Forward Protons from the SPS to the LHC

Andrew Brandt, University of Texas at Arlington

Thanks to Albert de Roeck, Brian Cox, Dino Goulianos, Mike Albrow, Michele Arneodo, Michael Strang, and others for slides
DOE, NSF, UTA, Texas ARP for support

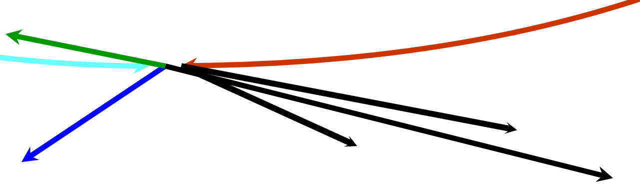
Physics Seminar
April 1, 2008
Louvain, Belgium

Outline

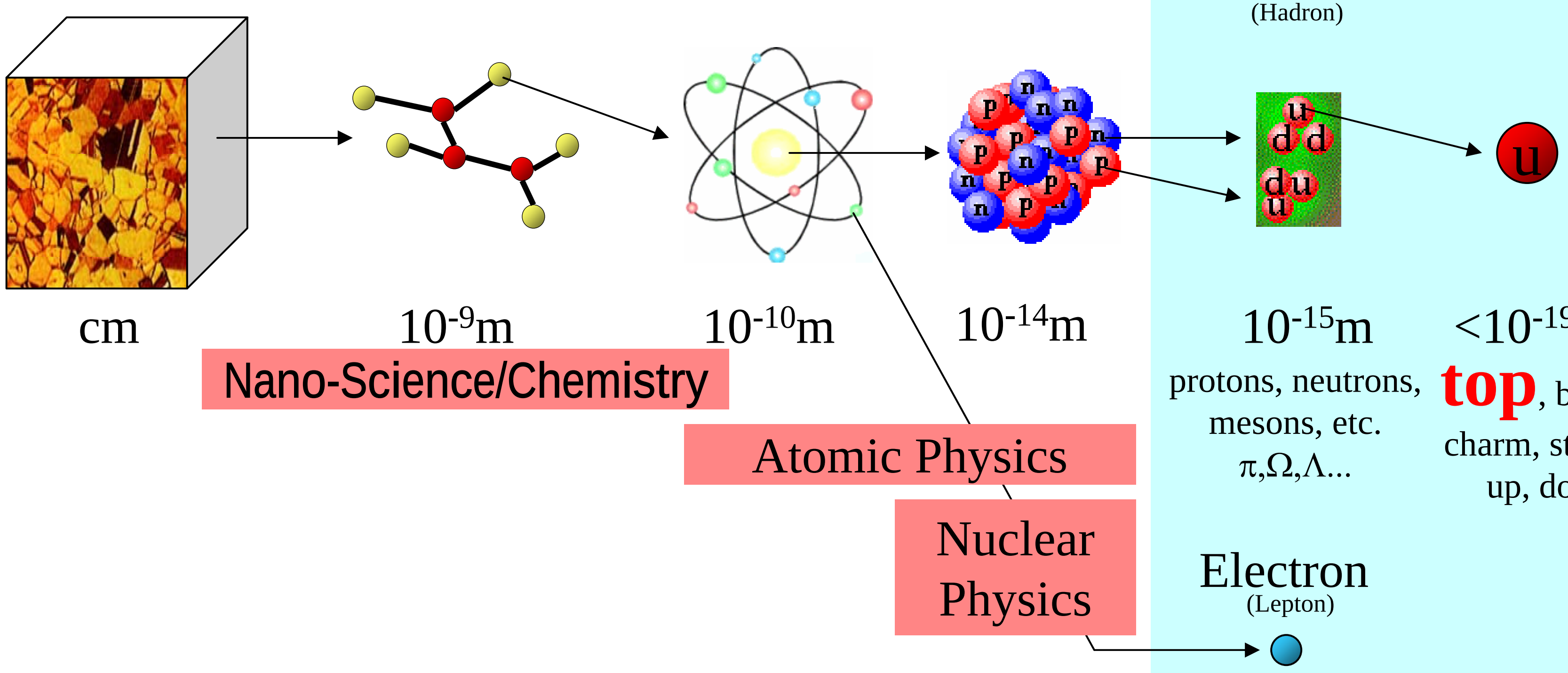
- HEP Intro/UTA Infomercial
- Elastic+diffractive scattering
- Forward protons at SPS
- Forward Protons at DØ
- Forward Protons at LHC
- Fast timing

High Energy Physics at UTA

UTA faculty **Andrew Brandt**, Kaushik De, Andrew White, Jae Yu, and Amir Farbin along with many post-docs, graduate and undergraduate students investigate the basic forces of nature through particle physics studies at the world’s highest energy accelerators



Structure of Matter



Matter

cm

Molecule

10^{-9}m

Atom

10^{-10}m

Nucleus

10^{-14}m

Nano-Science/Chemistry

Atomic Physics

Nuclear Physics

Baryon
(Hadron)

10^{-15}m

protons, neutrons,
mesons, etc.
π,Ω,Λ…

Quark

<10^{-19}m

top, bottom,
charm, strange,
up, down

Electron
(Lepton)

<10^{-18}m

High Energy Physics

High energy means small distances

What is High Energy Physics?

- Matter/Forces at the most fundamental level.
- Great progress! The "STANDARD MODEL"
- BUT… many mysteries

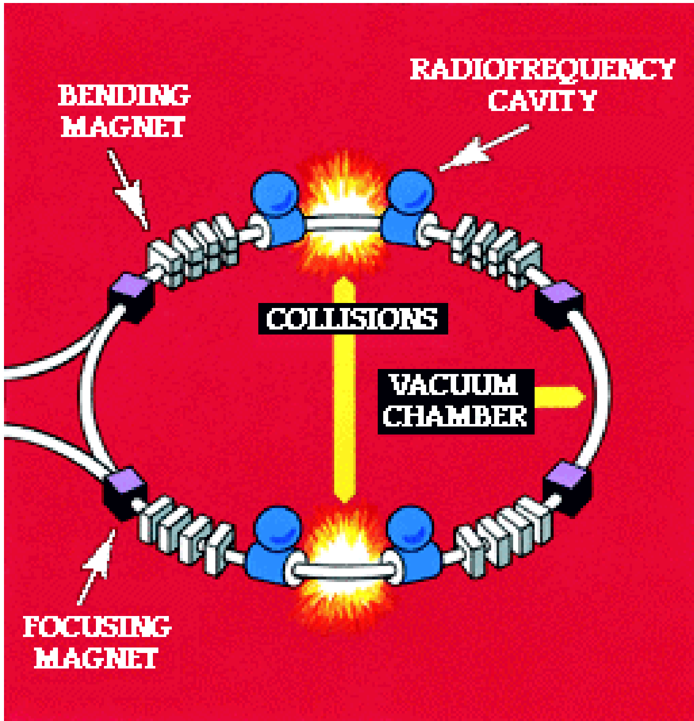
=> Why so many quarks/leptons??

=> Why four forces?? Unification?

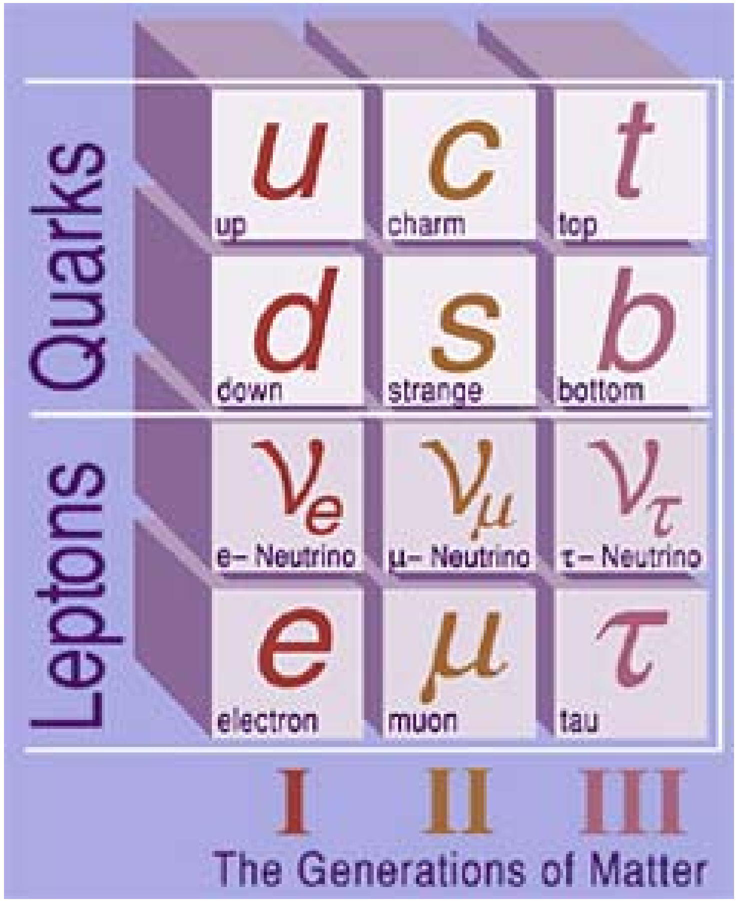
=> Where does mass come from??

=> Are there higher symmetries??

=> What is the "dark matter"??



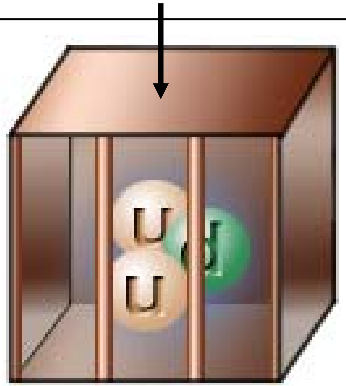
The Standard Model



- Current list of elementary (i.e. indivisible) particles
- Antiparticles have opposite charge, same mass

Standard Model has been very successful but has too many parameters, does not explain origin of mass. Continue to probe and attempt to extend model.

- the strong force is different!
- new property, color charge
- confinement - not usual $1/r^2$



Why High Energy Physics At UTA??

- **YOU can perform fundamental research using world’s highest energy particle accelerators:**

  The UTA HEP group has had leadership roles in current (Fermilab), future (CERN) and long-term future (ILC) experiments investigating the Origin of Mass (Higgs Searches), Supersymmetry, Extra-dimensions, and QCD.
  We are the leading experimental high energy group in Texas approaching $2M/year in external funding.

- **YOU can build state-of-the-art detectors:**

  The new Physics Building includes unparalleled facilities for detector construct

- **YOU can develop “The GRID”, the next step beyond the Internet:**

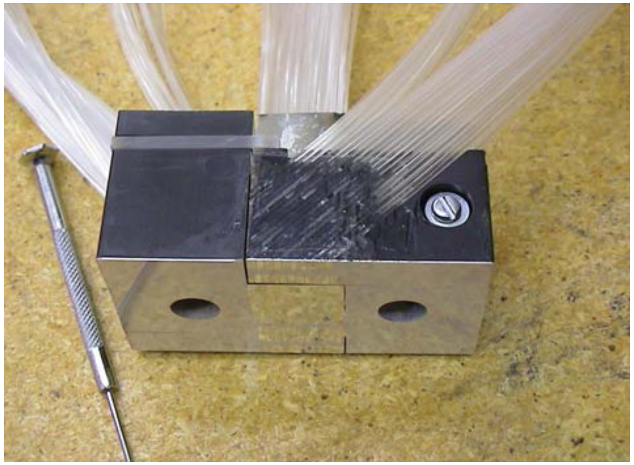
  UTA faculty leading international efforts in this area, including the new Tier 2 Computing Center which makes UTA one of the top ATLAS institutions in the U.S.

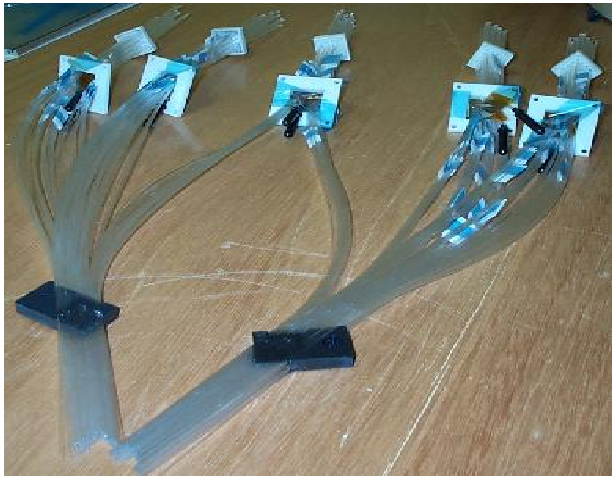
(http://www-hep.uta.edu)

Building Detectors at UTA

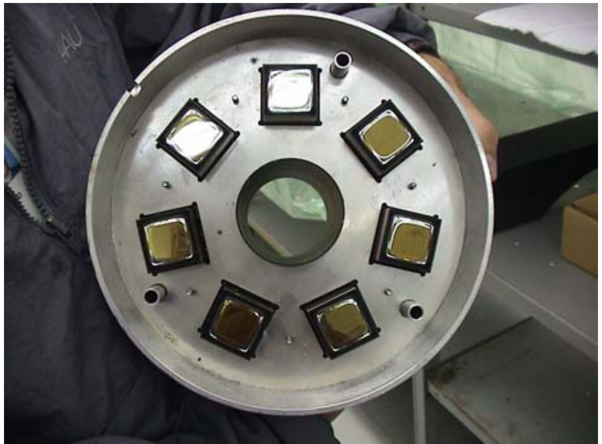
Forward Proton Detector Construction

At the University of Texas, Arlington (UTA), scintillating and optical fibers were spliced and inserted into the detector frames.

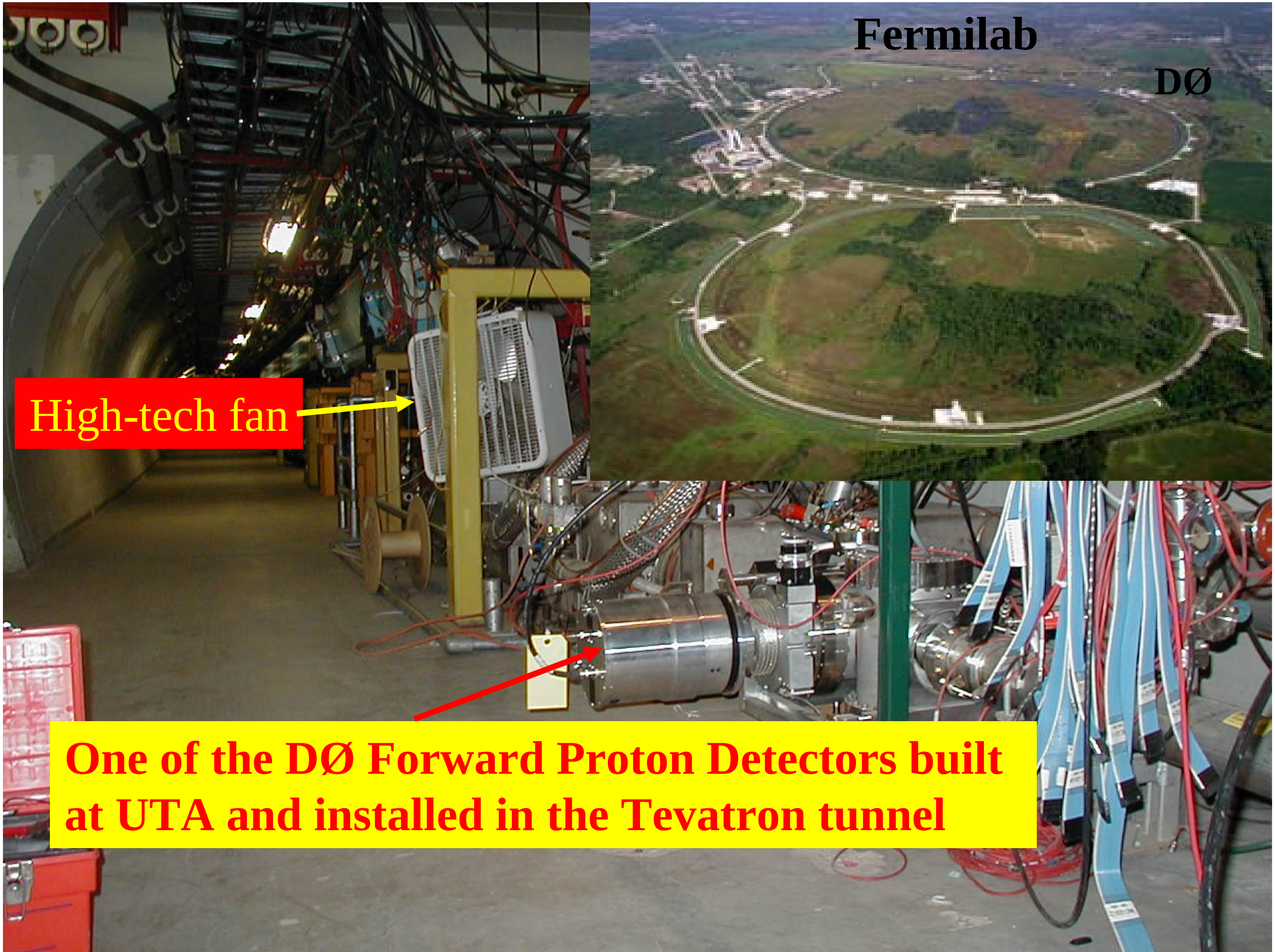




The cartridge bottom containing the detector is installed in the Roman pot and then the cartridge top with PMT's is attached.



