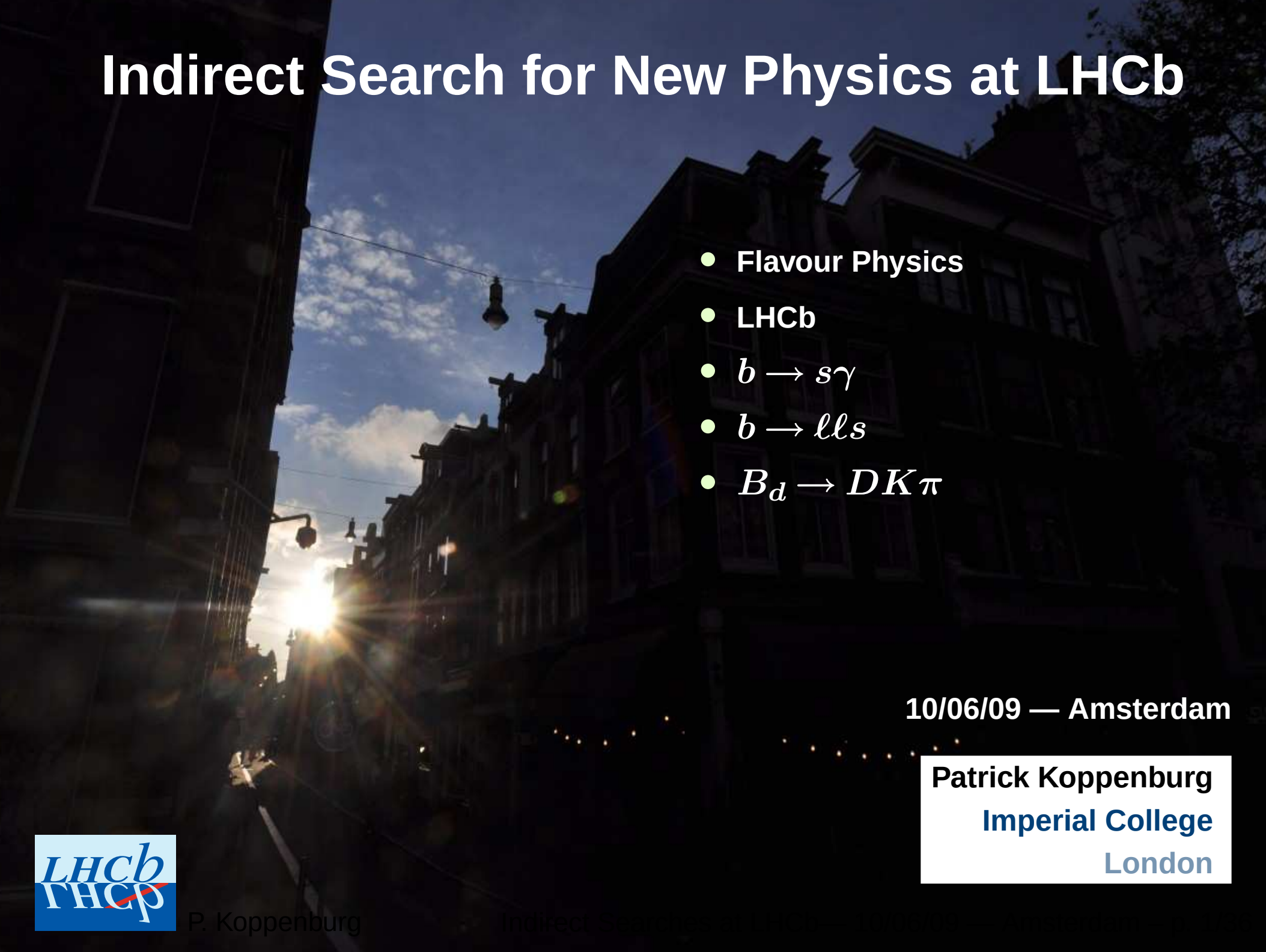
Indirect Search for New Physics at LHCb



- Flavour Physics
- LHCb
- $b \to s\gamma$
- $b \to \ell\ell s$
- $B_d \to DK\pi$

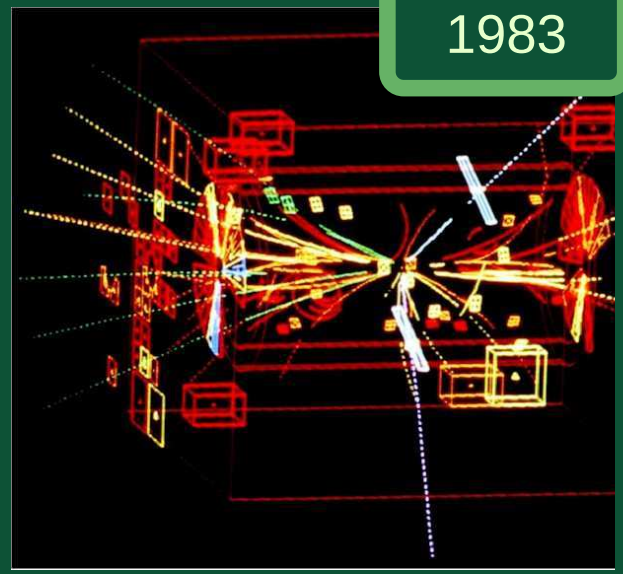
10/06/09 — Amsterdam

Patrick Koppenburg
Imperial College
London

Indirect searches

- Sensitive to New Physics effects
  - When was the Z discovered?
    - 1973 from $N\nu \to N\nu$?
    - 1983 at SpS?
  - c quark postulated by GIM, third family by KM
- Estimate masses
  - t quark from $B\overline{B}$ mixing
- Get phases of couplings
  - Half of new parameters
  - Needed for a full understanding
- Look in lepton and **flavour** sectors

  ➜ CP asymmetry in the Universe



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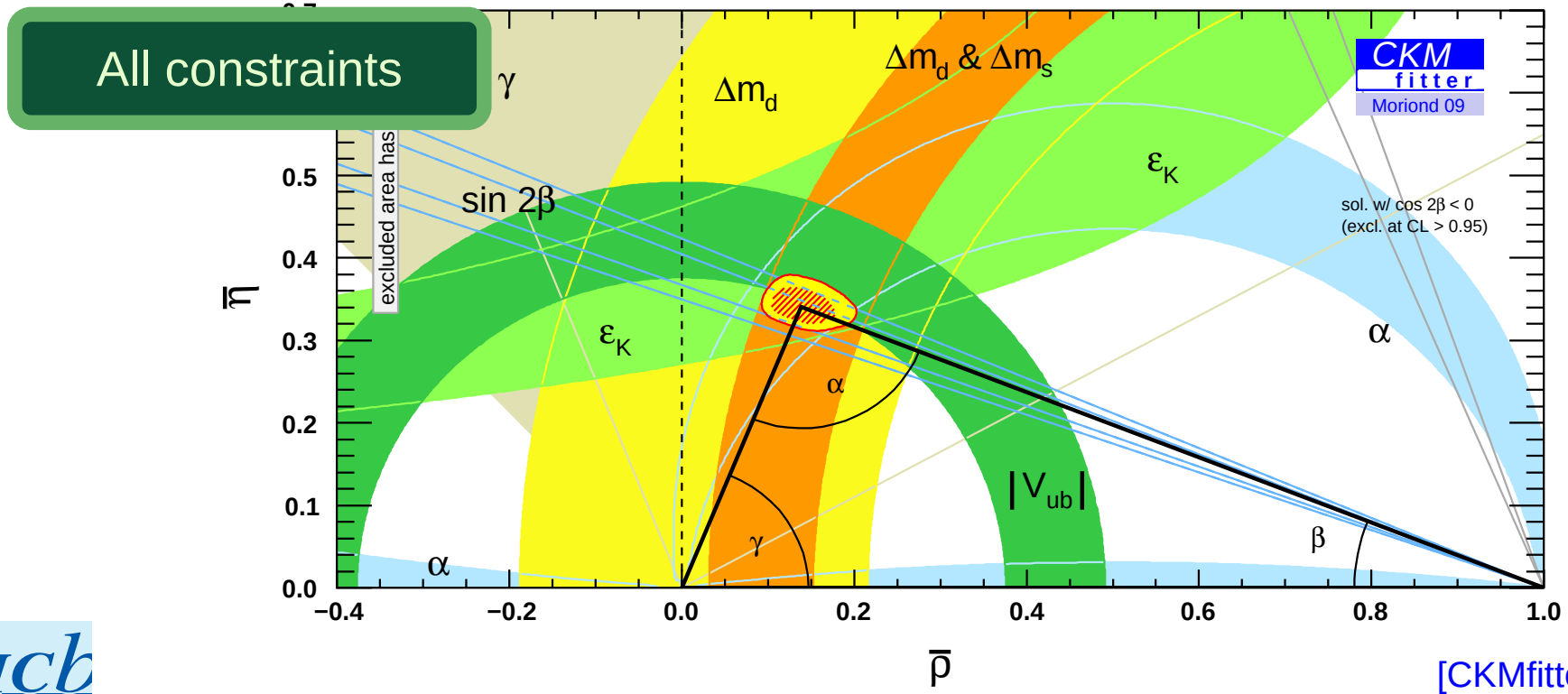
Successes not always where expecte

Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of **New Physics**
  - ➜ Discrepancies in measurements or unitarity triangle

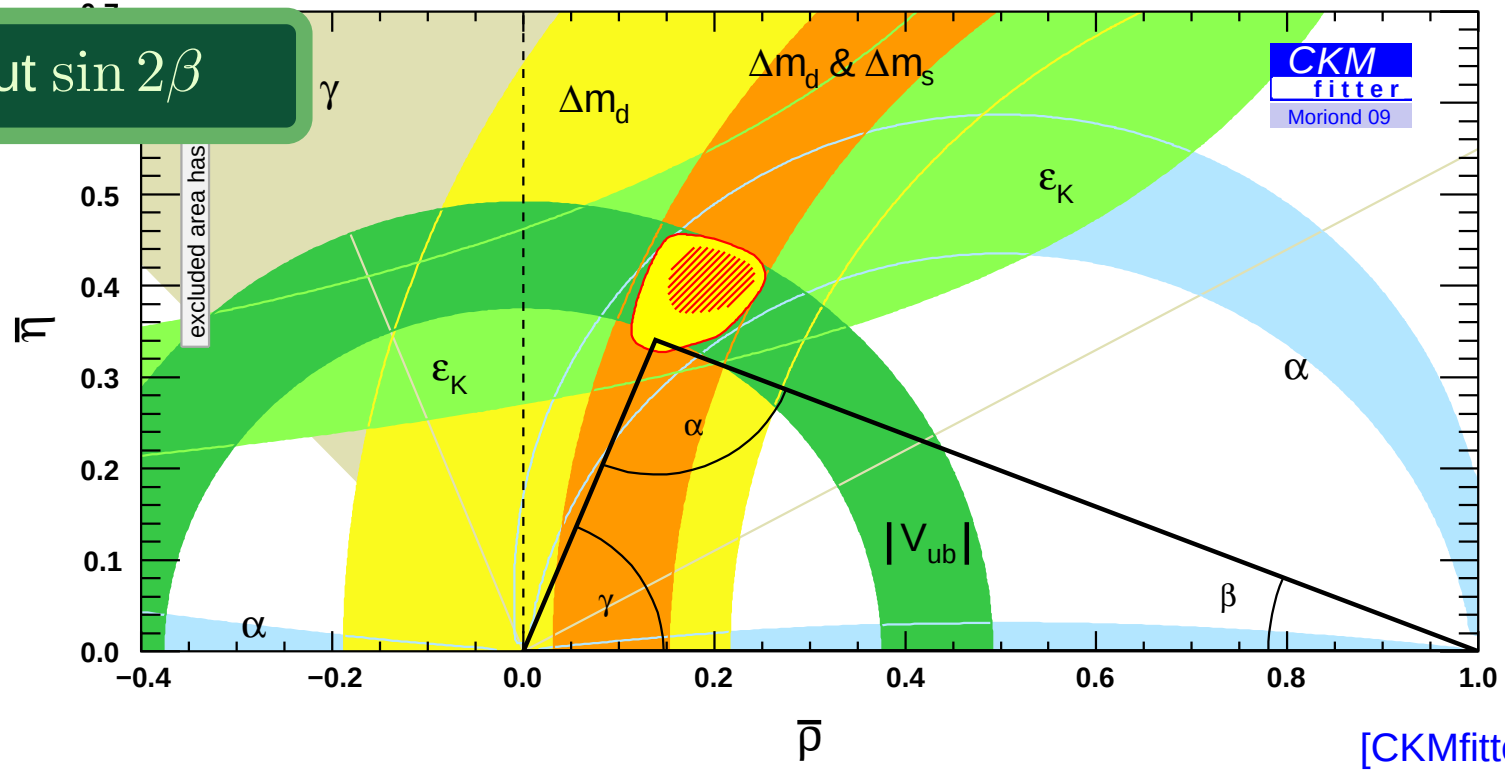


[CKMfitter 03/09]

Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of **New Physics**
  - ➜ Discrepancies in measurements or unitarity triangle
- $(\bar{\rho}, \bar{\eta})$ fit is dominated by $\sin 2\beta$

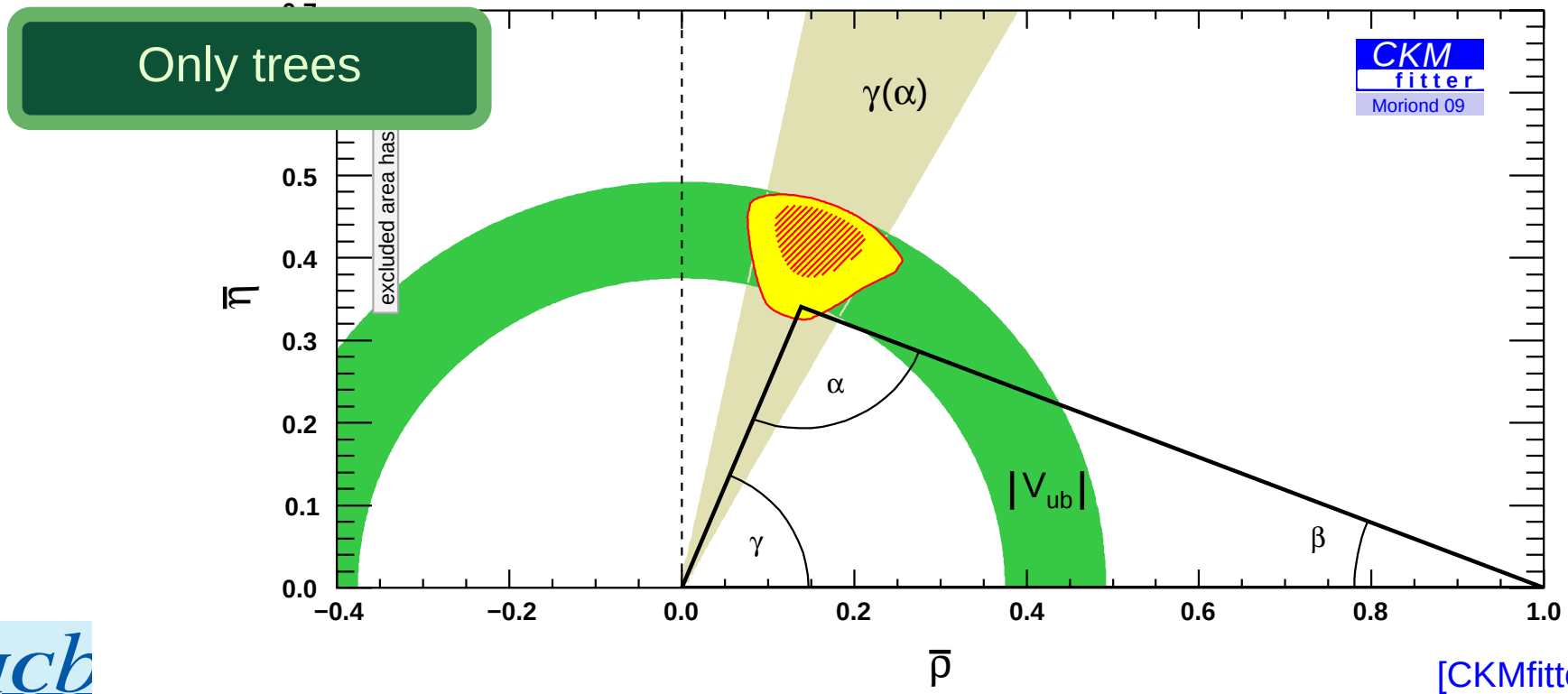
All but $\sin 2\beta$



[CKMfitter 03/09]

Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of **New Physics**
  - ➜ Discrepancies in measurements or unitarity triangle
- We don't know much about constraints from trees



[CKMfitter 03/09]

Unitarity Triangle

- Changed focus: No longer seeking to verify the CKM picture
- Instead look for signs of **New Physics**

  ➜ Discrepancies in measurements or unitarity triangle

✔ Need very good precision on all angles and sides.

  ✔ Precise measurement of γ

✔ Need B_s as well ➜ β_s and more

✔ Look for rare decays

  ➜ **Need a lot of data and a good precision**

A Large Hadron Collider Beauty Experiment for Precision Measurements of CP-Violation and Rare Decays

LHC

LHC Environment

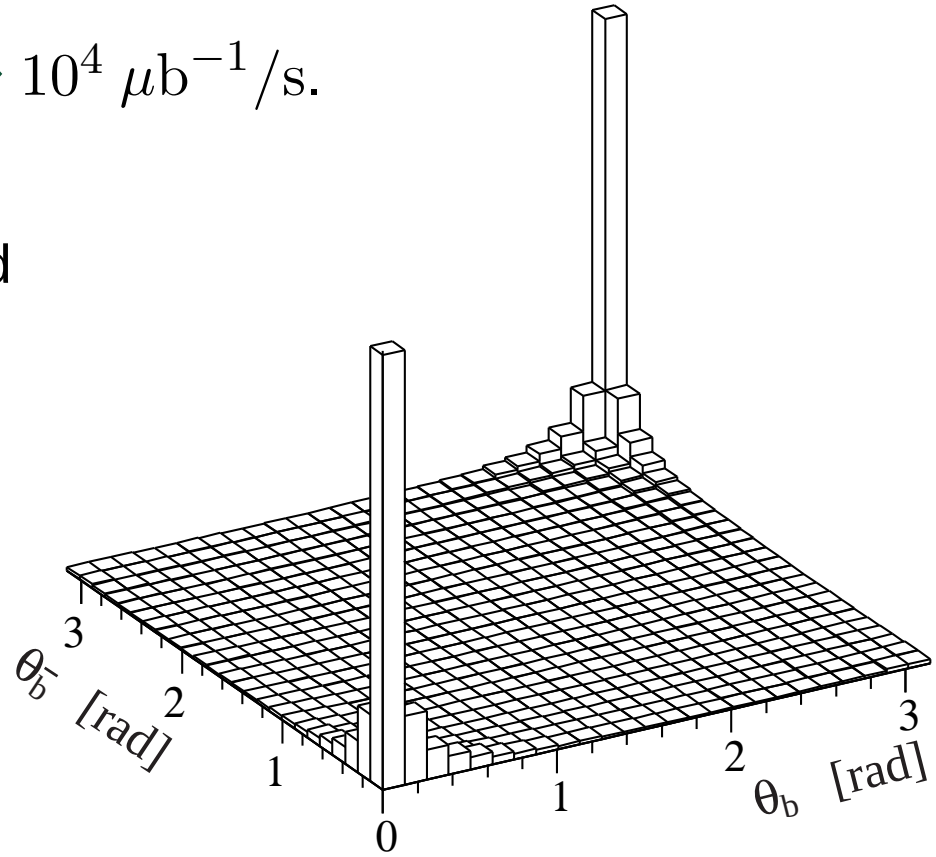
- pp collider at 14 TeV (**not next year!**)
  - Inelastic cross-section about $60\ \mathrm{mb}$
  - $b\bar{b}$ cross-section about $500\ \mu\mathrm{b}$ (one every 120)
- Bunch crossings at 40 MHz
- Luminosity up to $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ➜ $10^{4}\ \mu\mathrm{b}^{-1}/\mathrm{s}$.

  ➜ $5 \cdot 10^{6}\ b\bar{b}$ pairs per second
- Direction of b and $\bar{b}$ very correlated

  ➜ A 4π coverage not optimal

  ➜ Build a forward spectrometer

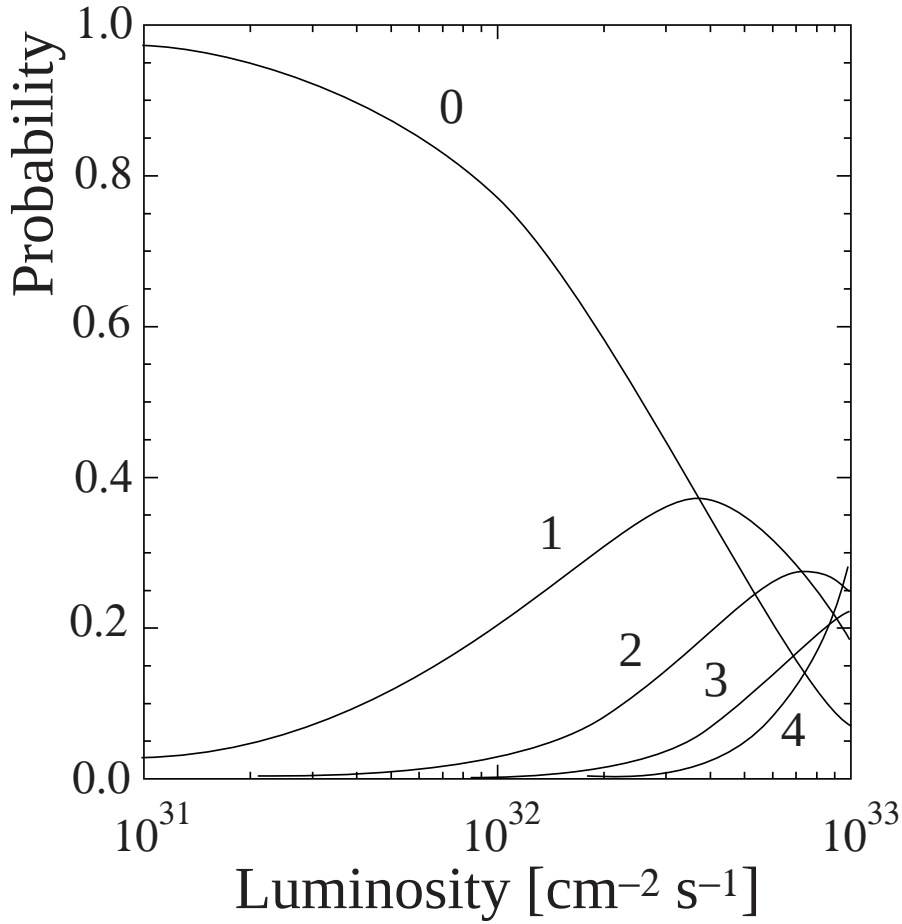
The choice of the LHCb collaboration



b physics at Hadron Colliders

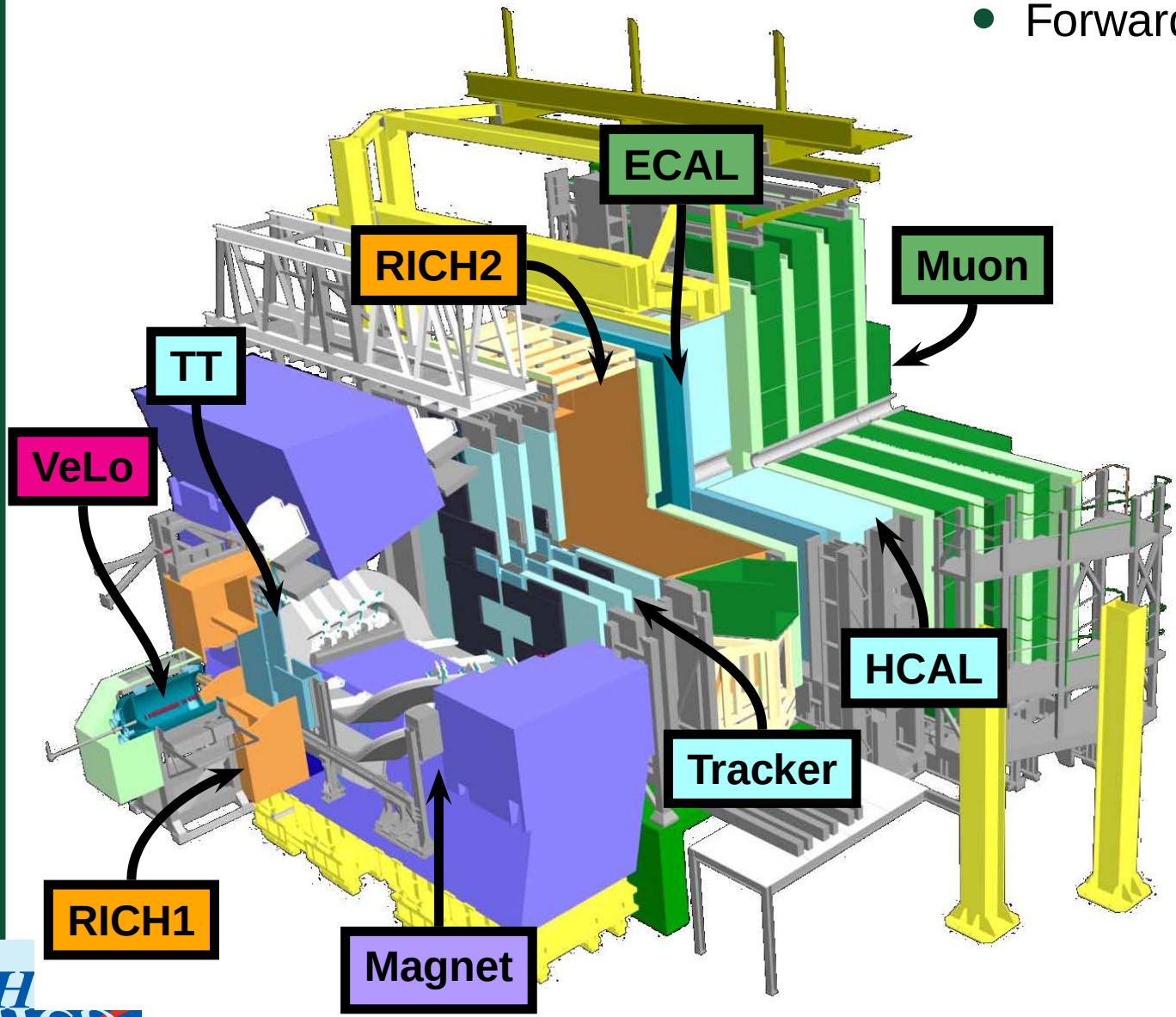
- B mesons have a long lifetime $c\tau = 0.5\,\mathrm{mm}$ with $\gamma = \mathcal{O}(10\text{–}100)$
  - You want to make lifetime-dependent measurements
    - ➜ Good vertex resolution

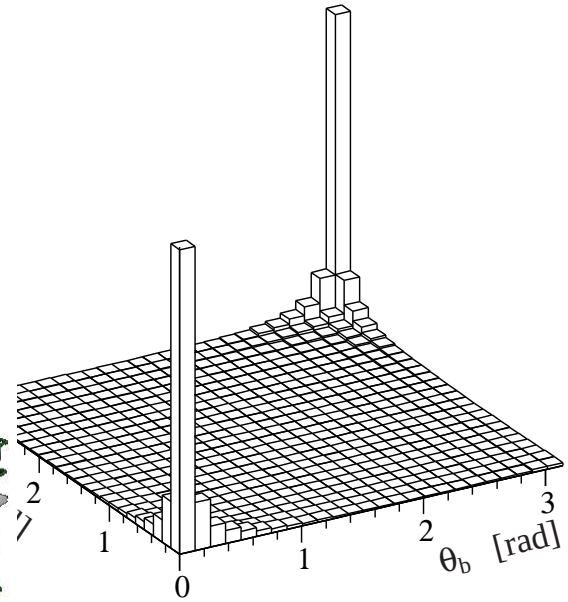
- ✗ Not too many pp interactions per bunch crossing
  - ➜ Aim for $2\text{–}5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    - Still $> 10^5$ b per second
    - We will reach baseline luminosity very early
- Good mass, i.e. momentum resolution
- Good particle ID to fight large background



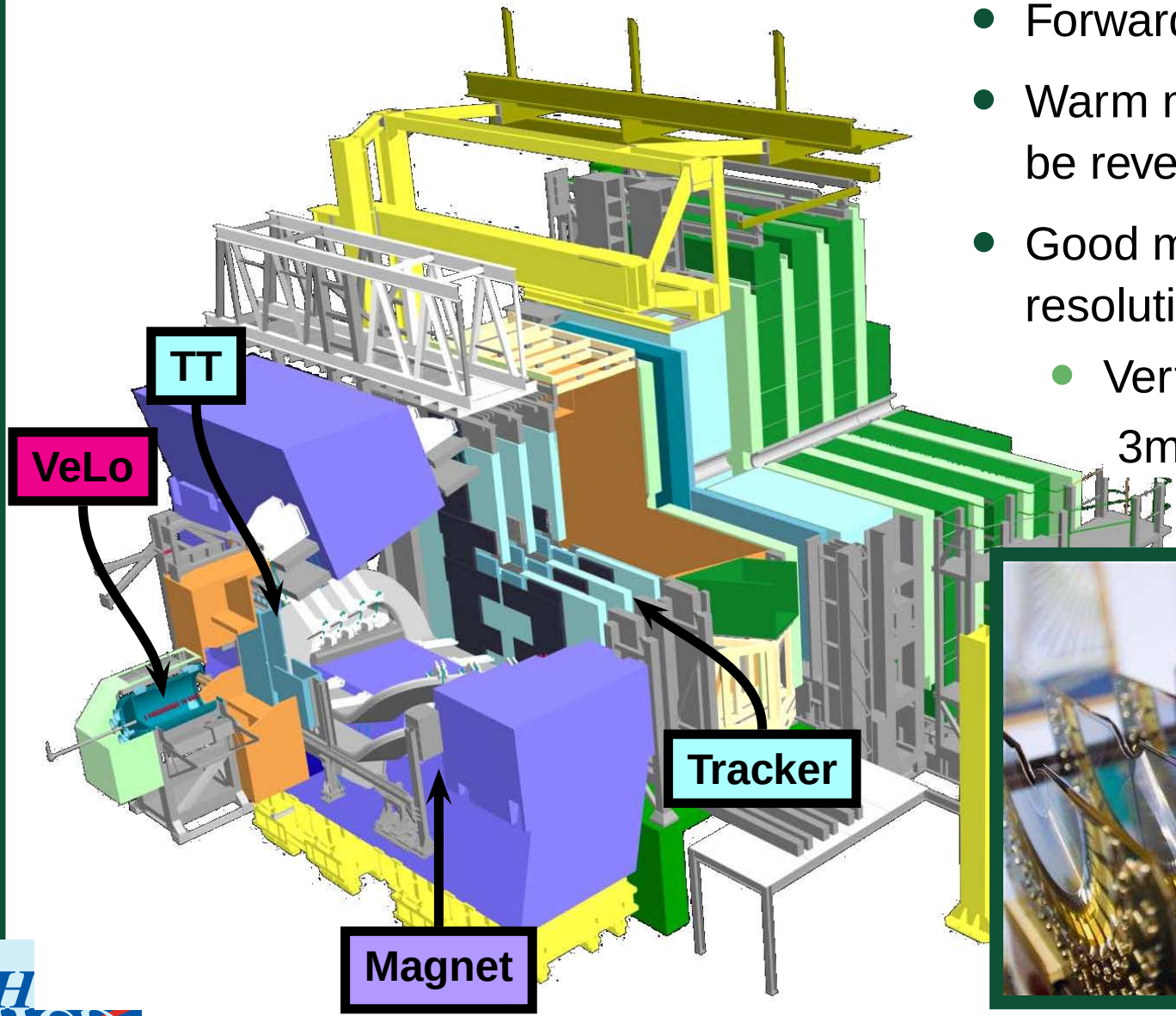
LHCb

- Forward detector



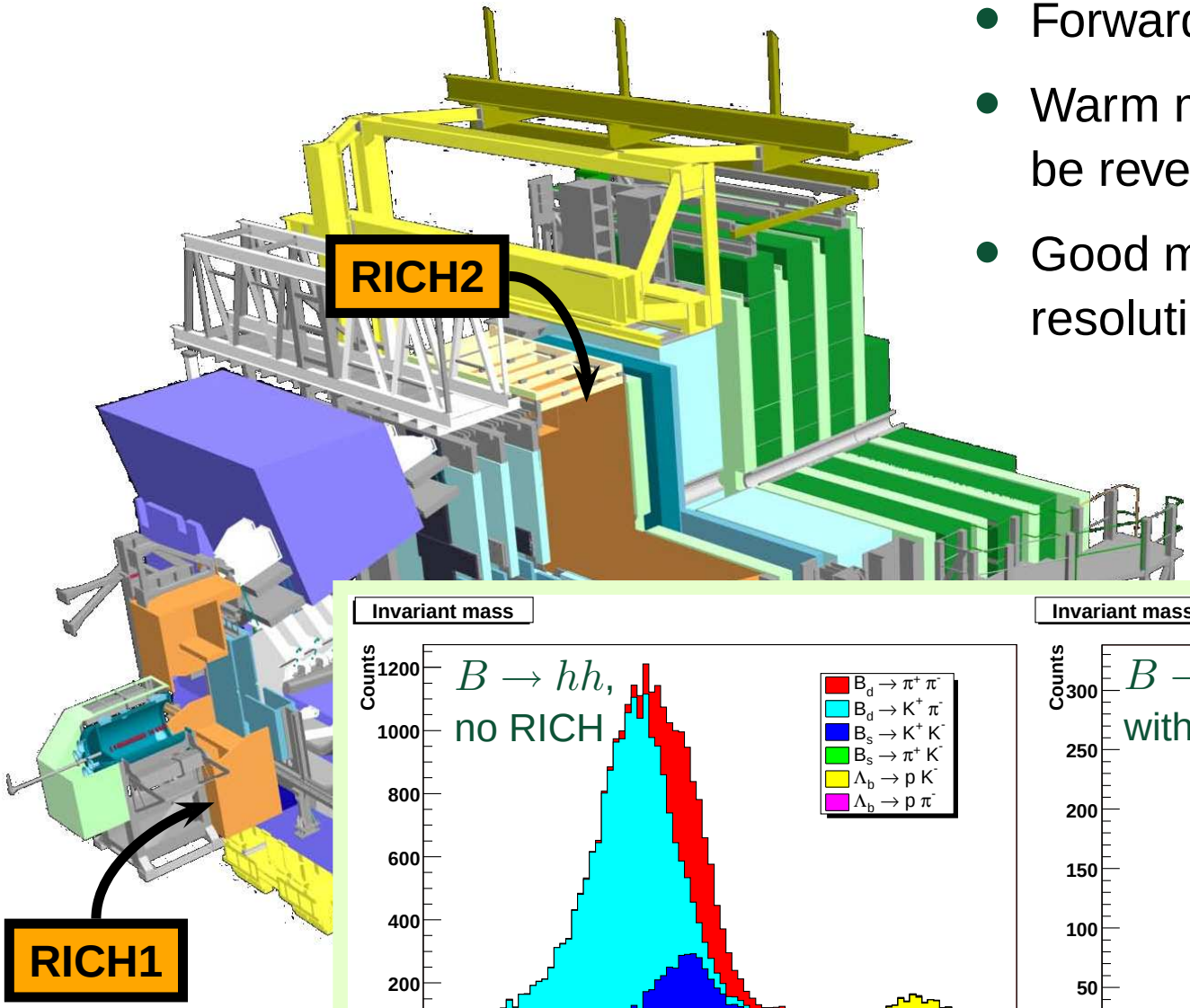


LHCb

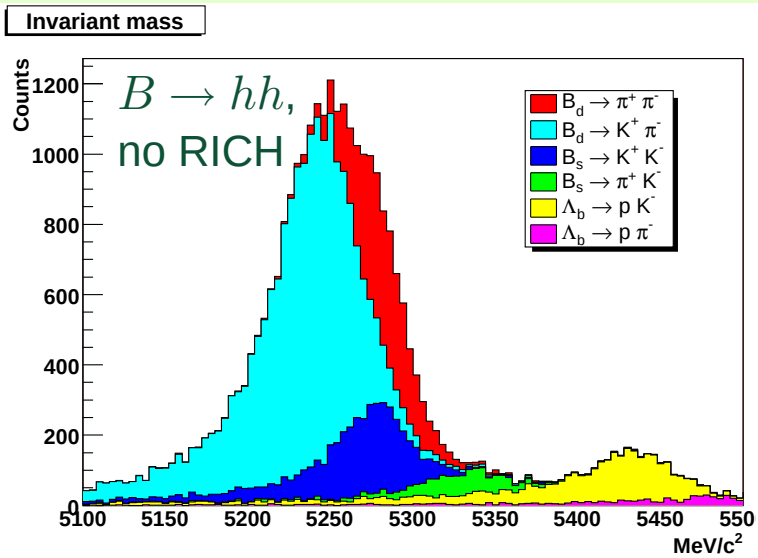


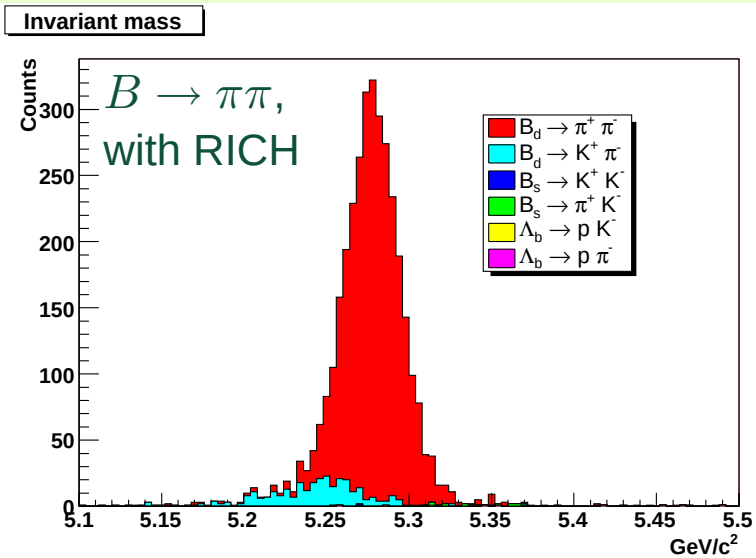
- Forward detector
- Warm magnet. Polarity can be reversed
- Good momentum and position resolution
  - Vertex detector gets 3mm to the beam

