Higgs measurements using forward proton tagging

Andy Pilkington

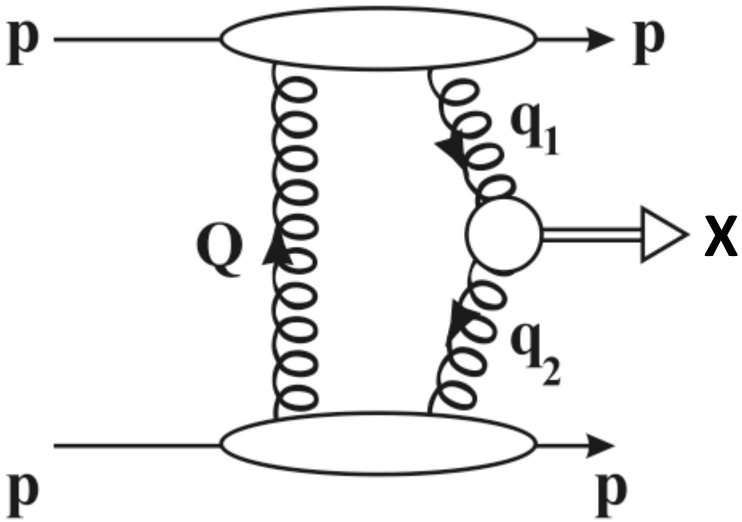
Institute of Particle Physics Phenomenology, Durham, and University of Manchester

Outline

1) Introduction to central exclusive production
2) Beyond the SM Higgs production at the LHC

Talk presented at 'Higgs-Maxwell Workshop', Edinburgh, February 2011.

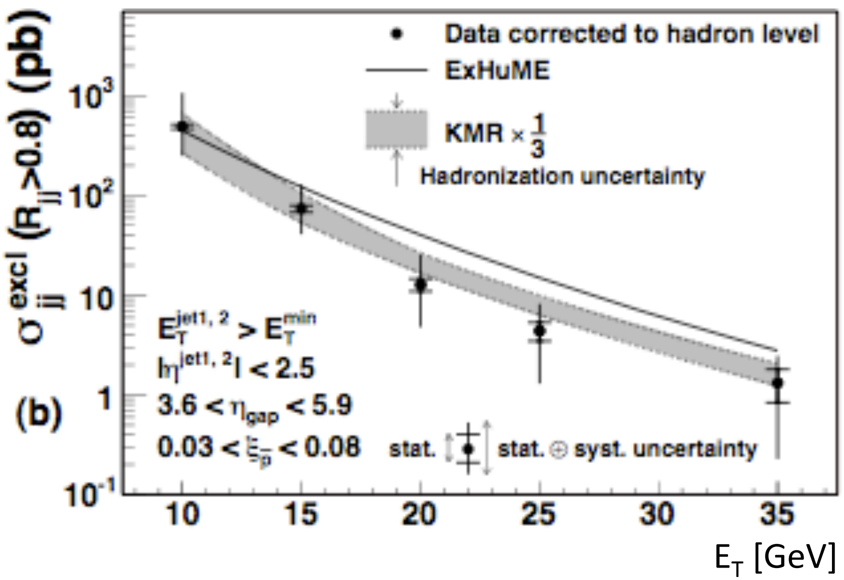
Introduction to central exclusive production

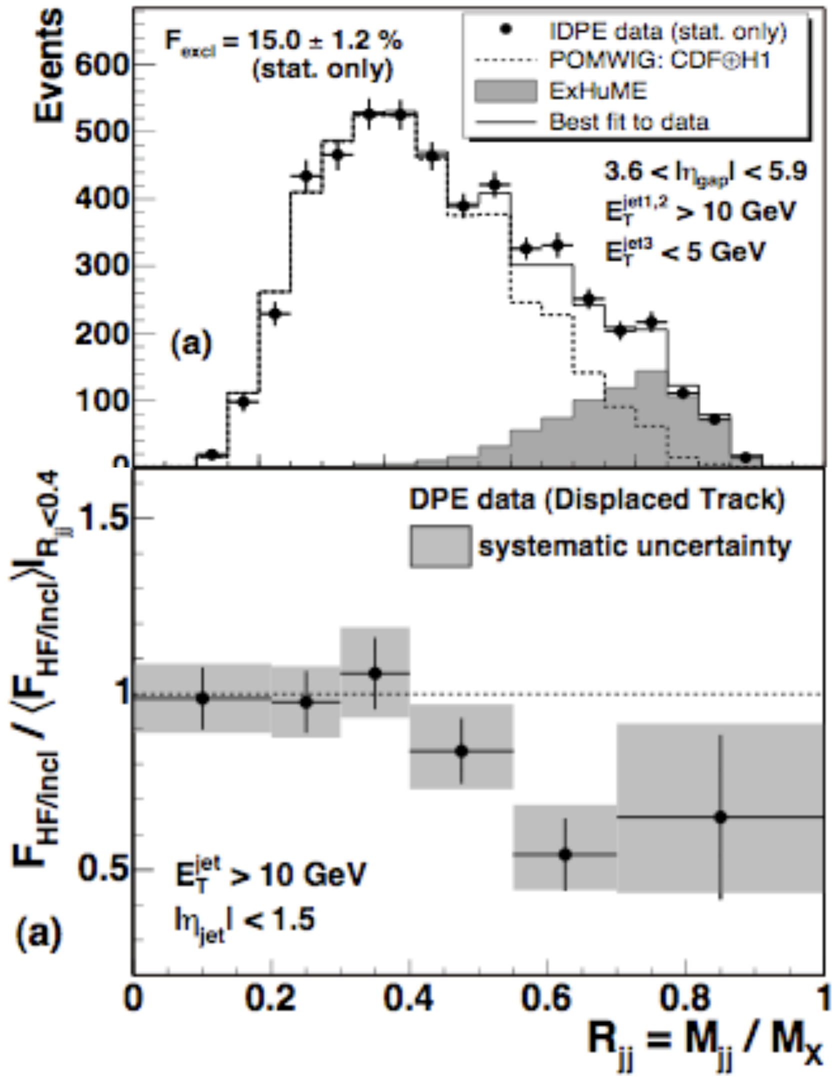


- **pp -> p + X + p**
- Protons remain intact and scatter through small angles: continue down the beam-line, thus not detected by conventional centralized detector setup.
- Clean *exclusive* environment: Central system 'X' is produced with no additional activity.
- X is produced in a $J_z=0$, C-even, P-even state.
  - Implies that only $J^{PC}=0^{++}$ resonances can be produced.
  - Di-quark production suppressed by m_q^2/ M_H^2

Evidence from the Tevatron

- CDF published 6σ observation of exclusive di-jet production.
- Data consistent with KMR calculations
  - Shape and size of exclusive contribution.
  - Observe suppression of b-jets as expected.





