High Precision Spectrometers (HPS) to add to CMS

for very forward protons

Forward Physics at LHC February 2013

Michael Albrow, Fermilab
(on behalf of many HPS collaborators)

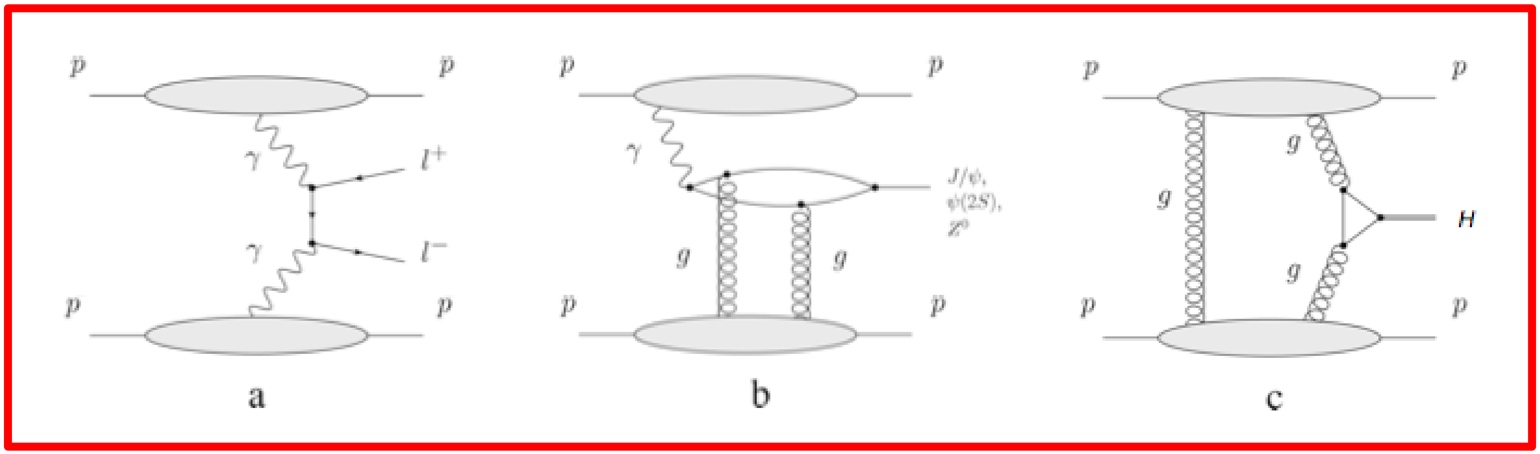
Prehistory
History
Overview
Physics at Stage 1 (and a little Stage 2)
Optics and acceptance
Tracking
Fast Timing detectors and reference time
Summary of situation

Exclusive Central Production: p + p → p + X + p

Some p + X studies also

Special high mass exclusive channels for LHC:

- Double "pomeron" interactions: IP + IP (or g+g [g]) → X, e.g X = **Higgs, JJ**
- Photoproduction: γ + IP (gg) → X, e.g. X = **Z**
- QED & Electroweak γ + γ → X, e.g. X = $\mathbf{W^+W^-}$



At Tevatron in CDF we have observed: X = e+e-, μ+μ-, J/ψ, ψ(2S), χ_{c0}, γγ, JJ

e+e-, μ+μ-: γ + γ

J/ψ, ψ(2S): γ + IP

χ_{c0}, γγ, JJ: IP + IP

At LHC more results come (this workshop)

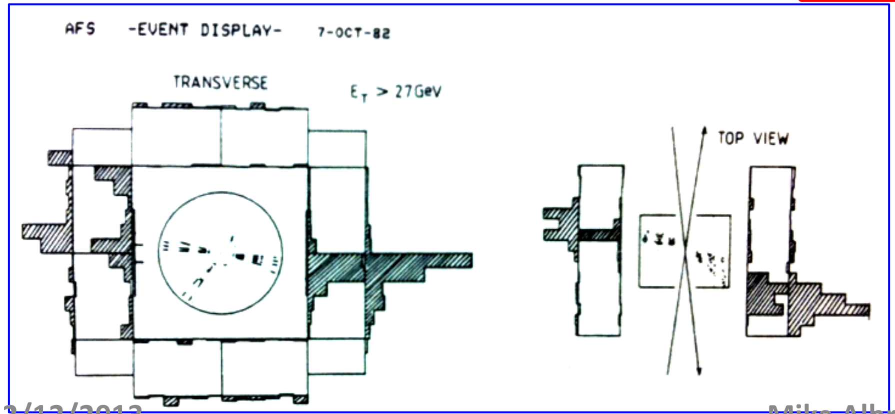
& $f_0(980)$, $f_2(1270)$, $f_0(1370)$, X?

Personal reminiscence: ISR R806 → R807: Axial Field Spectrometer

p + p at √s = 63 GeV

Homage to Bill Willis
1932-2012

1st liquid argon calorimeter   +Radeka + Palmer
1st transition radiation e/π separation
1st Uranium hadron calorimeter
Full azimuth drift "jet" chamber



1982: Co-discovery with UA2 of high-E_T jets in hadron-hadron collisions
← **on-line** event display (hits) : ~ exclusive dijet??

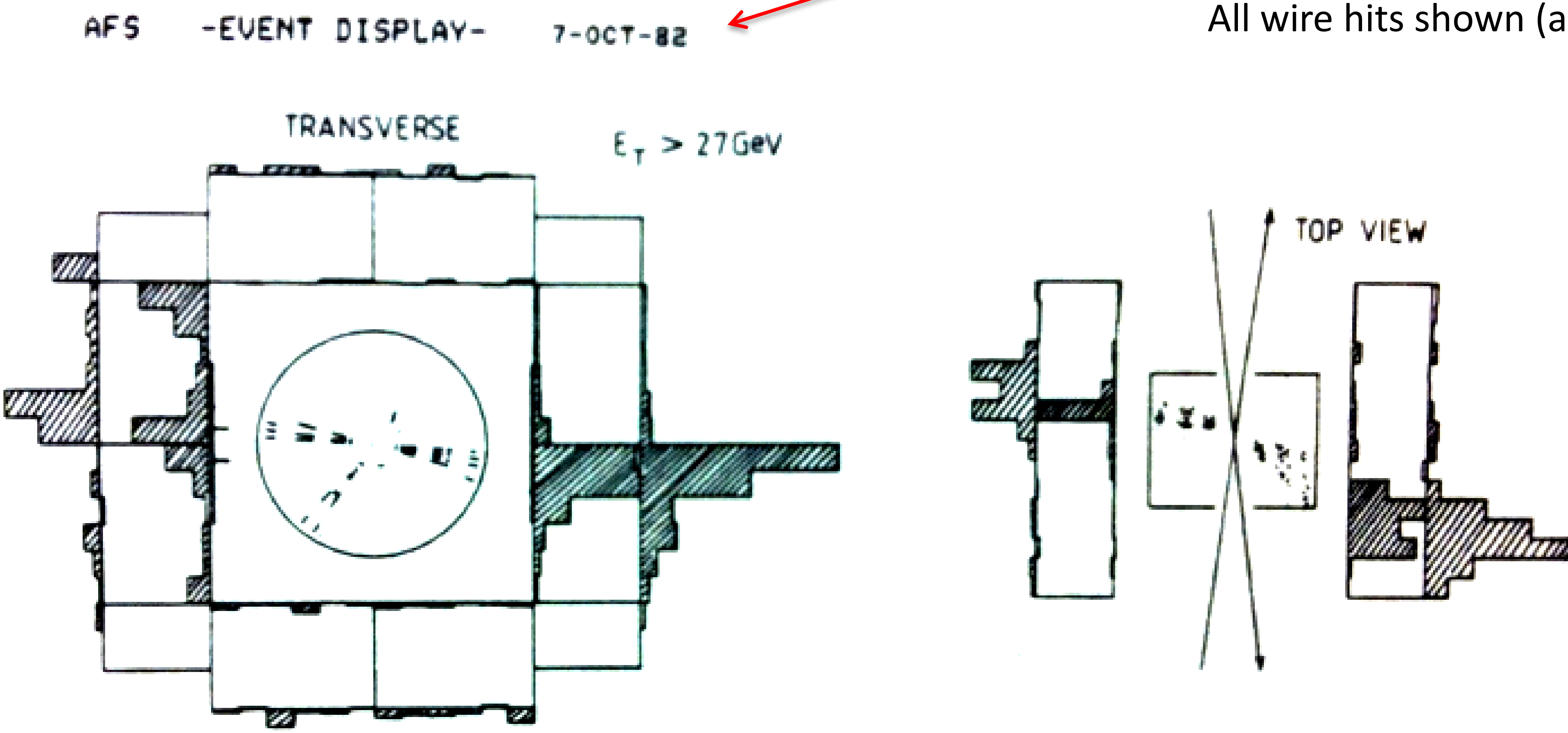
Deja vu:
AFS designed for high E_T, but we added forward proton trackers for p + X + p (double pomeron)

Axial Field Spectrometer

On-line event display selecting Σ ET > 25 GeV / 63 GeV √s (pp) ISR

> 30 years ago!

All wire hits shown (all)



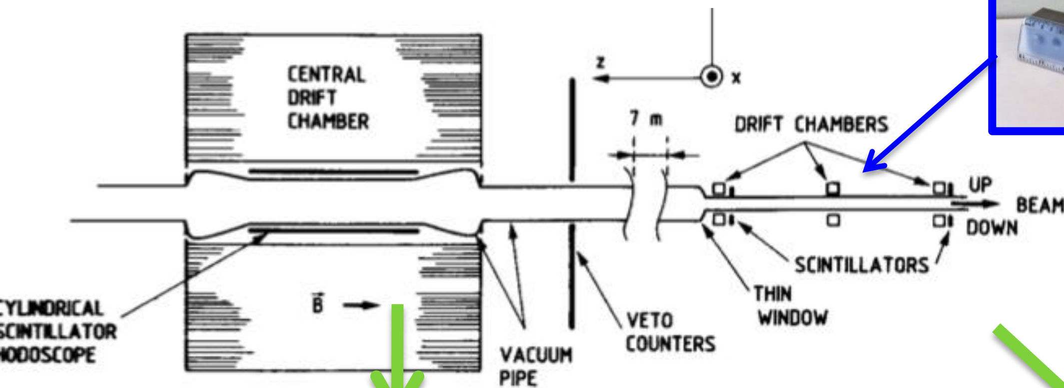
We had very forward proton tracking both sides at large |η| ...
Did not interrogate for these events! Low-β quadrupoles for ξ(p) (1st in collider) but off.

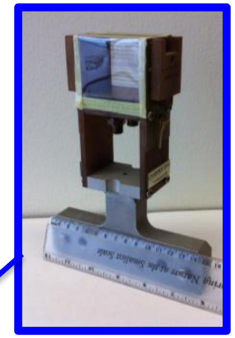
Nuclear Physics B264 (1986) 154–184
© North-Holland Publishing Company

Added forward p-tracking to Axial Field Spectrometer for DPE:
p + X + p. "Central Exclusive Production"
Maybe X = G = glueball?

