Instrumentation for the Intensity Frontier

In preparation for Snowmass 2013 we aim to identify the instrumentation needs of the different frontiers.

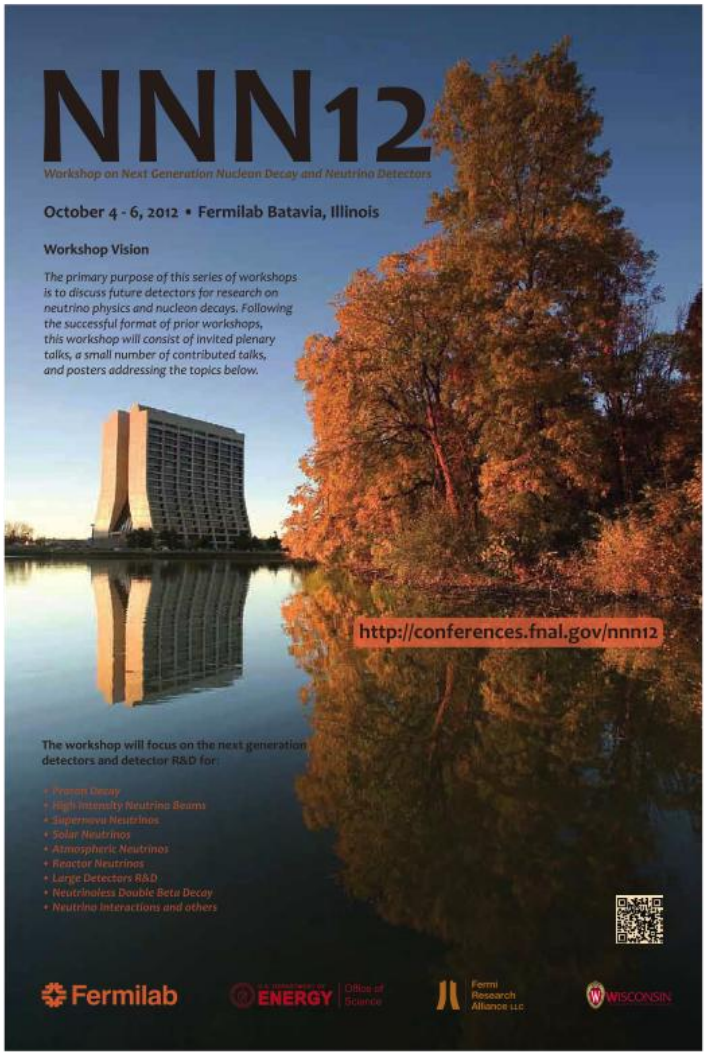
To start the process we have asked the speakers to prepare three short presentation on the science and instrumentation that needs followed by a short discussion.

This is a beginning of a discussion that will continue in a dedicated workshop organized by CPAD at ANL on January 9-11.

1. **Gina Rameika - Neutrino Program (p life time)**
2. **Steve Kettle - Rare Process (K-Decay, g-2, $\mu 2e$,…)**
3. **David Asner - Lepton Factories (b ,ϕ factories)**

Intensity Frontier Instrumentation for Neutrinos

- Charge : discussion of instrumentation needs for Intensity Frontier Neutrino Experiments
- Draw on most recent presentations at NNN12



