Search for Invisible Particles at LHC

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Outline

- Theoretical approach
- How we search DM candidates at LHC
- A new method to spot invisible particle creation using a proton spectrometer
- How we can measure the quantum properties of an eventual invisible particle?

DM at EW scale

- Effective Field Theories:
  - Λ - suppression factor
  - m_{DM}
- Couplings tuned on relic abundance.
- Mediator search.
  - Heavy Spin 1 particle with couplings with DM and quarks
  - Λ should be around or below TeV scale to have sensitivity at LHC
  - Unitarity problems for large momentum transfers

DM Simplified Models

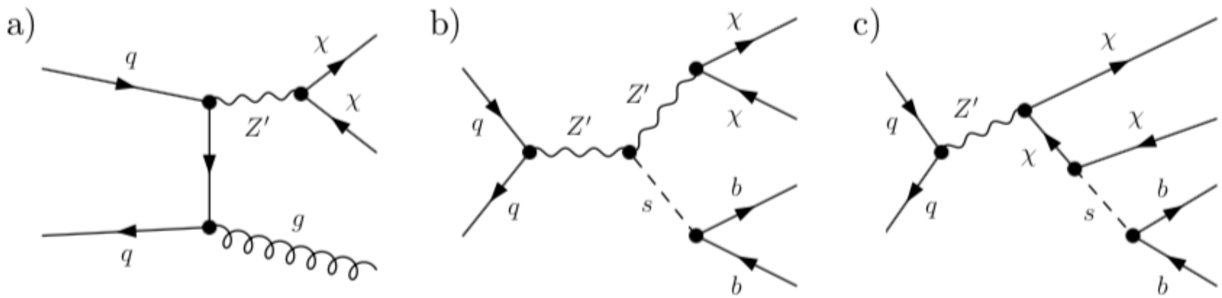
- Renormalizable models (4 dim)
- Light Mediators
- Relic abundance reproduced
- s-channel models
  - Coupling stronger on top quarks.
  - If $m_{med}>2m_{DM}$ the mediator can be produced on-shell and decay into 2 DM particles (resonant enhancement).
  - If $m_{med}<2m_{DM}$ the production is suppressed.

DM Simplified Models

- t-channel flavoured mediators models
  - Coulored scalar mediator (3-different)
  - DM a fermion
  - pp $\rightarrow \varphi\varphi^* \rightarrow \chi\bar{\chi}jj$ (typical signature)
    - Search on the dijet + missing momentum channel
    - Strong monojet signature
- Much more possibilities on models and different modulation on basic features such as masses and couplings.

DM Simplified Models

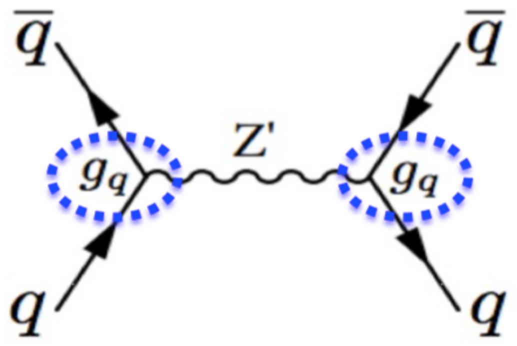
- Simplified Models with axial mediator tend to violate unitarity at high energies
- Introduce an additional Higgs boson that is a singlet under the SM gauge group
  - Dark Higgs
  - Generate mediator (Z’) mass
    - If decay to SM particles (dijet signature)
    - If not mono Dark Higgs (dijet signature) + missing Et