LHCb



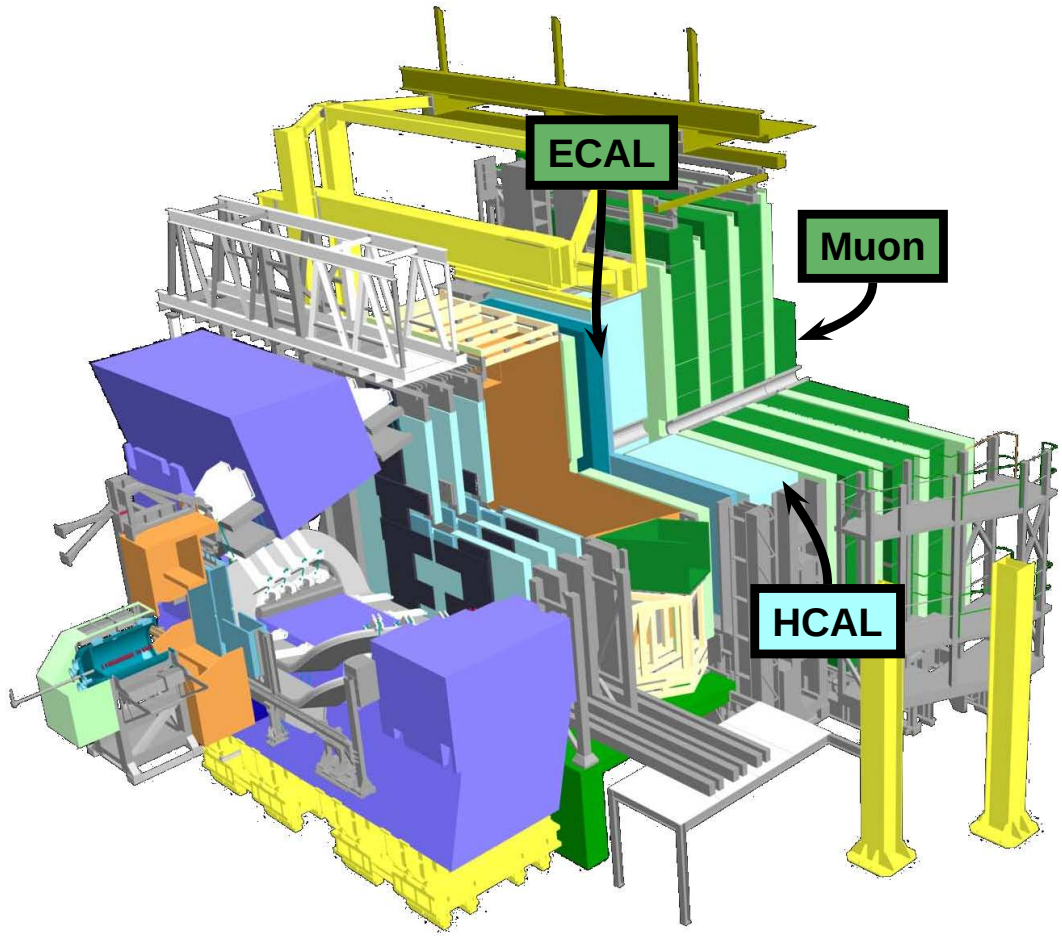
- Forward detector
- Warm magnet. Polarity can be reversed
- Good momentum and position resolution
- Good Particle Identification





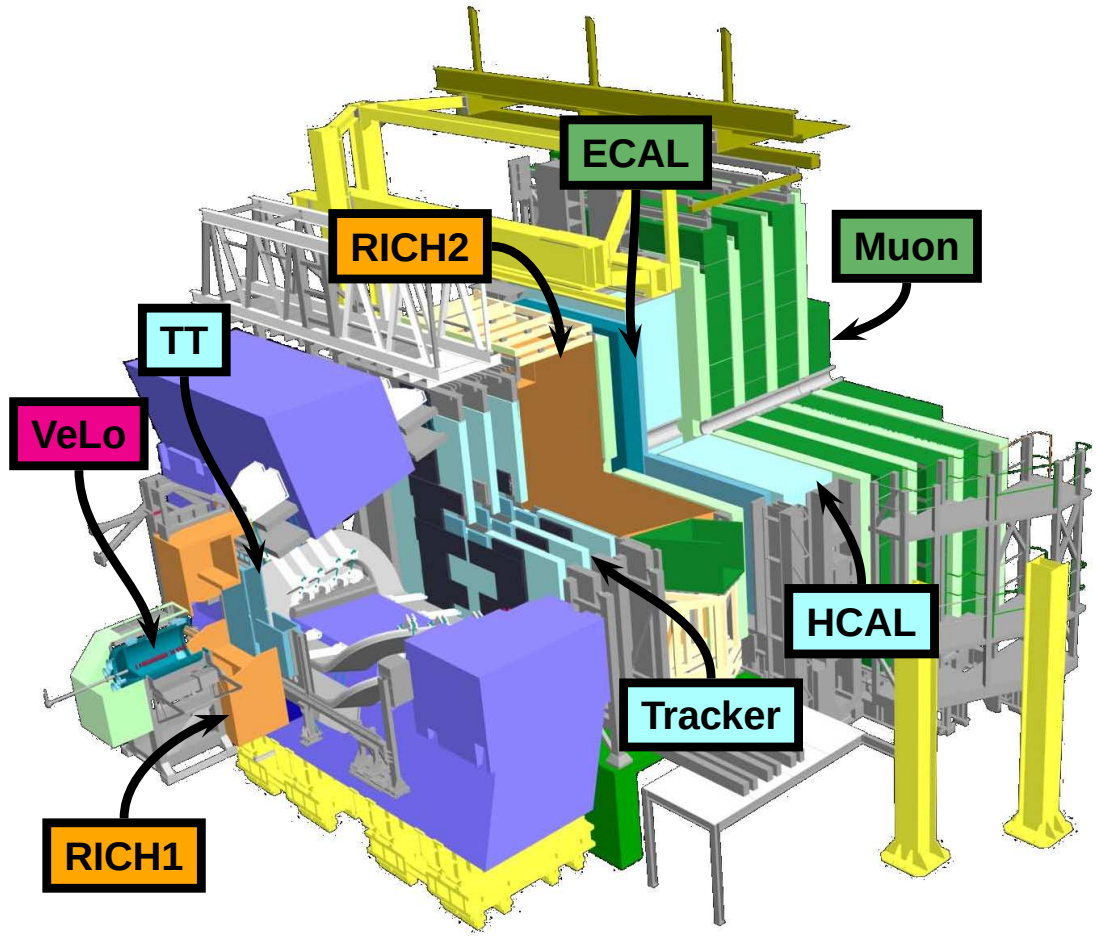
LHCb Trigger

- Hardware-based L0 trigger: moderate p_T cuts 40 MHz
  - ➜ 1 MHz
    - The whole data is then sent at 1 MHz to a farm of $\mathcal{O}(1000)$ CPUs



LHCb Trigger

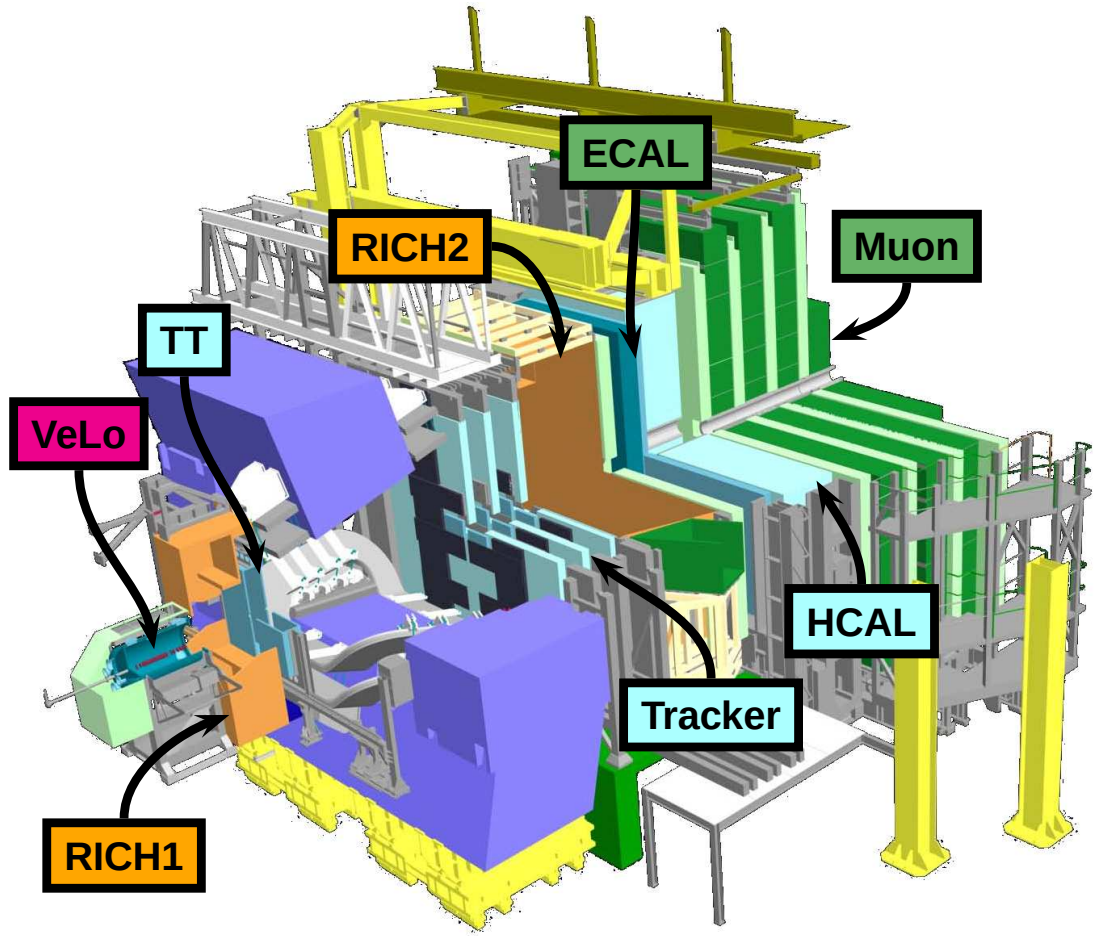
- Hardware-based L0 trigger: moderate p_T cuts 40 MHz
  - ➜ 1 MHz
    - The whole data is then sent at 1 MHz to a farm of $\mathcal{O}(1000)$ CPUs
- HLT1 tries to confirm a L0 decision by matching the L0 candidates to tracks.
  - ➜ $\mathcal{O}(40)$ kHz



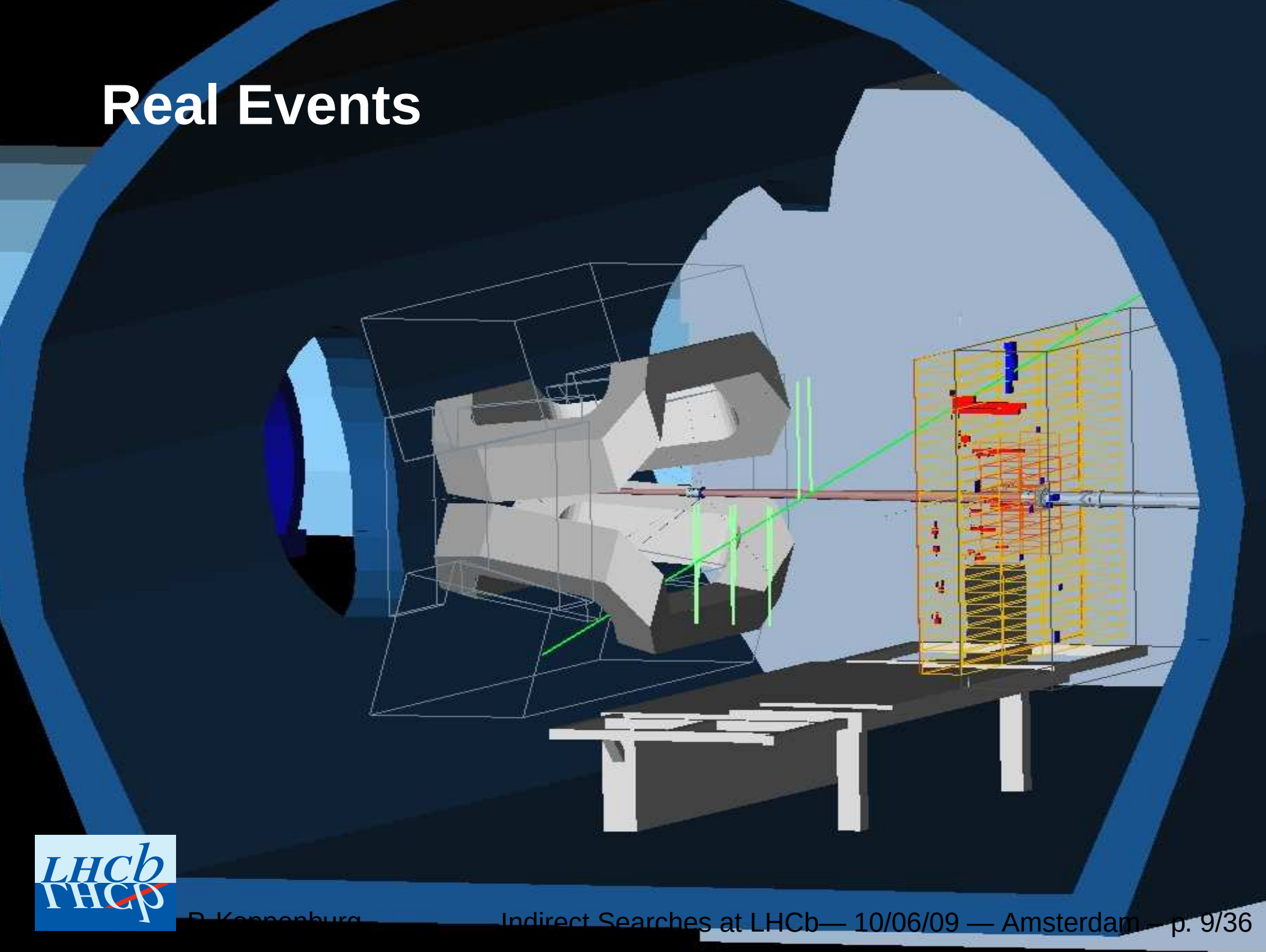
- HLT2 does the full reconstruction and loose selection of B/D candidates
  - ➜ 2 kHz
    - This is much less than the 10^5 b events per second

LHCb Trigger

- We want to keep all stages of reconstruction as similar as possible
  - ➜ Minimise systematics
- Getting the trigger to work will be the most important task of 2010
- It will be commissioned in stages. To be looked at carefully from physics.



Real Events

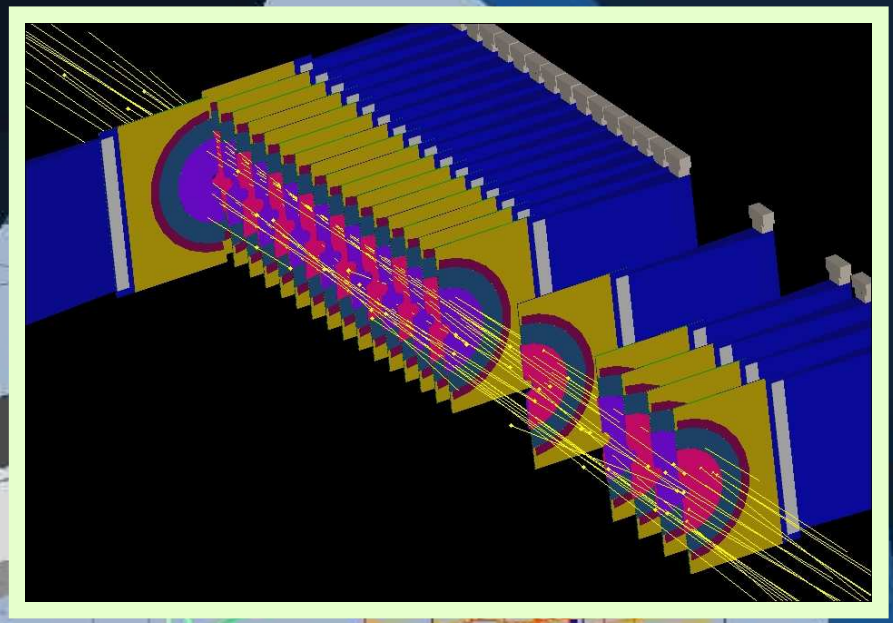


Real Events

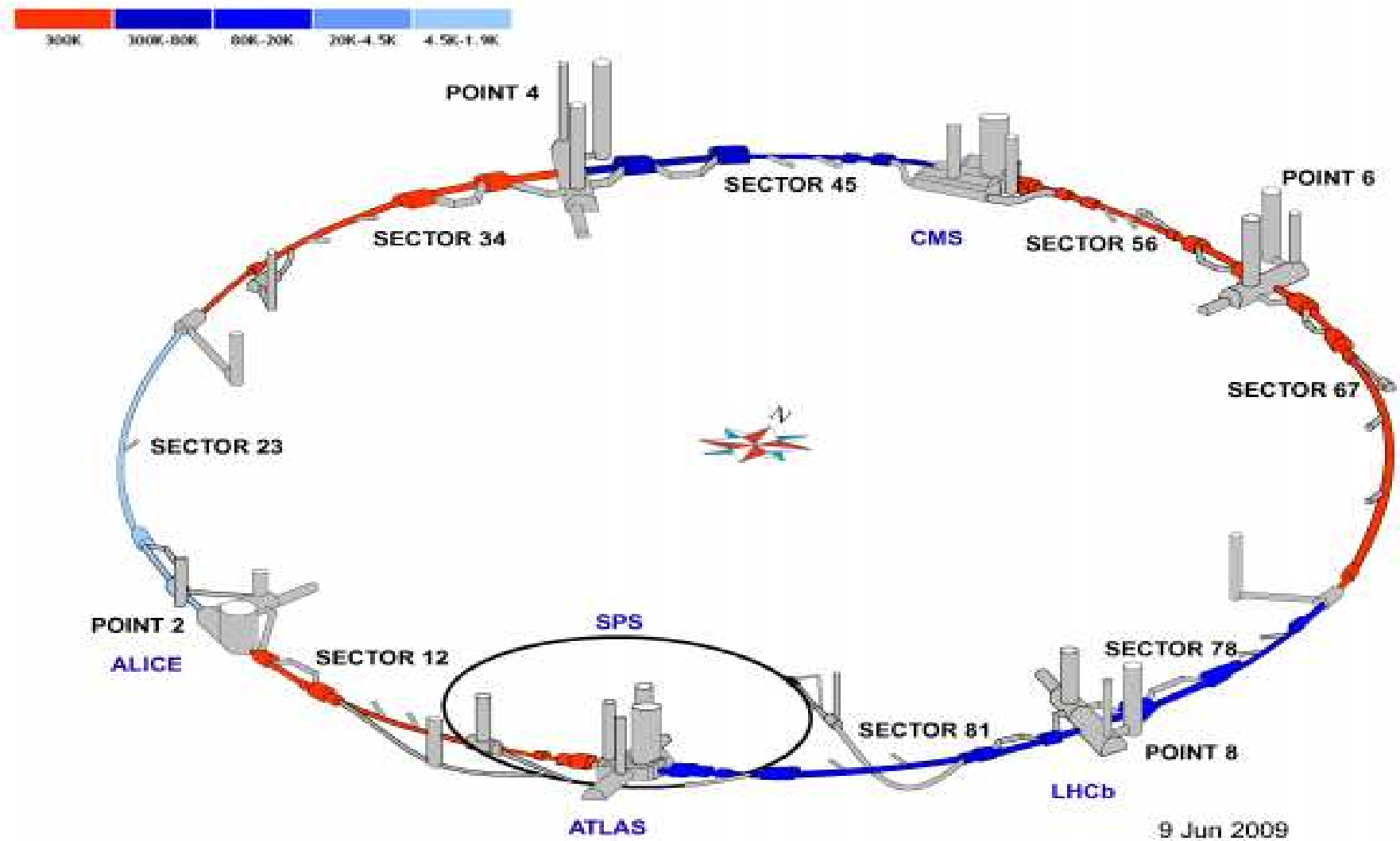
Commissioning

- All pieces are there
- We start to read out the whole detector
- We see some cosmic events
- And secondaries

➜ Waiting for collisions!

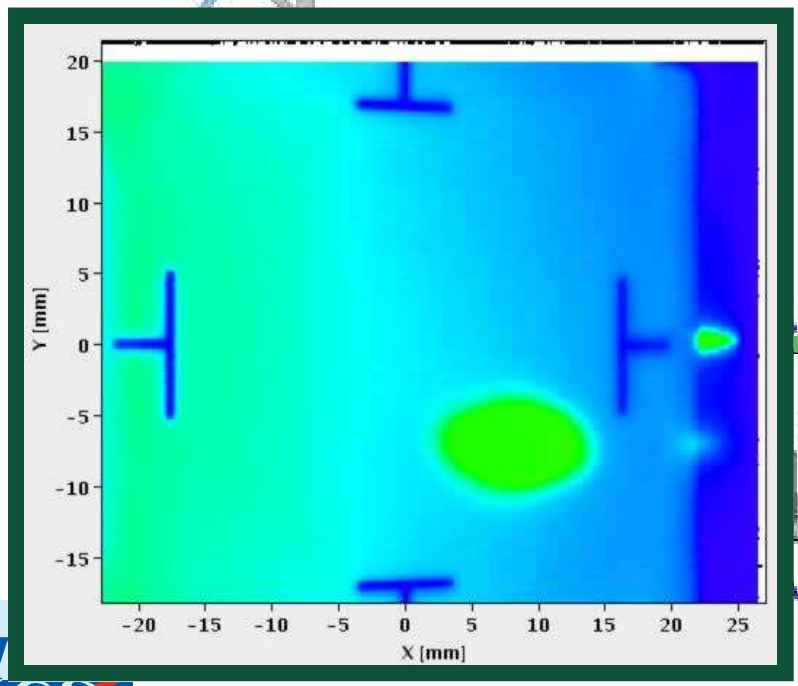


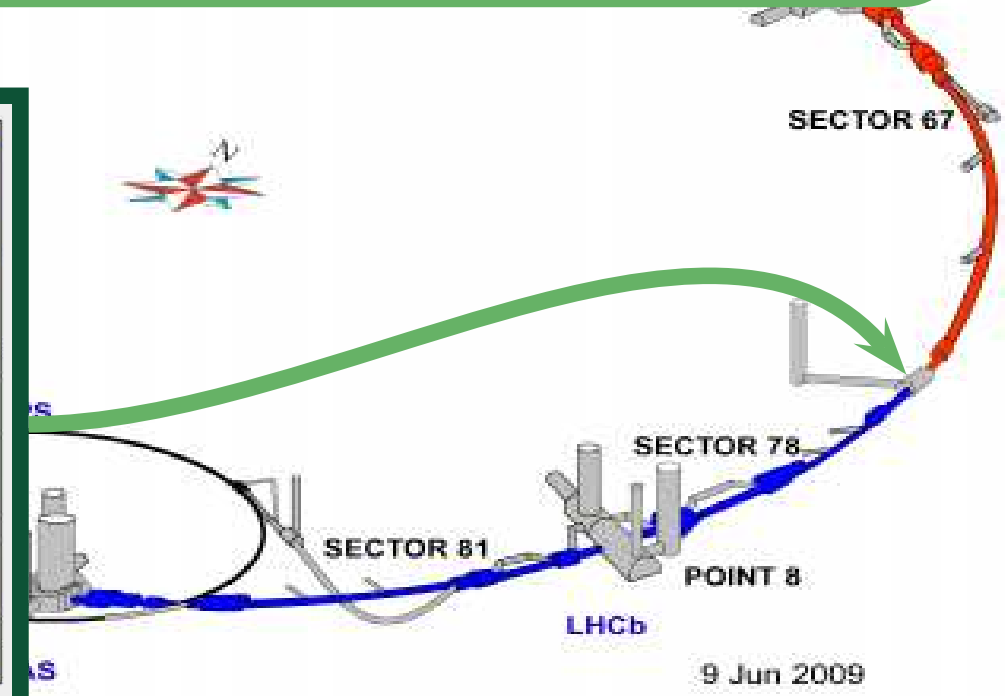
Status and Plans of LHC



Status and Plans of LHC

6–7 June	Synchronisation tests
Jul–Aug	Many more tests
September	First circulating beam





LHC start-up scenario (at LHCb)

month	Comment	Bunch	p/Bunch	β^*	$\mathcal{L}$	$\int \mathcal{L}$
1	Beam commissioning					
2	Pilot	19	$3 \cdot 10^{10}$	10 m	$2.4 \cdot 10^{29}$	$\sim 50\,\mathrm{nb}^{-1}$
3	No squeeze	19	$5 \cdot 10^{10}$	10 m	$6.0 \cdot 10^{29}$	$\sim 0.3\,\mathrm{pb}^{-1}$
4		72	$5 \cdot 10^{10}$	6 m	$3.8 \cdot 10^{30}$	$\sim 2\,\mathrm{pb}^{-1}$
5		72	$7 \cdot 10^{10}$	4 m	$1.1 \cdot 10^{31}$	$\sim 6\,\mathrm{pb}^{-1}$
6	50 ns	138	$7 \cdot 10^{10}$	4 m	$2.1 \cdot 10^{31}$	$\sim 11\,\mathrm{pb}^{-1}$
7	50 ns	276	$7 \cdot 10^{10}$	4 m	$4.2 \cdot 10^{31}$	$\sim 22\,\mathrm{pb}^{-1}$
8	50 ns	414	$7 \cdot 10^{10}$	4 m	$6.3 \cdot 10^{31}$	$\sim 34\,\mathrm{pb}^{-1}$
9	50 ns	414	$9 \cdot 10^{10}$	4 m	$1.0 \cdot 10^{32}$	$\sim 55\,\mathrm{pb}^{-1}$
10	50 ns	414	$9 \cdot 10^{10}$	4 m	$1.0 \cdot 10^{32}$	$\sim 55\,\mathrm{pb}^{-1}$
	All physics at 5&5 TeV				**TOTAL:** $\sim 200\,\mathrm{pb}^{-1}$	

http://lhc-commissioning.web.cern.ch/lhc-commissioning/luminosity/09-10-lumi-es

LHC start-up scenario (at LHCb)

mont						
1						
2						pb^{-1}
3						pb^{-1}
4						pb^{-1}
5						pb^{-1}
6						pb^{-1}
7						pb^{-1}
8						pb^{-1}
9	50 ns	414	$9 \cdot 10^{10}$	4 m	$1.0 \cdot 10^{32}$	$\sim 55\ \mathrm{pb}^{-1}$
10	50 ns	414	$9 \cdot 10^{10}$	4 m	$1.0 \cdot 10^{32}$	$\sim 55\ \mathrm{pb}^{-1}$
	All physics at 5&5 TeV				TOTAL: $\sim 200\ \mathrm{pb}^{-1}$	

LHC Schedule:

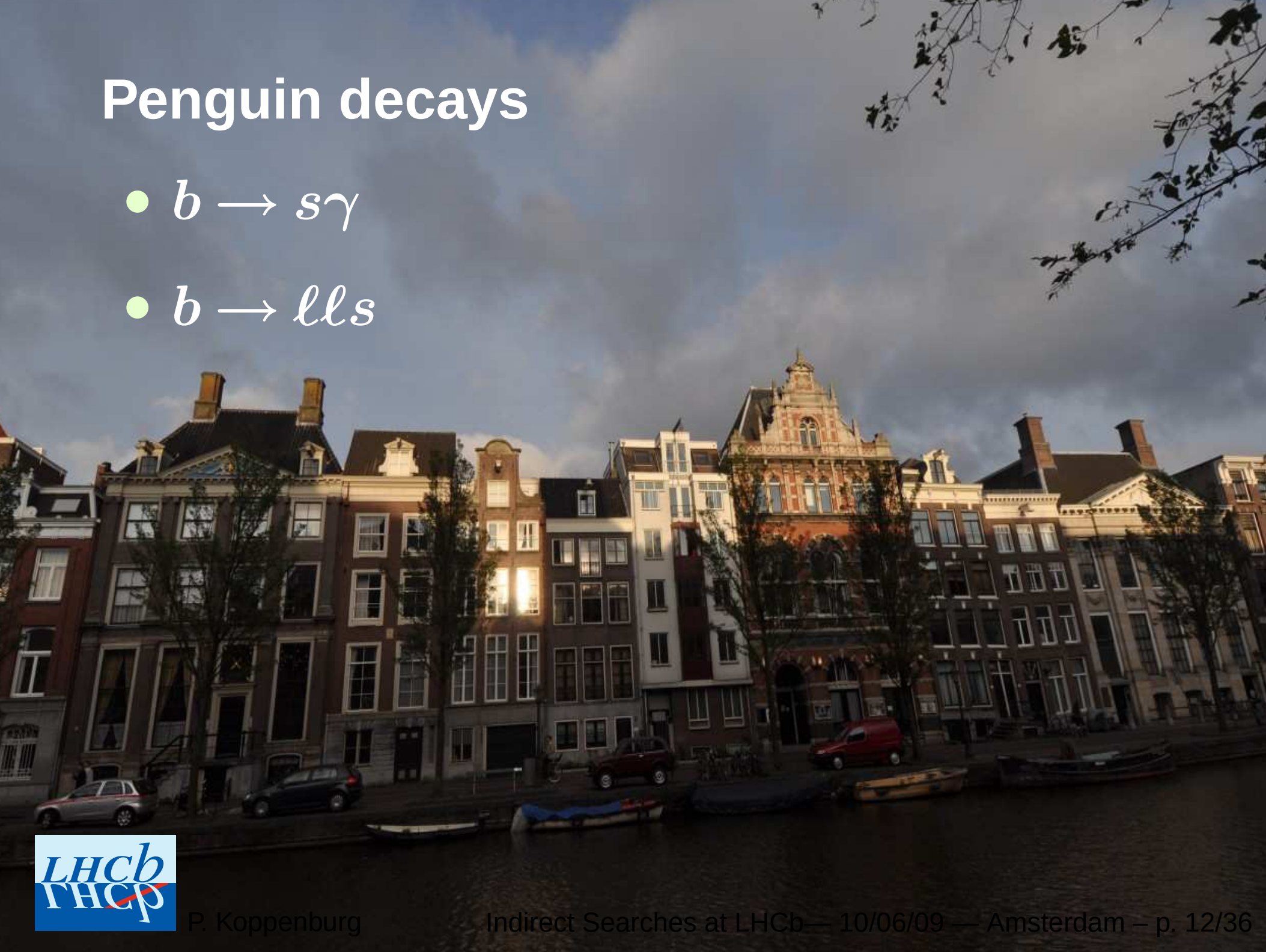
	$\sqrt{s}$	LHCb	Atlas & CMS
Sep–Jul	10 TeV	200 pb^{-1}	300 pb^{-1}
2011	14 TeV	1 fb^{-1}	A few fb^{-1}
2012+	14 TeV	2 fb^{-1}/ year	10 fb^{-1}/ year

Most sensitivity studies are for $2\ \mathrm{fb}^{-1}$ at LHCb

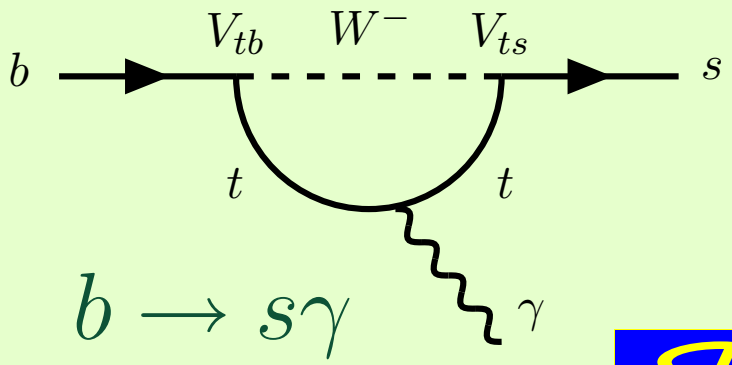
http://lhc-commissioning.web.cern.ch/lhc-commissioning/luminosity/09-10-lumi-es

Penguin decays

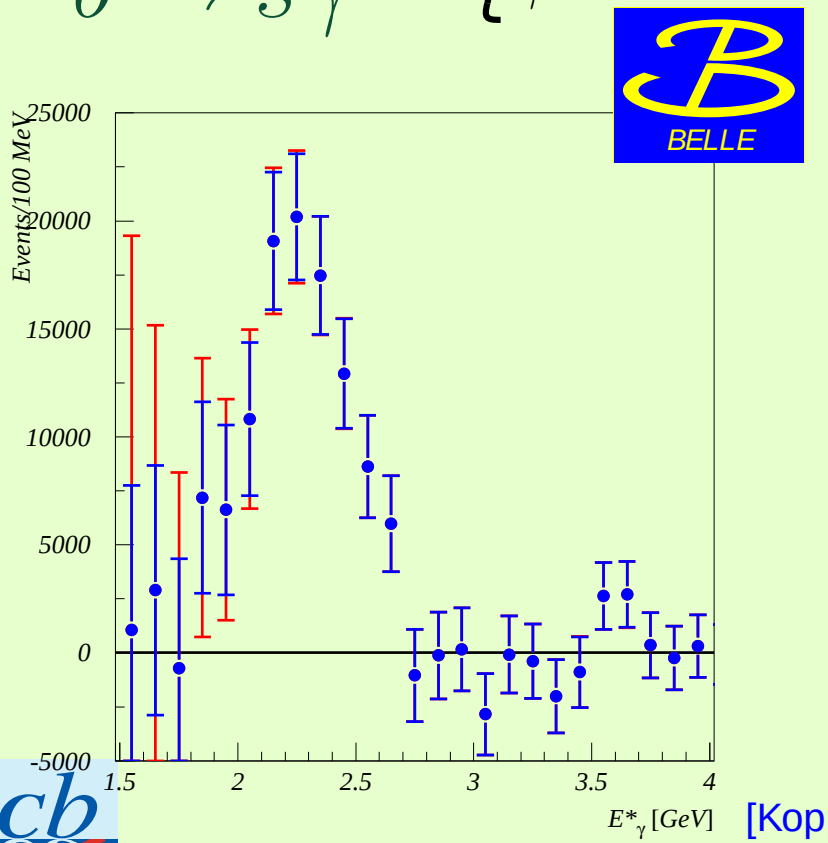
- $b \longrightarrow s\gamma$
- $b \longrightarrow \ell\ell s$



$b \to s\gamma$ photon polarisation



$b \to s\gamma$



BF sets strong constraints on New Physics

The photon polarisation is not well measured.

