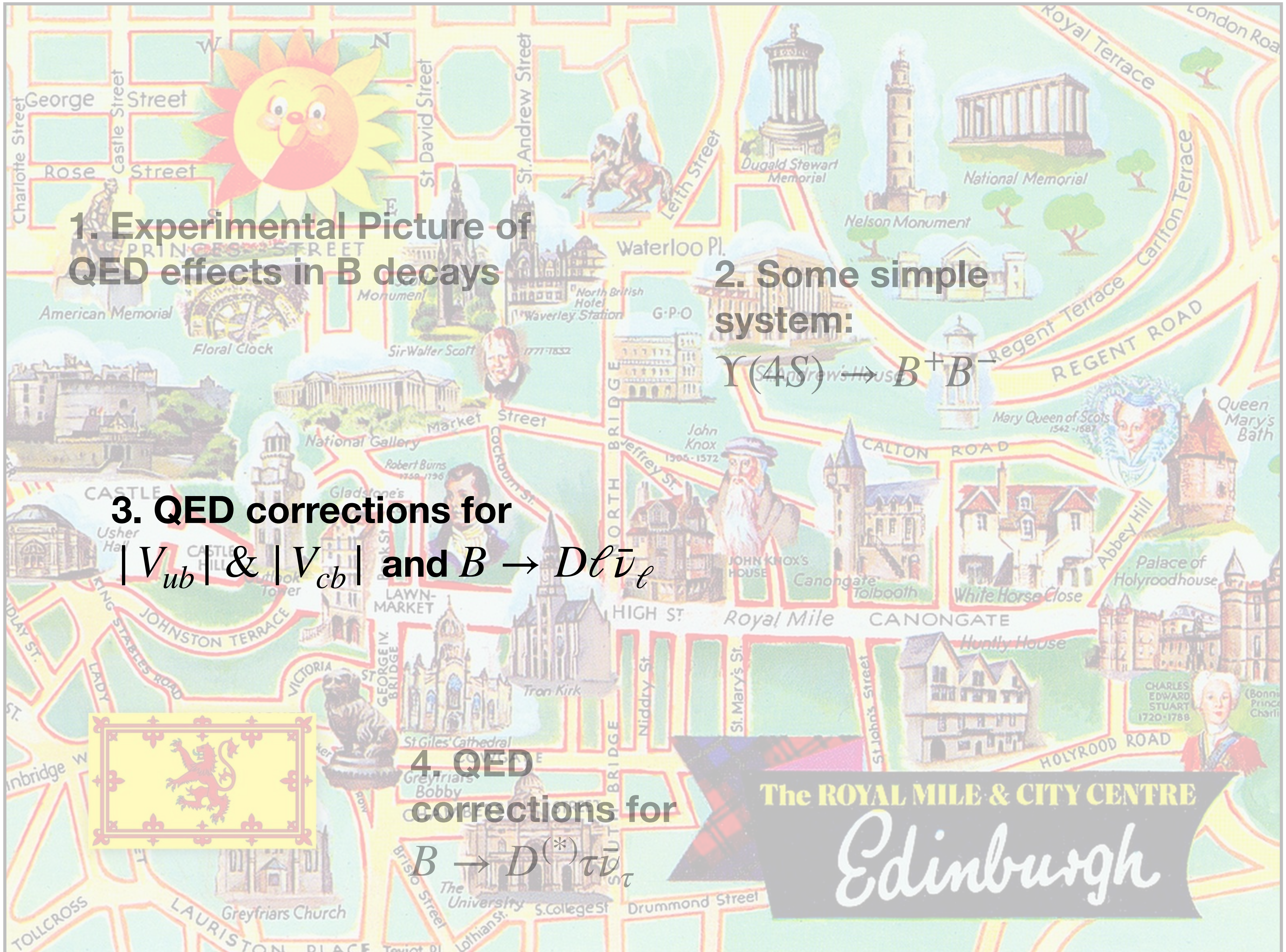

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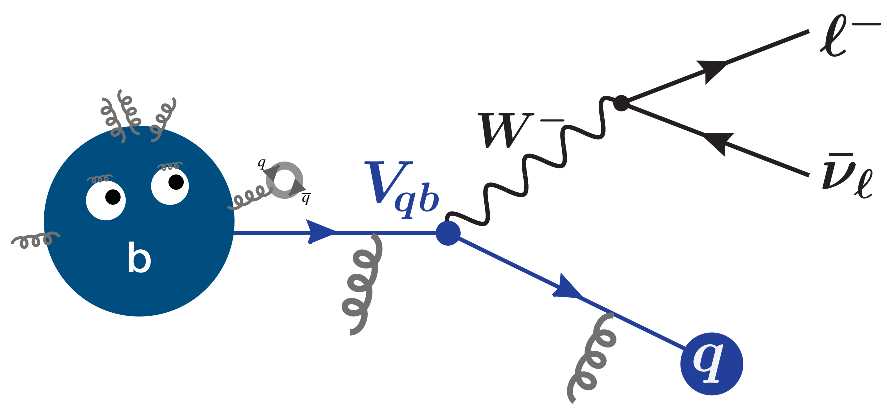
$\bar{\nu}_\ell$

s for

ν_τ

Corrections on $|V_{ub}|$ & $|V_{cb}|$

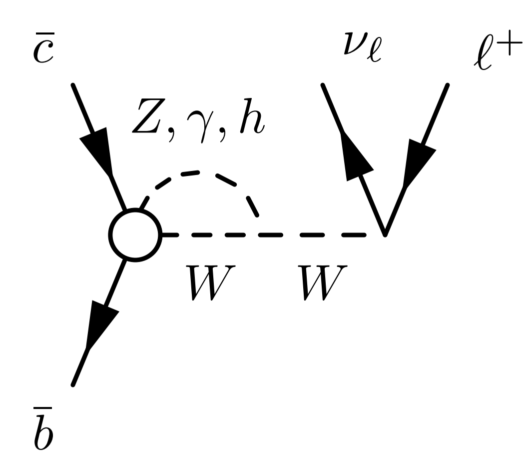


Measured
Branching Fraction

$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(\bar{B} \to X_q\, \ell\, \bar{\nu}_\ell)}{\tau\, \Gamma(\bar{B} \to X_q\, \ell\, \bar{\nu}_\ell)}}$$

Prediction from
Theory but often also constrained
from **measured differential distributions**

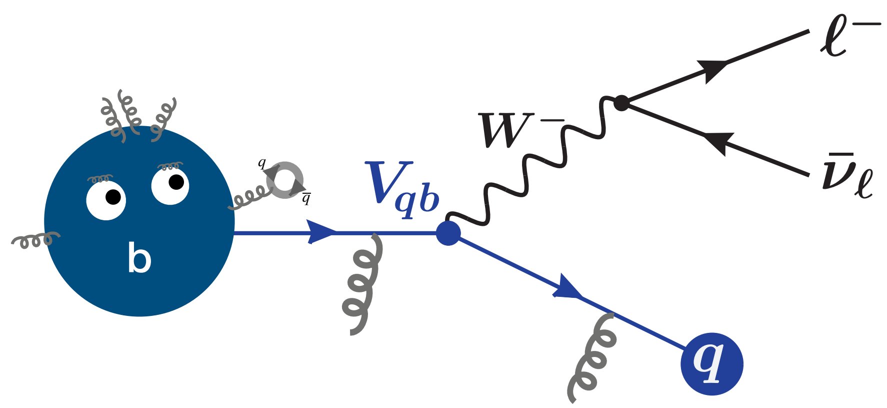
Correct for short-distance
EW effects (Sirlin)



$$\eta_{EW}^2 = 1.014$$

Sirlin, A. : Large m(W), m(Z) Behavior of the O(alpha) Corrections to Semileptonic Processes Mediated by W. In: *Nucl. Phys.* B196 (1982), S. 83. http://dx.doi.org/10.1016/0550-3213(82)90303-0. – DOI 10.1016/0550–3213(82)90303–0

Corrections on $|V_{ub}|$ & $|V_{cb}|$



Measured
Branching Fraction

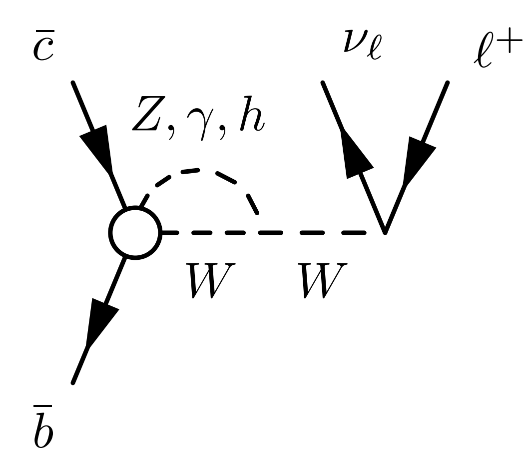
$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(\bar{B} \to X_q\, \ell\, \bar{\nu}_\ell)}{\tau\, \Gamma(\bar{B} \to X_q\, \ell\, \bar{\nu}_\ell)}}$$

Prediction from
Theory but often also constrained
from **measured differential distributions**

Measurement used to constrain theory corrected for **QED effects**

Also don't correct for Coulomb enhancement

Correct for short-distance EW effects (Sirlin)



$$\eta_{EW}^2 = 1.014$$

Sirlin, A.: Large m(W), m(Z) Behavior of the O(alpha) Corrections to Semileptonic Processes Mediated by W. In: *Nucl. Phys.* B196 (1982), S. 83. http://dx.doi.org/10.1016/0550-3213(82)90303-0. – DOI 10.1016/0550–3213(82)90303–0

RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 41, NUMBER 5 1 MARCH 1990

Radiative corrections and semileptonic B decays

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(Received 8 December 1989)

A prescription for approximating electroweak radiative corrections to weak decays is given. The method is illustrated for $\tau \rightarrow e\nu\bar{\nu}$ and a simplified (structureless) model of $B \rightarrow Me\bar{\nu}$, $M = D$ or π, where the complete $O(\alpha)$ corrections are known. Our procedure is shown to provide a proper description of radiation damping near the electron's end-point energy and a reasonable estimate of radiative corrections for much of the spectrum as well as the integrated rate. As a practical application, it is applied to the semileptonic decays $B \rightarrow Xe\bar{\nu}$, where an exact $O(\alpha)$ treatment of radiative corrections is very difficult, but an estimate of their effect is important for the extraction of V_{ub} and leptonic branching ratios. We also discuss an 18% enhancement of $\Upsilon(4S) \rightarrow B^+B^-$ relative to $B^0\bar{B}^0$ due to large Coulomb corrections near threshold.

As our next example, we consider the decays $B \rightarrow Me\bar{\nu}$, where M is either a π or D meson. Since this exercise is meant only to test our prescription, we study a somewhat

tions is to multiply (13) by the correction factors in (3) (with $m_Y = m_B$) and (5). In addition, for $\eta \simeq 1$ our condition on c gives $c \simeq \frac{2}{3}$, so we have[17]

$$\frac{d\Gamma(B \rightarrow Me\bar{\nu})}{dx} = \frac{G_\mu^2 m_B^5}{32\pi^3} |V_{ib}|^2 |f_+^M|^2 \eta^5 \frac{x^2(1-x)^2}{1-\eta x} \left[1 + \frac{2\alpha}{\pi} \ln \frac{m_Z}{m_B}\right] \left[\frac{1-x}{2x/3}\right]^{(2\alpha/\pi)[\ln(m_B x/m_e) - 1]} \qquad (14)$$

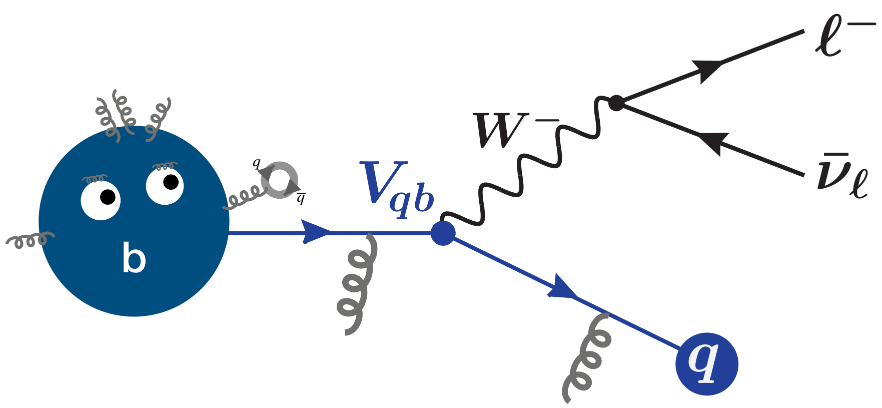
for charged B decays, while for neutral B decays, an additional $1 + \pi\alpha$ correction factor should be appended.[11] For comparison, we can use a complete $O(\alpha)$ calculation of radiative corrections for this simple model by Ginsberg.[15] Such a comparison is illustrated in Fig. 4 where Ginsberg's result has been (arbitrarily) normalized to agree with (14) at $x = 0.6$. One formula does quite well in correctly describing the high-energy electron spectrum shape. Because of strong-interaction uncertainties we do not worry about the low-x regime.

