THE KLOE-2 EXPERIMENT

ANDREA SELCE

UNIVERSITA' & INFN ROMA TRE
on behalf of the KLOE-2 COLLABORATION
Collider $e^+ e^-$

$\sqrt{s} = M(\phi) = 1019.4$ MeV

**KLOE@DAΦNE**

- **$\phi$-FACTORY**
  - $e^+ e^-$ Collider
  - $\sqrt{s} = M(\phi) = 1019.4$ MeV

- KLOE $\sim 2.5$ fb$^{-1}$ ($2.0 \equiv \sqrt{s}=M(\phi)$)
- KLOE-2 started 11/2014
KLOE-2 RUN IN PROGRESS

Data taking till 31/03/2018

BEST Achievements in KLOE-2

- Total delivery: 4351 pb⁻¹
- Total acquired: 3505 pb⁻¹
- Max instantaneous: 3.41x10³² cm⁻² s⁻¹
- Max hourly: 651.0 nb⁻¹
- Max daily delivery: 13.4 pb⁻¹
- Max daily acquired: 11.0 pb⁻¹
- Max weekly delivered: 76.3 pb⁻¹
- Max weekly acquired: 62.9 pb⁻¹

Goal
\[ \int L_{dt} > 5 \text{ fb}^{-1} \]

Integrated Luminosity (pb⁻¹)

<table>
<thead>
<tr>
<th>Run</th>
<th>Total Delivery (pb⁻¹)</th>
<th>Total Acquired (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1065.1</td>
<td>818</td>
</tr>
<tr>
<td>II</td>
<td>1950.1</td>
<td>1590.7</td>
</tr>
<tr>
<td>III</td>
<td></td>
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KLOE-2 TYPICAL DAY

Average values at run time:

- $I^- \sim 1.2 \pm 1.4 \, \text{A}$
- $I^+ \sim 0.7 \pm 1.0 \, \text{A}$
- $\mathcal{L} \sim 1.4 \pm 1.8 \times 10^{32} \, \text{cm}^2\text{s}^{-1}$

Higher background level than KLOE

Constant monitoring on background level & feedback to DAFNE

- ECAP bkg-average < 500 kHz
- DC current < 3000 µA
- IT current < 3000 nA
KLOE-2 DETECTORS - DC

Superconducting coil, $B = 0.52\ T$

Full stereo geometry, 4m diameter
52140 total wires, 12582 sense wires

- $\sigma_p/p = 0.4\%$ (for $45^0 < \theta < 135^0$ tracks)
- $\sigma_{x,y} \approx 150\ \mu m$, $\sigma_z \approx 2\ mm$
Superconducting coil, \( B = 0.52 \) T

\[
\sigma_{E/E} = 5.7\% / \sqrt{E} (\text{GeV})
\]

\[
\sigma_T = 54 \text{ ps} / \sqrt{E} (\text{GeV}) \oplus 100 \text{ ps}
\]

(\oplus 140 \text{ per } Q=0 )
KLOE-2 NEW DETECTORS

IMPROVE VERTEX AND TRACKING CLOSE TO IP

INNER TRACKER

- 4 layers of cylindrical triple GEM tracker
KLOE-2 NEW DETECTORS

IMPROVE VERTEX AND TRACKING CLOSE TO IP

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• 4 layers of cylindrical triple GEM tracker

INCREASE CALORIMETER HERMETICITY
KLOE-2 NEW DETECTORS

**IMPROVE VERTEX AND TRACKING CLOSE TO IP**

- **INNER TRACKER**
  - 4 layers of cylindrical triple GEM tracker

**INCREASE CALORIMETER HERMETICITY**

**QCALT**
- W + Scint. + WLS&SiPMs
- 'Low-beta' quadrupole coverage

**CCALT**
- LYSO+APDs
- Better photon/electron acceptance (20°-->10°)
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**ADD γγ EVENTS TAGGING DETECTORS**
KLOE-2 NEW DETECTORS