- Naively $r = \frac{C'_{7\gamma}}{C_{7\gamma}} \overset{\text{SM}}{\simeq} \frac{m_s}{m_b}$
- Right-handed operators could contribute

✔ Mixing-induced CP violation in $B_s \to \phi\gamma$

- Λ_b baryons
- $B \to \gamma K^{**}(K\pi\pi)$

✔ Virtual photons ($b \to \ell\ell s$)

- Converted photons

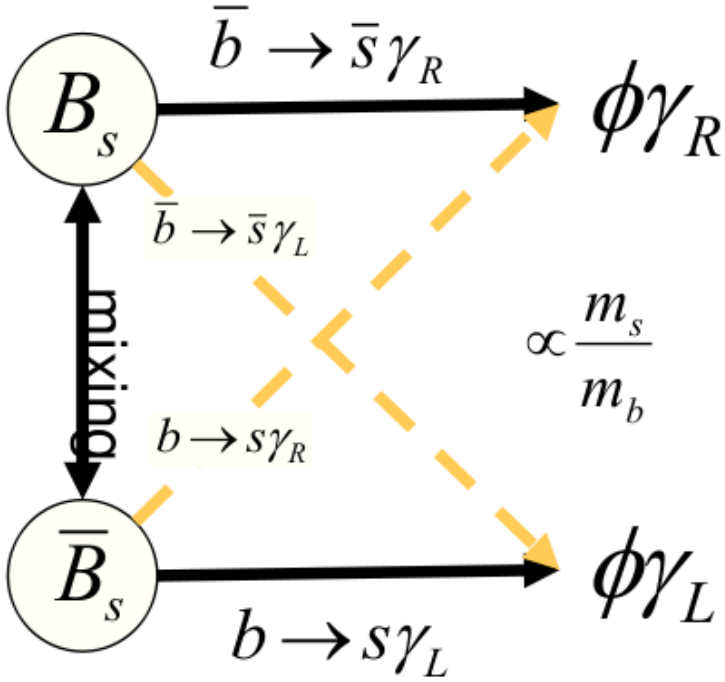
[Koppenburg et al., PRL93, 061803 (2004)]

$B_s \to \phi\gamma$

In SM mainly $B_s \to \phi\gamma_R$ and $\overline{B}_s \to \phi\gamma_L$. Mixing only if wrong polarisation.

$\mathcal{A}^{\text{mix}}$ tiny $\qquad \mathcal{A}^{\text{dir}} = 0$ in MFV $\qquad \mathcal{A}^{\Delta\Gamma} \propto r$

$$\mathcal{A}_s(t) = \frac{\Gamma_{\overline{B}_s \to \phi\gamma} - \Gamma_{B_s \to \phi\gamma}}{\Gamma_{\overline{B}_s \to \phi\gamma} + \Gamma_{B_s \to \phi\gamma}} = \frac{\mathcal{A}^{\text{dir}} \cos \Delta m_s t + \mathcal{A}^{\text{mix}} \sin \Delta m_s t}{\cosh \frac{1}{2}\Delta\Gamma t - \mathcal{A}^{\Delta\Gamma} \sinh \frac{1}{2}\Delta\Gamma t}$$



Tagged approach (measure all $\mathcal{A}$):

- ➜ 12% on $\mathcal{A}^{\text{mix}}$ (2 fb^{-1})
- ➜ 23% error on $\mathcal{A}^{\Delta\Gamma}$ (2 fb^{-1})

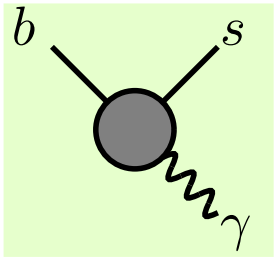
Untagged approach (only $\mathcal{A}^{\Delta\Gamma} \propto r$):

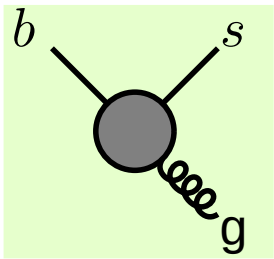
- ➜ 19% error (2 fb^{-1})
  - 9% with 10 fb^{-1}

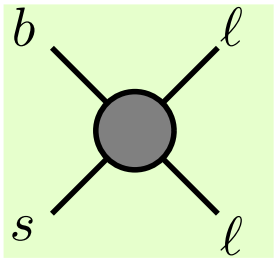
[LHCb-2007-147]

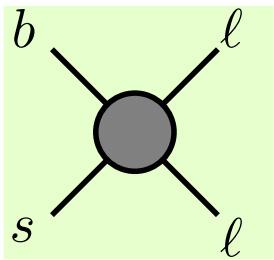
Operators

Operator

$\mathcal{O}_{7\gamma}$ 

$\mathcal{O}_{8g}$ 

$\mathcal{O}_{9\ell,10\ell}$ 

$\mathcal{O}_{S,P}$ 

Effective Hamiltonian $\mathcal{H}$

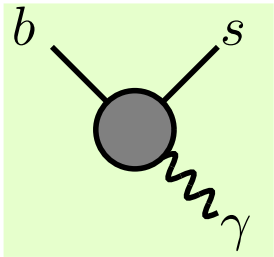
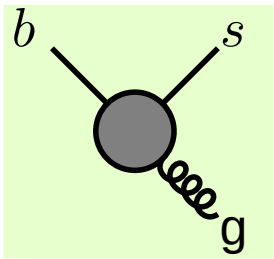
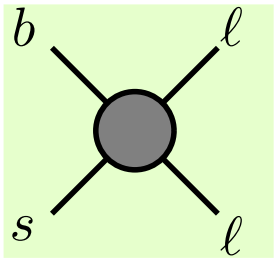
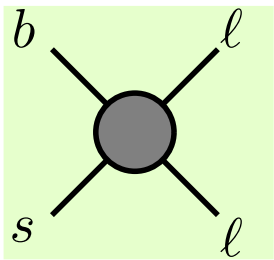
$$A(M \to F) = \langle F \,|\mathcal{H}_{\text{eff}}|\, M \rangle$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}{}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$

- Operators $\mathcal{O}_i$: Long-distance effects
- Wilson coefficients C_i: Short-distance effects (masses above μ are integrated out)

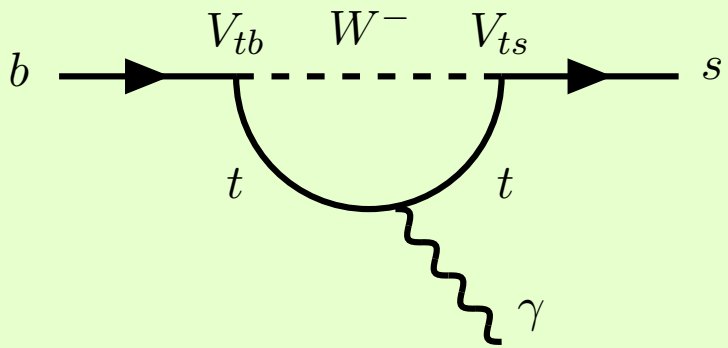
New physics can show up in new operators or modified Wilson coefficients

Operators

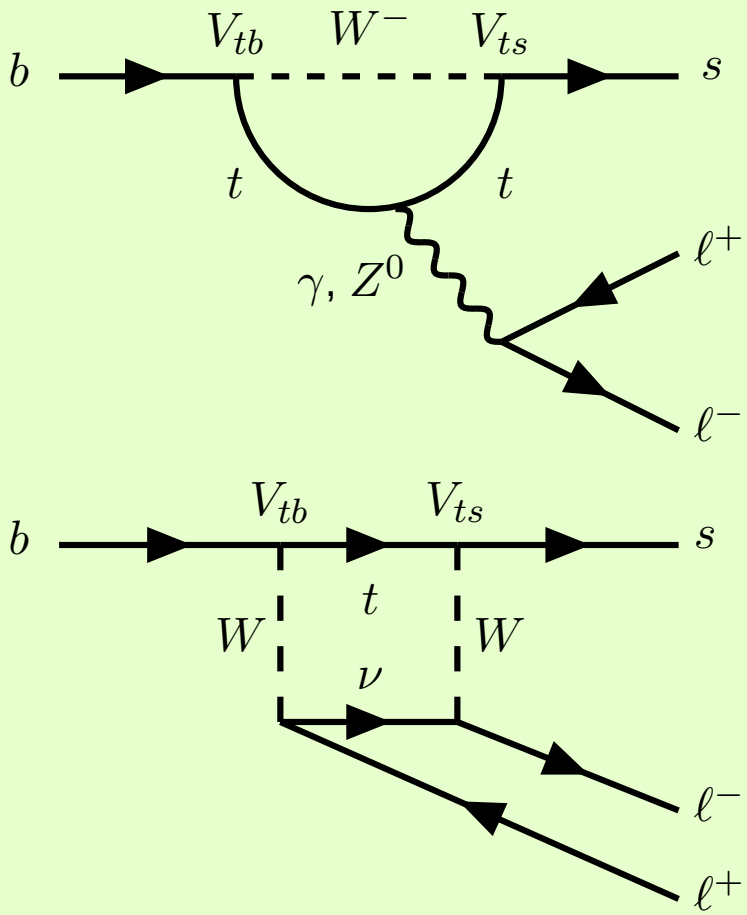
Operator		magnitude	phase	helicity flip $\mathcal{O}'_i$
$\mathcal{O}_{7\gamma}$		$b \to s\gamma$	$A_{CP}\,(b\to s\gamma)$	$\Lambda_b\to\Lambda\gamma$ $B_s\to\phi\gamma$ $B\to\ell\ell K^*$
$\mathcal{O}_{8g}$		$b \to s\gamma$ $b\to\{s,u,d\}$	$A_{CP}\,(b\to s\gamma)$ $B \to \phi K$	$\Lambda_b\to\Lambda\phi$ $B\to K^*\phi$
$\mathcal{O}_{9\ell,10\ell}$		$b \to \ell\ell s$	$A_{FB}\,(b\to\ell\ell s)$	$B\to\ell\ell K^*$
$\mathcal{O}_{S,P}$		$B \to \mu\mu$	$B \to \tau\tau$	$b \to s\tau\tau$

Adapted from [G.Hiller,hep-ph/0308180]

Semileptonic penguins

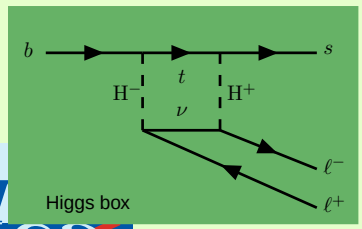


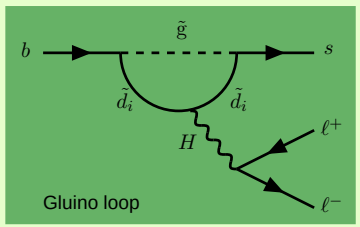
Semileptonic penguins

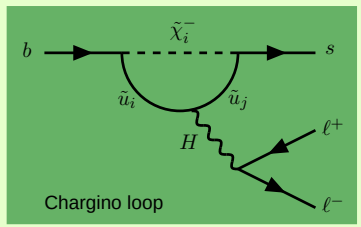


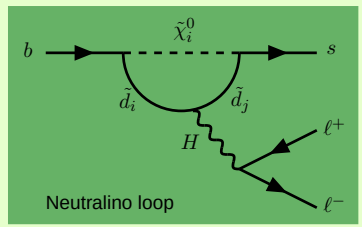
- $B \to \mu\mu K^*$ very rare in the SM
  $\mathcal{B}(B \to \ell\ell K^*) = (1.2 \pm 1.0) \cdot 10^{-6}$
  $\mathcal{B}(B \to \ell\ell K) = (0.5 \pm 0.1) \cdot 10^{-6}$
- Sensitive to
  - Supersymmetry,
  - Graviton exchanges,
  - Extra dimensions

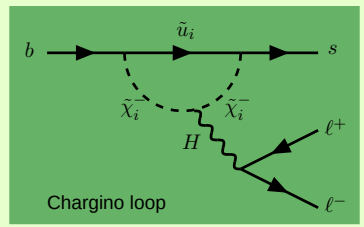
➜ Ideal place to look for new physics











$b \to \ell\ell s$ observables

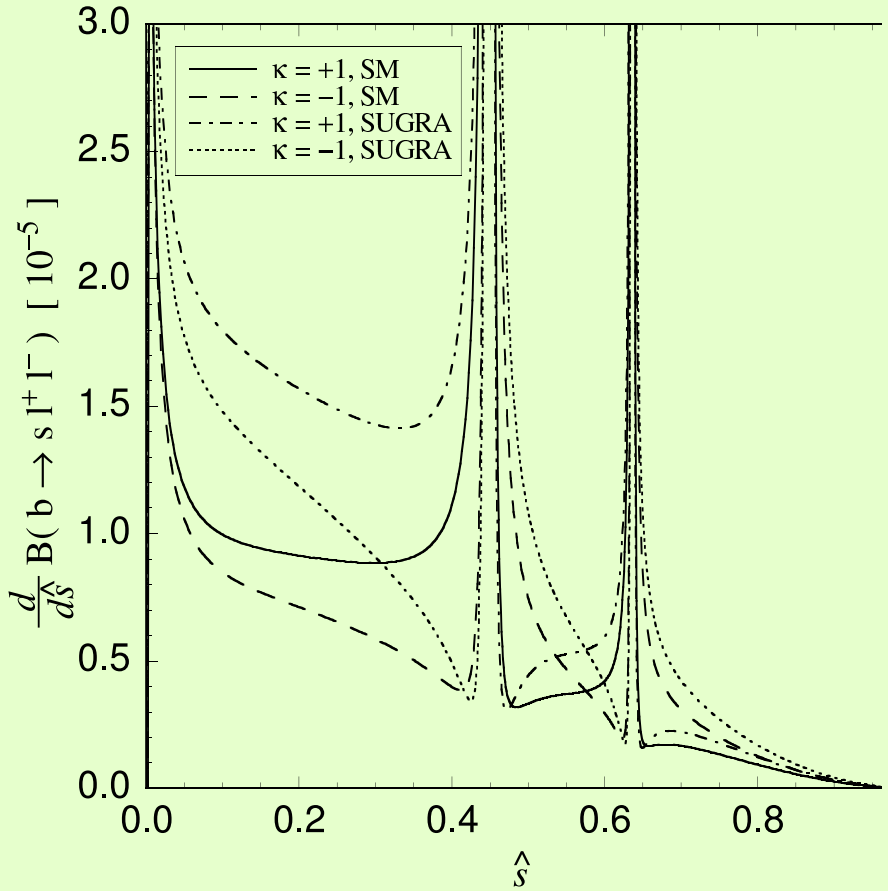
Inclusive decay well described theoretically

- Shape of dilepton mass distribution sensitive to NP
- SM branching ratio $(1.36 \pm 0.08) \cdot 10^{-6}$ (NNLL) for $s = q^2/m_b^2 < 0.25$

✗ Inclusive decays difficult to access experimentally

✗ Exclusive decays affected by hadronic uncertainties

➜ Use ratios where hadronic uncertainties cancel out



[Goto et al., PRD55 (1997) 4273]

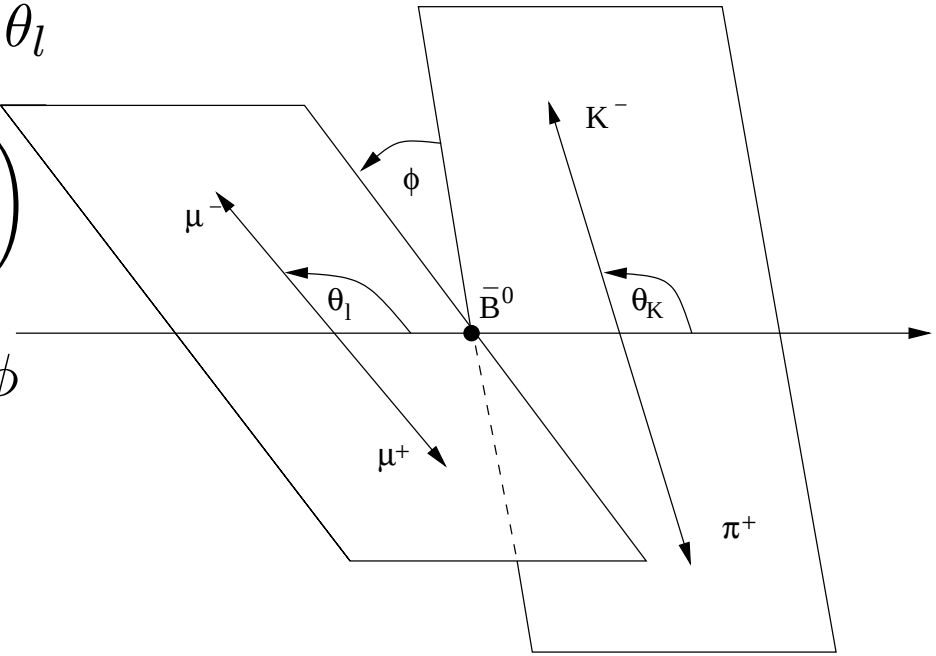
Angular Distributions

There's more information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_l} = \Gamma' \left(\frac{3}{4} F_L \sin^2\theta_l + A_{\mathsf{FB}} \cos\theta_l + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l) \right)$$

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\phi} = \frac{\Gamma'}{2\pi} \left(\frac{1}{2}(1-F_L) A_T^{(2)} \cos 2\phi + A_{\mathsf{Im}} \sin 2\phi + 1 \right)$$

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_K} = \frac{3\Gamma'}{4} \sin\theta_K \left(2F_L \cos^2\theta_K + (1-F_L)\sin^2\theta_K \right)$$



➜ **Many observables**

[Krüger & Matias] [Egede, et. al.]

Angular Distributions

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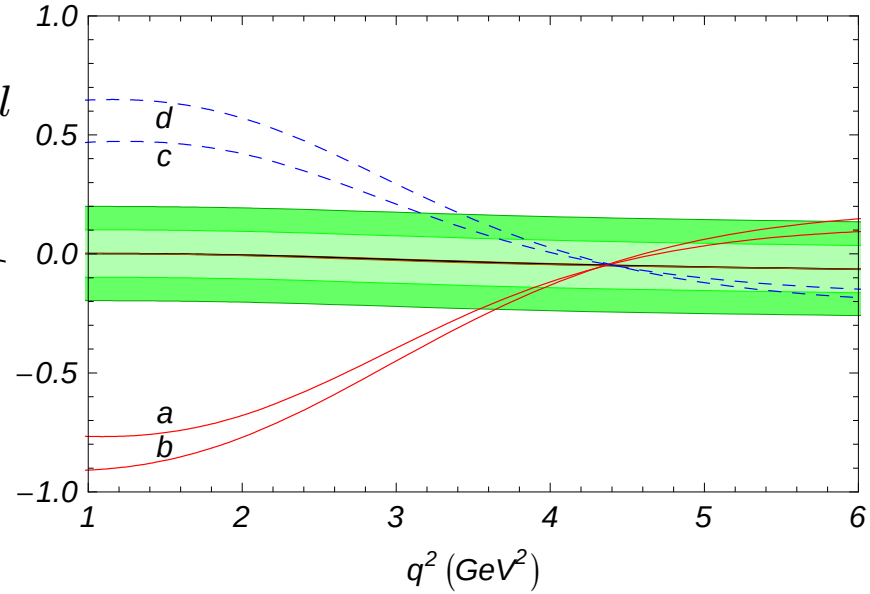


➜ **Transverse asymmetry $A_T^{(2)}$ (RH)**

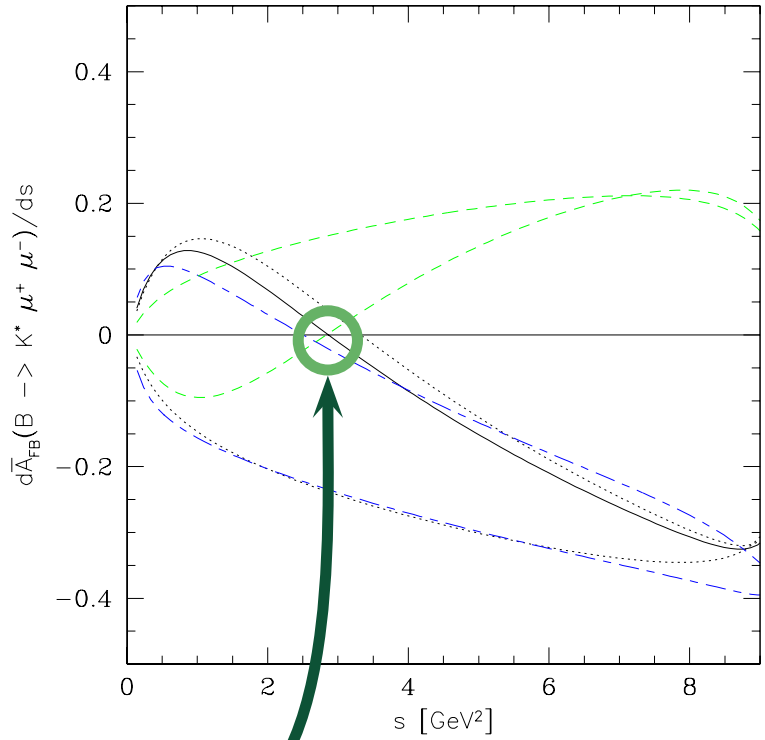
[Krüger & Matias] [Egede, et. al.]

Angular Distributions

There's more information in the full θ_ℓ, θ_K and ϕ distributions

$$\frac{\mathrm{d}\Gamma'}{\mathrm{d}\theta_l} = \Gamma' \left(\frac{3}{4} F_L \sin^2\theta_l + A_{\mathrm{FB}} \cos\theta_l + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l) \right)$$

$$A_{\mathrm{FB}} = \frac{\left(\int_0^1 - \int_{-1}^0 \right) \mathrm{d}\cos\theta_l \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_l}}{\int_{-1}^1 \mathrm{d}\cos\theta_l \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_l}}$$



➜ Zero point measures ratio of Wilson coeffs C_9/C_7.

➜ **Forward-backward asymmetry A_{FB}**

[Krüger & Matias] [Egede, et. al.]

Messages from the B factories

Belle: 160+250 $B \to \ell\ell K^{(*)}$ events in $657 \cdot 10^6$ $B\overline{B}$

[J.T. Wei et al., arXiv:0904.0770v1]

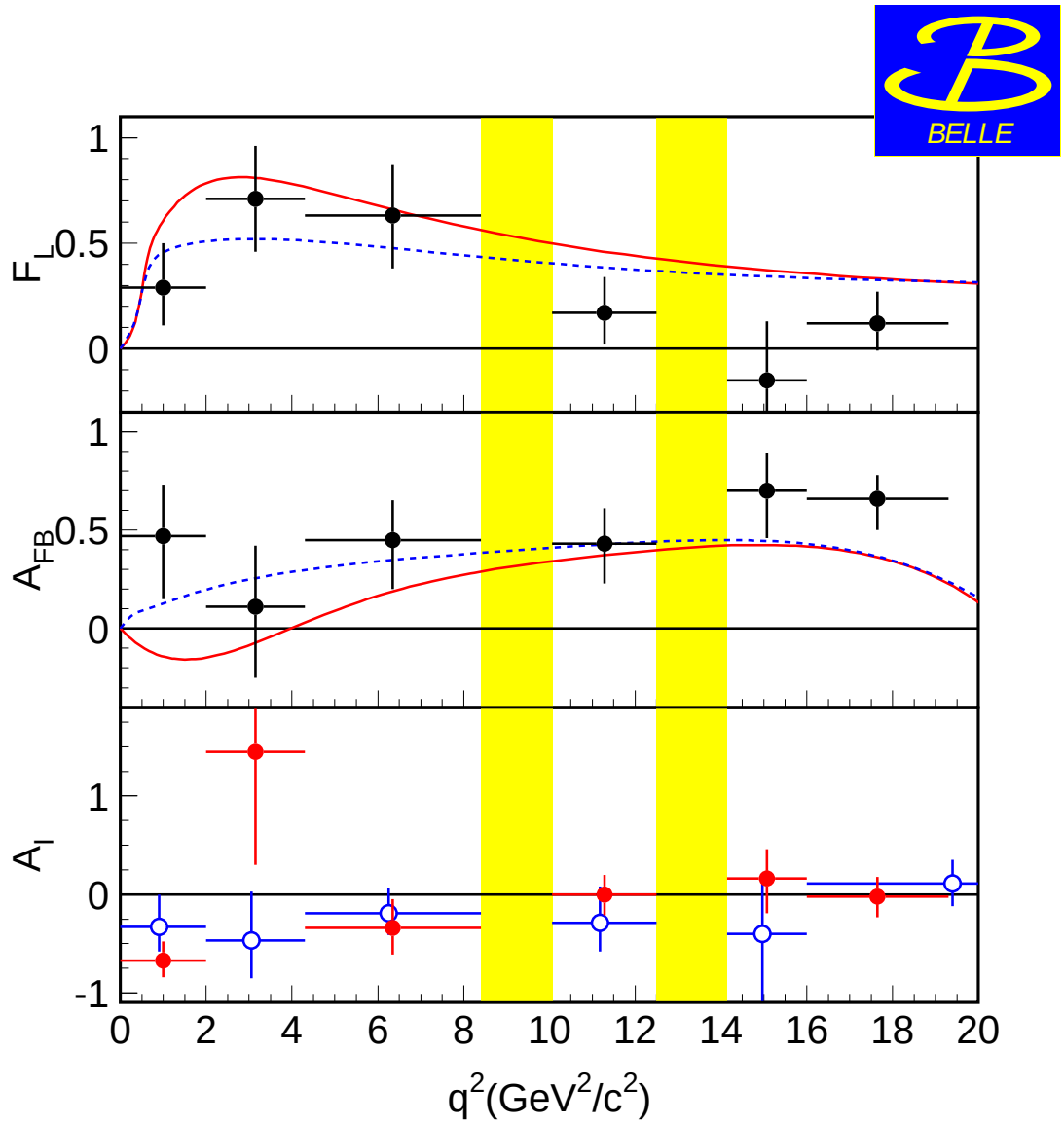
Babar: 50+60 $B \to \ell\ell K^{(*)}$ events in $384 \cdot 10^6$ $B\overline{B}$

[Aubert et al., PRD 79:031102,2009]

[Aubert et al., PRL 102:091803,2009]

F_L: Too little statistics

FB asymmetry: Not conclusive yet. . .



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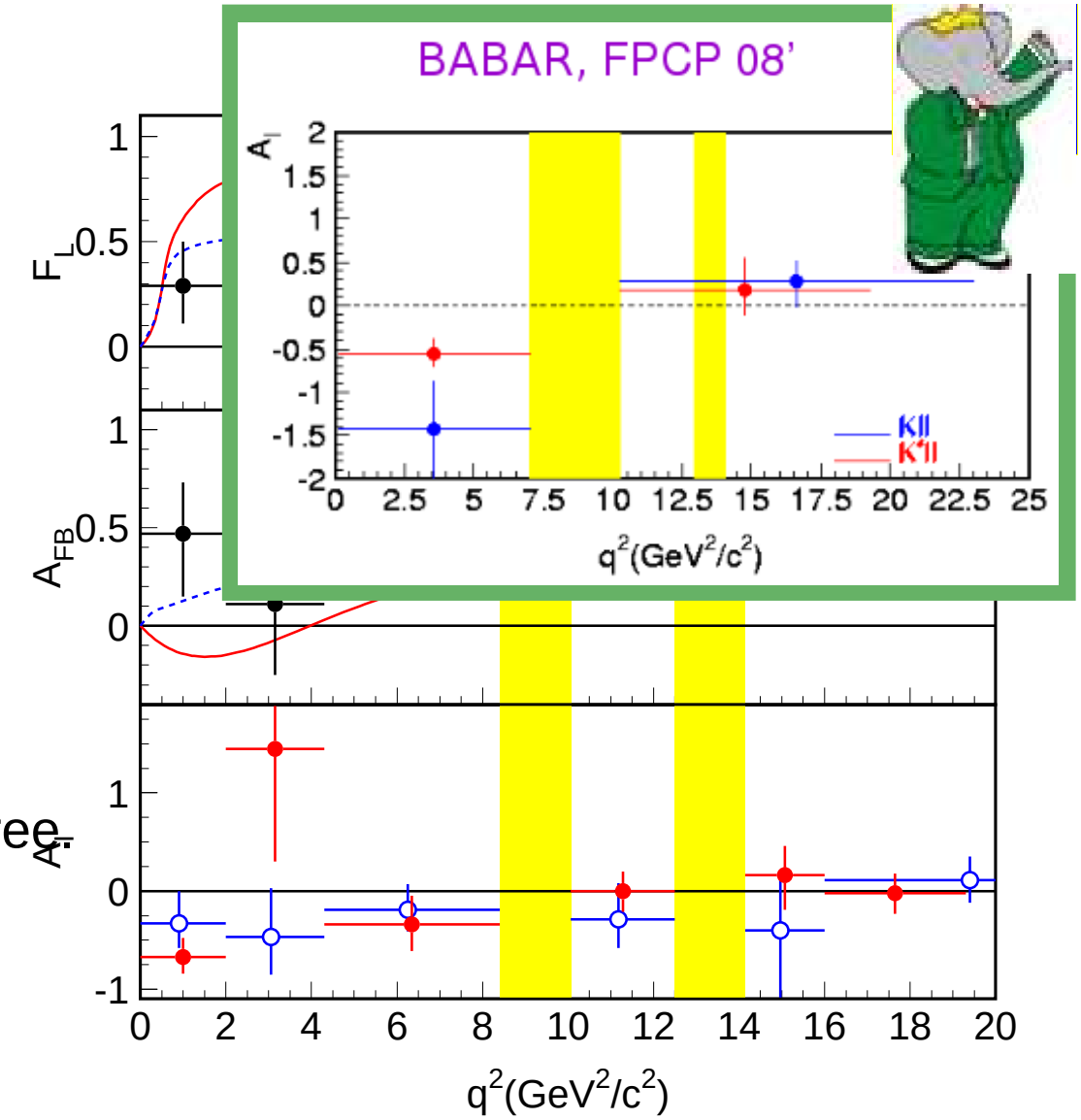
F_L: Too little statistics

FB asymmetry: Not conclusive yet. . .

Isospin: Belle and Babar disagree.

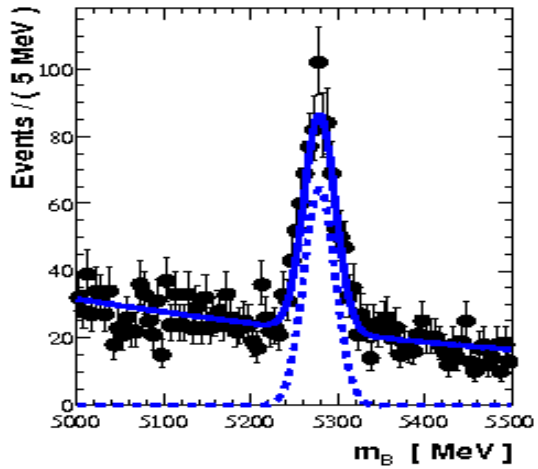
➜ Need much more statistics

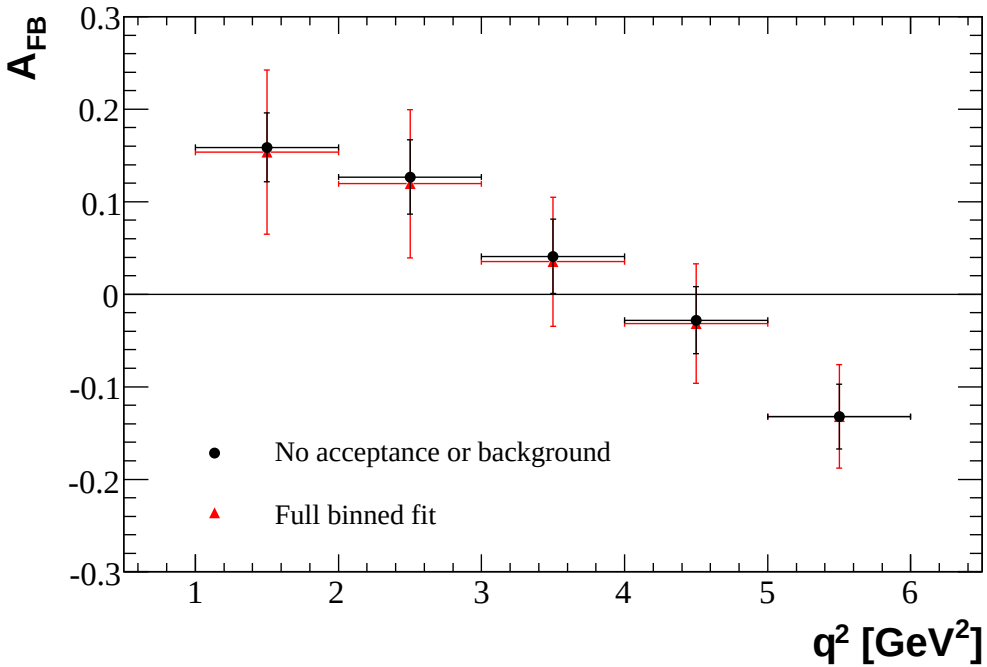


$B_d \to \mu\mu K^*$ yields with 2 fb^{-1}

Expected signal and background yields in 2 fb^{-1} of data (Assuming the SM BR of $\mathbf{12 \cdot 10^{-7}}$):

Sample	Yield
$\boldsymbol{B_d \to \mu\mu K^*}$	$\mathbf{7200 \pm 2100}$
$b \to \mu\mu s$	2000 ± 100
$2(b \to \mu)$	1050 ± 250
$b \to \mu c(\mu q)$	600 ± 200
Background	3700 ± 300
$\boldsymbol{B/S}$	$\mathbf{0.5 \pm 0.2}$



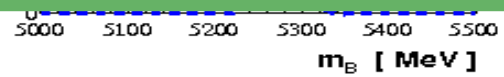


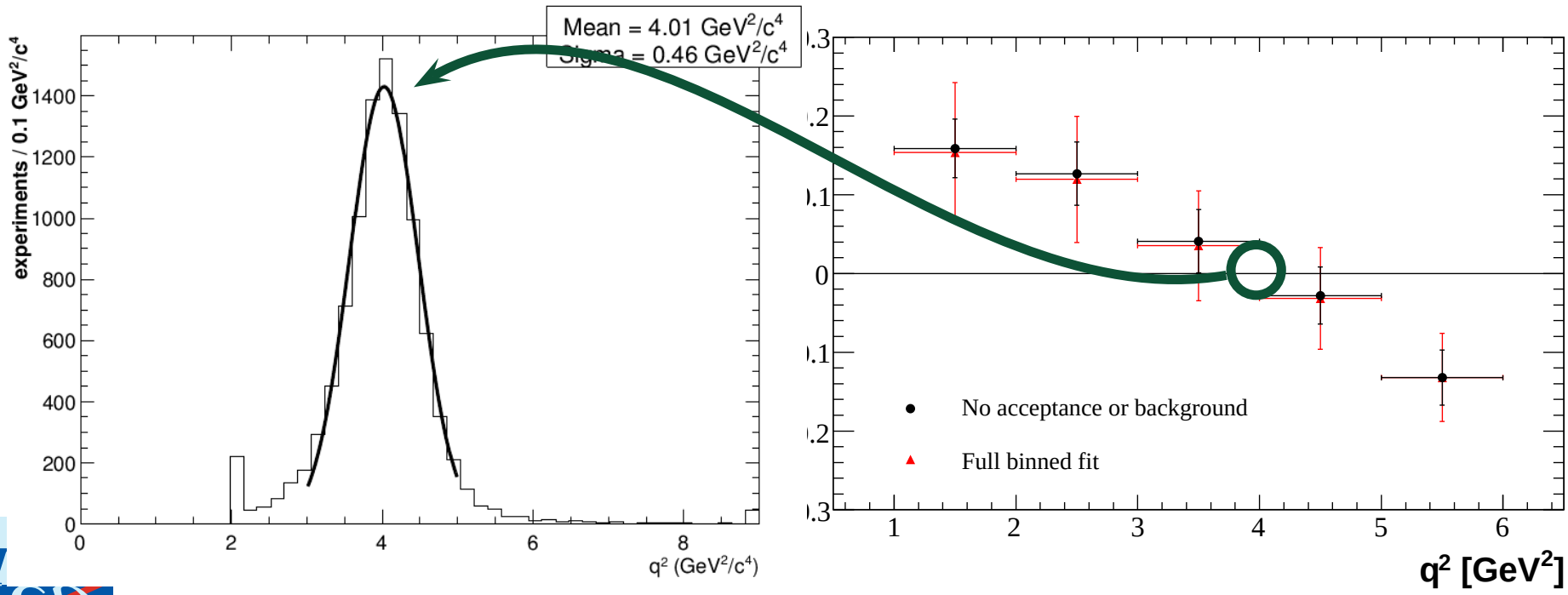
$B_d \to \mu\mu K^*$ yields with 2 fb^{-1}

Expected signal and background yields in 2 fb^{-1} of data (Assuming the SM BR of $\mathbf{12 \cdot 10^{-7}}$):

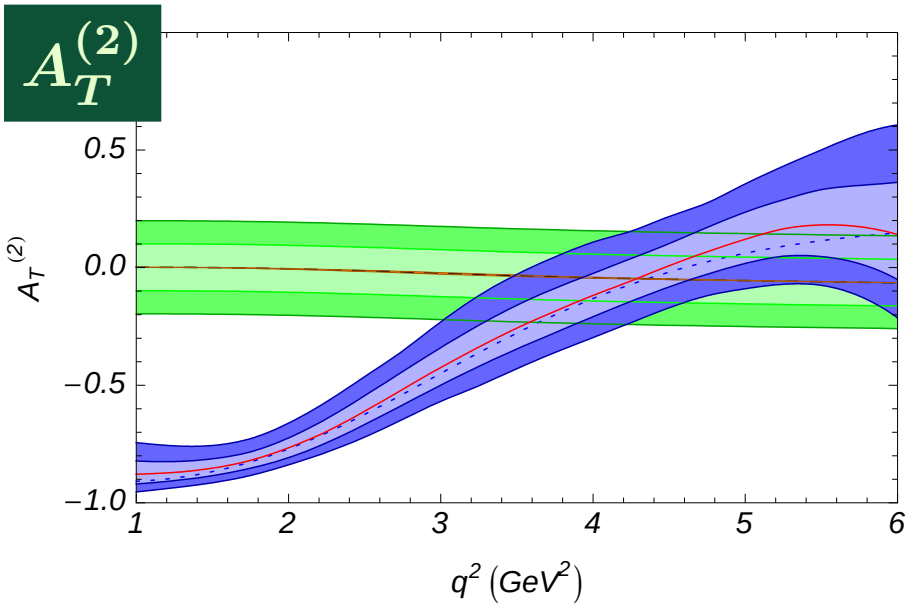
➜ Resolution on A_{FB} zero : ± 0.46 GeV^2 (12%) in 2 fb^{-1}

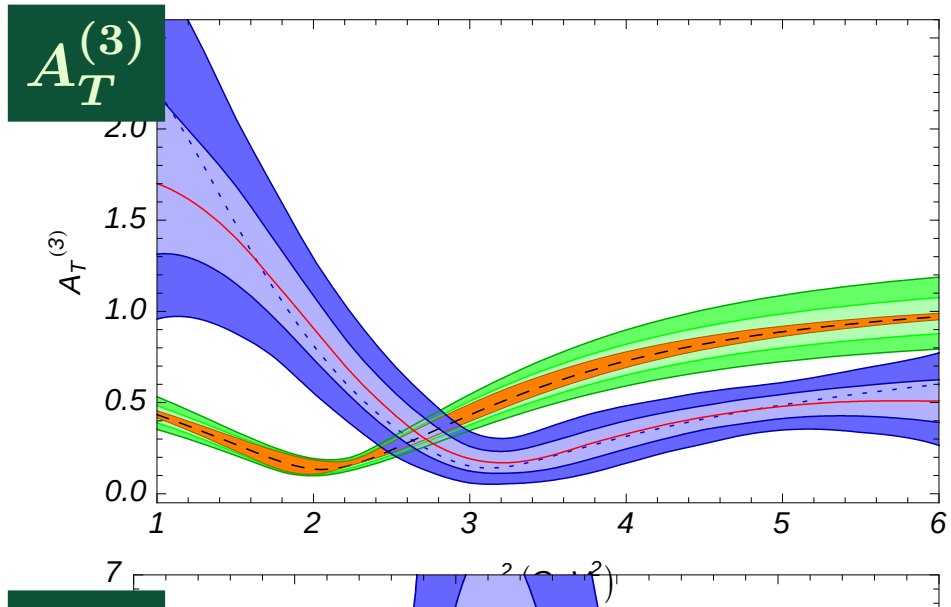
Several analyses being studied, including the very promising "Nikhef method".