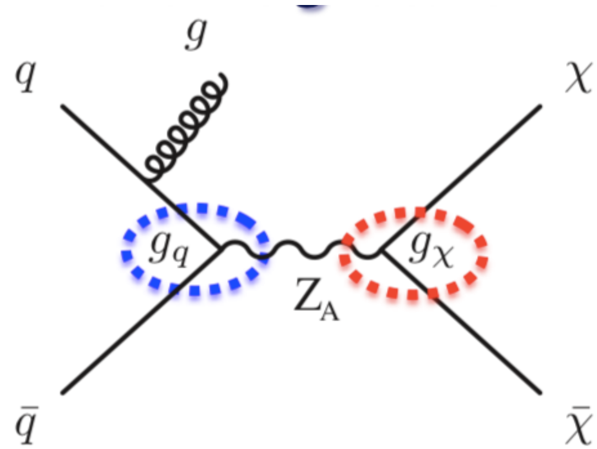
In case $m_{DH}<2m_{DF}$ Dark Higgs will decay into tt if phase space allows it or more likely bb

How to trigger such a phenomenology

- Direct resonant production is simply detected by dijet, ditop, dilepton or diphoton triggers



- Direct production of invisible particles is not "seen" by the experiments
  - Need of a specific trigger to select these strange configurations
- The MONOJET trigger
  - The MONOJET trigger select events in which one Jet is captured by the calorimeters coming from an isolated vertex (Pile Up)
  - The jet is generated by a gluon radiated by a quark or a gluon in the production vertex



Phenomenology

- While resonant production has a simple detection pattern the case of invisible particles is much more difficult
- It relays mostly to an unbalanced event in the calorimeter for the MonoJet trigger associated to Drell-Yan qq production.
- The search can span also to non quark mono triggers as the models can foreseen very clean trigger tag as:
  - Mono Photon
  - Mono Z
  - Mono W

Phenomenology

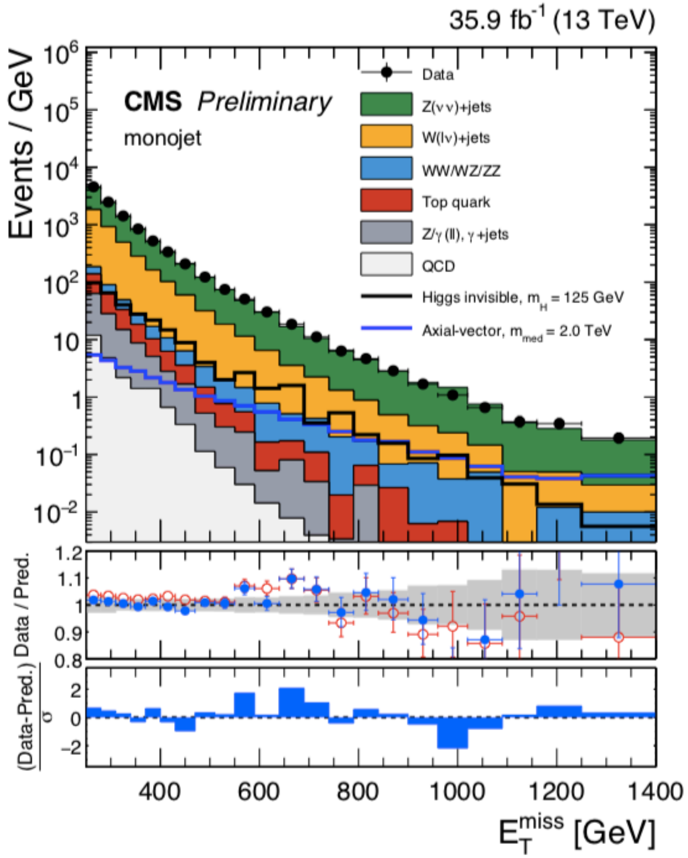
- Background:
  - Mostly QCD production
  - Templates from Montecarlo to predict the SM Missing Et spectrum
  - The spectrum spans over order of magnitude in missing Et and intensity
  - Most of the sensitivity for any excess is at high missing Et

Montecarlo generation

- A WG has been created at CERN for models production and create a tool for data comparison.
- A list of possible Simplified and EFT prediction has been studied and a report written:
  - https://arxiv.org/pdf/1507.00966.pdf

