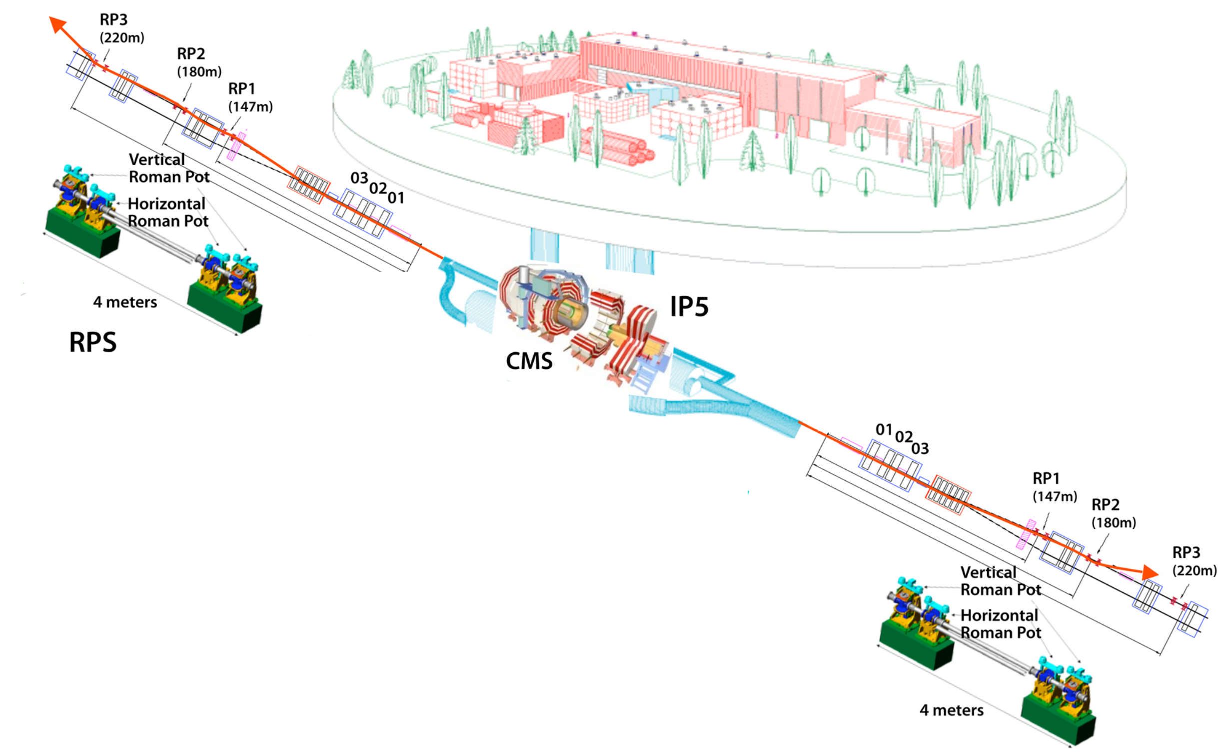
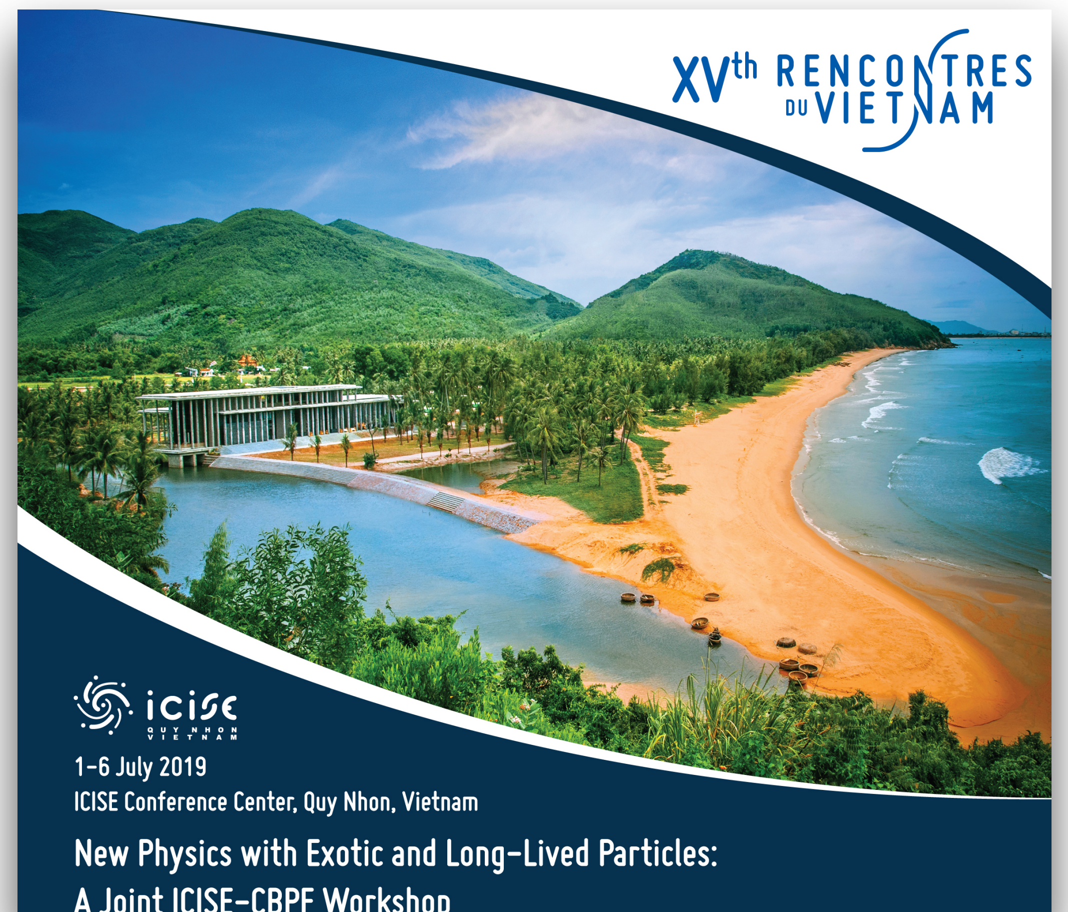
Exotica in the forward region at the LHC





Arthur M. Moraes

Centro Brasileiro de Pesquisas Físicas - CBPF

Outline:

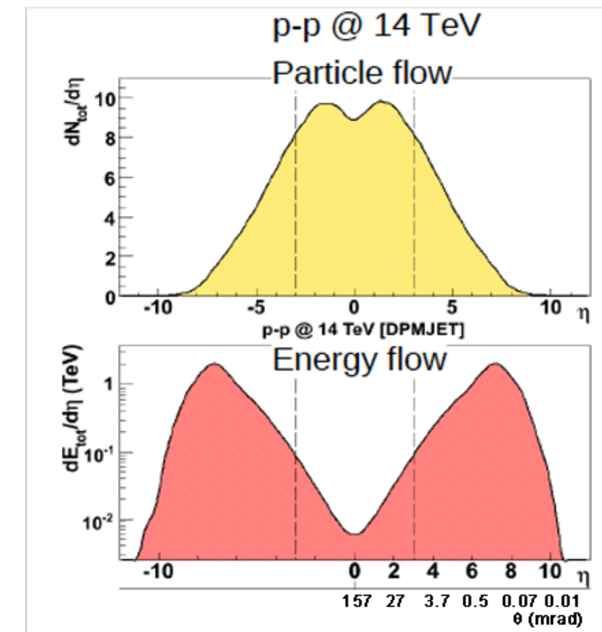
- *Forward detectors at the LHC: CMS-PPS and AFP*
- *Anomalous quartic gauge couplings (AQGC)*
- *Searches for axion-like particles*
- *Dark Matter and SUSY*

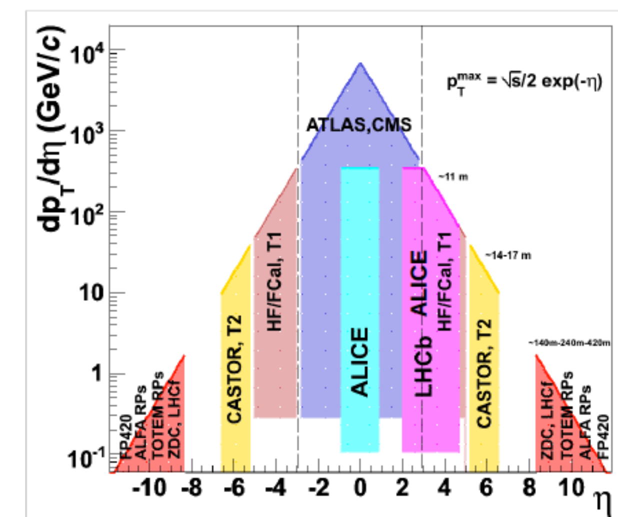
Disclaimer: obviously there are many results we will not be able to show in this talk! This talk is an attempt to present some of “selected” results on the use of forward proton tagging at the LHC. For a complete list of results, please check:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/

The Large Hadron Collider

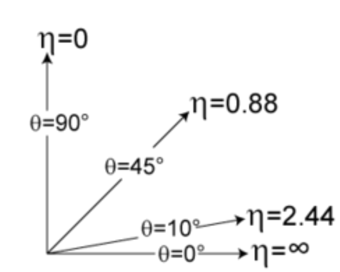


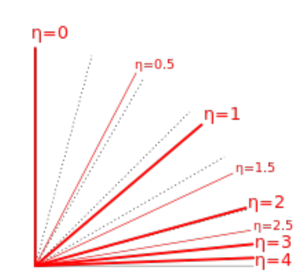


Searching for "new" physics at the LHC:

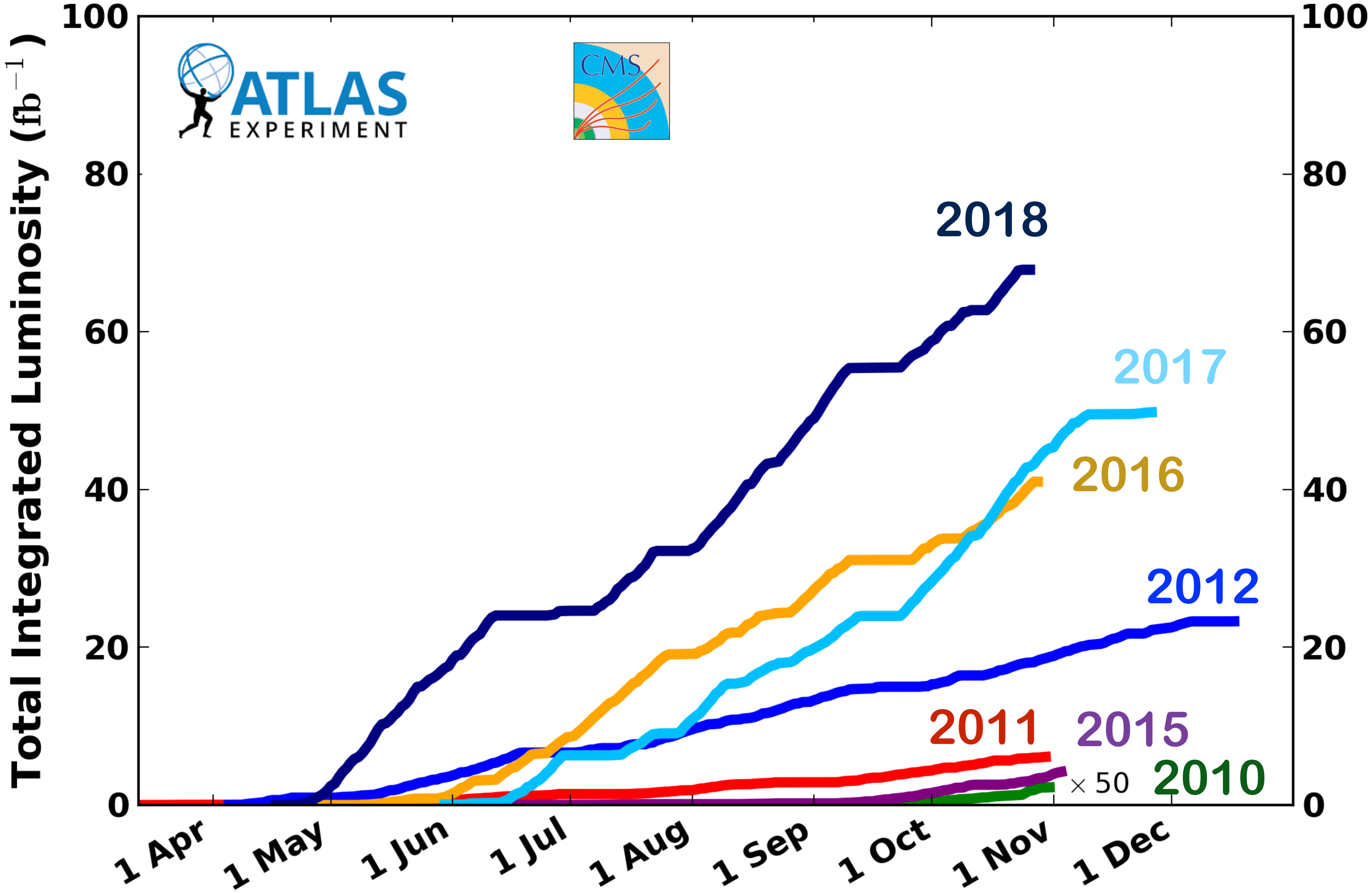
- test predictions at high(est) energies with large statistical samples of rare processes;
- detector allow measurements with remarkable precision and fiducial coverage (wide x-coverage; unprecedented high-Q^2 interactions)
- unprecedented coverage of the forward region ($|\eta| \gtrsim 5$)

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$





The Large Hadron Collider: pp collisions



The LHC has also delivered several runs on pA and AA collisions.