The University of Manchester

MANCHESTER 1824

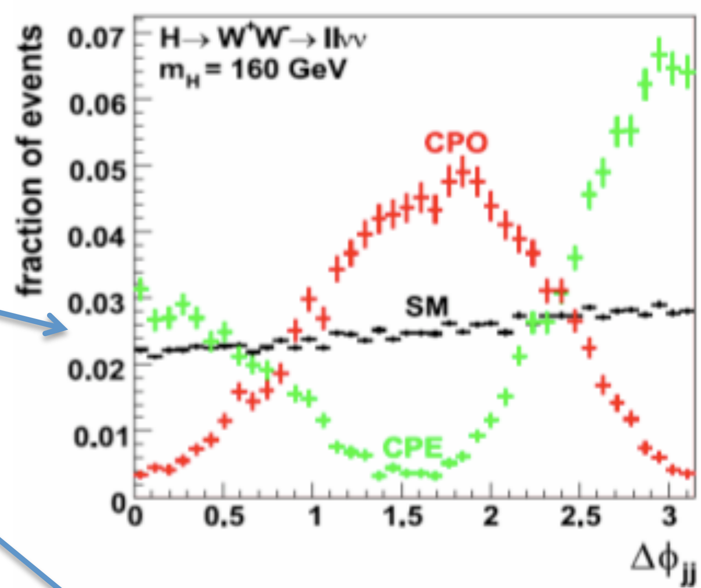
Exclusive Higgs measurements

IP3 University of Durham

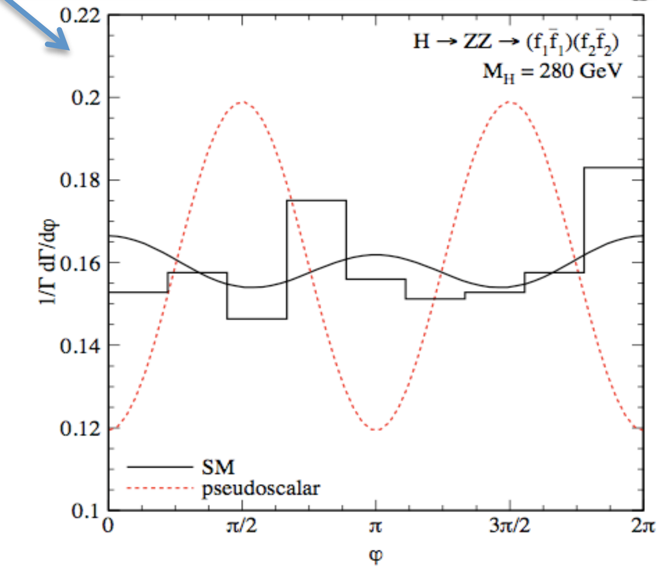
- Exclusive Higgs production has a number of desirable qualities:
- Spin selection rule means that:
  - Direct quantum number determination of produced resonance ($J^{PC}=0^{++}$).
  - Does not require final state angular measurements
  - Does not require coupling to vector bosons.
  - Di-quark production suppressed by m_q^2/M_H^2: H->bb channel available?
- Outgoing proton information allows determination of the kinematics of the centrally produced system
  - Higgs mass determination regardless of decay products
  - Additional information available for untangling Higgs-to-Higgs decays

Inclusive-exclusive complementarity

- Two inclusive methods of measuring Standard Model Higgs spin and CP studied:
  - Angles between tag-jets in vector-boson fusion.
  - Angles between Z decay planes in H->ZZ production

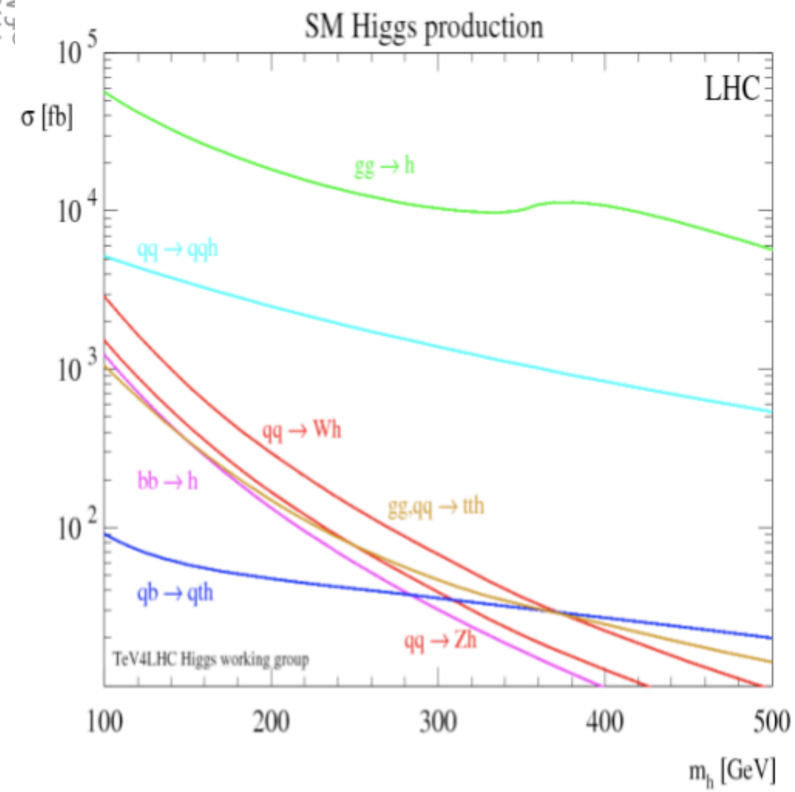


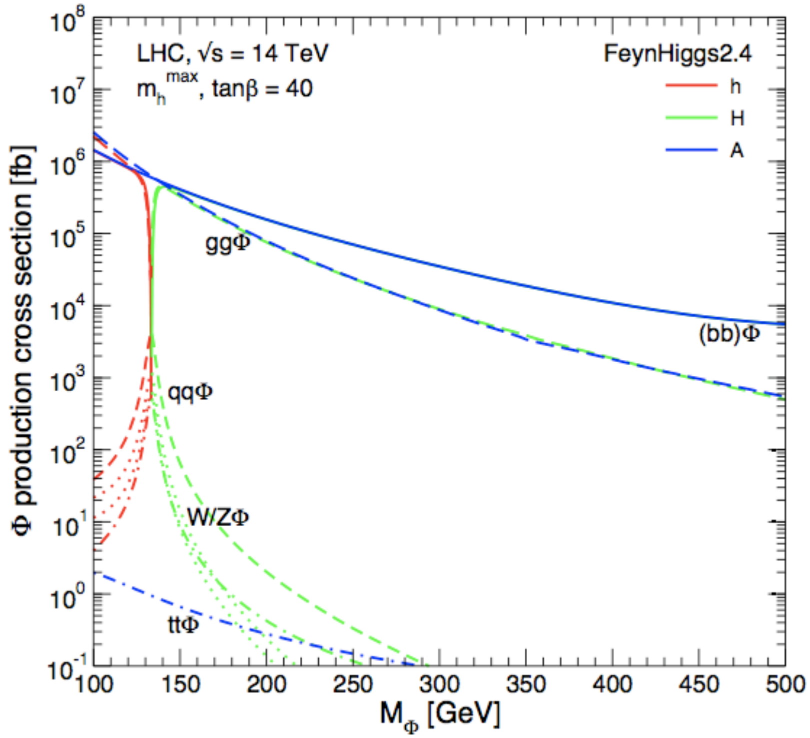
- Can only measure the spin and CP of Higgs if it has Standard Model-like couplings to the W/Z bosons
  - Any suppression of the coupling to vector bosons is a potentially a problem*



