Elementary Particle Physics at SLAC: Evolving to the Energy Frontier

David B. MacFarlane
Assistant Director, EPP Division

DOE Annual Program Review,
June 12, 2007

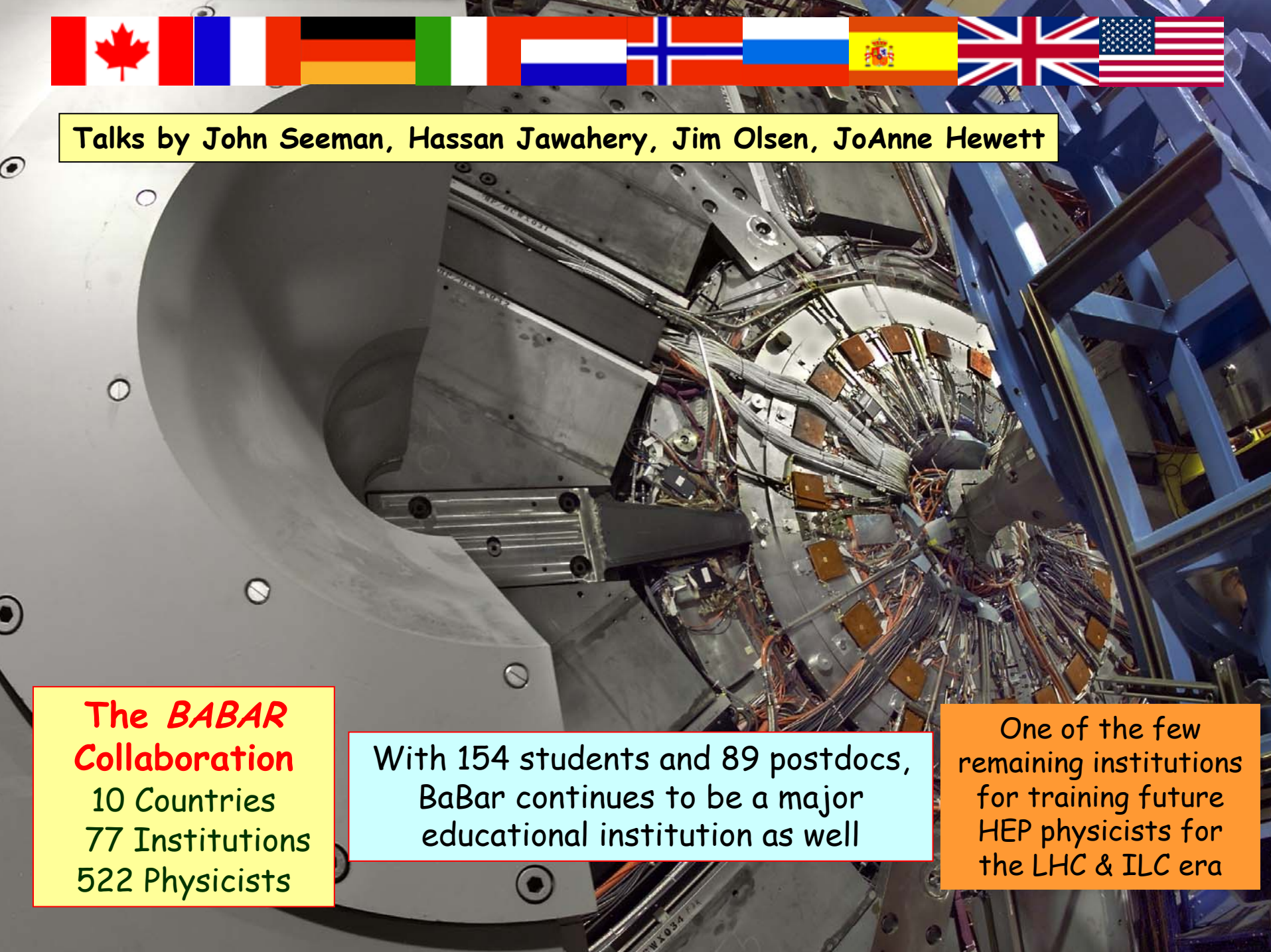
Stanford Linear Accelerator Center

Overview of EPP program: 2007

- ***Exploiting PEP-II upgrades to maximize accumulated data for the B-Factory program***
  - Rich program of heavy quark and lepton flavor physics as foundation for Standard Model and beyond
- ***Rapidly expanding activities in pursuit of physics at the Terascale energy frontier***
  - Atlas at the LHC and SiD for the ILC
- ***Pursuing program to explore the fundamental nature of the neutrino***
  - EXO-200 and full EXO
- ***All elements supported by strong program of theoretical investigations***

B-Factory Physics Program

- ***Highly constrained and redundant set of precision tests of weak interactions in the Standard Model***
  - Legacy of fundamental constraints on future New Physics discoveries
- ***Direct searches for physics beyond the Standard Model***
  - Sensitivity to New Physics at LHC mass scales and beyond
- ***B-factory program operates until end of FY2008***
  - Final upgrades to machine and detector were completed during FY06 shutdown
  - Goal is to double integrated luminosity 06->08



