Diffractive Higgs Production at the LHC

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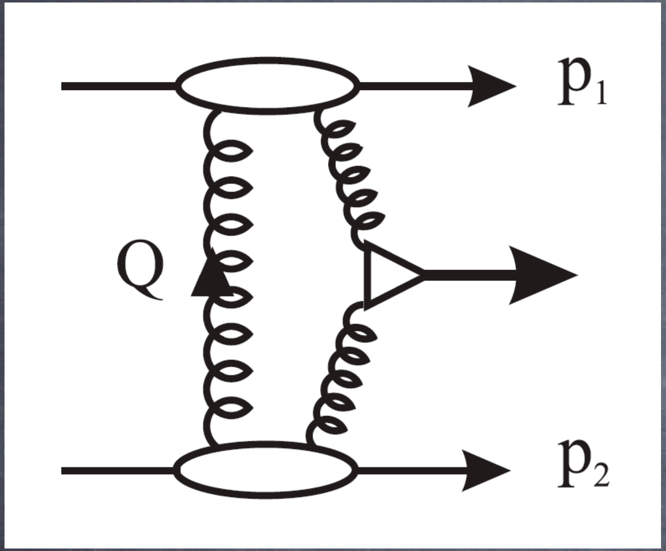
Overview

- Central exclusive production and the FP420 project.
- Luminosity dependent backgrounds
- $h \rightarrow aa \rightarrow 4\tau$ in the NMSSM

Central Exclusive Production



- Protons remain intact and typically lose 1% of their momentum during interaction.
- Protons scatter through very small angles (p_T of order 0.5 GeV).
- All of momentum lost during interaction goes into the production of a central system.

- Central system is produced in a J_z=0 state (true for zero angle scattering):
  - Resonance production is predominantly 0^{++}.
  - Di-quark backgrounds are suppressed by $\sim \frac{m_q^2}{M^2}$

Central Exclusive Production (II) - Kinematics

- If tag and measure each outgoing proton, can reconstruct the mass, M, and rapidity, y, of the central system from 4-momentum conservation:

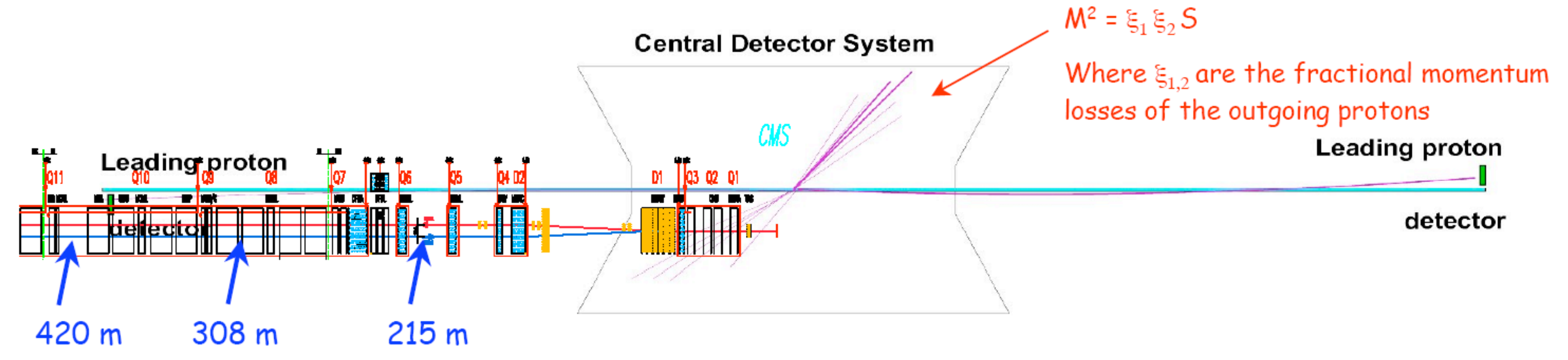
$$M^2 \approx \xi_1\, \xi_2\, s \qquad \text{and} \qquad y \approx \frac{1}{2} \ln\left(\frac{\xi_1}{\xi_2}\right).$$

- ξ_i is the fractional longitudinal momentum loss of proton i during the interaction

- Mass measurement of any resonance regardless of decay:
  - doesn't depend on jet energy resolution ($h \rightarrow b\bar{b}$)
  - or missing energy ($h \rightarrow WW^*$ and $h \rightarrow aa \rightarrow 4\tau$)

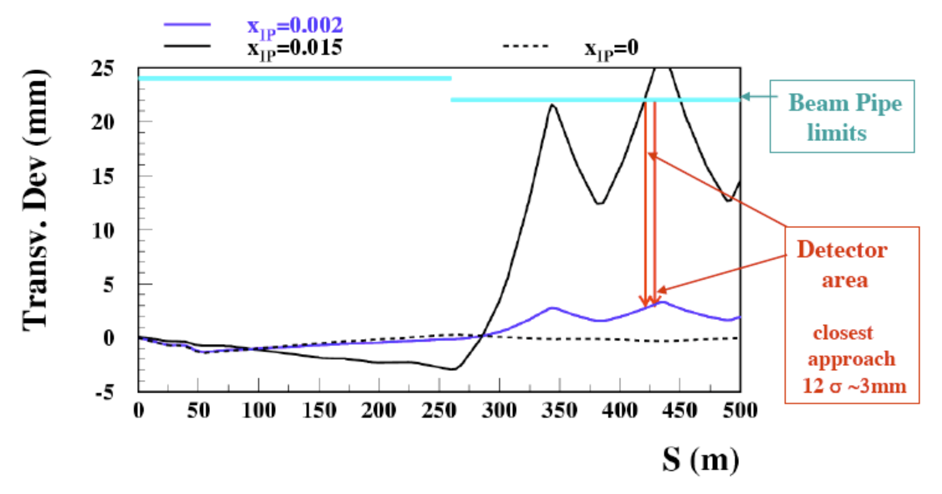
Forward Proton Detectors

- Installation of new detectors at 220m/420m from the interaction point turns the LHC into a magnetic spectrometer for off-momentum protons from CEP