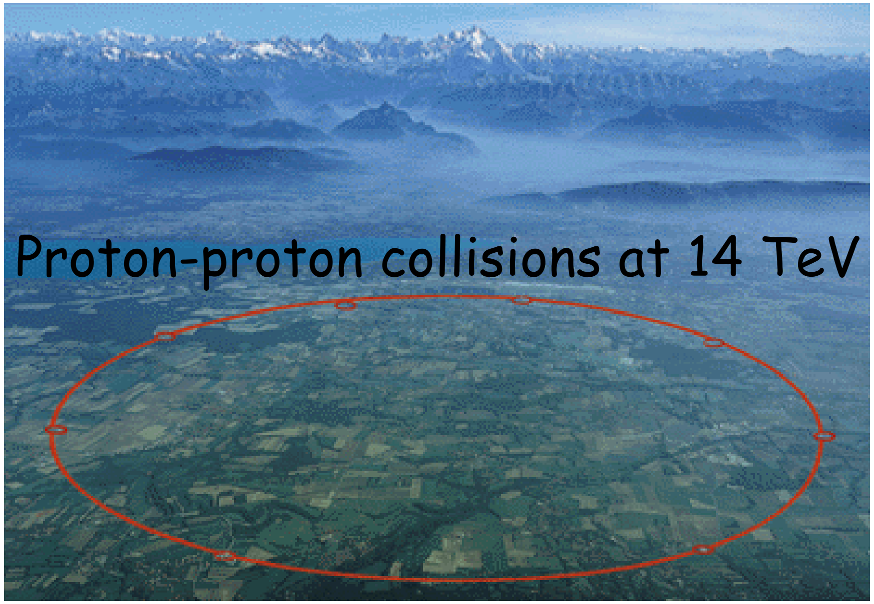
Tevatron: World's Highest Energy Collider



High-tech fan

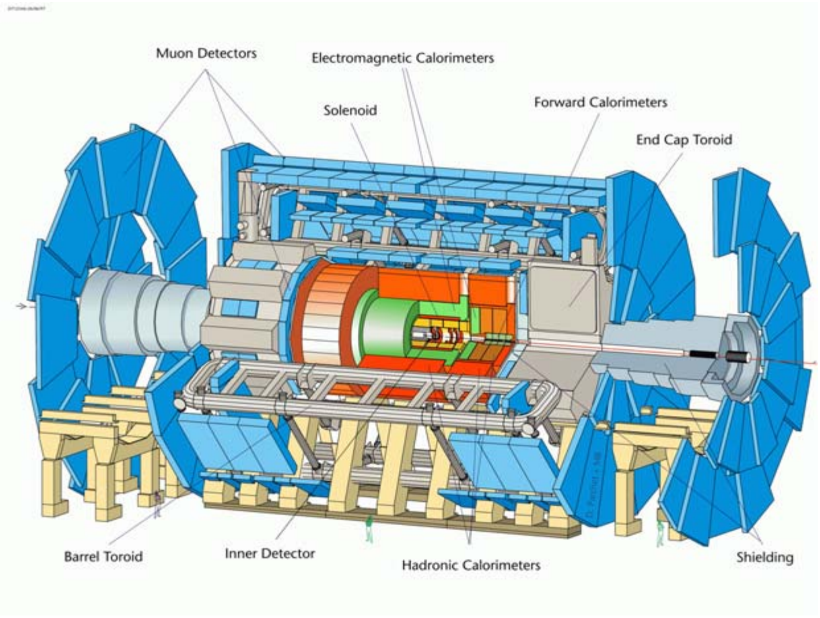
One of the DØ Forward Proton Detectors built at UTA and installed in the Tevatron tunnel

The CERN Large Hadron Collider



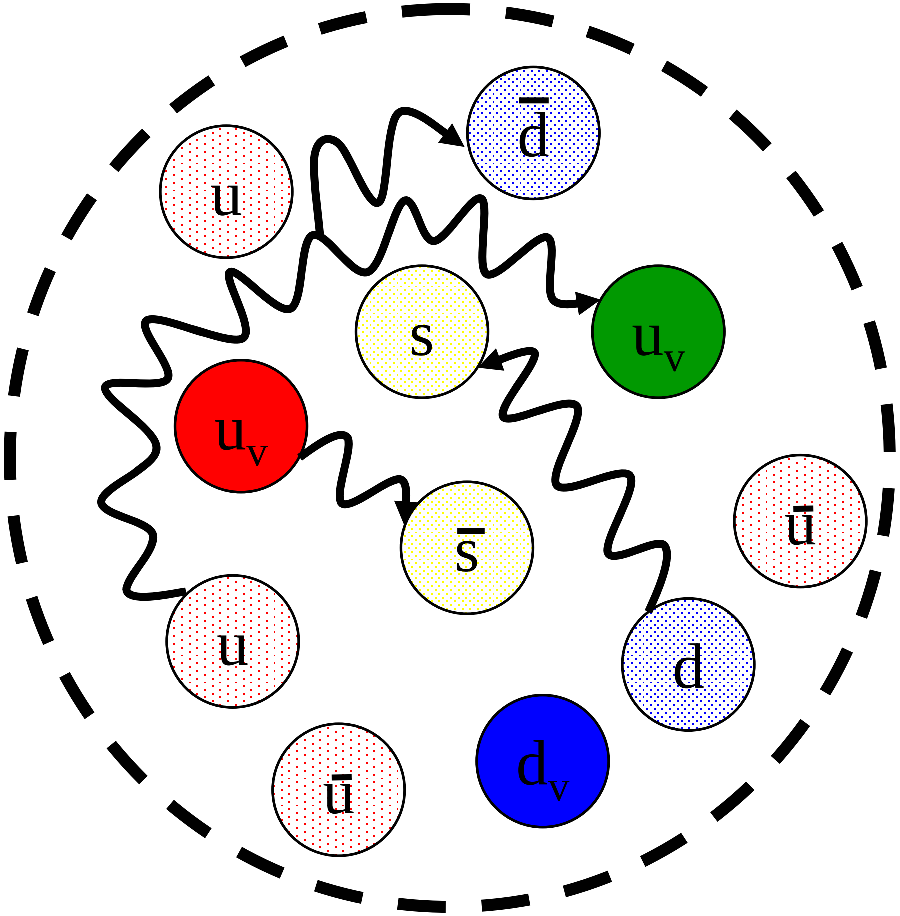
Location of LHC in France and Switzerland, with lake Geneva and the Alps in the background

The ATLAS detector was built at UTA and at 100's of other institutions all over the world and is ready to see first beam this summer



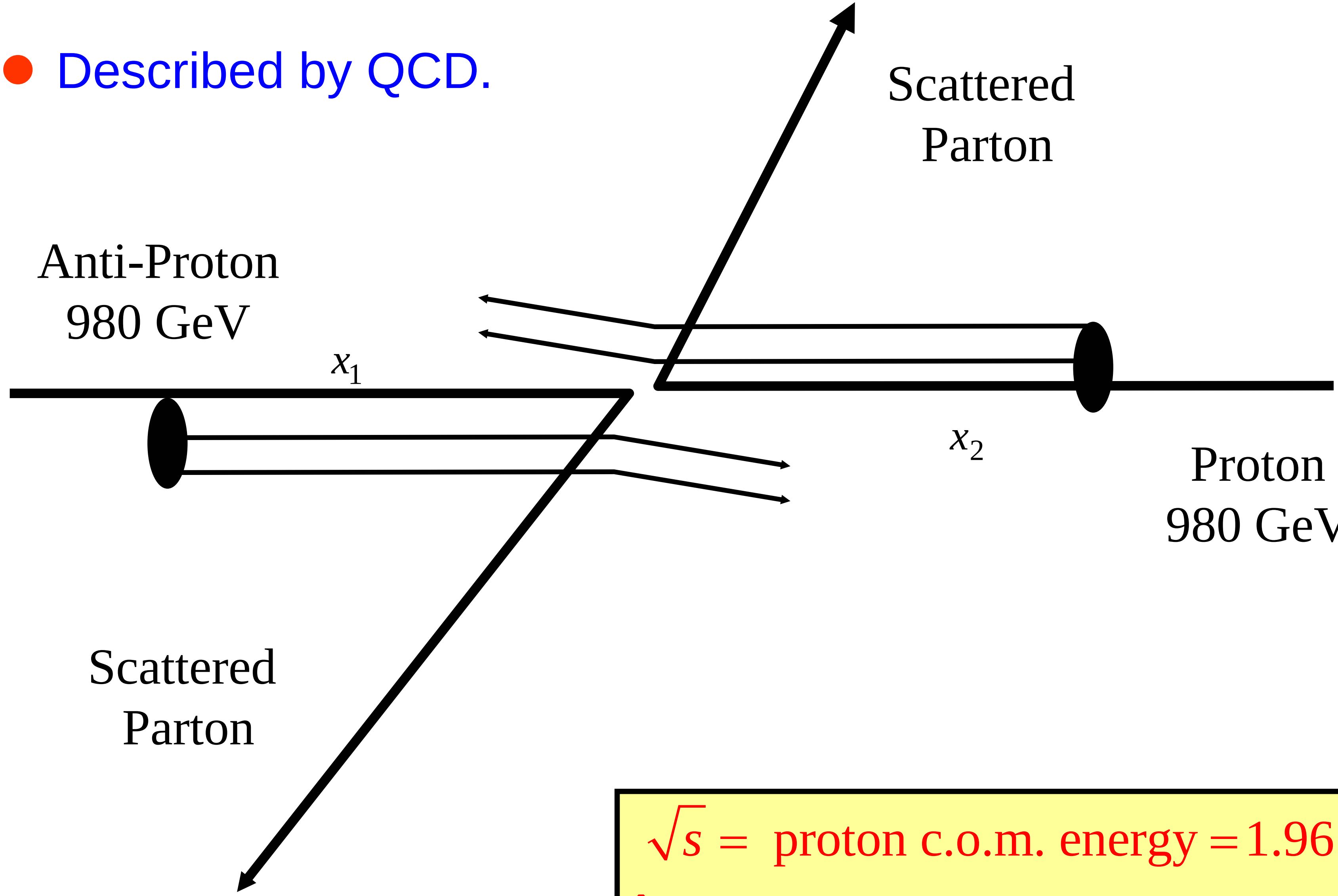
Proton Structure

- Proton contains three valance quarks: **uud**
- Also contains sea of virtual quark anti-quark pairs.
- All held together by gluons
- Quarks and gluons are called **partons**.
- Proton with momentum **P**. Individual parton carries momentum **xP**
- **Experiments have allowed us to determine the parton distribution function (PDF) giving a probabilistic description of the momenta carried by the partons**



Parton-Parton Scattering

- Described by QCD.

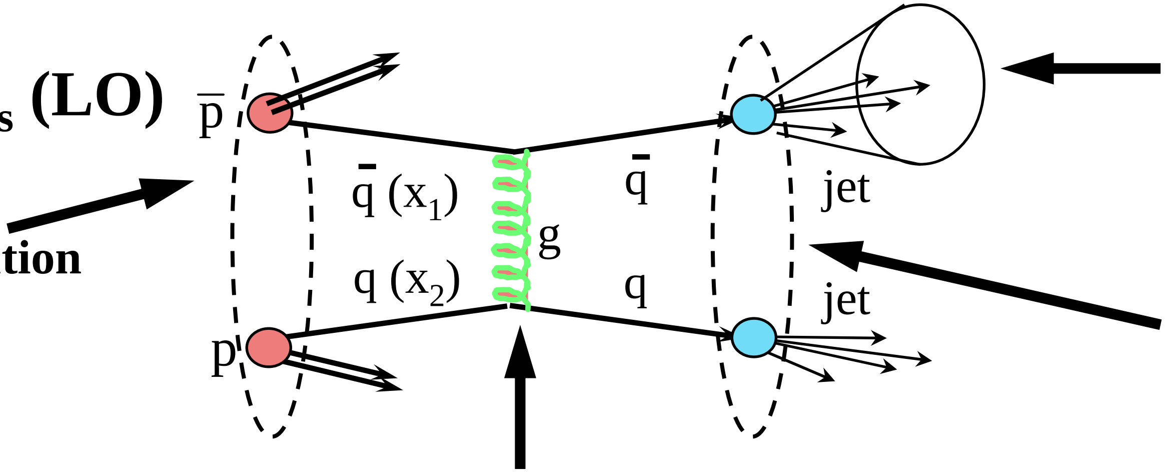


$\sqrt{s}$ = proton c.o.m. energy $= 1.96$ TeV

$\hat{s}$ = parton c.o.m. energy squared $= x_1 x_2 s$

Perturbative QCD and Jet Production

$\hat{\sigma} \sim \alpha_s^2$ (LO)



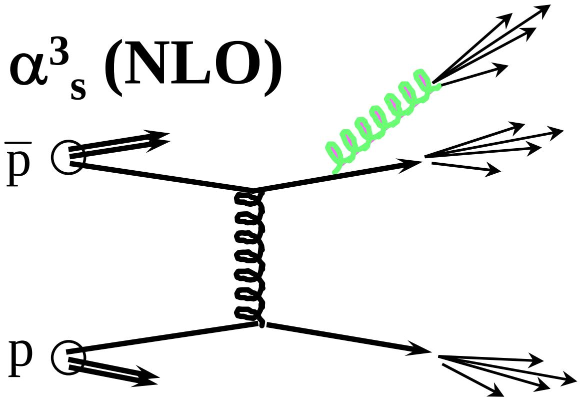
Parton distribution (PDF)

Observable jet of particles in detector

Fragmentation into hadrons

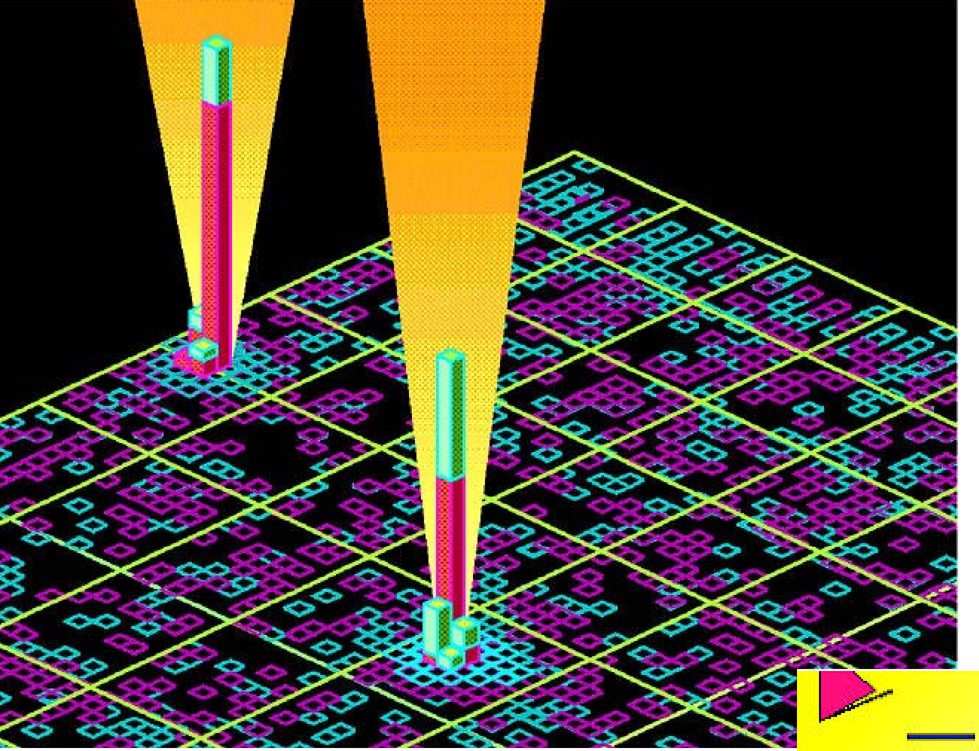
Hard scatter (pQCD)

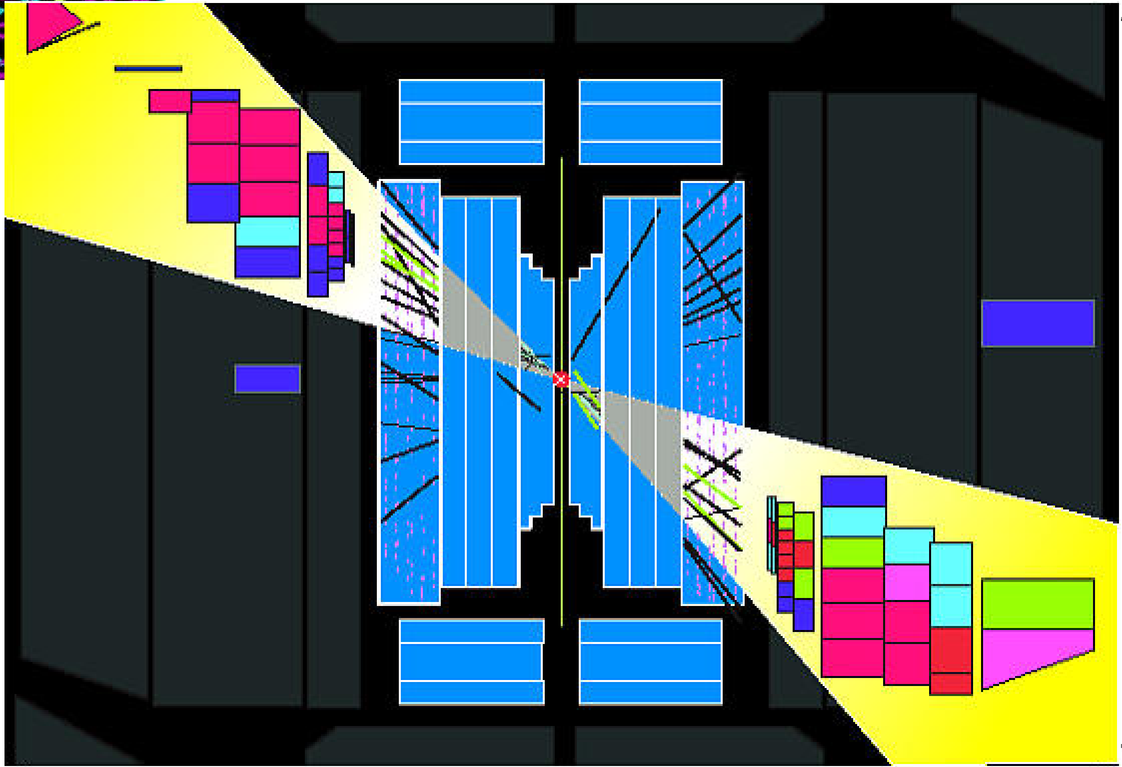
$\hat{\sigma} \sim \alpha_s^3$ (NLO)