https://lpc.web.cern.ch

$\sqrt{s}$=0.9 TeV

$\sqrt{s}$=7 TeV & 8 TeV

"Long Shutdown 1"

$\sqrt{s}$=13 TeV

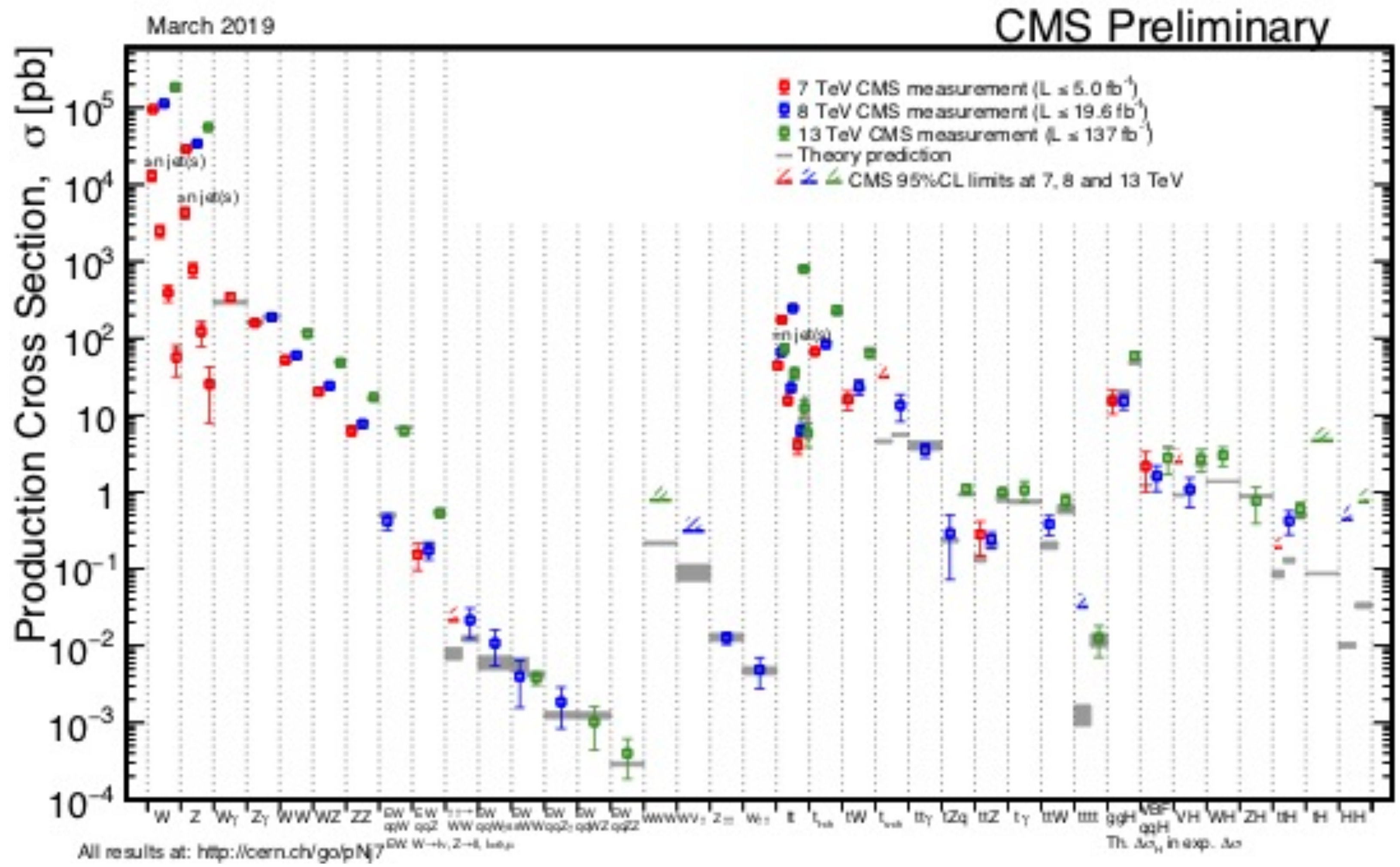
"Long Shutdown 2"

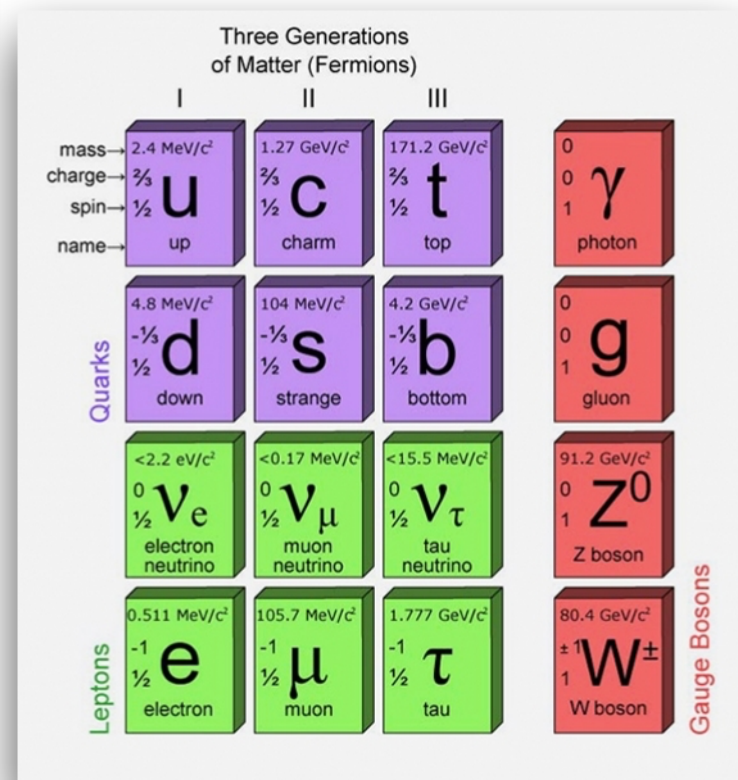
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Run 1

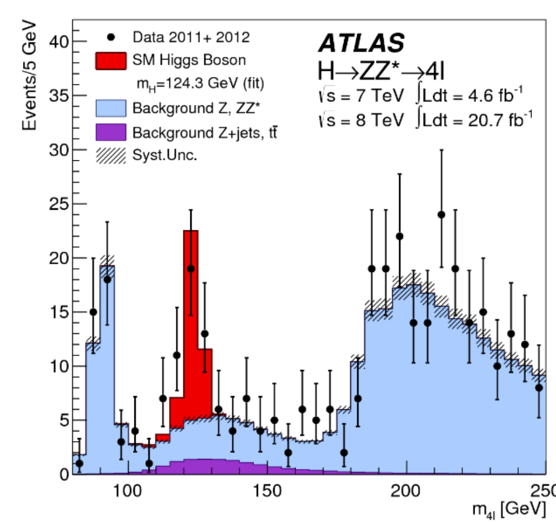
Run 2

What have we learned?





So far, the SM is very successful in describing our data.



François Englert (Belgium) Peter Higgs (United Kingdom)

Nobel Prize in Physics 2013

Many questions still not answered by the SM: we're looking for signals of "new" physics!

Needle in a haystack problem!

p-p collisions are messy!

QCD background

Unprecedented pile up

Higgs boson (?)

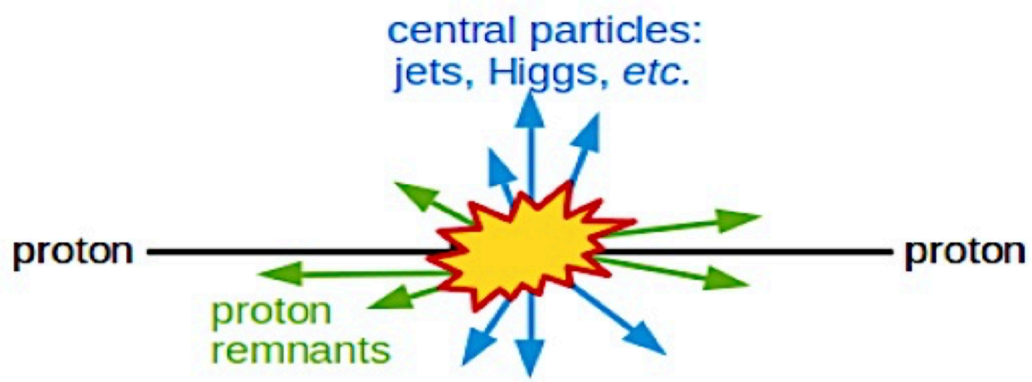
SUSY decay (?)

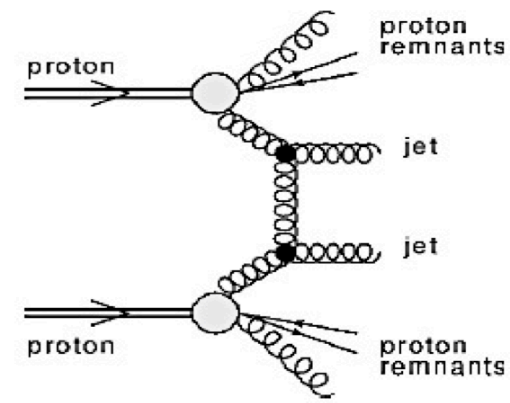
heavy resonance (?)

LLP (?)

Physics in the Forward Region

At the LHC p-p collisions will typically lead to particles produced in the central region and the fragmentation of the incoming protons (proton remnants)

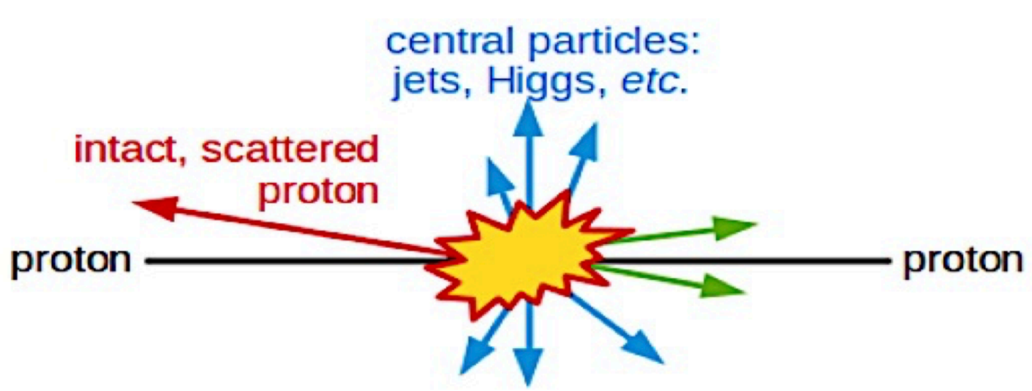


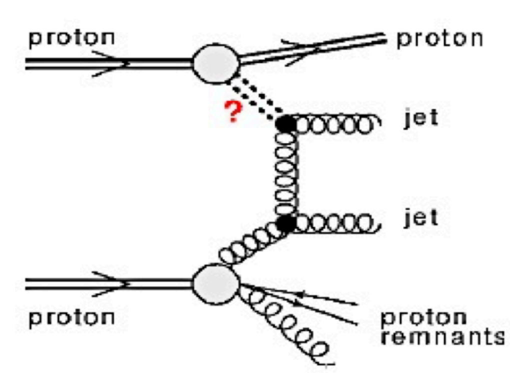


Can the colliding proton(s) remain intact?

Yes, but the exchanged object in the collision must not change the proton's quantum numbers:

- Electromagnetic interaction: photon exchange
- Strong interaction: Pomeron exchange

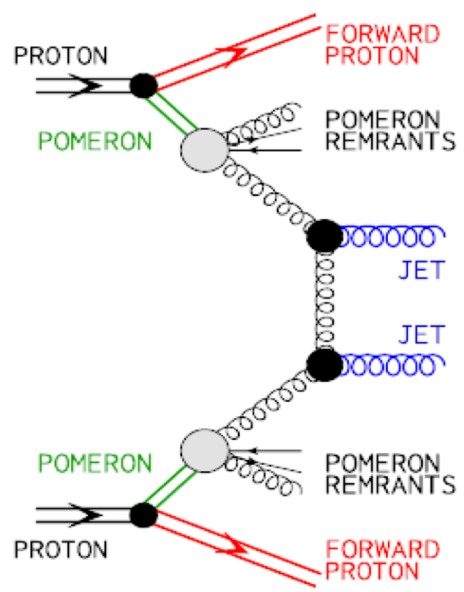




Physics in the Forward Region: diffractive and BSM processes

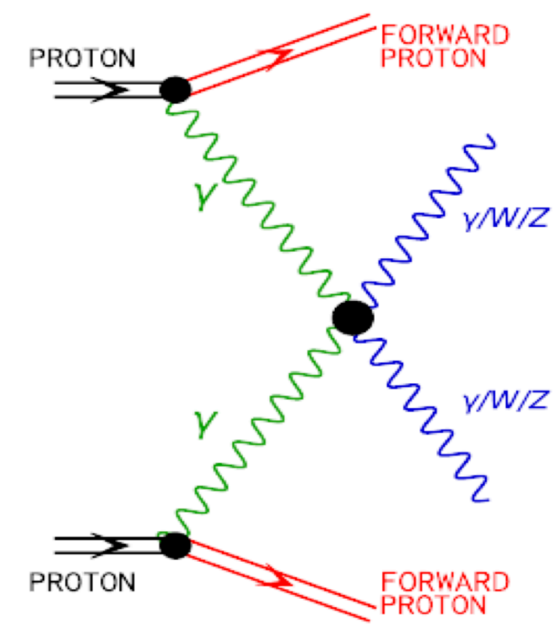
Hard diffractive processes

- perturbative calculation methods,
- one, or both interacting protons stay intact,
- example: double Pormeron exchange di-jet production.