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ADD **γγ EVENTS TAGGING DETECTORS**

**LET&HET**
LYSO+SiPMs&Scint+PMTs

- e⁺/e⁻ taggers for γγ physics
KLOE-2 INNER TRACKER

IMPROVE VERTEX AND TRACKING CLOSE TO IP

- INNER TRACKER
- 4 layers of cylindrical triple GEM tracker
KLOE-2 INNER TRACKER

**IMPROVE VERTEX AND TRACKING CLOSE TO IP**

\[ \phi \rightarrow \pi^+\pi^-\pi^0 \text{ PCA} \]

Narrow = 40%
Broad = 60%

\[
\begin{align*}
\text{sigma}_{\text{Narrow}} (\text{DC}) &= 0.5 \text{ mm} \\
\text{sigma}_{\text{Broad}} (\text{DC}) &= 2.1 \text{ mm} \\
\text{sigma}_{\text{PCA}} (\text{DC}) &= 1.7 \text{ mm}
\end{align*}
\]

Narrow = 40%
Broad = 60%

\[
\begin{align*}
\text{sigma}_{\text{Narrow}} (\text{DC+IT}) &= 0.4 \text{ mm} \\
\text{sigma}_{\text{Broad}} (\text{DC+IT}) &= 1.6 \text{ mm} \\
\text{sigma}_{\text{PCA}} (\text{DC+IT}) &= 1.1 \text{ mm}
\end{align*}
\]
KLOE-2 INNER TRACKER

- $\phi \rightarrow \pi^+\pi^-\pi^0$ VTX
  Measure directly vertex resolution with decay at IP

- $\phi \rightarrow \pi^+\pi^-\pi^0$ PCA

Y component due to smaller beam size (tens of $\mu$m)
KLOE-2 INNER TRACKER

IMPROVE VERTEX AND TRACKING CLOSE TO IP

• NEW CALIBRATION (vs OLD): cosmics, B off

Layer #4

Resx 360 µm (430 µm)

Layer #3

Resx 300 µm (400 µm)

Layer #2

Resx 300 µm (400 µm)

Layer #1

Resx 460 µm (520 µm)

A. Selce - KLOE-2 - IFAE 2017
SINGLE PHOTON TRIGGER (SPT)

Single photon trigger crucial for search of dark mediator (U-boson) not decaying in the apparatus

Barrel-only majority one, Bhabha nominal threshold (350 MeV) → exploring U boson mass below 600 MeV

Inserted permanently in the KLOE trigger logic since 28th November 2016

- SPT free running rate ~ 2.2 kHz
  SPT additional rate ~ 300 ÷ 350 Hz

- Efficiency studies on radiative bhabha events
PHYSICS@KLOE-2

- Kaon Physics
- Discrete symmetries test
- γγ physics e^+e^-→e^+e^-γγ*→e^+e^-X, thanks to new tagger detectors
- Search of dark force mediator in various channels (ex: e^+e^-→Uγ; e^+e^-→Uγ→l^+l^-γ)
- Hadronic physics below 1 GeV
## RECENT KLOE-2 RESULTS

| BR and Transition Form Factor of $\phi \to \pi^0 e^+ e^-$ | PLB 757 (2016) 362 |
| Dalitz plot analysis of $\eta \to \pi^+ \pi^- \pi^0$ | JHEP 1605 (2016) 019 |
| Hadron Vacuum Polarization in $e^+ e^- \to \mu^+ \mu^- \gamma$ (*) | PLB 767 (2017) 485 ([Link](http://dx.doi.org/10.1016/j.physletb.2016.12.015)) |
| U boson search in $e^+ e^- \to U \gamma$, $U \to \pi^+ \pi^-$ | PLB 757 (2016) 356 |
| U boson search: combined limit from $\mu \mu \gamma/\pi \gamma$ | In progress |
| BR of $\eta \to \pi^0 \gamma$, $\chi_{\rho \eta}$ Golden mode | In progress |
| B boson search in $\phi \to \eta \pi^0 \gamma$ | In progress |
| CPT test with $\phi \to K_S K_L \to 3\pi^0 \pi^+ \pi^-$ | $\Delta T$ distributions ready (in progress) |
| BR and charge asymmetry in $K_S \to \pi e\nu$ | Finalizing Systematics |
| BR in $K_S \to \pi^+ \pi^- \pi^0$ | In progress |
First measurement of the running of the effective $\alpha_{\text{QED}}(s)$ below 1 GeV