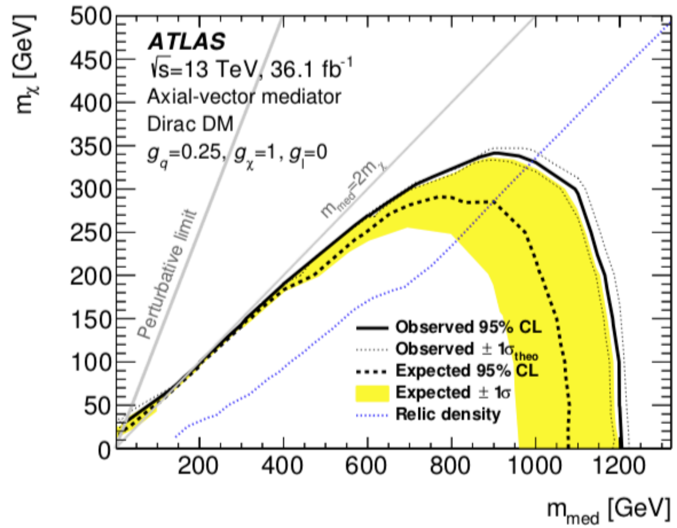
Search of invisible particles

- Reduced sensitivity for small production cross section.



Example of an analysis for the monojet triggerin CMS (~35 fb^{-1}).
The SM background template show the limited sensitivity even for a non negligible mediator production.

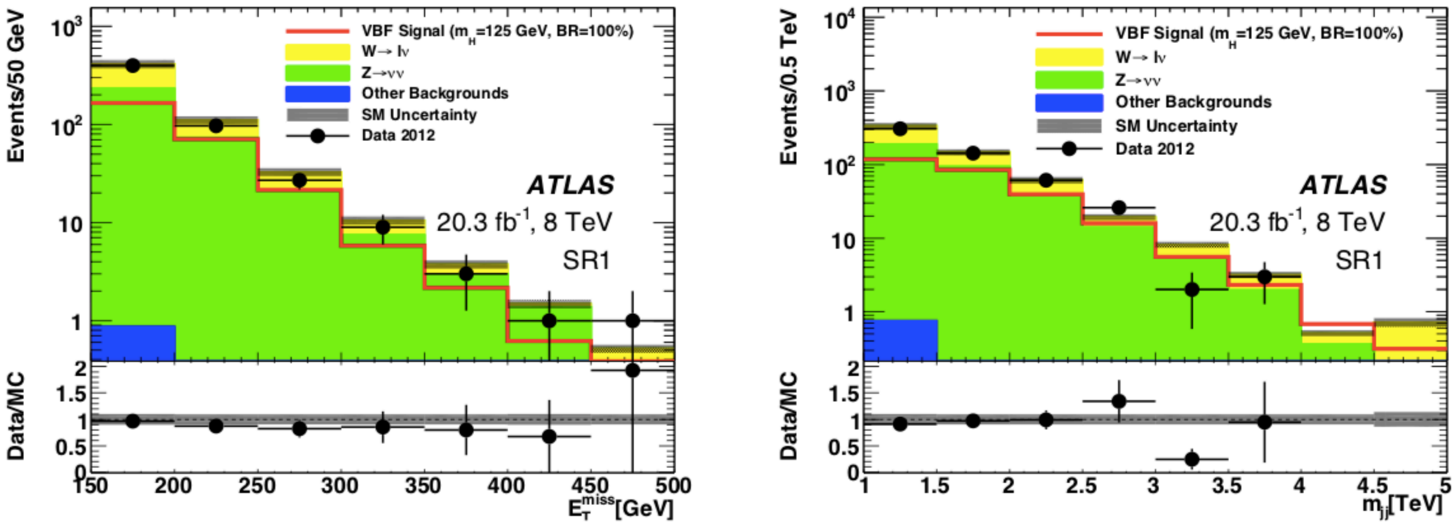
Only On-Shell production can be excluded



(c) Mono-photon exclusion [6]

Search of invisible particles

- Searches on dijet + missing Et and similaria have a better background rejection. As an example I show here invisible Higgs production, as a portal to DM, together to a dijet.