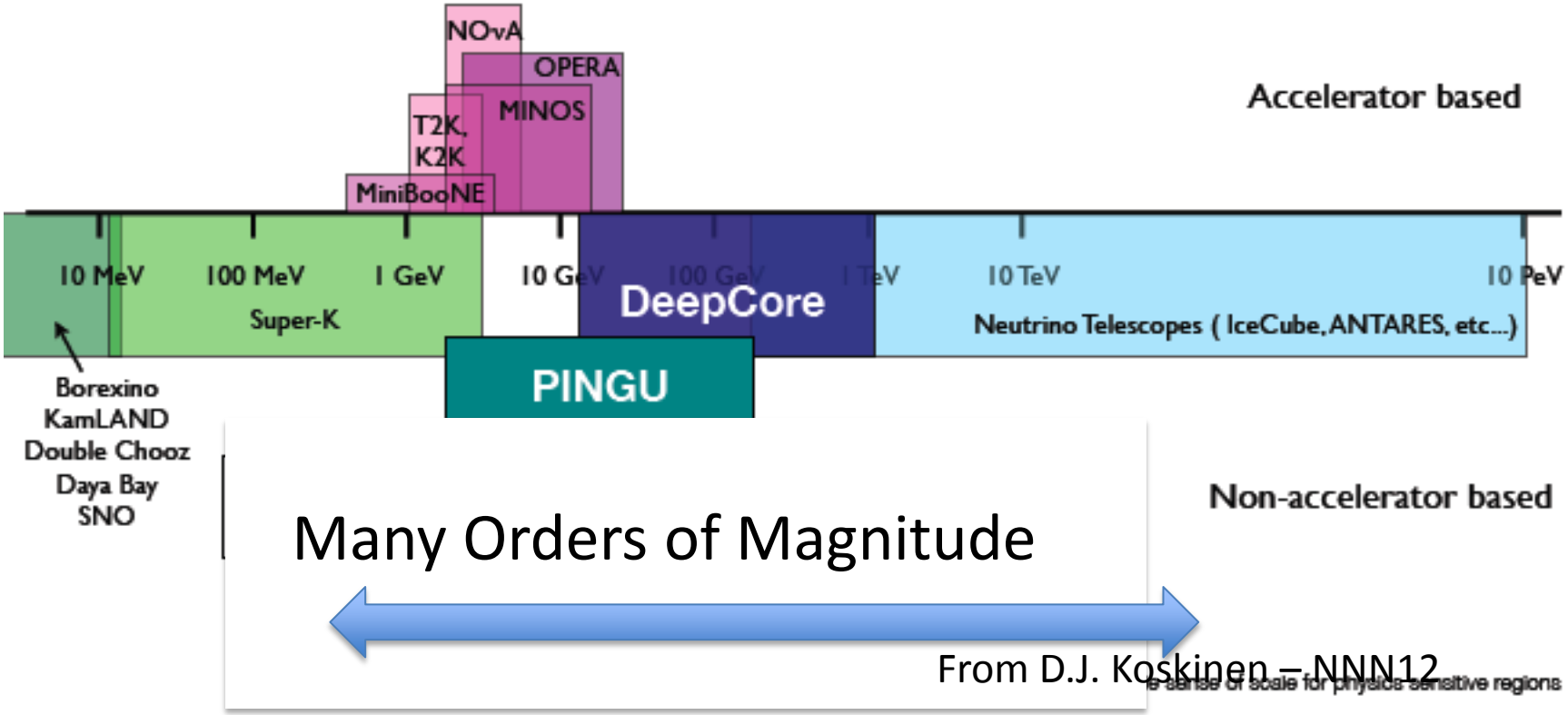
https://indico.fnal.gov/conferenceTimeTable.py?confId=5755#all

Major themes of research

- Neutrino Mass and Mixing
  - 3 neutrino model : $\theta_{13}, \theta_{23}, \Delta m^{2}{}'s$
  - Anomalies and sterile neutrino searches
- Very low energy neutrinos
  - Supernova bursts, diffuse supernova relic neutrinos, geo-neutrinos, solar neutrinos, reactor neutrinos
- Ultra High energy neutrinos
  - Atmospheric neutrinos, UHE cosmic rays, GZK neutrinos
- Plus all of the neutrinos in between

Experimental Programs

- Accelerator Based
- Non-accelerator
  - Man-made Sources
  - Natural Sources



Instrumentation Needs

- Detector Mass
- High efficiency particle ID
- Background identification and rejection
- Low energy thresholds
- Precision tracking and calorimetry
- Light collection
- Neutron tagging

Instrumentation Solutions (just some examples)

- Detecting scintillation light, cherenkov radiation
- Ionization, Charge collection, measuring dE/dx, …
- Photon-detection : PMTs, SiPD, MCPs, APDs …
- Cherenkov Imaging
  - Super-K, mini-BooNE, SNO
- Liquid Scintillator/Photo-detection
  - KamLand, Borexino,…
- Scintillator : Solid and Liquid
  - MINOS, NOvA
- Liquid Argon – ICARUS
- Emulsion – DONUT, OPERA

Next Generation Detectors Need to See the Light!

- Large Liquid Detectors (water, scintillator, argon) – large surface areas to be instrumented
  - ~On Order 100K conventional PMTs