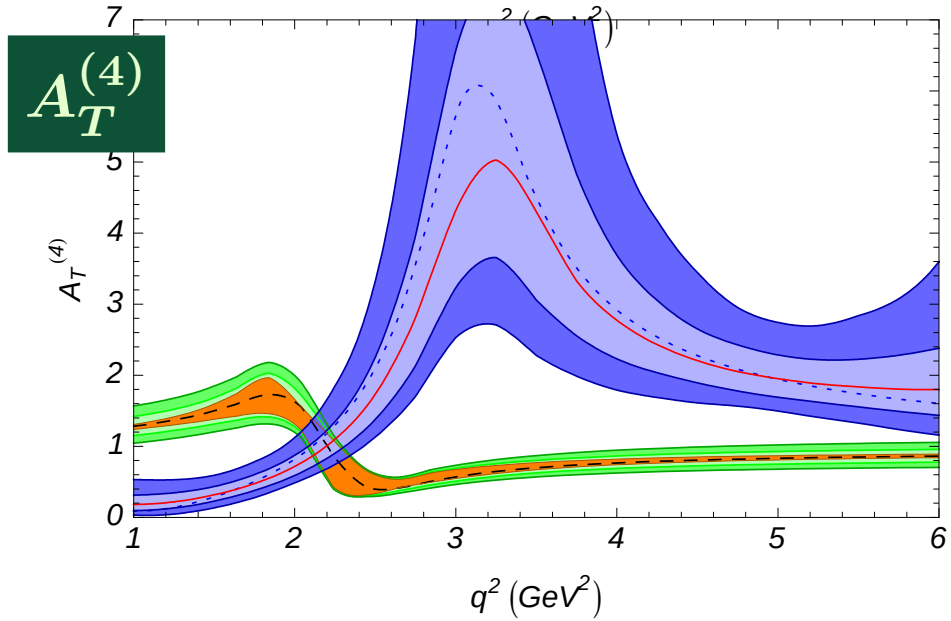




More asymmetries







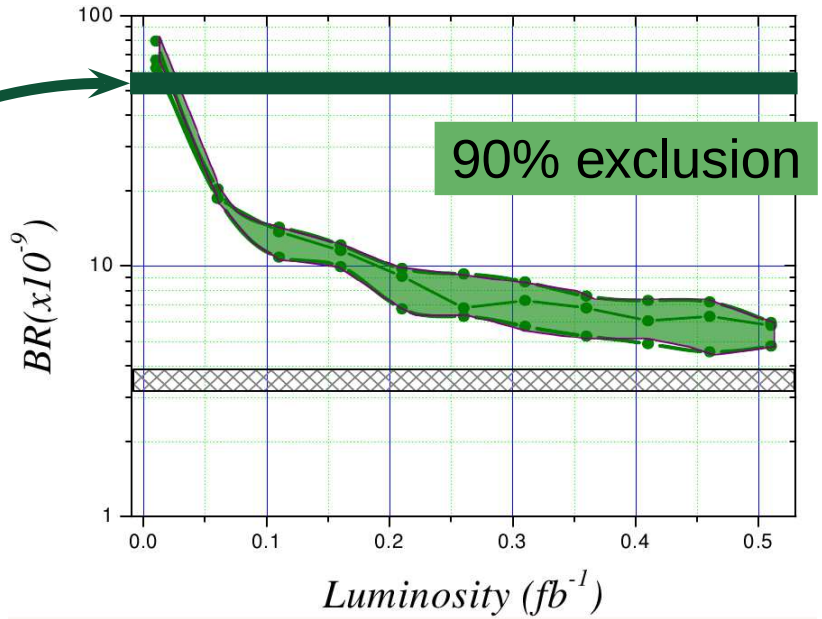
Experimental sensitivity for $10\,\text{fb}^{-1}$ for selected asymmetries [Egede, et. al.]

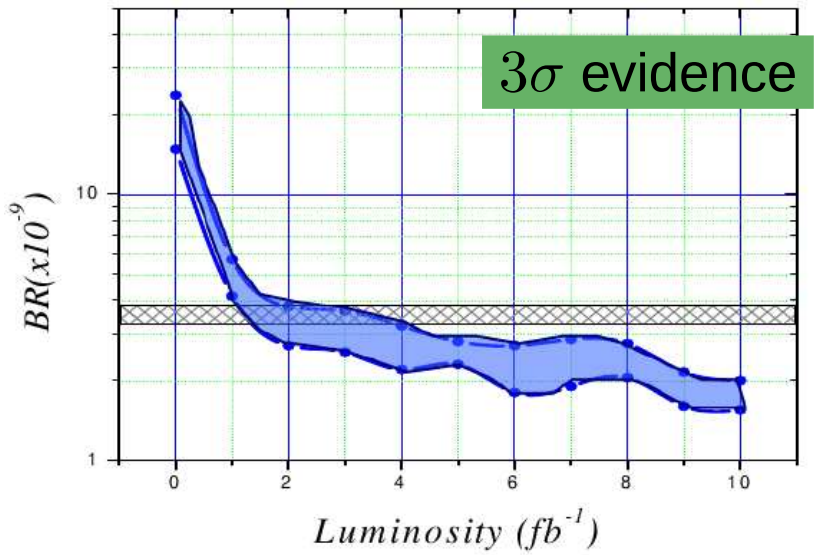
Blue band: experimental sensitivity assuming a susy model with large gluino mass.

Green band: Standard model expectation with error

$B_s \to \mu\mu$

- Very rare but SM BF well predicted
  $\mathcal{B} = (3.55 \pm 0.33) \cdot 10^{-9}$
- Sensitive to (pseudo)scalar operators
  - MSSM: $\mathcal{B} \propto \frac{\tan^6 \beta}{M_A^4}$
- Present limit from CDF $\mathcal{B} < 5.8 \cdot 10^{-8}$ (95% CL)
- With SM BF, expect 8 signal and 12 background events in most sensitive bin in 2 fb^{-1}
  - ➜ 3σ evidence with 2 fb^{-1}
  - ➜ 5σ observation with 6 fb^{-1}





R_K in $B_u \to \ell\ell K$

$$R_X = \frac{\int_{4m_\mu^2}^{q^2_{\text{max}}} \mathrm{d}s \frac{d\Gamma(B\to X\mu^+\mu^-)}{\mathrm{d}s}}{\int_{4m_\mu^2}^{q^2_{\text{max}}} \mathrm{d}s \frac{d\Gamma(B\to Xe^+e^-)}{\mathrm{d}s}} \overset{\text{SM}}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

[Hiller & Krüger, PRD69 (2004) 074020]

Corrections can be $\mathcal{O}(10\%)$ for instance with neutral Higgs boson exchanges.

R_K in $B_u \to \ell\ell K$

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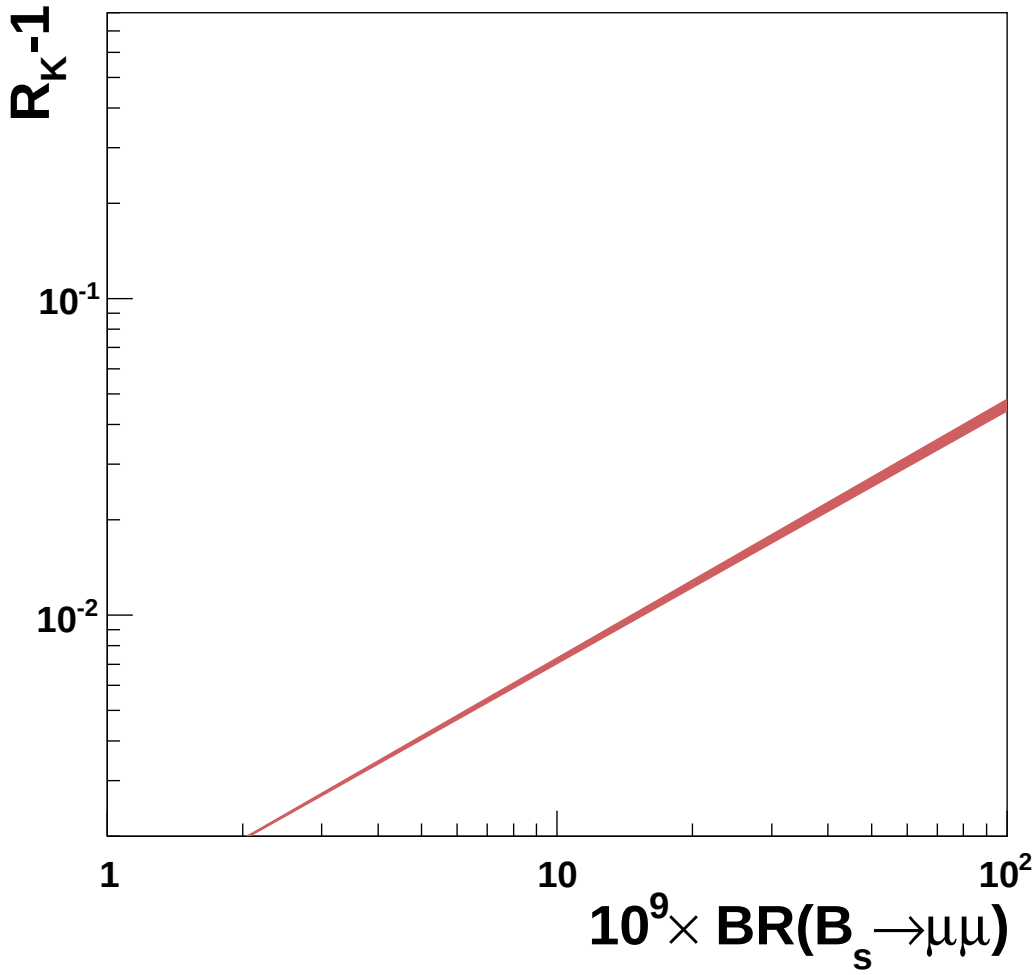
$$R_K - 1 \propto \mathcal{B}(B_s \to \mu\mu)$$

- Right-handed currents negligible
- (Pseudo-)scalar couplings $\propto m_\ell$,
- No CP-phases beyond the SM



[Hiller & Krüger, PRD69 (2004) 074020]

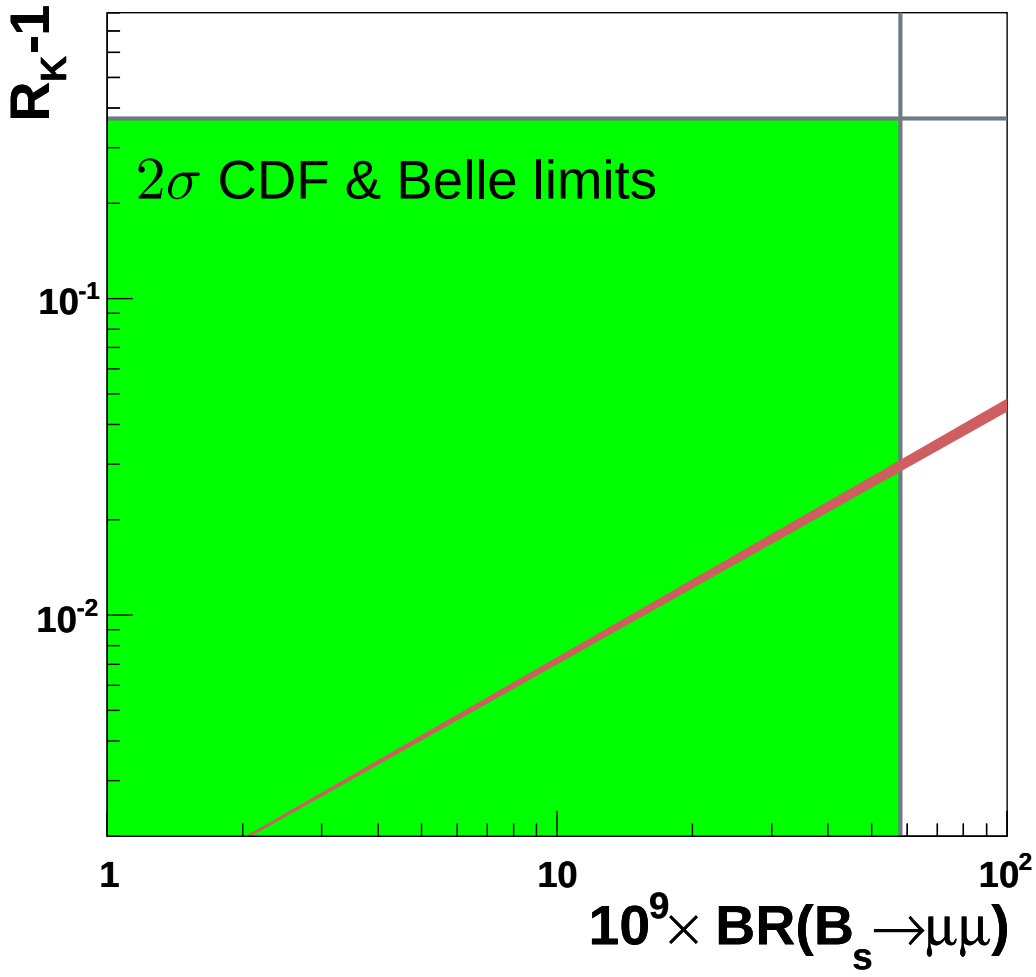
R_K in $B_u \to \ell\ell K$

Experimental status:

	BaBar ($384 \cdot 10^6\ B\overline{B}$) [PRL 102:091803,2009]
R_K	$0.40\ ^{+0.30}_{-0.23} \pm 0.02$
R_{K^*}	$1.01\ ^{+0.42}_{-0.32} \pm 0.08$
	Belle ($657 \cdot 10^6\ B\overline{B}$) [arXiv:0904.0770v1]
R_K	$1.03 \pm 0.17 \pm 0.05$
R_{K^*}	$0.83 \pm 0.17 \pm 0.05$

$B_s \to \mu\mu$: The present CDF limit is $5.8 \cdot 10^{-8}$ at 95% CL

[PRL 100:101802,2008]



R_K in $B_u \to \ell\ell K$

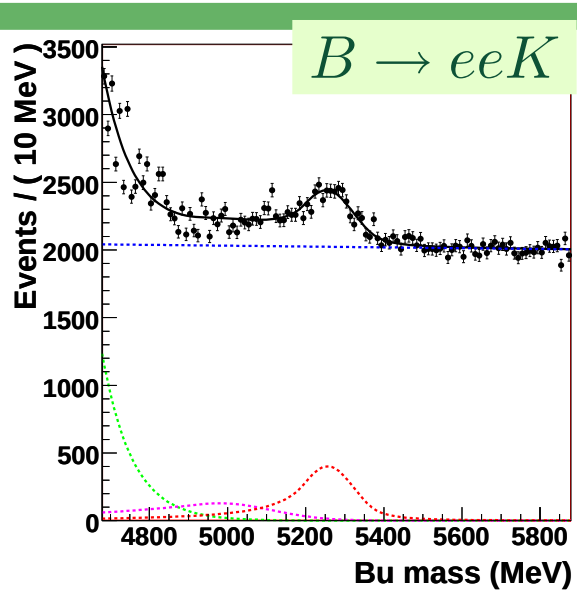
At LHCb for 10 fb^{-1} :

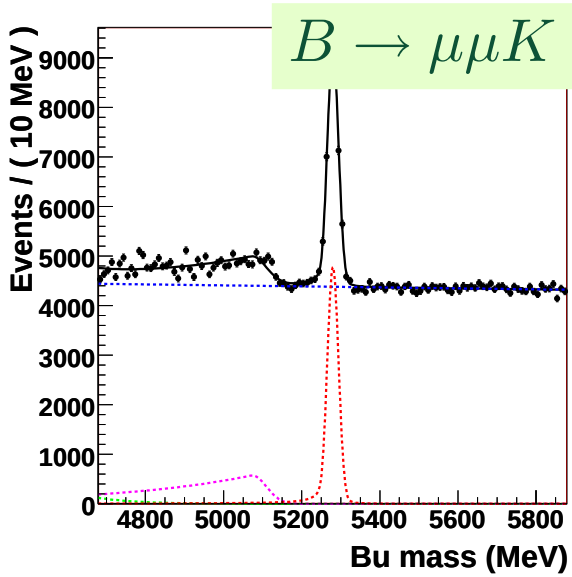
Species	Yield	Error
$B \to eeK$	$9\,240 \pm 379$	4.10%
$B \to \mu\mu K$	$18\,774 \pm 227$	1.21%

Including control samples, one gets an error:

➜ $\mathbf{R_K = 1}$ (fixed) $\pm\, \mathbf{0.043}$

for 10 fb^{-1} . [LHCb note 2007-034]





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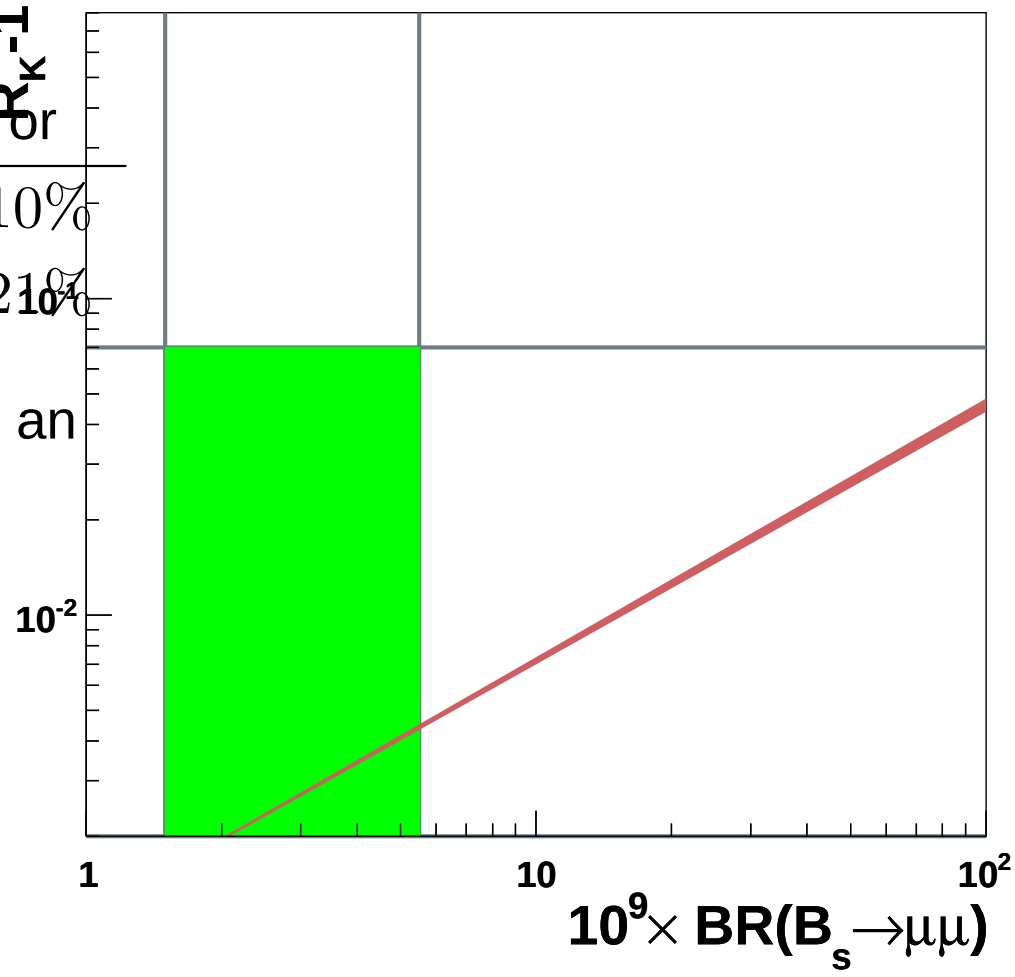

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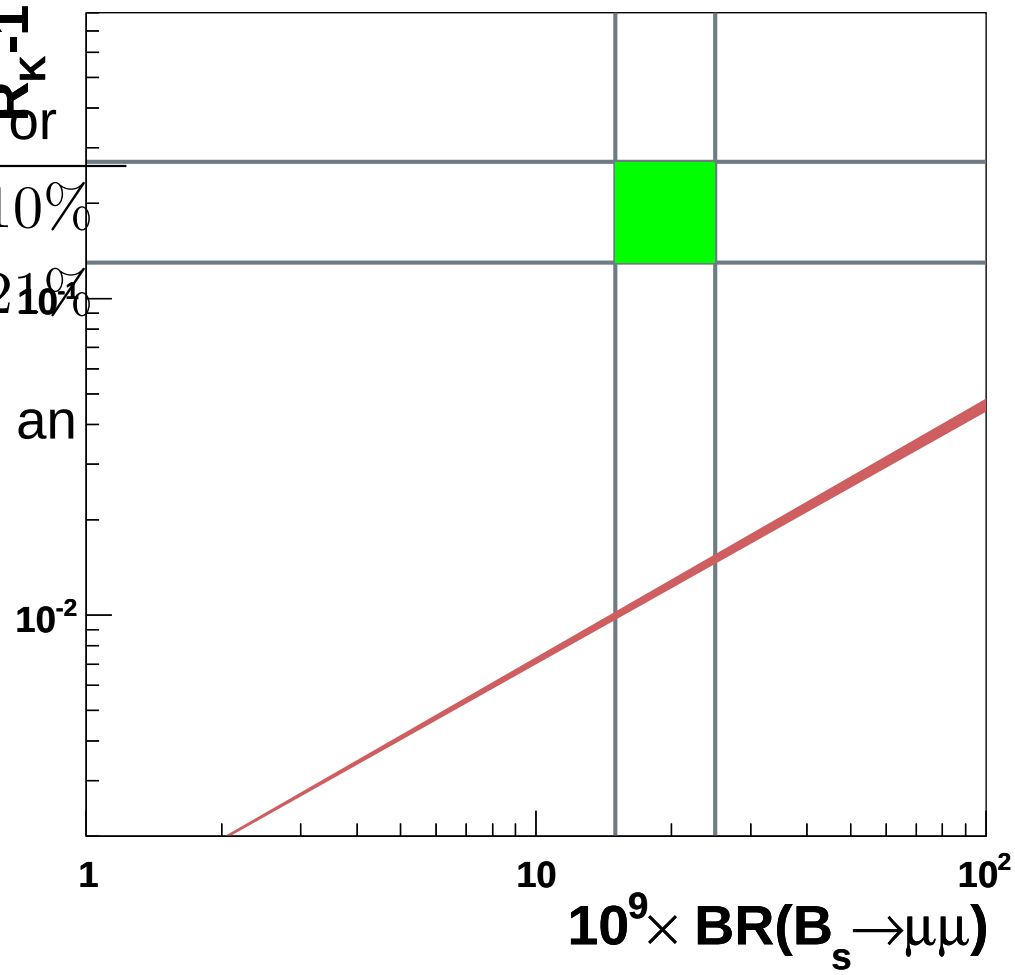


γ in Tree Decays

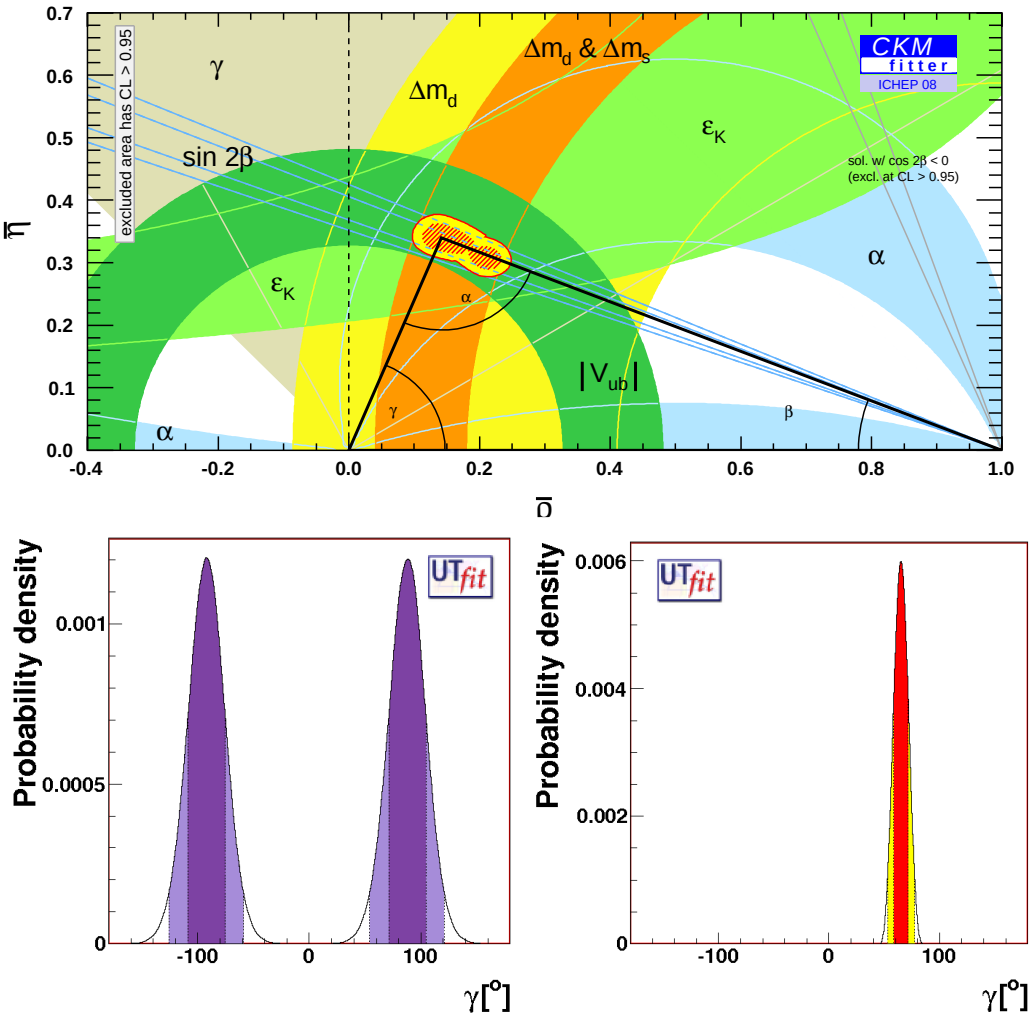
- $B_d \to DK\pi$

Health warning: This is a feasibility study.

CKM angle γ

- γ is hardly measured
- Main constraints from $\sin 2\beta$ and Δm_s
- Can be measured in tree decays
  - ➜ The “real” γ (no NP expected)
- Can be measured in loops
  - ➜ Sensitive to new physics

✔ Any discrepancy is new physics



Direct and indirect determinations of γ

γ in Trees at LHCb

ADS method: $D^0 \to K^-\pi^+$ and doubly-Cabibbo-suppressed $D^0 \to K^+\pi^-$

- ✗ Low rate
- ✔ Large interference

GLW method: $D^0 \to$ CP eigenstate

- ✔ Large rate
- ✗ Low interference

Dalitz analysis in $D \to K^0_S\pi\pi$

Method	$\sigma(\gamma)$
$B_u \to D(hh)K$	11–13°
$B_d \to D(hh)K^*$	6–13°
$B_u \to D(3K\pi)K$	5–10°
$B_u \to D(K^0_S\pi\pi)K$	6–9°
$B_s \to D_s\{K,\pi\}$	9–12°

➜ Error on γ between 5° and 13° with 2 fb^{-1}

All the above time-independent

Time dependent CP asymmetry in $B_s \to D_s^+K^-$ and $B_s \to D_s^-K^+$

- Fit $B_s \to D_sK$ and $B_s \to D_s\pi$ for Δm_s, $\Delta\Gamma$, mis-tag and $\gamma + \phi_s$

$B_d \to DK\pi$: The Idea

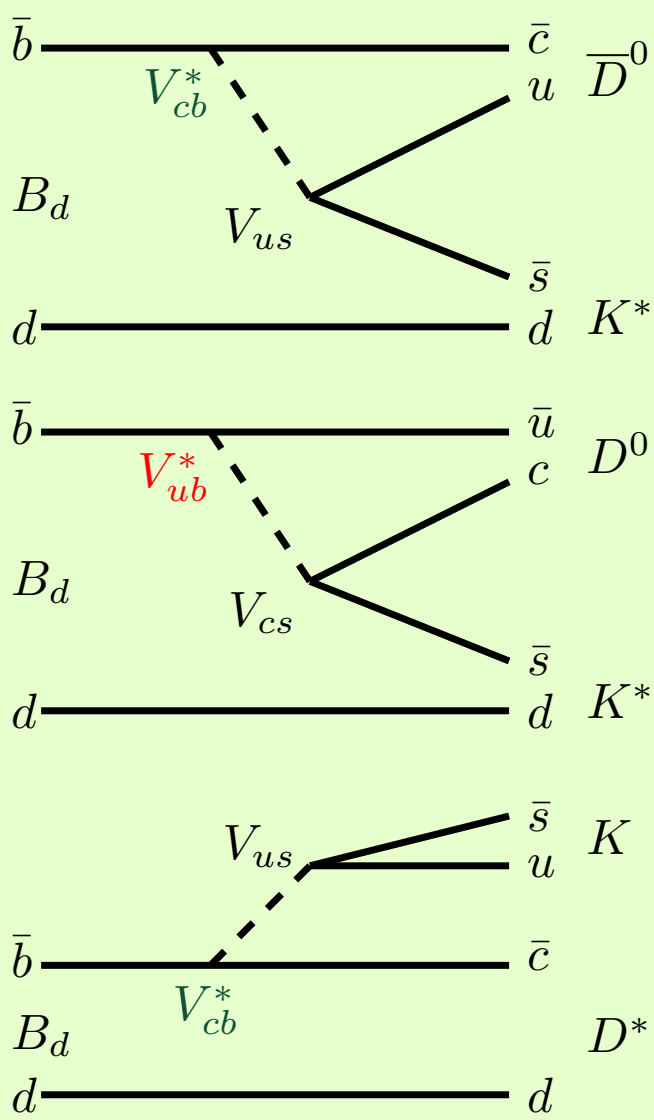
- Interference between DK^* and D^*K is sensitive to

$$\gamma = \arg \frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

[T. Gershon, PRD.79.051301]

- Charge of K tags flavour of B
- Reconstruct $D \to K^-\pi^+$ and $K^+\pi^-$
- And $D \to KK$ and $D \to \pi\pi$ (CP-even)
- No need of CP-odd ($K_S^0\pi^0 \ldots$)

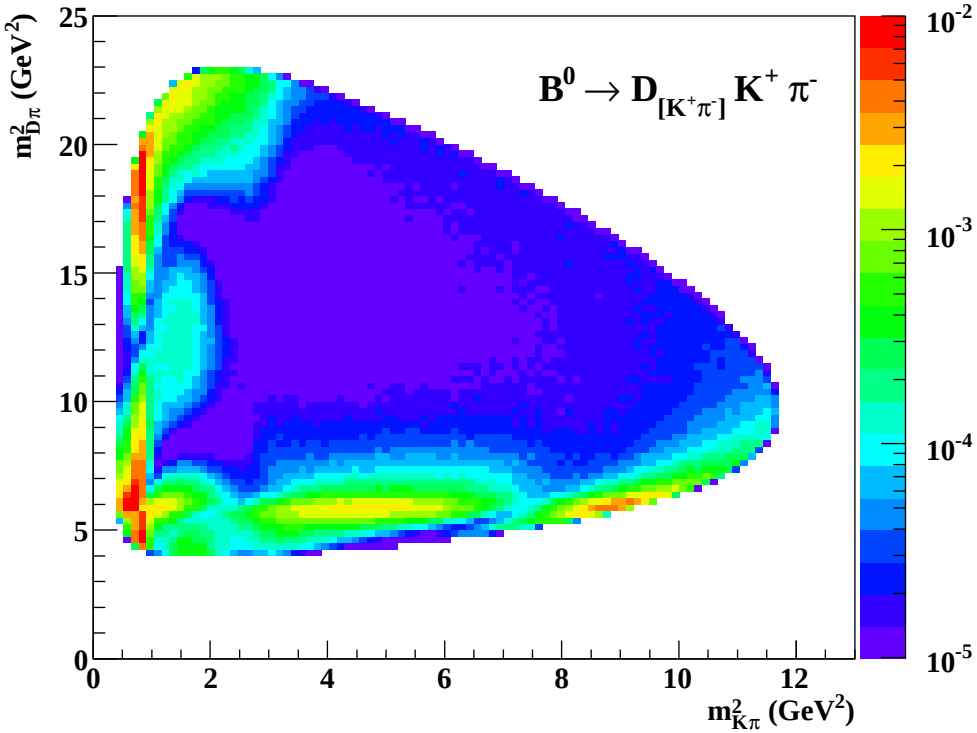
➜ Dalitz plot analysis in $DK\pi$ plane



Dalitz plane

The Dalitz plot contains:

- ✔ $K^+\pi^-$ resonances ($K^{*0}(892), K_0^{*0}(1430), \ldots$)
- ✔ $\overline{D}^0\pi^-$ resonances ($D_0^{*-}(2400), D_2^{*-}(2460), \ldots$)
- ✔ D^0K^+ resonances (D_s^{*+}-type states)
- ✗ No $D^0\pi^-$ resonances ($c\bar{u}d\bar{u}$)
- ✗ No $\overline{D}^0K^+$ resonances ($u\bar{c}u\bar{s}$)



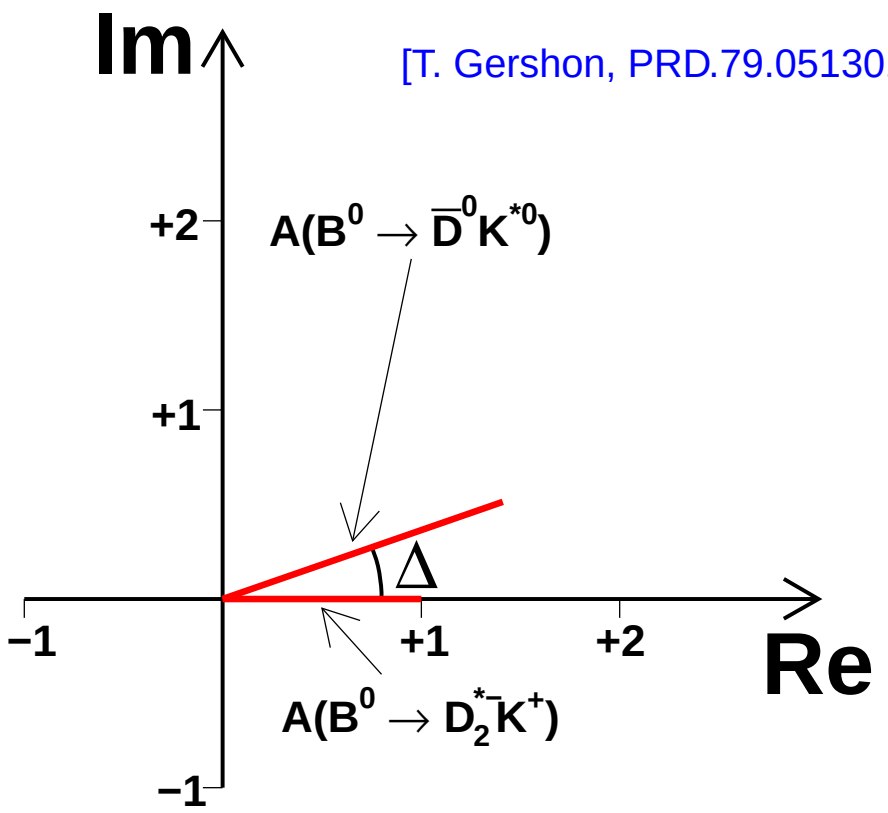
Thus, the charge of the pion flavour tags the D^*'s and the charge of the kaon flavour tags the (possible) D_s^*'s!