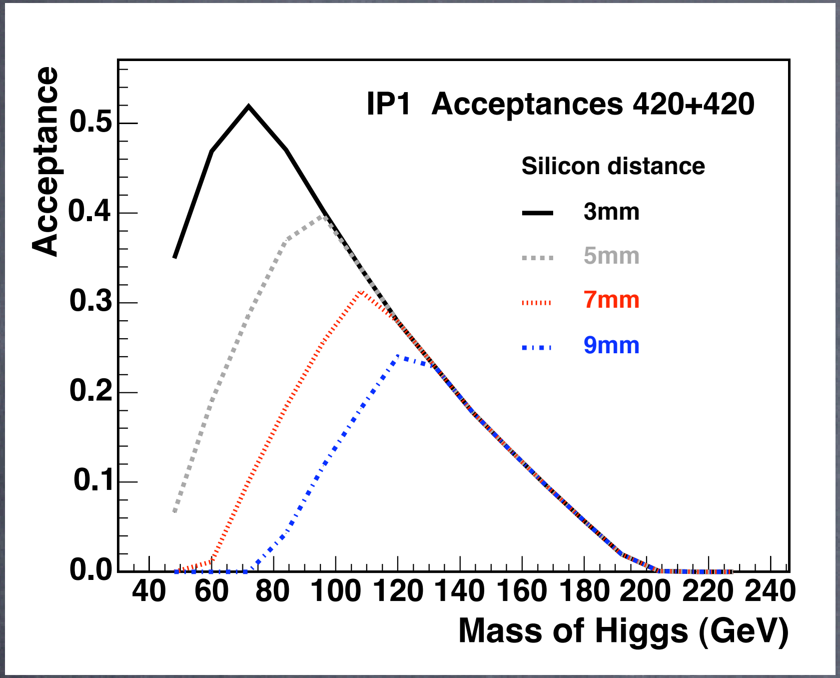
$M^2 = \xi_1 \xi_2 S$

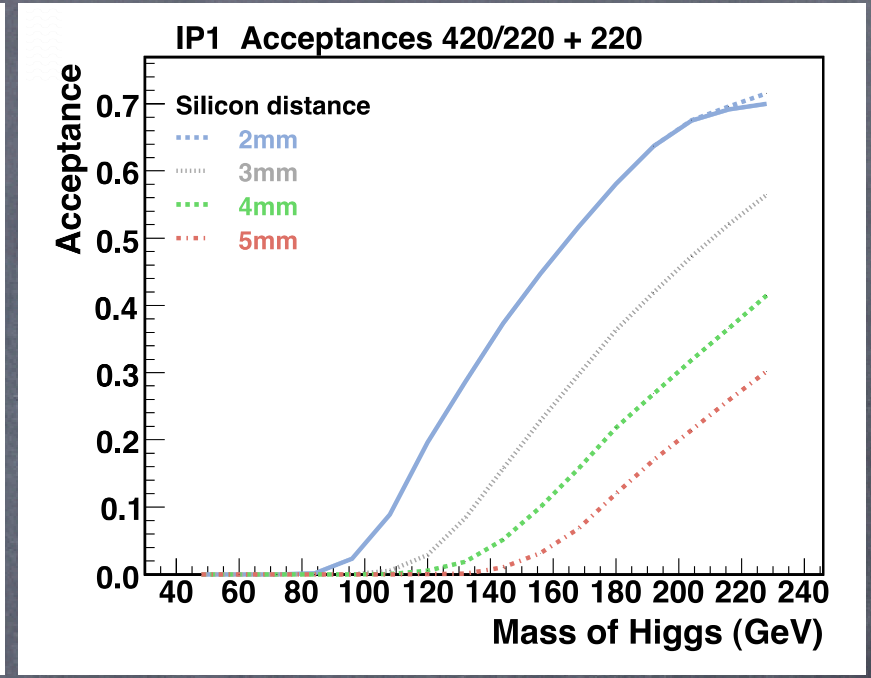
Where $\xi_{1,2}$ are the fractional momentum losses of the outgoing protons



- ξ determined from distance of proton hit to beam
- Lower ξ acceptance determined from distance of active detector edge to beam
- Upper acceptance from beam pipe.

Forward Detector Acceptance



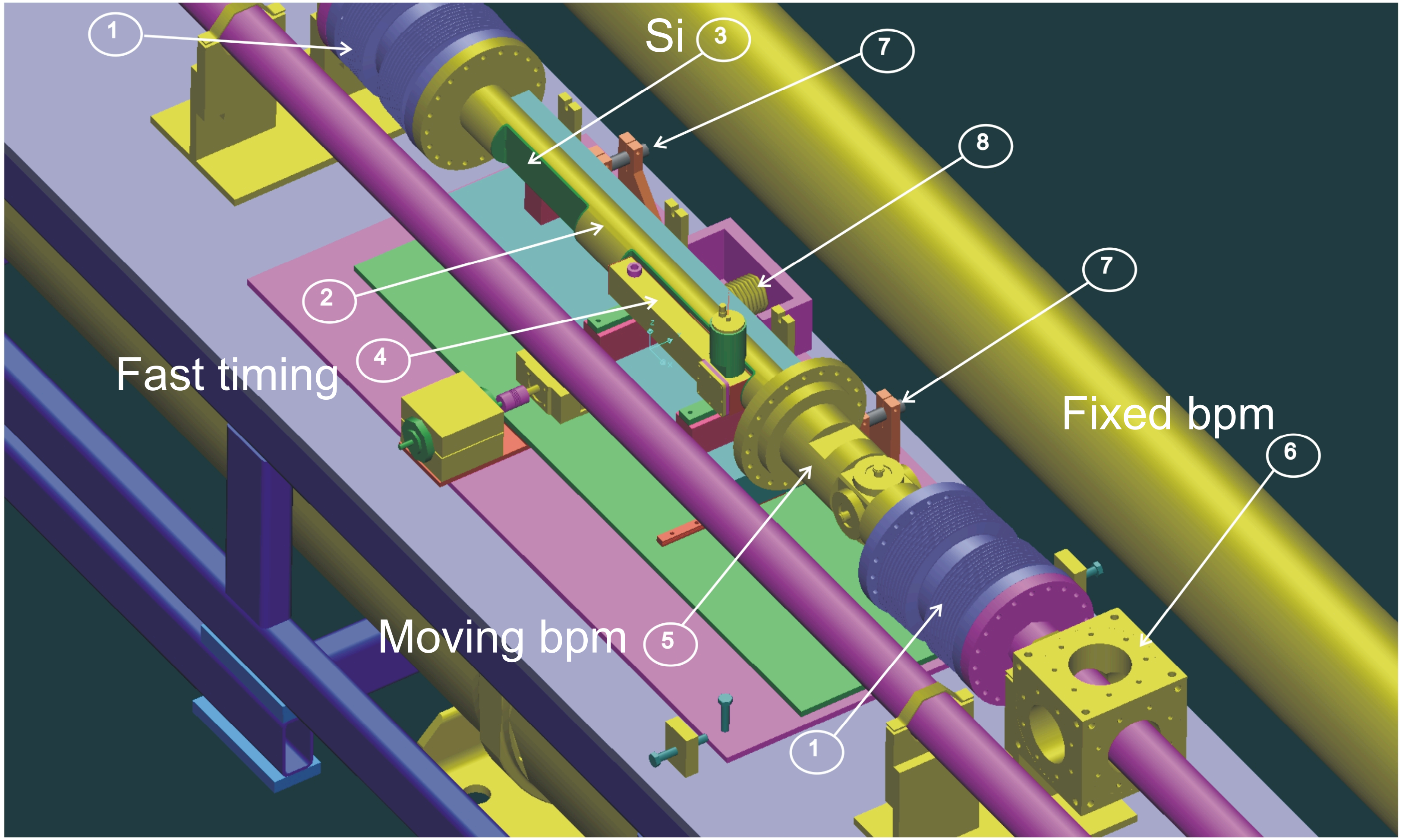


- Low mass acceptance depends on how close detectors are to the beam
- Good coverage of 60 - 200 GeV, a scalar Higgs hunting ground?

