# Rare decays at LHCb

Birmingham particle physics seminar
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LHCb

# Outline

- LHCb experiment
  - Why build LHCb
  - Detector status
- $B_d \to K^*\mu^+\mu^-$
  - Introduction
  - Theory
  - LHCb analysis
- $B_s \to \mu^+\mu^-$

# LHCb Experiment

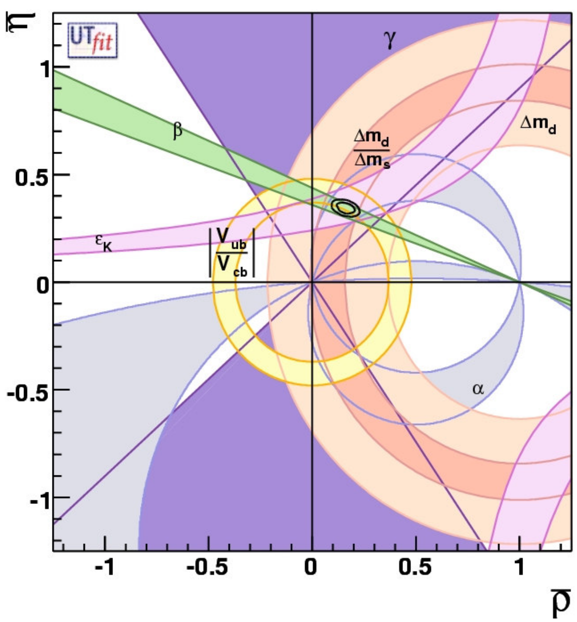
# Introduction

- Many potential extensions to Standard Model that could appear at TeV scale – SUSY, extra dimensions etc:
- Complementary approaches of:
  - Direct searches – ATLAS, CMS
  - Indirect searches – LHCb
- We know we need CP-violation beyond the SM (CKM picture) to explain the observed matter anti-matter asymmetry
  - Make precision measurements of CKM parameters $\rightarrow$ over-constrain the unitarity triangle
  - Search for new physics in CP-violating processes
  - Search for new physics in rare or forbidden SM processes

# LHCb experiment

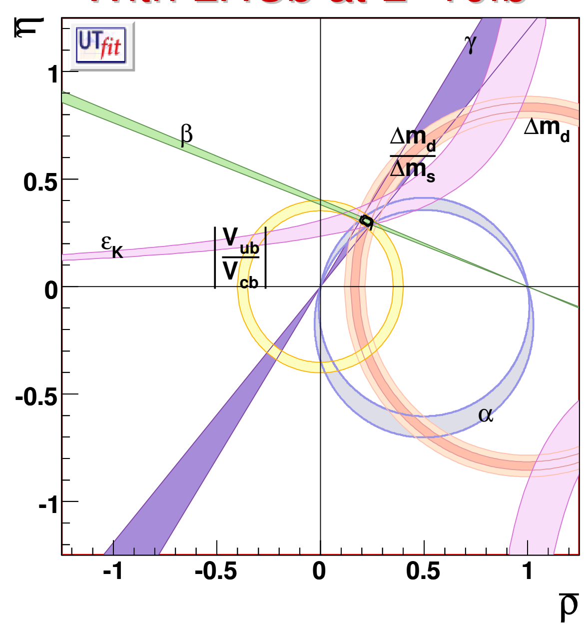
- Dedicated B-physics experiment to measure CP-violation and rare decays
  - Provide sensitive tests of the Standard Model in many channels and possible new physics at higher mass scales
  - Complementary to direct searches of the general purpose detectors

Summer 2006



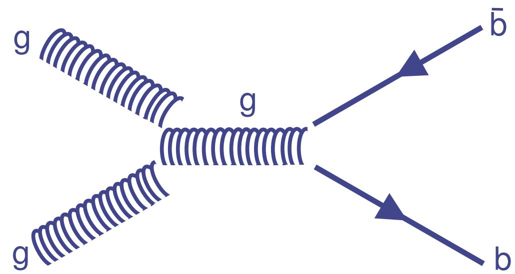

~ 5 years running

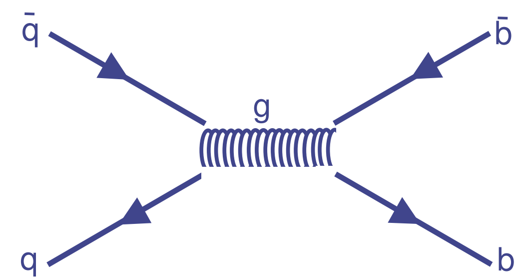
With LHCb at L=10fb$^{-1}$



# b-production at LHC

- Heavy flavour production
  - gluon-gluon fusion (dominant) vs quark-quark annihilation

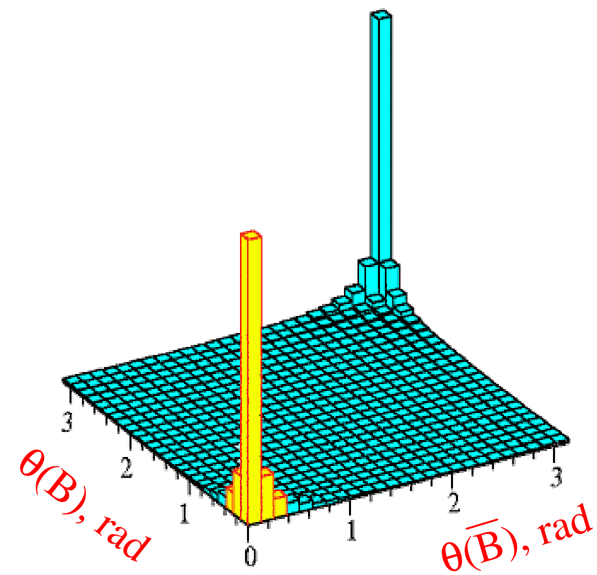



- Forward peaked, correlated bb-pair production
  - Cross section falls with rapidity difference between the two quarks

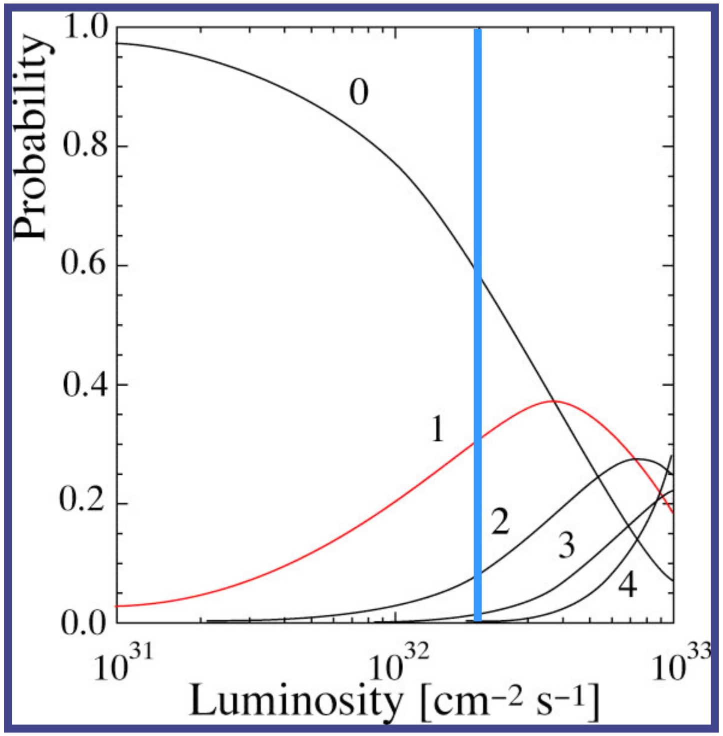
    → correlated b-, b̄- production
  - Cross section falls with increasing transverse mass: $\sqrt{p_T^{\ 2} + m^2}$

    → forward production



# b-production at LHC

- GPDs run at nominal luminosity of L = $10^{34}$ $cm^{-2}s^{-1}$
  - Mean number of interactions given by Poisson: $$\mu = \frac{L\sigma}{f}$$
  - $f$ = 40 MHz, $\sigma = (111.5 \pm 1.2^{+4.1}_{-2.1})$ mb
    - Average of 37 inelastic pp interactions per crossing!!
    - Very hard to distinguish individual B-decays



# b-production at LHC

- LHCb will run at $L = 2\times10^{32}$ cm$^{-2}$s$^{-1}$
  - Max probability for single interaction
  - 20 MHz interaction rate

  - 100 kHz b-production (500$\mu$b cross section)
    - Typical B-hadron branching ratios ~ $10^{-4}$

      $\rightarrow$ require robust trigger (~0.01%)

- Nominal "year" $10^7$ sec (2 fb$^{-1}$)
  - Expect $10^{12}$ bb-pair

    $\rightarrow$ access to very rare-phenomena

# LHCb Detector Design

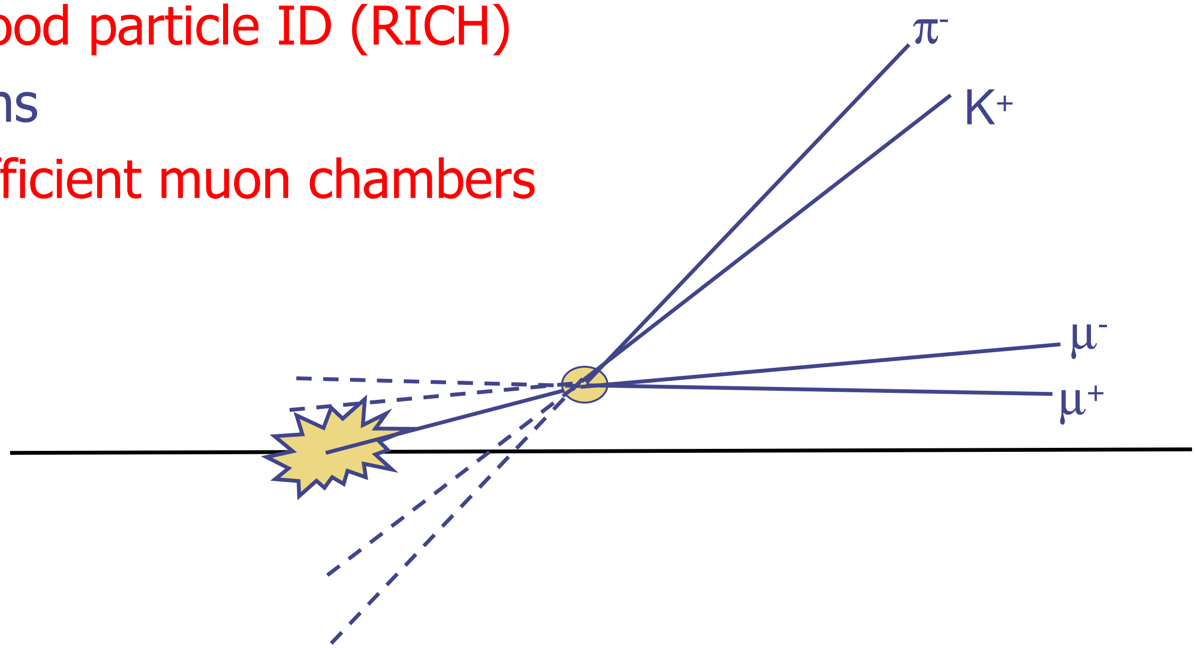
- Motivated by properties of the B-hadron:
  - Heavy (~5 GeV/$c^2$)

    $\rightarrow$ detect high $p_T$ tracks
  - Long lived (CKM suppressed b $\rightarrow$ c, u decays)

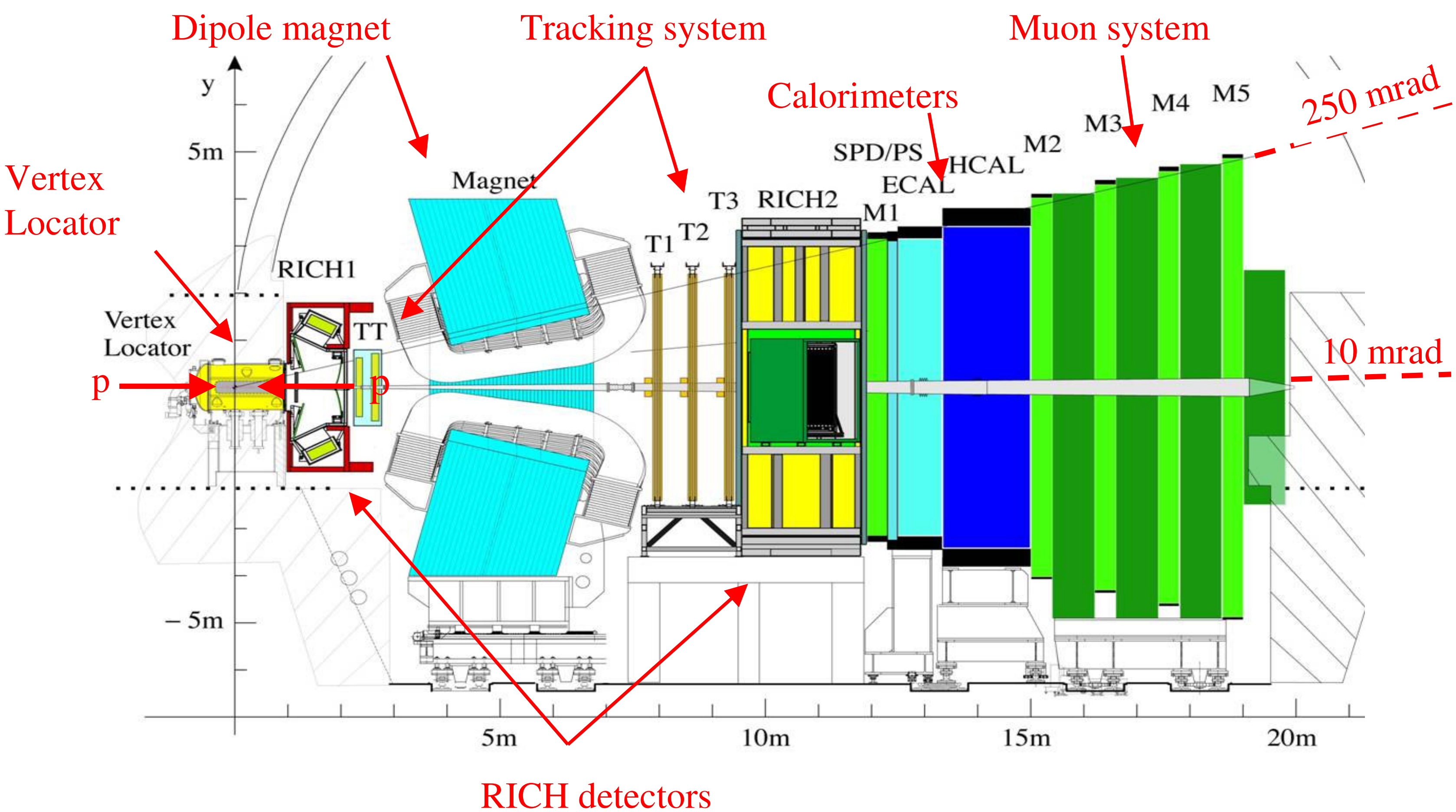
    $\rightarrow$ resolve displaced vertex (VELO)
  - Decay to hadrons ($K^\pm$, $\pi^\pm$)

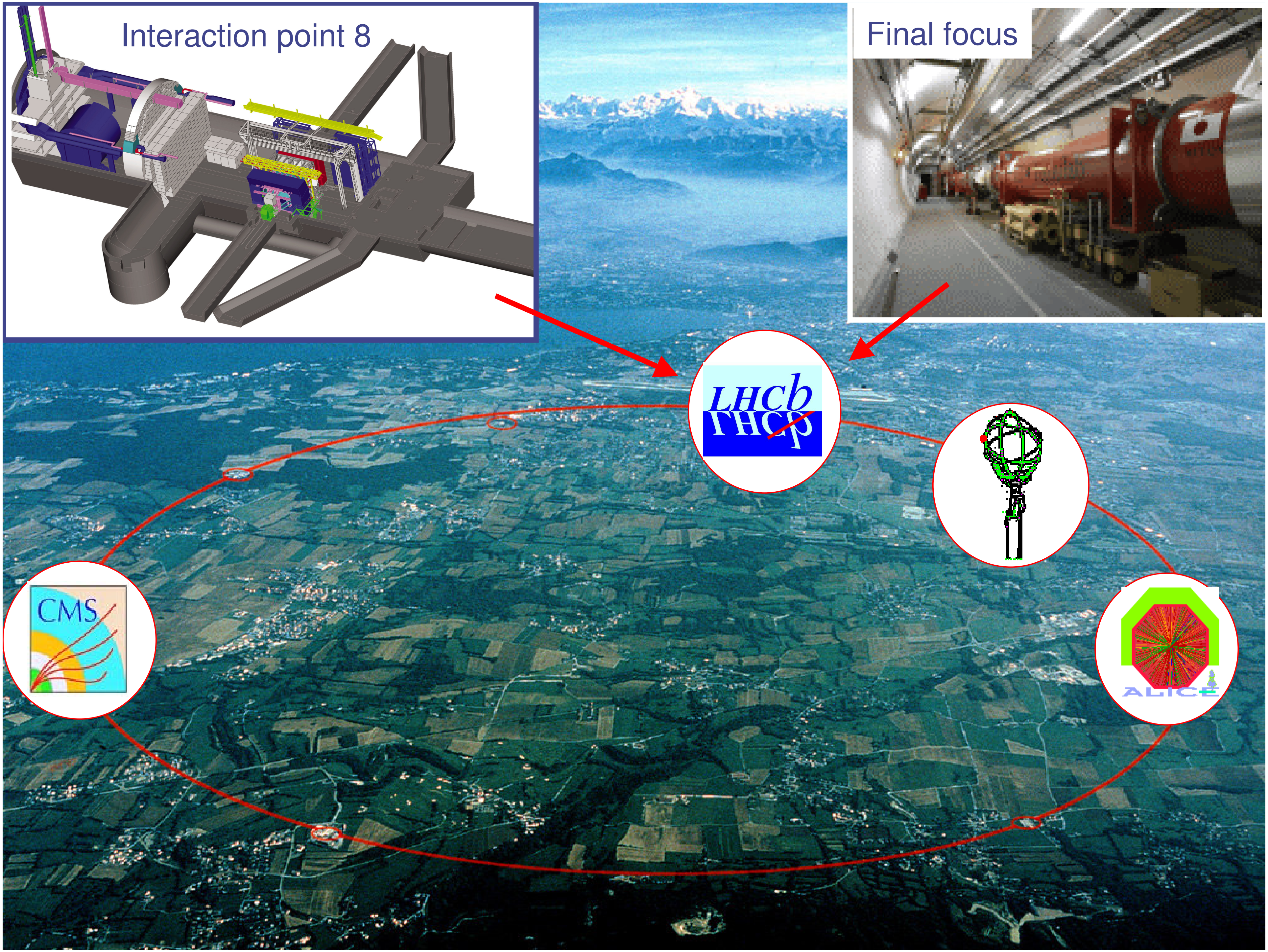
    $\rightarrow$ good particle ID (RICH)
  - Decay to muons

    $\rightarrow$ efficient muon chambers



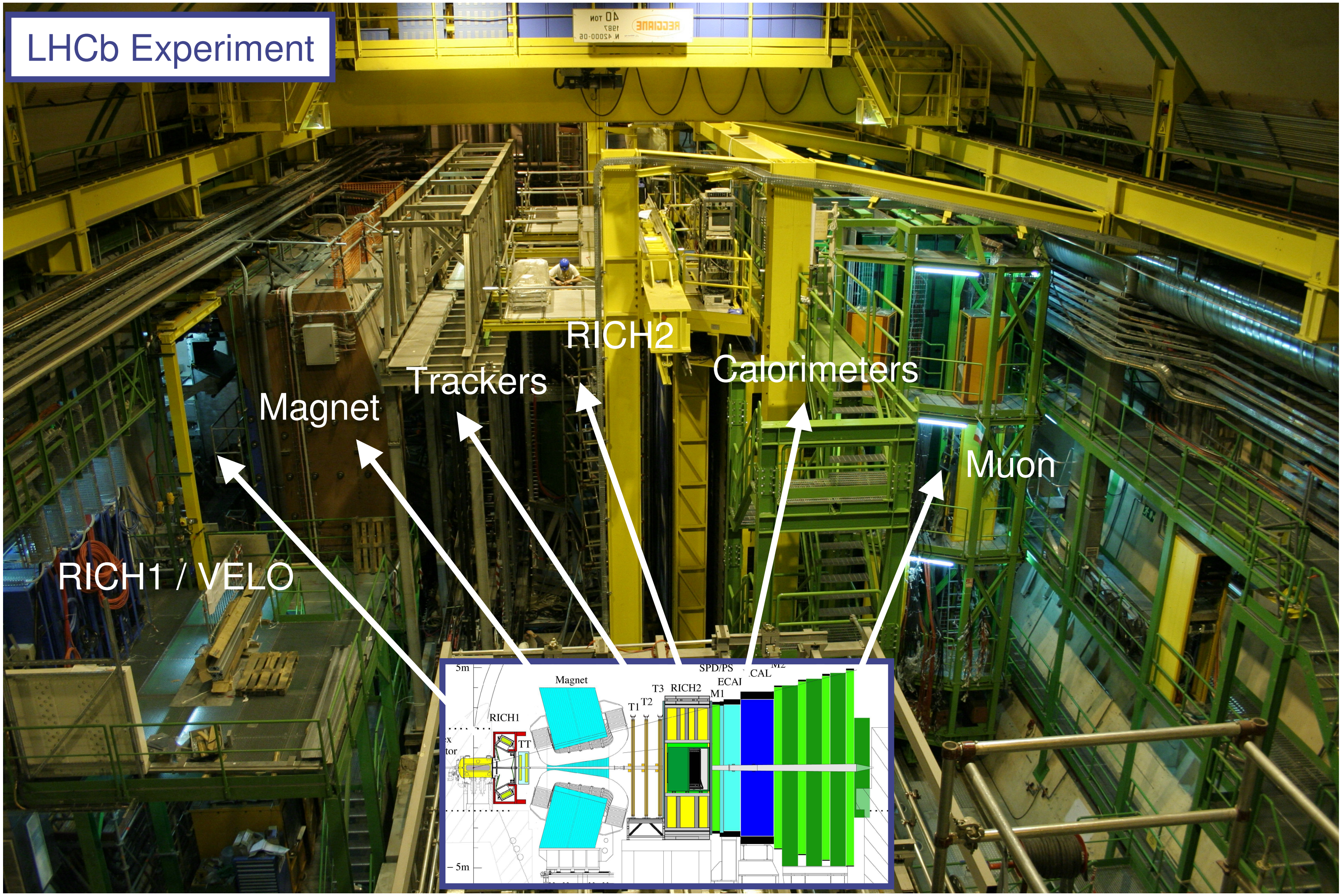
# LHCb Experiment





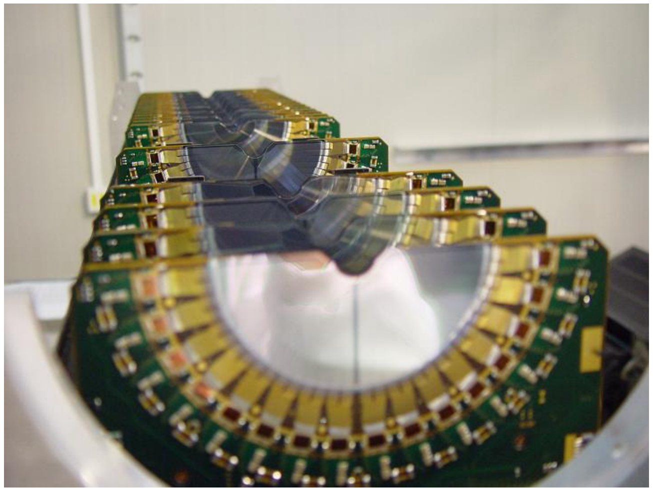
Interaction point 8
Final focus
LHCb
CMS
ALICE