Note: More resonances is better but for now we'll only consider the $K^{*0}(892)$ and $D_2^{*-}(2460)$.

The Method

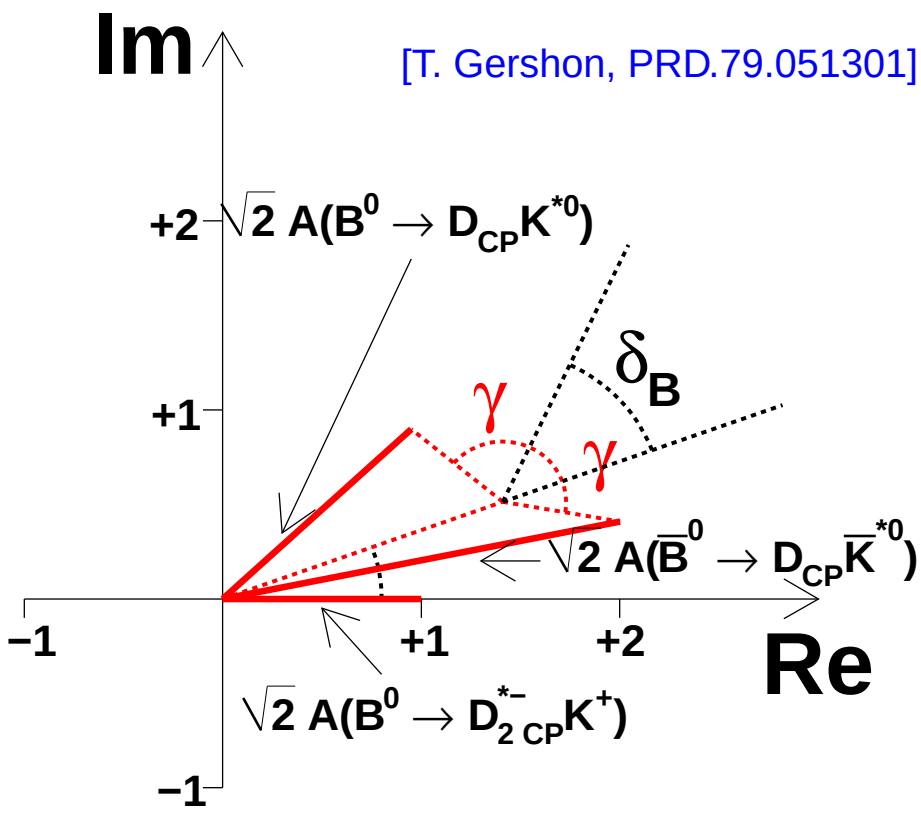
$\boldsymbol{D_{K\pi} \to K\pi}$ **:** $B_d \to \overline{D}^0 K^*$ and $B_d \to D_2^{*-} K^+$ have relative phase Δ

$$A(B^0 \to \overline{D}^0 K^{*0}) = A_{K^*}$$
$$A(B^0 \to D_2^{*-} K^+) = A_{D_2^*} e^{i\Delta}$$



[T. Gershon, PRD.79.051301]

The Method



[T. Gershon, PRD.79.051301]

$\boldsymbol{D_{K\pi} \to K\pi}$: $B_d \to \overline{D}^0 K^*$ and $B_d \to D_2^{*-} K^+$ have relative phase Δ

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$$A(B^0 \to D_2^{*-} K^+) = A_{D_2^*} e^{i\Delta}$$

$\boldsymbol{D_E \to KK,\pi\pi}$:

$$A(B^0 \to D_E K^{*0}) = \frac{A_{K^*}}{\sqrt{2}} \left(1 + r_B e^{i(\delta_B + \gamma)}\right)$$
$$A(B^0 \to D_{2_E}^{*-} K^+) = \frac{1}{\sqrt{2}} A(B^0 \to D_2^{*-} K^+)$$

- D_2^{*-} can decay to $\overline{D}^0 \pi^-$ and **not** $D^0 \pi^-$
- $r_B \sim 0.4$: ratio of $B \to D/B \to \overline{D}$

Amplitudes, with suppressed decays

Including the suppressed D decays, we get:

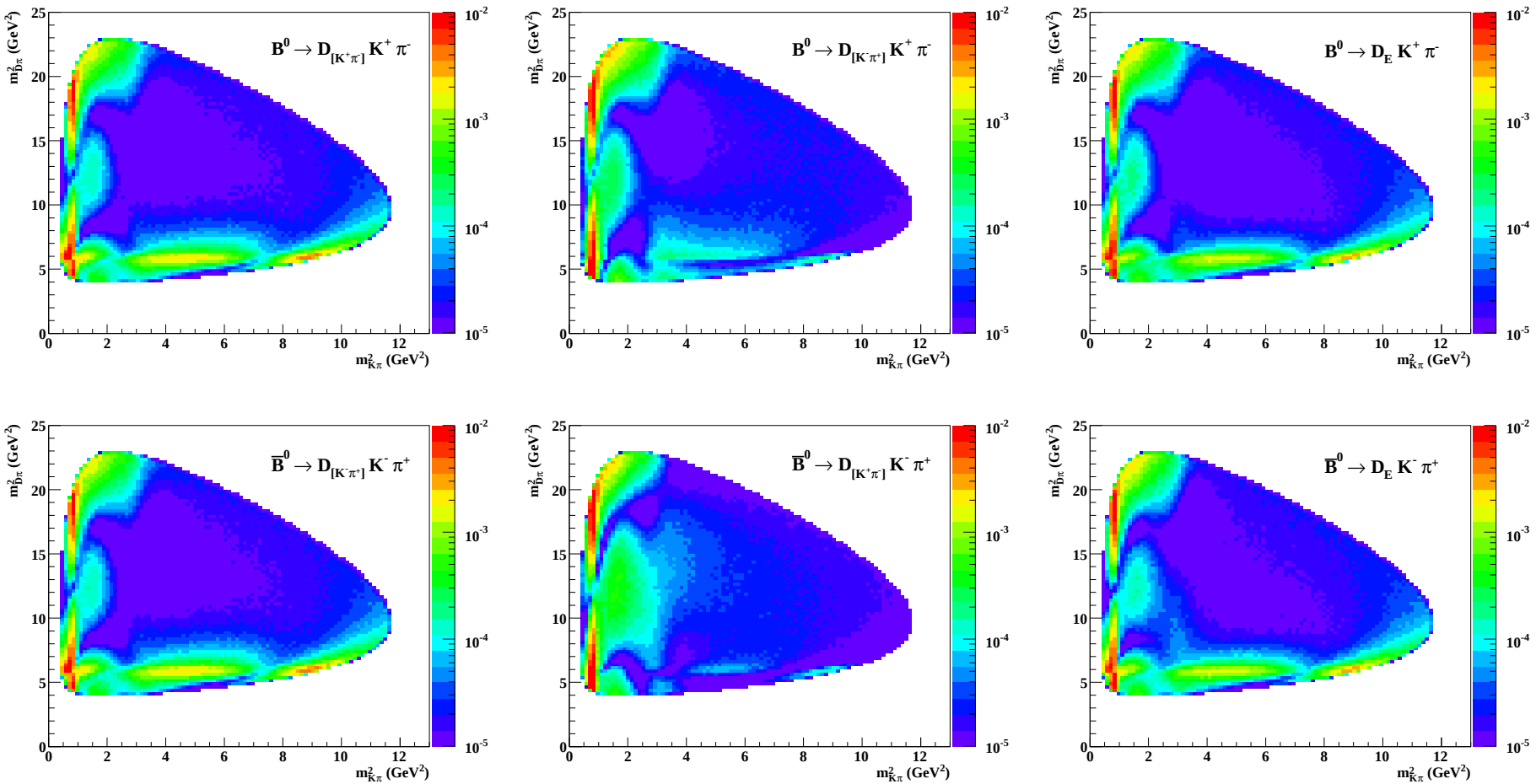
$$
\begin{aligned}
A(B^0 \to D_{[K^+\pi^-]}K^{*0}) &= A_{K^*}\left(1 + r_B e^{i(\delta_B+\gamma)} r_D e^{i\delta_D}\right) \\
A(B^0 \to D_{[K^-\pi^+]}K^{*0}) &= A_{K^*}\left(r_D e^{i\delta_D} + r_B e^{i(\delta_B+\gamma)}\right) \\
A(B^0 \to D_E K^{*0}) &= \frac{A_{K^*}}{\sqrt{2}}\left(1 + r_B e^{i(\delta_B+\gamma)}\right) \\
A(B^0 \to D_2^{*-}(D_{[K^+\pi^-]}\pi^-)K^+) &= A_{D_2^*} e^{i\Delta} \\
A(B^0 \to D_2^{*-}(D_{[K^-\pi^+]}\pi^-)K^+) &= A_{D_2^*} e^{i\Delta} r_D e^{i\delta_D} \\
A(B^0 \to D_2^{*-}(D_E\pi^-)K^+) &= \frac{A_{D_2^*}}{\sqrt{2}} e^{i\Delta}
\end{aligned}
$$

where we're ignoring the dependence on $m^2_{D\pi}$ and $m^2_{K\pi}$.

→ 5 unknowns and 8-ish observables

Dalitz Model

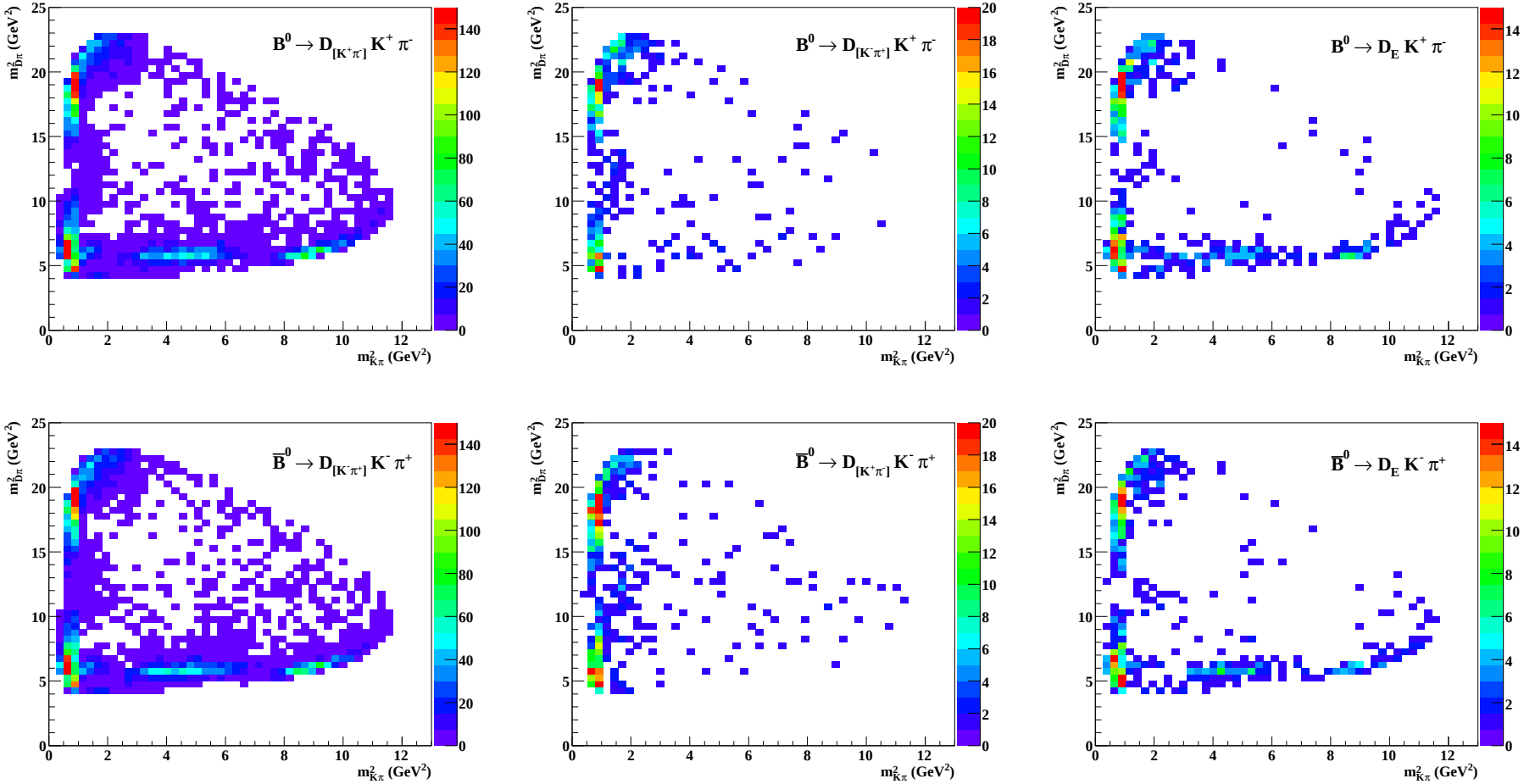
Model Dalitz Distributions ($\delta_B = 0°$)



Note: Log scale, arbitrary normalisation

LHCb 4 fb^{-1}

Generated Dalitz distributions (2 nominal years with $\delta_B = 0°$)

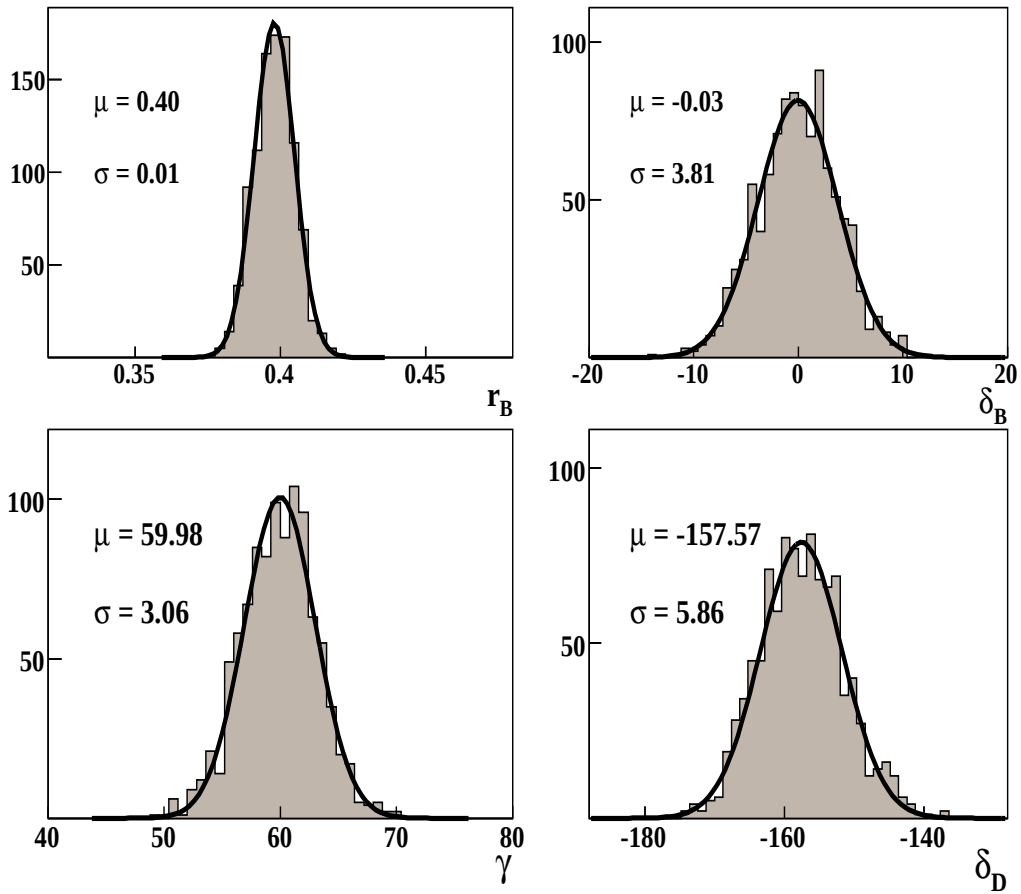


We have generated 1000 such datasets for each δ_B value considered.

Fit result

No background:

$$\gamma = 60.0 \pm 3.1^\circ$$



Extracted Parameters w/ $\delta_D \in [0, 2\pi)$

2 Nominal Years w/ $\delta_B = 0^\circ$

Fit result

No background:

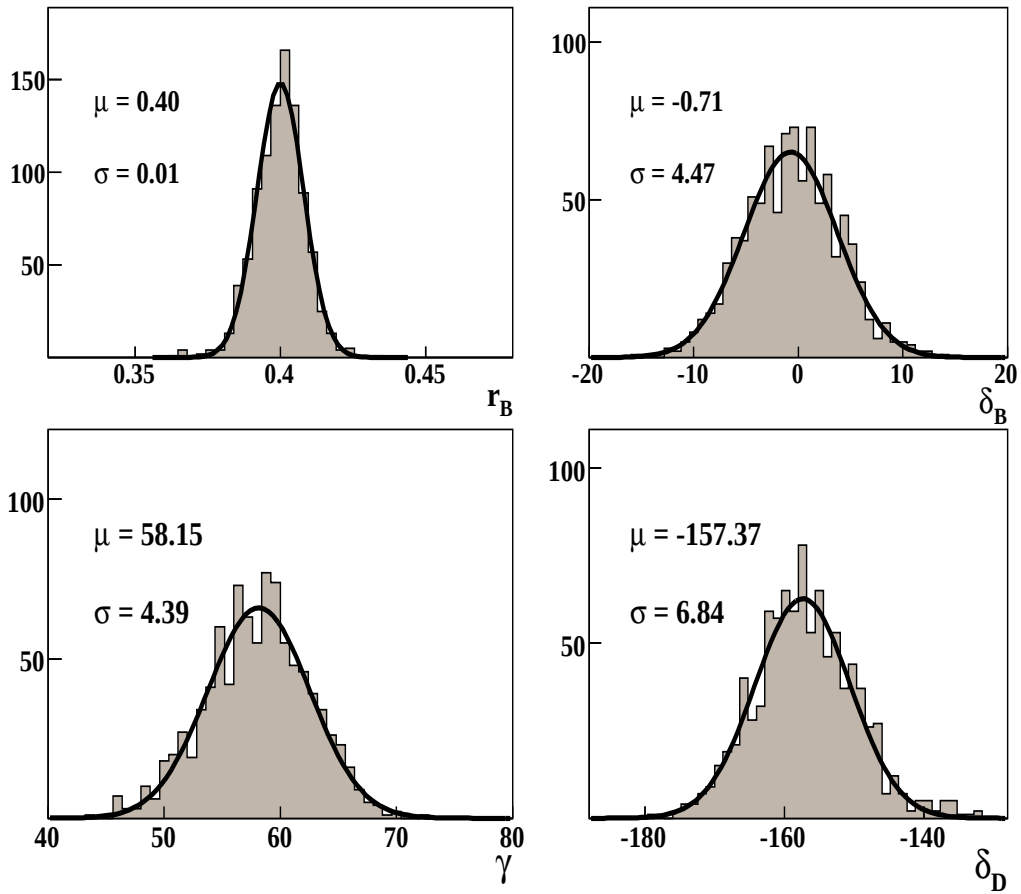
$$\gamma = 60.0 \pm 3.1^\circ$$

$N_B = 1300$ in all final states:

$(0.2 < S/B < 2)$

$$\gamma = 58.2 \pm 4.4^\circ$$

The small bias is understood (B and S defined positive) and will be corrected in the fit.



Extracted Parameters w/ $\delta_D \in [0, 2\pi)$

2 Nominal Years w/ $\delta_B = 0^\circ$

Dependence on parameters

δ_B: Resolution depends marginally on δ_B:

δ_B	$0°$	$45°$	$90°$	$135°$	$180°$
σ_γ	$3.1°$	$3.7°$	$3.7°$	$3.5°$	$2.8°$

r_D and δ_D: That's with r_D and δ_D fixed to CLEO-c values. Ignoring this constraint does not affect γ!

r_B: No reason to think it's much lower than 0.4, but . . .

r_B	0.4	0.3	0.2	0.1
σ_γ	$3.1°$	$3.9°$	$5.5°$	$9.0°$

$\Delta\phi(K^*, D_2^*(2460)^-)$: The value of this phase is irrelevant

γ: Resolution gets better at higher γ:

γ	$45°$	$60°$	$75°$
σ_γ	$3.5°$	$3.1°$	$2.9°$

LHCb Programme

2009-10 (200 pb^{-1}): Commissioning

- ✔ Unique opportunity to make production studies at 10 TeV
- ✔ Charged, K^0_S, $\Lambda/\overline{\Lambda}$, J/ψ ...
- ✗ Too little data to compete with B-factories & TeVatron
- ? Except maybe $B_s \to \mu\mu$

2011 (1 fb^{-1}): Some B physics becomes competitive

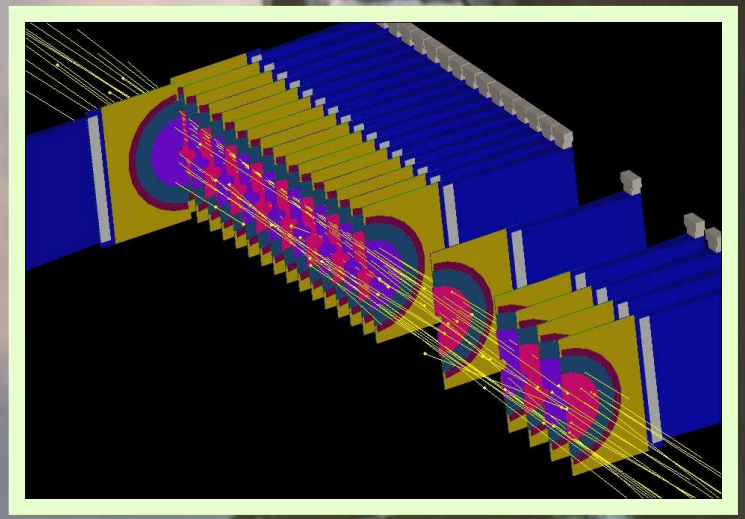
- ✔ $B \to \mu\mu K^*$ ($10\times$ Belle statistics)
- ✔ $B_s \to J/\psi\phi$, $B_s \to \mu\mu$

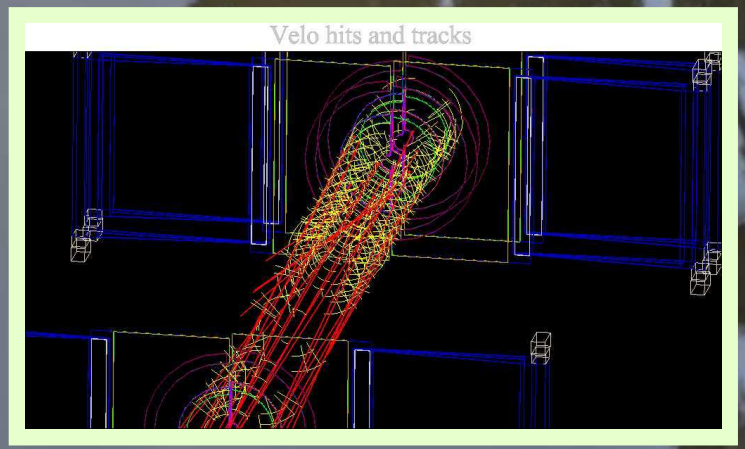
2012 (> 2 fb^{-1}): Hadronic channels become competitive

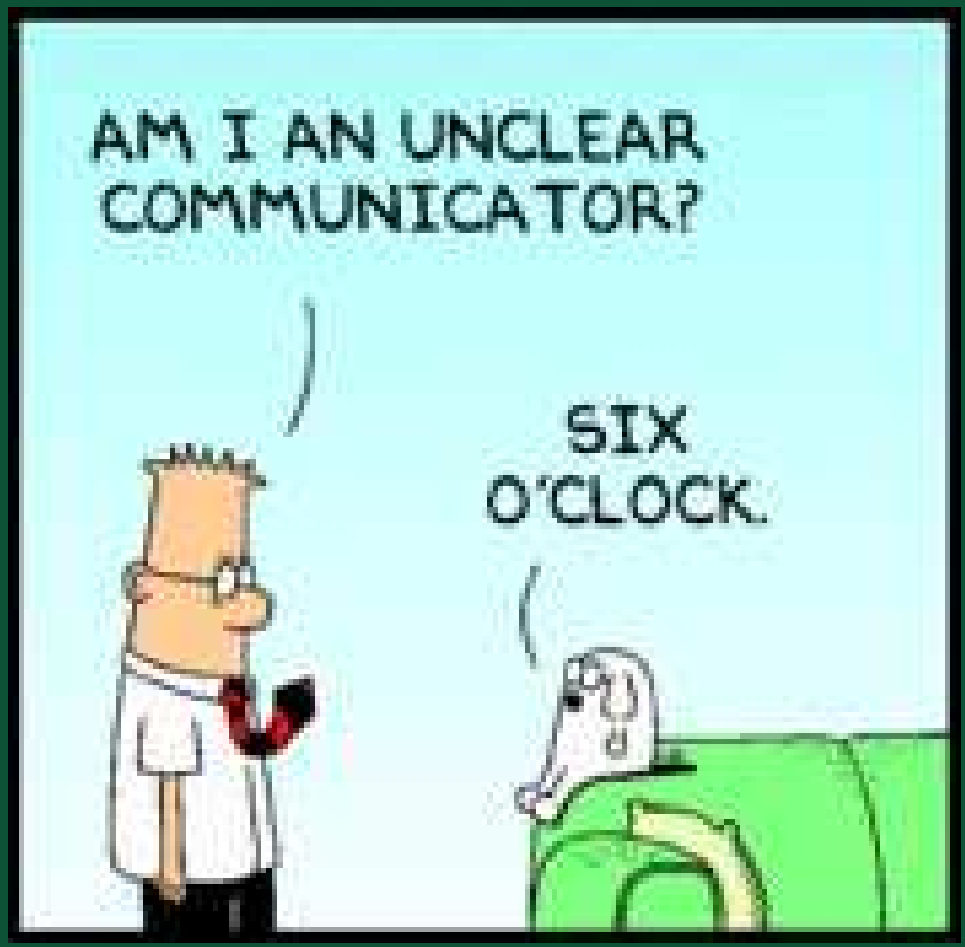
- ✔ γ in loops : $B \to hh$
- ✔ γ in trees : $B \to Dh$
- ✔ $B_s \to \phi\gamma$
- And much more

Conclusion

- LHCb is ready and waiting for events
- We hope to see new physics soon
- $B \to \mu\mu K^*$ is my best bet
- Or maybe there are right-handed photons
- We might have surprises in the measurements of γ
- But it will take some time to make sense of the data
  - The trigger will be crucial



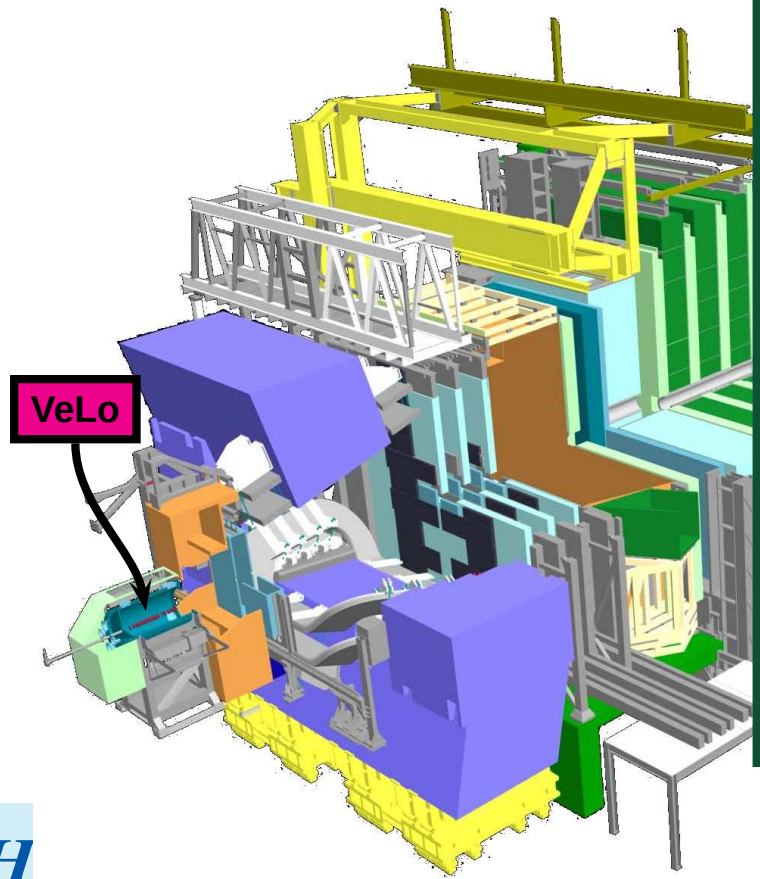




Backup Slides

LHCb Vertex Locator

- 21 stations with r and ϕ strips
- In secondary vacuum and retracted during injection



LHCb Vertex Locator

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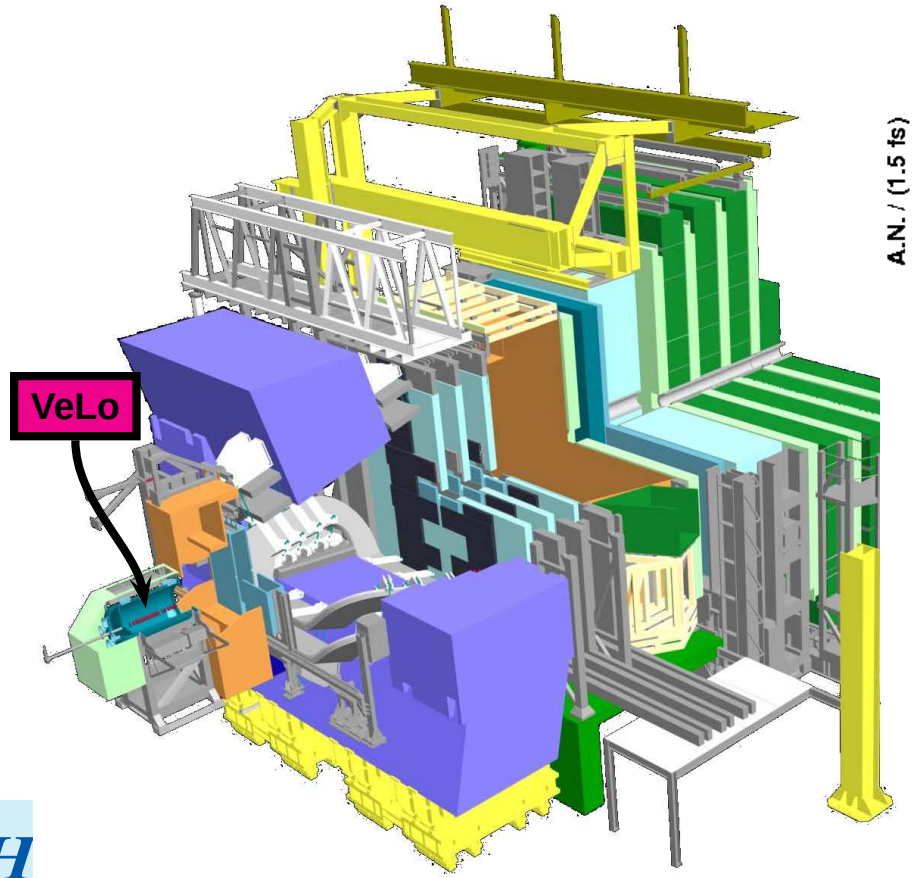
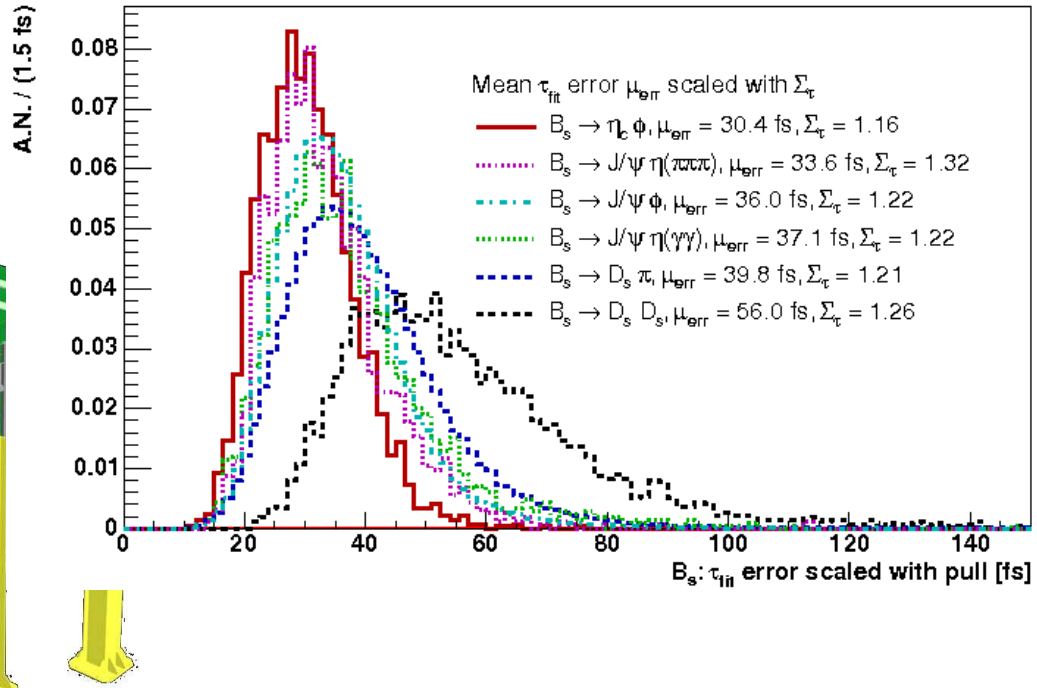
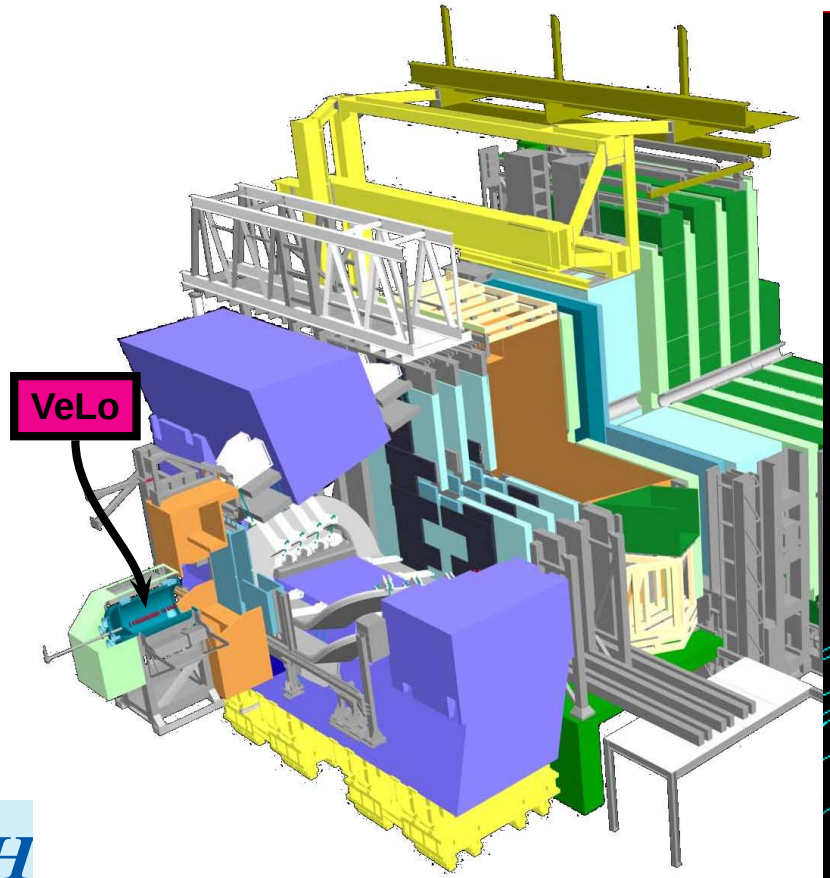


