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Flavour physics at the LHC

prospects for B-physics at the LHC

Introduction
Rare decays
CP violation
Production

Selected topics

22nd International Workshop on
Weak Interactions and Neutrinos WIN'09
Electroweak Symmetry Breaking
Weak Decays, CP Violation and CKM
Neutrino Physics
Dark Matter

Search for "New Physics"

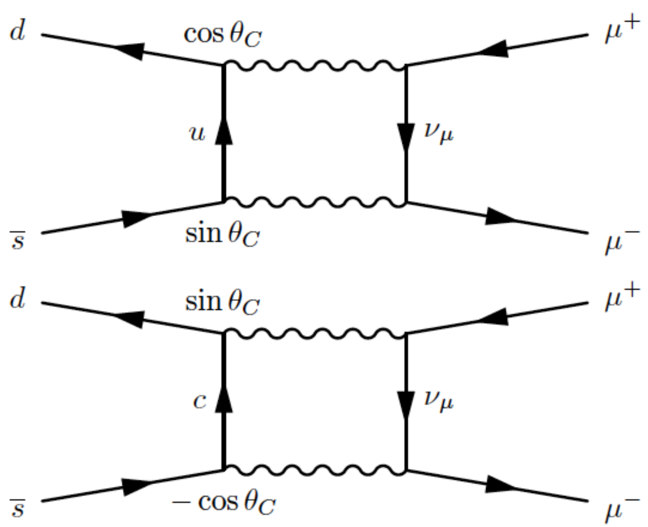
Direct searches for new particles

Need centre-of-mass energy

Searches for indirect effects of new particles/couplings

Loop diagrams are sensitive to new physics effects
Limited by precision (experiment&prediction) not by CM energy
Flavour physics can provide hints before direct discovery of new particles

Historical example
GIM mechanism:
Explains absence of FCNC
Predicts not too heavy charm quark

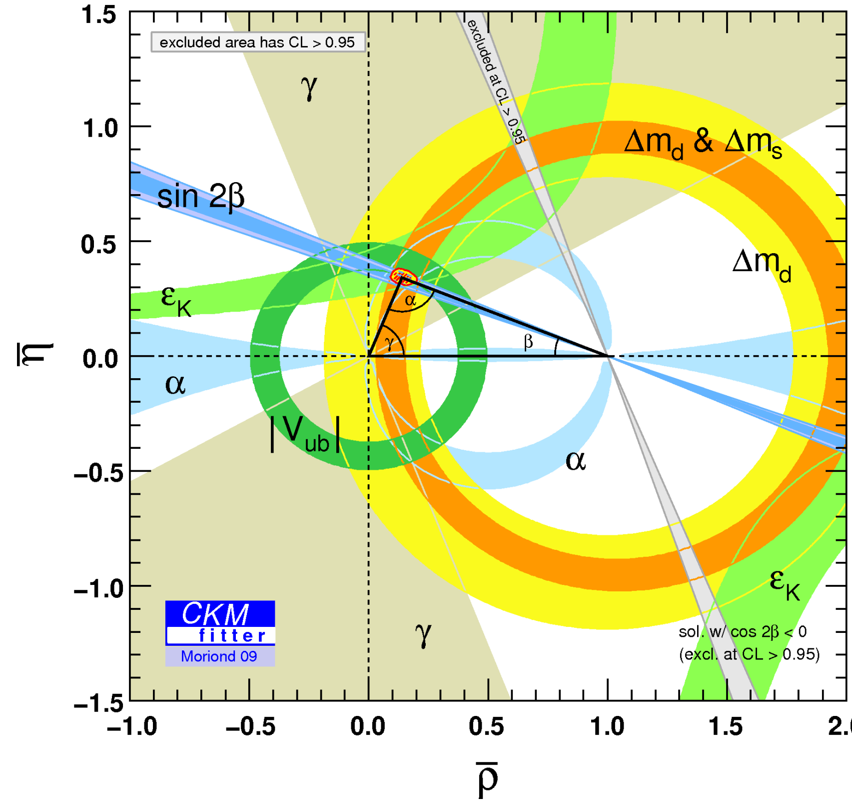


Flavour Physics

***Standard Model** established in B-physics by measurements at LEP, SLC, Tevatron, and B-factories.*
Analysis in terms of Unitarity Triangle

*Discussion of parameters usually with **Wolfenstein** parametrization:*

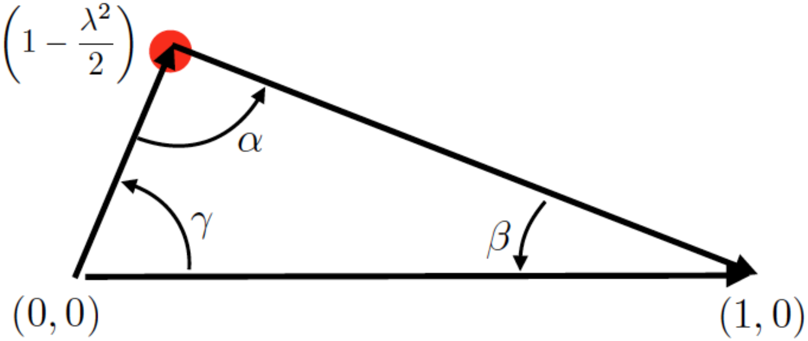
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



CP violating effects shown in $\bar{\rho}$-$\bar{\eta}$ plane

Accuracy of amplitudes (sides) limited by theory

$$\bar{\rho} + i\bar{\eta} \equiv (\rho + i\eta)\left(1 - \frac{\lambda^2}{2}\right)$$

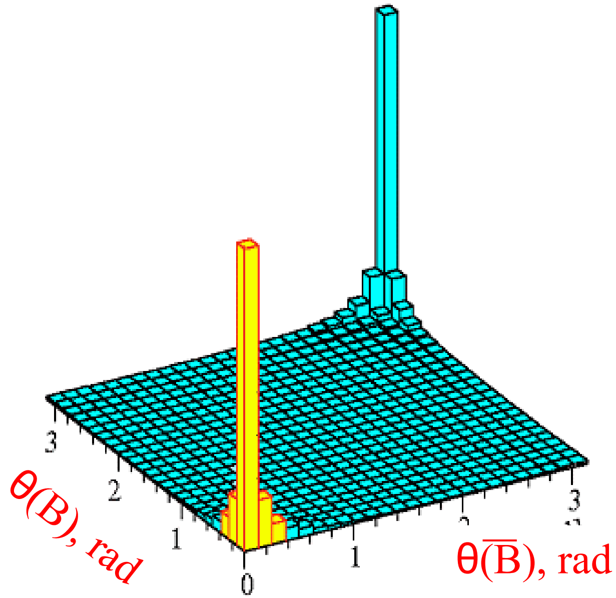


Angles limited by experiment
$\sigma(\alpha) \approx 5^o$
$\sigma(\beta) \approx 1^o$
$\sigma(\gamma) \approx 20^o$
φ_s ($-2\beta_s$) not measured } ***LHC***

B-physics at the LHC

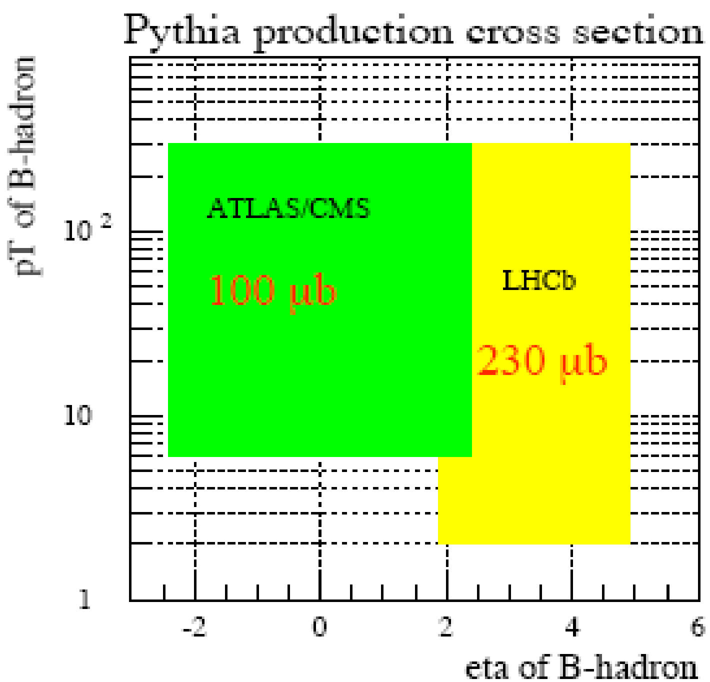
High cross-sections compared to B-factories and to Tevatron:

500 μb at 2x7 TeV (300 μb at 2x5 TeV)
1% of cross-section and small BR – need selective trigger
Correlated production in forward direction
High track multiplicities in underlying events
All B-mesons/baryons produced



General purpose detectors (ATLAS, CMS)

Optimized for new (heavy) particle searches
Barrel region
Highest possible luminosity
High PT triggers



Dedicated detector (LHCb)

Forward region – highest rate/sr
Moderate luminosity → tracking in forward region
Triggering on moderate PT
PID for hadrons and leptons
Good proper time resolution

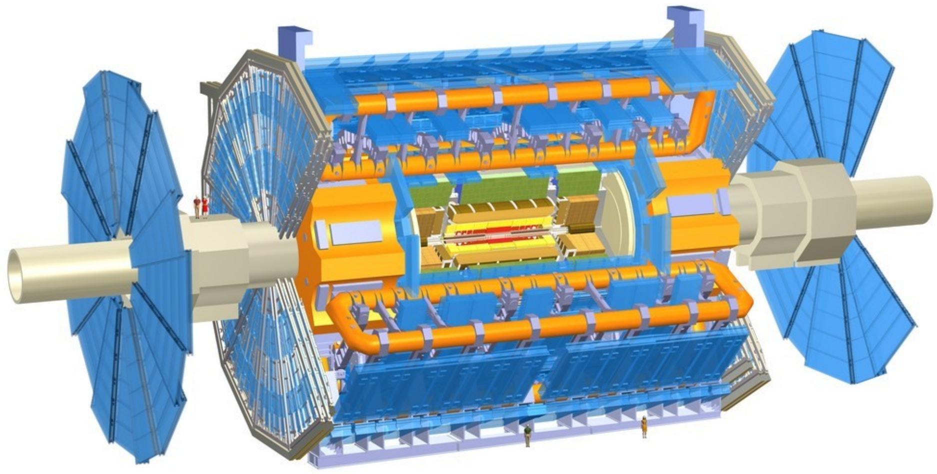
B_d	B_u	B_s	B_c	baryons
40%	40%	10%	~0.1%	10%