Hypothesis of only-leptonic contribution to $\alpha_{\text{QED}}(s)$ excluded at 6 sigmas
$\kappa_{s} \rightarrow \pi^{0}\pi^{0}\pi^{0}$

Analyzing KLOE-2 new data
(224 pb$^{-1}$)

Direct search for the CP violating decay

Best KLOE upper limit:
$\text{BR}(Ks \rightarrow 3\pi^{0}) < 2.6 \times 10^{-8}$
with 1.7 fb$^{-1}$

KLOE-2:
Hardened selection criteria to cope with increase of background

$N_{\text{obs}} = 0$ event selected as a signal
upper limit on $\text{BR}(Ks \rightarrow 3\pi^{0}) < 1.8 \times 10^{-7}$
SUMMARY

- KLOE-2 is currently taking data at the DAFNE collider
- All subdetectors are properly working
- Goal: \( \int L dt > 5 \text{ fb}^{-1} \), until 31 March 2018
- Analyses ongoing on old and new data
SUMMARY

- KLOE-2 is currently taking data at the DAFNE collider
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THANK YOU FOR YOUR ATTENTION!!!
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SPARES
**Physics@KLOE-2**

- Kaon Physics
- Discrete symmetries test

\[ \Delta t = t_1 - t_2 \]

\[ f_1 \]

\[ f_2 \]

- \( \gamma \gamma \) physics \( e^+ e^- \rightarrow e^+ e^- \gamma \gamma \rightarrow e^+ e^- X \), thanks to new tagger detectors

- Search of dark force mediator in various channels
  (ex: \( e^+ e^- \rightarrow U \gamma \); \( e^+ e^- \rightarrow U \gamma \rightarrow l^+ l^- \gamma \))

- Hadronic physics below 1 GeV
ENERGY SCAN

Scan performed by DAFNE shifting central RF:

Count events:
- $\phi \rightarrow K_S K_L$, with $K_S \rightarrow \pi^+ \pi^-$
- $\phi \rightarrow \eta \gamma$, with $\eta \rightarrow \gamma \gamma$, $\eta \rightarrow 3\pi^0$

KLOE absolute $\sqrt{s}$ fine calibration: -240 keV

DAFNE $\sqrt{s}$ value shifted by +550 keV to run exactly on peak

Events normalized to large angle Bhabhas
Analyses on benchmark channels show general agreement with KLOE data despite increase of background

\[ \phi \rightarrow \eta \gamma \text{ with } \eta \rightarrow 3\pi^0 \]

\[ K_L \text{ inv mass with } K_L \rightarrow \pi^+\pi^- \]

\[ K_S \text{ lifetime with } K_S \rightarrow \pi^+\pi^- \]
DAΦNE UPGRADE

Crab Waist Scheme: beam crossing at large angle, sextuple correction

Implemented in DAFNE and tested in 2008 on SIDDARTHA experiment (no magnetic field)

In KLOE B=0.52T require specific tuning and background control
Physics Motivations

Knowledge of the QED coupling constant fundamental for testing the Standard Model

Modification of the QED coupling constant due to the Vacuum Polarization diagram:

\[ e^2 \rightarrow e^2(q^2) = \frac{e^2}{1 + \Pi'(q^2) - \Pi'(0)}; \]

\[ \alpha(q^2) = \frac{\alpha(0)}{1 - \Delta\alpha(q^2)} \]

\[ \Delta\alpha(q^2) = \Delta\alpha_{lep}(q^2) + \Delta\alpha_{had}(q^2) \]

