SuperKEKB/Belle II

New intensity frontier facility at KEK

- Target luminosity; \( L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \)
  \[ \Rightarrow \sim 10^{10} \text{BB, } \tau^+\tau^- \text{ and charms per year!} \]
  \[ L_{\text{int}} > 50 \text{ ab}^{-1} \]

- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors) + more

The first particle collider after the LHC!
Advantage of $e^+e^-$ Flavor Factory

- Clean environment
  - Efficient detection of neutrals ($\gamma, \pi^0, \eta, \ldots$)
- Quantum correlated $B^0\bar{B}^0$ pairs
  - High effective flavor tagging efficiency: $\sim 34\%$ (Belle II) $\leftrightarrow \sim 3\%$ (LHCb)
- Large sample of $\tau$ leptons
  - Search for LFV $\tau$ decays at $O(10^{-9})$
- Full reconstruction tagging possible
  - A powerful tool to measure;
    - $b \to u$ semileptonic decays (CKM)
    - decays with large missing energy
    - etc.
- Systematics different from LHCb
  - Two experiments are required to establish NP

\[
\begin{align*}
B_{\text{tag}} & \to D\pi, D \to K\pi\pi \\
B_{\text{sig}} & \to \tau\nu, \pi\ell\nu
\end{align*}
\]
SuperKEKB Accelerator

- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

### Machine parameters

<table>
<thead>
<tr>
<th></th>
<th>SuperKEKB LER/HER</th>
<th>KEKB LER/HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$(GeV)</td>
<td>4.0/7.0</td>
<td>3.5/8.0</td>
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<tr>
<td>$\varepsilon_x$ (nm)</td>
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<td>18/24</td>
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<td>$\beta_x$ at IP(mm)</td>
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<td>Half crossing angle(mrad)</td>
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<tr>
<td>$I$(A)</td>
<td>3.6/2.6</td>
<td>1.6/1.2</td>
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<tr>
<td>Lifetime</td>
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<td>130min/200min</td>
</tr>
<tr>
<td>$L$(cm(^{-2})s(^{-1}))</td>
<td>$80 \times 10^{34}$</td>
<td>$2.1 \times 10^{34}$</td>
</tr>
</tbody>
</table>
Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity

---

**EM Calorimeter**
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later

**Vertex Detector**
2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD

**Central Drift Chamber**
Smaller cell size, long lever arm

**KL and muon detector**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

**Particle Identification**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)
Fake rate >2 x lower than in Belle

---

Belle II TDR, arXiv:1011.0352
As of Oct. 2017

**Europe**

<table>
<thead>
<tr>
<th>Country</th>
<th>Number</th>
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**Asia**

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<td>Japan</td>
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<td>Korea</td>
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<td>Malaysia</td>
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<td>Vietnam</td>
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<tr>
<td>Taiwan</td>
<td>28</td>
</tr>
<tr>
<td>Thailand</td>
<td>2</td>
</tr>
<tr>
<td>Turkey</td>
<td>3</td>
</tr>
</tbody>
</table>

**America**

<table>
<thead>
<tr>
<th>Country</th>
<th>Number</th>
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<tbody>
<tr>
<td>Canada</td>
<td>28</td>
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<tr>
<td>Mexico</td>
<td>12</td>
</tr>
<tr>
<td>USA</td>
<td>89</td>
</tr>
</tbody>
</table>

25 countries/regions
105 institutions
~750 researchers
Phase 1 (w/o final focusing Q, w/o Belle II):
- Accelerator system test and basic tuning,
- Vacuum scrubbing,
- Low emittance tuning, and
- Beam background studies

Phase 2 (w/ final focusing Q, w/Belle II but background monitors instead of vertex detectors)
- Verification of nano-beam scheme
target: L>10^{34} cm^{-2}s^{-1}
- Understand beam background especially in vertex detector volume
Phase 1 Commissioning
Feb. - June 2016

Phase 1 milestones (in 2016)
- Feb. 1: BT tuning started
- Feb. 8: LER injection tuning started
- Feb. 10: beam storage in LER
- Feb. 22: HER injection tuning started
- Feb. 26: beam storage in HER

<table>
<thead>
<tr>
<th></th>
<th>HER</th>
<th>LER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. current [mA]</td>
<td>870</td>
<td>1010</td>
</tr>
<tr>
<td>Integrated current [Ah]</td>
<td>660</td>
<td>780</td>
</tr>
<tr>
<td>Avg. pressure [Pa]</td>
<td>$\sim 2 \times 10^{-7}$</td>
<td>$\sim 1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Lifetime [min.]</td>
<td>~ 400</td>
<td>~ 70</td>
</tr>
</tbody>
</table>
Low Emittance Tuning

- Optics corrections have been worked successfully in both rings.
- Phase 1 target of vertical emittance has been achieved in LER.
- More calibration of X-ray monitor in HER needed in Phase 2.

