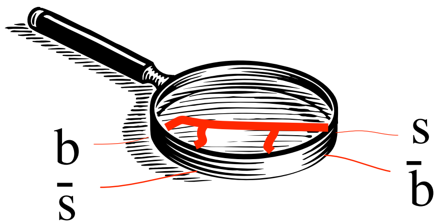
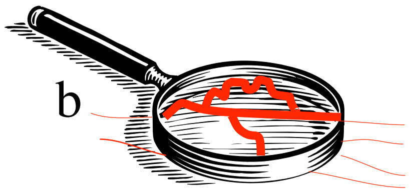
Thanks to M. Smizanska (ATLAS), T. Speer and M. Spiropulu (CMS)

Flavour Physics at LHC





3nd Workshop on Flavour in the era of LHC
15.5-17.5, 2006

Tatsuya Nakada
CERN and EPFL

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Introduction

Flavour physics with B mesons

- Test the CKM picture within the Standard Model framework

  fantastic success by the both B factories, BABAR and BELLE
  and by the Standard Model, which is much more than just a model!

- Recent addition

  CDF observed B_s-$\overline{B}_s$ oscillation with ~3σ significance

  Δm_s with 1σ error is $17.33\,^{+0.42}_{-0.21}$ (stat) ± 0.07 (syst) ps

  a similar but less significant result from D0

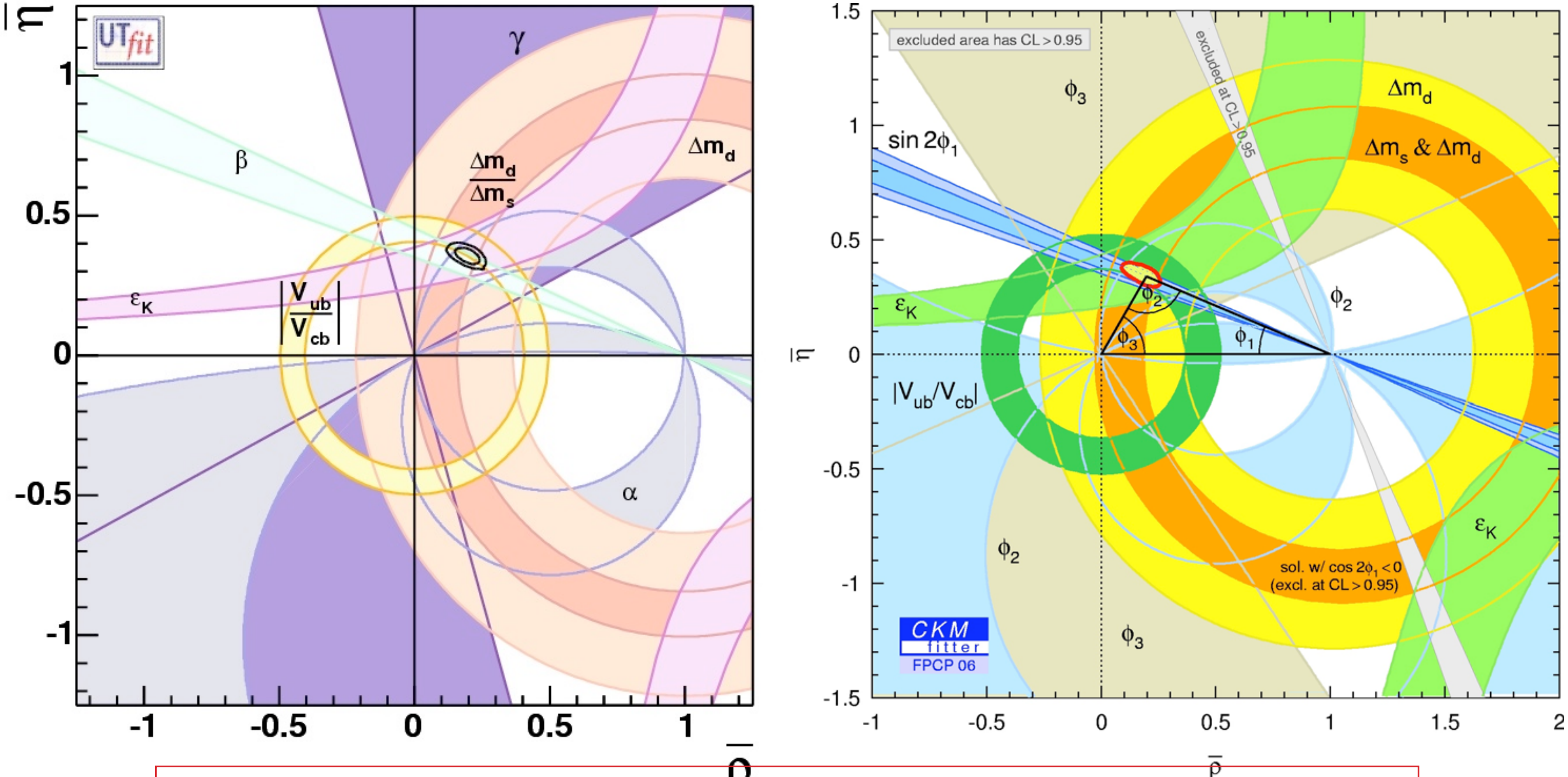
  BELLE observed $B \to \tau\nu$ with a significance of 4.2σ

  $Br = [1.06\,^{+0.34}_{-0.28}\,(\text{stat})\,^{+0.18}_{-0.60}\,(\text{syst})\,] \times 10^{-4}$

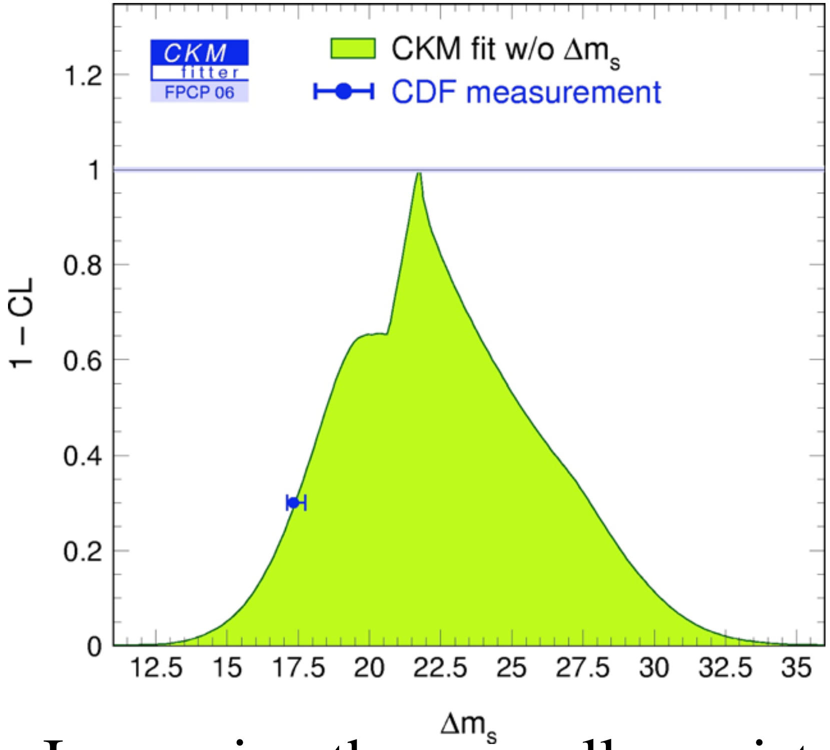
very good agreement with the SM predictions

NB A single experiment observing B_s-$\overline{B}_s$ oscillations
with >5σ significance still needed:
one of the first goals of LHCb in 2008 vs. CDF/D0

Global CKM fit now



$\Delta m_d / \Delta m_s$ reduced the errors on $(1-\rho)^2+\eta^2$ to that of $\rho^2+\eta^2$



Some people mumble (or shout) about:

1) slight inconsistency between $|V_{ub}/V_{cb}|$ and sin 2β

2) measured Δm_s is smaller than the expectation

They require improvements in theory...

Improving the over all consistency test of CKM should still be pursued

-tree only determination of CKM

$|V_{ub}/V_{cb}|$ + γ (B→DK and $B_s \to D_sK$)

σ(γ) should be reduced by at least ~5 to be comparable

further improvement on $|V_{ub}/V_{cb}|$

-β and γ with penguin contributions

$B \to \phi K_s$, ηK_s etc, $B_s \to \phi\phi$, $B \to \pi\pi + B_s \to KK$, etc.

LHC can contributes

And improve **promising measurements** where the current errors are too large to be interesting

- phase of B_s-$\overline{B}_s$ oscillation amplitude ϕ_s
  - CP violation in $B_s \to J/\psi\phi$, $\eta_c\phi$ etc.
  - CP violation in B_s-$\overline{B}_s$ oscillations
- Very rare decays
  - B_s (B_d) $\to \mu\mu$
  - $B^{\pm} \to \tau\nu$, $\mu\nu$, $e\nu$
- Lorentz structure of $b \to s+$"γ" ($b \to d+$"γ") amplitude
  - FB asymmetry in $B_d \to K^{*0}\mu\mu$, $\rho^0\mu\mu$, $B_s \to \phi\mu\mu$, $\overline{K}^{*0}\mu\mu$

Is $\Delta b=2$ FCNC always $2\times(\Delta b=1$ FCNC$)$?