- Smaller Detectors – need excellent energy resolution

Liquid Scintillator – Daya Bay II

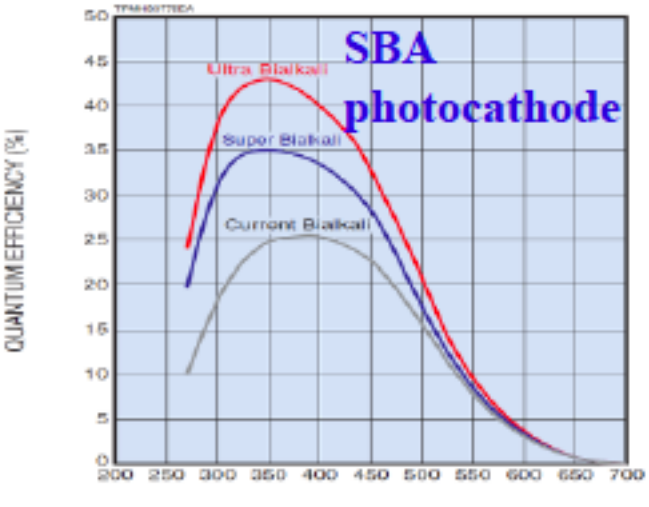
Technical Challenges

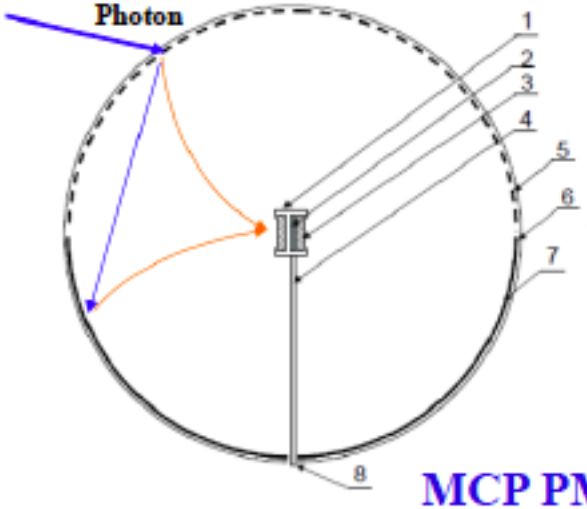
- **Requirements:**
  - ⇨ Large detector: 20 kt LS
  - ⇨ Energy resolution: 3%/√E ➔ 1200 p.e./MeV
- **Ongoing R&D:**
  - ⇨ Low cost, high QE "PMT"
  - ⇨ Highly transparent LS: 15m ➔ 30m

	KamLAND	Daya Bay II
LS mass	~1 kt	20 kt
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

From Miao HE – NNN12

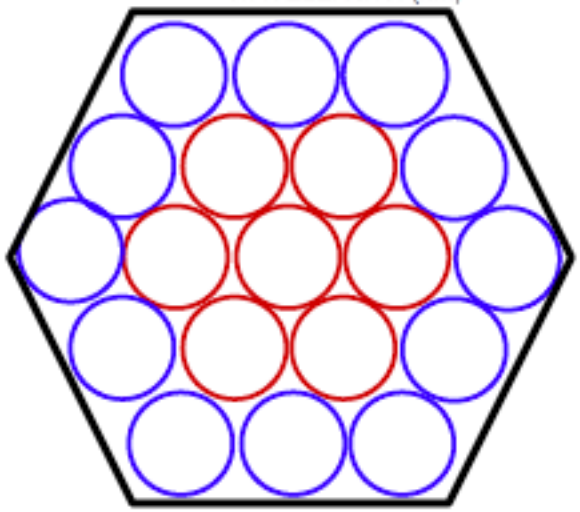
More Photoelectrons -- PMT





1.Insulated trestle table
2.Anode
3.MCP dodule
4.Bracket of the cables
5.Transmission Photoca
6.Glass shell
7.Reflection Photocatho
8.Glass joint

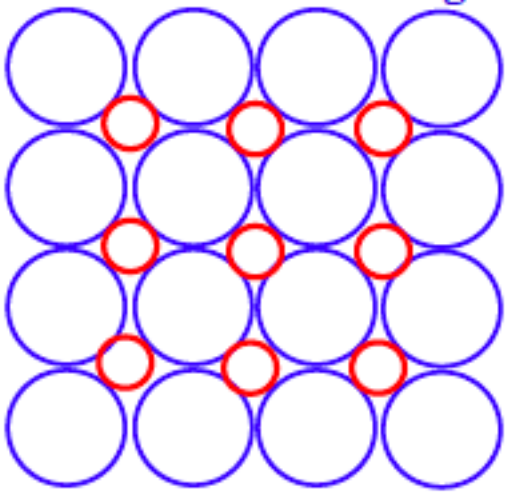
MCP PMT with reflection photocathode at bottom



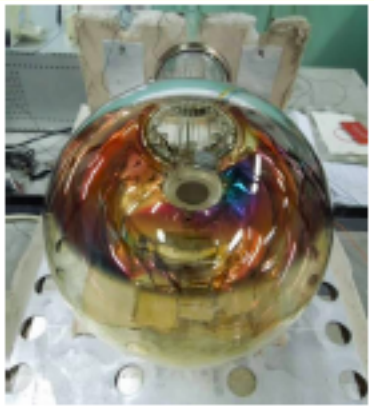
1cm clearance: coverage: 83% *(d/D)^2= 73%