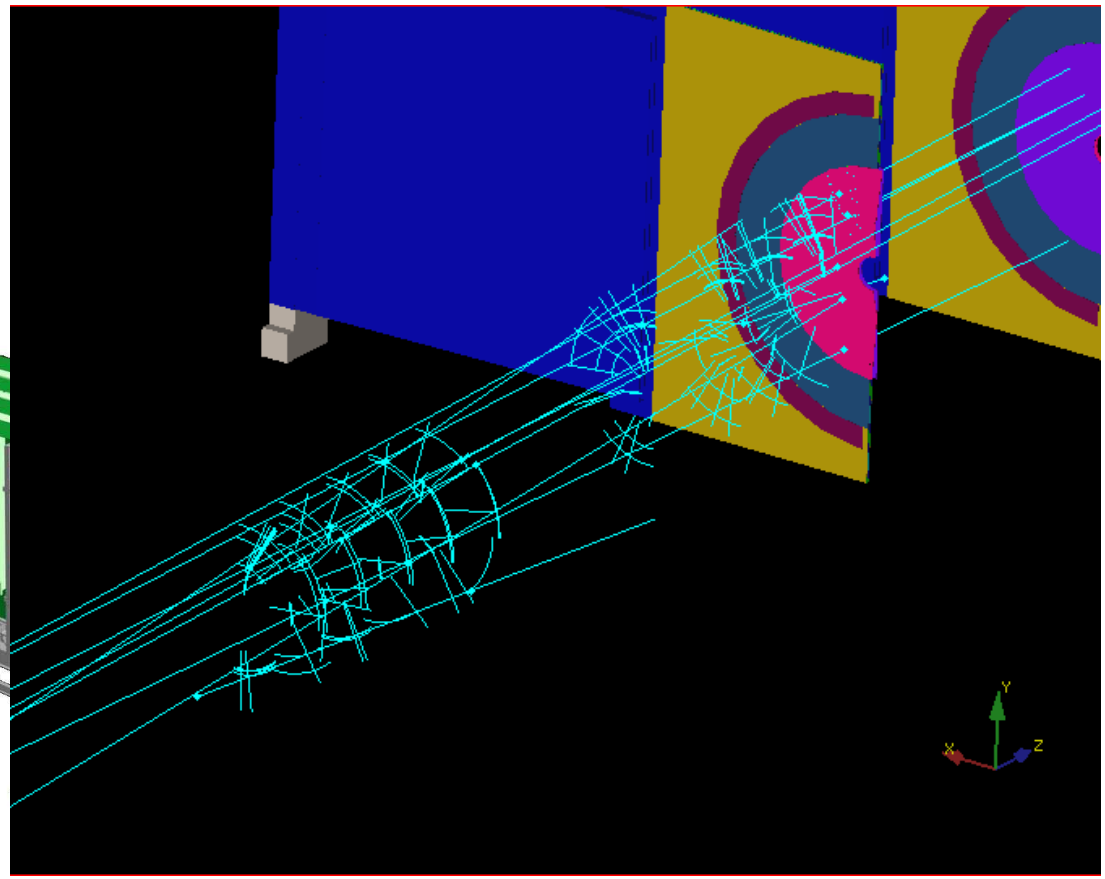
- Proper time resolution between 30 and 50 fs, depending on channel



LHCb Vertex Locator

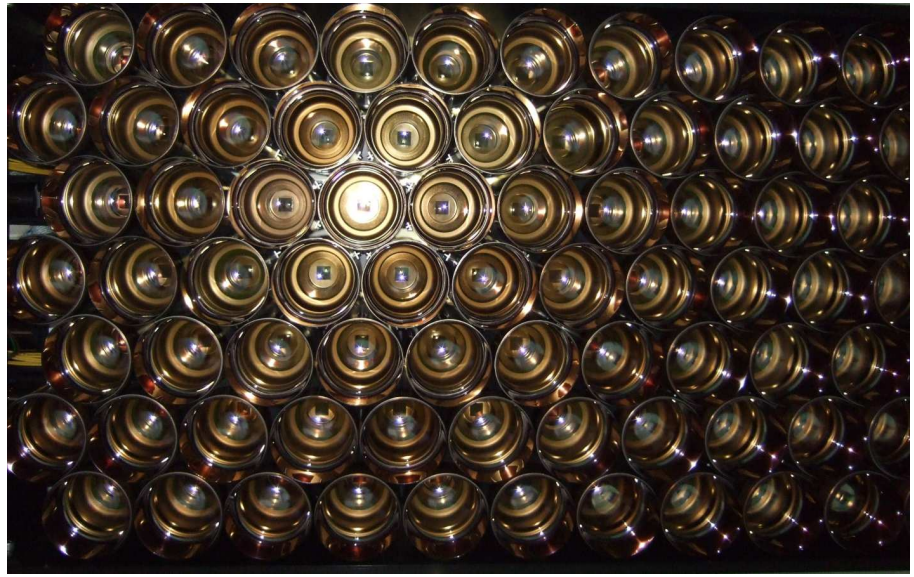
- 21 stations with r and ϕ strips
- In secondary vacuum and retracted during injection
- First tracks reconstructed during final LHC synchronisation tests

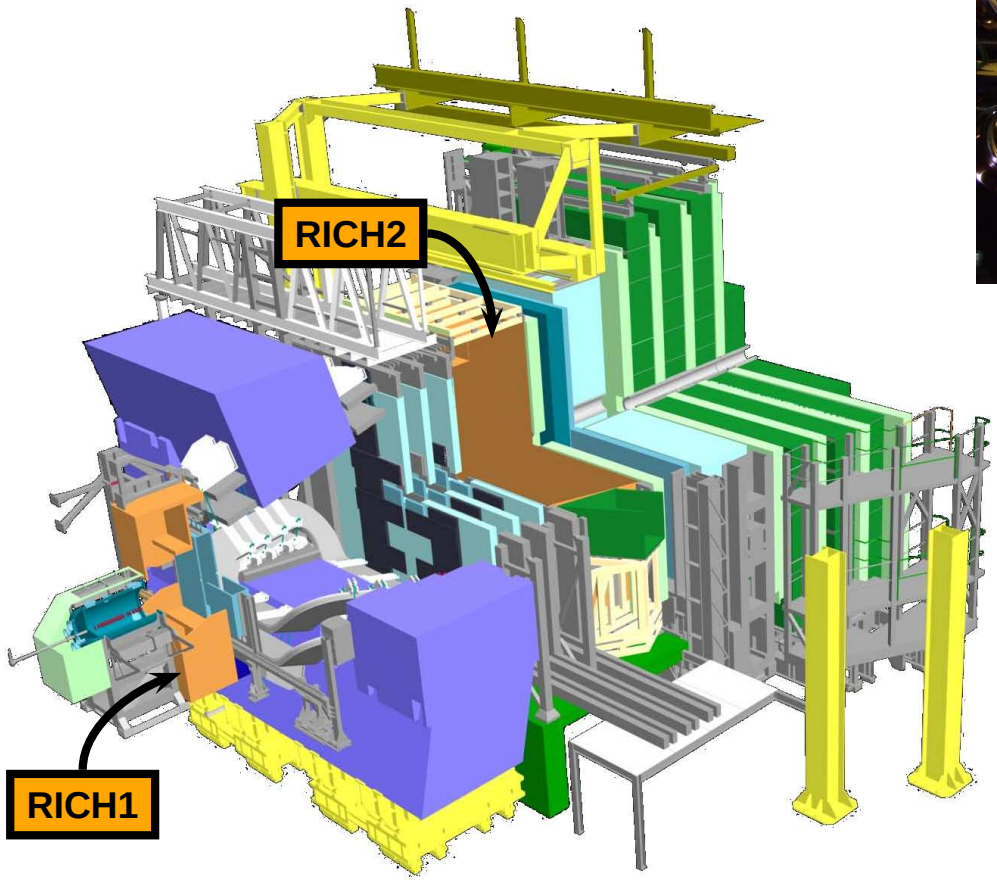




LHCb RICH

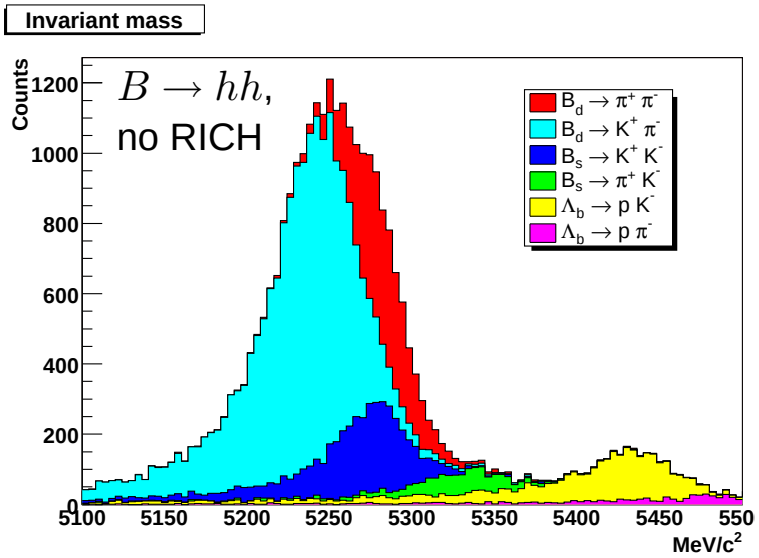
- RICH provides K/π separation using Cherenkov radiation

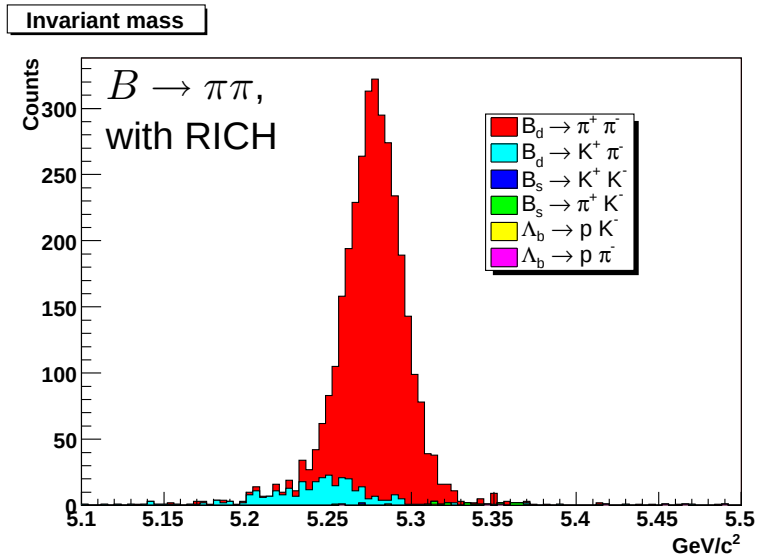


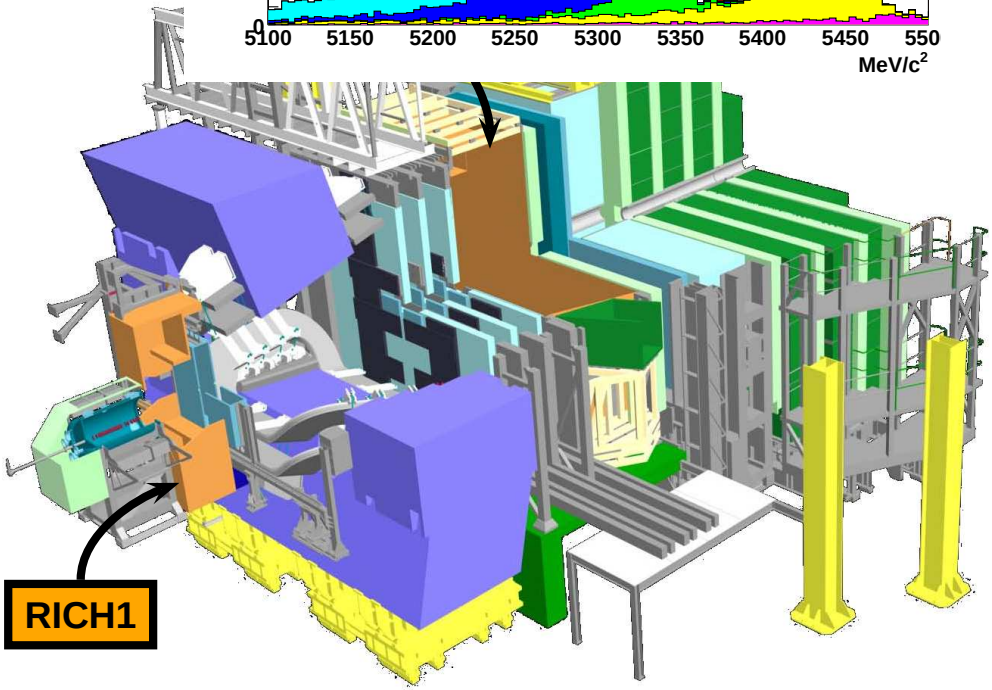


- Use gas and aerogel radiators
- Two detectors for different momentum ranges

LHCb RICH







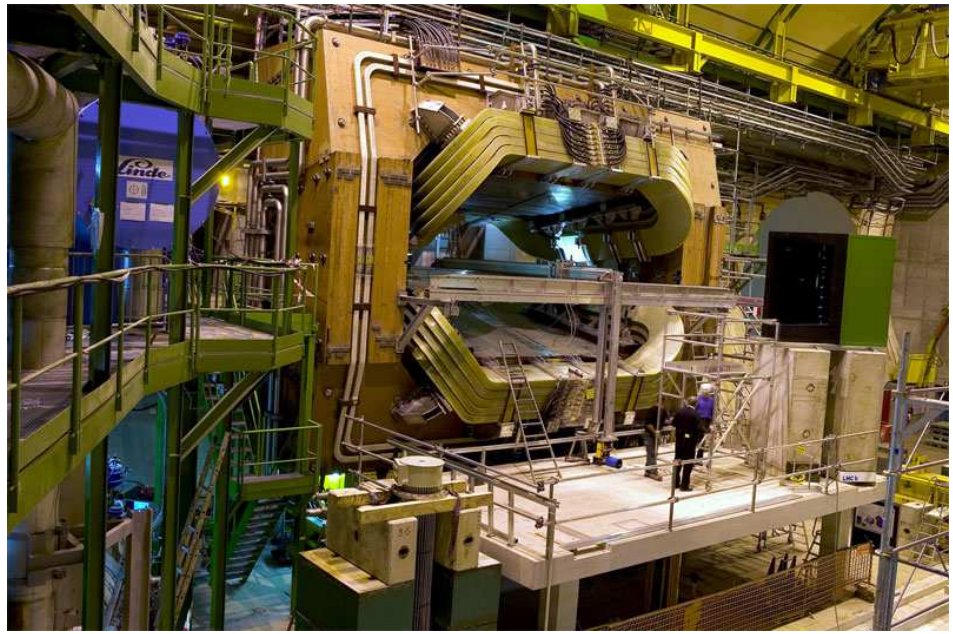
- Use gas and aerogel radiators
- Two detectors for different momentum ranges

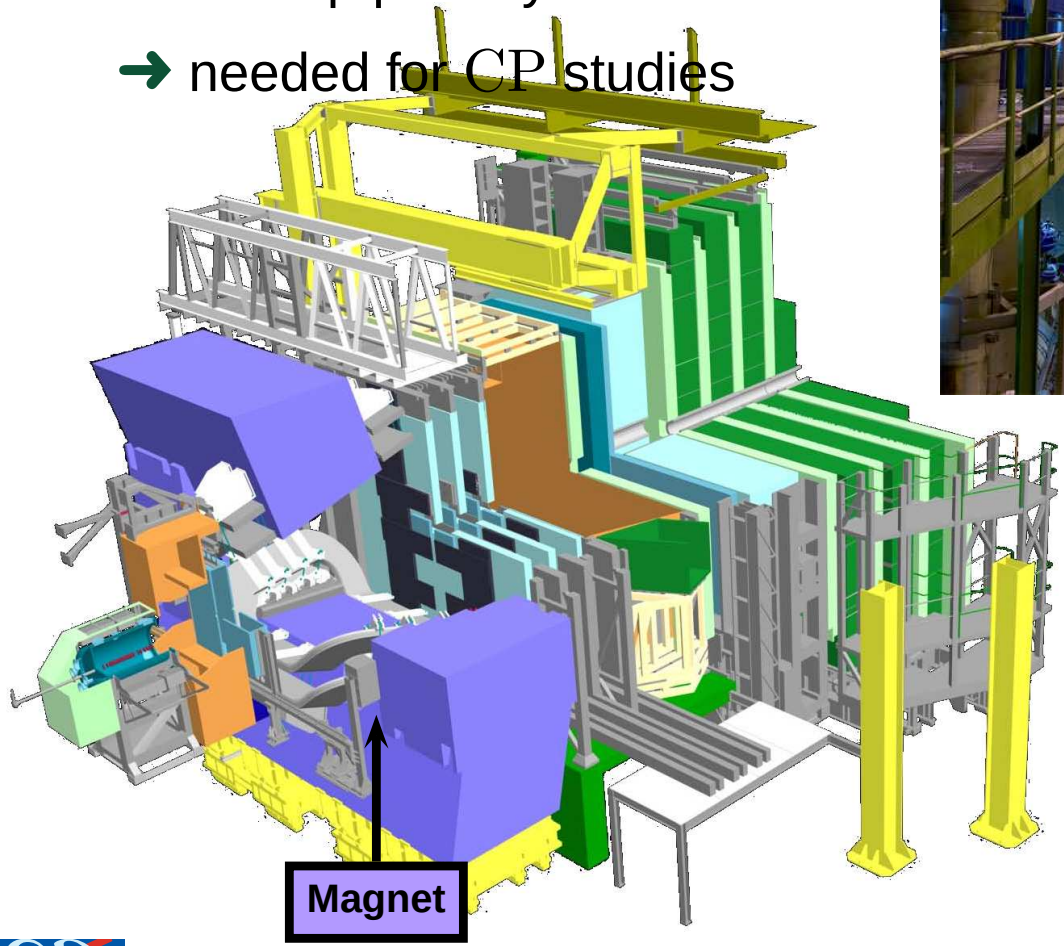
➜ Important for $B \to hh$ and $B_s \to D_s \pi$

LHCb Magnet

- Warm solenoid magnet
- $3\ \mathrm{Tm}$ integrated field
- Can swap polarity

  ➜ needed for CP studies



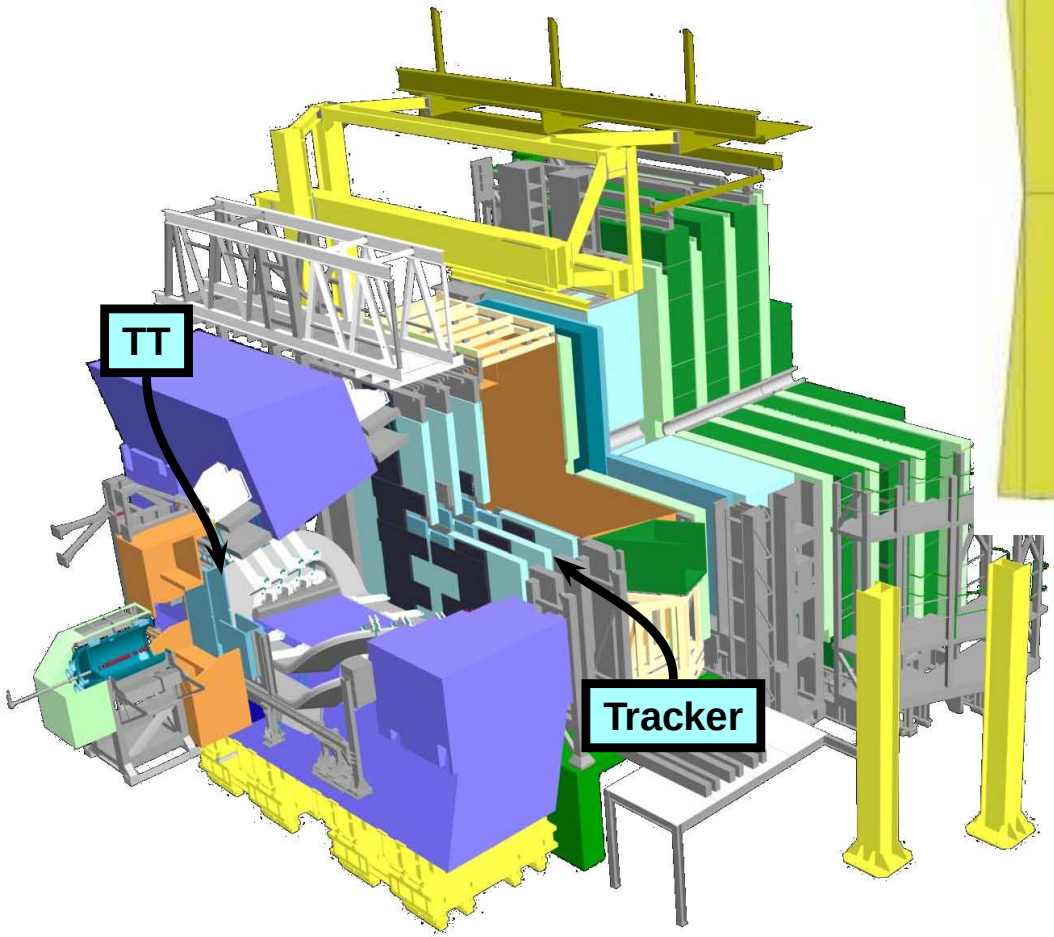


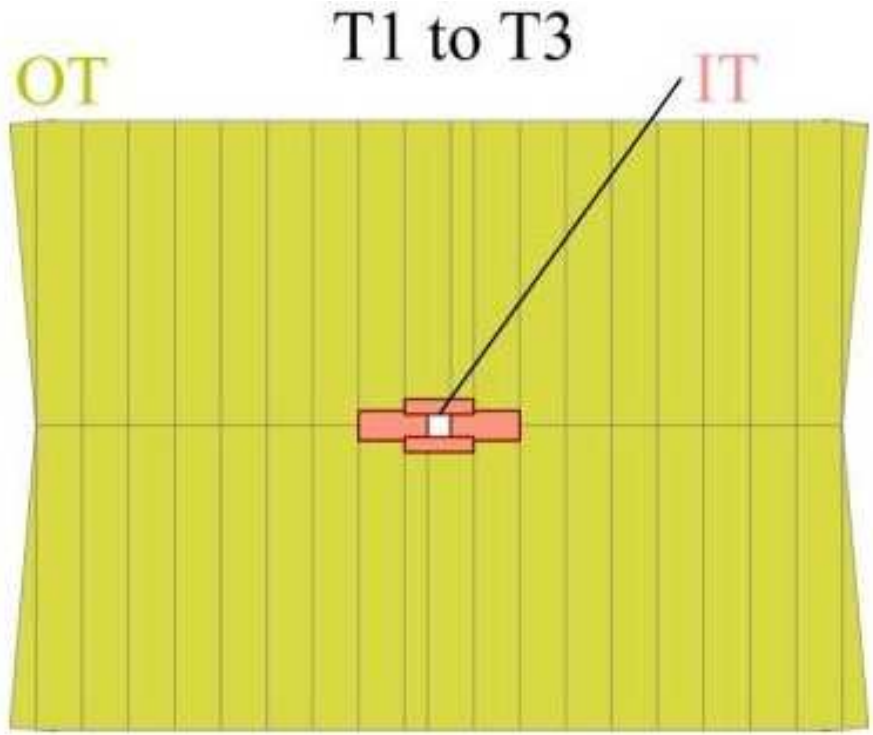
LHCb Trackers

Trigger Tracker: before the magnet

Inner Tracker: around the beam pipe

Outer Tracker: around IT





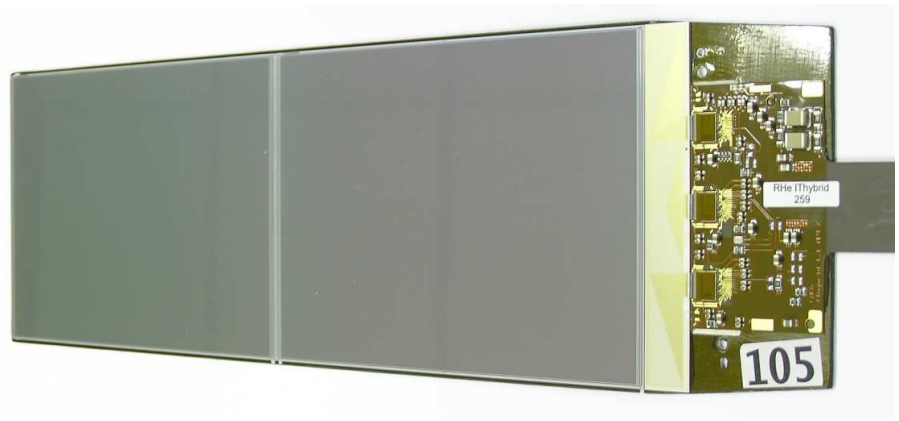
LHCb Trackers

Trigger Tracker: before the magnet

Inner Tracker: around the beam pipe

Outer Tracker: around IT

- OT are straw tubes.
  - Close to the beam pipe the occupancy is too high
- TT and IT are silicon strip detectors

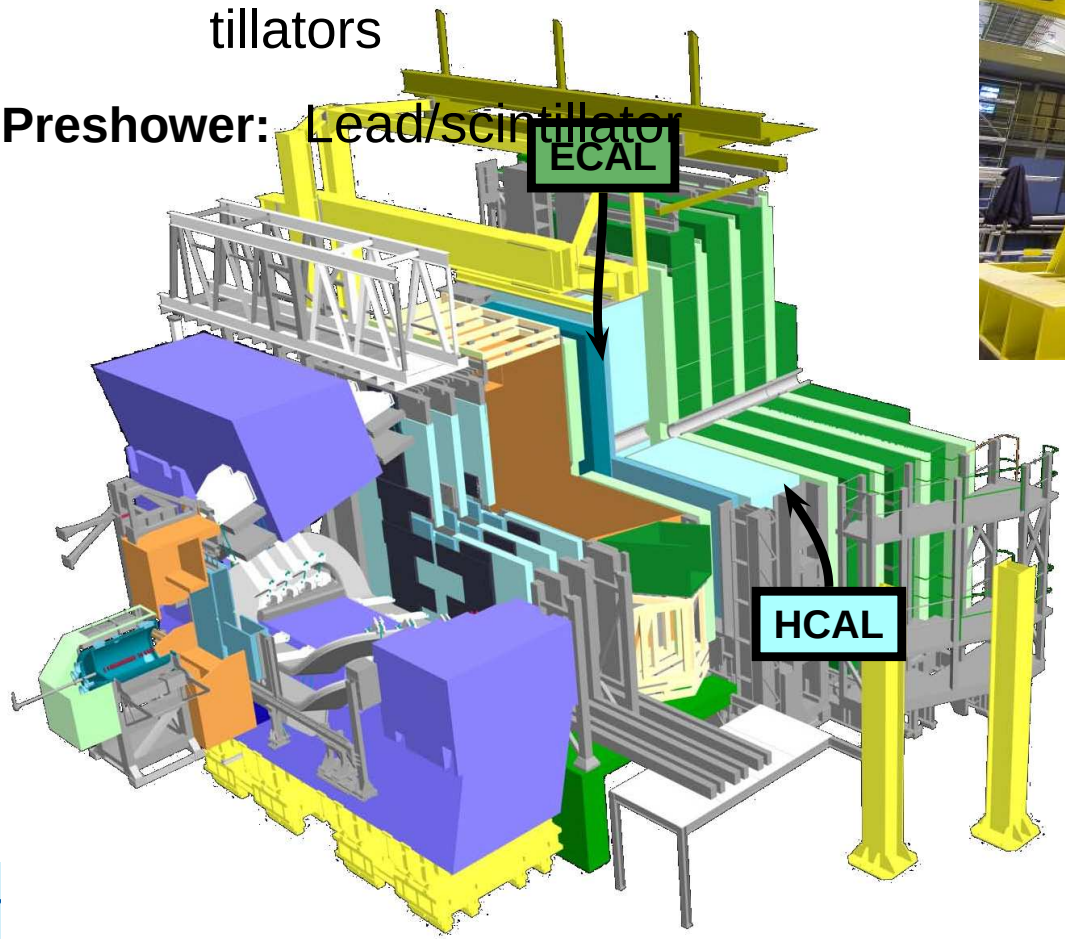


Calorimetry

ECAL: For γ and π^0 detection, and e identification

- Layers of lead and plastic scintillators

Preshower: Lead/scintillator



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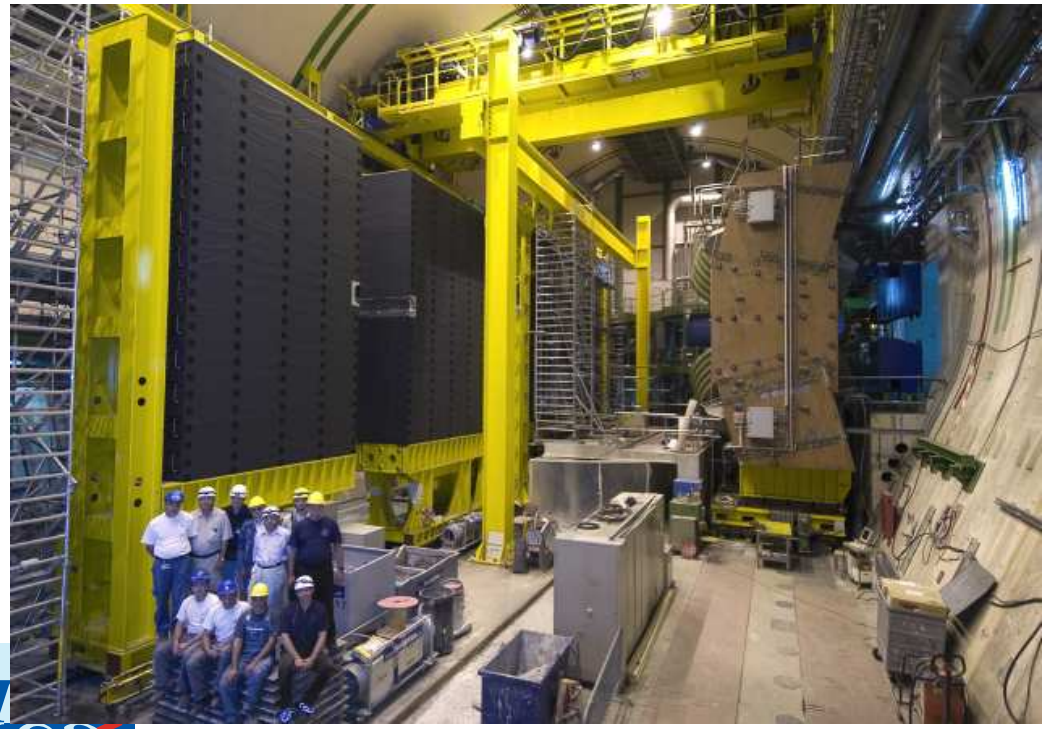
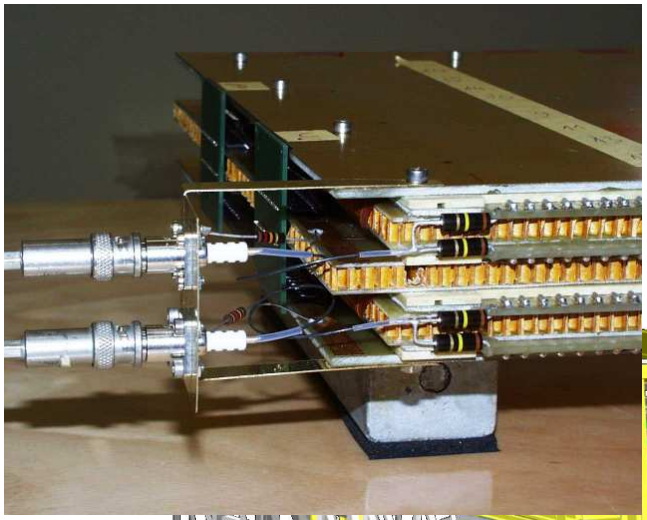


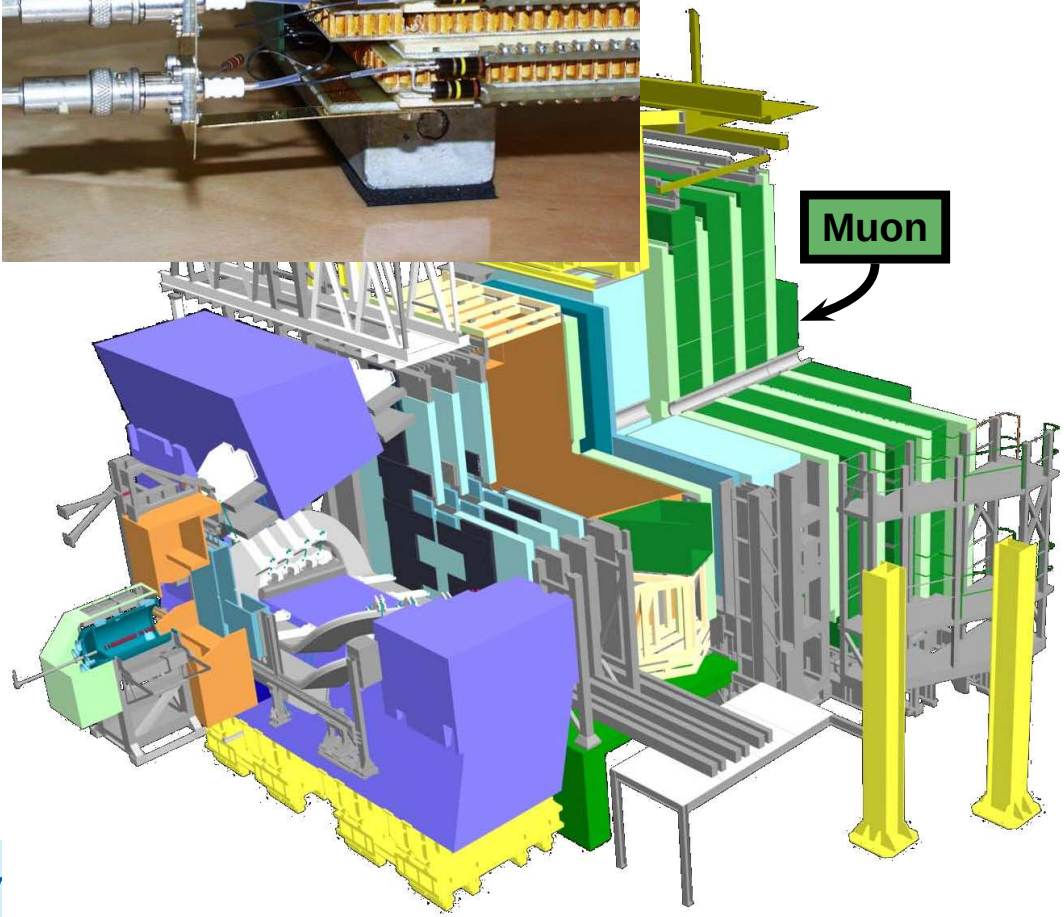
HCAL: For any hadron

- Scintillator tiles embedded in an iron structure
- The HCAL is actually only used in the trigger