A SEARCH FOR GLUEBALLS AND A STUDY OF DOUBLE POMERON EXCHANGE AT THE CERN INTERSECTING STORAGE RINGS

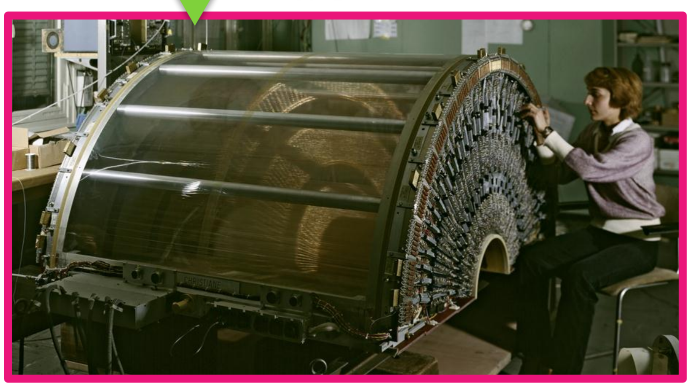
(The Axial Field Spectrometer Collaboration)

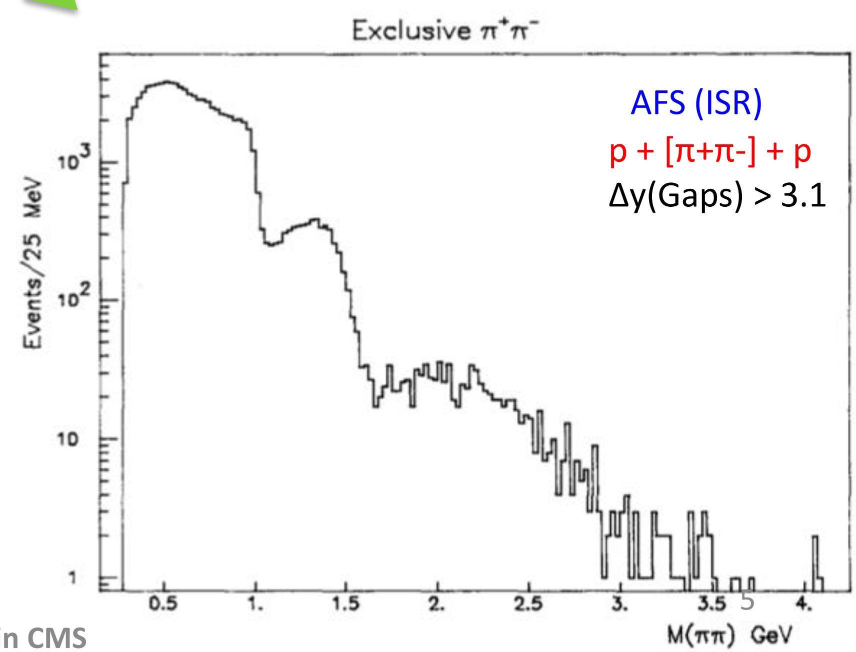




12 such drift chambers,
4 wires with Q-div (2mm)

90,000 p-G-$\pi^+\pi^-$-G-p events with gaps G with $\Delta y > 3.1$.
f0(980, 1370) f2(1270) & ...???
(Now have at CDF 900 & 1960 GeV)





Looked for vacuum excitation of scalar glueballs, **G**
That search continues at Tevatron (CDF) and LHC.
Next:
Look for vacuum excitation of scalar Higgs, **H**
Both are scalars $J^{PC} = 0^{++}$

AFP/HPS for p + H + p : Long History

March 2001: MGA et al., LoI to Fermilab PAC :
"A search for the Higgs boson using very forward tracking detectors with CDF"
Later posted: hep-ex/0511057 Silicon tracking, Roman pots, z = +/- 55m
Novel: Missing mass M(pp) [MGA+ Andrei Rostvtsev, hep-ph/0009336]
Timing for z(pp) & pile-up rejection, Quartz Cherenkov hodoscope. p + γγ + p
Durham Theorists Khoze et al: Signal small but backgrounds v small too (JJ = gg)
Huge uncertainty in σ(H ~ 120 GeV) from 0.06 fb (KMR Durham) to ~ 100 fb !
CDF program to measure exclusive γγ, χc, Jet+Jet to test theory. (Durham wins)
Dec 2003 (- 2010): First of 8 "Manchester Christmas Meetings"

MANCHESTER 1824 | IP3 University of Durham

Forward Physics At The LHC

Organizing committee

Brian Cox (Manchester)
Jeff Forshaw (Manchester)
Valery Khoze (Durham)
Robin Marshall (Manchester)
James Stirling (Durham)
Cinzia Da Via (Brunell)
Alber De Roeck (CERN)

→ FP420 : Forward protons at 420 m
Higgs on the menu

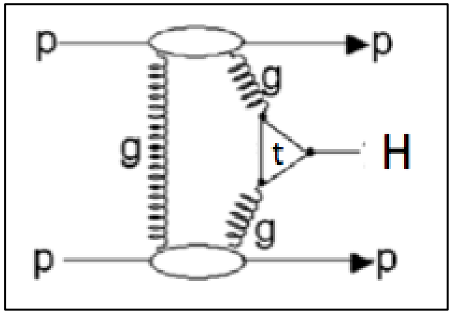
May 2004, Fermilab workshop on Future QCD at Tevatron... GTeV (died with BTeV)

~ 2008/9 ATLAS concentrates on AFP and CMS on HPS (continue sharing R&D)

ATLAS and CMS have now found a "Higgs-like particle" at 125 GeV

Is it a Standard Model Higgs, or BSM Higgs or something else?
Now LHC has a > 10 year program to measure all its properties:
Branching fractions and couplings, production mechanisms, spin, CP, width etc.

OBVIOUSLY : We should measure it every way we can.
We propose a different, complementary way:



CENTRAL EXCLUSIVE PRODUCTION: p + p → p + H + p

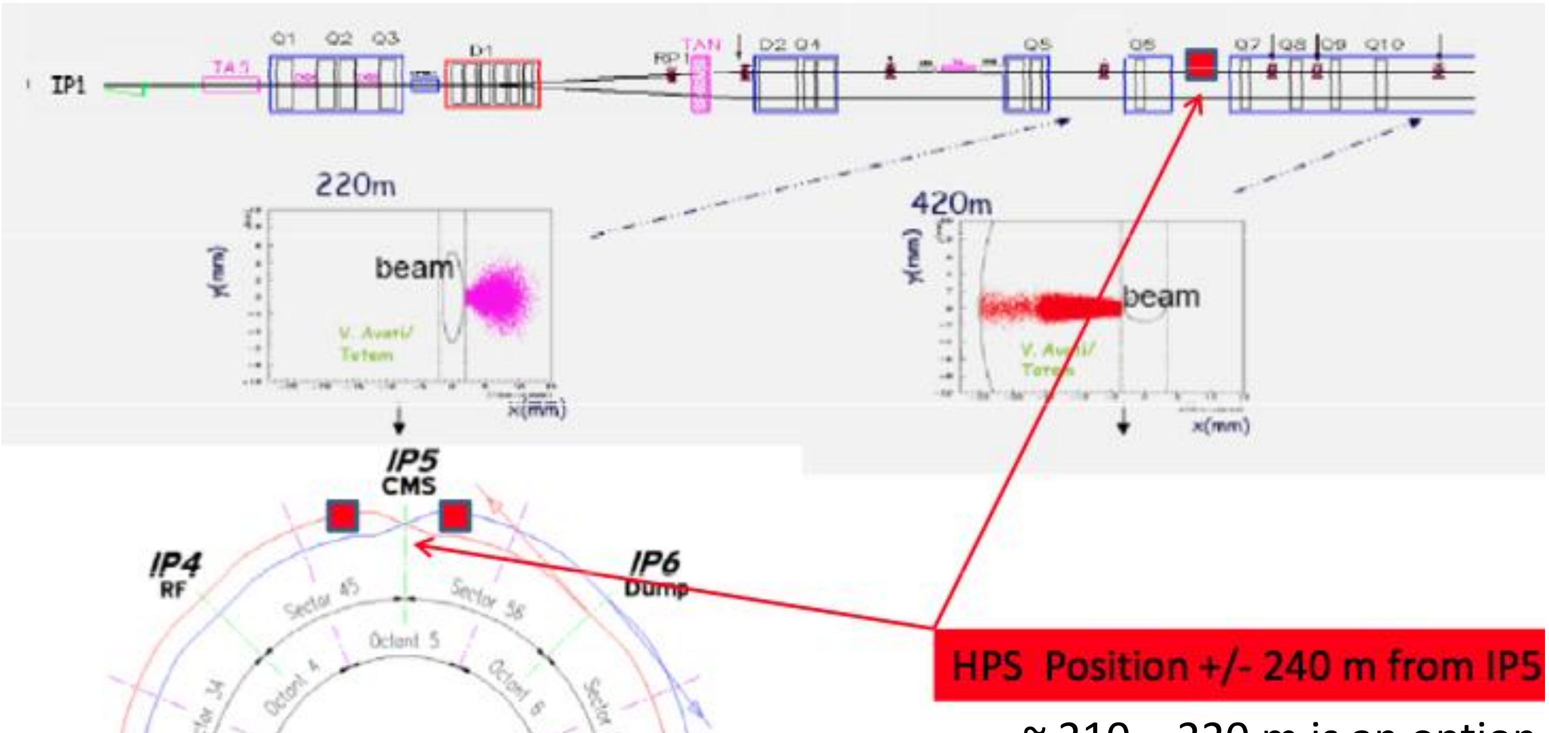
CP must be ++ Determination in ZZ* assumes CP conserved (Tx VK)
Suppose (Gunion inter alia) in NMSSM H(125) is heavier one
and h'(98 GeV) → b+bbar/τ+τ- Hard to see inclusively
Belanger et al. arXiv:1210.1976 (2013)
Higgs Bosons at 98 and 125 GeV at LEP and the LHC

Needs proton detectors at z = +/- 420 m (later)

Spin must be J = 0 or 2, and we can distinguish the
Coupling to gluons via q-loop
(May want exclusive γγ to calibrate σ)
Mass (σ(M) ~ 2 GeV per event, Missing Mass to protons, and can calibrate that)

HPS: High Precision Spectrometer @ CMS

Detectors to measure leading protons, tracks for momenta
and timing for pile-up rejection. (ATLAS has equivalent ATLAS Fwd Protons)
Designed for L = 10^{34} with ~ 30 ints/X. Read out for every CMS recorded event

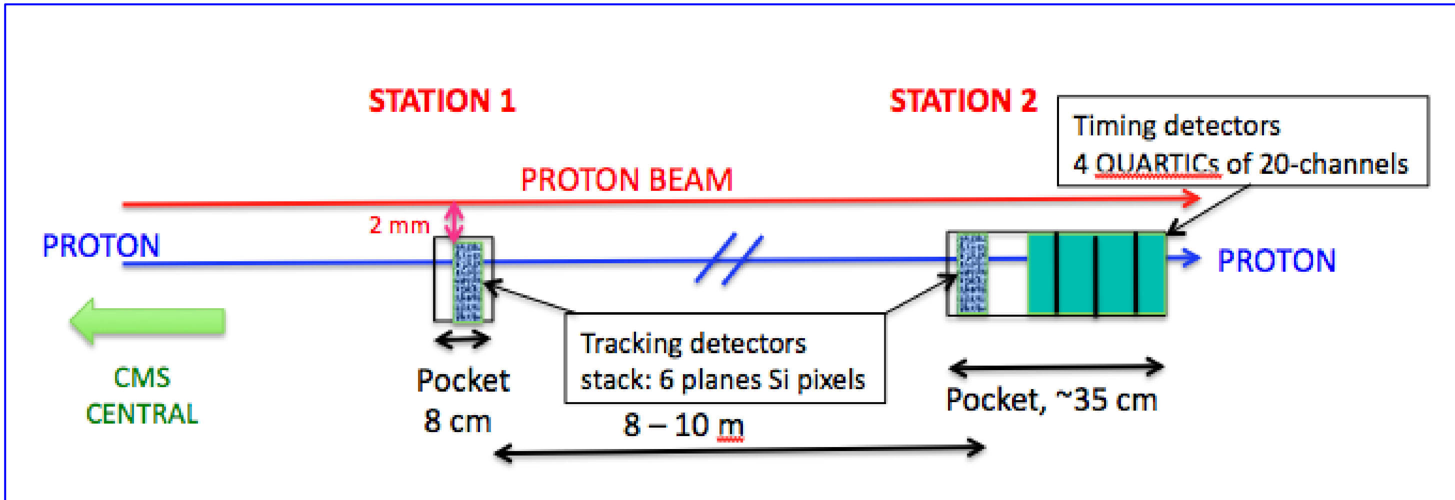


~ 210 – 220 m is an option
(interleaved/with TOTEM)

HPS will have two pairs of stations:
1) At z = +/- 240m,
to install in LS1 or 2015, data in 2015/6
2) At z = +/- 420m (2016-18?) → needed to see H(125)

We are working on phase I, the
detectors at +/- 240 m.
L1 trigger just in reach.

