Flavour Physics (III)

Sixth CERN-Fermilab Hadron Collider Physics Summer School

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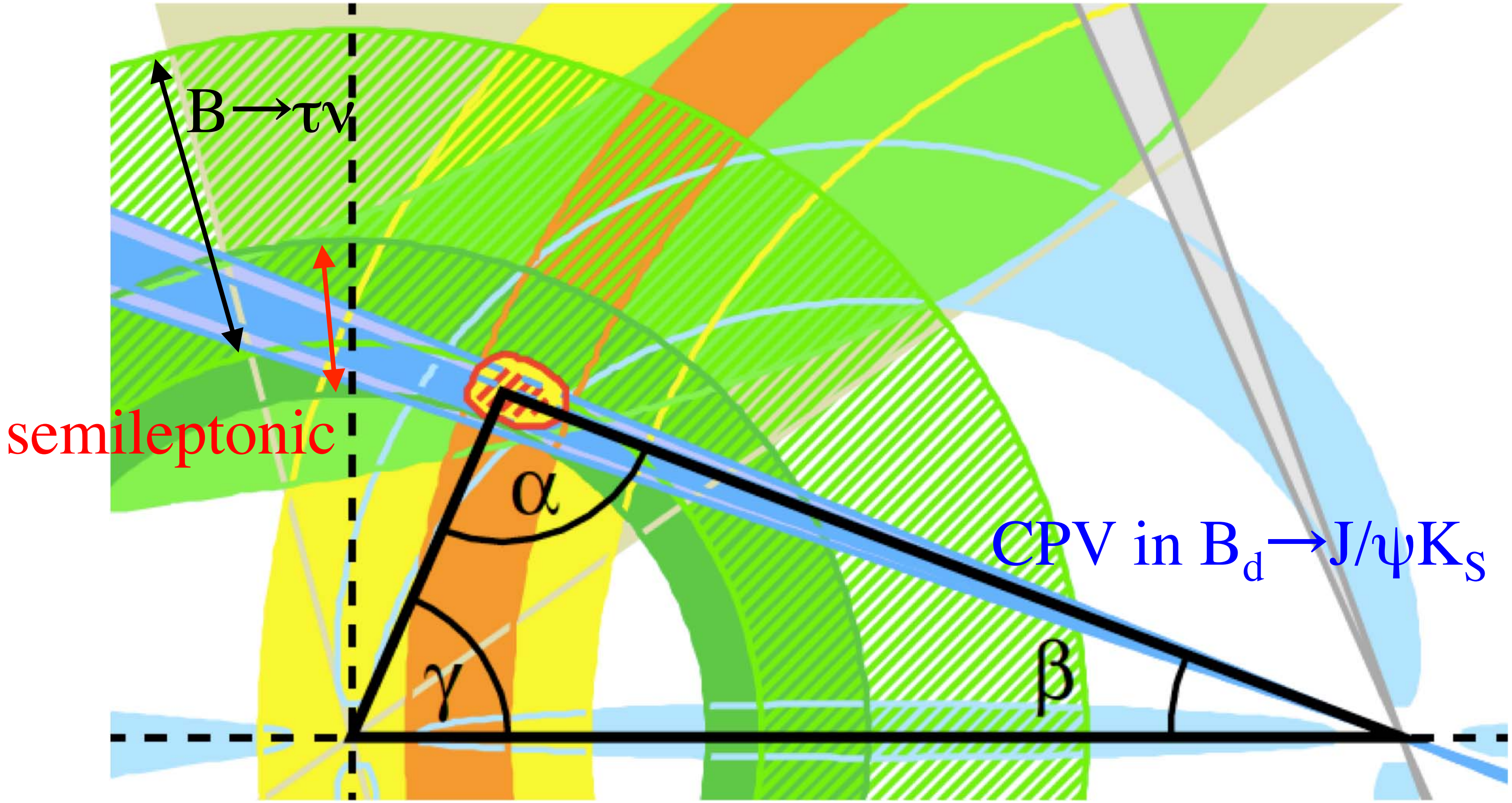
Plan of the lecture today

- Closer Look
- Flavour Physics at Hadron Machines

Closer Look

- If one looks closer, there exists some hint of discrepancies
  - "sin 2β" extracted from CPV in $B_d \to J/\psi K_S$ somewhat small
  - $|V_{ub}|$ extracted from $B \to \tau\nu$ decays larger than $|V_{ub}|$ extracted from the semileptonic decays.



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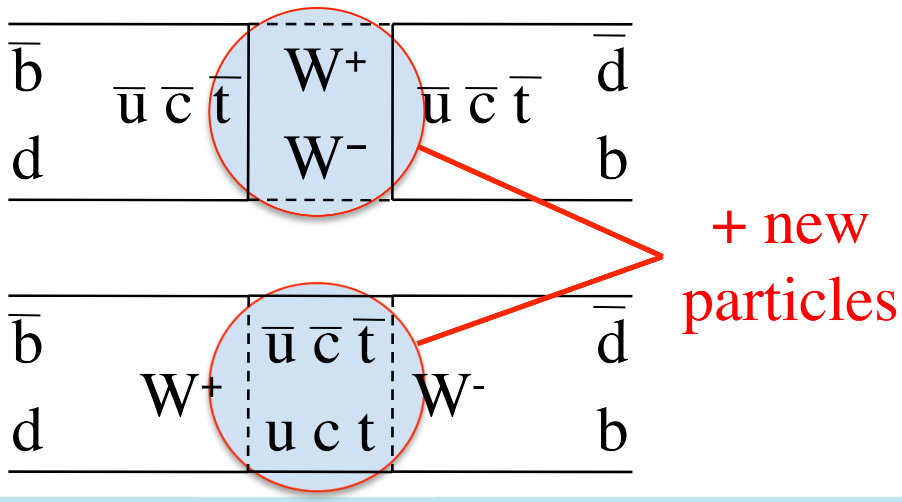
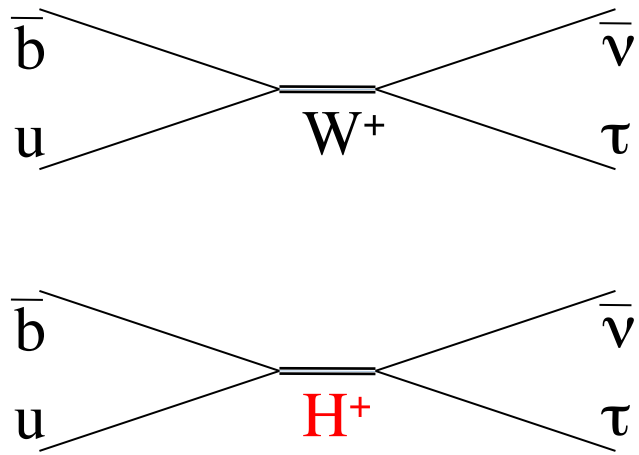
- This could be due to
  1. Problem with extracting $|V_{ub}/V_{cb}|$ due to the hadronic uncertainties

     OR
  2. New Physics in B^0-B^0 oscillations and charged Higgs in $B \rightarrow \tau\nu$





Closer Look

$|V_{cb}|$ and $|V_{ub}|$

Errors are dominated by the theoretical uncertainties in the strong interaction for the semleptonic decays.

⇒can be reduced by studying the decay kinematics,

e.g. lepton momentum, hadronic-mass distribution, etc.

with higher statistics in a clean environment

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with higher statistics in a clean environment

Case for Super B Factories: One B fully reconstructed, all remaining particles belong to other B!

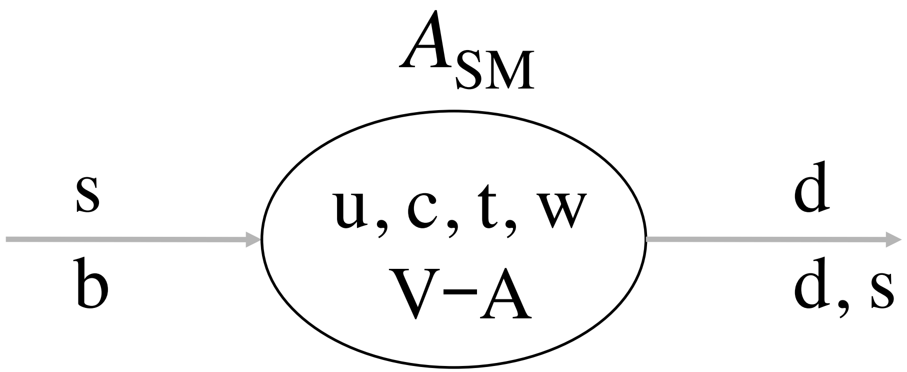
$|V_{ub}|$ from $B^{\pm} \to \tau^{\pm}\nu$ error still statistics limited.

Another case Super B Factories

But there are more…

Closer Look

In general, new physics can enter in the loop diagrams as virtual states



Closer Look

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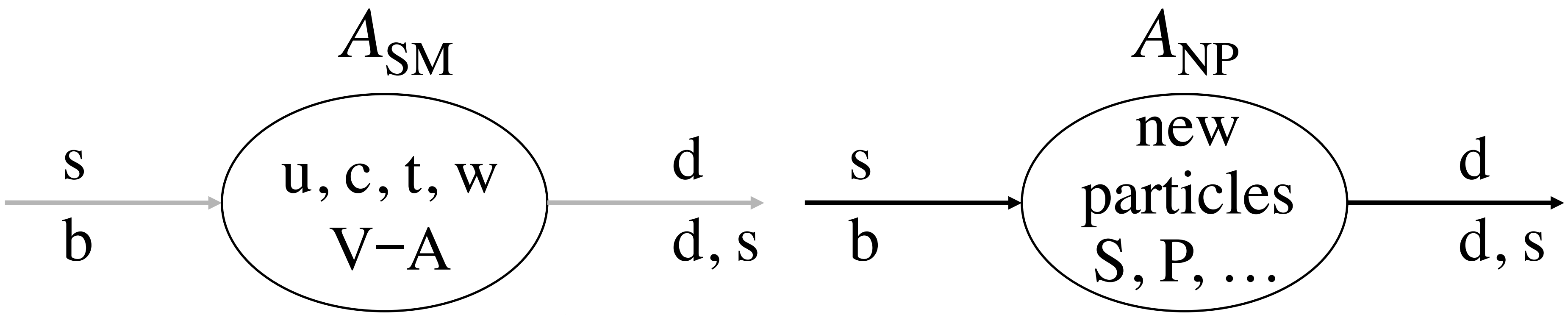

amplitude: $A = A_{SM} + A_{NP}$

Closer Look

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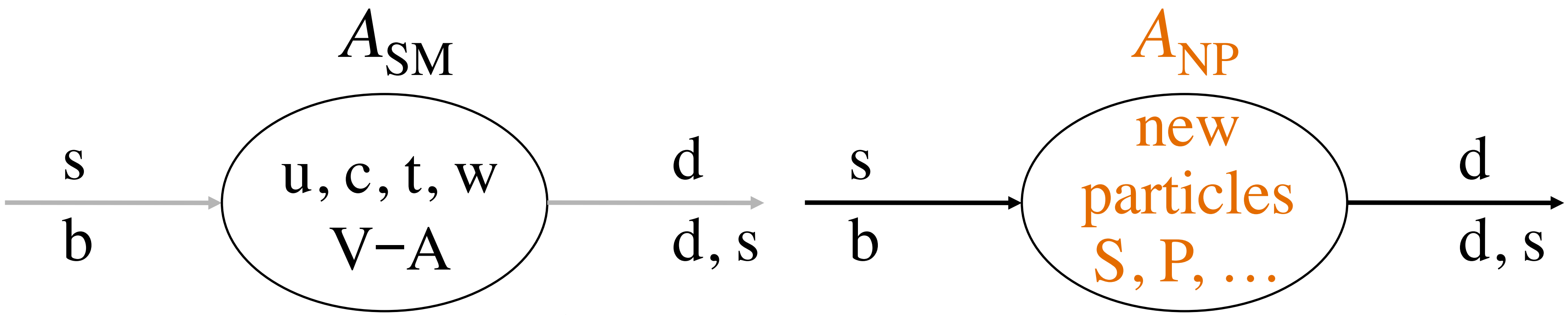

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$|A|$: rare decays, Δm

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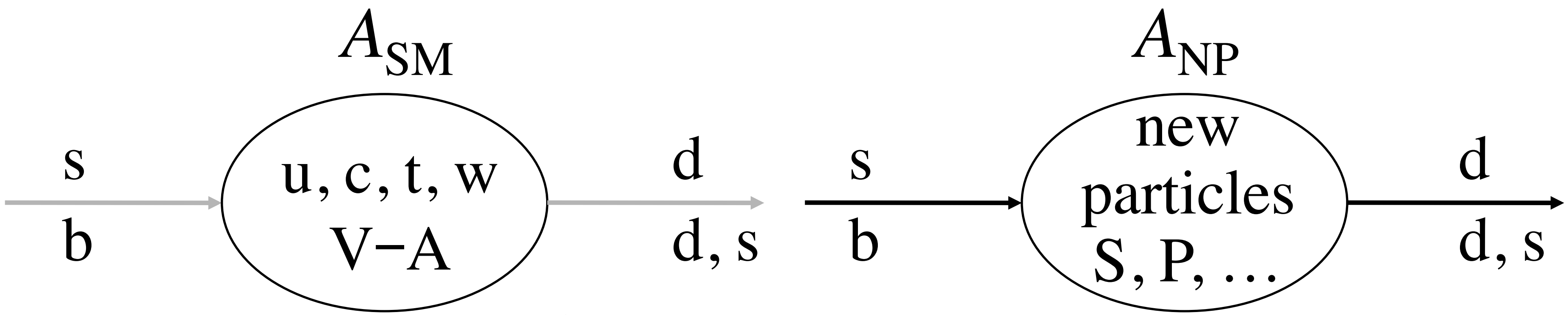

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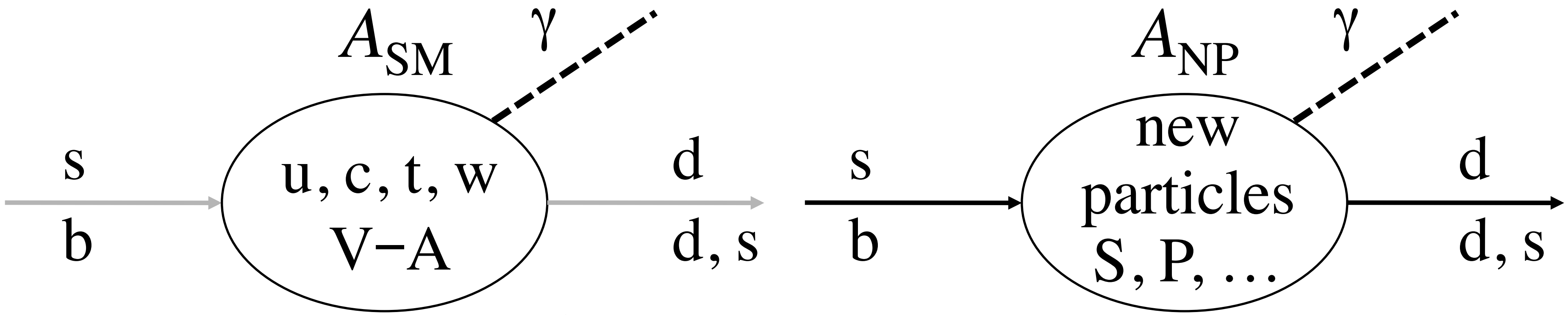

amplitude: $A = A_{SM} + A_{NP}$

|A|: rare decays, Δm

arg A: CP violation

Lorentz structure of A: "photon" polarization via

final state angular distribution or mixing-decay CP violation

Closer Look

- Current experimental limits on new physics are still very large, up to *O*(10) or more above the SM values:
  - $B_s \rightarrow \mu^+\mu^-$
  - CPV in $B_s \rightarrow J/\psi\phi$
  - Lorentz structure in $b \rightarrow s$ radiative decays, $B^0 \rightarrow K^{*0}\mu^+\mu^-$, CPV in $B \rightarrow \phi\gamma$, etc.
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  - CP violation in D system
- Comparison of (ρ, η) determined from the tree processes, i.e. $|V_{ub}|$ and γ ($B \to DK$), and (ρ, η) from the loop processes, i.e. ε_K, β, and $|V_{td}|$.