No data in the low energy region
Analysis Method

where:

\[
\frac{d\sigma^{ISR}}{dM_{\mu\mu}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{dM_{\mu\mu}} \frac{1}{c(\sqrt{s}_\mu) L}
\]

- \( \theta_\gamma < 15^\circ \) (\( \theta_\gamma > 165^\circ \))
- \( 0 < \theta_\mu < 180^\circ \)

with FSR effects removed

\[
\left| \frac{\alpha_{QED}(s)}{\alpha_{QED}(0)} \right|^2 = \frac{d\sigma^{ISR}}{dM_{\mu\mu}} = \frac{d\sigma^{MC}}{dM_{\mu\mu}}
\]

obtained from PHOKARA gen.

with the following
- \( \theta_\gamma < 15^\circ \)
- \( 0 < \theta_\mu < \)

Inclusive of the VP contribution removed
Event selection: Small Angle (SA)

- Two tracks of opposite sign with $50^\circ < \theta < 130^\circ$
- Photons (not detected) at small angles:
  \[ \theta < 15^\circ \text{ or } \theta > 165^\circ \]
- Photon momentum from kinematics:
  \[ \vec{p}_\gamma \simeq \vec{p}_{\text{miss}} = -(\vec{p}_+ + \vec{p}_-) \]
  - High statistics for ISR photons
  - Very small contribution from FSR
  - Reduced background contamination
Daφne upgrade

Crabbed waist scheme at DAΦNE

CRAB Optics
21/12/2008 SIDDHARTA
18/04/2012 KLOE2

Present commissioning phase
New coll. scheme + KLOE det.

Old collision scheme

$\frac{N_{\text{harmonic}}}{N_{\text{bunches}}}$ $[A^2]$

max. expected at KLOE-2 : $L_{\text{int}} \approx 20 \text{ pb}^{-1}/\text{day} \times 200 \text{ dd/year} = 4 \text{ fb}^{-1}/\text{year}$
DETECTOR UPGRADE: INNER TRACKER, QCALT, CCALT

INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low $p_t$ tracks

QCALT

- $W + \text{scintillator tiles} + \text{SiPM/WLS}$
- Low-beta quadrupoles: coverage for $K_L$ decays

CCALT

- LYSO + APD
- Increase acceptance for $\gamma$'s from IP ($21^\circ \rightarrow 10^\circ$)
Measurement of leptons momenta in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$

**LET:** $E_e \sim 160-230$ MeV

- Inside KLOE detector
- LYSO+SiPM
- $\sigma_E < 10\%$ for $E > 150$ MeV

**HET:** $E_e > 400$ MeV

- 11 m from IP
- Scintillator hodoscopes
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps
SPT SOURCE

- **Cosmics**
  - Runs 87070 + 87071
  
  SPT only trigger rate $\approx 60$ Hz

'Special' cosmics is triggered by SPT: one hit over Bhabha threshold and no other trigger over LET threshold

- Overfluctuate on upper sectors and underfluctuate on down one
- enter the barrel EMC almost horizontally
- stop inside the detector
- cross some cracks
- ...

Tnx2 E.Graziani
• Machine background

3 special runs (87452, 87453, 87455) with non-colliding, longitudinally separated, beams.
Analysis in progress

Within ~ 10 Hz, all the SPT 300 Hz trigger rate is explained by 60 Hz cosmics + machine background (Touschek, beam gas, etc...)
Barrel photon in L3BHA
(isolated clusters with no track association)

The effective (average) threshold seems to be consistently lower than the nominal one

Bhabha trigger bit is set, as a function of the cluster energy

Does not include calorimeter efficiency, cluster reconstruction efficiency, etc ...
$\kappa_{K} \rightarrow \pi^{0}\pi^{0}\pi^{0}$

Analyzing KLOE-2 new data (224 pb$^{-1}$)