**LER**

Beam-size measurement by X-ray monitor

\[ \varepsilon_y = \frac{\sigma_y^2}{\beta_y} \]

Phase 1 Target: 10 [pm]

- start optics correction
- additional skew-Q coils @Focusing Sextupoles
- permanent skew-Q magnet @Lambertson
- permanent skew-Q to correct error field of Lambertson

skew-Q corrector coil on sextupole
Phase I Beam Background Study

Interaction region during Phase I

Beam Exorcism for A Stable Experiment
Dedicated Background Monitors
7- detector system providing:

• Thermal neutron rate
• Fast neutron tracking
• Neutral and charged dose rates
• EM spectrum and dose
• Bunch-by-bunch injection background
• More…
Phase 1 Beam Background Study

Interaction region during Phase 1

7- detector system providing:
- Thermal neutron rate
- Fast neutron tracking
- Neutral and charged dose rates
- EM spectrum and dose
- Bunch-by-bunch injection background
- More…
Phase 1 Beam Background Study

Interaction region during Phase 1

7- detector system providing:
• Thermal neutron rate
• Fast neutron tracking
• Neutral and charged dose rates
• EM spectrum and dose
• Bunch-by-bunch injection background
• More…

Beam background
Change beam size to decompose Touschek (intra-bunch Coulomb) and beam-gas scatterings

Beam scrubbing
Belle II Integration
2013 - 2017 Feb. at roll-out position

B-KLM, 2013
B-KLM module installation, 2013

TOP, 2016 Feb-May
TOP module installation 2016 Feb-May

B field meas., 2016 Jun-July
B field measurement by CERN mapper 2016 June-July

E-KLM, 2014
E-KLM module installation, 2014

CDC 2016 Oct-Dec
CDC installation 2016 Oct-Dec

BW endcap, 2017 Jan-Feb
BWD end-cap installation 2017 Jan-Feb
Belle II Integration

2013 - 2017 Feb. at roll-out position
Belle II rolled-in to the beam line on April 11th, 2017
One of the most significant milestones in the construction phase
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One of the most significant milestones in the construction phase
Belle II rolled-in to the beam line on April 11th, 2017
One of the most significant milestones in the construction phase
Field Measurement of QCS + Solenoid

- The QCS system is the key ingredient of the nano-beam collisions.
  - 55 superconducting coils in 2 cryostats
- Performance test of the QCS system carried out May - August, 2017.
  - Cool-down and excitation together with the Belle II solenoid at 1.5 T.
- Careful magnetic field measurements with Single Stretched Wire (SSW), Harmonic coils and hall probe.

SSW
A Φ0.1 mm BeCu wire stretched on the beam line through the two cryostats, moved in the field to measure the center and angle from induced voltage. (collaboration with Fermilab)

Harmonic coils
The multipole field components as the error components were measured with the 6 harmonic coils.
Forward End-cap Installation

Sep.-Oct., 2017

- Two sub-detectors (A-RICH + FW ECL) are combined and installed into Belle II.
Belle II Vertex Detector

- Critical component for CPV measurements
- New vertex detectors:
  - PXD: 2-layer pixel detector based on DEPFET (Depleted P-channel Field Effect Transistor) technology.
  - SVD: 4-layer DSSD (Double Sided Silicon Detector).
- Smaller beam pipe radius
  - $1 \text{ cm}$ ($2 \text{ cm} \to 1.5 \text{ cm} @ \text{ Belle}$)
- Larger outer radius
- Improved $K_s$ acceptance
- Excellent performance (position resolution, efficiency) confirmed in beam test at DESY.