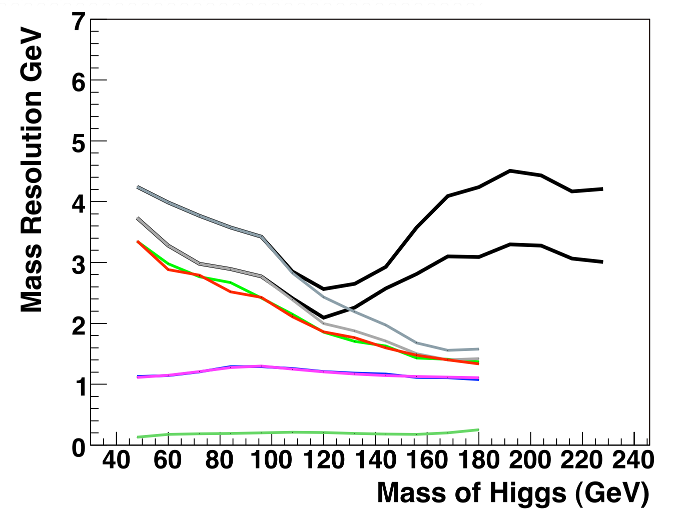
The FP420 design

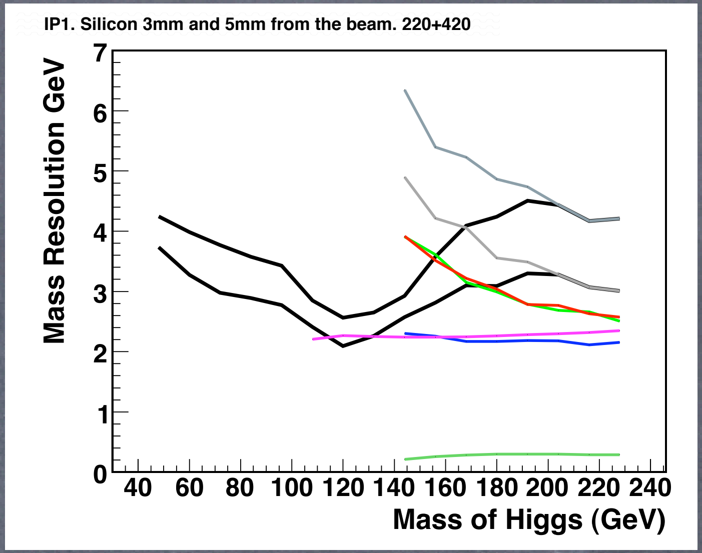
- Proposal to install forward proton taggers at 420m either side of IP.
- Each side has 2 stations which are 8m apart. Each station consists of:
  - 3D silicon detectors fixed to pocket in beam-pipe. Proton hit within silicon measured to 10 μm.
  - Beam-pipe moved closer to beam when beam is stable (Hamburg Pipe).
  - Position of pocket w.r.t beam measured to 50 μm by beam positioning monitors (BPMs).
  - Cerenkov fast timing detectors (GASTOF front station, QUARTIC rear) measure time-of-flight (TOF) of each proton from the IP to 10 ps.

FP420 layout



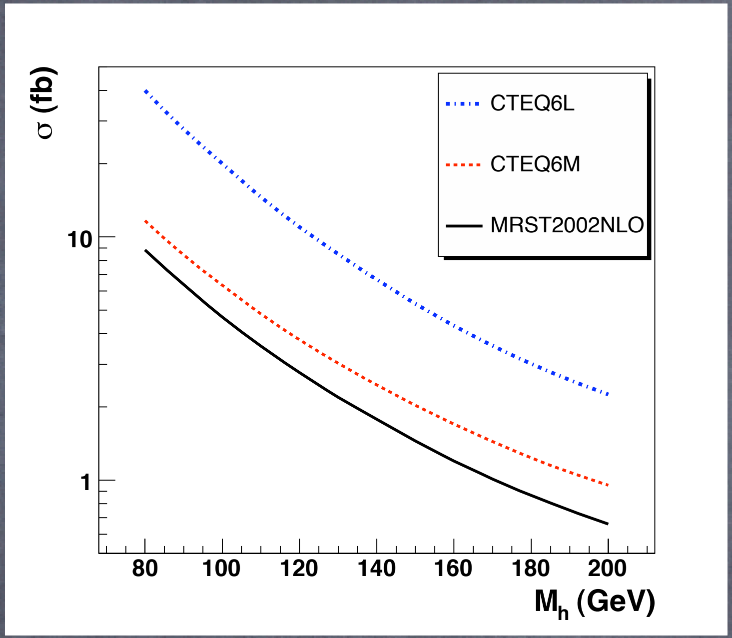
Forward Proton Resolution


IP1. Silicon 3mm and 5mm from the beam. 420+420


IP1. Silicon 3mm and 5mm from the beam. 220+420

- Purple curve is primary momentum spread uncertainty.
- Realistically aim for red/green curve which are the effects of the proton displacement measurement and transverse beam spot size respectively.
- Mass measurement accurate to approximately 2.3 GeV for 90 GeV central system and 2 GeV for 120 GeV central system

Unfortunately.....



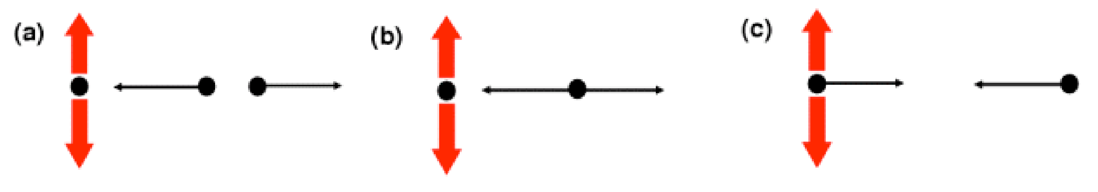
<-Standard Model

- CEP cross sections are typically small; $\sigma \sim 1 \text{ to } 20 \text{ fb}^{-1}$ (CTEQ6M)
- Have to fight against
  - Trigger efficiencies at low p_T.
  - Luminosity dependent backgrounds

Trigger Strategy

- Typically CEP rates are low, $\sigma \sim 1 \text{ to } 20 \text{ fb}^{-1}$, therefore need a good trigger.
- Can't trigger on forward protons at 420m as signal arrives too late for L1 decision.
    - At L2, can require two `in-time' proton hits to reject non-diffractive events and substantially reduce the rate.
- Have to trigger on central detector quantities at L1
    - Lepton triggers are easiest, low thresholds.
    - Jets very hard. Standard triggers always have high thresholds.
    - Possibility for jets: Rapidity gap triggers (low lumi), low p_T muons for b-jets, fixed (large) jet rate (rejected at L2). None are that successful at high luminosity.