20" + 8" PMT

8" PMT better timing

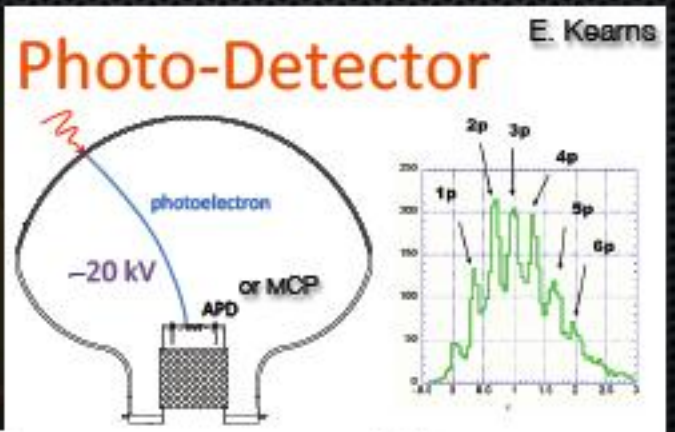


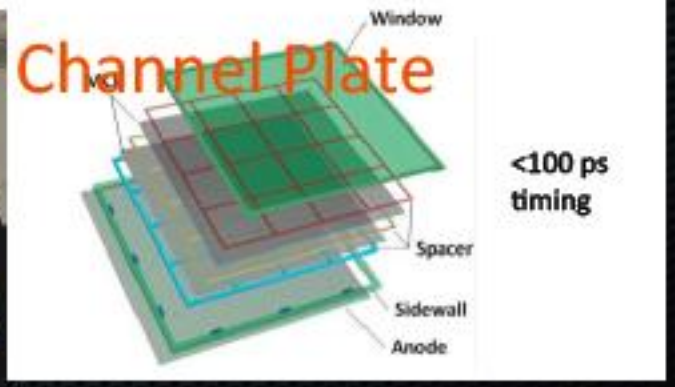
MCP-PMT prototype



Photodetector R&D

Building your detector within the next decade





Large-Area Photodetector options

Scintillator and other additives

- Adding Gd to water or water soluble scintillator enables observing neutron capture.
- It enables:
  - Full de-convolution of a galactic supernova's ν signals
  - Early warning of an approaching SN ν burst
  - Proton decay background reduction (5X)
  - New long-baseline flux normalization (T2K/Project X)
  - Matter- vs. antimatter-enhanced atmospheric ν samples

Inverse Beta Decay Detection with Gd

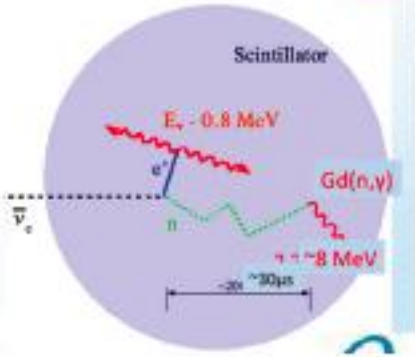
M. Vagins (IPMU)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd} + \gamma's$$

- $E_{threshold} = 1.8$ *MeV*
- *'Large' cross section* $\sigma \sim 10^{-42}$ cm^2
- *Distinctive coincidence signature in a large liquid scintillator detector*

Cowan & Reines, Savannah River 1956



Background events for $p \rightarrow e^+ \pi^0$ (4.5Megaton years)

	ν interactions	secondary interactions in water
1	$\nu n \rightarrow e^- p \pi^+$	Neutron production by the proton
2	$\nu p \rightarrow e^- p \pi^+$	Neutron by π^+
3	$\nu p \rightarrow e^- p \pi^+ \pi^0$	
4	$\nu n \rightarrow e^- p \pi^0$	
5	$\nu n \rightarrow e^- p$	Neutron by the proton
6	$\nu n \rightarrow e^- n \pi^+$	
7	$\nu p \rightarrow e^- p \pi^+ \pi^0$	
8	$\nu p \rightarrow \nu p \gamma$	
9	$\nu O \rightarrow e^- O \pi^+$	Neutron by π^+
10	$\nu n \rightarrow n p$	neutron and π^- by the neutron

M. Shiozawa NNN06

- high energy neutrino events are accompanied by n
- assume proton decay is not accompanied by n
  - * surely not for free proton
  - * also not for γ-tag states
- consider Gd addition to WC to increase n-capture tag efficiency
- Gadolinium R&D underway at SK