Those measurements can be done at LHC, in particular with LHCb!

Flavour Physics at Hadron Machines

- fixed target contribution to B had been marginal: i.e. σ_{bb}

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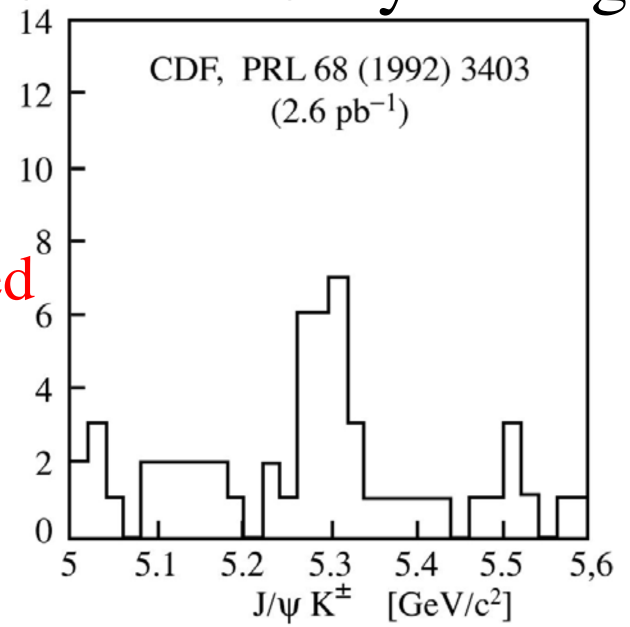
- Tevatron showed its potential already during Run I, thanks to large σ_{bb}

largest number of reconstructed $B^{\pm} \rightarrow J/\psi K^{\pm}$ at that time



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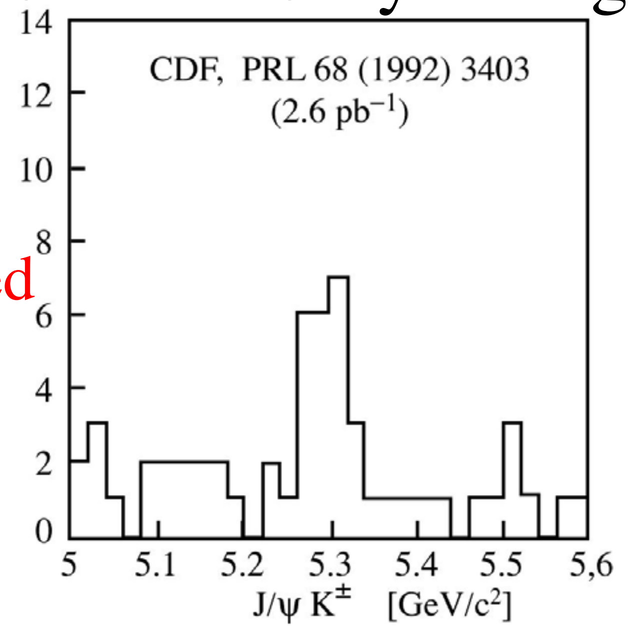

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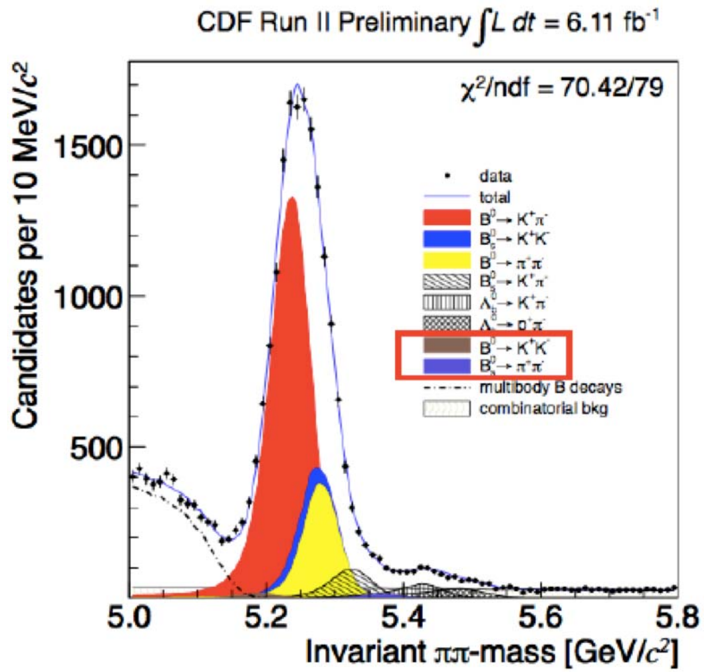
- But significant contributions are during Run II: due to improved *L*, good vertex detectors, and trigger (DCF): b-baryon spectroscopy, lifetimes, B_s-$\bar{B}_s$ oscillation (Δm_s), and $\cancel{CP}$ in $B\to J/\psi\phi$, $\cancel{CP}$ in B_s-$\bar{B}_s$ oscillations, $B^0\to K^{*0}\mu^+\mu^-$, $B_s\to\mu^+\mu^-$, and D physics…

Flavour Physics at Hadron Machines

- CDF and D0 demonstrated that
  - Exclusive b-hadron decay modes (with charged particles, including semileptonic decays) can be well reconstructed
    b-baryon and B_s: very unique and B_s oscillation can be resolved
    B_d: for some decay modes as good as B factories or even better



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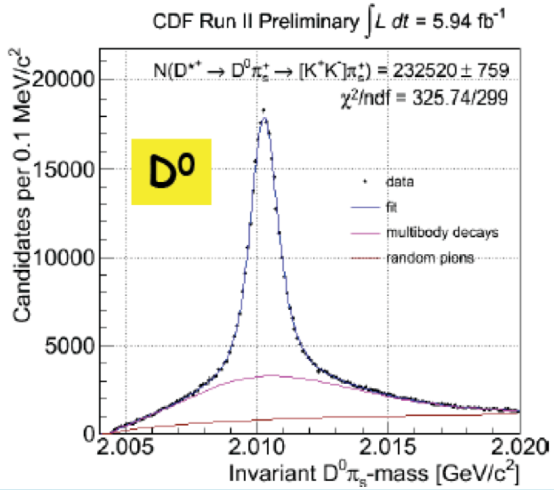
  - Oscillations and CPV study in D system can be done even better than B factories

CDF-Pub-10296

$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24 \pm 0.11]\%$$

$$A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22 \pm 0.10]\%$$



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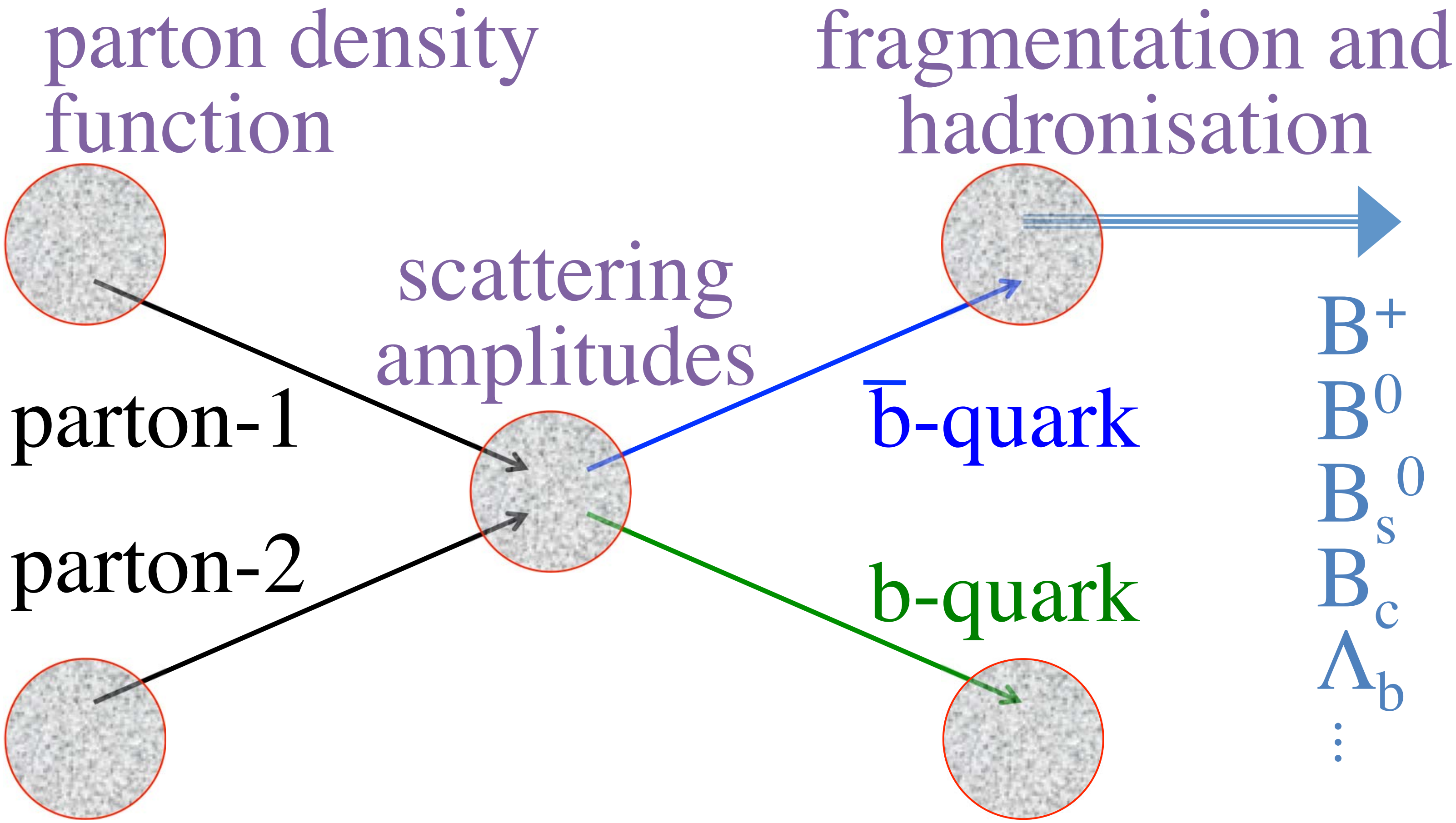
- But, LHC has started with an experiment dedicated for flavour physics, LHCb.

Flavour Physics at Hadron Machines

Production of heavy flavour



Flavour Physics at Hadron Machines

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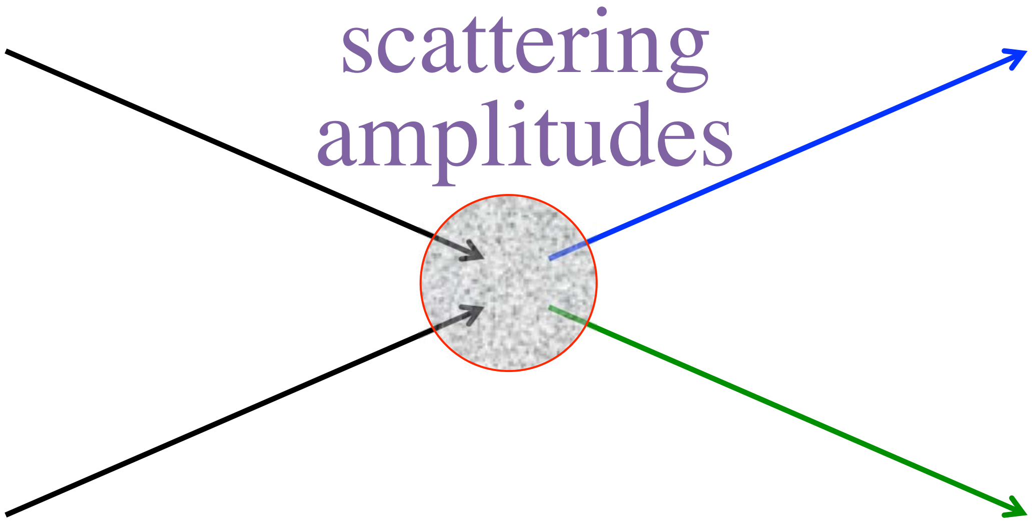
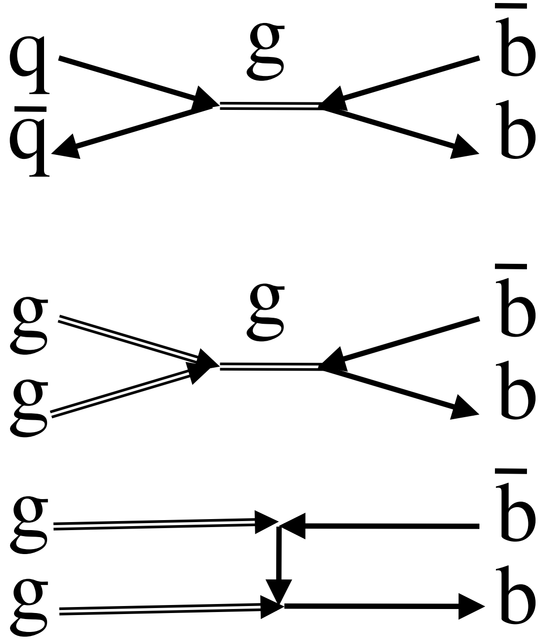