Having used two examples to illustrate and test our scheme, we now tackle a practical problem, radiative corrections to inclusive semileptonic decays $B \rightarrow X_c e\bar{\nu}$ and $B \rightarrow X_u e\bar{\nu}$, where X_q represents an inclusive hadron state containing q. A precise knowledge of the electron spectrum shape, particularly near the end point, is important for extracting V_{ub}/V_{cb} and measuring semileptonic branching ratios. In our approach, the radiative corrections are approximated by the same correction factors as

$$\left(1 + \frac{2\alpha}{\pi} \ln[\frac{m_Z}{m_b}]\right)(1 + \alpha\pi) = 1.0375 \quad \rightarrow$$

Would lead to a reduction of $|V_{cb}|$ of ~1.1% from B^0 decays, but does not correspond to **a fully consistent treatment at $\mathcal{O}(\alpha)$**

Corrections on $|V_{ub}|$ & $|V_{cb}|$



Measured
Branching Fraction

$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(\bar{B} \to X_q \, \ell \, \bar{\nu}_\ell)}{\tau \, \Gamma(\bar{B} \to X_q \, \ell \, \bar{\nu}_\ell)}}$$

Prediction from
Theory but often also constrained
from **measured differential distributions**

Measurement used to constrain theory
corrected for **QED effects**

Also don't correct for Coulomb enhancement

So bit of a "mess", although at least we are throughout consistent of course

- Theory usually assumes QED does not exist
- Measurements correct for FSR using PHOTOS; unfold into observables w/o QED effects

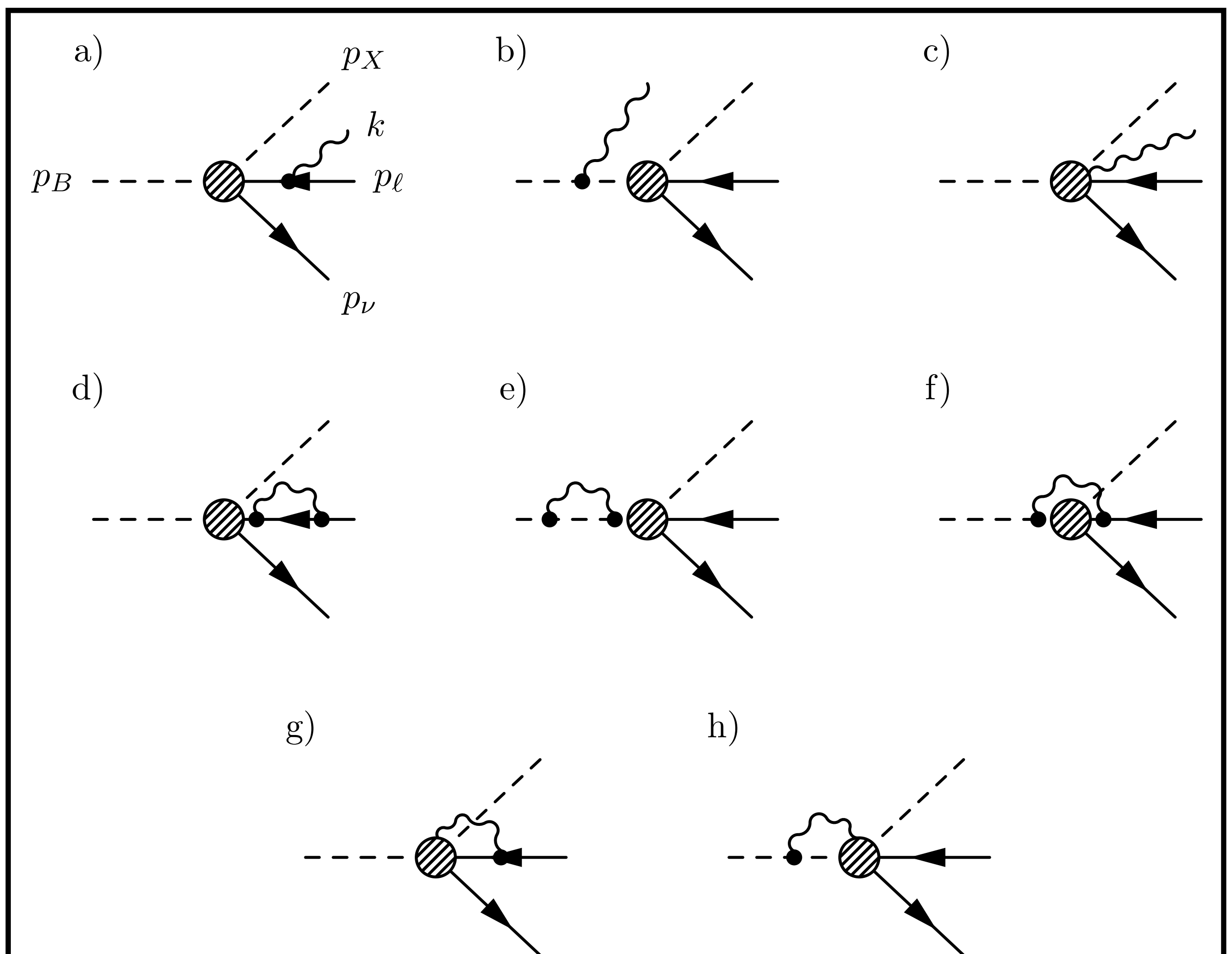
With current precision a priori ok; but unclear if with future datasets of O(50/ab) this is still a good choice

Studies with scalar QED

FB, M. Schönherr
arXiv:1010.5997 [hep-ph]

Used scalar QED to study semileptonic $B \to P \ell \bar{\nu}_\ell$ decays

$$
\begin{aligned}
\mathcal{L}_{\text{int,QED}} \quad = & \quad - eQ_\ell \bar{\psi}_\ell \gamma^\mu \psi_\ell A_\mu - ieQ_\phi A_\mu (\phi^+ \partial^\mu \phi^- - \phi^- \partial^\mu \phi^+) + e^2 Q_\phi^2 A_\mu A^\mu \phi^+ \phi^- \\
& + ie\sqrt{2} G_{\text{F}} V_{xy} \text{f}_\pm (Q_B \pm Q_X) \phi_B \phi_X A_\mu \, \bar{\psi}_\nu P_R \gamma^\mu \psi_\ell \quad + \quad \text{h.c.} \quad ,
\end{aligned}
$$



- Several **ad-hoc assumptions**, e.g. incorporate FF dynamics ad-hoc for off-shell states
- Compare to **PHOTOS** and **PHOTONS++** YFS resummation improved prediction from Sherpa

We were young and did not know better…

The “backdrop”

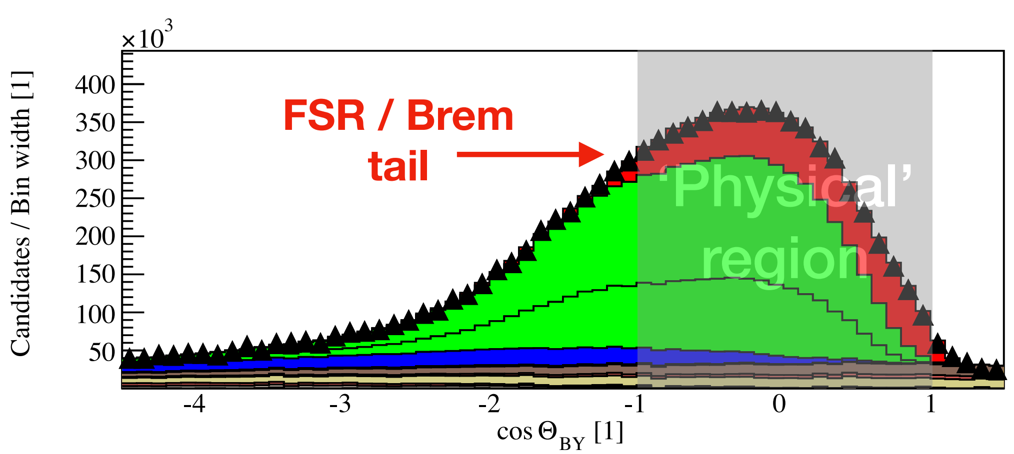
The “backdrop”

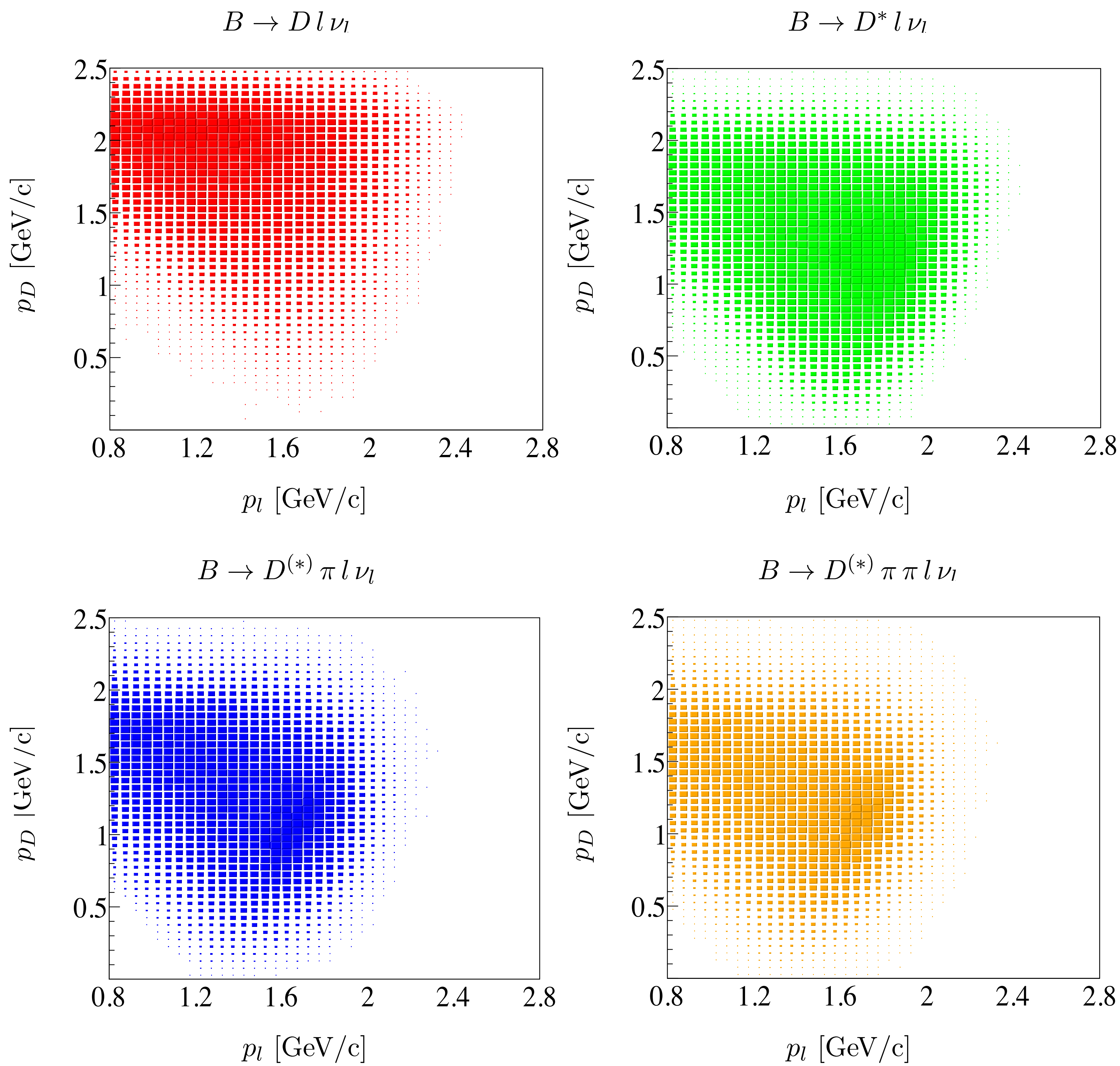
The “backdrop”

3D Fit of $B \to DX\ell\nu_\ell$
in lepton momentum,
D momentum,
cosBY

$$\cos\theta_{BY} = \frac{2E_B\,E_{Dl} - m_B^2 - m_{Dl}^2}{2\,|\vec{p}_B|\,|\vec{p}_{Dl}|}$$

QED effects change shape of all of these variables





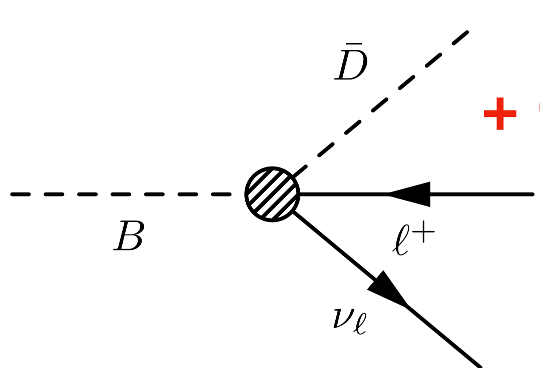
BaBar Global Fit
[arXiv:0809.0828]
Phys.Rev.D79:012002,2009

	Electron sample						Muon sample					
item	ρ^2_D	$\rho^2_{D^*}$	$\mathcal{B}(D\ell\overline{\nu})$	$\mathcal{B}(D^*\ell\overline{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$	ρ^2_D	$\rho^2_{D^*}$	$\mathcal{B}(D\ell\overline{\nu})$	$\mathcal{B}(D^*\ell\overline{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$
R'_1	0.44	2.74	0.71	−0.38	0.60	0.71	0.50	2.67	0.74	−0.40	0.63	0.70
R'_2	−0.40	1.02	−0.18	0.30	−0.32	0.49	−0.45	0.96	−0.19	0.30	−0.33	0.48
D^{**} slope	−1.42	−2.52	−0.07	−0.09	−0.82	−0.87	−1.42	−2.58	−0.10	−0.10	−0.77	−0.92
D^{**} FF approximation	−0.87	0.33	−0.12	0.19	−0.54	0.20	−0.99	0.59	−0.12	0.21	−0.59	0.30
$\mathcal{B}(B^- \to D^{(*)}\pi\ell\overline{\nu})$	0.28	−0.27	−0.22	−0.80	0.04	−0.49	0.59	−0.32	−0.13	−0.86	0.24	−0.54
$f_{D_2^*/D_1}$	−0.39	0.16	−0.38	0.16	−0.41	0.13	−0.50	0.17	−0.41	0.18	−0.47	0.15
$f_{D_0^* D\pi/D_1 D_2^*}$	−2.30	1.12	−1.53	0.97	−2.07	0.85	−3.13	1.23	−1.53	1.02	−2.41	0.93
$f_{D_1' D^*\pi/D_1 D_2^*}$	1.82	−1.14	1.30	−0.65	1.65	−0.70	2.44	−1.15	1.35	−0.72	1.91	−0.75
$f_{D\pi/D_0^*}$	−0.88	−1.28	0.36	0.17	−0.31	−0.34	−0.83	−1.23	0.31	0.18	−0.27	−0.33
$f_{D^*\pi/D_1'}$	−0.21	−0.05	−0.13	0.21	−0.18	0.09	−0.30	−0.04	−0.15	0.23	−0.23	0.10
NR D^*/D ratio	0.58	−0.16	0.11	−0.09	0.38	−0.04	0.66	−0.16	0.11	−0.09	0.40	−0.03
$\mathcal{B}(B^- \to D^{(*)}\pi\pi\ell\overline{\nu})$	1.19	−1.97	0.25	−1.28	0.78	−1.28	1.98	−1.71	0.40	−1.20	1.20	−1.18
X^*/X and Y^*/Y ratio	0.61	−1.15	0.09	−0.27	0.39	−0.52	0.74	−1.02	0.08	−0.24	0.42	−0.47
X/Y and X^*/Y^* ratio	0.76	−0.83	0.21	−0.65	0.52	−0.60	1.09	−0.76	0.25	−0.63	0.68	−0.57
$D_1 \to D\pi\pi$	2.22	−1.54	0.74	−1.08	1.63	−1.05	2.74	−1.48	0.76	−1.06	1.81	−1.03
$f_{D_2^*}$	−0.14	−0.01	−0.10	0.07	−0.12	0.03	−0.16	−0.01	−0.10	0.07	−0.13	0.03
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.73	−0.01	0.43	−0.34	0.62	−0.17	0.80	−0.00	0.41	−0.33	0.61	−0.17
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.69	0.02	−0.21	−1.63	0.29	−0.80	0.92	0.12	−0.27	−1.68	0.35	−0.80
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	−1.46	−0.42	−2.17	0.30	−1.89	0.01	−1.43	−0.42	−2.10	0.28	−1.77	−0.01
τ_{B^-}/τ_{B^0}	0.26	0.16	0.63	0.27	0.46	0.19	0.22	0.16	0.58	0.28	0.41	0.19
f_{+-}/f_{00}	0.88	0.43	0.66	−0.53	0.82	−0.12	0.91	0.48	0.57	−0.52	0.75	−0.10
Number of $B\overline{B}$ events	0.00	−0.00	−1.11	−1.11	−0.55	−0.55	0.00	−0.00	−1.11	−1.11	−0.55	−0.55
Off-peak Luminosity	0.05	0.01	−0.02	−0.00	0.02	0.00	0.07	0.00	−0.02	−0.00	0.02	−0.00
B momentum distrib.	−0.96	0.63	1.29	−0.54	−1.15	0.48	1.30	−0.10	1.27	−0.64	1.31	−0.35
Lepton PID eff	0.52	0.16	1.21	0.82	0.90	0.46	3.30	0.06	5.11	5.83	1.99	2.90
Lepton mis-ID	0.03	0.01	−0.01	−0.01	0.01	−0.00	2.65	0.70	−0.59	−0.50	1.06	−0.01
Kaon PID	0.07	0.80	0.28	0.23	0.18	0.38	1.02	0.71	0.35	0.29	0.70	0.39
Tracking eff	−1.02	−0.43	−3.35	−2.00	−2.25	−1.15	−0.63	−0.28	−3.37	−2.09	−2.02	−1.14
Radiative corrections	−3.13	−1.04	−2.87	−0.74	−3.02	−0.71	−0.76	−0.61	−0.82	−0.25	−0.79	−0.33
Bremsstrahlung	0.07	0.00	−0.13	−0.28	−0.04	−0.14	0.00	0.00	0.00	0.00	0.00	0.00
Vertexing	0.83	−0.64	0.63	0.60	0.78	0.09	1.79	−0.76	0.97	0.54	1.41	0.01
Background total	1.39	1.12	0.64	0.34	1.07	0.51	1.58	1.09	0.67	0.38	1.16	0.49
Total	**6.25**	**5.66**	**6.01**	**4.03**	**5.99**	**3.20**	**8.12**	**5.47**	**7.35**	**7.07**	**6.06**	**4.23**