Beyond Standard Model (BSM) processes

- focus on processes with two intact protons,
- exclusivity - all produced particles are measured (strong background suppression w.r.t. standard analysis)
- examples: Anomalous Quartic Couplings, Dark Matter, etc.



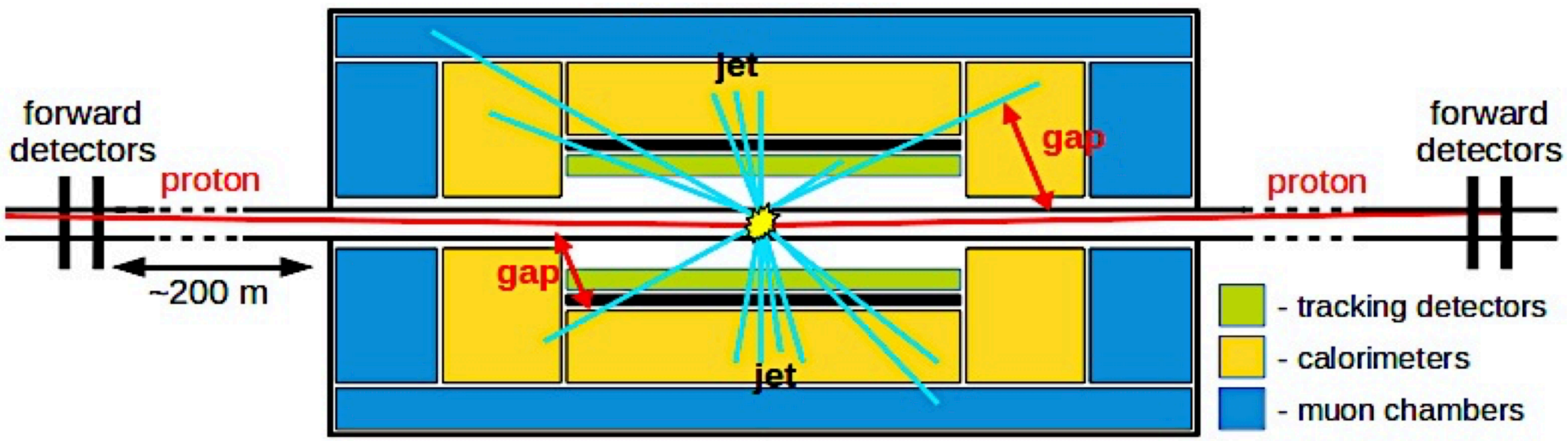
Characteristic observables:

- **presence of scattered forward proton,**
- **rapidity gap: no particles produced between central system and scattered proton**

Physics in the Forward Region: detection methods

Diffractive topology (“typical”)

- rapidity gaps
- central system and one or both interacting proton(s) stays intact



Method 1 (rapidity gap):

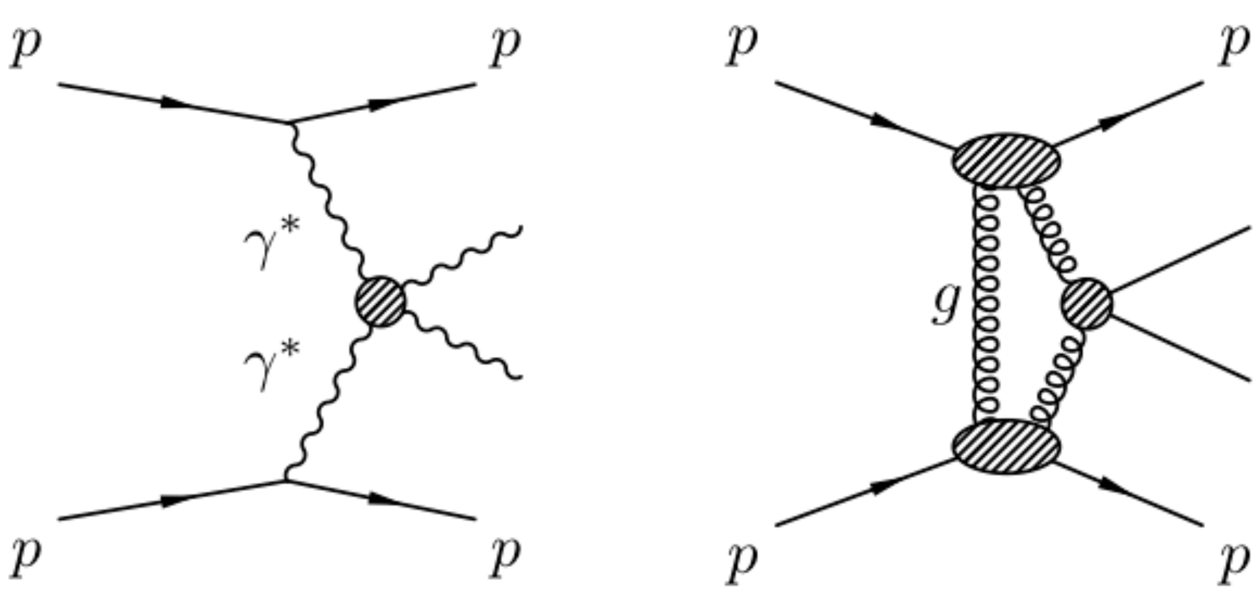
+ classical recognition method
+ no need for additional detectors “very forward”
- gap may be killed by e.g. particles from pile-up
- gap may be outside acceptance of central detectors

Method 2 (forward protons):

+ protons are directly measured
+ can be used in pile-up events
- protons scattered at very small angles
- forward detectors need far away from IP

Forward Region at the LHC: opening new horizons for BSM searches

The physics program consists of interesting events giving intact protons in the forward region



The **CMS Precision Proton Spectrometer** (CMS-PPS) and the **ATLAS Forward Proton** detectors (AFP) provide an opportunity for new searches and measurements

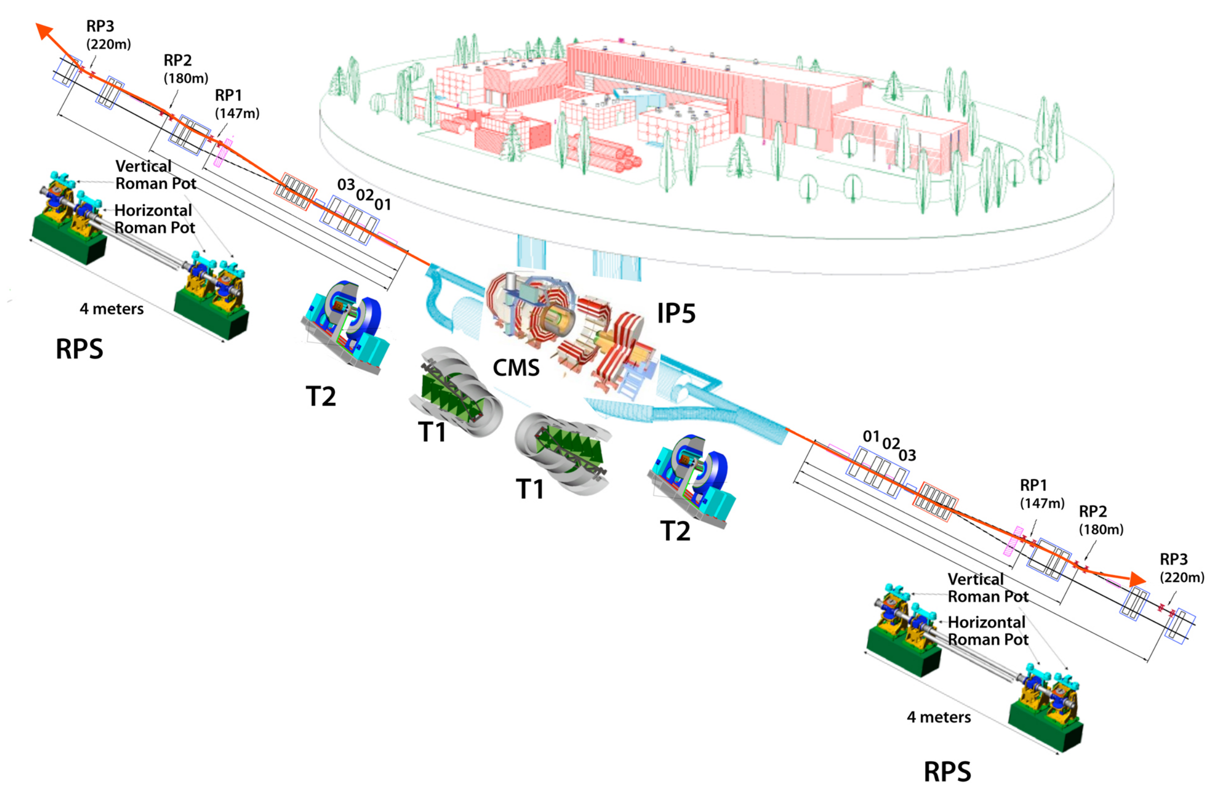
Possibility of a **very strong background suppression** using intact protons in the forward region.

Forward proton tagging: complementary to the “central” (standard) searches.

Searches in the Forward Region at the LHC

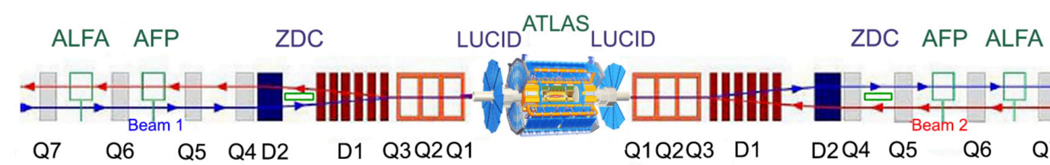
CMS - PPS

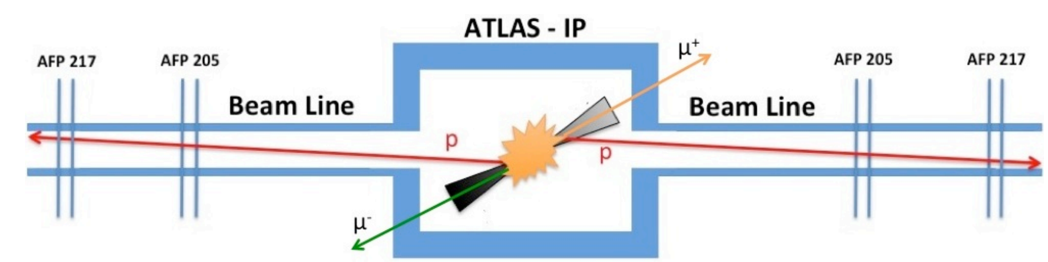
CMS Precision Proton Spectrometer



AFP

ATLAS Forward Proton detectors





LHC magnets bend scattered protons out of the beam envelope.

Detect protons at about ± 200m from the interaction point (IP1 for ATLAS and IP5 for CMS)

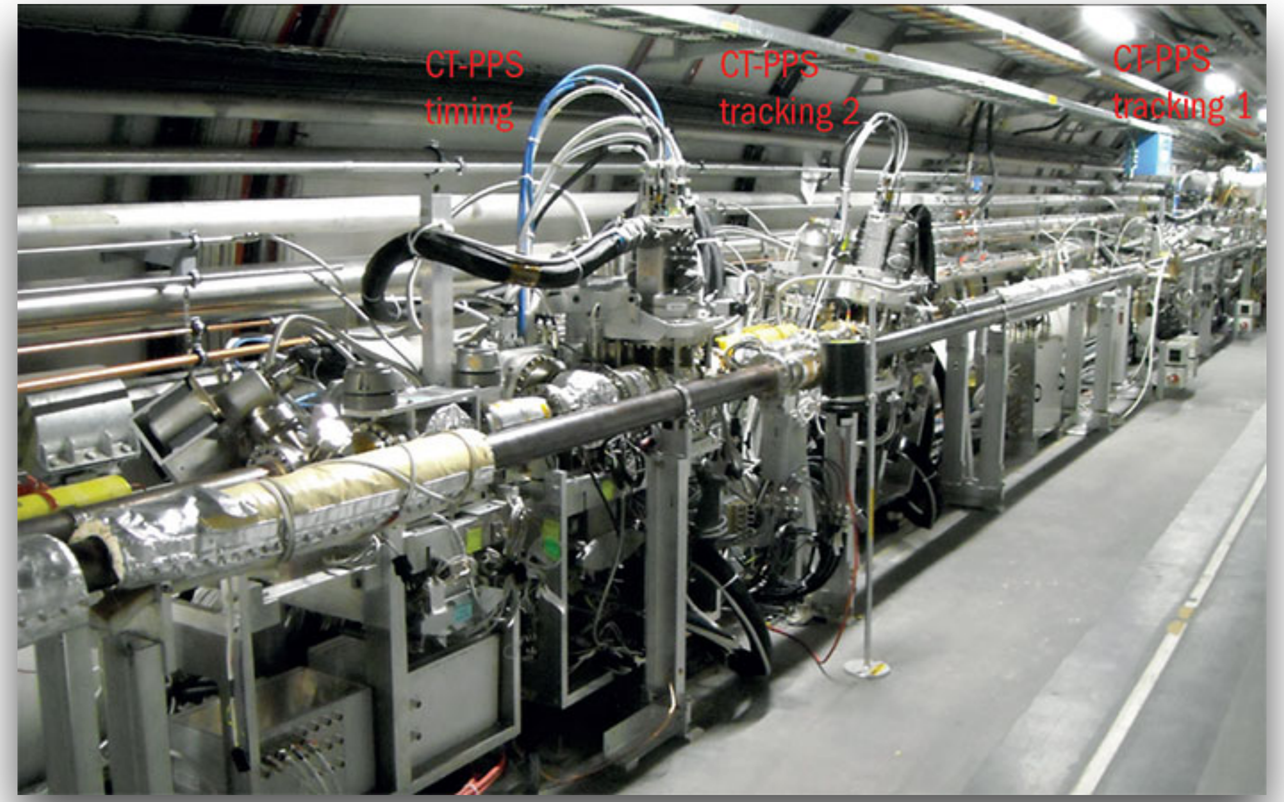
Detect scattered protons a few mm from the beam on both sides of CMS and ATLAS

The LHC was built as a discovery machine. Forward region instrumentation allow us to do it with extreme precision!