*Using tag jet angles in Higgs+2jet production via gluon-gluon fusion is an interesting option, but a few more studies needed by the experiments to see if the signal can be extracted

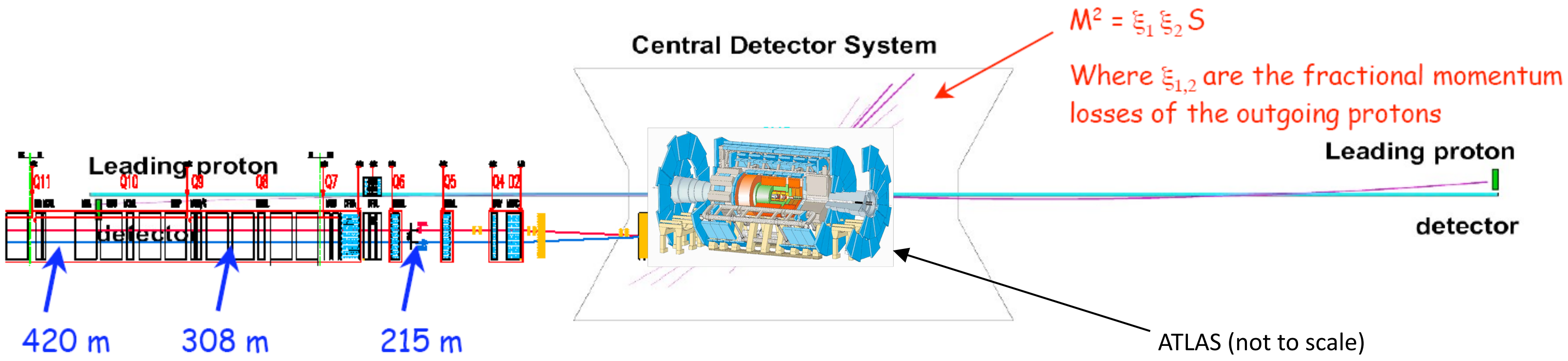
Example of BSM problems: the MSSM

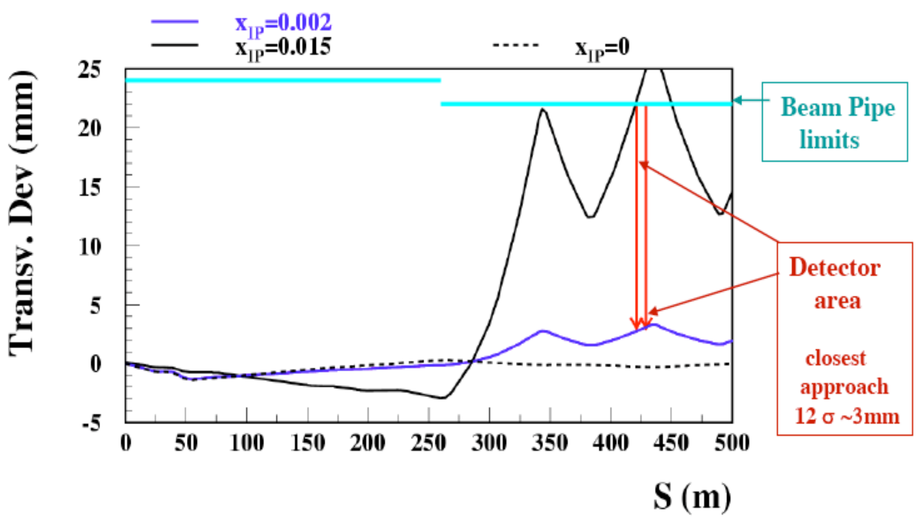




- Typical that VBF production is suppressed for one of the neutral scalar Higgs bosons in large areas of MSSM parameter space.
  - ATLAS/CMS can only measure the quantum numbers of one of the Higgs bosons using the standard approaches
  - Exclusive production offers the opportunity to measure the Q.N. of the additional Higgs

Forward proton tagging at the LHC (I)





- Protons from CEP continue down beam pipe after interaction.
- Protons have lost energy/momentum and are bent out of beam
- At any point downstream:
  - Distance from beam proportional to proton momentum loss.

Forward proton tagging at the LHC (II)

- Information about the Higgs can be obtained by measuring the outgoing proton momentum.
  - In fact, to a good approximation, just the longitudinal momentum will suffice.
- Define the fractional longitudinal momentum loss of each proton during the interaction, ξ:

$$\xi_i = \left| \frac{p_{z,i}^{out}}{p_{z,i}^{in}} \right|$$

The mass of the central system, M, is then given by:

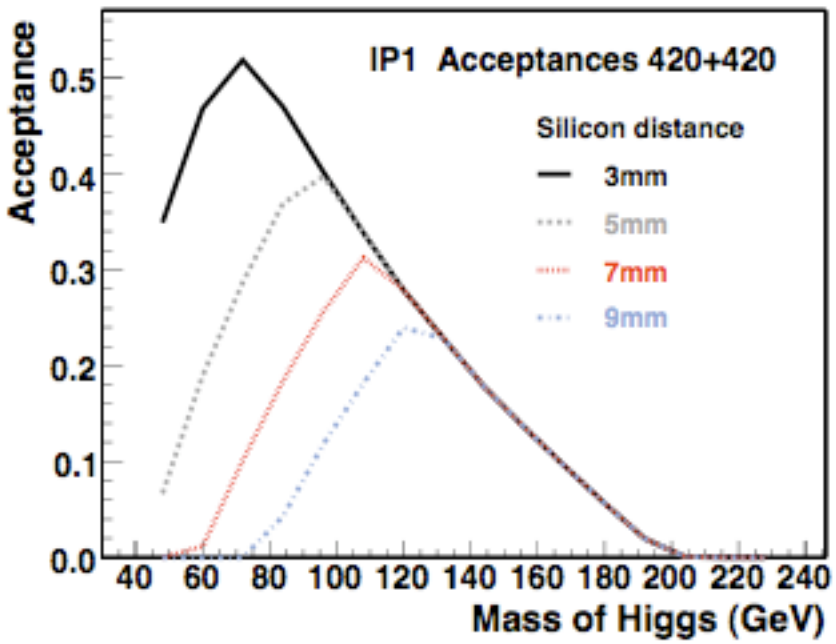
$$M^2 = \xi_1 \xi_2 s$$

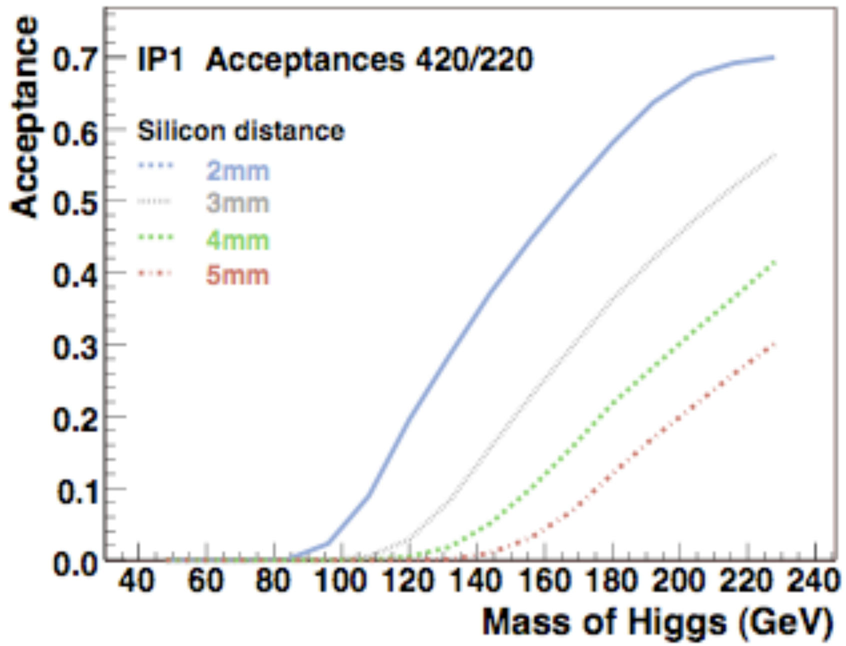
Mass of any resonance measured
Regardless of the decay products

And the rapidity of the central system, y, by:

$$y = \frac{1}{2} \ln \left(\frac{\xi_1}{\xi_2} \right)$$

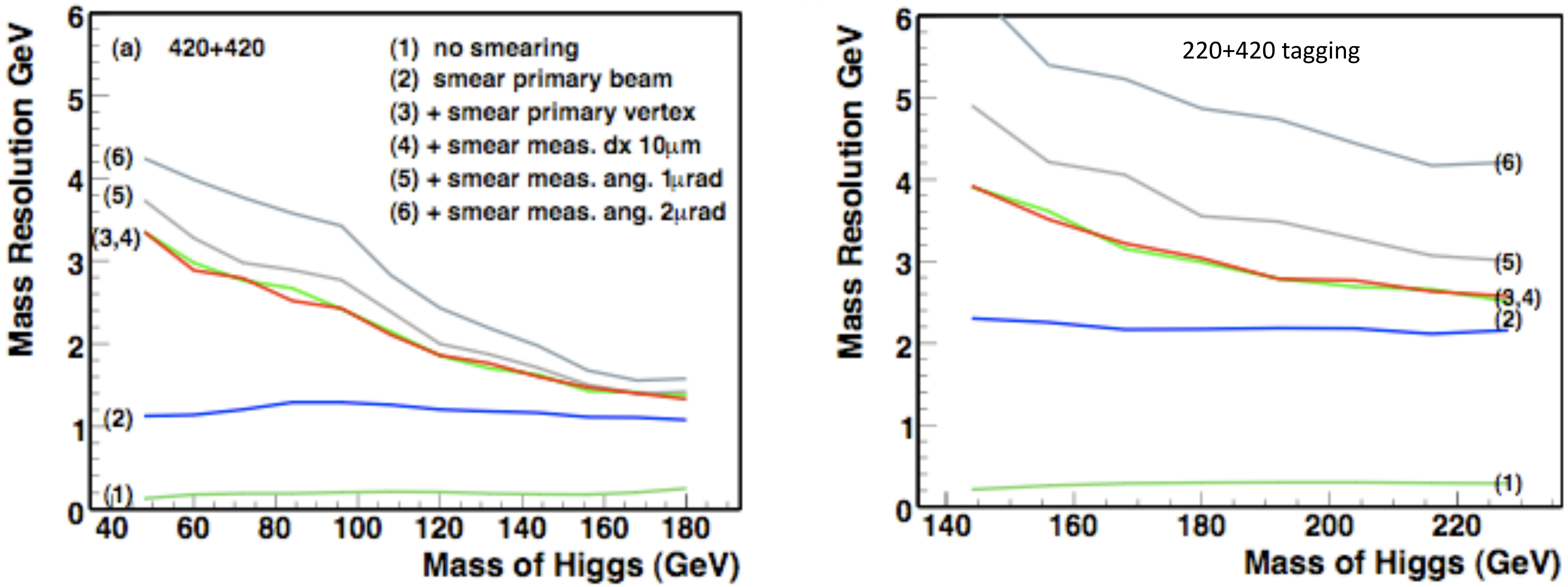
Acceptance of Detectors





- $M^2=\xi_1\xi_2 s$
- Low mass acceptance depends on distance of closest approach to LHC beam
- If both protons detected at 420m (left), same acceptance given a 120GeV Higgs for detectors 3,5,7mm from beam.