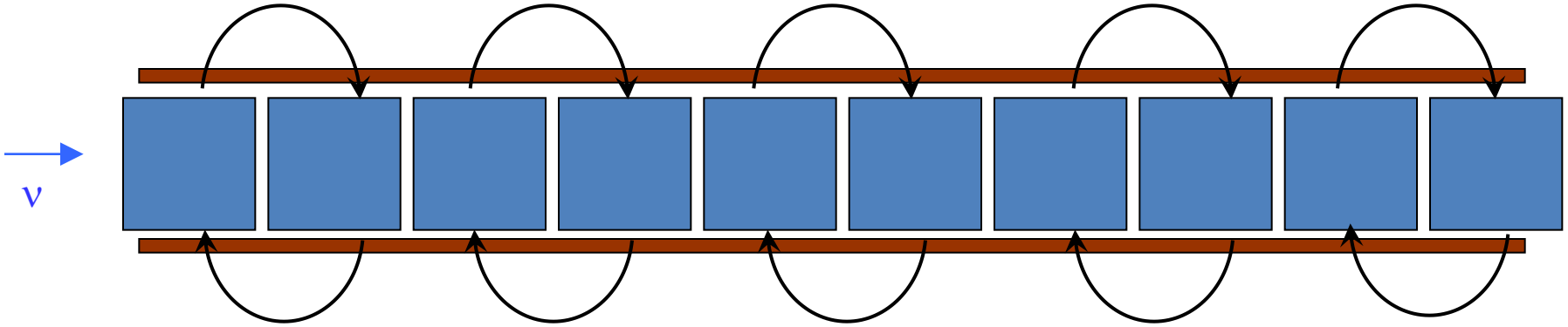
Magnetized Detectors

- Hard to do for large totally active detectors
- Need to do for neutrino factory beams
- Nee new technology

Multiple Solenoids - Conceptual Layouts

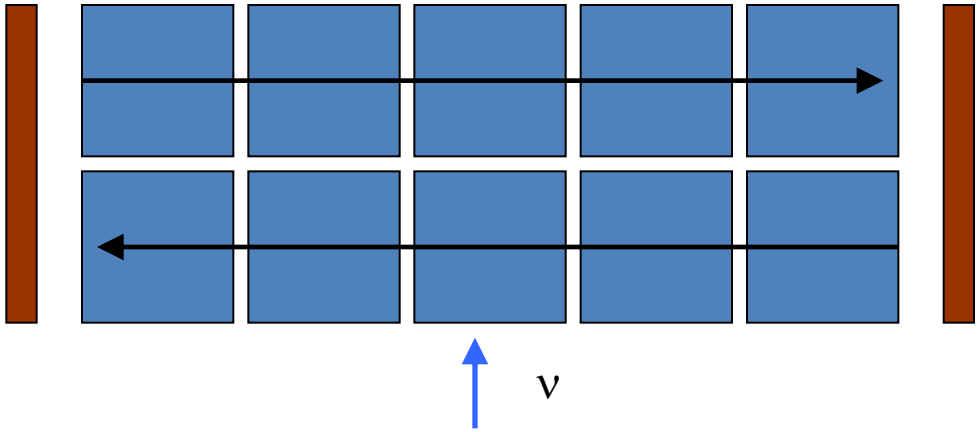
From Alan Bross

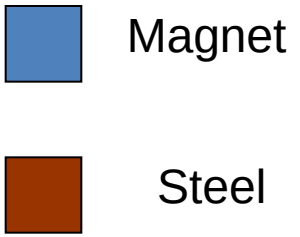
Magnetic Tunnel



15 m x 15 m x 15m modules; B = 0.5T

Magnetic Cavern





Homework for the IF-neutrino detector developers/proposers

- Survey the detectors currently being built and proposed for the next decade's experiments
- Evaluate capabilities, pro's and con's, successes and challenges
- Determine what's *really* needed to take the next steps in improving the experiments
  - Cost drivers
  - Performance requirements
- Instrumentation Frontier :
  - go beyond incremental improvements
  - Work on breakthroughs and new ideas

Intensity Frontier Instrumentation for Rare Processes

Charge: discussion of instrumentation needs for Intensity Frontier rare processes at fixed targets → kaons and muons

A lot to draw on:

Intensity Frontier Workshop
November 30, 2011
www.intensityfrontier.org

Project-X Physics Study
June 14, 2012
https://indico.fnal.gov/conferenceDisplay.py?confId=5276

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Primary motivations

Golden Modes

Muons: $\mu^-N \rightarrow e^-N$, g-2, $\mu^+ \rightarrow e^+\gamma$, EDM

Kaons: $K \rightarrow \pi\nu\nu$

(covered elsewhere: B, D, τ, ν, proton decay)

Current Experiments (Booster/Main Injector)

Muon campus: g-2, Mu2e

Kaons: ORKA

$\mu^-N \rightarrow e^-N$ and $\mu^+ \rightarrow e^+\gamma$ are effectively not allowed in the SM. For these and $K_L \rightarrow \pi^0\nu\nu$ we are only limited by beam, detectors and good ideas. g-2 and $K^+ \rightarrow \pi^+\nu\nu$ are likely to be limited by systematics, but improvements may be possible.