Searches in the Forward Region at the LHC

CMS - PPS

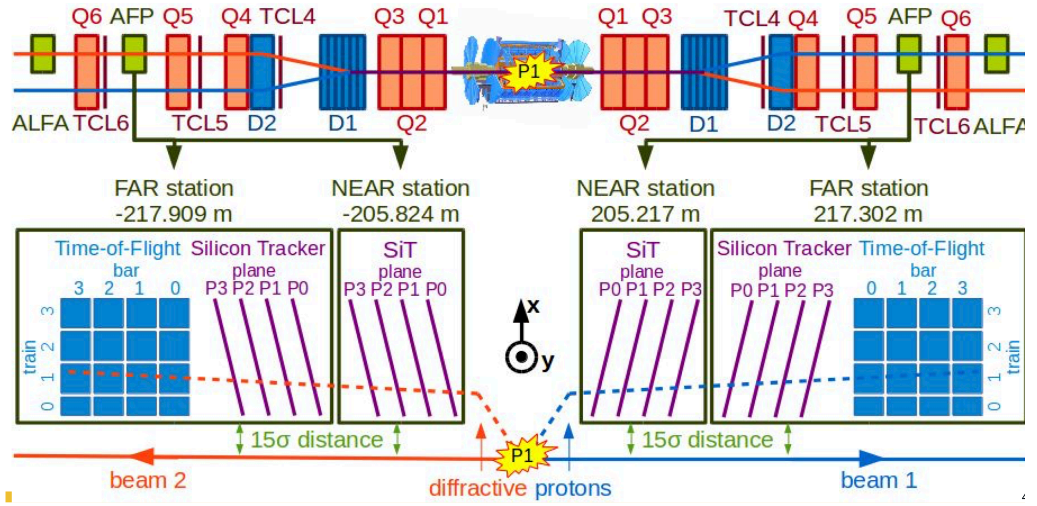
CMS Precision Proton Spectrometer

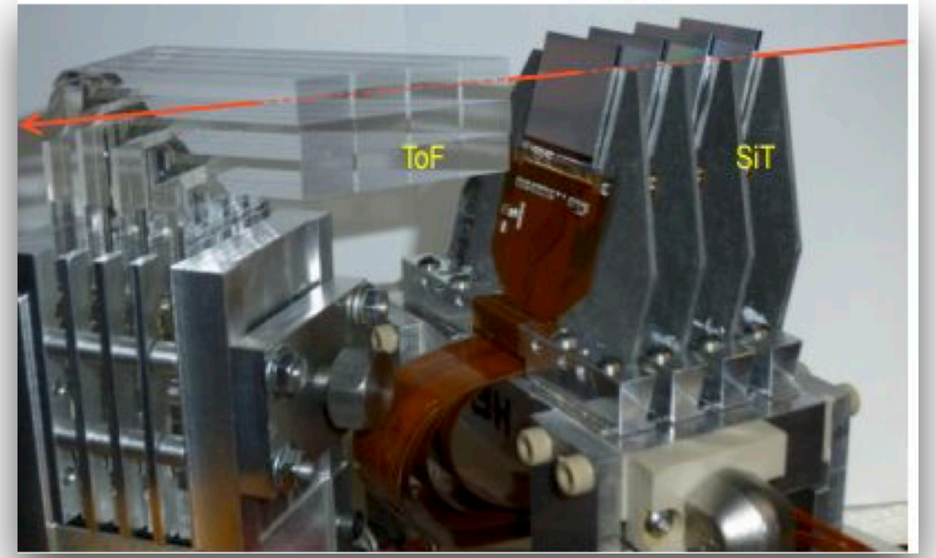


Operation in high-luminosity environment causes radiation damage to the sensors
(damage is proportional to integrated luminosity and is visible in the increase of Low Voltage in SiT modules)

AFP

ATLAS Forward Proton detectors

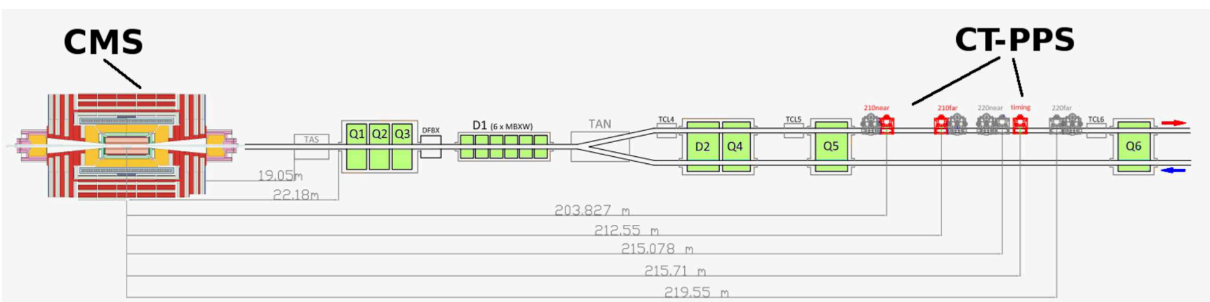




Searches in the Forward Region at the LHC

CMS - PPS

CMS Precision Proton Spectrometer



Near and far stations on both sides

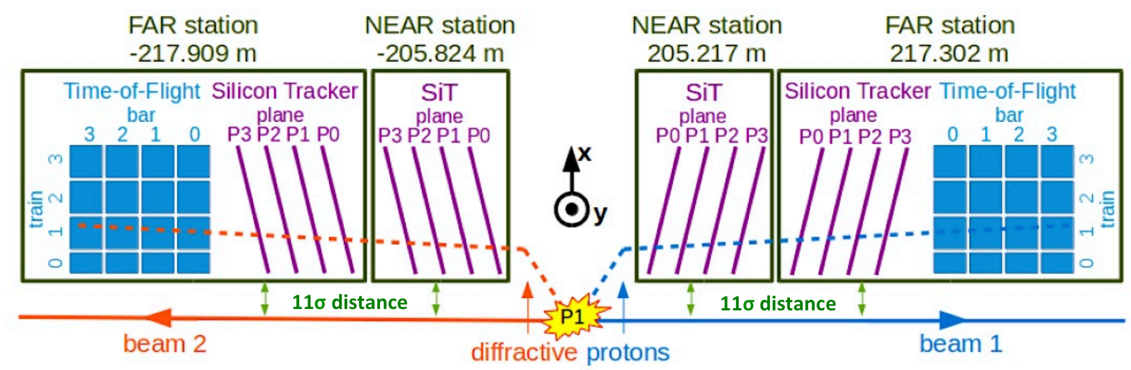
Reconstruct $\xi = 1 - p_f/p_i$

Central system mass acceptance
350 GeV < M_X < 2 TeV

Collected ~10 fb^{-1}, 40 fb^{-1}, 58 fb^{-1} in 2016, 2017 and 2018 respectively

AFP

ATLAS Forward Proton detectors

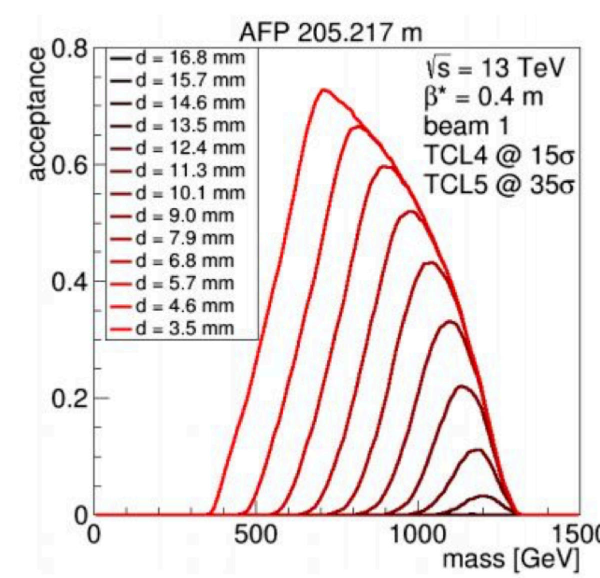


In 2016 AFP was only inserted during special, low luminosity runs (single-arm with two detectors - SiT).

The 2017 data recorded from AFP was almost 32 fb^{-1}

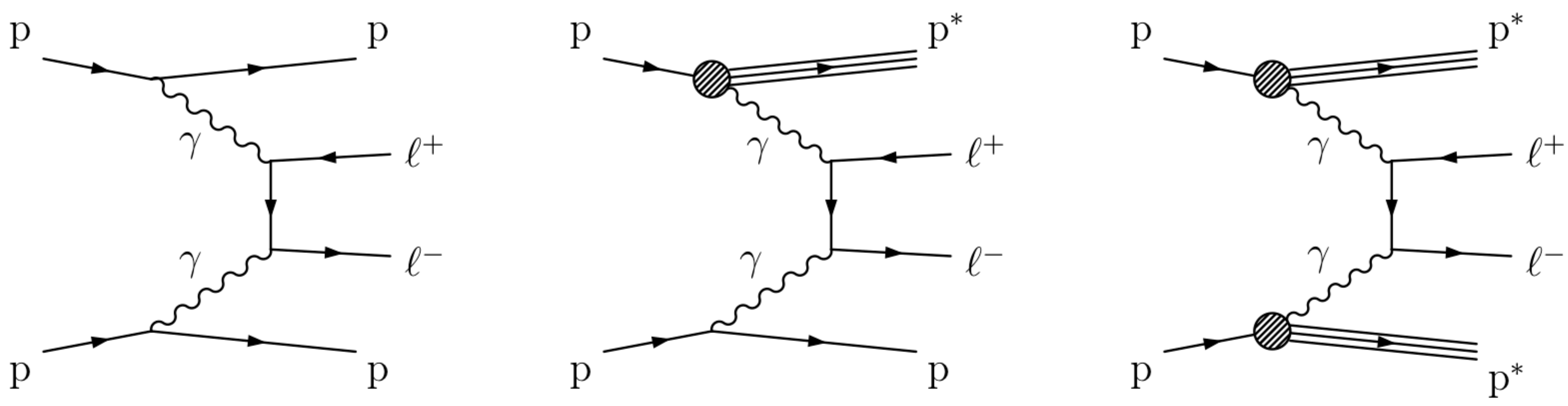
The 2018 data recorded from AFP was almost 49 fb^{-1}

AFP mass acceptance



Exclusive di-lepton production

(making sure the idea works!)



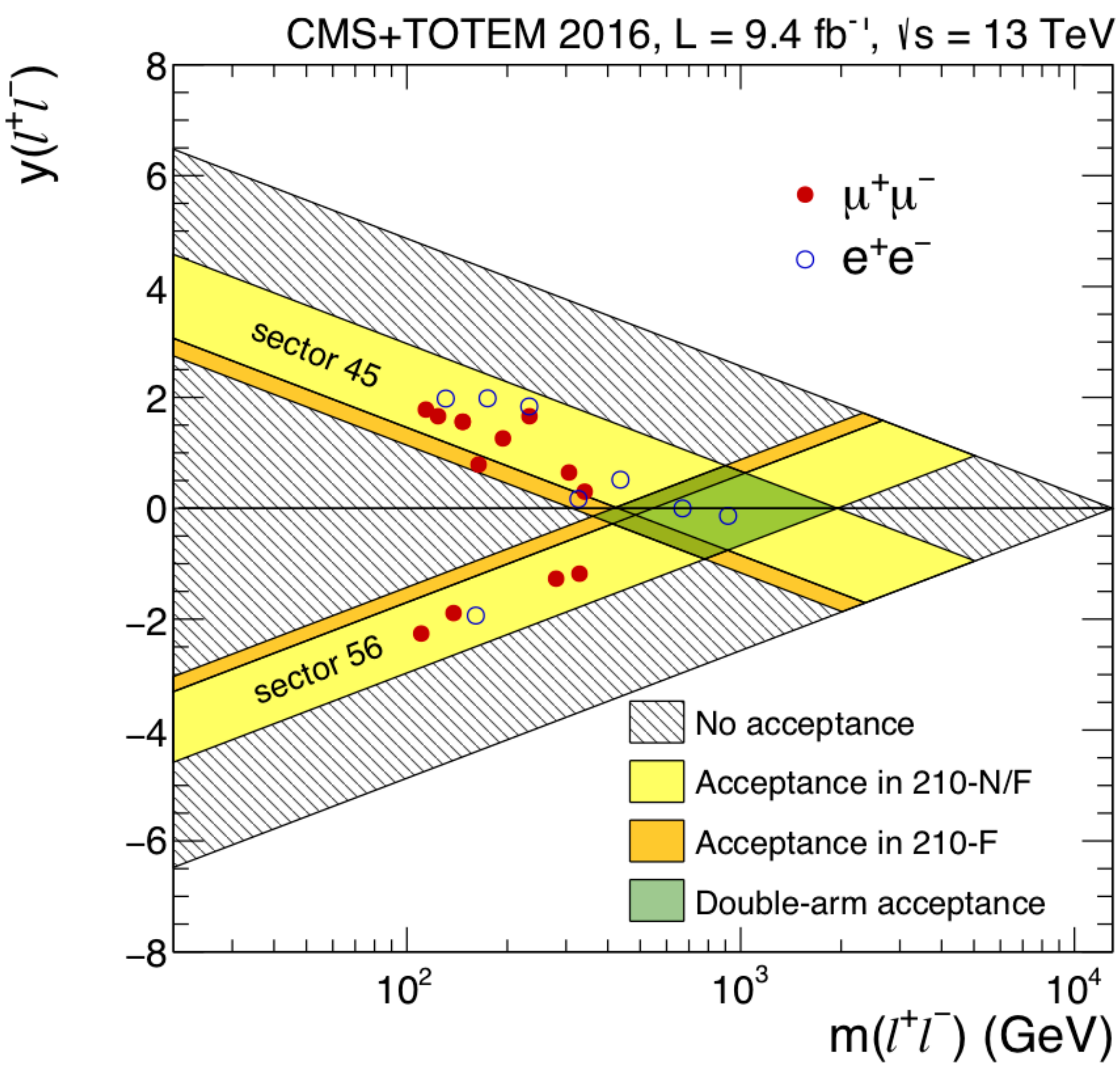
First observation (5.1σ) of the process at high mass with intact protons