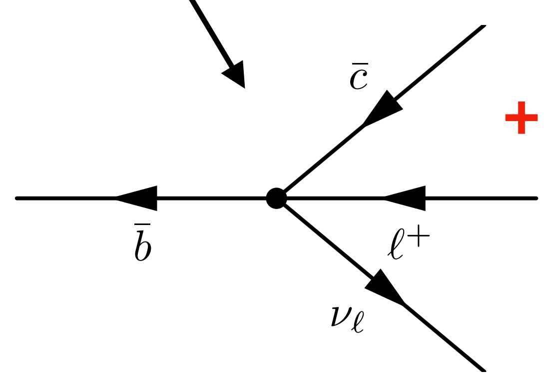
Memory lane:

- I was a bit annoyed, that a QED effect should be one of the largest systematics.
  - “Can’t we just calculate this somehow? Why 20%? Why not 10% or 30%?”
- Teamed up with Marek Schönherr to develop a “NLO” model & benchmark against PHOTOS
- Heavily influenced what was done for Kaons by **Troy Andre**
  - arXiv:hep-ph/0406006, AnnalsPhys.322:2518-2544,2007
- It builds on several assumptions: (some of them likely not entirely great or even justified for B mesons nor fully rigorous!)
  - First, we assumed we can split long-distance and short-distance physics

$$\mathcal{M}_0^1 \;=\; \mathcal{M}_{0,\mathrm{ld}}^1(\Lambda) + \mathcal{M}_{0,\mathrm{sd}}^1(\Lambda)\,.$$



+ QED



+ EW/QED

Matching on scale , $\Lambda \sim m_D$; used to regularize any UV divergencies in LD part

Short-Distance

- Short-distance parts: Sirlin

LARGE m_W, m_Z BEHAVIOUR OF THE O(α) CORRECTIONS TO SEMILEPTONIC PROCESSES MEDIATED BY W

A. SIRLIN[1]

Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA

Received 17 August 1981

Using the current algebra formulation of radiative corrections and working in the framework of the $SU(2)_L \times U(1) \times SU(3)_c$ theory, we derive a theorem that governs the large m_W, m_Z behaviour of the O(α) corrections to general semileptonic processes mediated by W. The leading asymptotic dependence is logarithmic with a universal coefficient not affected by the strong interactions. As a byproduct, we obtain the leading asymptotic effect induced perturbatively by the strong interactions, which is of O(ln ln (m_W/Λ)).

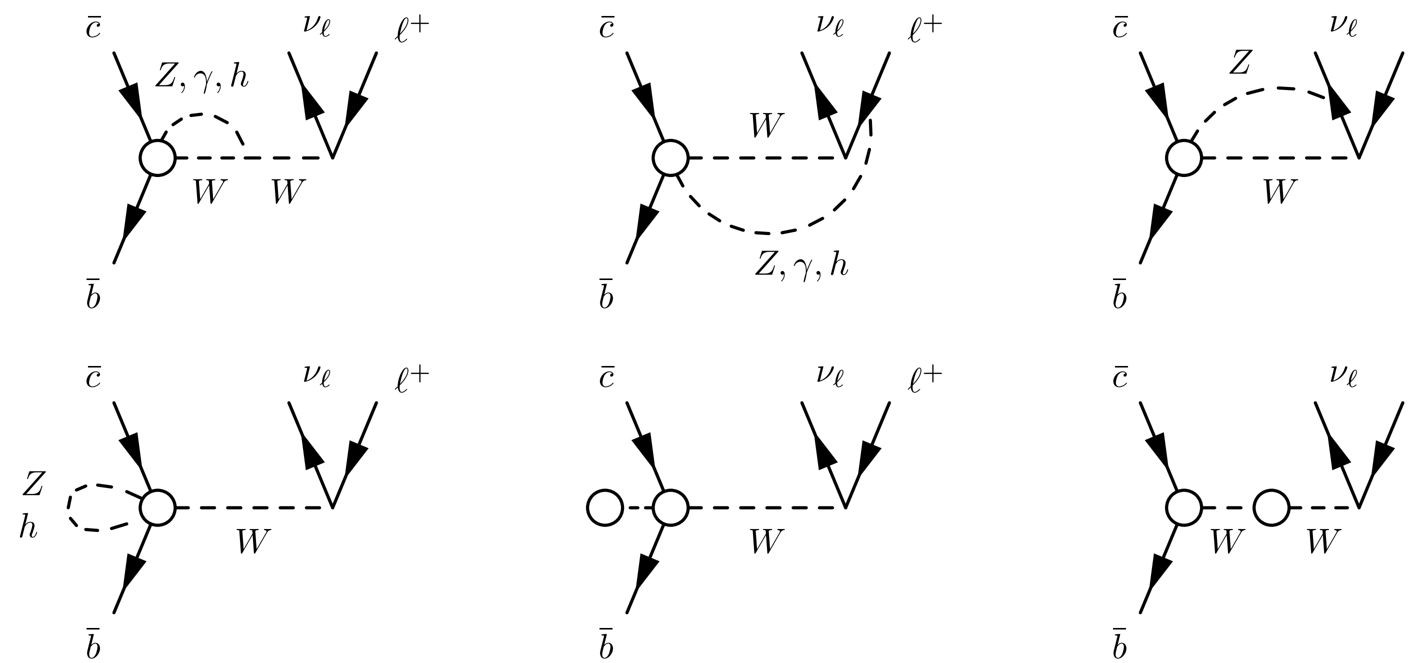
The aim of this paper is to analyze the large m_W, m_Z behaviour of the O(α) corrections to semileptonic processes mediated by the W meson, in the framework of the $SU(2)_L \times U(1) \times SU(3)_c$ theory.

Our main results are summarized in the following theorem:

(a) In the simplest version of the theory in which $\cos\theta_W = m_W/m_Z$ at the tree level, the leading asymptotic behaviour in m_Z of the O(α) corrections to an arbitrary semileptonic process mediated by W is given by

$$\boxed{\frac{M}{M^0} = 1 + \frac{3\alpha}{4\pi}(1+2\bar{Q})\ln\frac{m_Z}{\mu} + \cdots,} \qquad (1)$$

where M is the amplitude up to terms of O(α), M^0 is the zeroth-order amplitude but expressed in terms of the conventionally defined* muon decay coupling constant G_μ, μ is an unspecified mass scale characteristic of the process, and $\bar{Q}$ is the average charge of the quarks in a $SU(2)_L$ isodoublet. Henceforth . . . indicates non-leading contributions as m_W^2 or $m_Z^2 \to \infty$. For the usual charge assignments, $\bar{Q} = \frac{1}{6}$. It is also



$$\boxed{\mathcal{M}^1_{0,\mathrm{sd}} = \frac{\alpha_{\mathrm{em}}}{\pi} \ln\frac{m_Z}{\Lambda}\,\mathcal{M}^0_0 + \ldots\,.}$$

$$\eta^2_{EW} = 1.014$$

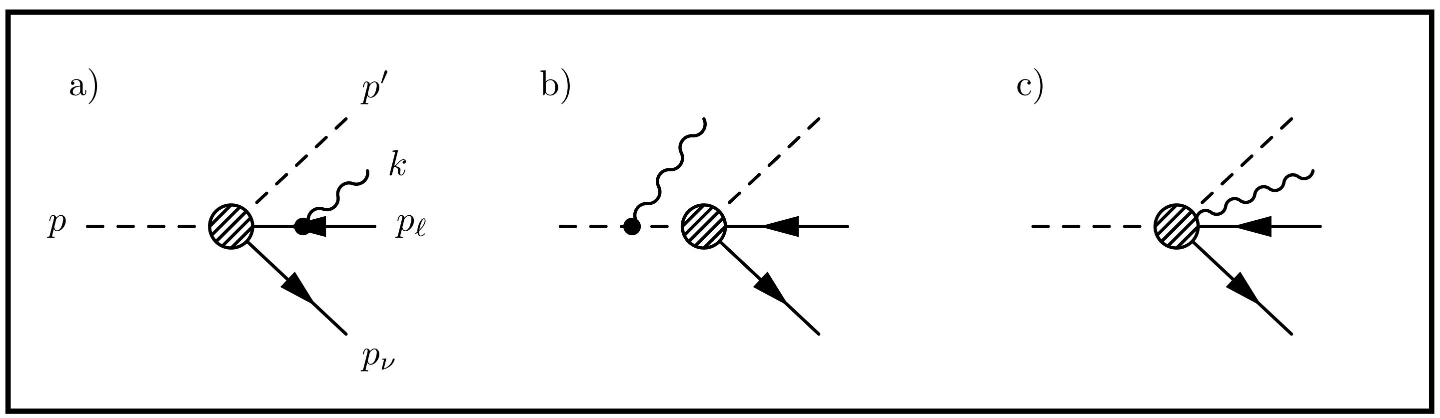
[115] Sirlin, A. : Current Algebra Formulation of Radiative Corrections in Gauge Theories and the Universality of the Weak Interactions. In: *Rev. Mod. Phys.* 50 (1978), S. 573. http://dx.doi.org/10.1103/RevModPhys.50.573. – DOI 10.1103/RevModPhys.50.573

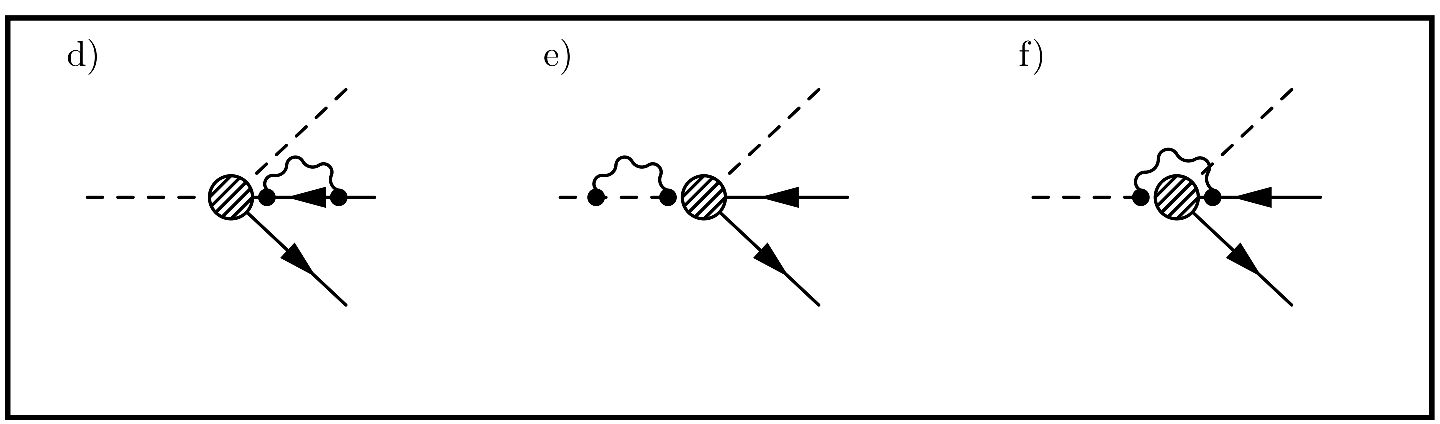
[116] Sirlin, A. : Large m(W), m(Z) Behavior of the O(alpha) Corrections to Semileptonic Processes Mediated by W. In: *Nucl. Phys.* B196 (1982), S. 83. http://dx.doi.org/10.1016/0550-3213(82)90303-0. – DOI 10.1016/0550–3213(82)90303–0

Long-Distance

- Long-distance part: Scalar QED with some ad-hoc QCD evolution

$$\mathcal{L}_{\mathrm{W}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{\mathrm{cb}} \left[(f_+ + f_-)\, \phi' \, \partial^\mu \phi + (f_+ - f_-)\, \phi \, \partial^\mu \phi' \right] \bar{\psi}_\nu \, P_{\mathrm{R}} \, \gamma_\mu \, \psi_\ell + \mathrm{h.c.}\,,$$