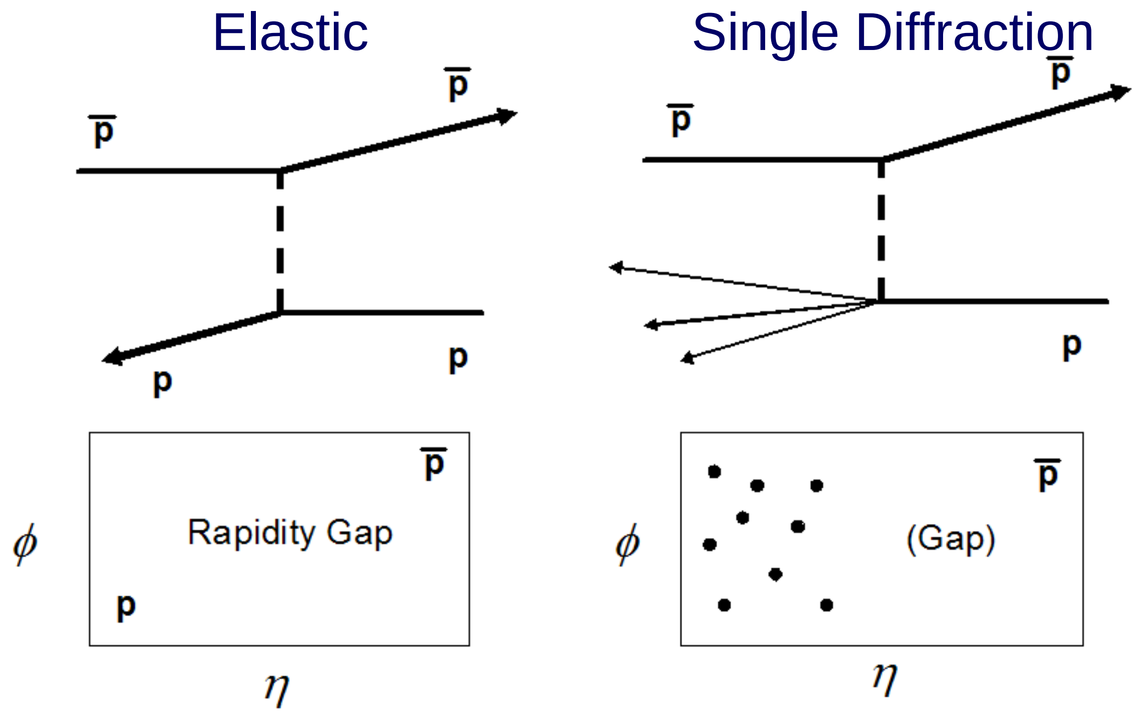
Includes radiative corrections and gluon emission - much of current QCD is a study of this additional radiation

High Energy Art





Elastic and Diffractive Scattering



(a) (b)

- Modeled phenomenologically as the exchange of a color singlet object with quantum numbers of the vacuum (Pomeron $\mathbb{P}$ exchange)

- Now believed to be non-perturbative QCD

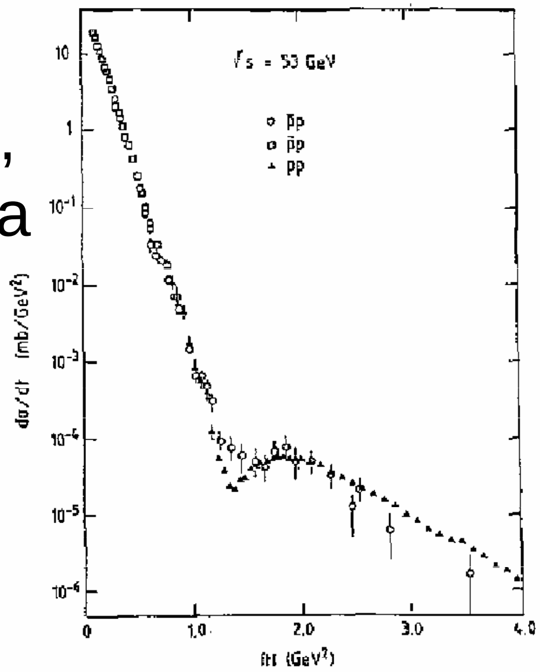
- Signatures of diffraction include rapidity gaps (regions of the detector with no particles) and intact final state beam particle(s) which can be tagged with a forward proton detector

Elastic Scattering

- The particles after scattering are the same as the incident particles
- The cross section can be written as:

$$\frac{d\sigma/dt}{(d\sigma/dt)_{t=0}} = e^{bt} \cong 1 - b(p\theta)^2$$

- This has the same form as light diffracting from a small absorbing disk, hence the name diffractive phenomena



Elastic "dip" Structure from Phys. Rev. Lett. 54, 2180 (1985).

Learning about the Pomeron

- **QCD** is theory of strong interactions, but **40%** of total cross section is attributable to **Pomeron** exchange -- not calculable and poorly understood

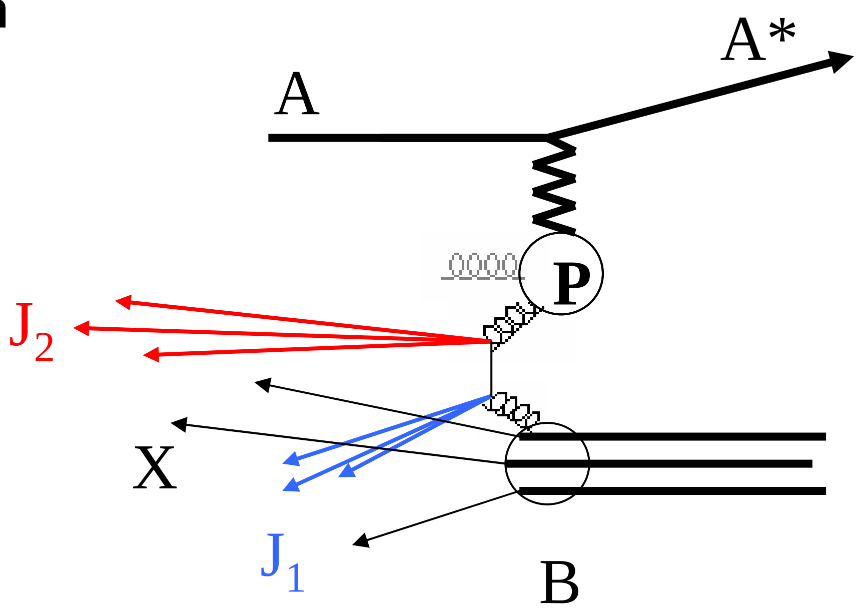
- Does it have partonic structure? Is it universal -- same in ***ep*** and $p\bar{p}$? Is it the same with and without **jet** production?

- Answer questions in HEP tradition -- collide it with something that you understand to learn its structure

- Note: variables of diffraction are ***t*** (momentum transfer) and $\xi \sim \mathbf{M^2}$ (fractional momentum loss) with a proton detector measure $\frac{d^2\sigma}{dt d\xi}$ without one just measure σ

Ingelman-Schlein

- **Factorization allows us to look at the diffractive reaction as a two step process. Hadron A emits a Pomeron (pomeron flux) then partons in the Pomeron interact with hadron B.**
- **The Pomeron to leading order is proposed to have a minimal structure of two gluons in order to have quantum numbers of the vacuum**



G. Ingelman and P. Schlein, Phys. Lett. B 152, 256 (1985)

UA8

UA8 EXPERIMENT

UCLA (P. SCHLEIN et al)

$$\underbrace{p\bar{p}}_{s} \rightarrow \underbrace{p_f}_{x_p} + (\text{jet} \underbrace{+\text{jet}}_{s'=s(1-x_p)} + X) + \text{c.c.}$$

$\sqrt{s} = 630\ \text{GeV} \quad \therefore\ x_p = 0.9 \ \Rightarrow\ \sqrt{s'} = 200\ \text{GeV}$

p_f DETECTED IN ROMAN POT SPECTROMETER (MOMENTUM CALCULATED ONLINE WITH DATA DRIVEN PROCESSOR)

JETS IN UA2' CALORIMETER

JET $E_T > 8$ GeV IN CONE $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 1$

BASIC JET TRIGGER = PROTON (UA8) + ΣE_T (UA2)

HARD DIFFRACTION ISSUES

- DOES IT EXIST? $p\bar{p} \rightarrow p + \text{JETS}$
- DOES $(1-x_p)$ COMPONENT (POMERON) HAVE PARTONIC STRUCTURE?
- IS IT REASONABLE TO THINK OF $I\!P$ AS STATE IN p ON WHICH $\bar{p}$ SCATTERS?

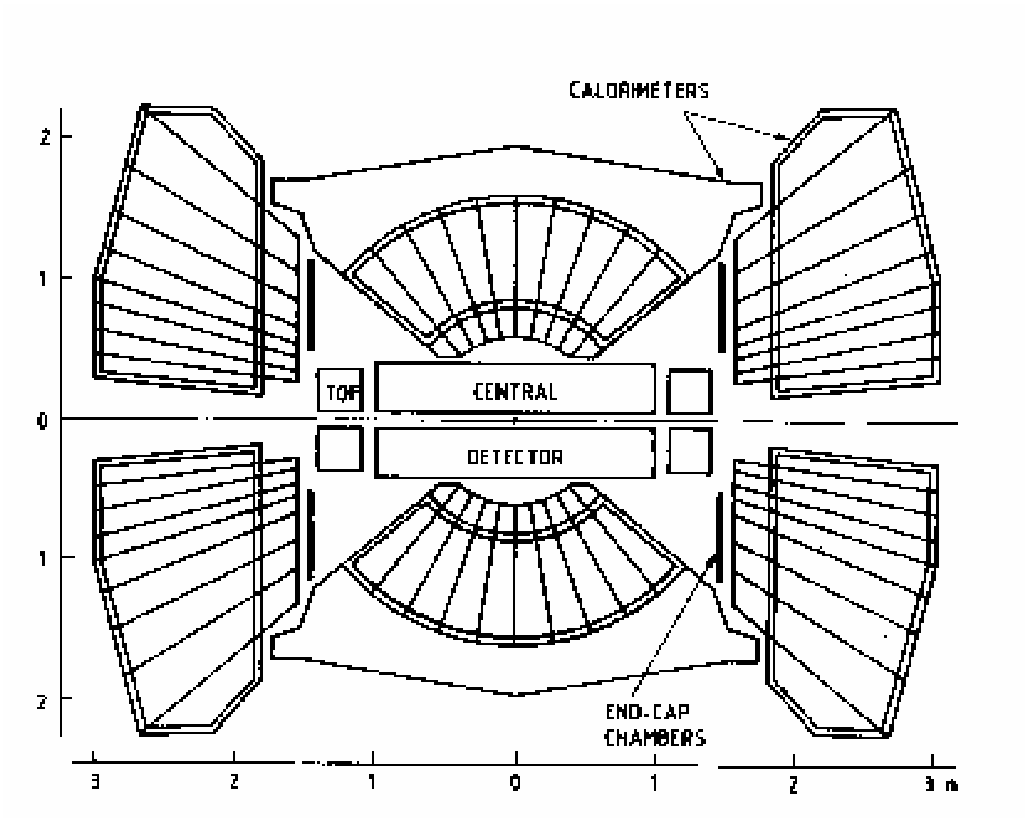
$\Rightarrow$ UNIVERSAL "FLUX FACTOR" FOR $I\!P$ IN PROTON INDEPENDENT OF INTERACTION

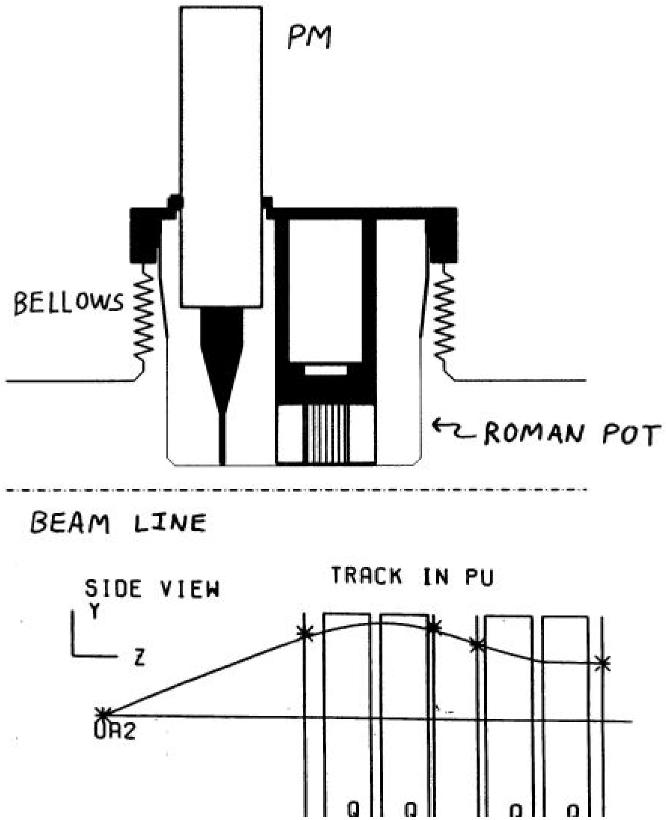
SHOULD COMPARE DIFFERENT INTERACTIONS

$p\bar{p} \rightarrow pX$
$e^-p \rightarrow e^-pX$
$\bar{p}p \rightarrow \bar{p}pX$

