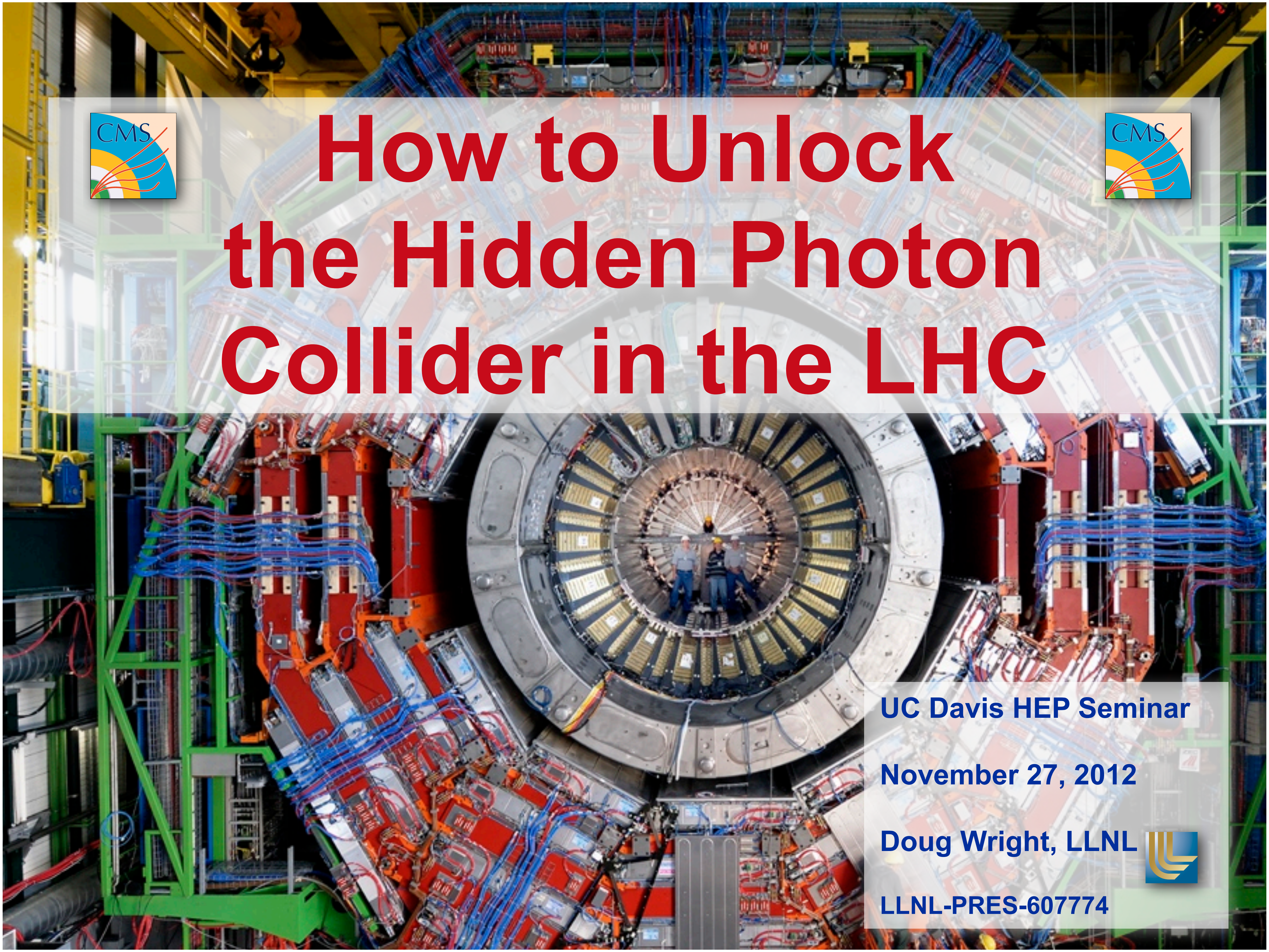
How to Unlock the Hidden Photon Collider in the LHC



UC Davis HEP Seminar

November 27, 2012

Doug Wright, LLNL

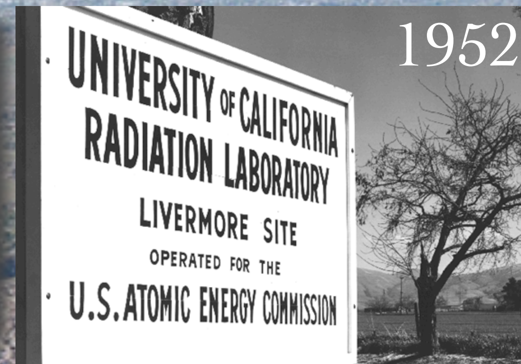
LLNL-PRES-607774

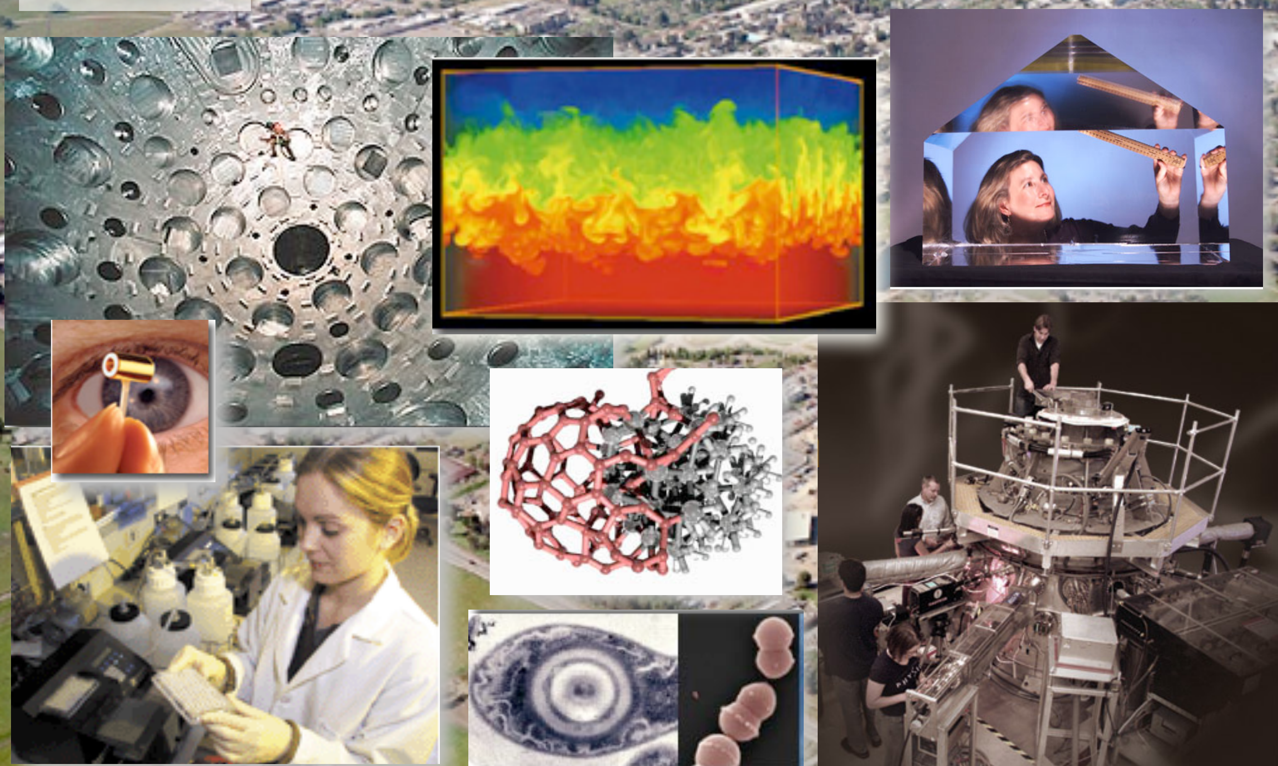
Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory

Co-founder
E.O. Lawrence

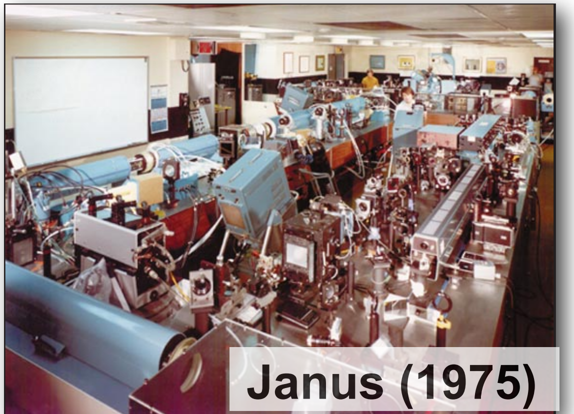
- DOE multidisciplinary lab
- 7,000 employees (1000 Ph.D. scientists, 1300 engineers and technicians)
- Mission: National security, energy, environment, bioscience and basic science

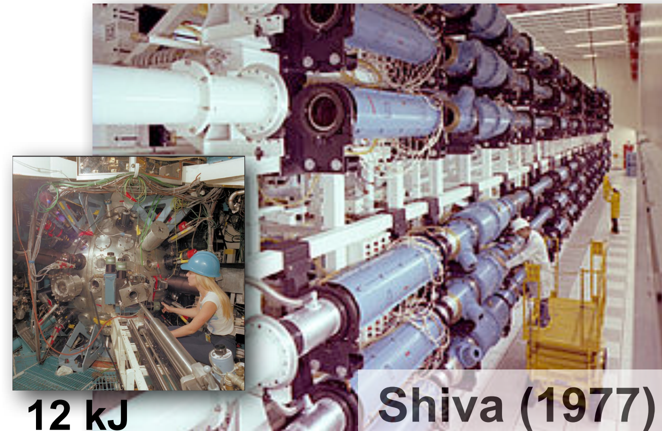




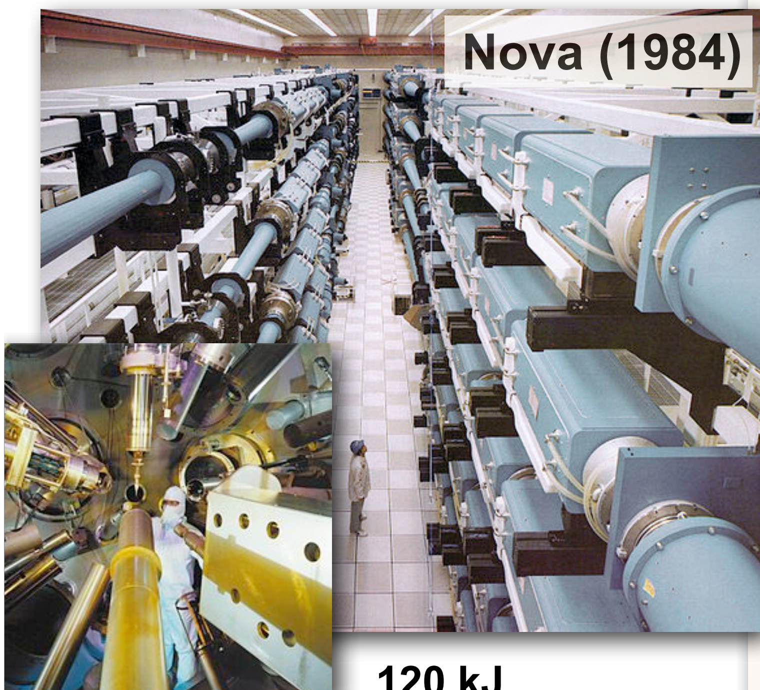
HEP collider effort built up around SSC/GEM and PEP-II/BABAR

Long history of high power lasers at LLNL (Inertial Confinement Fusion Program)