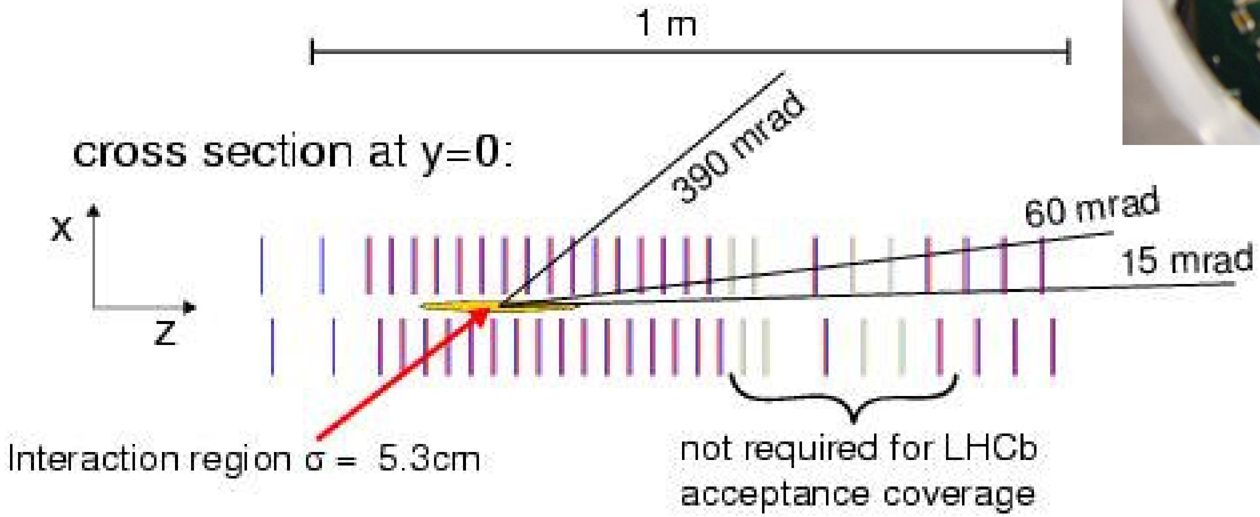
# LHCb Experiment

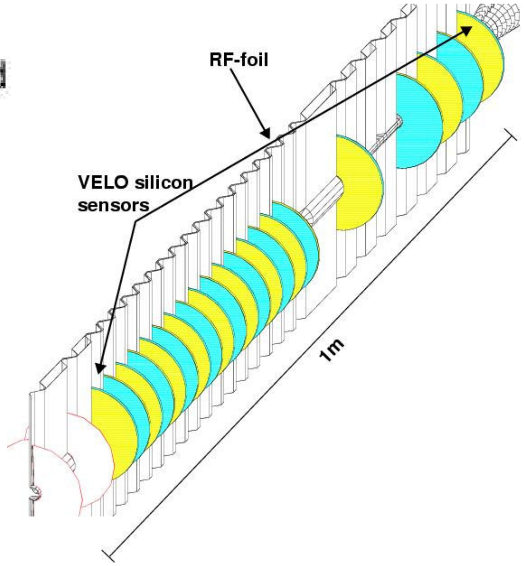


# Vertex Locator (VELO)

- Detector halves retractable during injection
  - Sensors ~ 5mm from nominal beam line during running
  - Move out by ~ 3cm for injection
- 21 tracking stations (R and $\phi$ silicon strip sensors)
  - ~ 100k readout channels
  - Strip pitch between 40 and 100$\mu$m



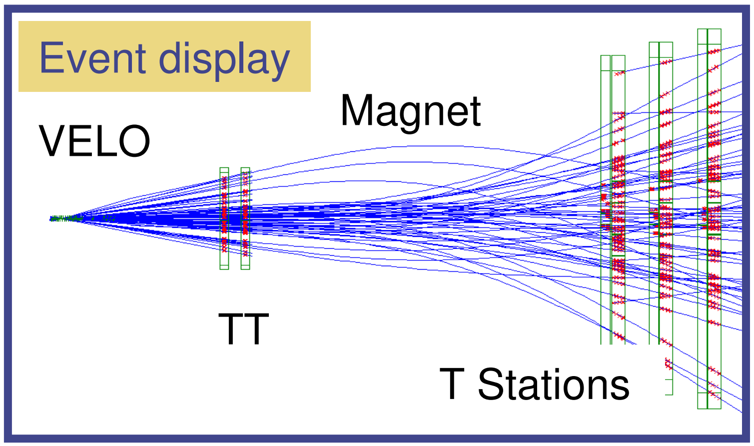


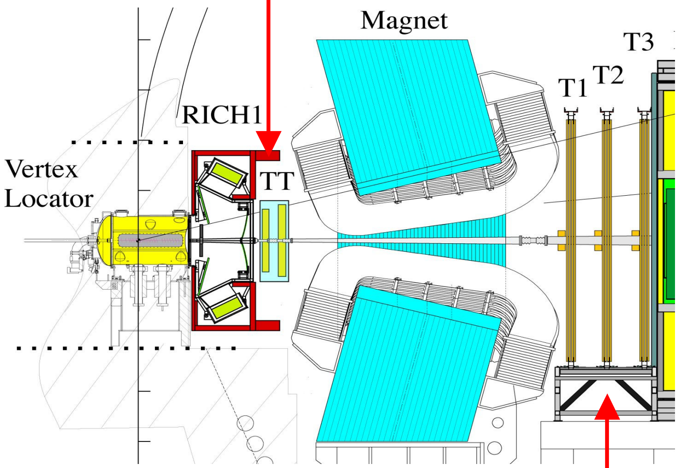




- Provides ~50$\mu$m longitudinal, ~13$\mu$m transverse resolution
  - Displaced secondary vertices
  - Large impact parameter tracks
- Upstream stations used in pile-up trigger to veto multiple interaction events

# Tracking

- One station upstream of magnet (TT):
  - Used with VELO for $p_T$ measurement in trigger
  - Low momentum particles swept out by magnet

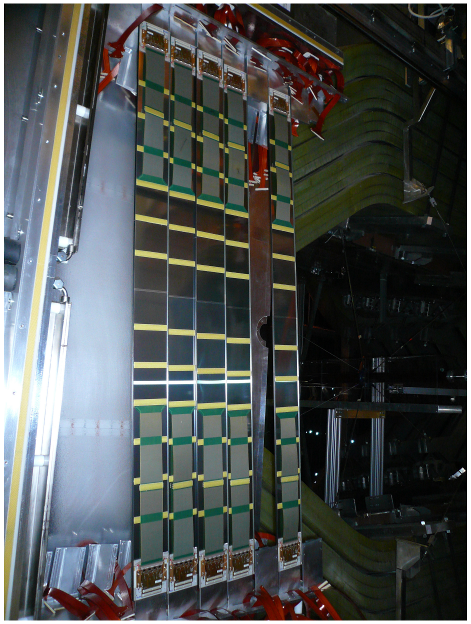



- Three stations downstream of magnet (T1 – T3):
  - Largely provide tracking in magnet bending plane
  - Also provide position information of tracks in non-bending plane, needed for RICH ring finding

# Tracking (2)

- Inner tracker: TT station and inner regions of T1 – T3
  - High occupancy region: 2% of acceptance but 20% of tracks
  - Silicon strip sensors at pitch of ~ 200μm (8cm x 11cm)
  - Each sensor 384 strips → 324k readout channels

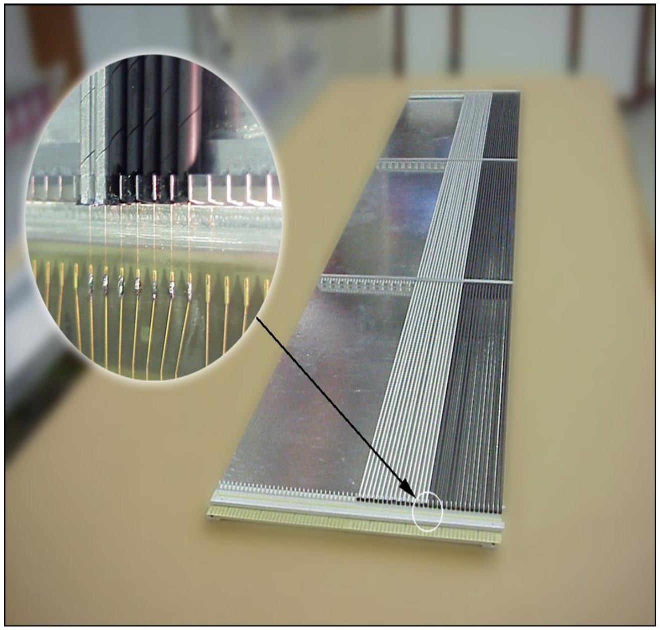


Upstream tracks (VELO + TT)

- $\delta p/p \sim 15\%$
- Used in trigger and $K_S$ tracking

Long tracks (VELO+TT+T1-T3)

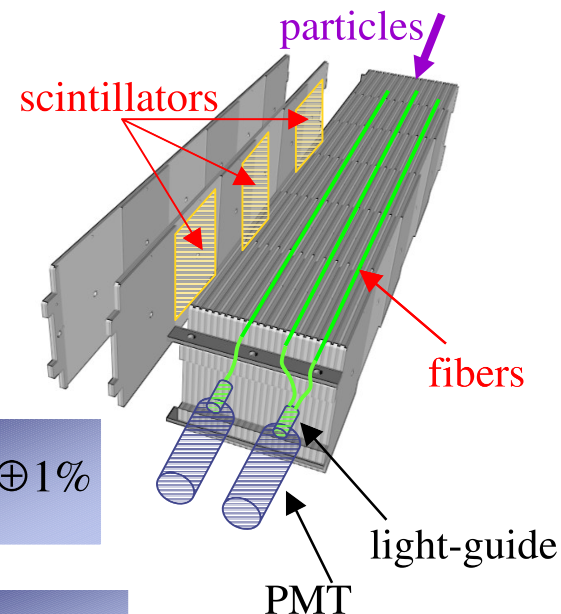
- 96% efficiency
- 3% ghost rate
- $\delta p/p \sim 0.4\%$



- Outer tracker: remainder of T1 – T3
  - Straw tube drift cells, filled with Argon, $CO_2$ and $CF_4$ mixture
    - $CF_4$ concentration varied to keep max drift time below 50ns.

# Calorimeters

- Used to provide high $E_T$ info. for first level trigger (L0)
  - Essential for measurement of neutral particles e.g. $B_d \rightarrow K^{*}\gamma$
- Four sub-systems:
  1) Scintillating pad-detector
     - 15mm thick scintillation pad $\rightarrow e^{\pm} / \gamma$ separation
  2) Pre-shower
     - 12mm thick lead pad ($2X_0$ for $e^{\pm}$) $\rightarrow e^{\pm} / \pi^{\pm}$ separation
  3) ECAL
     - 2mm lead sheets sandwiched with 4mm scintillation tiles
  4) HCAL
     - Steel sheets interspersed with scintillation tiles



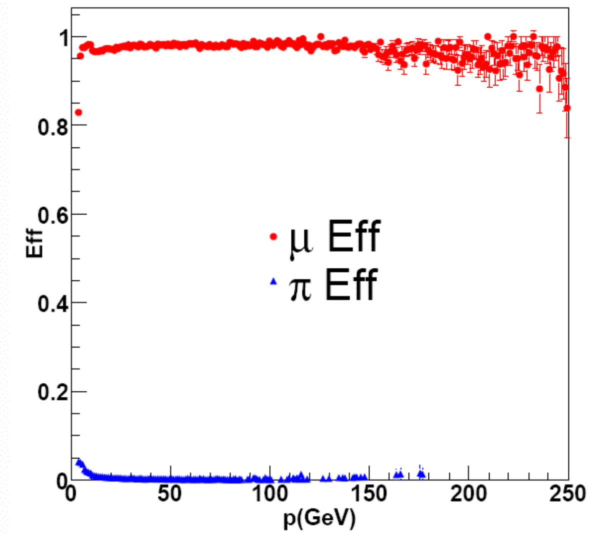


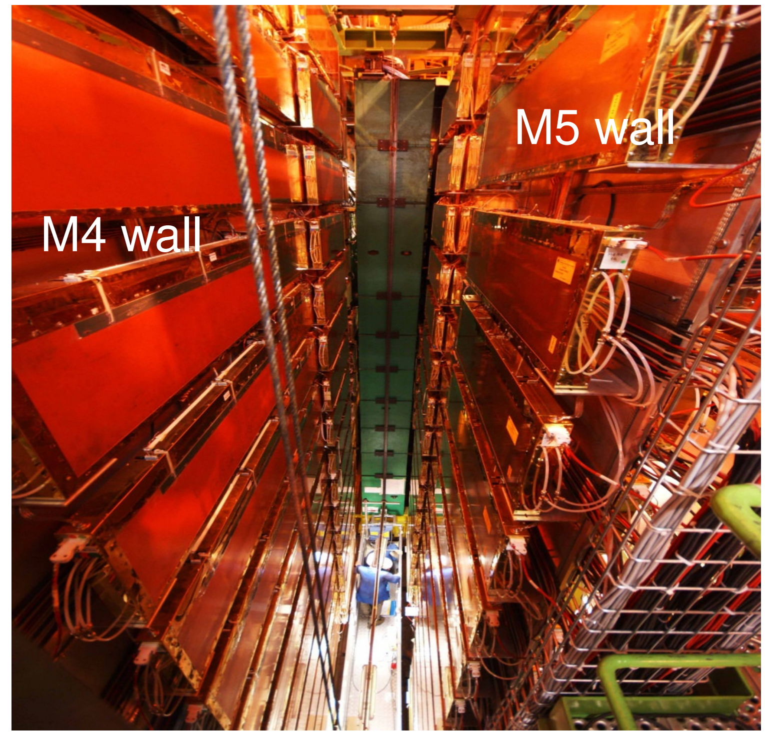
ECAL: $$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$$

HCAL: $$\frac{\sigma_E}{E} = \frac{80\%}{\sqrt{E}} \oplus 10\%$$

# Muons

- Muon ID crucial for many physics analyses (rare-decays, CP-violation)
- Provide useful trigger signal → easy readout and processing required



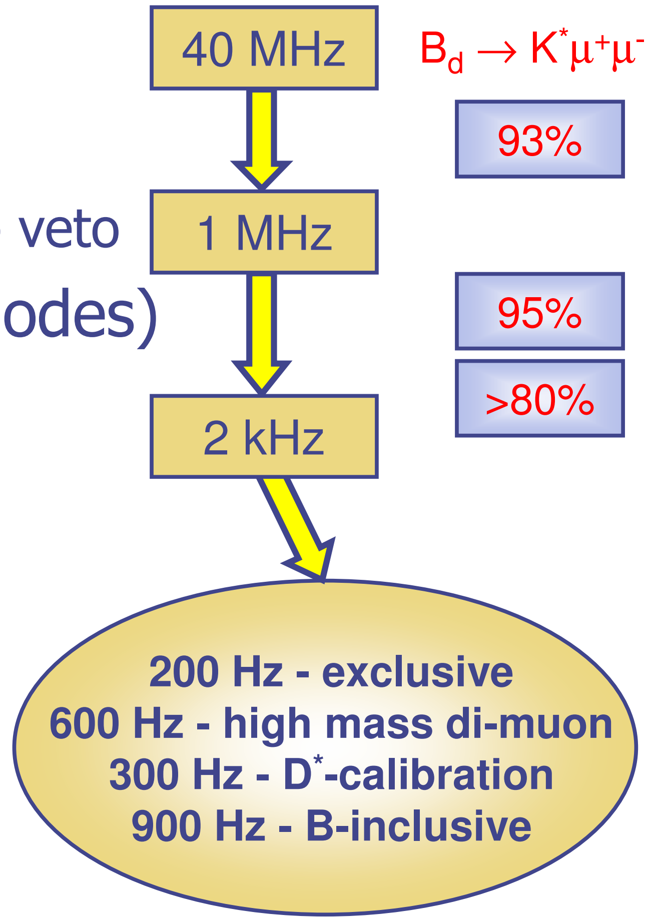




- 5 stations: 1 upstream of ECAL/HCAL (M1), 4 downstream (M2 – M5)
  - Triple-GEM detectors used in inner region of M1
  - Multi-wire proportional chambers used elsewhere
- Chamber size matched to z-distance from IP → constant angular size
  - Coincidence across stations easy to check quickly for trigger

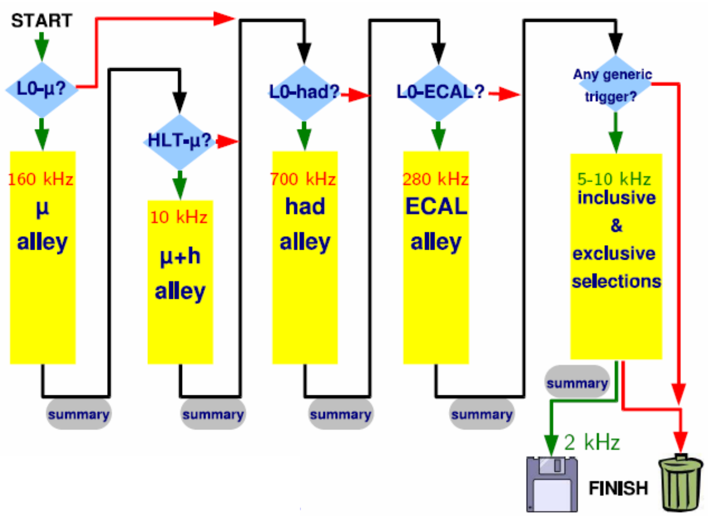
# Trigger

- Two level trigger scheme: hardware L0 and software HLT
  - Total inelastic pp cross section ~ 100mb
  - Total $bb_{bar}$ cross section ~0.5mb

Efficient trigger required!!




- L0 trigger – fixed 4μs latency
  - Info from muon, calorimeters and pile-up veto
- HLT – dedicated trigger farm (1800 nodes)
  - Alleys – confirmation of L0 decision
  - Inclusive / exclusive selections



# L0 Trigger (hardware)

- Three sub-triggers:
  - L0 muon – select high $p_T$ muons
    - Field of Interest search – project to PV to get $p_T$ measurement
  - L0 calorimeter – select high $E_T$ clusters
    - Use SPD and PS to separate electron, photon and $\pi^0$ candidates
  - L0 pile-up – veto multiple interaction events
    - Use two dedicated VELO sensors upstream of nominal IP to detect events with multiple interactions
      - Project tracks back to beam line and run peak finding algorithms
- Info combined in L0 decision unit (programmable)
  - Trigger on high $p_T$ single / di-muons
  - OR trigger on high $E_T$ single / di-electron, photon etc
  - NOT pile-up veto trigger
- Can be over-ridden by Readout Supervisor
  - Insert random triggers – minimum bias events
  - Throttle rate if too high

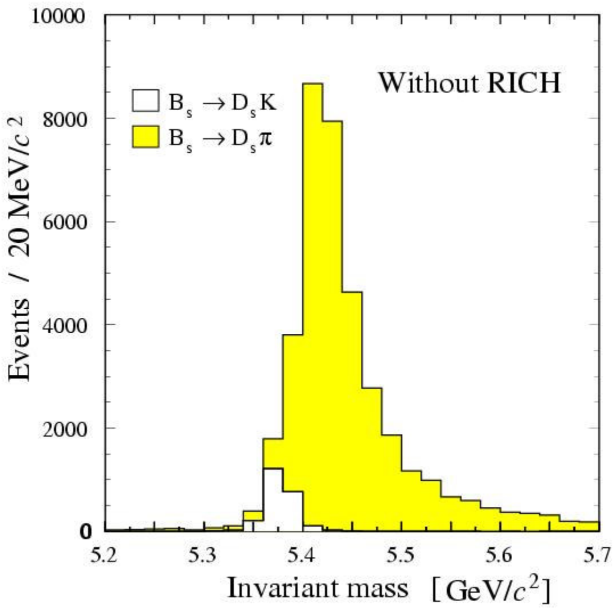
# HLT Trigger (software)

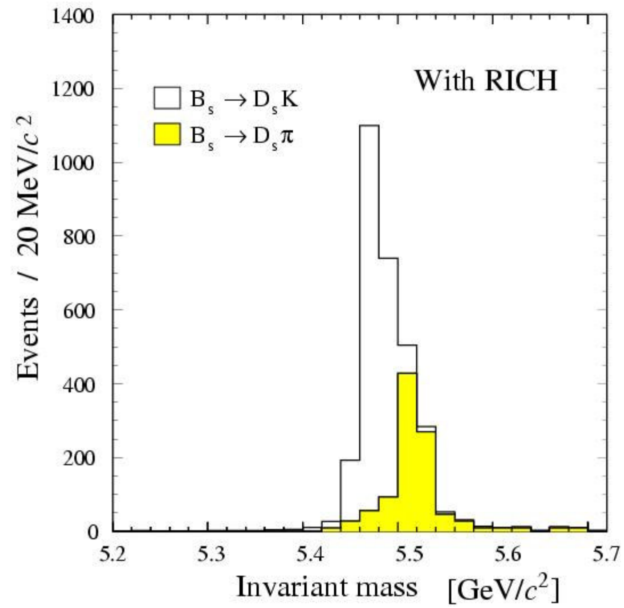
- Runs on dedicated computing farm (1800 nodes)
- Confirmation principle
  - e.g. only search for HLT muon if L0 muon triggered
  - Reduces trigger paths – easier correlations offline
- Alleys stage has access to more detector information
- Final HLT2 stage has access to full sub-detector info
  - Runs reduced resolution reconstruction (e.g. no full track fit)
  - Can reproduce offline-like selections
- Output rate of ~2kHz written to disk
  - Bandwidth still being divided up
    - Probably large muon & $D^*$ streams, smaller exclusive streams
- Probably not needed in 2009!

# LHCb RICH

# Why have a RICH?

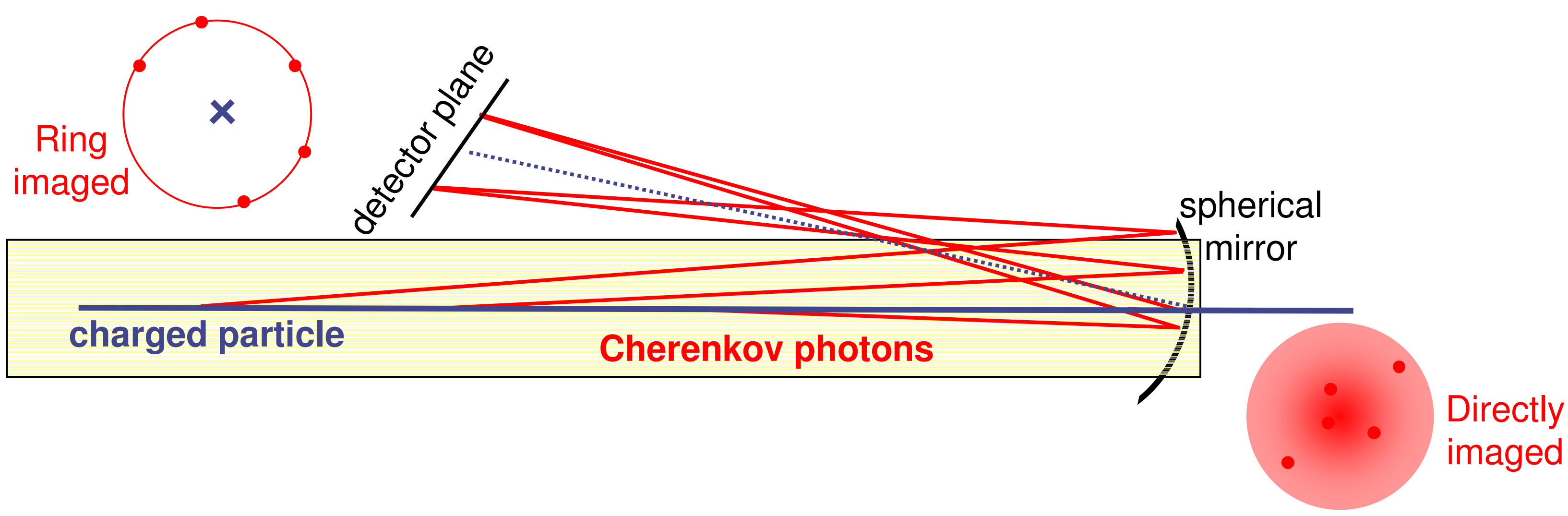
- Many physics analyses require good $\pi/K$ separation
  - Reject $B_s \to \phi\mu\mu$ background in $B_d \to K^*\mu\mu$
  - CP-angle $\gamma$ from $B_s \to D_s K^{\pm}$



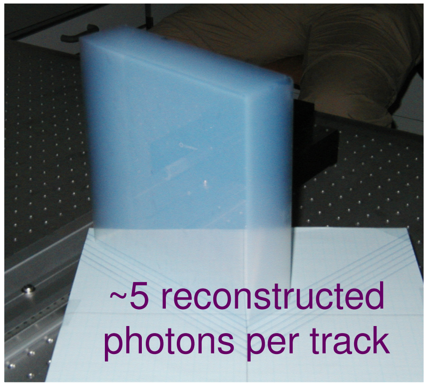
# What is a RICH?