Overlap Backgrounds (I)



- The overlap (OLAP) background is a coincidence between two or more interactions in one bunch crossing, that result in two forward protons and a hard scatter that mimics the signal.

- Largest background is [p][X][p], where [p] is a SD event that produces one forward proton within the acceptance of FP420 (1% of all events at LHC) and [X] is an event that produces a hard scatter to mimic the signal (i.e. [X] is a normal QCD $b\bar{b}$ event if we are looking for $h \to b\bar{b}$.

- At this stage, at all luminosities, the OLAP background is usually many orders of magnitude larger than the signal (shown later).

Overlap backgrounds (II)

- It should be noted that there are many sources of forward protons, not just SD:
  - At 420m, usually only care about SD events.
  - At 220m, large number of forward protons from non-diffractive events. Also large uncertainty, factor of two difference between PYTHIA and PHOJET.
  - Machine induced backgrounds from beam-halo, beam-gas and momentum cleaning. Beam-halo is negligible, others not well known at this time.

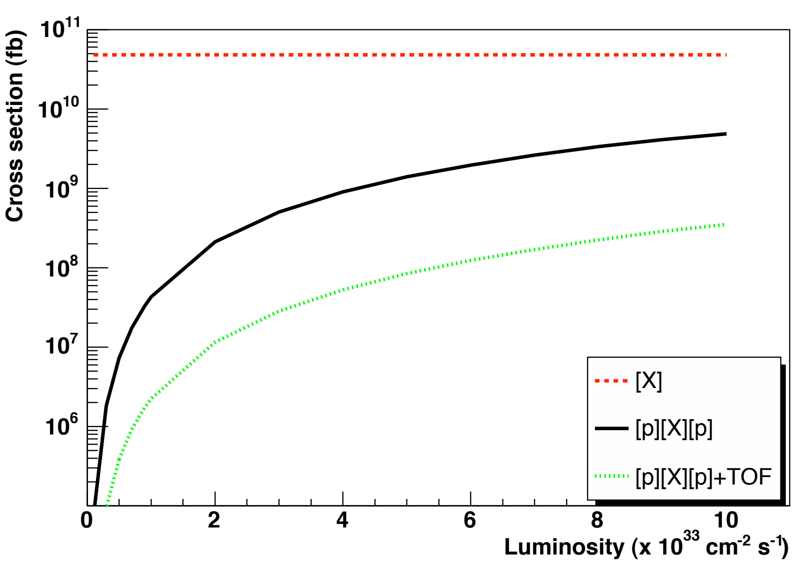
Overlap backgrounds (III) - TOF rejection

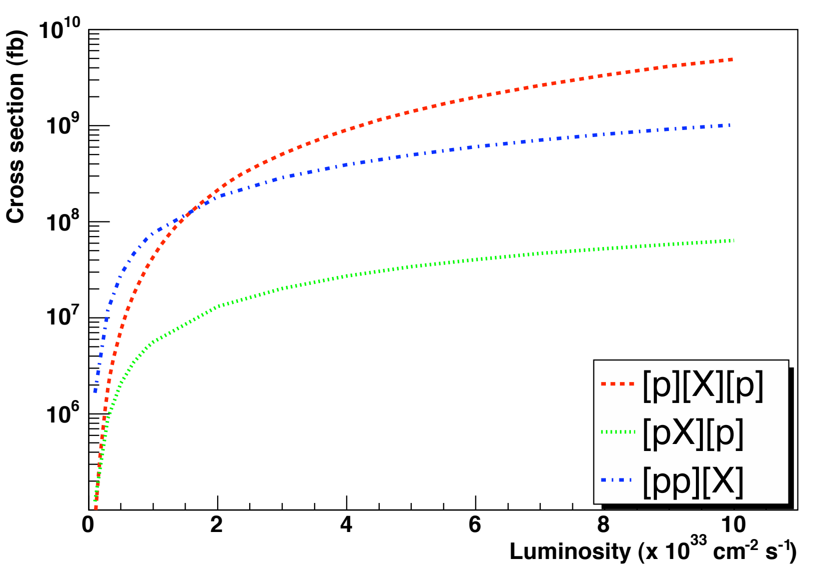
- Both protons TOF measured to 10ps accuracy. Reference clock accurate to 5ps.
- Vertex location from difference in time-of-flight, if optics are well known, i.e.

$$z = \frac{c}{2}(t_2 - t_1)$$

- This measurement is accurate to 2.1mm.
- Compare TOF vertex to central system vertex (di-jets, muon etc):
  - Rejection factor of approximately 20 over OLAP background (95% of signal retained).
  - If TOF accuracy improved to 2ps, rejection factor increases to 100.
    - Would need new design or new ideas.

Overlap background (IV) - Luminosity dependence





- As luminosity increases, so does the average number of interactions in a bunch crossing:
  - From 3.5 per B.C. at 10^{33} cm^{-2} s^{-1} to 35 per B.C. at 10^{34} cm^{-2} s^{-1}.
  - The probability for three-fold coincidence [p][X][p] also increases.

Example CEP analysis: $h \rightarrow aa \rightarrow 4\tau$ in NMSSM

- At least 4 neutrinos in the final state:
  - Mass hard to obtain from decay products
  - Mass obtained from forward protons if produced in CEP.
- Point chosen results in (NMHDECAY):

$$\begin{aligned} m_h &= 92.9 \text{ GeV} \\ m_a &= 9.7 \text{ GeV} \\ \mathrm{BR}(h \rightarrow aa) &= 92\% \\ \mathrm{BR}(a \rightarrow \tau^+\tau^-) &= 81\% \end{aligned}$$

- Simulated with ExHuME event generator. Cross section = 4.8fb.