At 240 m (& 220 m) the beam pipe is exposed, so it's relatively easy to install the detectors:



HPS detector schematic arrangement, not to scale

At 420 m missing magnet,
pipe straight but cold.
It requires a cryogenic by-pass

Looking downstream (CMS behind you)

Physics for Stage 1:

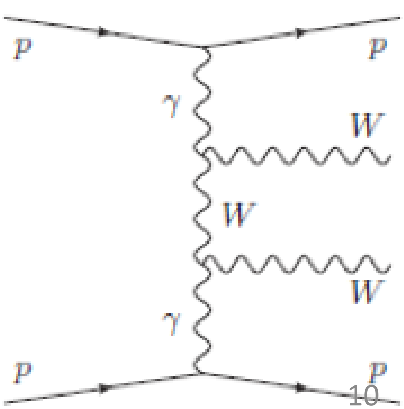
Both protons measured, M(min) ~ 200 GeV:

Exclusive dijets, M(JJ) to ~ 750-1000 GeV. Pure g-jets
< 1% b-bbar dijets (need double b-tag). Test of $J_z = 0$ rule. (Khoze, Martin, Ryskin)
(q-qbar dijets forbidden for massless quarks at t = 0.)

Test of pQCD mechanisms of exclusive production, "superhard" pomeron.
Unintegrated $g_1 g_2(x_1,x_2,Q^2)$, Sudakov form factor, gap survival probability, etc.
Measure exclusive bJ-bJ spectrum (important for later).

Measure γγ → W+W-. Anomalies in WW final state interactions (but transverse, so H would not appear in γγ). Triple, quartic gauge boson couplings: more sensitive than standard techniques (C.Royon et al.)

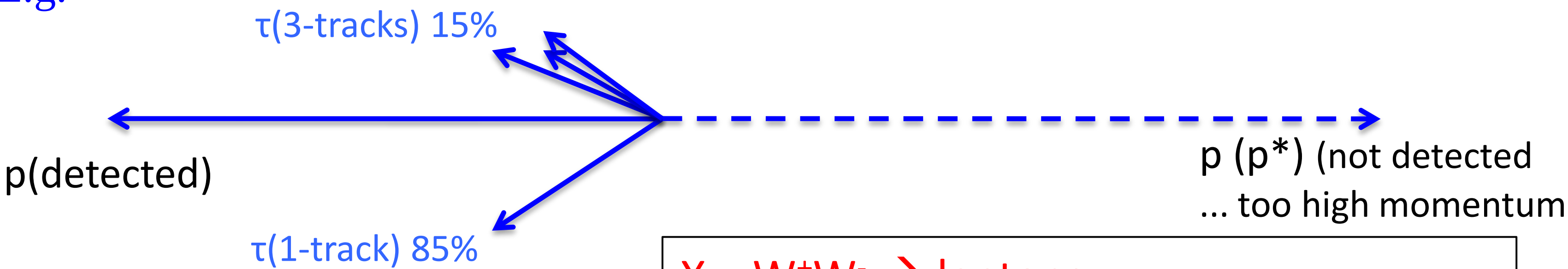
BSMH not fully excluded in M ~ 200 – 600 GeV.
May be visible in τ+τ- channel e.g.
Other exotic heavy states with "vacuum" Q.Nos & J = 0,2 coupling (even indirectly like H) to gg.



One proton measured, still some physics at high PU?:

High mass diffraction well explored in ~ 1 week of μ = <n/x> ~ 1 running ~100/pb.

M(min) ~ 100 GeV.
No M(X) from p's, no PH rejection by timing, but very clean central states may be accessible.
E.g.



X = W^+W^- → leptons
X = e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$ from $\gamma\gamma$ (or H !?)
X = Z photoproduction → e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$

No additional tracks on X vertex (already very selective)
In e^+e^- , $\mu^+\mu^-$, **$\tau^+\tau^-$ cases $\Delta\phi = \pi$ and p_T(X) ~ 0.**
Can we see p + [H125 → $\tau^+\tau^-$] + p(*)(undetected) in Stage 1 ??
(Study with Harland-Lang, Khoze, Ryskin)
3-momentum of X (~ p_z) determines both proton momenta
e^+e^- , $\mu^+\mu^-$ already calibrates HPS spectrometers (don't need both p's)

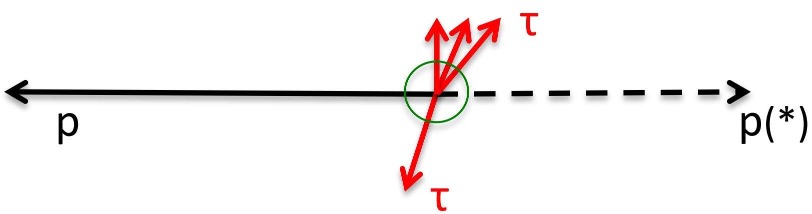
Can we see H(125) in Stage 1 with one proton?

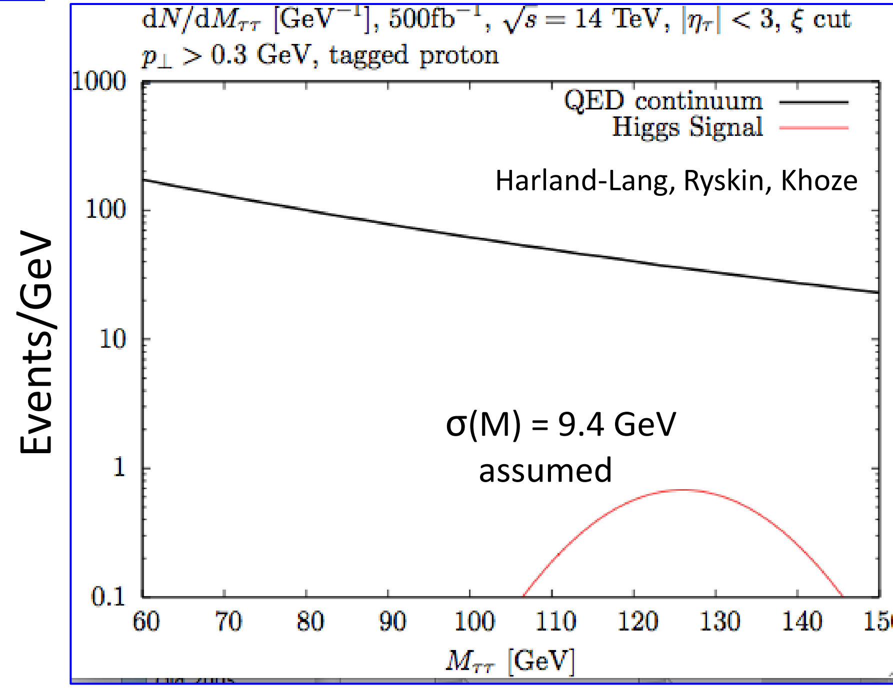
Exclusive p + τ+τ- + p (clean) :

Only 3 sources:

1) QED: γγ → τ+τ-
2) Photoproduction: γ+IP → Z (BR = 3.7%)
3) Gluon fusion IP + IP → H (BR = 6%)

1st two same in e+e-and μ+μ- (control)





Two neutrinos missing, but 4-momentum constraints & two M(τ) constraints.

a) If fully optimised, how good can M(τ+τ-) be?
   Factor x2 better σ(M) → factor x2 peak height and in S:B. (possible??)

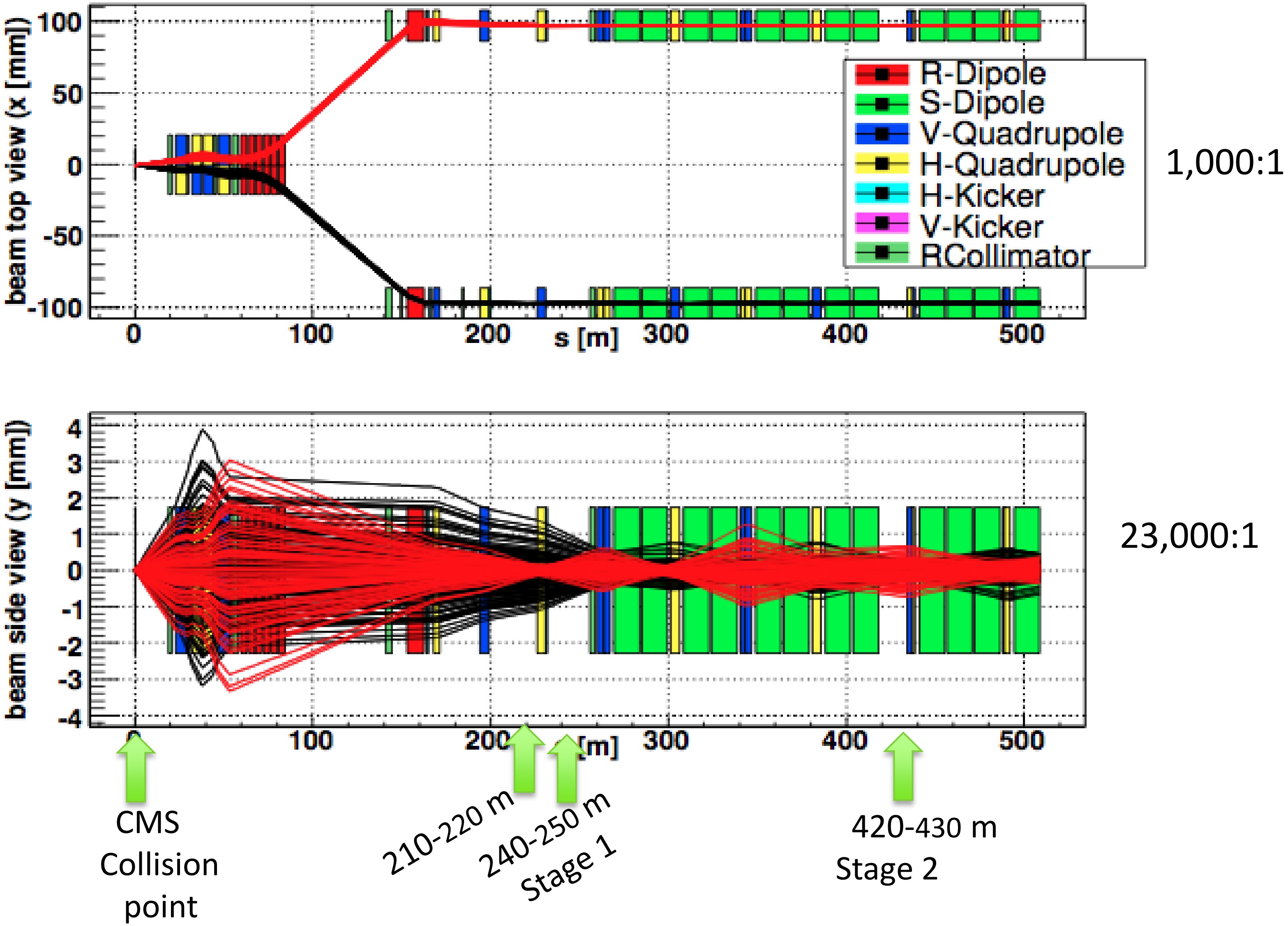
b) QED continuum, γγ → τ+τ- , p_T(p) < p_T(p) in H → τ+τ- (gluons, or IP)
   pT > 0.3 GeV cut (as in plot) reduces QED by factor ~ 5, only 10% reduction in H.

