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Rare decays in LHCb

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What do we mean by Rare Decays?

- “Rare” decays with leptonic or electromagnetic final states
  - $B_s \to \varphi\gamma$, $B_d \to K^{*0}\mu^+\mu^-$, $B_s \to \mu^+\mu^-$, ...
- Flavour Changing Neutral Current decays are only allowed in the SM at loop level
  - SM and New Physics on equal footing opening up possibility for large NP effects
- As LHCb is a hadron collider experiment
  - We can only look at exclusive final states ☹.
  - But the number of triggered events in the exclusive final states are huge ☺.

An effective theory for New Physics

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_i, \Psi_j; \mathbf{Y}, \mathbf{C}) + \mathscr{L}_{\text{Higgs}}(A_i, \Psi_j, \phi; \langle\phi\rangle) +$$

$$\sum_{d>4} \frac{c^n}{\Lambda^{d-4}} O_n^d$$

O_d^n: All possible operators with heavy d.o.f

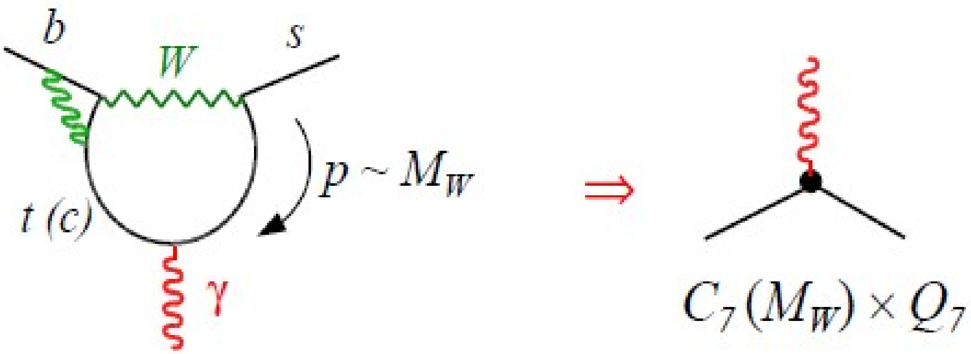
c^n: Parameters arising from New Physics

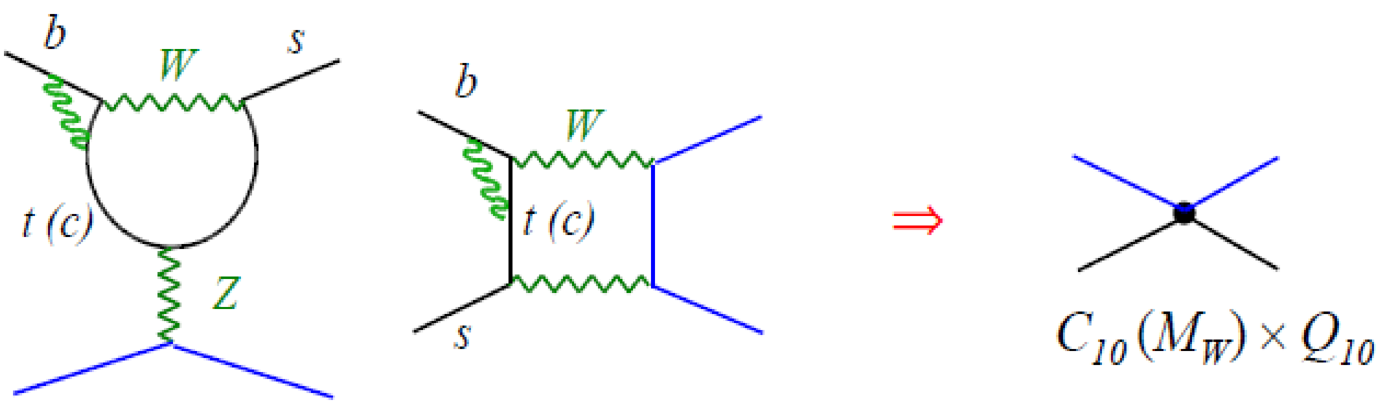
Λ: Energy scale of New Physics

Separate terms for left and right handed currents

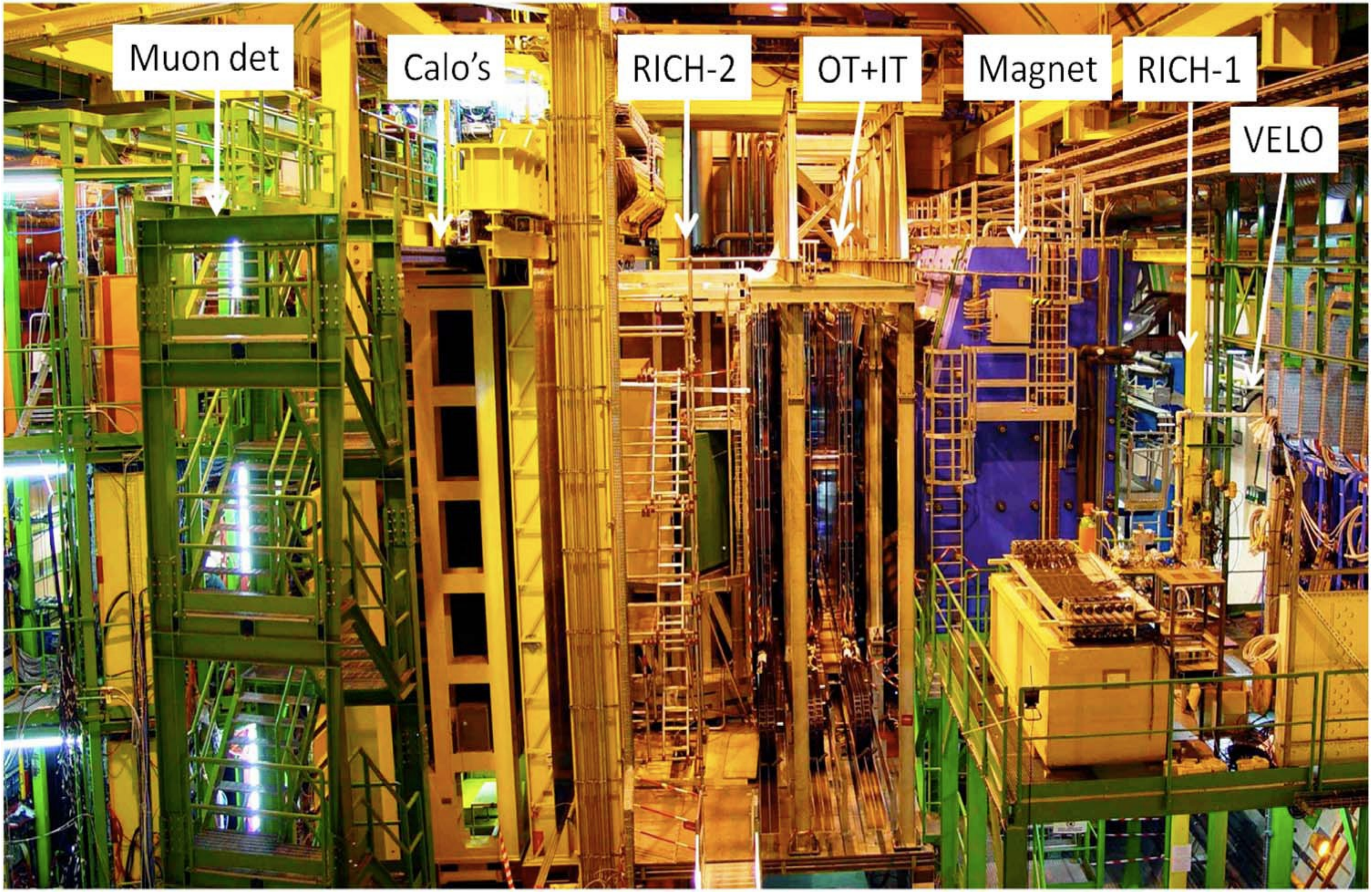
- Some left handed (C_7, C_{10}) are present through loops in the SM
- Significant right handed currents represent NP.