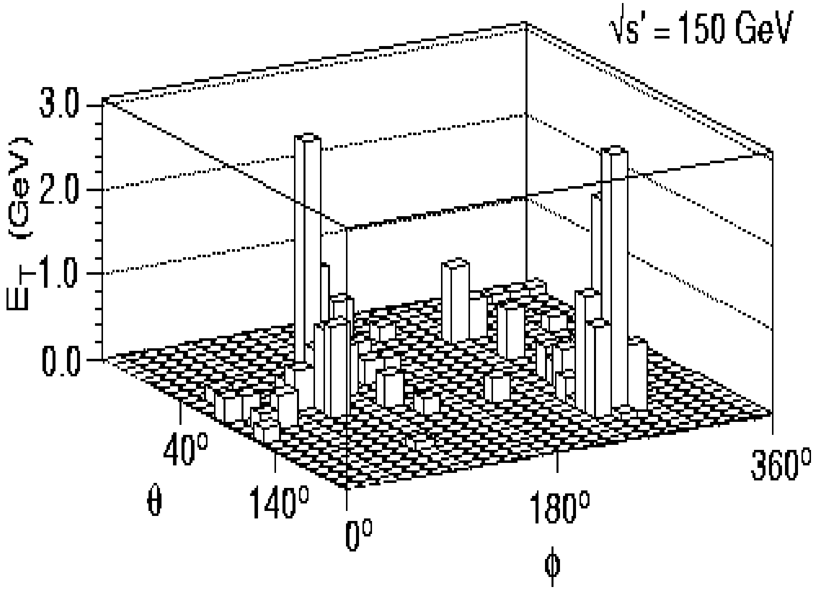
AT DIFFERENT ENERGIES

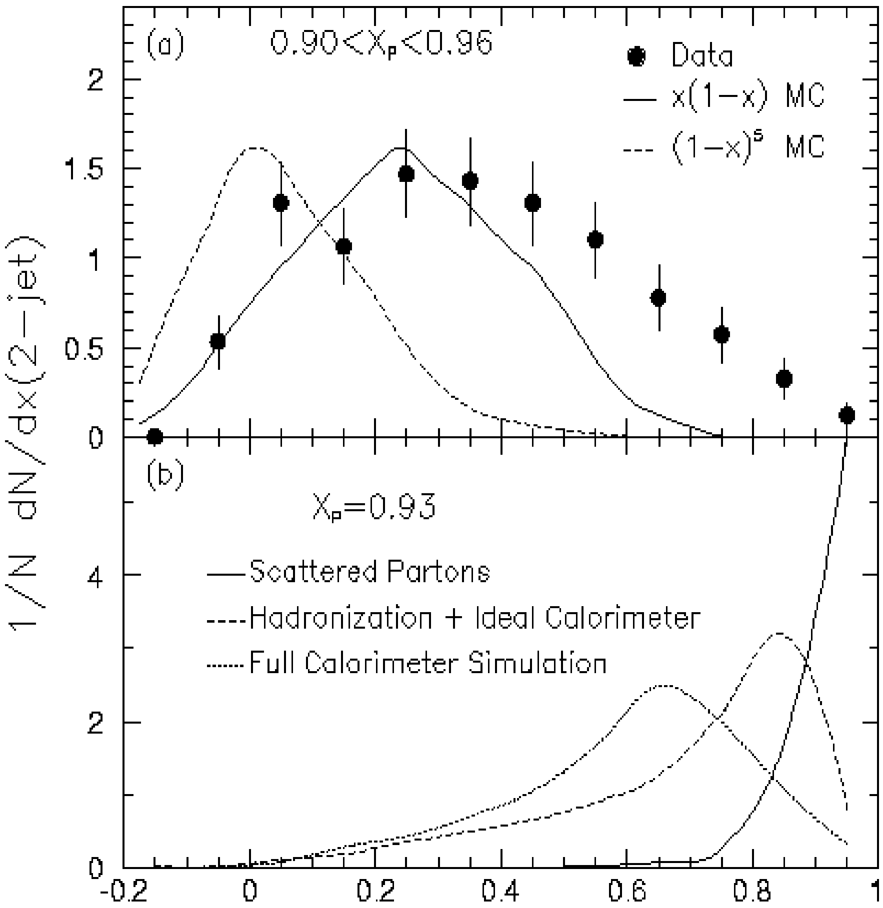
UA8 = UA2 + Roman-pot Spectrometer





UA8 Dijet Production in Diffraction





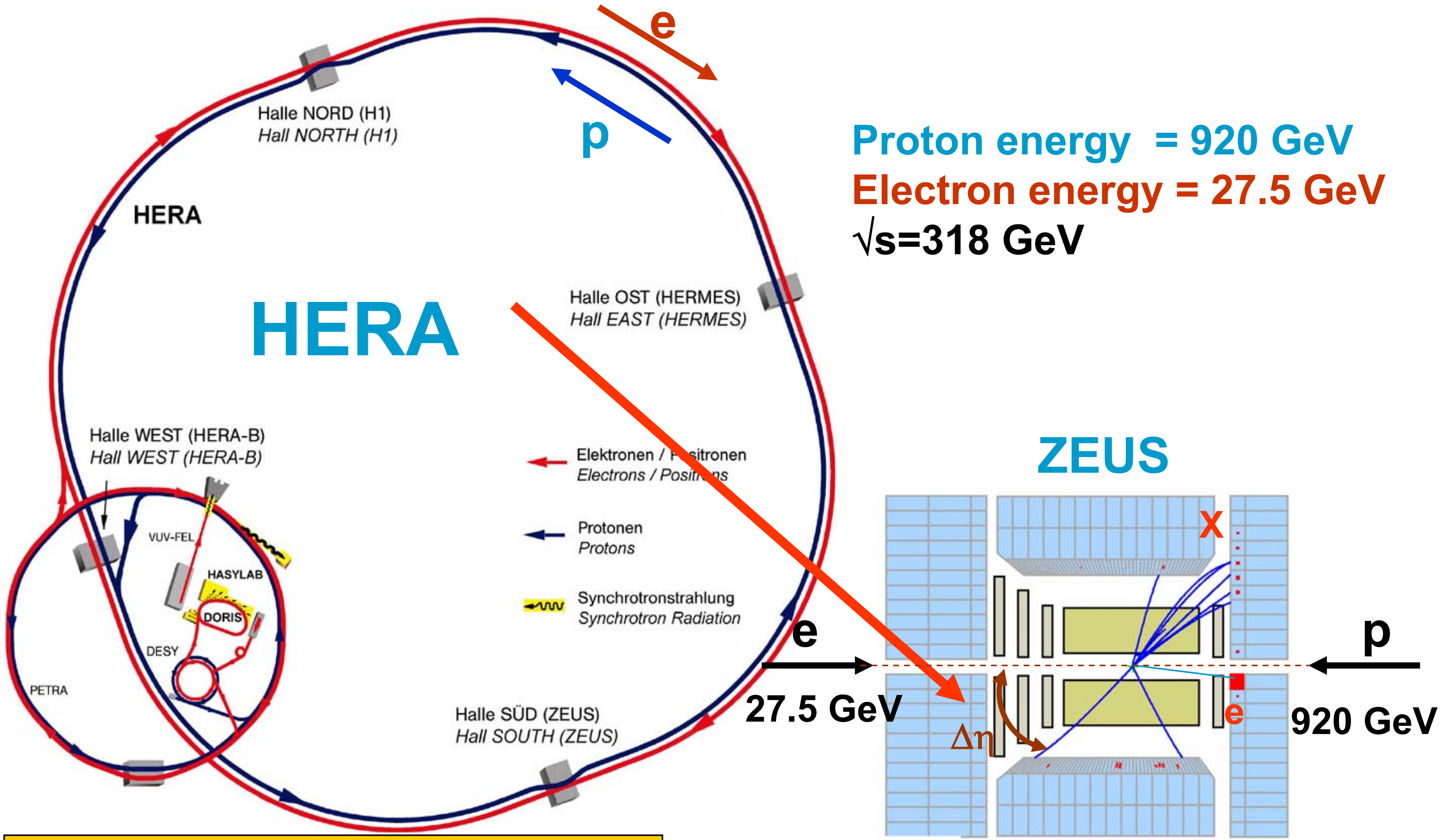
x(2-jet)

A. Brandt et al., P.L. B 297 (1992) 417 **(206 citations!)**

→ Hard Diffraction exists!

Pomeron has a “super-hard” component.

Diffractive Deep Inelastic Scattering



Proton energy = 920 GeV

Electron energy = 27.5 GeV

$\sqrt{s}$=318 GeV

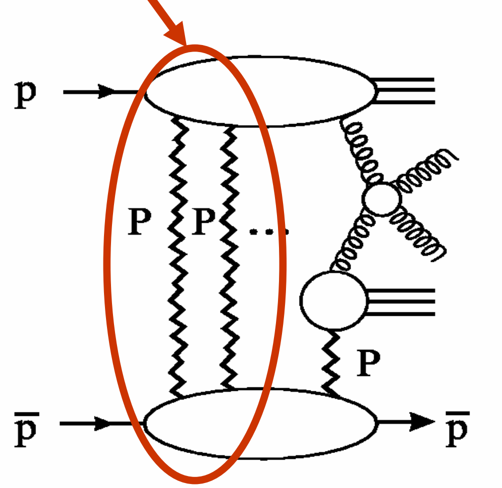
$\sqrt{s} \approx 320$ GeV

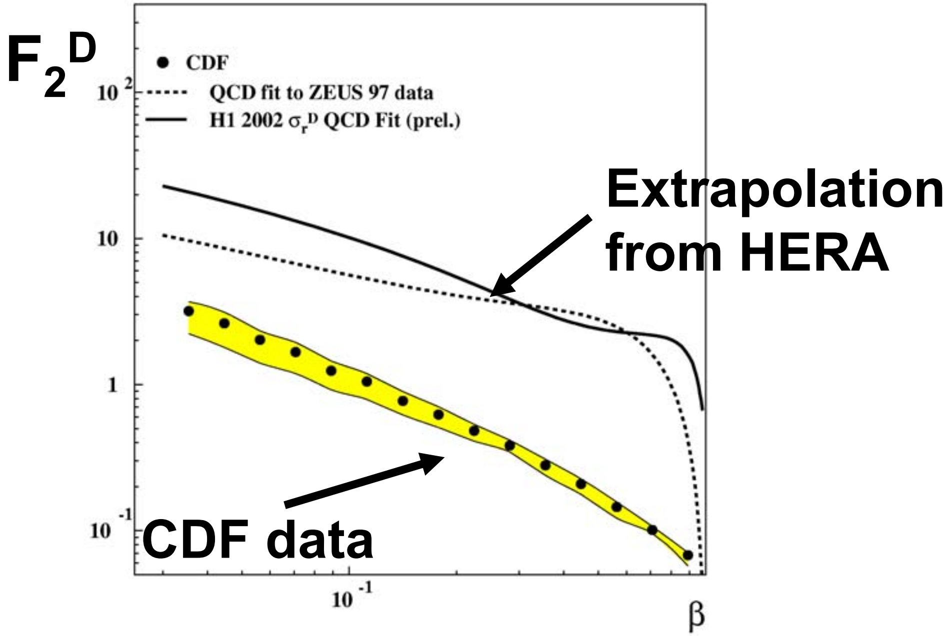
Rather than IP exchange: probe diffractive PDFs of proton

Applying dPDFs to FNAL/LHC Requires Care

Diffractive PDFs measured at HERA cannot be used blindly in pp (or ppbar) interactions.

In addition to the hard diffractive scattering, there are soft interactions among spectator partons. They fill the rapidity gap and reduce the rate of diffractive events.



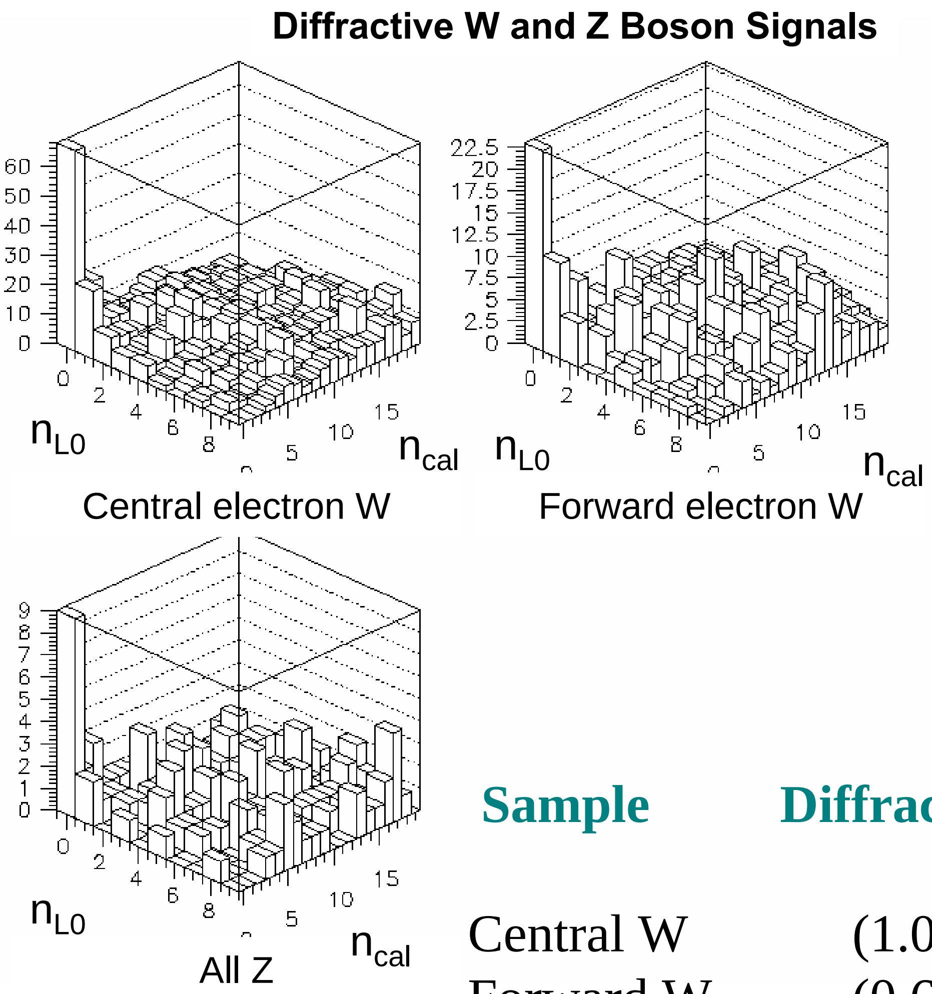


Extrapolation from HERA

CDF data

Multi-Pomeron-exchange effects (a.k.a. “renormalization”, “screening”,“shadowing”, “damping”, “absorption”)

DØ Observation of Diffractive W/Z


Diffractive W and Z Boson Signals

Central electron W

Forward electron W

All Z

•Phys. Lett. B 574, 169 (2003)

- **Observed clear Diffractively produced W and Z boson signals**
- **Events have typical W/Z characteristics**
- **Background from fake W/Z gives negligible change in gap fractions**

Sample	Diffractive/All	Probability Background Fluctuates to Data
Central W	(1.08 + 0.19 - 0.17)%	**7.7σ**
Forward W	(0.64 + 0.18 - 0.16)%	**5.3σ**
All W	**(0.89 + 0.19 – 0.17)%**	**7.5σ**
All Z	(1.44 + 0.61 - 0.52)%	**4.4σ**

DØ Run II Diffractive Topics

Soft Diffraction and Elastic Scattering:

- Inclusive Single Diffraction
- Elastic scattering (t dependence)
- Inclusive double pomeron

Hard Diffraction:

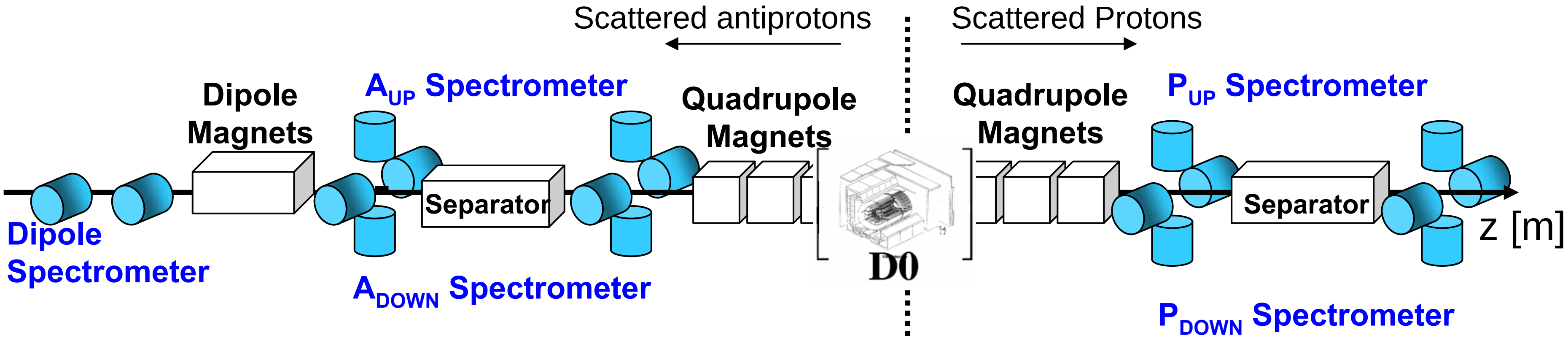
- **Diffractive jet**
- Diffractive heavy flavor
- **Diffractive W/Z**
- Diffractive photon
- **Double Pomeron + jets**

Exclusive Production of Dijets

Topics in **RED** were studied with gaps only in Run I

DØ Forward Proton Detector

Nine independent spectrometers each consisting of two detectors



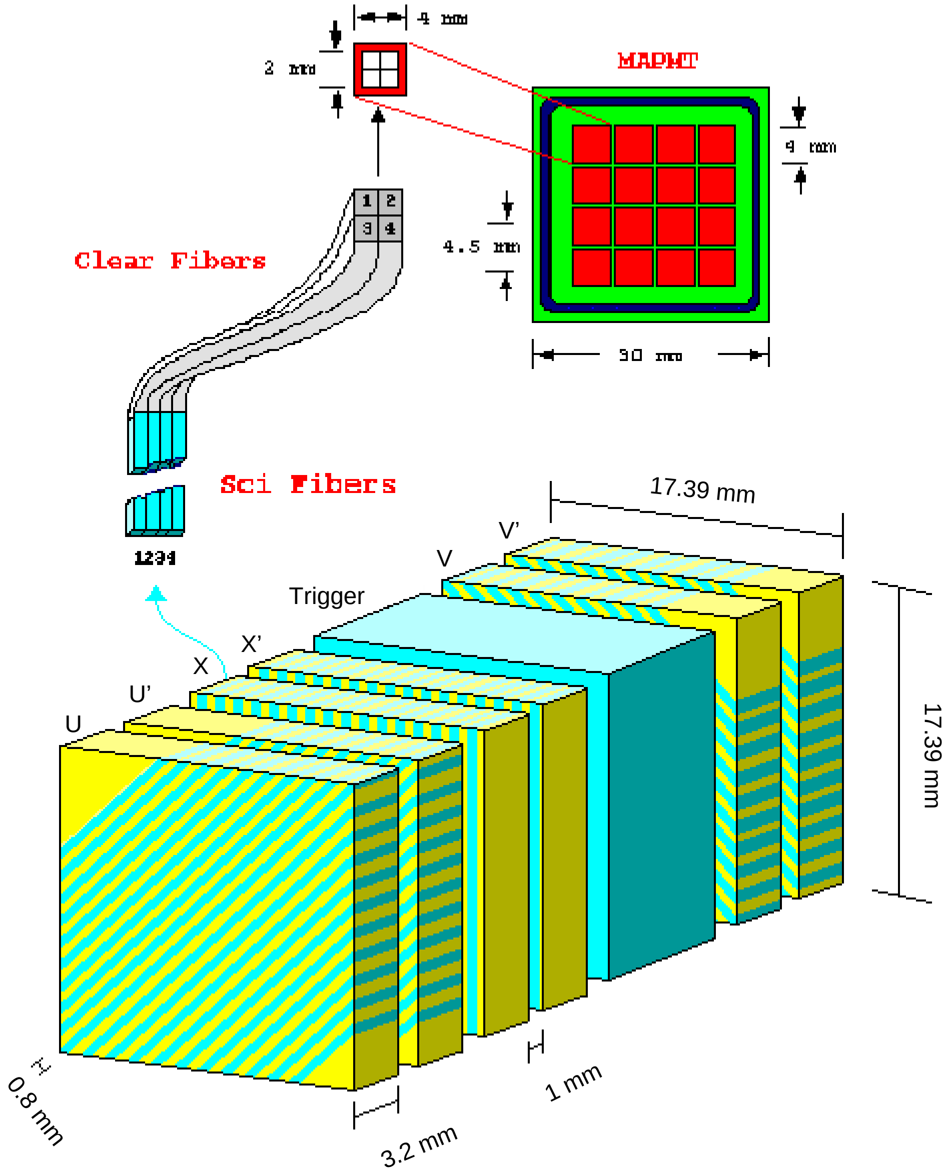
⇨ **Reconstruct particle tracks from detector (scintillating fiber) hits**

Dipole Spectrometer	Quadrupole Spectrometers
$\|t\| \sim 0.0$ GeV^2	$\|t\| > 0.8$ GeV^2
$\xi > 0.04$	$\xi > 0.0$

⇨ **18 Pots integrated into DØ readout and inserted every store between Jan 2004 and Feb. 2006**

