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 $B_d \rightarrow J/\psi K_S$ somewhat small
  – $|V_{ub}|$ extracted from $B \rightarrow \tau \nu$ decays larger than $|V_{ub}|$ extracted from the semileptonic decays.
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  1. Problem with extracting $|V_{ub}/V_{cb}|$ due to the hadronic uncertainties
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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 $B^0$-$\bar{B}^0$ oscillations and charged Higgs in $B \rightarrow \tau \nu$

\[ \begin{array}{c|c}
  \bar{b} & W^+ \\
  \bar{u} & \bar{c} & \bar{t} \\
  d & W^- \\
\end{array} \quad \text{+ new particles} \]

\[ \begin{array}{c|c}
  \bar{b} & W^+ \\
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\[ \begin{array}{c|c}
  b & \bar{v} \\
  u & W^+ & \tau \\
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\[ \begin{array}{c|c}
  b & \bar{v} \\
  u & H^+ & \tau \\
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|V_{cb}| and |V_{ub}|

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

⇒ can be reduced by studying the decay kinematics, e.g. lepton momentum, hadronic-mass distribution, etc. with higher statistics in a clean environment.
Closer Look

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

Errors are dominated by the theoretical uncertainties in the strong interaction for the semileptonic decays. $\Rightarrow$ can be reduced by studying the decay kinematics, e.g. lepton momentum, hadronic-mass distribution, etc. 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 $B^{\pm} \rightarrow \tau^{\pm} \nu$ 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

\[
\begin{align*}
A_{SM} & \quad s \\
& b \rightarrow u, c, t, w \\
& V-A \\
& d \rightarrow d, s
\end{align*}
\]
In general, new physics can enter in the loop diagrams as virtual states

$$A = A_{SM} + A_{NP}$$
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rare decays, $\Delta m$
In general, new physics can enter in the loop diagrams as virtual states:

\[ A = A_{\text{SM}} + A_{\text{NP}} \]

- \( |A| \): rare decays, \( \Delta m \)
- \( \arg A \): CP violation
In general, new physics can enter in the loop diagrams as virtual states

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

|A|: rare decays, $\Delta m$

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.
  – CP violation in D system
Closer Look

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• Comparison of $(\rho, \eta)$ determined from the tree processes, i.e. $|V_{ub}|$ and $\gamma$ ($B \rightarrow D K$), and $(\rho, \eta)$ from the loop processes, i.e. $\varepsilon_K$, $\beta$, 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. $\sigma_{bb}$
Flavour Physics at Hadron Machines

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

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

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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 ($\Delta m_s$), and $CP$ in $B \rightarrow J/\psi \phi$, $CP$ in $B_s$-$\bar{B}_s$ oscillations, $B^0 \rightarrow K^{*0} \mu^+\mu^-$, $B_s \rightarrow \mu^+\mu^-$, 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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• CDF and D0 will stop data taking this year with \( \sim 10 \text{ fb}^{-1}/\text{experiment} \). More results will come with improved sensitivities, but most probably not enough to unambiguously establish new effect
Flavour Physics at Hadron Machines

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  $\sim 10\ fb^{-1}/\text{experiment}$. More results will come with improved sensitivities, but most probably not enough to unambiguously establish new effect

• But, LHC has started with an experiment dedicated for flavour physics, LHCb.
Production of heavy flavour

- Parton density function
- Scattering amplitudes
- Fragmentation and hadronisation
- $b$-quark production
- $\bar{b}$-quark production

$B^+$, $B^0$, $B_s^0$, $B_c$, $\Lambda_b$, ...
Flavour Physics at Hadron Machines

Production of heavy flavour

Leading Order
\[ q\bar{q} \rightarrow b\bar{b} \]
\[ gg \rightarrow b\bar{b} \]

scattering amplitudes
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

\[ g \rightarrow b \]
\[ g \rightarrow \bar{b} \]

scattering amplitudes
Production of heavy flavour

A study by CMS

Leading Order
\[ q\bar{q} \rightarrow b\bar{b} \]
\[ gg \rightarrow b\bar{b} \]
+ Next to LO