Next Generation (Project-X):

KOPIO+, upgrades to current experiments, other good ideas?

Instrumentation Needs

Most intensity frontier rare process experiments stop the kaon/muon and work in the CM

Calorimeters

- **Fast (Mu2e→LYSO, g-2→PbF2, MEG→ LXe, ORKA→Pb-scint.)**
- **$\varepsilon_{\pi 0}$ >99.9999% ($K \to \pi\nu\nu$) with 4π fully hermetic photon detection**
- **KOPIO+ needs energy, time, position and direction**

Trackers:

- **Low mass (drift chambers, straws, Si?)**
- **Good space/timing resolution**
- **Operation in vacuum (g-2, Mu2e, NA62/CKM straws in vacuum)**

TOF

- **Time photons to bunched p-beam for K_L momentum in $K_L \to \pi^0\nu\nu$**

Other

- **$\mu^+ \to e^+\gamma$ with γ conversion**
- **$K^+ \to \pi^+\nu\nu$ needs active target to stop/track K^+ and track π^+**

Instrumentation Needs (2)

Stop 10^{11}–10^{13} muons/sec, ~few ×10MHz low mom. K decays

Hard to generalize, but need:

- **Macro accelerator duty factor approaching 100% (some need micro-structure, incl. good extinction)**
- **$\sigma_t \leq 100\text{ps} \times E^{-0.5}$**
- **$\sigma_E \leq 2\text{-}3\% \times E^{-0.5}$**

- Calorimetry - https://indico.fnal.gov/getFile.py/access?contribId=183&sessionId=17&resId=0&materialId=paper&confId=5276
- Tracking - https://indico.fnal.gov/getFile.py/access?contribId=186&sessionId=17&resId=0&materialId=paper&confId=5276
- TOF - https://indico.fnal.gov/getFile.py/access?contribId=184&sessionId=17&resId=0&materialId=slides&confId=5276

Intensity Frontier Instrumentation for Heavy Quark Experiments

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- Charge: To seed the discussion of instrumentation needs and opportunities at Experiments

- Incomplete list of reference material
  - CKM2012 talk: Mike Roney on e+e-
    - https://indico.cern.ch/getFile.py/access?contribId=8&sessionId=4&resId=2&materialId=slides&confId=208832
  - CKM2012 talk: Marie-Helene Schune on LHCb
    - https://indico.cern.ch/getFile.py/access?contribId=9&sessionId=4&resId=0&materialId=slides&confId=208832
  - Intensity Frontier WorkshopNovember 30, 2011 www.intensityfrontier.org
    - There are links to summary contributions from several experiments at
      - http://www.ph.utexas.edu/~heavyquark/

LHCb: Physics opportunities with LHCb and its planned upgrade
CMS Prospects for Heavy Flavor Physics
SuperB Report for Intensity Frontier Workshop
The Physics of the SuperKEKB/Belle II Super Flavor Factory
BES-III: Overview of the Key BES-III Physics Opportunities

Primary Physics Motivation

- Questions
  - Are there new CP violating phases?
  - Are there new operators with quarks enhanced by New Physics?
  - Are there right handed currents from New Physics?
  - Are there sources of FCNC beyond the Standard Model?

- Recent/Current/Future Experiments
  - e+e- near Charm Threshold
    - CLEO-c, BESIII, INFN-SuperB, Super-taucharm (BINP, China)
  - e+e- near $\Upsilon(4S)$ Threshold
    - Babar, Belle, INFN-SuperB (2018), Belle II (2015)
  - Flavor physics experiments at Hadron Machines
    - CDF, D0, ATLAS, CMS, LHCb, LHCb upgrade (2020)

Broad and Prolific Physics Programs
CLEO+BABAR+Belle > 1300 publications

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Rely on Silicon

Rely on Calorimeter

Rely on ParticleID

B Physics @ Y(4S)

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ $(J/\psi K^0)$	0.018	0.005 (†)
$\cos(2\beta)$ $(J/\psi K^{*0})$	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi\,\pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (∗)
$S(K^0_S\pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_S)$	0.17	0.03 (∗)
$S(f_0 K^0_S)$	0.12	0.02 (∗)
γ ($B \to DK$, $D \to CP$ eigenstates)	$\sim 15°$	2.5°
γ ($B \to DK$, $D \to$ suppressed states)	$\sim 12°$	2.0°
γ ($B \to DK$, $D \to$ multibody states)	$\sim 9°$	1.5°
γ ($B \to DK$, combined)	$\sim 6°$	1–2°
α ($B \to \pi\pi$)	$\sim 16°$	3°
α ($B \to \rho\rho$)	$\sim 7°$	1–2° (∗)
α ($B \to \rho\pi$)	$\sim 12°$	2°
α (combined)	$\sim 6°$	1–2° (∗)
$2\beta+\gamma$ ($D^{(*)\pm}\pi^\mp$, $D^\pm K^0_S\pi^\mp$)	20°	5°