LHCb Muon Detector



- Four stations M2–M5 embedded in an ion filter, M1 in front of ECAL
- Read out by gas detectors (triple GEM and

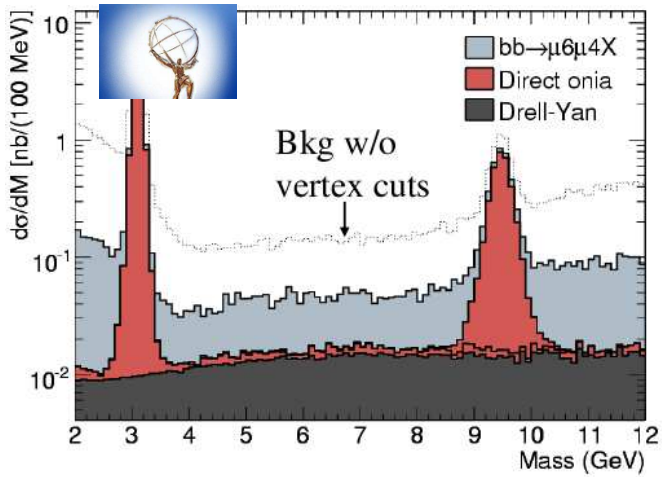


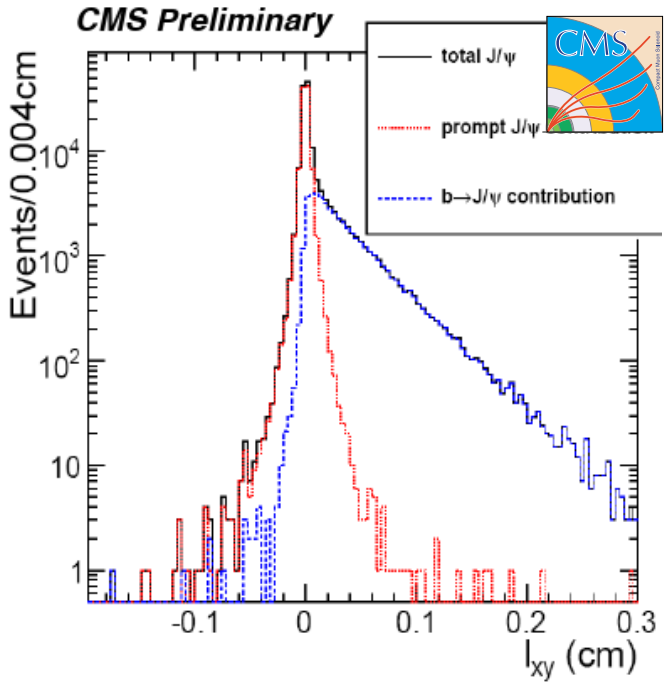
Very early data

- Very early data will be taken unbiased
- Data will mostly be used to calibrate detector, exercise trigger . . .
  - ➜ Do not expect too much
- But still some first measurements can be made with little data
  - Multiplicities
  - Cross sections (K^0_S, Λ, J/ψ, B)

➜ 10 TeV is new territory

➜ These measurements will allow to understand our detectors





LHCb Upgrade plans

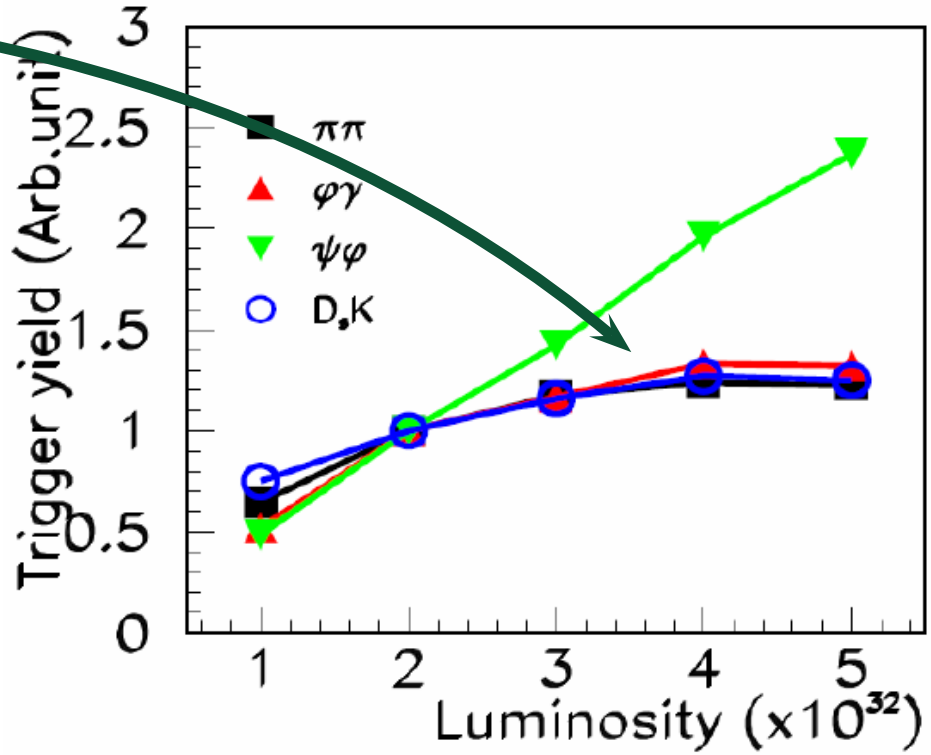
- Expect that integrated luminosity increases linearly with time. After $10\ \text{fb}^{-1}$, would take $>$3 years to double statistics
  - Need a factor 10 increase in luminosity ➜ $\sim 10^{33}$
  - ✔ Most of the detector can cope, efficiencies don't degrade

✗ L0 saturates for hadronic channels

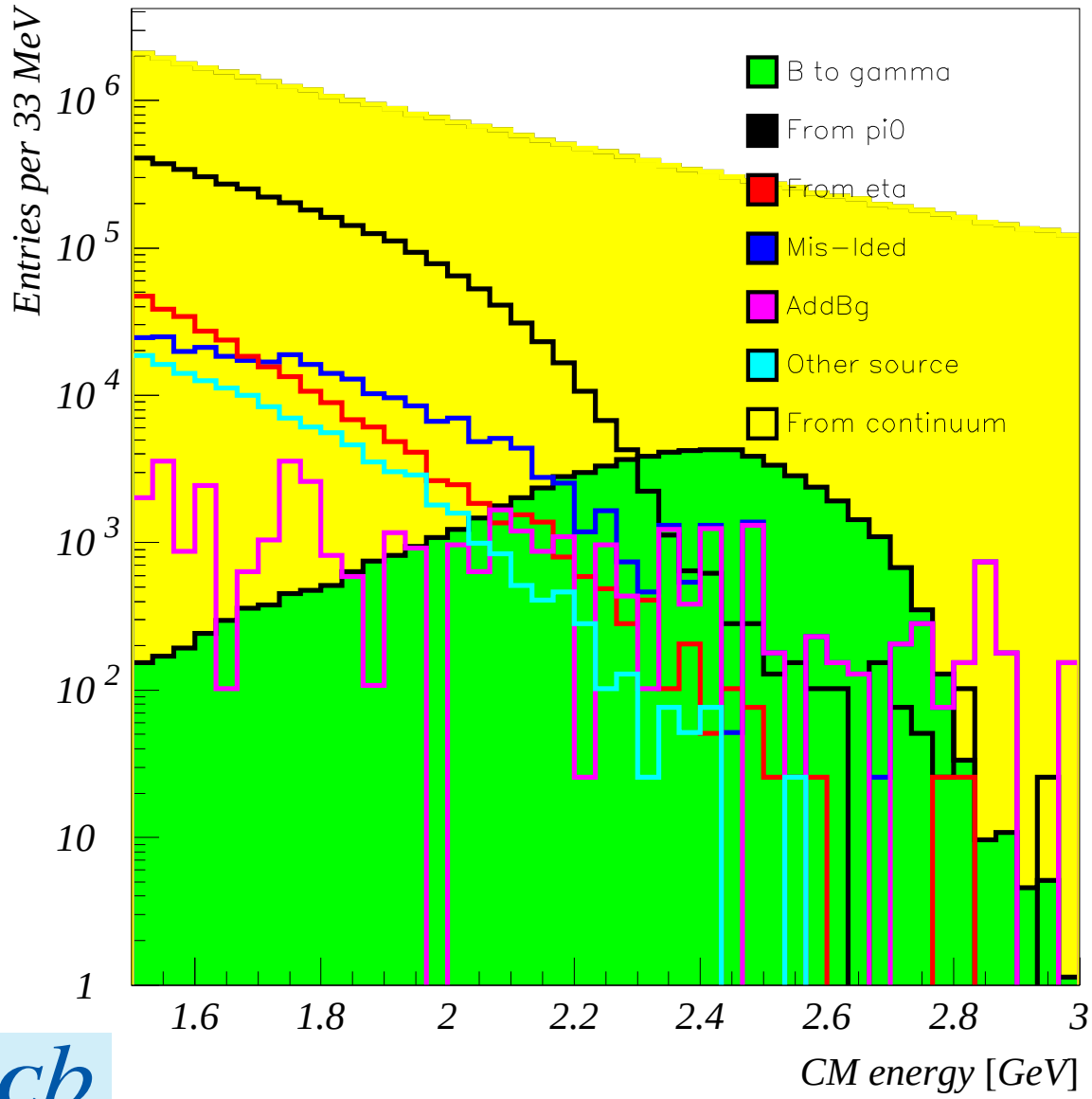
  - p_T is not a discriminating variable anymore
  - ➜ Cut on impact parameter

➜ Read all out at 40 MHz

  - Most of the electronics to be replaced



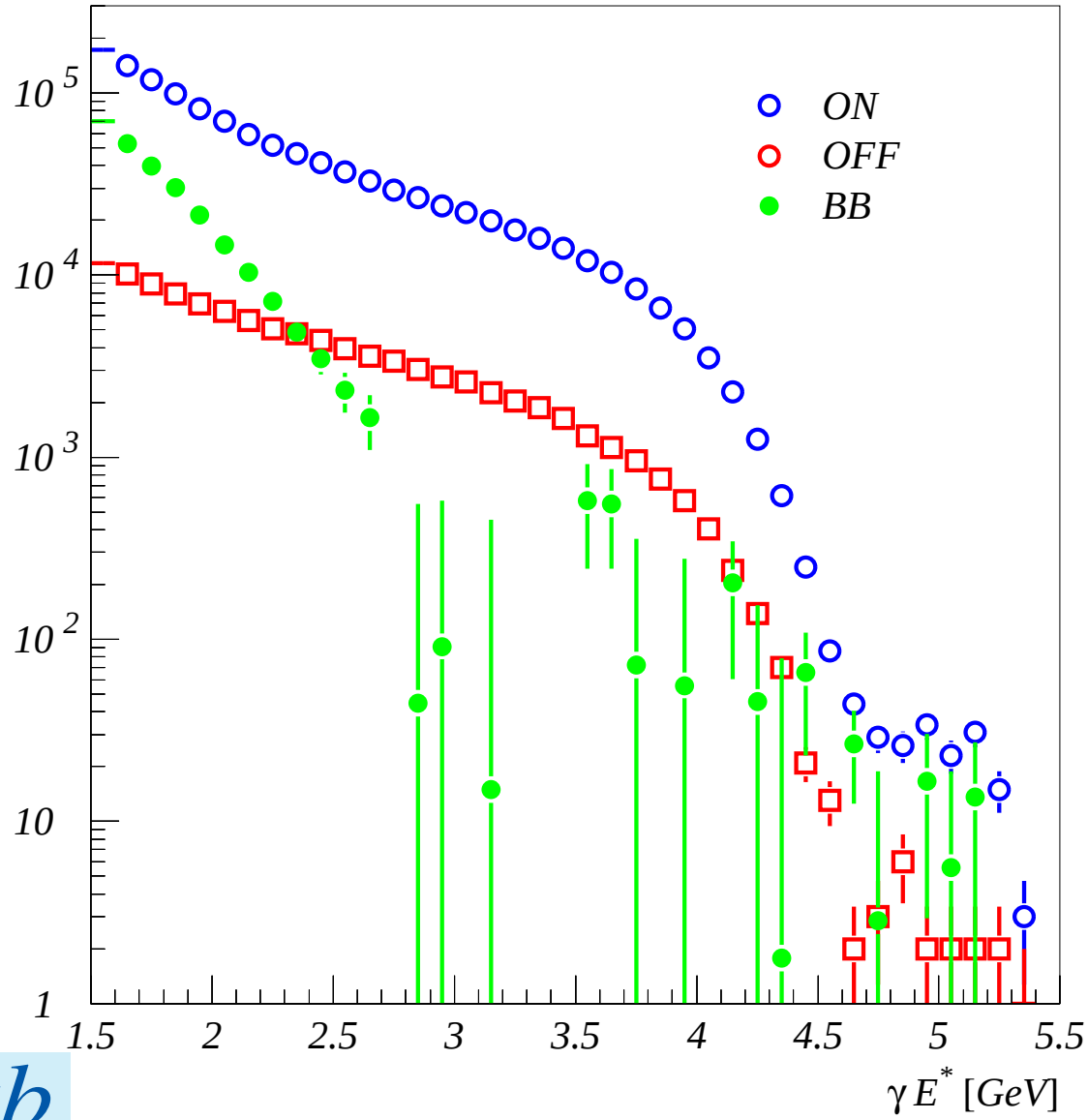
Belle: $b \longrightarrow s\gamma$ spectrum



Event selection:

- Hadronic events with isolated photon(s) in ECL. $E^* > 1.5$.
- Veto γ from π^0 and η.
- Apply event shape cuts to suppress continuum background.

Belle: $b \longrightarrow s\gamma$ spectrum

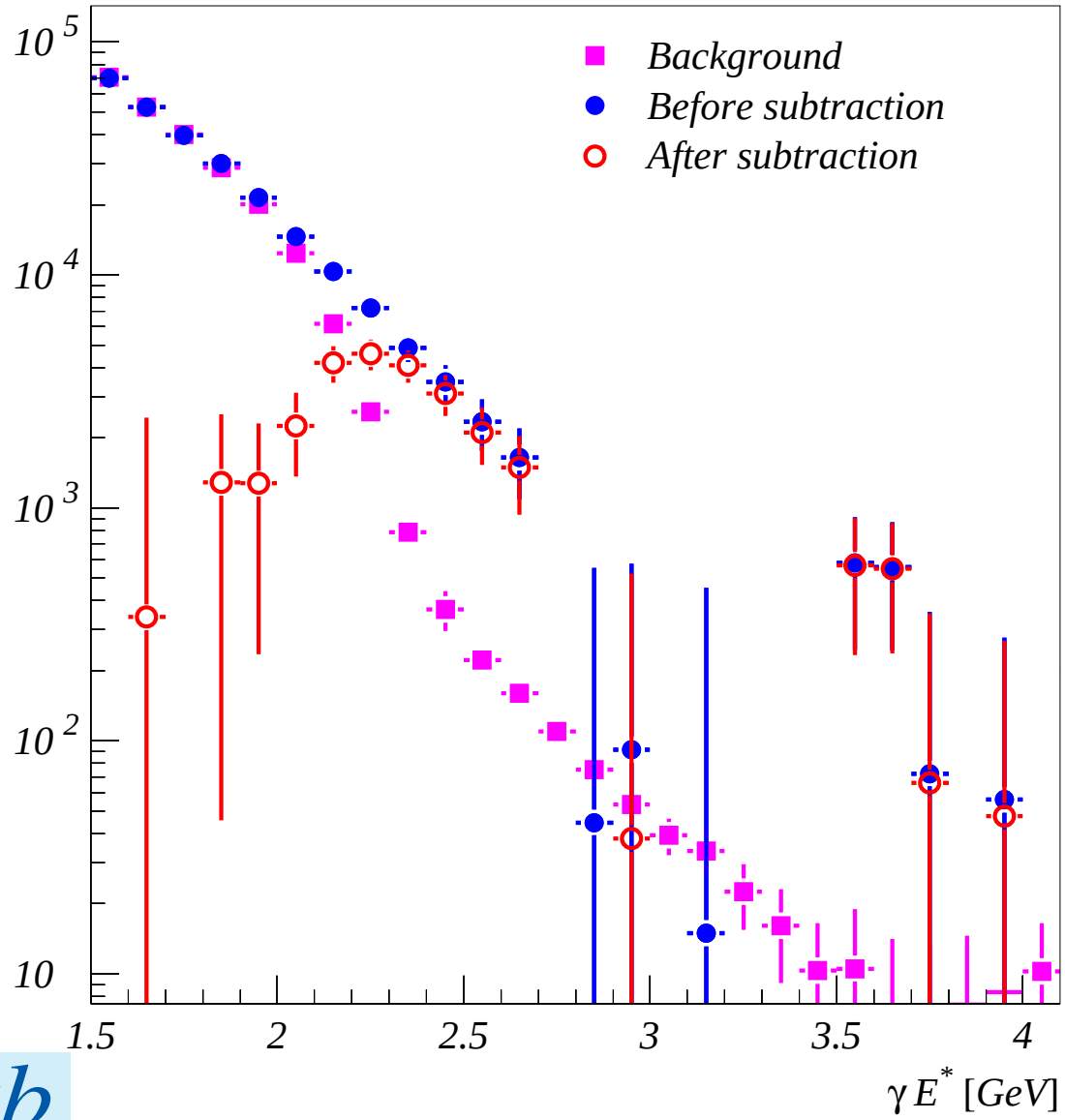


ON, OFF and $B\overline{B}$

OFF-resonance data is subtracted from ON-resonance data

Need to understand differences at $\mathbf{10^{-4}}$ level.

Belle: $b \longrightarrow s\gamma$ spectrum

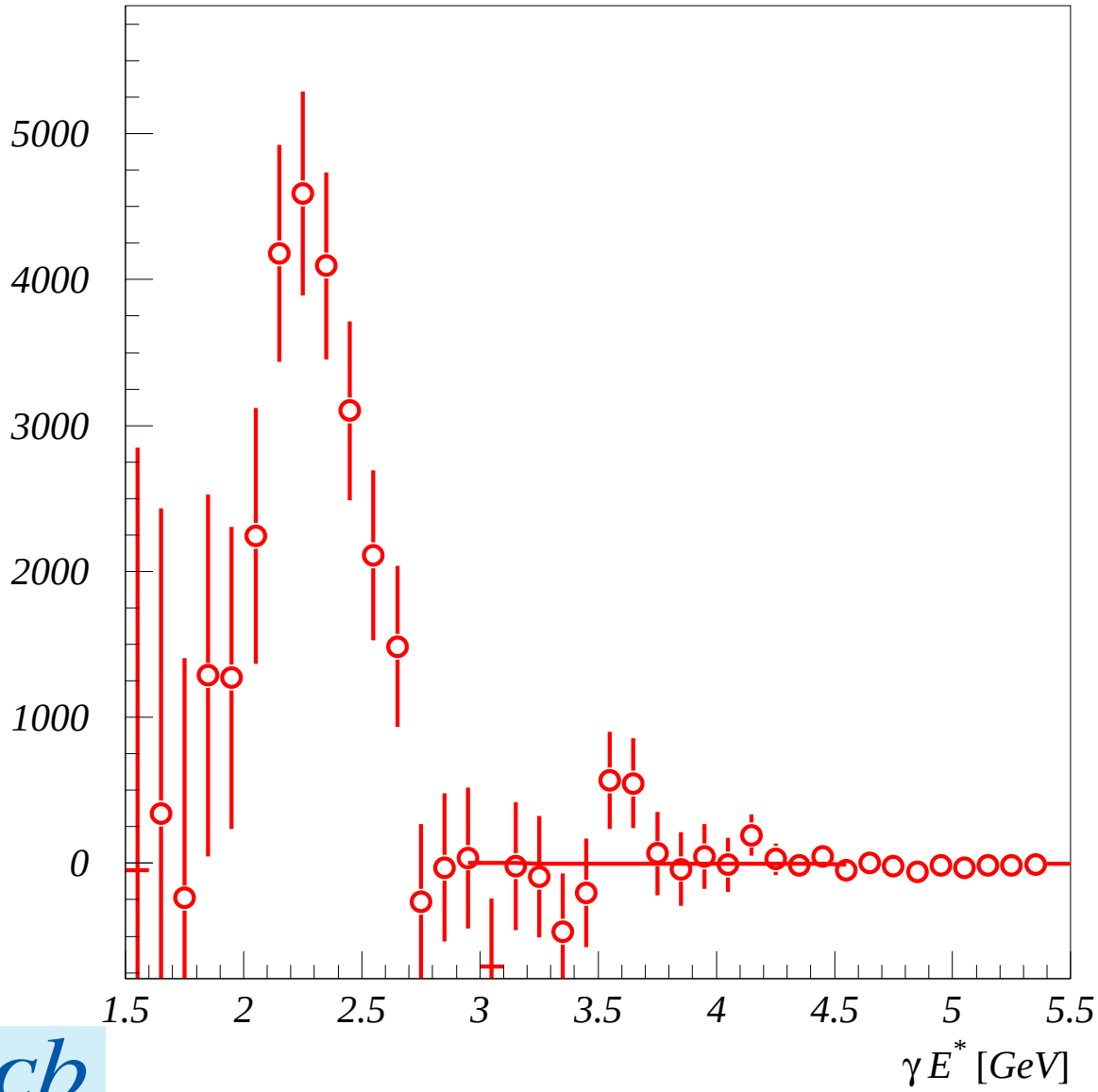


$B\overline{B}$ subtraction.

Using MC and applying efficiency and yield corrections.

$B \to \pi^0 X$ and $B \to \eta X$ spectra are measured (by-product of analysis).

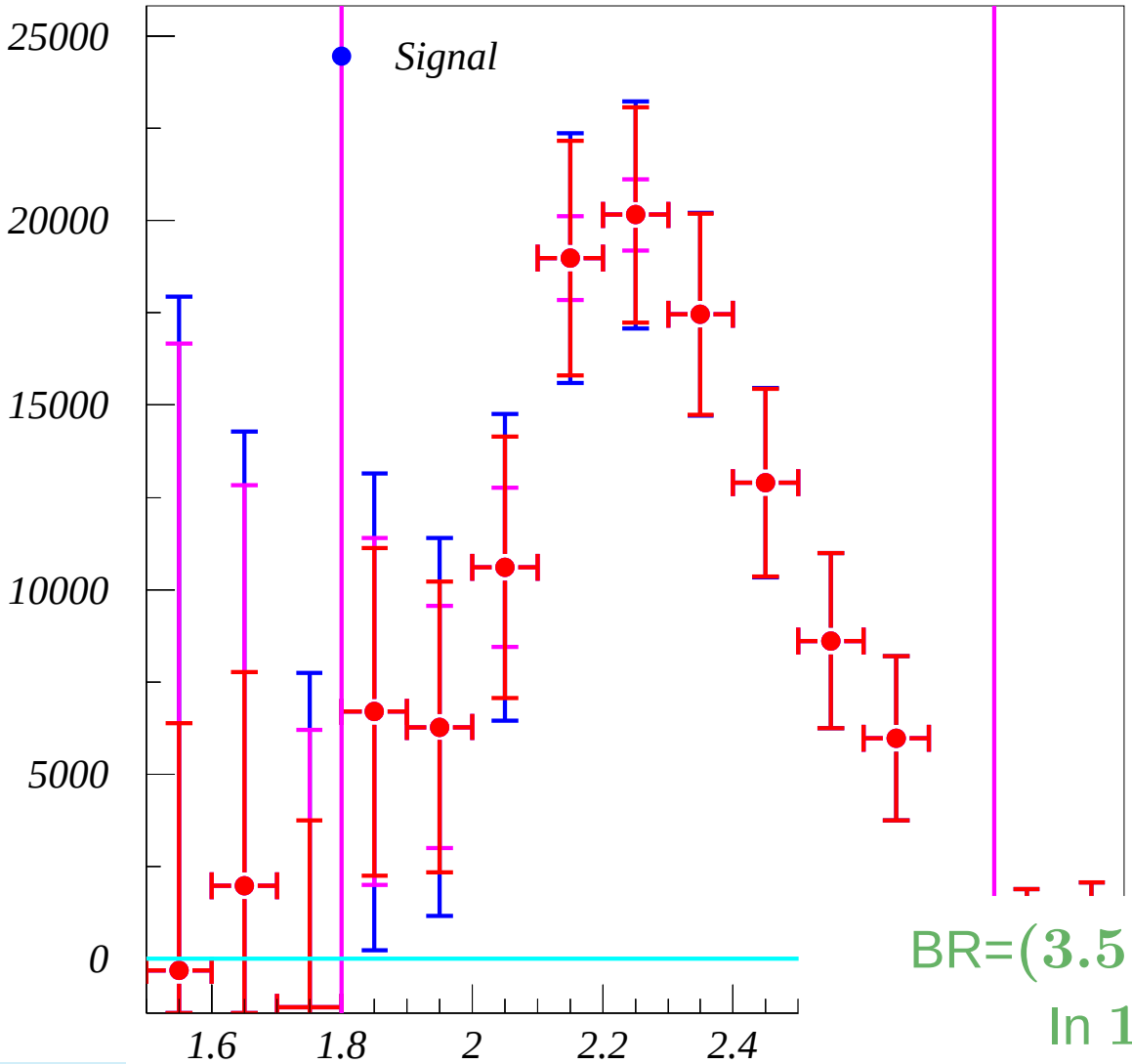
Belle: $b \longrightarrow s\gamma$ spectrum



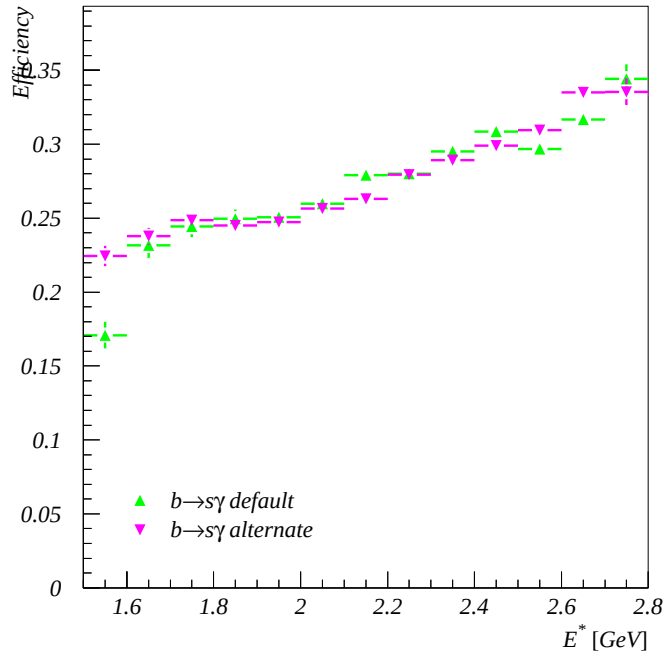
Raw spectrum after all cuts and background corrections

Signal yield:
$\mathbf{24100 \pm 2200}$ events.

Belle: $b \longrightarrow s\gamma$ spectrum



Efficiency corrected spectrum.



BR=$(3.51 \pm 0.32\,^{+0.28}_{-0.29}) \cdot 10^{-4}$

In 1.8–2.8 GeV range.

PRL 93 (2004) 061803

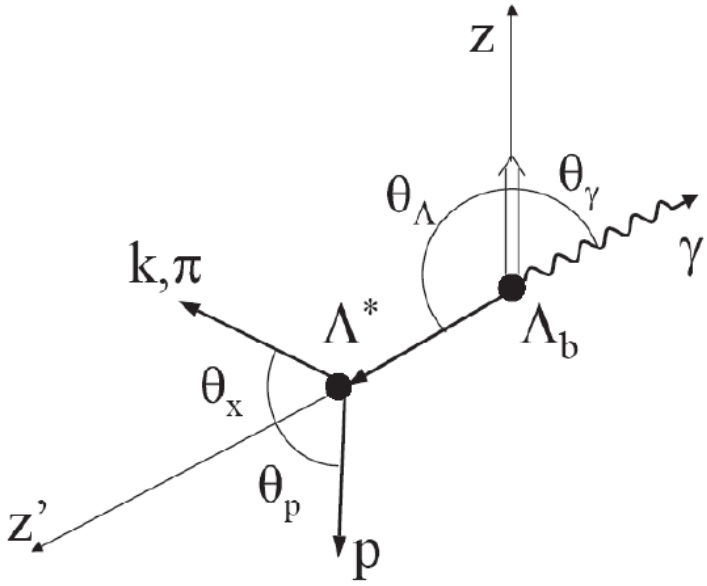
$\Lambda_b \to \Lambda\gamma$ polarisation

$$r = \frac{C'_{7\gamma}}{C_{7\gamma}} \quad \to \quad \alpha_\gamma = \frac{1-|r|^2}{1+|r|^2}$$

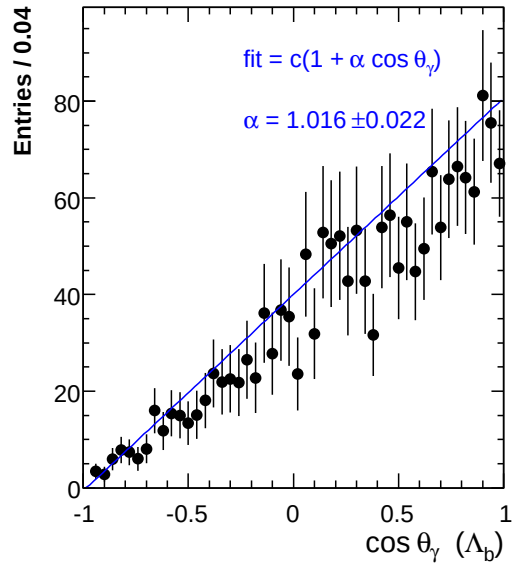
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,\frac{1}{2}} \cos\theta_\gamma$$

$$\alpha_{p,\frac{1}{2}} = 0.642 \pm 0.013$$



- Λ_b is polarised at LHC. Assume 20%.
  - Measure it at 1% with $\Lambda_b \to J/\psi\Lambda$.
    [E. Leader] [Hřivnác et al, hep-ph/9405231]
- But: $\Lambda\gamma$ does not form a good vertex
  - Most Λ decay outside of vertex detector



[F. Legger, T. Schietinger, hep-ph/0605245]

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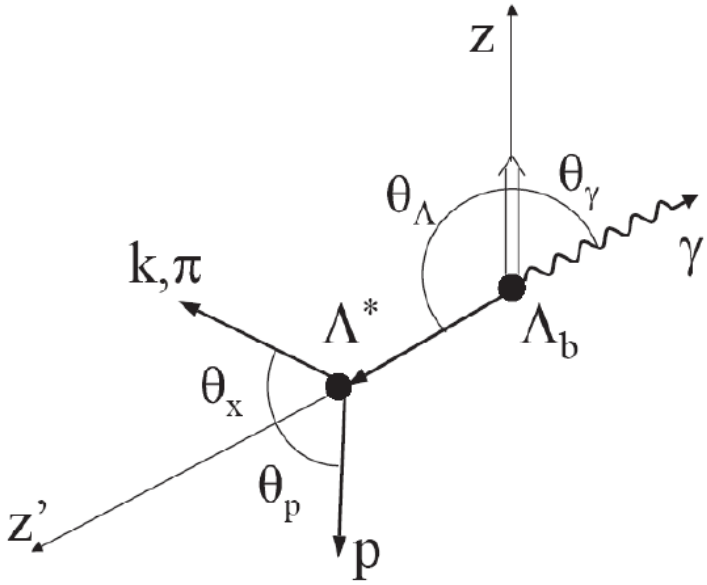
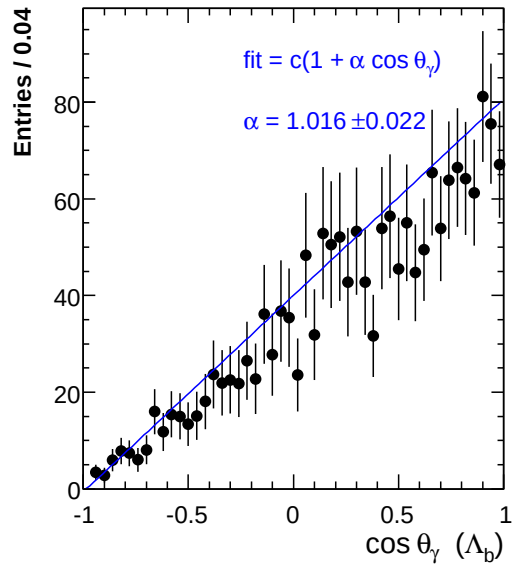
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,\frac{1}{2}} \cos\theta_\gamma = 1$$

$$\alpha_{p,\frac{1}{2}} = 0$$





- ➜ Use also $\Lambda_b \to \Lambda(1670)\gamma$, $\Lambda(1670) \to Kp$
  - Proton polarisation is flat ➜ less information
- Spin $\frac{3}{2}$ $\Lambda(1520)$ and $\Lambda(1690)$ can also be used.
  - Need to be disentangled from $\Lambda(1670)$

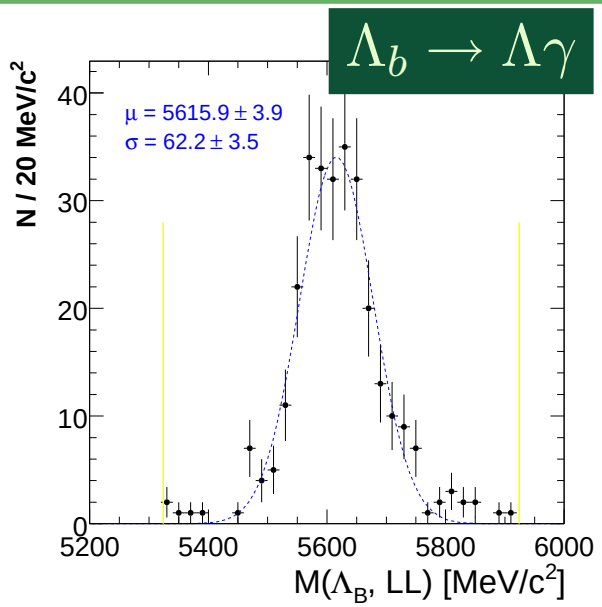
[F. Legger, T. Schietinger, hep-ph/0605245]

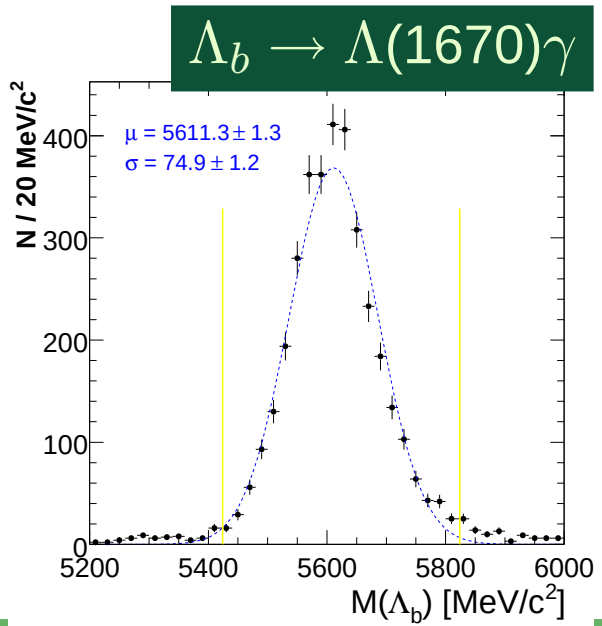
$\Lambda_b \to \Lambda\gamma$ yields

Yields/2 fb^{-1}		B/S
$\Lambda_b \to \Lambda\gamma$	750	< 42
$\Lambda_b \to \Lambda(1520)\gamma$	4200	< 10
$\Lambda_b \to \Lambda(1670)\gamma$	2500	< 18
$\Lambda_b \to \Lambda(1690)\gamma$	2200	< 18

- Λ^* modes have less statistical power because of strong decay
- Combined resolution on r is $\sim 20\%$ after 2 fb^{-1} .
- That's far from SM but already interesting for NP searches.