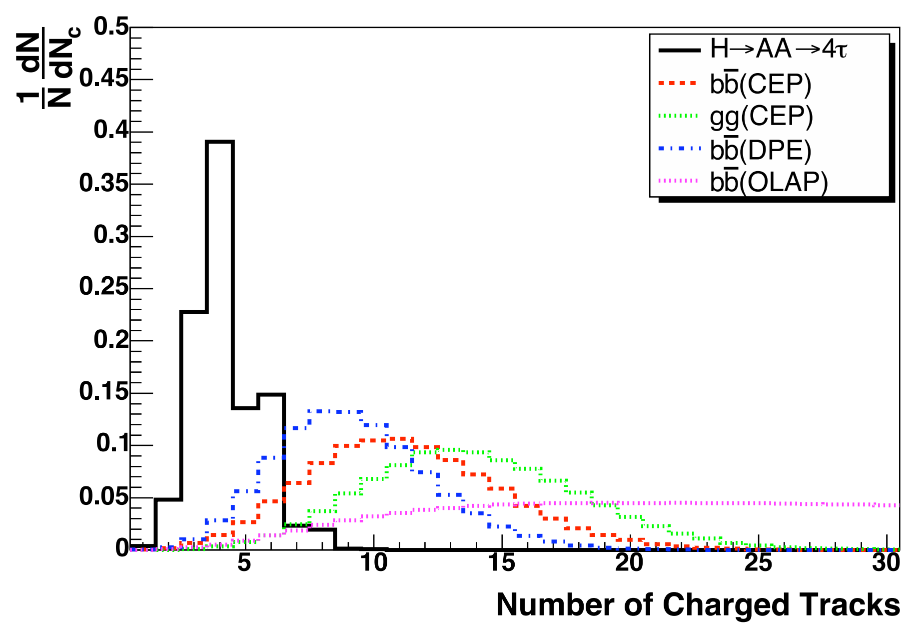
Backgrounds

- Four types of background
  - CEP: $b\bar{b}$ and gg simulated using ExHuME.
  - DPE: dijets simulated by POMWIG with H1 2006 Fit B dPDF.
  - OLAP: [p][jj][p] simulated with PYTHIA.
  - QED: $pp \rightarrow p + 4\tau + p$ and $pp \rightarrow p + 2\tau\, 2l + p$ simulated with MADGRAPH/PYTHIA. ($l = e, \mu$)
- Focus on those cuts used to reduce overlap background rejection in this talk - there are others that are used to generally reject dijets.

Ethos of Analysis

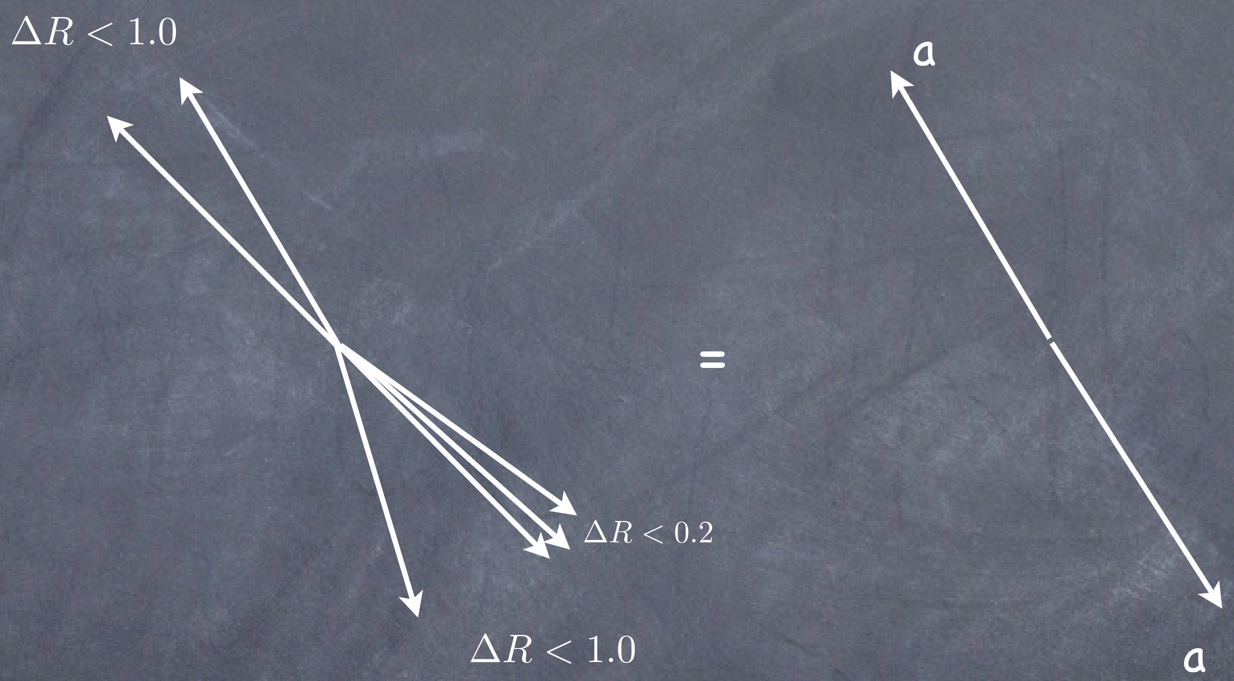
- Perform a track based analysis:
  - Don't need neutrals as we have lots of missing energy anyway.
  - Tracks can be associated with a specific vertex and a specific interaction. Reduces effect of pile-up on results.
- Trigger on a low transverse momentum muon:
  - Low p_T muon triggers foreseen at ATLAS/CMS.
  - Hadronic decay of taus too low in energy to trigger the tau threshold triggers.

Charged Track Multiplicity Cut



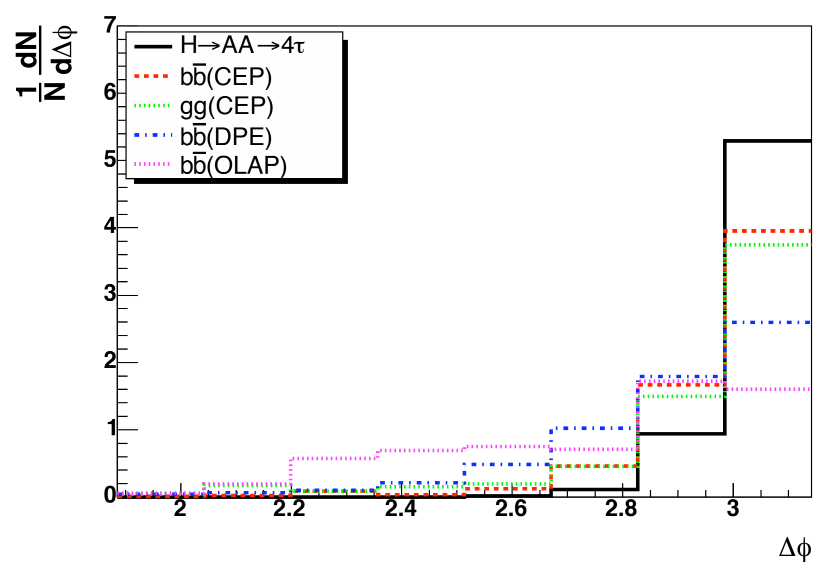
- Require 4 or 6 charged tracks within 2.5mm of vertex defined by the muon (smaller => lose signal; greater => pile-up contamination).
- Large rejection against dijet backgrounds.
- Very efficient at removing OLAP backgrounds due to underlying event activity producing a large number of tracks.