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\lvert V_{cb}\rvert$ (exclusive)	4% (∗)	1.0% (∗)
$\lvert V_{cb}\rvert$ (inclusive)	1% (∗)	0.5% (∗)
$\lvert V_{ub}\rvert$ (exclusive)	8% (∗)	3.0% (∗)
$\lvert V_{ub}\rvert$ (inclusive)	8% (∗)	2.0% (∗)
$\mathcal{B}(B \to \tau\nu)$	20%	4% (†)
$\mathcal{B}(B \to \mu\nu)$	visible	5%
$\mathcal{B}(B \to D\tau\nu)$	10%	2%
$\mathcal{B}(B \to \rho\gamma)$	15%	3% (†)
$\mathcal{B}(B \to \omega\gamma)$	30%	5%
$A_{CP}(B \to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S\pi^0\gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%
$\mathcal{B}(B \to K\nu\bar{\nu})$	visible	20%
$\mathcal{B}(B \to \pi\nu\bar{\nu})$	–	possible

Charm mixing and CP

Mode	Observable	$\Upsilon(4S)$ (75 ab^{-1})	$\psi(3770)$ (300 fb^{-1})
$D^0 \to K^+\pi^-$	x'^2	3×10^{-5}	
	y'	7×10^{-4}	
$D^0 \to K^+K^-$	y_{CP}	5×10^{-4}	
$D^0 \to K^0_S\pi^+\pi^-$	x	4.9×10^{-4}	
	y	3.5×10^{-4}	
	$\lvert q/p\rvert$	3×10^{-2}	
	ϕ	$2°$	
$\psi(3770) \to D^0\bar{D}^0$	x^2		$(1-2) \times 10^{-5}$
	y		$(1-2) \times 10^{-3}$
	$\cos\delta$		(0.01 – 0.02)

Charm FCNC

	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	3×10^{-8}
$D^0 \to K^0_S e^+e^-$, $D^0 \to K^0_S\mu^+\mu^-$	3×10^{-8}
$D^+ \to \pi^+e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	1×10^{-8}
$D^+ \to \pi^+e^\pm\mu^\mp$	1×10^{-8}
$D^0 \to \pi^0 e^\pm\mu^\mp$	2×10^{-8}
$D^0 \to \eta e^\pm\mu^\mp$	3×10^{-8}
$D^0 \to K^0_S e^\pm\mu^\mp$	3×10^{-8}
$D^+ \to \pi^-e^+e^+$, $D^+ \to K^-e^+e^+$	1×10^{-8}
$D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^-e^\pm\mu^\mp$, $D^+ \to K^-e^\pm\mu^\mp$	1×10^{-8}

τ Physics

	Sensitivity
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K^0_S)$	2×10^{-10}

B_s Physics @ Y(5S)

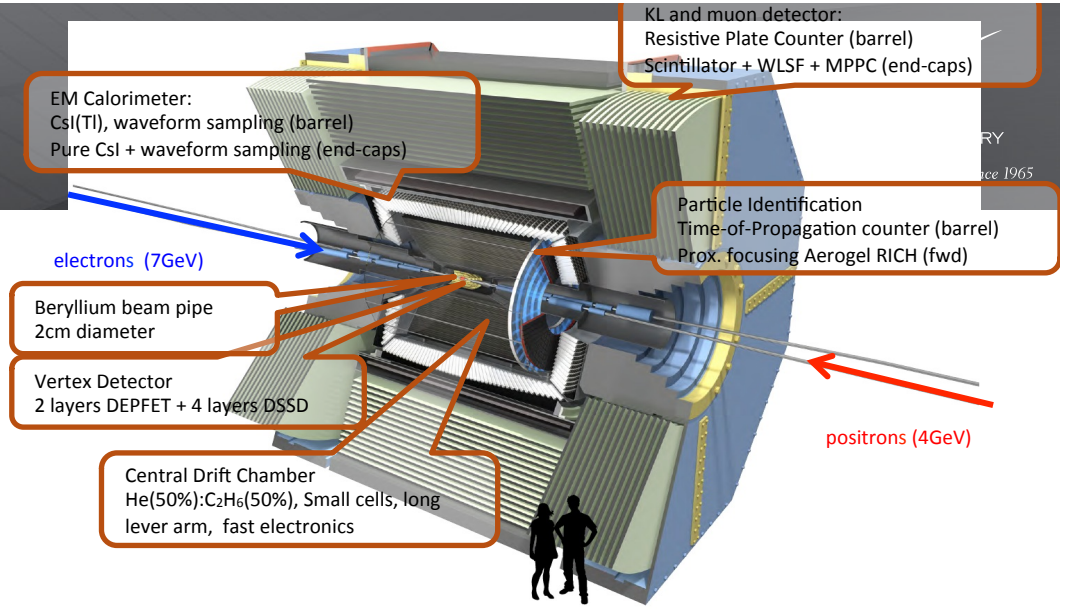
Observable	Error with 1 ab^{-1}	Error with 30 ab^{-1}
$\Delta\Gamma$	0.16 ps^{-1}	0.03 ps^{-1}
Γ	0.07 ps^{-1}	0.01 ps^{-1}
β_s from angular analysis	20°	8°
A^s_{SL}	0.006	0.004
A_{CH}	0.004	0.004
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	$< 8 \times 10^{-9}$
$\lvert V_{td}/V_{ts}\rvert$	0.08	0.017
$\mathcal{B}(B_s \to \gamma\gamma)$	38%	7%
β_s from $J/\psi\phi$	10°	3°
β_s from $B_s \to K^0\bar{K}^0$	24°	11°