c) Unseen low mass p-dissociation on other side increases σ, factor ~ 2(?) without spoiling kinematics. σ(H) also uncertain by a factor ~ 2-3 each way.

Still, SMH(125) → p + τ+τ- + p(*) probably too small to see in Stage 1.

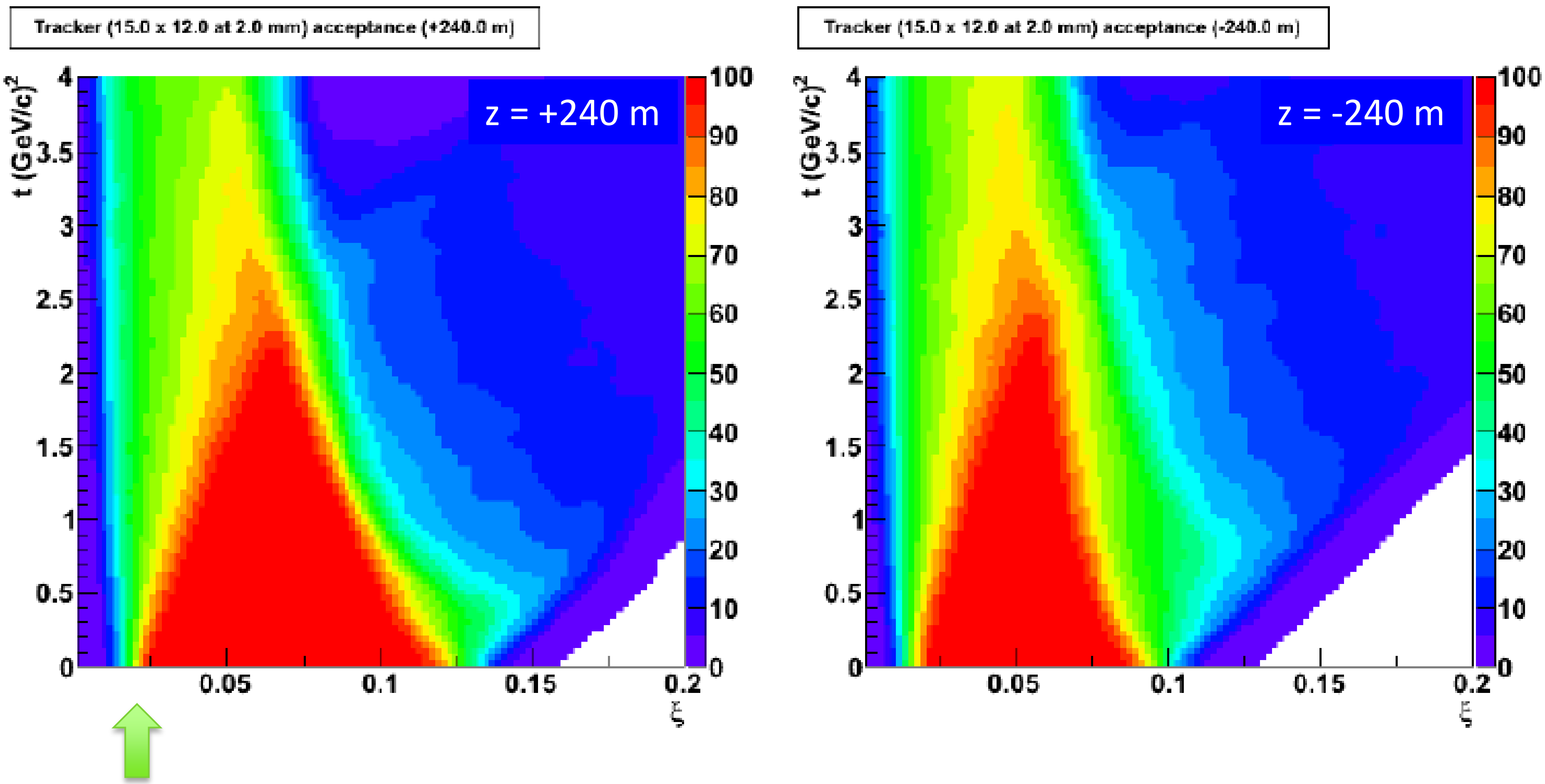
>> at Stage 2 with 420+240 have other p, better mass resolution, & timing for z(vtx) constraint. **:-)**

Several tracking programs have been used (HECTOR, FPTrack).
Full transport line simulation in CMSSW.



Machine optics LHCB1(2)IR5_v6.500.tfs for Beam 1(2)
Private particle gun (t,ξ,ϕ) based on HECTOR at √s = 14 TeV

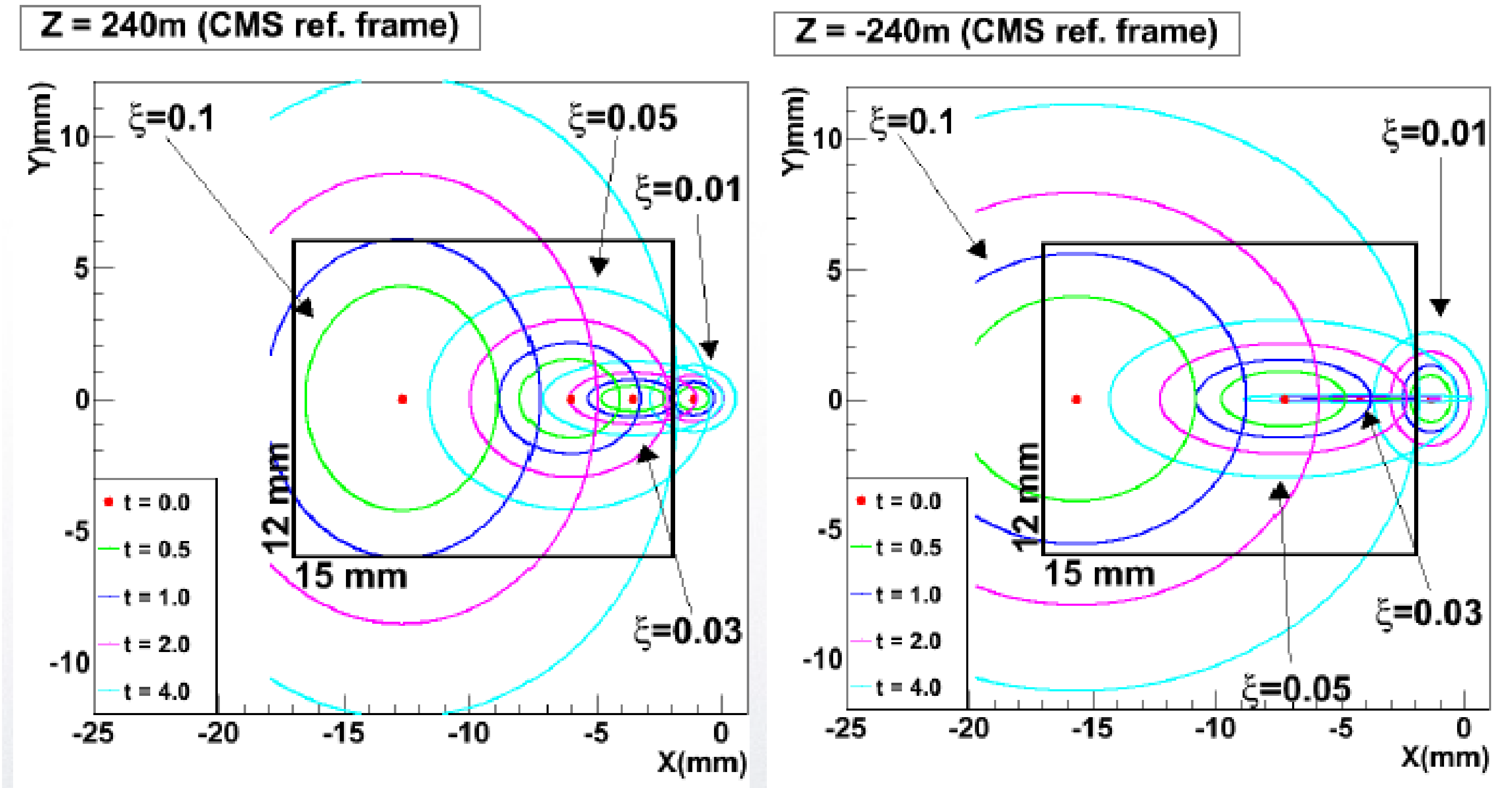
Single arm acceptance in t,ξ
15mm x 12mm detector (QUARTIC) at 2 mm from beam



ξ = 0.02, Δpz ~ 150 GeV

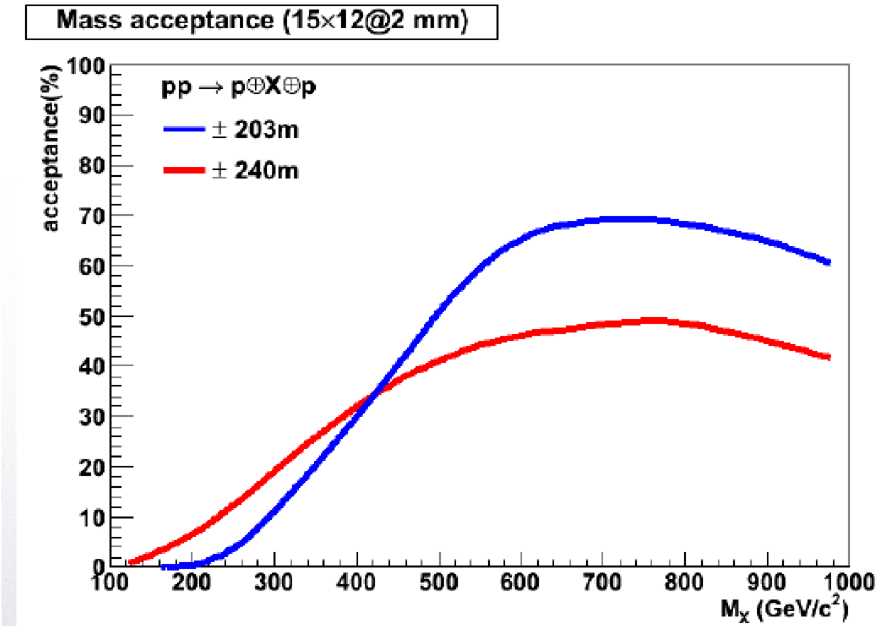
t, ξ contours in x,y plane at +/- 240m

For any |t| up to 4 GeV^2 and ξ 0.01 – 0.1 see fraction of azimuth ϕ accepted, hence A(t,ξ)
Can see effect if Δx = 2mm → 3mm e.g. 15mm in x not bad unless ξ > 0.1 is important.
Note: All small t (Photon exchange) near y = 0.