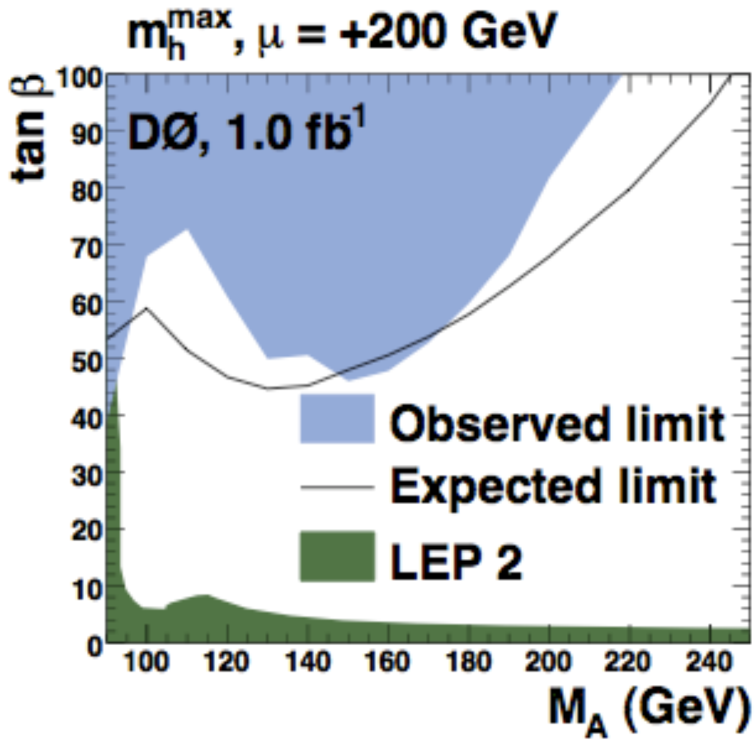
Potential mass resolution



- Irreducible smearing from
  - primary beam energy spread (0.77GeV) [2]
  - primary lateral interaction spread (~12μm) [3]
- 10μm position measurement and 1μm angular resolution [5] is the likely performance.

The MSSM Higgs sector

- Two Higgs doublet model.
- 5 physical states:
  - Two neutral scalars (h,H)
  - neutral pseudo-scalar (A)
  - charged Higgs ($H^{\pm}$).
- At tree level, completely specified by 2 parameters (to be determined experimentally):
  - $\tan\beta$ - ratio of vacuum expectation values of the two Higgs doublets
  - m_A - mass of pseudo-scalar.



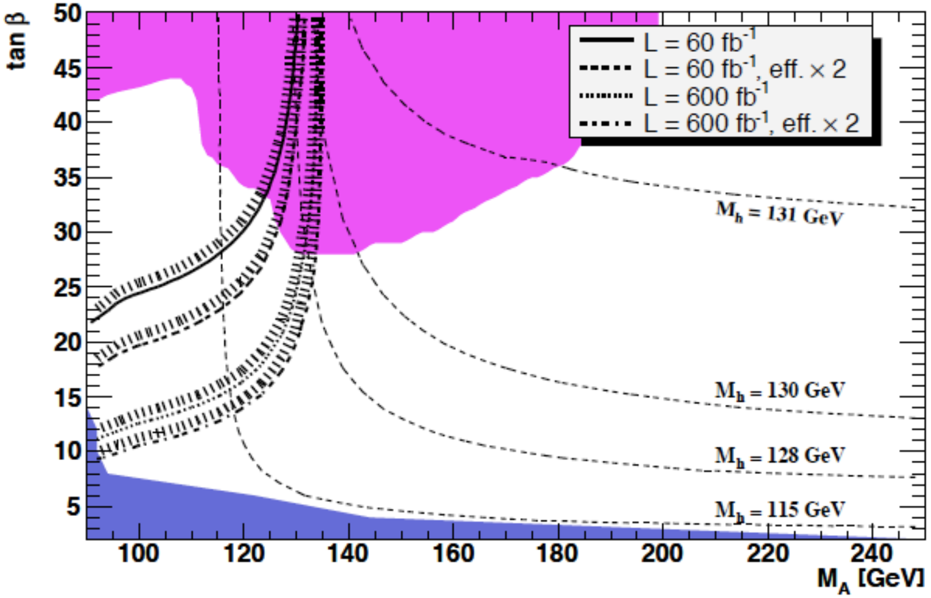
Limits on $h,H \rightarrow \tau^+\tau^-$ in m_h^{max} scenario of MSSM. (D0 collaboration, arXiv:0805.2491)