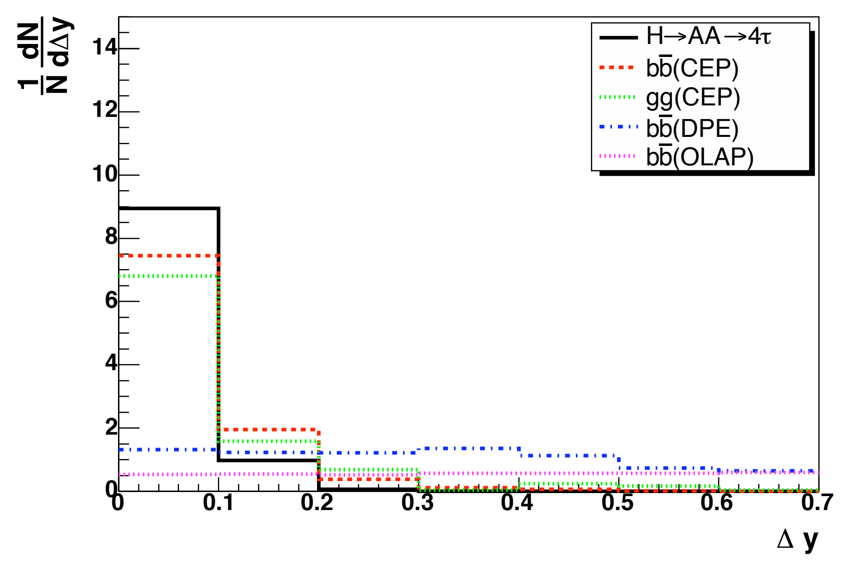
Topology Cuts (I) - clustering



- Cluster tracks to make four ‘tau’ objects
- Cluster the tau objects to create `pseudo-scalar’ objects.

Topology cuts (II)





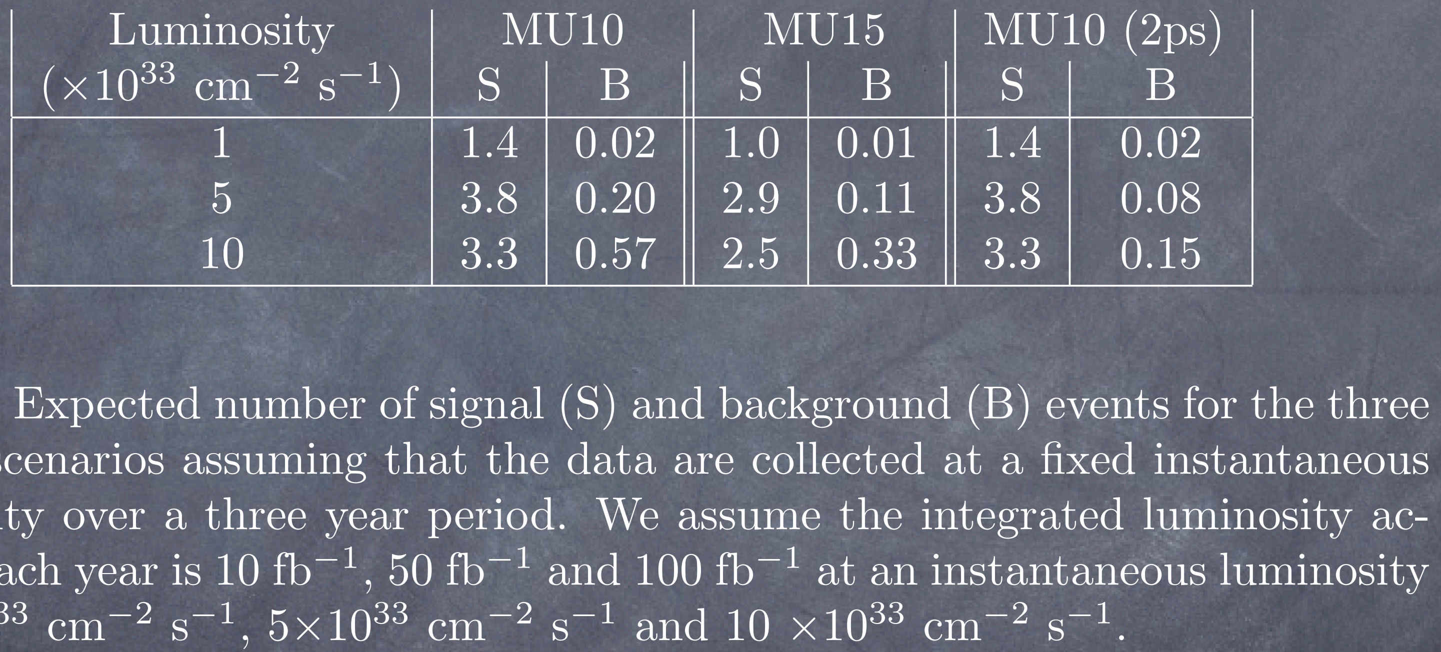
- Require pseudo-scalars are back to back, $\Delta\phi > 2.8$; this does not affect CEP events, which have no initial state radiation.

- Require average rapidity of pseudo-scalars matches that predicted by FP420, i.e

$$\Delta y = \left| y - \left(\frac{\eta_{a_1} + \eta_{a_2}}{2} \right) \right| \leq 0.1$$

- This is a typical approach to reject overlap backgrounds: the forward protons do not come from the same interaction as the hard scatter and hence the kinematics do not match up.

Final event rates



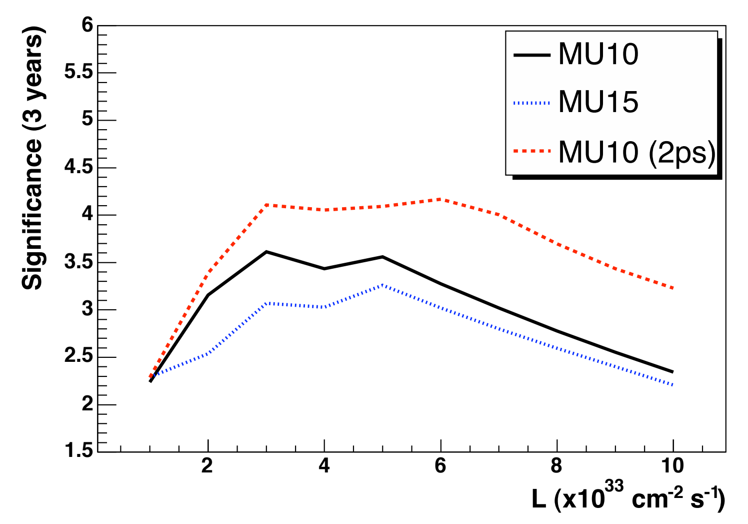
Luminosity ($\times 10^{33}$ cm^{-2} s^{-1})	MU10		MU15		MU10 (2ps)	
	S	B	S	B	S	B
1	1.4	0.02	1.0	0.01	1.4	0.02
5	3.8	0.20	2.9	0.11	3.8	0.08
10	3.3	0.57	2.5	0.33	3.3	0.15