→ **Will create off-shell hadronic matrix elements**

Long-Distance

- Long-distance part: Scalar QED with some ad-hoc QCD evolution

$$\mathcal{L}_{\rm W} \;=\; \frac{G_{\rm F}}{\sqrt{2}} V_{\rm cb} \left[(f_+ + f_-)\,\phi'\,\partial^\mu \phi + (f_+ - f_-)\,\phi\,\partial^\mu \phi' \right] \bar{\psi}_\nu\, P_{\rm R}\, \gamma_\mu\, \psi_\ell + {\rm h.c.}\,,$$

- Assumed that the off-shell hadronic current can be modeled using the on-shell current; in particular that the form factors depend on **t = q²** only

$$\langle D(p') | \widehat{V}_\mu - \widehat{A}_\mu | B(p-k) \rangle \;=\; \widehat{f}_+(t', r', s')\,(p-k+p')_\mu + \widehat{f}_-(t', r', s')\,(p-k-p')_\mu\,,$$

$t' = (p - p' - k)^2$

r', s': other lorentz scalars

$$\downarrow$$

$$H'_\mu(t') \;=\; \langle D(p') | \widehat{V}_\mu - \widehat{A}_\mu | B(p-k) \rangle \;=\; f_+(t')\,(p-k+p')_\mu + f_-(t')\,(p-k-p')_\mu\,,$$

More formal:

- More formal: coupling an electromagnetic current to LO decay results in

lepton leg coupling   hadronic coupling

$$\boxed{i\,e\,\frac{G_{\rm F}}{\sqrt{2}}\,V_{\rm cb}\,\bar{u}_\nu\,\gamma^\mu\,P_{\rm L}\,\left(-\frac{H_\mu}{2p_\ell\cdot k}\left(\gamma_\nu \not{k} + 2(p_\ell)_\nu\right) + V_{\mu\nu} - A_{\mu\nu}\right)\,v_l\,,}$$

hadronic current

$$H_\mu(t) = \langle D(p')|\widehat{V}_\mu - \widehat{A}_\mu|B(p)\rangle$$

with a non-local operator describing the B-ɣ and D-ɣ coupling

$$V_{\mu\nu} - A_{\mu\nu} = \int \mathrm{d}^4x\, e^{ik\cdot x}\langle D|\mathcal{T}\{h_\mu(0)\,J_\nu^{\rm em}(x)\}|B\rangle\,,$$

Ward identities

$$\boxed{\begin{aligned} k^\nu\,V_{\mu\nu} &= H_\mu\,, \\ k^\nu\,A_{\mu\nu} &= 0\,, \end{aligned}}$$

which can be expanded around first few resonant states

$$\begin{aligned} V_{\mu\nu} - A_{\mu\nu} &= \frac{\langle D(p')|\widehat{V}_\mu - \widehat{A}_\mu|B(p-k)\rangle\langle B(p-k)|J_\nu^{\rm em}|B(p)\rangle}{m_B^2 - (p-k)^2} \\ &+ \frac{\langle D(p')|\widehat{V}_\mu - \widehat{A}_\mu|B^*(p-k)\rangle\langle B^*(p-k)|J_\nu^{\rm em}|B(p)\rangle}{m_{B^*}^2 - (p-k)^2} \\ &+ \frac{\langle D(p'-k)|J_\nu^{\rm em}|D^*(p')\rangle\langle D^*(p')|\widehat{V}_\mu - \widehat{A}_\mu|B(p)\rangle}{m_{D^*}^2 - (p'-k)^2} + \ldots\,, \end{aligned}$$

See also D. Becirevic, N. Kosnik
arXiv:0910.5031 [hep-ph]

More formal:

- More formal: coupling an electromagnetic current to LO decay results in

lepton leg coupling hadronic coupling

$$\boxed{i\,e\,\frac{G_F}{\sqrt{2}}\,V_{cb}\,\bar{u}_\nu\,\gamma^\mu\,P_L\left(-\frac{H_\mu}{2p_\ell\cdot k}\left(\gamma_\nu\not{k}+2(p_\ell)_\nu\right)+V_{\mu\nu}-A_{\mu\nu}\right)v_l\,,}$$

hadronic current

$$H_\mu(t) = \langle D(p')|\widehat{V}_\mu-\widehat{A}_\mu|B(p)\rangle$$

with a non-local operator describing the B-ɣ and D-ɣ coupling

$$V_{\mu\nu}-A_{\mu\nu} = \int d^4x\,e^{ik\cdot x}\langle D|\mathcal{T}\{h_\mu(0)\,J_\nu^{\text{em}}(x)\}|B\rangle\,,$$

Ward identities

$$\boxed{\begin{aligned} k^\nu\,V_{\mu\nu} &= H_\mu\,, \\ k^\nu\,A_{\mu\nu} &= 0\,, \end{aligned}}$$

which can be expanded around first few resonant states

$$\begin{aligned} V_{\mu\nu}-A_{\mu\nu} = {} & \frac{\langle D(p')|\widehat{V}_\mu-\widehat{A}_\mu|B(p-k)\rangle\langle B(p-k)|J_\nu^{\text{em}}|B(p)\rangle}{m_B^2-(p-k)^2} \\ & +\frac{\langle D(p')|\widehat{V}_\mu-\widehat{A}_\mu|B^*(p-k)\rangle\langle B^*(p-k)|J_\nu^{\text{em}}|B(p)\rangle}{m_{B^*}^2-(p-k)^2} \\ & +\frac{\langle D(p'-k)|J_\nu^{\text{em}}|D^*(p')\rangle\langle D^*(p')|\widehat{V}_\mu-\widehat{A}_\mu|B(p)\rangle}{m_{D^*}^2-(p'-k)^2}+\ldots\,, \end{aligned}$$

$$\longrightarrow \boxed{k^\nu\,V_{\mu\nu} = H'_\mu(t')\,\frac{k\cdot(2p-k)}{2p\cdot k}+\ldots}$$

with

$$\langle B(p-k)|J_\nu^{\text{em}}|B(p)\rangle = (2p-k)_\nu\,F_{\text{em}}\,,$$

$$F_{\text{em}} \approx 1$$

in soft photon limit

More formal:

$$k^\nu \, V_{\mu\nu} \quad = \quad H'_\mu(t') \frac{k \cdot (2p-k)}{2p \cdot k} + \ldots$$

- For the hadronic current: Taylor expand

$$k^\nu \, V_{\mu\nu} \quad = \quad H_\mu(t) + k' \, \frac{\mathrm{d}H'_\mu}{\mathrm{d}t'}\bigg|_{k'=0} + k'^2 \, \frac{\mathrm{d}^2 H'_\mu}{\mathrm{d}t'^2}\bigg|_{k'=0} + \ldots \, ,$$

and neglect all higher order terms, plus introduce seagull terms to make sure matrix element fulfills the Ward identity / is gauge invariant:

$$V_{\mu\nu} - A_{\mu\nu}$$

$$i \, e \, \frac{G_\mathrm{F}}{\sqrt{2}} \, V_\mathrm{cb} \, \bar{u}_\nu \, \gamma^\mu \, P_\mathrm{L} \left(- \frac{H_\mu}{2 p_\ell \cdot k} \left(\gamma_\nu \not{k} + 2 (p_\ell)_\nu \right) + \frac{H_\mu \, p_\nu}{p \cdot k} + f_3(t) \left(\frac{k_\mu \, p_\nu}{p \cdot k} - g_{\mu\nu} \right) \right.$$
$$\left. + \left(-2 (p - p')^\alpha \, \frac{\mathrm{d}H_\mu(t')}{\mathrm{d}t'}\bigg|_{k'=0} \right) \left(\frac{k_\alpha \, p_\nu}{p \cdot k} - g_{\alpha\nu} \right) \right) v_l \, ,$$

More assumptions:

1. The non-local operator Eq. (3.4) was expanded in a number of matrix elements which correspond to intermediate resonances allowed in the soft photon part of phase-space.

2. The off-shell hadronic current was approximated by the on-shell hadronic current.

3. The higher order terms of Eq. (3.13) which are ambiguous and depend on the parametrization of the on-shell matrix element were neglected.

4. No intermediate excited resonances were considered.

- Certainly not a bad set of approximations in the soft-photon limit, **unclear how well this** describes **nature** if one really wants achieve precision

More problems:

- Form factors enter into all of the calculations
  - All of them are measured by “factoring out QED”
    - E.g. tagged measurements simply use q^2 as calculated from hadronic systems

$$q^2 = (p_B - p_D)^2 = \left(p_\ell + p_\nu + \sum_i k_i\right)^2$$

    - Even untagged measurements factorize QED effects out, i.e. change the shape of the templates are calculated using “true” q^2 values as defined w/o QED corrections

Shape differences due to inadequate QED modelling are just absorbed into form factor parameters.

Thus any theory based prediction you make on how fundamental parameters change based on kinematic changes, will likely not be valid.

Regularization

- We regularized the UV poles using **Pauli-Villars,** made it easy to match to Sirlin's quark-level calculation

$$\mathcal{L}_{\rm PV} = \boxed{}\frac{1}{4}\tilde{F}^2 + \boxed{\Lambda^2}\tilde{A}^2 \,, \quad \xrightarrow{\text{e.g.}} \quad \begin{array}{lcl} B_0(m_\ell^2, m_\ell^2, \lambda^2) & \to & B_0(m_\ell^2; m_\ell^2, \lambda^2) - B_0(m_l^2; m_\ell^2, \Lambda^2)\,, \\ \dot{B}_i(m_\ell^2, m_\ell^2, \lambda^2) & \to & \dot{B}_i(m_\ell^2, m_\ell^2, \lambda^2) - \dot{B}_i(m_\ell^2, m_\ell^2, \Lambda^2)\,, \end{array}$$

plus sign instead of -

- After that we also determined the total rate via

Born + Virtual

$$\mathrm{d}\Gamma_0^0 + \mathrm{d}\Gamma_0^1 = \frac{1}{64\pi^3 m}\left(\left|\mathcal{M}_0^0\right|^2 + 2\Re\sum_{d)-h)}\mathcal{M}_0^0\,\mathcal{M}_0^1 + 2\left|\mathcal{M}_0^0\right|^2\left(\frac{\alpha_{\rm em}}{\pi}\ln\frac{m_Z}{\Lambda}\right)\right)\mathrm{d}E'\,\mathrm{d}E_\ell\,,$$

Real emission

$$\mathrm{d}\Gamma_1^1 = \frac{1}{(2\pi)^{12}}\delta^{(4)}(m - p' - p_\ell - p_{\nu_l} - k)\left|\sum_{a)-c)}\mathcal{M}_1^{\frac{1}{2}}\right|^2 \frac{\mathrm{d}^3p'}{E'}\frac{\mathrm{d}^3p_\ell}{E_\ell}\frac{\mathrm{d}^3p_{\nu_l}}{E_{\nu_l}}\frac{\mathrm{d}^3k}{E_\gamma}\,, \quad \longrightarrow$$

same IR cut-off
λ

- And we produced **NLO events** using the corresponding matrix elements and mixed them according to these integrals

Revised EW corrections

- We also calculated corrections to Sirlin's correction using

Sirlin's correction

revised EW correction

$$\Gamma_0^0 + \Gamma_0^1 + \Gamma_1^1 = (1 + \delta_{\text{sd}} + \delta_{\text{ld}})\,\Gamma_0^0 = \eta_{\text{EW}}^2\,\Gamma_0^0\,,$$

My new long-distance correction

$$B^0 \to D^- e^+ \bar\nu_e(\gamma)$$

$$\eta_{\text{EW}}^2 = 1.0235 \pm 0.0002_{\text{stat}} \pm 0.0023_{\text{theo}}\,,$$

$$B^+ \to \bar D^0 e^+ \bar\nu_e(\gamma)$$

$$\eta_{\text{EW}}^2 = 1.0147 \pm 0.0001_{\text{stat}} \pm 0.0045_{\text{theo}}\,,$$

$$B^0 \to D^- \mu^+ \bar\nu_\mu(\gamma)$$

$$\eta_{\text{EW}}^2 = 1.0237 \pm 0.0001_{\text{stat}} \pm 0.0020_{\text{theo}}\,,$$

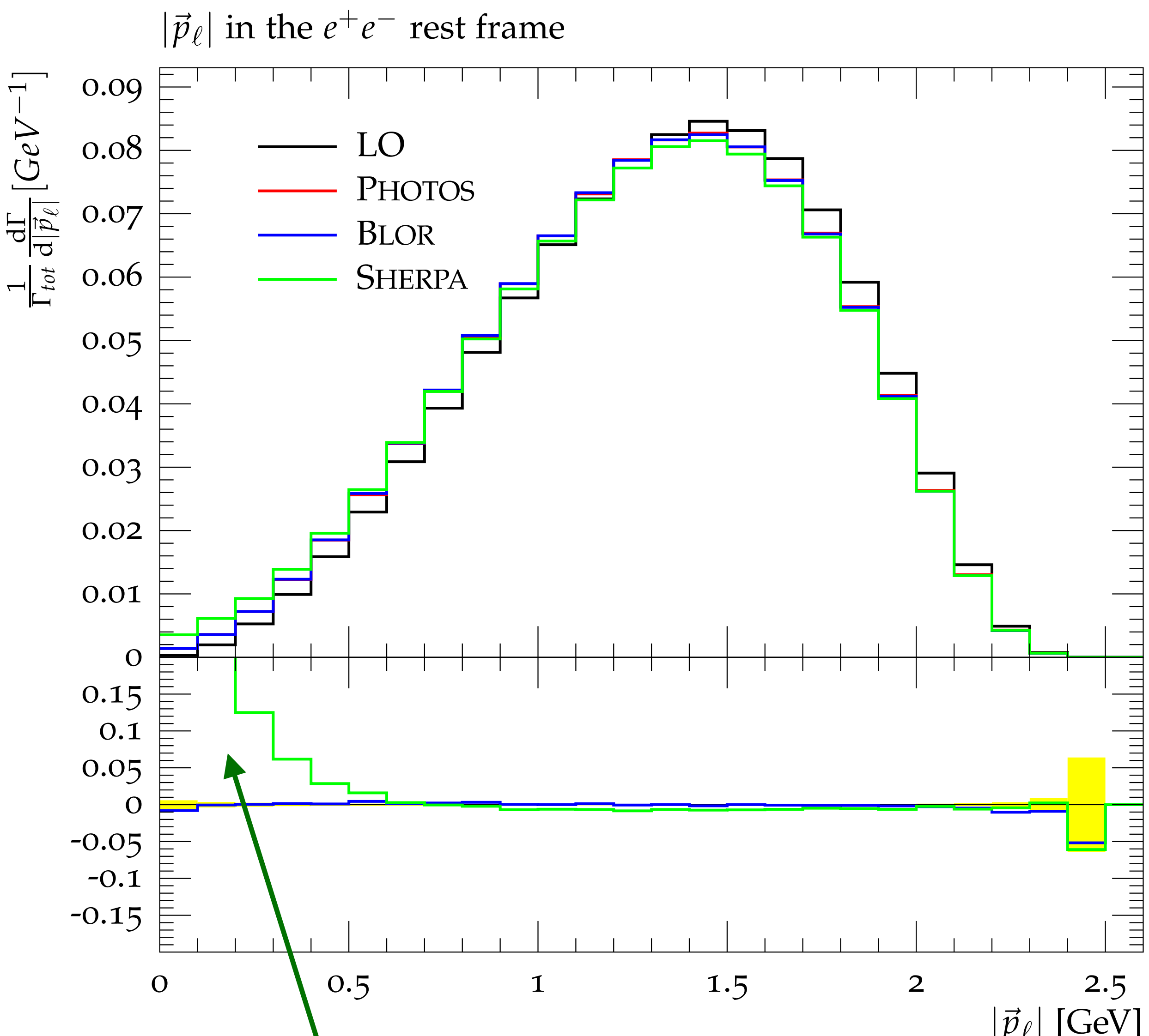
$$B^+ \to \bar D^0 \mu^+ \bar\nu_\mu(\gamma)$$

$$\eta_{\text{EW}}^2 = 1.0150 \pm 0.0001_{\text{stat}} \pm 0.0045_{\text{theo}}\,,$$