General purpose detectors

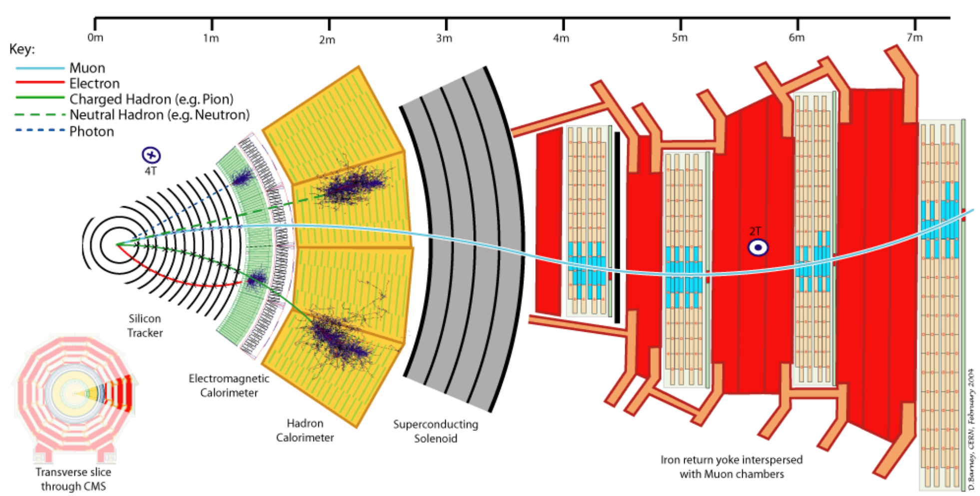
ATLAS and CMS

B-physics at moderate luminosity 10^{33} $cm^{-2}s^{-1}$
Trigger for B: mainly muons
Multiple interactions/crossing
Excellent muon ID
No hadron ID
Annual luminosity (nominal) 10 fb^{-1}

ATLAS



CMS



General purpose detectors

ATLAS and CMS

B-physics at moderate luminosity 10^{33} cm^{-2}s^{-1}
Trigger for B: mainly muons
Multiple interactions/crossing
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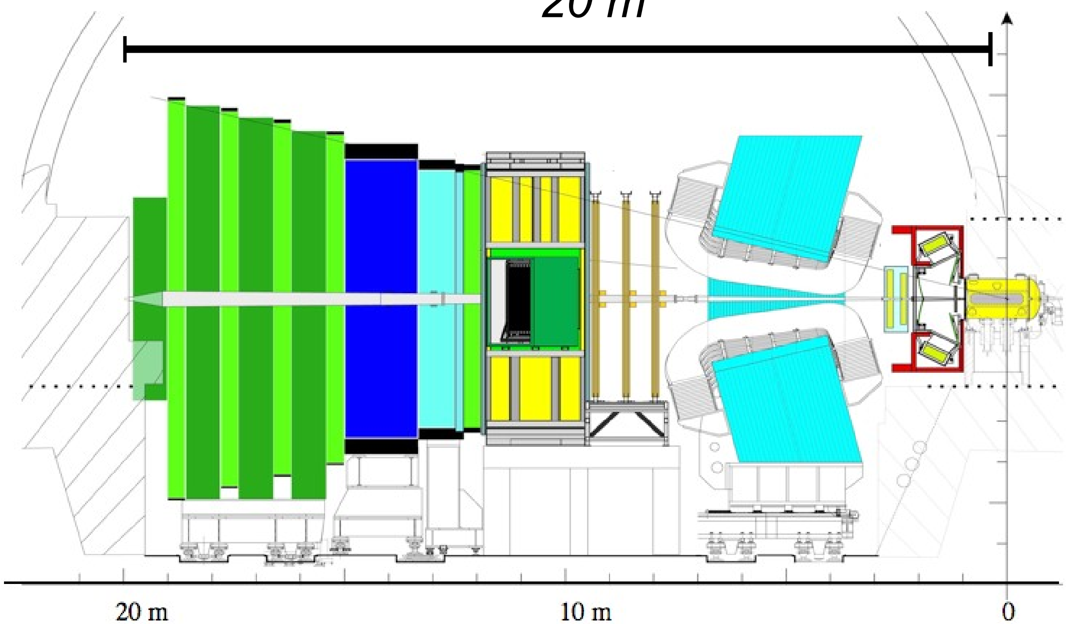
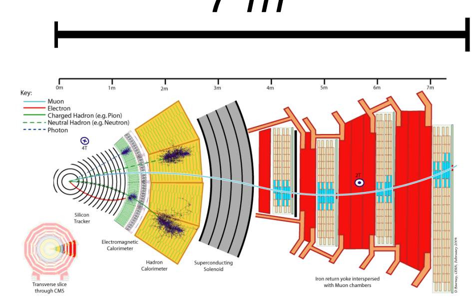
20 m



CMS

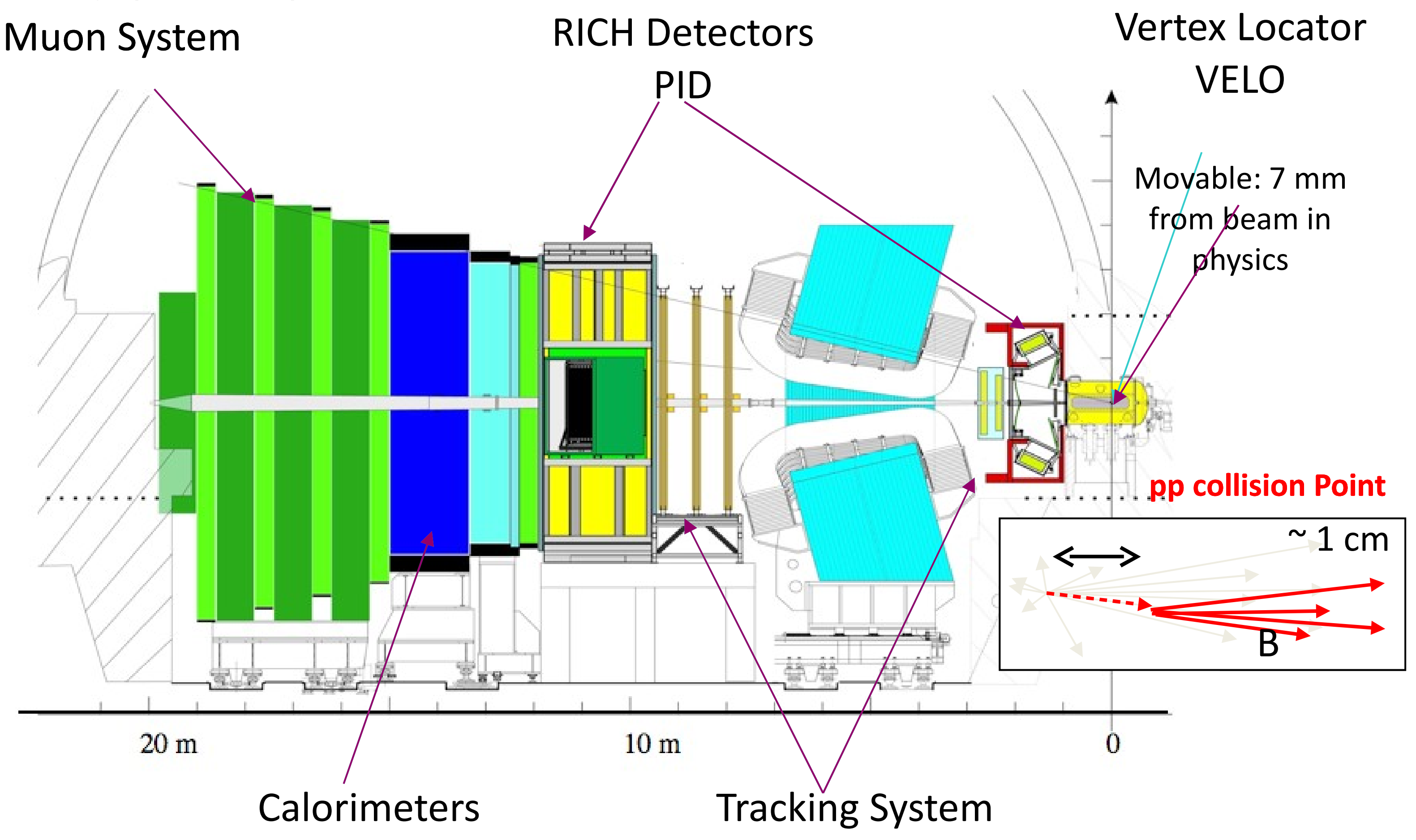
7 m



LHCb is like an enlarged and specialized sector

LHCb detector

Dedicated for B-physics
Maximize single interaction/crossing luminosity $2x10^{32}$ $cm^{-2}s^{-1}$
Excellent PID: muons, electron and hadrons
Excellent mass resolution
Trigger on muons, electrons, photons, hadrons
Relatively low PT triggers and Impact parameter triggers – decay vertices
Annual luminosity (nominal) 2 fb^{-1}



Search for new physics

Phases

New Physics enters through the phases of CP violating processes:

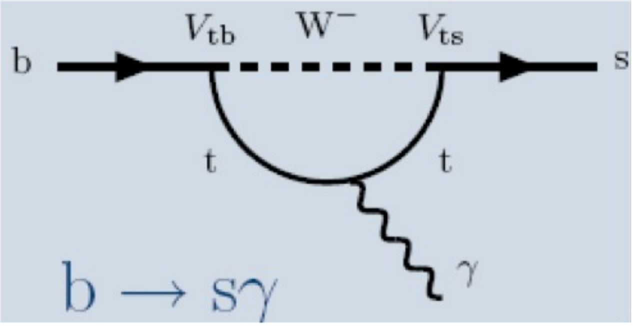
- *Measurements of β, $\boldsymbol{\beta_s}$, $\boldsymbol{\gamma}$*
- *Comparison of measurements of $_s$ ($-2\beta_S$) in different processes sensitive to different diagrams*