Vector Boson Fusion (VBF) Higgs production decaying into invisible particles

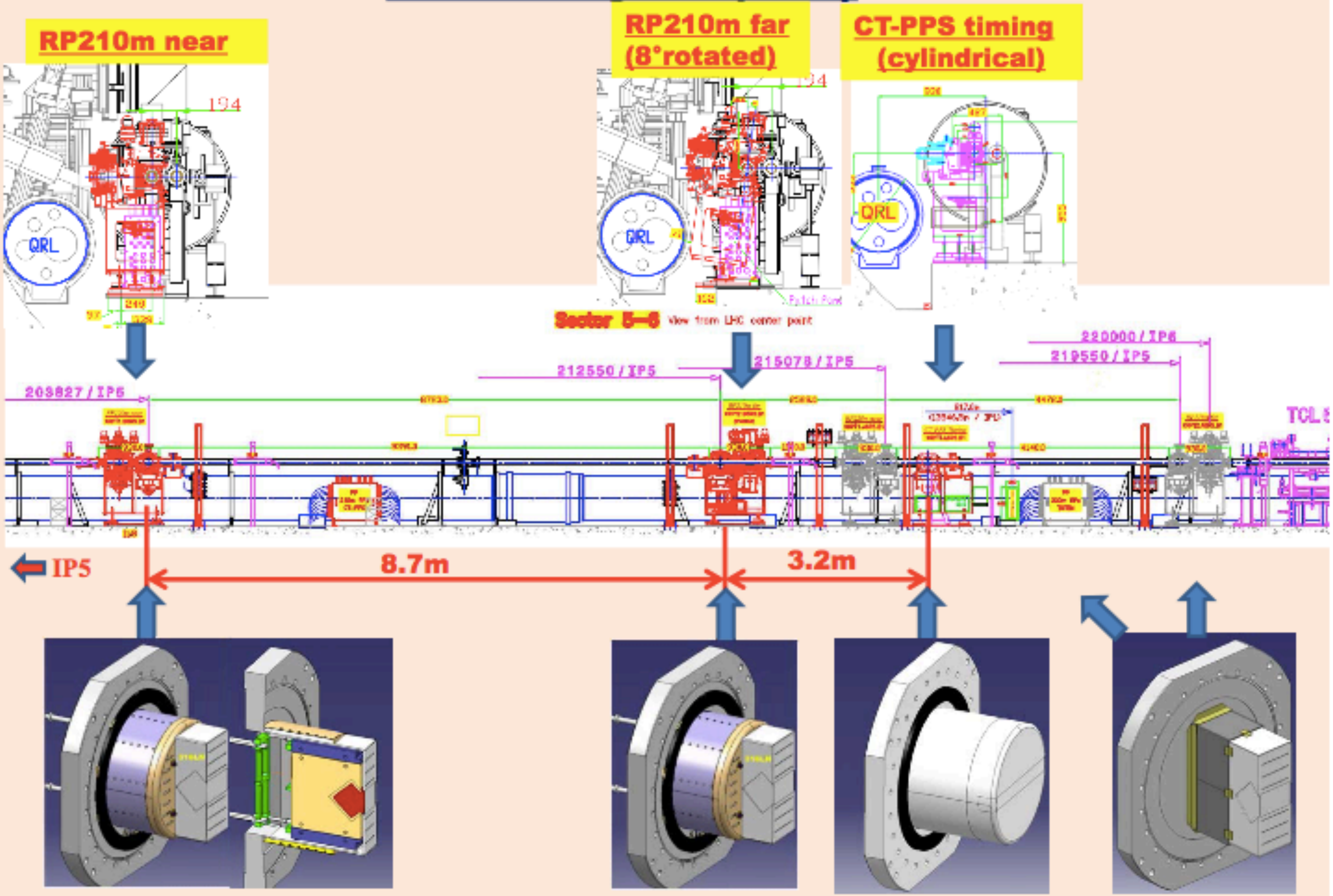
New methods

- The best way to detect an escaping mass is to have the production kinematics fully measured and compare it to the decay products.
  - This type of search can be performed in ee colliders where the production kinematics is fixed by the machine parameters and at lower energy scale has been performed by BaBar and will be performed in Belle II.
  - In this case the escaping mass is seen as a mass peak with the width dominated by the detectors resolution.
  - On the hadron colliders the initial state is completely unknown due to the compositness of the proton.
  - The Diffractive interactions although can bring some new insight on the production vertex if the two interacting protons survive the collision
    - Protons escaping the Exclusive Central Production in diffractive physics can be measured by forward spectrometers which give the interaction vertex information.

AFP and PPS

- Atlas and CMS/Totem have developed forward proton spectrometers.
- Proton detectors have been placed around 220m from the respective interaction region that can be placed at ~1.5mm from the LHC beam and measure the momentum lost by diffractive inelastic protons.