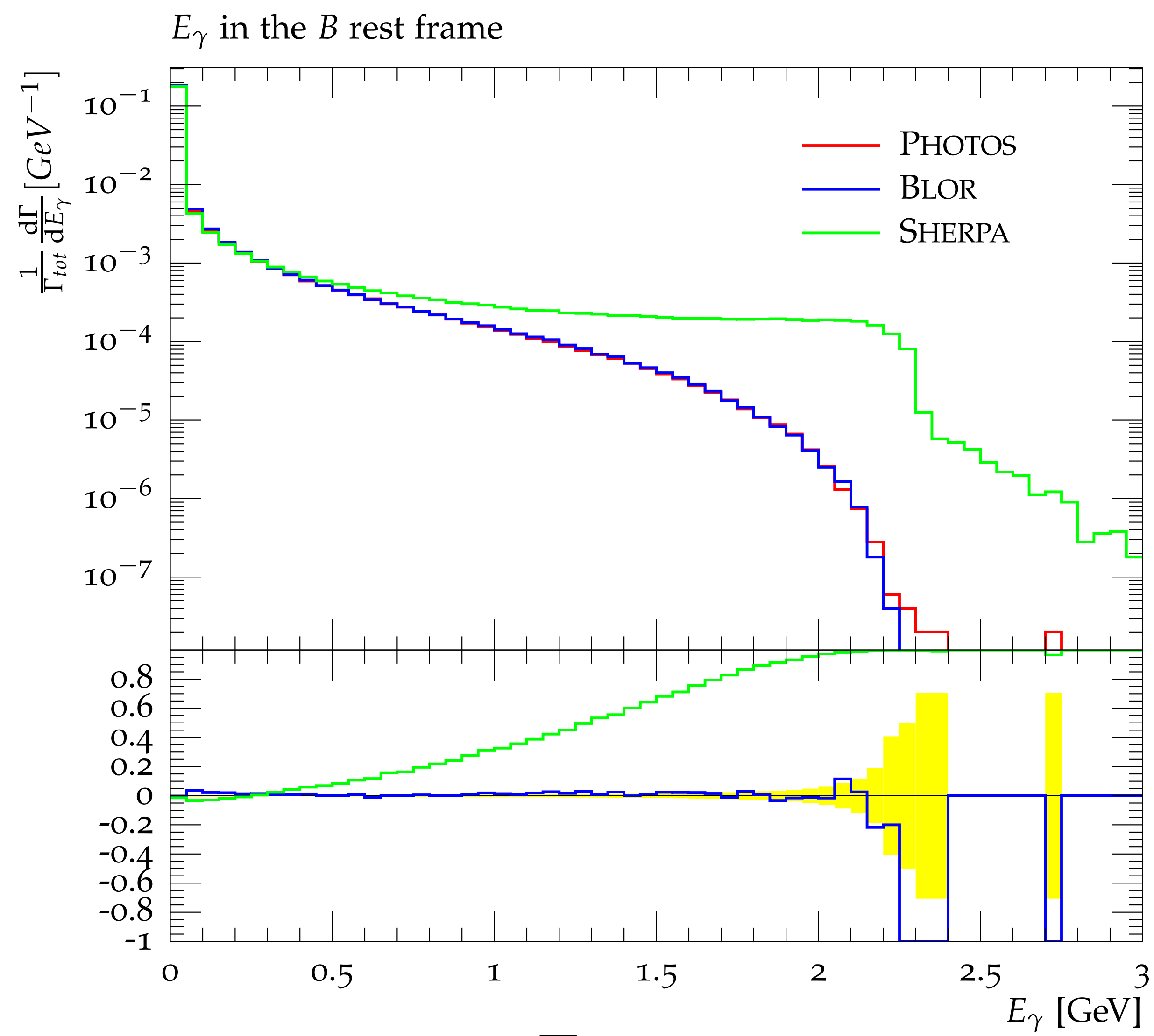
Sirlin's correction: $\eta_{EW}^2 = 1.014$

- **Theory errors:** Variation of the matching scale

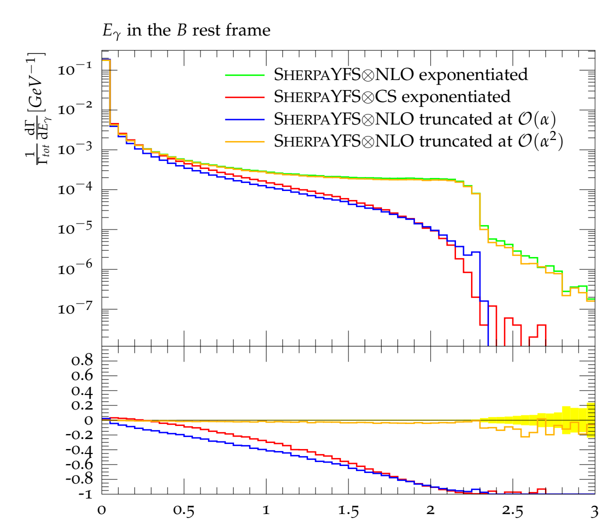
Example: $B^0 \to D^- e^+ \nu_e$



p_ℓ



E_γ



* Fair agreement between **PHOTOS** & NLO; YFS enhanced simulation radiates more high-energy photons

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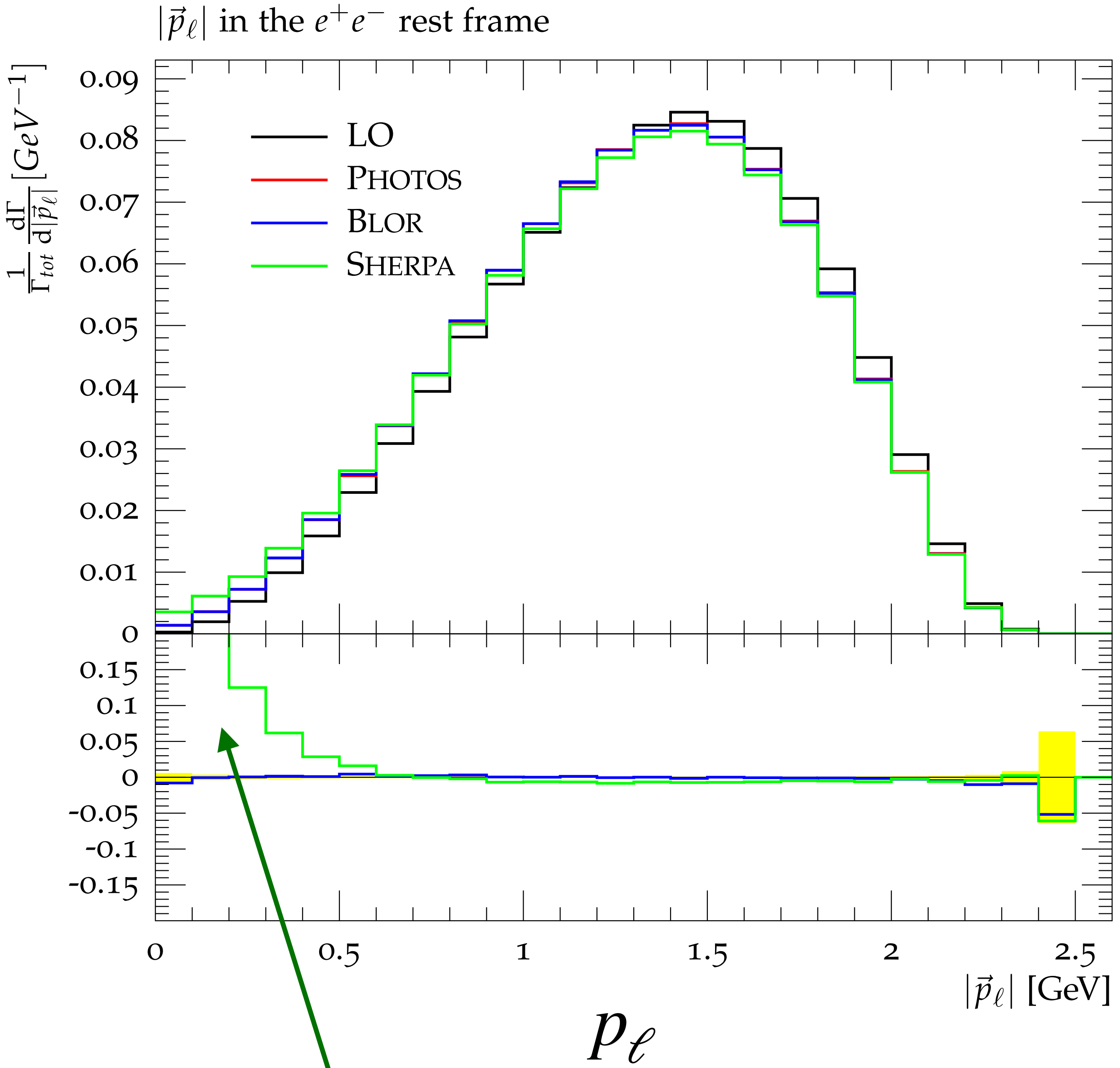
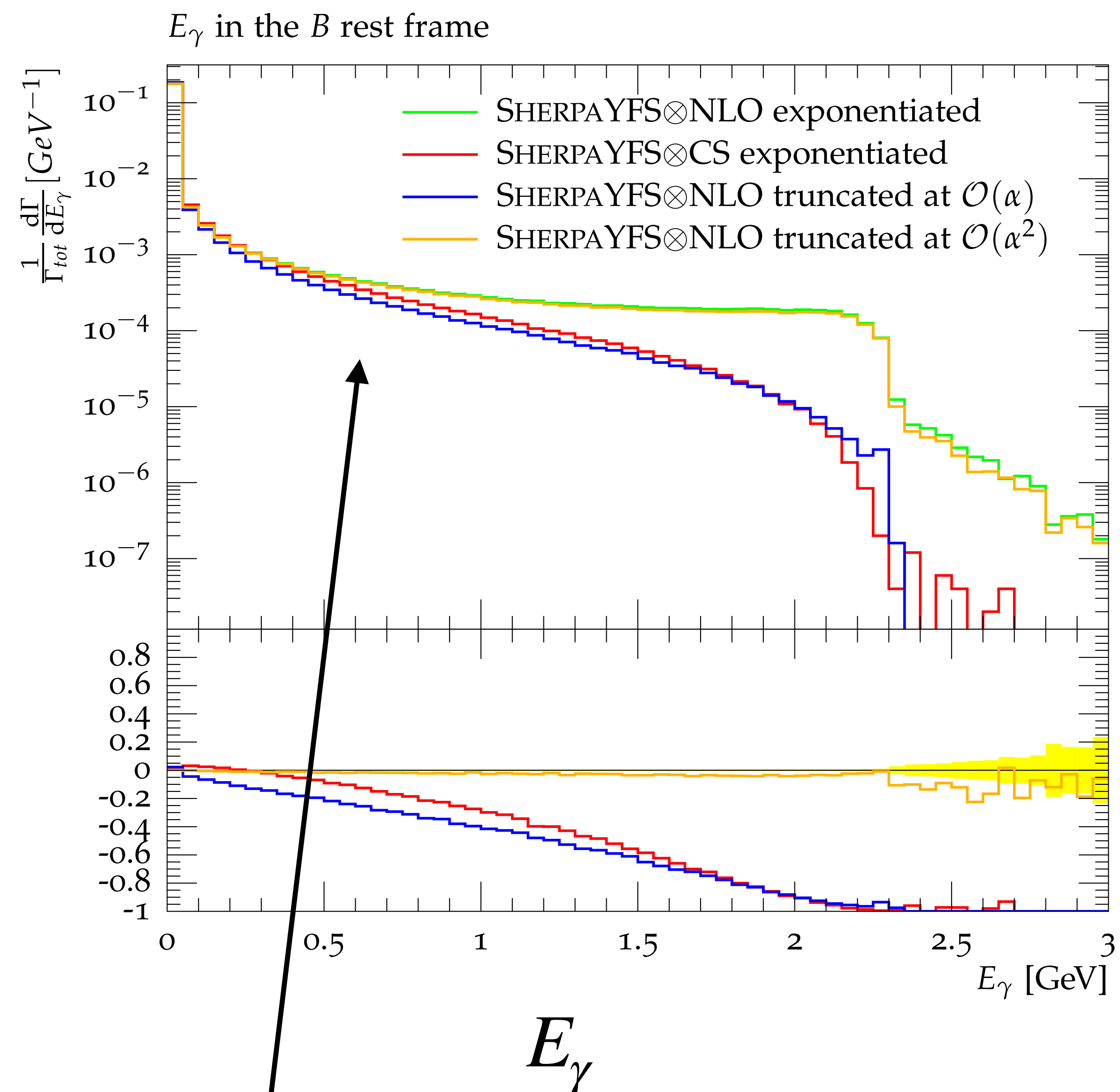