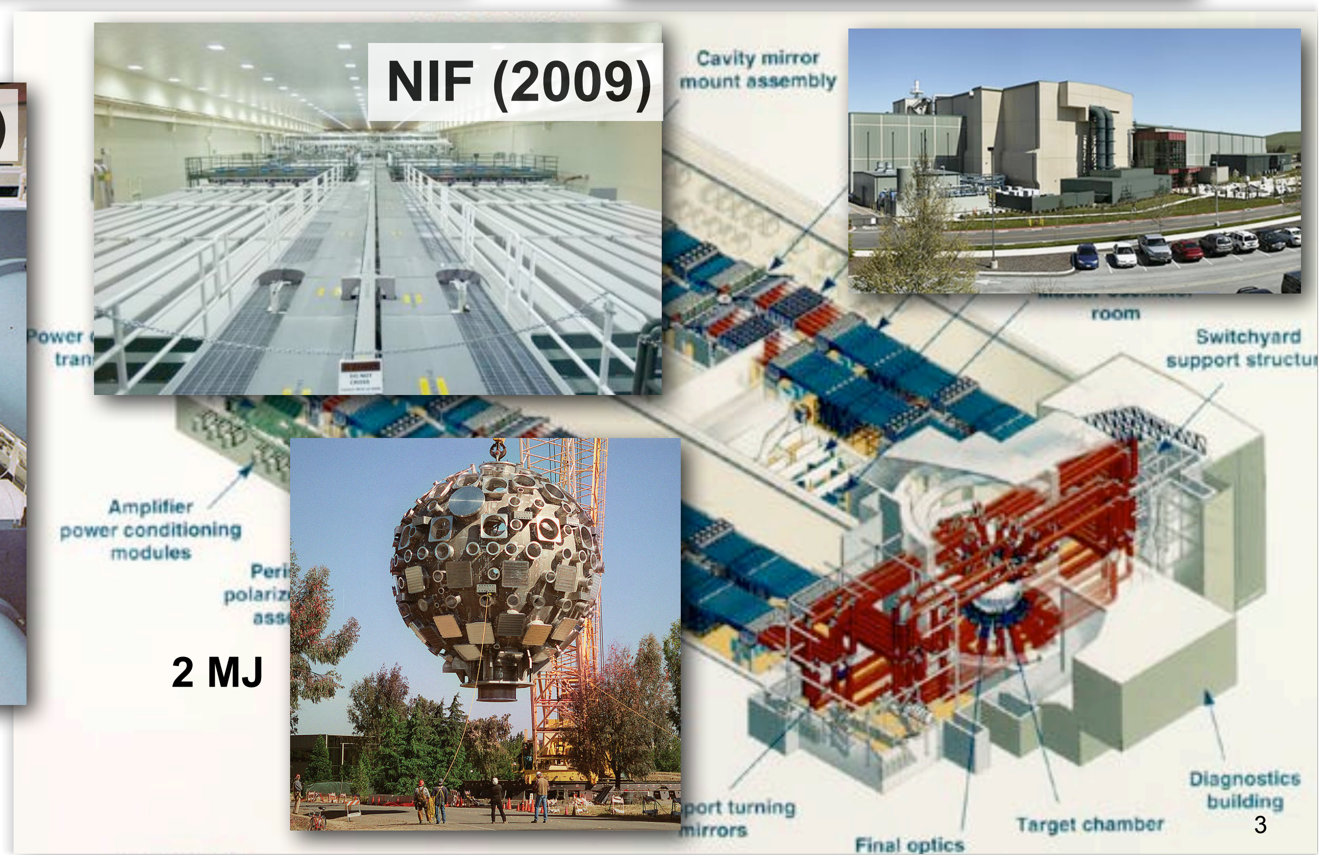




12 kJ

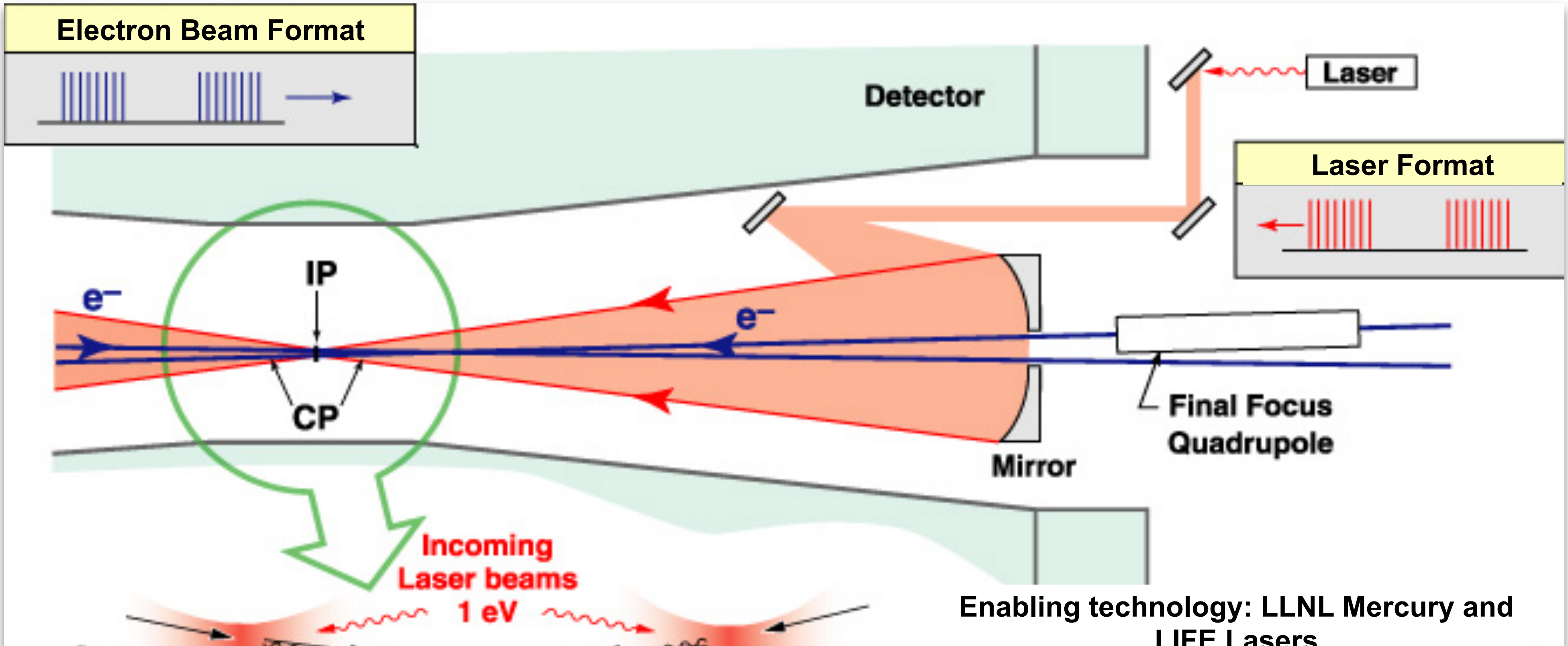


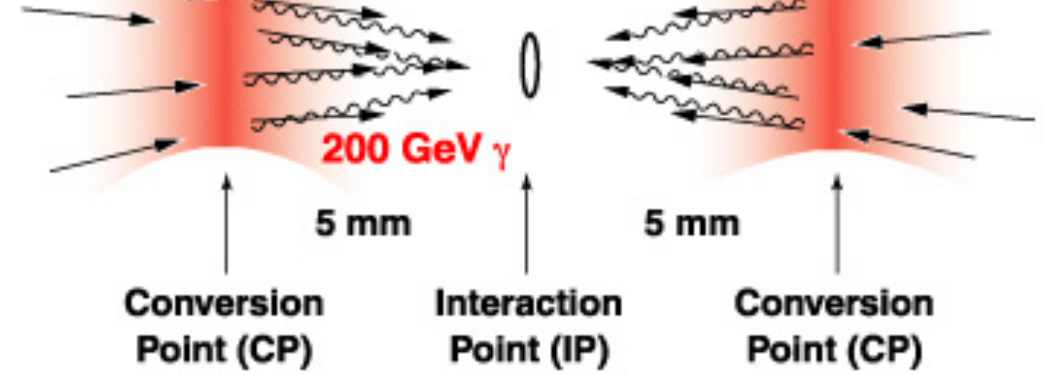
120 kJ



2 MJ

This technology enables a γγ collider (only need e- beams)

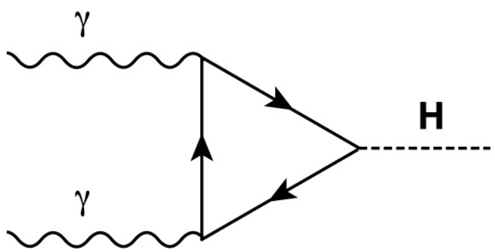




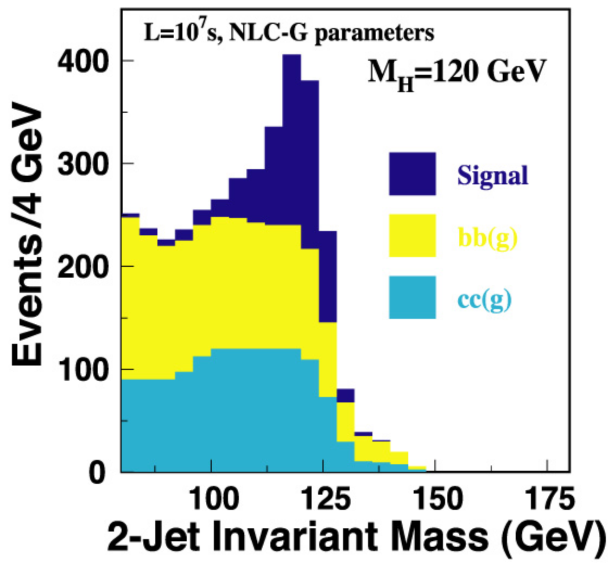
Enabling technology: LLNL Mercury and LIFE Lasers

First proposed 1981; Ginzburg, Kotkin, Serbo, Telnov

γγ collider provides unique physics capability (Good candidate for Higgs factory)

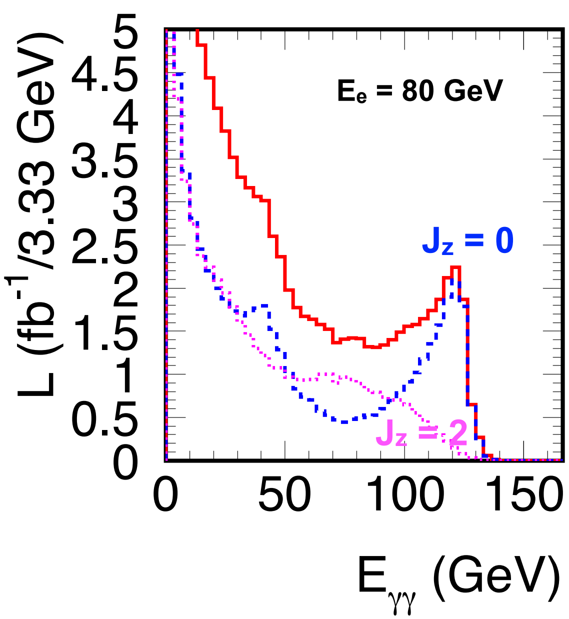


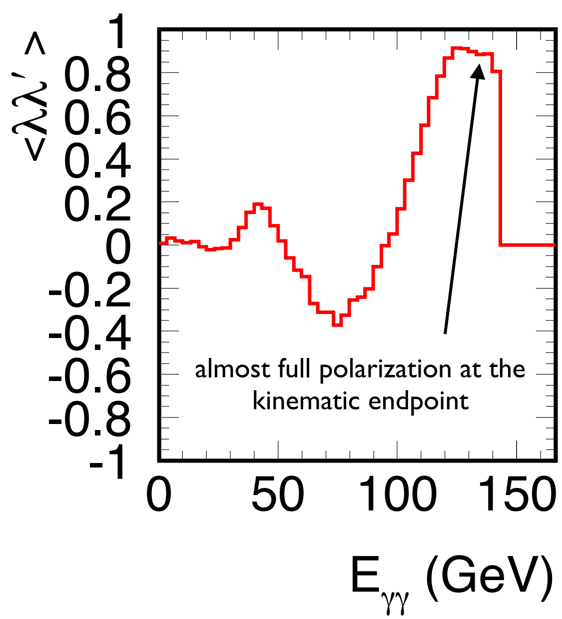
Direct production of Higgs (J_z=0)
e+e- requires ZH



80% polarized e- beams and circular polarization of laser enhances J_z = 0 (signal) and suppresses J_z=2 (background)

need polarized e- gun

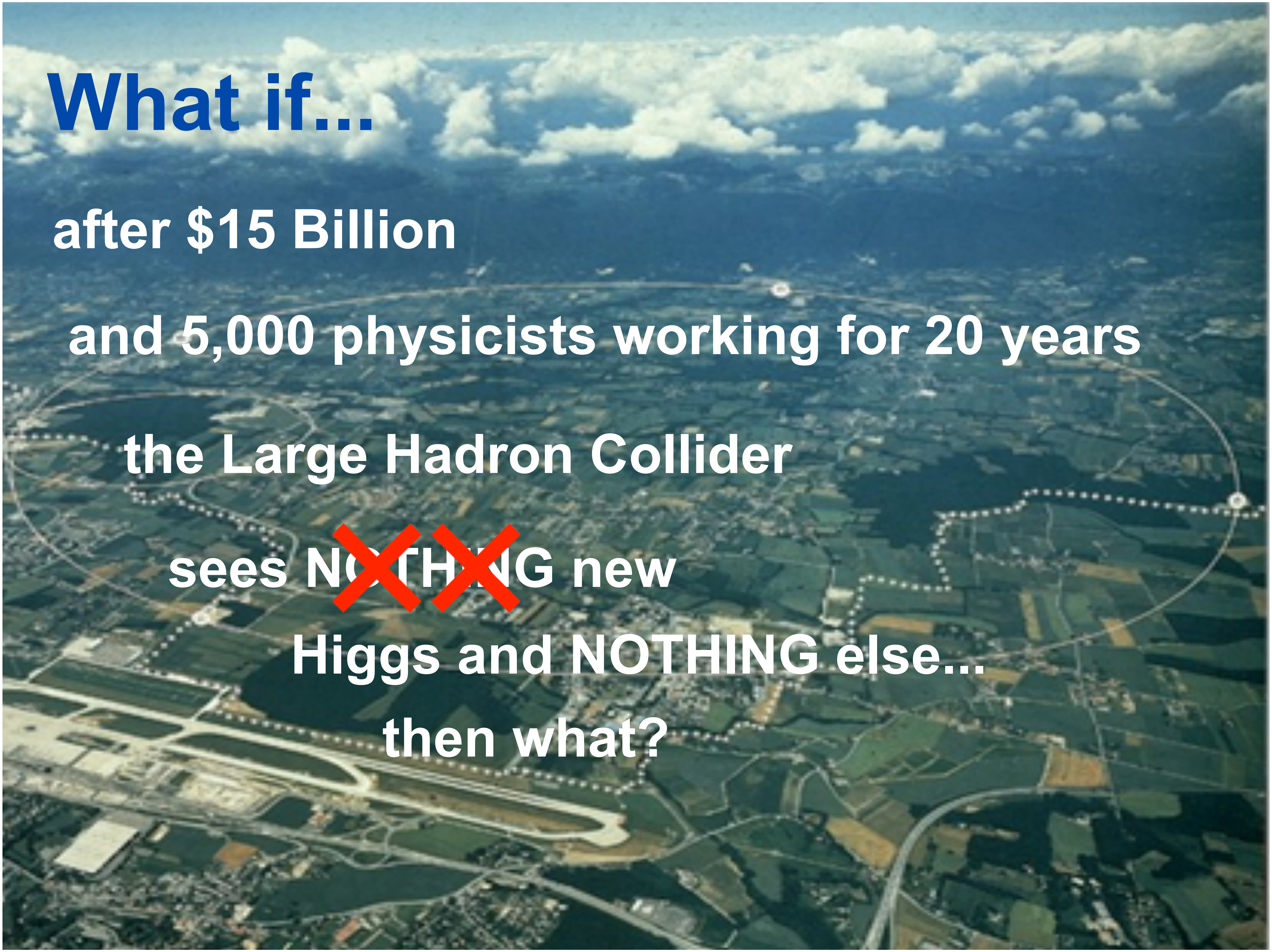




- Circular polarization (laser) enhances signal to background
- Linear polarization (laser) allow an initial state of definite CP (±1)
- Distinguish SM from SUSY Higgs