Talks by John Seeman, Hassan Jawahery, Jim Olsen, JoAnne Hewett

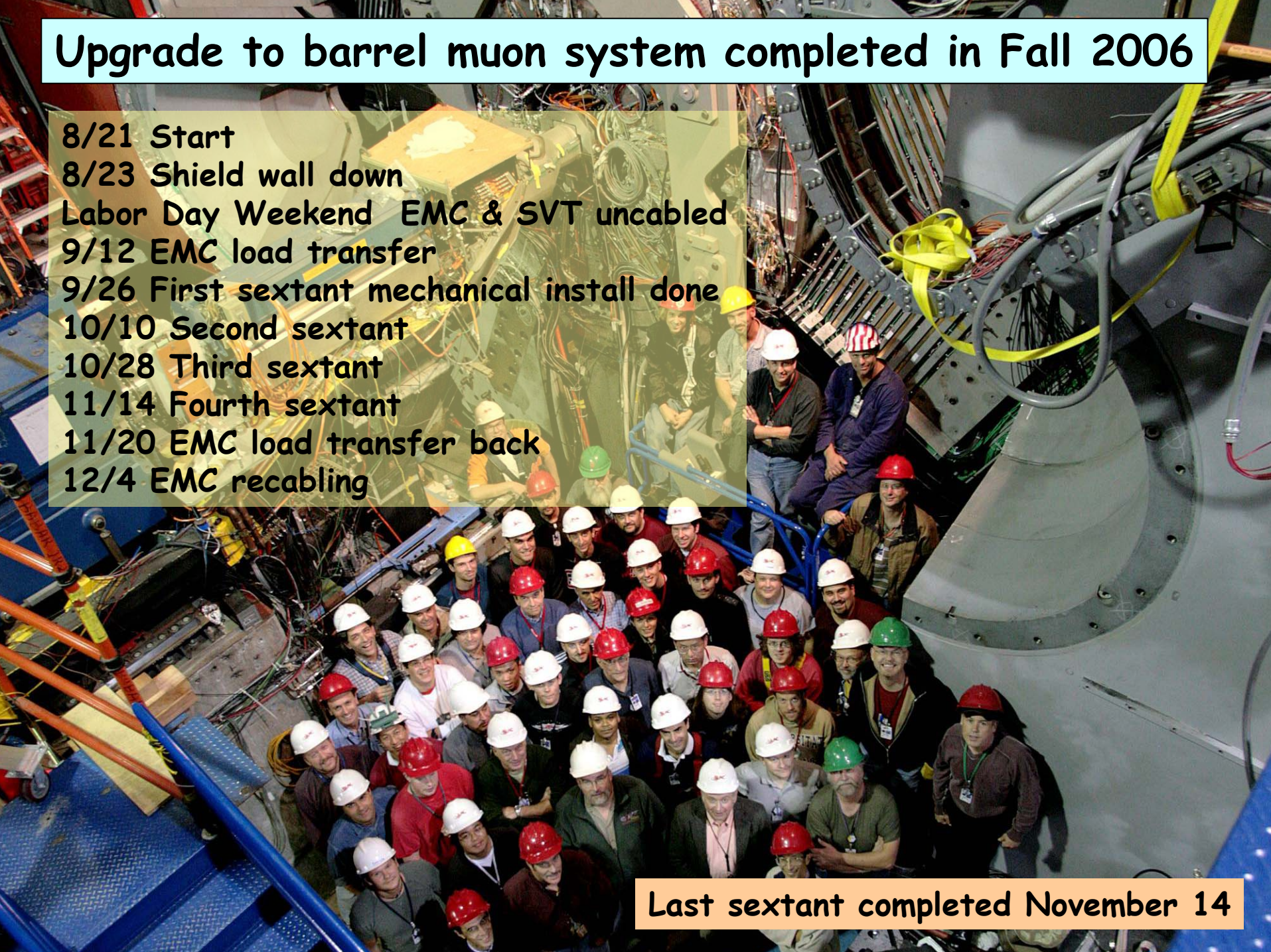
The *BABAR* Collaboration

10 Countries
77 Institutions
522 Physicists

With 154 students and 89 postdocs, BaBar continues to be a major educational institution as well

One of the few remaining institutions for training future HEP physicists for the LHC & ILC era

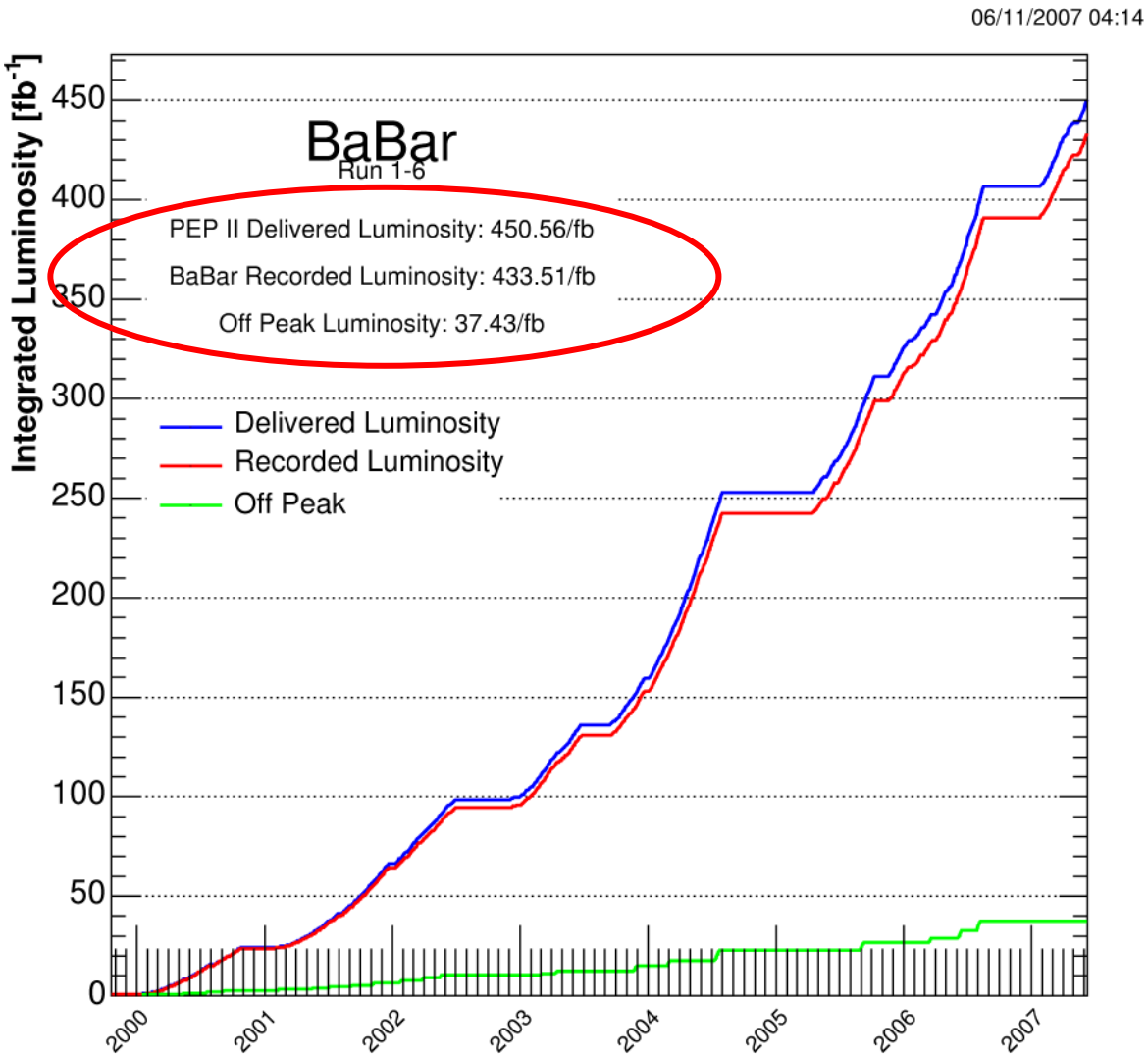
Upgrade to barrel muon system completed in Fall 2006



8/21 Start
8/23 Shield wall down
Labor Day Weekend EMC & SVT uncabled
9/12 EMC load transfer
9/26 First sextant mechanical install done
10/10 Second sextant
10/28 Third sextant
11/14 Fourth sextant
11/20 EMC load transfer back
12/4 EMC recabling