- Ring Imaging Cherenkov detector
  - Cherenkov photons produced in radiator at a fixed angle to particle direction $\cos(\theta_C) = 1 / \beta n$
  - Photons produced randomly along radiator length ($\rightarrow$ cone)
    - Direct imaging $\rightarrow$ solid disc
    - Reflection from spherical mirror $\rightarrow$ photons focussed to ring

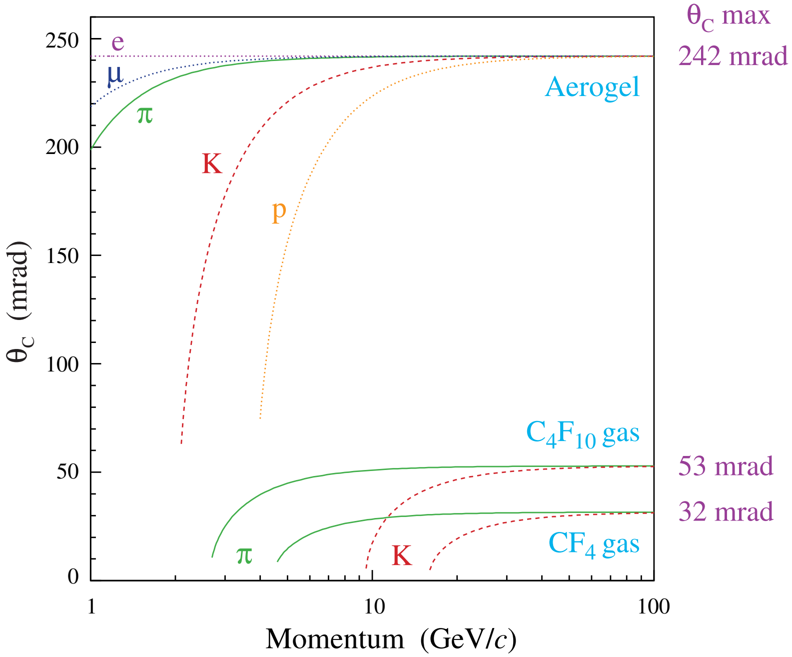


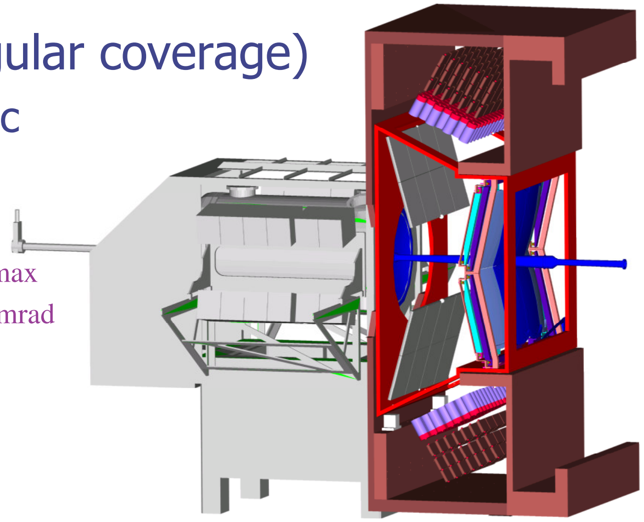
# LHCb RICH detectors

- RICH1 upstream of magnet (reduced size for full angular coverage)
  - π/K separation over low momentum range 2 – 60 GeV/c
  - Aerogel and $C_4F_{10}$ radiators







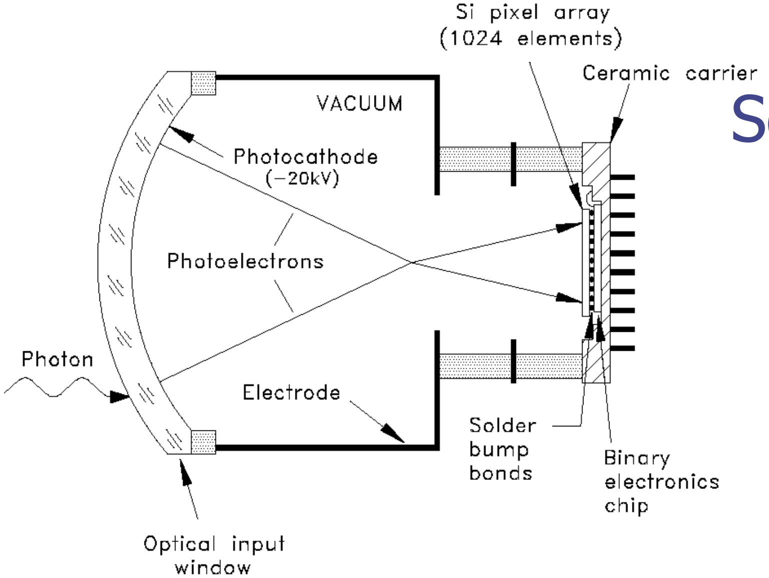



- RICH2 downstream of magnet
  - π/K separation over high momentum range 20 – 100 GeV/c
  - $CF_4$ radiator

# RICH photon detectors

Require:

- Single photon sensitivity
- Total coverage ~$2.8m^2$
- Granularity 2.5mm x 2.5mm
- Visible and near-UV sensitivity
- 25ns time resolution

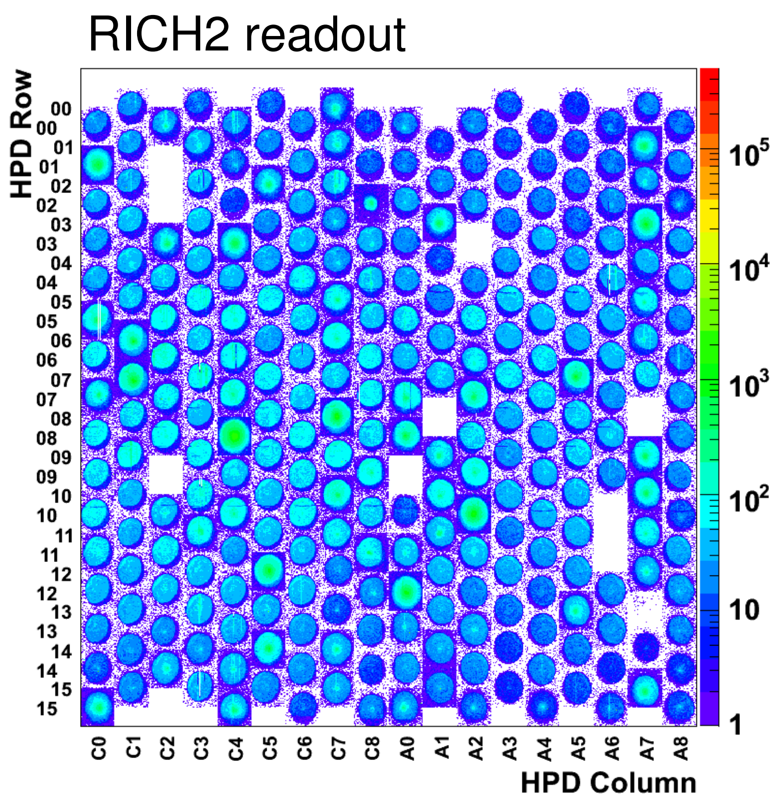



Solution: Hybrid Photon Detector

- Cross focussed electron optics (~ x5)
- Single stage amplification – typical photoelectron produces ~5000 $e^-$
- Silicon pixel chip, bump-bonded to binary readout chip (8192 pixels, ORed to 1024)
- Each pixel 500μm x 62.5μm, threshold ~1500 $e^-$ (pixel-pixel RMS 200 $e^-$)

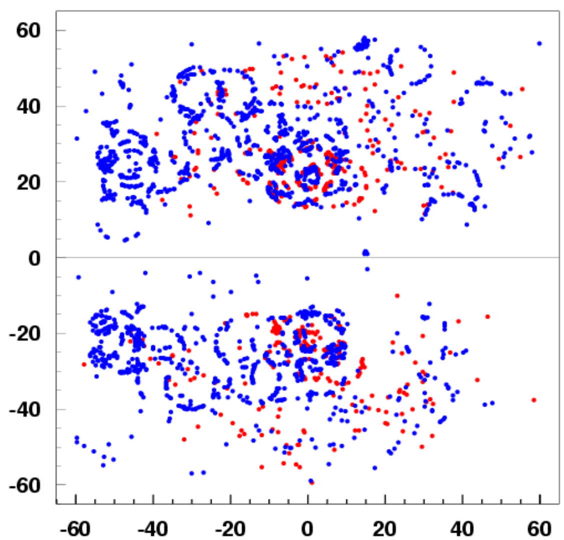
# RICH Commissioning

- RICH commissioning nearing completion:
  - Data collected at full (1MHz) rate
  - Rough time alignment of HPDs done (pulsed laser system)
  - Successful operation of the detector at 20kV for many months

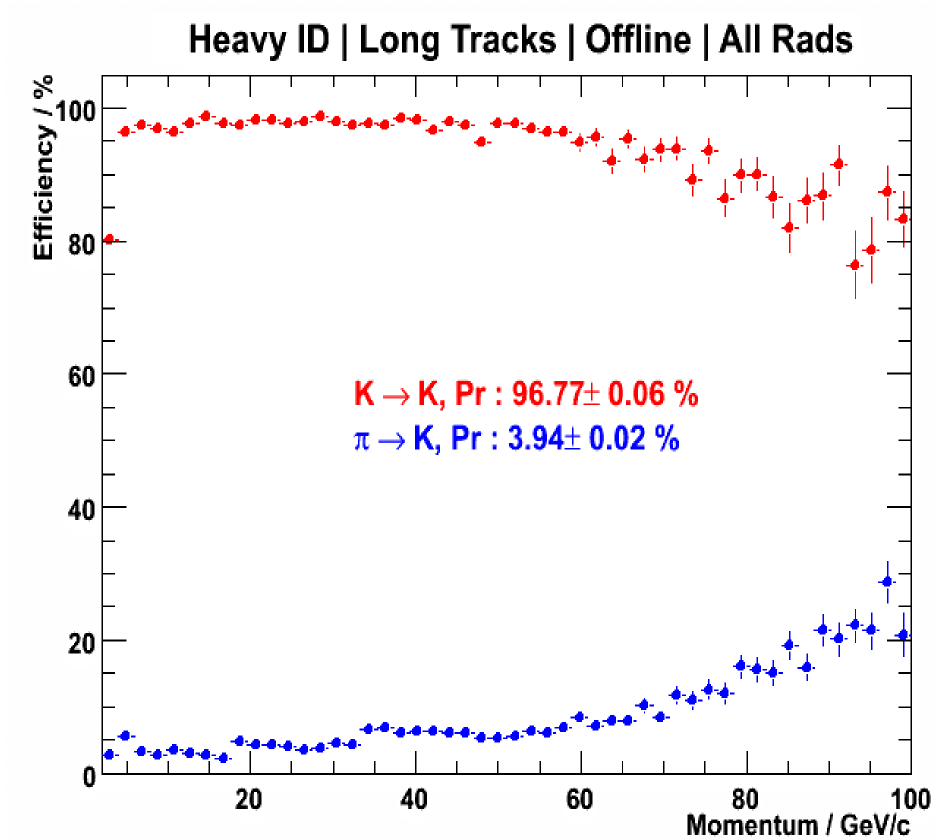


# LHCb RICH performance

- Cherenkov theta resolution ~ 1 mrad
  - Calibration using $D^* \to D\ (\to K\pi)\ \pi$
    - Kinematics such that can identify the particles without RICH information

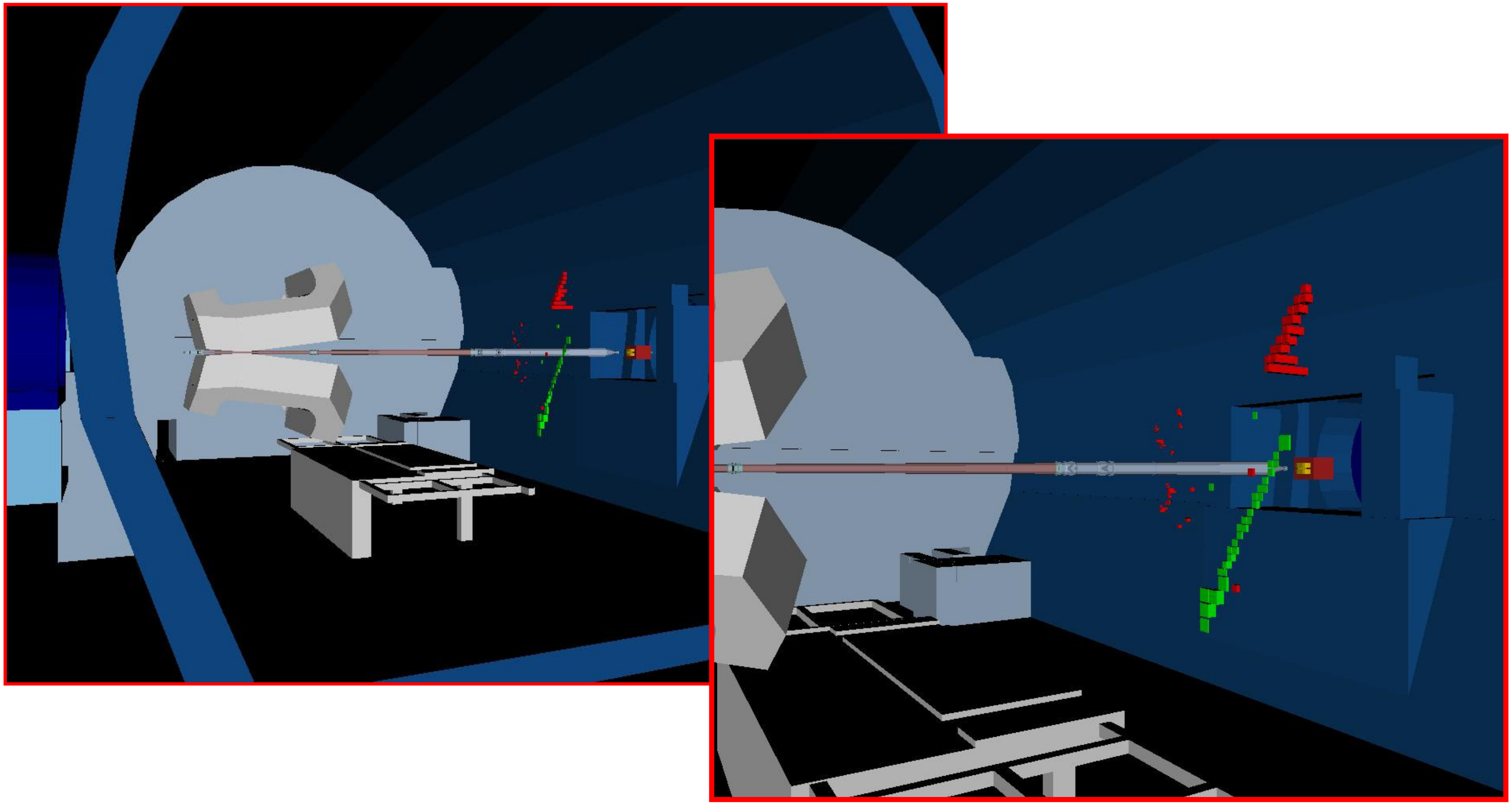



Simulation of photons on RICH1 detector plane



# LHCb Cosmics

- Calorimeter commissioning – trigger and readout a cosmic



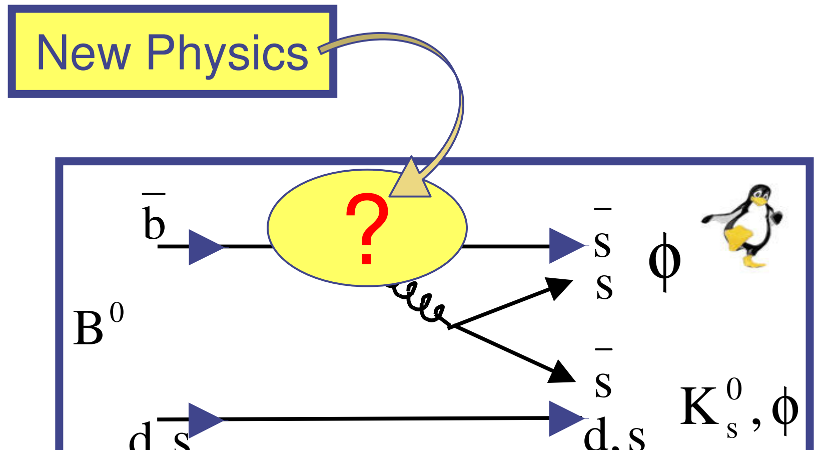
# Rare decays

# Introduction

- Actually, rare is not-so-rare…
  - Typical branching ratio <~ $10^{-6}$ (e.g. $B_d \rightarrow K^{*}\mu^{+}\mu^{-}$)
    - With $10^{12}$ bb-pairs per year ⇒ expect ~$10^{5}$ decays in detector

- Proceed only via loop diagrams
  - Sensitive to New Physics (e.g. new particles – SUSY?) in loops
  - Typically measure branching ratios and asymmetries

- Will briefly discuss
  - $B_s \rightarrow \mu^{+}\mu^{-}$
  - $B_d \rightarrow K^{*}\mu^{+}\mu^{-}$



Penguin diagram

# LHCb Monte Carlo

- Events generated using Pythia and EvtGen
  - Tuned to match particle production in LEP/CDF data
- Full detector response simulated in GEANT4
- Full data pattern recognition algorithms then run

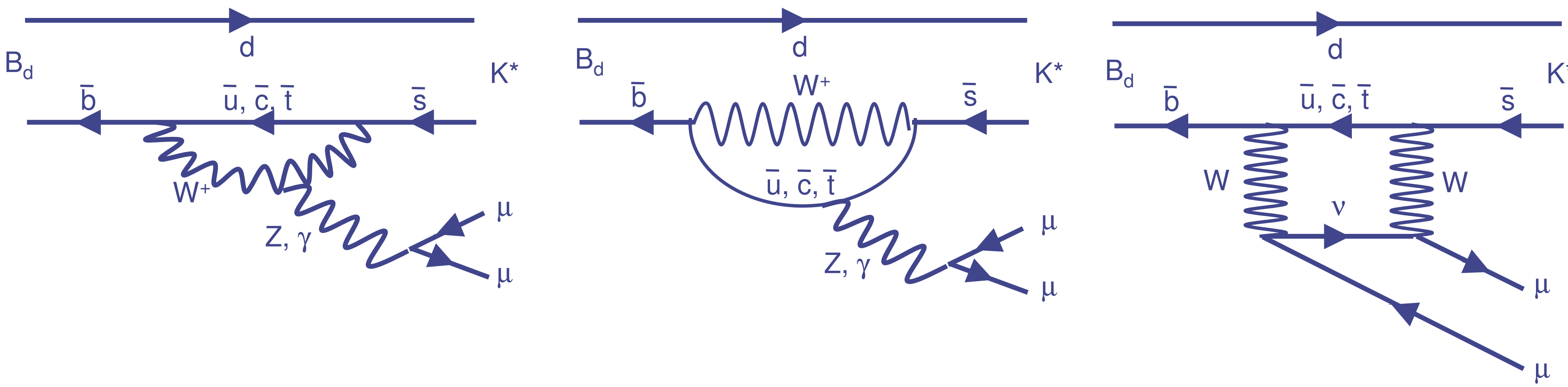
- Dedicated signal samples
  - $B_s \to \mu^+\mu^-$ 99.5k events ≡ 400 years data-taking
  - $B_d \to K^*\mu^+\mu^-$ 52.5k events ≡ 6 months data-taking

- Background expected to be dominated by b-events
  - Inclusive $bb_{bar}$ 24M events ≡ 10 mins data-taking
  - Specific b-decay modes (e.g. $B_d \to s\ \mu^+\mu^-$)

# $B_d \rightarrow K^{*}\mu^{+}\mu^{-}$

# Introduction

- Rare decay which proceeds only via loop diagrams
  - $B_d \rightarrow K^* \mu^+\mu^-$ (where $K^* \rightarrow K^+\pi^-$)
    - Exploit RICH PID performance, good mass resolution (~20 MeV/$c^2$)
    - Two muons provide relatively easy, clean trigger




- New Physics can enter at the same level as SM processes
  - In general, expect new physics can modify branching ratio and angular correlations (more later)

# Theory

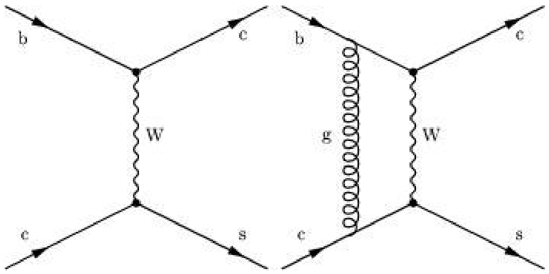
- Quarks bound in hadrons $\rightarrow$ QCD effects inextricably linked with weak interaction
  - Use Operator Product Expansion (OPE) to factorise amplitude
    - Separate short- and long-distance physics

$$A(I \rightarrow F) = \langle F | H_{eff} | I \rangle = \sum_i C_i(\mu) \times \langle F | O_i(\mu) | I \rangle$$

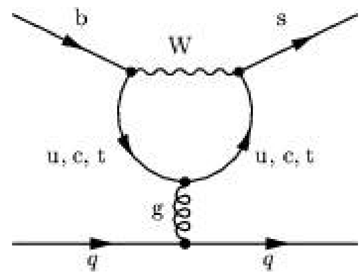
    - Amplitude for a process factorised into sum of local operators ($O_i$) and Wilson coefficients ($C_i$)
  - Short distance ($C_i$): can calculate perturbatively (well, theorists can!)
  - Long distance ($O_i$): non perturbative – use various approximations

- $B_d \rightarrow K^* \mu^+ \mu^-$ sensitive to $C_7$, $C_9$ and $C_{10}$ coefficients

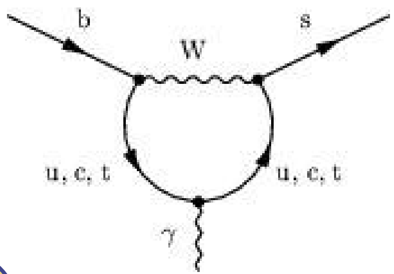
# Theory (2)