- The distance of the detectors from the beam and the crossing angles of the incoming protons give a lower cut in the lower mass acceptance.
  - AFP (Atlas) has vertical crossing angle and the acceptance is almost fixed due to the limited impact of the beam optics variations.
  - PPS (CMS) has horizontal crossing angle and the acceptance vary considerably during a fill.
- The maximum mass acceptance is given by the collimators aperture and is around 2TeV, a bit higher for PPS due to the crossing angle.

Tunnel layout (LSS)



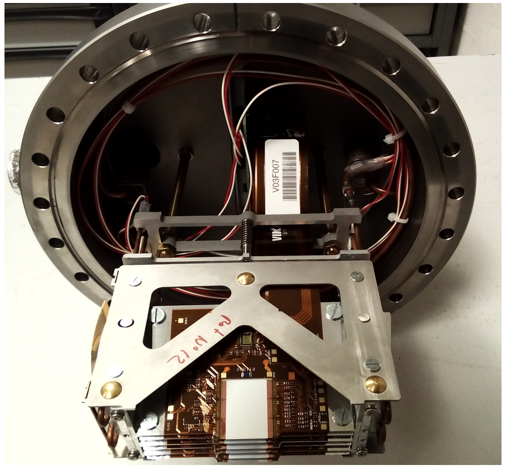
Faraday cage and circular ferrite; N1

Faraday cage and circular ferrite; N2

Cylindrical shape, circular ferrite; N3

Present rectangular

PPS detectors

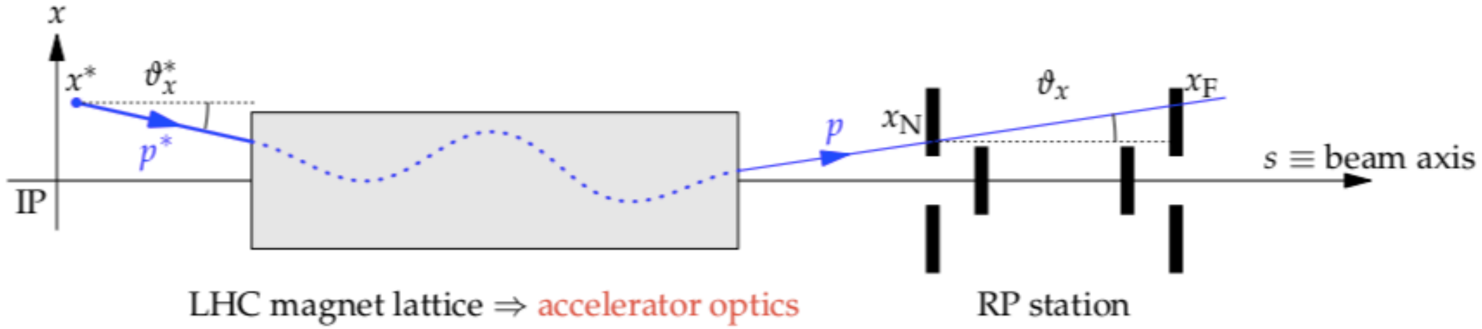


Silicon 3D pixels placed in 2 stations at 210m and 220m from the interaction point measure the deflection of the protons surviving the collision

Diamond detectors measure the time of arrival of the protons and disentangle the vertex position to cope with the pileup (50 interacting protons per bunch).
A special clock distribution electronics has been developed for this purpose.