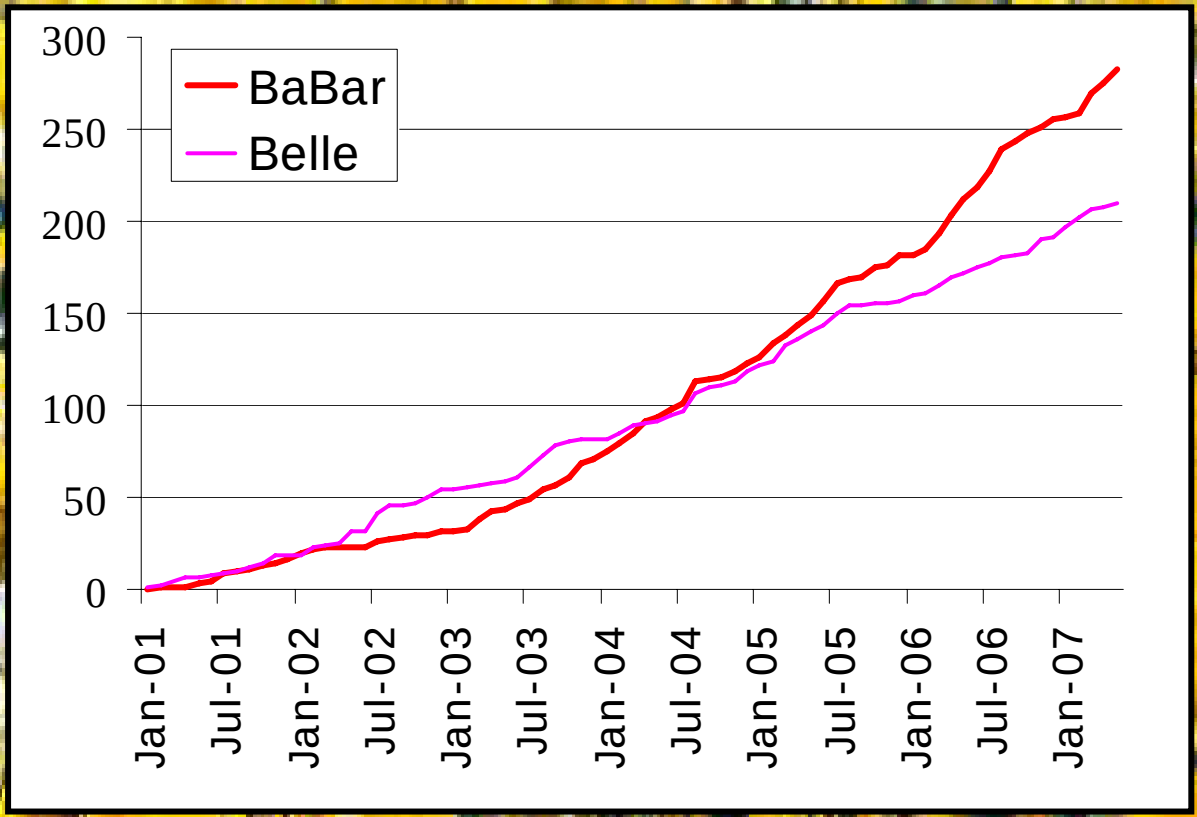
Last sextant completed November 14

Integrated data sample to date



BABAR collects ~97% of PEP II delivery

BABAR & Belle physics results



	BABAR	Belle
Journal Papers	283	210

Winter physics harvest: some highlights

- Update of sin2β in charmonium modes (with golden modes separated out)
- Measurement of CP Violation in B → $\pi^+\pi^-$ (5 sigma effect)
- Measurement of TDCP asymmetry in B → $D^{(*)}D$
- Measurement of TDCP asymmetry in B → $D_{CP}h^0$ (sin2β in tree-dominated mode)
- New results on D^0 mixing
- New states in B → $D^{(*)}D^{(*)}K$: first observation of $D_{s1}(2536)$, evidence for X(3872) and Y(3770)

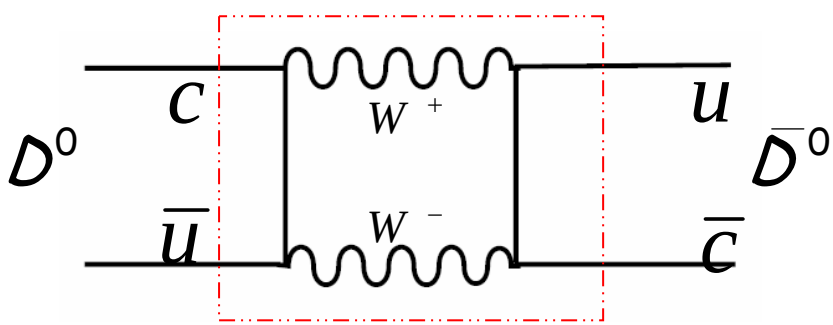
Missing piece of particle anti-particle mixing puzzle

Already seen for :

$$K^0(\bar{s}d) \Leftrightarrow \bar{K}^0(s\bar{d})$$
$$B^0(\bar{b}d) \Leftrightarrow \bar{B}^0(b\bar{d})$$
$$B_s^0(\bar{b}s) \Leftrightarrow \bar{B}_s^0(b\bar{s})$$

Missing piece - till now: $D^0(c\bar{u}) \Leftrightarrow \bar{D}^0(\bar{c}u)$

In the Standard Model: allowed process

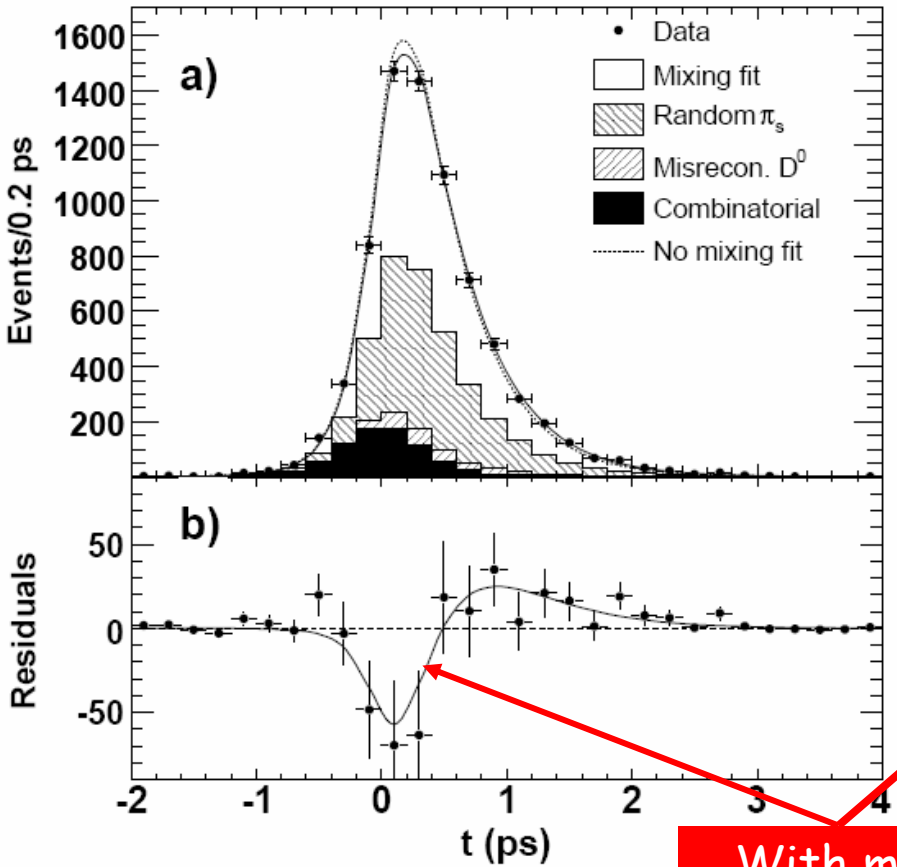


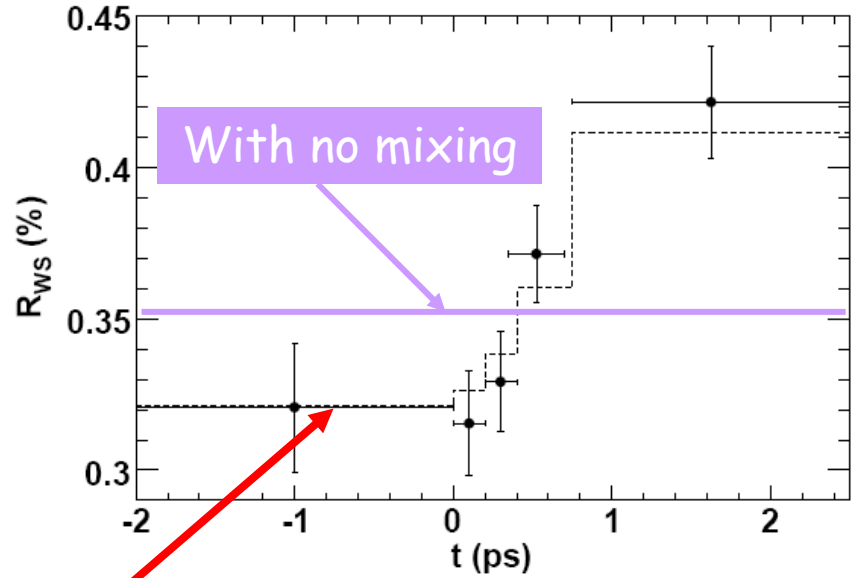
Highly suppressed in SM: an opportunity to search for New Physics contributions