SM processes in higher order operators

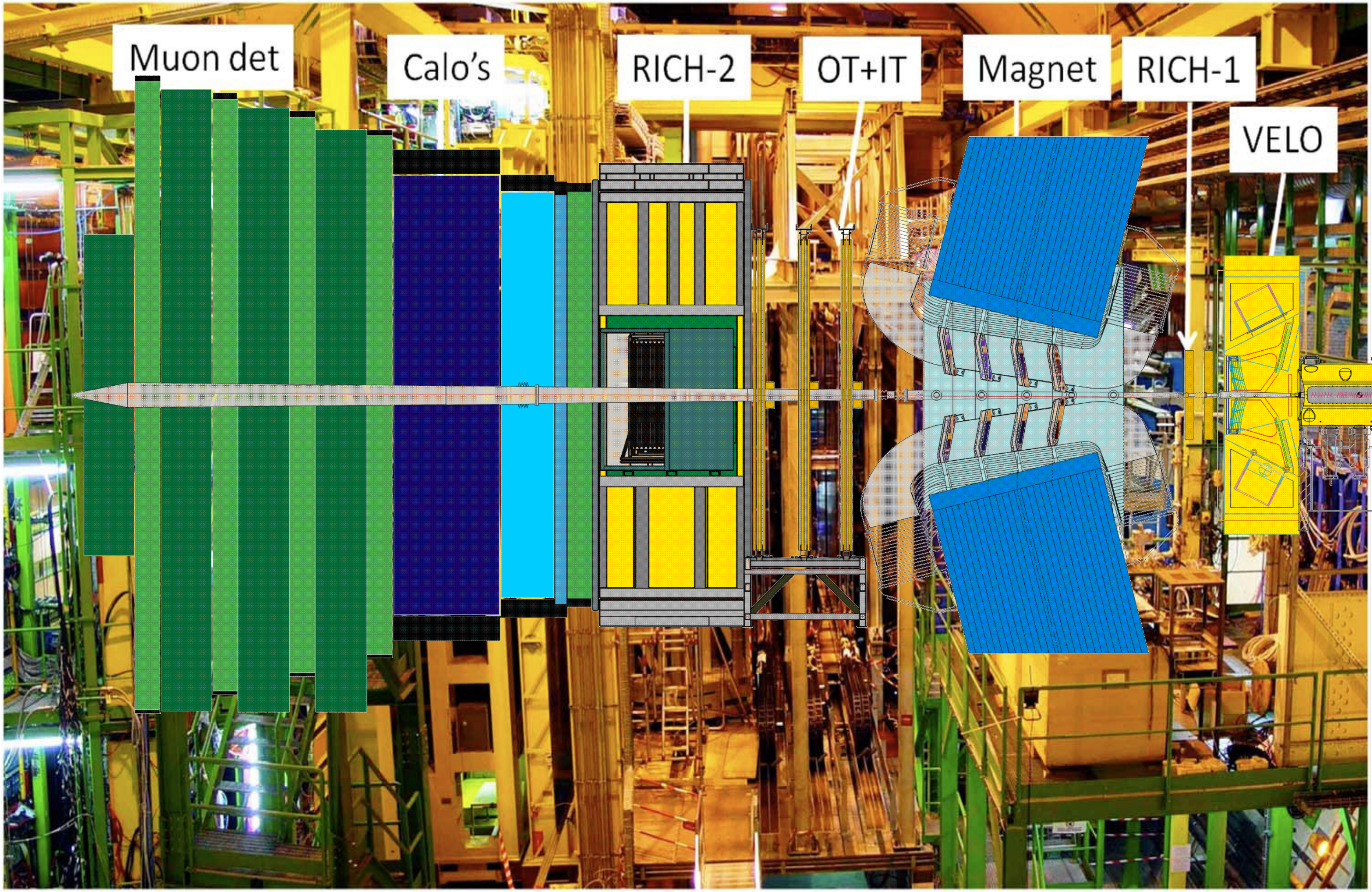




LHCb layout



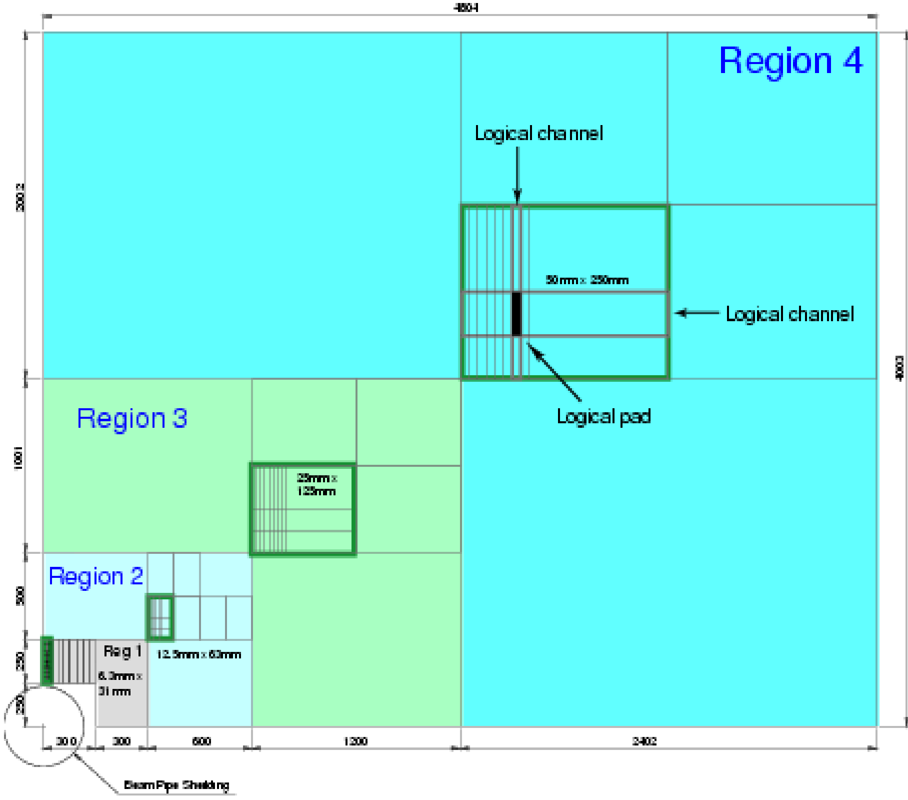
LHCb layout

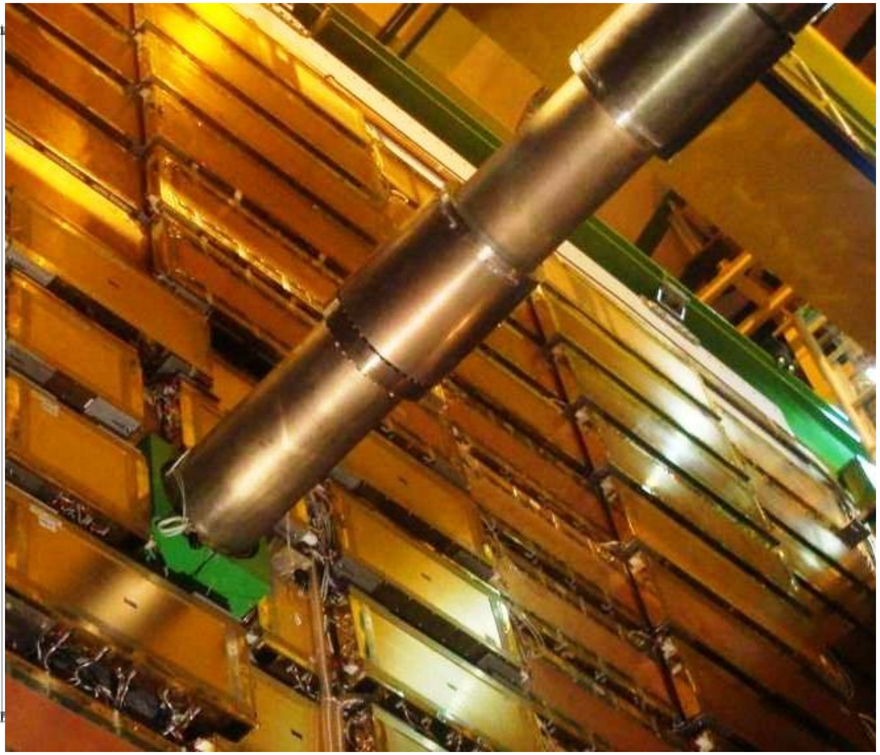


Muon system

5 tracking stations

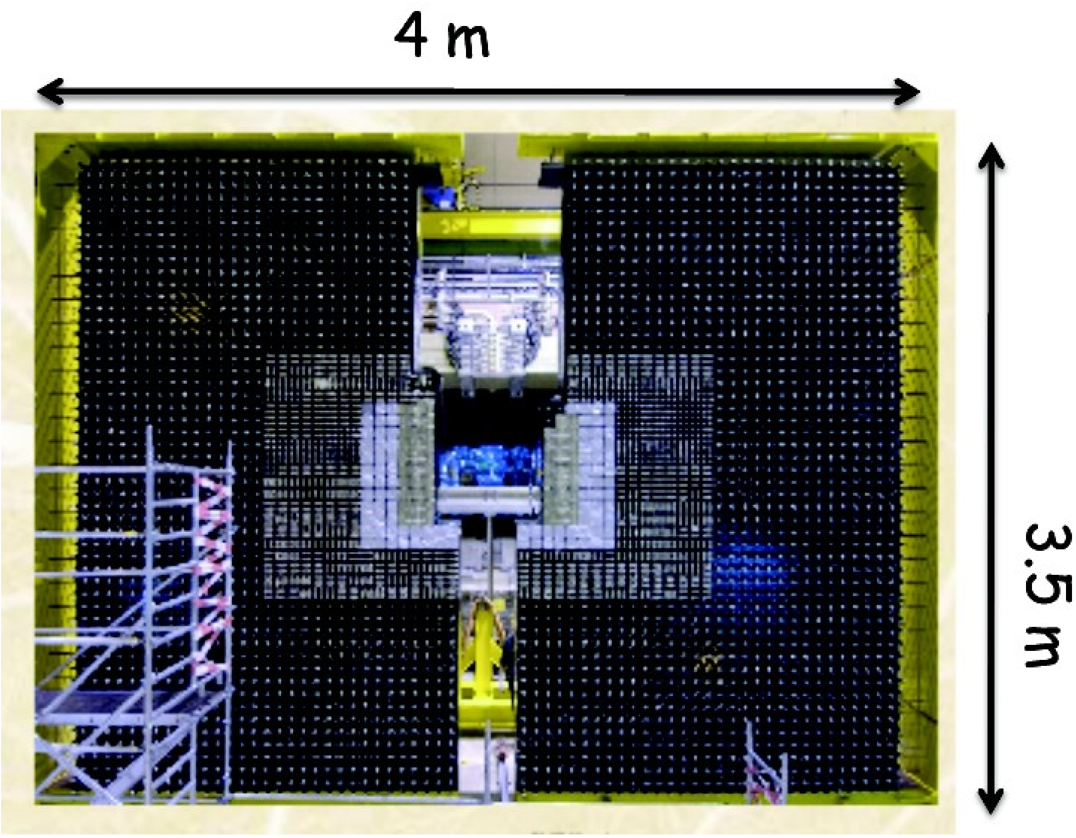
- Each station with 4 regions with different granularities
- Stations equipped with Multi Wire Proportional Chambers (MWPCs) and GEMs (high rate region)