Spectrometer principle

- *proton transport*: $(x^*, y^*, \theta_x^*, \theta_y^*, \xi) \longrightarrow (x, y)$ at a RP
  - x^*, y^*: transverse position at $z = 0$
  - θ_x^*, θ_y^*: scattering angles
  - $\xi = \Delta p/p$: relative momentum loss



- for PPS (low β^* optics), coordinates at RPs (wrt. beam):

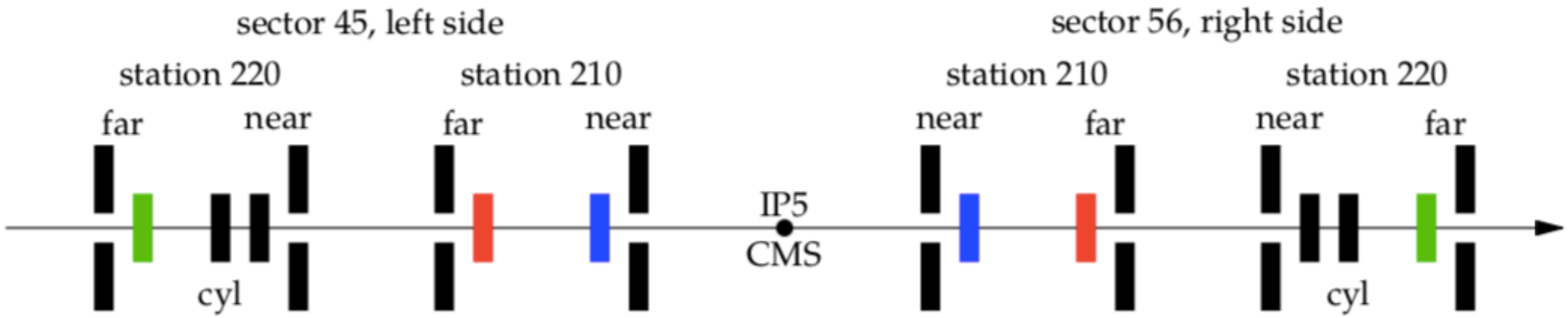
$$x = D_x(\xi)\xi + L_x(\xi)\theta_x^* + \dots$$
$$y = D_y(\xi)\xi + L_y(\xi)\theta_y^* + \dots$$

  - leading terms in red
  - optical functions: D = "dispersion", L = "effective length"
    - depend on crossing-angle, etc.

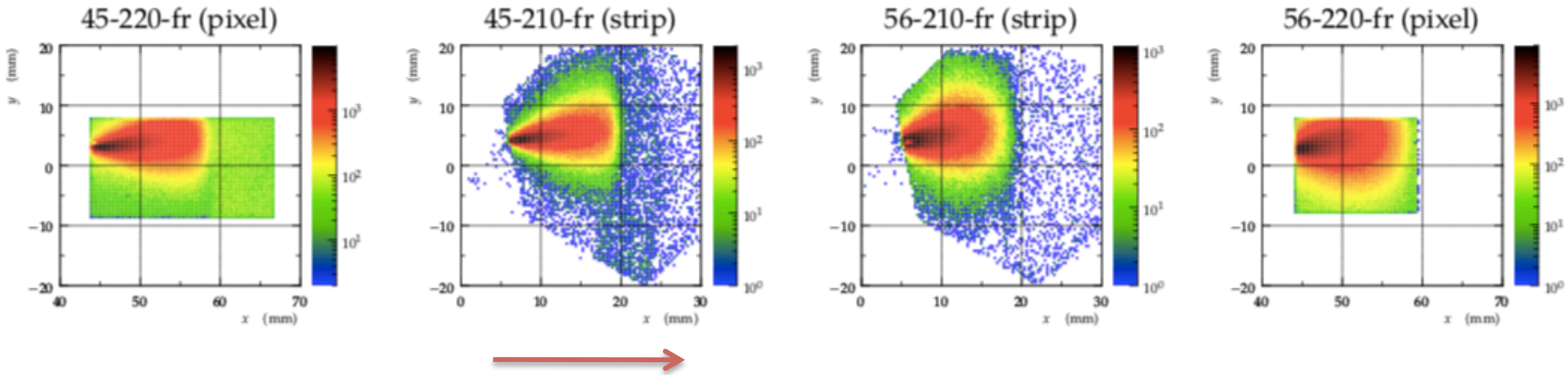
- *proton reconstruction* = inverted transport: RP measurements $\longrightarrow$ IP
  - "single RP" reconstruction: "$\xi = x/D_x$"
  - "multi RP" reconstruction: χ^2 minimisation to find proton kinematics that reproduce RP measurements