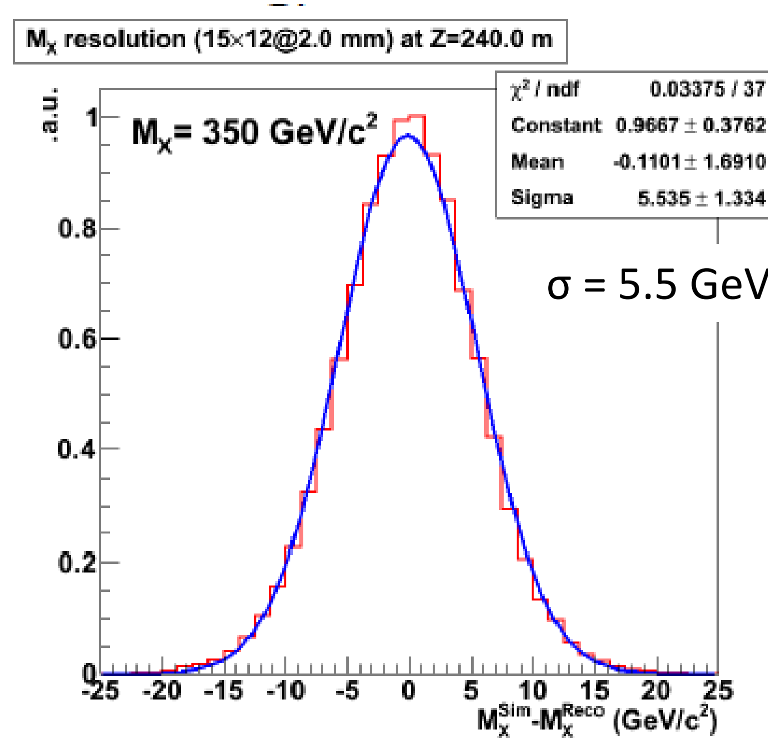


Maria Elena Pol & Luiz Mundim

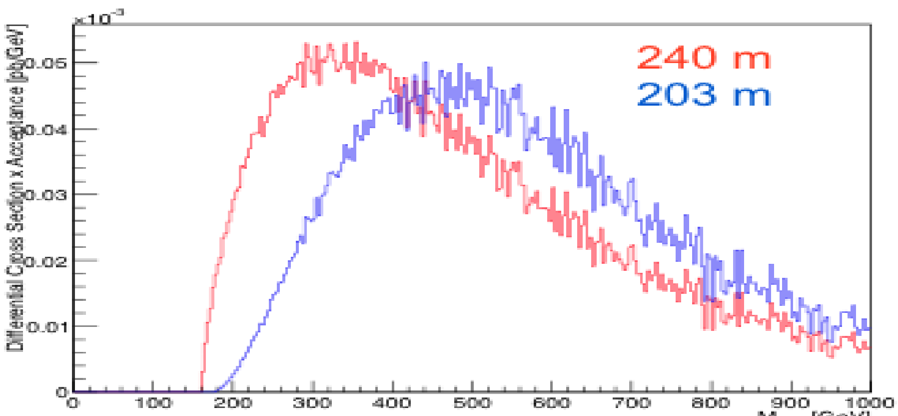
Mass acceptance differences before (203m) and after (240m) Q6
Assuming Δx = 2mm at both locations.



More W+W- events < 350 GeV, but similar total numbers
Closer to H(125) for bbar:gg ratio and J_z = 0 tests



Simulation of mass resolution with
240 + 240 m with full smearing.
Assumes 10 μm x-resolution and
1 μrad angular resolution

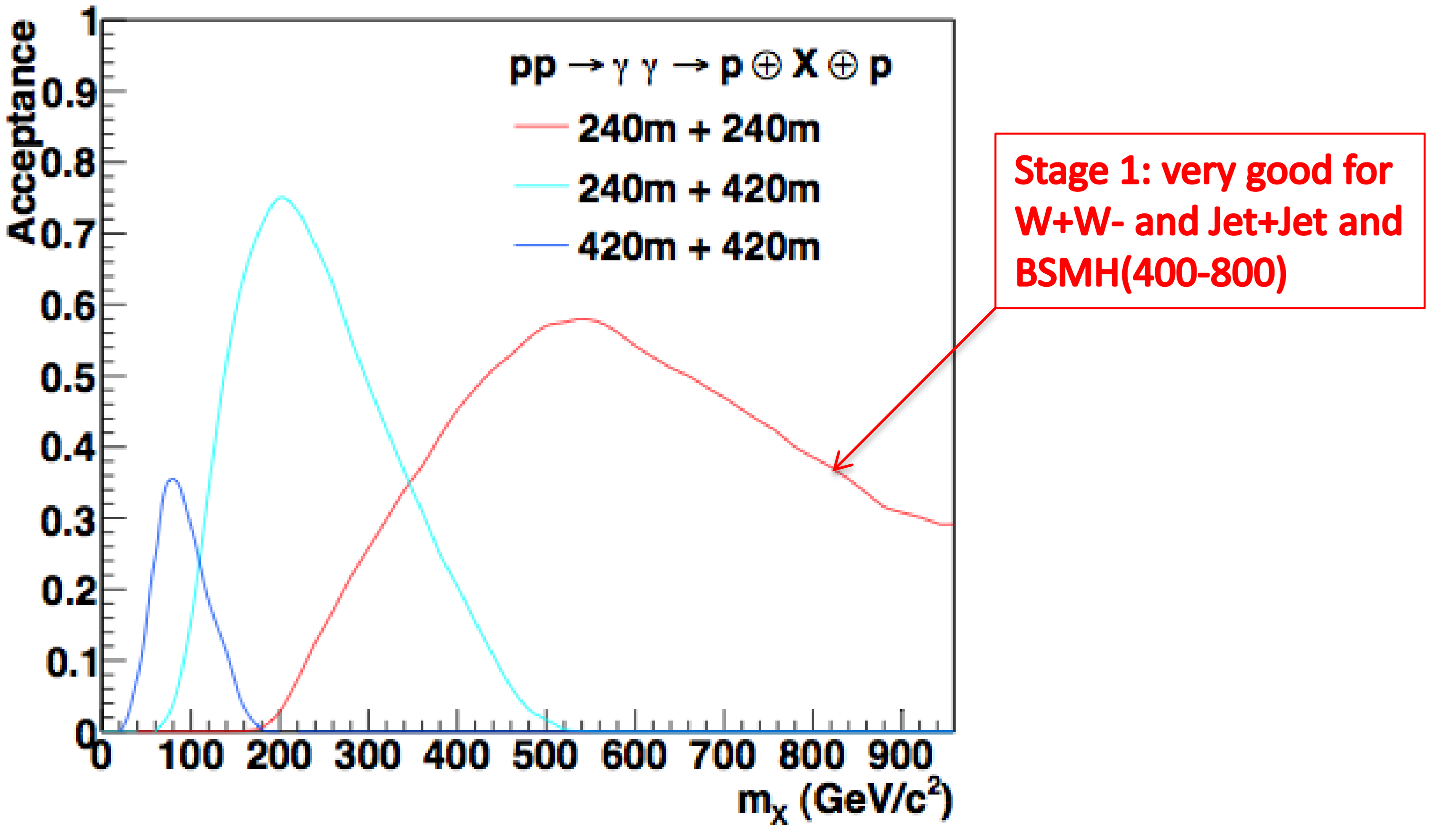


Finn Rebassoo

Maria Elena Pol & Luiz Mundim

Mass acceptance for two arms for small |t| at Stations 1 & 2

(Assumes Δx(min) from beam = 3 mm at 240m)



Each arm at 240m by itself has ~ superimposed light blue and red.

Stage 2 has ~ all 3 superimposed, and light blue x 2.

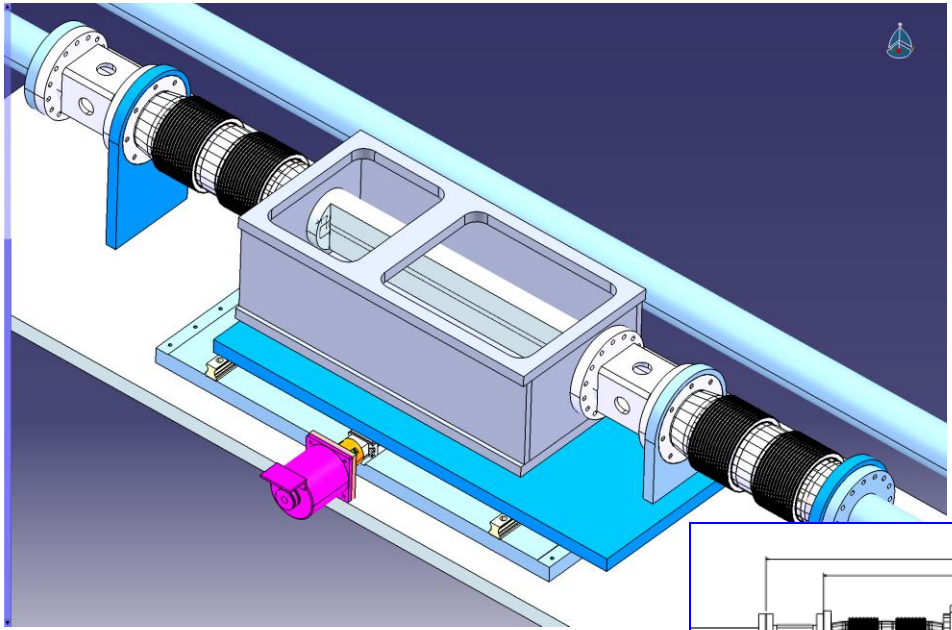
For IP + IP |t| is larger and acceptance shifts.