Gluon splitting
\[ g \quad g \rightarrow \bar{b} \quad b \]

Flavour excitation
\[ g \quad g \rightarrow \bar{b} \quad b \]
Production of heavy flavour

important input for designing an experiment

\[ p \rightarrow \text{parton-1} \rightarrow \text{parton-2} \]

\[ b \rightarrow \bar{b} \]
Production of heavy flavour

important input for designing an experiment

\[ \bar{b} \]

No

\[ b \]

\[ \theta_{\bar{b}} \]

both \( b \) and \( \bar{b} \) are in the forward (backward) region
that is why LHCb is a forward spectrometer
and additional advantage is

For triggering…. \( p > p_{\text{min}} \)
muon: identification
hadron: energy resolution

\[
\frac{\sigma_E}{E} \approx \sqrt{70\%} / \sqrt{E}
\]

\[
\begin{align*}
p < p_{\text{min}} & \quad \rightarrow \quad \text{Fe} \\
p > p_{\text{min}} & \quad \rightarrow \\
\end{align*}
\]
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For triggering…. $p > p_{\text{min}}$

- muon: identification
- hadron: energy resolution

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

central detector

$\muon$: identification
$\text{hadron: energy resolution}$

forward: $p_T$ threshold can be set low: $\rightarrow$ high $b$ efficiency
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Can exploit low $p_T$ particles

$pp @ 14$ TeV

- ATLAS/CMS: $100 \mu$b
- LHCb: $230 \mu$b

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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
   $D^0(K^−π^+)$, $D_s(K^+K^−π^+)$, etc., also $K_S$
examples are
   $B^{(s)}_s \rightarrow ℓ^+ℓ^−$, $h^+h^−$, $B^0_s \rightarrow D_s(K^+K^−π^−)\ π^+$, $B^+ \rightarrow D(K_Sπ^+π^-)\ K^+$
Reconstruction of B decay vertex with a good resolution is essential to reduce combinatorial background:

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

Examples are

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

- \( K_S \) not seen by the vertex detector, \( \pi^0 \) and \( \gamma \) 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

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

- \( B^+ \to \mu^+\nu, K^+\nu\nu, \tau^+\nu \)
Advantage of LHCb over CDF and D0 are:
- larger cross section (measured also by ATLAS and CMS)
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- larger cross section (measured also by ATLAS and CMS)
  one of the very early measurements at LHCb

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An interesting example of semi inclusive reconstruction

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

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

\[ +D^0(\rightarrow K^-\pi^+) \]

\[ \overline{D}^0 \text{ and } D^0 \]

created at the primary vertex: pointing to PV, small IP
decay from b: not pointing to PV, large IP

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An interesting example of semi inclusive reconstruction

\[ B^+ \to \bar{D}^0(\to K^-\pi^+)X\mu^+\nu \]

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

**Non-B component form**

\[ D(K^-\pi^+)\mu^- \]

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Advantage of LHCb over CDF and D0 are:

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

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

$$B_s^0 \text{ initial} \Rightarrow \bar{B}_s^0 \text{ at } t$$
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flavour tagging of the initial state

$B_s^0$ initial
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flavour tagging of the initial state

\[ \begin{align*}
\bar{s} & \quad \rightarrow K^+ \quad \text{same side tag} \\
\bar{s} & \quad \rightarrow s \quad B_s^0 \quad \text{initial} \\
\bar{b} & \quad \rightarrow b \quad \rightarrow \downarrow \ell^-X, c\rightarrow s\rightarrow K^-, \text{secondary vertex with } - \text{charge} \\
& \quad \rightarrow \text{oposit side tag}
\end{align*} \]
Flavour Physics at Hadron Machines