* Fair agreement between **PHOTOS** & NLO; YFS enhanced simulation radiates more high-energy photons

* If truncated at $\mathcal{O}(\alpha)$ or $\mathcal{O}(\alpha^2)$ good agreement

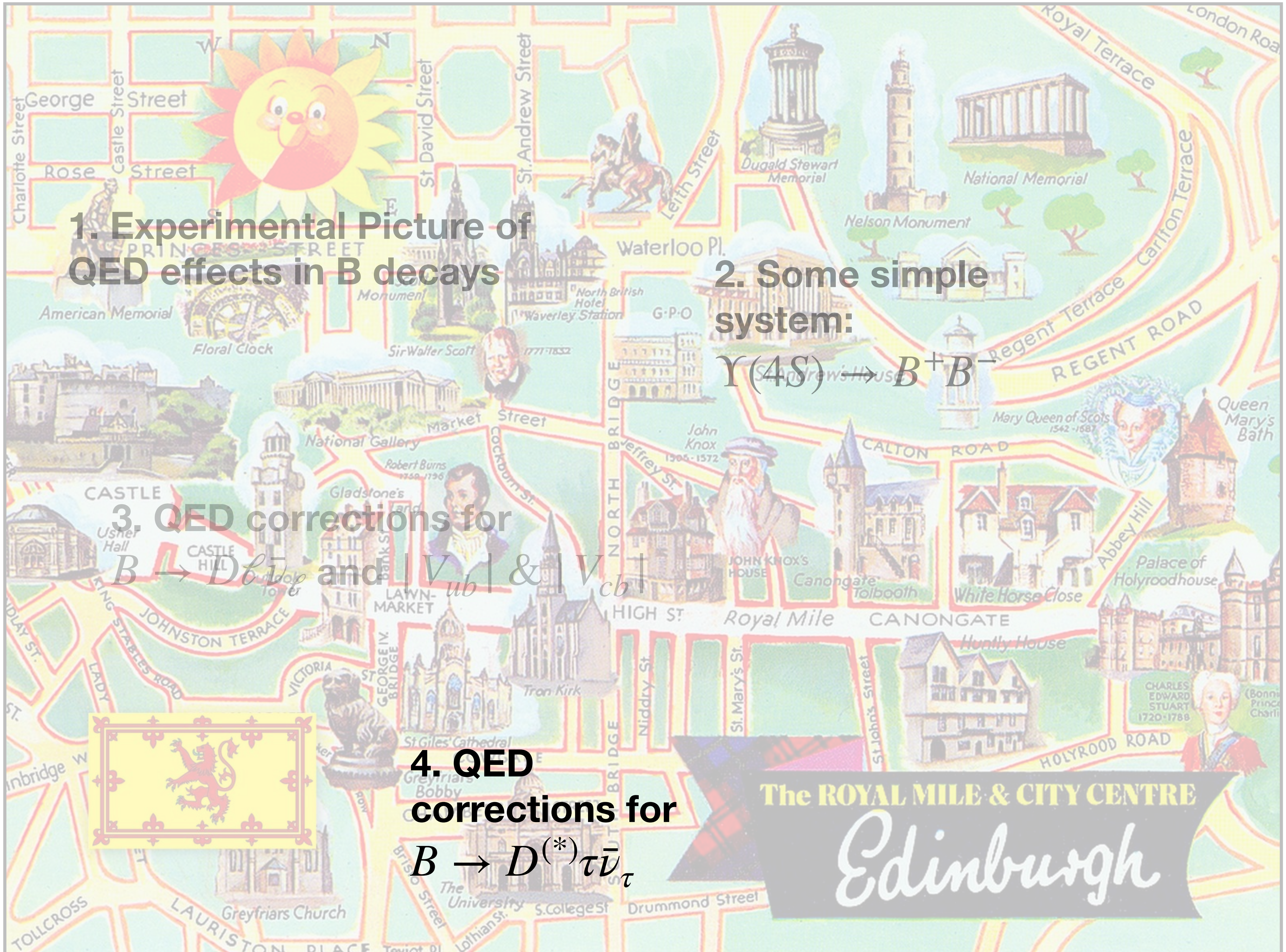
Revised Systematics:

	ρ^2_D	$\rho^2_{D^*}$	$\mathcal{B}(D^0\,l\,\nu_l)$	$\mathcal{B}(D^{*0}\,l\,\nu_l)$
$R'_1(1)$	1.248	3.046	0.841	−0.253
$R'_2(1)$	1.351	−1.343	0.550	−0.481
f_{D_2/D_1}	−0.206	0.051	−0.153	0.057
$f_{\mathcal{A}_1/D_0}$	−0.637	−0.641	0.165	0.071
$f_{\mathcal{A}_2/D'_1}$	−0.224	−0.163	−0.134	0.240
$f_{D_0\mathcal{A}_1/D_1D_2}$	−1.199	0.430	−0.576	0.327
$f_{D'_1\mathcal{A}_2/D_1D_2}$	0.572	−0.284	0.335	−0.109
f_{+0}	1.334	0.444	0.786	−0.529
τ_{+0}	0.253	0.108	0.438	0.176
f_{D_2}	−0.089	−0.004	−0.048	0.027
$\mathcal{B}(B^+ \to D^{(*)}\,\pi\,l\,\nu_l)$	0.490	−0.350	−0.130	−0.736
$\mathcal{B}(D^0 \to K^+\,\pi^-)$	1.032	0.026	−0.138	−1.612
$\mathcal{B}(D^+ \to K^+\,\pi^-\,\pi^+)$	−1.932	−0.361	−1.966	0.253
$\mathcal{B}(D^{*+} \to \bar{D}^0\,\pi^+)'$	1.116	−0.019	0.464	−0.314
$\mathcal{B}(D^{*+} \to D^+\,\pi^0)'$	0.508	−0.008	0.212	−0.143
Tracking	−0.371	−0.157	−1.000	−0.732
Vertexing	[illegible]	[illegible]	[illegible]	0.698
Lepton mis-ID	[illegible]	[illegible]	[illegible]	0.010
Lepton PID	[illegible]	[illegible]	[illegible]	1.469
Kaon PID	[illegible]	[illegible]	[illegible]	0.065
Bremsstrahlung	[illegible]	[illegible]	[illegible]	0.290
D^{**} Slope	[illegible]	[illegible]	[illegible]	0.189
D^{**} FF approximation	0.920	−0.511	0.145	−0.195
Number of $B\bar{B}$ events	−0.123	−0.100	−0.670	−0.669
Off-resonance luminosity	0.059	0.003	−0.019	−0.003
Radiative corrections for $B \to D\,l\,\nu_l$	−0.126	−0.056	−0.289	0.045
Radiative corrections for $B \to D^*\,l\,\nu_l$	1.657	0.056	0.574	1.187
Radiative corrections for $B \to D^{**}\,l\,\nu_l$	−0.023	0.072	0.111	0.298
Correction to off-resonance	−1.057	0.155	−0.236	0.064
$D^{**}(2S) \to D^{(*)}\pi$ contributions	−0.463	−0.998	−0.184	−0.374
$B \to D^{(*)}\,\pi\,\pi\,l\,\nu_l$ contributions	0.876	0.364	0.245	0.445
Further background	0.595	0.699	0.354	0.099
Total	4.856	4.515	3.318	3.124

From difference of PHOTOS & Our Calculation

	Electron sample					
item	ρ^2_D	$\rho^2_{D^*}$	$\mathcal{B}(D\ell\overline{\nu})$	$\mathcal{B}(D^*\ell\overline{\nu})$	$\mathcal{G}(1)\lvert V_{cb}\rvert$	$\mathcal{F}(1)\lvert V_{cb}\rvert$
R'_1	0.44	2.74	0.71	−0.38	0.60	0.71
R'_2	−0.40	1.02	−0.18	0.30	−0.32	0.49
D^{**} slope	−1.42	−2.52	−0.07	−0.09	−0.82	−0.87
D^{**} FF approximation	−0.87	0.33	−0.12	0.19	−0.54	0.20
$\mathcal{B}(B^- \to D^{(*)}\pi\ell\overline{\nu})$	0.28	−0.27	−0.22	−0.80	0.04	−0.49
$f_{D_2^*/D_1}$	−0.39	0.16	−0.38	0.16	−0.41	0.13
$f_{D_0^*D\pi/D_1D_2^*}$	−2.30	1.12	−1.53	0.97	−2.07	0.85
$f_{D'_1D^*\pi/D_1D_2^*}$	1.82	−1.14	1.30	−0.65	1.65	−0.70
$f_{D\pi/D_0^*}$	−0.88	−1.28	0.36	0.17	−0.31	−0.34
$f_{D^*\pi/D'_1}$	−0.21	−0.05	−0.13	0.21	−0.18	0.09
NR D^*/D ratio	0.58	−0.16	0.11	−0.09	0.38	−0.04
$\mathcal{B}(B^- \to D^{(*)}\pi\pi\ell\overline{\nu})$	1.19	−1.97	0.25	−1.28	0.78	−1.28
X^*/X and Y^*/Y ratio	0.61	−1.15	0.09	−0.27	0.39	−0.52
X/Y and X^*/Y^* ratio	0.76	−0.83	0.21	−0.65	0.52	−0.60
$D_1 \to D\pi\pi$	2.22	−1.54	0.74	−1.08	1.63	−1.05
$f_{D_2^*}$	−0.14	−0.01	−0.10	0.07	−0.12	0.03
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.73	−0.01	0.43	−0.34	0.62	−0.17
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.69	0.02	−0.21	−1.63	0.29	−0.80
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	−1.46	−0.42	−2.17	0.30	−1.89	0.01
τ_{B^-}/τ_{B^0}	0.26	0.16	0.63	0.27	0.46	0.19
f_{+-}/f_{00}	0.88	0.43	0.66	−0.53	0.82	−0.12
Number of $B\overline{B}$ events	0.00	−0.00	−1.11	−1.11	−0.55	−0.55
Off-peak Luminosity	0.05	0.01	−0.02	−0.00	0.02	0.00
B momentum distrib.	−0.96	0.63	1.29	−0.54	−1.15	0.48
Lepton PID eff	0.52	0.16	1.21	0.82	0.90	0.46
Lepton mis-ID	0.03	0.01	−0.01	−0.01	0.01	−0.00
Kaon PID	0.07	0.80	0.28	0.23	0.18	0.38
Tracking eff	−1.02	−0.43	−3.35	−2.00	−2.25	−1.15
Radiative corrections	−3.13	−1.04	−2.87	−0.74	−3.02	−0.71
Bremsstrahlung	0.07	0.00	−0.13	−0.28	−0.04	−0.14
Vertexing	0.83	−0.64	0.63	0.60	0.78	0.09
Background total	1.39	1.12	0.64	0.34	1.07	0.51
Total	**6.25**	**5.66**	**6.01**	**4.03**	**5.99**	**3.20**

Talk Outline



1. **Experimental Picture of QED effects in B decays**

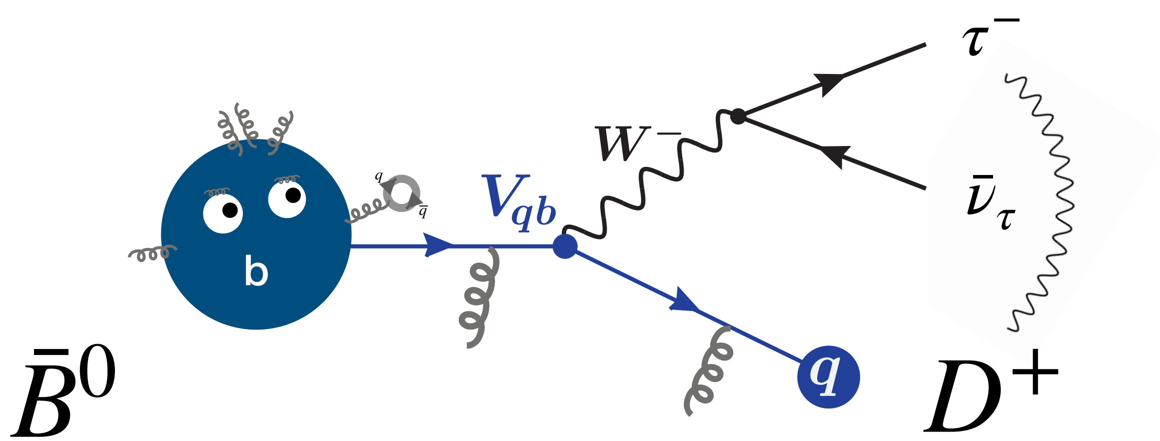
2. **Some simple system:** $\Upsilon(4S) \to B^+ B^-$

3. **QED corrections for** $B \to D \ell \bar{\nu}_\ell$ **and** $|V_{ub}|$ & $|V_{cb}|$

4. **QED corrections for** $B \to D^{(*)} \tau \bar{\nu}_\tau$

Another slow moving system

S. Calí, S. Klaver, M. Rotondo, B. Sciascia, arXiv:1905.02702 [hep-ph]
Eur. Phys. J. C79 (2019) no.9, 744



PHOTOS seems to be doing a fine job with light leptons as far as we can tell.