Greater outer radius enhances $K_s$ acceptance
Status of VXD production

SVD

- Ladder production: completed at 3 out of 5 sites.
  - will be finished by Feb. 2018.
- Ladder mount started (Sep. 7, 2017)
  - L3 mount completed (Sep. 19, 2017)
- Completion of the 1st half shell (Dec. 2017)
- Completion of the 2nd half shell (Apr. 2018)

Ladder mount tools and procedures have undergone a series of technical reviews and were finally approved on Sep 5, 2017

PXD

- Almost twice the required number of prime grade sensors
  - 40 sensors are required.
- Module assembly has started
  - Module assembly yield is ~100% so far
- Arrival of the assembled PXD at KEK: mid. of April, 2018

DEPFET sensor wafer produced at MPG-HLL (Munich)

Two PXD sensor glued together to make a module
Readout Integration

• Readout integration of installed sub-detectors and central DAQ is in progress.
• Global cosmic ray runs with B=1.5 Tesla in July and August, 2017.
  • Trigger rate at $\sim$100Hz → plan to do stress test up to 30kHz

Belle II control room

Typical cosmic ray event
Belle II Computing

Distributed computing following the LHC model

• Manage the processing of massive data sets
• Production of large MC samples
• Many concurrent user analysis jobs

Running jobs by Country
243 Weeks from Week 52 of 2012 to Week 34 of 2017

Max: 23.5, Average: 5.46, Current: 11.4

High speed networking data challenge in 2016:

• Belle II networking requirements are satisfied
SuperKEKB phase 2

Renovation for phase 2 ongoing.

- Add collimators
- More mitigation for e-cloud
- RF cavities for DR
- DR arc section
- New e+ Damping Ring
- QCS and related works at IR
- Change injection part for injection from DR
- Injector Linac upgrade
  - RF electron gun
  - improve e+ source
  - pulse magnets for top-up injection
- Collision feedback
- Colliding bunches

SuperKEKB phase 2
Phase 2 Commissioning

Machine commissioning strategy

1. Start with low beam current

2. Squeeze beams to achieve specific Luminosity
   \[ L_{sp} = \frac{L}{(I_+ + I_- n_b)} = 2 \times 10^{31}/\text{cm}^2/\text{s}/\text{mA}^2 \]
   cf. \[ L_{sp} = 1.7 \times 10^{31}/\text{cm}^2/\text{s}/\text{mA}^2 @\text{KEKB} \]

3. Increase number of bunches \( n_b \) from 394 to 1576, keeping bunch current constant:
   \( I_+ = 0.64\text{mA}, I_- = 0.51\text{mA} \)

4. Further squeeze beam to achieve \[ L_{sp} = 4 \times 10^{31}/\text{cm}^2/\text{s}/\text{mA}^2, \text{and even} 8 \times 10^{31}/\text{cm}^2/\text{s}/\text{mA}^2 \]
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Beam background study

<table>
<thead>
<tr>
<th>Study</th>
<th>Purpose</th>
</tr>
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<tbody>
<tr>
<td>Beam-size scan</td>
<td>Measure Touschek BG component</td>
</tr>
<tr>
<td>Vacuum bump study</td>
<td>Measure Beam-gas BG component</td>
</tr>
<tr>
<td>Collimator study</td>
<td>Find optimal setting</td>
</tr>
<tr>
<td>Injection study</td>
<td>Measure injection BG time structure, improve injection efficiency</td>
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<td>Luminosity scan</td>
<td>Measure lumi. BG component</td>
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Phase 2 Commissioning

Machine commissioning strategy

1. Start with low beam current
2. Squeeze beams to achieve specific Luminosity
   \[ L_{sp} = \frac{L}{I_+ + I_- + n_b} = 2 \times 10^{31} \text{cm}^2/\text{s}/\text{mA}^2 \]
   cf. \[ L_{sp} = 1.7 \times 10^{31} \text{cm}^2/\text{s}/\text{mA}^2 \] @KEKB
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<td>Measure lumi. BG component</td>
</tr>
</tbody>
</table>
Phase 2 Physics

Plan for 4-5 months of machine studies → 1-2 months may contain useful data, w/ $L \sim 1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \rightarrow 20-40 \text{fb}^{-1}$

- Runs on unique $E_{\text{CM}}$, e.g. $\Upsilon(6S)$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scans</th>
<th>$\Upsilon(6S)$</th>
<th>$\Upsilon(5S)$</th>
<th>$\Upsilon(4S)$</th>
<th>$\Upsilon(3S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(1S)$</th>
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<td></td>
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<td>$\text{fb}^{-1}$</td>
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<tr>
<td>Belle</td>
<td>100</td>
<td>$\sim 5.5$</td>
<td>36</td>
<td>121</td>
<td>711</td>
<td>772</td>
<td>3</td>
</tr>
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</table>