Observation of D^0-$\bar{D}^0$ mixing

Identified about 1 million $D^0 \rightarrow K^-\pi^+$ (RS) decays & 4000 $D^0 \rightarrow K^+\pi^-$ (WS)

Found evidence for ~500 that had switched to anti-D^0 before decaying
D^0 lifetime ~ 0.4 ps (4 sigma effect)





With mixing

Path from now to FY09

- ***Run 6 has had unusually slow turn-on since January***
  - Myriad of technical issues compromising our ability to integrate efficiently or push peak luminosity above Run 5
  - Must do better (and can do better!)
- ***In FY09 the B-factory will stop operations; LCLS will start operations***
  - The challenge we face between now and 2009 is the balance of the B-factory priorities with LCLS
  - We recognize this challenge and it is being actively and aggressively managed
- ***Transition and ramp down planning well underway***
  - In FY 09, accelerator and detector will go to 'minimum maintenance' state immediately after turn off
  - Dismantle & disposal at a time TBD, perhaps FY15

Physics and computing beyond 2008

- ***Major long-term post-data taking commitment***
  - *BABAR* is planning on 2-3 year intense data analysis period to address key physics questions; ongoing analysis beyond with unique data sample extending well into next decade
- ***Planning assumptions to support BABAR plans***
  - FY09-FY11: Intense data analysis period with aim to publish main physics results
    - Final reprocessing of data set Apr-Dec, 2008 for optimal performance: modest increment in resources and personnel
  - FY11-FY14: Long-term analysis at reduced level
    - Assume *BABAR* Tier A centers will start to phase out from October 2010; analysis fully reliant on SLAC by end of 2011
    - Assume some reduction in data replication factor, i.e., not all skims on disk; no reprocessing allowance, etc
- ***Long-term***
  - SLAC as the archival site for a unique data sample

Core BABAR physics program

Charmless:
- sin2β in $b \to s$ penguin: $K^0 + (\eta', K^+K^-, K^0_S K^0_S, \pi^0, f_0, \rho, \omega, \pi^0\pi^0)$
- BFs of color-suppressed decays for SU(3) limits: $B \to \eta'\pi^0, \eta\pi^0, \eta'\eta, \eta'\eta', \eta\eta)$
- 2-body (TD, BFs, $\mathcal{A}_{ch}$): $\pi\pi$ (also TD for α), $K\pi$, KK
- Dalitz plots: 3π, $K\pi\pi$, $3K$
- VV decays (BFs, $\mathcal{A}_{ch}$, polarization): $\rho\rho$ (also TD for α), ϕK^*, ρK^*, $\omega\rho$, ωK^*
- Direct CP: $\rho^0 K^+$, ηK^+, ...

$B \to$ Charmonium $+X$:
- sin2β with $B \to c\bar{c}K^0$, $\cos 2\beta$ with $B \to J/\psi K^*$

Measurements of γ:
- $B \to DK$ (Dalitz,GLW,ADS), $D^{(*)0}K^{(*)0}$, $D^{(*)}\pi$, $D^{(*)}\rho$

B semileptonic:
- V_{ub} with both inclusive and exclusive $b \to X_u \ell\nu$

Radiative B decays:
- inclusive and exclusive $b \to s\gamma$, $b \to d\gamma$ (BFs, $\mathcal{A}_{ch}$), $B \to K^*\gamma$ TD

Rare B decays:
- inclusive and exclusive $b \to s\ell\ell$ (BFs, A_{FB}), $B \to K^{(*)}\nu\bar{\nu}$

B leptonic decays:
- $B \to \ell\nu(\gamma)$, $B \to \ell\ell$

LFV in τ decays:
- $\tau \to \ell + (\ell\ell, \gamma, \pi^0, \eta, \eta', K^0_S, ...)$

Rare charm decays:
- $D \to \ell\ell$, FCNC in D decays

D mixing and CPV:
- Mixing ($D^0 \to K\pi$, $K\pi\pi$, $K3\pi$); CPV (KK, ϕK^0_S, $K^0_S\pi^0$)

The Terascale energy frontier

- ***The highest priority for the international field of particle physics is the full, direct exploration of the TeV energy scale.***
  - Compelling arguments point to New Physics at these mass scales
- ***TeV scale will first be explored by the LHC at CERN***
  - SLAC is a member of LARP and ATLAS
- ***The highest priority new machine for the field (after the LHC) is the ILC***
  - Will allow a full exploration of the nature of any New Physics that will be discovered at LHC

Talk by Su Dong

Atlas at the LHC

The Energy Frontier: LHC

- ***Participation in LHC Accelerator Research Program***
  - SLAC designing collimators for LHC/LHC Upgrades
  - Will also support beam commissioning
- ***SLAC/HEP group ramping up on ATLAS***
  - Already impacting pixel detector commissioning, higher-level trigger, and computing efforts
  - Attracting excellent new talent to the SLAC/ATLAS team:
    - FY07: 1 faculty, 1 Panofsky Fellow, ~10 staff physicists, 3 postdocs, 2 graduate students
    - FY08: Junior faculty position offered; expect an additional ~5 FTE staff, postdoc, & students
  - Won competition to host ATLAS Tier 2 at SLAC
    - Partnering with UCSC and LBNL to form a very strong west coast hub for ATLAS community

Arguments for SLAC entry into Atlas

- ✓ ***Allows exploitation of the physics synergy between LHC and ILC at the energy frontier***
  - Direct involvement in both is best path to gaining a first-hand understanding of the full physics opportunity
  - ILC approval is now also tied to the initial outcome of LHC and its potential for new physics discovery
- ✓ ***After BABAR data taking & before physics at the ILC, there will be a significant gap in accelerator-based HEP***
  - Joining LHC an obvious way of maintaining & developing a healthy work force for ILC, by continuing to attract the best young people to SLAC
- ✓ ***Responds to the needs of our user community***
  - Supports traditional SLAC-University partnerships, now in the commissioning, operation, and physics exploitation of the LHC
  - Provides an avenue for other University user groups to join the LHC, while also working on *BABAR*, for example

Western Tier 2 center at SLAC

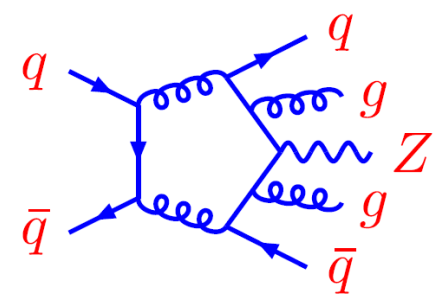
- ***Proposed a premier Tier 2 center = simulation, calibration & detector studies, and physics analysis***
  - Good data access and strong technical support is crucial for analysis
  - Proposal supported and developed in conjunction with LBNL, Arizona, UCSC, UCI, Oregon, Wisconsin Madison, & Washington
- ***Leverages existing & planned investments for BABAR***
  - Investment level about 25% of typical *BABAR* computing needs
  - Proven management tools and scalable infrastructure
  - "Lights out" no operator 24x7 operation for last 10 years
  - Common CPU pool with *BABAR* can benefit both experiments by exploiting staggered peak usage
- ***SLAC, in partnership with LBNL & UCSC, will help support a vibrant west coast center for physics on Atlas***
  - Many common interests in Atlas: pixel and inner detector tracking/alignment, trigger and event simulation, & physics analysis
  - User facilities exist to house many visitors on site
  - New mode for HEP that we are keen to develop with our users