Leading Order

$q\bar{q} \rightarrow b\bar{b}$

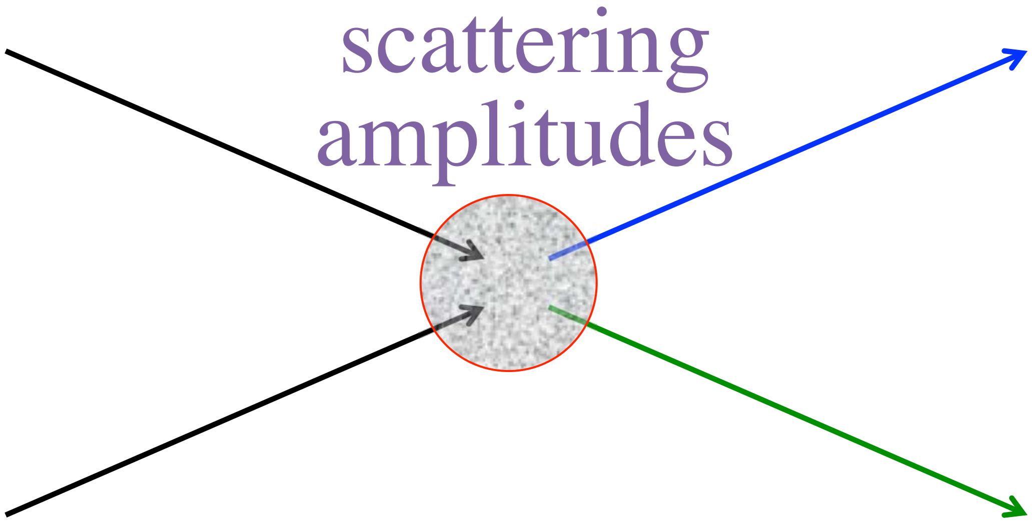
$gg \rightarrow b\bar{b}$

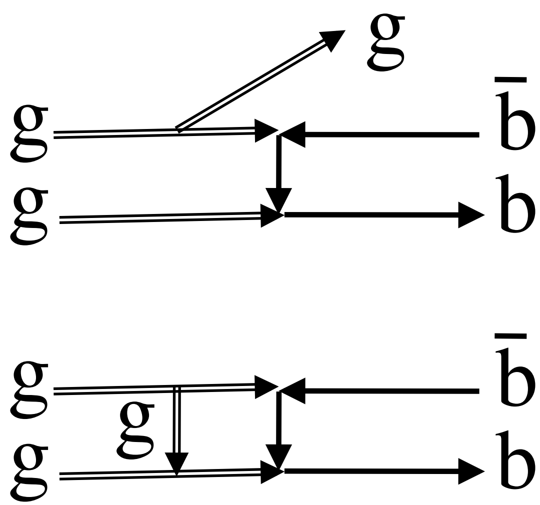


Flavour Physics at Hadron Machines

Production of heavy flavour

Leading Order
$q\bar{q} \rightarrow b\bar{b}$
$gg \rightarrow b\bar{b}$
+ Next to LO
i.e. adding one g





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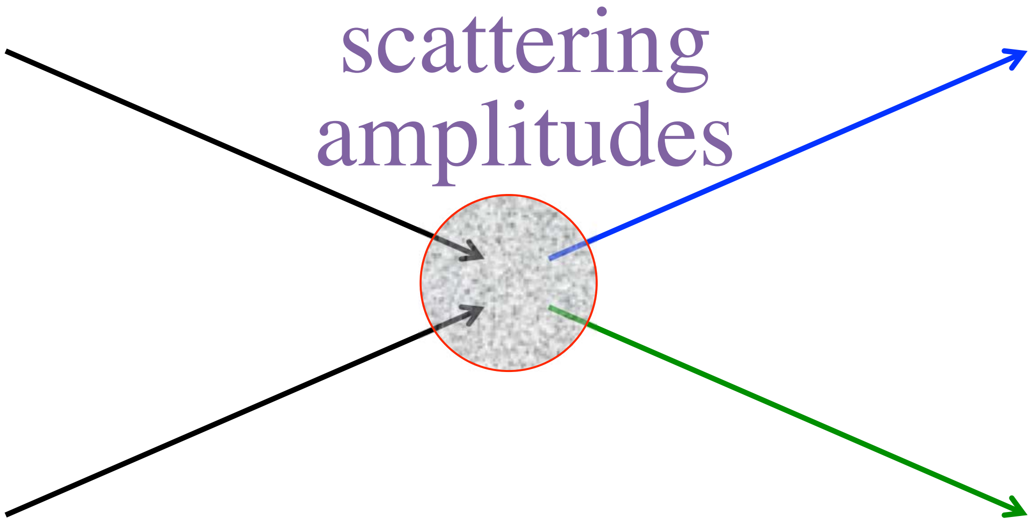
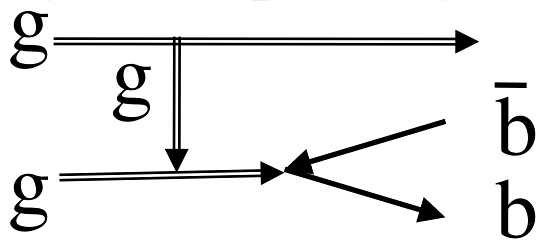
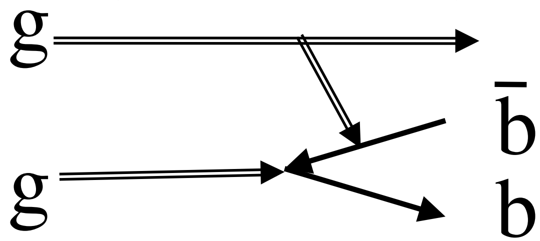


A study by CMS

gluon splitting



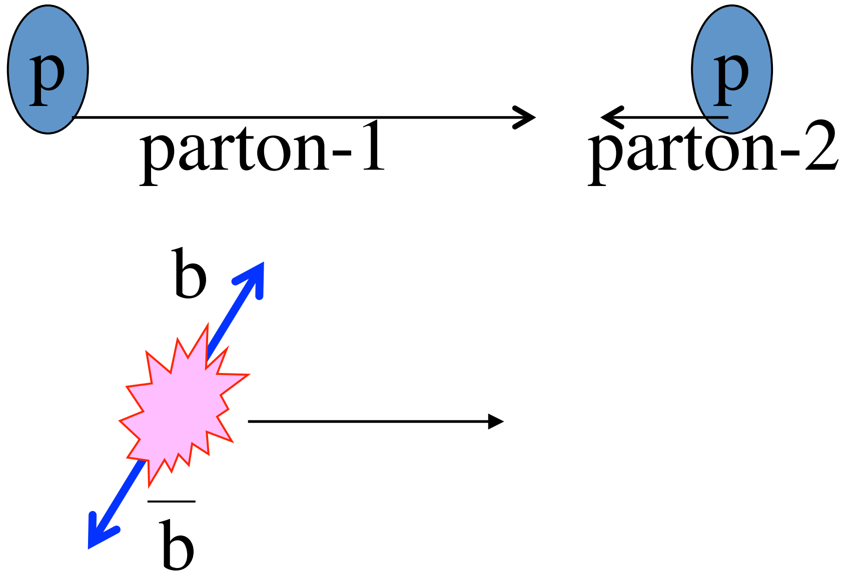
flavour excitation



Flavour Physics at Hadron Machines

Production of heavy flavour

important input for designing an experiment



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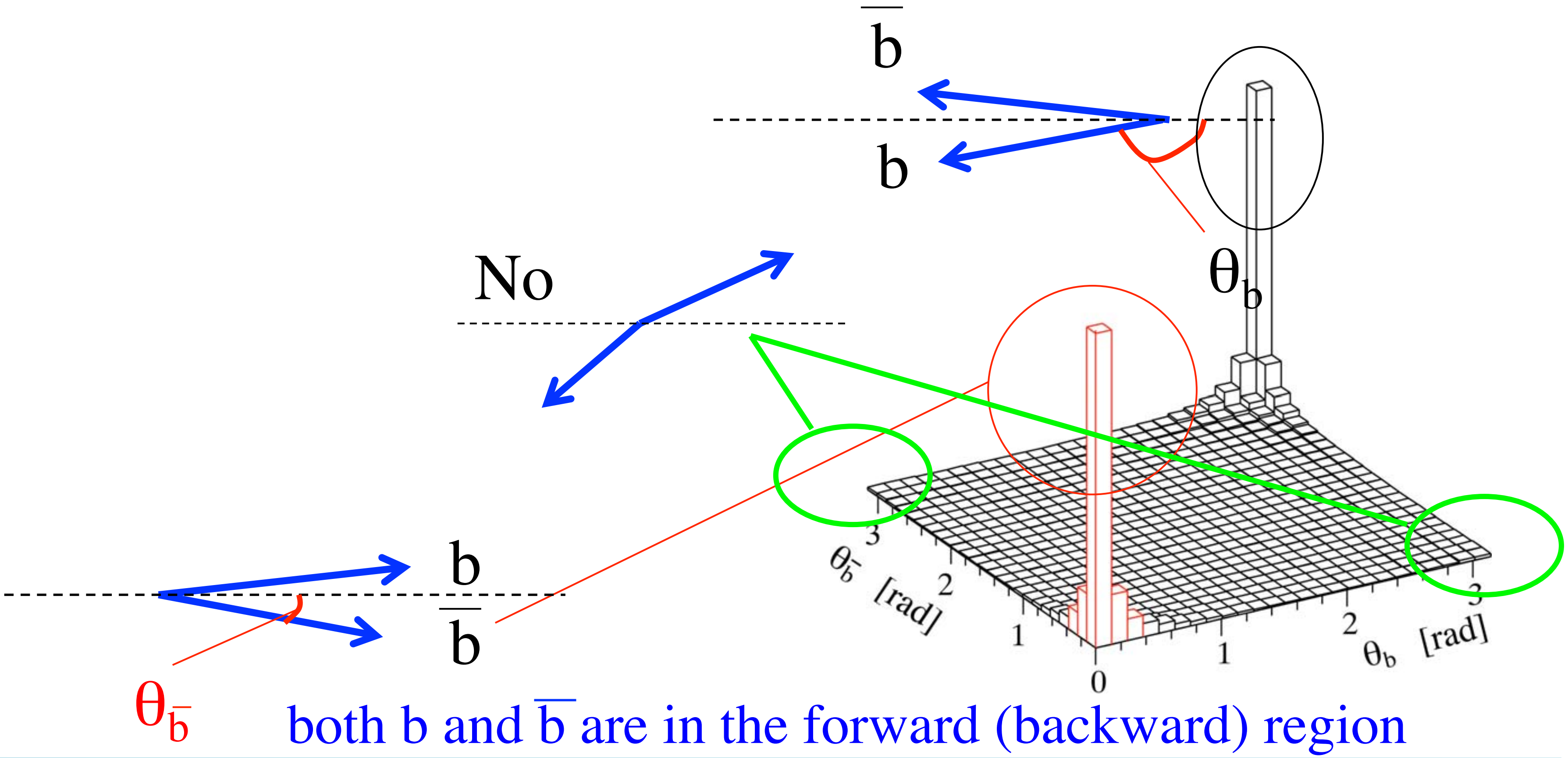
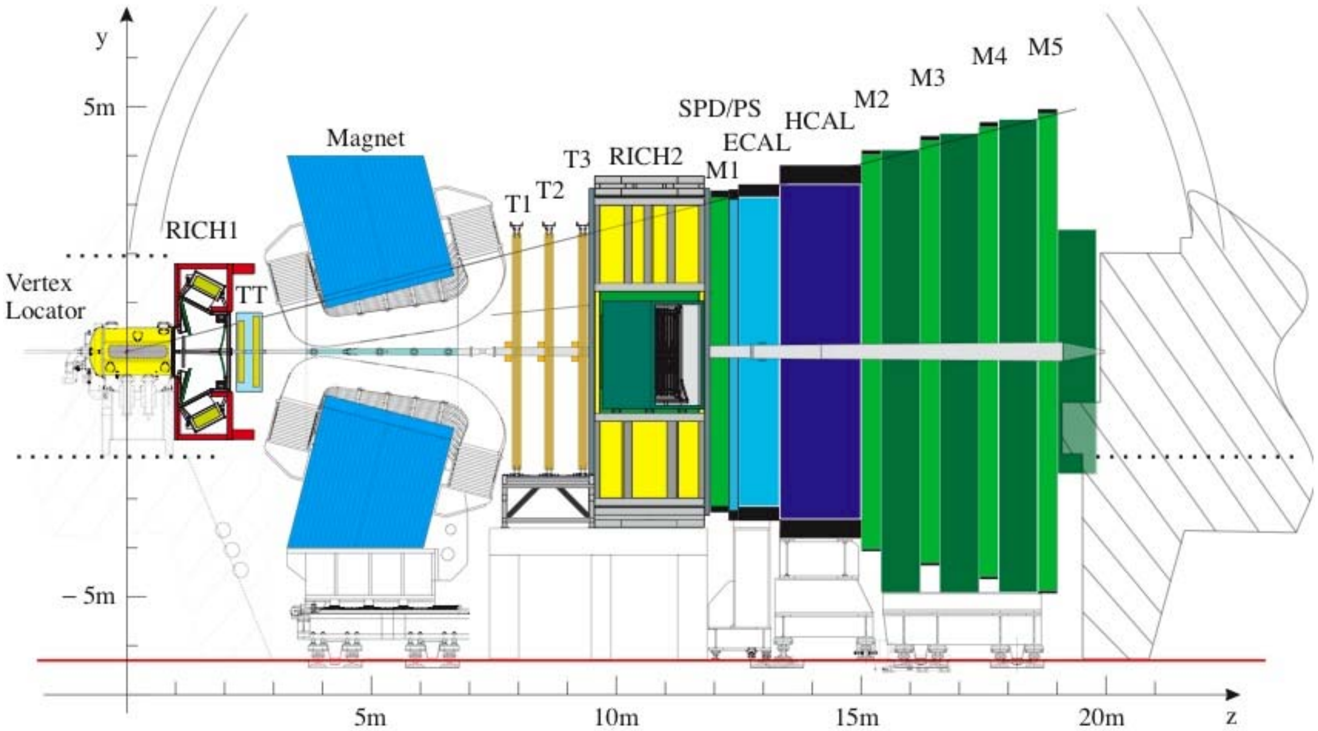


