Proton Precision Spectrometer (PPS) and its physics potentials at LHC

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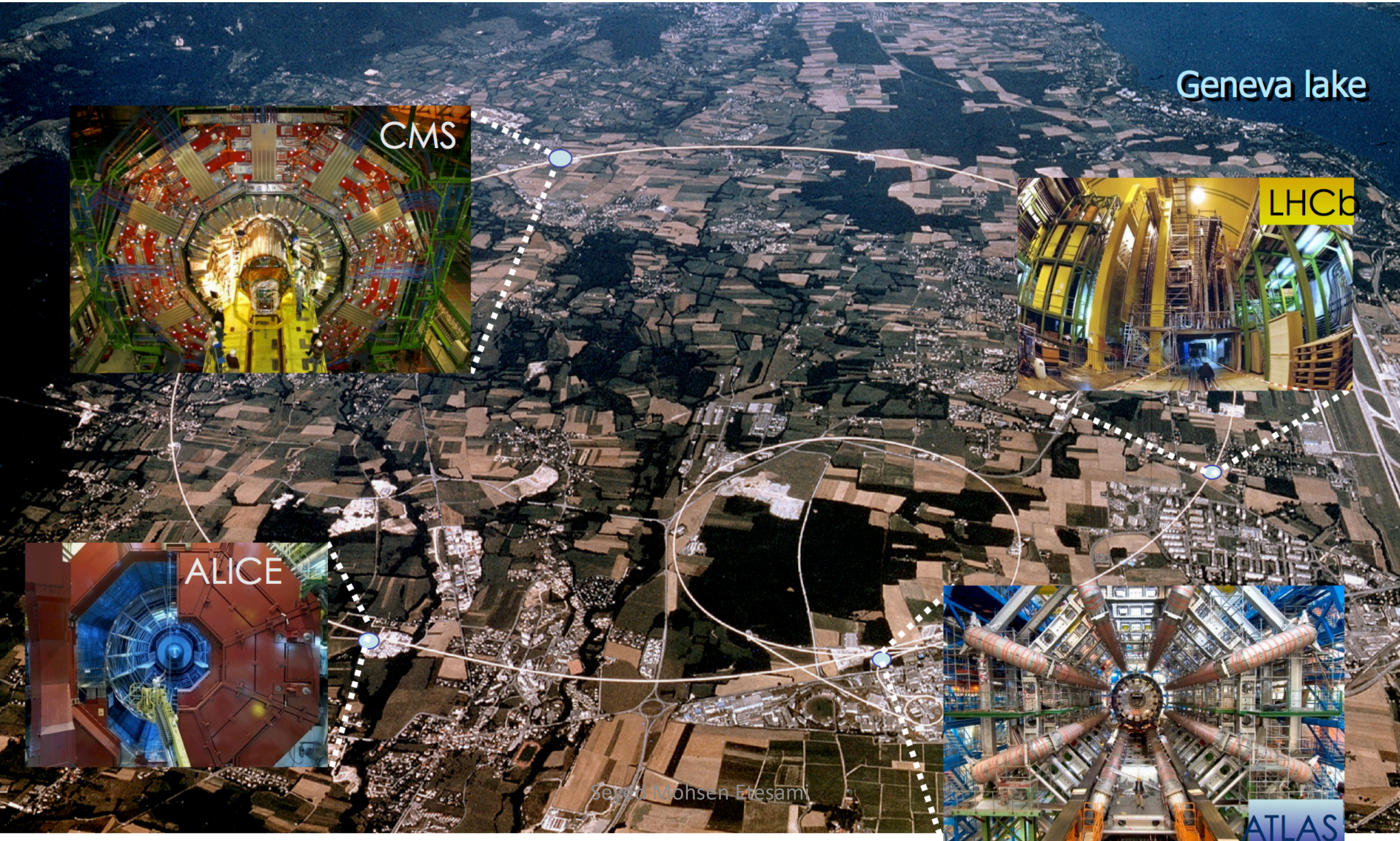
September 14th 2021