$O_{1,2}$ : current-current



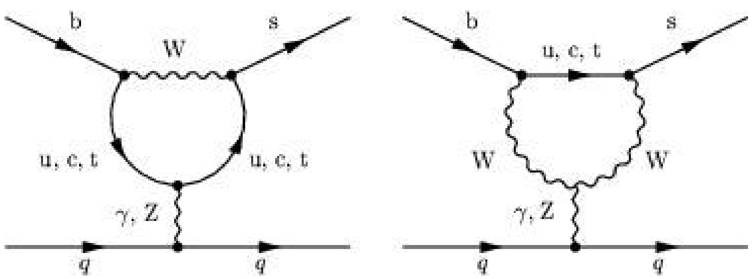

$O_{3,4,5,6}$ : QCD penguin



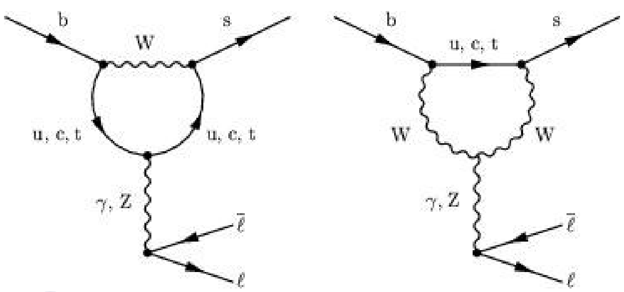

$O_{7\gamma,8g}$ : magnetic penguin

$$H_{eff} = -4\frac{G_F}{\sqrt{2}} V_{ts}^{*} V_{td} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

Sensitive to these coefficients



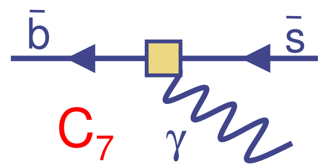

$O_{7,8,9,10}$ : electroweak penguin



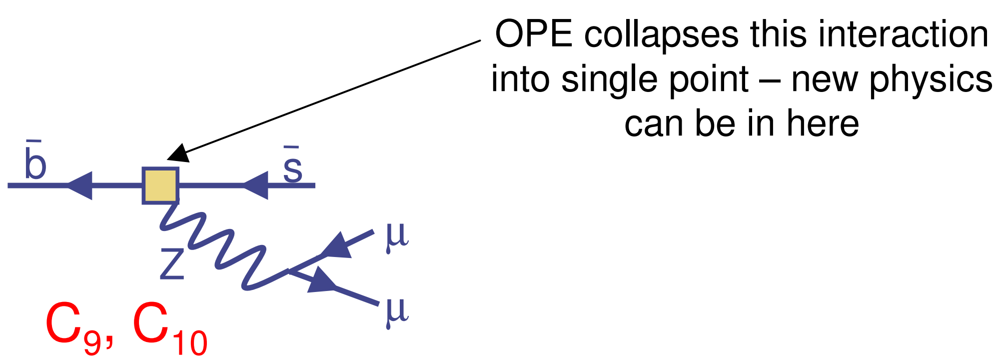

$O_{9V,\ 10A}$ : semi-leptonic penguin

# Theory (3)

- $C_7$ measured in radiative decays (good agreement with SM)

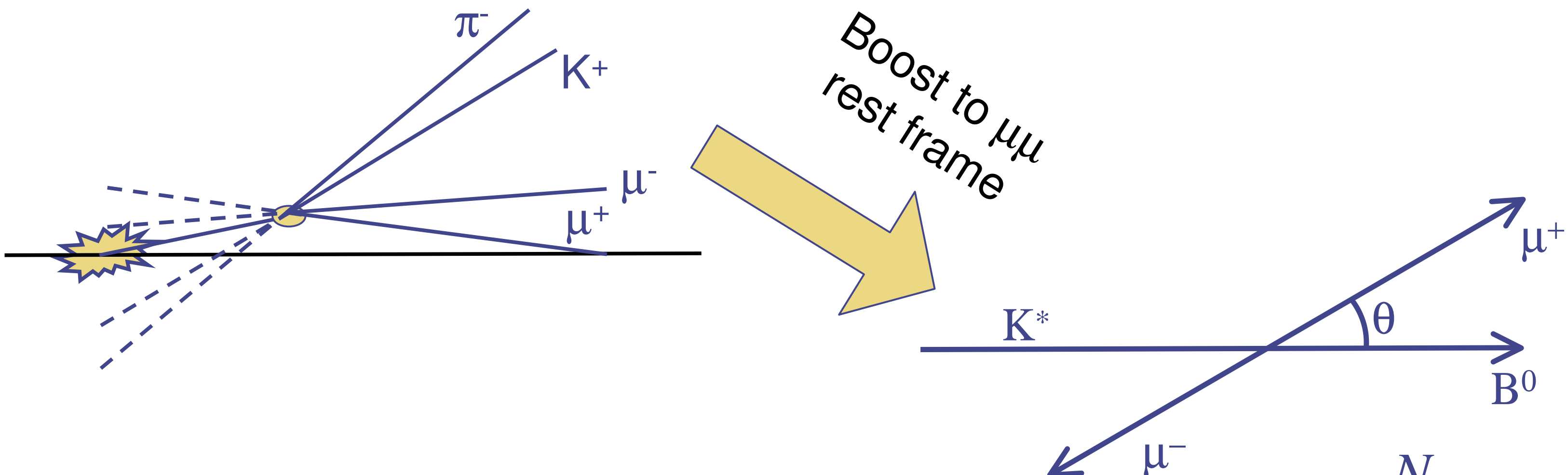



- In $B_d \rightarrow K^* \mu^+ \mu^-$ interference between $C_9$ and $C_{10}$ produces the famous forward-backward asymmetry ($A_{FB}$)
  - Interference between diagrams with muons produced in vector and axial-vector states



# Theory Predictions

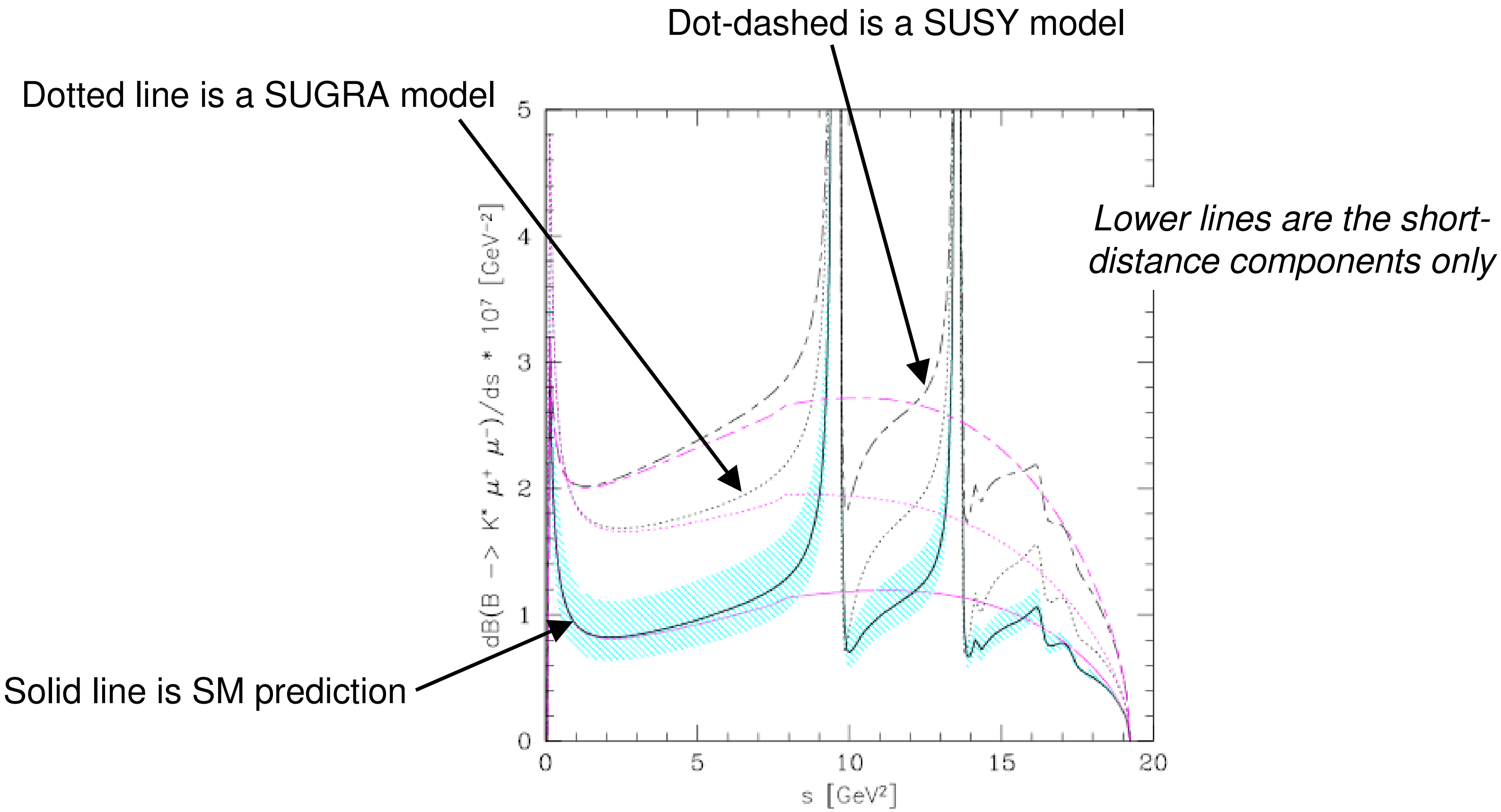
- Branching ratio potentially sensitive to new physics
  - Calculated to be = $(1.19\ ^{+0.39}_{-0.39}) \times 10^{-6}$ in SM
  - PDG average = $(1.22\ ^{+0.38}_{-0.32}) \times 10^{-6}$
- $A_{FB}$ can still be sensitive to new physics
  - Measure the angle ($\theta_l$) between the $\mu^+$ and the $B^0$ momenta, in the $\mu\mu$ rest frame




$$A_{FB} = \frac{N_{\theta<\pi/2} - N_{\theta>\pi/2}}{N_{\theta<\pi/2} + N_{\theta>\pi/2}}$$

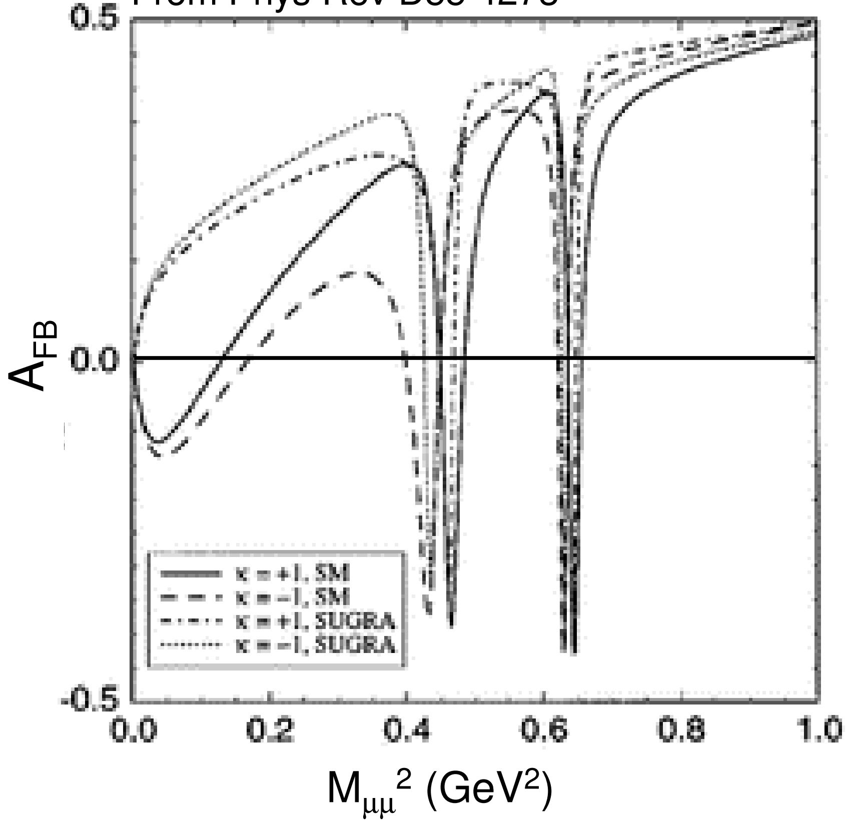
# Di-muon mass spectrum

- $M_{\mu\mu}^2$ distribution can be modified in new physics models eg: SUSY

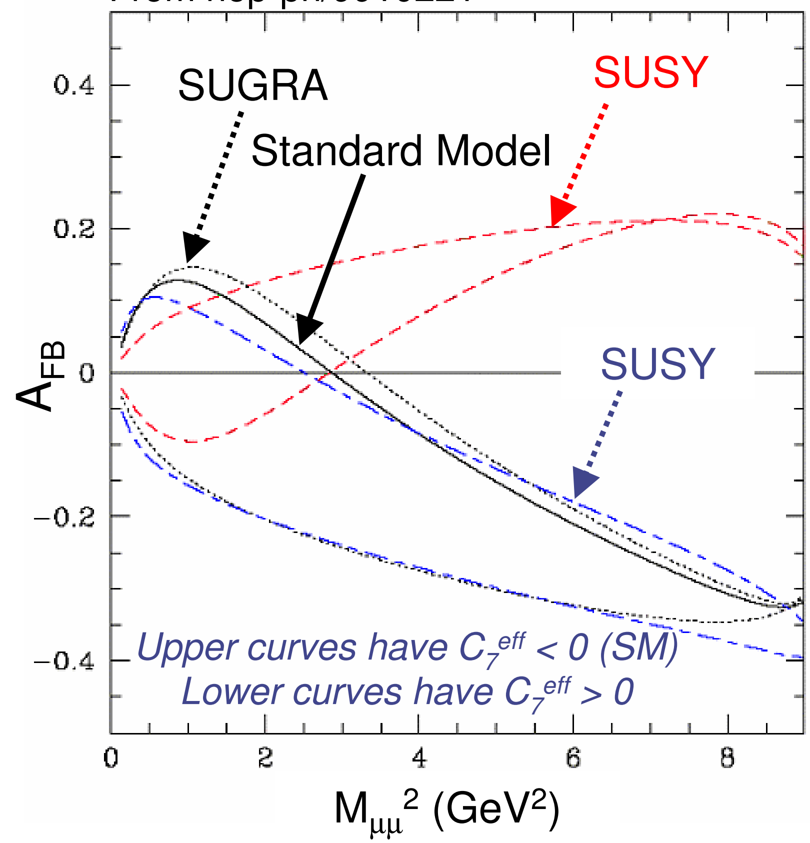


# Forward Backward Asymmetry

From Phys Rev D55 4273




From hep-ph/9910221

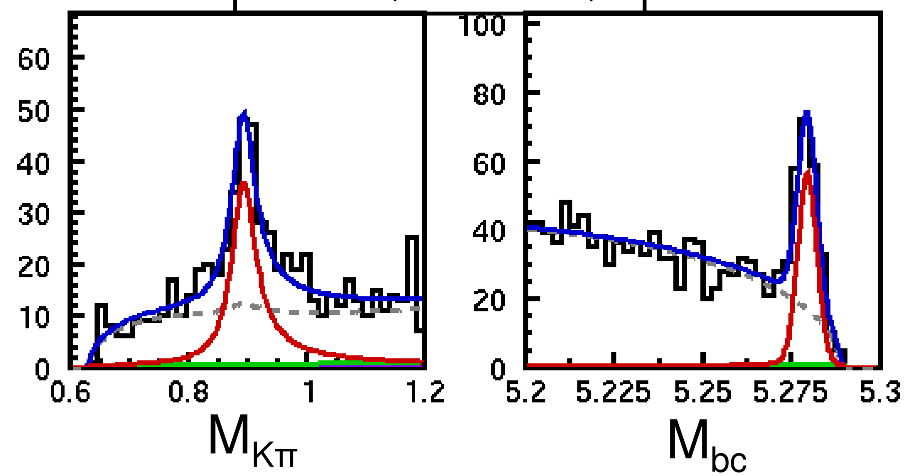



- SM calculation: $s_0 = \left(4.36^{+0.33}_{-0.31}\right)\mathrm{GeV}^2$ (hep-ph/0505155)

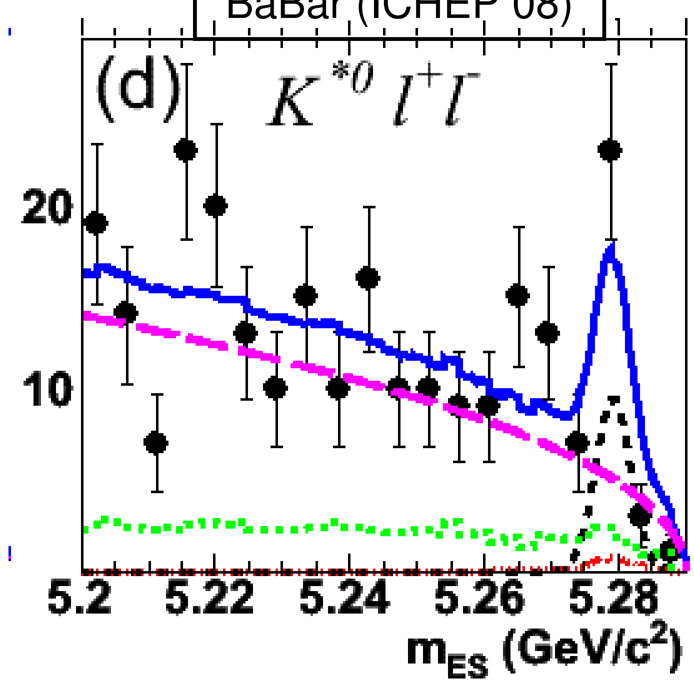
# Current $K^*\mu^+\mu^-$ measurements

- B-factories have collected ~100s events
  - BaBar: $64 \pm 11$ $B_d \rightarrow K^*l^+l^-$ events (Jan 09 from 384M BB)
  - Belle: $230 \pm 23$ $B_d \rightarrow K^*l^+l^-$ events (July 08 from 657M BB)
- CDF reports similar statistics

Belle (ICHEP 08)

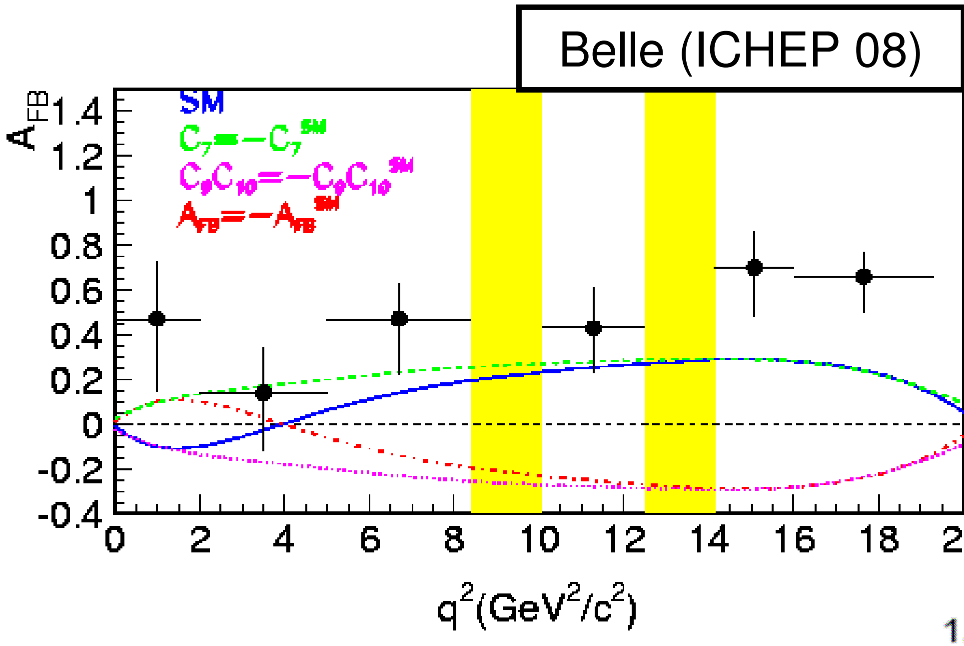



BaBar (ICHEP 08)



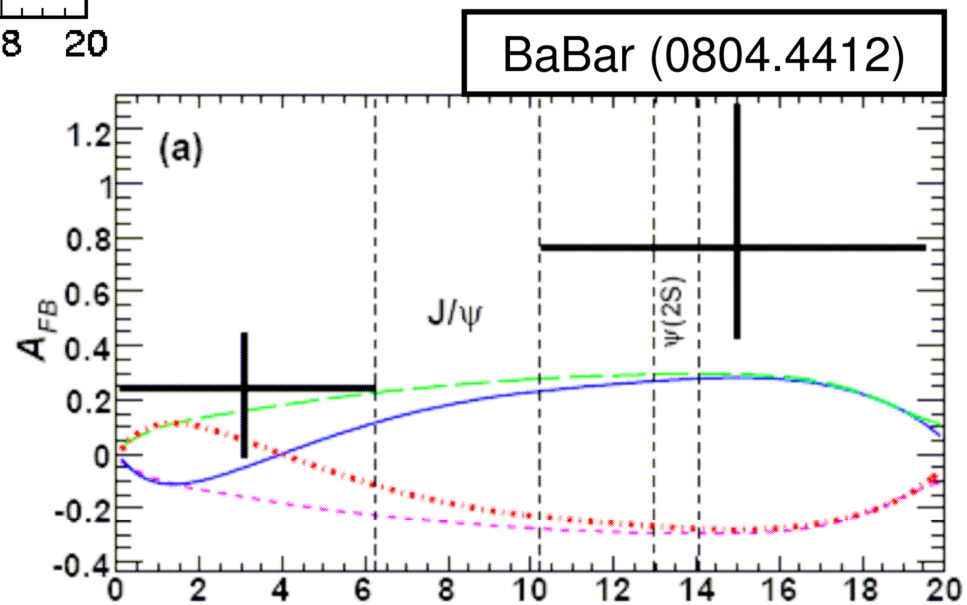

- Measurements of $A_{FB}$ and other angular correlations (plus iso-spin and CP-violation) now being made…

# Current $A_{FB}$ measurements



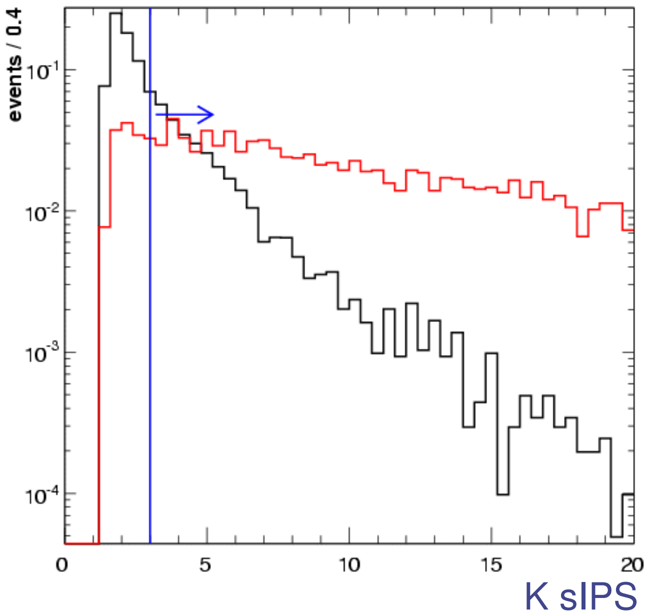

- Current measurements:
  - BaBar & Belle – now constrain some new physics models (eg: $|C_{10}^{(NP)}| < 7$)

- Missing regions are J/ψ mass vetos – large theory uncertainties, from long-distance effects



# LHCb Event Selection

- Event selection exploits displaced secondary vertices:
  - Require two well identified muons + K and $\pi$ (from RICH)
  - Cut on daughter (K, $\pi$, $\mu$) impact parameters
  - Cut on B flight distance
  - Also cut on vertex $\chi^2$ etc




- Previously used cut based analysis (results presented here)
- Now moving to multi-variant analysis
  - Fisher discriminant method (linear combination of variables)