both b and $\bar{b}$ are in the forward (backward) region

Flavour Physics at Hadron Machines

that is why LHCb is a forward spectrometer



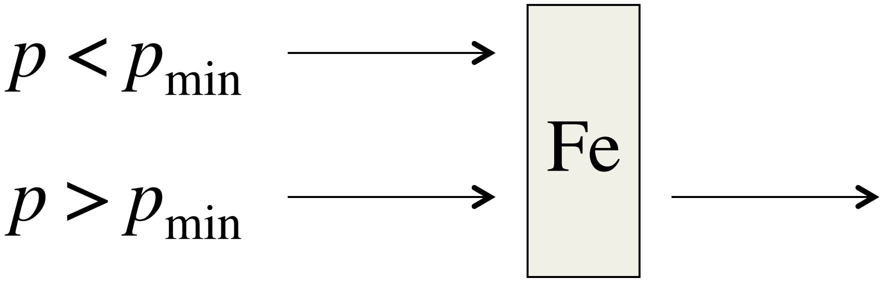
Flavour Physics at Hadron Machines

and additional advantage is

For triggering…. $p > p_{\text{min}}$

muon: identification

hadron: energy resolution



$\sigma_E/E \approx \sqrt{70\%}/\sqrt{E}$

Flavour Physics at Hadron Machines

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muon: identification

$p < p_{\mathrm{min}}$ $\longrightarrow$ Fe

$p > p_{\mathrm{min}}$ $\longrightarrow$ Fe $\longrightarrow$

hadron: energy resolution

$$\sigma_E/E \approx \surd 70\%/\surd E$$

central detector

$p \approx p_T > p_{\mathrm{min}}$

p $\longrightarrow$ $\longleftarrow$ p

forward detector

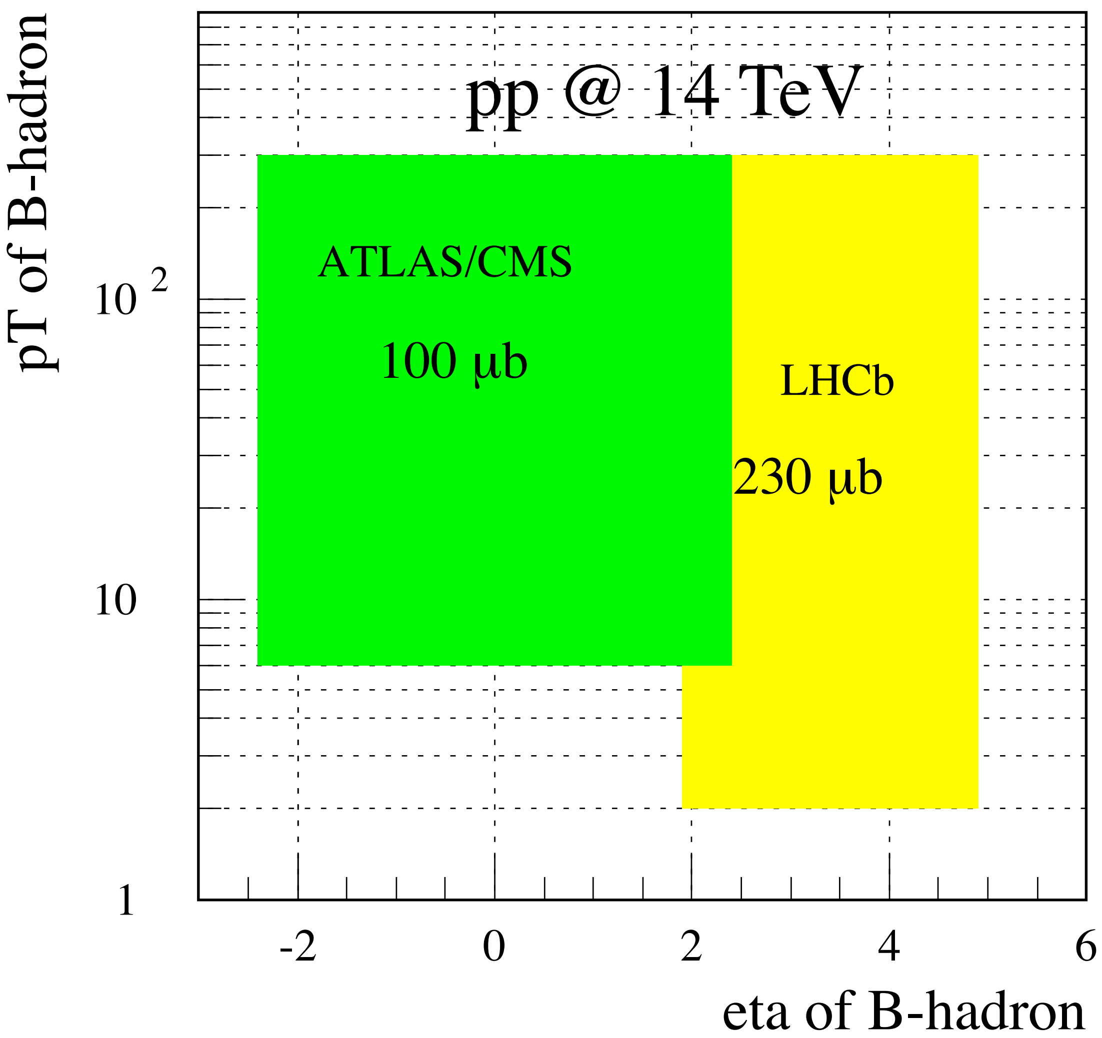
$p \approx p_L > p_{\mathrm{min}}$

p $\longrightarrow$ $\longleftarrow$ p

forward: p_T threshold can be set low: → high b efficiency

Flavour Physics at Hadron Machines

can exploit low p_T particles



Flavour Physics at Hadron Machines

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

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

examples are

$B_{(s)}^0 \to l^+l^-$, h^+h^-, $B_s^0 \to D_s(K^+K^-\pi^-)\,\pi^+$, $B^+ \to D(K_S\pi^+\pi^-)\,K^+$

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K_S not seen by the vertex detector, π^0 and γ can be **associated** to a reconstructed vertex (if not too many)

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

but not

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

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

Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:

-larger cross section (measured also by ATLAS and CMS)

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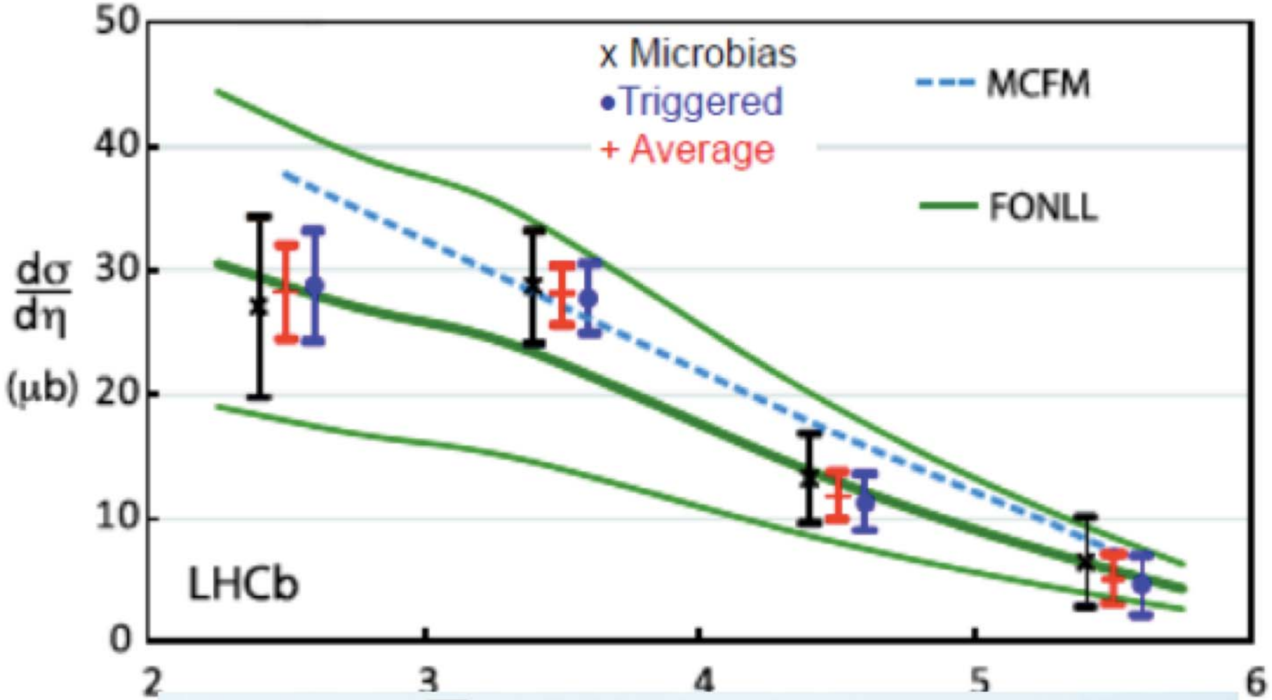
one of the very early measurements at LHCb

Phys Lett B 694 (2010)



$\sigma(pp \rightarrow b\bar{b}X) = 284 \pm 20 \pm 49\ \mu b$

Flavour Physics at Hadron Machines

An interesting example of semi inclusive reconstruction

$B^+ \rightarrow \overline{D}^0(\rightarrow K^- \pi^+) X \mu^+ \nu$

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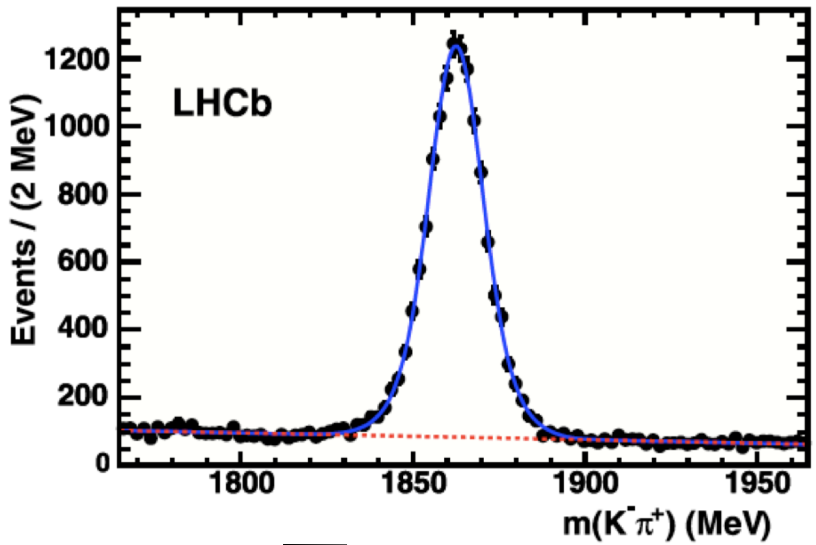
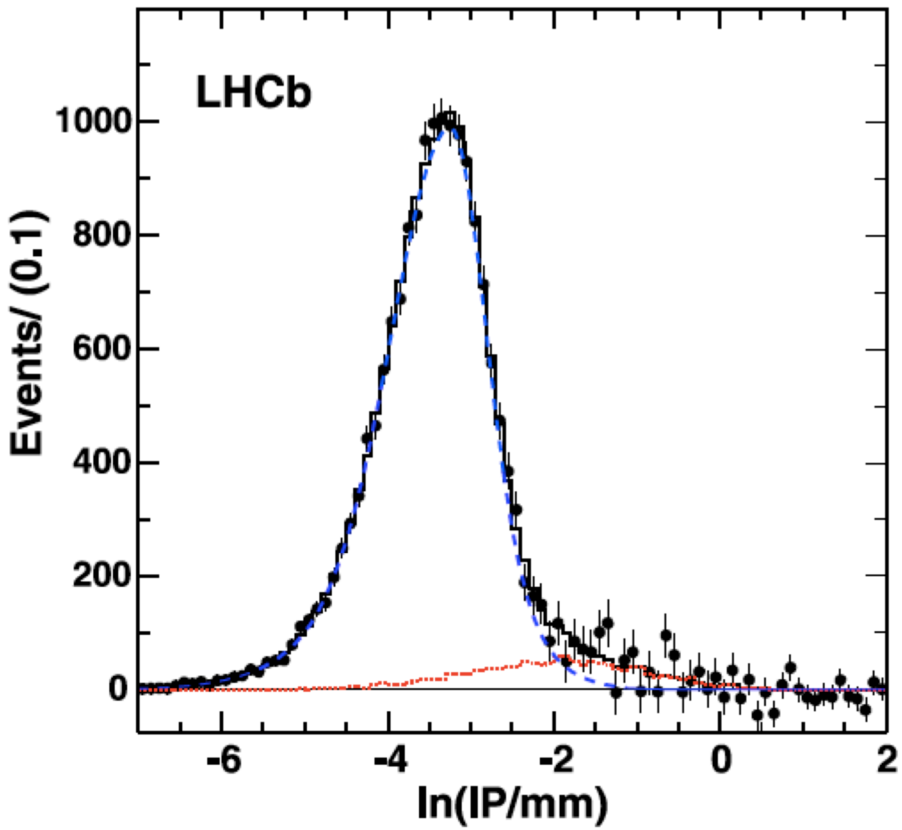


$\overline{D}^0(\rightarrow K^- \pi^+)$

$+D^0(\rightarrow K^- \pi^+)$



$\overline{D}^0$ and D^0

created at the primary vertex: pointing to PV, small IP

decay from b: not pointing to PV, large IP

Flavour Physics at Hadron Machines

An interesting example of semi inclusive reconstruction

$B^+ \to \overline{D}^0(\to K^-\pi^+)X\mu^+\nu$

B component can be increased by combining with μ^+ with appropriate $D(K^-\pi^+)\mu^+$ invariant mass