Largest scientific instrument ever constructed:
Large Hadron Collider (LHC)
proton - proton collider
27 km ring circumference
14 TeV center-of-mass energy
2012 8 TeV
2010 7 TeV
p
p
Geneva (Switzerland) Airport

What if...



after $15 Billion

and 5,000 physicists working for 20 years

the Large Hadron Collider

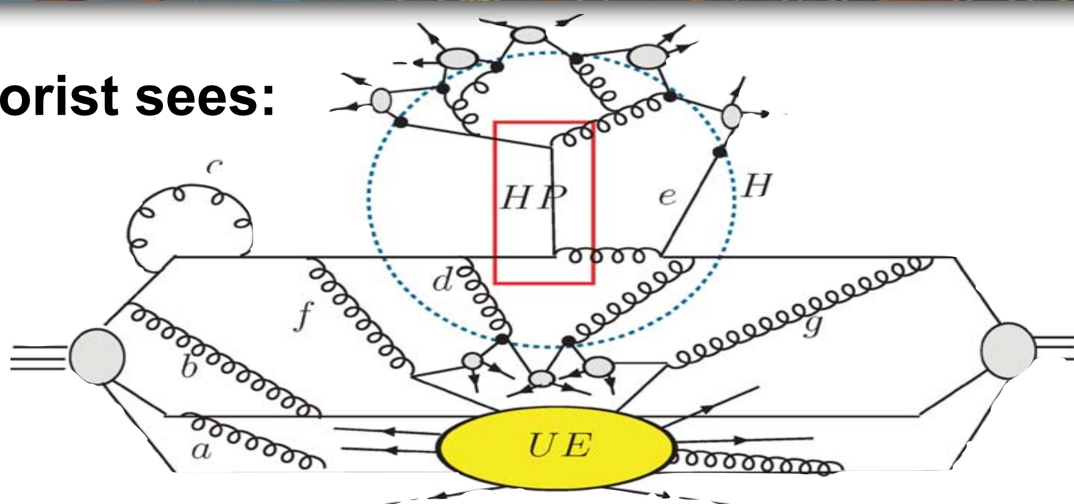
sees ~~NOTHING~~ new

Higgs and NOTHING else...

then what?

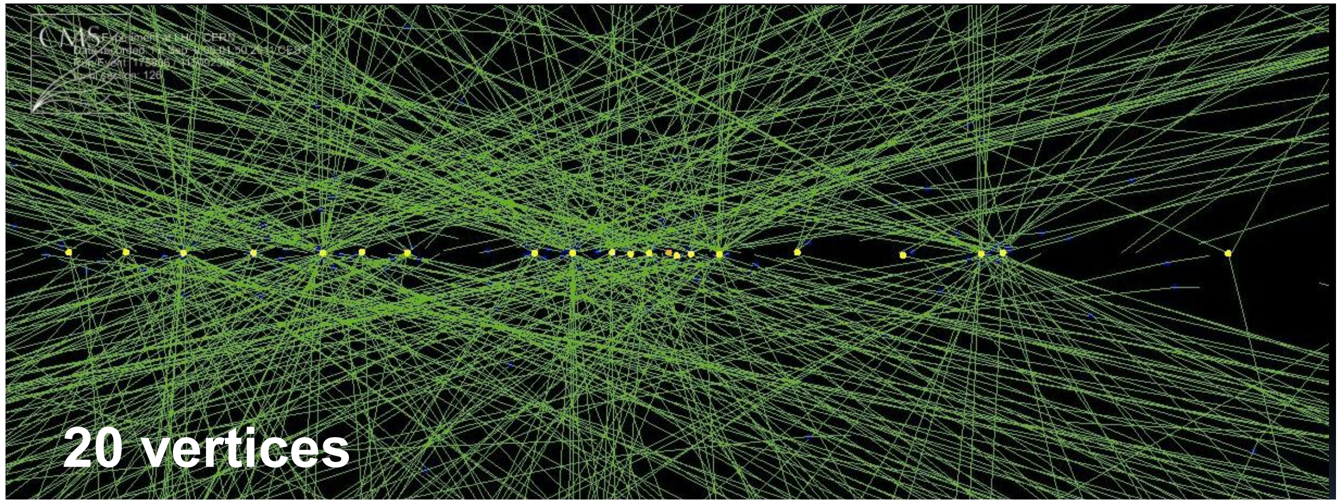
General issue for the LHC: Background easily obscures new physics signals

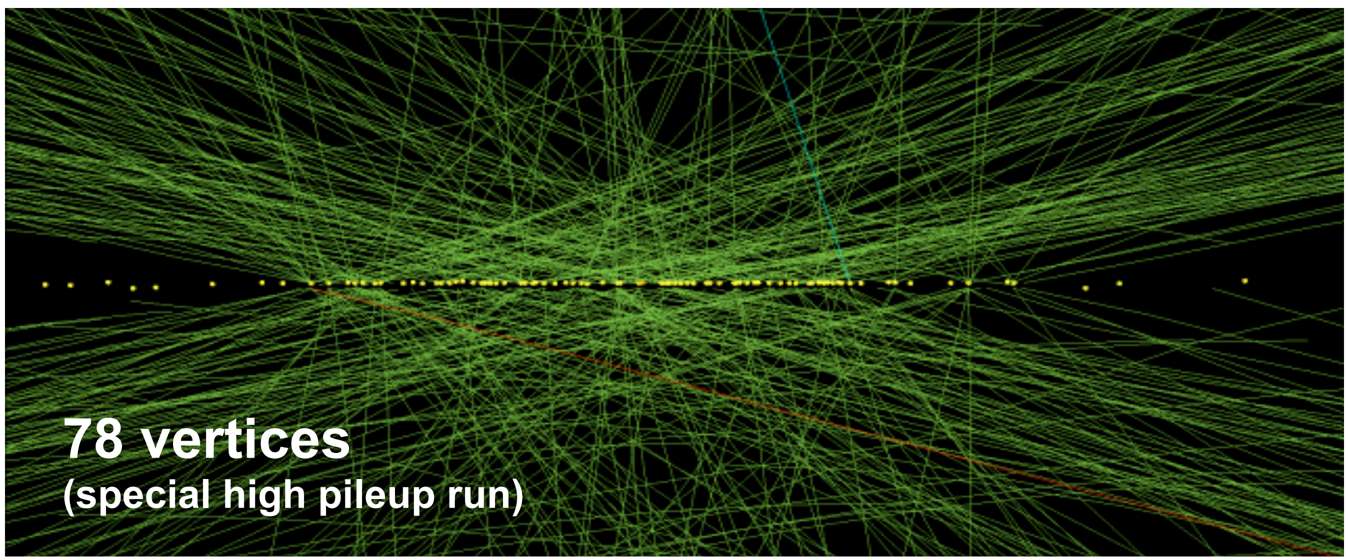
What the theorist sees:

p  **p**

Pileup continues to grow as LHC extracts the maximum luminosity

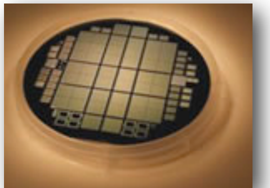
2010 7 TeV ~ 2
2011 7 TeV ~ 10
2012 8 TeV ~ 20

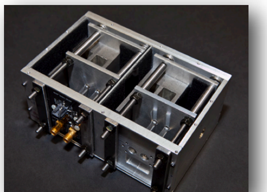




A (new) way out

Add this:





To this:

CERN-LHCC-2005-025

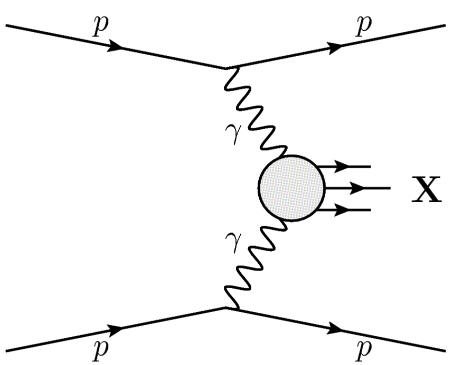
FP420 : An R&D Proposal to Investigate the Feasibility of Installing Proton Tagging Detectors in the 420m Region at LHC

CMS + ATLAS

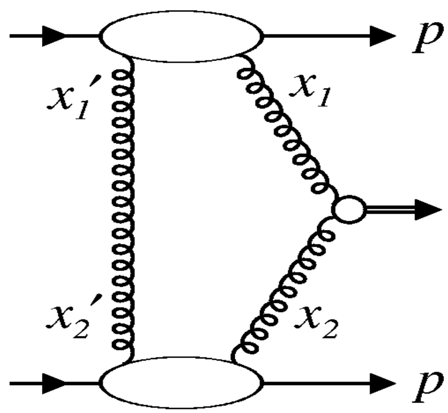
M. G. Albrow[1], T. Anthonis[2], M. Arneodo[3], R. Barlow[2,4], W. Beaumont[5], A. Brandt[6], P. Bussey[7], C. Buttar[7], M. Capua[8], J. E. Cole[9], B. E. Cox[2,*], C. DaVià[10], A. DeRoeck[11,*], E. A. De Wolf[5], J. R. Forshaw[2], J. Freeman[1], P. Grafstrom[11,+], J. Gronberg[12], M. Grothe[13] , J. Hasi[10], G. P. Heath[9], V. Hedberg[14,+], B. W. Kennedy[15], C. Kenney[16], V. A. Khoze[17], H. Kowalski[18], J. Lamsa[19], D. Lange[12], V. Lemaitre[20], F. K. Loebinger[2], A. Mastroberardino[8], O. Militaru[20], D. M. Newbold[9,15], R. Orava[19], V. O'Shea[7], K. Osterberg[19], S. Parker[21], P. Petroff[22], J. Pinfold[23], K. Piotrzkowski[20], M. Rijssenbeek[24], J. Rohlf[25], L. Rurua[5], M. Ruspa[3], M. G. Ryskin[17], D. H. Saxon[7], P. Schlein[26], G. Snow[27], A. Sobol[27], A. Solano[13], W. J. Stirling[17], M. Tasevsky[28], E. Tassi[8], P. Van Mechelen[5], S. J. Watts[10], T. Wengler[2], S. White[29], D. Wright[12]

Access discovery channels via virtual γγ and gluon gluon production

Central Exclusive Production (CEP)



QED

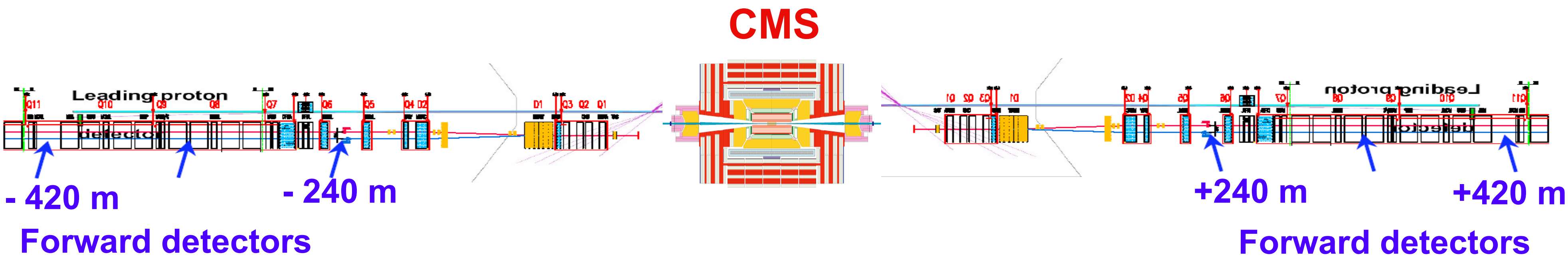


QCD = Double Pomeron Exchange

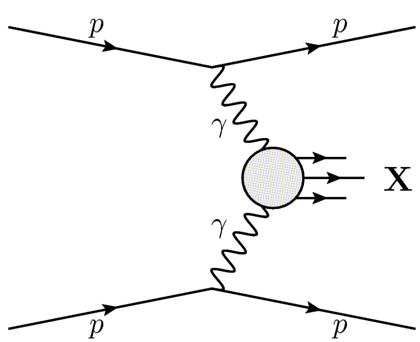
- **Protons remain intact**
- **No underlying event!**
- **Clear signature in central detector**
- **Theoretically clean**
- **Cross sections in fb to sub nb range**