Helicity structure of couplings

e.g. ***$B_s \to \varphi\gamma$***

Photon polarization is correlated with b flavour – no interference and therefore no CP asymmetry

Non-zero asymmetry reveals presence of RH currents in penguin



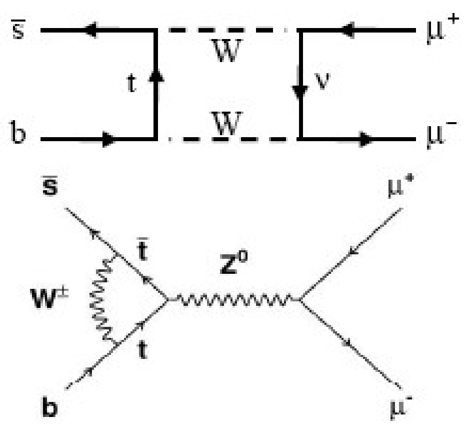
Masses and couplings of new particles

Rare decays

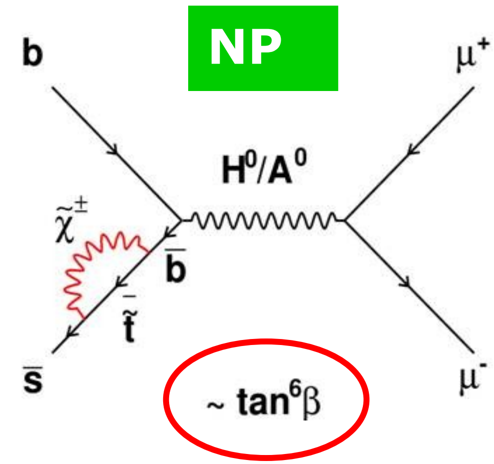
e.g. In SM ***$B_s \to \mu\mu$*** *small due to helicity suppression,*
increased sensitivity to SUSY

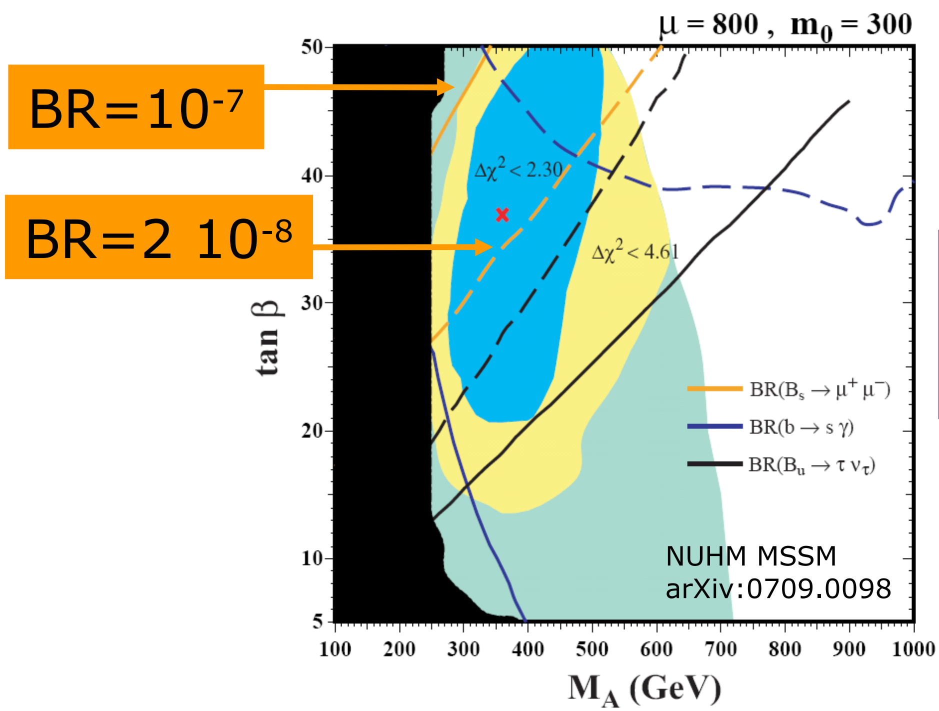
$B_s \rightarrow \mu\mu$

Very rare decay with well predicted BR in SM
$BR(B_s \rightarrow \mu\mu) = (3.55 \pm 0.33) \times 10^{-9}$



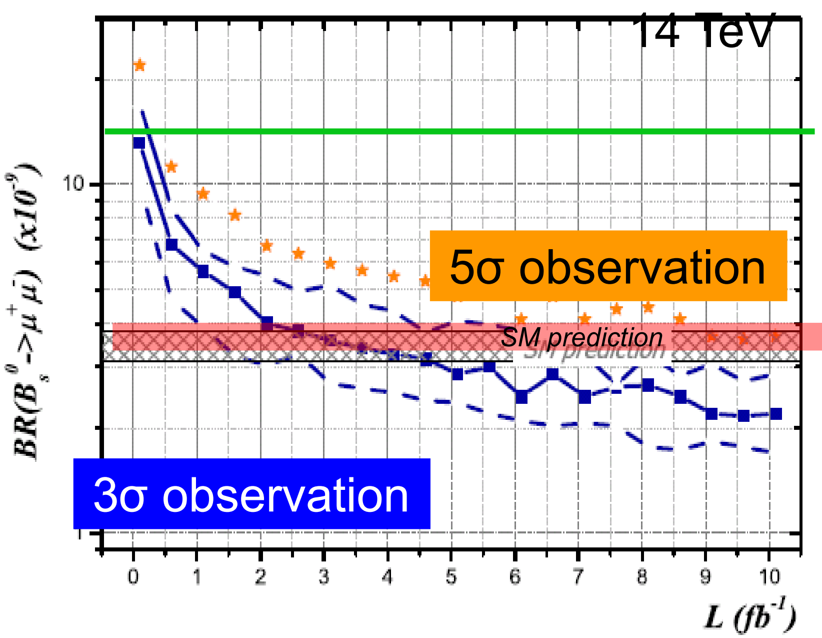
Sensitive to NP, in particular new scalars
In MSSM: $BR \sim \tan^6\beta / M^4_A$





Example: sensitivity to NP

Sensitivities for $B_s \to \mu\mu$

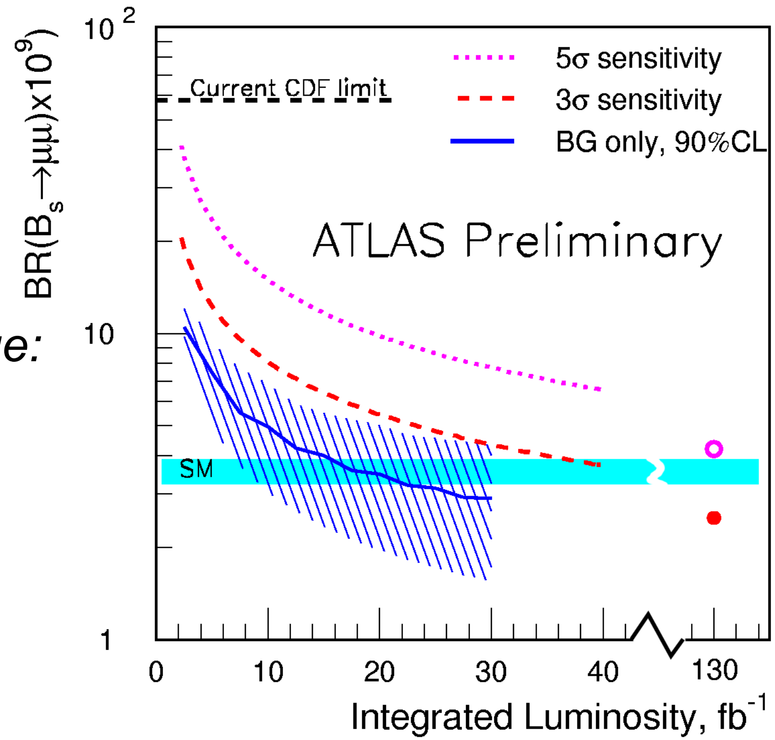


Best present limit is from CDF:
$BR(B_s \to \mu\mu) < 4.3\times10^{-8}$ @ 90% CL

LHCb sensitivity for the SM value:
3σ evidence with 3 fb^{-1}
5σ observation with 10 fb^{-1}

ATLAS and CMS can also study this channel – competitive owing to muon capabilities

e.g. ATLAS sensitivity for the SM value:
3σ evidence with 40 fb^{-1}



Yield in a nominal year	
ATLAS	*5.7 evts*
CMS	*6.1*
LHCb	*21*

Normalization for $B_s \to \mu\mu$

Control channels can be used to avoid reliance on MC:

Control channels used in $B_s \to \mu\mu$ analysis

Channel	Use	Yield (1 fb^{-1})
Inclusive $J/\psi(\mu\mu)$	μ-ID calibration	1.7G
Inclusive $\Lambda(\pi p)$	μ-ID calibration	740G
$B \to hh'$	Mass calibration GL calibration Normalization	220k
$B^+ \to J/\psi(\mu\mu)K^+$	Normalization	790k
$B^0 \to J/\psi(\mu\mu)K^{*0}(\pi K)$	Normalization	640k

LHCb can trigger on hadronic B decays:

Ultimate limitation:
Normalization *to known BR such as $B^+ \to J/\psi(\mu\mu)K^+$ with similar detector dependencies*
Limited due to uncertainty in B_s/B production ratio: about 13%.

Important when close to SM value!