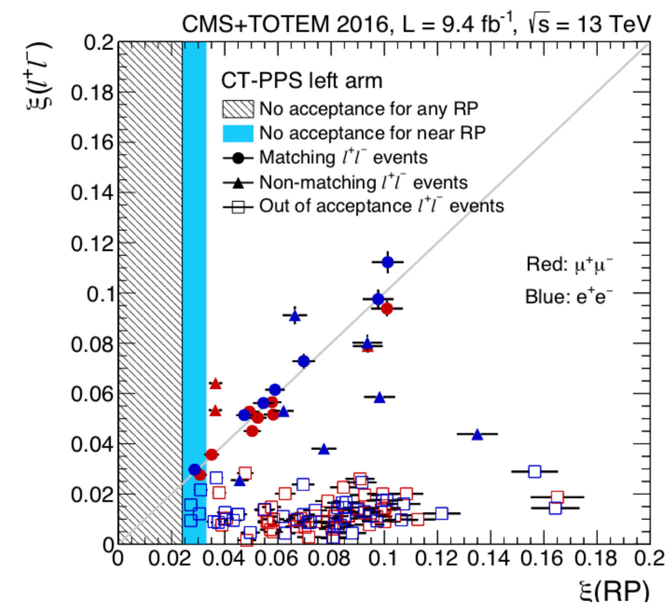
(first observation of proton-tagged $\gamma\gamma$ collisions at the electroweak scale)

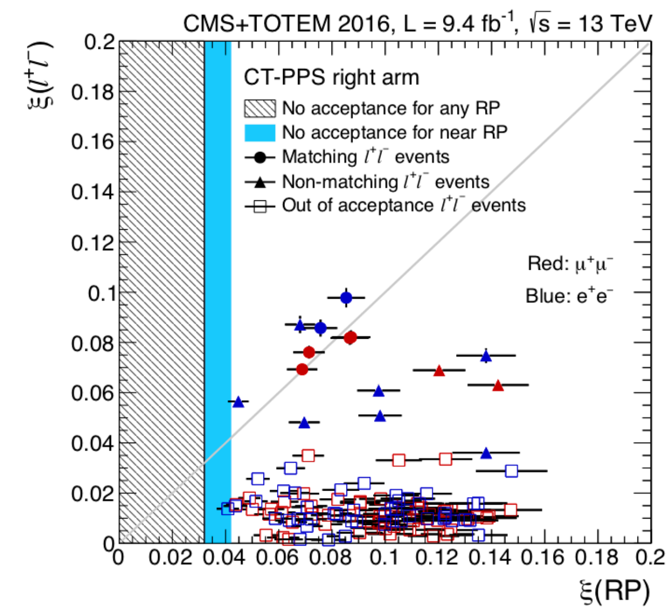
Searching for exclusive and semi-exclusive events. Event selection:

- Request pair of opposite sign leptons
- p_T > 50 GeV
- **M_{ll} > 110 GeV (above Z peak)**
- Back-to-back acoplanarity and cleanliness of the dilepton vertex
- At least one forward proton PPS

Exclusive di-lepton production

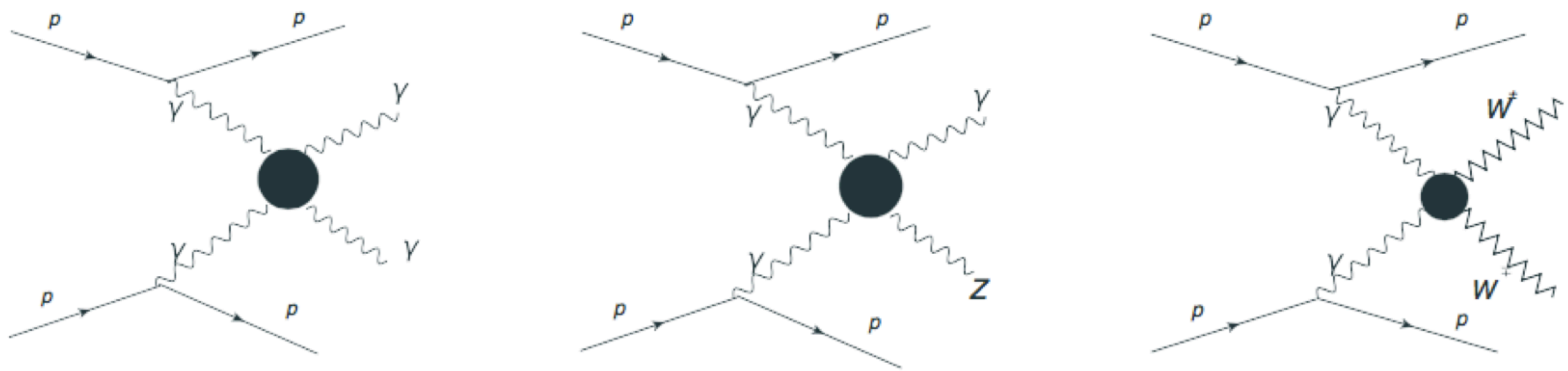






- Di-lepton invariant mass and rapidity within expected range of acceptance
- A total of 12 $\mu^+\mu^-$ and 8 e^+e^- pairs with $m(\ell^+\ell^-) > 110$ GeV, and matching forward proton kinematics, are observed
- Highest mass events - **342 GeV** (μ+μ-), **917 GeV** (e+e-)
- All events are semi-exclusive (single tagged)

Anomalous quartic gauge boson (aQGC)



- Photon induced processes with intact protons in forward regions
- Exclusive processes with a very clean signal

$$\mathscr{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_S m)^{-2} d_{1,s}$ where f_S is the γγX coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$ GeV^{-4}.

- PPS and AFP provide the best sensitivity to anomalous couplings due to proton tagging

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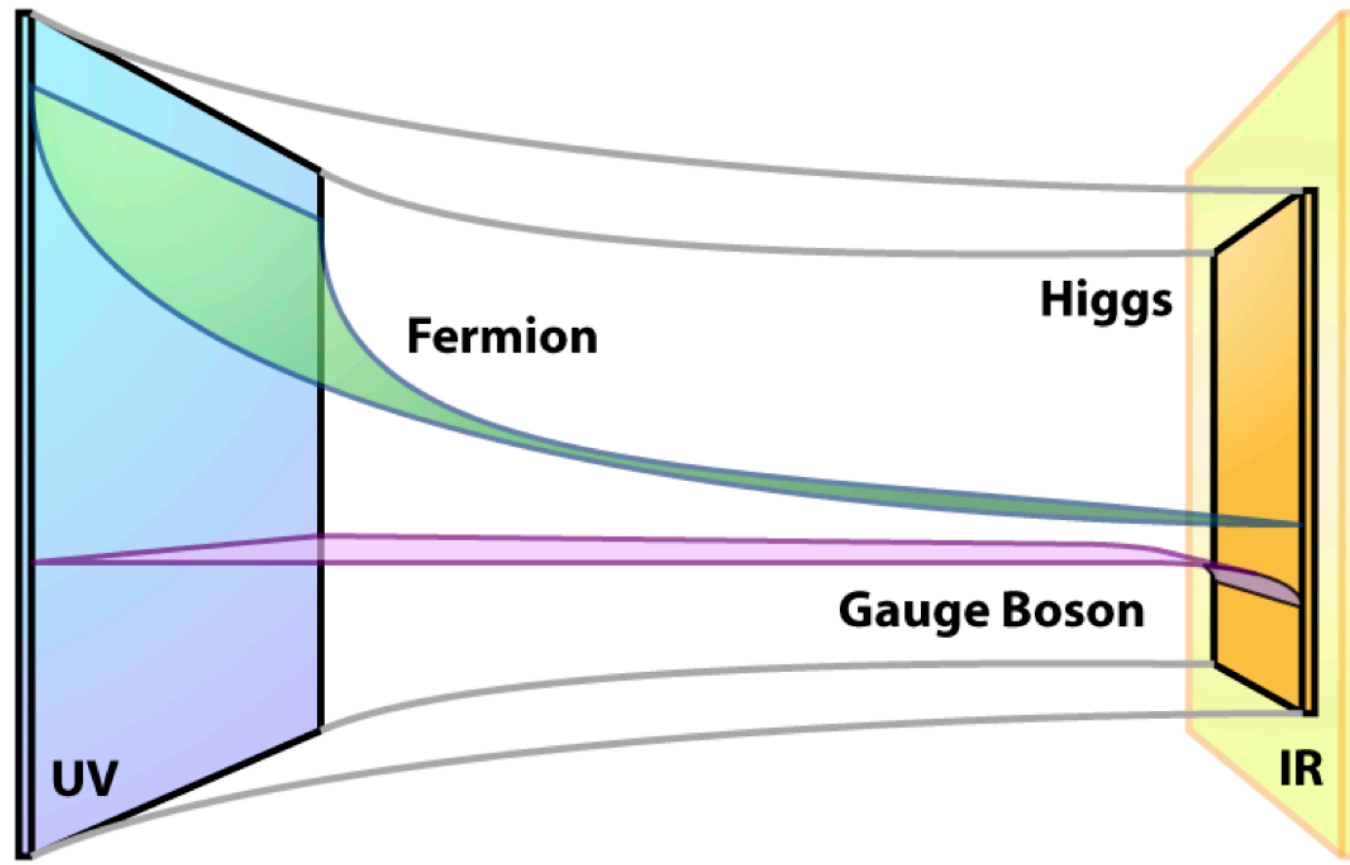
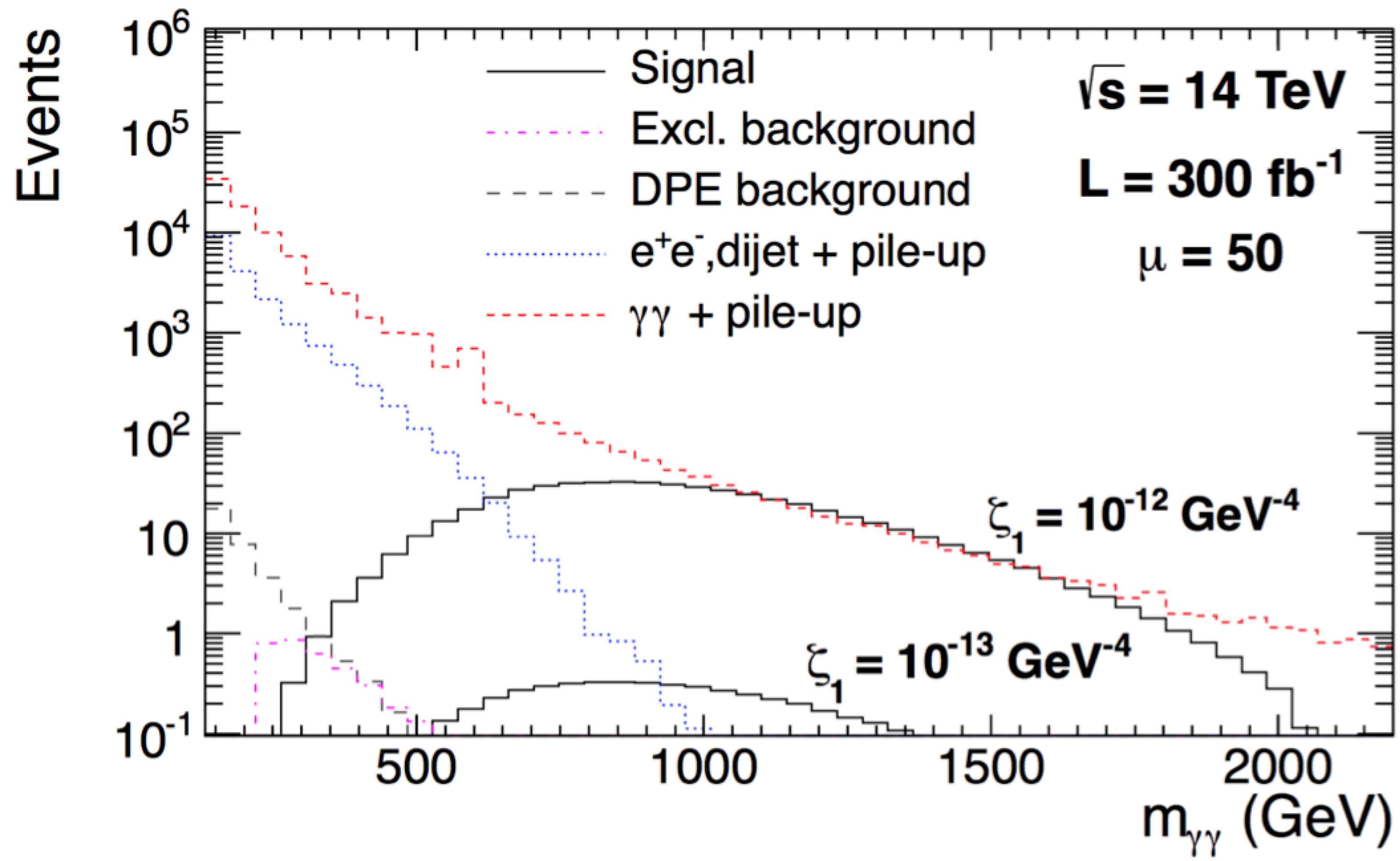
Motivations for aQGC