The calorimeter

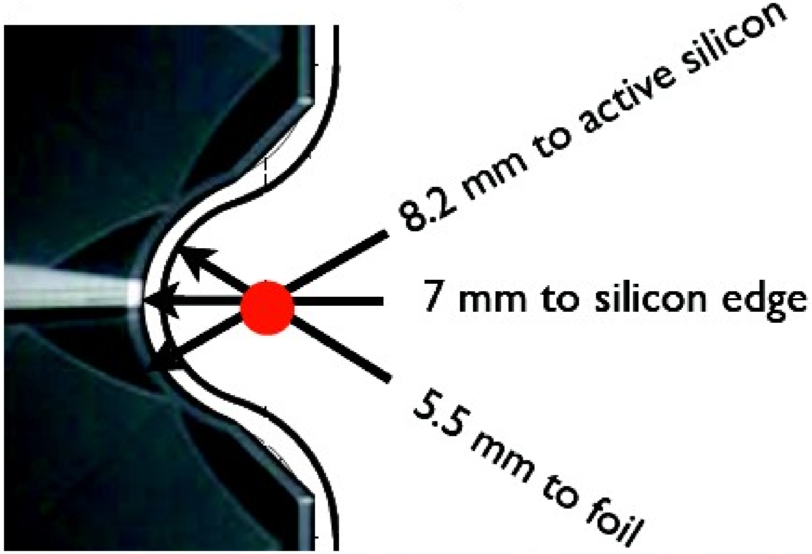
- Scintillator Pad Detector (SPD) & Preshower (PRS)
  - 2.5 X0 Pb converter between two scintillator planes.
- Shashlik Electromagnetic calorimeter (ECAL)
  - Pb/Scintillator
- Hadronic calorimeter
  - Fe/Scintillator

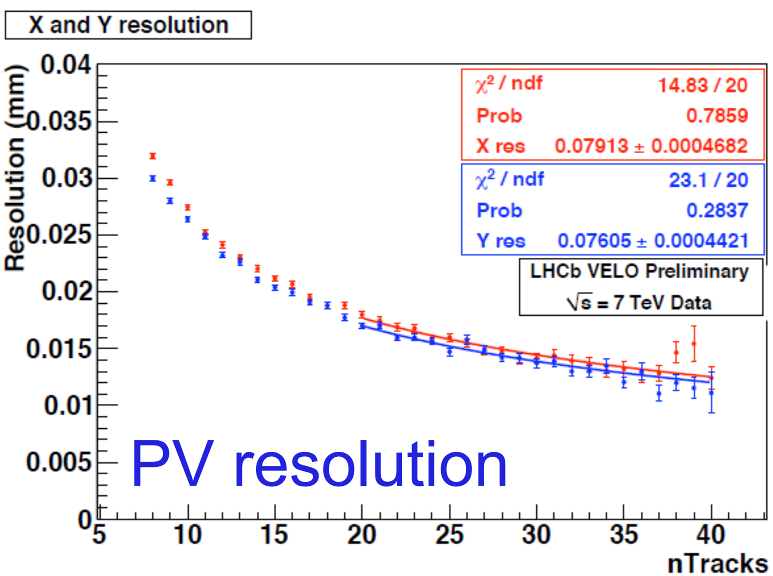


The Vertex Detector (VELO)

- Silicon strip modules arranged in two halves
- Move into interaction point when stable beams
- Primary vertex resolution as expected

Zoom of silicon and foil





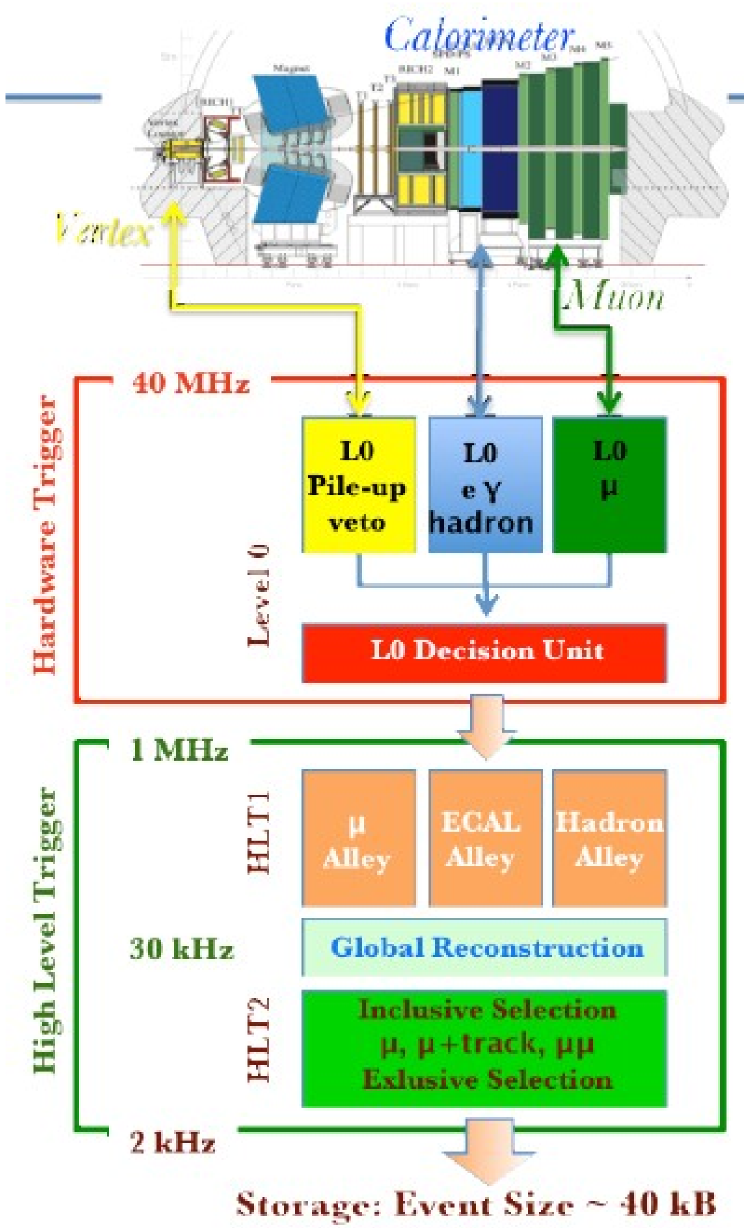
Trigger

A hardware L0 trigger based on high transverse energy or momentum

A software High Level Trigger

- Confirms L0
- Adds vertexing
- Makes inclusive and exclusive B reconstruction

High rate output at 2 kHz



$B_s \to \mu^+\mu^-$ introduction

- Decay a very sensitive probe for Higgs sector of any New Physics model
- SM BR predicted to 10% precision at $3.6 \pm 0.3\ 10^{-9}$
- Currently best result is from CDF 3.7 fb^{-1}
  - BR < $4.3\ 10^{-8}$ 95%CL
- LHC will quickly catch up.
- We will very soon know if this is exciting.
- On the other hand, if limit goes below $\sim 5\ 10^{-9}$ it will be hard to identify New Physics.

Analysis validation

The search for $B_s \to \mu^+\mu^-$ is based on counting in bins based on 3 independent variables

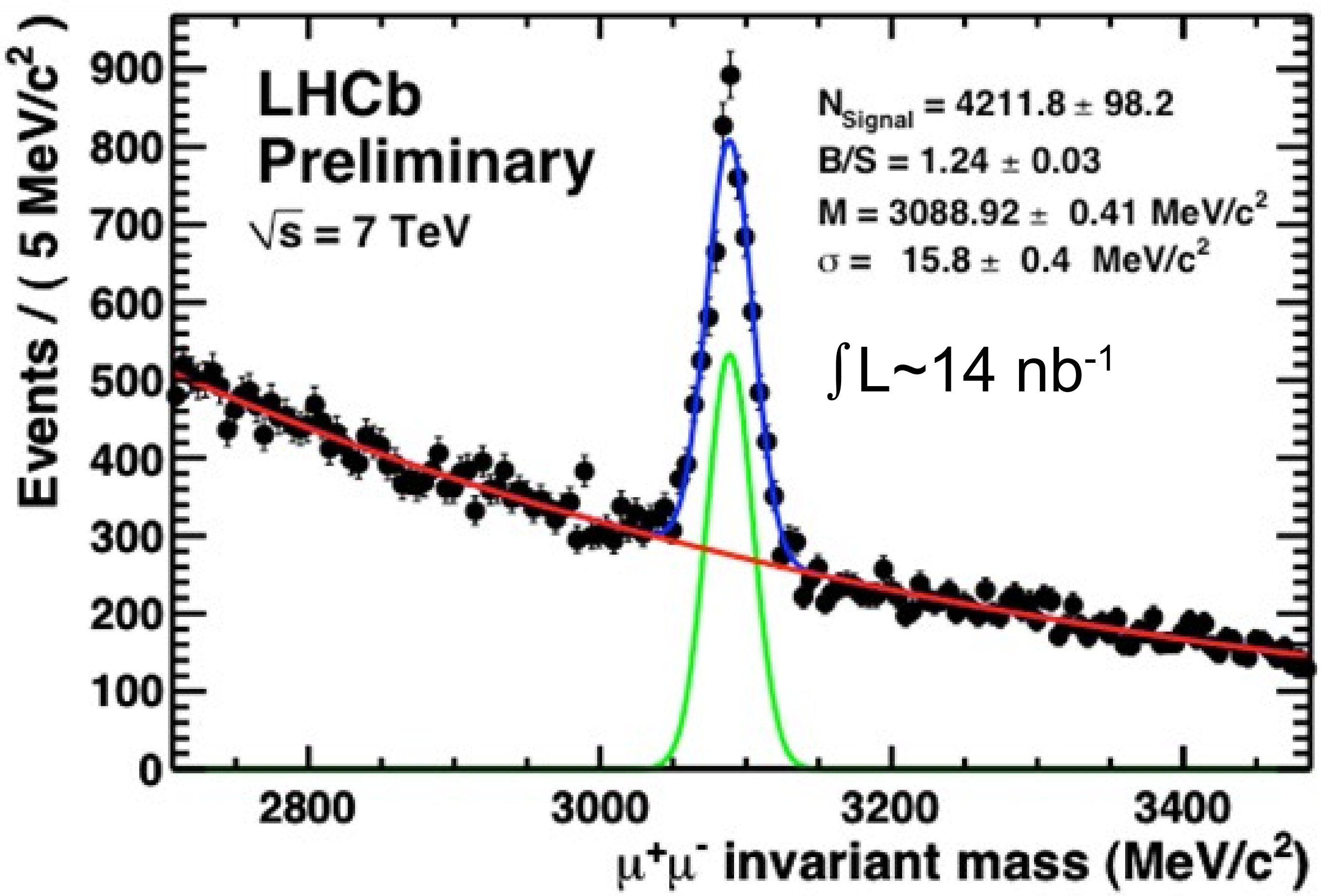
- Invariant mass of the muon pair
  - Power determined by the tracking system resolution and alignment
- Muon identification likelihood
  - Dominated by muon system but also use information from calorimeters and RICH detectors
- Geometrical likelihood
  - Quantities where the vertex detector provides the main discrimination: impact parameters, isolation, lifetime.