ATLAS community activities at SLAC

- ***Support to ATLAS users in common physics and detector efforts***
  - Strong engagement of outstanding SLAC theory group
- ***Weekly SLAC ATLAS forum***
  - Participation from CERN and other west coast groups on a wide range of LHC physics discussions and experimental issues.
- ***Informal ATLAS physics retreat***
  - Participants from many west coast groups, and more such events expected in near future.
- ***SLAC will host the inaugural "First ATLAS Physics Workshop of the Americas" in Aug/07.***

More precise background estimates for LHC

Talk by Michael Peskin



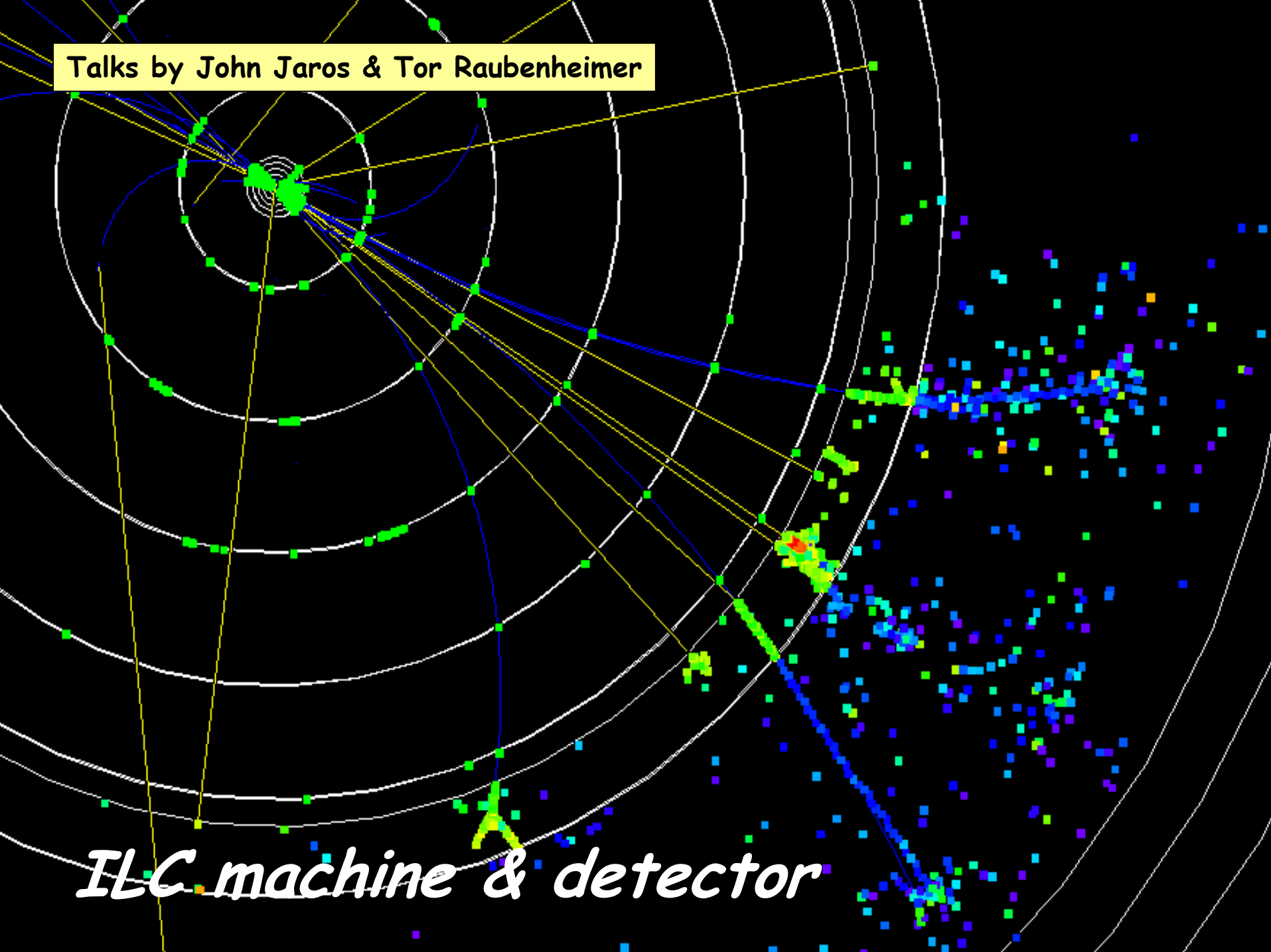
Standard Model processes like $pp \to Z + 4$ jets with $Z \to \nu\bar{\nu}$ (invisible) mimic missing energy + jets signals for supersymmetry, other models of new physics

- Precise estimates need one-loop QCD scattering amplitudes require thousands of complicated Feynman diagrams
- Better to construct amplitudes using their basic analytic properties: "unitarity-factorization bootstrap" method
- Main concepts in method established

  Bern, Dixon, Kosower, Phys. Rev. D71:105013 (2005); D73:065013 (2006); BDK + Berger + Forde, D74:036009 (2006); D75:016006 (2007); Forde, arXiv:0704.1835 [hep-ph]

- Next steps will include much automation
- At SLAC: Dixon, Berger and Forde, with Maitre (just arrived) and Gleisberg (arriving in Fall)