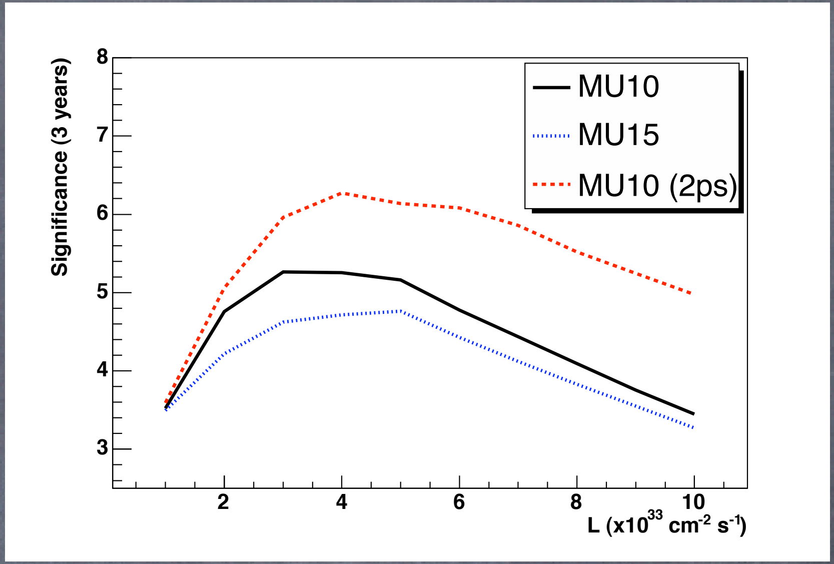
Table 1: Expected number of signal (S) and background (B) events for the three trigger scenarios assuming that the data are collected at a fixed instantaneous luminosity over a three year period. We assume the integrated luminosity acquired each year is 10 fb^{-1}, 50 fb^{-1} and 100 fb^{-1} at an instantaneous luminosity of 1×10^{33} cm^{-2} s^{-1}, 5×10^{33} cm^{-2} s^{-1} and 10 $\times10^{33}$ cm^{-2} s^{-1}.

- Note that signal drops between mid-high luminosity, due to events failing charge track requirement as pile-up tracks are wrongly associated with interaction.

- Background increases due to OLAP background rate increasing rapidly.

Significances; assuming 10 fb^{-1} yr^{-1} at $L=10^{33}$ cm^{-2} s^{-1}.





- Left: analysis presented in this talk.
- Right: Significance for double data, i.e. combined ATLAS/CMS results or improved trigger (using (di-)electron, di-muon, electron-muon triggers expected to increase efficiency by factor of 2.5)
- Improving the timing to 2ps dramatically reduces OLAP
- S determined using Poisson statistics: $\frac{1}{\sqrt{2\pi}}\int_S^\infty \mathrm{e}^{\frac{-x^2}{2}}dx = \sum_{n=s+b}^{\infty}\frac{b^n\mathrm{e}^{-b}}{n!}$

Pseudo-scalar mass reconstruction (I)

- Reconstruct pseudo-scalar mass from forward proton information, given that

$$p_{a_1} + p_{a_2} = p_h$$

- Assume that the decay products of the pseudo-scalar are collinear with the pseudo-scalar (a good approximation as the a's are highly boosted), Thus the momentum of each pseudo-scalar is given by

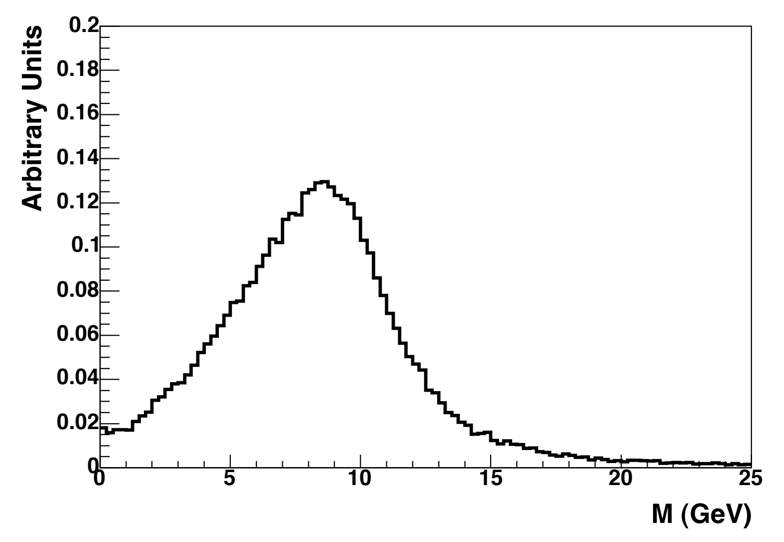
$$p_i^{vis} = f_i \; p_{a,i}$$

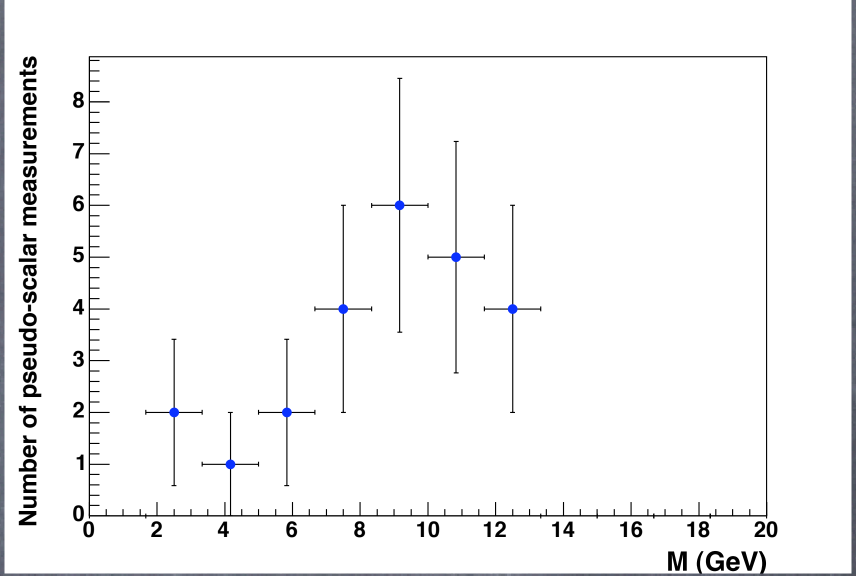
- We obtain from the above equations, and information from FP420,

$$\begin{aligned} \frac{(p_1^{vis})_{x,y}}{f_1} + \frac{(p_2^{vis})_{x,y}}{f_2} &= 0 \\ \frac{(p_1^{vis})_z}{f_1} + \frac{(p_2^{vis})_z}{f_2} &= (\xi_1 - \xi_2)\frac{\sqrt{s}}{2} \end{aligned}$$

- Which can be solved to give 4 independent pseudo-scalar mass measurements per event!