Measure trigger efficiency

Mass resolution

Use $J/\Psi \to \mu^+\mu^-$ as a proxy

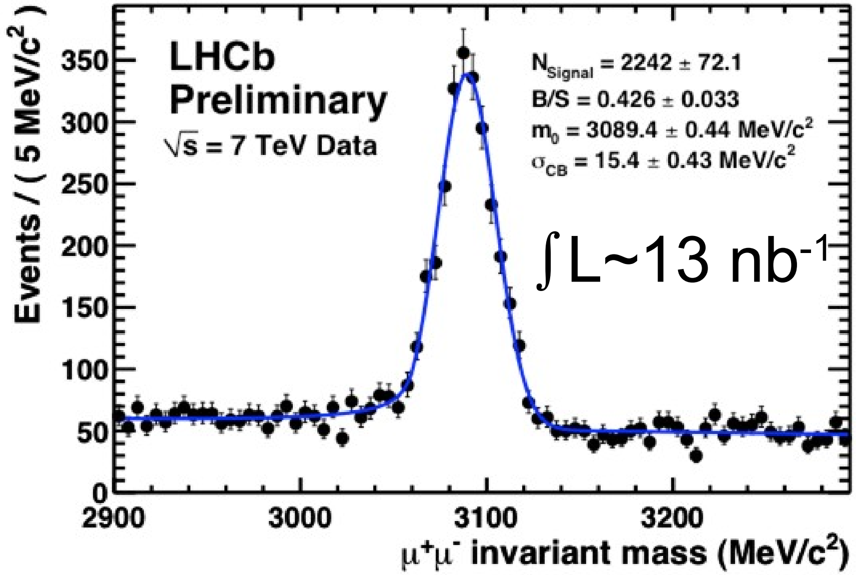
See a resolution of around 16 MeV/c^2

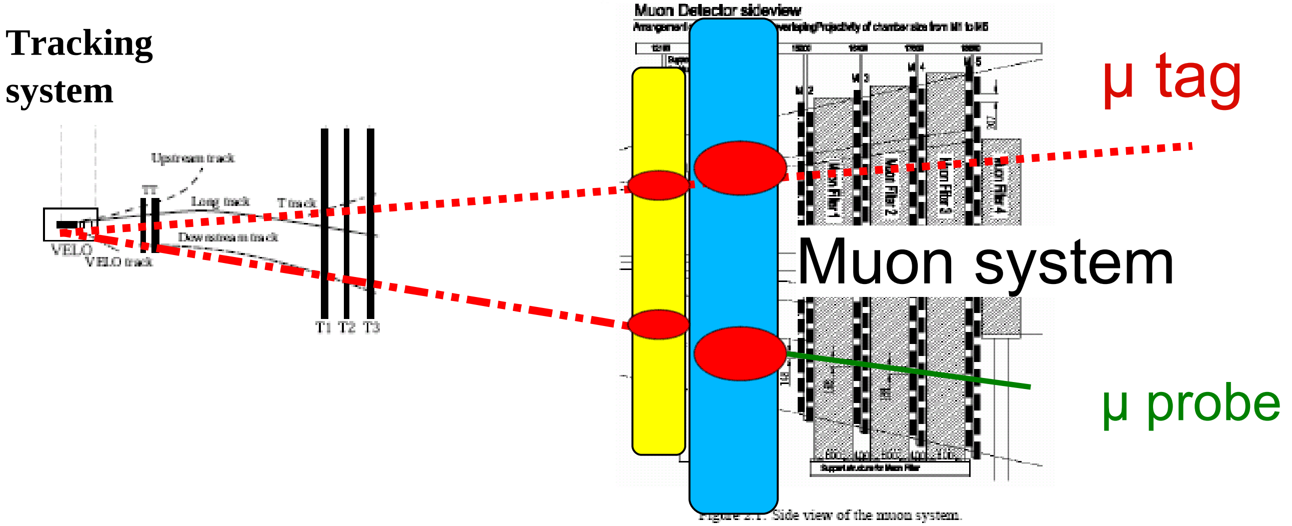


Tag & Probe for Muon efficiency studies

J/Ψ sample is identified using

- One fully reconstructed muon (the tag)
- One identified from tracking system and as MIP in calorimeters (the probe)

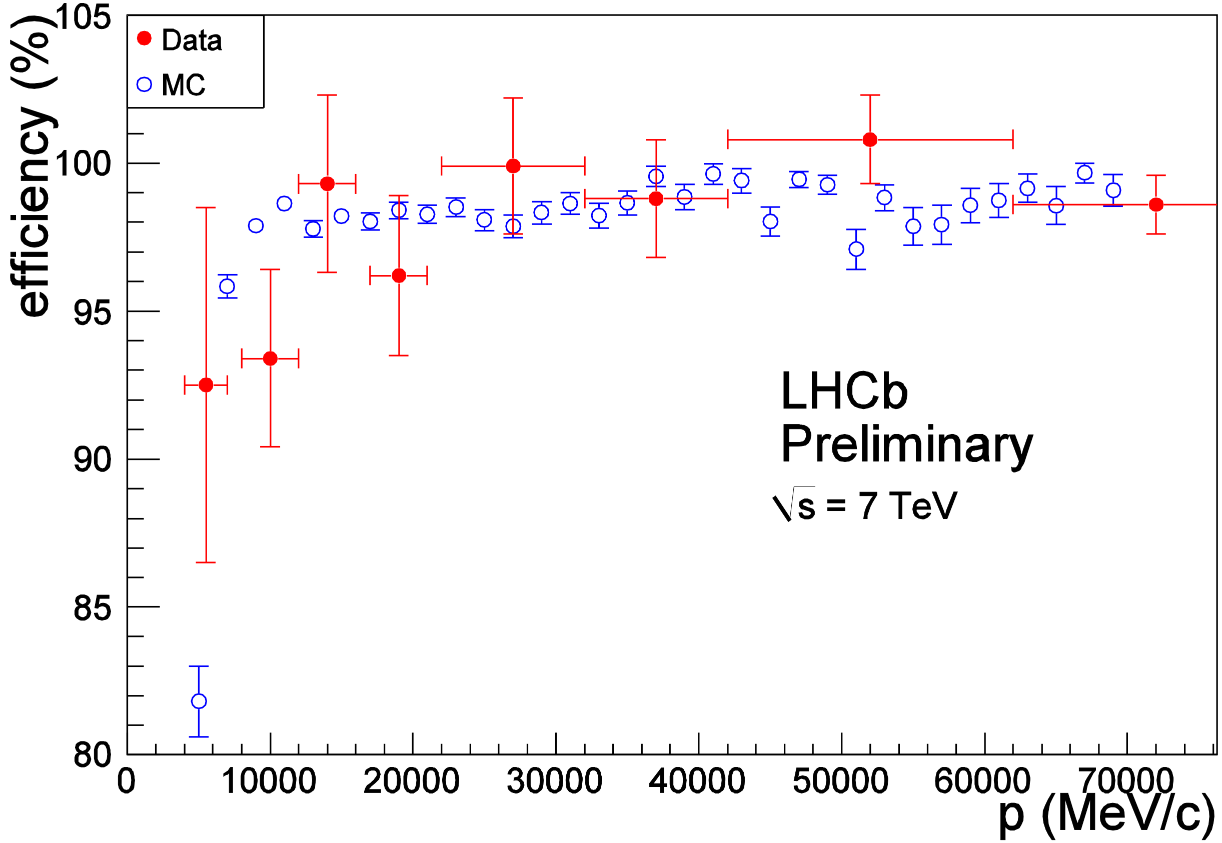




Tag & Probe for Muon efficiency studies

Data from 2010 can now be compared to our Monte Carlo

When plotting against probe momentum agreement is good.