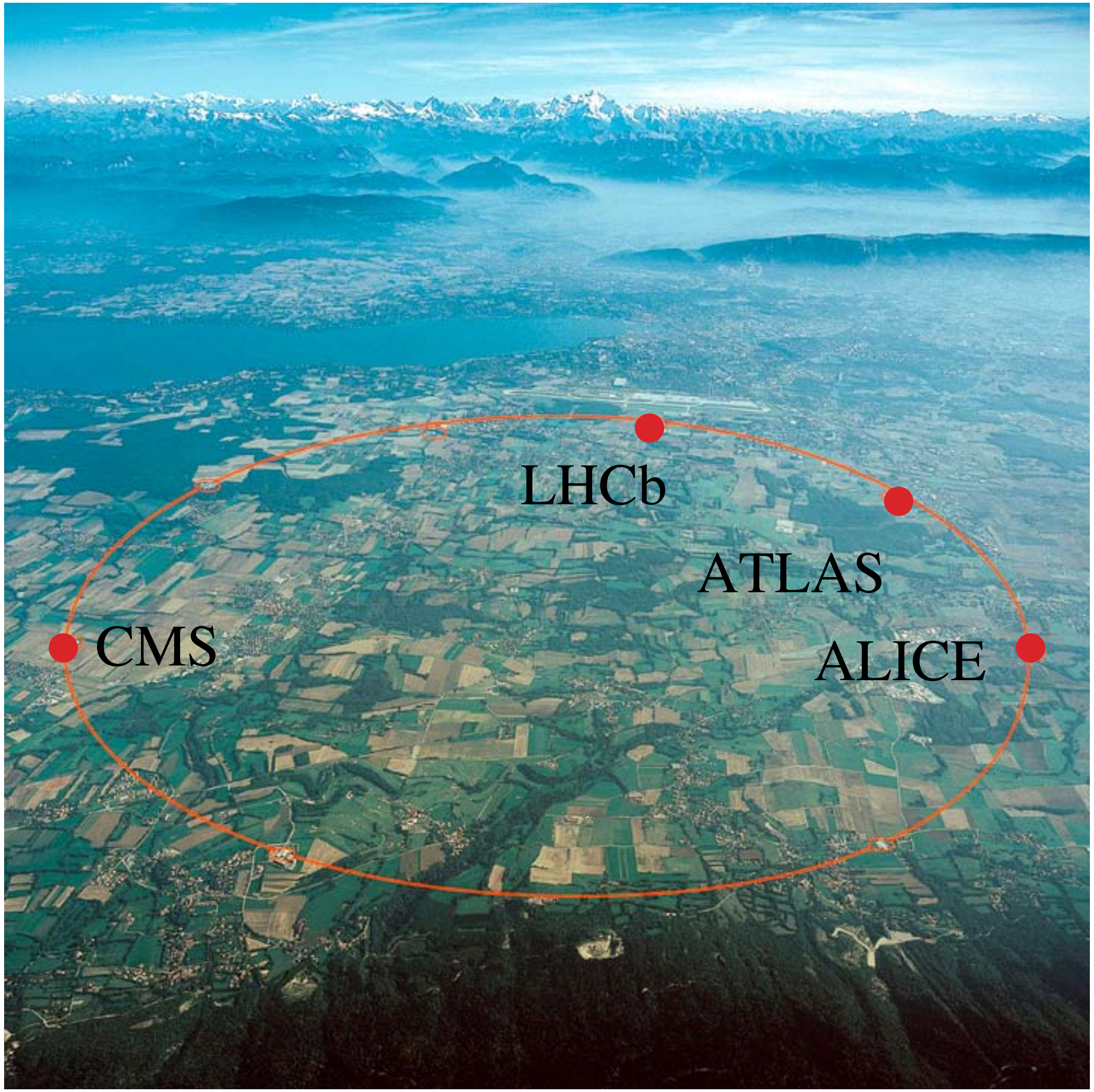
Other interesting physics

- Oscillation and CP violation in D mesons
- lepton number violating tau decays
  - $\tau \to 3\mu$, $\mu\gamma$

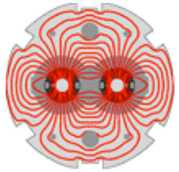
LHC can contributes

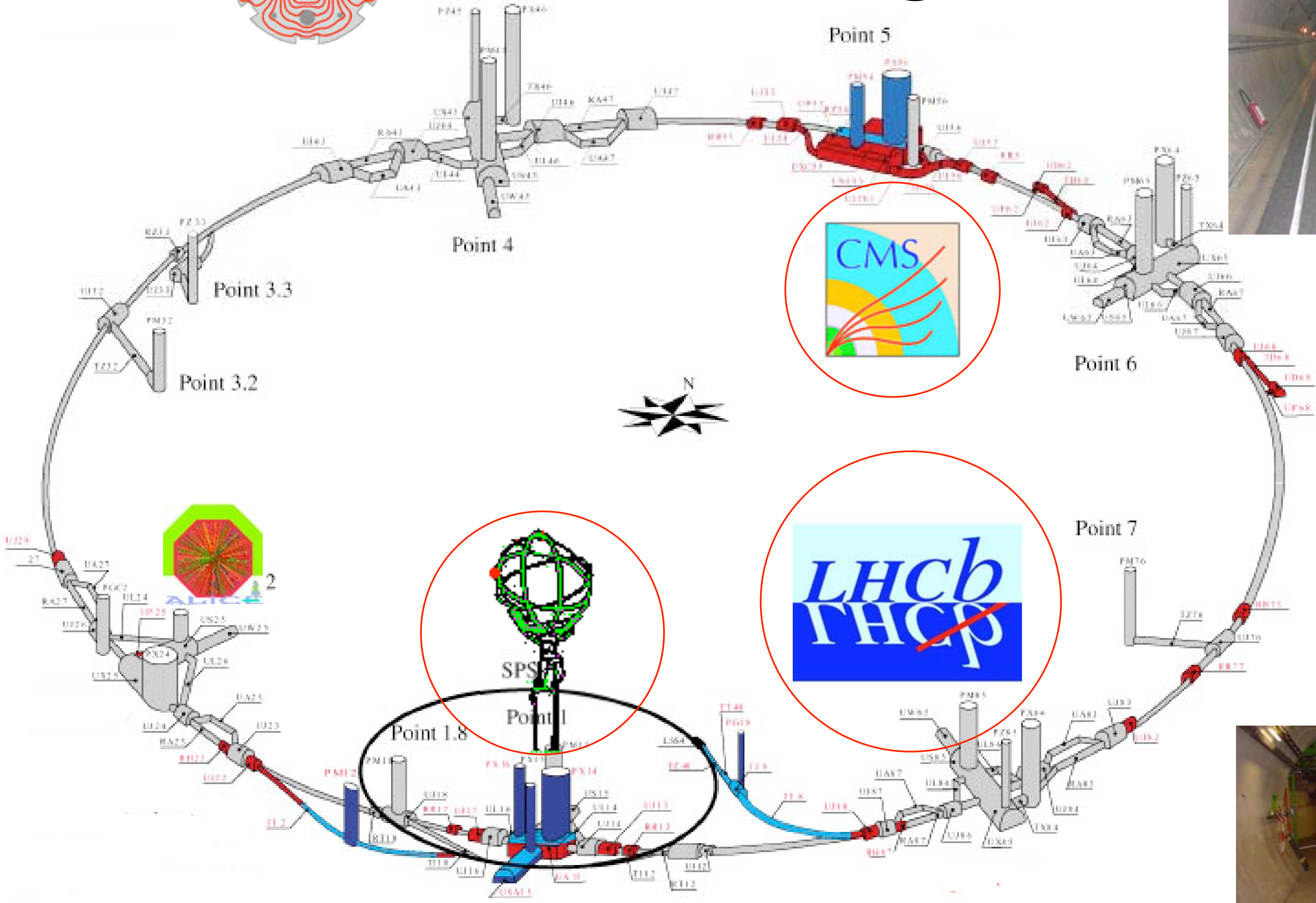
‡B_c and b-baryons are also physics at LHC