# Event yields and backgrounds

- Numbers are for ~1 year (2 $fb^{-1}$) of data, after L0 trigger

$$\#evts = N_{bb} \times f_B \times BR \times \varepsilon_{TOT}$$

| Sample | | 2 $fb^{-1}$ yield |
|---|---|---|
| $B_d \to s\mu\mu$ | $B_d \to K\pi\mu\mu$ ("non-res") | 1730 ± 75 |
| | Other | 20 ± 7 |
| $B_u \to s\mu\mu$ | | 9 ± 3 |
| 2x single muon ($b \to \mu$, $\bar{b} \to \mu$) | | 1050 ± 250 |
| Charm intermediate ($b \to \mu\, c$), $c \to \mu$ | | 640 ± 180 |
| TOTAL background | | 3400 ± 320 |
| Signal | | 7200 ± 180 ± 2100 |

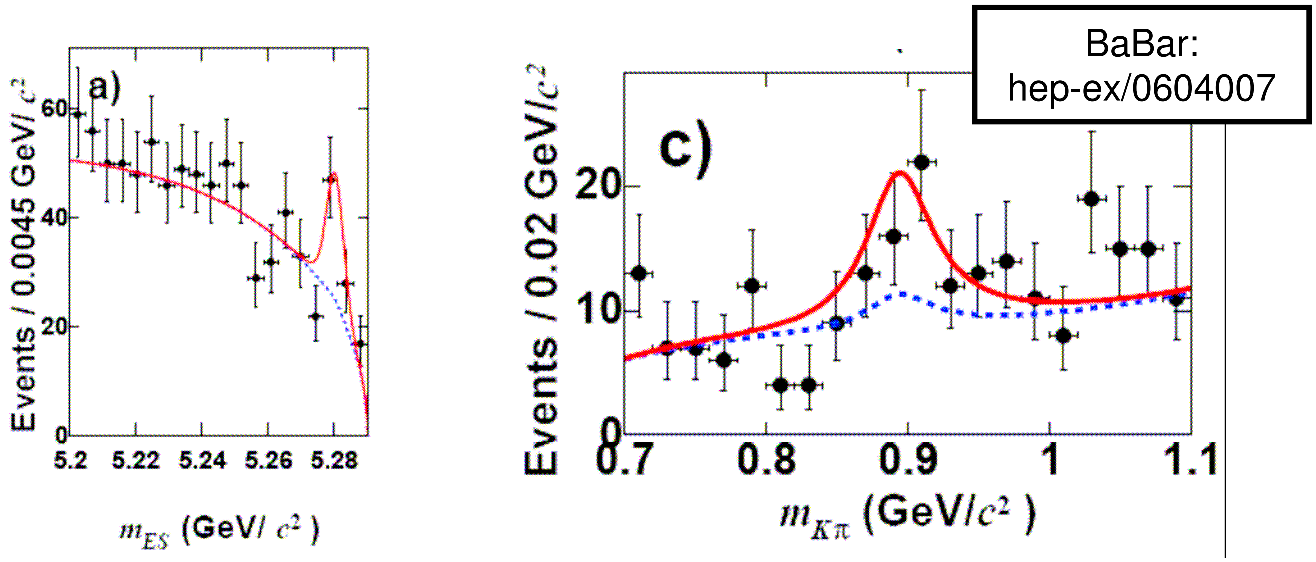
Statistical

From BR measurement

# $B_d \to K\pi\mu\mu$: Non-resonant events

- Expect some background from non-resonant events
  - Although this mode has not been observed…

Compare #events in B-mass and $K^*$-mass peaks

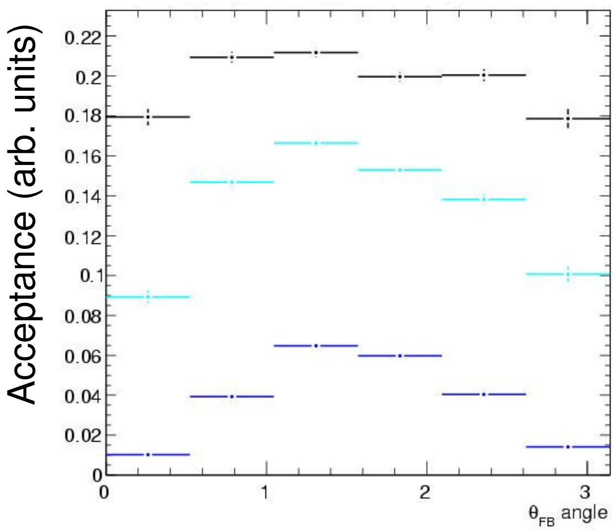



- Identical from a selection point of view, but no $K^*$ mass constraint
- Spectra and rate are very uncertain in simulation!
- For $A_{FB}$, can be treated as signal, under certain conditions…
- Ignore any background from this source
  - Will need to check if this is fair, when data arrives!

# Acceptance issues?

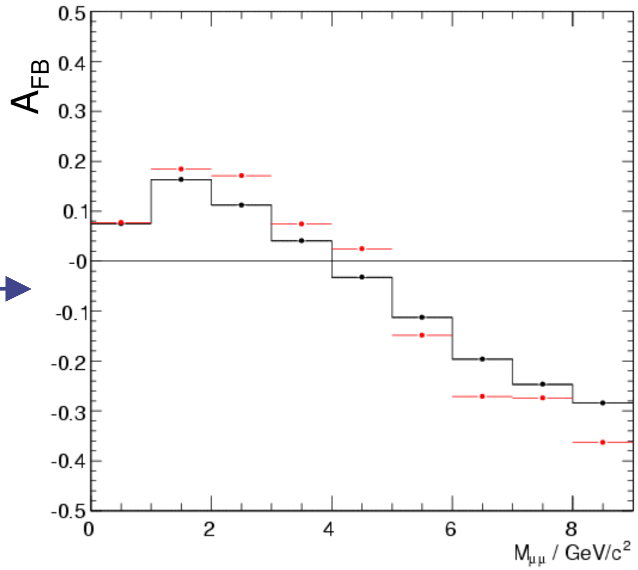
- Need to know acceptance function
  - Removing correction in toy model gives shift of ~0.2 $GeV^2$
- Acceptance bias from requirement for muons to reach M1 (p > 3 GeV/c)
  - Remaining bias from cuts is small (dominated by muon $p_T$)

Black – no PID acceptance
Turqoise – require muon ID
Blue – require muon ID + all cuts




Significant shift in $A_{FB}$

Black – apply and unfold acceptance
Red – apply acceptance, unfold nothing



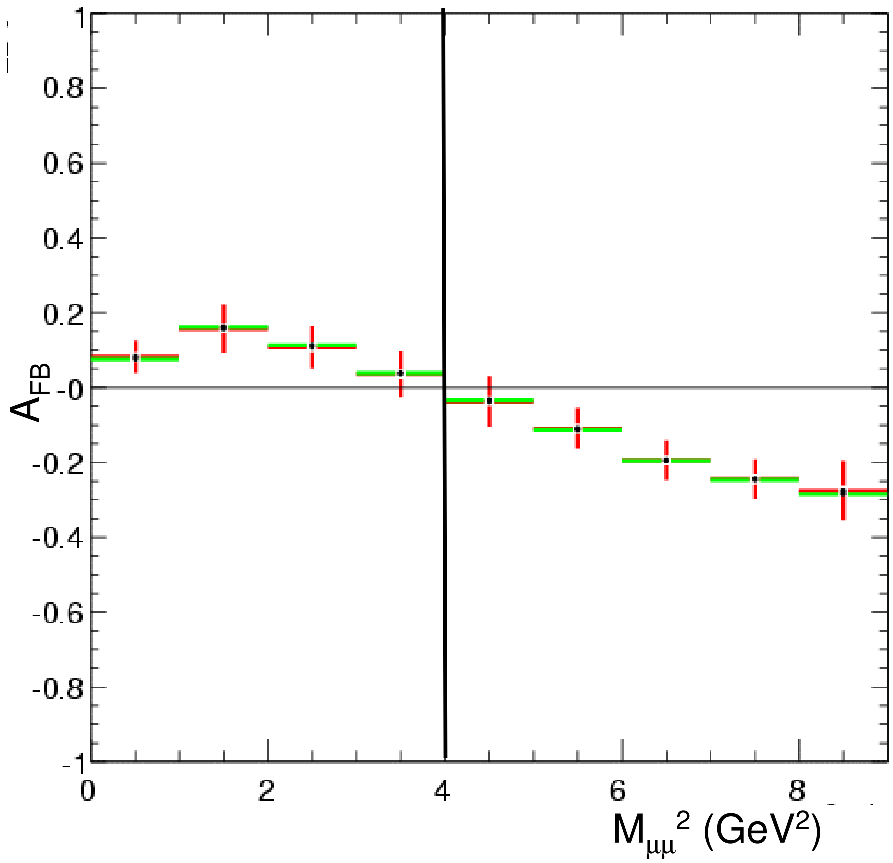

- Ongoing work to establish how to measure acceptance from data
  - Current plan to use $B \to J/\psi\ K^*$ (expect ~100k events per year)

# $B_d \to K^*\mu\mu$: $A_{FB}$ sensitivity

- Toy model based on LHCb simulation (statistical errors only):
  - Large sample of generator level events (6.5M)
  - Smaller sample of fully simulated events, includes detector sim. (1M)
  - Take resolutions, acceptances and background from the fully simulated events, in bins of $M_{\mu\mu}$ ($0 \to 3$ GeV) and $\theta_{FBA}$ ($0 \to \pi$)
    - $M_{\mu\mu}$ ($\theta_{FBA}$) resolution ~ 10 MeV (4 mrad) $\Rightarrow$ ~3% (~1%) of bin width
  - Sample from (fluctuated) generator level distributions, applying the acceptance functions, to simulate a large number of 2 (10) $fb^{-1}$ experiments.
  - Calculate and fit $A_{FB}$ for each data set to find the zero-crossing point
  - Quoted sensitivity is then the standard deviation of the fitted zero points from a large number of "experiments" (~10k)

# $A_{FB}$ Sensitivity

- Check (no background) toy model reproduces right $A_{FB}$
  - Green – generated $A_{FB}$ (from 6.5M events)
  - Red – $A_{FB}$ from toy model, averaged over 10k experiments




- No visible difference between the curves
  - Averaged over large number of experiment, toy model does reproduce the generated distribution
- Generator zero point at $M_{\mu\mu}^2 = 4\ GeV^2$
  - Largely irrelevant where it lies – just want to check we can measure the "right" answer
- Focus on region $0 \leq M_{\mu\mu} \leq 3$ GeV
  - Below the first $J/\psi$ resonance

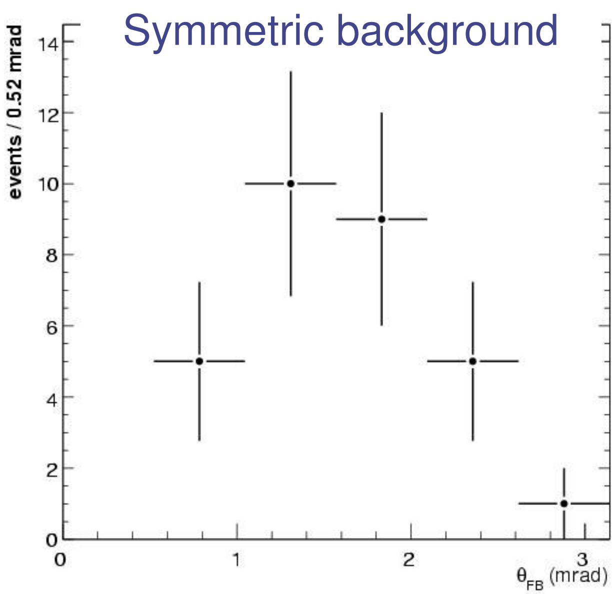
# Background for $A_{FB}$ study

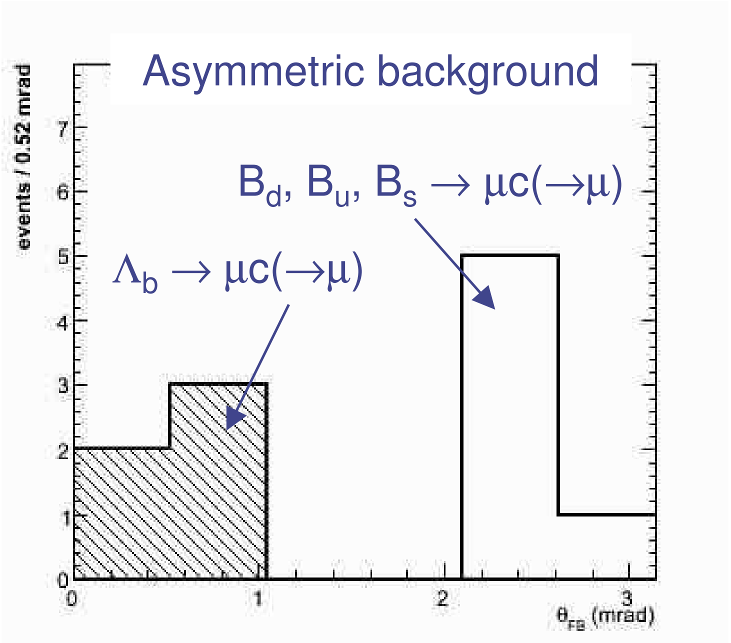
- Have neglected non-resonant background for now

- Consider two types of background:
  - In reduced $M_{\mu\mu}$ range ($0 \to 3$ GeV)
  - Asymmetric in $\theta_{FBA}$ (expect $280 \pm 100$ events per 2 $fb^{-1}$)
    - Fraction of the $b \to \mu\ c\ (\to \mu)$ sample
      - For example: $B^+ \to \mu^+ \nu\ D^0 (\to K^+ \mu^- \nu)$ and $B^- \to \mu^- \nu\ D^0 (\to K^- \mu^+ \nu)$
      - For both cases, we make the angle with the muon direct from the b, which tends to have higher momentum than the muon from the charm, so is more likely to be forward in the $\mu\mu$ rest frame
  - In reduced $M_{\mu\mu}$ range ($0 \to 3$ GeV)
  - Symmetric in $\theta_{FBA}$ (expect $820 \pm 160$ events per 2 $fb^{-1}$)
    - All events in the $b \to \mu X$, $\bar{b} \to \mu X$ sample (muons from different b-decays)
    - Some events in the $b \to \mu\ c\ (\to \mu)$ sample, where the K and $\pi$ come from different b-decays to the two muons – the charge of the K is uncorrelated with the charge of the muon direct from the b

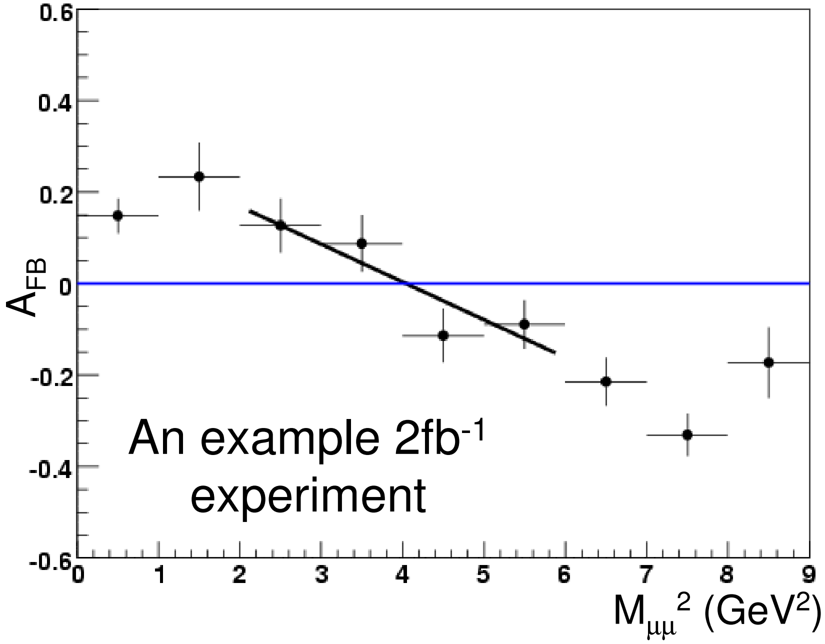
# Background for $A_{FB}$ study

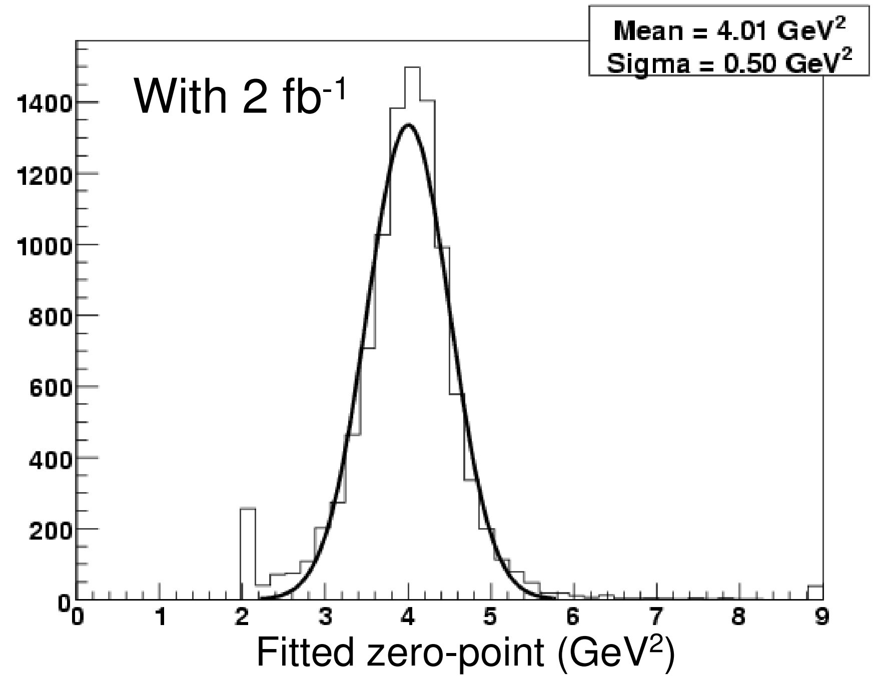
- Asymmetric background:
  - Most events are "forward" asymmetric
  - Events from $\Lambda_b$ are "backward" asymmetric (opposite flavour b-quark)
    - Some of the asymmetric background will cancel
    - Conservatively, don't use this for now…
- With limited statistics, remaining background is symmetric



# $A_{FB}$ sensitivity

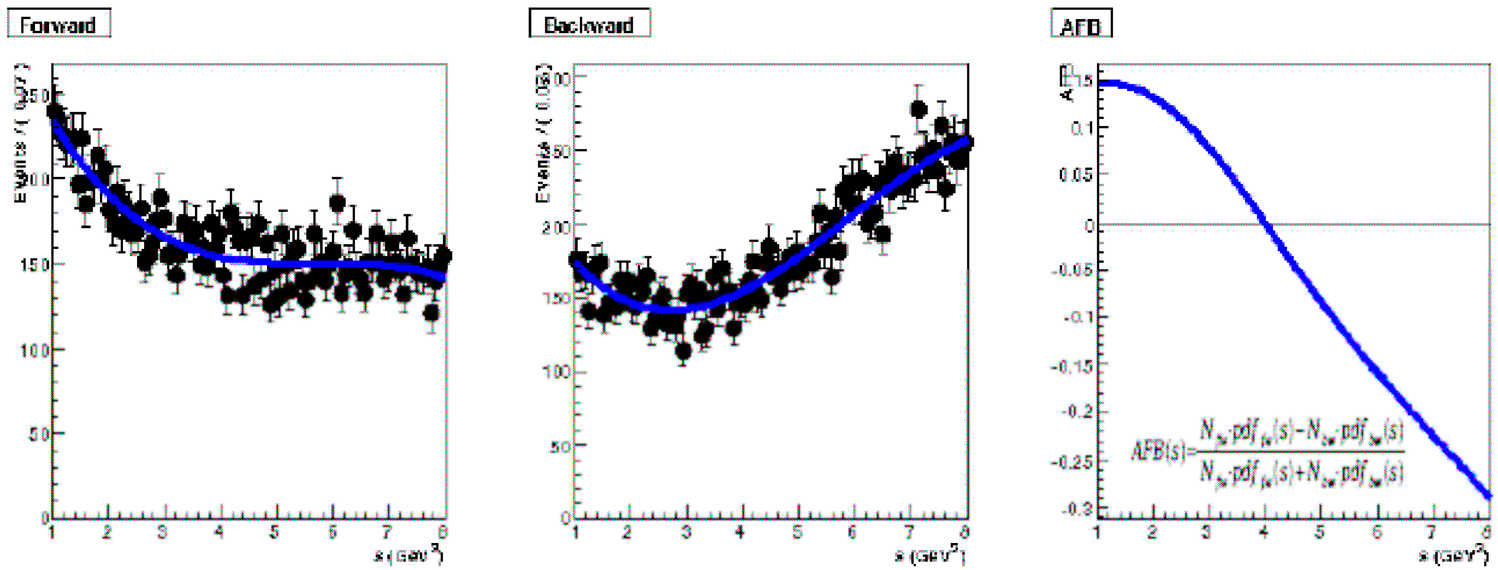



- Recall generator has: $s_0 = 4.0\ \mathrm{GeV}^2$
- With no background: $s_0 = 4.0 \pm 0.4\ \mathrm{GeV}^2$
- With background added:
  - With 2 fb$^{-1}$ (1 year): $s_0 = 4.0 \pm 0.5\ \mathrm{GeV}^2$
  - With 10 fb$^{-1}$ (5 years): $s_0 = 4.0 \pm 0.3\ \mathrm{GeV}^2$

# $A_{FB}$ fitting

- Can do better than simple linear fit to $A_{FB}$ crossing point
  - For example: un-binned (as function of s) fit to forward and backward events



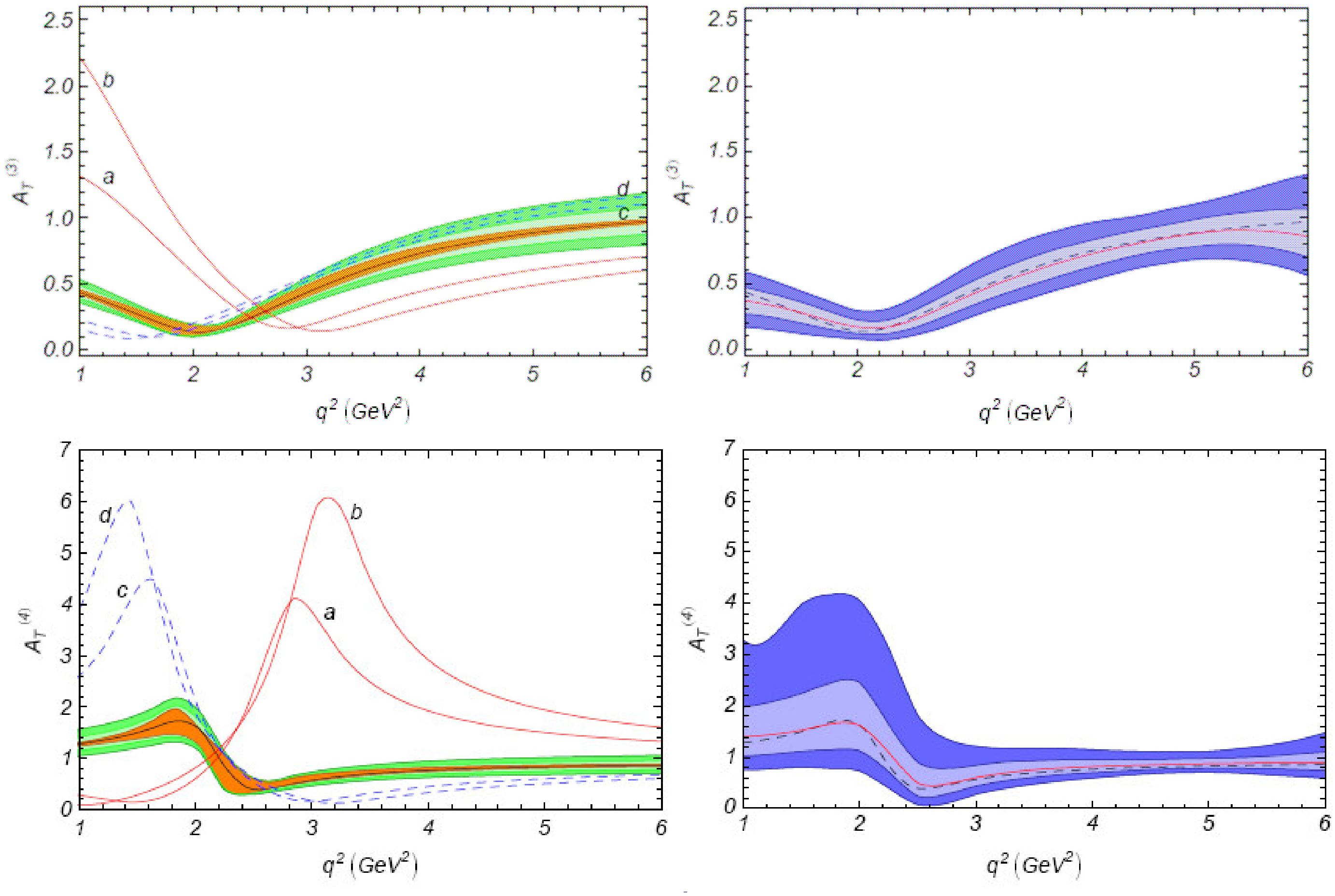

  - Or, angular projection fits (fit $\theta_l$, $\theta_K$ and $\phi$ projections)
  - Or, full angular fit – simultaneous of all angles and s together

need more data!