- Bottomonium (-like) physics

- Light DM search w/ 20fb$^{-1}$
  dark photon: $A' \rightarrow \gamma + \text{invisible}$
Physics Prospects (Phase 3)

Goal of Belle II/SuperKEKB

- 5σ NP observation
- 3σ NP evidence based on HFAG 2017 + B2TIP
- $X_s \ell^+ \ell^-$
- $C^\text{NP}_9$
- $S(\phi K^0)$
- $S(K_S \pi^0 \gamma)$
- $S(\eta' K^0)$
- $B \rightarrow \tau \nu$
- $R(D^* \tau \nu)_{\text{baryon]} (K\pi)$
- $S(\rho^0 \gamma)$
- $P^\text{tree} / P^s_{\text{higg}}$

Integrated luminosity (ab$^{-1}$)

Calendar Year

- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024

9 months/year
20 days/month
Physics Prospects (Phase 3)

**Goal of Belle II/SuperKEKB**

- $5\sigma$ NP observation
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- $X_s \ell^+\ell^-$
- $C_{9}^{\text{NP}}$
- $S(\phi K^0)$
- $S(K_S \pi^0 \gamma)$
- $S(\eta' K^0)$
- $B \rightarrow \pi \nu$
- $R(D^+ \tau \nu)$
- $R(D^0 \pi \nu)$
- $P_{\text{See}}/P_{\text{SU3}}$
- $S(\rho^0 \gamma)$

**Calendar Year**

- 9 months/year
- 20 days/month

CKM
Physics Prospects (Phase 3)

Goal of Belle II/SuperKEKB

Integrated luminosity (ab$^{-1}$)

- 5σ NP observation
- 3σ NP evidence based on HFAG 2017 + B2TIP

Calderon Year


9 months/year
20 days/month

CKM
Physics Prospects (Phase 3)

Goal of Belle II/SuperKEKB

Integrated luminosity (ab$^{-1}$)

- $5\sigma$ NP observation
- $X_s\ell^+\ell^-$
- $C^\text{NP}_9$
- $S(\phi K^0)$
- $S(K_S\pi^0\gamma)$
- $S(\pi'K^0)$
- $B \rightarrow \tau\nu$
- $R(D^{(*)}\tau\nu)$
- $R(D^{(*)}\tau\nu)_{\text{llmm}}(K\pi)$
- $S(\rho^0\gamma)$
- $P_{ee}/P_{\mu\mu}$

9 months/year
20 days/month

Calendar Year

CKM
Physics Prospects (Phase 3)

**Goal of Belle II/SuperKEKB**

- 5σ NP observation
- 3σ NP evidence based on HFAG 2017 + B2TP
- $X_s \ell^+\ell^-$
- $C_g^{NP}$
- $S(\phi K^0)$
- $S(K_S \pi^0 \gamma)$
- $S(\pi' K^0)$
- $B \rightarrow \tau \nu$
- $R(D^+ \tau \nu)$
- $S(\rho^0 \gamma)$
- $P_{see}/P_{SHH}$

**Calendar Year**

- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024

- 9 months/year
- 20 days/month

**CKM**

- $D^{(*)} \tau \nu$

**ICHEP 2016 Preliminary**

- Belle II Projection
- Belle Combination
- BABAR
- LHCb
- World Combination

- $1\sigma$ contours

- $|V_{ub}|$
- $\sin 2\phi_1$
- $\Delta m_d$ & $\Delta m_s$

- $\rho$
- $\Delta$

- $\phi_2$
- $\phi_3$
Most theories involving NP include additional CP-violating phases. Some allow large deviations from SM predictions for B meson decays. Search for new sources of CPV by comparing mixing-induced CP-asymmetries in penguin transitions with tree-dominated modes. Time-dependent CPV in $b \rightarrow s$ decays such as $B \rightarrow \phi K^0$, $\eta' K^0$, $K^0 K^0 K^0$, ... Discrepancies with respect to $J/\psi K^0$ could provide evidence for NP.
Physics Prospects (Phase 3)

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Discrepancies with respect to $J/\psi K^0$ could provide evidence for NP.