CERN and LHC



LHC





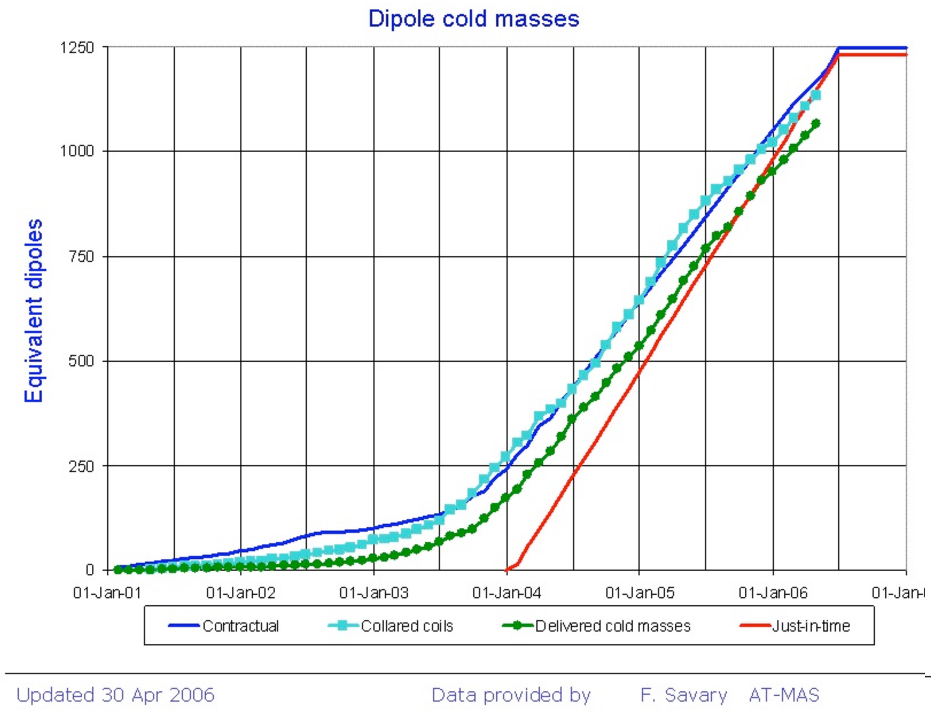
Point 5
Point 4
Point 3.3
Point 3.2
Point 6
Point 7
Point 1.8
Point 1
SPS
N
CMS
LHCb

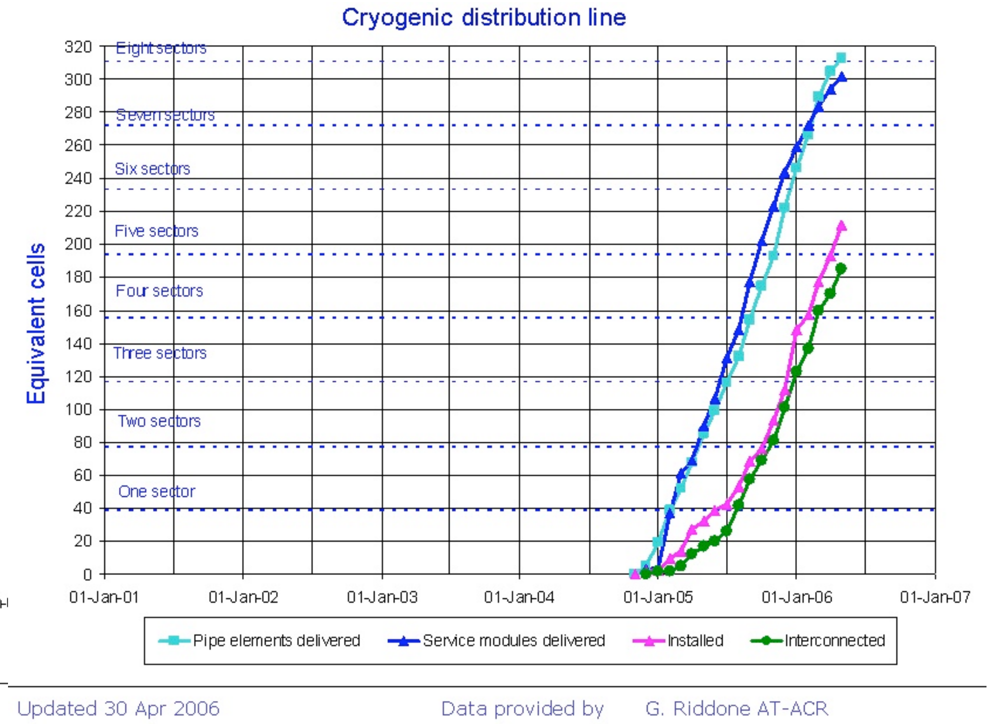
B Physics at LHC + and –

LHC is a b factory! (“b” not “B”)

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEPII, KEKB	$pp \to b\bar{b}X$ ($\sqrt{s}$ = 14 TeV, Δt_{bunch}=25 ns) LHC (LHCb, ATLAS, CMS)	
Production $\sigma_{b\bar{b}}$	1 nb	~500 μb	☺
Typical $b\bar{b}$ rate	10 Hz	100–1000 kHz	
$b\bar{b}$ purity	~1/4	$\sigma_{b\bar{b}}/\sigma_{inel}$ = 0.6% Trigger is a major issue !	☹
Pileup	0	0.5–5	
b-hadron types	B^+B^- (50%) $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s (10%) B_c (< 0.1%), b-baryons (10%)	☺
b-hadron boost	Small	Large (decay vertexes well separated)	
Production vertex	Not reconstructed	Reconstructed (many tracks)	
Neutral B mixing	Coherent $B^0\bar{B}^0$ pair mixing	Incoherent B^0 and B_s mixing (extra flavour-tagging dilution)	☹
Event structure	$B\bar{B}$ pair alone	Many particles not associated with the two b hadrons	