# Full angular fit examples

- New variables $AT_3$ and $AT_4$
  - Left are theory predictions (and errors)
  - Right are toy-model LHCb predictions for SM

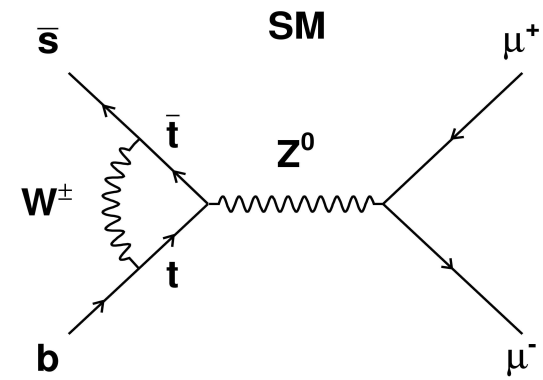
hep-ph/0807.2589

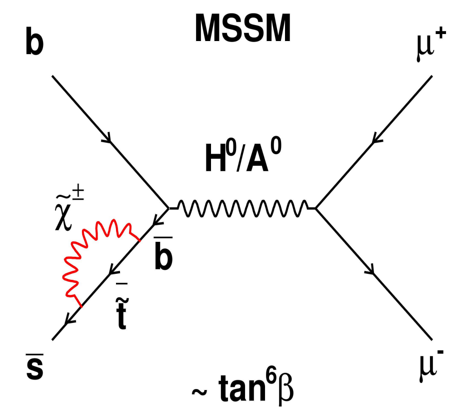


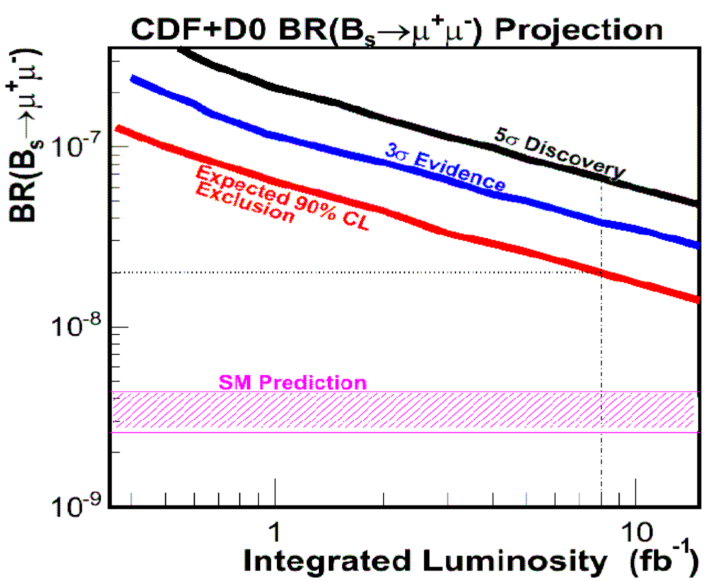
# $B_s \rightarrow \mu^+\mu^-$

# $B_s \to \mu\mu$

- Branching ratio ~ 3.5 x $10^{-9}$ in Standard Model
  - Sensitive to New Physics and can be strongly enhanced by SUSY (by up to factor ~100)
- Current limit from Tevatron with 2fb$^{-1}$ is:
  - BR < 5.8 x $10^{-8}$ @ 95% CL (CDF)
  - BR < 9.3 x $10^{-8}$ @ 95% CL (D0)
- Expected limit with 8fb$^{-1}$ is ~ 2 x $10^{-8}$ @ 90% CL



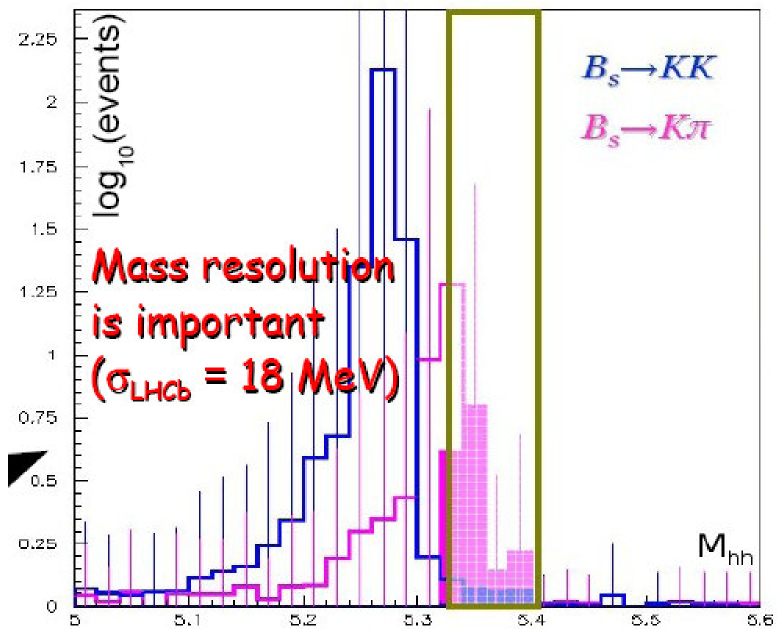




- At LHCb, expect ~250 evts/year in detector acceptance
  - Assuming SM branching ratio

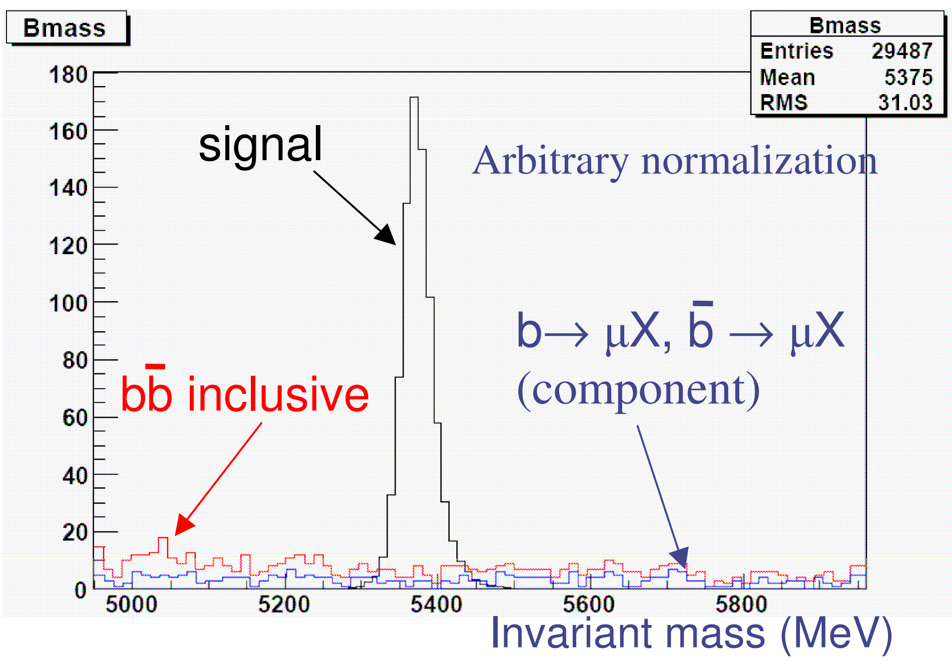
# $B_s \to \mu\mu$: Mis-ID background

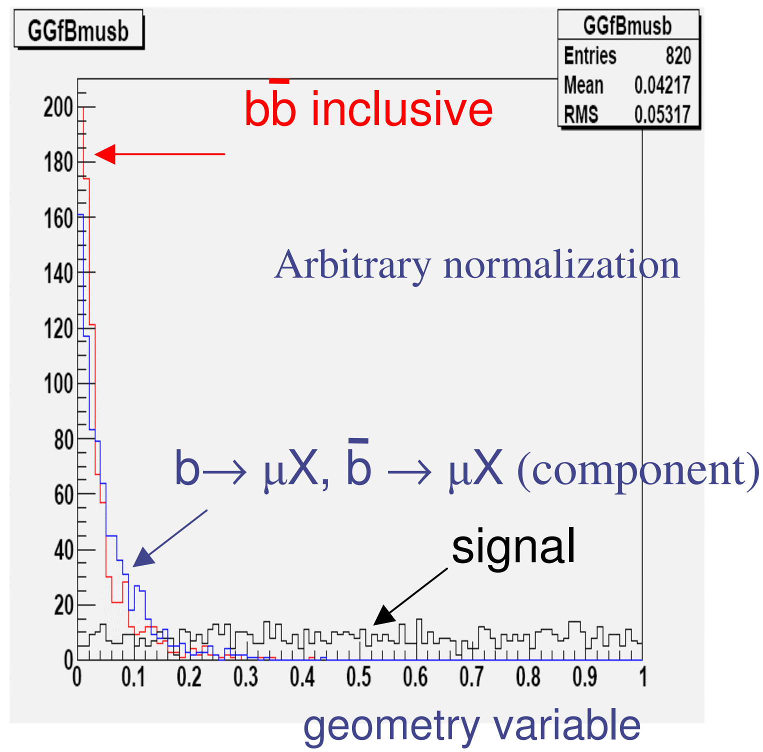
- Extremely low branching ratio → issue is background rejection
  - Combinatorial – with muons mainly from b decays
    - Studied with $b\bar{b}$ and $b \to \mu X$, $\bar{b} \to \mu X$ samples
  - Mis-identified Hadrons – eg $B_s \to \pi\pi$, $K\pi$ and KK
    - For example $Br(B_s \to K\pi) \approx 5 \times 10^{-6}$, so need mis-id rate O(1%) per track
    - For a 1% mis-id rate, LHCb expects of order 1 event per $fb^{-1}$ in $2\sigma$ mass window



# $B_s \to \mu\mu$: N-counting experiment

- Perform N-counting experiment in 3 variables:
  - Combined geometry variable (impact parameters, distance of closest approach, lifetime, vertex isolation)
  - Particle-ID (likelihood for $\pi$ or K to be mis-id as $\mu$)
  - Invariant mass




For geometry variable > 0.4 background is dominated by $b \to \mu X$, $\bar{b} \to \mu X$

# $B_s \to \mu\mu$: N-counting experiment

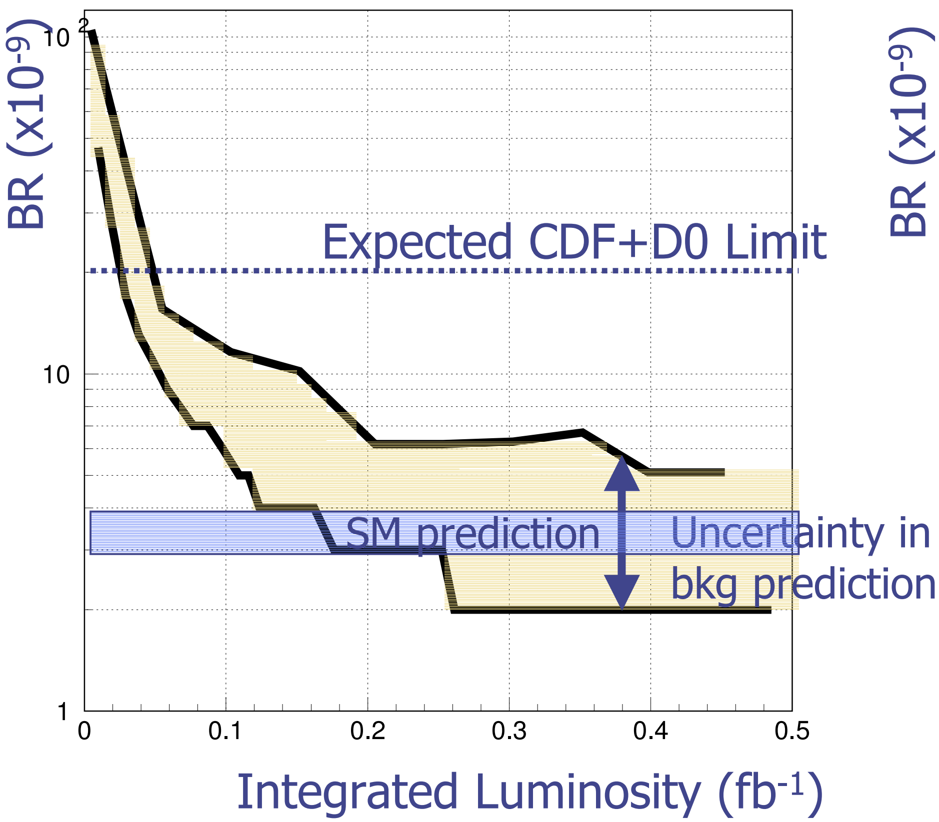
- For example, with a cut on geometry (> 0.4) and invariant mass (± 30 MeV) expect:
  - ~19 signal events per $fb^{-1}$ (SM)
  - [54, 295] background events per $fb^{-1}$ (90% CL)

No cut actually applied in the analysis

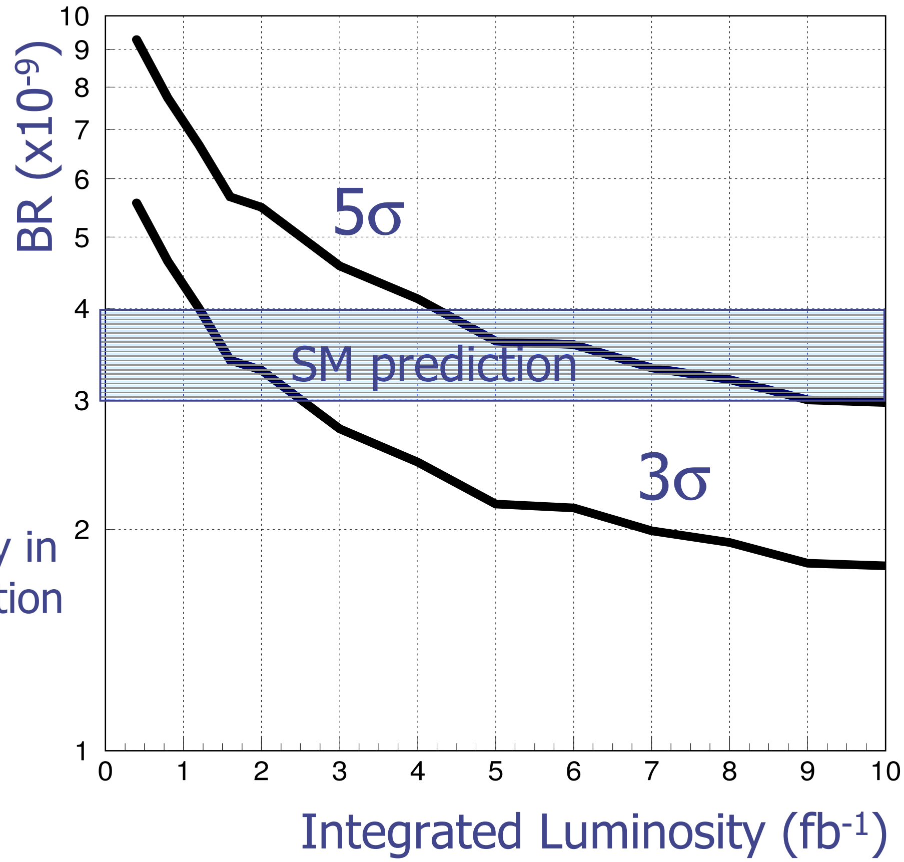
- Better sensitivity from N-counting method
  - Each variable is divided into several bins
    - $b \to \mu^- X$, $\bar{b} \to \mu^+ X$ used to compute expected background in each 3D bin
    - Limited MC statistics → many bins have little or zero background
      - Background is shifted upward in each bin so that total background has 90% probability to be below this value
    - Compute confidence levels for observation and exclusion

# $B_s \to \mu\mu$

Limit at 90% CL *(only bkg is observed)*




LHCb Sensitivity *(signal+bkg is observed)*




- Background assumed to be dominated by combinations of $b \to \mu^- X$ and $\bar{b} \to \mu^+ X$

# Conclusions

- LHCb detector installation nearing completion
  - Global commissioning now taking place
  - Experience in operating RICH system – both in the pit and analysis from testbeams

- $B_d \rightarrow K^*\mu\mu$ exciting channel to study as LHC starts
  - Potential early (new?) physics measurement in $A_{FB}$
  - Potential to measure other angular correlations with more data
  - Expect 7200 events per year (2 $fb^{-1}$) with B/S = 0.24 ± 0.04
  - Sensitivity to zero-point of $A_{FB}$ is ± 0.5 $GeV^2$ with 2 $fb^{-1}$
    - With 10 $fb^{-1}$ (~5 years), expect sensitivity of ± 0.3 $GeV^2$

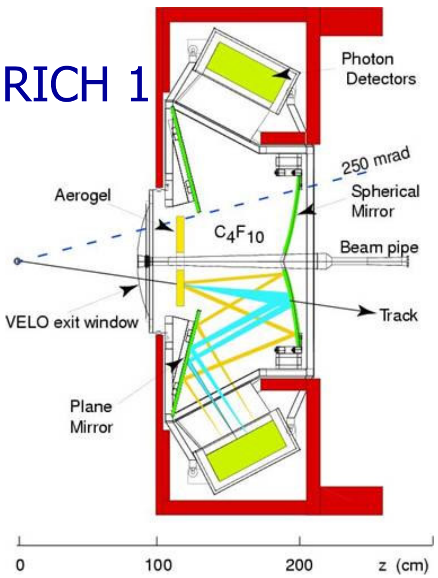
- $B_s \rightarrow \mu\mu$: potential for $3\sigma$ observation down to SM branching ratio with ~ 1 year data

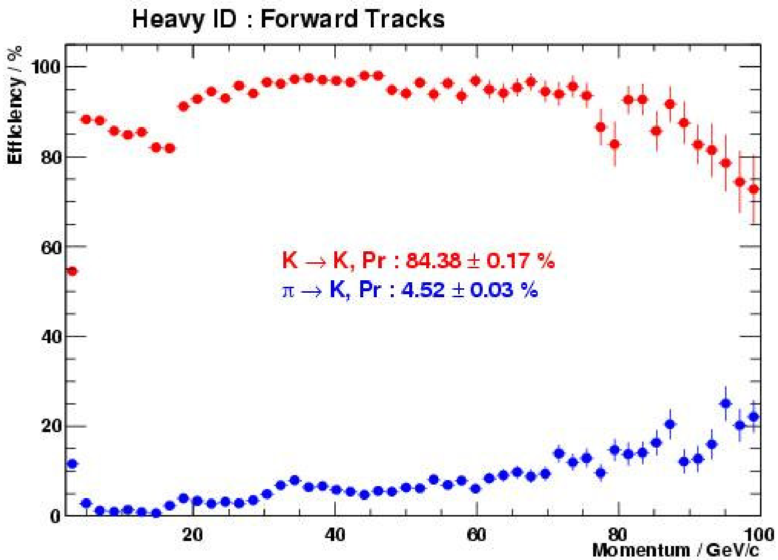
# SPARE

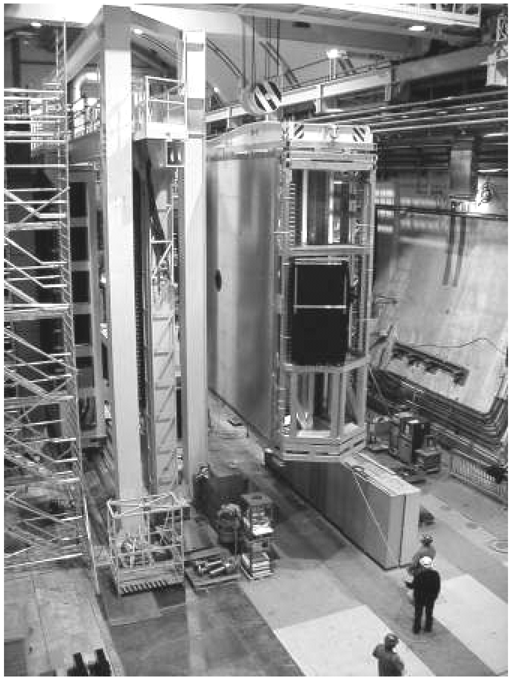
# RICH Detectors

- RICH 1 has aerogel and $C_4F_{10}$ radiators
  - Provides K – π separation over the range 2 – 60 GeV/c
- RICH 2 has $CF_4$ radiator
  - Provides K – π separation over the range 20 – 100 GeV/c

RICH 1



- Current-Current operators :

$$\mathcal{O}_1 = (\bar{s}_\alpha \gamma_\mu P_L c_\beta)(\bar{c}_\beta \gamma^\mu P_L b_\alpha) \quad \mathcal{O}_1^{(u)} = (\bar{s}_\alpha \gamma_\mu P_L u_\beta)(\bar{u}_\beta \gamma^\mu P_L b_\alpha)$$
$$\mathcal{O}_2 = (\bar{s}_\alpha \gamma_\mu P_L c_\alpha)(\bar{c}_\beta \gamma^\mu P_L b_\beta) \quad \mathcal{O}_2^{(u)} = (\bar{s}_\alpha \gamma_\mu P_L u_\alpha)(\bar{u}_\beta \gamma^\mu P_L b_\beta), \tag{1.10}$$

for the example of $b \to c\bar{c}s$ and $b \to u\bar{u}s$ transitions, where, in these and the following equations, $P_{L,R}$ are the chiral projection operators $(\frac{1}{2}(1 \mp \gamma_5))$ and $\alpha$, $\beta$ denote the quark colour indices.

- *QCD* penguin operators :

$$\begin{aligned}
\mathcal{O}_3 &= (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_L q_\beta) \\
\mathcal{O}_4 &= (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_L q_\alpha) \\
\mathcal{O}_5 &= (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_R q_\beta) \\
\mathcal{O}_6 &= (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_R q_\alpha),
\end{aligned} \tag{1}$$

where the quark current from the gluon has been decomposed into a $(V - A)$ and a $(V + A)$ part.