Pseudo-scalar mass reconstruction (II)





- Left: Distribution is broad due to breakdown of collinearity approximation, not detector effects.

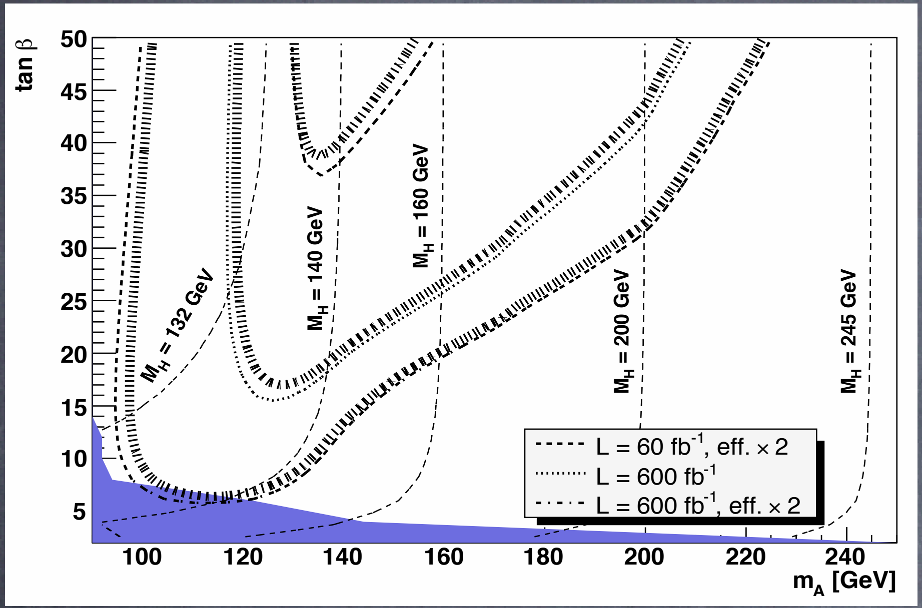
- Right: Typical a mass measurement assuming double data for 150 fb^{-1} of data collected at 5x10^{33} cm^{-2} s^{-1}. Expect from examining many such samples that $m_a = 9.3 \pm 2.3\mathrm{GeV}$

Summary

- Central exclusive production offers a unique way to measure the properties of the Higgs boson at the LHC:
  - Measurement of the quantum numbers of the Higgs.
  - Mass measurement to just a few GeV, regardless of decay channel.
- Difficult decay channels, such as $h \to aa \to 4\tau$, become possible with CEP.
- The outstanding experimental challenges are:
  - Can we trigger with high efficiency on jets if the Higgs decays that way.
  - Can we reduce the overlap backgrounds further by improved time-of-flight? Or can we reject the overlap background another way?

Some PR slides……

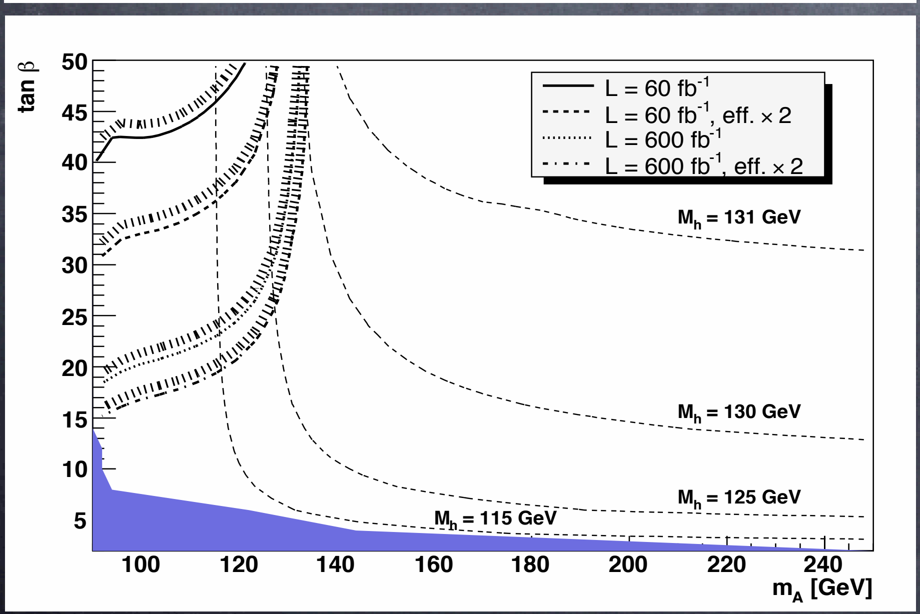
$h \to b\bar{b}$ in the MSSM

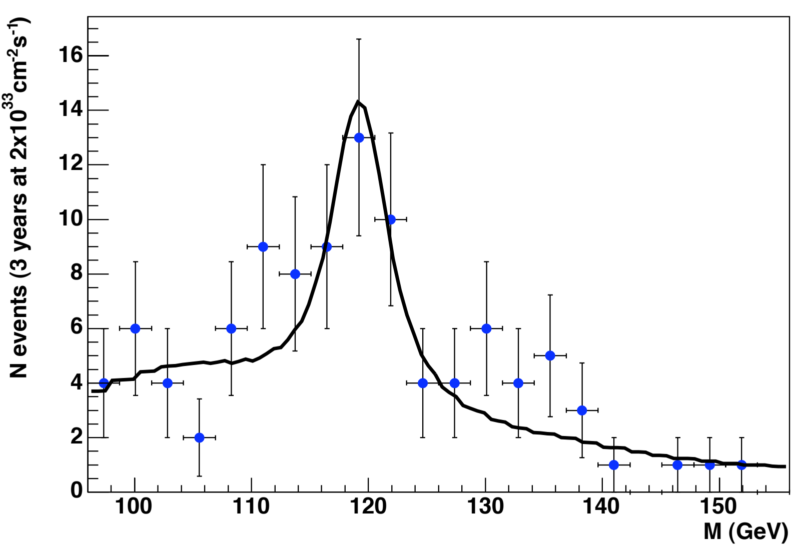


Upper left: 5σ contours for heavy Higgs observation using CEP.

Lower left: 5σ contours for light Higgs observation using CEP.

Lower right: Mass plot for light (119.5GeV) Higgs for 60 fb^{-1} of data ($\tan\beta = 40,\ M_A = 120\text{GeV}$)





First observation of CEP at CDF

- Looked for an excess of events in the double pomeron exchange (DPE) dijet sample. The dijets are produced in DPE by pomeron-pomeron fusion.
- In DPE: Two forward protons + dijets + pomeron remnants.
- Look at dijet mass fraction (Rjj) - the mass of the central system that is contained in the jets.