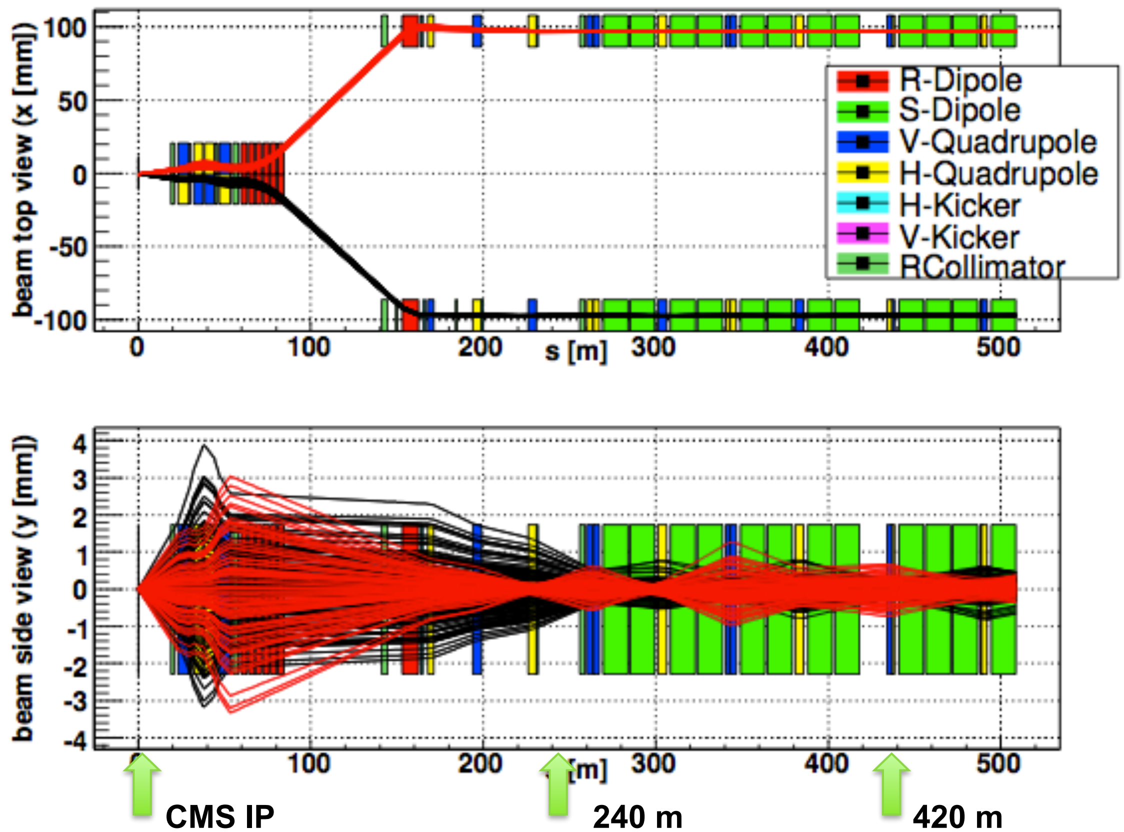
Sensitive to new physics up to ~ 1.3 TeV

Instrument the LHC beam pipe to enable a powerful new way to reject background



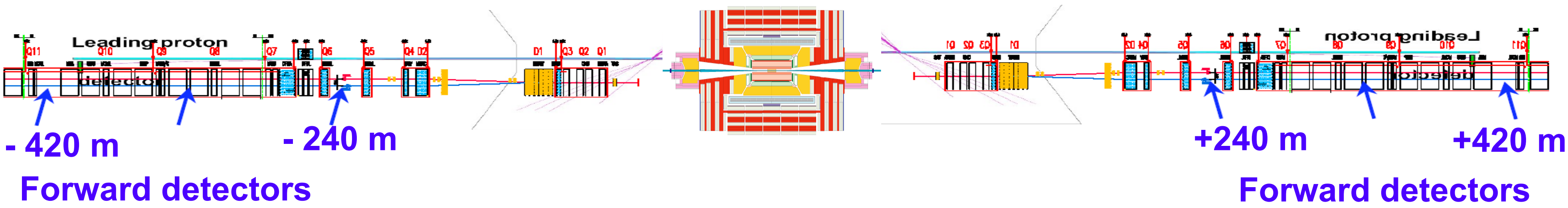
- **Extra information by detecting scattered forward protons:**
  - Interaction vertex point
  - Mass of the produced particle
  - Boost of the produced particles



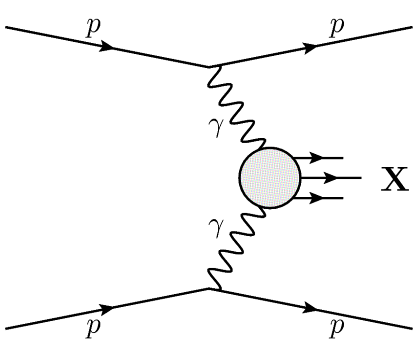


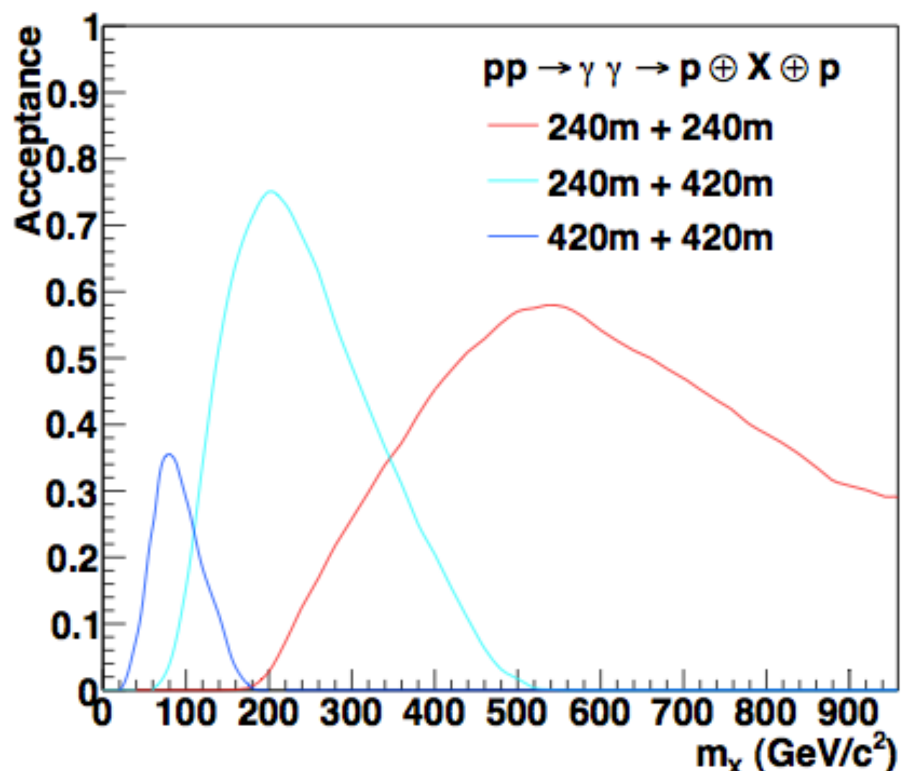
Use LHC as a magnetic spectrometer

Instrument the LHC beam pipe to enable a powerful new way to reject background



- **Extra information by detecting scattered forward protons:**
  - **Interaction vertex point**
  - **Mass of the produced particle**
  - **Boost of the produced particles**



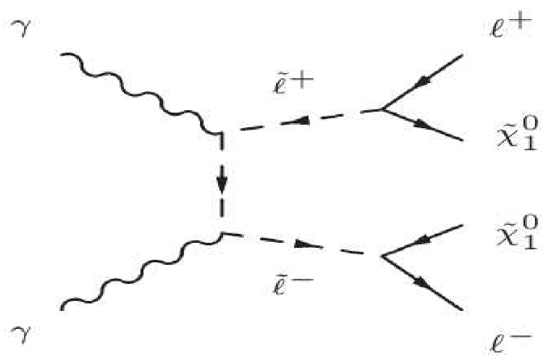


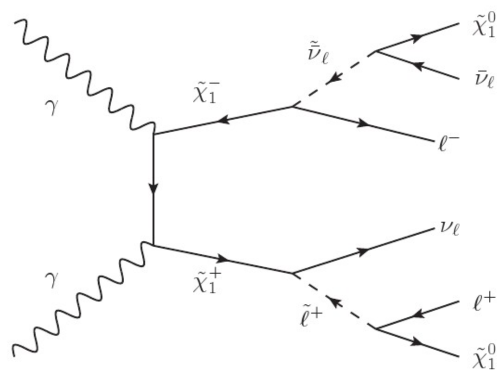
Turns LHC into virtual γγ collider

Δx(min) 3 mm at 240 m

For example: Proton tagging enables unique direct slepton observation

- **Relatively light SUSY leptons (< 200 GeV) difficult to exclude**
  - **Squark production rate relatively high through strong coupling**
  - **Drell-Yan production of slepton pairs rate relatively low and depend on assumed SUSY weak couplings**
- **Clean signature with forward protons**
  - **Signal: isolated dilepton with two proton tags and missing energy**





  - **QED production (SUSY model independent)**
  - **Directly measure slepton mass via edge in proton c.o.m. energy distribution**

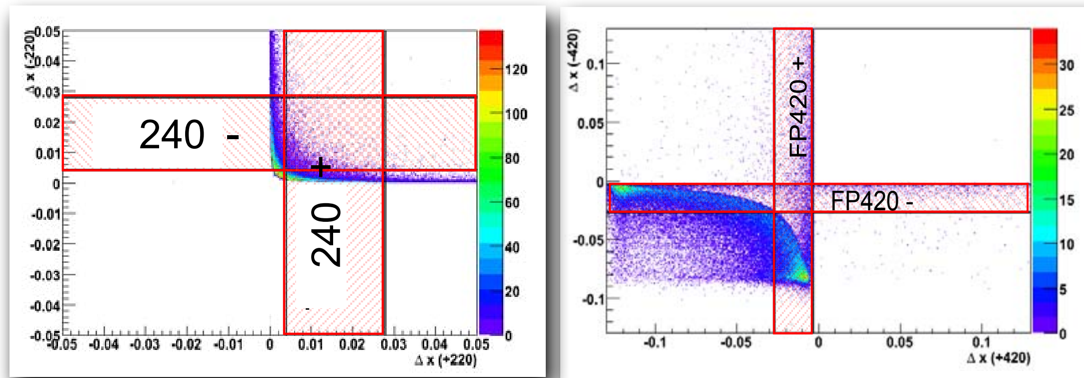
Can detect sleptons <u>and</u> measure its mass

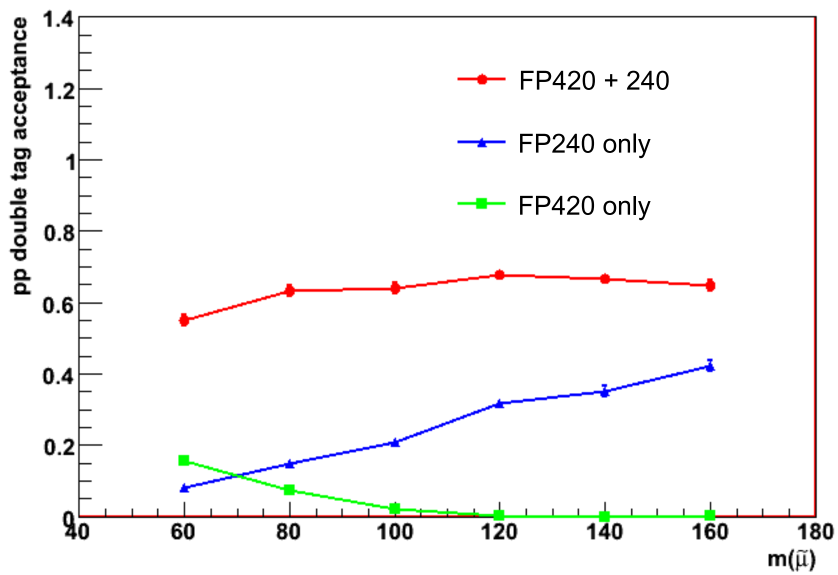
Slepton pair acceptance by proton tags in forward detectors

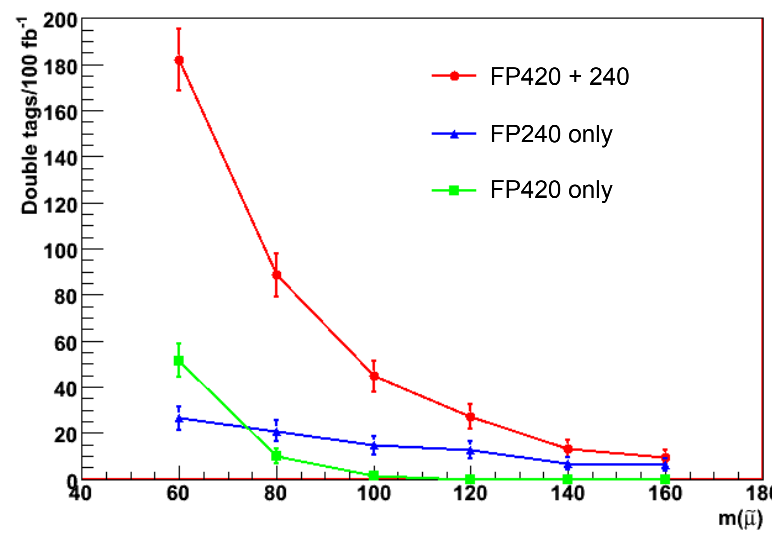
CompHEP+HECTOR transport through LHC optics

- **Proton tag efficiency**
  - **Both 59%**
  - **Positive arm only 79%**
  - **Negative arm only 73%**

proton displacement from beam





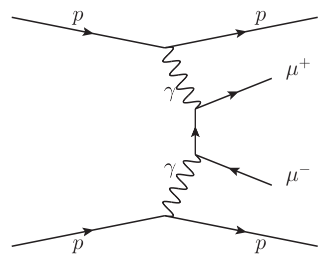


Double tag signal ~ few fb.
Need both locations for low mass reach.