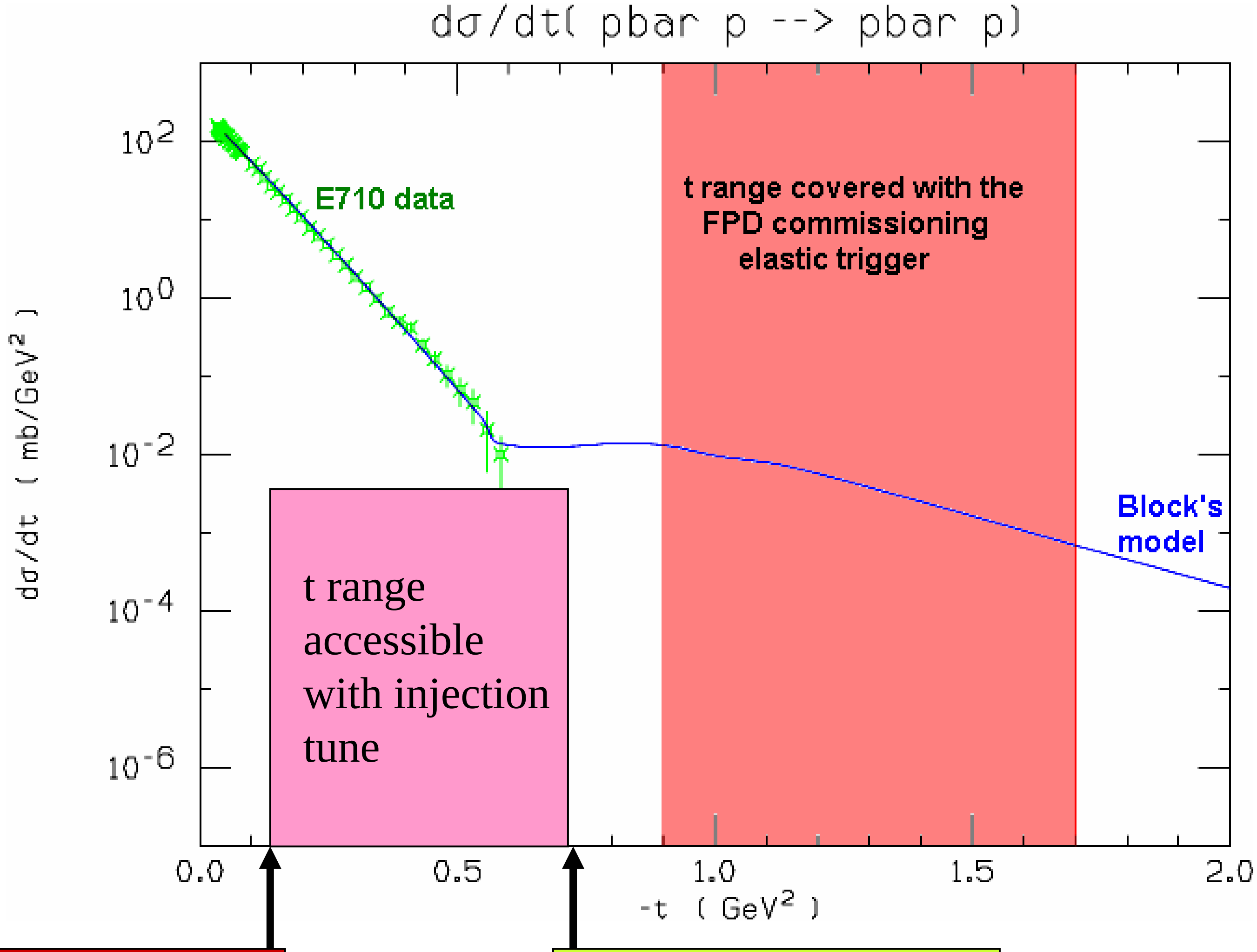
⇨ **Simultaneously tag/reconstruct protons and antiprotons**

FPD Detectors



- 6 planes per detector in 3 frames and a trigger scintillator
- U and V at 45 degrees to X, 90 degrees to each other
- U and V planes have 20 fibers, X planes have 16 fibers
- Planes in a frame offset by ~2/3 fiber
- Each channel filled with four fibers
- 2 detectors in a spectrometer

Large β* Store



t range covered with the FPD commissioning elastic trigger

t range accessible with injection tune

pot position

integ. luminosity

Two day run of accelerator at injection tune

β^*=1.6 m

1x1 bunch

Lum=0.5E30

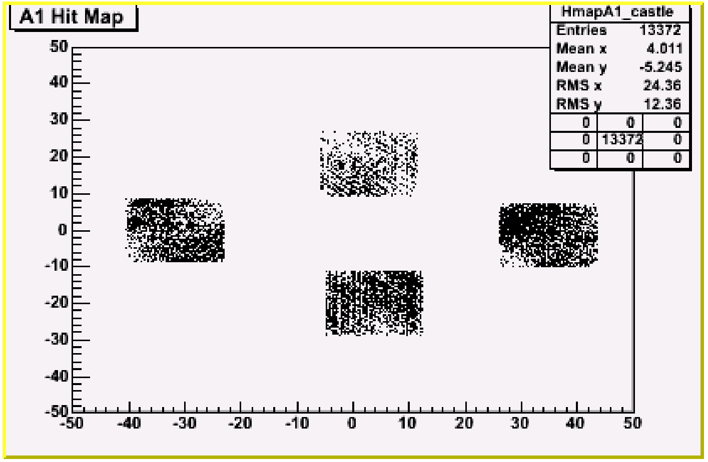
Physics Goals:

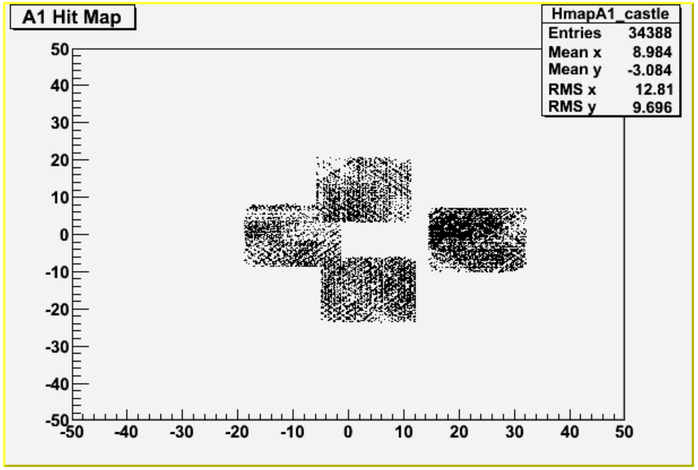
1. Low-t elastic scattering
2. Low-t single diffractive and double pomeron scattering

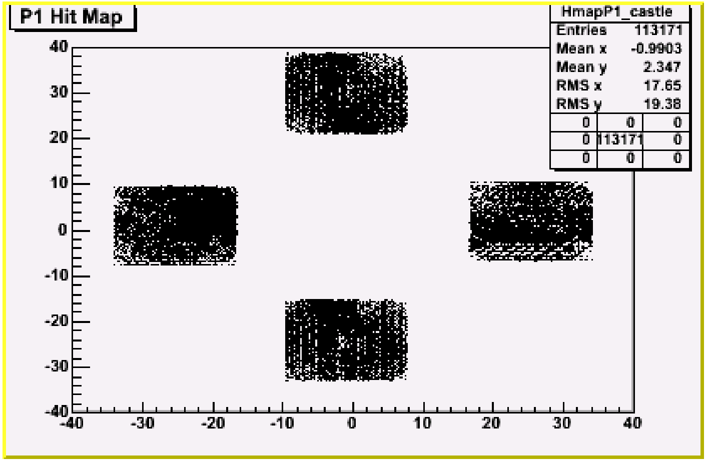
Hit Maps from Large β* Store

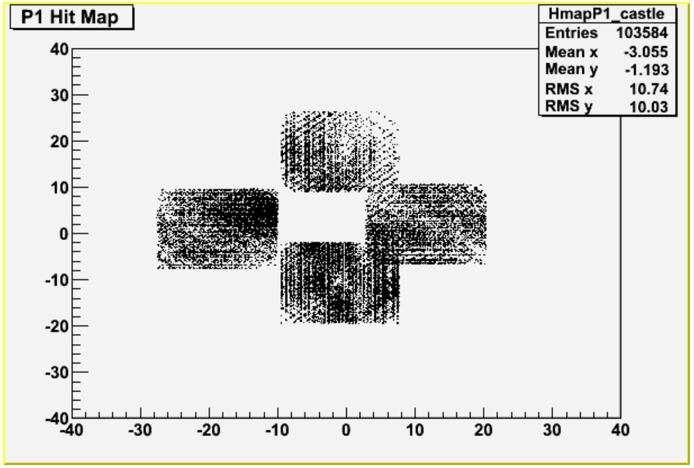
Typical Store

Large β* store (4647)
(no low β squeeze)



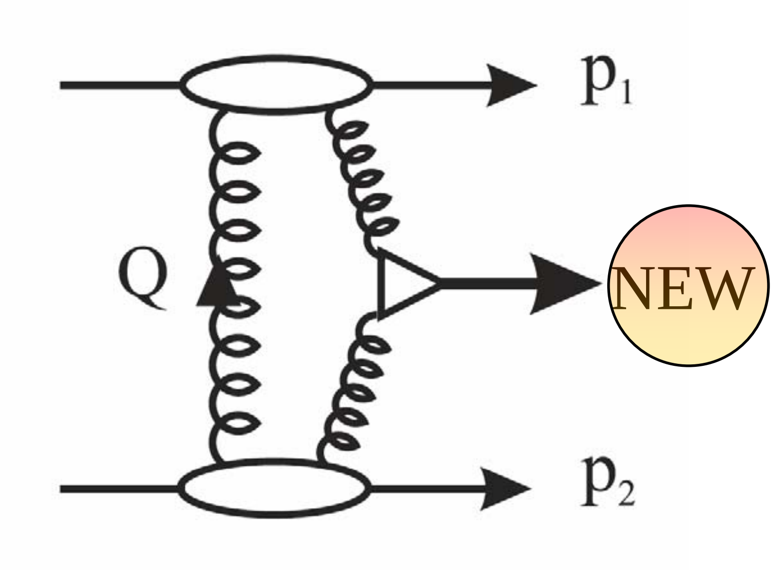






FP420 Overview

FP420: Double proton tagging at 420m as a means to discover new physics



- Tagging the protons means excellent mass resolution (~ 1 to few GeV) independent of decay channel
- Selection rules mean that central system is dominantly 0^{++} (CP even)
- If you see a new particle in any decay channel with proton tags, you know its quantum numbers
- Proton tagging may be ***THE*** discovery channel in certain regions of the MSSM

Used to be called Double Pomeron Exchange

now Central Exclusive Diffraction

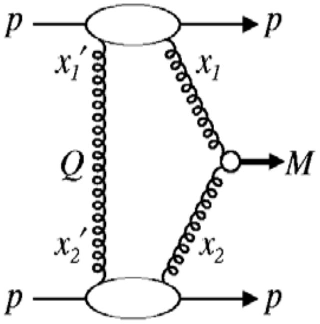
0^{++} Selection rule

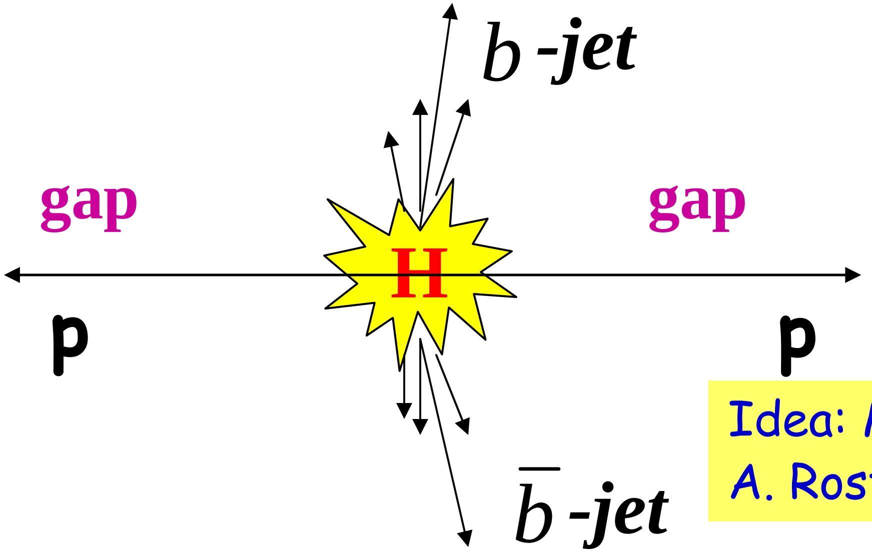
QCD Background ~ $\frac{m_b^2}{E_T^2} \frac{\alpha_S^2}{M_{b\bar{b}}^2 E_T^2}$

Central Exclusive Higgs Production

Central Exclusive Higgs production pp→ p H p : 3-10 fb

E.g. V. Khoze et al
M. Boonekamp et al.
B. Cox et al.
V. Petrov et al…
Levin et al…

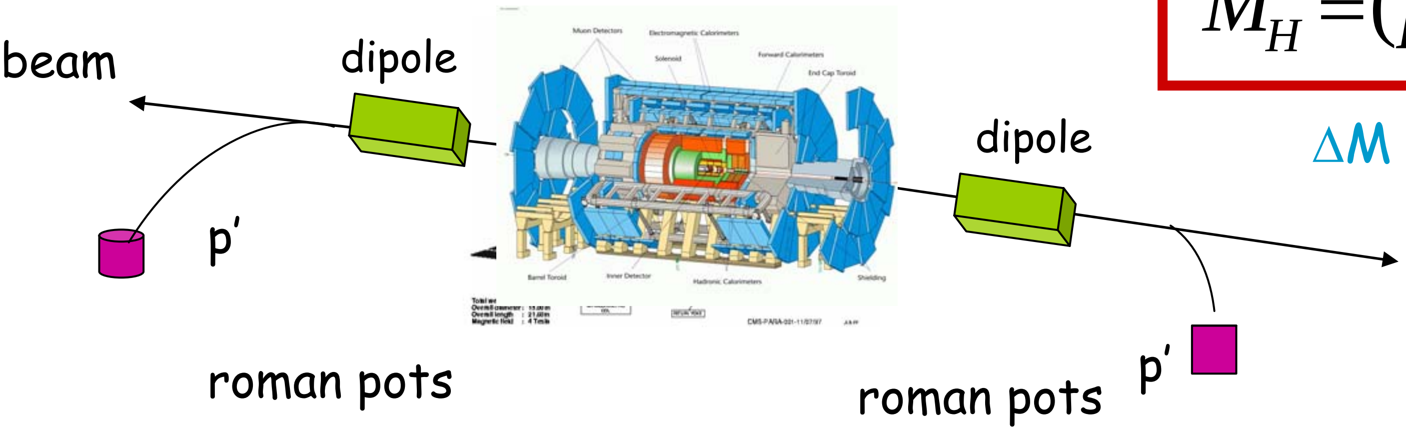




Idea: M. Albrow &
A. Rostovtsev for Tevatron

$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

ΔM = O(1.0 - 2.0) GeV



Physics with Forward Protons

- At low to intermediate luminosity (30-100 fb-1) we can :

Establish the quantum numbers and measure mass of SM Higgs
Be the discovery channel in certain regions of the MSSM
Wide range of γγ physics including anomalous couplings
Perform interesting QCD measurements (0.002 < xIP < 0.015)

- In addition, at higher luminosity (> 100 fb-1) we can :

Discover exotic bound states such as gluinoballs
Make direct observation of CP violation in some SUSY Higgs scenarios
Disentangle wide range of SUSY scenarios, including ~degenerate Higgs

- FP420 turns the LHC into a energy tunable glue-glue (and γγ) collider

Recent Phenomenological Work

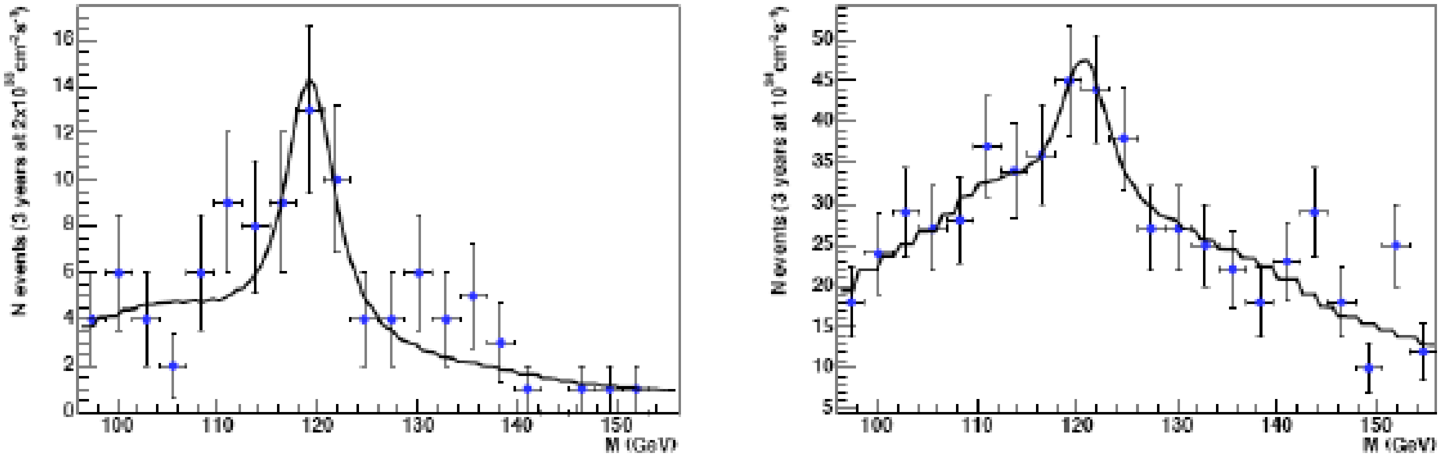
- **Detecting Higgs bosons in the bb decay channel using forward proton tagging at the LHC B. E. Cox, F. K. Loebinger, A. D. Pilkington arXiv:0709.3035v1 [hep-ph]**

  A detailed study of the search for Higgs bosons in the b-decay channel in the central exclusive production process at the LHC. We present results for proton tagging detectors at both 220m and 420m around ATLAS or CMS. We consider two benchmark scenarios: SM and MSSM (mhmax) Higgs Detector acceptance, smearing and event trigger strategies are considered. We find that the SM Higgs will be challenging to observe in the b-jet channel but a neutral scalar MSSM Higgs Boson could be observable in the b-jet channel with a significance of 3--5σ sigma or greater within three years of data taking at all luminosities between 2 x 10^{33} and 10^{34}cm^{-2} s^{-1}

- **Studying the MSSM Higgs sector by forward proton tagging at the LHC S. Heinemeyer, V.A. Khoze, M.G. Ryskin, W.J. Stirling, M. Tasevsky, G. Weigle in arXiv:0709.3035v1 [hep-ph]**

  We show that the use of forward proton detectors at the LHC installed at 220 m and 420 m distance around ATLAS and / or CMS can provide important information on the Higgs sector of the MSSM.