LHC construction is advancing

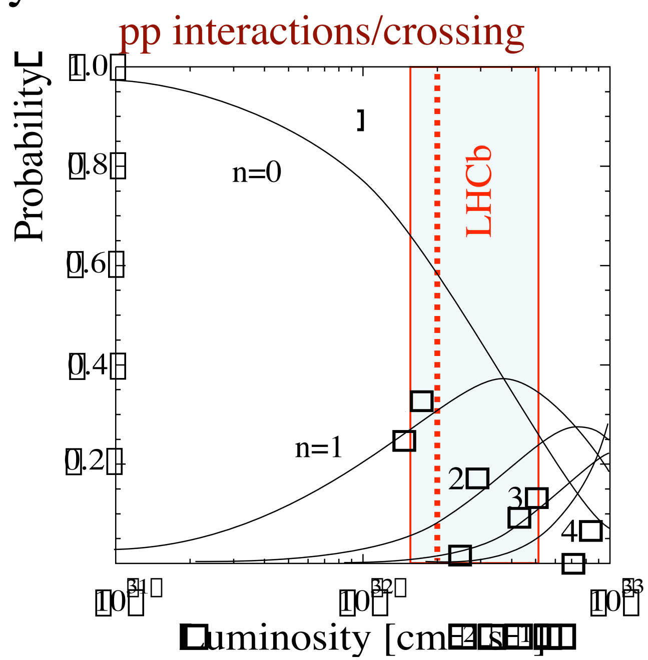


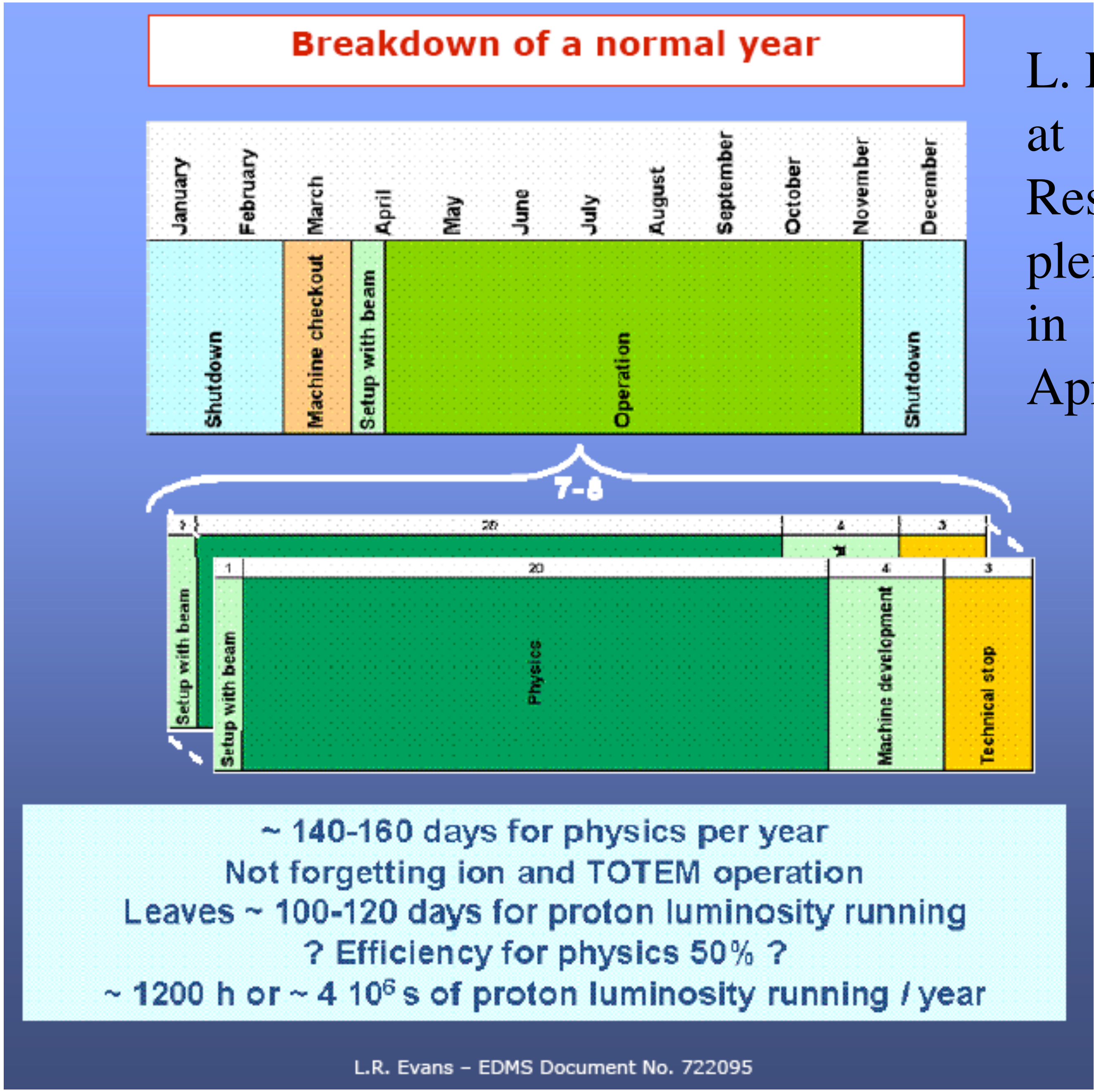


Beam collisions in 2007
New schedule to be released in mid June

Luminosities

- LHC machine, pp collisions at $\sqrt{s}$ = 14 TeV:
  - – design luminosity $L = 10^{34}$ cm^{-2}s^{-1}, bunch crossing rate = 40 MHz
  - – average non-empty bunch crossing rate f = 30–32 MHz
  - – Pileup:
    - n = number of inelastic pp interactions occurring in the same bunch crossing
    - Poisson distribution with mean $\langle n\rangle = L\sigma_{inel}/f$, with σ_{inel}= 80 mb
    - $\langle n\rangle$ = 25 at 10^{34} cm^{-2}s^{-1} → not good for B physics (except $B_s \to \mu\mu$?)
- ATLAS and CMS
  - – B physics in the early stage of the LHC operation ~3 years with $L = 10^{33}$ cm^{-2}s^{-1}
- At LHCb:
  - – L tuneable by adjusting final beam focusing
  - – Choose to $\langle L\rangle \sim 2\times10^{32}$ cm^{-2}s^{-1} (max. ~5×10^{32})
    - Clean environment: $\langle n\rangle$=0.5
    - Less radiation damage
    - Will be available from "first" physics run
- A "standard" year
  - – In one "nominal year" = 10^7 s:
    - At LHCb 2 fb^{-1} of data, 10^{12} bb pairs produced
    - At ATLAS/CMS 10 fb^{-1} of data





L. Evans talk at Resource Review Board plenary meeting in April 06

half of the "normal year" so far assumed

A committee has been set up to discuss running scenarios for the first several years of the LHC operation:

machine experts + experiments + theoreticians

to optimise the LHC physics output

2007 detector alignment and calibration
possibly a J/ψ signal?

Then..., my personal wish, guess, etc. for LHCb

2008: 0.5 fb^{-1} (25 % of the original "nominal" year)
2009: 1.0 fb^{-1}
2010: 1.5 fb^{-1}

i.e. ~3 fb^{-1} by the end of 2010
(required average luminosity $\sim 2\times 10^{32}$ $cm^{-1}s^{-1}$ is OK...)

rather than 3×2 fb^{-1} $= 6$ fb^{-1}

Reconstructable final states

Reconstruction of B **decay vertex with a good resolution** is essential to **reduce combinatorial background**:

decay vertex: >1 well reconstructed tracks

well reconstructed track =

- charged particle seen by vertex detector
- reconstructed particle from tracks measured by vertex detector

$D^0(\to K^-\pi^+)$, $D_s(K^+K^-\pi^+)$, etc.

examples are

$B_{(s)}{}^0 \to l^+l^-$, h^+h^-, ..., $B_s{}^0 \to \overline{D}_s(\to K^+K^-\pi^-)\,\pi^+$

π^0 and γ may be **associated** to a reconstructed vertex (if not too many)

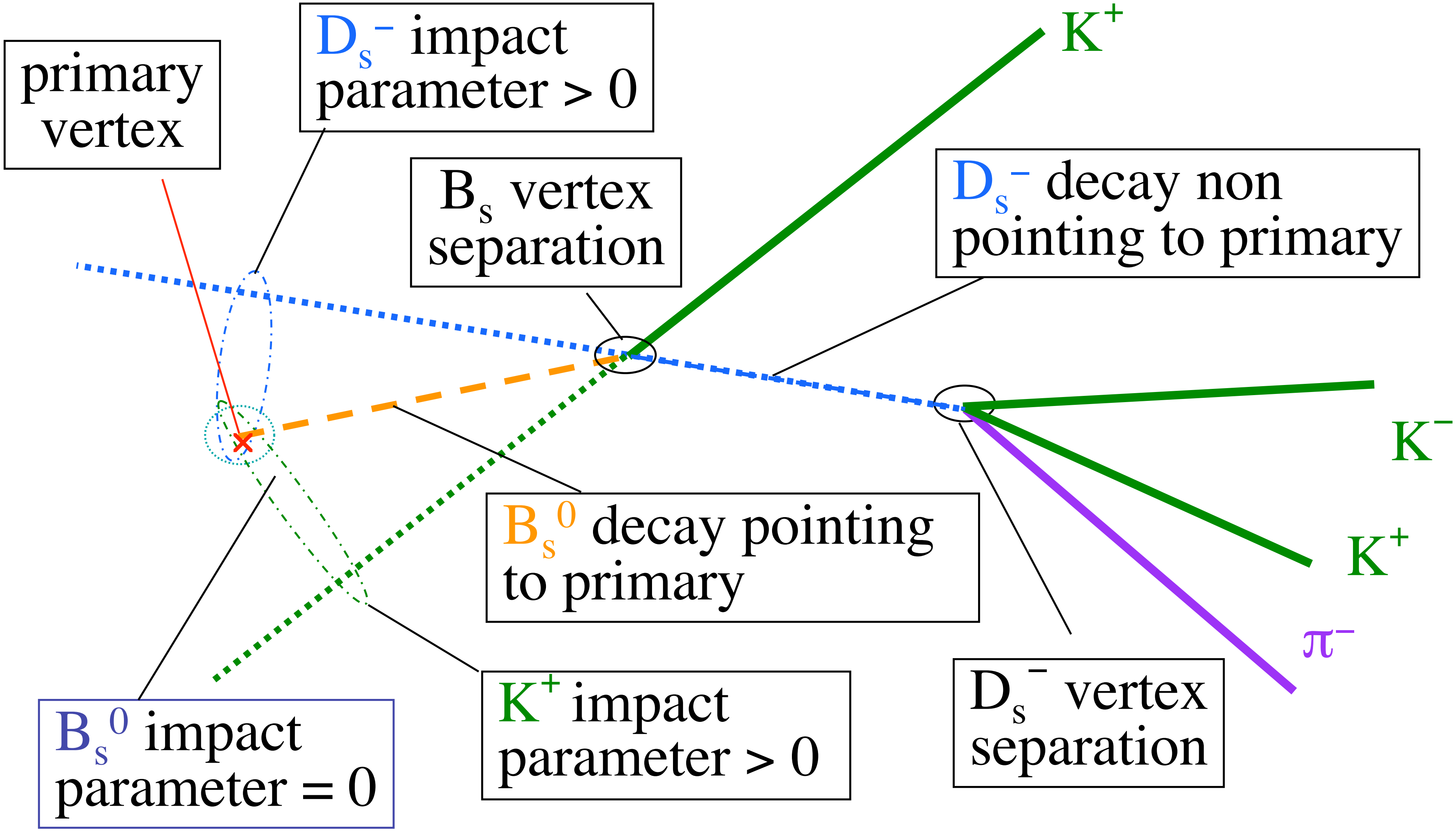
$B^0 \to K^{*0}(K^+\pi^-)\gamma$, $\rho^0(\to\pi^+\pi^-)\pi^0$, etc. are possible

but not

$B^0 \to K_S\pi^0$, $\rho^+(\to\pi^+\pi^0)\pi^0$, $\pi^0\nu\nu$, etc.