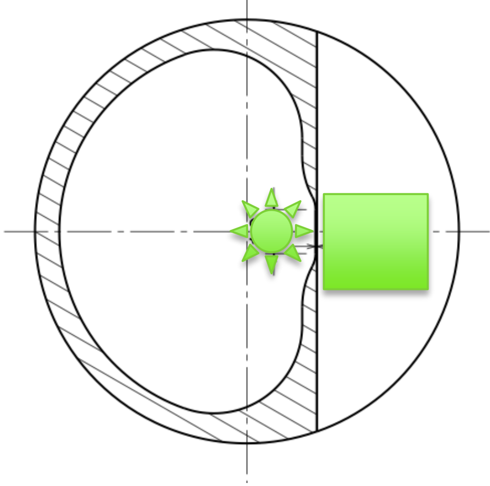
For H(125) best is [240 + 420] & [420 + 240]

For NMSSM h_1(98) 420+420 is better

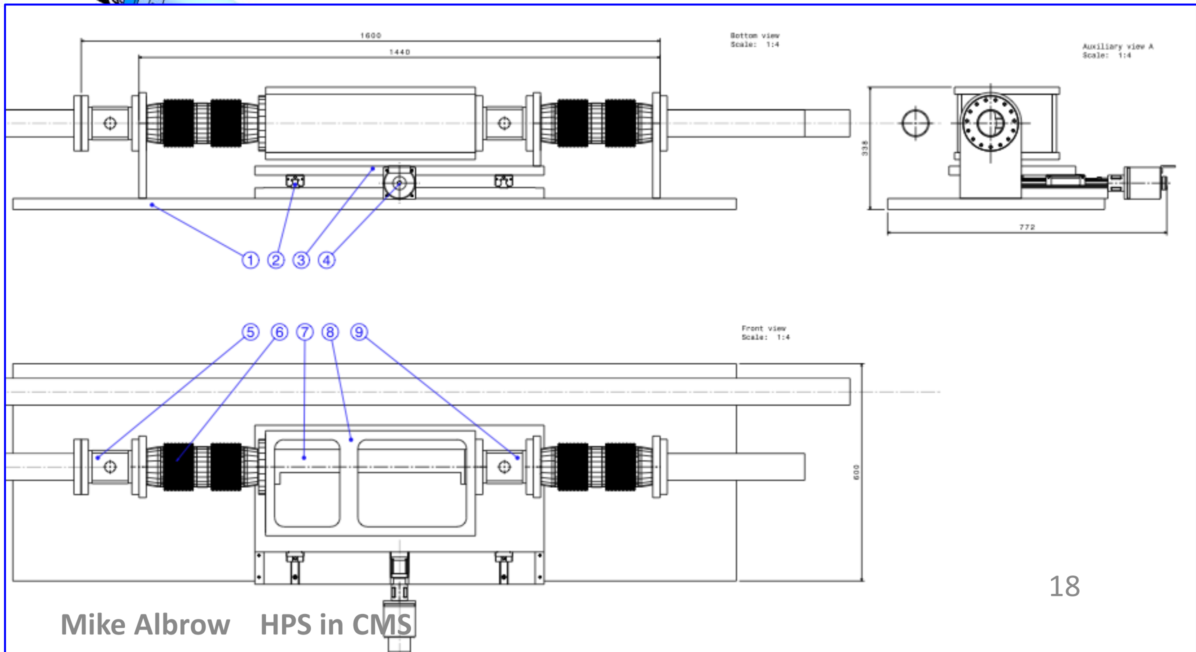
Moving pipe mechanics – "Hamburg" moving beam pipe

Long pockets 30 – 40 cm for long detectors (Tracking + timing + extra).
No atmosphere-vacuum forces, easily accessible.
Only developed solution for Stage 2 at 420 m.





Domenico Dattola (INFN)



HPS has 2 main components: tracking and timing:

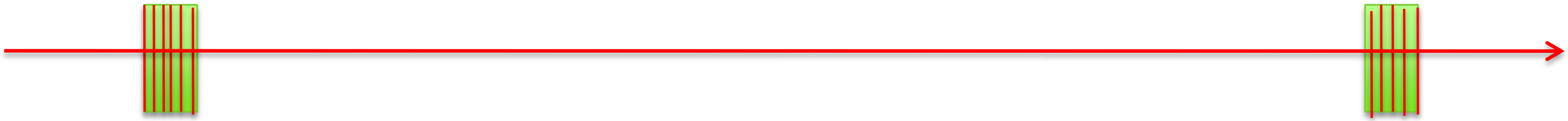
A tracking detector (silicon pixels – perhaps 3D) to measure
➔ Position and angle, combined with the beam magnets, allow to determine the momentum of the scattered proton and in turn the missing mass (from both p's)

Two pockets ~ 8 - 10 meters apart:
Momentum reconstruction: $\Delta p/p \sim 2\ 10^{-4}$ (at 420m: 120m of 8T dipoles)
➔ Position precision of 10 μm
➔ Angular resolution of 1-2 μrad

Need precision track detectors (~ 10 μm/stack), Rad Hard, edgeless (on one side) but small: ~ 2 cm^2 per layer, ~ 6 + 6 layers per arm.
Can be same but <~ 10^{-3} of CMS Central tracker upgrade
Good first use! + space for innovative tracking (diamond e.g.) or timing devices

Working with CMS tracking experts (especially pixel upgrades, Simon Kwan et al)
Cooperation with several manufactures and with ATLAS

TRACKING (no details here)



Front and back stations, each with a 6-plane stack ~ 32 x 16 mm2
PSI46 ROCs read 80 x 52 pixels each 100 x 150 μm^2

Use CMS Central tracker upgrade detectors (and some of the people!)

Silicon : 3D pixels .... tested among others CNM/D+T Microelectronica (Barcelona)
or slim-edge (0.2 – 0.3 mm) planar pixels .... e.g. VTT (Finland) and SINTEF (Norway)

Tests in Fermilab test beam of several CNM and FBK 3D sensors,
different electrode spacings and sensor thicknesses.

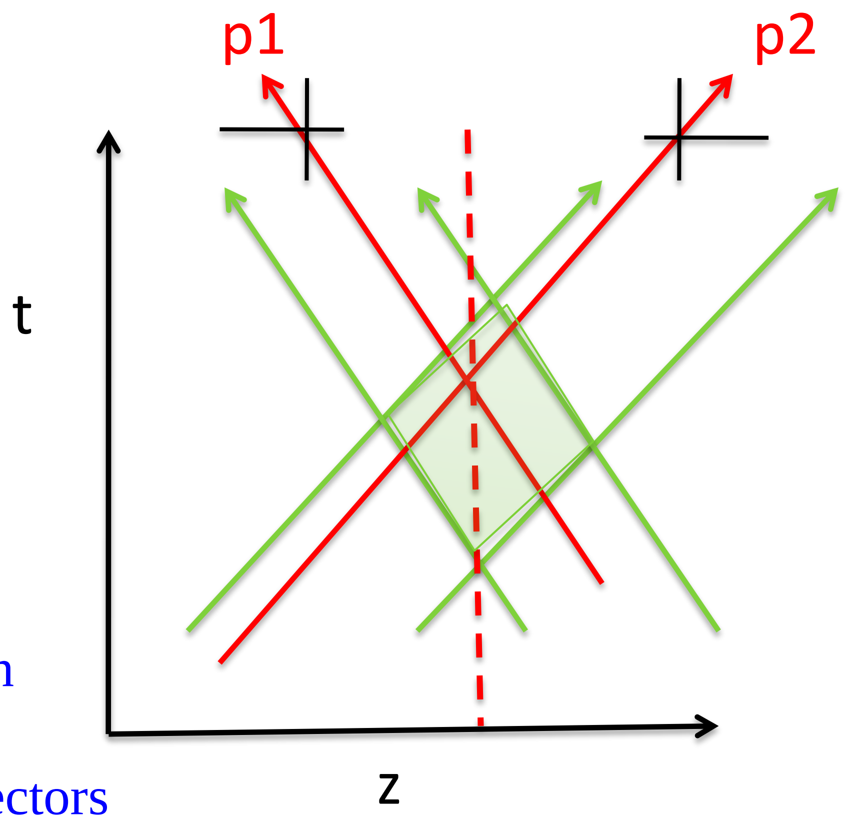
Irradiation at Los Alamos to 10^{15} neq/cm^2 under evaluation

Further tests in Summer at Fermilab (possibly combined with QUARTIC module)

Timing detectors, to measure the vertex position to reject Pile-Up.

Timing measurement (Cherenkovs) from both sides of CMS allows to determine the vertex of the protons and reject pile-up (proton from different pile-up collisions)

Time resolution ~10 ps
Vertex z-by-timing: ~ 2 mm
Segmentation for > 1 proton/bunch
Edgeless, active to ~ 200 um from pipe
Radiation hard
Lifetime > ~ 1 year at LHC at L = 10^{34}
Rate: 25 ns sensitivity

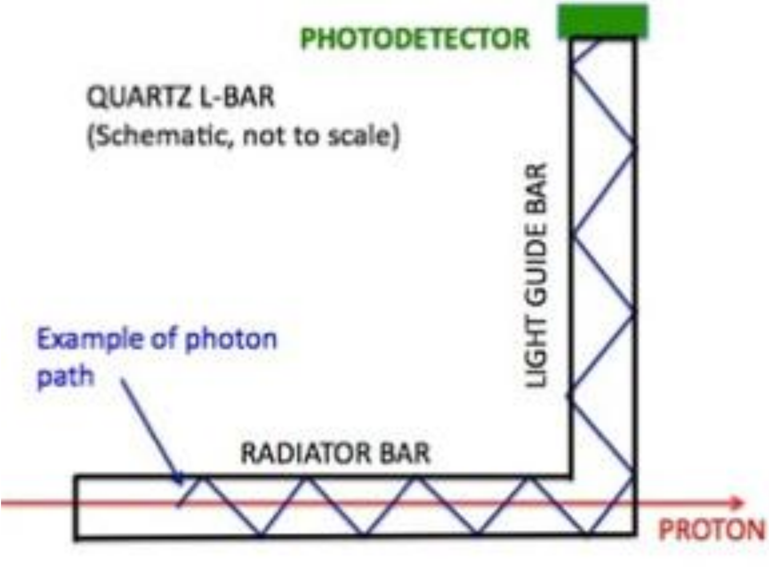


Note: time difference only used,
calibrated with common DPE events.

Time sum would provide additional rejection
iff central event time well known ...
needs added timing capability to central detectors
(Forward region also (HF) : as veto by timing)

SiPM (MCP-PMT option)

L-BAR QUARTIC: LBQ

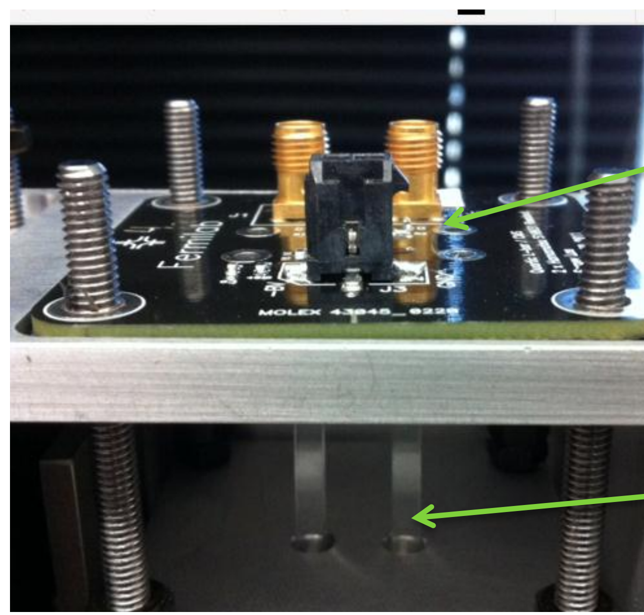


Design of test module (made 2)

Principle: All Cherenkov light is totally internally reflected to back of radiator bar. ~ 2/3 goes up light guide bar promptly, rest folllows.