- Warped Extra Dimensions solve hierarchy problem of the SM
- Predicted by Composite Higgs, Kaluza-Klein, Extra Dimensional models
- Couplings can be probed independently of models
- Effective 4-photon couplings $\zeta_i \sim 10^{-14}$ - 10^{-13} GeV^{-4} possible

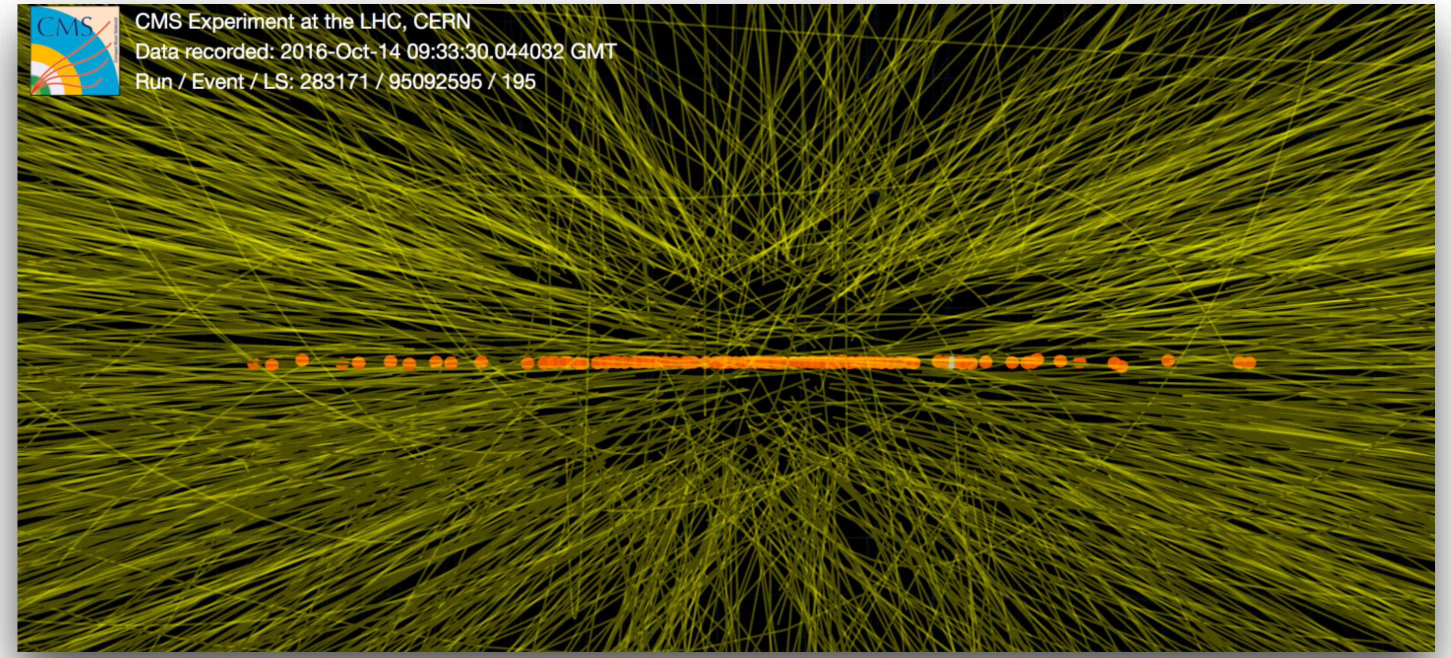


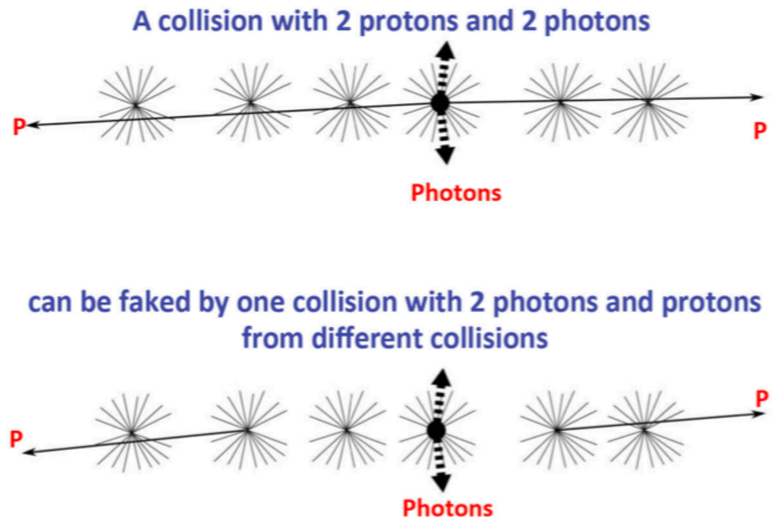
aQGC - Backgrounds

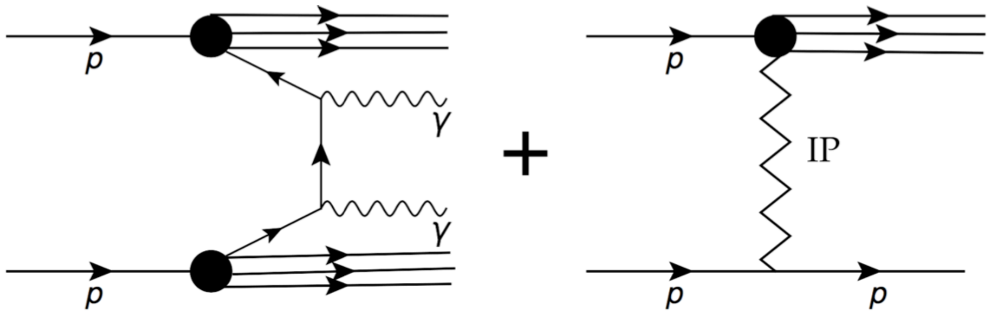


- Requesting two protons identified in forward detectors + two converted photons in central detector
- All backgrounds considered: DPE diphoton production, H→γγ, exclusive γγ production, dilepton misidentification, pile-up, Drell-Yan,…
- **Pile-up is the main source of background**

Pile-up: background source



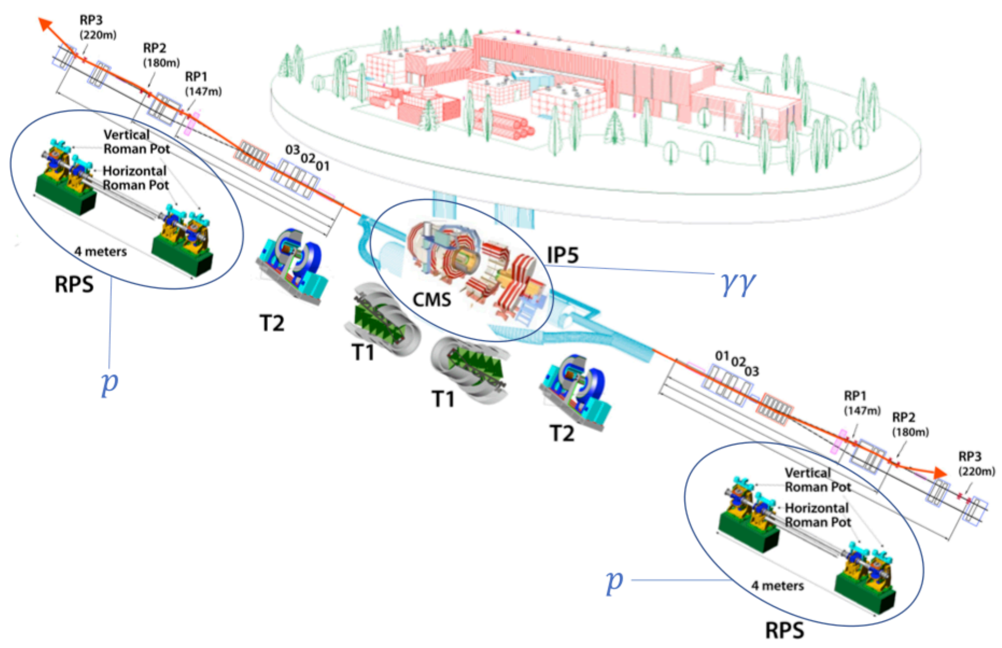




The dominant background for central exclusive diphoton production comes from non-exclusive photon pair production (left) overlapped with uncorrelated protons coming from soft diffractive processes in the additional interactions per bunch crossing (right).

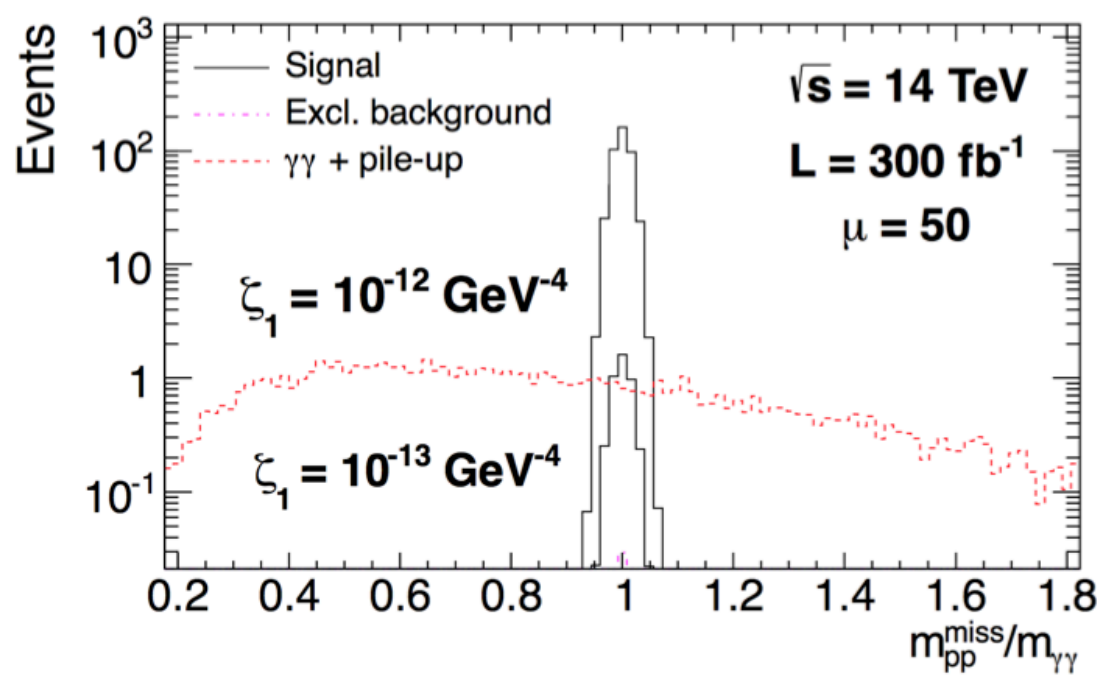
- The LHC collides “packets” of protons
- Pile-up causes interference from particles generated at unrelated vertices
- For LHC beam conditions in 2017-18: ~50 pile-up vertices

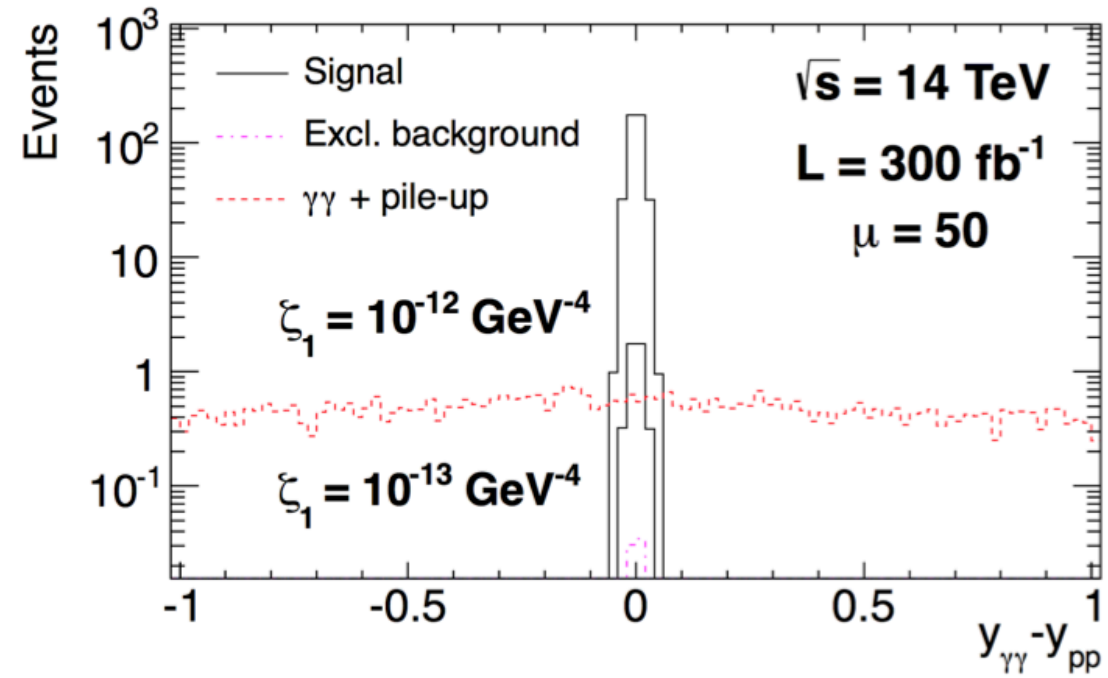
Dealing with pile-up



Cut / Process	Signal	Excl.	DPE	e^+e^-, di-jet + pile up	$\gamma\gamma$ + pile up
standard	20.8	3.7	48.2	$2.8 \cdot 10^4$	$1.0 \cdot 10^5$
$p_{T1} > 200\text{GeV}, p_{T2} > 100$ GeV	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	16.6	0.2	0	0.2	1023
$p_{T2}/p_{T1} > 0.95, \lvert\Delta\phi\rvert > \pi - 0.01$	16.2	0.1	0	0	80.2
$\sqrt{\xi_1 \xi_2 s} = m_{\gamma\gamma} \pm 3\%$	15.7	0.1	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	15.1	0.1	0	0	0

Exclusivity cuts using proton tagging needed to suppress background!