- Electroweak penguin operators :

$$\begin{aligned}
\mathcal{O}_7 &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} e_q(\bar{q}_\beta \gamma^\mu P_R q_\beta) \\
\mathcal{O}_8 &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} e_q(\bar{q}_\beta \gamma^\mu P_R q_\alpha) \\
\mathcal{O}_9 &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} e_q(\bar{q}_\beta \gamma^\mu P_L q_\beta) \\
\mathcal{O}_{10} &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} e_q(\bar{q}_\beta \gamma^\mu P_L q_\alpha)
\end{aligned} \tag{1.12}$$

- Magnetic penguin operators :

$$\begin{aligned}
\mathcal{O}_{7\gamma} &= \frac{e}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_b P_R) b_\alpha F^{\mu\nu} \\
\mathcal{O}_{8g} &= \frac{g_s}{16\pi^2} \bar{s}_\alpha T^a_{\alpha\beta} \sigma_{\mu\nu} (m_b P_R) b_\beta G^{a\mu\nu},
\end{aligned} \tag{1.13}$$

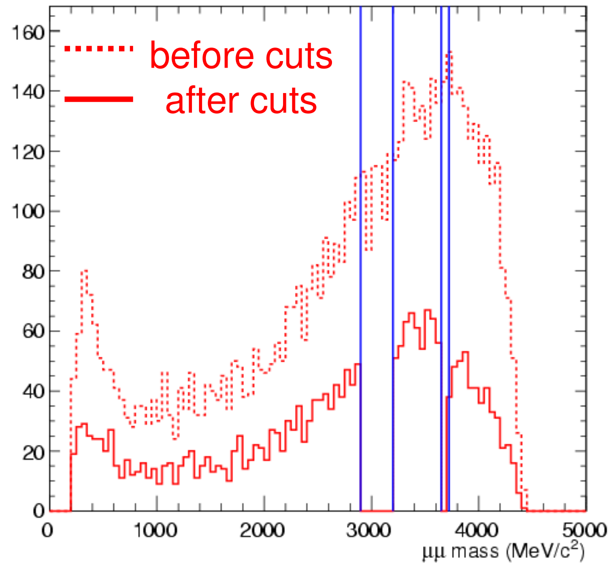
where the mass of the s-quark has been neglected in comparison with the mass of b-quark [27, 28].

- Semi-leptonic operators :

$$\begin{aligned}
\mathcal{O}_{9V} &= \frac{e}{16\pi^2}(\bar{s}_\alpha \gamma^\mu P_L b_\alpha)(\bar{\ell}\gamma_\mu \ell) \\
\mathcal{O}_{10A} &= \frac{e}{16\pi^2}(\bar{s}_\alpha \gamma^\mu P_L b_\alpha)(\bar{\ell}\gamma_\mu \gamma_5 \ell),
\end{aligned} \tag{1.14}$$

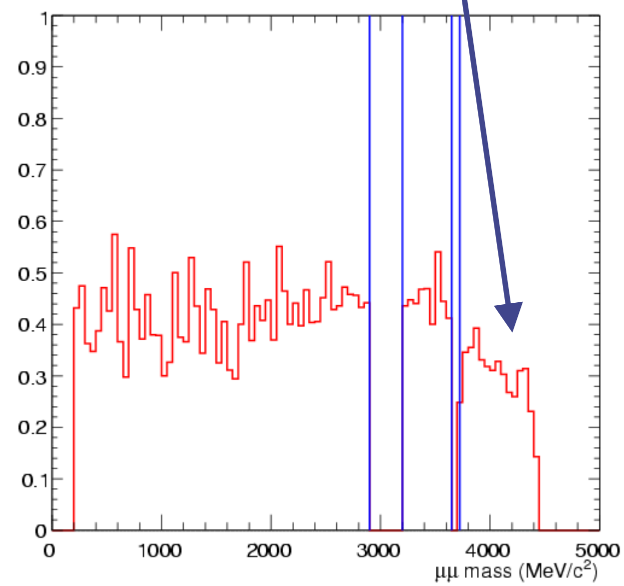
where the lepton pair are produced in a vector and axial-vector state respectively.

# $\mu\mu$ mass distribution




Ratio of plots on the left

Fall off in efficiency at high $M_{\mu\mu}$ is mainly from the K, $\pi$ sIPS cuts



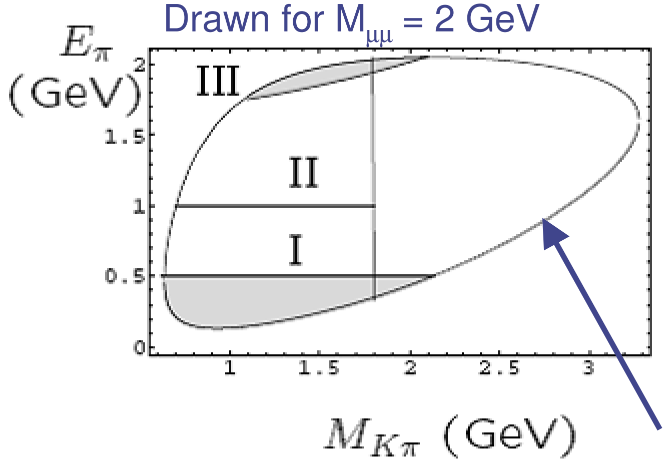

- Selection slightly favors low $\mu\mu$ mass
  - This is where the SM zero of the FBA lies

# $B_d \rightarrow K^*\mu\mu$: Non-resonant events

- Simulation of these events is currently Jetset fragmentation
  - Spectra and rate are very uncertain!
  - LHCb simulation uses $BR(B_d \rightarrow K\pi\mu\mu) = 1 \times 10^{-6}$ in full mass range
    - Probably an overestimate – rate estimated from BR() limit from BaBar
    - Gives non-resonant background of 1730 ± 75 events per 2 $fb^{-1}$
- Identical from a selection point of view, but without the $K^*$ mass constraint
- For FBA, can be treated as signal, under certain conditions…

(hep-ph/0505155)

Drawn for $M_{\mu\mu}$ = 2 GeV




Defined by kinematics

- Region I: soft pion, energetic kaon
  - Shifts zero of FBA and larger theory errors
- Region II: energetic $K\pi$ pair
  - Can be treated as $B \rightarrow X\mu\mu$ and $X \rightarrow K\pi$
- Region III: soft kaon, energetic pion
  - Amplitude suppressed so very few events…

# $B_d \to K^*\mu\mu$: Non-resonant events

- Simulation of these events is currently Jetset fragmentation
  - Spectra and rate are very uncertain!
  - LHCb simulation uses $BR(B_d \to K\pi\mu\mu) = 1 \times 10^{-6}$ in full mass range
    - Probably an overestimate – rate estimated from BR() limit from BaBar
    - Gives non-resonant background of 1730 ± 75 events per 2 $fb^{-1}$
- Identical from a selection point of view, but without the $K^*$ mass constraint
- For FBA, can be treated as signal, under certain conditions…

(hep-ph/0505155)

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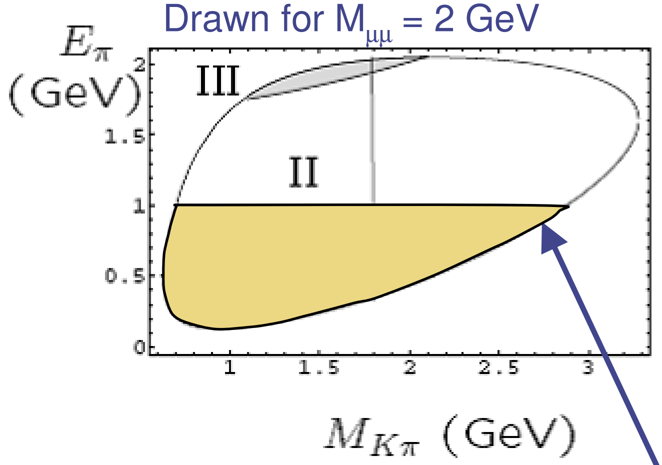


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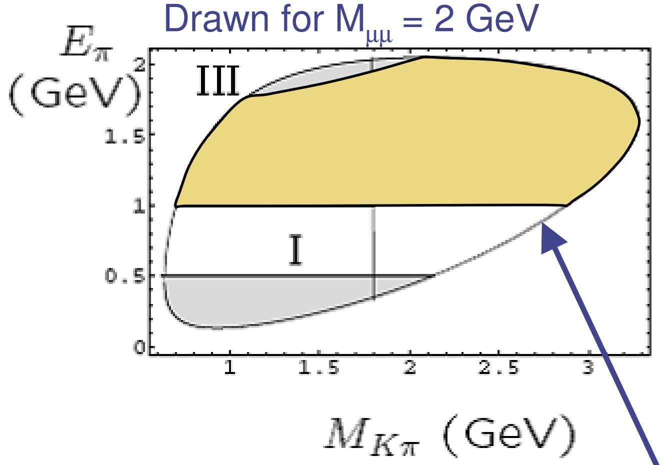


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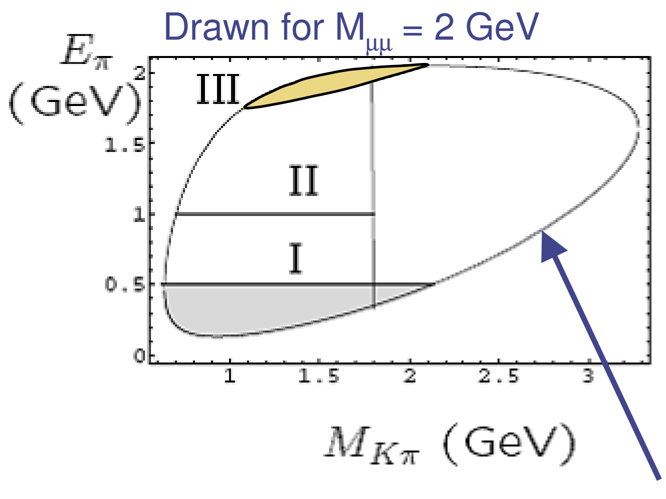


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# Decay Distributions

Work in progress!

- Imagine for time being, everything is just a function of momentum:
  - Number of events selected depends on underlying "generated" distribution and the efficiency function, integrated over some momentum range…

$$\#Sel\left(P_{K^*}\right) = \iint \varepsilon\left(P_{K^*}, P_{\mu_1}, P_{\mu_2}\right) f\left(P_{K^*}, P_{\mu_1}, P_{\mu_2}\right) dP_{\mu_1} dP_{\mu_2}$$

$$\varepsilon\left(P_{K^*}\right)\varepsilon\left(P_{\mu_1}\right)\varepsilon\left(P_{\mu_2}\right)$$

True underlying distribution

$$\#Sel\left(P_{K^*}\right) \approx \iint \varepsilon\left(P_{K^*}\right)\varepsilon\left(P_{\mu_1}\right)\varepsilon\left(P_{\mu_2}\right) f\left(P_{K^*}, P_{\mu_1}, P_{\mu_2}\right) dP_{\mu_1} dP_{\mu_2}$$

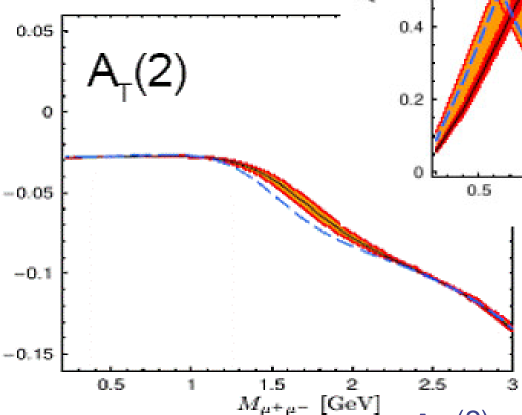
$$\#Sel\left(P_{\mu_1}\right) \approx \iint \varepsilon\left(P_{K^*}\right)\varepsilon\left(P_{\mu_1}\right)\varepsilon\left(P_{\mu_2}\right) f\left(P_{K^*}, P_{\mu_1}, P_{\mu_2}\right) dP_{K^*} dP_{\mu_2}$$

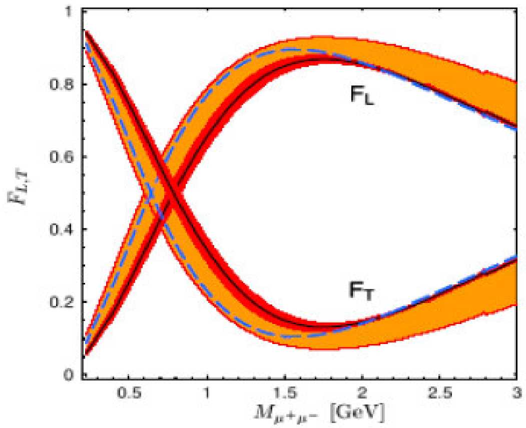
$$\#Sel\left(P_{\mu_2}\right) \approx \iint \varepsilon\left(P_{K^*}\right)\varepsilon\left(P_{\mu_1}\right)\varepsilon\left(P_{\mu_2}\right) f\left(P_{K^*}, P_{\mu_1}, P_{\mu_2}\right) dP_{K^*} dP_{\mu_1}$$

- Initially, just consider as a function of P – later include $\theta$ (equivalently $p_T$)
- Will use MC to check factorisation step

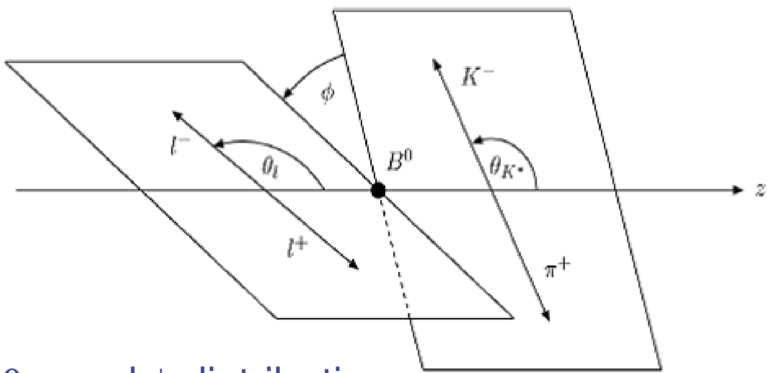
# $B_d \to K^*\mu\mu$: Transversity angles

- Recent theoretical work has highlighted other asymmetries to study (Phys Rev D71: 094009, 2500)
- Describe the decay in terms of 4 parameters
  - $s = \mu\mu$ mass squared
  - $\theta_l$ = FBA angle (between $\mu$ and B in $\mu\mu$ rest-frame)
  - $\theta_{K*}$ = equivalent $K^*$ angle (between K and B in $K^*$ rest-frame)
  - $\phi$ = angle between $K^*$ and $\mu\mu$ decay planes




$$d^4\Gamma = \frac{9}{32\pi} I(s, \theta_l, \theta_{K^*}, \phi) ds\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi$$



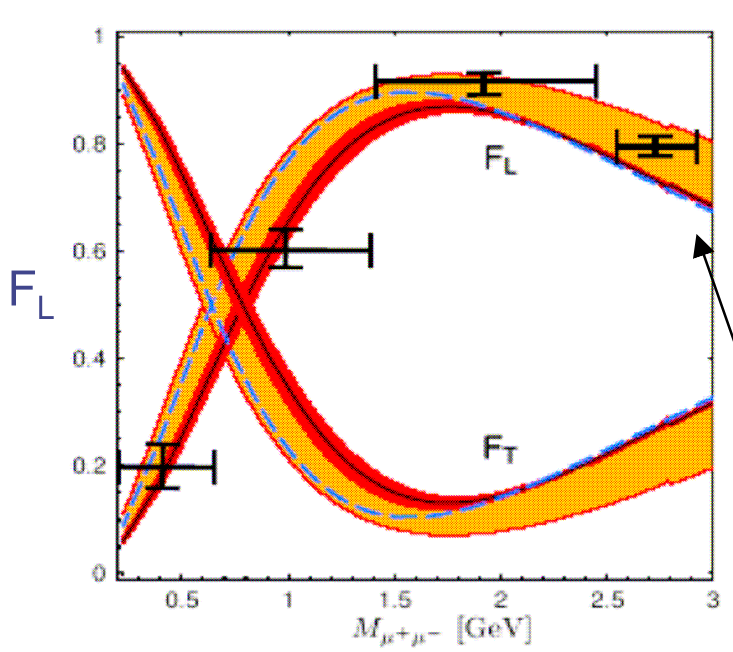

$F_L$ extracted from $\theta_l$, $\theta_{K^*}$ and $\phi$ distributions

$A_T^{(2)}$ extracted from $\theta_{K^*}$ and $\phi$ distributions

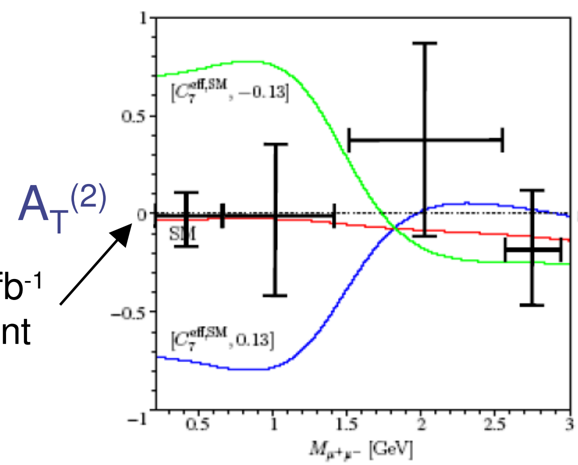
# $B_d \to K^*\mu\mu$: Transversity angles

- Toy MC created to describe $\theta_l$, $\theta_{K*}$ and $\phi$ distributions
  - SM predictions used as input values
    - Inputs are averaged (weighted by cross-section in each bin)
  - Background distributions added (without non-resonant component)
  - Analysis performed in 4 bins of s ($0 < s < 9$ GeV$^2$)

| $M_{\mu\mu}^2$ range | Resolutions | |
|---|---|---|
| | $A_T^{(2)}$ | $F_L$ |
| $0.05 \to 0.49$ | 0.180 | 0.037 |
| $0.49 \to 1.96$ | 0.400 | 0.033 |
| $1.96 \to 6.25$ | 0.470 | 0.018 |
| $6.25 \to 9.0$ | 0.31 | 0.020 |

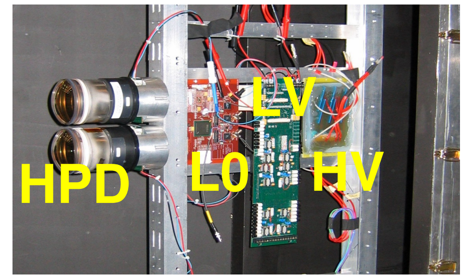


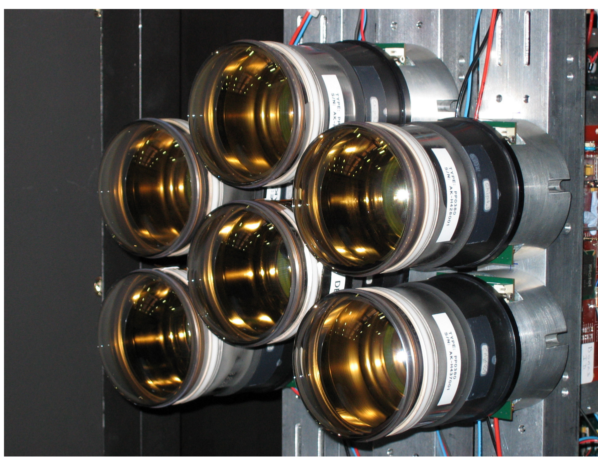

A possible 2fb$^{-1}$ measurement

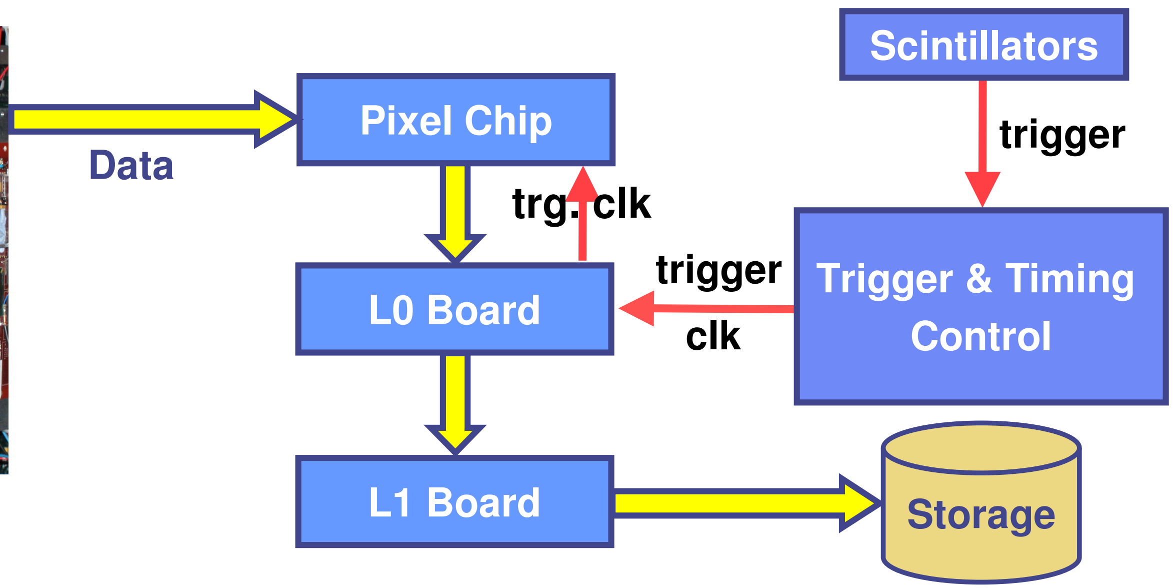


# RICH Testbeam Electronics

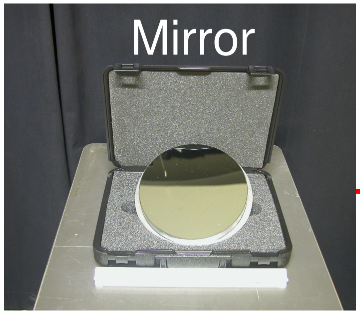
- Test of 6 prototype HPDs in close packed array
  (Final LHCb experiment has 484 HPDs)
- ~2 weeks beam time in Oct / Nov 2004
  - 10 GeV mixed $\pi$ / e beam
- Test of full on-detector readout chain
  - Prototype off-detector electronics