Total Internal Reflection:
Bars separated by fine wire (100 um)

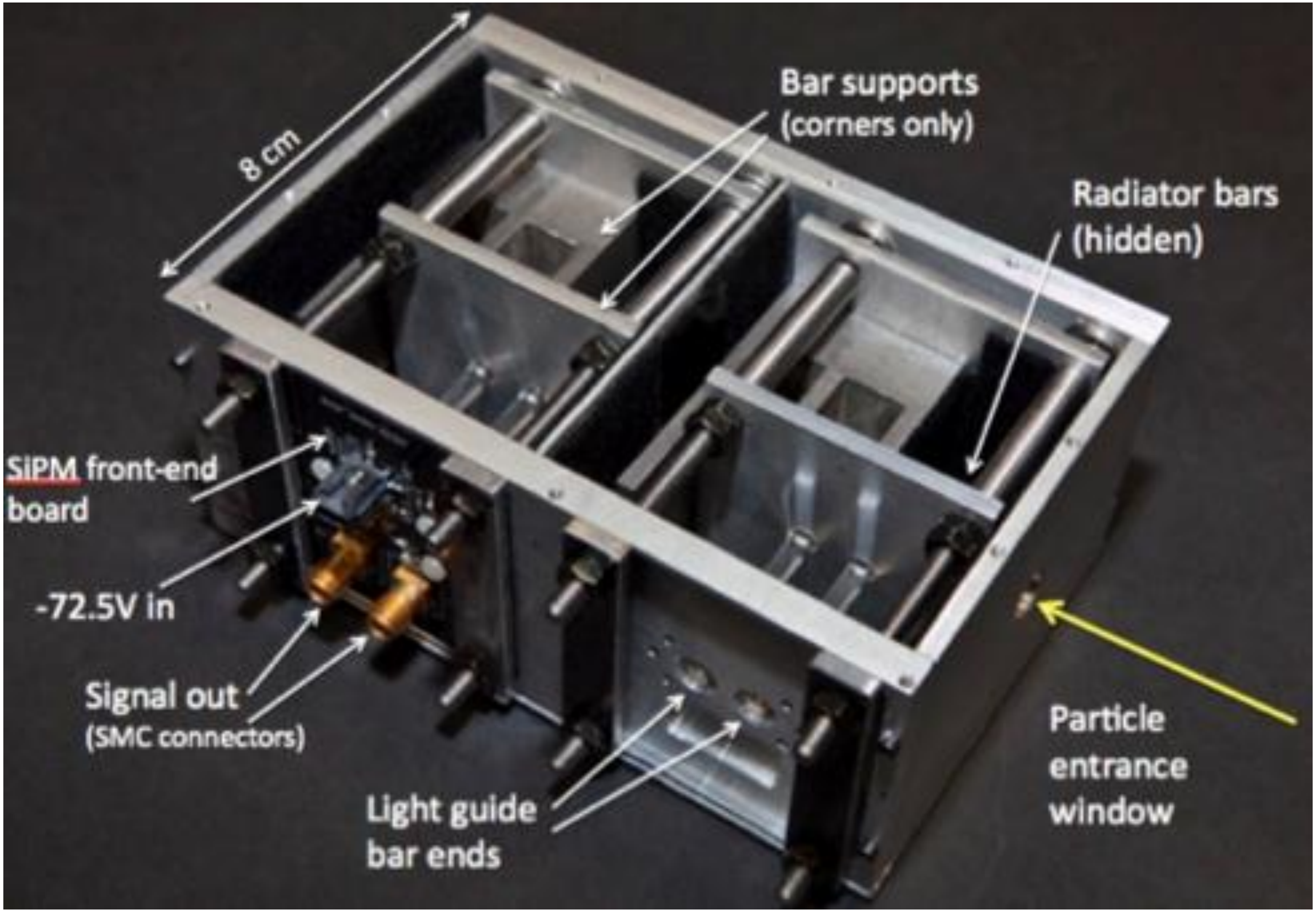
Will inject light pulses at front of each bar for monitoring



SiPMs

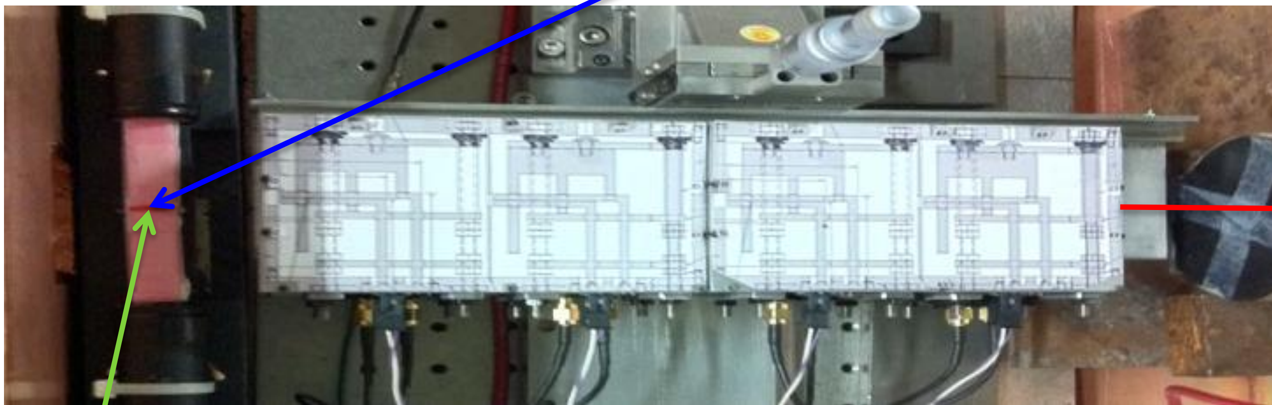
Q-bars

Test beam L-bar QUARTIC box (1 of 2)



Steve Hentschel (Fermilab)

Four units in test beam, 2mm x 2mm trigger counter + 40mm MCPPMT reference



proton

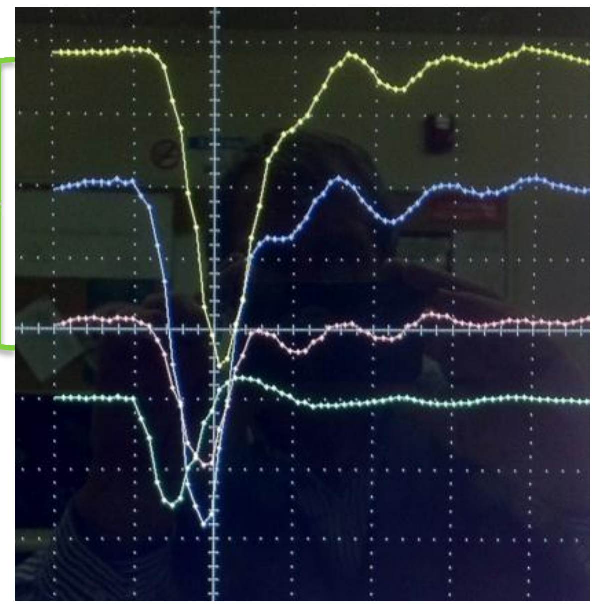
trigger counter

(Drawings glued on boxes for alignment only)
Two boxes can be slid apart in z

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

One event:
3 bars in line

MCPPMT ref

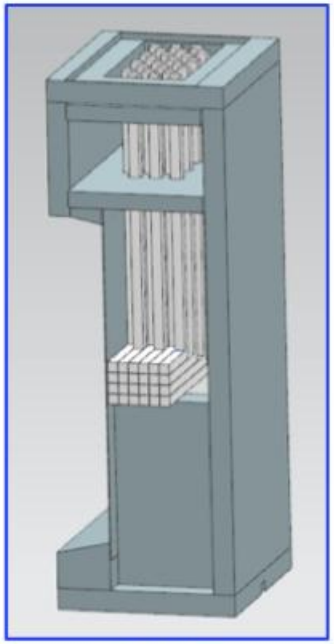


$\sigma(t)$ = 30 ps/bar = 15 ps/4bars

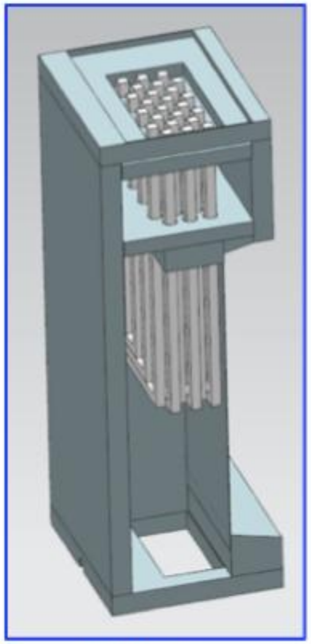
Technical issues solved, but radiation levels in SiPM "cave" still under evaluation