$B^+ \to \mu^+\nu$, $K^+\nu\nu$, $\tau^+\nu$

Illustration

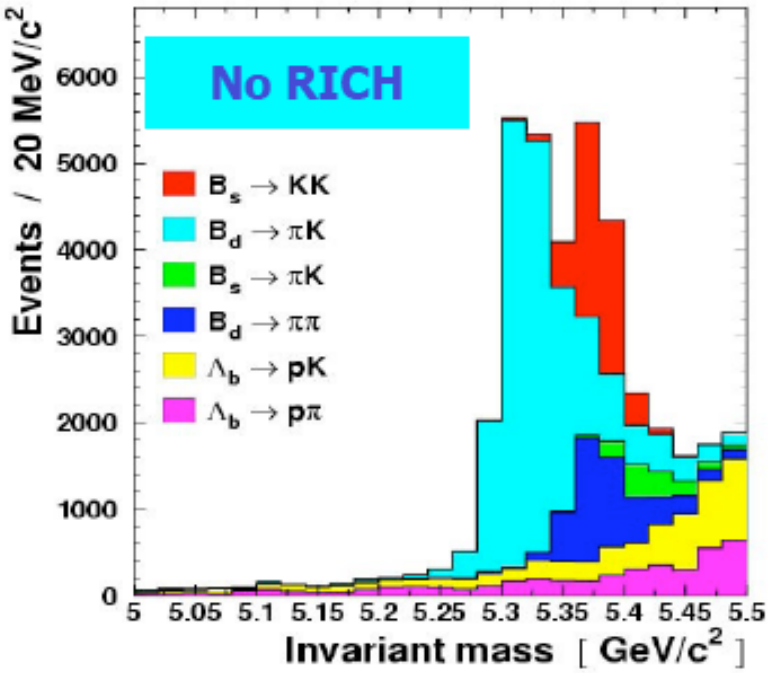


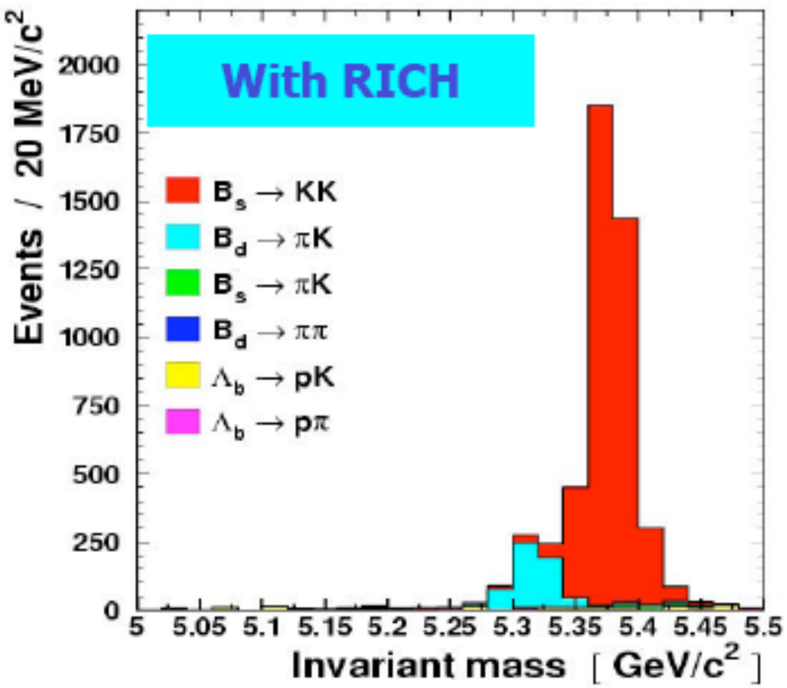
plus p_T cut (LHCb) or isolation cut (ATLAS/CMS)
and for some cases, decay angle cut

Particle identification and good mass resolution is essential to **reduce same topology background**:

$B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, $B_s^0 \to K^+\pi^-$, $B_s^0 \to \mu^+\mu^-$

$B_s^0 \to \overline{D}_s(\to K^+K^-\pi^-)\pi^+$, $B_s^0 \to \overline{D}_s(\to K^+K^-\pi^-)K^+$





Particle identification is very useful to reduce **combinatorial** background for many body decays

$B^0 \to D^0(K^+\pi^-)K^{*0}(K^+\pi^-)$, etc.

Relevant LHC experiments

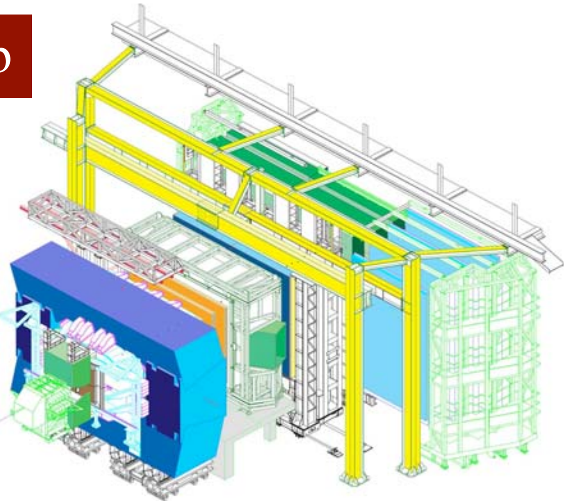
LHCb: (Not LHCB nor LHC-B)

dedicated B physics experiment, locally adjusted luminosity of 2×10^{32} c.f. LHC design luminosity 10^{34}

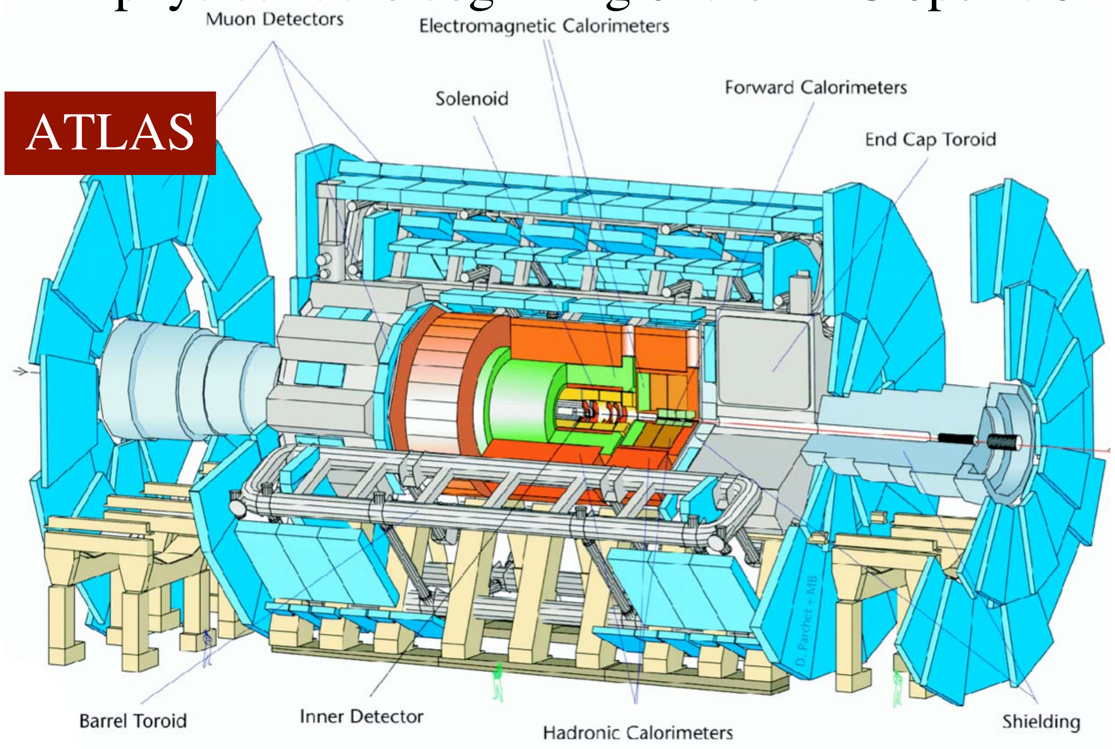
ATLAS/CMS:

general purpose experiments,
optimized for high-p_T discovery physics at 10^{34} cm^{-2}s^{-1}
B physics at the beginning of the LHC operation with 10^{33}