Non-B component form $D(K^-\pi^+)\mu^-$

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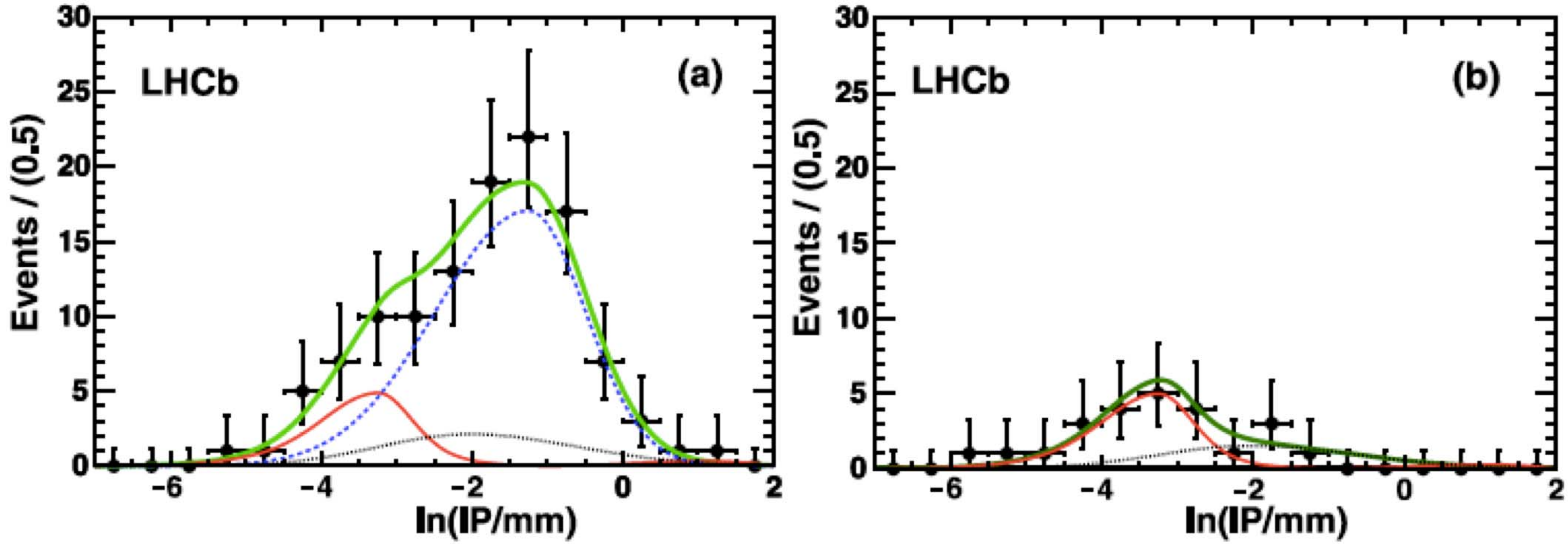

Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:

- -larger cross section
- -better invariant mass and proper time resolutions

B_s^0-$\overline{B}_s^0$ oscillations: measure time dependent rates for

$$B_s^0{}_{\text{initial}} \Rightarrow \overline{B}_s^0{}_{\text{at } t}$$

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flavour tagging of the initial state

$B_s^0{}_{\text{initial}}$

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$\bar{s}$ K^+ same side tag

s

$\bar{b}$ $B_{s\ \mathrm{initial}}^0$

b

↳ l^-X, $c \to s \to K^-$, secondary vertex with − charge

oposit side tag

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$\bar{s}$ K^+ same side tag

flavour tagging of the final state

s

$\bar{b}$ $B_s^0{}_{\text{initial}} \Rightarrow \overline{B}_s^0{}_{\text{at } t}$

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s

$\overline{b}$ $B_s^0{}_{\text{initial}} \Rightarrow \overline{B}_s^0{}_{\text{at } t}\,(\rightarrow D_s^+\pi^-)$

↳ $K^+K^-\pi^+$

b

↳ l^-X, $c\rightarrow s\rightarrow K^-$, secondary vertex with − charge

opposit side tag

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Advantage of LHCb over CDF and D0 are:

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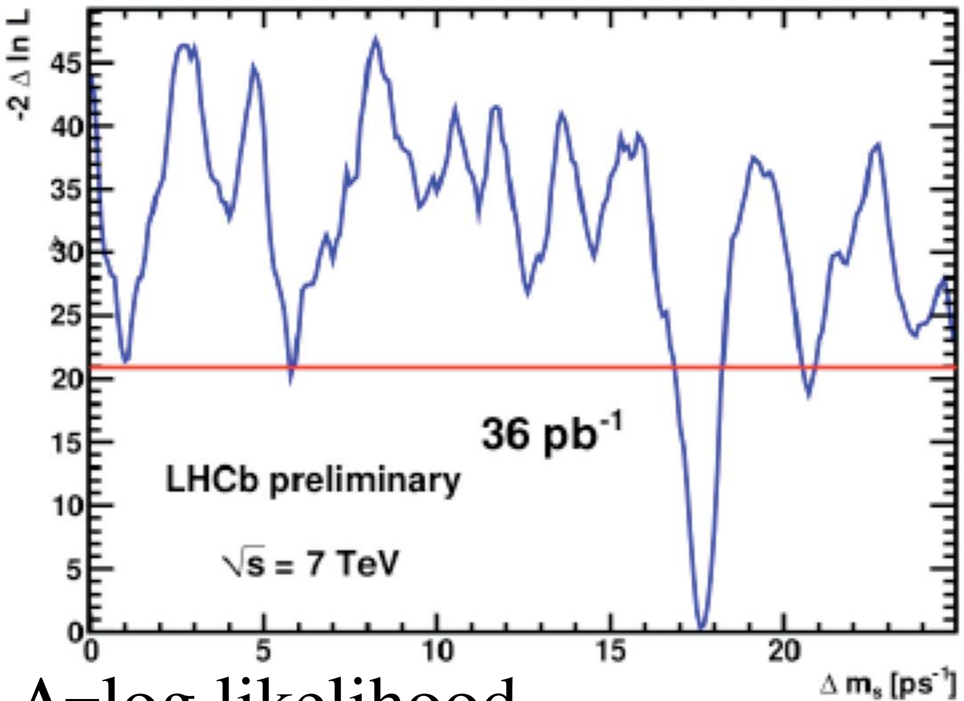
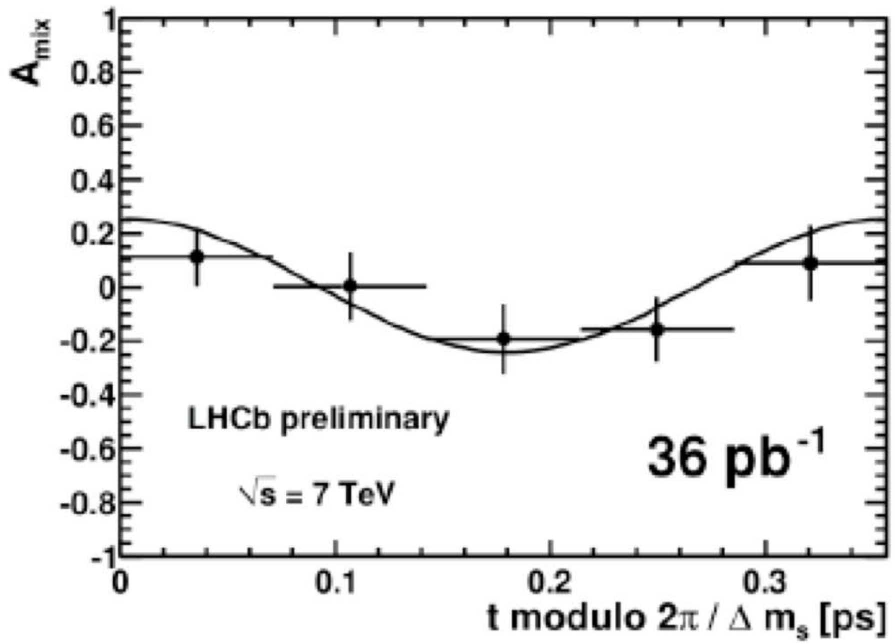
B_s^0-$\overline{B}_s^0$ oscillations: $\frac{1-2\omega}{2}\cos\Delta m_s\times t \otimes \sigma_t$-effect

LHCb-CONF-2011-005



ω = wrong-tag / all-tag



Δ−log likelihood

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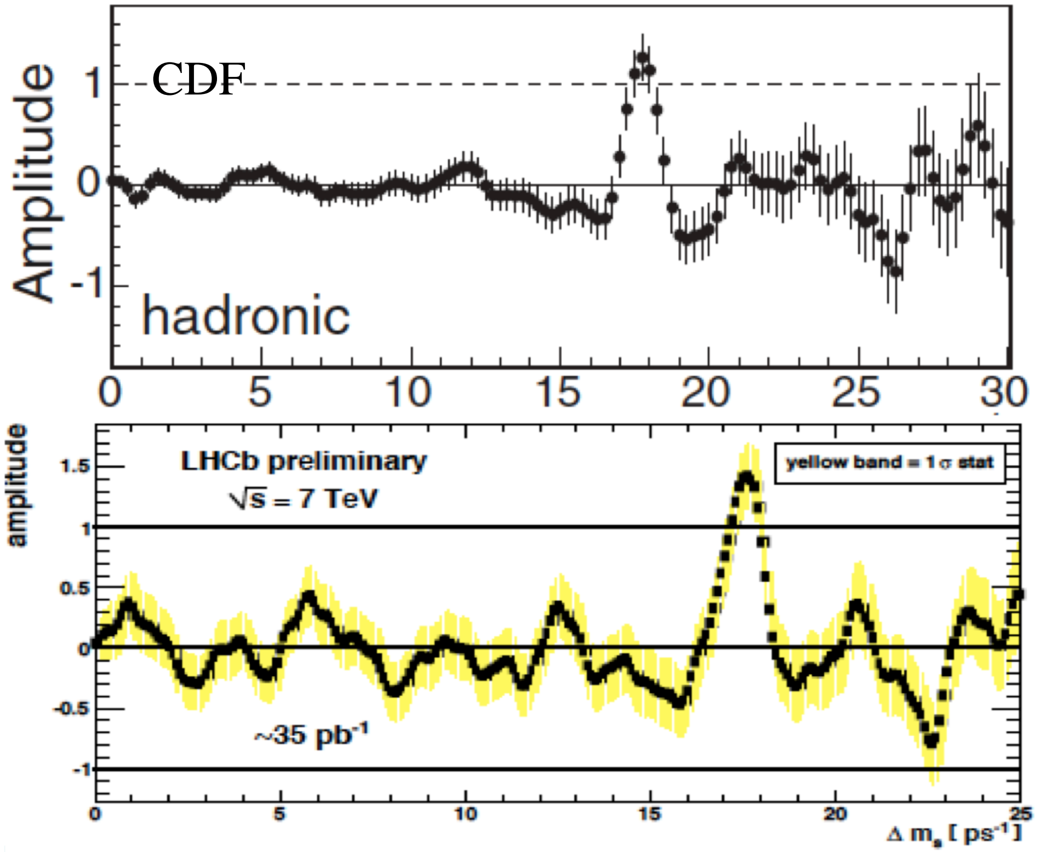

CDF:
1 fb^{-1}

PhysRevLett.97.242003

LHCb:
36 pb^{-1}

LHCb-CONF-2011-005

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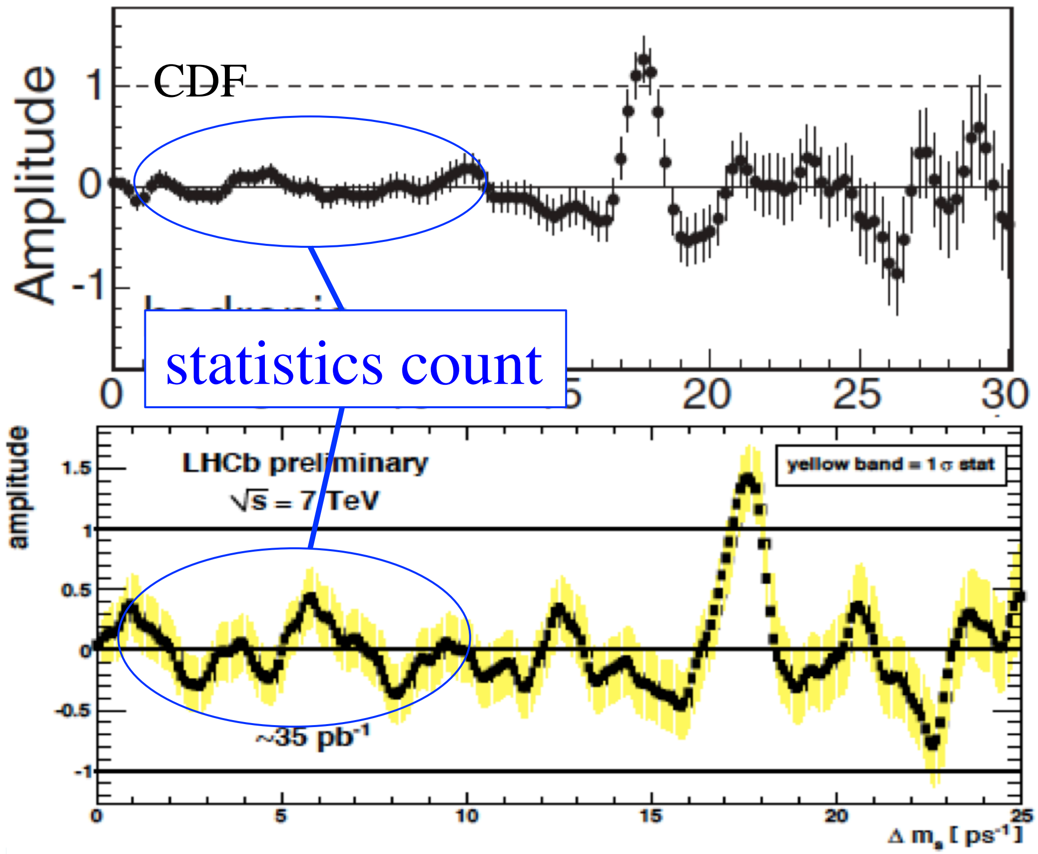