It does not include **Coulomb corrections**, but there they seem not very relevant as all final state particles have considerable momentum

But there is one final state, for which this is not true: τ has $\beta \approx 0.5 - 0.75$

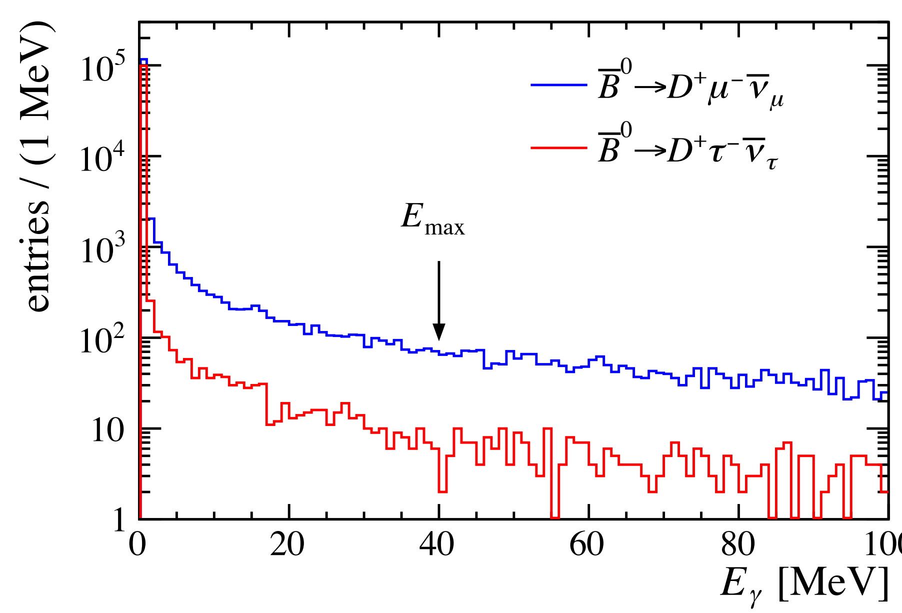
Coulomb Correction scales as

$$\Omega_{\mathrm{C}} = \frac{2\pi\alpha}{\beta_{D\ell}} \frac{1}{1 - e^{-\frac{2\pi\alpha}{\beta_{D\ell}}}},$$

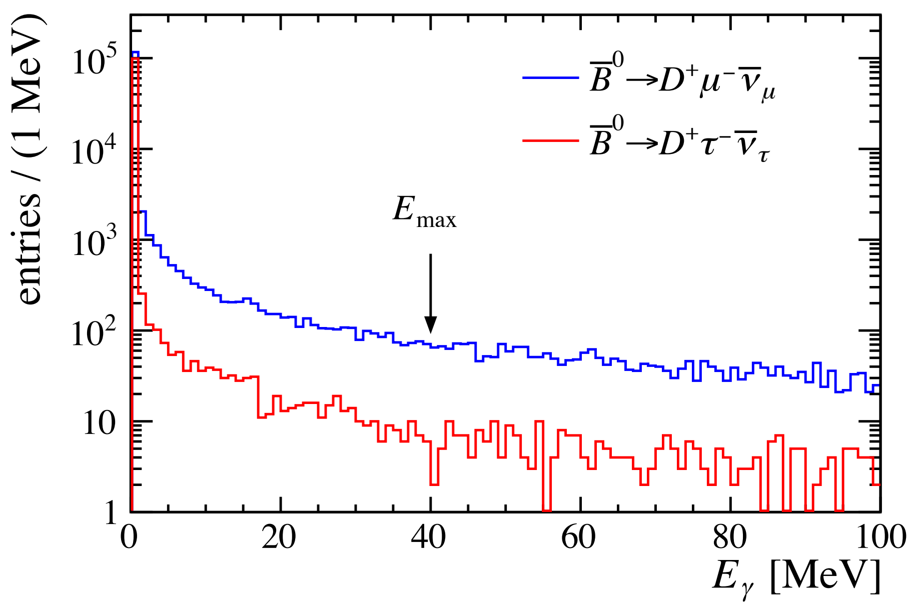
$$\beta_{D\ell} = \left[1 - \frac{4m_D^2 m_\ell^2}{(s_{D\ell} - m_D^2 - m_\ell^2)^2}\right]^{1/2}$$

Changes kinematic distributions, breaks isospin

Second concern: τ and ℓ radiate differently



Let's first talk about the **second concern**



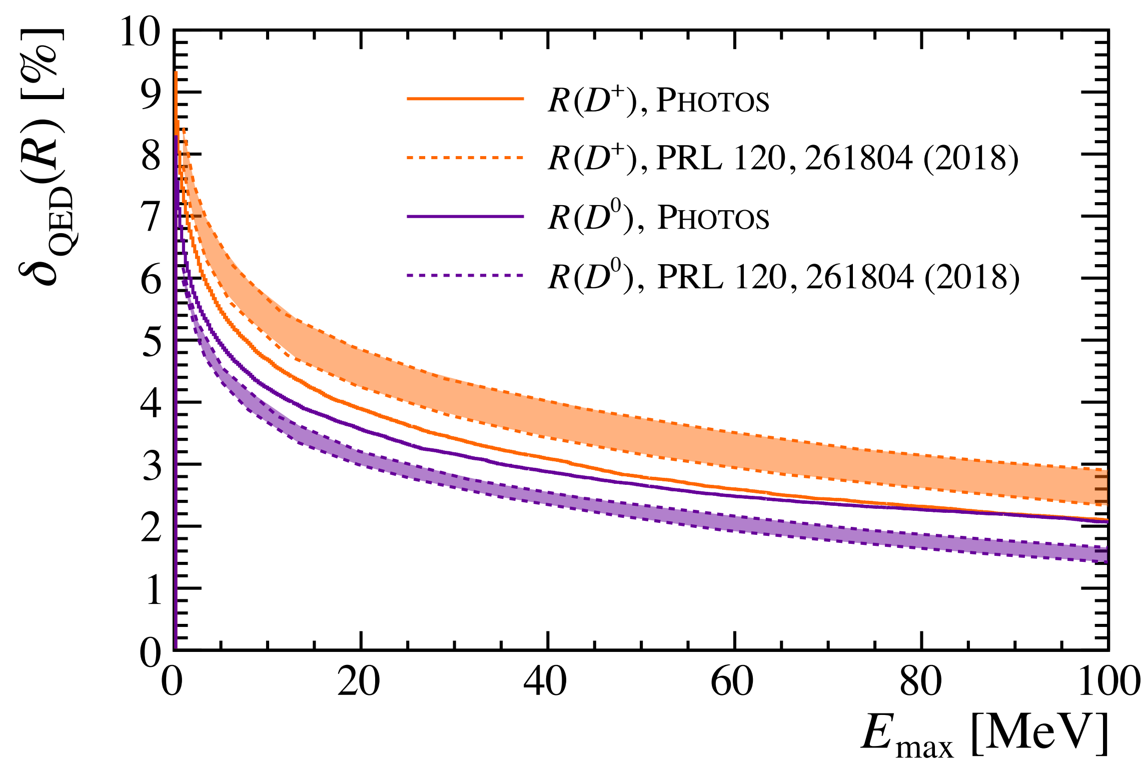
Let's be more precise:

Of course experiments simulate this with PHOTOS
(and there are additional FSR photons from the τ decay)

Problems could arise if real QED effects would differ between PHOTOS and e.g. full NLO rate

You can make this fairly dramatic looking by defining a cut-off E_{max}, which defines the maximal value of the photon energy that we would identify $B \to D\ell\bar{\nu}_\ell\gamma$ still as signal

$$\delta_{\mathrm{QED}} = \frac{\int_0^{E_{\mathrm{max}}} N(E_\gamma) dE_\gamma}{\int_0^{\infty} N(E_\gamma) dE_\gamma} - 1 \, ,$$



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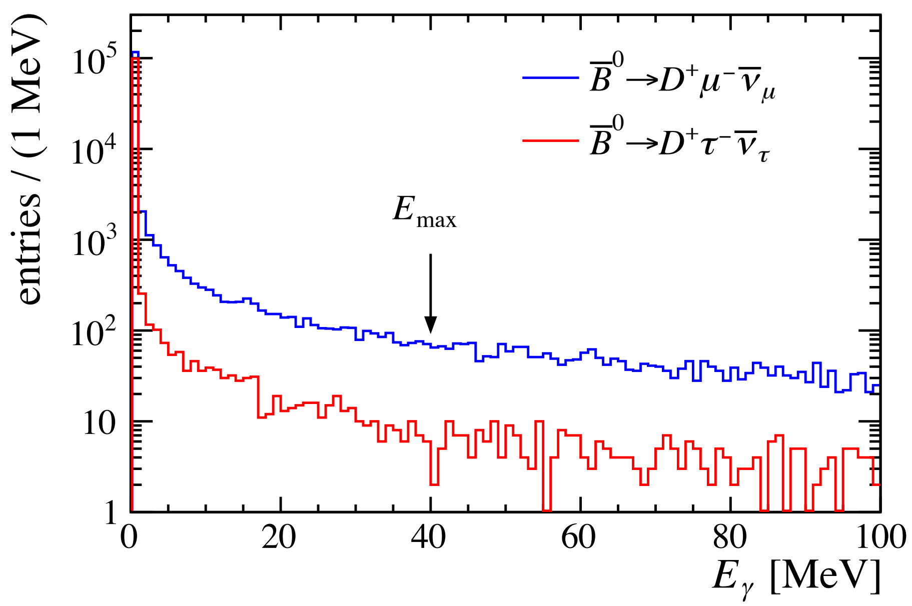
S. de Boer, T. Kitahara, I. Nisandzic
Phys. Rev. Lett. 120, 261804 (2018)



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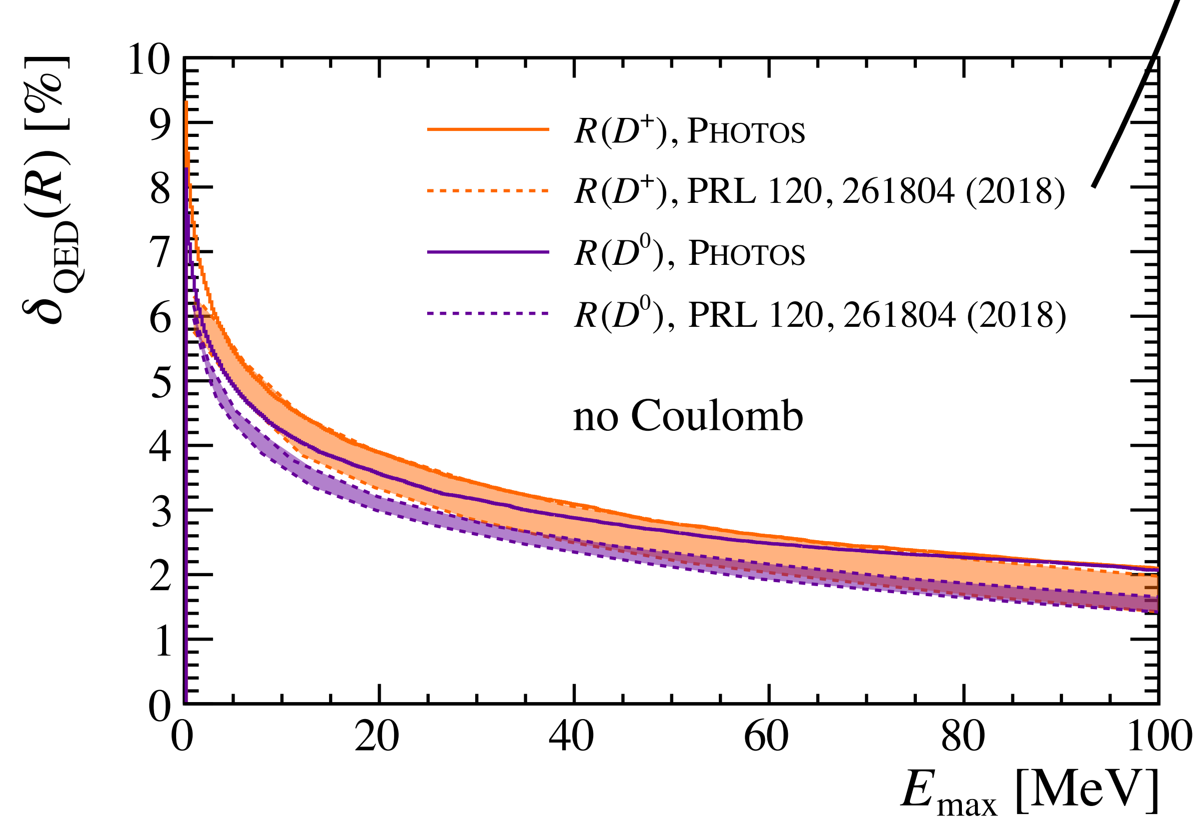
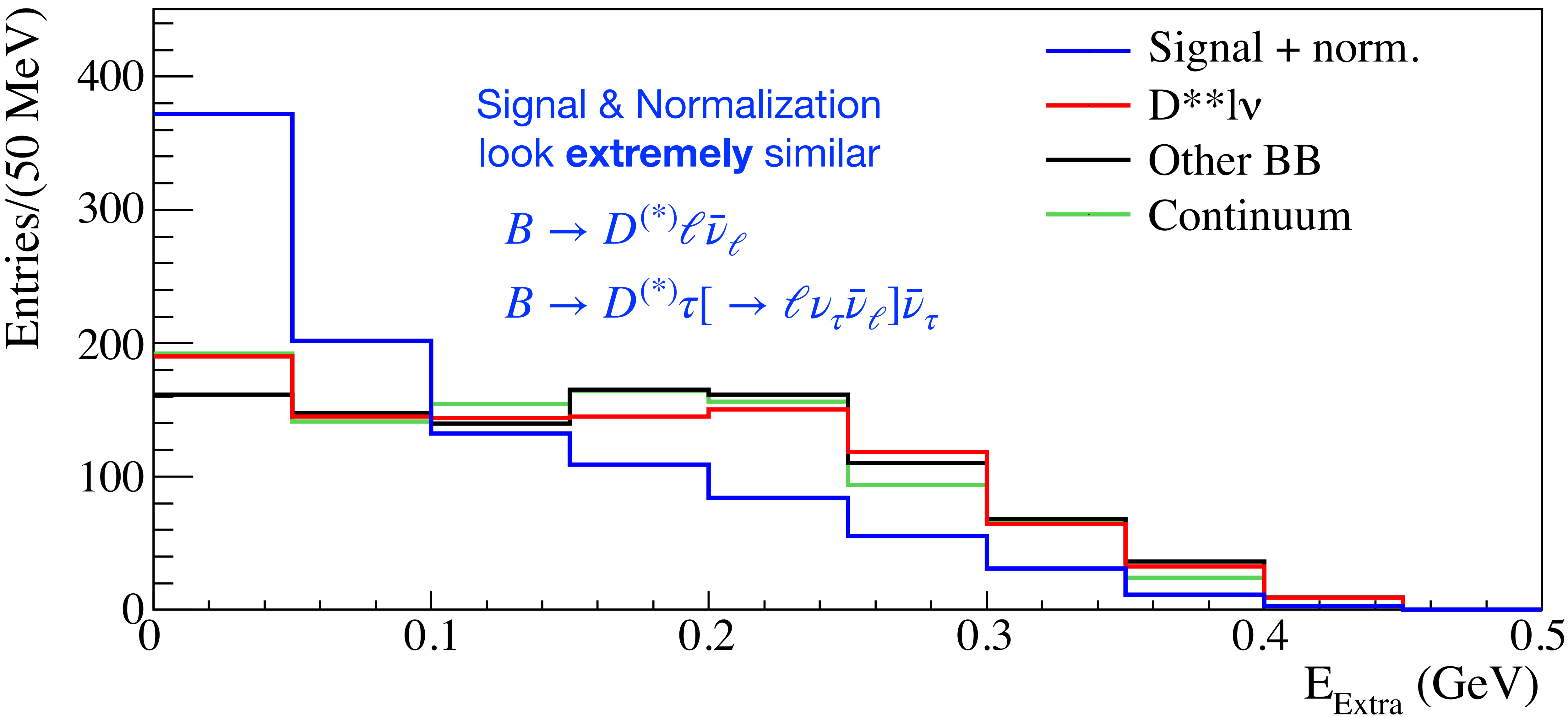