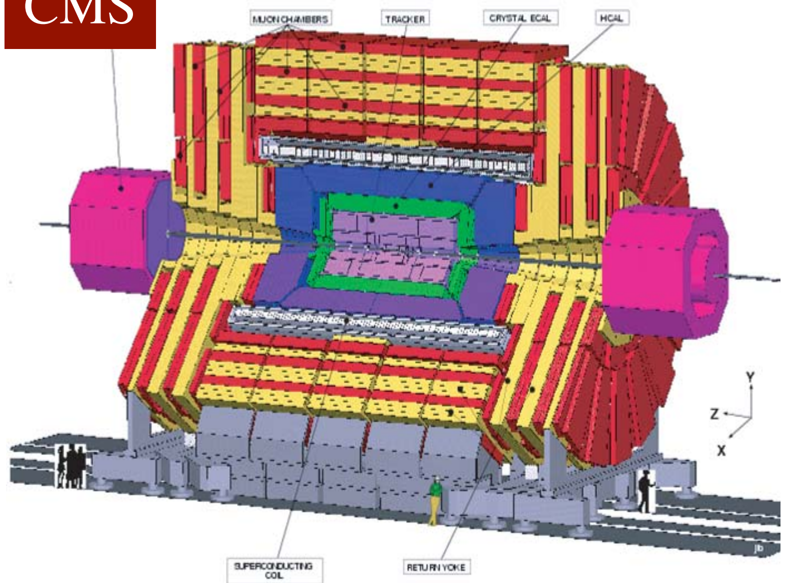
LHCb



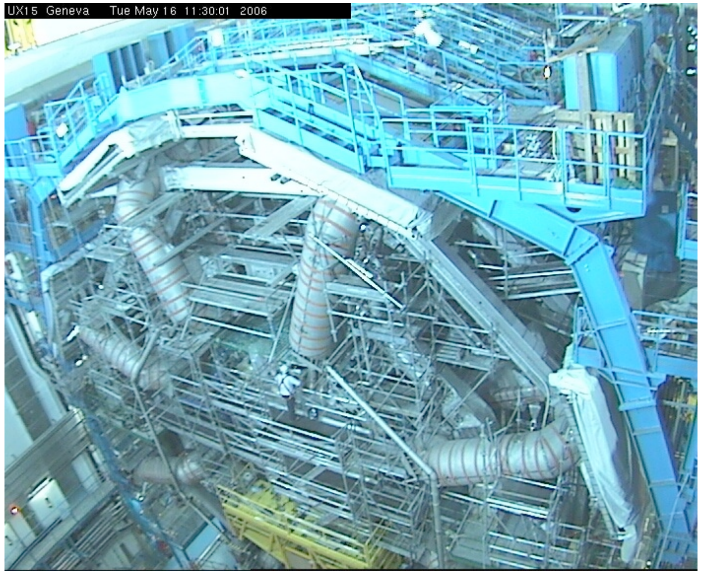
ATLAS

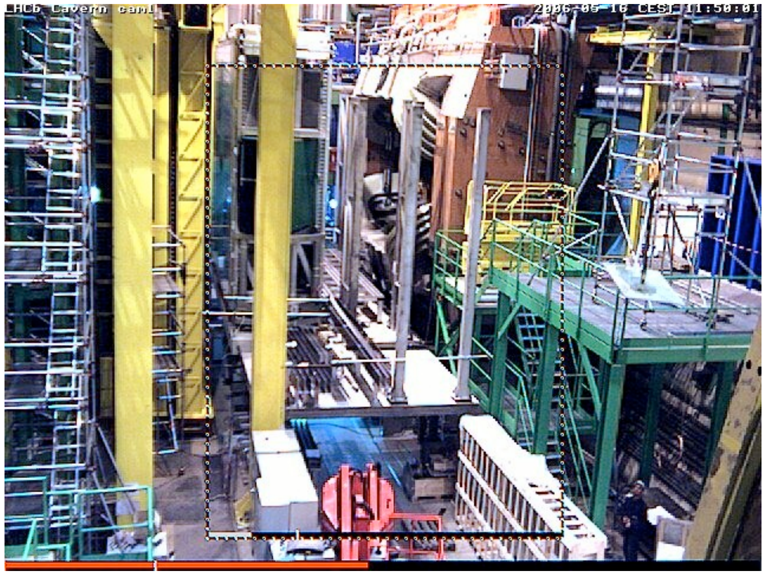


CMS



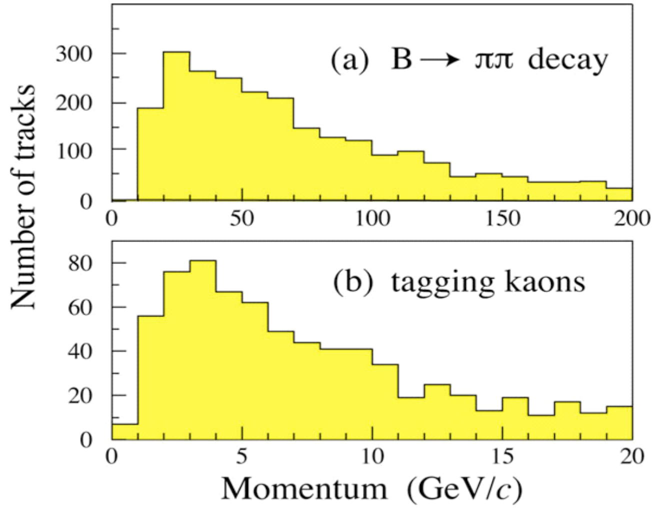
Construction advancing

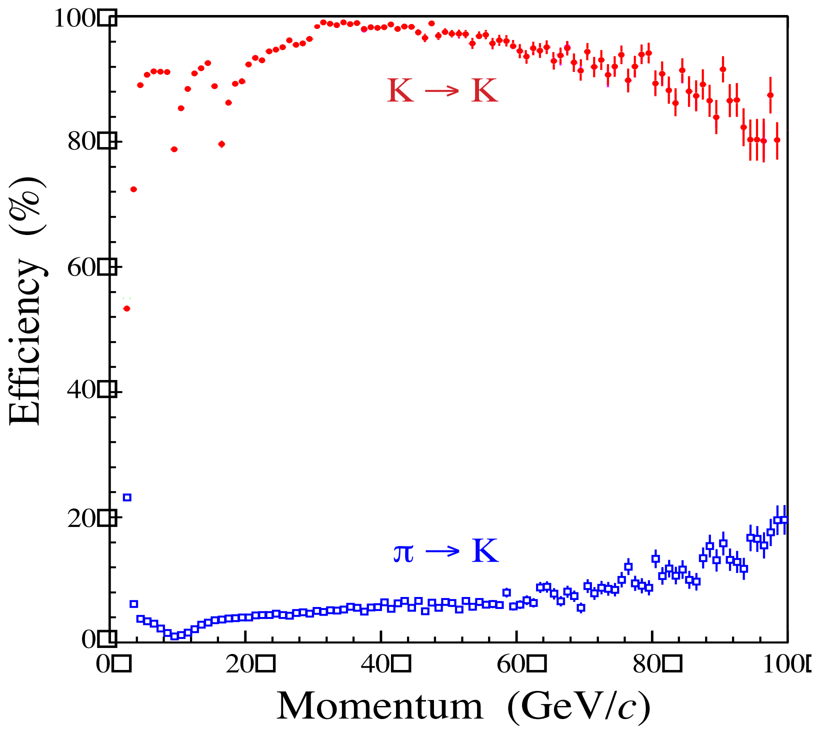


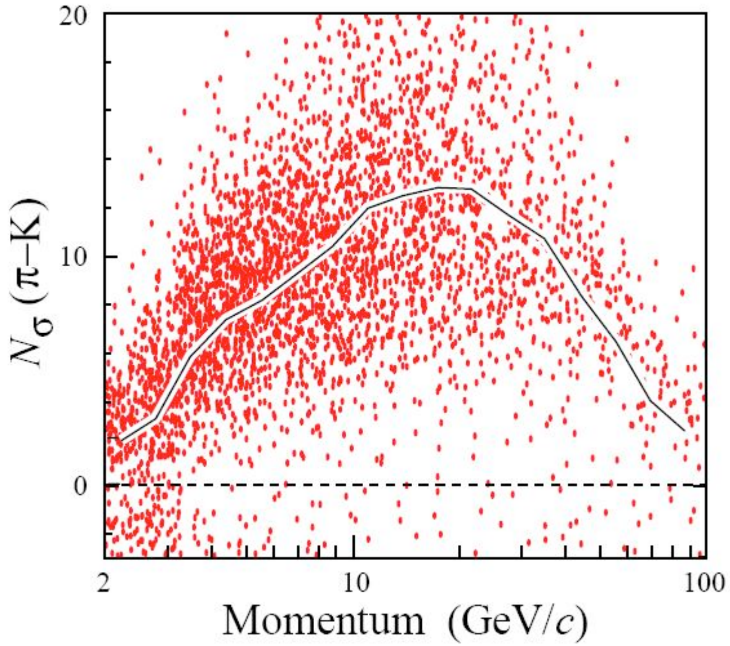


LHCb Particle identification

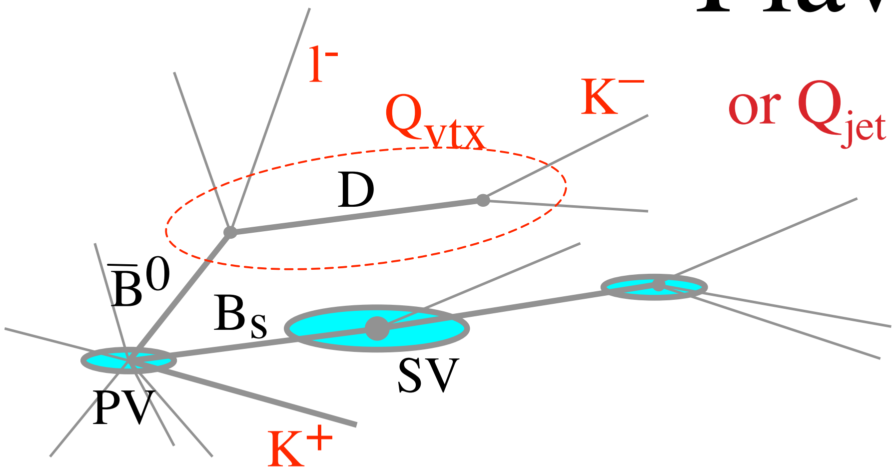
Hadron PID over p = 1 to 100 GeV/c with two Ring Imaging Cherenkov detectors (three radiators),
essential for the Kaon tag and hadronic final states reconstruction







Flavour tag



ATLAS

Tag	$\varepsilon D^2 = \varepsilon(1-2w)^2$
Opposite μ	0.7%
Opposite e	0.3%
Opposite Q_{jet}	3.6%