CDF:
1 fb^{-1}
5600 signal

LHCb:
36 pb^{-1}
1350 signal

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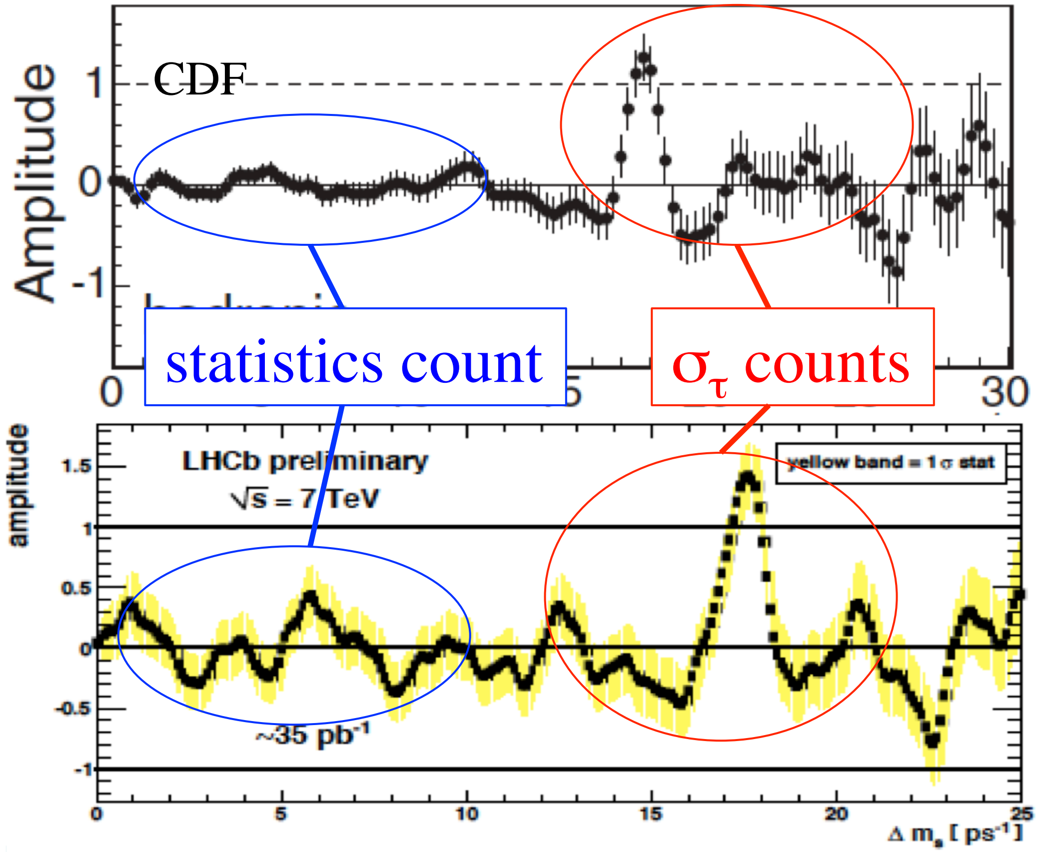
B_s^0-$\overline{B}_s^0$ oscillations: $A \times \cos \Delta m_s \times t \otimes \sigma_t$-effect



CDF:

1 fb^{-1}

5600 signal, σ_τ=87 fs

LHCb:

36 pb^{-1}

1350 signal, σ_τ=36 or 44 fs

Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:

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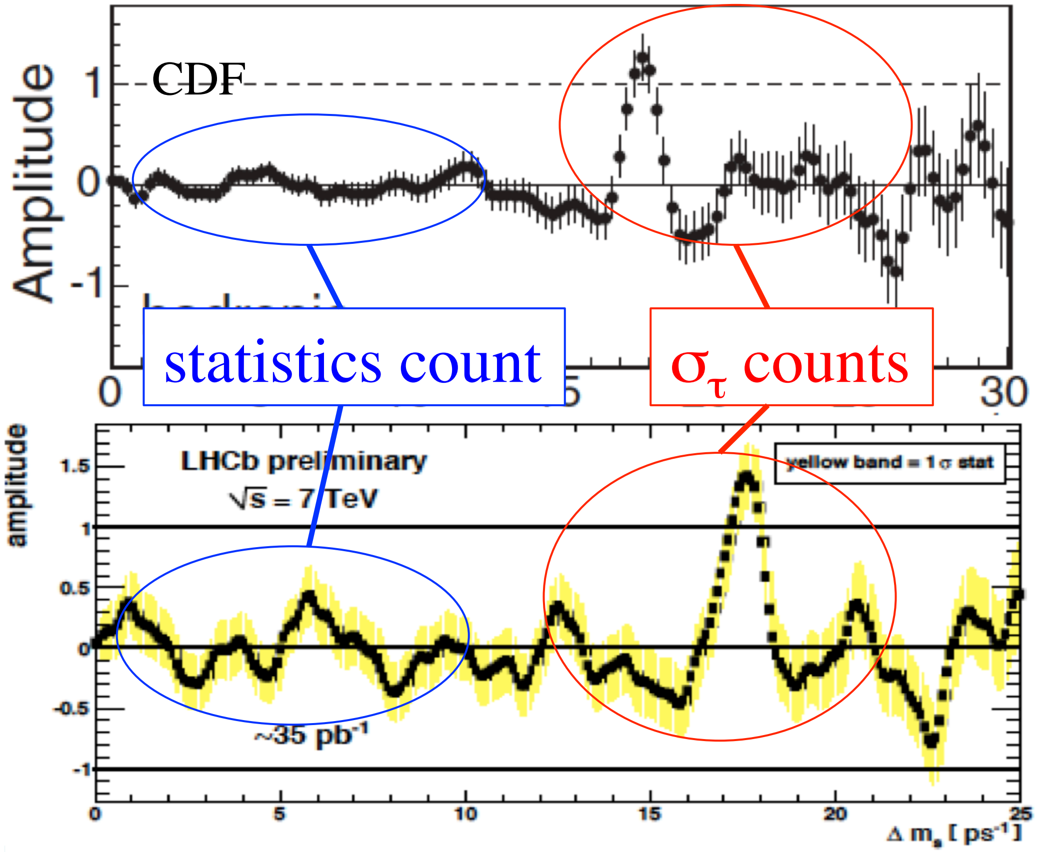

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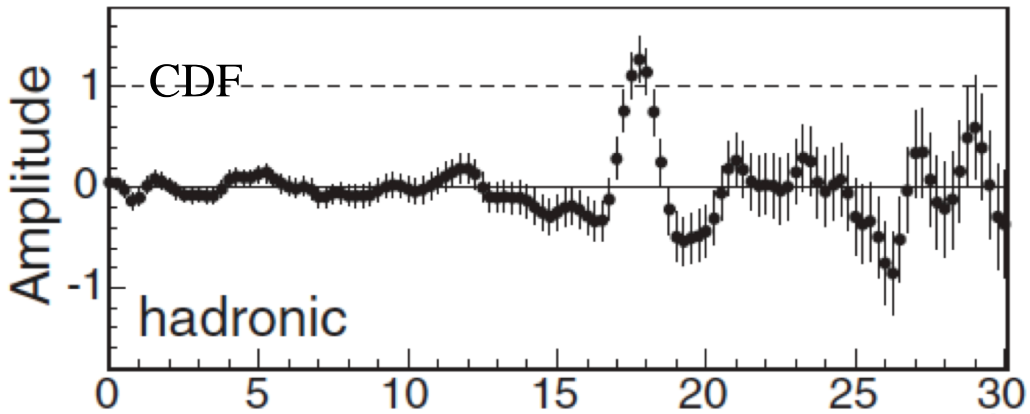

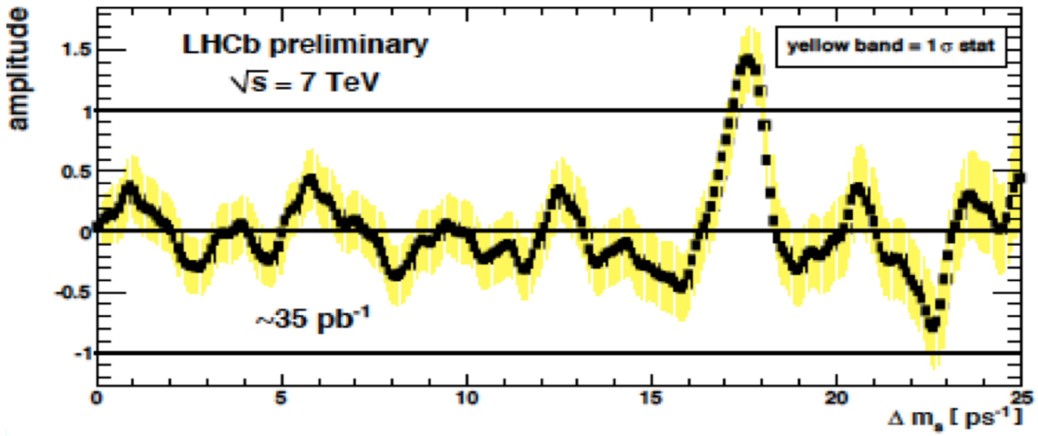

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$\beta\gamma c\tau_B \approx 1\mathrm{cm}$

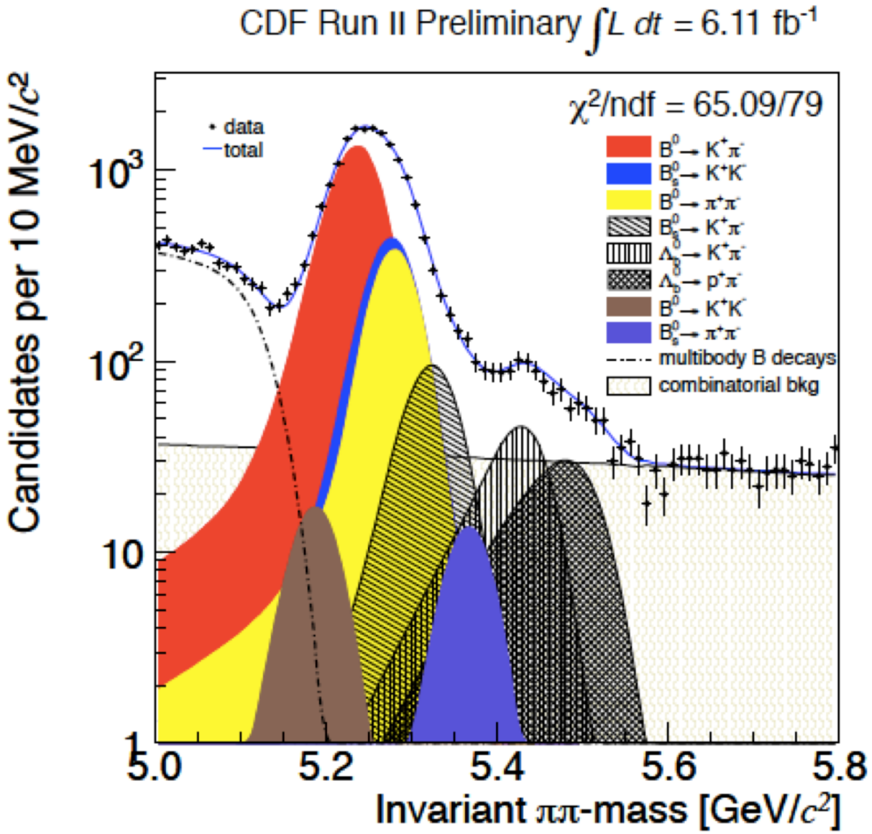
Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:

-larger cross section

-better invariant mass and proper time resolutions

-hadron PID



Public Note 10498

Flavour Physics at Hadron Machines

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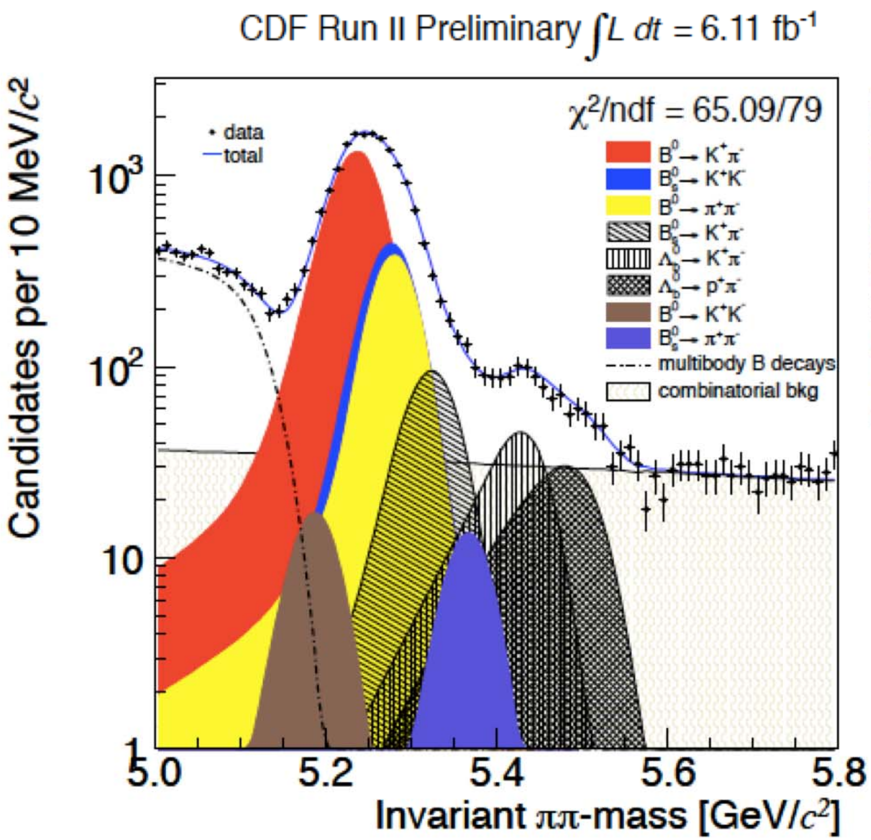

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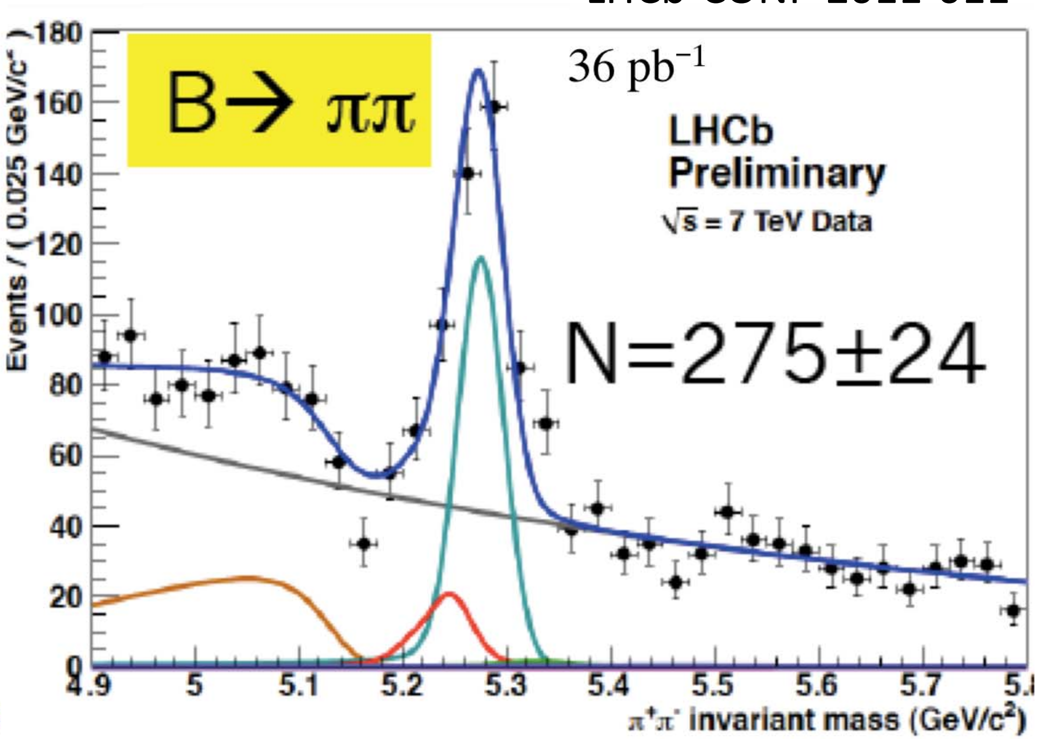

Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:

-larger cross section

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-hadron PID

Reflects on the systematic errors

$A_{CP}(B_d \to K^+\pi^-)$

CDF	$-0.086 \pm 0.023 \pm 0.009$	$1\ fb^{-1}$
LHCb	$-0.074 \pm 0.033 \pm 0.008$	$36\ pb^{-1}$

σ_{stat} for BABAR: ± 0.016 BELLE: ± 0.018

Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:

- -larger cross section
- -better invariant mass and proper time resolutions
- -hadron PID
- -more efficient trigger, particularly for hadronic final states

CP violation in D decays is getting attention and trigger efficiency is an issue!