Recent Belle measurement for $B_s \to D_s^- \pi^+$ (20% now) is promising if Belle continues to run further at Y(5s)

Sensitivity to Right-Handed currents

Radiative decays:

$B_s \to \varphi\gamma$

$B \to K^*\gamma$

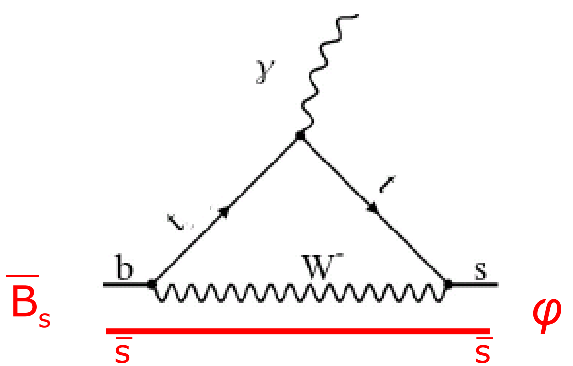
Decay Mode	Branching ratio
$B^+ \to K^{*+}\gamma$	$(4.6 \pm 1.4) \times 10^{-5}$
$B^0 \to K^{*0}\gamma$	$(4.3 \pm 1.4) \times 10^{-5}$
$B^0_s \to \phi\gamma$	$(4.3 \pm 1.4) \times 10^{-5}$

Relatively high rate:

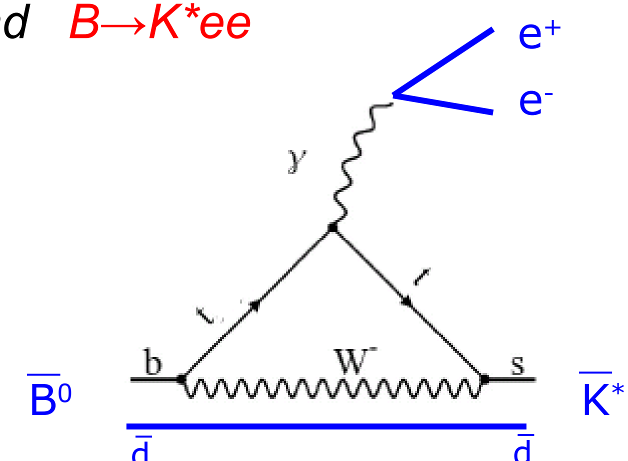
Expected signal yield for $B_s \to \varphi\gamma$ at LHCb is 11k for 2 fb^{-1}

Similar diagrams:

$B_s \to \varphi\gamma$ and $B \to K^*ee$



$B_s \to \varphi\gamma$



$B \to K^* e^+e^-$

$B \to K^*\mu\mu$ is sensitive to higher q^2 than $B \to K^*ee$ and has contributions from virtual photons and Z, W
Similar precision reachable as for $B_s \to \varphi\gamma$

$B_s \to \varphi\gamma$

*Measurement of the **photon polarization** in **$B_s \to \varphi\gamma$** decay*

Opposite helicity of photon in SM for B/$\overline{B}$ – no interference

CPV small in SM (~0.04) due to m_s/m_b and gluon effects

BaBar & BELLE used CPV analysis in $B \to K^*(K^0\pi^0)\gamma$ decay

$\sigma\,(A\,(B \to f^{CP}{}_R)\,/\,A\,(B \to f^{CP}{}_L))$ ~ 0.16 (HFAG)

In the $B_s \to \varphi\gamma$ decay CPV analysis can be performed without flavour tagging (A^Δ term):

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

SM:

C = 0 direct CP-violation

*S = **sin2ψ** $\sin\varphi_s$*

*A^Δ = **sin2ψ** $\cos\varphi_s$*

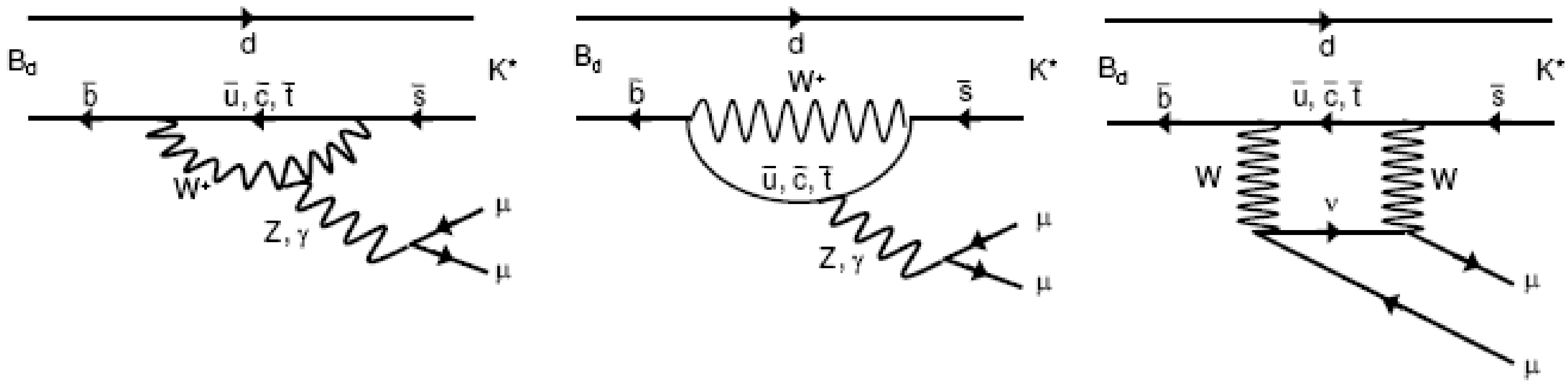
$$\tan\psi \equiv \left|\frac{A(\bar{\mathrm{B}} \to f^{CP}\gamma_R)}{A(\bar{\mathrm{B}} \to f^{CP}\gamma_L)}\right|$$

*C and S only accessable with **flavour tagging***

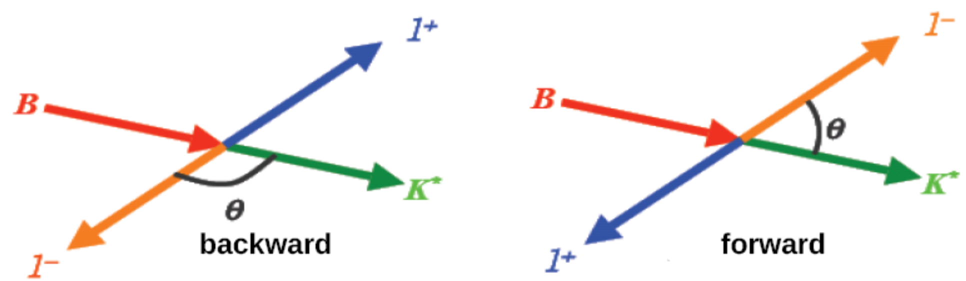
Sensitivity: $\sigma\,(A\,(B \to f^{CP}{}_R)\,/\,A\,(B \to f^{CP}{}_L))$ = 0.11 for $2fb^{-1}$

B→K*μμ

In SM this b→s penguin decay contains well calculable ***right-handed contribution*** *but this can be modified by NP giving different angular distributions*



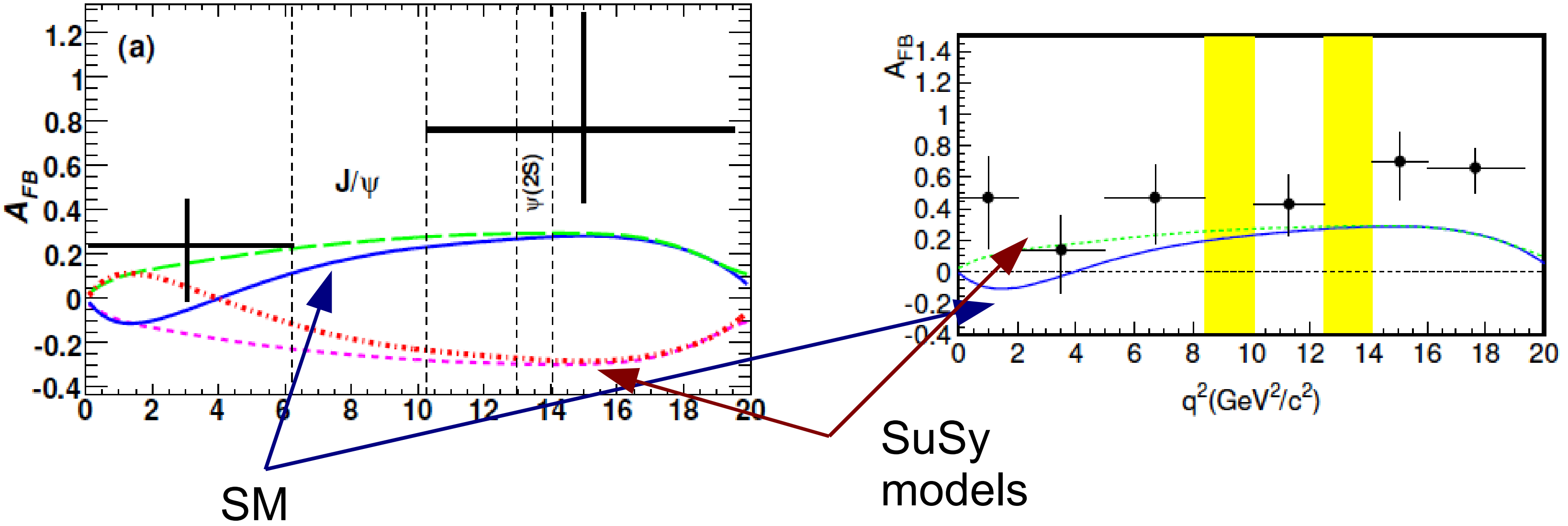
Zero-crossing point *as function of* $\mathbf{q^2 = m^2_{\mu\mu}}$ *of forward-backward asymmetry AFB is almost* ***free of hadronic uncertainties***



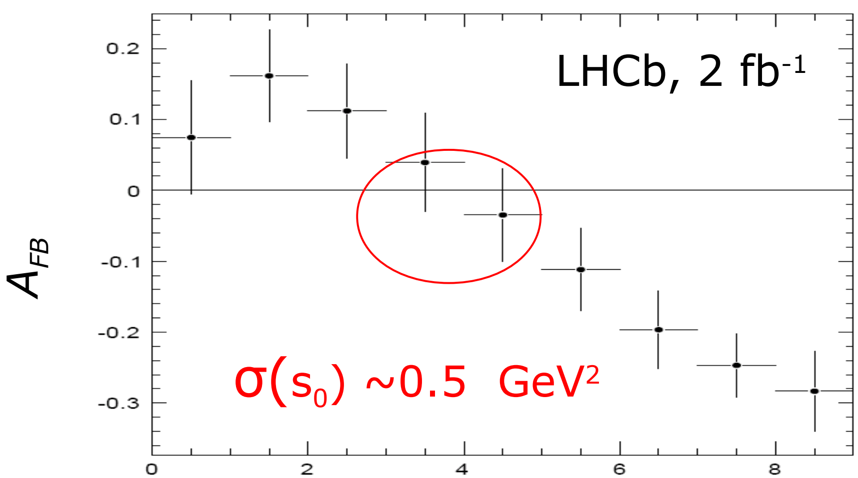
Precise SM prediction for ZCP: $\mathbf{q^2 = (4.36+0.33-0.31)\ GeV^2/c^4}$