Direct search for the CP violating decay

Best KLOE upper limit:
$\text{BR}(K_{S} \rightarrow 3\pi^{0}) < 2.6 \times 10^{-8}$
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KLOE-2:
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$N_{\text{obs}}=0$ event selected as a signal
upper limit on $\text{BR}(K_{S} \rightarrow 3\pi^{0}) < 1.8 \times 10^{-7}$
KLOE-2 Data Analysis: $K_S \rightarrow 3\pi^0$

- Analyzing KLOE-2 data.
  - From 23 pb$^{-1}$@ Sep CSN1 to present 224 pb$^{-1}$

- $K_S \rightarrow 2\pi^0$ (4 prompt photons) used for normalization.
  - Selection based on: 4-momentum conservation - $K_S$ mass - Energy and timing for photons

- Hardened selection criteria to cope with increased background wrt KLOE run ($>3$ prompt $\gamma + K_L$-crash):

**Old Selection**
- $K_L$-crash: $E>150$ MeV, $0.2<\beta<0.25$
- Prompt photons: $E_{\gamma}>7$ MeV;
  - $|\cos \theta_{\gamma}| \leq 0.915$ and
  - $|\Delta T_{\gamma}| \leq \min(3.5\sigma_T(E_{\gamma}),2 \text{ ns})$

  Signal Efficiency 47%

**New Selection**
- $K_L$-crash: $E>150$ MeV, $0.2<\beta<0.25$
- Prompt photons: $E_{\gamma}>20$ MeV;
  - $|\cos \theta_{\gamma}| \leq 0.915$ and
  - $|\Delta T_{\gamma}| \leq \min(3.0\sigma_T(E_{\gamma}),2 \text{ ns})$

  Signal Efficiency 43%
  10x Background Rejection
# $K_L^0$ Decay Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>Scale factor/Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Semileptonic modes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_1$</td>
<td>$\pi^\pm e^\mp \nu_\bar{e}$</td>
<td>[a] (40.55 $\pm$ 0.11) %</td>
</tr>
<tr>
<td>Called $K_{e3}^0$.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$\pi^\pm \mu^\mp \nu_\bar{\mu}$</td>
<td>[a] (27.04 $\pm$ 0.07) %</td>
</tr>
<tr>
<td>Called $K_{\mu3}^0$.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>$(\pi\mu\text{atom})\nu$</td>
<td>(1.05 $\pm$ 0.11) x $10^{-7}$</td>
</tr>
<tr>
<td>$\Gamma_4$</td>
<td>$\pi^0\pi^\pm e^\mp \nu$</td>
<td>[a] (5.20 $\pm$ 0.11) x $10^{-5}$</td>
</tr>
<tr>
<td>$\Gamma_5$</td>
<td>$\pi^\pm e^\mp \nu e^+ e^-$</td>
<td>[a] (1.26 $\pm$ 0.04) x $10^{-5}$</td>
</tr>
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<td><strong>Hadronic modes, including Charge conjugation x Parity Violating (CPV) modes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_6$</td>
<td>$3\pi^0$</td>
<td>(19.52 $\pm$ 0.12) %</td>
</tr>
<tr>
<td>$\Gamma_7$</td>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>(12.54 $\pm$ 0.05) %</td>
</tr>
<tr>
<td>$\Gamma_8$</td>
<td>$\pi^+ \pi^-$</td>
<td>CPV [b] (1.967$\pm$0.010)x$10^{-3}$</td>
</tr>
<tr>
<td>$\Gamma_9$</td>
<td>$\pi^0 \pi^0$</td>
<td>CPV (8.64$\pm$0.06)x$10^{-4}$</td>
</tr>
<tr>
<td><strong>Semileptonic modes with photons</strong></td>
<td></td>
<td></td>
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<tr>
<td>$\Gamma_{10}$</td>
<td>$\pi^\pm e^\mp \nu_\gamma$</td>
<td>[a,c,d] (3.79 $\pm$ 0.06) x $10^{-3}$</td>
</tr>
<tr>
<td>$\Gamma_{11}$</td>
<td>$\pi^\pm \mu^\mp \nu_\mu \gamma$</td>
<td>(5.65 $\pm$ 0.23) x $10^{-4}$</td>
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<td><strong>Hadronic modes with photons or $\ell \ell$ pairs</strong></td>
<td></td>
<td></td>
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<tr>
<td>$\Gamma_{12}$</td>
<td>$\pi^0 \pi^0 \gamma$</td>
<td>&lt; 2.43 x $10^{-7}$</td>
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<tr>
<td>$\Gamma_{13}$</td>
<td>$\pi^+ \pi^- \gamma$</td>
<td>[c,d] (4.15 $\pm$ 0.15) x $10^{-5}$</td>
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<tr>
<td>$\Gamma_{14}$</td>
<td>$\pi^+ \pi^- \gamma$ (DE)</td>
<td>(2.84 $\pm$ 0.11) x $10^{-5}$</td>
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<tr>
<td>$\Gamma_{15}$</td>
<td>$\pi^0 2\gamma$</td>
<td>[c] (1.273$\pm$0.033)x$10^{-6}$</td>
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<tr>
<td>$\Gamma_{16}$</td>
<td>$\pi^0 \gamma e^+ e^-$</td>
<td>(1.62 $\pm$ 0.17) x $10^{-8}$</td>
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<td><strong>Other modes with photons or $\ell \ell$ pairs</strong></td>
<td></td>
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<tr>
<td>$\Gamma_{17}$</td>
<td>$2\gamma$</td>
<td>(5.47 $\pm$ 0.04) x $10^{-4}$</td>
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<tr>
<td>$\Gamma_{18}$</td>
<td>3$\gamma$</td>
<td>&lt; 7.4 x $10^{-8}$</td>
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<tr>
<td>$\Gamma_{19}$</td>
<td>$e^+ e^- \gamma$</td>
<td>(9.4 $\pm$ 0.4) x $10^{-6}$</td>
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<td>$\pi^+ \pi^- \pi^0$</td>
<td>$(3.5 \pm 1.1 \mp 0.9) \times 10^{-7}$</td>
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</table>