The Physics case : MSSM h/H

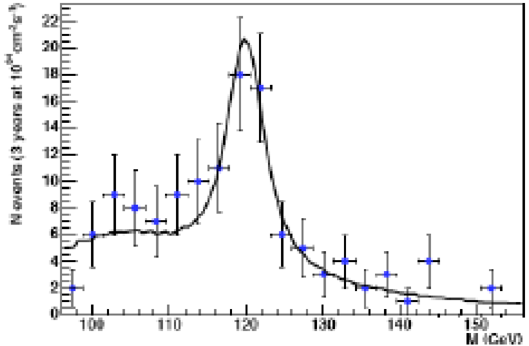


(a)

(b)

Fig. 6: Figure (a) shows a typical mass fit for 3 years of data taking at 2×10^{33} cm^{-2} s^{-1} (60 fb^{-1}). The significance of the fit is 3.5σ and uses only events with both protons tagged at 420m. Figure (b) shows a mass fit for 3 years of data taking at 10^{34} cm^{-2} s^{-1}. The significance is 3σ The L1 trigger strategy and analysis cuts are described in the text.

Better pileup rejection



B. E. Cox, F. K. Loebinger and A. D. Pilkington, JHEP **0710** (2007) 090 [arXiv:0709.3035 [hep-ph]].

Key Components of FP420

- Space in LHC tunnel for detectors (cryostat mods)

- Edgeless silicon detector

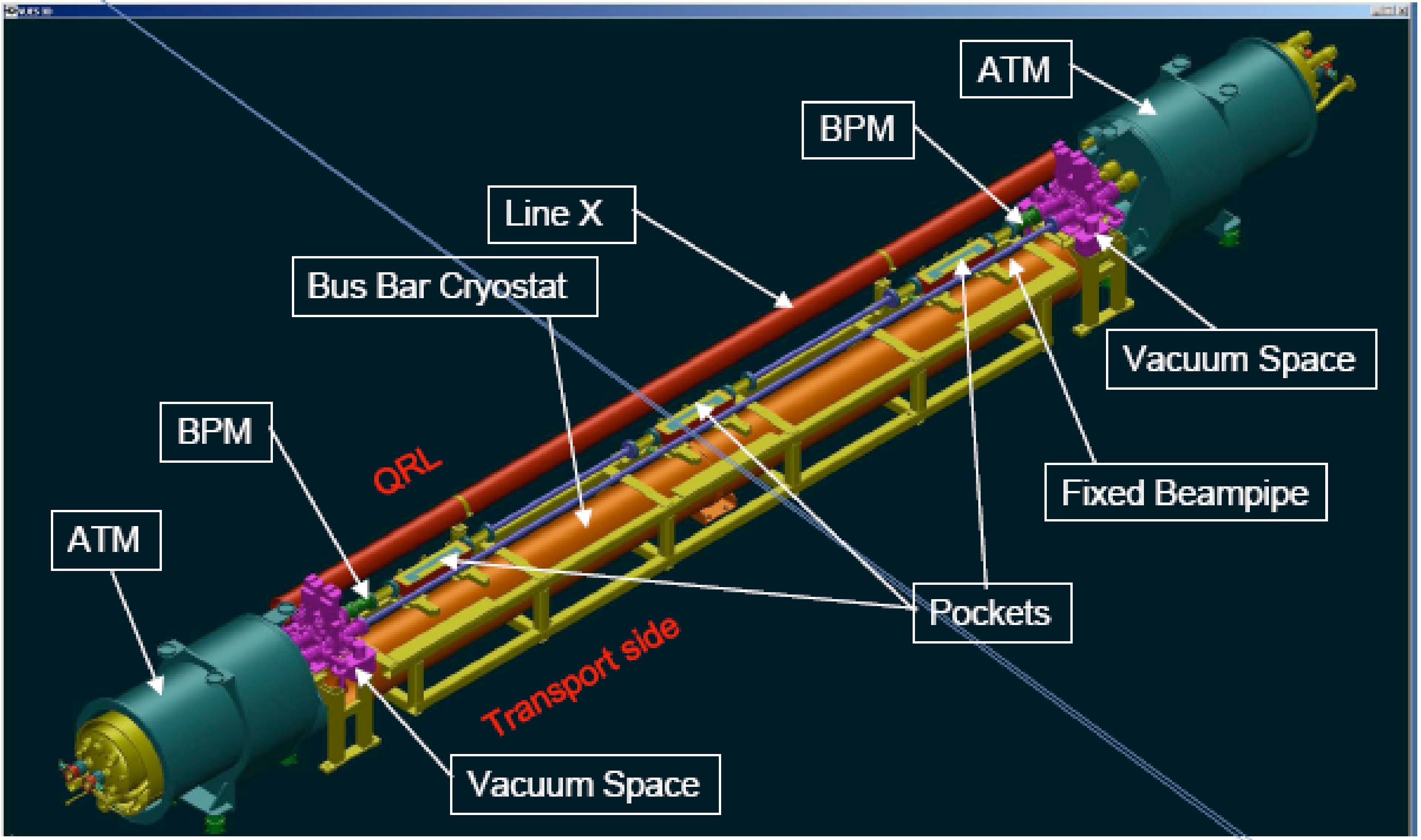
- Trigger and readout

- **“Hamburg Pipe” mechanics to house and move detector**

- **Fast TOF detector**

UTA Focus

Integration of the moving beampipe and detectors

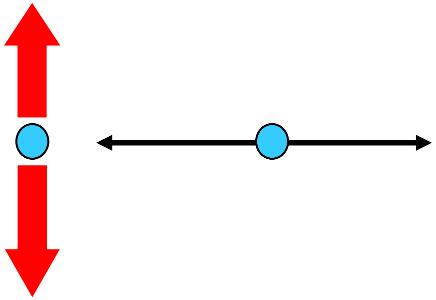


Fast Timing Detectors for ATLAS/CMS

WHO? UTA (**Brandt**), Alberta, **Louvain**, FNAL

WHY? **Background Rejection**

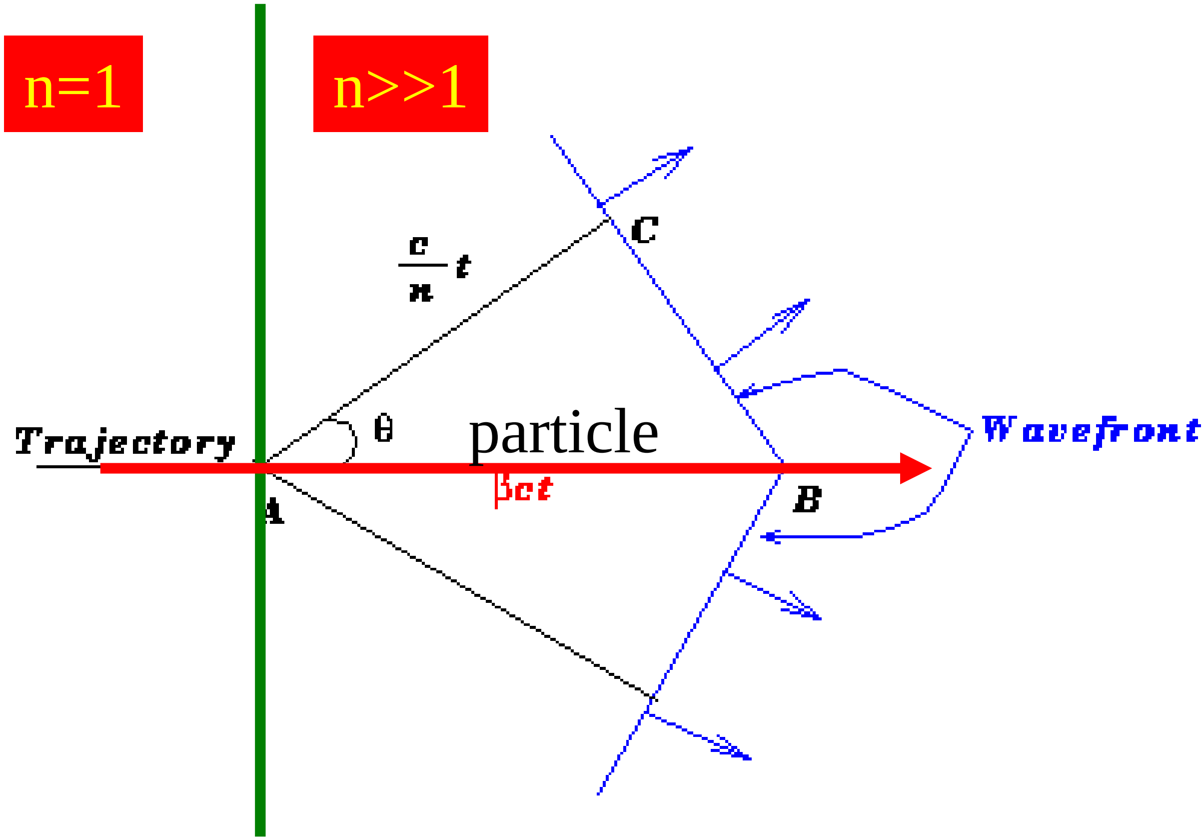
Ex, Two protons from one interaction and two b-jets from another



How? **Use time difference between protons to measure vertex and compare with tracking vertex**

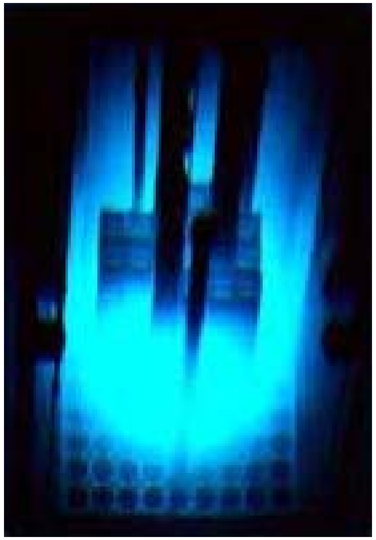
How Fast? **10 picoseconds (light travels 3mm in 10 psec!)**
gives factor 40 background rejection

Cerenkov Effect



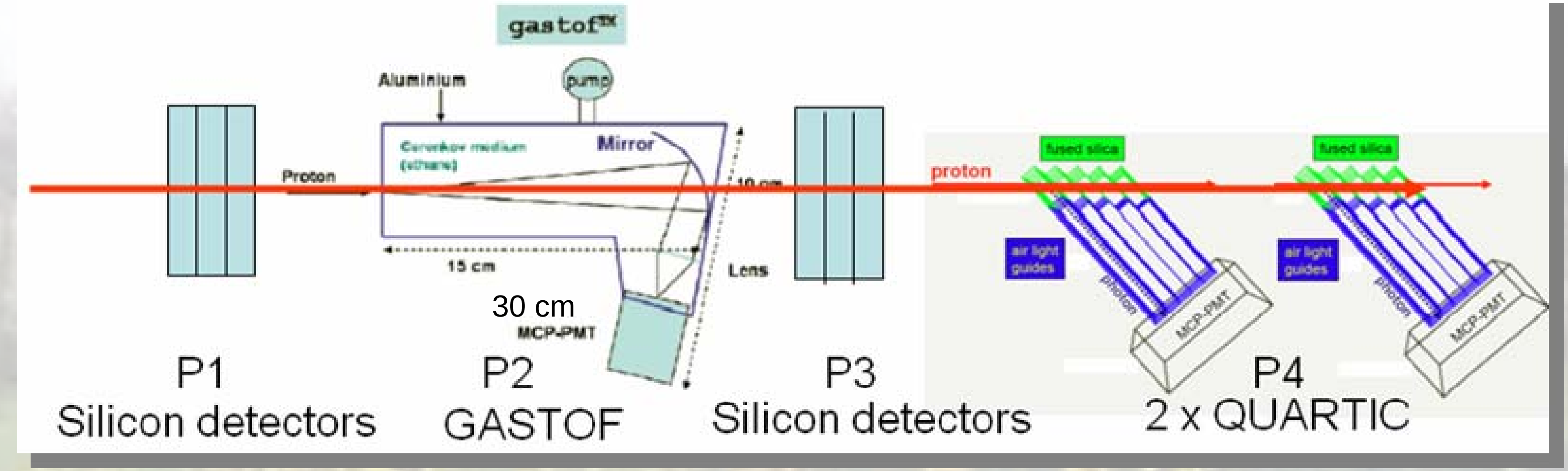
βc = speed of particle

$\frac{c}{n}$ = speed of radiation



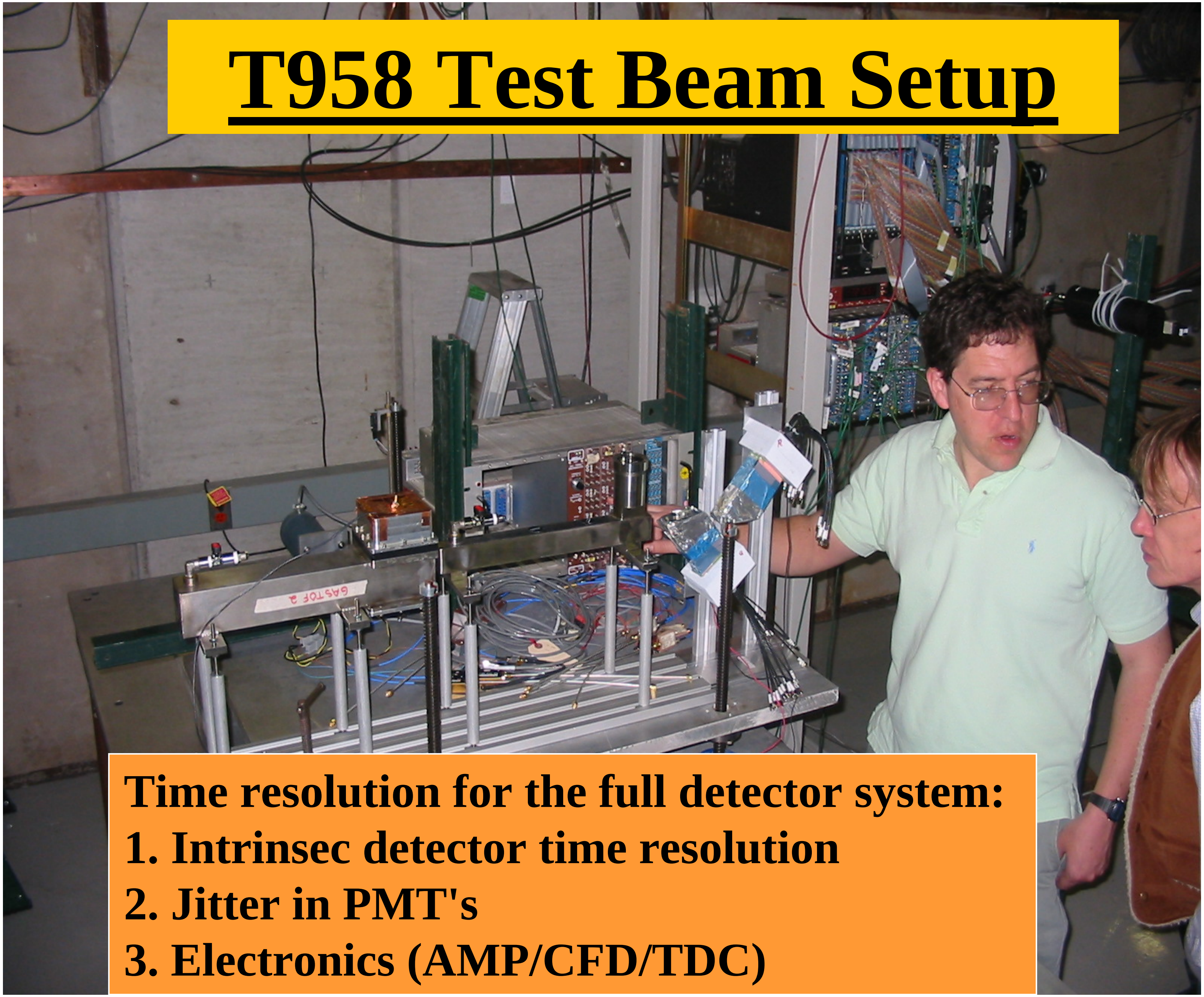
Use this property of prompt radiation to develop a fast timing counter

FP420 Baseline Plan



- Two types of Cerenkov detector are employed:
  - GASTOF – a gas Cerenkov detector that makes a single measurement
  - QUARTIC – two QUARTIC detectors each with 4 rows of 8 15 mm long fused silica bar allowing up to a 4-fold improvement of resolution over that of a single bar
  - Both detectors employ Micro Channel Plate PMTs (MCP-PMTs)