$B \to K^* \mu\mu$

Measurements from Babar (384 fb^{-1}) and Belle (657 fb^{-1})



opposite sign convention wrt B factories

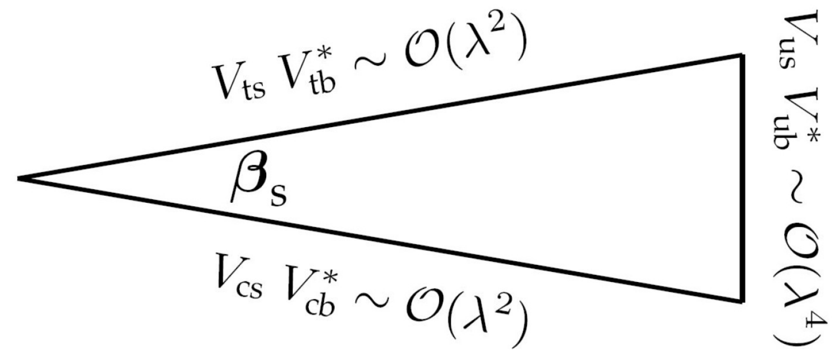


***ATLAS** precision for 30 fb^{-1}*

Decay channels	σ (pb)	Events	$\sigma_{A_{FB}}/A_{FB}$
$B^0 \to K^{*0}\mu^+\mu^-$	2.5	2500	4.8%
$B^0_s \to \phi\mu^+\mu^-$	0.57	900	6%
$B^+ \to K^+\mu^+\mu^-$	2.0	4000	3%
$B^+ \to K^{+*}\mu^+\mu^-$	2.1	2300	5.2%
$\Lambda_b \to \Lambda\mu^+\mu^-$	1.2	800	6%

B_s mixing

Weak mixing phase $_s$ **= -2β_s** ***in SM is the*** B_s ***meson counterpart of 2β***



Meaning of the measurement of $_s$ *depends on the process:*

In ***B_s→J/ψφ tree contribution*** *dominates*

penguin contribution ≤ 10^{-3}

$_s^{J/\psi}$ *= -2β_s is precisely predicted in SM with*

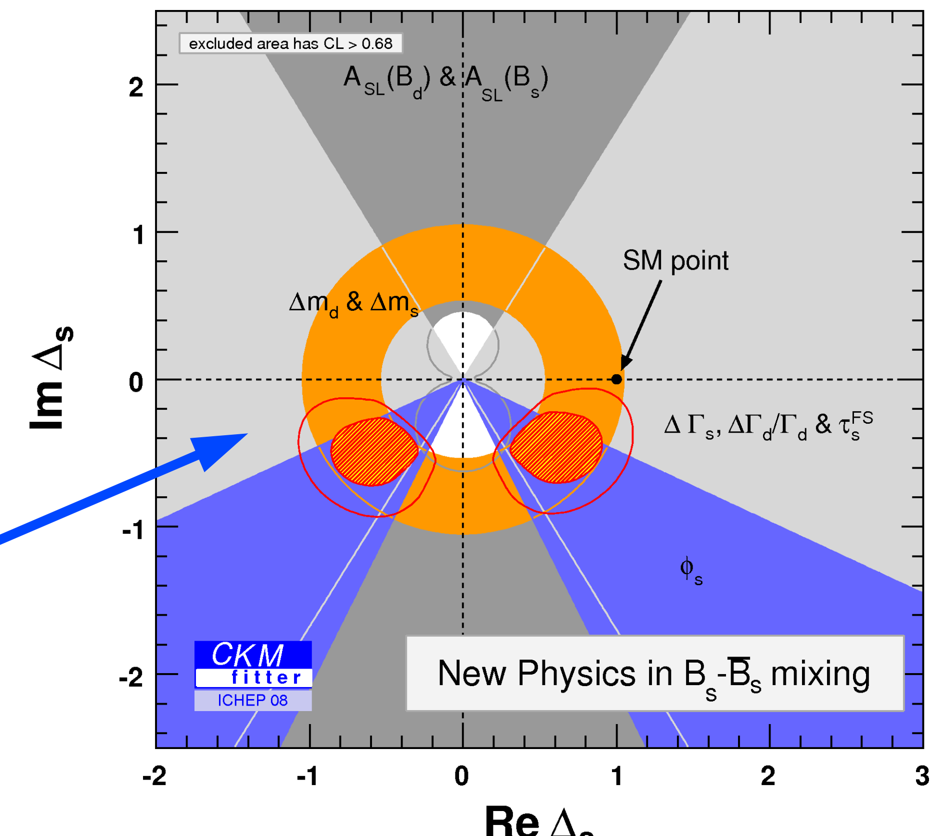
small theoretical uncertainty:

- 2β_s = - 0.0368±0.0017 (CKMfitter 2007)

$_s^{J/\psi}$ ***is not measured accurately***

indication of large value from CDF/D0

"tension" with SM



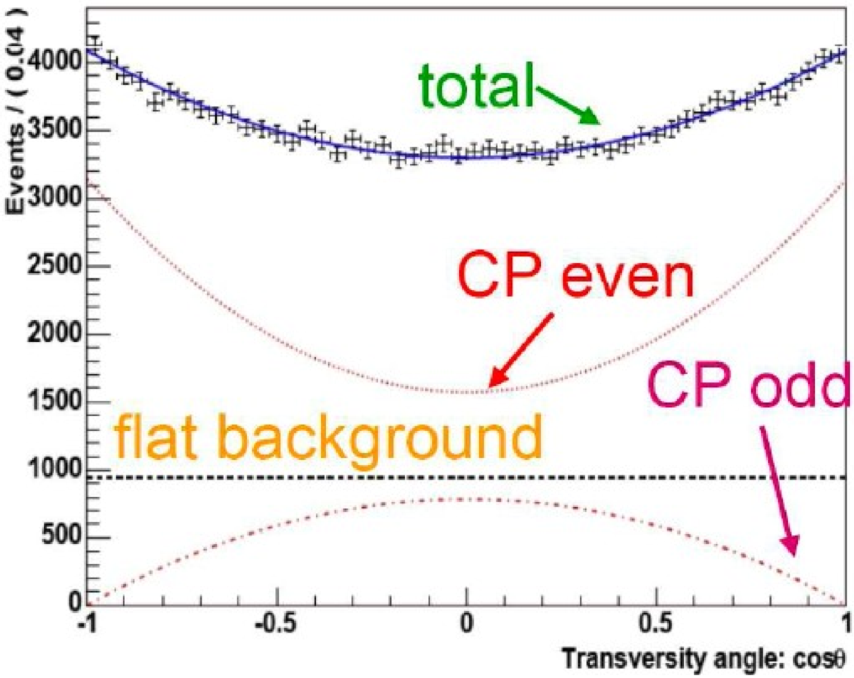
$B_s \to J/\psi\varphi$

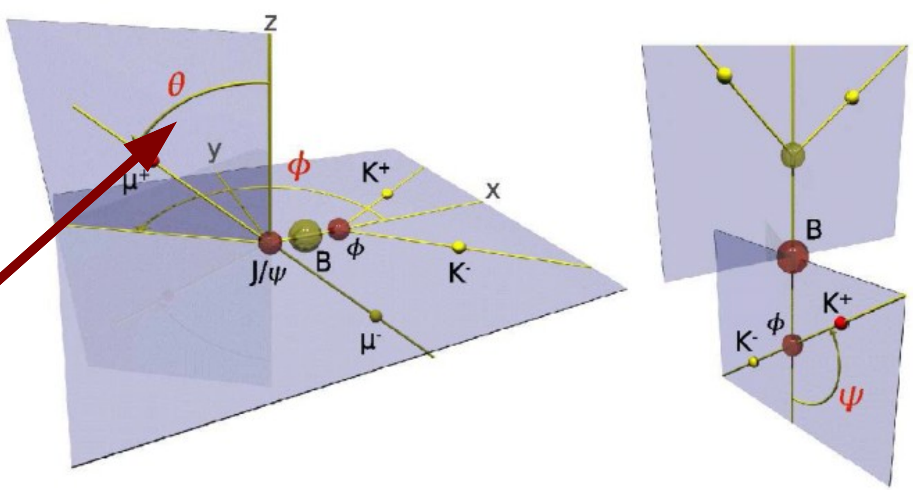
*Measure $_s$ from **time dependent asymmetry** in decay rate*

$$A_{CP}(t) = -\frac{\eta_f \sin\phi_S \sin(\Delta m_S t)}{\cosh\left(\frac{\Delta\Gamma_S t}{2}\right) - \eta_f \cos\phi_S \sinh\left(\frac{\Delta\Gamma_S t}{2}\right)}$$

Use angular dependence to distinguish
CP-even: $\eta_f = -1$
CP-odd: $\eta_f = +1$