#### Hadronic modes

#### Modes with photons or $\ell\bar{\ell}$ pairs

| $\Gamma_4$ | $\pi^+ \pi^- \gamma$ | [a,b] | $(1.79\pm0.05) \times 10^{-3}$ |
| $\Gamma_5$ | $\pi^+ \pi^- e^+ e^-$ | [a] | $(4.79\pm0.15) \times 10^{-5}$ |
| $\Gamma_6$ | $\pi^0 \gamma \gamma$ | [a] | $(4.9 \pm 1.8) \times 10^{-8}$ |
| $\Gamma_7$ | $\gamma \gamma$ | [a] | $(2.63\pm0.17) \times 10^{-6}$ |

#### Semileptonic modes

| $\Gamma_8$ | $\pi^+ e^- \nu_e$ | [c] | $(7.04\pm0.08) \times 10^{-4}$ |
| $\Gamma_9$ | $\pi^\pm \mu^\mp \nu_{\mu}$ | [c,d] | $(4.69\pm0.05) \times 10^{-4}$ |

#### $CP$ violating ($CP$) and $\Delta S = 1$ weak neutral current ($S1$) modes

| $\Gamma_{10}$ | $\pi^0$ | $CP$ | $< 2.6 \times 10^{-8}$ | CL=90% |
| $\Gamma_{11}$ | $\mu^+ \mu^-$ | $S1$ | $< 9 \times 10^{-9}$ | CL=90% |
| $\Gamma_{12}$ | $e^+ e^-$ | $S1$ | $< 9 \times 10^{-9}$ | CL=90% |
| $\Gamma_{13}$ | $\pi^0 e^+ e^-$ | $S1$ | $(3.0 \pm 1.5 \mp 1.2) \times 10^{-9}$ | |
| $\Gamma_{14}$ | $\pi^0 \mu^+ \mu^-$ | $S1$ | $(2.9 \pm 1.5 \mp 1.2) \times 10^{-9}$ | |