Di-lepton background

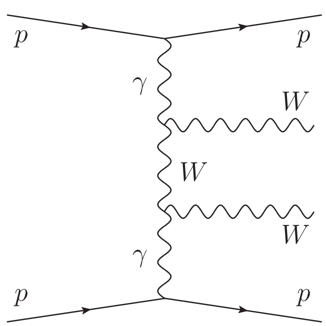
- **Cleanly separate slepton pairs from dimuon background using kinematics (thanks to proton tagging)**
  - **Low-mass CEP production**

    CEP ee, $\mu\mu$ (co-linear)
    CEP $\tau\tau \rightarrow ll\nu\nu$ (nearly co-linear)

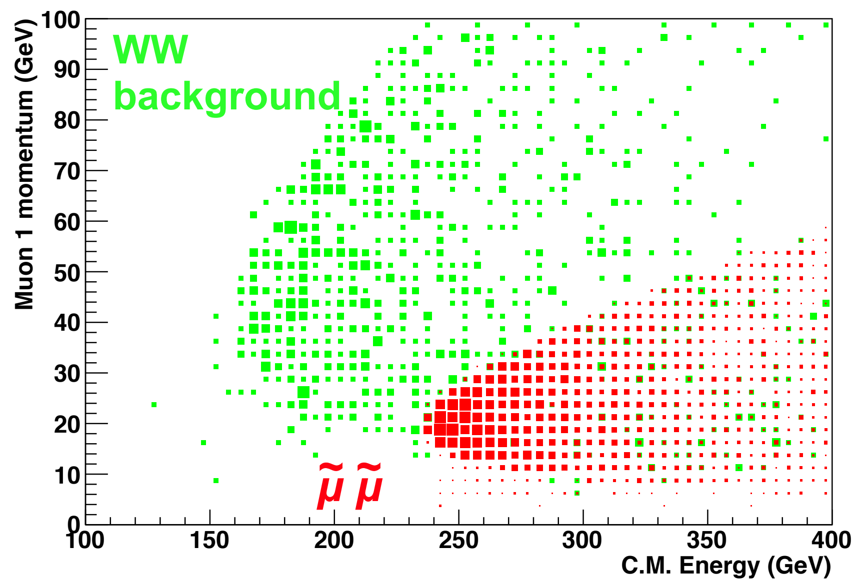


  - **High-mass CEP production**

    CEP WW $\rightarrow \mu\nu\mu\nu$



e.g. LM1: μ = 118 GeV $\tilde{\chi}^0$ = 98 GeV



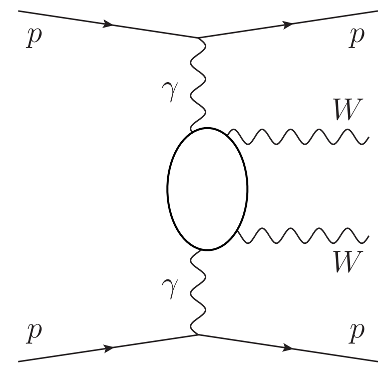
- **Eventually triple co-incidence background becomes problem (more on that later)**

CEP WW is also a discovery channel: Anomalous quartic boson coupling WWγγ

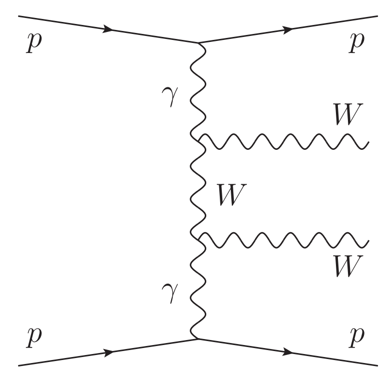
- **Anomalous quartic-boson coupling (WWγγ and ZZγγ) sensitive to beyond SM physics including heavy non SM-Higgs and Higgsless models such as extra dimensions**

$$\mathscr{L}_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathscr{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$



- **Standard WW measurements sensitive to triple-boson coupling (WWγ), which may be zero for new physics model**
- **Standard Model CEP WW**
  - **σ = 96 fb, with proton tag ~ 40 fb**
- **No first order Standard Model CEP ZZ**

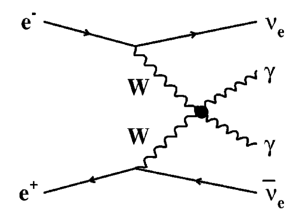


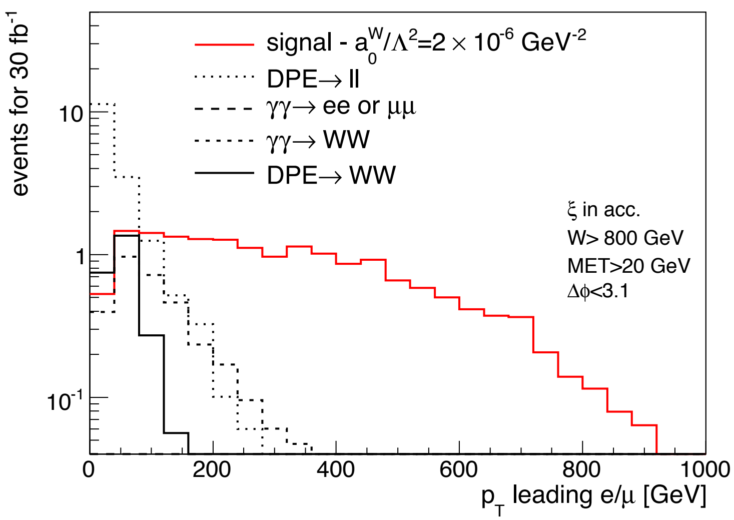
Will help reveal nature of EWSB, sensitive to new physics up to 1.3 TeV

Anomalous coupling sensitivity with proton tags

- **Signal is high lepton pt, high dilepton mass, high mass from proton tags**
- **Can measure Standard Model CEP WW rate with ~ 10 fb^{-1}**
- **Higgsless/Heavy Higgs physics models predict $a_{0,C}$ ~ few 10^{-6}**
- **Best current limit from OPAL at LEP2 $a_{0,C}$ ~ 0.02**
- **Without pileup:**

OPAL LEP2





Factor 10,000 improvement over LEP2

Couplings	OPAL limits $[\mathrm{GeV}^{-2}]$	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 10^{-6} (2.5 10^{-6})
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10^{-5} (2.0 10^{-5})	2.4 10^{-5} (9.2 10^{-6})

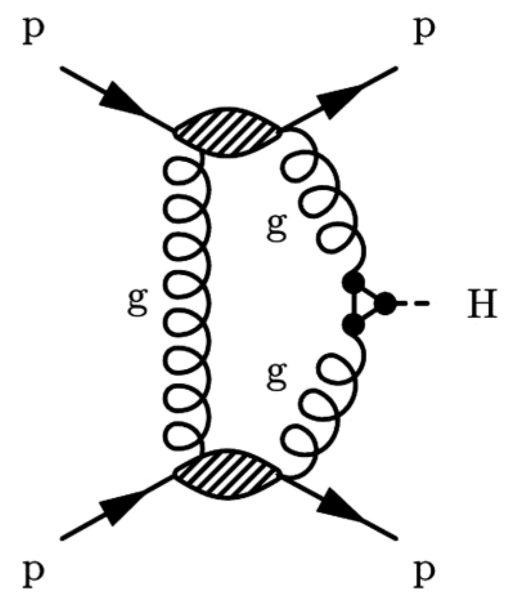
Royon, Chapon, Kepka 2010

- **Including pileup effects (assuming 10 ps timing resolution)**

	5σ	95% CL	LEP limit
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$	5.5 10^{-6}	2.4 10^{-6}	0.02
$\mathcal{L} = 300\ fb^{-1}, \mu = 46$	3.2 10^{-6}	1.3 10^{-6}	

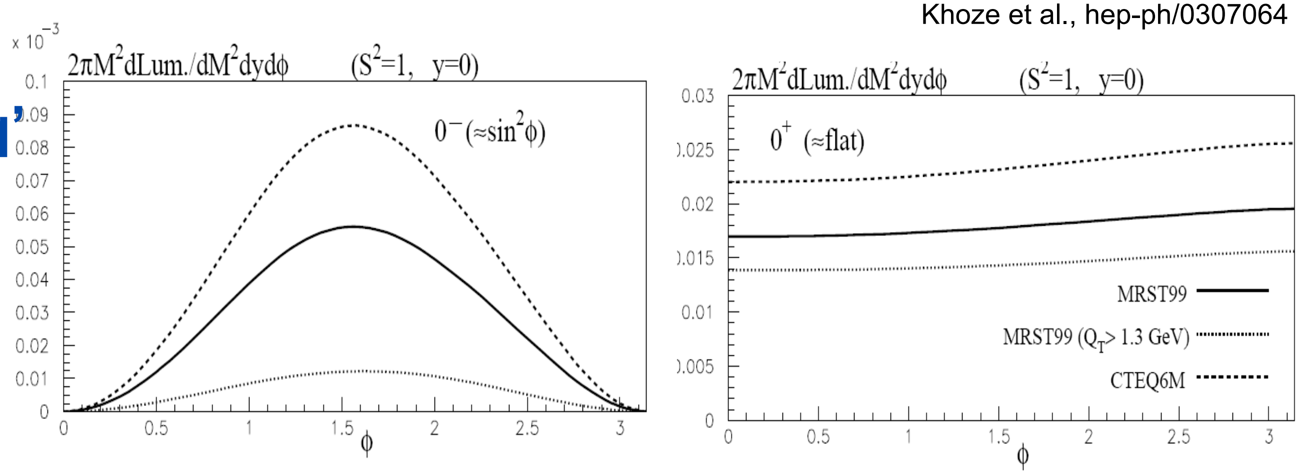
Unique handle on Higgs

- **Exclusive DPE Production**
  - 10 times larger than $\gamma\gamma$ production
  - SM Higgs $\rightarrow$ bb (σ ~ 2-10 fb tagged)
  - MSSM better (σ ~ 10-100 fb tagged)
  - Access Higgs spin from proton φ correlation
  - Higgs mass from proton kinematics ΔM ~ 1 GeV: Could resolve degenerate Higgs
  - NMSSM: h$\rightarrow$ aa $\rightarrow \tau\tau\tau\tau$



J. Ellis et al. hep-ph/0502251
Khoze et al., hep-ph/0307064

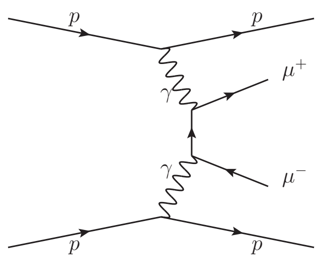
- **Other (single tag)**
  - Photoproduction WHq'
  - Single diffraction H



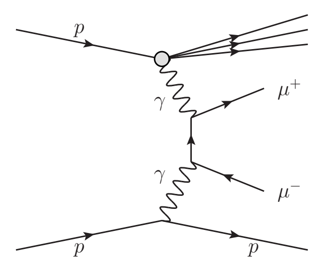
Physics opportunity here. Needs a lot of luminosity

Under low-pileup conditions, can start exclusive analyses (e.g. dimuons) without proton tags

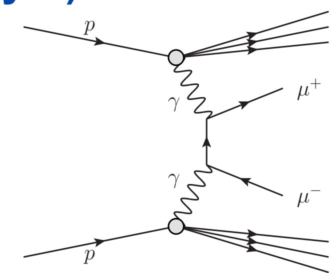
- **Signal: Co-linear muons: ~4000 events/fb^{-1} (if no pileup)**