Need flavour tagging

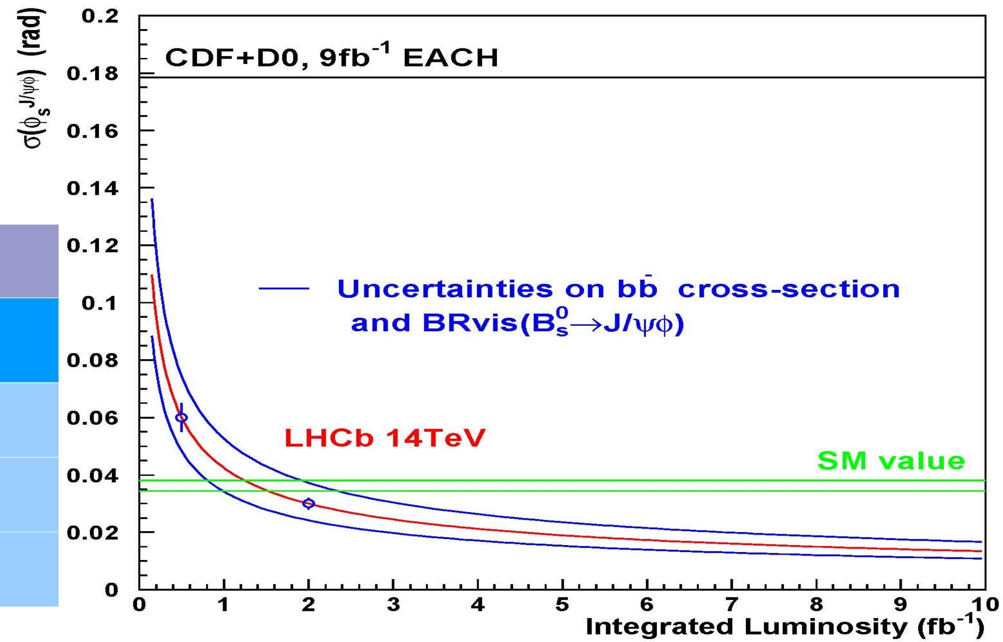




$B_s \to J/\psi\varphi$

LHCb prospects (2 fb^{-1}) sample
Expected yield 117k Bs → J/ψ events

Sensitivities (one nominal year)			
	Lumi. Int.	**φ_s**	**$\Delta\Gamma_s$**
LHCb	2 fb^{-1}	0.03	0.01
CMS	10 fb^{-1}	0.06	0.01
ATLAS	10 fb^{-1}	Under study	



In $B_s \to \varphi\varphi$ tree and penguin contributions are about equal and opposite

$_s$ $= -2\beta_s + \Delta$ ≈ 0 in SM

Good indicator for new physics: $\phi_s^{NP} = \phi_s^{\phi\phi} - \phi_s^{J/\psi\phi}$

Other channels are under study e.g.
$B_s \to J/\psi$ f0 , f0 → $^+$ $^-$. Looks promising
if this CP-eigenstate mode has sufficiently large BR as indicated by CLEO

The angle γ

Present precision in γ is obtained largely from processes involving box diagrams

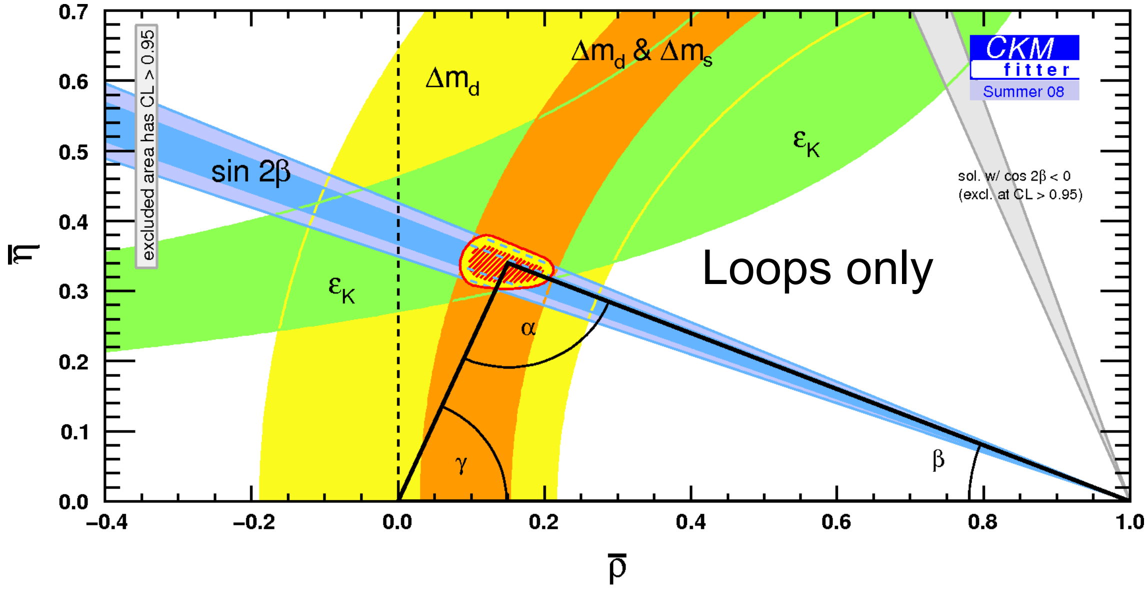
Not yet very precise (20 degrees):

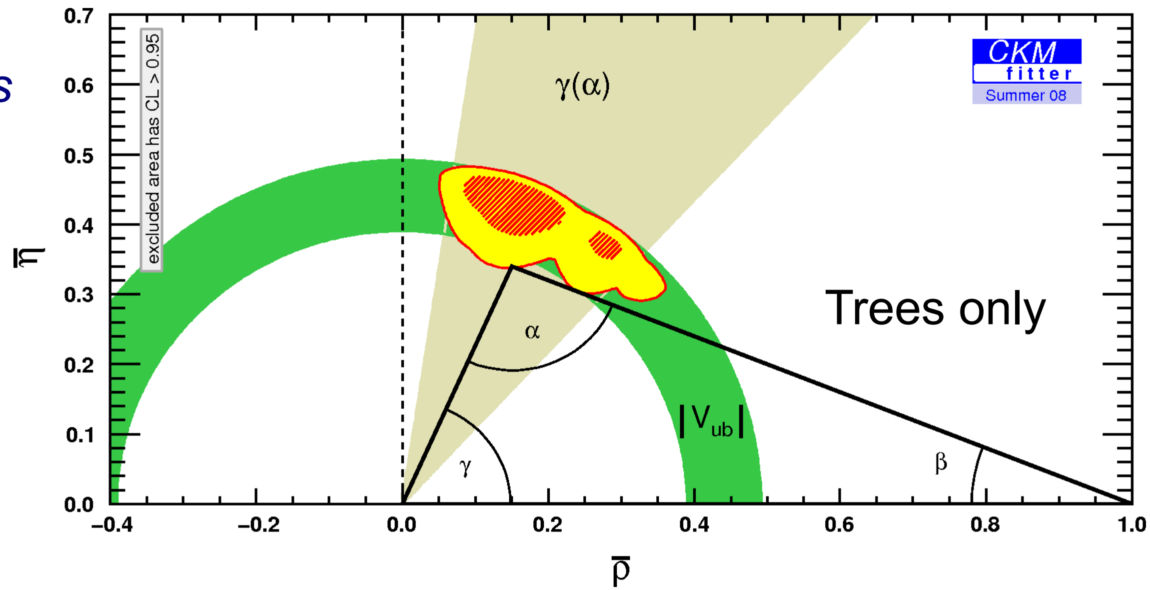
Dalitz analyses:
BELLE: γ = (78.4 ±10.8/11.6±3.6±8.9)°
BABAR: γ = (76±22±5±5)°
(see talk of Tagir Aushev)

Interesting to compare loop and tree measurements

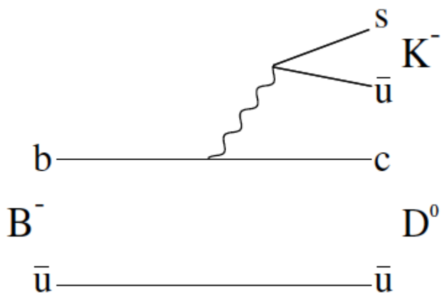
Tree-only measurements can be used as "SM values" and are not sensitive to NP

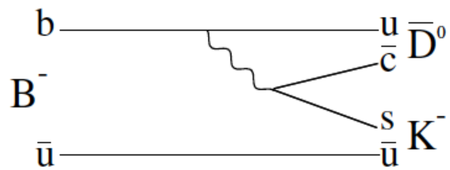
At the LHC measurement unique to LHCb:
Involves B→D decays

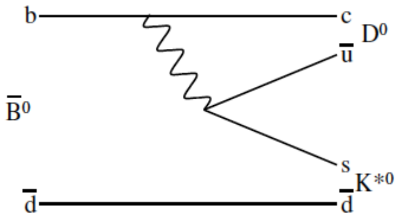


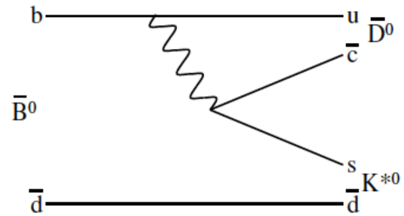


γ in tree processes









Many decay channels can be used – ***decay of D flags CP/flavour eigenstate***

Direct CP violation in asymmetries (rates)

GLW method: B→DK with D→ CP eigenstates

*$B^{\pm}\to D(K^+K^-)K^{\pm}$ and $B^{\pm}\to D(\pi^+\pi^-)K^{\pm}$ and neutral B with K**

ADS method: B→DK with D→ flavour eigenstates

*$B^{\pm}\to D(K^+\pi^-)K^{\pm}$ and $B^{\pm}\to D(\pi^+K^-)K^{\pm}$ and neutral B with K**

GGSZ method: Dalitz analysis of $D\to\pi^+\pi^-K_s$

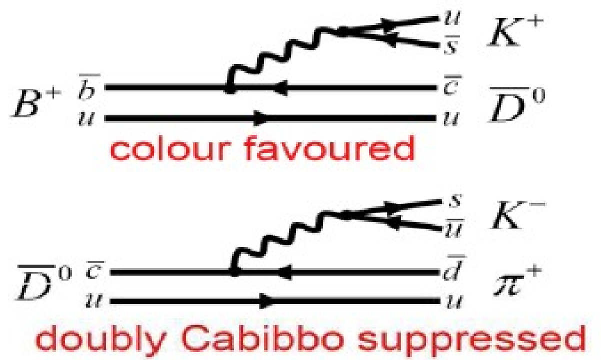
*$B^{\pm}\to D(\pi^+\pi^-K_s)K^{\pm}$ and neutral B with K**

Time-dependent analyses:

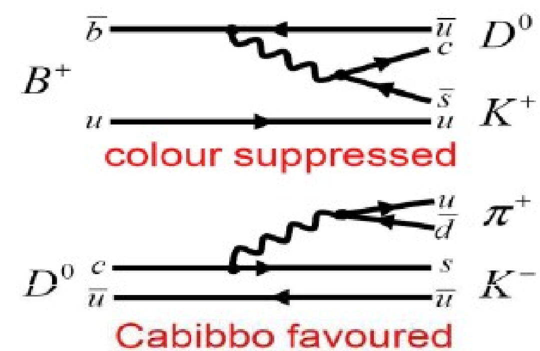
$B_s\to D_sK$ and $B\to D\pi$

Combined ADS/GLW analysis

Combination of ***colour suppressed/Cabibbo favoured*** *D decays and* ***Cabibbo suppressed/colour favoured*** *modes increases CPV sensitivity*