CMS under study

LHCb

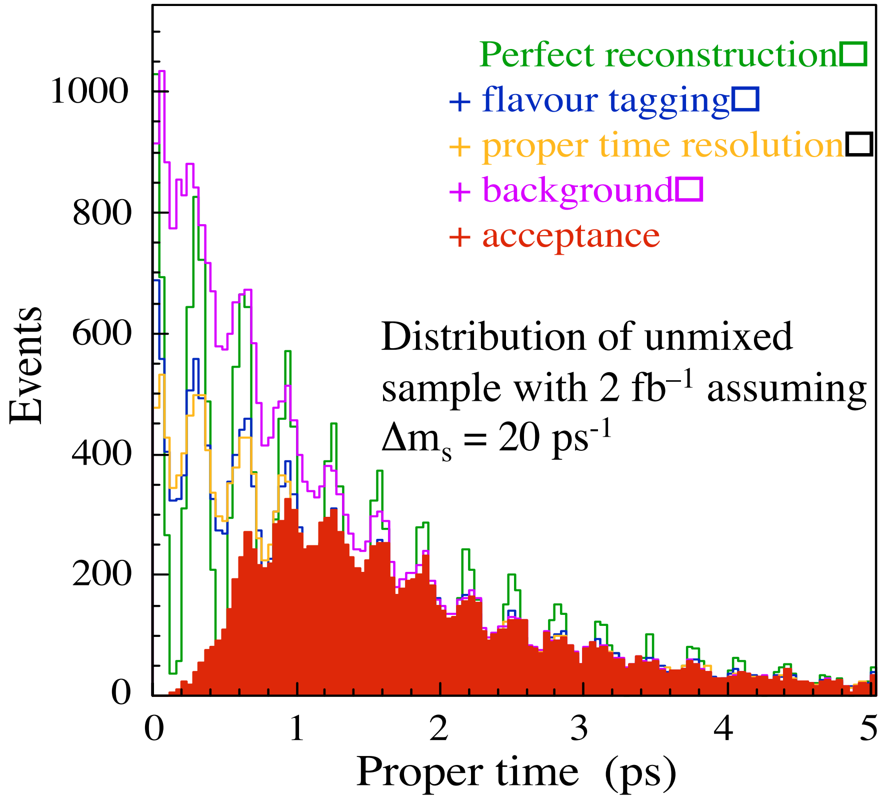
Tag	$\varepsilon D^2 = \varepsilon(1-2w)^2$
Opposite μ	0.7%–1.8%
Opposite e	0.4%–0.6%
Opposite K	1.6%–2.4%
Opposite Q_{vtx}	0.9%–1.3%
Same side π (B^0)	0.8%–1.0%
Same side K (B_s)	2.7%–3.3%
Combined (B^0)	4%–5%
Combined (B_s)	7%–9%

B_S oscillations

Measurement of Δm_s is one of the first LHCb physics goals

Expect 80k $B_s \rightarrow D_s^- \pi^+$ events with 2 fb^{-1}, average $\sigma_t \sim 40$ fs

S/B ~ 3 (derived from 10^7 fully simulated inclusive $b\bar{b}$ events)



c.f. now
3.7 k for the CDF result with a similar tagging power and worse σ_τ

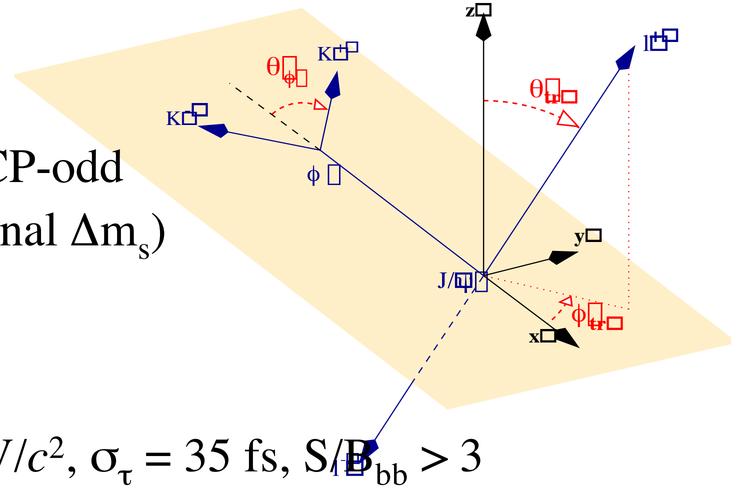
With less than a month of good data LHCb should achieve >5σ significance measurement in 2008

We should also study ~~CP~~ in oscillations

ϕ_s and $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$, …

$B_s \to J/\psi\phi$ is the B_s counterpart of $B^0 \to J/\psi\, K_S$:

- B_s mixing phase ϕ_s is very small in SM: $\phi_s = -\arg(V_{ts}^2) = -2\lambda\eta^2 \sim -0.04$
  $\Rightarrow$ sensitive probe for new physics
- $J/\psi\phi$ final state contains two vectors:
  - Angular analysis needed to separate CP-even and CP-odd
  - Fit for $\sin\phi_s$, $\Delta\Gamma_s$ and CP-odd fraction (needs external Δm_s)



Sensitivity (at $\Delta m_s = 20\ \mathrm{ps}^{-1}$):

- LHCb:
  - 125k $B_s \to J/\psi\phi$ untagged events/2 fb^{-1}, $\sigma_m = 8\ \mathrm{MeV}/c^2$, $\sigma_\tau = 35$ fs, $S/B_{bb} > 3$
    $\Rightarrow \sigma_{stat}(\sin\phi_s) \sim 0.031$, $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.011$
  - can also add pure CP modes such as $J/\psi\eta$, $J/\psi\eta'$, $\eta_c\phi$ (small improvement)
    $\Rightarrow \sigma_{stat}(\sin\phi_s) \sim 0.013$ (5×10^7s) $\rightarrow$ will eventually cover down to ~SM
- ATLAS:
  - 90k $B_s \to J/\psi\phi$ untagged events/10 fb^{-1}, $\sigma_m = 16.5\ \mathrm{MeV}/c^2$, $\sigma_\tau = 83$ fs, S/B = 5.6
    $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.023$, $\sigma(\sin\phi_s) = 0.08$ (fit incl. strong phases in helicity amplitude)
- CMS:
  - 110k $B_s \to J/\psi\phi$ untagged events/10 fb^{-1}, $\sigma_m = 13\ \mathrm{MeV}/c^2$, $\sigma_\tau = 77$ fs,
    $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.011$ stat. with untagged sample, $\sigma(\sin\phi_s)$ in progress

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

Very rare decay, i.e. sensitive to new physics:

SM BR ~ 3.5×10^{-9}, can be strongly enhanced in SUSY

Current limit from Tevatron (CDF+D0): ~1×10^{-7} at 95% CL

LHC has prospect for significant measurement,
difficult to get reliable estimate of expected background:

LHCb: Full simulation: 10M inclusive bb events + 10M $b \to \mu$, $b \to \mu$ events (all rejected)

ATLAS: 80k $bb \to \mu\mu$ events with generator cuts, efficiency assuming cut factorization

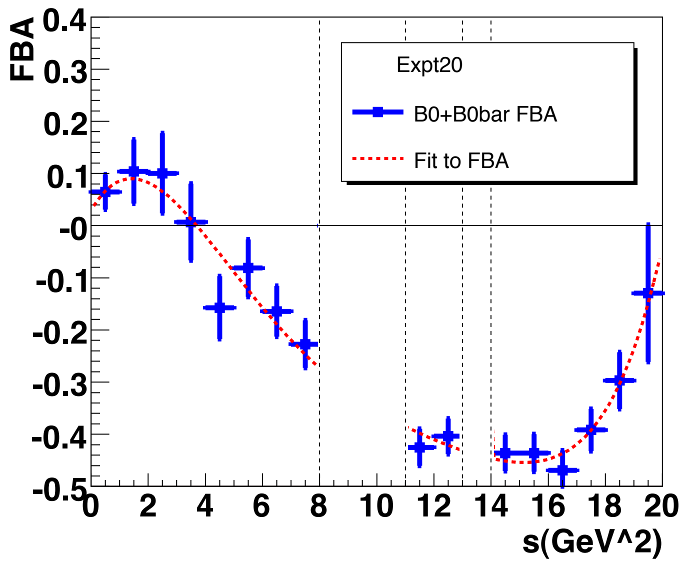
CMS: 10k $b \to \mu$, $b \to \mu$ events with generator cuts, trigger simulated at generator level efficiency assuming cut factorization

	10^7 s	$B_s \to \mu+ \mu^-$ signal (SM)	$b \to \mu$, $b \to \mu$ background	Inclusive $b\bar{b}$ background	Mass resolution
LHCb	2 fb^{-1}	17	< 100	< 7500	18 MeV/c^2
ATLAS	10 fb^{-1}	7	~ 20	?	75 MeV/c^2
CMS (1999)	10 fb^{-1}	7	< 1	?	48 MeV/c^2