Several improvements possible → 10 ps
Option: Improved MCP-PMT replacing SiPMs

L-BAR QUARTICs



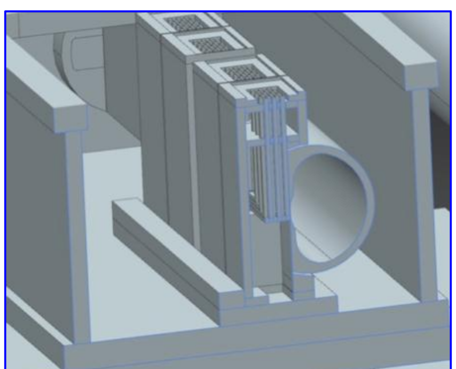
Front View

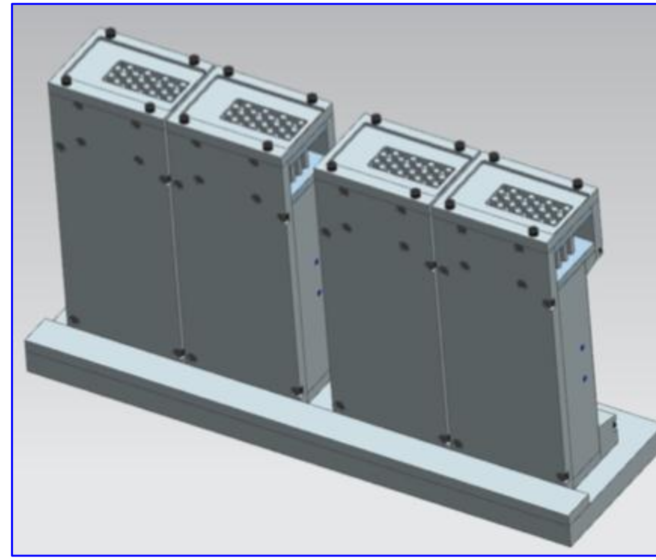


Back View

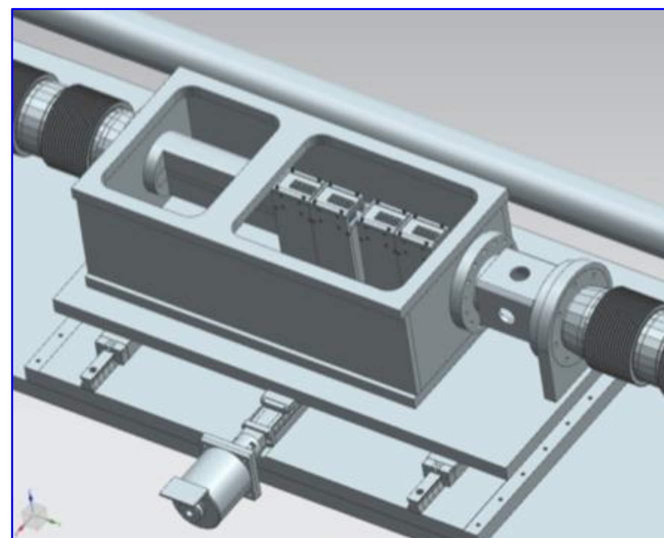
One L-bar QUARTIC module

15mm x 12mm, 20 3x3mm^2 elements





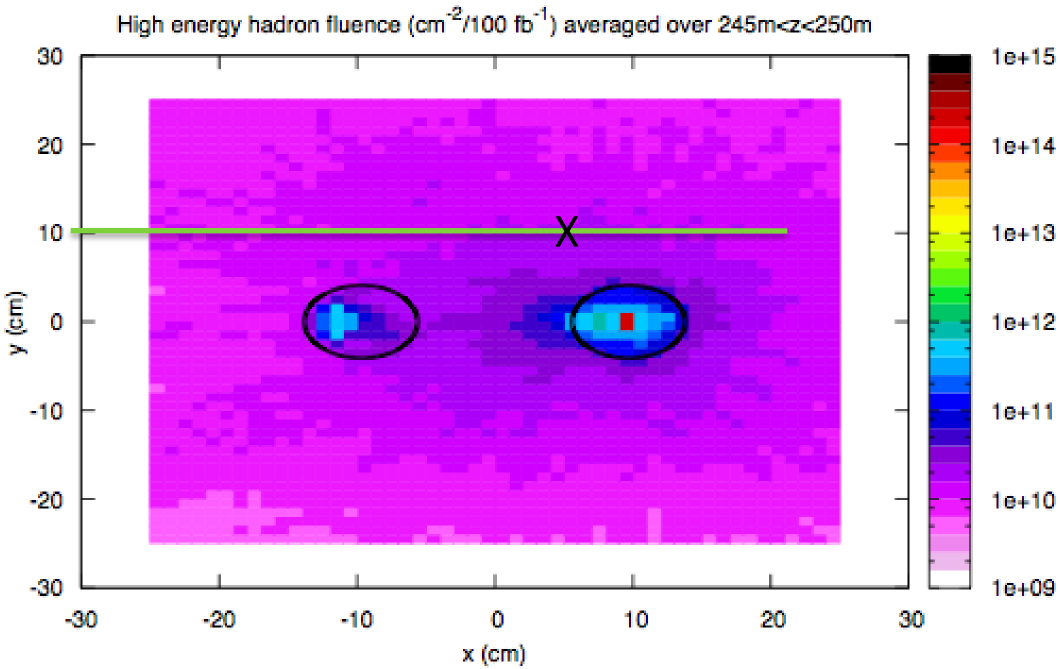
Set of four modules on support...
and in moving pipe assembly:



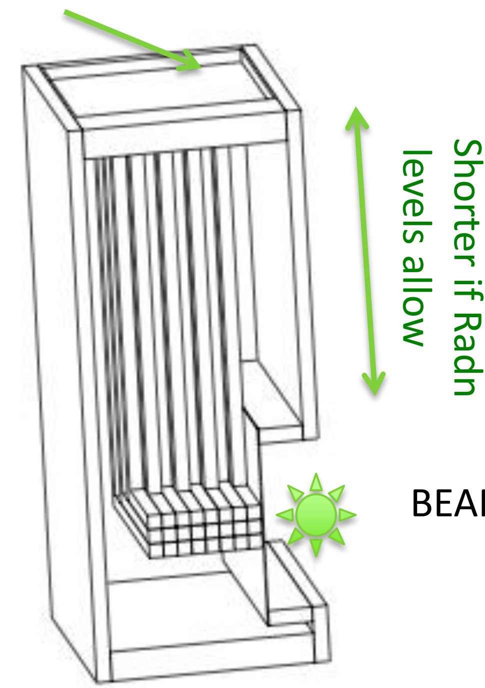
Steve Hentschel & MGA (Fermilab)

Having SiPMs out of beam plane minimizes radiation exposure

Light guide bars to be > 4 cm
but as short as radiation levels allow
Shorter → better timing



Mounting for SiPM array board

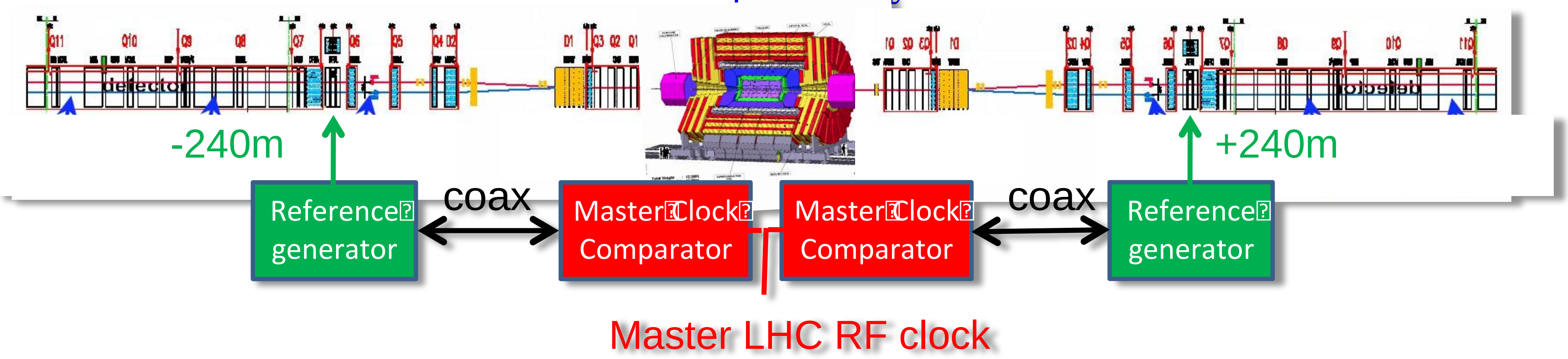


Hadron fluences fall fast with y: few 10^{10} / cm^2 at y = 10cm in 100 fb-1
Can also shield at that position

Reference Timing system

w to synchronize two points separated by a significant distance?

LLNL adapting system demonstrated by SLAC for LCLS experiments.
RF cable with feedback to keep clocks synchronized at each end



Measured timing jitter = 1.2 ps/C using LCLS spare system and 520 m coax

=> well within HPS timing requirements

Jitter < 2 ps at stations 500 m apart. input to TDCs

Summary of Situation (February 2013)

HPS @ 240 - 250 metres: Installation during LS1 in 2014 or 2015-16 shutdown, pipe sections with tracking and timing detectors.
This is Stage 1 . Making proposal to CMS, hope for approval/funding "soon"

Some colleagues are working with TOTEM on a fully Roman pot solution (back moving pipe replaced with a triplet (probably) of Roman pots)
.... INFN Italy + Brazil groups. (next talk?)
We will see what develops.

HPS@240 is a learning step towards HPS @ 420: Installation in ~2016-18; new connecting cryostats and four (2x2) stations with tracking and timing detectors. 240+420 and 420+240 are important combinations

Join the exclusive crowd of forward-looking people!

Thank you

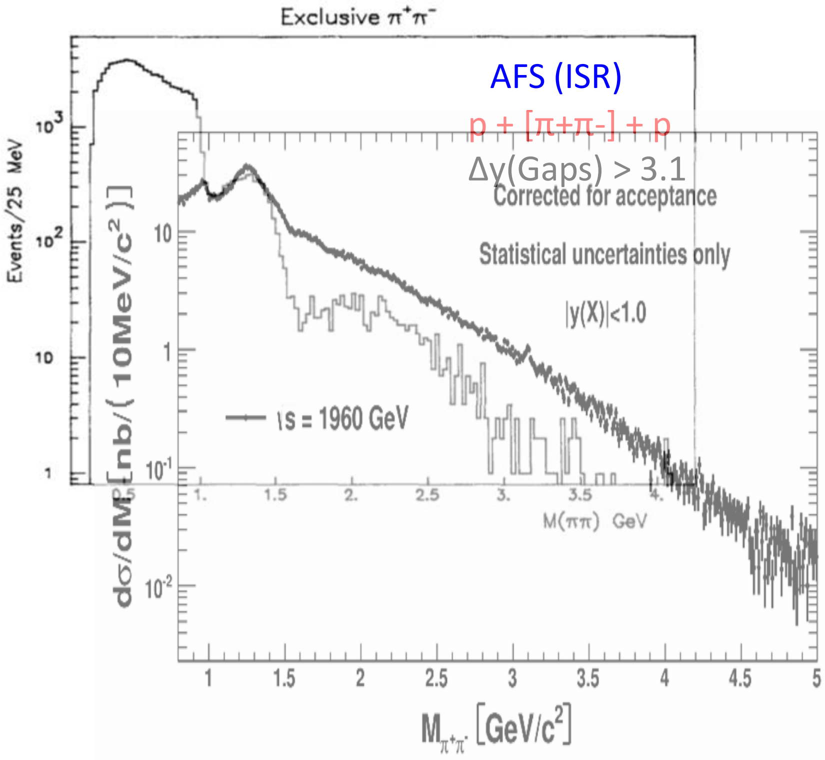
Back-ups

HPS groups February 2013

(Boston University, USA)
(Eric Hazen, James Rohlf)
CERN
Sorina Popescu
Fermi National Accelerator Lab., USA
Michael Albrow, Joel Butler, Simon Kwan, Sergey Los, Anatoly Ronzhin
IHEP, Protvino, Russia
Igor Azhgirey, Igor Bayshev, Vladimir Samoylenko
University of Iowa, USA
Duane Ingram, Edwin Norbeck, Yasar Onel
ITEP, Moscow, Russia
Alexander Zhokin, Vladimir Popov, Andrey Rostovtsev
University of Kansas, USA
Michael Murray
Lawrence Livermore National Lab., USA
Jeff Gronberg, Douglas Wright, Finn Rebassoo
Universite Catholique de Louvain, Belgium
Gustavo Da Silveira, Laurent Forthomme, Jonathan Hollar, Krzysztof Piotrzkowski
(Univ. of Nebraska – Lincoln, USA)
(Gregory Snow)
Rockefeller University, USA
Robert Ciesielski, Christina Mesropian, Konstantin Goulianos
IPM, Teheran, Iran
Mohsen Khakzad

(not confirmed):

This is NOT to do with HPS, but interesting anyway!
Exclusive central π+ π- production



CDF(Tevatron)

Gap + [π+π-] + Gap

Δy(Gaps) > 4.6

L_{eff}(no-PU) = 1.18/pb at 1960 GeV

σ(M > 1 GeV) ~ 2 μb

100/s with 1300b at μ = 0.3

If efficient trigger, about

1 hour of LHC data!