Talks by John Jaros & Tor Raubenheimer

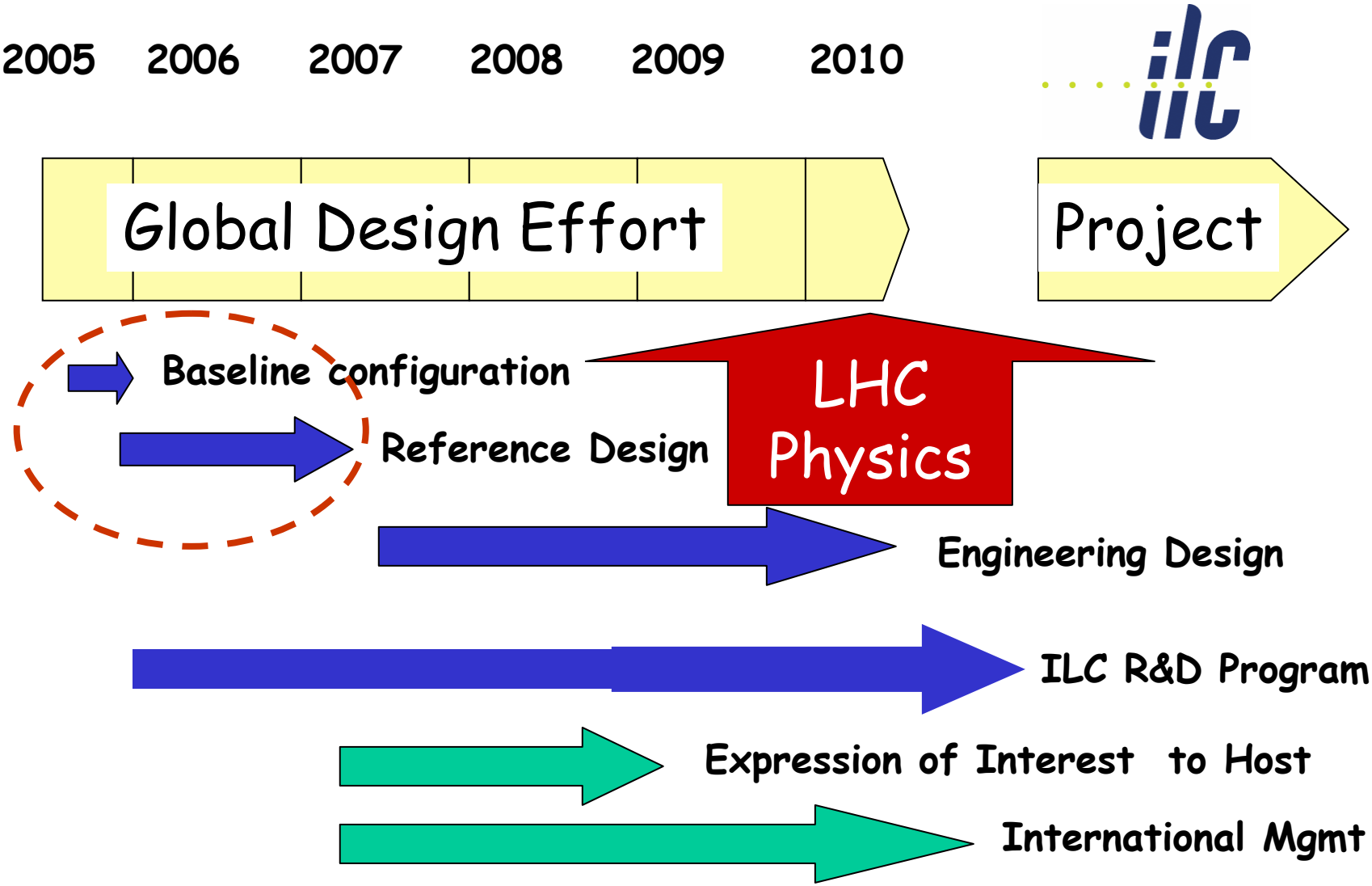


ILC machine & detector

The Energy Frontier: ILC & detector

- ***International Linear Collider: a world wide effort to design and build the next great particle physics accelerator***
  - SLAC is broadly involved in all aspects of the ILC machine design and development
  - Partnering with university community in developing concept for detector
- ***Major focus of SLAC ILC effort as part of GDE coordinated effort***
  - Leadership in developing Reference Design Report (RDR) and Detector Concept Report (DCR)
  - RF power sources, operational issues, particle sources, beam delivery system, machine-detector interface and instrumentation
- ***SLAC leading Silicon Detector design study as one of four ILC detector concepts***
  - Focus on R&D for silicon tracking, particle-flow calorimetry, detector simulation, and overall detector concept

GDE Machine Roadmap

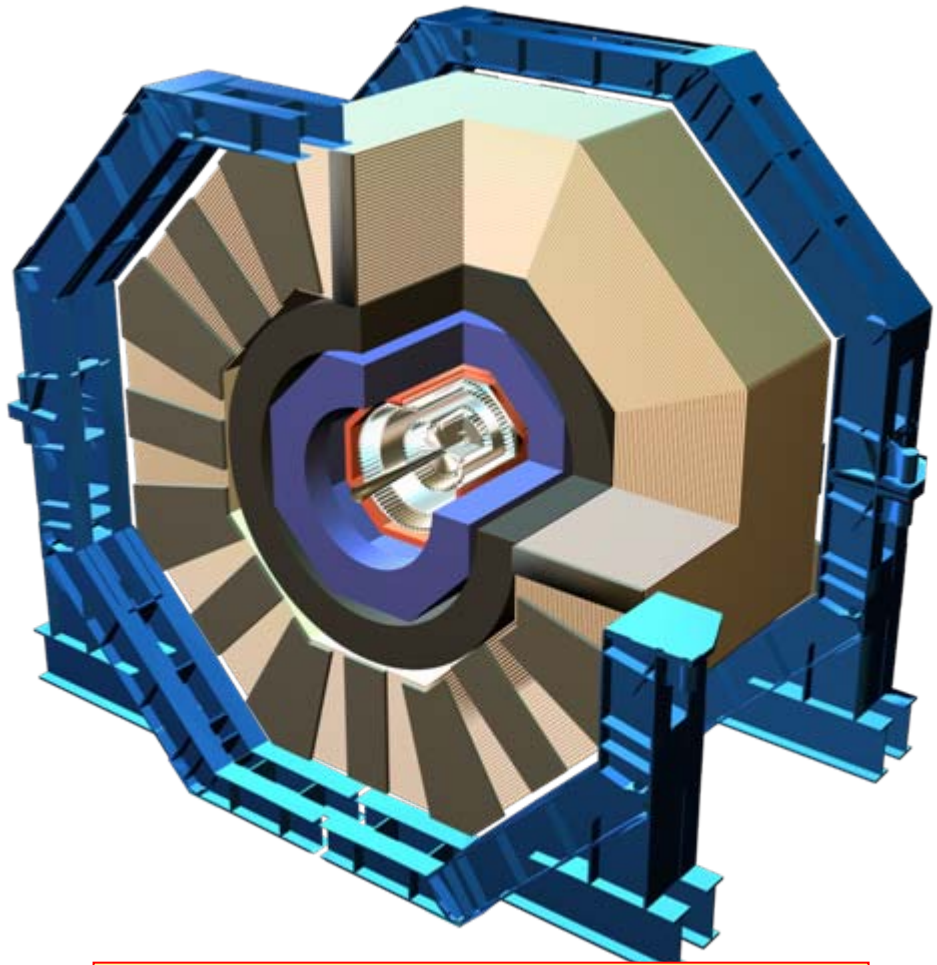


The detector roadmap as proposed by WWS

- *Key elements of roadmap proposal are:*
  - A call for LOIs by ILCSC this summer, due summer 2008
    - Provide a description of the proposed detector and its performance, and inidicate the intent of those planning to collaborate on developing the EDR.
  - LOIs will be reviewed by the IDAG, an International Detector Advisory Group of experts chosen by ILCSC.
  - IDAG will facilitate the definition of two, complementary and contrasting detector designs, and report the result to ILCSC.
- *The result of this process should be two proto-collaborations operating by the beginning of 2009 to produce EDR documents by end 2010.*
- *Process begun by the ILCSC in reaction to proposal*
  - Issue Call for Detector LOIs summer 2007.
  - Search for, & appoint a Research Director, to oversee the experimental program for the ILC, coordinate reviews of the LOIs, facilitate the selection of two, complementary detector designs, help generate support for two detector EDRs, & monitor EDR development.