2th IUT workshop

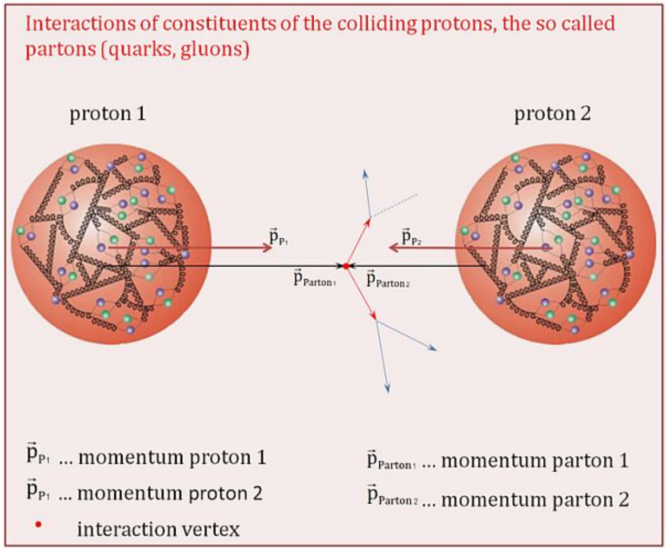
Outlines

- Introduction to PPS
- Experimental apparatus
- Physics motivations
- Detectors
- Physics prospects

Large Hadron Collider



What we collide at LHC



Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)

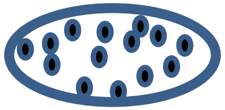
$\vec{p}_{P_1}$ ... momentum proton 1

$\vec{p}_{P_1}$ ... momentum proton 2

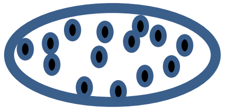
• interaction vertex

$\vec{p}_{Parton_1}$ ... momentum parton 1

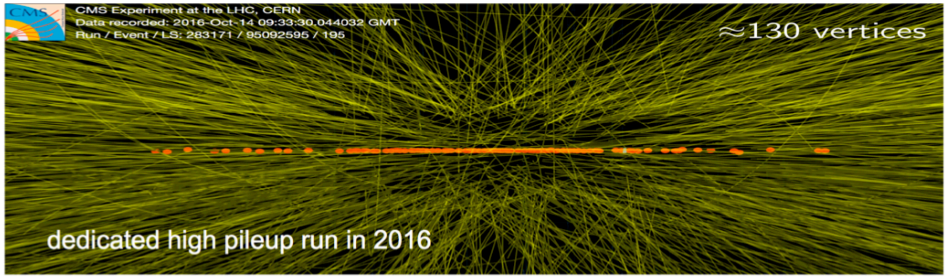
$\vec{p}_{Parton_2}$ ... momentum parton 2