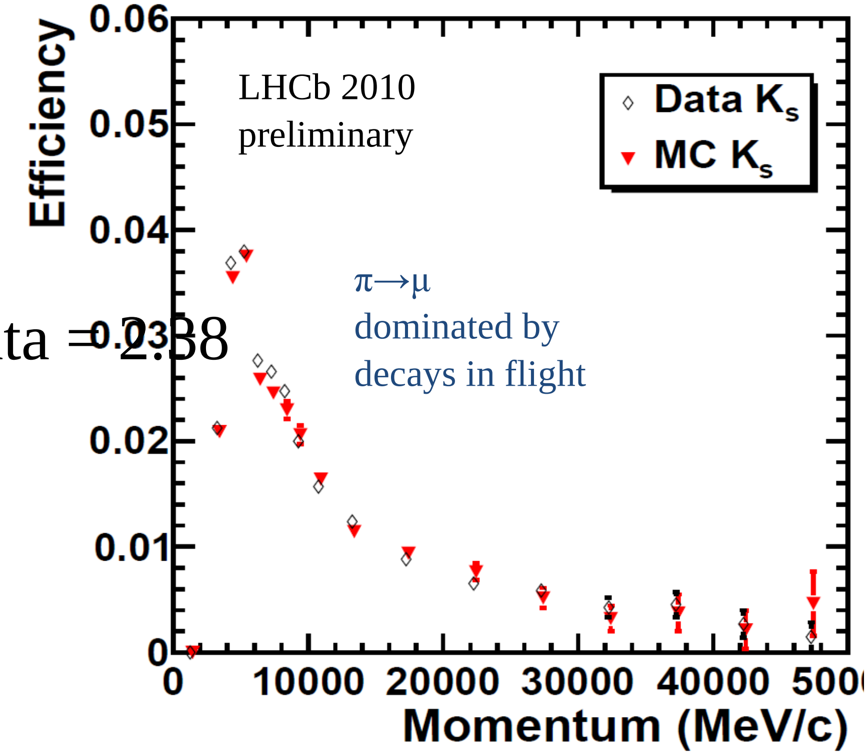
$\varepsilon_{data} = 97.3 \pm 1.2\%$

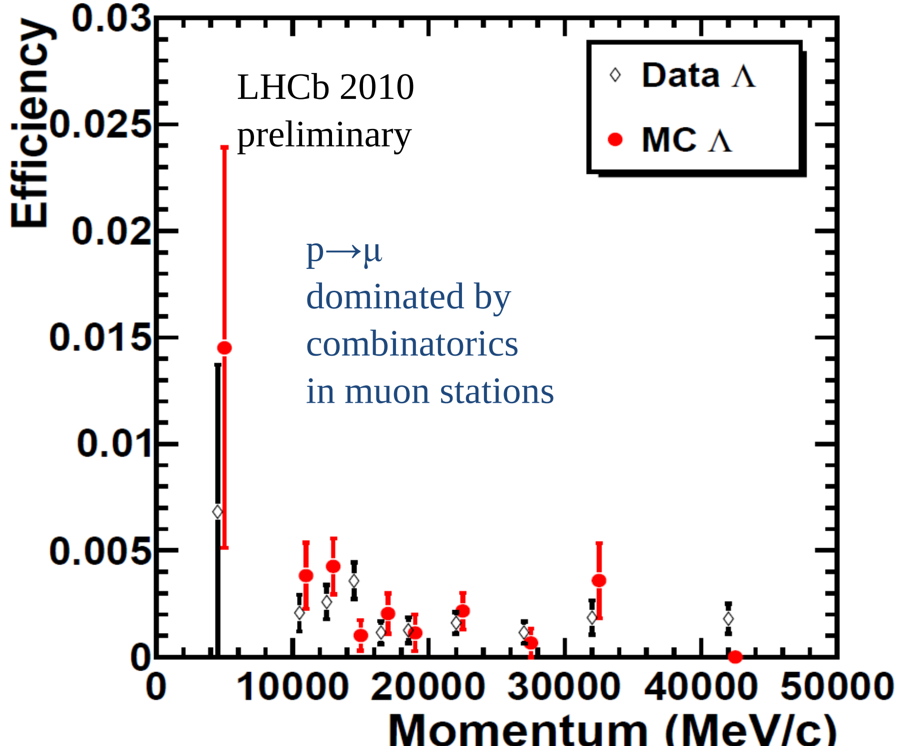
$\varepsilon_{MC} = 98\%$

Muon mis-identification

Identification studies are useless without corresponding mis-ID studies

Pion sample from $K^0_s \to \pi^+\pi^-$, proton sample from $\Lambda \to p\pi^-$



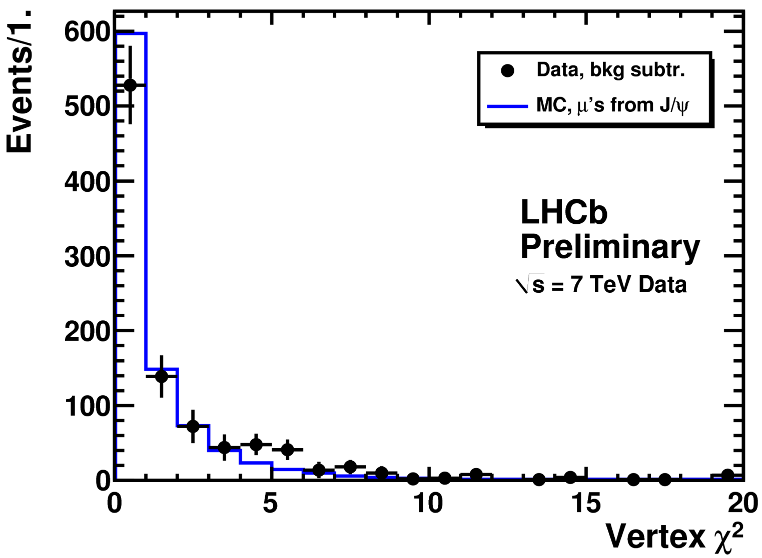


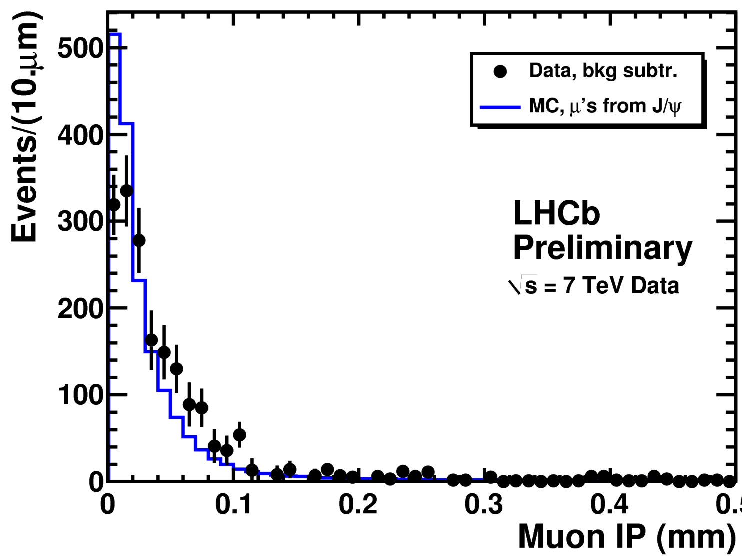
$P(\pi \to \mu)_{Data} = 2.38 \pm 0.02$ $\quad$ $P(p \to \mu)_{Data} = 0.18 \pm 0.02$

$P(\pi \to \mu)_{MC} = 2.34 \pm 0.02$ $\quad$ $P(p \to \mu)_{MC} = 0.21 \pm 0.04$

Geometrical Likelihood

- Likelihood built from
  - B_s lifetime
  - μ impact parameter significance
  - B_s impact parameter
  - Distance of closest approach of muons
  - Isolation
- Use J/Ψ as proxy for signal
  - Compare Monte Carlo simulation to background subtracted data
  - Agreement is good



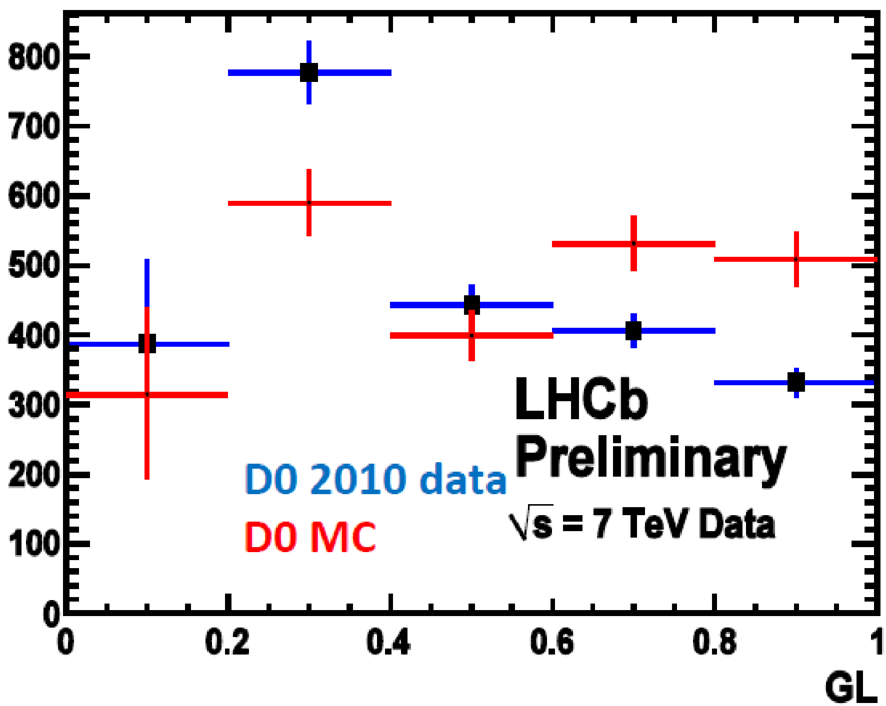


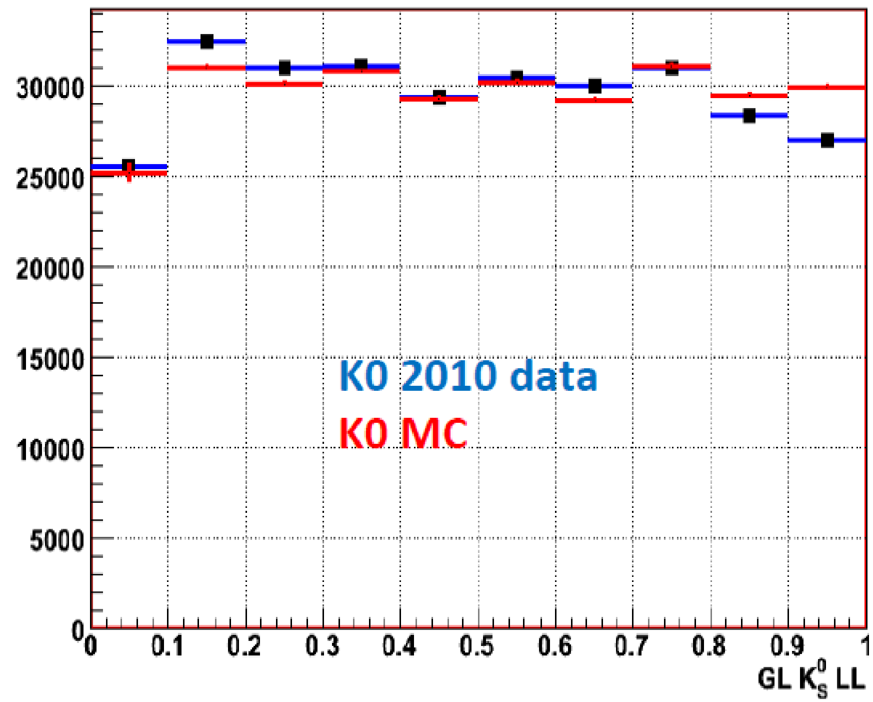
Geometrical Likelihood

Developed on MC simulations

Signal response calibrated with data

- So far $K^0_s \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$
- Eventually $B \to h^+h^-$