Are there new CP violating phases? Unambiguous sign of New Physics, easily detectable at Belle II.

$D(\ast)_{TV}$

$K(\ast)_{ll}$

$Xs_{ll}$

$S(\eta' Ks)$
Most theories involving NP include additional CP-violating phases. Some allow large deviations from SM predictions for B meson decays. Search for new sources of CPV by comparing mixing-induced CP asymmetries in penguin transitions with tree-dominated modes. Time-dependent CPV in $b \rightarrow s$ decays such as $B \rightarrow \phi K^0, \eta' K^0, K^0 K^0$.

Discrepancies with respect to $J/\psi K^0$ could provide evidence for NP.

Are there new CP violating phases? Unambiguous sign of New Physics, easily detectable at Belle II.

$K^{(*) \tau \nu}$

$X_s \ell^+ \ell^- C^{NP}$

$S(\phi K^0 \gamma)$

$S(K_S \pi^0 \gamma)$

$D(\tau \nu)$

$P_{3\nu}/P_{0\mu\mu}$

$R(D_{\tau \nu})_{\text{bare}}(K^n \pi)$

$9$ months/year

$20$ days/month

D(\tau \nu)$

$S(\eta' K_s)$
Summary

• Phase 1 commissioning in 2016 was successful.
• Phase 2 preparation in progress
  • All sub-detectors except for VXD have been installed.
  • Global cosmic ray runs with B field in Summer 2017.
  • Plan for background study and physics programs under discussion.
• Vertex detectors (SVD+PXD) construction in full swing. They will be installed after phase 2
• Phase 3 will start in late JFY2018.

*Rich physics results will come soon!*
Belle II Outreach

Also public HP: belle2.jp
Belle II Outreach

Follow Us & Like Us

Also public HP: belle2.jp

Thank you!
Backup Slides
<table>
<thead>
<tr>
<th>Parameter</th>
<th>KEKB LER/HER</th>
<th>Phase 1</th>
<th>Phase 2 4x8</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x^*$ (mm)</td>
<td>1200 / 1200</td>
<td>/</td>
<td>128 / 100</td>
<td>32 / 25</td>
</tr>
<tr>
<td>$\beta_y^*$ (mm)</td>
<td>5.9 / 5.9</td>
<td>/</td>
<td>2.16 / 2.4</td>
<td>0.27 / 0.30</td>
</tr>
<tr>
<td>$\varepsilon_x$ (nm)</td>
<td>18 / 24</td>
<td>2.0 / 4.6</td>
<td>2.1 / 4.6</td>
<td>3.2 / 4.6</td>
</tr>
<tr>
<td>$\varepsilon_y$ (pm), coupling</td>
<td>1498 / 1598</td>
<td>$\sim$ 10 / -</td>
<td>29.4 / 64.4, 1.4% (105 / 230, 5.0%)</td>
<td>8.64 / 12.9 (0.27% / 0.28%)</td>
</tr>
<tr>
<td>$\xi_y$</td>
<td>0.129 / 0.090</td>
<td>-</td>
<td>0.0484 / 0.0500 (0.0257 / 0.0265)</td>
<td>0.088/0.081</td>
</tr>
<tr>
<td>$\sigma_y^*$ (µm)</td>
<td>0.94 / 0.94</td>
<td>-</td>
<td>0.25 / 0.39 (0.48 / 0.74)</td>
<td>0.048/0.062</td>
</tr>
<tr>
<td>$I_{\text{beam}}$ (A)</td>
<td>1.64/1.19</td>
<td>1.01/0.87</td>
<td>1.0/0.8</td>
<td>3.6/2.6</td>
</tr>
<tr>
<td>$N_{\text{bunches}}$</td>
<td>1584</td>
<td>1576</td>
<td>1576</td>
<td>2500</td>
</tr>
<tr>
<td>Luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$)</td>
<td>2.1</td>
<td>-</td>
<td>2 (1)</td>
<td>80</td>
</tr>
</tbody>
</table>
Belle II Expected Performance

**IP resolution**
- Better with no background, worse with background

**Energy resolution**
- Preliminary

**Tracking efficiency vs. $p_t$**

**$K/\pi$ PID**

**$B^0 \rightarrow \rho^0 \gamma$ vs. $K^*\gamma$**

**Expected events in $s^{-1}$ (w/o PID)**

**Expected events in $s^{-1}$ (w/ PID)**