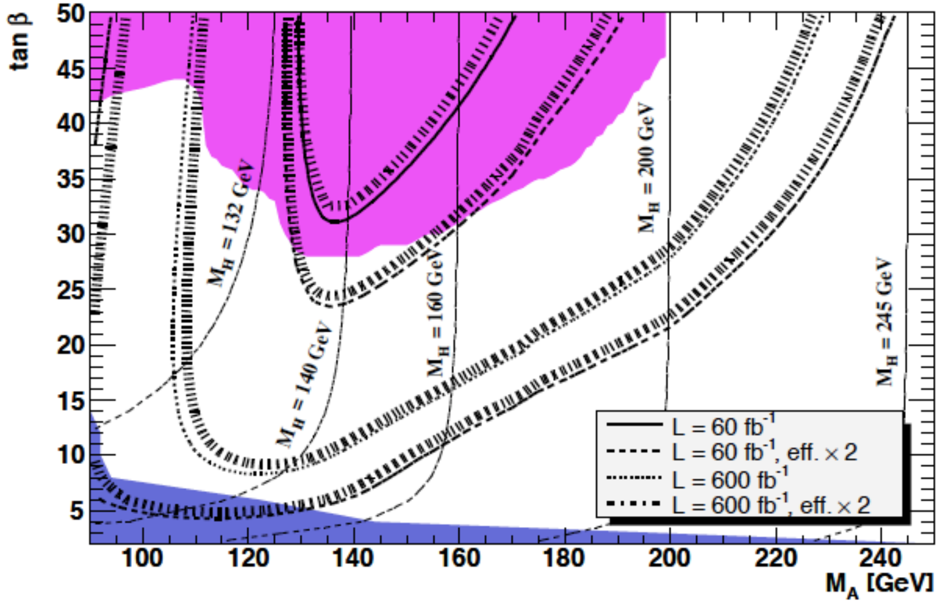
MANCHESTER 1824

The University of Manchester

MSSM parameter coverage

University of Durham



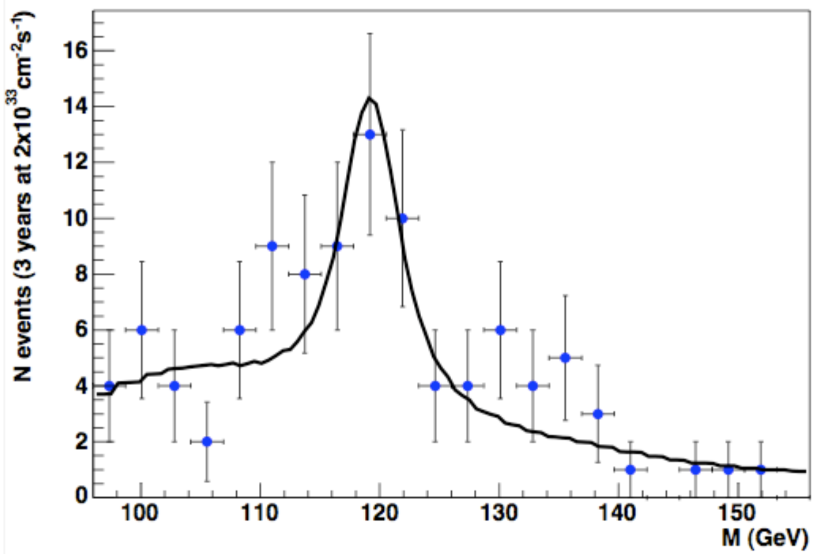


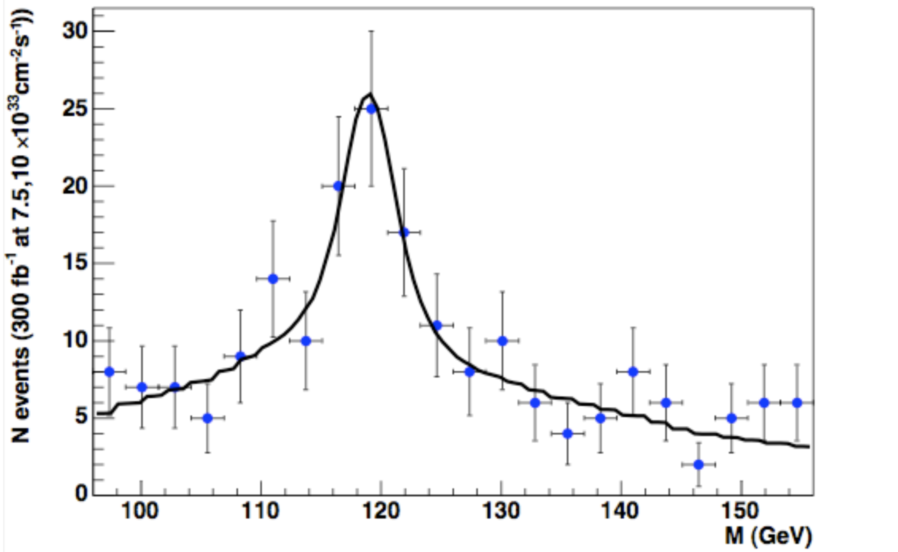
- Coverage of tanβ-m_A plane studied in Eur.Phys.J.C53:231-256,2008 and arXiv:1012.5007.
- Similar experimental efficiency to that assumed in previous slides (signal: 2.5% vs 2.7% for comparable mass windows). Trigger: (i) low p_T muon, (ii) jet + proton tag at 220m.
- Plots show 5σ contours for different integrated luminosity scenarios for h (left) and H (right) for detectors at 220m and 420m from the IP.

MANCHESTER 1824
The University of Manchester

University of Durham

MSSM results: Example mass distributions





60fb^{-1}, collected at 2x10^{33}cm^{-2}s^{-1}

1) Protons tagged at 420m from IP.
2) TOF resolution: 10ps,
3) Trigger: Muon (p_T>6GeV) and high L1 jet rate (~2.5kHz).
4) Significance = 3.5σ

150fb^{-1} collected at 7.5x10^{33}cm^{-2}s^{-1} plus 150fb-1 collected at 10^{34}cm-2s-1

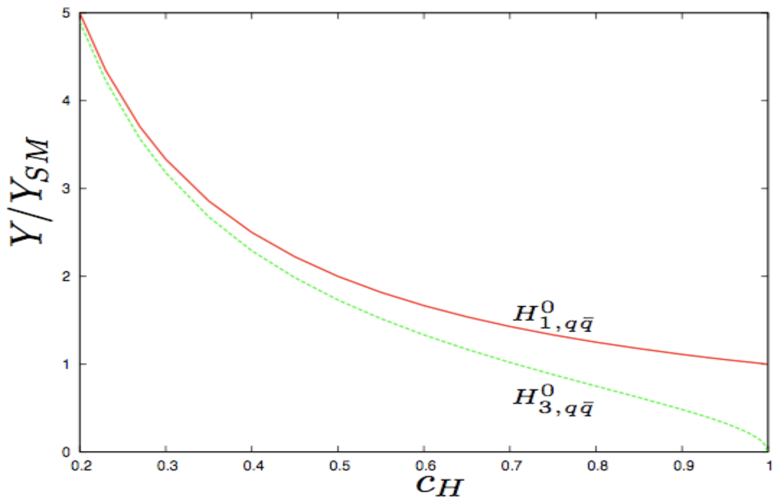
1) Protons tagged at 420m from IP.
2) TOF resolution=5ps
3) Trigger: Muon (pT>6GeV) and high L1 jet rate (~2.5kHz).
4) Significance = 4.5σ

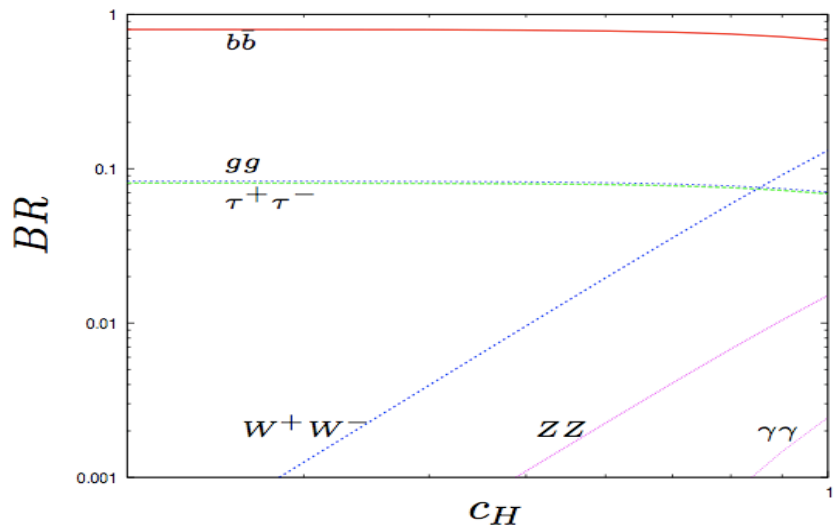
Triplet Higgs models

- Standard Model Higgs sector can be extended by adding higher representations in addition to the doublet.
  - In this case, one real and one complex triplet (Georgi and Machacek).