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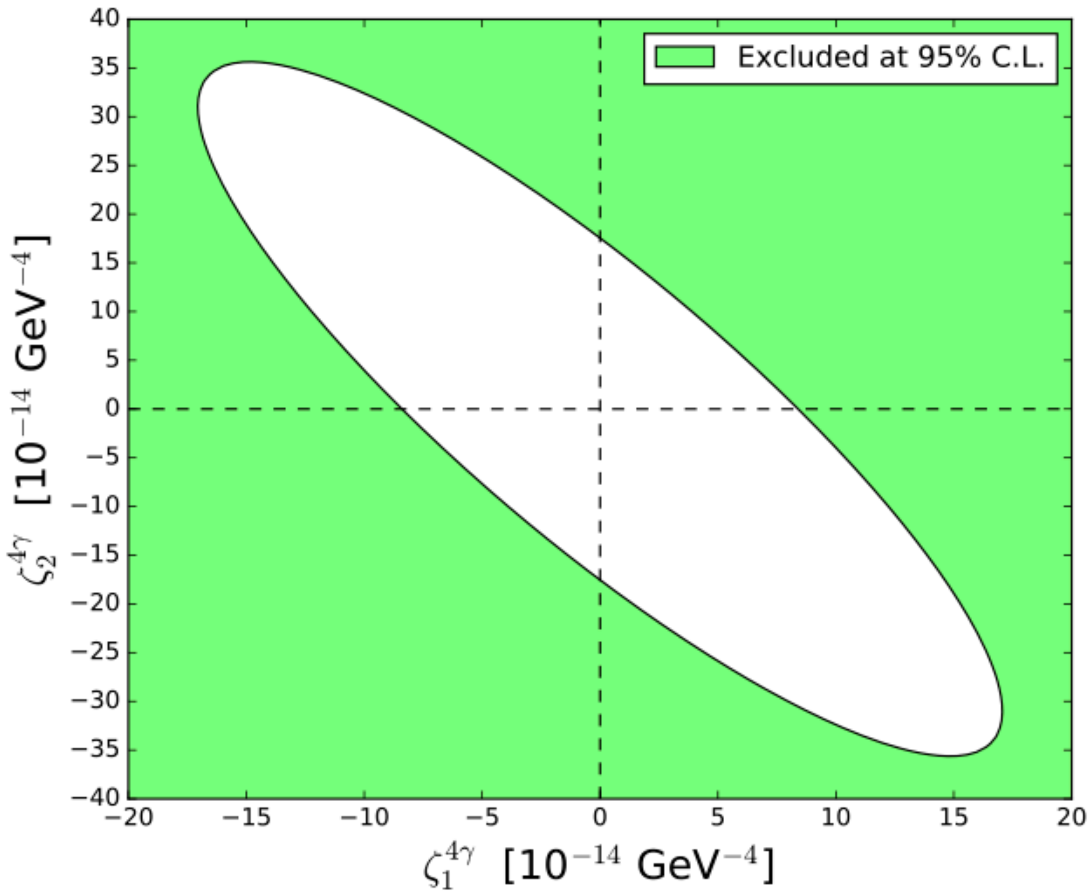
Potential for limits



- Cross section scales as a function of the coupling variable ζ_1, ζ_2

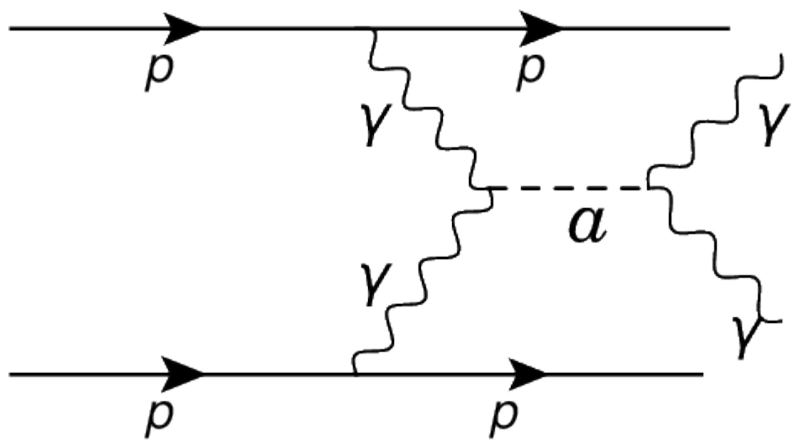
$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s}\left(s^2 + t^2 + st\right)^2\left[48\left(\zeta_1\right)^2 + 40\zeta_1\zeta_2 + 11\left(\zeta_2\right)^2\right]$$

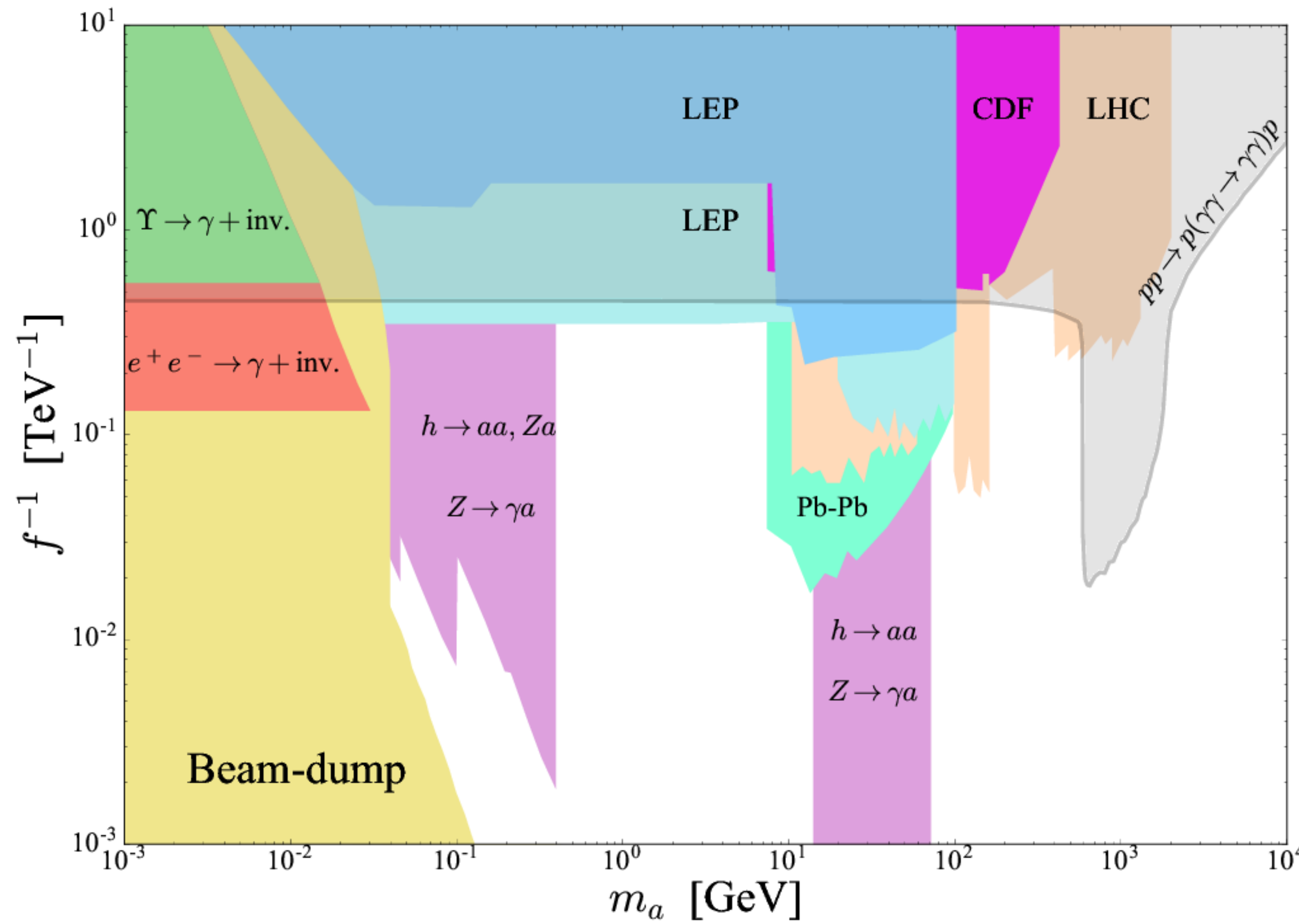
- Based on 9.41 fb^{-1} of data from 2016 with PPS
- Assume signal and background obey a Poisson distribution
- Assume expected background 0 and observed events is 0

$$\sqrt{48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2} \geq 5.8 \times 10^{-13}\text{GeV}^{-4}$$

Search for Axion-like particles

- We can study the production of ALPs via photon exchange with intact protons





- Study the production of ALPs via photon exchange with intact protons
- **Sensitivity is enhanced since ALP production rate increases with $m_{\gamma\gamma}$**
- PPS and AFP can provide sensitivity that is competitive and complementary to other collider searches above 600 GeV

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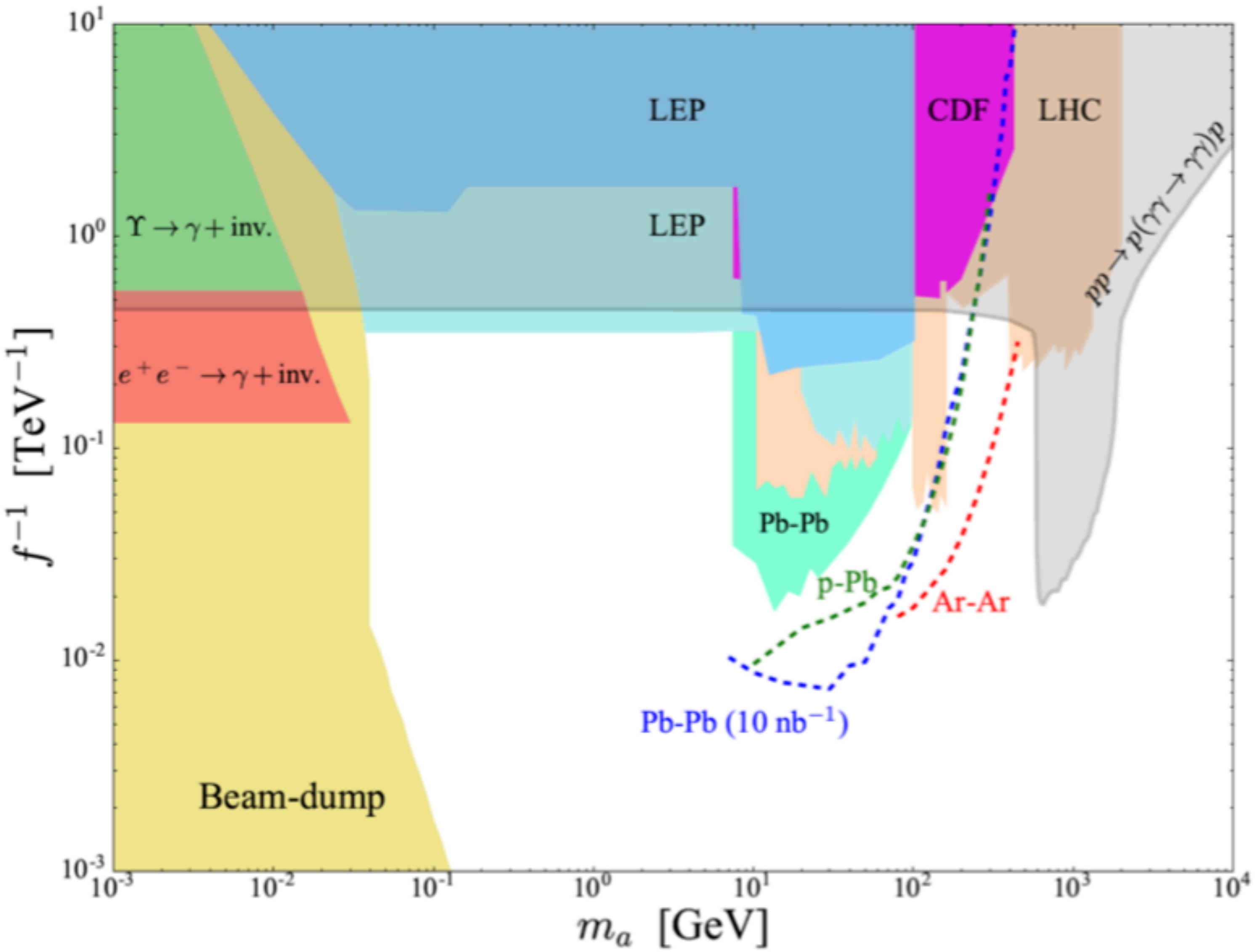
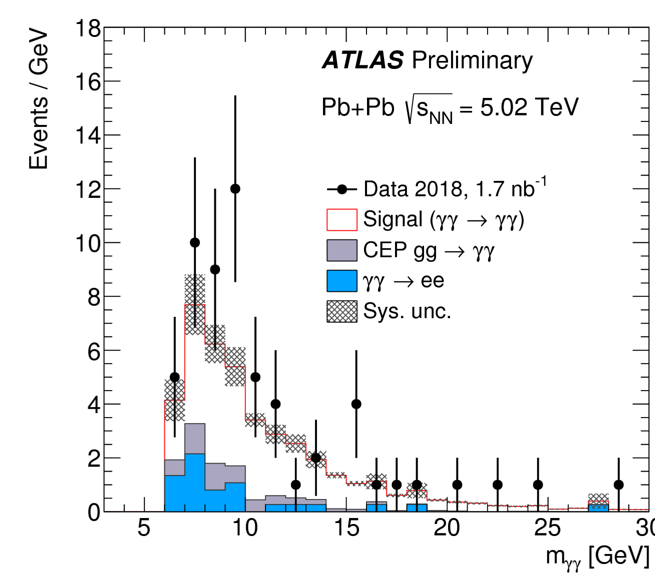
Search for Axion-like particles

- We can study the production of ALPs via photon exchange with intact protons



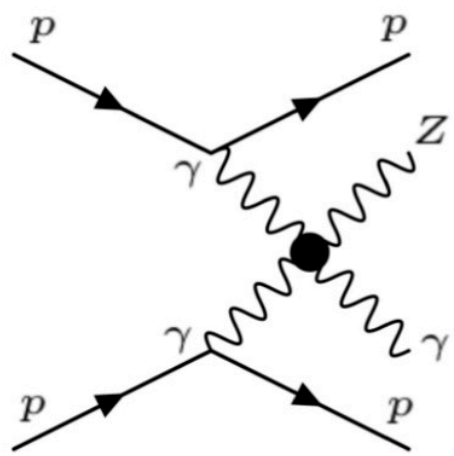
- Production of ALPs via photon exchange in heavy ion runs: complementary to pp data.