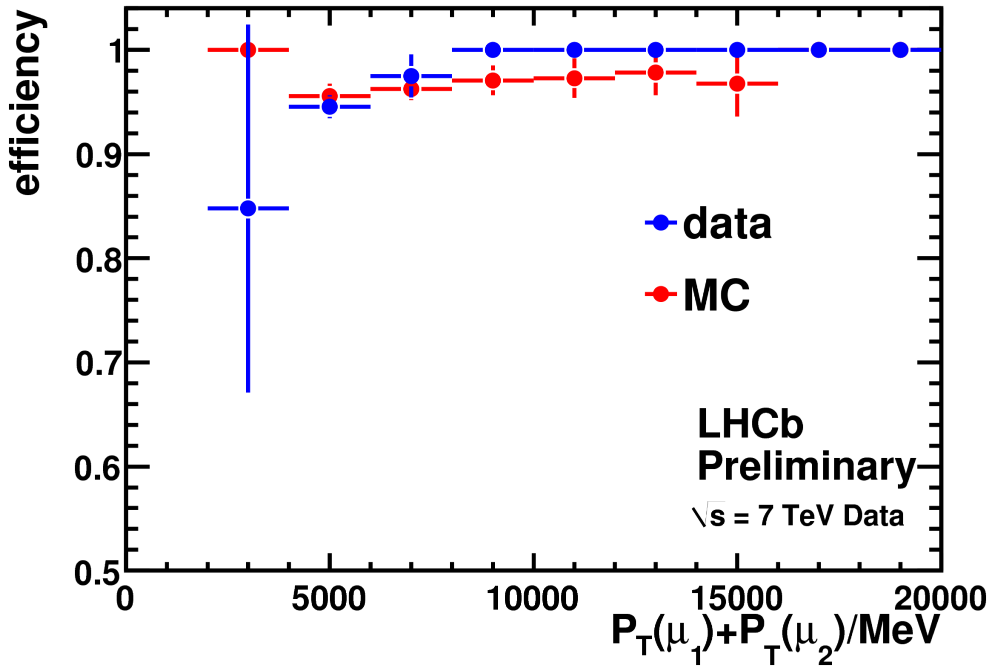




Muon trigger

Compare $J/\Psi \to \mu^+\mu^-$ candidates that pass L0μ and HLT1to candidates that are in pass-through line

- Excellent data/MC simulation agreement



Weighting with p_T spectra from MC simulation

- Trigger efficiency for $B_s \to \mu^+\mu^-$ is 94%

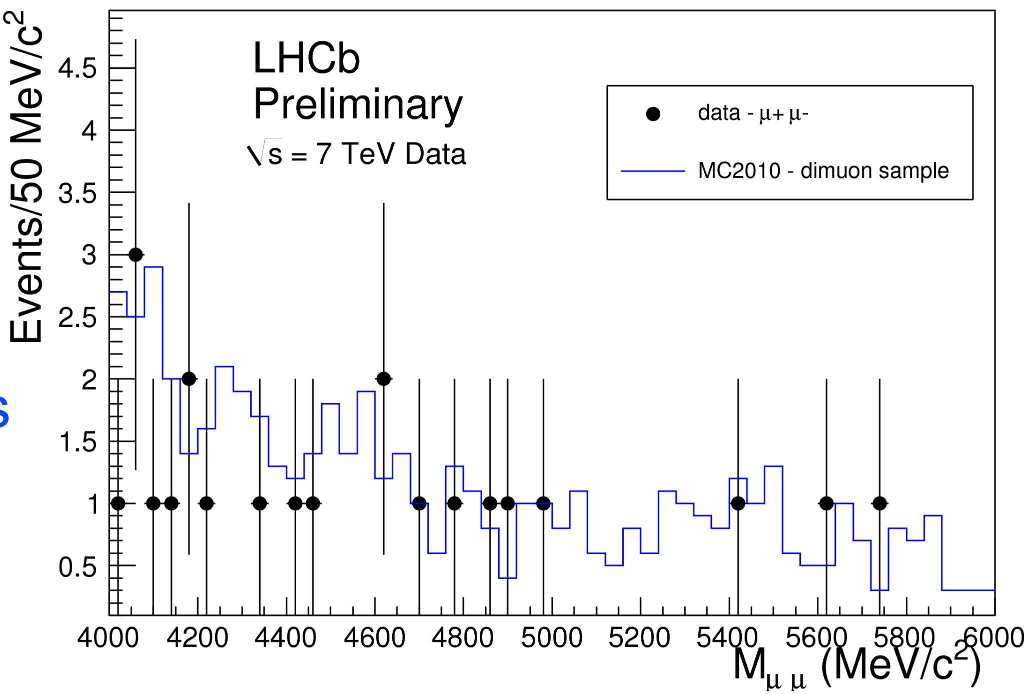
Background

When using a loose cut on Geometric Likelihood:

- Compare background in data and in LHCb 2010 MC data
- Agreement gives confidence in our understanding of performance.

Not corrected for data versus MC differences in:

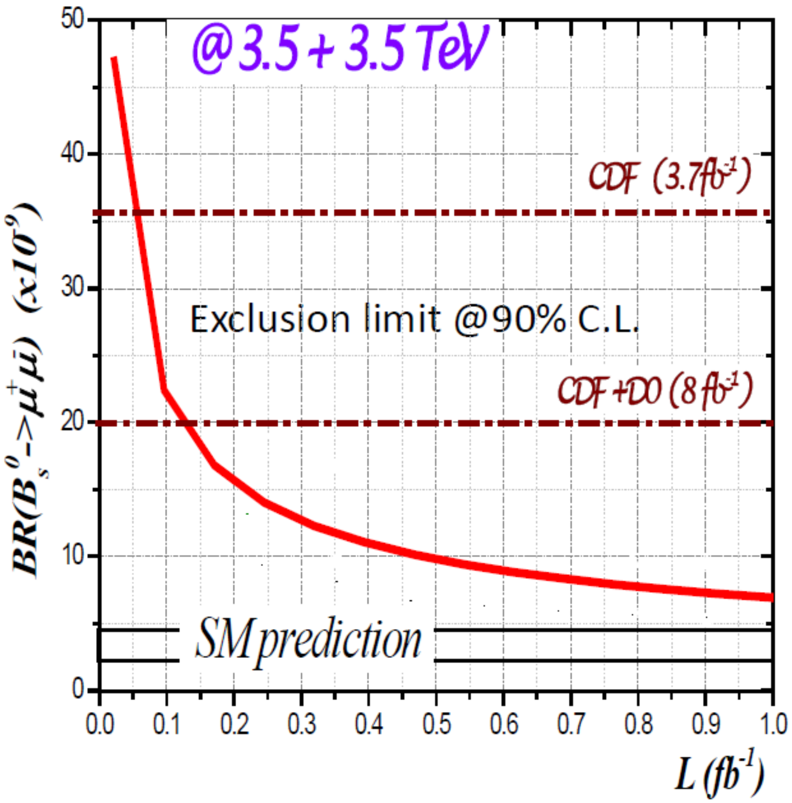
- Overall charm and bottom cross sections
- Kinematic distributions

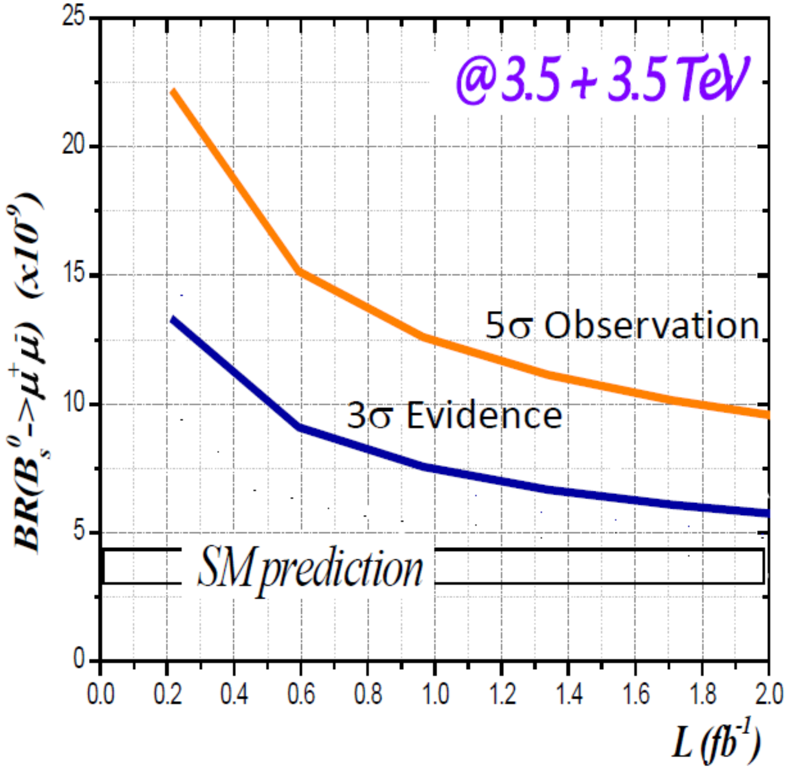


Outlook

With main parts of analysis validated we estimate

- 200 pb^{-1} (2010) of data to give us worlds best limit
- 5σ observation down to BR = 5 x SM with 1 fb^{-1} (2011)