Flavour Physics at Hadron Machines

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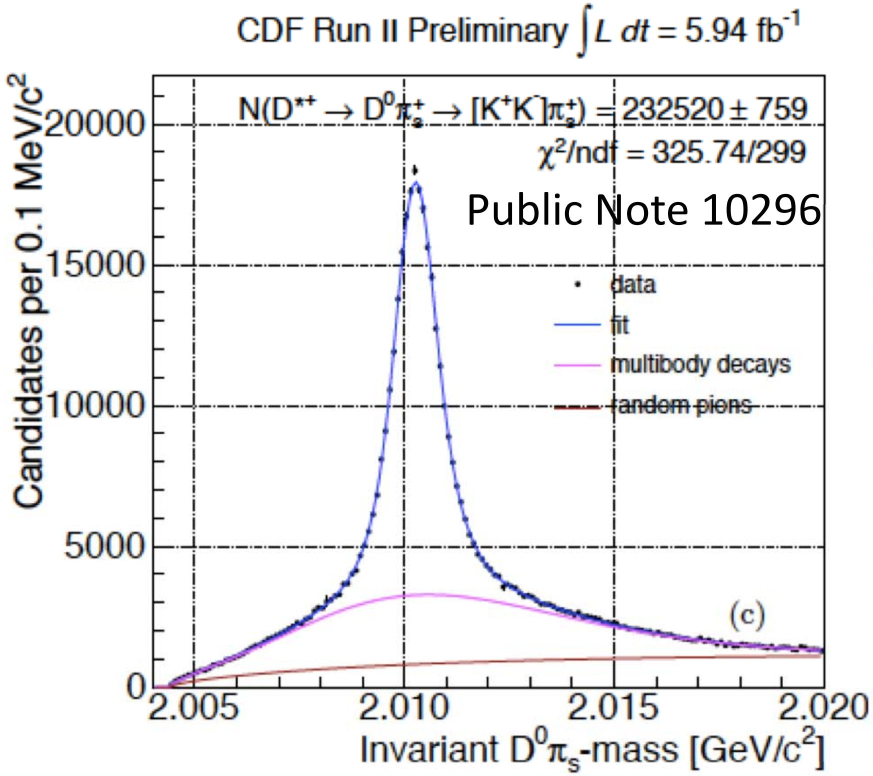

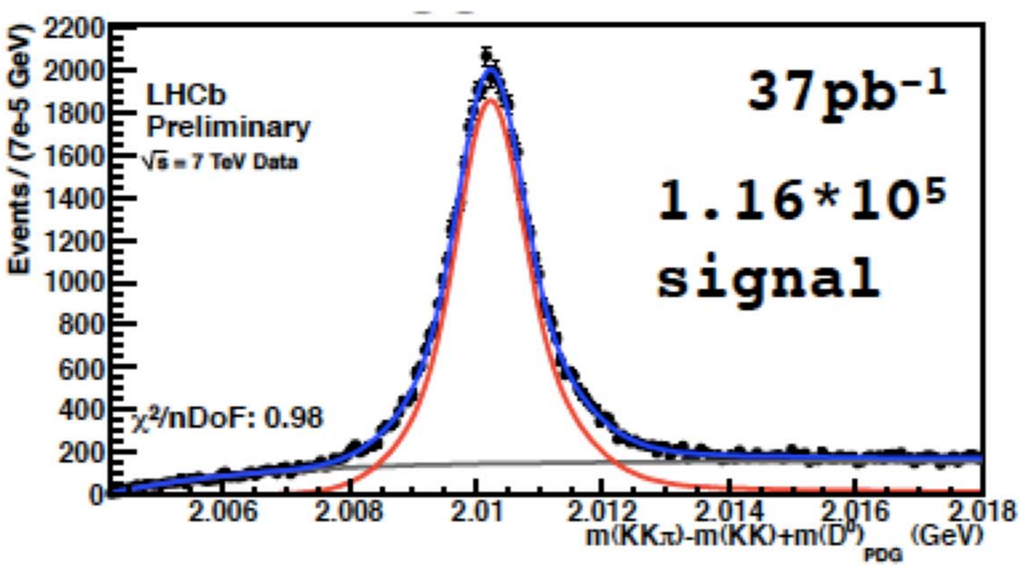

Flavour Physics at Hadron Machines

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CP violation in D decays is getting attention and trigger efficiency is an issue!

Flavour tagged D^0 and $\overline{D}^0 \rightarrow K^+K^-$

CDF	0.48×10^6	6 fb^{-1}
LHCb	0.12×10^6	36 pb^{-1}

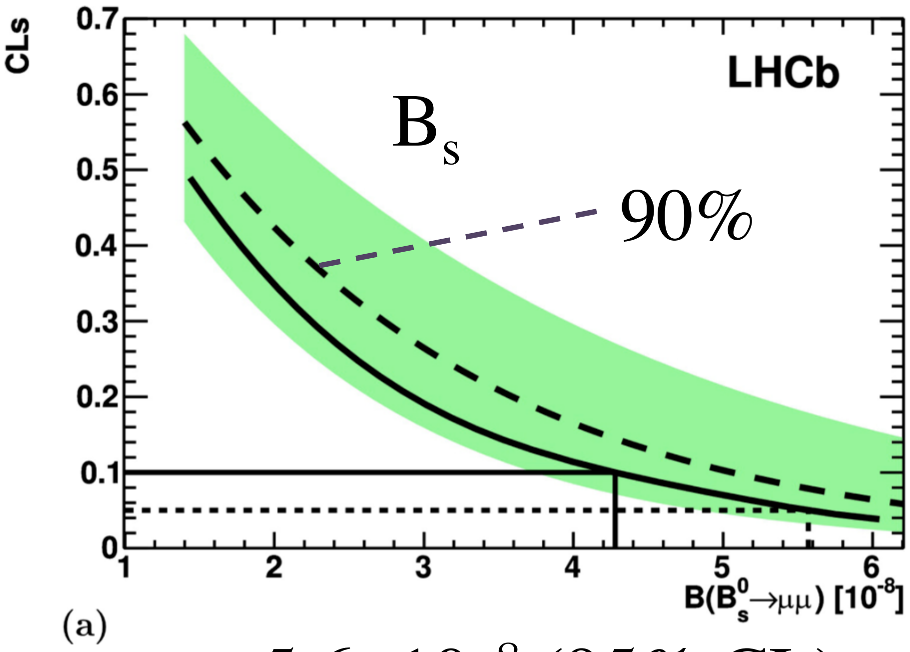
LHCb get 40 times more events for the same $\int L\, dt$

Flavour Physics at Hadron Machines

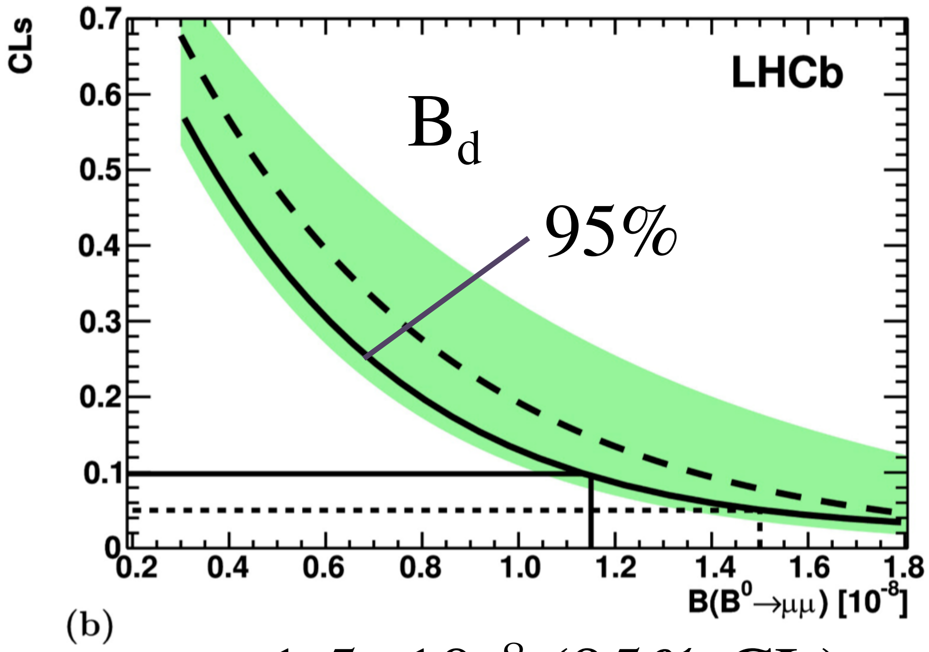
- By the end of 2012, LHCb will correct $\gtrsim 2\ \mathrm{fb}^{-1}$ of data
  - Exclude NP physics contribution to $B_s \to \mu^+\mu^-$ up to a level of SM (currently up to ~10 times SM) or find one (current best limit: 4.3×10^{-8} by CDF 3.7 fb^{-1})

SM prediction: $(0.32 \pm 0.02)\times10^{-8}$
$(0.010 \pm 0.001)\times10^{-8}$

36 pb^{-1}



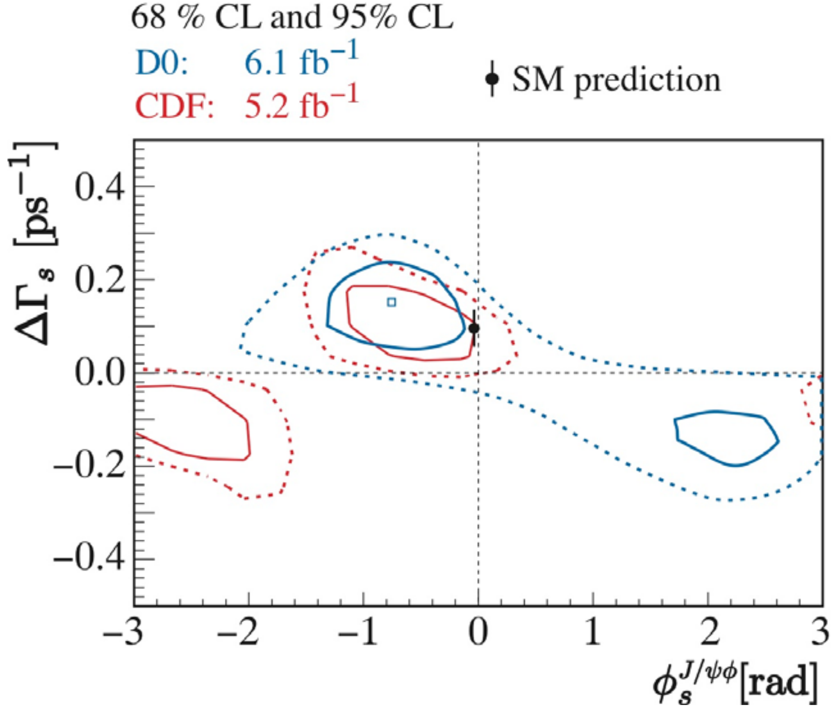
$< 5.6\times10^{-8}$ (95% CL)



$< 1.5\times10^{-8}$ (95% CL)

Flavour Physics at Hadron Machines

- By the end of 2012, LHCb will correct ≳ 2 fb^{-1} of data
  - Exclude NP physics contribution to $B_s \to \mu^+\mu^-$ up to a level of SM (currently up to ~10 times SM) or find one
  - CPV in $B_s \to J/\psi\phi$ to be measured with $\sigma(\phi_s) \approx 0.1$ (current most probable value ~−0.6 but less than 2σ effect and SM expectation −0.036±0.002)



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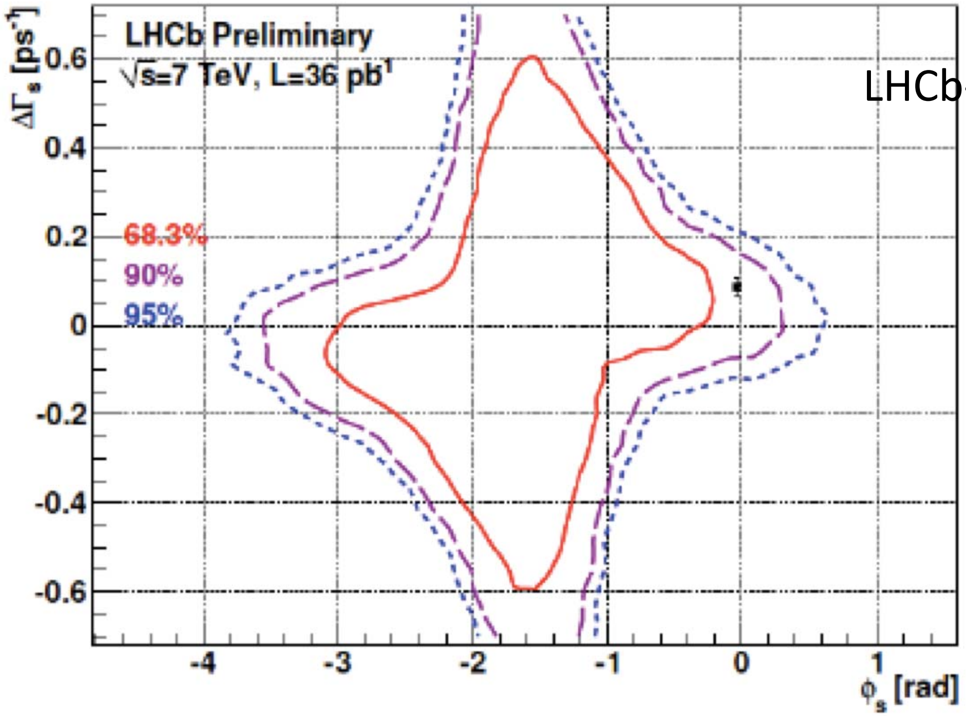