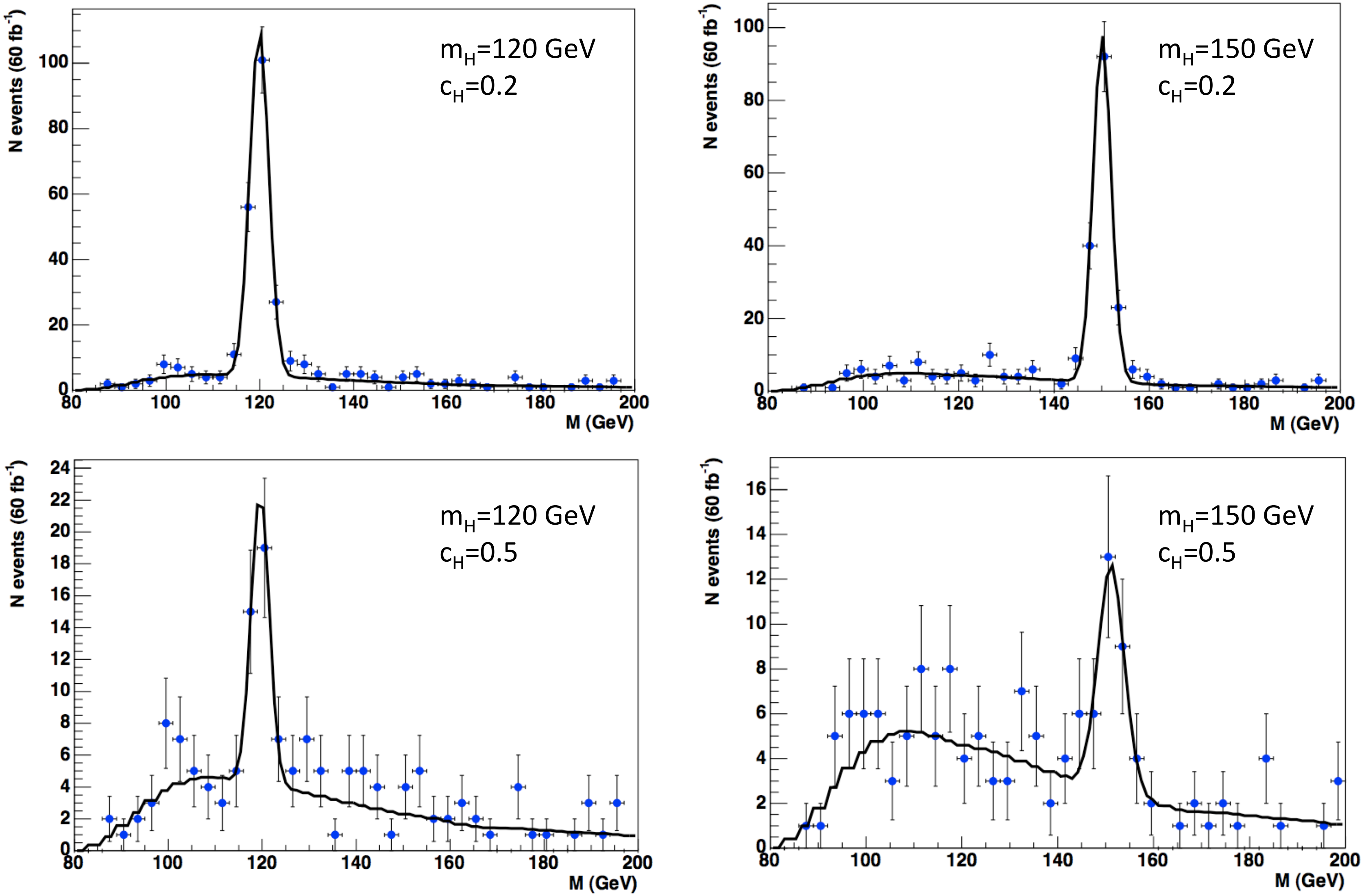
- 4 neutral scalar Higgs' bosons, charged and doubly charged Higgs.
- Enhancement of Higgs-fermion-antifermion coupling by $1/c_H^2$ where c_H is a doublet-triplet mixing parameter.
- hVV coupling suppressed by c_H^2

- Exclusive production required for spin-CP measurements for lightest Higgs (for small c_H)





Triplet results: 60fb^{-1} data



The NMSSM Higgs sector

- Extends the MSSM by inclusion of a singlet superfield, S ($\mu \mathbf{H_u H_d} \rightarrow \lambda \mathbf{S H_U H_d}$).
- 3 scalars (h1, h2, h3), 2 pseudo-scalars (a,A) and the charged Higgs ($H^{\pm}$).
  - 'preferred' mass of lightest scalar is $m_h \approx 100$GeV.
  - 'preferred' mass of lightest pseudo-scalar is $2m_\tau < m_a < 2m_b$.
- Dominant decay is $\mathbf{h} \rightarrow \mathbf{aa} \rightarrow 4\tau$
- Standard search channels at LHC could fail to discover any of the NMSSM Higgs bosons [Phys.Rev.Lett.95, 041801(2005)].
  - Standard ATLAS studies (for example) indicate that 4τ->4μ decay chain can be observed in VBF production, but possibly not enough events to study angular correlations of tag jets, therefore no spin-CP measurements in standard search channels?

NMSSM results

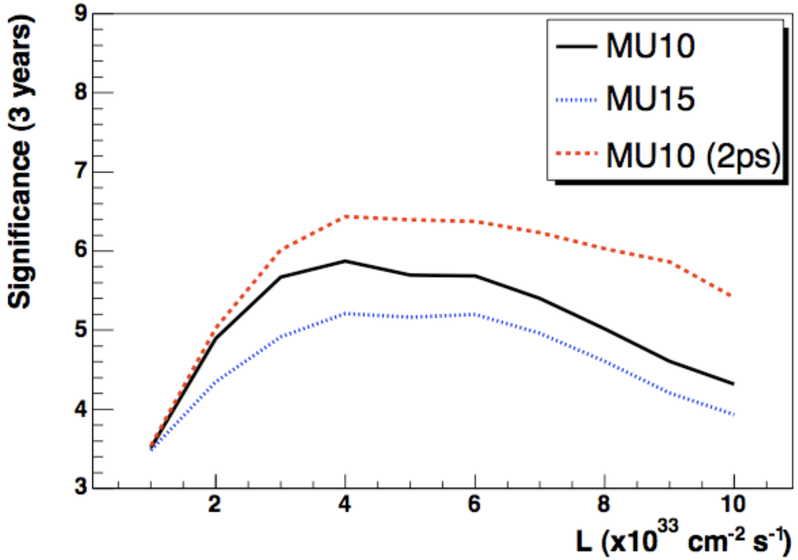
- After all experimental cuts, have a S/B ratio larger than 10, significance larger than 4.
- Also obtain the mass of the pseudo-scalar using a colinearity approximation:
  - Visible decay products of each pseudo-scalar are collinear with the pseudo-scalar:

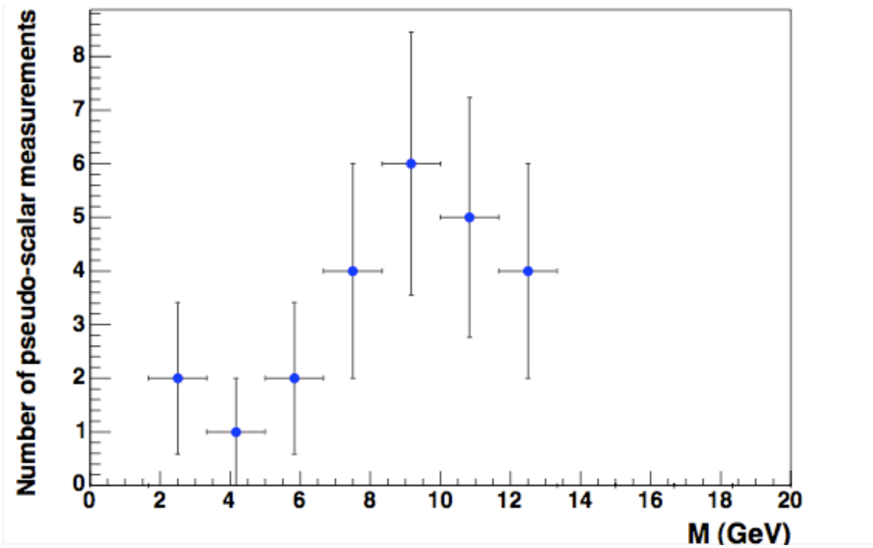
$$\mathbf{p_i^{vis} = f_i \, p_{a,i}}$$

  - Charged tracks used as visible input.
  - Use fact that 4-momentum of Higgs is constrained by forward proton taggers.

$$\mathbf{p_{a,1} + p_{a,2} = p_h}$$

  - Leads to 4 independent mass measurements per event.





The University of Manchester

MANCHESTER 1824

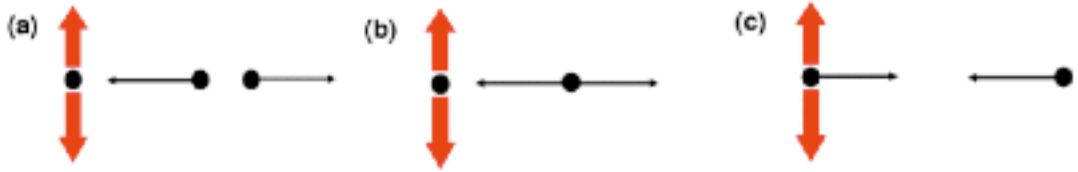
University of Durham

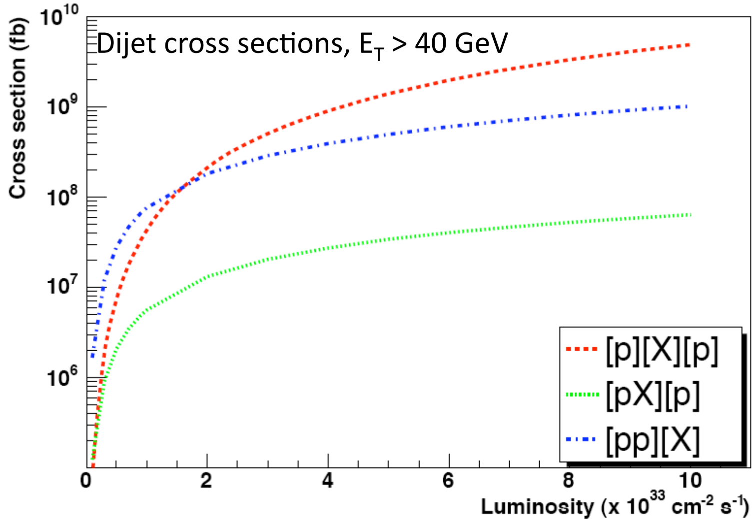
Summary

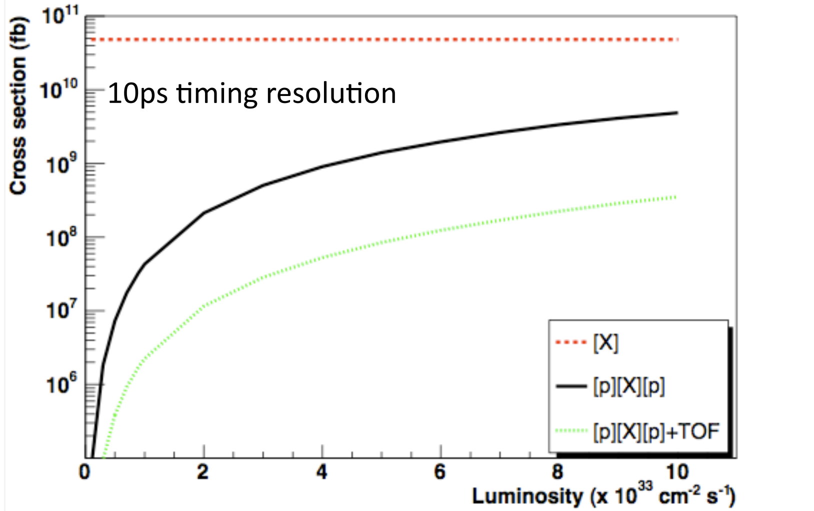
- Exclusive production offers a method to measure Higgs boson quantum numbers that does not rely on coupling to vector bosons
  – Complementary to the standard inclusive searches.

- A great deal of work has been done in exploring/confirming the theoretical calculations and designing the detectors and experimental technique used to extract the signal events:
  – H->bb is feasible in the MSSM and triplet models.
  – H->4τ is possible in the NMSSM.
  – The Higgs bosons that can be measured in exclusive production are exactly those that need to be measured in order to get the quantum numbers!

Experimental challenges



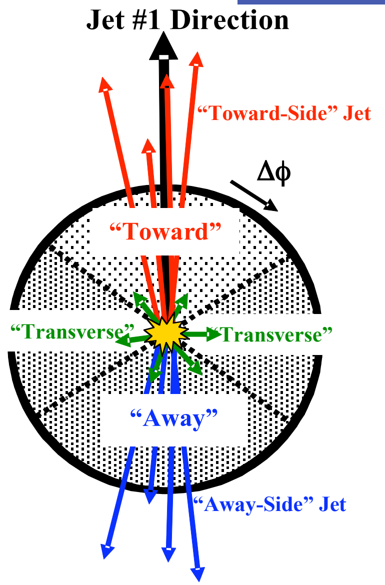




- At high luminosity, many proton-proton interactions in the same bunch crossing.
  - Can have, one di-jet event plus two events that produce forward protons, [p][X][p].
- Proton time-of-flight gives us an estimate of the primary vertex location: $z=c(t_2-t_1)/2$
- 10ps timing resolution is equivalent to a vertex measurement accurate to 2.1mm

Experimental solutions (example)

- Tagged protons imply no multiple parton-parton interactions in CEP/DPE events.
- However, [p][X][p] events have a pp→X interaction as the primary vertex.
  - Increased track multiplicity at main vertex.



<u>For di-jet events</u>

1) Construct back-to-back jets:
2) Require few tracks in the transverse region (perpendicular to jets).

Can also look for total number of tracks outside of jet cones.