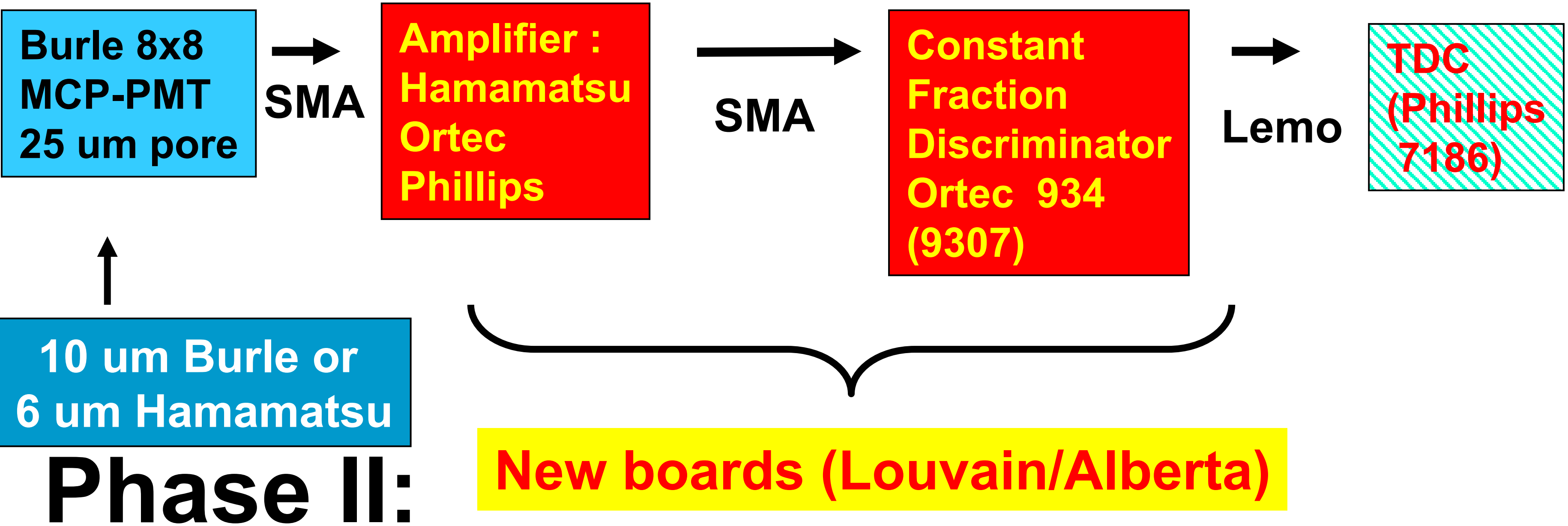
T958 Test Beam Setup



Time resolution for the full detector system:
1. **Intrinsec detector time resolution**
2. **Jitter in PMT's**
3. **Electronics (AMP/CFD/TDC)**

T958 Electronics

Phase I:



Burle 8x8
MCP-PMT
25 um pore

SMA

Amplifier :
Hamamatsu
Ortec
Phillips

SMA

Constant
Fraction
Discriminator
Ortec 934
(9307)

Lemo

TDC
(Phillips
7186)

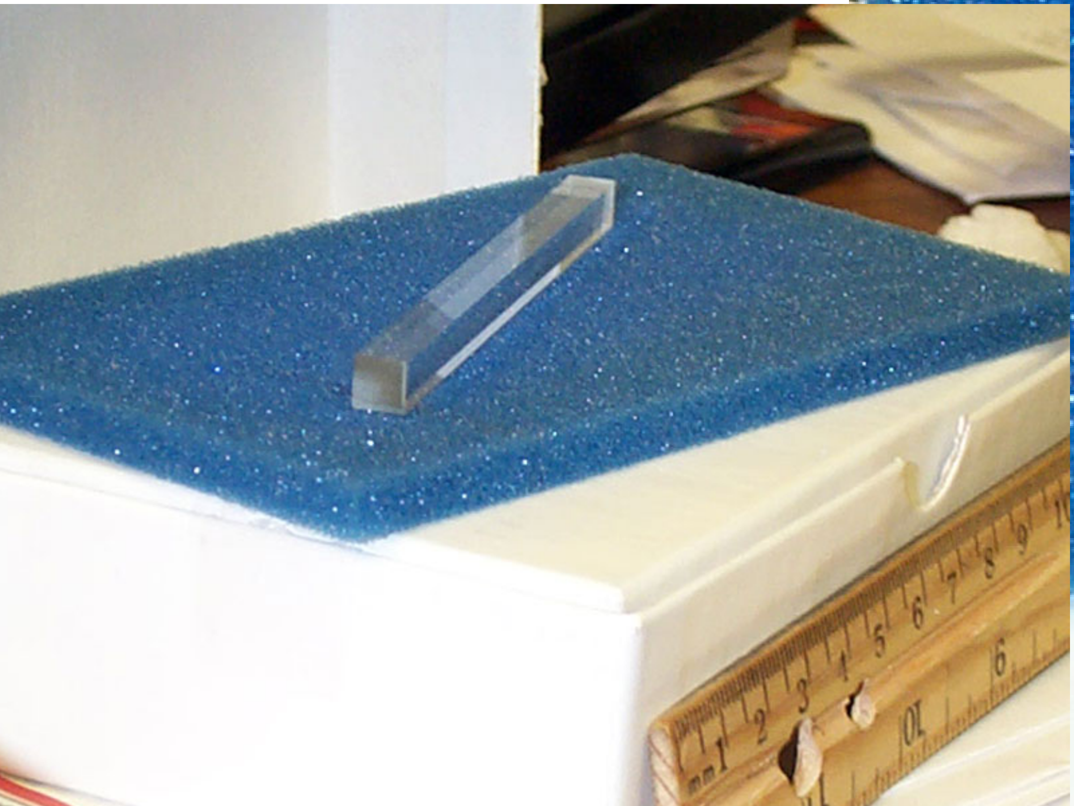
10 um Burle or
6 um Hamamatsu

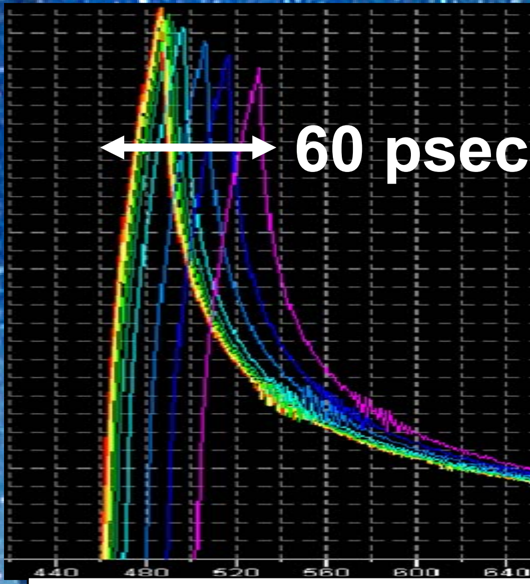
New boards (Louvain/Alberta)

Phase II:

Fused Silica Bars

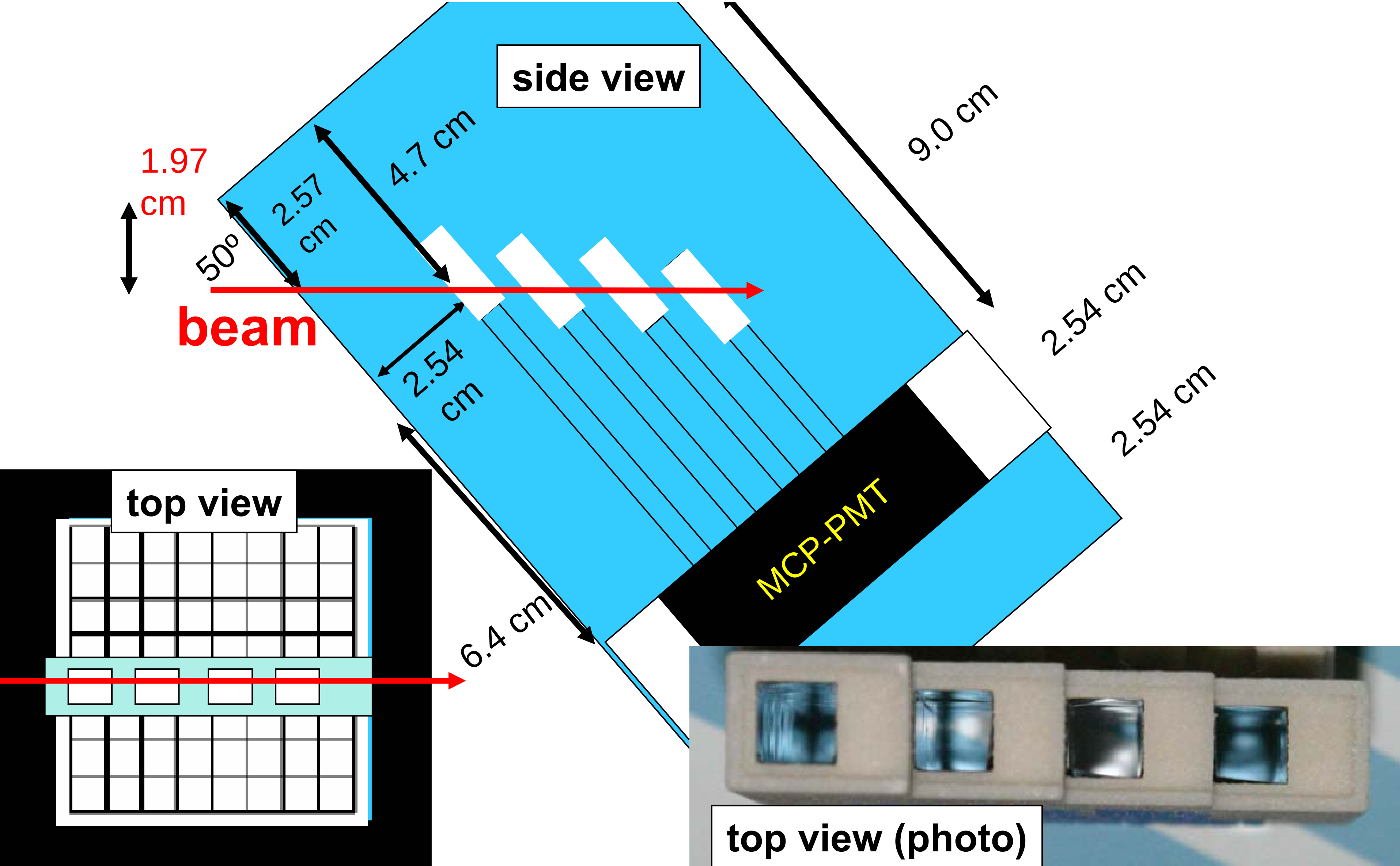
- 9 cm bars
- Some converted to mini-bars





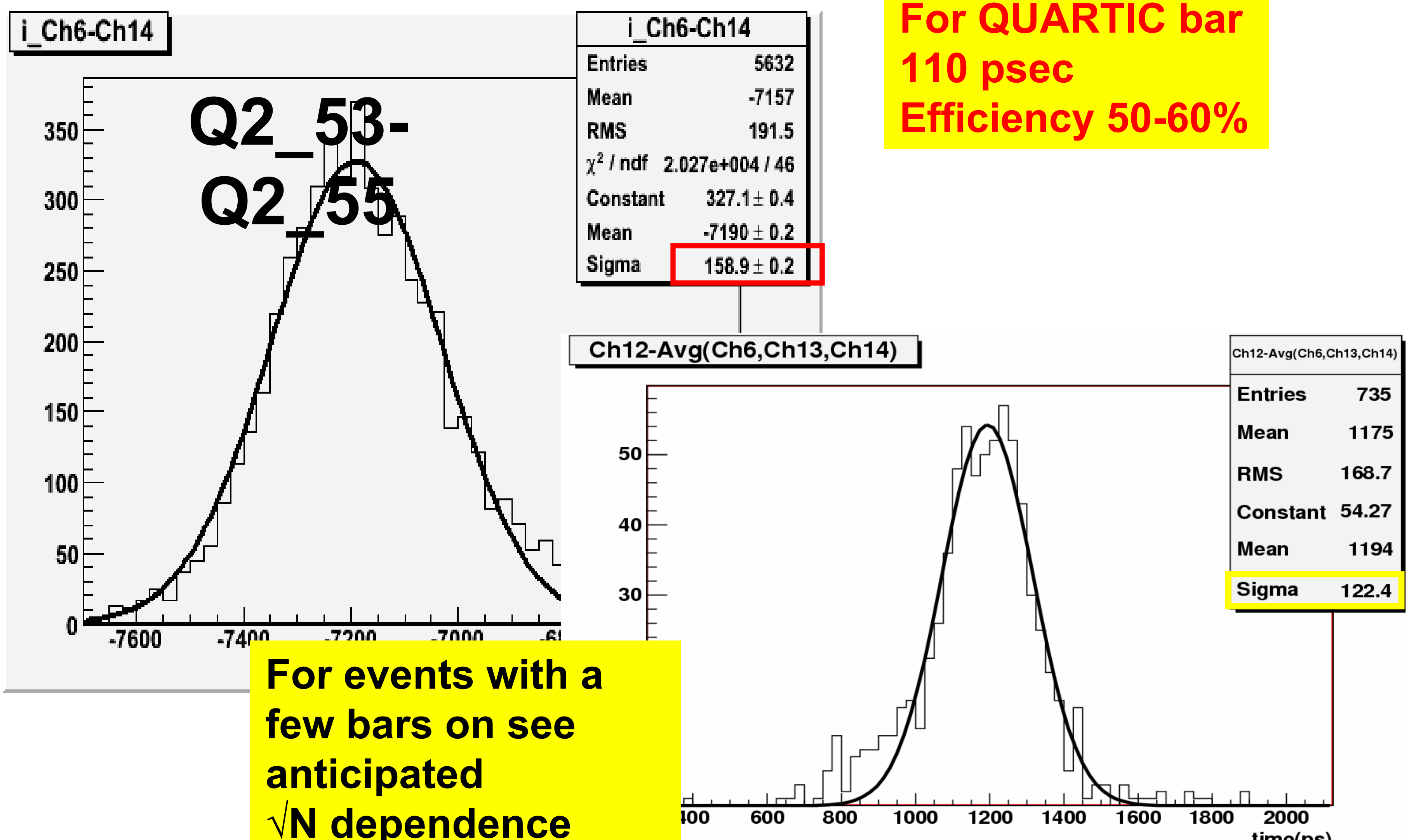
Spread in timing as f(λ) since n(λ)

QUARTIC Preprototype



2006 TB QUARTIC Results

For QUARTIC bar
110 psec
Efficiency 50-60%

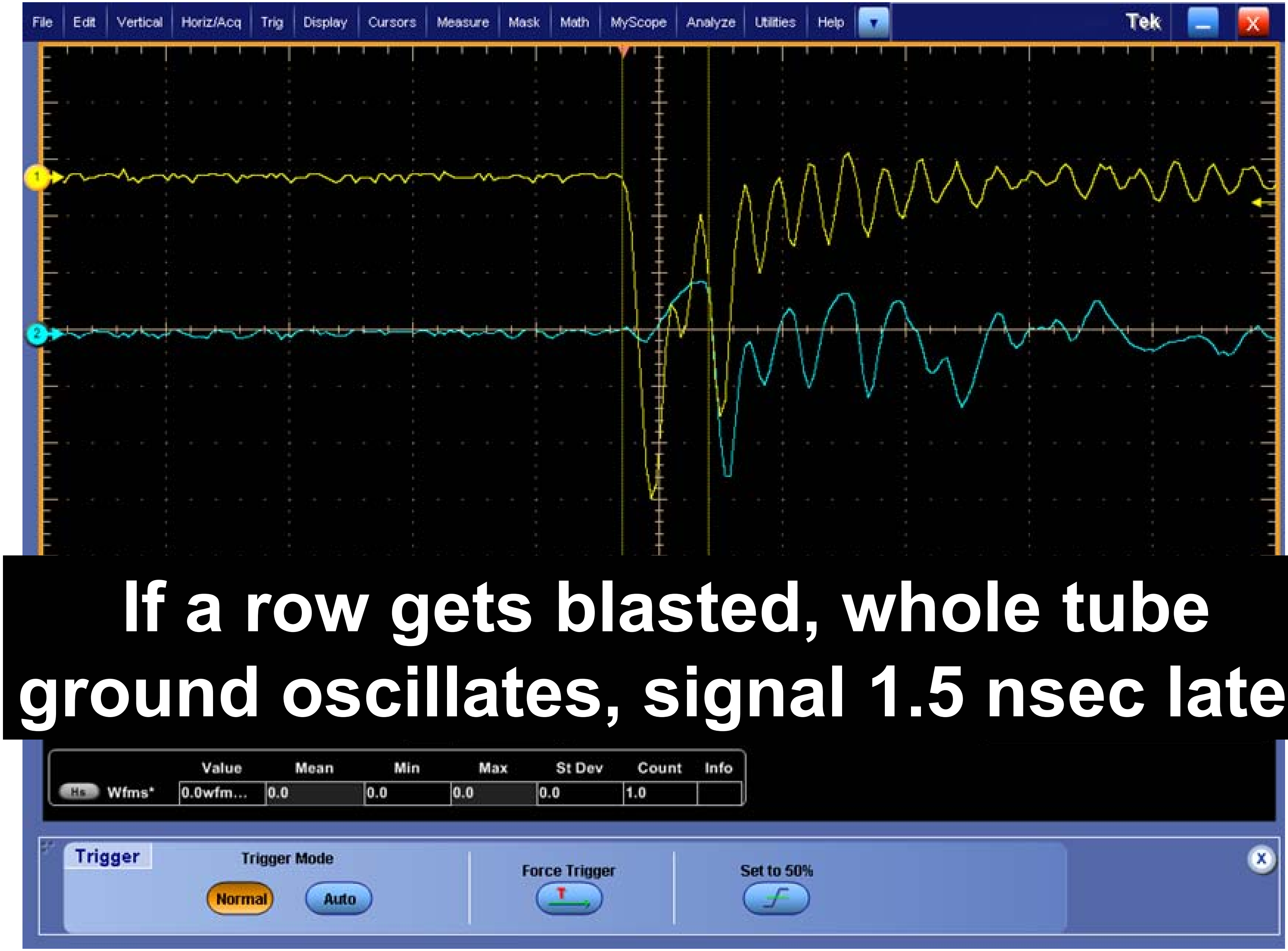


i_Ch6-Ch14	
Entries	5632
Mean	-7157
RMS	191.5
χ^2 / ndf	2.027e+004 / 46
Constant	327.1 ± 0.4
Mean	-7190 ± 0.2
Sigma	158.9 ± 0.2