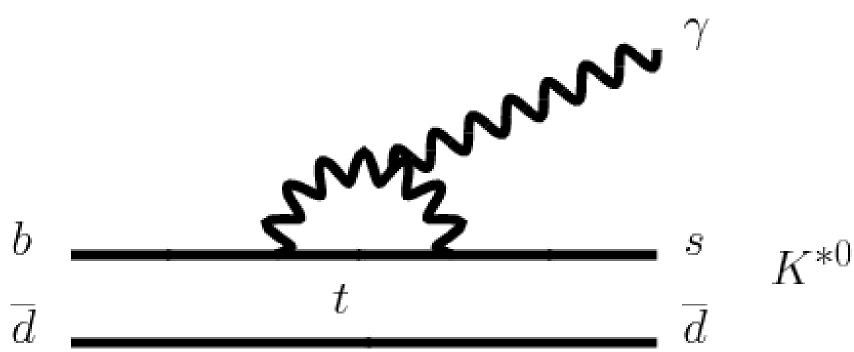


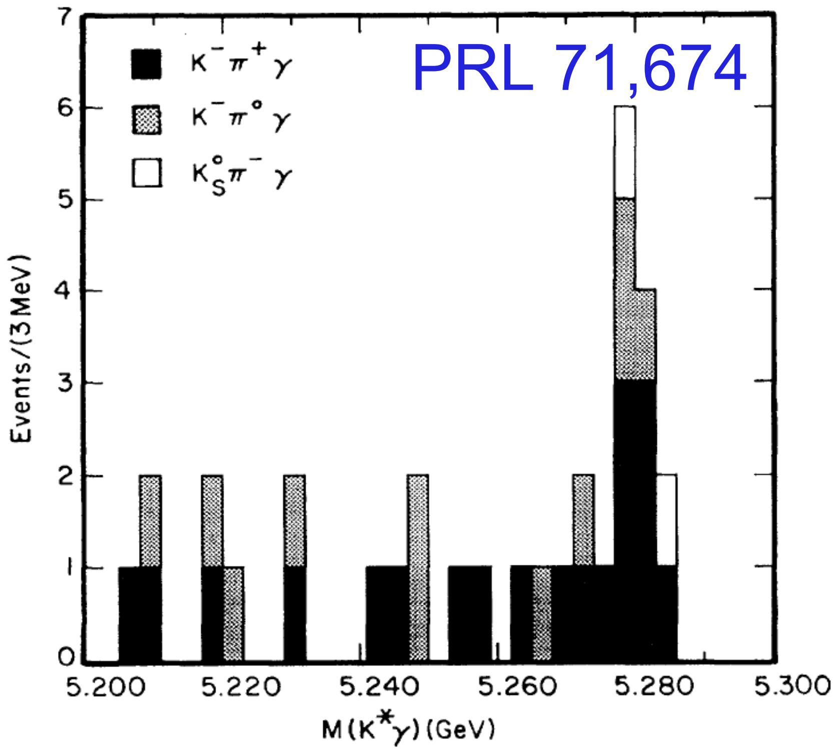


Radiative decays

Discovery of $B \to K^*\gamma$ by CLEO in 1993 was a clear evidence for the existence of penguin decays

- The BR fitted well with the expectations from the SM at the time.
- SM is the dominant contributor to FCNC decays





PRL 71,674

Properties of $b \to s\gamma$ exclusive decays

- The decays are sensitive to two Wilson coefficients
  - $C_7^{(eff)}$ and $C_7'^{(eff)}$
- In SM these are well calculated
  - $C_7^{(eff)}$ known with 10% relative accuracy
  - $C_7'^{(eff)}/C_7^{(eff)} \sim 0.04$ (more or less m_s/m_b)
- Exclusive BR measures $|C_7^{(eff)}|^2 + |C_7'^{(eff)}|^2$
  - Measurements destroyed by form factor that adds large uncertainty
- Instead look at γ_R/γ_L which directly measures $C_7'^{(eff)}/C_7^{(eff)}$
  - But how to measure the polarisation of a final state photon!?

Introduce $B_s \to \varphi\gamma$

The decay $B_s \to \varphi\gamma$ looks in principle hopeless

- Should measure time dependent CPV in $B_s \to J/\Psi\varphi$ reduced by factor 2 $C_7^{'(eff)}/C_7^{(eff)}$
- CPV in $B_s \to J/\Psi\varphi$ in SM is around 0.04

(Expected) width difference $\Delta\Gamma$ between B_s eigenstates comes to the rescue.

$$\Gamma(B_q(\bar{B}_q) \to f^{CP}\gamma) \propto e^{-\Gamma_q t}\left(\cosh\frac{\Delta\Gamma_q t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_q t}{2} \pm \pm\mathcal{C}\cos\Delta m_q t \mp \mathcal{S}\sin\Delta m_q t\right)$$

$A^{\Delta} \sim 2\ C_7^{'(eff)}/C_7^{(eff)}$

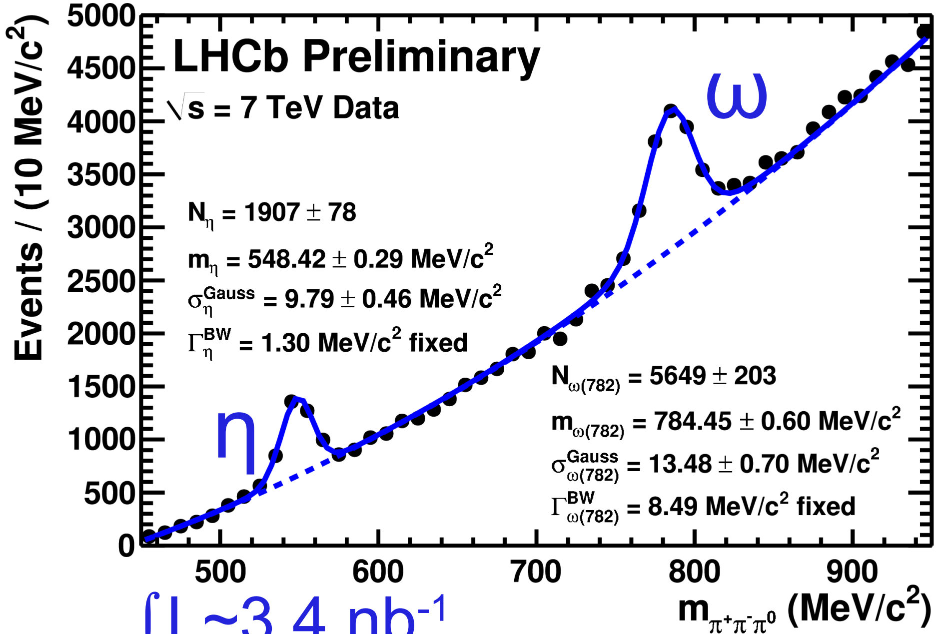
F.Muheim, Y.Xie & R.Zwicky, Phys.Lett.B664:174-179,2008

- No flavour tagging required
- Only charged particles in $\varphi \to K^+K^-$ decay

Validation

Energy calibration very promising

- Calibration is based on low mass resonances
- High energy calibration will first come when $B_d \to K^{*0}\gamma$ available.



$\int L \sim 3.4\ nb^{-1}$

Lifetime calibration

- Measurement sensitive to bias in lifetime.
- Need to know acceptance very well
- Validation started with prompt $\varphi \to K^+K^-$ events

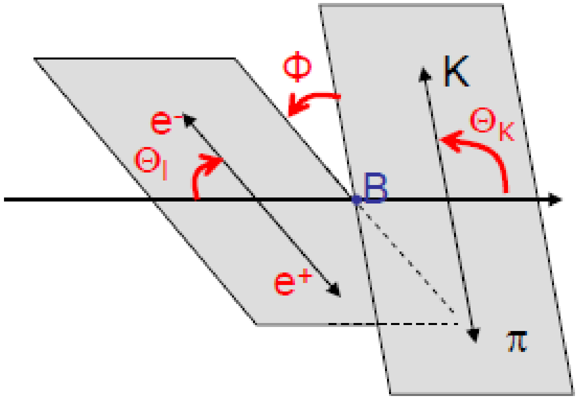
Outlook

- LHCb expects 11k events in a nominal year (2 fb^{-1}) of running.
- Gives statistical resolution in $C_7^{'(eff)}/C_7^{(eff)}$ of around 0.1

Look at $B_d \to K^{*0} e^+ e^-$

Another way to find the photon polarisation is $B_d \to K^{*0} e^+ e^-$ for very low e^+e^- invariant masses

- Distribution in φ angle measures $C_7^{'(eff)}/C_7^{(eff)}$

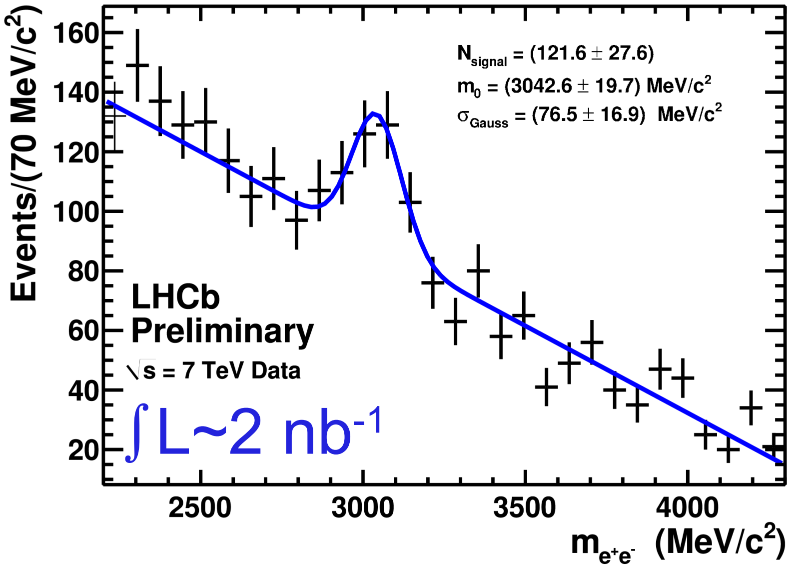


Small statistics

- Background rejection a big issue

Easy systematics

As good as $B_s \to \varphi\gamma$?