- Sensitivity to low mass ALPs: low luminosity but cross section increases by Z^4

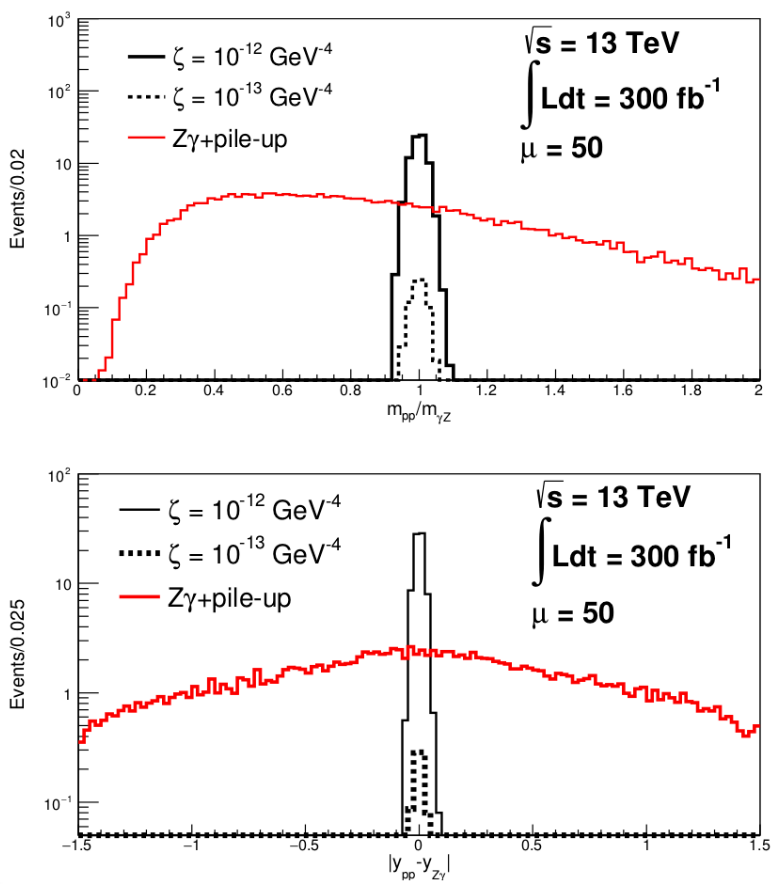


ATLAS light-by-light scattering:
Nature Physics **13**, 852-858 (2017)
arXiv:1904.03536 [hep-ex]

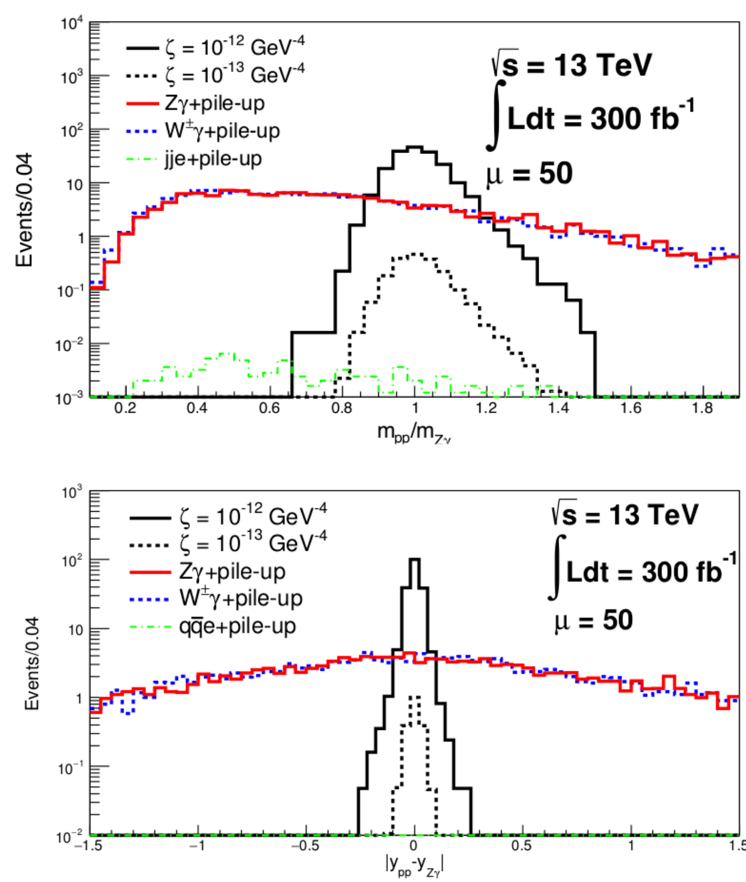
γγγZ quartic anomalous coupling



- Look for Zγ anomalous production
- Z can decay leptonically or hadronically: the fact that we can control the background using mass/ rapidity matching technique allows us to look in both channels (very small background)



lepton channel



hadron channel

- **Expect gain of three orders of magnitude on sensitivity for γγγZ couplings** compared to current LHC bounds on Z→γγγ (assuming 300 fb-1)

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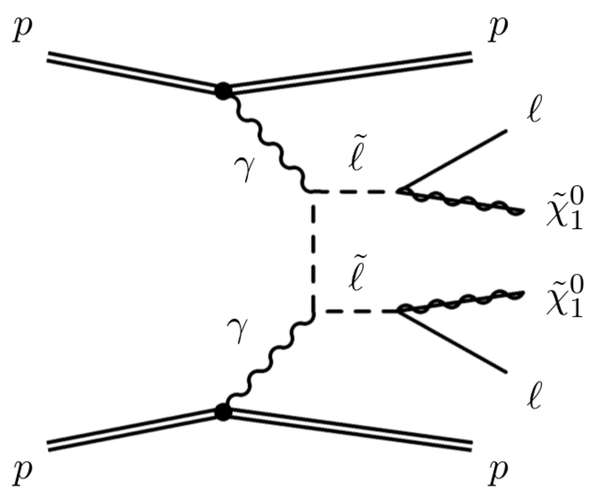
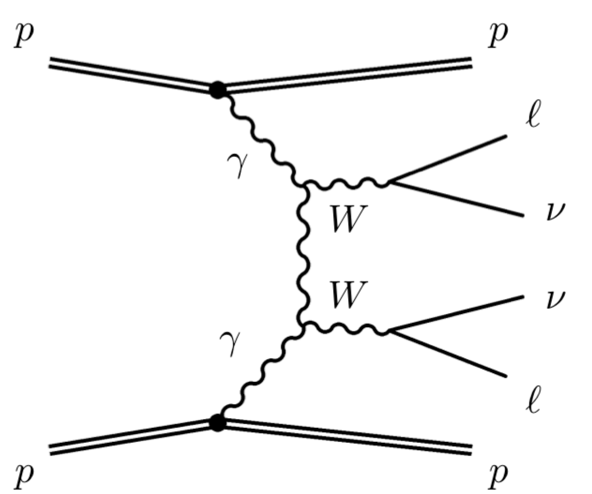
Compressed SUSY searches with intact forward proton tagging



signal



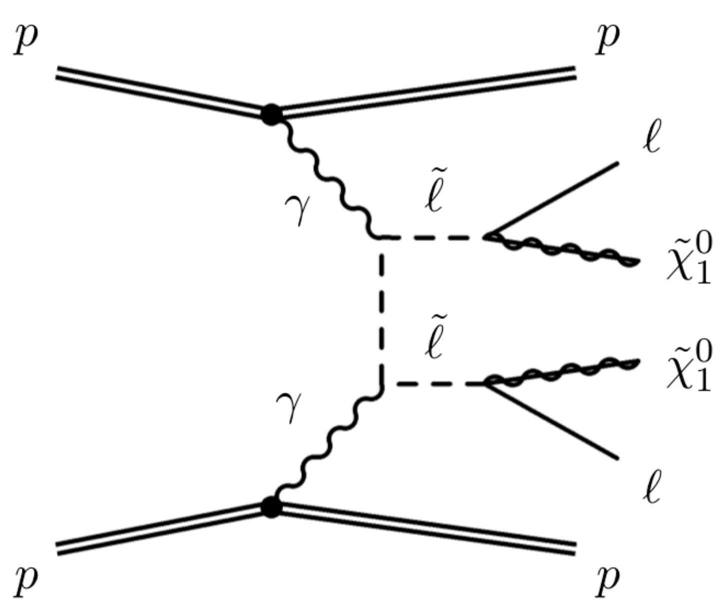
background

Possibility of ~ 100 GeV mass slepton/chargino production at LHC being swamped by huge inclusive backgrounds.

Exclusive photon-initiated production a natural mechanism:

- Well understood, model-independent signal cross section
- Irreducible WW background can be controlled. No need for large missing E_T
- Proton tagging: can reconstruct mass of central system from proton alone (missing mass). Crucial handle on background!

Compressed SUSY searches with intact forward proton tagging



Cross section for ~ 100 GeV slepton pair production via CEP **~fb**. It is essential to take data during **normal high-luminosity** running.

Recent study investigating challenges/background for these searches in CEP **(looks promising!)**

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LHC searches for Dark Matter in compressed mass scenarios: challenges in the forward proton mode

L.A. Harland-Lang,[a] V.A. Khoze,[b,c] M.G. Ryskin[c] and M. Tasevsky[d]

[a] *Rudolf Peierls Centre, Beecroft Building, Parks Road, Oxford, OX1 3PU, U.K.*
[b] *IPPP, Department of Physics, University of Durham, Durham, DH1 3LE, U.K.*
[c] *Petersburg Nuclear Physics Institute, NRC "Kurchatov Institute", Gatchina, St. Petersburg, 188300, Russia*
[d] *Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 18221 Prague, Czech Republic*

E-mail: lucian.harland-lang@physics.ox.ac.uk, V.A.Khoze@durham.ac.uk, ryskin@thd.pnpi.spb.ru, Marek.Tasevsky@cern.ch

ABSTRACT: We analyze in detail the LHC prospects at the center-of-mass enery of $\sqrt{s}$ = 14 TeV for charged electroweakino searches, decaying to leptons, in compressed supersymmetry scenarios, via exclusive photon-initiated pair production. This provides a potentially increased sensitivity in comparison to inclusive channels, where the background is often overwhelming. We pay particular attention to the challenges that such searches would

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Summary (I)

- Forward detectors with proton taggers can contribute to searches for exotica: provide precise measurements (even at high-luminosity) + complementary to central inclusive analyses
- Growing experience in using these detectors: results with Run-2 data already available and more to come out in a short time scale.

AFP - ATLAS Forward Proton detectors

- The 2016-2017 low-μ data: SD analysis in advanced stage (Soft-QCD)
- The 2017 data with 32 fb^{-1} have been analyzed *(Exclusive muon pair production with AFP is at finalizing stage)*
  - Exclusive muon pair production with AFP tag at 13 TeV - ATLAS Internal AFP draft in preparation
- 2018 data: analyses have started! There is a Combined Performance Working Group set up to coordinate the activities (conveners: P. Newman and R. Staszewski)
- Run 3: (possibly) improved ToF detectors, running with higher luminosity

Summary (II)

CMS - PPS

- With its 2016 operation, PPS has proven for the first time the feasibility of operating a near-beam proton spectrometer at a high luminosity hadron collider on a regular basis.

- First observation of $\gamma\gamma \rightarrow ll$ with single proton tag!

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- Prospects for anomalous couplings, ALP searches, and more.

- PPS has > 110 fb^{-1} and has plans for Run 3

Summary (III)

LPCC: LHC Physics Centre at CERN

LHC WG on Forward Physics and diffraction

http://lpcc.web.cern.ch/lhc-wg-forward-physics-and-diffraction

To subscribe to the WG mailing list, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-fwdlhcwg
The WG is a forum for:

- interaction between theorists and experimentalists from the LHC experiments about forward physics
- definition of a physics programme for diffraction either using the rapidity gap method or proton tagging
- definition of a common strategy between the different LHC experiments (special runs...)
- discussion of the different forward detectors (roman pots, movable beam pipes, timing and position detectors)
- application to cosmic ray physics

Dedicated subgroup meetings and more general meetings will take place every 5-6 weeks and are opened to everybody.
WG documents and meeting agendas: see links in the right menu
Steering group members:

- Paul Newman (co-chair) (ATLAS)
- Ralf Ulrich (co-chair) (CMS)
- Christophe Royon (co-chair) (CMS TOTEM)