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

\[ B_s^0 \rightarrow \overline{B}_s^0 \]

\[ l^- X, c \rightarrow s \rightarrow K^- \]

flavour tagging of the initial state
\[ \bar{s} \rightarrow K^+ \text{ same side tag} \]
\[ s \rightarrow B_s^0 \text{ initial } \Rightarrow \overline{B}_s^0 \text{ at } t \]

flavour tagging of the final state
\[ \bar{b} \rightarrow l^- X, c \rightarrow s \rightarrow K^- \text{, secondary vertex with } - \text{ charge} \]

oposit side tag
Flavour Physics at Hadron Machines

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\begin{align*}
\text{flavour tagging of the initial state} \\
\overline{s} & \quad \text{K}^+ \quad \text{same side tag} \\
\overline{s} & \quad s \\
\overline{b} & \quad B_s^0 \text{ initial} \Rightarrow \overline{B}_s^0 \text{ at } t \quad (\rightarrow D_s^{+}\pi^-) \\
\overline{b} & \quad b \\
\downarrow & \quad l^- X, c \rightarrow s \rightarrow K^- \quad \text{secondary vertex with } - \text{ charge} \\
\text{oposit side tag} \\
\end{align*}
Flavour Physics at Hadron Machines

Advantage of LHCb over CDF and D0 are:
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$B_s^0 - \overline{B}_s^0$ oscillations:

$$\frac{1-2\omega}{2} \cos \Delta m_s x t \otimes \sigma_t\text{-effect}$$

$\omega = \text{wrong-tag / all-tag}$

$\Delta - \log$ likelihood
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Advantage of LHCb over CDF and D0 are:

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$B_s^0 - \overline{B}_s^0$ oscillations:

$$A \times \cos \Delta m_s \times t \otimes \sigma_t$$

CDF:

1 fb$^{-1}$

PhysRevLett.97.242003

LHCb:

36 pb$^{-1}$

LHCb-CONF-2011-005
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$B_\text{s}^0 - \overline{B}_\text{s}^0$ oscillations: $A \times \cos \Delta m_s t \otimes \sigma_t$-effect

CDF:
1 fb$^{-1}$
5600 signal

LHCb:
36 pb$^{-1}$
1350 signal
Flavour Physics at Hadron Machines

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CDF:

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5600 signal, $\sigma_t = 87$ fs

LHCb:

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1350 signal, $\sigma_t = 36$ or 44 fs
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CDF:
1 fb$^{-1}$
5600 signal, $\sigma_t = 87$ fs
$\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps$^{-1}$

LHCb:
36 pb$^{-1}$
1350 signal, $\sigma_t = 36$ or 44 fs
$\Delta m_s = 17.63 \pm 0.11 \pm 0.04$ ps$^{-1}$
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$\beta \gamma c \tau_B \approx 1$ 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

![CDF Run II Preliminary $\int L dt = 6.11 \text{ fb}^{-1}$](image.png)

$\chi^2/\text{ndf} = 65.09/79$

Public Note 10498
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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\(^{-1}\)

$$\sigma_{\text{stat}}$$ for BABAR: ±0.016  BELLE: ±0.018
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- 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!
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![Graph showing the comparison between LHCb, CDF, and D0]

Public Note 10296

CDF Run II Preliminary $\int L\,dt = 5.94\,fb^{-1}$

$N(D^{**} \rightarrow D^0 \pi^0 \rightarrow [K^+ K] \pi^0) = 232520 \pm 759$

$\chi^2/ndf = 325.74/299$

![Graph showing the distribution of candidates per 0.1 MeV/c^2]

Events / (8e-5 GeV)

$37\,pb^{-1}$

$1.16 \times 10^5$ signal

![Graph showing the invariant mass distribution]
Advantage of LHCb over CDF and D0 are:

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

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Number of Events</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$0.48 \times 10^6$</td>
<td>6 fb$^{-1}$</td>
</tr>
<tr>
<td>LHCb</td>
<td>$0.12 \times 10^6$</td>
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</tbody>
</table>

LHCb get 40 times more events for the same $\int L \, dt$
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- By the end of 2012, LHCb will correct $\gtrsim 2 \text{ fb}^{-1}$ of data
  - Exclude NP physics contribution to $B_s \rightarrow \mu^+\mu^-$ up to a level of SM (currently up to $\sim 10$ times SM) or find one (current best limit: $4.3 \times 10^{-8}$ by CDF $3.7 \text{ fb}^{-1}$)