- **Must account for diffraction background (since no proton tag yet)**

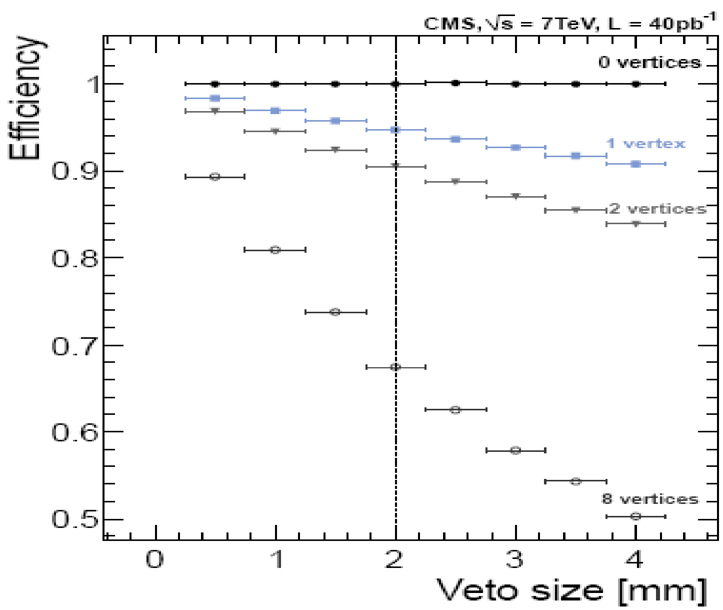


(single dissociation)



(double dissociation)

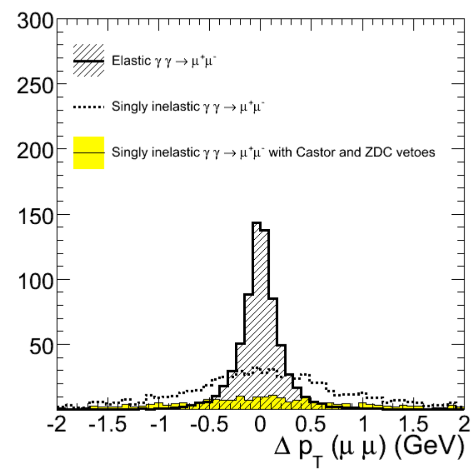
- **Isolation requirement for dimuon vertex (2 mm) to separate from pileup**

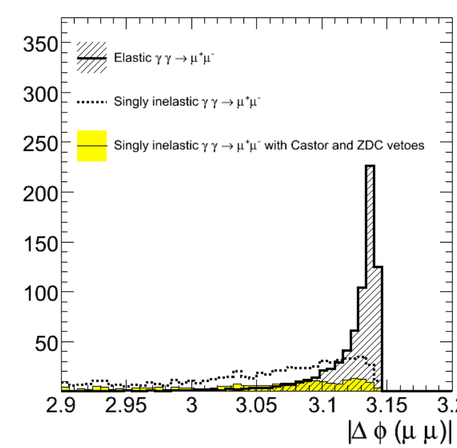


~65% efficiency for pileup of 8

Forward calorimeters provide some suppression (if no pileup):

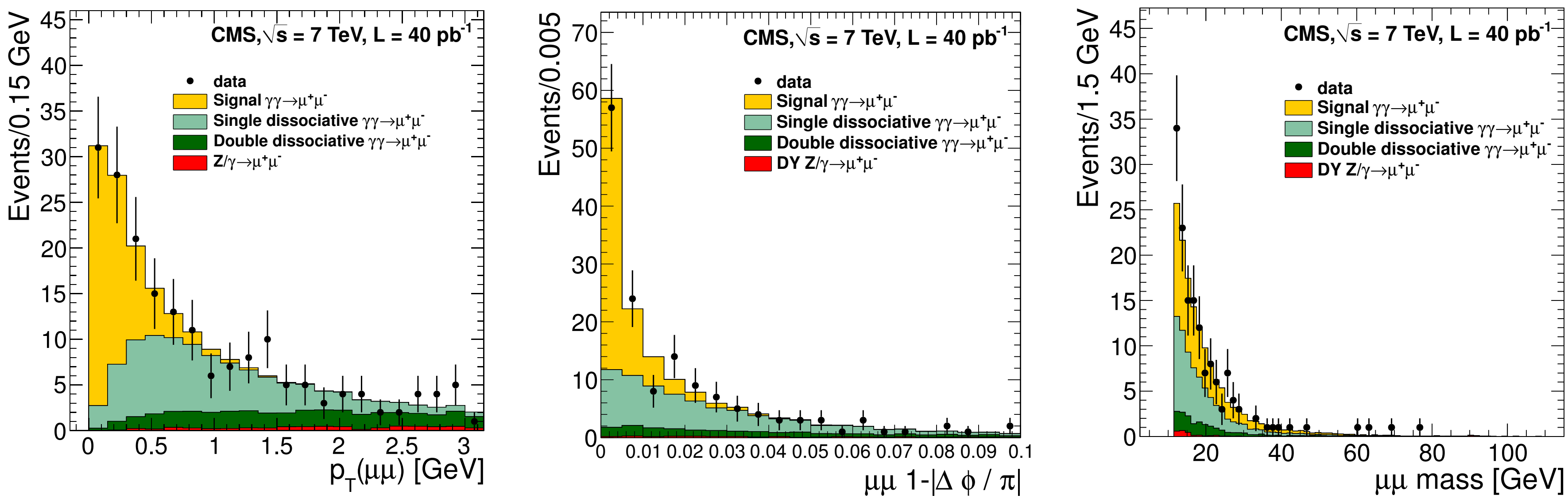
CMS calorimeter |η| < 5
Castor 5.2 < |η| < 6.6 and
ZDC |η| > 8.6 (neutral particles)





Measured $\gamma\gamma \rightarrow \mu^+\mu^-$ in 2010 data

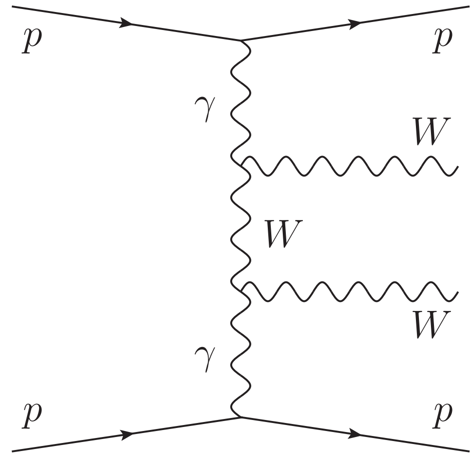
- **Analysis based on full 2010 sample (40 pb^{-1})**
  - Trigger on two 3 GeV muons
  - Offline $p_T(\mu)$>4 GeV, $|(\eta)|$ < 2.1
  - m(μμ)>11.5 GeV to remove $\Upsilon \rightarrow \mu\mu$
  - Control samples of muons from inclusive J/ψ and Z
  - Pileup ~ 2
- **Ratio σ predicted/measured = 0.83 ± 0.15**
  - Extracted from fit to p_T distribution, using SD shape from MC

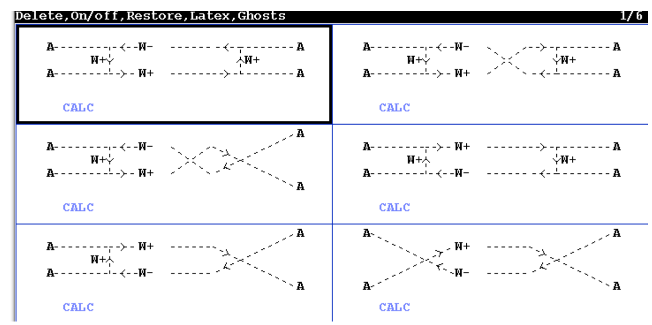


2010 data published: JHEP 1201, 052 (2012)

Coming attraction…
Extending this to dilepton analysis of CEP WW

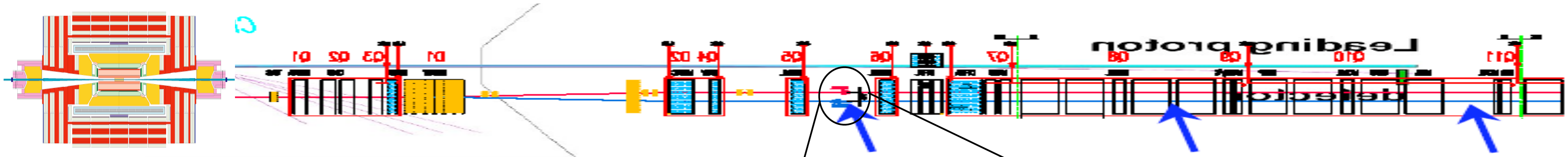
- **CEP WW → μμ, μe, ee + νν**
  - **Higher p_T leptons than $\gamma\gamma \rightarrow \mu^+\mu^-$**
  - **Leptons no longer back-to-back**
- **Analysis of 2011 data is nearing completion**
  - **WW → μeνν (avoids Drell-Yan Z background)**
  - **Estimate anomalous quartic gauge coupling with CalcHEP + CMS full simulation**
    - **Customized model with form-factor for unitarity constraint**





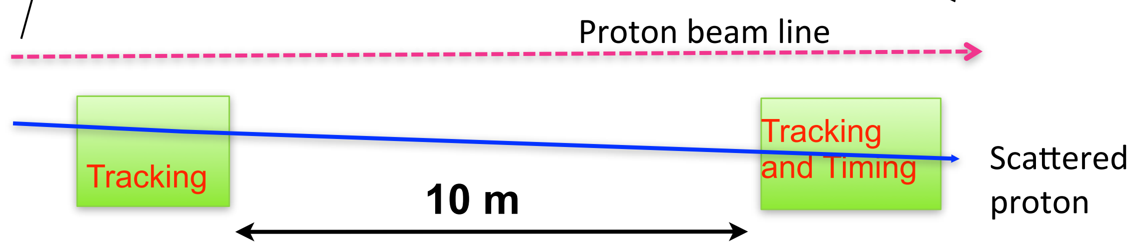
Expect factor ~20 improvement on AQGC limit from 2011 data vs LEP

High Precision Spectrometer (HPS) upgrade for CMS



240 m
Phase I
(2014)

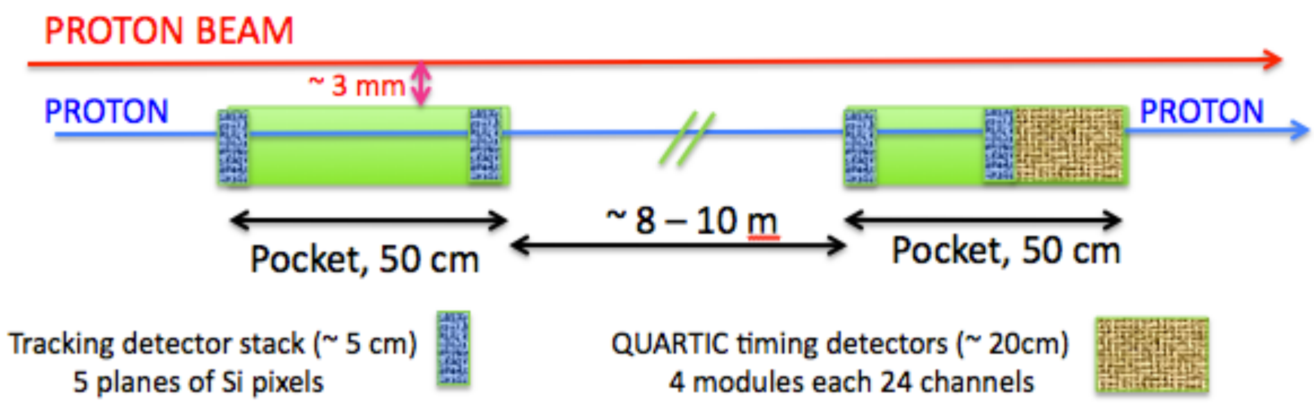
420 m
Phase II
(2017)

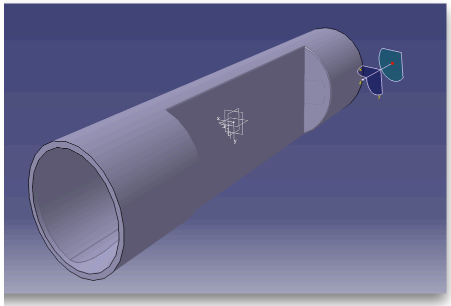


Each station consists of:
- **Two moving beam pipes**
- **Silicon tracking**
- **Cherenkov timing detectors**

R&D approved in 2010, now in discussions with CMS upgrade management for Phase I installation (240 m)

HPS station basic design: tracking & timing

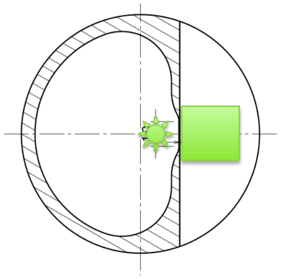


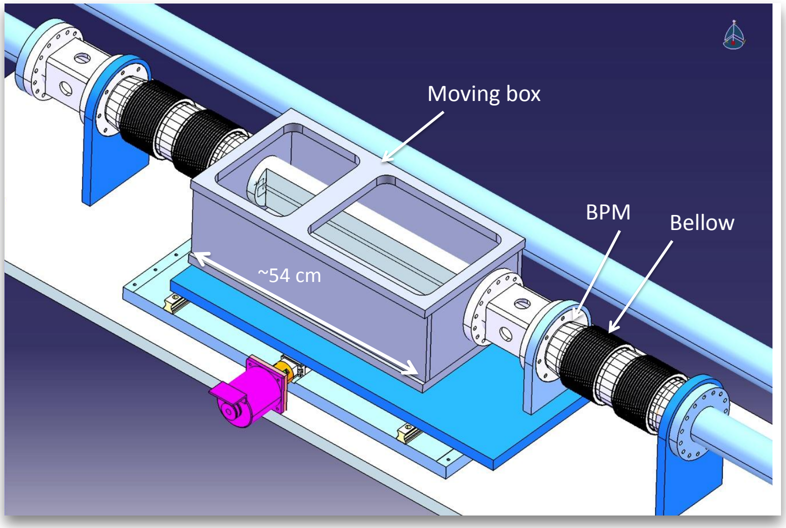


Two modules ~ 10 meters apart:

- **Tracking: silicon pixels**
  - Momentum reconstruction: $\Delta p/p \sim 2 \times 10^{-4}$
  - Position precision of 10 μm
  - Angular resolution of 1-2 μrad
- **Timing: Cherenkov quartz bars**
  - Time resolution ~20 ps
  - Segmentation for > 1 proton/bunch
  - Radhard: Lifetime > year at LHC at 10^{34}
- **Timing reference across both arms**
  ~ 20 ps resolution

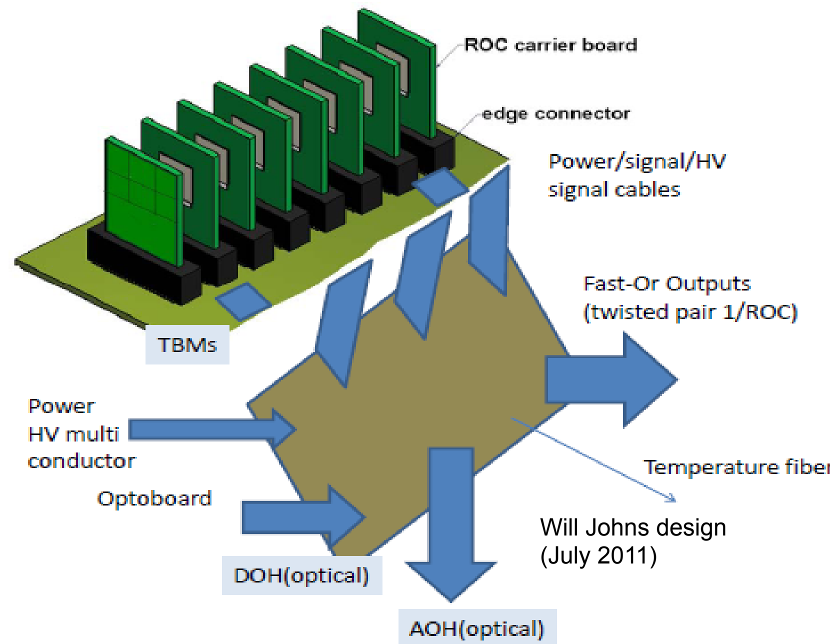
- **Moving beam pipe**
  - No vacuum forces
  - Detectors remain at atmosphere

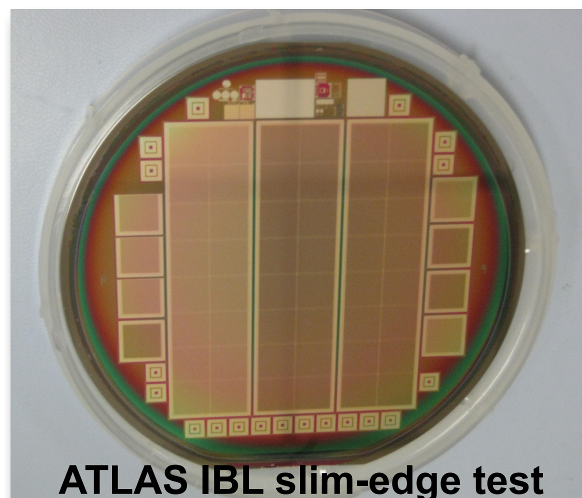




Silicon pixels

- **Phase I requires 32 total planes**
  - 2x3 modules = 16 mm x 24 mm each
  - Current FPIX has unacceptably large (1.1 mm) dead region around edges (guard ring)
- **Pursuing two options simultaneously (both based on CMS FPIX detector/ upgrade)**
  - Edgeless 3D pixels with FPIX upgrade
    - Nearly final test iteration with vendors
    - Vendor production facility upgrades (to 15 cm wafers) affects scheule
  - Slim-edge version of current FPIX based on design pioneered by ATLAS pixel detector
    - Overlap active region on one side with reduced guard ring on the other: Testing 250 μm to 450 μm edge designs

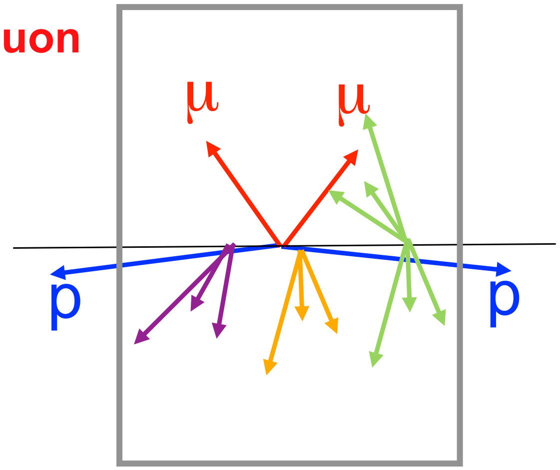




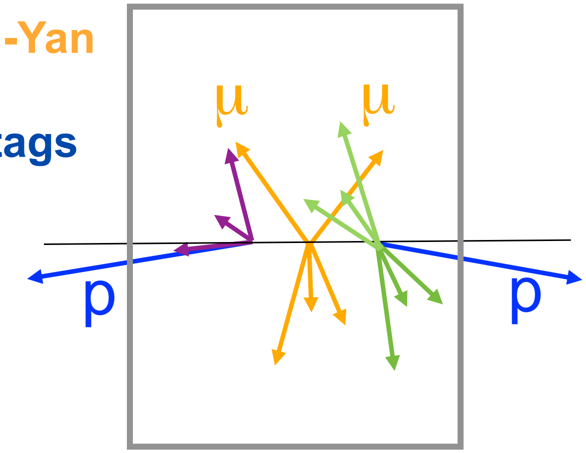
ATLAS IBL slim-edge test

Pileup is a serious problem for all analyses, fast timing is a solution

Signal: Di-smuon with pileup (double tag)



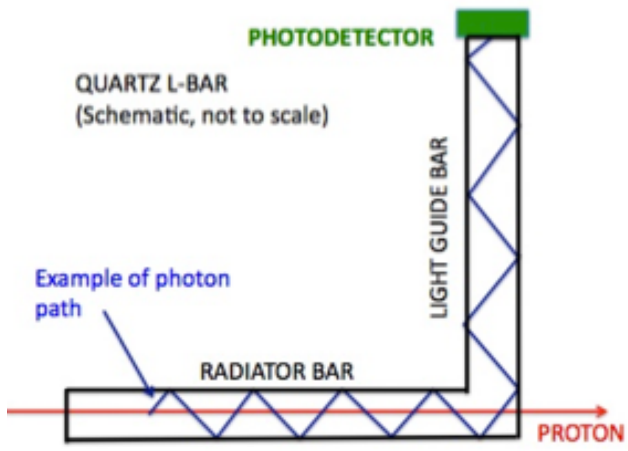
Background: Drell-Yan di-muon with two single diffraction tags (fake double tag)



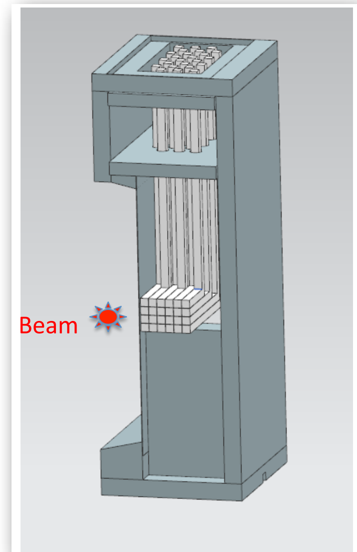
- **Multiple-events per crossing makes "empty detector" cuts ineffective**
  - Vertexing within the event helps, but efficiency goes to zero at high pileup
  - Proton tag provides z position and recovers efficiency
- **Triple coincidence involving two single-diffractions becomes a problem**
  - 20 ps resolution on proton tags gives factor 24 rejection
- **At max luminosity multiple proton tags per crossing becomes a problem**
  - Reject with more precise and accurate (absolute) timing reference

Precision timing of protons is critical to forward detector upgrade

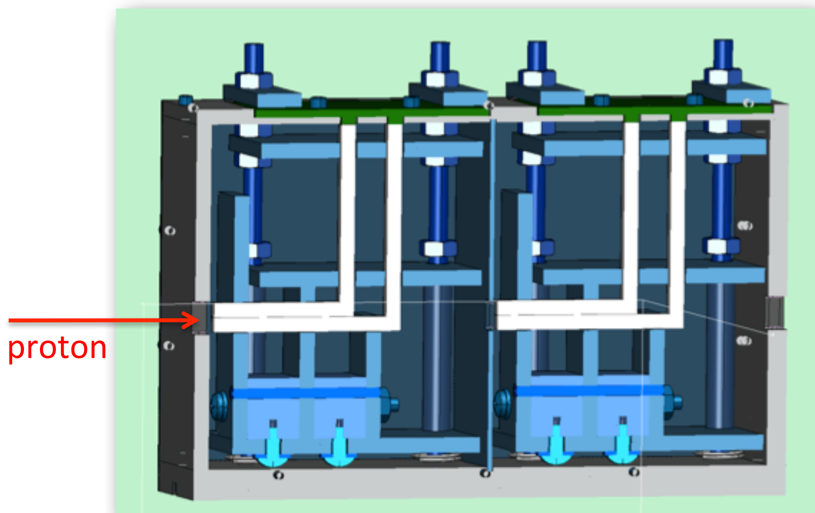
Cherenkov detectors for timing measurement



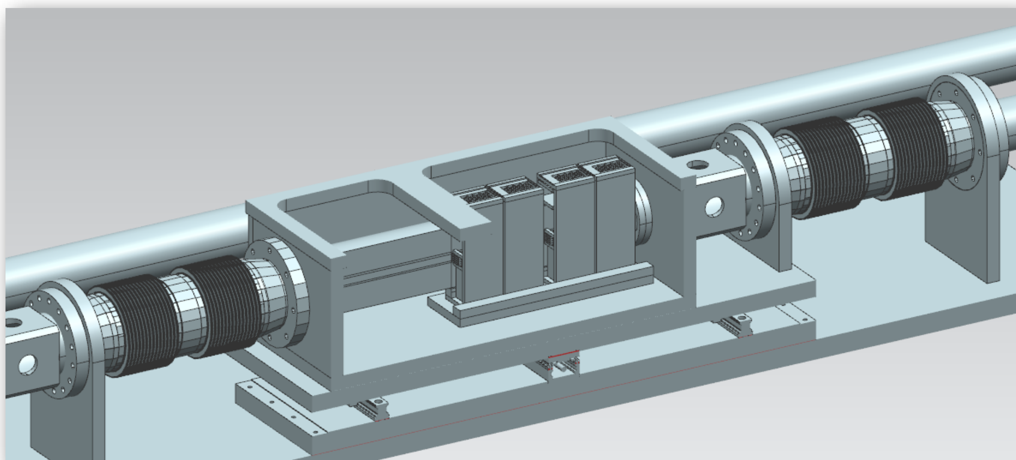
- **Novel quartz bar configuration**
  - All Cherenkov light is totally internally reflected to back of radiator bar
  - ~2/3 of light reaches photodetector promptly
  - Maintain total internal reflection: Nothing touches surface, except at corners, separate bars with fine wire (100 μm)



Prototype

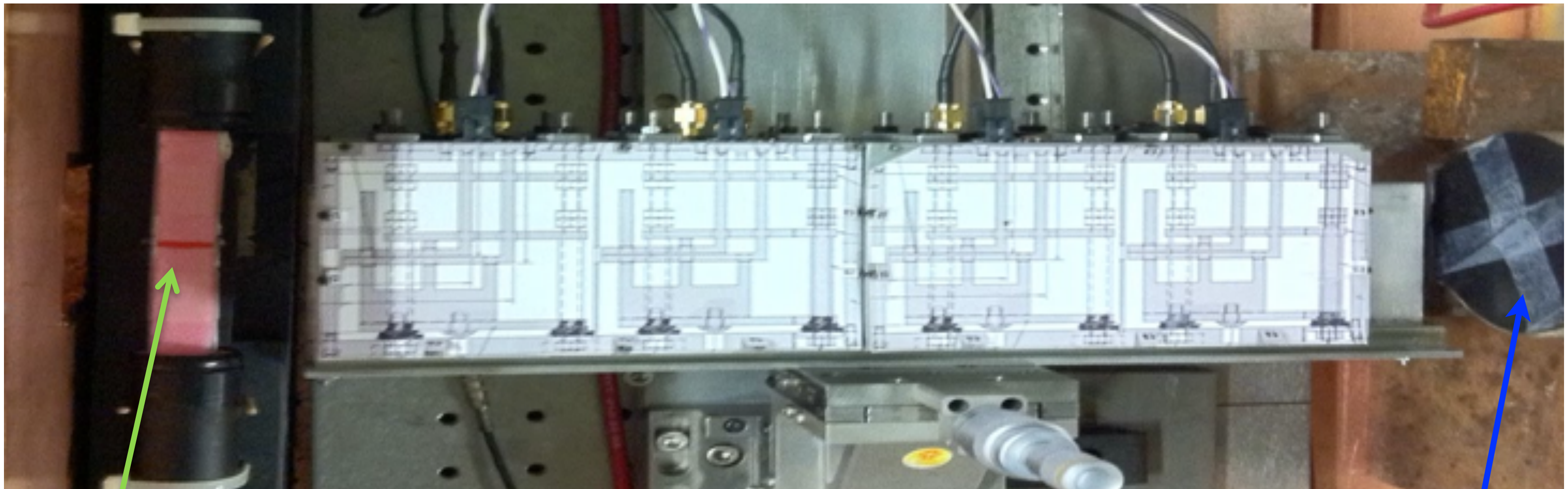


Integration in moving beam pipe



Mike Albrow, Fermilab

Cherenkov achieved 16 ps resolution in Fermilab test beam



2mm x 2mm trigger counter

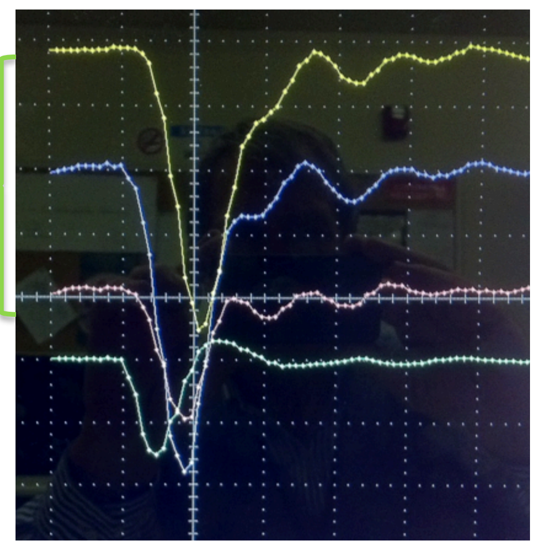
Four units in test beam
(Drawings glued on boxes for alignment only)