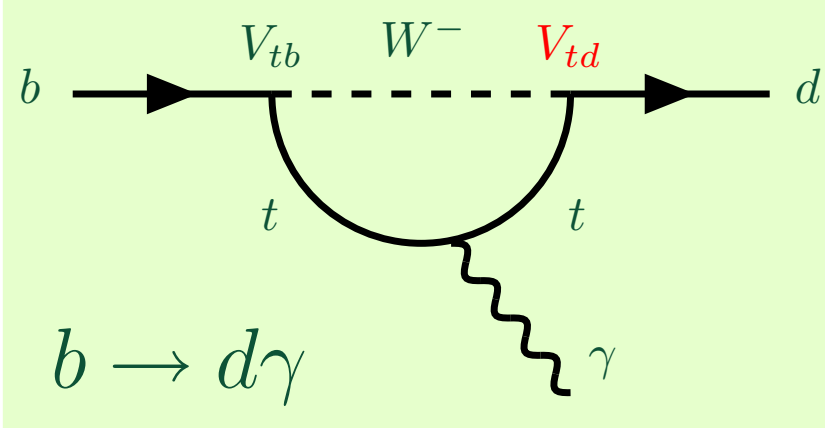
[LHCb note 2006-012] [LHCb note 2006-013]





$B_d \to \omega\gamma$ and $B_d \to \rho\gamma$

$B_d \to \omega\gamma$ and $B_d \to \rho\gamma$ are suppressed by $|V_{td}/V_{ts}|^2 \sim 1/23$.



They are selected the same way as $K^*\gamma$

$B_d \to \omega\gamma$: Additional π^0 reduces efficiency.
Earlier study expects ~ 40 events for 2 fb^{-1} .

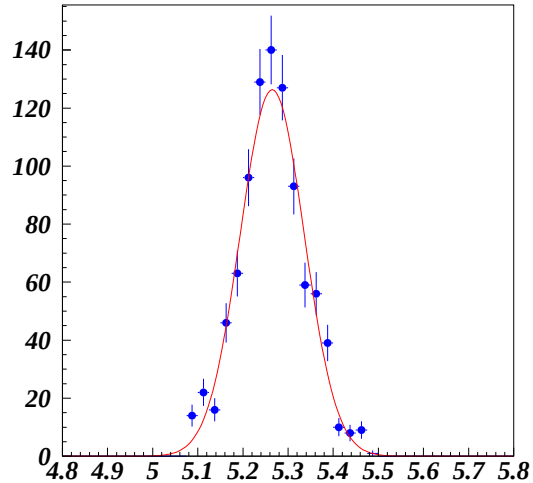
$B_d \to \rho\gamma$: More work on photon ID and suppression of merged π^0 is required to get the sensitivity to $B_d \to \rho\gamma$. We are optimistic.

- $|V_{td}/V_{ts}|$ from $\mathcal{B}(B_d \to (\rho,\omega)\gamma)/\mathcal{B}(B_d \to K^*\gamma)$ is likely to be theory-dominated soon.
- It's difficult to make statements about CP asymmetries

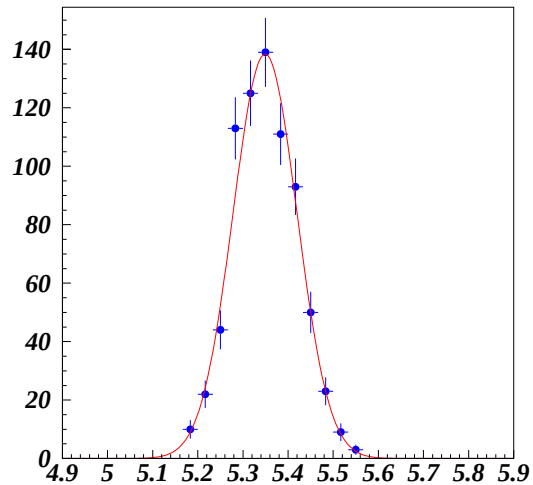
$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$ yields for 2 fb^{-1}

	$B_d \to K^*\gamma$	$B_s \to \phi\gamma$
Visible BR	$2.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
η_{rec}	5.6%	5.4%
η_{sel}	13.3%	11.7%
η_{trg}	46%	44%
η_{tot}	0.34%	0.28%
Signal Yield	$73\,000$	$11\,000$
B/S	0.59 ± 0.26	< 0.55

The B mass resolution is 70 MeV.



$K^*\gamma$ mass [GeV/c^2]



$\phi\gamma$ mass [GeV/c^2]

$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$ yields for 2 fb^{-1}

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Running on 13 minutes equivalent of $b\bar{b}$ events one already gets a peak.

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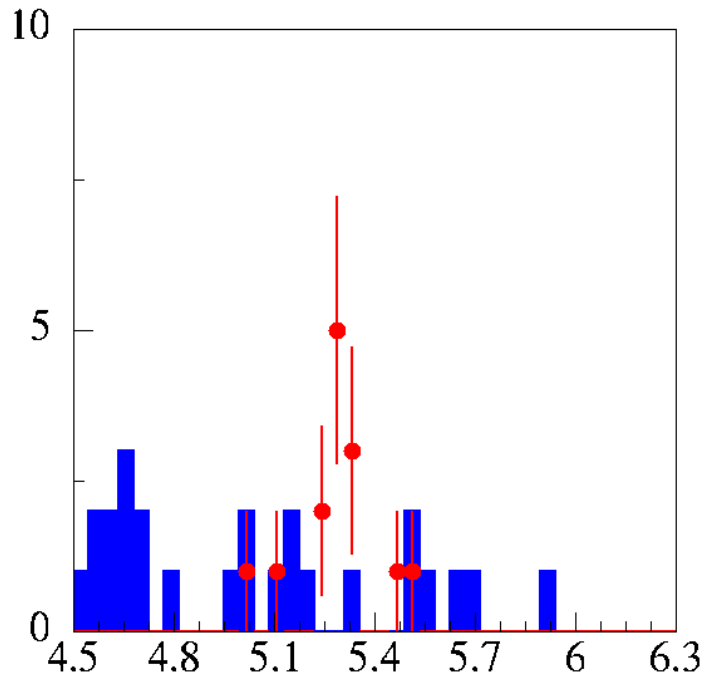


$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$ yields for $2\,\text{fb}^{-1}$

	$B_d \to K^*\gamma$	$B_s \to \phi\gamma$
Signal Yield	$73\,000$	$11\,000$
B/S	0.59 ± 0.26	< 0.55

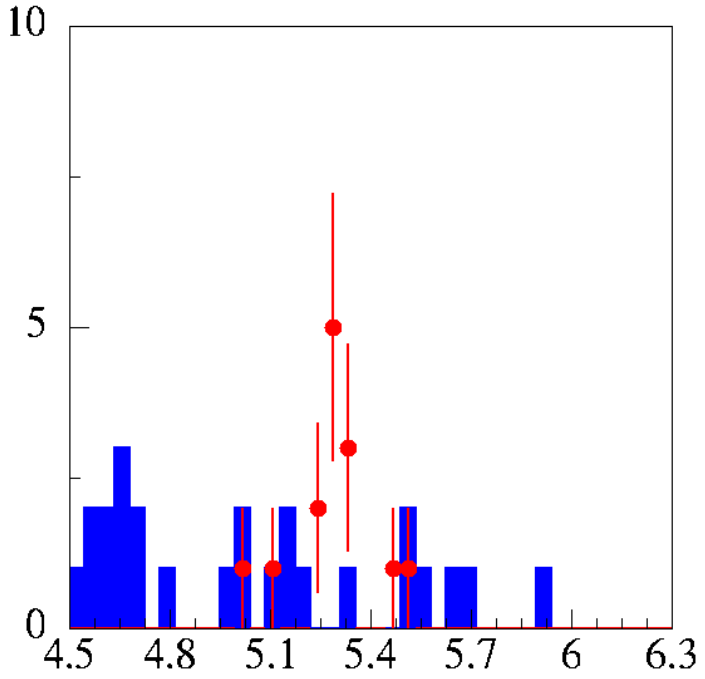
Running on 13 minutes equivalent of $b\bar{b}$ events one already gets a peak.

Expecting a *statistical* error on $A_{\text{CP}}(B_d \to K^*\gamma)$ of 0.5%

➜ Will be dominated by systematics

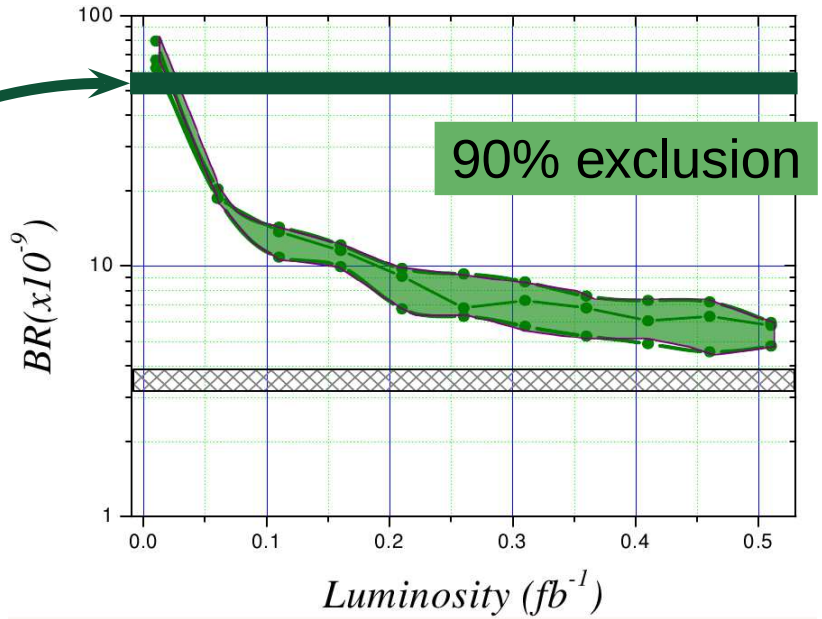
- $K^\pm$ interaction with matter
- B_d, $\overline{B}_d$ production asymmetries . . .

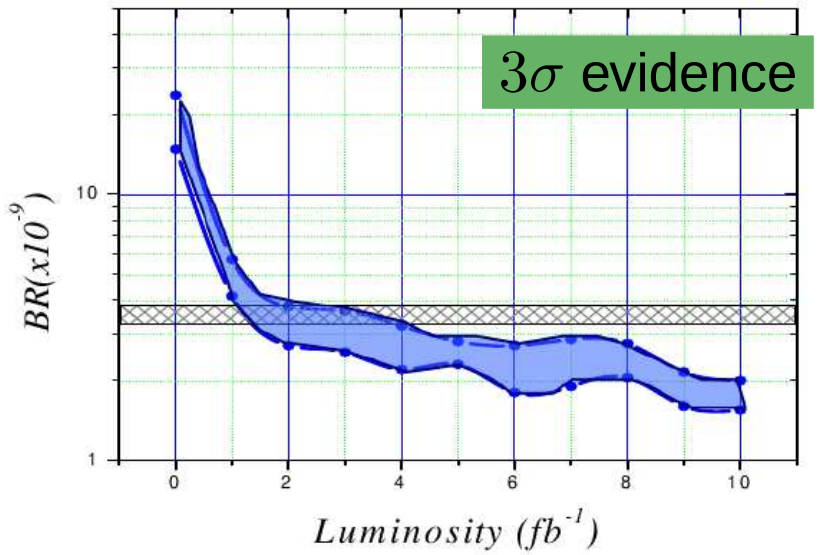
[LHCb note 2007-030]



$B_s \to \mu\mu$

- Very rare but SM BF well predicted
  $\mathcal{B} = (3.55 \pm 0.33) \cdot 10^{-9}$
- Sensitive to (pseudo)scalar operators
  - MSSM: $\mathcal{B} \propto \frac{\tan^6 \beta}{M_A^4}$
- Present limit from CDF $\mathcal{B} < 5.8 \cdot 10^{-8}$ (95% CL)
- With SM BF, expect 8 signal and 12 background events in most sensitive bin in 2 fb^{-1}
  - ➜ 3σ evidence with 2 fb^{-1}
  - ➜ 5σ observation with 6 fb^{-1}





γ in Trees

Favoured $B^- \to K^- D^0$ and colour-suppressed $B^- \to K^- \overline{D}^0$

ADS method: $D^0 \to K^- \pi^+$ and doubly-Cabibbo-suppressed $D^0 \to K^+ \pi^-$

- ✗ Low rate
- ✔ Large interference

GLW method: $D^0 \to$ CP eigenstate

- ✔ Large rate
- ✗ Low interference

Dalitz analysis in $D \to K^0_S \pi\pi$

➜ All analyses time independent

Method	$\sigma(\gamma)$
$B_u \to D(hh)K$	11–13°
$B_d \to D(hh)K^*$	6–13°
$B_u \to D(3K\pi)K$	5–10°
$B_u \to D(K^0_S\pi\pi)K$	6–9°

➜ Error on γ between 5° and 13° with 2 fb^{-1}

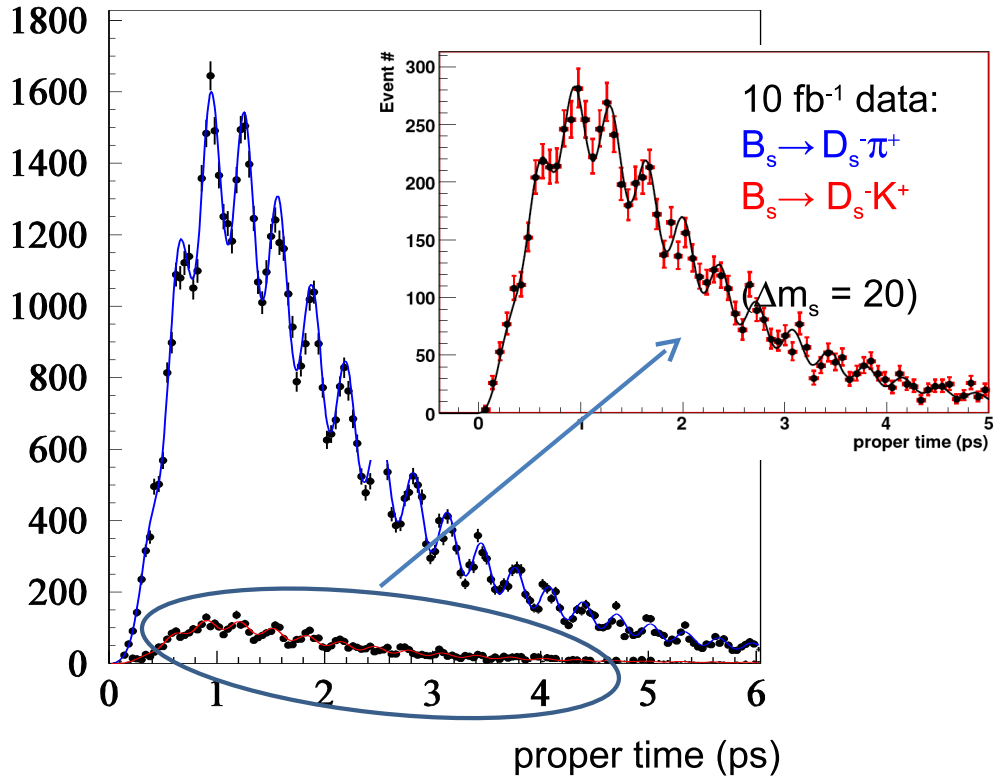
$B \to DK$: Combined $\sim 5°$

γ in Trees

Time dependent CP asymmetry in $B_s \to D_s^+ K^-$ and $B_s \to D_s^- K^+$

➜ Fit $B_s \to D_s K$ and $B_s \to D_s \pi$ for Δm_s, $\Delta\Gamma$, mis-tag and $\gamma + \beta_s$

$2\ \text{fb}^{-1}$	Sig	B/S
$B_s \to D_s K$	$6.2\,\text{k}$	< 0.4
$B_s \to D_s \pi$	$140\,\text{k}$	< 0.4



$B_s \to D_s K$: $9°$–$12°$

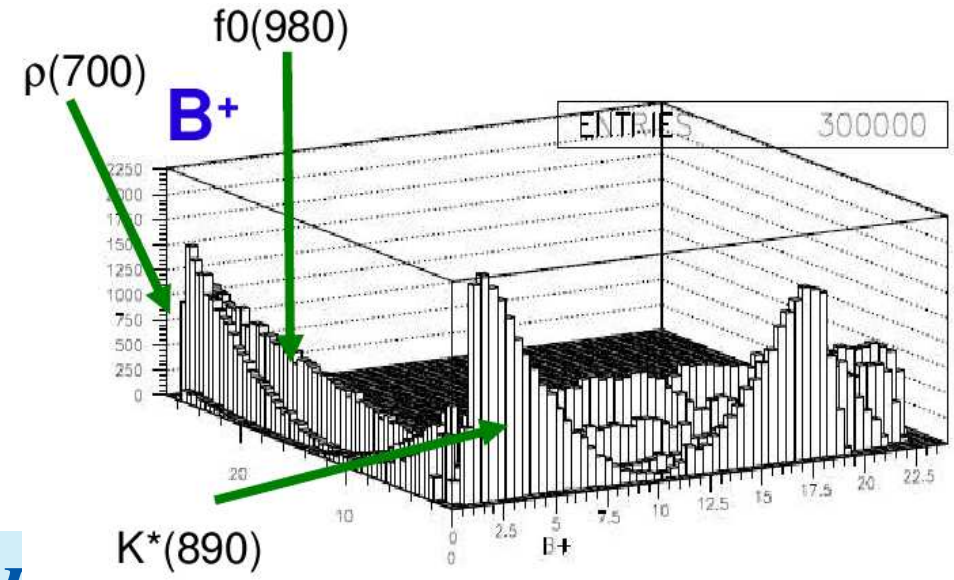
$B \to DK$: Combined $\sim 5°$

γ in Loops

Interference of tree and penguin diagrams in $b \to u$ and $b \to d$ (s)

$B \to hh$: Lifetime-dependent CP in $B_d \to \pi\pi$ and $B_s \to KK$ and direct CP in $B \to K\pi$

Dalitz: analysis of $B_d \to K^0_S\pi\pi$ and $B_d \to K\pi\pi$



2 fb^{-1}	Sig	B/S
$B_d \to \pi\pi$	36 k	0.5
$B_s \to KK$	36 k	0.15
$B_d \to K\pi$	140 k	< 0.06
$B_s \to \pi K$	10 k	1.9
$B_u \to K\pi\pi$	500 k	1
$B_d \to K^0_S\pi\pi$	40 k	TBD

$B \to hh$ 7–10°

$B \to K\pi\pi$ $\sim 5°$

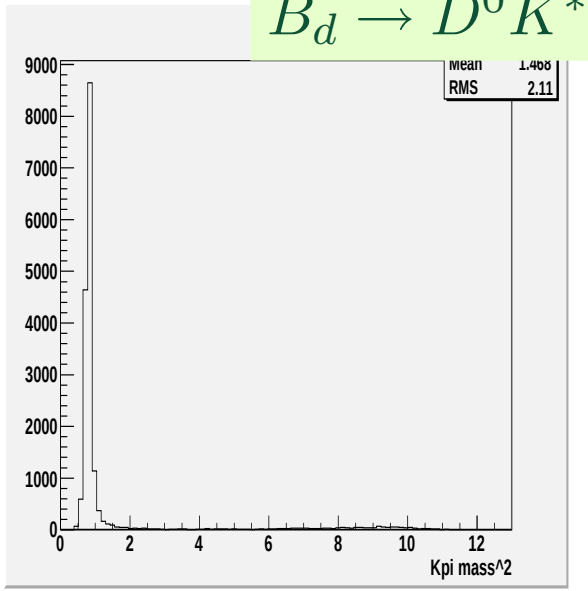
$B_s \to D_s K$: 9°–12°

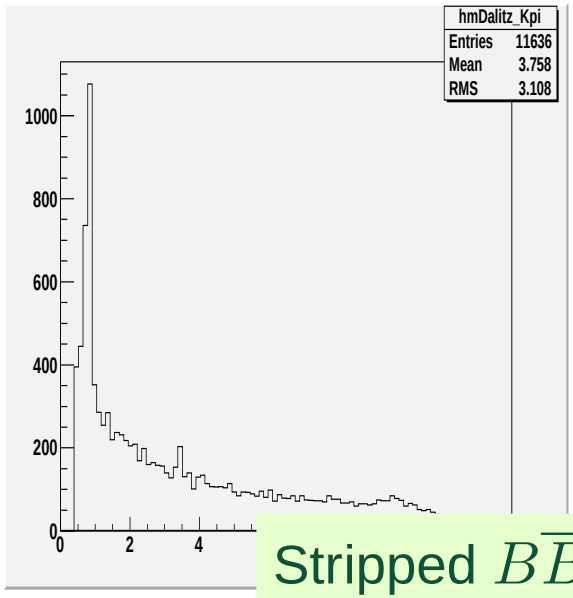
$B \to DK$: Combined $\sim 5°$

Running on Full Simulation

- We run a standard loose $B \to DX$ selection
  1. $B_d \to \overline{D}^0 K^*$
  2. Stripped $B\overline{B}$
- The quasi-two-body is a good approximation of the signal for everything except the Dalitz plot
- The $B\overline{B}$ is used as an estimate of what the background may look like.
- There are some signal, and low mass background events peaking at the B mass
- We don't care about relative normalisations

$B_d \to D^0 K^*$





Stripped $B\overline{B}$

Extracting γ

From these amplitudes, we then obtain

$$\frac{\sqrt{2}A(B^0 \to D_E K^{*0})}{A(B^0 \to D_{[K^+\pi^-]}K^{*0})} = \frac{1 + r_B e^{i(\delta_B+\gamma)}}{1 + r_B e^{i(\delta_B+\gamma)} r_D e^{i\delta_D}}$$

$$\frac{A(B^0 \to D_{[K^-\pi^+]}K^{*0})}{A(B^0 \to D_{[K^+\pi^-]}K^{*0})} = \frac{r_D e^{i\delta_D} + r_B e^{i(\delta_B+\gamma)}}{1 + r_B e^{i(\delta_B+\gamma)} r_D e^{i\delta_D}}$$

and similarly for the conjugate decays

$$\frac{\sqrt{2}A(\bar{B}^0 \to D_E \bar{K}^{*0})}{A(\bar{B}^0 \to D_{[K^-\pi^+]}\bar{K}^{*0})} = \frac{1 + r_B e^{i(\delta_B-\gamma)}}{1 + r_B e^{i(\delta_B-\gamma)} r_D e^{i\delta_D}}$$

$$\frac{A(\bar{B}^0 \to D_{[K^+\pi^-]}\bar{K}^{*0})}{A(\bar{B}^0 \to D_{[K^-\pi^+]}\bar{K}^{*0})} = \frac{r_D e^{i\delta_D} + r_B e^{i(\delta_B-\gamma)}}{1 + r_B e^{i(\delta_B-\gamma)} r_D e^{i\delta_D}}$$

Note: All relevant normalisation factors are automatically accounted for!

Extracting γ

- Thus, we are left with 5 unknowns ($r_B, \delta_B, \gamma, r_D, \delta_D$) and *8-ish observables* which can be taken to be the 4 complex amplitude ratios.
- Of course, this is an over simplified (but illustrative) way of looking at it since we really have distributions and other *uninteresting* unknown parameters in the PDF.
- External constraints exist from CLEO-c $r_D = 0.0616$ and $\delta_D = -158^\circ(^{+14^\circ}_{-16^\circ})$ which can be used to reduce the number of unknowns.
- The presence of more overlapping resonances let us make the same measurement simultaneously in multiple channels.
- This method extracts γ with only a single ambiguity ($\gamma \rightarrow \gamma + \pi$)!

LHCb 4 fb^{-1}

Prediction for **four** fb^{-1}, based $B_d \to D^0 K^*$ w/ $\delta_B = 90°$:

	$\delta_B = 0°$	$\delta_B = 45°$	$\delta_B = 90°$	$\delta_B = 135°$	$\delta_B = 180°$
$N(B^0 \to D_{[K^+\pi^-]}K^+\pi^-)$	7190	7300	7360	7330	7240
$N(B^0 \to D_{[K^-\pi^+]}K^+\pi^-)$	592	667	779	863	868
$N(B^0 \to D_{[CP+]}K^+\pi^-)$	693	566	474	450	529
$N(\bar{B}^0 \to D_{[K^-\pi^+]}K^-\pi^+)$	7080	7050	7100	7210	7310
$N(\bar{B}^0 \to D_{[K^+\pi^-]}K^-\pi^+)$	732	612	587	671	816
$N(\bar{B}^0 \to D_{[CP+]}K^-\pi^+)$	678	754	738	639	516

Expected events per 4 fb^{-1} assuming flat efficiency.

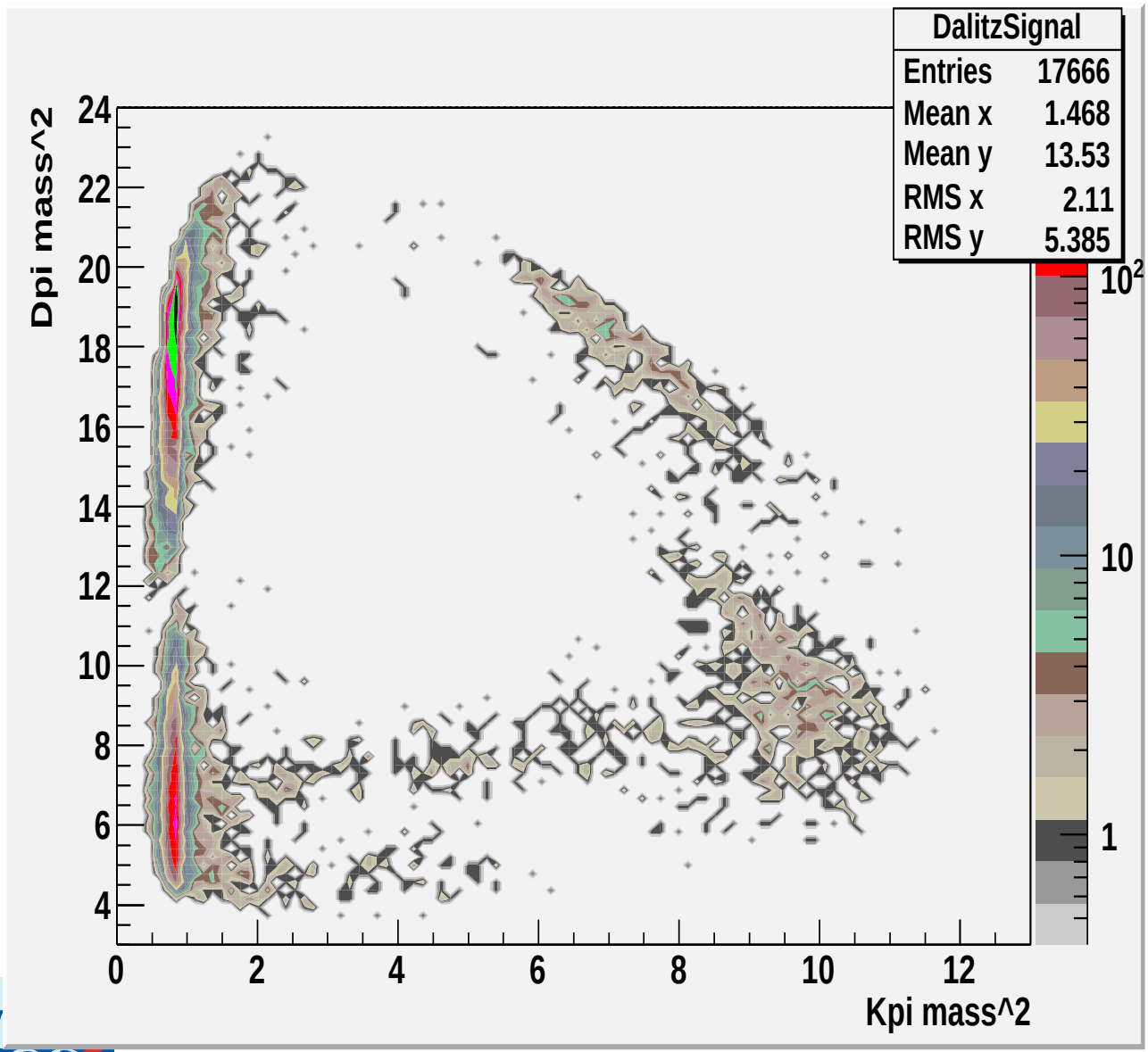
Fit

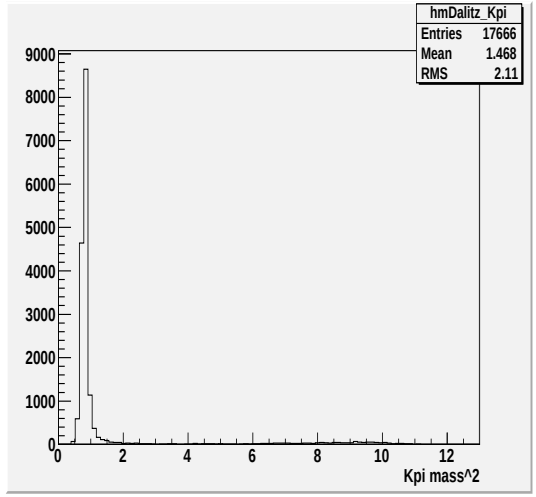
Fit the data using the *extended unbinned maximum likelihood* method:

- For each fit iteration, start all parameters at random values in the ranges: $\gamma \in [0, 2\pi), r_B \in [0, 1), a \in [0, 25), \phi \in [0, 2\pi), \delta_B \in [0, 2\pi)$.
- For each dataset, run 25 fit iterations (each starting at a different random point in parameter space).
- Extract parameters using the best iteration (*i.e.* the one with the best likelihood).

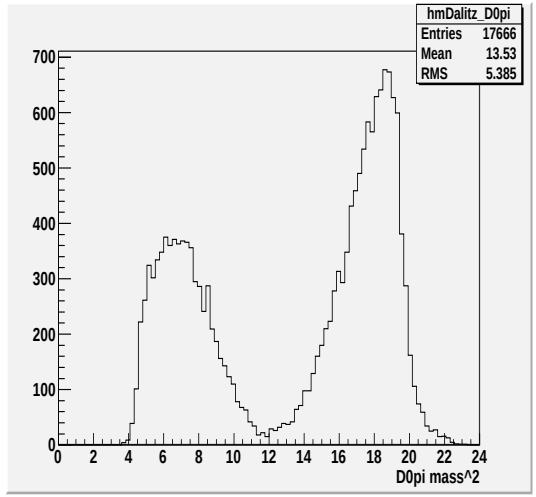
It would be better to fit in Cartesian coordinates and the fitter could also be improved by adding analytic derivatives, but these issues won't affect this study.

$B \to \overline{D} K^*$ Dalitz



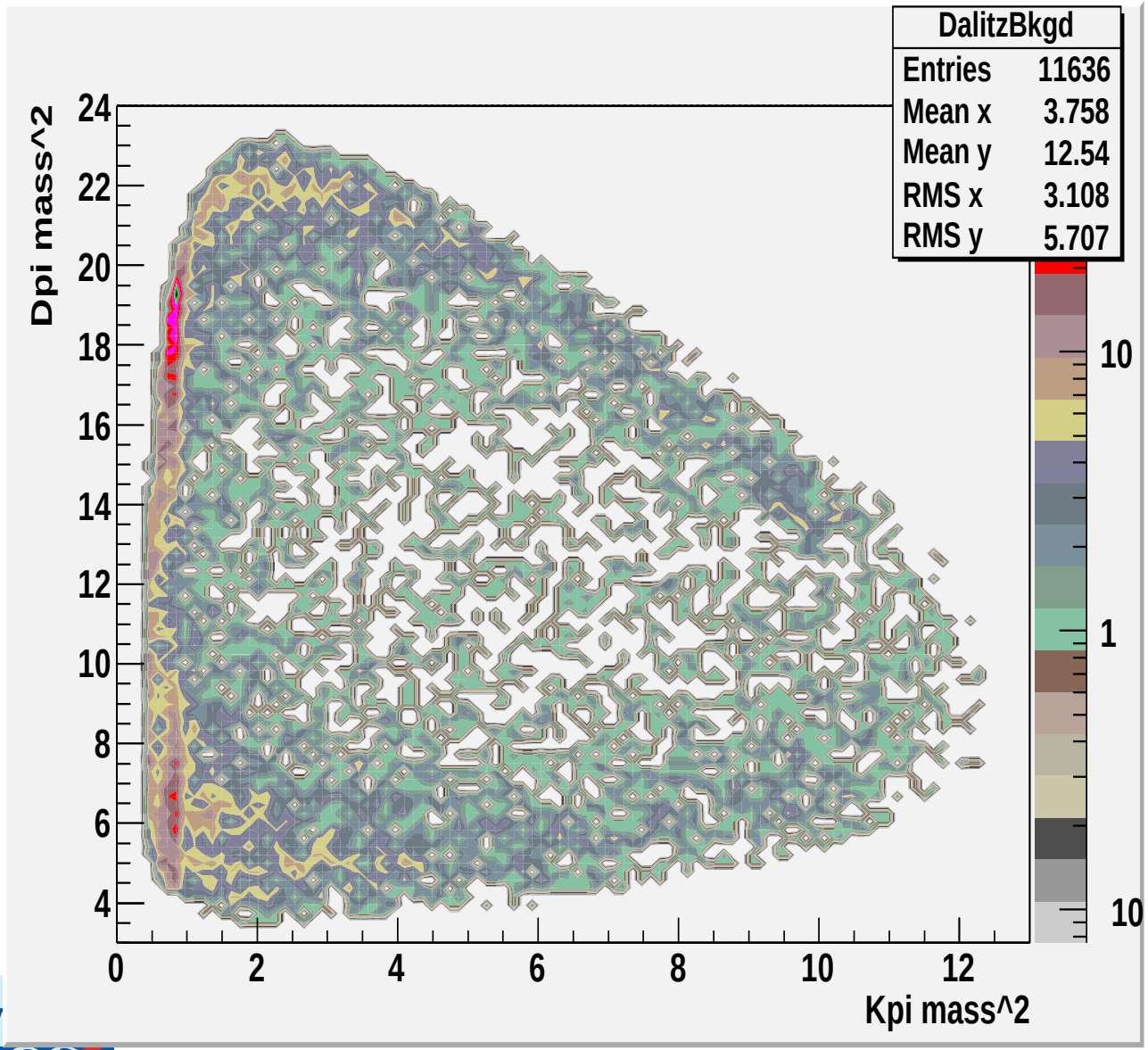


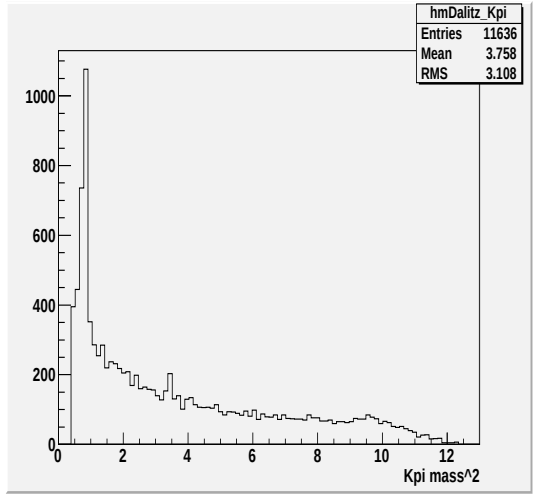
$K\pi\ m^2$



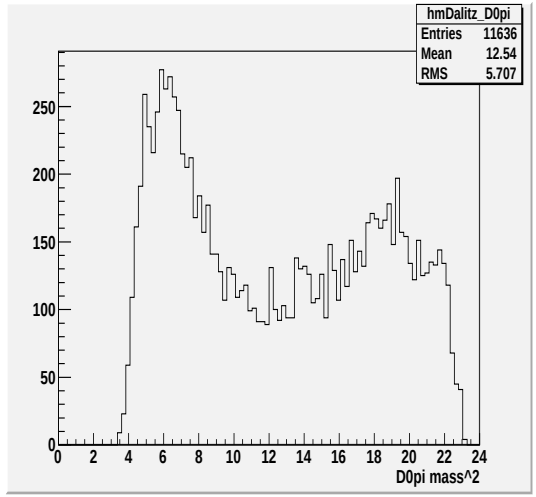
$D\pi\ m^2$

$B\overline{B}$ background Dalitz





$K\pi\ m^2$



$D\pi\ m^2$