New assessment of ATLAS/CMS reach at 10^{34} $cm^{-2}s^{-1}$ in progress

With several years measurement, σ<10% possible

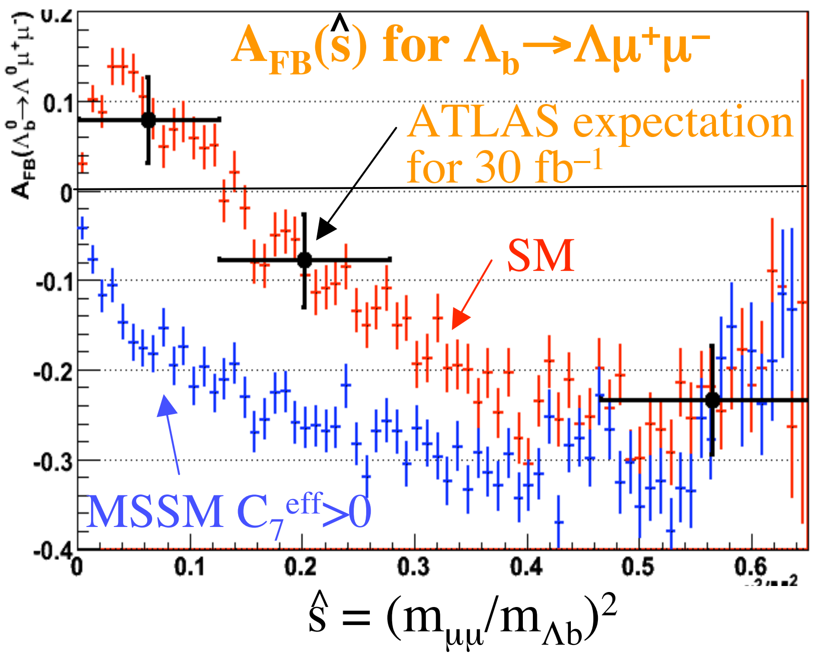
$b \to s\mu^+\mu^-$



Suppressed decays, SM BR ~ 10^{-6}

Forward-backward asymmetry $A_{FB}(s)$ in the μμ rest-frame is sensitive probe of New Physics:

— Zero can be predicted with small hadronic uncertainties, depends on Wilson coefficients



LHCb: σ_m= 40 MeB/c^2

4400 $B^0 \to K^{*0}\mu^+\mu^-$ events/2fb^{-1}, S/B > 0.4

Zero of $A_{FB}(s)$ located to ±0.53 GeV^2 with 10 fb^{-1}

→ determine C_7^{eff}/C_9^{eff} with 13% error (SM)

ATLAS: σ_m= 40 MeB/c^2

1000 $B^0 \to K^{*0}\mu^+\mu^-$ events/10fb^{-1}, S/B > 1

Other exclusive b→sμμ feasible (B_s, Λ_b)

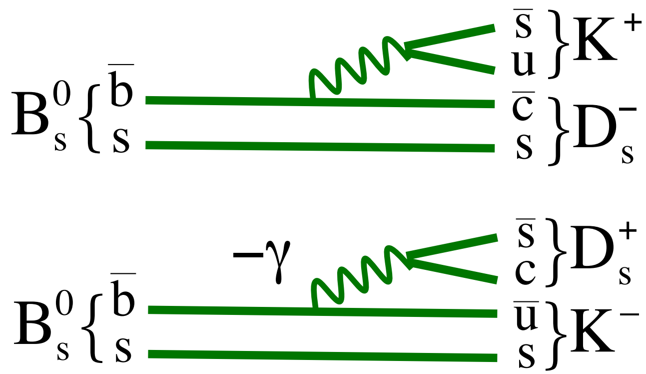
LHCb also 9.3K $B_s \to \phi\gamma$/year
35K $B_d \to K^{*0}\gamma$/year

LHCb γ from $B_s \to D_sK + J/\psi\phi$

$B_s \to D_sK$

Two tree decays ($b \to c$ and $b \to u$), which interfere via B_s mixing:

- Can determine $\phi_s + \gamma$,
- Similar to $2\beta+\gamma$ extraction with $B^0 \to D^*\pi$, but with the advantage that the two decay amplitudes are similar ($\sim\lambda^3$) and that their ratio can be extracted from data



By combining ϕ_s from $B_s \to J/\psi\phi$, extracting γ free from New Physics

LHCb: $\sigma(\gamma) \sim 14°$ in one year ($\Delta m_s = 20$ ps^{-1})

Good σ_τ, K/π separation and hadronic trigger are essential

LHCb γ from $D \to DK$

LHCb: γ from $B^0 \to DK^{*0}$

Dunietz variant of Gronau-Wyler method

$\sigma(\gamma) \sim 8°$ in one year

LHCb: γ from $B^{\pm} \to DK^{\pm}$

ADS (Atwood, Dunietz, Soni) method

Favoured $D \to K\pi$: 60,000 events/year

DC-unfavoured: 2,000 events/year

with B/S~0.5

$\sigma(\gamma) \sim 5°$ in one year

LHCb: γ from $B^{\pm} \to DK^{\pm}$ (and also $B^0 \to DK^{*0}$)

with $D \to K_s \pi^+ \pi^-$ Dalitz study (BELL and Giri et al.)

is under investigation

1800 events with the current HLT, could be increased

as much as 6000 events per year ($B^{\pm}$)

K/π separation and hadronic trigger are essential

Please note a presentation by

I. Beleyaev: LHCb radiative penguin
O. Deschamps: $B \to \rho\pi$, $\rho\rho$ studies at LHCb
E. Conte $\Lambda_b \to \Lambda\ J/\psi$ decay at LHCb

in during this workshop.

And charm physics

NB Studies are still preliminary

500×10^6 $D^* \rightarrow \pi\, D^0(K\pi)$ + c.c. per year with the standard trigger

D-$\overline{D}$ oscillations

Estimated statistical reach of LHCb in one year

$\sigma_y = 0.0002, \quad \sigma_x = 0.004$

CP violation in $D \rightarrow K^+K^-$ decays

$$A_{CP} = \frac{(D^0 \rightarrow KK - \overline{D}^0 \rightarrow KK)}{(D^0 \rightarrow KK + \overline{D}^0 \rightarrow KK)}$$

Standard Model $\sim 10^{-3}$

LHCb expects 50×10^6 KK events

Estimated statistical precision 1.4×10^{-4} in one year

Systematics must be controlled by the $K\pi$ mode

Detailed study, in particular background, starts now...

Tau Physics

ATLAS study on Lepton number violation in $\tau \rightarrow \mu\gamma$
for integrated luminosity 30 fb^{-1} (3×10^7s of $L=10^{33}$)
90% CL UL < 0.6×10^{-6}
using τ from $W \rightarrow \tau\nu$ events.

CMS study on Lepton number violation in $\tau \rightarrow 3\mu$
for integrated luminosity 10 fb^{-1} (10^7s of $L=10^{33}$)
$\tau \rightarrow 3\mu$, 90% CL UL < 3.8×10^{-7}
$\tau \rightarrow \mu\gamma$, 90% CL UL < 10^{-6}

LHCb under study

Remark on the trigger

Flavour physics continues to evolve and the number of interesting channels increases ⇒ flexible trigger and large DAQ bandwidths

ATLAS, CMS
lepton trigger

LHCb Trigger

10 MHz (visible bunch crossings)

custom electronics boards

Hardware trigger
- Fully synchronized (40 MHz), 4 μs fixed latency
- "High p_T" μ, μμ, e, γ and hadron + pileup info (e.g. $p_T(\mu) > 1.3$ GeV/c)

1 MHz (full detector readout)

PC farm
~ 2000 CPUs

Software trigger
- Full detector info available, only limit is CPU time
- 1st stage: ~1 ms → 40 kHz (could change)
  Tracks with min. impact param. and p_T + (di)muon
- High-Level trigger: ~ 10 ms
  Full event reconstr.: excl. and incl. streams

Main changes since original design:

2003: IP+p_T at 1 MHz
2005: increased output rate
2005: full readout at 1 MHz

~ 2 kHz (storage)

Software trigger can be further optimized to cope with the evolving physics requirements

LHC B physics beyond the first three years

ATLAS and CMS

will move to high luminosity operation toward $10^{34}\text{cm}^{-2}\text{s}^{-1}$

no general B physics, possible exceptions are

$B \rightarrow \mu\mu$, may be τ? to be seen.

LHCb

While accumulating 5 to 10 fb^{-1}, try to learn how to work with some what higher luminosities $\sim 5\times10^{32}$:

-event reconstruction, combinatorial background, detector operation, ...

For a longer term, possible increase of statistics by >3 for could be considered by a combination of $L\sim10^{33}$ and High-$p_T\otimes$displaced vertex as the first level for some channels, depending on physics...

Conclusions

ATLAS, CMS and LHCb can collect high statistics b hadron decays with leptons in the final state

- -sensitivity to $B_s \to \mu^+\mu^-$ to the level expected by the Standard Model
- -FB asymmetry study with $B \to K^{*0}\mu^+\mu^-$ and other $b \to s\mu^+\mu^-$

Hadron trigger, K/π separation and excellent σ_τ allow LHCb to further improve the CKM consistency test

- -Δm_s 5σ significance measurement with the first data
- -γ measurements with several different methods
- -σ's for α, β and γ per 10^7s are ~ or < than $\int dt$ B-factories@2008

oscillations and ~~CP~~ studies with D^0

and other physics....

Flexible LHCb trigger can cope with evolving physics requirements

LHC will extend the success of flavour physics established by BABAR, BELLE, CDF and D0 starting from 2008