Spectrometer principle (PPS)

- Roman Pot layout in 2017: strips (red) and pixels (green)



- example hit distribution



Proportional to the momentum lost.

Spectrometer validation

- A first study performed by the PPS spectrometer has been the search for exclusive diffractive production in SM physics.
- A first paper has been published by CMS and Totem for semiexclusive dilepton production, using two mu or two electrons with proton tag.(https://arxiv.org/abs/1803.04496)
- The study certify the instrumentation and calibrate absolutely the spectrometer.

Missing Masses search with forward spectrometers

- One can measure the mass produced in a exclusive diffractive event with two proton tagged by the simple relation:

$$\Delta\eta_{1,2} = -\ln \xi_{1,2}, \quad M^2 = \xi_1 \xi_2 s$$

  - Where ξ is $\Delta p/p$ for each proton respectively
- An exclusive escaping mass cannot be triggered unless a proton trigger is setup.
- For the moment, due to the difficulty to get tracks information at trigger level the proton trigger is not yet conceived.
- In any case one can trigger on specific mono channels or dijet/dilepton channels and start a search.

Missing Masses search with forward spectrometers

- The basic search is just the four momentum balancing of the protons and the visible particles from the interaction vertex, the escaping mass can be seen as a peak in the missing mass spectrum
- This search is very efficient for masses above 400 GeV up to 2/2.5 TeV and absolutely model independent.
- The main background is given by pileup protons from single diffractive events (from different vertices) that have one order of magnitude more cross section than the central production with both protons surviving.
- The shape and the templates for the background can be easily calculated by the data themselves.
- Production cross section of about 10fb can be reached if such event type happens.

Missing Masses search with forward spectrometers

- A typical diffractive event is mediated by gluon-gluon fusion and photon-photon interaction.
- While for low masses the gluon gluon fusion is the main interaction the second become the most important for masses above 200 GeV.
- This means that the main processes that involve qq interaction have a production suppression factor due to a fermion loop with the photons.
- A Higgs portal can be conceived with photons although suppressed.
- The main gain is that if an invisible particle is produced by a photon photon collision, the quantum numbers of the particle are automatically fixed by the the production mechanism. Indeed the diffractive interaction has two possible option 0++ or 2++.

Conclusions

- Invisible particle detection at LHC is far from the easiest task for the experiments.
- Several methods have been studied for this task.
  - Resonances from a new particle is among the most studied (suppressed by branching fractions)
  - Missing Et on special trigger configurations, like the MonoJet or mono-anything, dijet, dilepton etc. are the main tool for DM searches.
  - All these methods show a minimal sensitivity for small production cross section.
  - Quantum properties of a new detection are among the most difficult tasks for these channels and it requires the detection on different searches.
- A new method, based on the forward proton spectrometers is very promising although the production mechanism has suppression factors.
- The sensitivity instead is relevant.
- The acceptance for any event is quite high and only limited by proton acceptance ~0.5, and central detector forward acceptance ~0.5.
- If any signal will be detected with the proton spectrometers, the quantum properties of the new detected particles will be measured easily.