40mm MCPPMT reference (10 ps)

σ(t) = 32 ps/bar = 16 ps/4bars

One event:
3 bars in line

MCPPMT ref

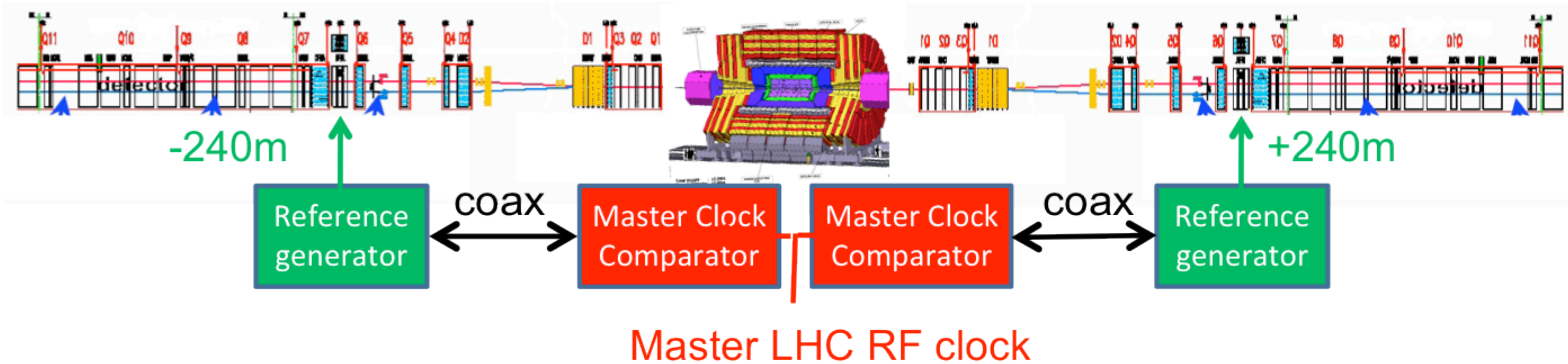


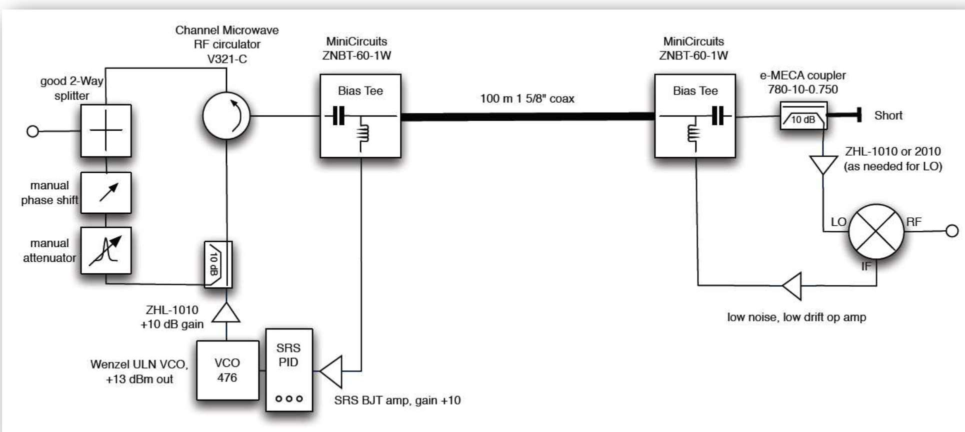
DRS4 5 GHz waveform digitiser
200 ps/point 20 mV/div. & 2 ns/div)

Technical issues solved, except:
Radiation levels in SiPM "cave" to be calculated and measured.
HPTDC-DAQ to integrate CMS readout.

Several improvements possible → 10 ps

Reference clock: 10 ps or better relative timing



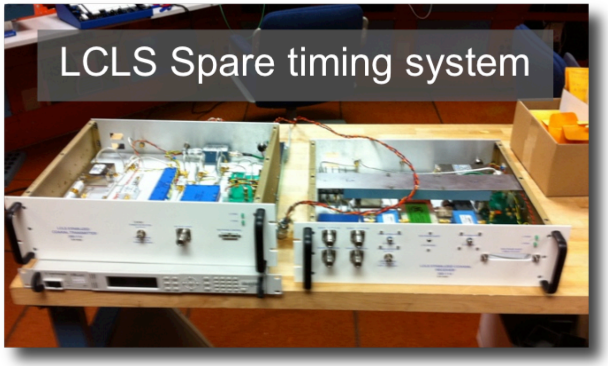


- **RF cable with feedback to keep clocks at each end in sync**
  - **Leverage system developed by SLAC as trigger for LCLS detectors**
  - **CMS application came from LLNL ILC engineering collab. with SLAC accelerator group**
  - **We shared this with ATLAS**

Jeff Gronberg, LLNL

Reference timing system R&D and calibration

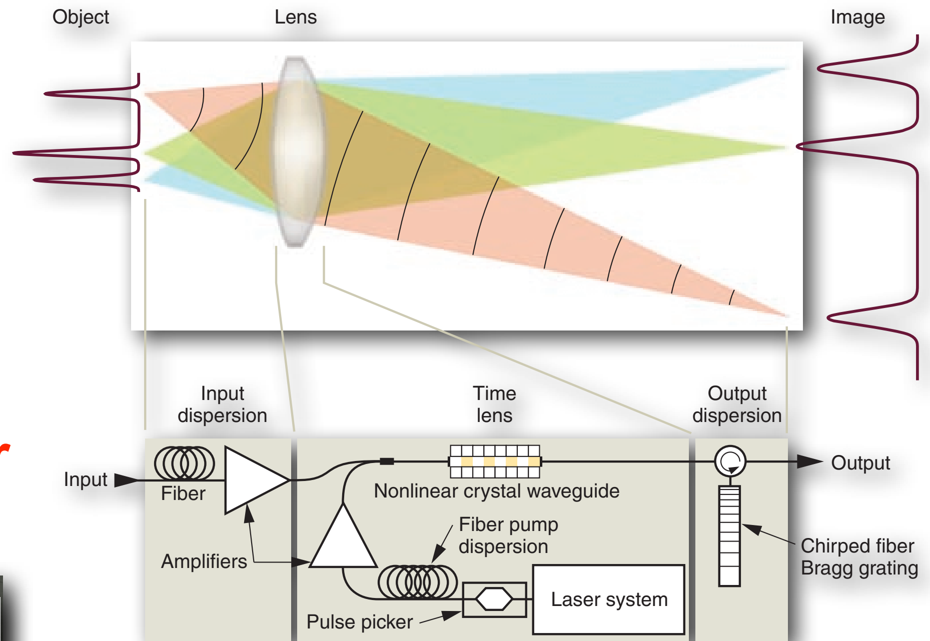
- **Completed signal stability tests for max length of 520 m using LCLS spare system**
  - **Short time, jitter < 1 ps**
  - **Phase stability = 1.2 ps/C well within HPS timing requirements**
- **To complete LHC capable system:**
  - **Modify LCLS design to use 40 MHz LHC bunch clock**
  - **Measure performance using Ckov signals + PECL gate with TDCs (to date all timing based only on RF phase comparison)**
  - **Remeasure with CMS high-rate TDCs**
- **2015: Commissioning and calibration with real data (synchronize absolute time with correct bunch crossing)**

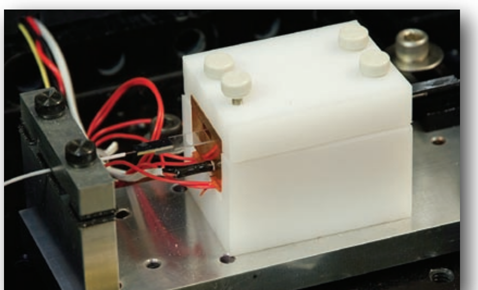


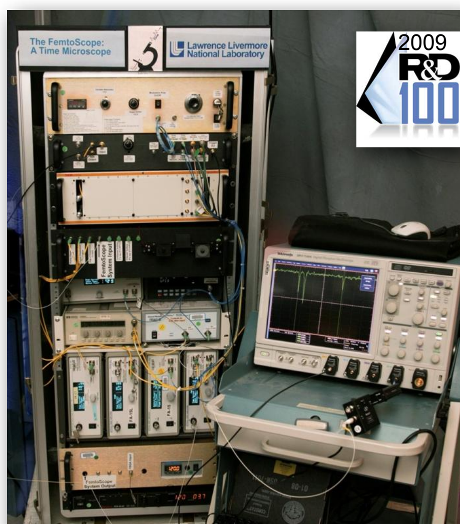
Jeff Gronberg, LLNL

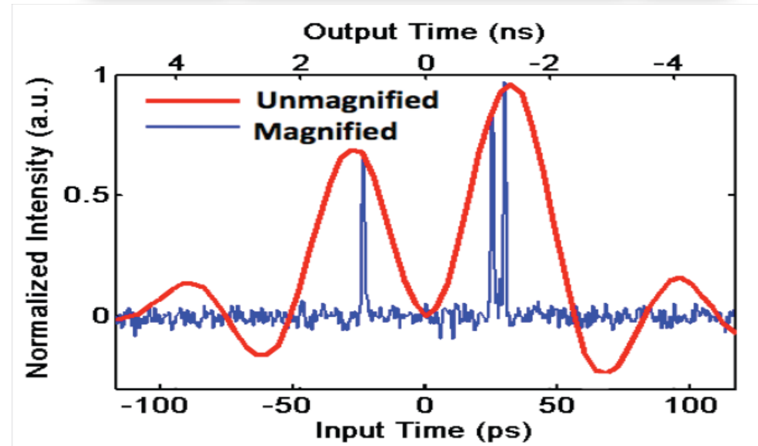
Terahertz oscilloscope solves multiple proton detection problem for HPS

- **Optical time-stretcher permits 1 ps time resolution**
  - Chirped laser pump pulse on non-linear mixing crystal acts like a lens
  - Demonstrated factor of 100 time stretch and 0.75 ps resolution
- **Future R&D: couple with proton detectors and design pump laser for LHC pulse structure**





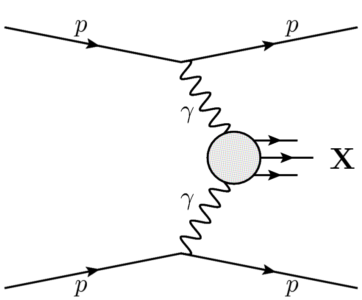


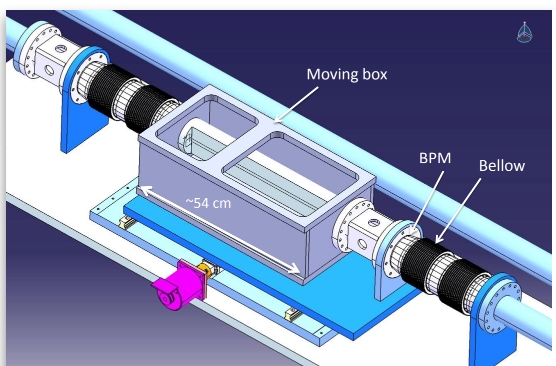


Unique LLNL technology developed from outside of HEP

Conclusion: Addition of small proton detectors have a big impact on CMS physics

- **Extra information by detecting scattered forward protons:**
  - **Interaction vertex point**
  - **Mass of the produced particle**
  - **Boost of the produced particles**
- **Enables Higgs, SUSY, BSM, QCD physics otherwise unattainable with CMS**
- **Sensitive to new physics up to 1.3 TeV**





Great things are done by a series of small things brought together.
– Vincent Van Gogh