Ch12-Avg(Ch6,Ch13,Ch14)	
Entries	735
Mean	1175
RMS	168.7
Constant	54.27
Mean	1194
Sigma	122.4

For events with a few bars on see anticipated
√N dependence

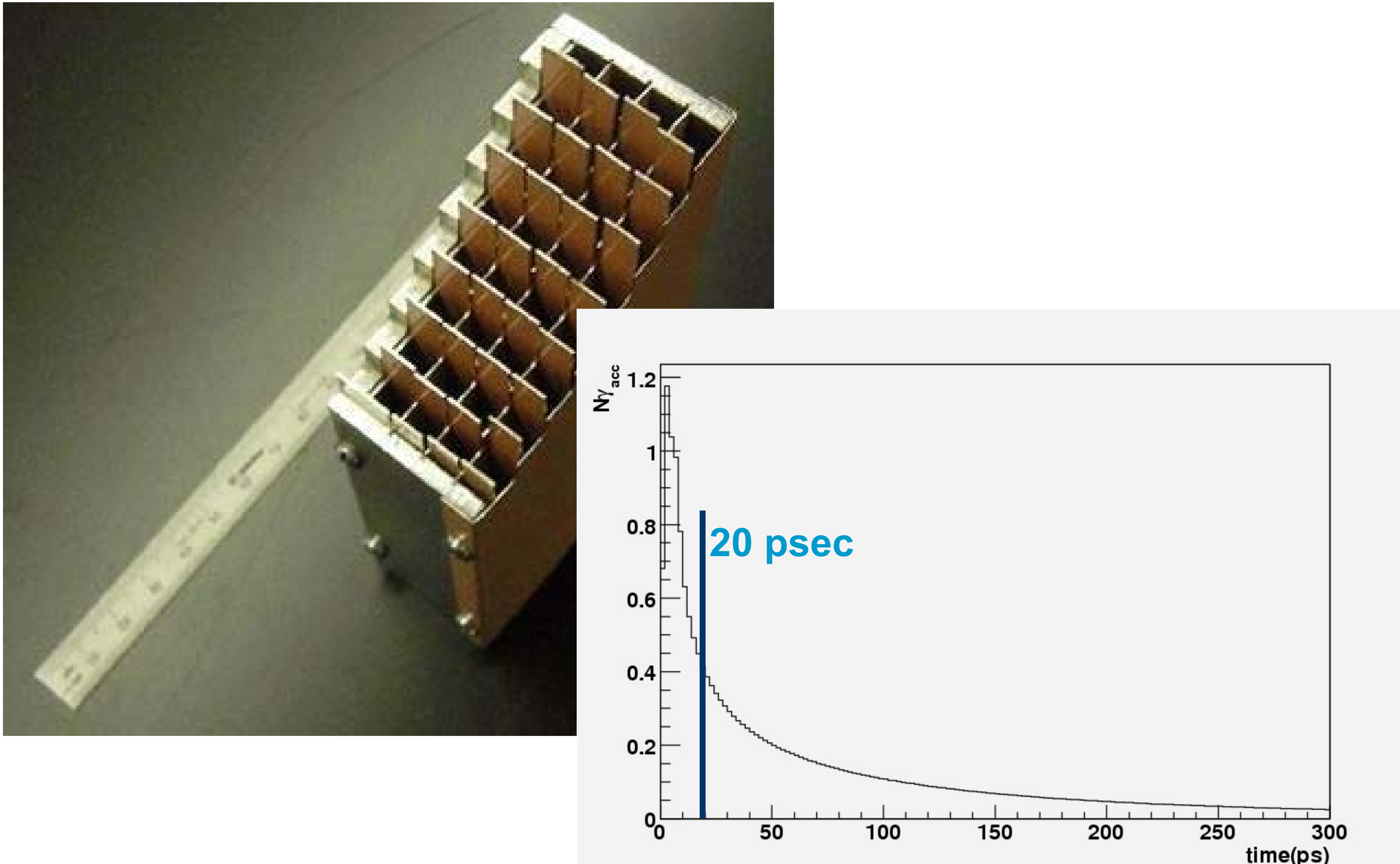
Coherent Noise!



	Value	Mean	Min	Max	St Dev	Count	Info
Wfms*	0.0wfm...	0.0	0.0	0.0	0.0	1.0	

If a row gets blasted, whole tube ground oscillates, signal 1.5 nsec later

QUARTIC (V2)



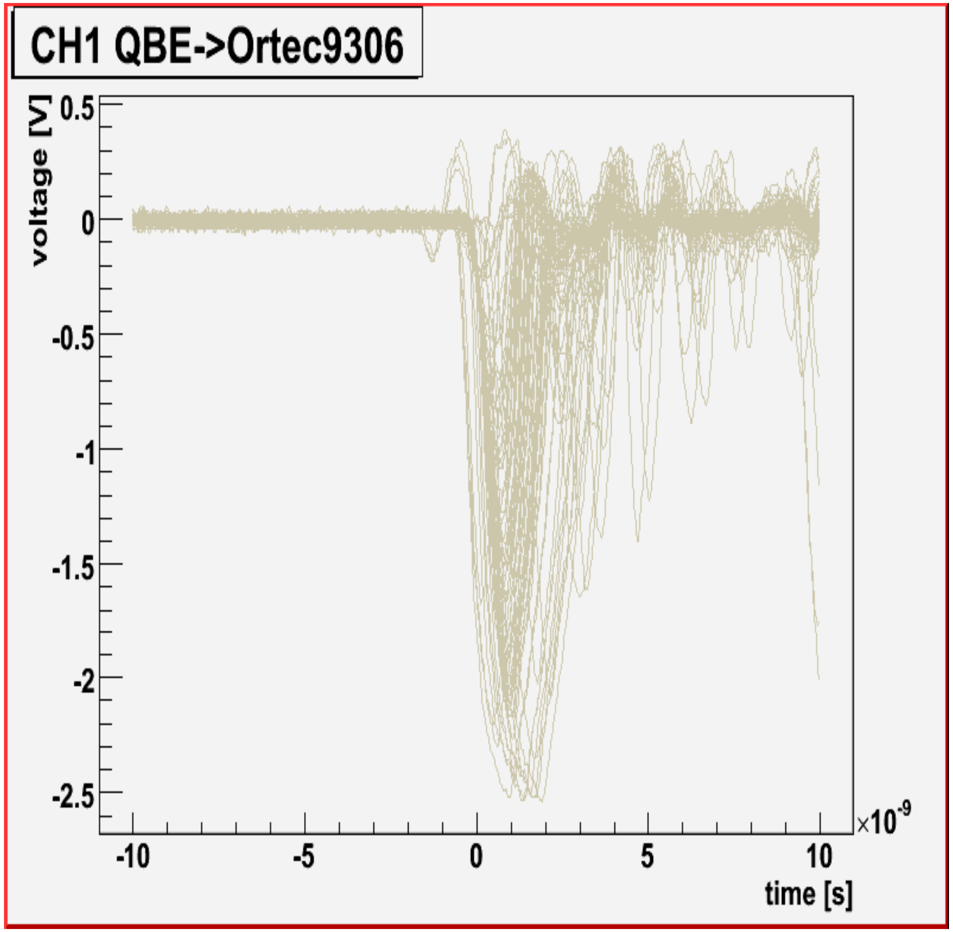
20 psec

TB Phase II Analysis

I) Pedro Duarte data analysis of CAMAC data (TDC tracking) leads to understanding of coherent noise, tracking, efficiency, cross talk.

II) Tomek Pierzchala scope data analysis gives data base of pulses, allows separation of detector/tube response from electronics.

Scope (Tektronix DPO70404) Analysis

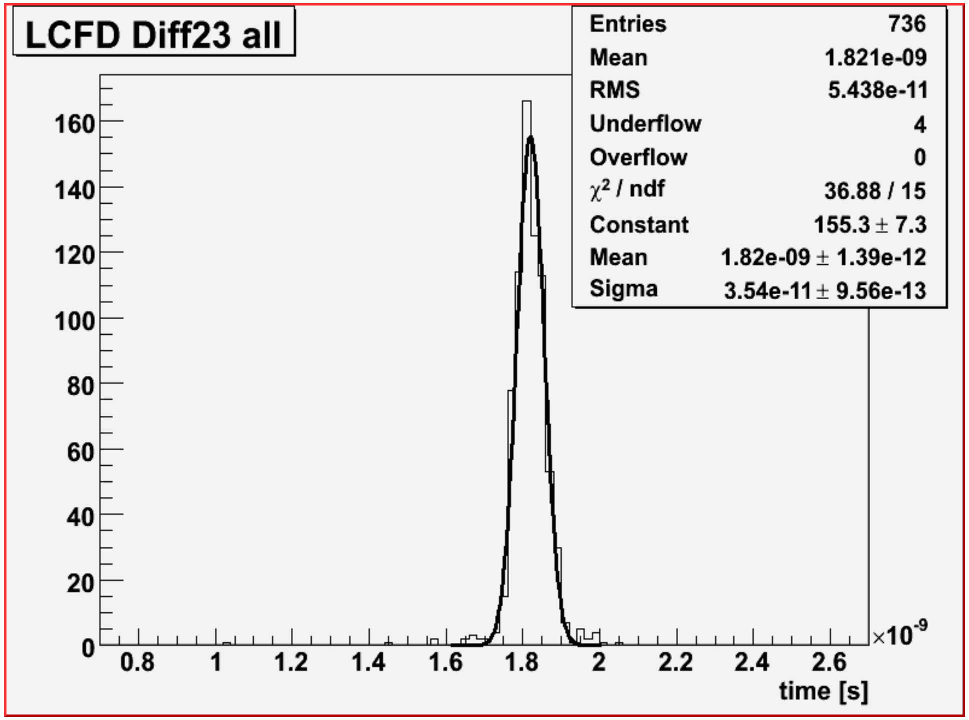


Using time differences of four channels and a simulated CFD algorithm we obtained a single channel QUARTIC bar resolution of 60 ps (detector+PMT only); using TDC's we obtained 80 ps

Scope Analysis: TOF Resolution

time difference using LCFD

23 GASTOFs	35±1ps
14 QUARTICs	63±2ps
12	74±3ps
13	69±3ps
24	64±3ps
43	50±3ps



Over-constrained setup allows extraction of individual resolutions:
G1 = 32 ps G2=13 ps Q1=59 ps Q4=40 ps (detector +PMT)

Taking into account multiple measurements (many bars) implies a current overall resolution of 15 to 20 ps with a corresponding rejection factor of 25 to 30

Extrapolating Phase II QUARTIC Results

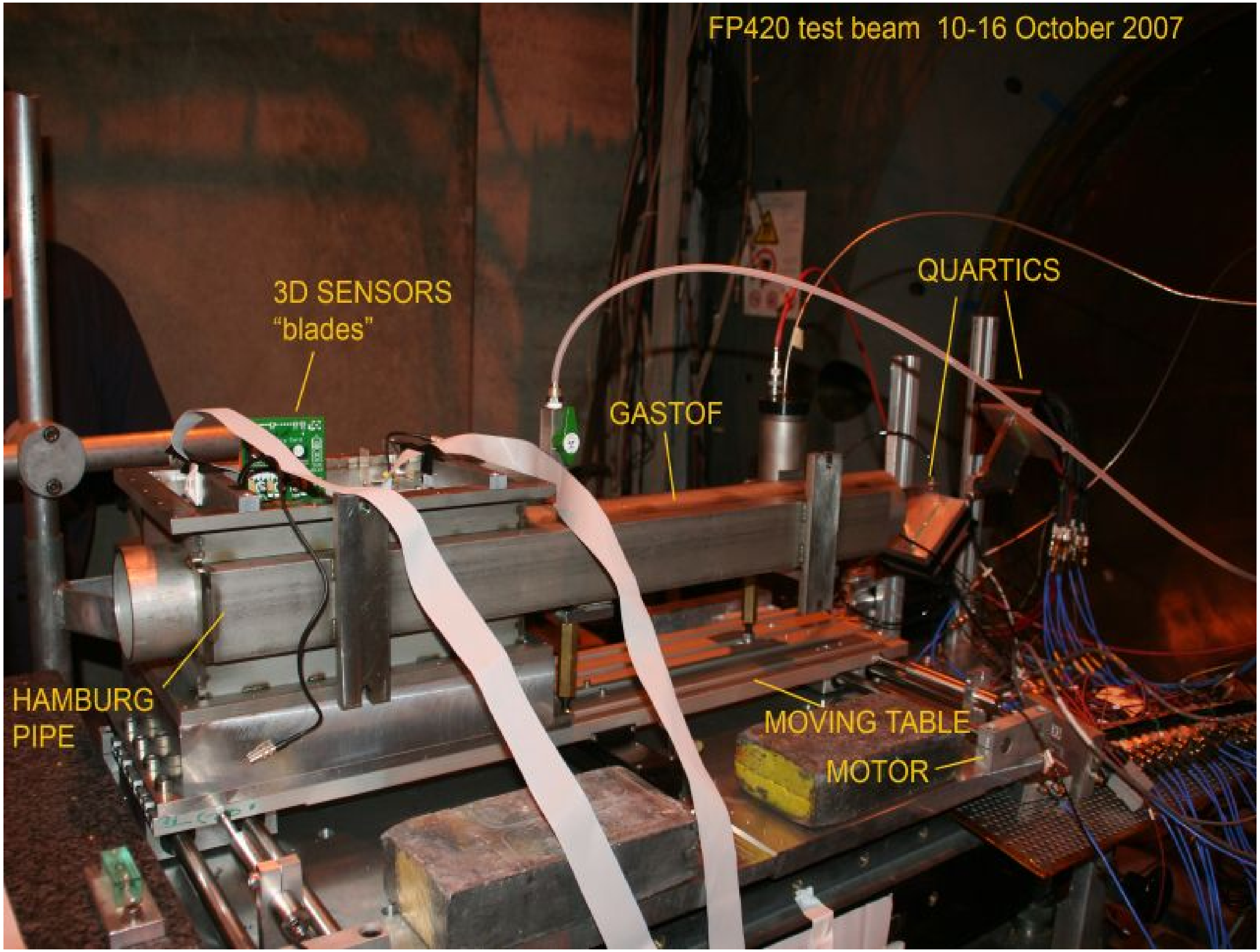
Current QUARTIC/PMT resolution ~60ps
Louvain CFD ~40 ps, software optimization
implies might reduce this to 20 ps,
combined with TDC resolution of 20 ps gives

66 ps/bar (Measured 82 ps in Phase II)

80% efficiency implies 13 measurements instead of 16
with two QUARTICs gives

20-25 ps QUARTICs only resolution gives
rejection factor of about 25 for pileup background

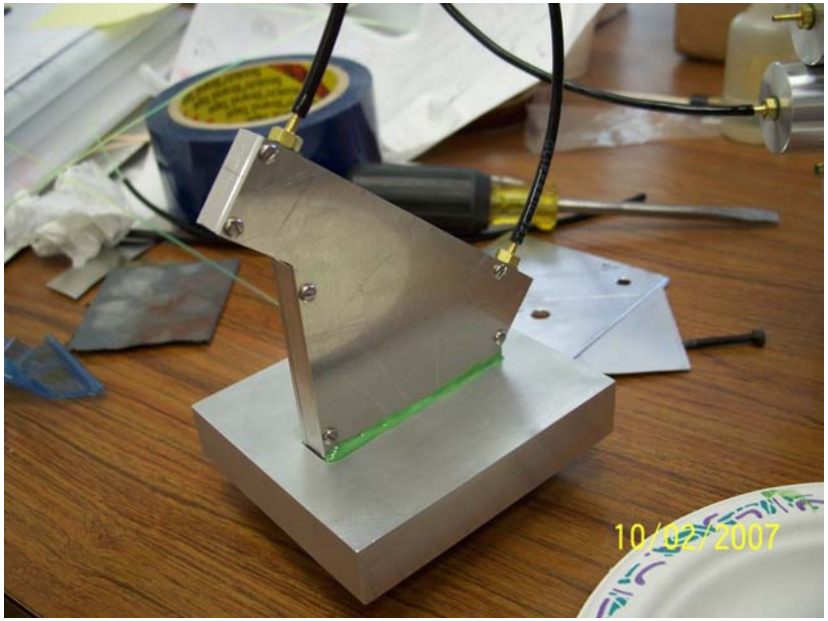
CERN Test Beam 10/08



October 2007 CERN Test beam

Added new QUARTIC detector, comprehensive scope data


10/02/2007


10/02/2007

Analysis in progress, integration with silicon telescope not wildly successful, but got tons of scope data, using new found knowledge from scope purchase demos to dramatically increase data taking rate

June 12 Test Beam:
Primary goal timing development

- Two New GASTOFS
- Two New QUARTICS
- Bonn Telescope with Turbodaq
- HPTDC in Turbodaq

AFP Status+ Plans

- R&D fully funded and quite advanced
- TDR to collaboration within next couple months (integrated 220/420 proposal)
- Test beam June, September 2008
- ATLAS Approval needed by fall 2008 for cryostat installation in 2009
- Hope to start with 220 on one side 420 on other some time in 2010

Hard Diffraction has come a long way from UA8 days (from the SPS to LHC via HERA and Fermilab)