SiD design studies at SLAC

- Providing Computing/Simulation infrastructure for all SiD
- Engaging collaborators at Fermilab, BNL, Argonne, many US Universities. Developing international ties (KEK, Tokyo, Annecy, Oxford)
- Coordinating & pursuing detector R&D
  - Si/W calorimetry and KPiX ASIC
  - Tracker design/Si microstrips
  - CMOS pixels for vertex detector
- Optimizing & benchmarking SiD Design



SiD detector outline document completed with 130 authors

Ongoing R&D goals for SiD at SLAC

- ***Ecal***
  - KPiX, new Si sensors, prototype, beam test, mechanical design, proof of principle
- ***Main Tracker***
  - Tracker Si sensor, prototype sensor modules, beam test
- ***Vertex Tracker***
  - Evaluate performance, mechanical design (with FNAL), develop sensor
- ***Reconstruction Code***
  - Perfect particle-flow algorithm, tracking pattern recognition
- ***Benchmarking/Analysis/Design Optimization***
  - Detector performance requirements, new physics analyses, global optimization, subsystem optimization

EXO: Enriched Xenon Observatory

Talks by Giorgio Gratta

Neutrinos—EXO

- ***Determining fundamental nature of neutrino with search for $0\nu\beta\beta$ decay in $^{136}Xe \dashrightarrow {}^{136}Ba^{++}e^{-}e^{-}$***
  - What is absolute mass scale for neutrinos?
  - Is the neutrino its own antiparticle?
- ***Strategy:***
  - Currently building EXO 200 for installation in July 2007
    - Study detector performance (no Ba^{++} tagging)
    - Sensitivity of ~0.2 eV to $0\nu\beta\beta$ mode
  - Continue R&D on Ba^{++} tagging for next 2-3 years
  - Develop a full system design for large-scale implementation
- ***Successful R&D would lead to proposal for full EXO (ton scale experiment)***
  - EXO goal: $\langle m(\nu_e)\rangle$~10's of meV

EXO experimental strategy

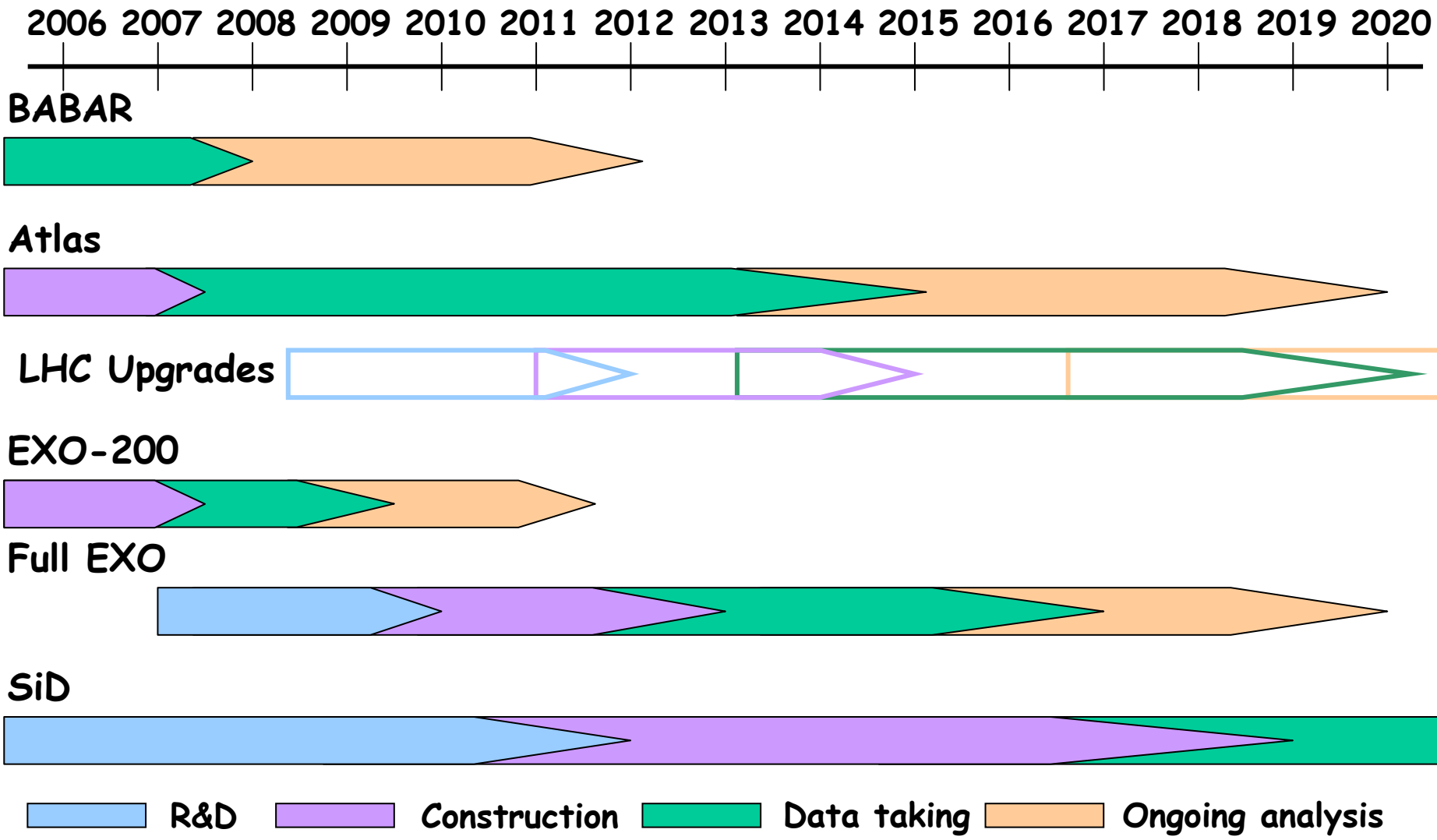
- ***Detect Standard Model 2ν double beta decays***
  - Use (liquid) xenon as source and detector
  - Xe^{136} is a relatively easy isotope to enrich – and – EXO has 200 Kg on campus!!
- ***Developing background free next generation experiment***
  - Rejecting 2 neutrino decay backgrounds:
    - Energy resolution in TPC using ionization and scintillation light
  - Rejecting external backgrounds:
    - Use radiologically quiet materials to build and shield apparatus
    - Locate apparatus in radiologically quiet area = deep underground salt deposit at WIPP
  - Turn experiment into coincidence experiment by detecting nuclear daughter of double beta decay of Xe^{136} to Ba^{136} (one single ion at a time!)

$$^{136}Xe \rightarrow {}^{136}Ba^{++} e^- e^-$$

Unique feature of EXO

Identify event-by-event

Program view: evolution of EPP science



Core competencies view: EPP program

- ***Design, commissioning, operation of complex detector systems***
- ***Mechanical engineering for large-scale projects***
  - Design, fabrication and assembly of large-scale detector projects, systems engineering, and project management
- ***Electronics engineering for large-scale projects***
  - Design and development of forefront analog and digital electronic systems, systems engineering, and project management
- ***Data acquisition and trigger systems***
  - Design, development, and operation of high-performance real-time data acquisition, control and trigger systems based on embedded processors, high-performance networking, and online compute farms
- ***Computing solutions for large-scale data handling & analysis***
  - Assembly and operation of large-scale compute farms
- ***Forefront fundamental detector research and development***
- ***Design and operation of beamlines and test facilities***

Example: detector R&D at SLAC

- **SiD**
  - Tracker sensors, mechanics, & readout; EMCal readout and mechanics; FCal, HCal, & muon system readout; simulation systems, tools, & reconstruction; higher level DAQ system with no hardware triggers; overall detector optimization & design
- **EXO**
  - Liquid Xenon TPC; large area APDs; Xenon purity & cryogenics; Ba++ grabbing; low-noise, continuous sampling, triggerable readout electronics; overall system design
- **LSST**
  - Materials tests for use in high vacuum with coated optical elements; sub-micron metrology over large areas; limits of kinematic couplings; metrology systems and in situ calibration systems; in situ capacitive position monitoring; x-ray calibration systems for large arrays; imaging sensor characterization