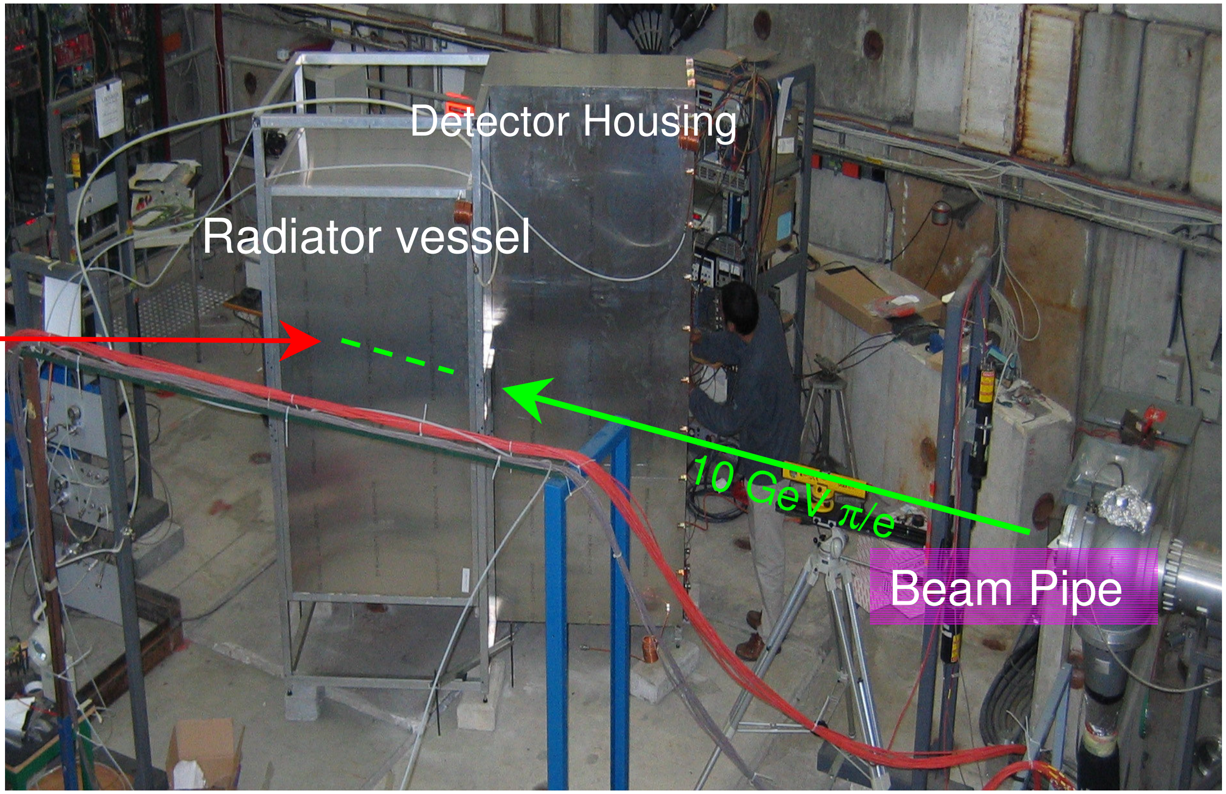




# RICH Testbeam Setup

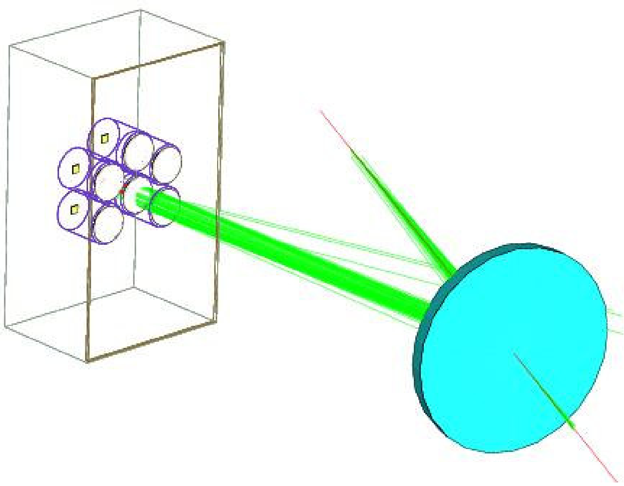


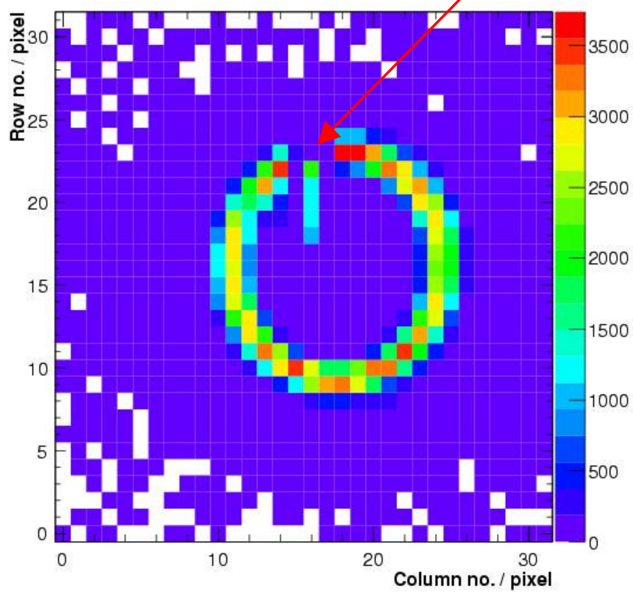

- Detector and mirror laser aligned to beam line
- Choice of $N_2$ or $C_4F_{10}$ radiators
  - Focus on $N_2$ – rings fully contained in one HPD
- Trigger from scintillators in beam line $\rightarrow$ asynchronous to 25ns clock
  - Photon counting made much more complicated…

# RICH Testbeam – some rings

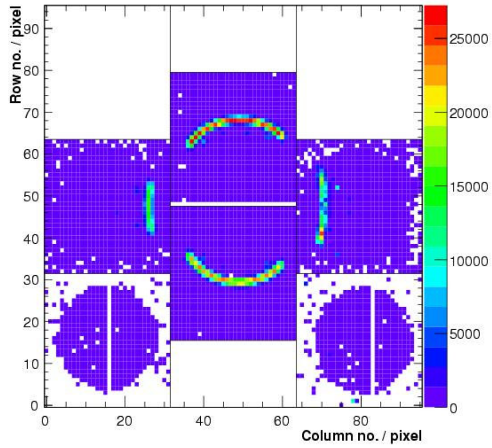
- Low intensity beam → negligible probability of multiple particle events
- Majority of analysis based on $N_2$ runs:
  - Rings fully contained in one HPD → relative alignment unnecessary
  - Typically ~7 photons per event with ~30k events per run



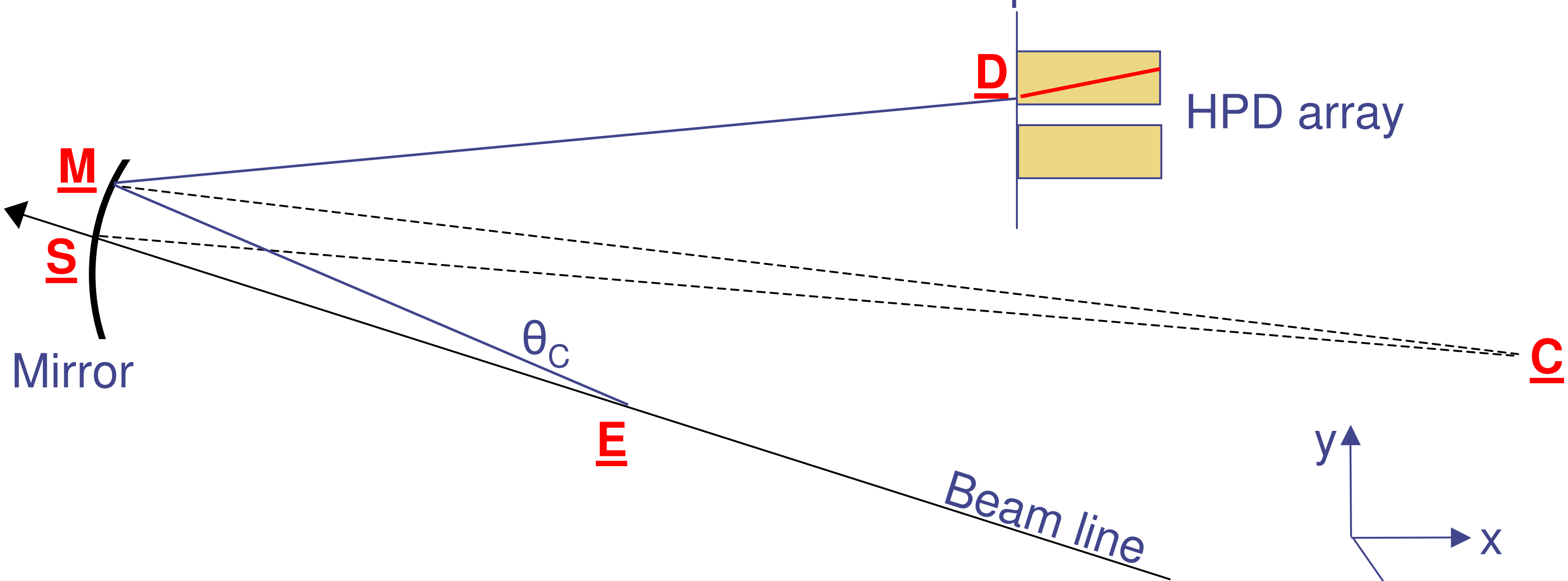
Readout problem on these 3 columns




- $C_4F_{10}$ rings spread over 3 or 4 HPDs

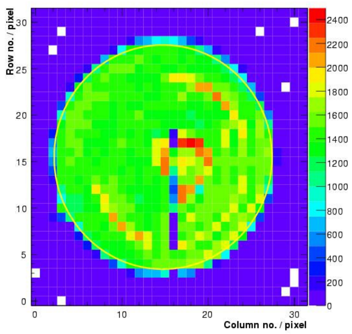


# Cherenkov Angle reconstruction (1)

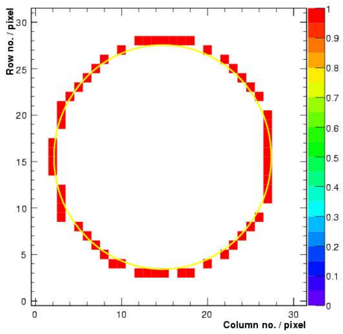



- Unfold effect of HPD electron optics
  - Demagnification factor ~5 & cross focussing

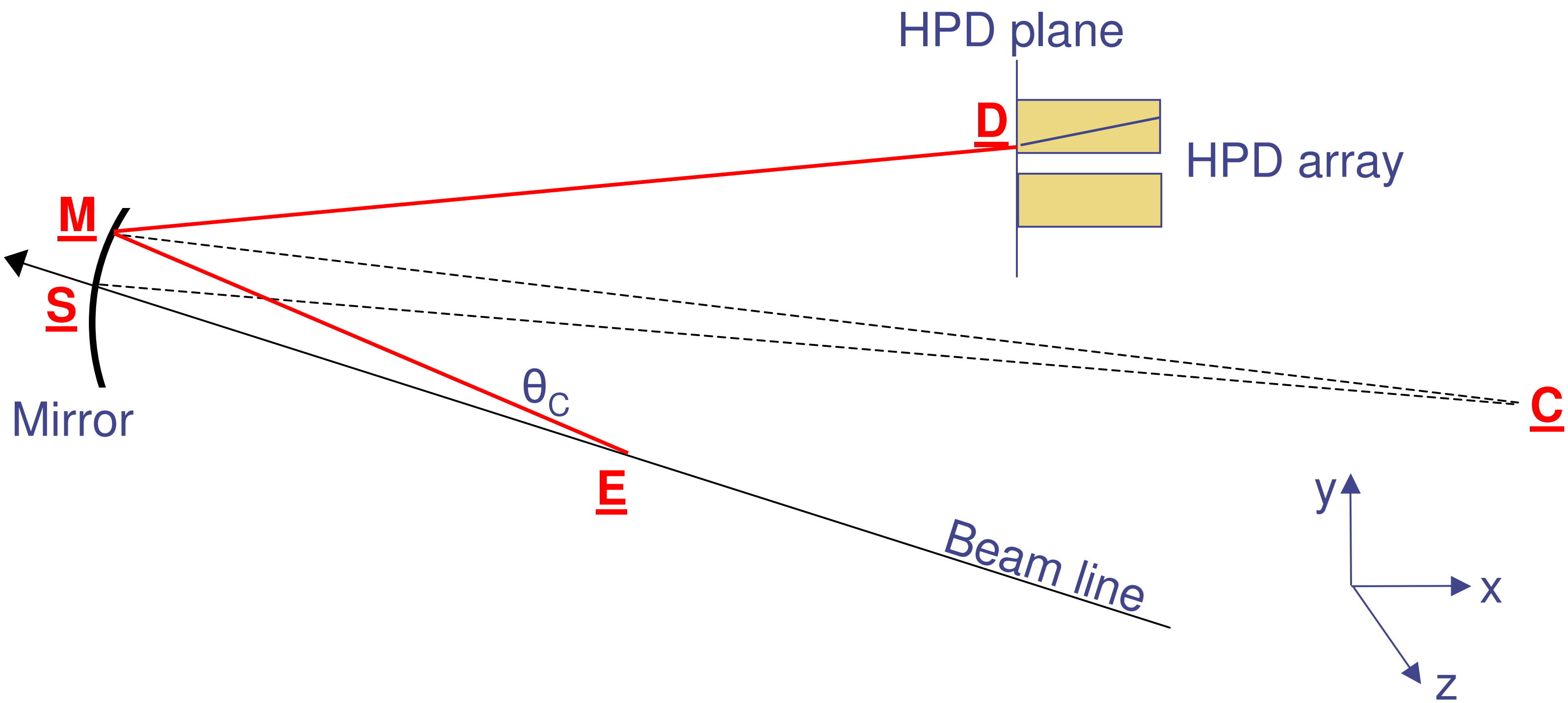
LED image




Edge finding to extract chip offsets

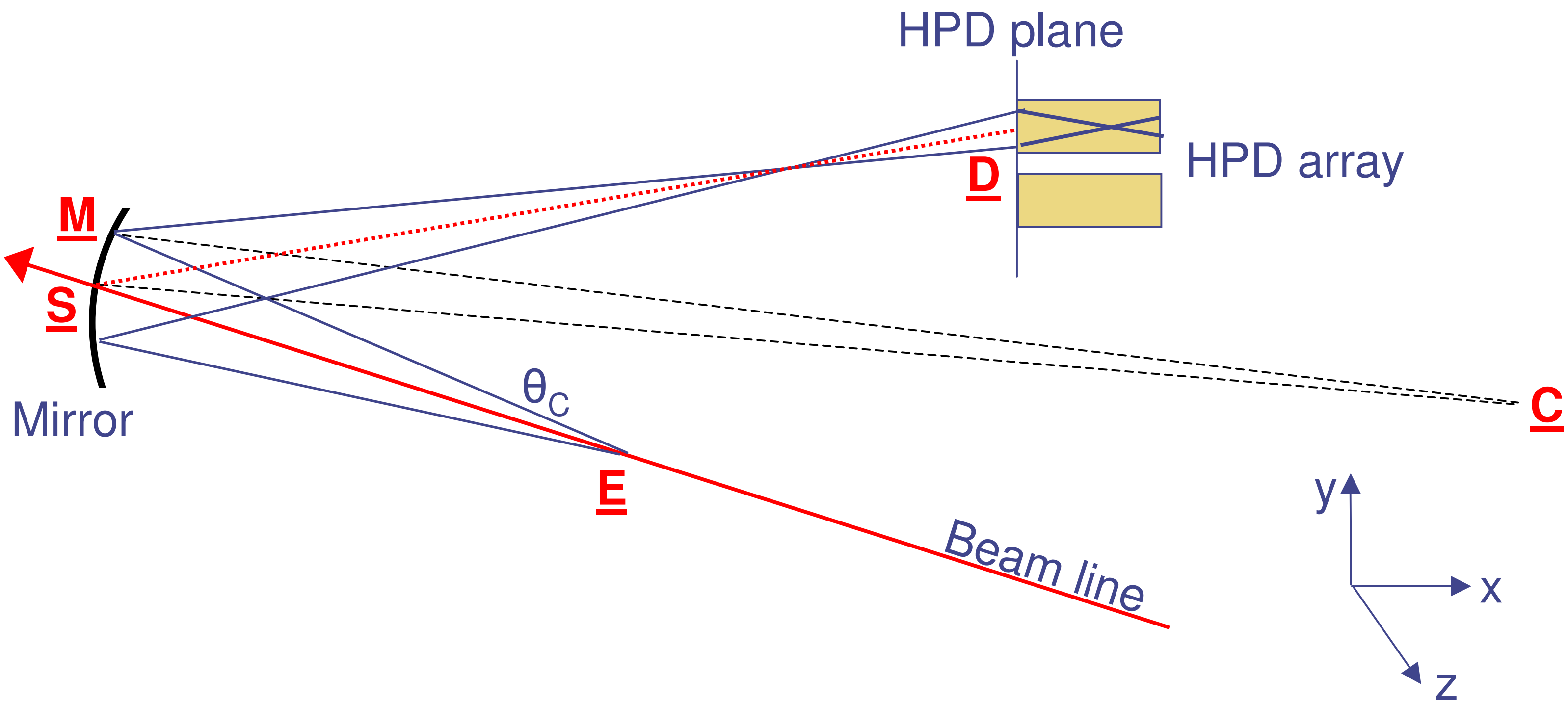


# Cherenkov Angle reconstruction (2)



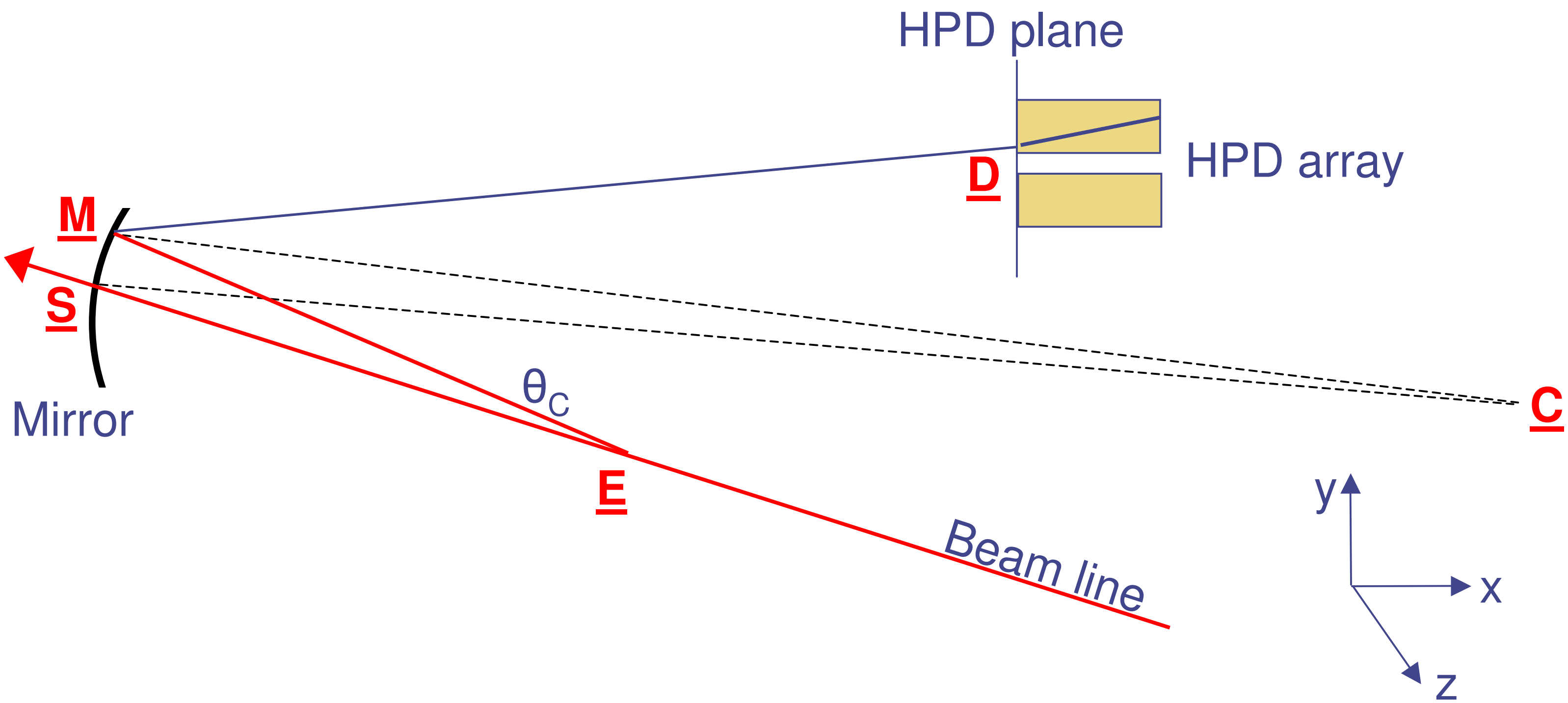

- Solve mirror optic equations
  - Assume emission point half way along radiator length
  - Mirror tilt (defined by **S** and **C**) aligned to match data

# Cherenkov Angle reconstruction (3)




- Fit circle to hits on detector plane
  - Centre of fitted circle is "reflected" beam position
  - Now solve mirror optics to calculate beam direction

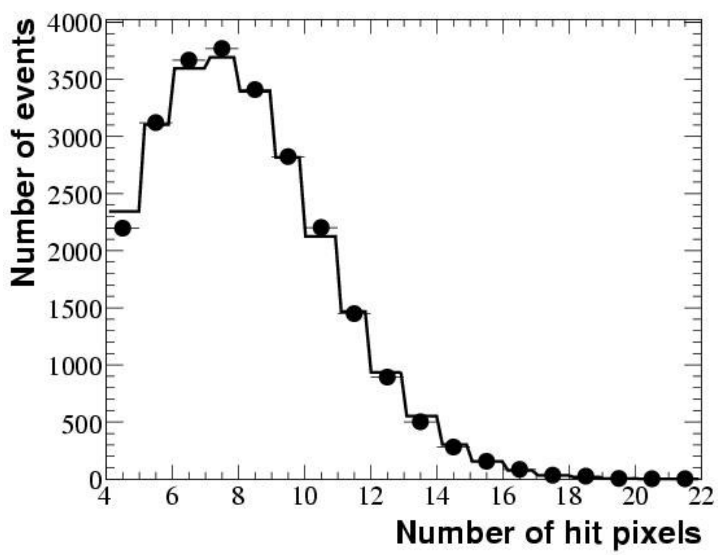
# Cherenkov Angle reconstruction (4)

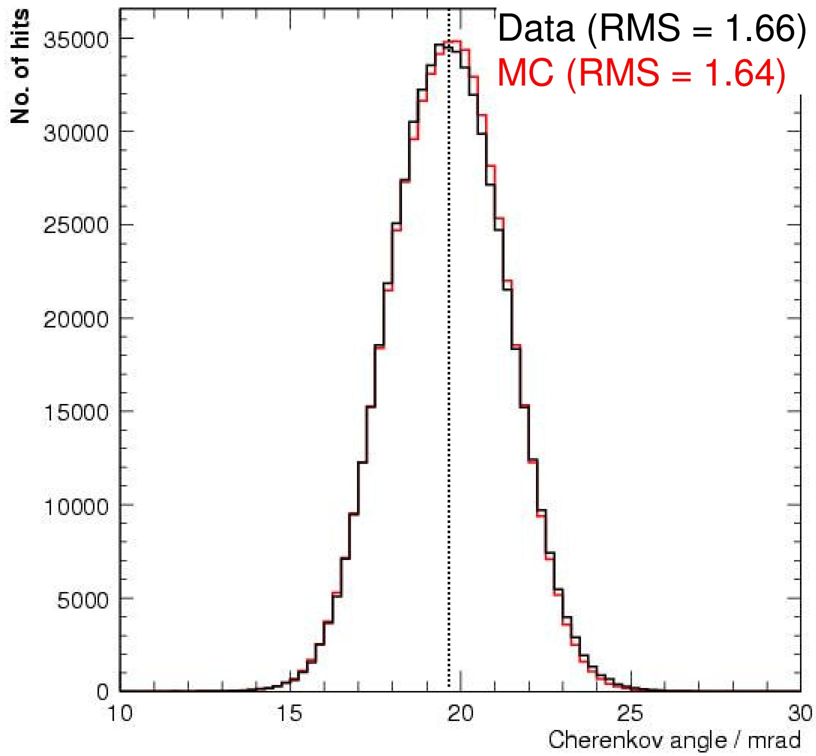



- Cherenkov angle is angle between photon and beam directions
  - Decouple photon and beam reconstruction by fitting circle only to other hits in the event

# RICH Testbeam – Cherenkov angle

- Reconstructed Cherenkov angle for data and MC:
  - Mean angle 19.64 mrad
    - Expected ~ 19.5 mrad
  - Data / MC RMS in good agreement
- #hits also in good agreement



# RICH Testbeam - Resolution

<table>
<tr><td colspan="3">Chromatic Effect</td><td>0.41</td><td rowspan="10">1.65</td></tr>
<tr><td colspan="3">Photon Reconstruction</td><td rowspan="9">1.59</td></tr>
<tr><td>Pixelisation</td><td>0.78</td><td rowspan="3">1.28</td></tr>
<tr><td>HPD psf</td><td>1.00</td></tr>
<tr><td>Emission (effect & error)</td><td>0.19</td></tr>
<tr><td colspan="3">Beam Reconstruction</td></tr>
<tr><td>Pixelisation</td><td>0.49</td><td rowspan="3">0.97</td></tr>
<tr><td>HPD psf</td><td>0.63</td></tr>
<tr><td>Intrinsic beam (emission point and beam divergence)</td><td>0.52</td></tr>
<tr><td colspan="3">TOTAL (All in mrad)</td></tr>
</table>

- Good agreement with value from full MC simulation (1.64 mrad) and data (1.66 mrad)
  - Systematic errors ~ 0.03 mrad
  - Statistical errors negligible