Disagreement vanishes when **Coulomb term** is **removed**

Very interesting point; but in measurements variables like E_{max} are not so well defined

One variable that is **similar** is E_{extra} : **Unassigned neutral energy** in ECL



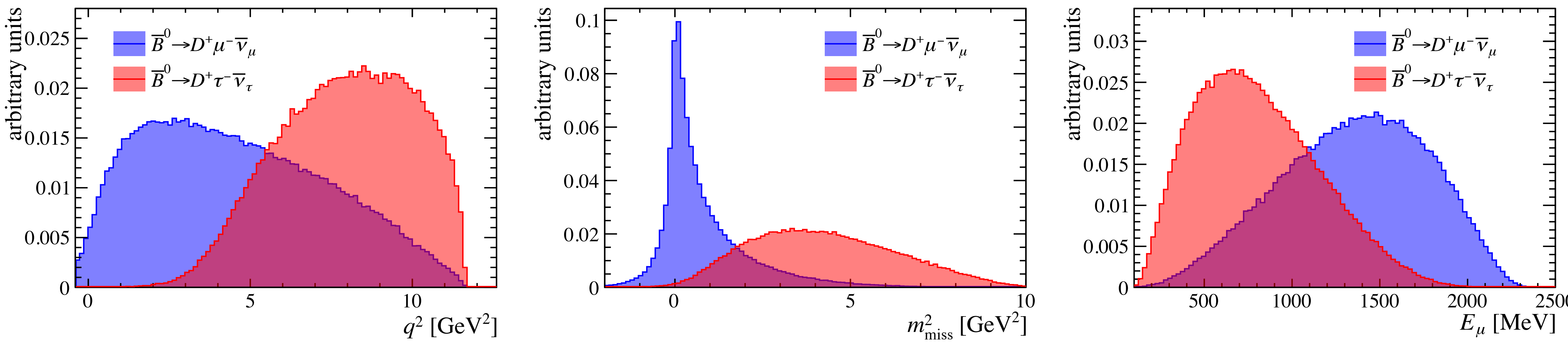
In fact so similar, that it's impossible to separate both processes with E_{extra}

Why similar? 1) more FSR when τ decays

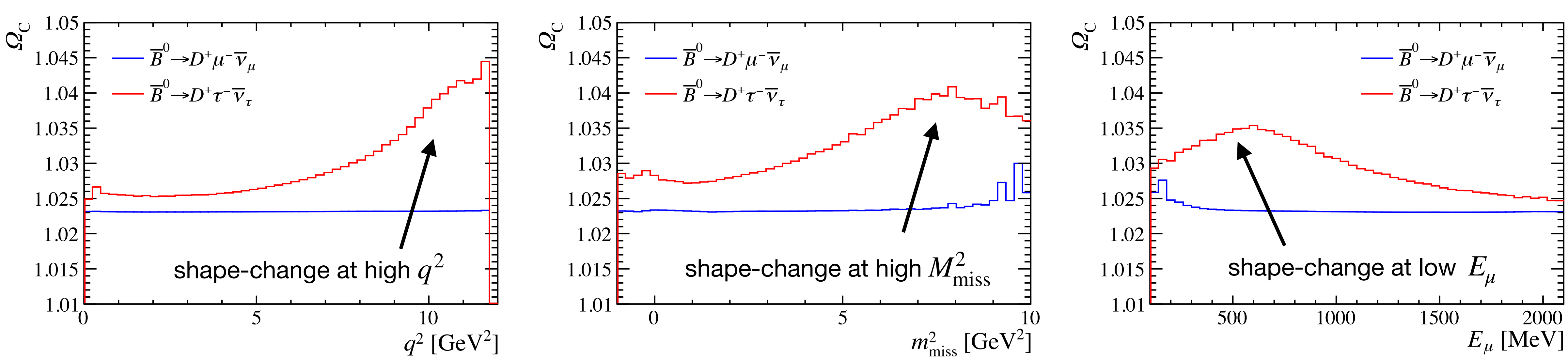
2) Brem, Beam Backgrounds, not reconstructed π^0 or photons in the event

Ok, back to the **first concern**

Typical extraction variables for $R(D^{(*)})$: $q^2 = (p_B - p_{D^*})^2$; $M^2_{\text{miss}} = (p_B - p_{D^*} - p_\ell)^2$; E_μ



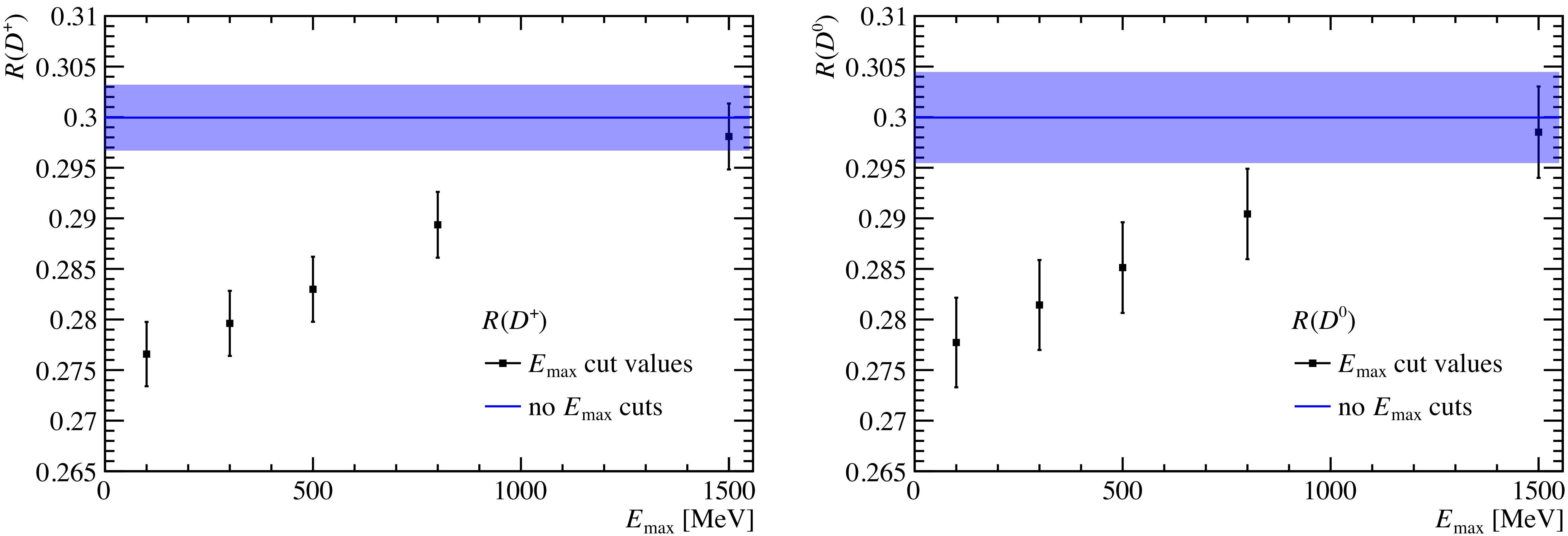
Coulomb correction factor:



Ok, this could lead to **some bias** in $R(D^{(*)+})$ due to shape changes in the fit templates

Paper quantifies that this could give a shift of **about** 1%

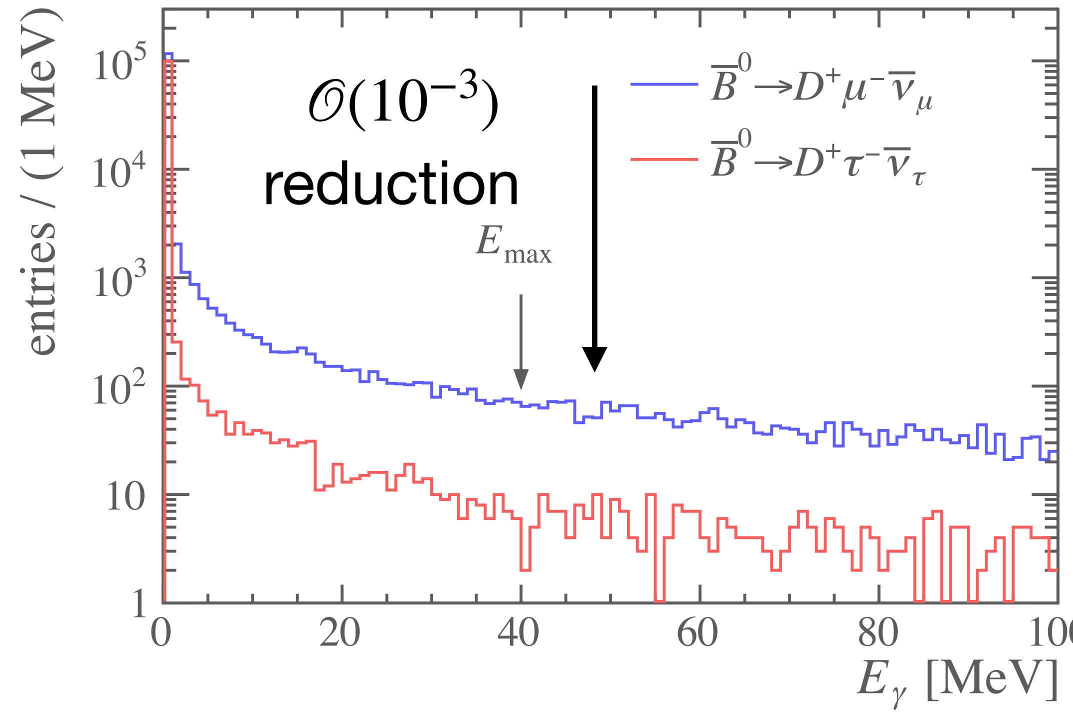
One can also put both effects together:

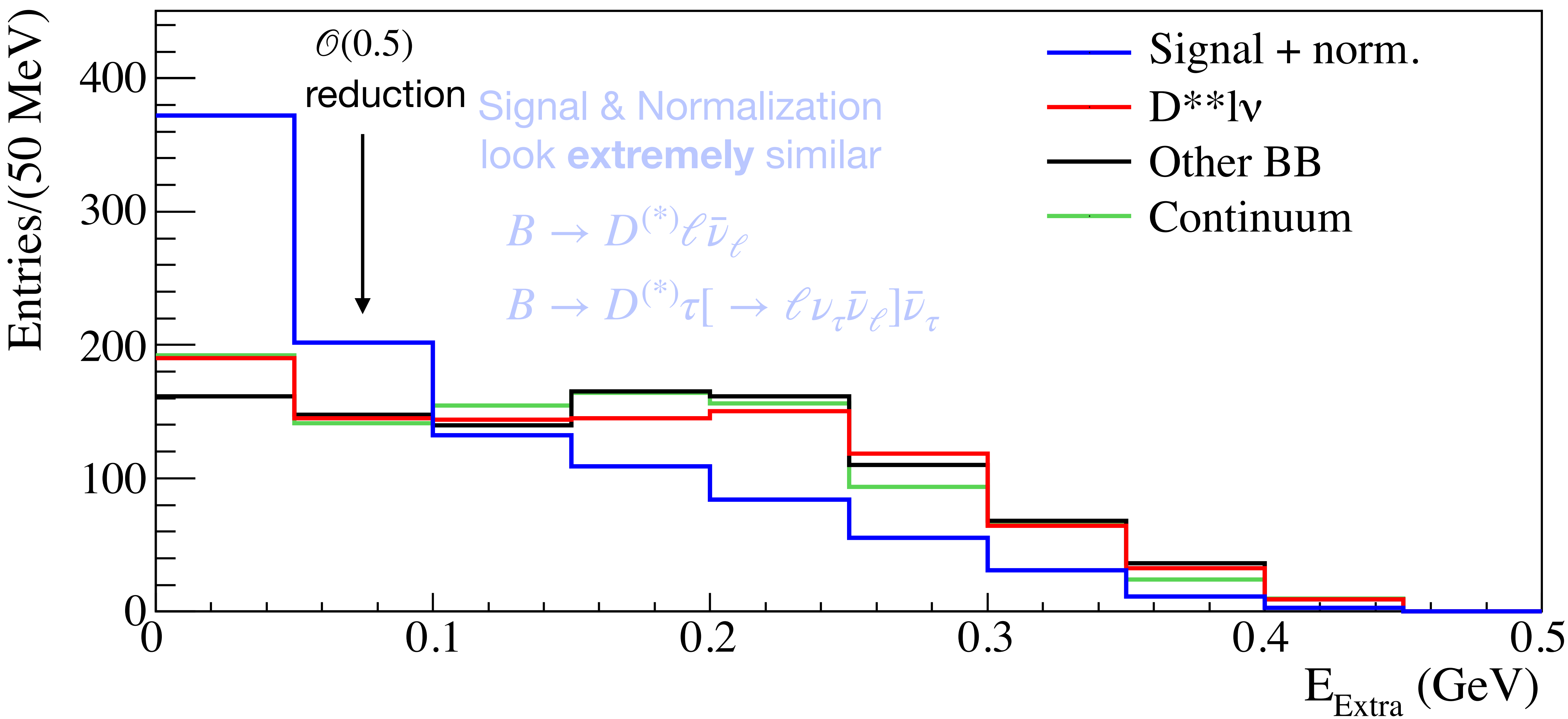


As the paper writes, this is somehow a worst case scenario, not a realistic assessment what the actual bias could be (as it is the difference to PHOTOS that drives any efficiency differences)

Experimental effects broaden the experimental equivalent of E_{max} considerably

Reduction from [0,50 MeV] wildly **different**





Summary

Summary

I am personally excited about the renewed attention that QED effects are getting!

We are stepping into an exciting era with

- Precision measurements of $B_{s,d} \to \mu\mu(\gamma)$ at the LHC

- Exciting prospects of $B \to \ell\nu\gamma$ and $B \to \ell\nu\gamma^*[\to \ell\ell]$ at Belle II & LHCb

- Belle II will discover $B \to \mu\nu$, how to deal with $B \to \mu\nu\gamma$ interesting question

- QED effects for $H_b \to H_{u,c}\ell\bar{\nu}_\ell(\gamma)$ will become more and more for $|V_{qb}|$ determinations

Many thanks to Roman and all the organizers for bringing us all together here!