LHCb-CONF-2011-006

Flavour Physics at Hadron Machines

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  - A_{FB} for $B^0 \to K^{*0}\mu^+\mu^-$ with ~2k events.
    (currently ~400 events with all experiments. With the current value $>5\sigma$ deviation from SM expected where q^2 between 1 to 6 GeV^2)

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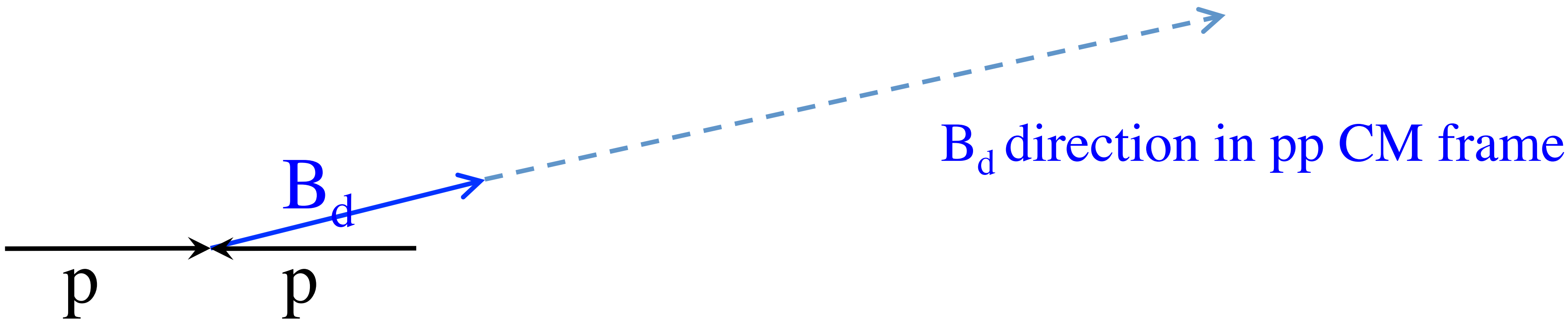

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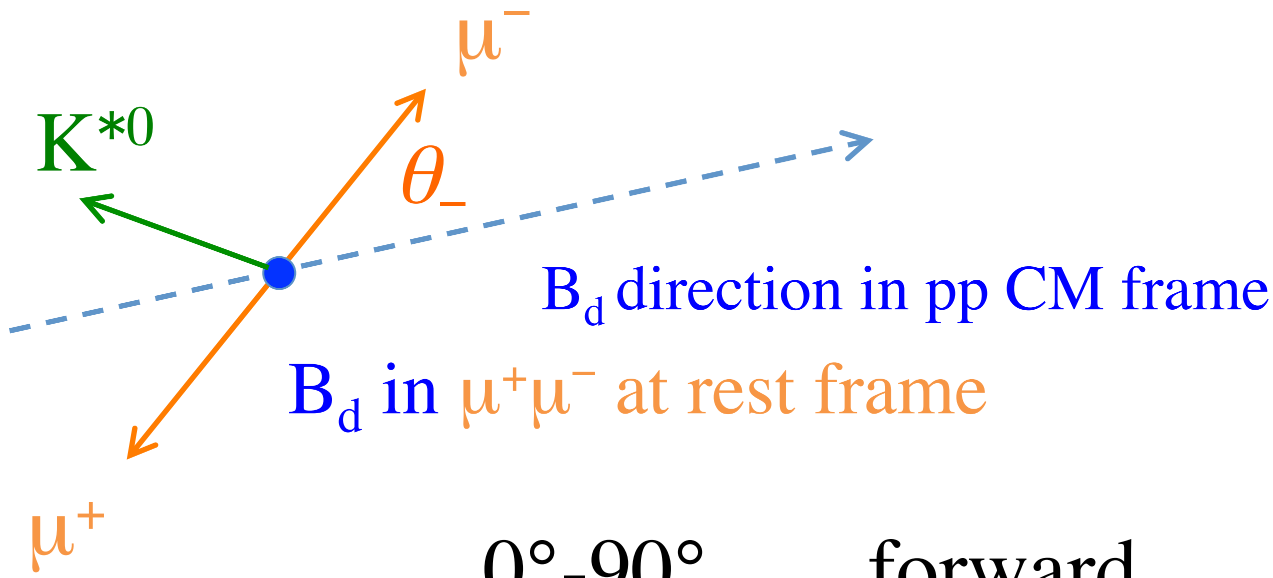

θ_-	0°-90°	forward
	90°-180°	backward

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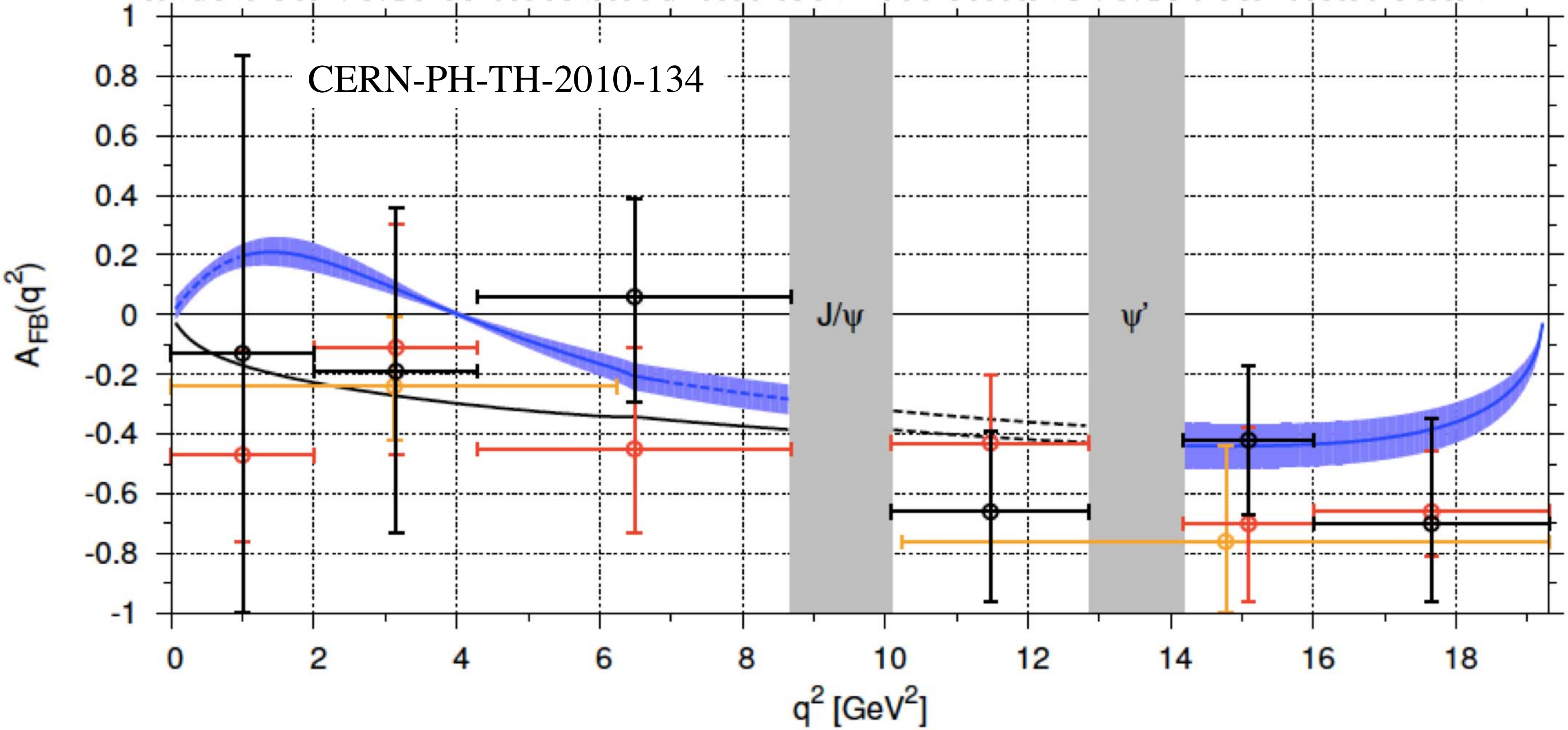

BABAR(75%) BELLE(80%) CDF (4.4 fb^{-1}) SM prediction

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And much more

Flavour Physics at Hadron Machines

- And more than 5 fb^{-1} by the end of 2017!

Epilogue

- There exists solid observations for physics beyond the Standard Model

Epilogue

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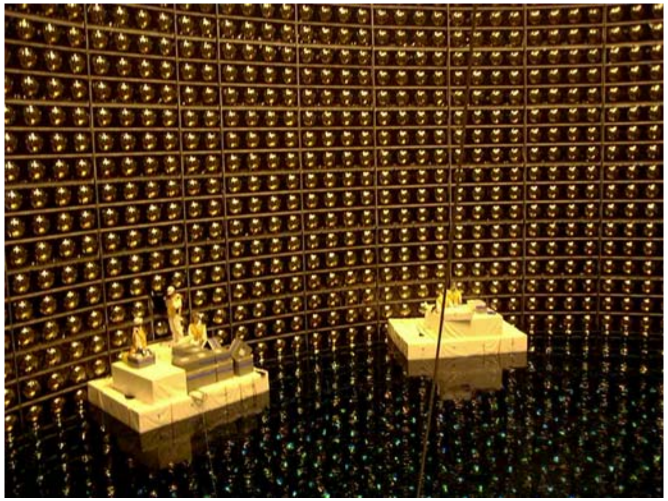
  Neutrino oscillations

S-KAMIOKANDE



Epilogue

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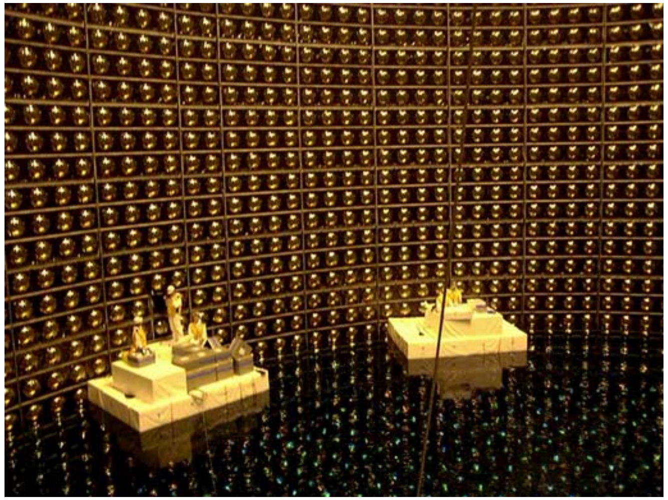
  Neutrino oscillations
  Dark matter

S-KAMIOKANDE

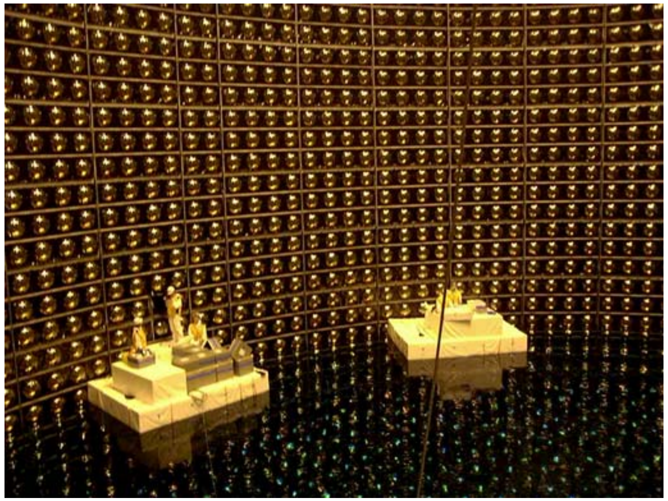


Bullet Galaxy Clusters

Epilogue

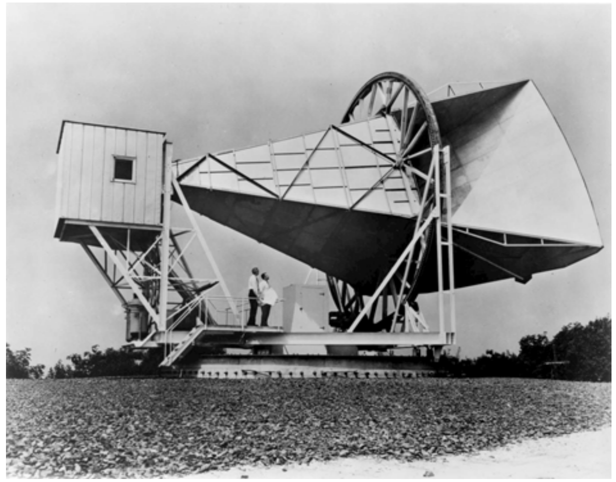
- There exists solid observations for physics beyond the Standard Model
  - Neutrino oscillations
  - Dark matter
  - $N_{\mathrm{B}} / N_{\gamma}=10^{-10}$

S-KAMIOKANDE



Bullet Galaxy Clusters

The Horn Antenna
Bell Telephone Laboratory



Epilogue

- There exists a strong anticipation that new physics is just around the corner…

Epilogue

By the middle of 2012…

ATLAS CMS high p_T physics
LHCb flavour physics
Particle Physics

Epilogue

By the middle of 2012…

ATLAS CMS high p_T physics	BSM
LHCb flavour physics	Only SM
Particle Physics	☺

Epilogue

By the middle of 2012…

ATLAS CMS high p_T physics	BSM	Only SM
LHCb flavour physics	Only SM	BSM
Particle Physics	☺	☺

Epilogue

By the middle of 2012…

ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

Epilogue

By the middle of 2012…

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Oh, no more space left…

Epilogue

In any case,

Exciting time is ahead of us all.

Epilogue

T2K preprint,

(Dated: June 13, 2011)

the expected number of such events is 1.5 ± 0.3(syst.). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to 2.5σ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\delta_{\mathrm{CP}} = 0$ and normal (inverted) hierarchy.

Exciting time is ahead of us all.