Example: detector R&D at SLAC

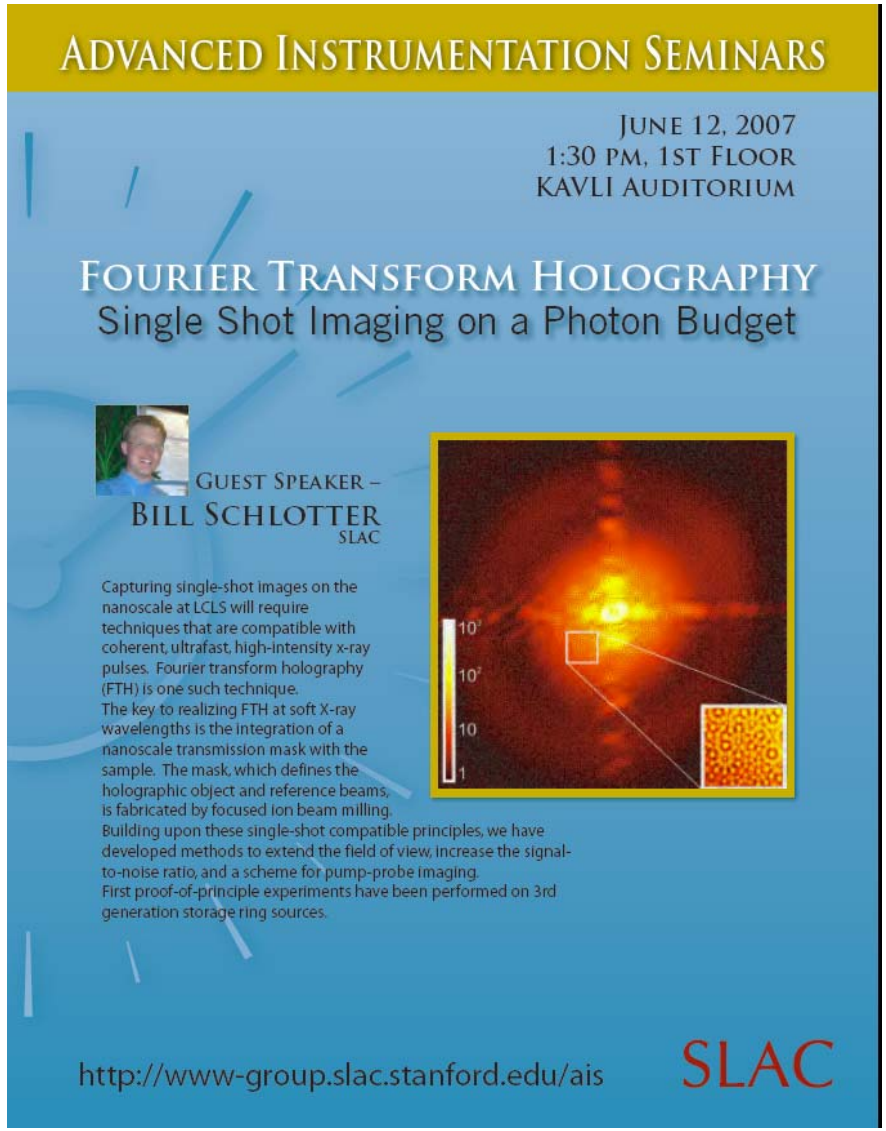
- ***Machine-detector interface & instrumentation***
  - Luminosity, energy, & polarization measurements; collimation & backgrounds; forward detectors; EMI
- ***General development***
  - Cell design, gas optimization, for future collider applications; characterization & development of pixellated photon detectors & high-precision timing applications; development of highly scalable solutions for high data rate applications; development of low noise, low power ASICs; development of silicon PMTs
- ***Photon science instrumentation***
  - LCLS experiments starting to explore design complexity, data logging and analysis regimes that resemble HEP experiments

Currently in initial stages of exploring synergies across PPA & PS

Advanced Instrumentation Seminars

Speakers this spring

Helmuth Spieler
Peter Hommelhoff
Lothar Struder
Jesse Wodin
Peter Denes
Joe Incandela
Cameron Geddes
Jessamyn Fairfield
Peter Weilheimer
Joe Dwyer
Kirk Gilmore



Where will EPP be in 10 Years?

- ***SLAC-EPP is evolving & diversifying, while also embracing the energy frontier opportunities***
  - Engaged and providing leadership and user support for the highest priority elements of the national program
  - Recognizing the crucially important need for maintaining strong ties with the university community in the future program
- ***We face significant challenges and uncertainties along with the entire field***
  - Working to identify and strengthen core competencies and technical capabilities that will serve a broad spectrum of scientific opportunities and users
  - Flexibility in supporting a spectrum of physics opportunities
- ***An integral part of the broader SLAC-PPA program, with a diverse and exciting HEP program***

Backup Slides

SiD related detector R&D

- SCCCD – Short Column CCD for vertex detector sensors.
- Tracker sensor development – design of a Si strip sensor with a metal layer organized for bump bonding to 2 KPiX chips.
- Tracker mechanics – development of a complete package to hold a sensor, cable etc with required precision.
- Tracker readout – KPiX with nearest neighbor logic, etc.
- EMCal readout – KpiX is a 1024 channel readout chip with low noise, large dynamic range, low power, time measurement, and 4 sets of measurements per train – all optimized for the ILC. All digitization is on chip, and the KPiX bump bonds to the sensor.
- EMCal mechanics – Conceptual development of W-Si system with 1 mm gaps between tungsten sheets.
- FCal readout – 32 channel Si pixel readout chip digitizes every pulse of the train and also provides a fast sum measurement for machine diagnostics. May be used in polarimeters and energy spectrometers.
- HCal readout – KPiX for GEM, RPC with input polarity inversion, etc.
- Muon system readout – KPiX with 64 channels.
- SiD system design – Development of a parametric detector design code that calculates self consistent detector parameter and costs.

SiD related detector R&D

- Detector simulation systems and tools- development of geometry, IO packages, etc that enable simulation studies and collaboration even across detector concepts.
- SiD simulation – particularly vertex detector, tracking, and calorimetry studies.
- SiD reconstruction and physics performance. Use of various fast and slow Monte Carlo tools to evaluate the SiD performance for various physics benchmarks.
- Higher Level DAQ- Conceptual design of the SiD data acquisition system with no hardware triggers. A system of low mass data concentrators and power distribution is being developed.

EXO related detector R&D

- Liquid xenon TPC – Simulation, detailed design, and construction of the cathode, anode and grid structures, and field shaping structures for EXO 200.
- Large area APD's – Characterization of the scintillation detectors for EXO 200
- Low noise, continuous sampling, triggerable readout electronics – design and construction of the readout/DAQ for EXO 200.
- Xenon purity measurement – development of a moderate drift, electron attachment monitor for lab use and EXO 200 use.
- EXO Cryogenics: Simulation, design, & construction of xenon condensers, evaporators, and transfer lines. Simulation & design of the refrigeration system, including performance of HFE-7000 thermal transfer fluids. Design of the HFE and Xenon systems, including pressure balance system to permit thin walls on the xenon TPC.
- Ba+ grabbing – Fundamental R&D on the extraction of single ions from liquid xenon and their release into a near vacuum.
- EXO system design – Integration of concepts and requirements for full EXO into a coherent design (just beginning).

General detector R&D

- Optimization of cell design and gas choices for future collider detectors
- Gas detector development for high-rate TPC and gaseous cathode development
- Characterization and development of pixellated photon detection systems with high-precision timing capability for Cherenkov or Time-of-Flight applications at future detectors
- Characterization of MCP PMT's, from various vendors for absolute quantum efficiency, uniformity of cathode response, and behavior in high (10 to 25 kilogauss) magnetic fields.
- Development of front end electronics to support picosecond timing (with the Universities of Hawaii and Chicago).
- Development of a technology to provide high performance, relatively inexpensive, highly scalable building blocks to be used in any application which requires the transport of large amounts of data (many terabytes) to large scale computing structures in relatively short periods of time with unprecedented low latency requirements. This technology has direct applications to LSST, as well as to LUSI.