Time-integrated measurements of self-tagging modes
Combined analysis needed to constrain "nuisance parameters" (amplitude ratio of suppressed mode, and strong phases)



Rates in one nominal year in LHCb

Mode	Rate in 2 fb^{-1}
$B^\pm \to D(K\pi)_{FAV} K^\pm$	83800
$B^\pm \to D(K\pi)_{SUP} K^\pm$	1600
$B^\pm \to D(KK) K^\pm$	8460
$B^\pm \to D(\pi\pi) K^\pm$	3000
$B^0 \to D(K\pi)_{FAV} K^*$	4000
$B^0 \to D(K\pi)_{SUP} K^*$	360
$B^0 \to D(hh) K^0$	460

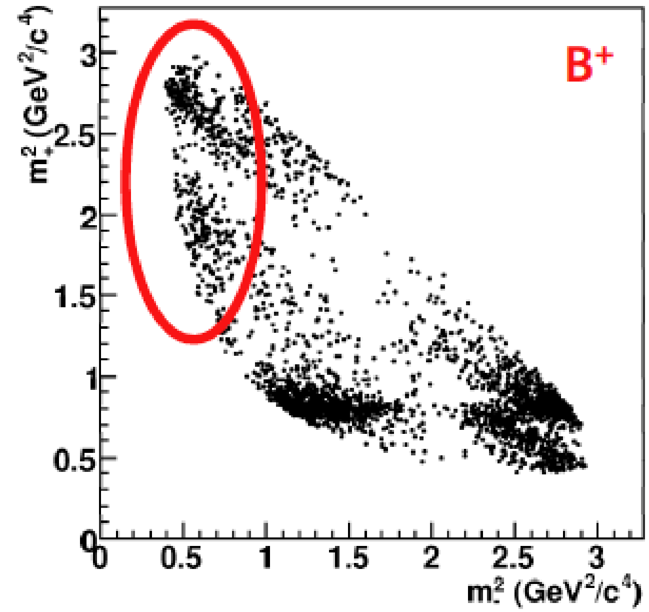
Neutral modes can give similar precision

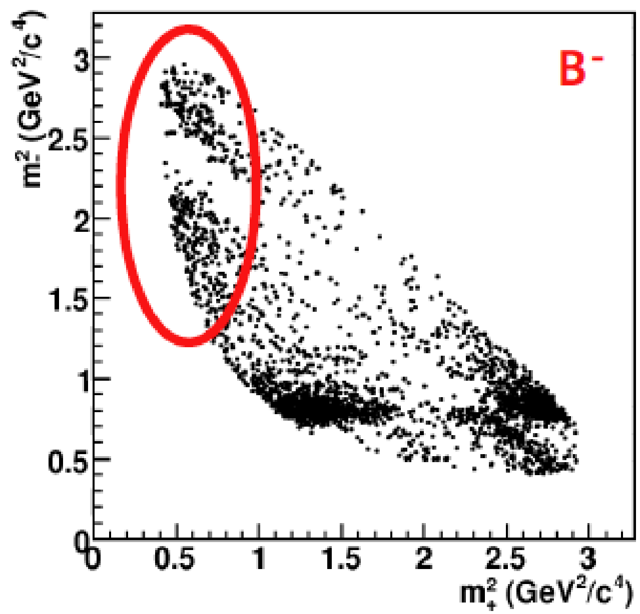
Combined tree analysis for γ

Final result will come from combination of time-integrated rates (ADS/GLW), Dalitz analyses, and time dependent analyses

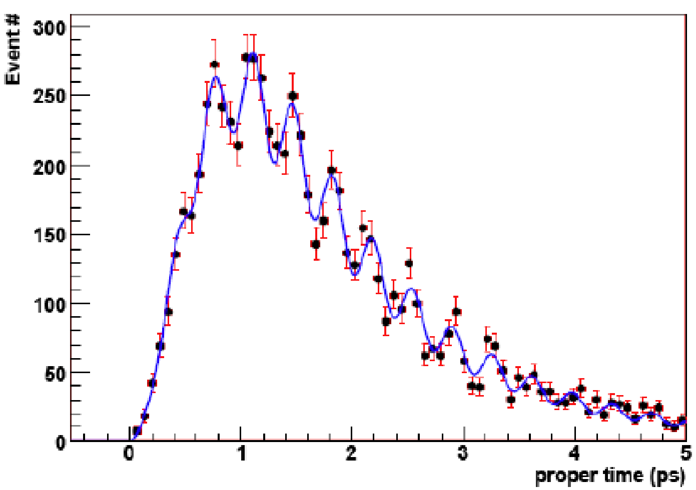
GGZW analysis exploits differences in B^+ and B^- modes in $D(\pi^+\pi^- K_s)$ decay

Single analysis with highest sensitivity





*Combination of **time-dependent** analyses: $B_s \rightarrow D_s K$ and $B \rightarrow D\pi$ time dependent asymmetry*

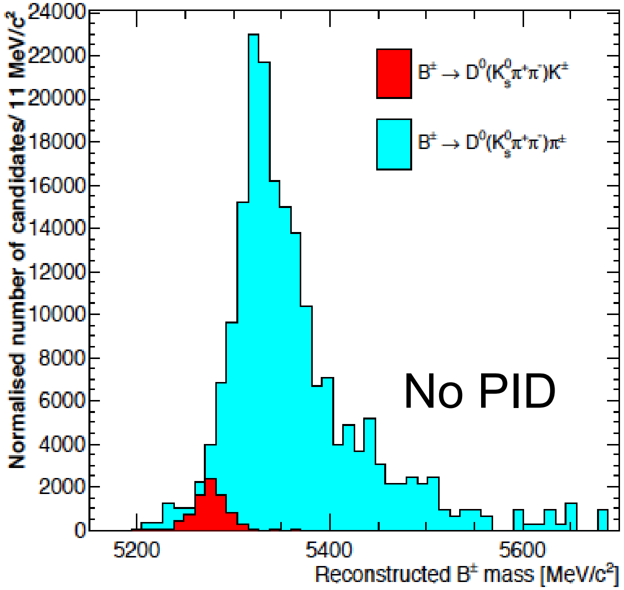


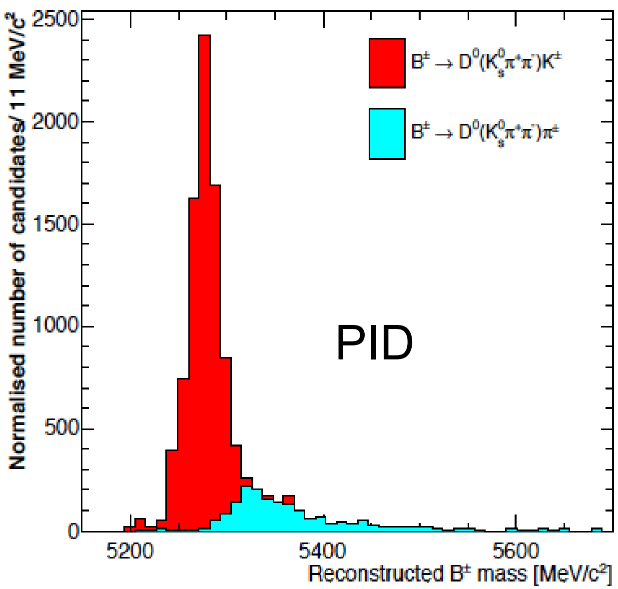
sensitivity reachable in γ if all methods combined In 2 fb^{-1}:

σ(γ) = 4-5°

Importance of hadron PID

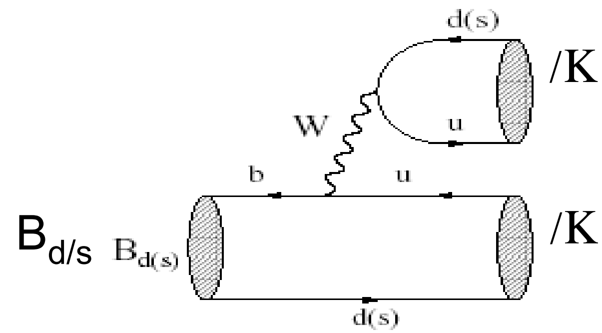
Analysis of $B^{\pm}\rightarrow D(\pi^{+}\pi^{-}K_{s})K^{\pm}$

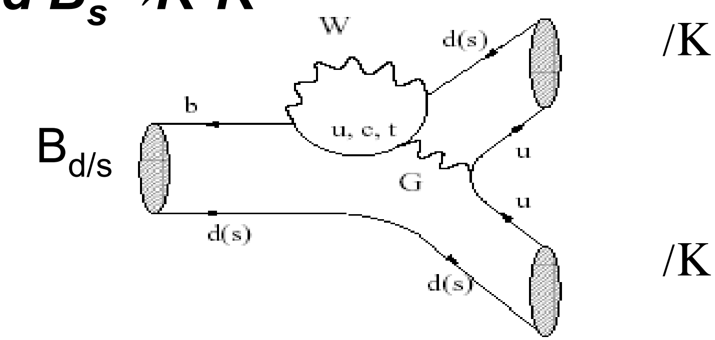




Measurement of γ in penguins

Large penguin contribution in both $B^0 \to\ ^+\ ^-$ and $B_s \to K^+K^-$ sensitive to NP