M. Giorgi, ICHEP2010

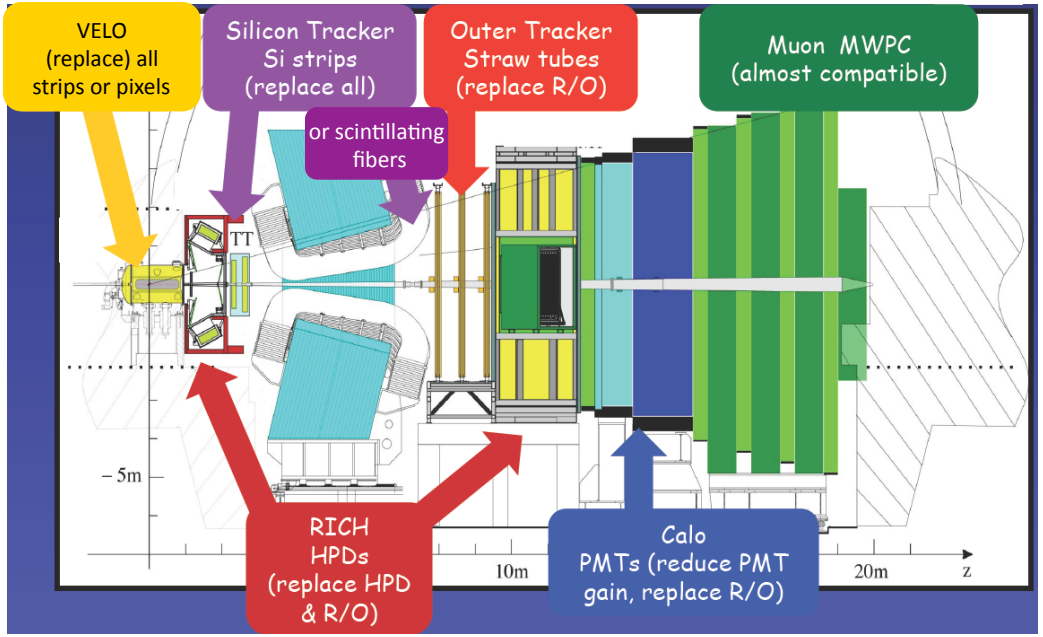
Instrumentation Needs and Opportunities

- Large data volume
  - Ex. Belle II raw data 50 pb/yr
- Super-taucharm
  - BES III (no planned upgrade) – could use CLEO-like RICH
  - BINP – no US participation
- Super B-factories
  - Rad hard&thin silicon trackers
  - Barrel and Endcap PID
  - Endcap Calorimetry
  - Opportunities to contribute to detector upgrades
- LHCb - only NSF support in US
  - Upgrade approved by LHCC

http://cdsweb.cern.ch/record/1333091/files/LHCC-I-018.pdf)



LHCb detector Upgrade : overview



Summary of Facilities

- BES III with run for another 8–10yrs
- Promising developments for c/τ factory in Novosibirsk
- SuperB: hosted in CabibboLab:
  - Italian parliament approved funding for ~ first half; undergoing cost & schedule review now for the balance
  - ground breaking in 2013, first collisions in 2018
- SuperKEKB received Japanese Diet approval for complete project in 2011, construction proceeding well,
  - DOE CD-1 approval Sept 18, 2012, first collisions in 2015
- LHCb upgrade approved in 2012
  - installation in 2018, ready for 14 TeV run ~2020