- SM prediction: $(0.32 \pm 0.02) \times 10^{-8} \quad (0.010 \pm 0.001) \times 10^{-8}$

\[ < 5.6 \times 10^{-8} \ (95\% \ CL) \quad < 1.5 \times 10^{-8} \ (95\% \ CL) \]
Flavour Physics at Hadron Machines

- By the end of 2012, LHCb will correct ≥ 2 fb\(^{-1}\) of data
  - Exclude NP physics contribution to \(B_s \rightarrow \mu^+\mu^-\) up to a level of SM (currently up to ~10 times SM) or find one
  - CPV in \(B_s \rightarrow J/\psi\phi\) to be measured with \(\sigma(\phi_s) \approx 0.1\) (current most probable value ~−0.6 but less than 2\(\sigma\) effect and SM expectation −0.036±0.002)
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  – $A_{FB}$ for $B^0 \rightarrow K^{*0}\mu^+\mu^-$ with $\sim 2k$ events.
    (currently $\sim 400$ events with all experiments. With the current value $>5\sigma$ deviation from SM expected where $q^2$ between 1 to 6 GeV$^2$)
Flavour Physics at Hadron Machines

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\[ q^2 \approx 0.1 \text{ (current most probable value } \approx 0.6 \text{ but less than } 2\sigma \text{ effect and SM expectation) } \]

- $A_{FB}$ for $B_0 \rightarrow K\mu^+\mu^-$ with $\approx 2k$ 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$^2$)
Flavour Physics at Hadron Machines

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- $B_d$ direction in pp CM frame
  - $0^\circ$-$90^\circ$ forward
  - $90^\circ$-$180^\circ$ backward
Flavour Physics at Hadron Machines

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BABAR(75%)  BELLE(80%)  CDF (4.4 fb$^{-1}$)  SM prediction
Flavour Physics at Hadron Machines

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  – CPV in $B_s \rightarrow J/\psi \phi$ to be measured with $\sigma(\phi_s) \approx 0.1$ (current most probable value $\sim -0.6$ but less than $2\sigma$ effect and SM expectation $0.036 \pm 0.002$)

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

  – CP asymmetry in $D \rightarrow hh$ decays to a level of $10^{-3}$
Flavour Physics at Hadron Machines

• By the end of 2012, LHCb will correct ≥ 2 fb⁻¹ of data

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  – $A_{FB}$ for $B^0 \rightarrow K^*\mu^+\mu^-$ with ~2k events. (currently ~400 events with all experiments. With the current value >5σ deviation from SM expected where $q^2$ between 1 to 6 GeV²)

  – CP asymmetry in $D \rightarrow hh$ decays to a level of $10^{-3}$

  – CP asymmetry $\sigma(B \rightarrow K\pi)=4 \times 10^{-3}$ (current world average 0.01), $\sigma(B_s \rightarrow \pi K)=0.025$ (CDF will be ~0.047)
Flavour Physics at Hadron Machines

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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

• There exists solid observations for physics beyond the Standard Model
  Neutrino oscillations

S-KAMIOKANDE
Epilogue

- There exists solid observations for physics beyond the Standard Model
  - Neutrino oscillations
  - Dark matter

![S-KAMIOKANDE](image1)
![Bullet Galaxy Clusters](image2)
Epilogue

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

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

By the middle of 2012…

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
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Epilogue
By the middle of 2012…

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ATLAS and CMS focus on high $p_T$ physics, which is considered BSM. LHCb focuses on flavour physics, using only the Standard Model. The overall sentiment is positive, indicated by the smiley face in Particle Physics.
Epilogue

By the middle of 2012…

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Only SM
BSM
Epilogue

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## Epilogue

By the middle of 2012...

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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 $1.5\pm0.3$ (syst.). Under this hypothesis, the probability to observe six or more candidate events is $7\times10^{-3}$, equivalent to $2.5\sigma$ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^22\theta_{13} < 0.28(0.34)$ for $\delta_{\text{CP}} = 0$ and normal (inverted) hierarchy.

Exciting time is ahead of us all.