Time-dependent CP asymmetries *$ACP(t) = A_{dir} \cos(\Delta mt) + A_{mix} \sin(\Delta mt)$*

depend on γ, mixing phases, and ratio of penguin to tree = $d\, e^{i\theta}$

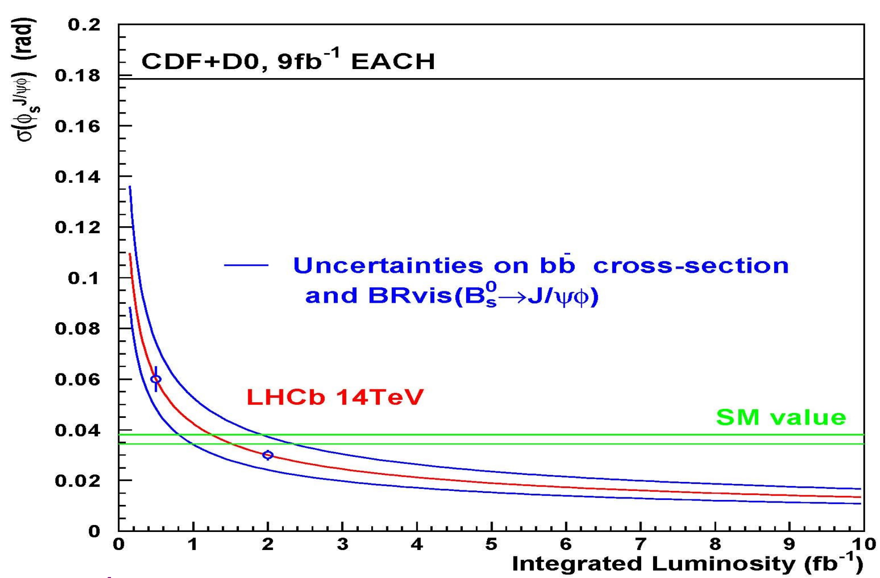
exploit "U-spin" symmetry (d↔s)

assume $d_{\pi\pi} \approx d_{KK}$ within ±20% and

$\theta_{\pi\pi} \approx \theta_{KK}$ within ±20°

4 measurements and 3 unknowns,

if mixing phase 2β taken from $B^0 \to J/\psi K_S$



Expected sensitivity:

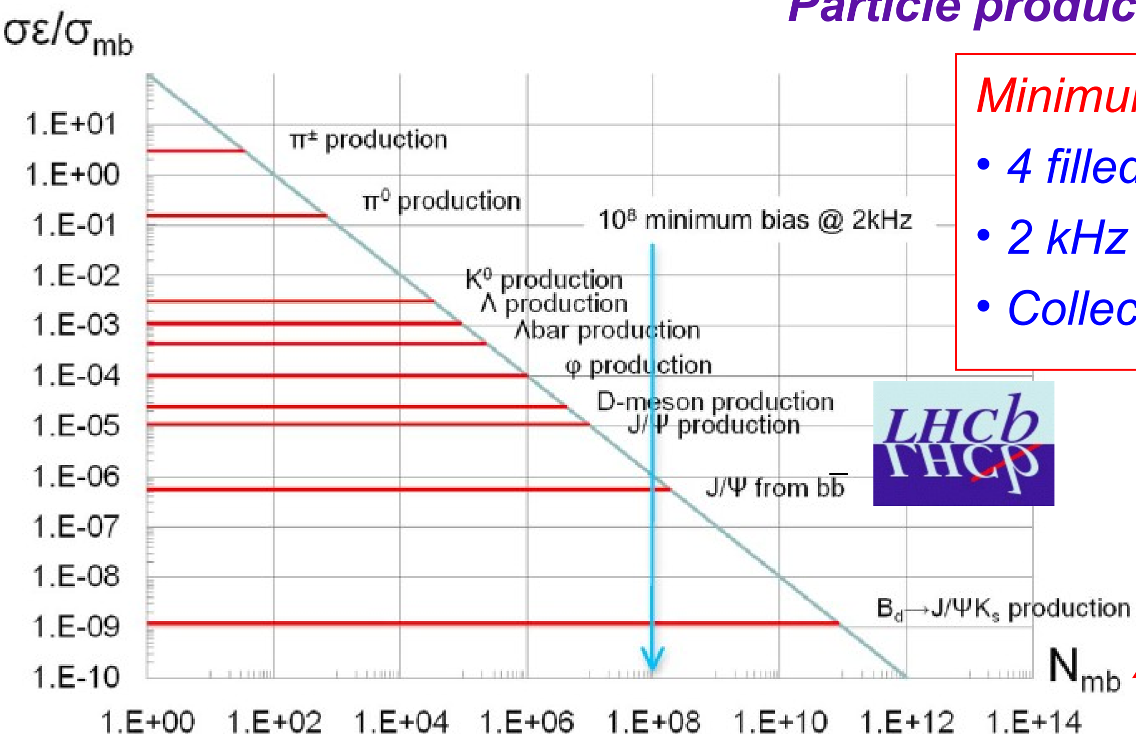
59k $B^0 \to\ ^+\ ^-$ with B/S~0.5

72k $B_s \to K^+K^-$ with B/S~0.07

σ(γ) ~ 7° in 1 year/2fb^{-1}
assuming U-spin symmetry to hold within 20%
Precision comparable to J/ψφ analysis

First physics measurements

Particle production



Minimum bias running

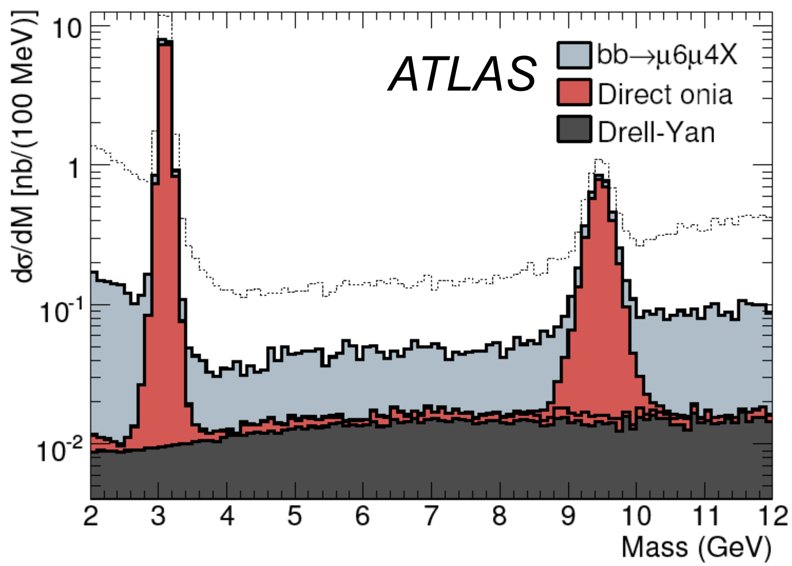
- *4 filled bunches L = 1.1 x 10^{29} $cm^{-2}s^{-1}$*
- *2 kHz minimum bias to disk*
- *Collect 2 x10^{8} events in 100 hours*

 # min bias events needed to perform 10 % measurement

Sample will contain ~500, 000 reconstructed K_s and 2000 J/ψ

- *Alignment, calibration of tracking/PID*
- *Studies of single particle production, generator tuning*
- *K_s , Λ production + polarization + hyperon production*
- *Vector meson production (K*, ϕ)*

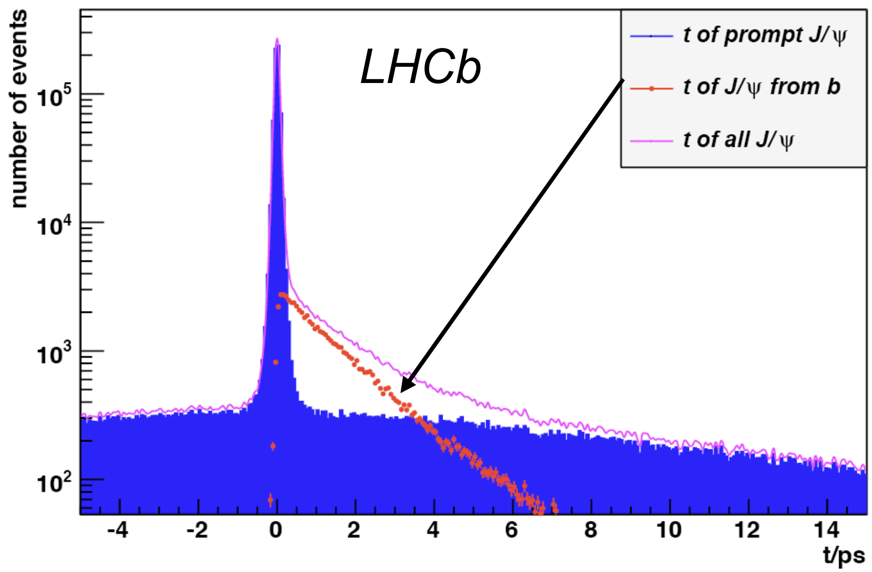
B-production measurements

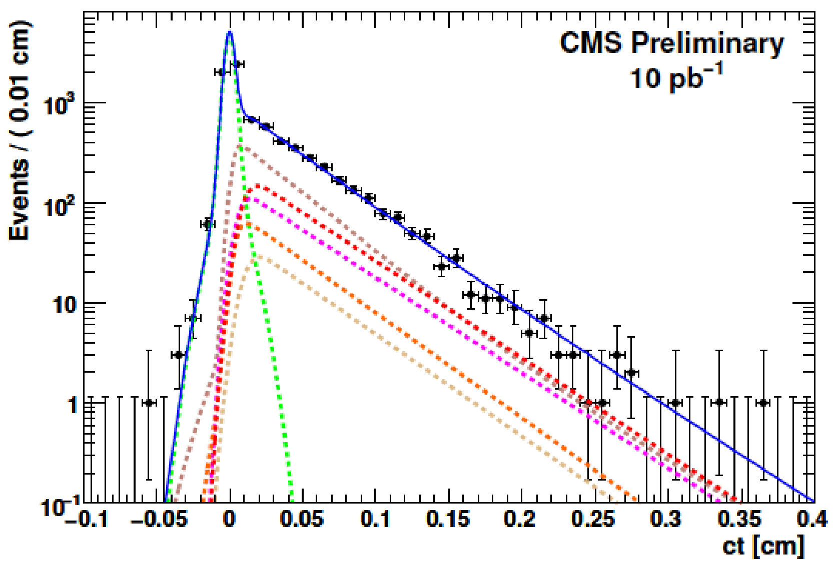


Initial measurements of J/ψ production to establish B production cross-section in new energy domain

Techniques:
- mass peaks
- prompt vs B decay

J/ψ polarization modifies cross-section measurement – must be measured at the same time





Summary

Only some selected key measurements have been shown

Many other interesting measurements will be performed

e.g. Did not mention measurements of α and β

CPV measurements with charm decays (early data!)

B-baryon production

Etc..

LEP, Tevatron, B-factories, have established SM picture in B-decays

The LHC flavour physics programme has the potential to go beyond the standard model