We clearly see $J/\Psi \to e^+e^-$ with almost no radiative tail

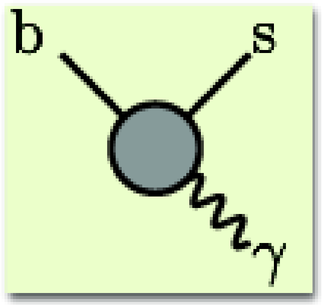
- Energy recovery working.

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

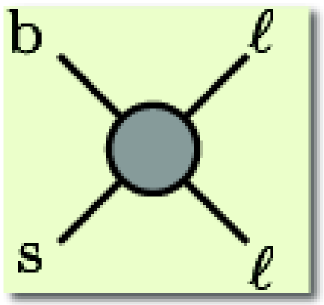
Much better statistics for $B_d \to K^{*0} \mu^+ \mu^-$ compared to $B_d \to K^{*0} e^+ e^-$ as muons are easier to trigger and reconstruct.

- Muon mass means we can't replicate the previous measurement.
- However, we get access to so much more

Interference between these

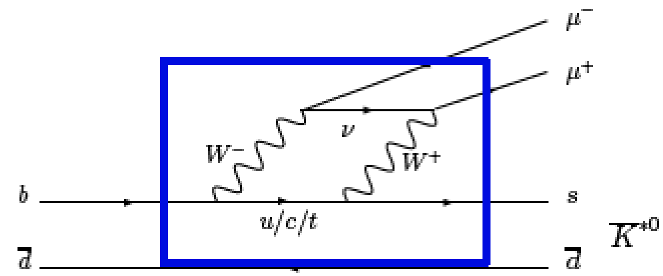


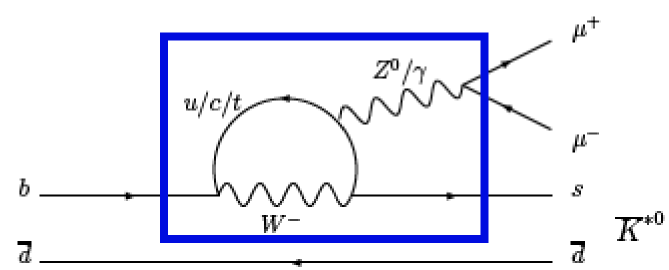
$O_{7\gamma}$



$O_{9,10}$

... and their primed counterparts





What to measure in $B_d \to K^{*0}\mu^+\mu^-$

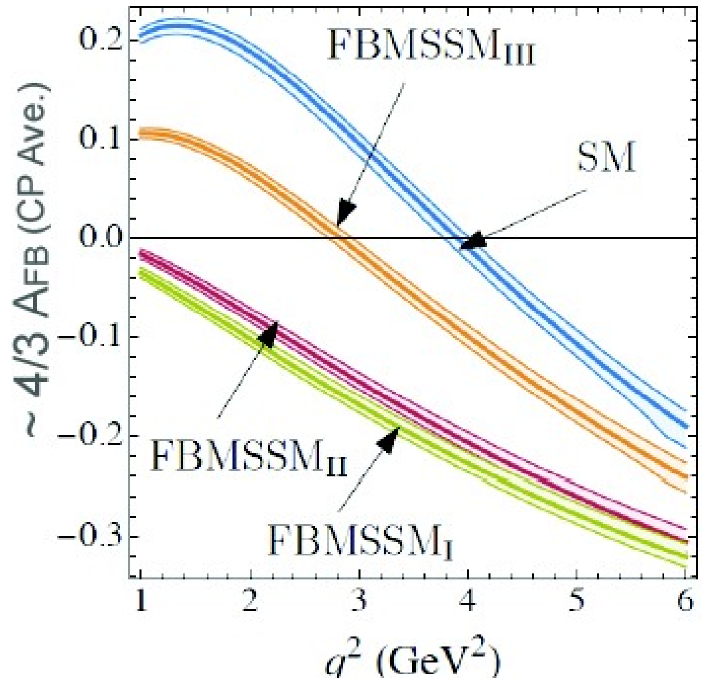
As an exclusive decay we need to find a way to cancel form factors

Most well known is A_{FB}, the forward-backward asymmetry

- FF cancellation only at zero crossing point

Sensitive to changes in C_7 and C_9

Multitude of other observables with high statistics of data



Altmannshofer et al, JHEP 0901:019,2009

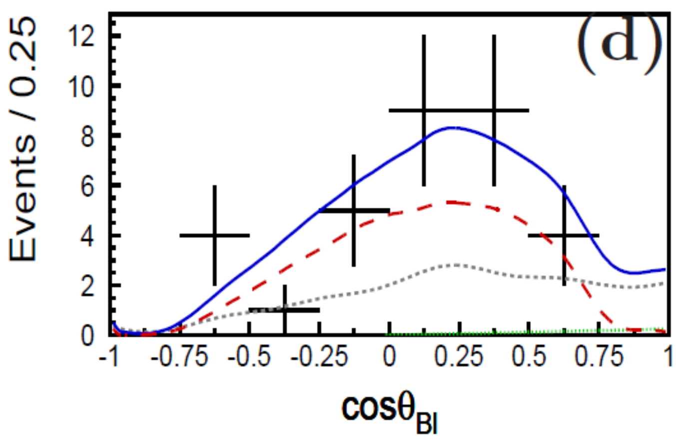
Current measurements of A_{FB}

Three results have arrived in the past 2 years

- Belle PRL 103:171801 (2009).
- BaBar PRD 79:031102 (2009)
- CDF preliminary (HCP 2009)

Example below of θ_l in $q^2 < 2$ GeV^2 from Belle

- Clearly statistics are still very limited for this type of measurement.

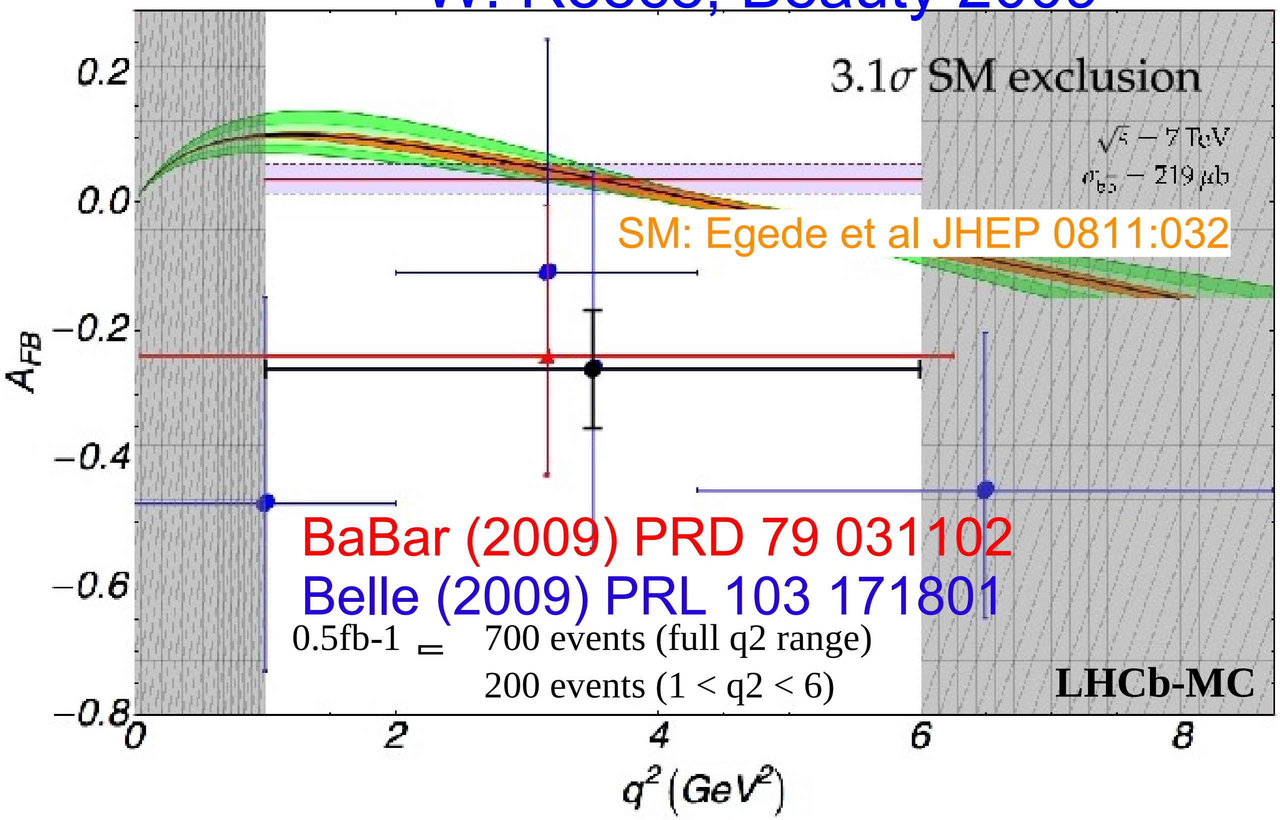


Outlook for $B_d \to K^{*0}\mu^+\mu^-$

Just 0.1 fb^{-1} will give equivalent error to current B-factory measurements

0.5 fb^{-1} enough to exclude SM at 3.1σ level if Belle central value correct

W. Reece, Beauty 2009



Conclusion

The LHCb detector is fully functional

- Validation of many aspects of detector done with control channels
- Performance for Rare Decays is very promising

First $B_d \rightarrow K^{*0}\gamma$ candidates just around the corner

$B_s \rightarrow \mu^+\mu^-$ limits will be competitive with below 200 pb^{-1} (2010)

Potential to discover New Physics with $Bd \rightarrow K^{*0}\mu^+\mu^-$ with below 1 fb^{-1} (2011)

Stay tuned ☺