10^{11} protons



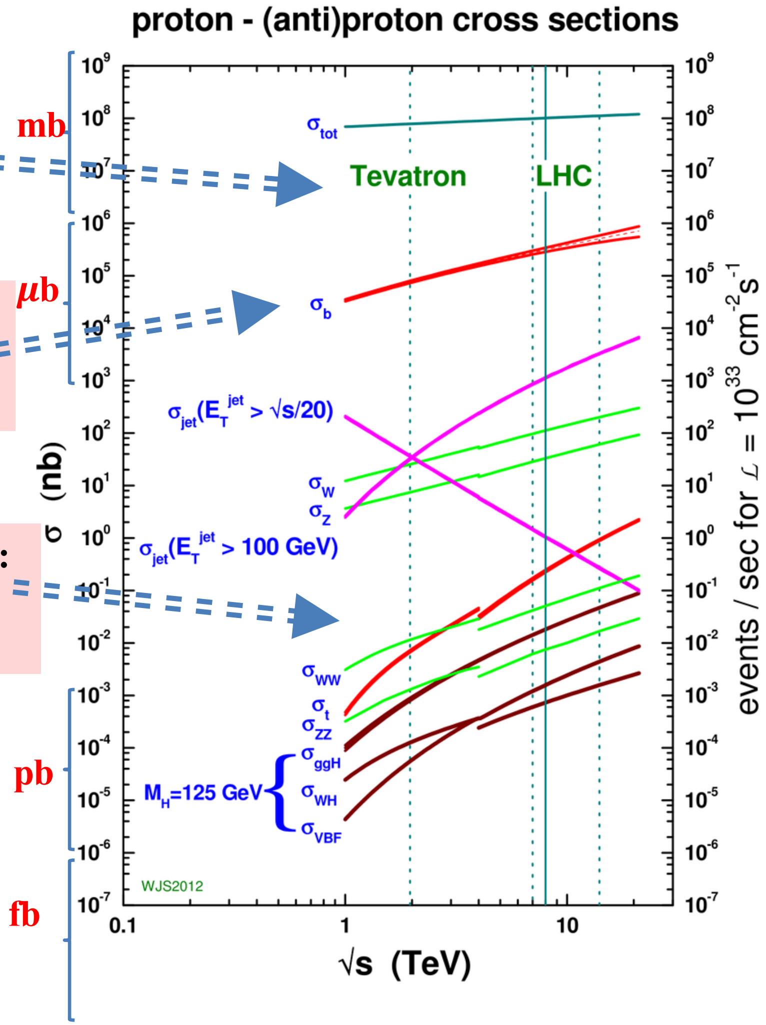
10^{11} protons



ALICE:
QCD/QGP

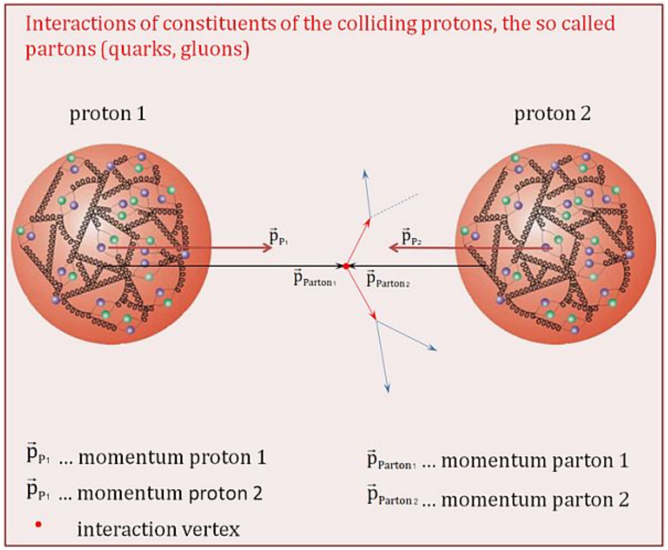
LHCb:
Flavor physics(b,c)
CP violation

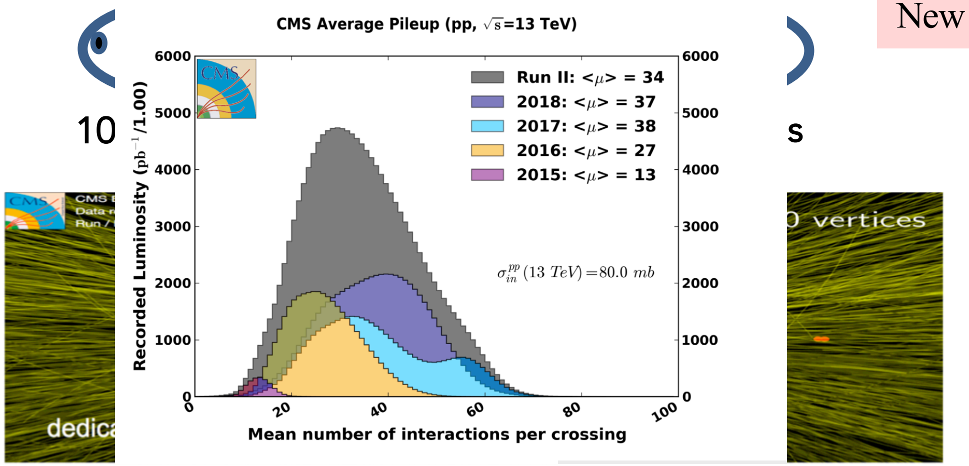
CMS & ATLAS:
Higgs
New physics



proton - (anti)proton cross sections

What we collide at CERN





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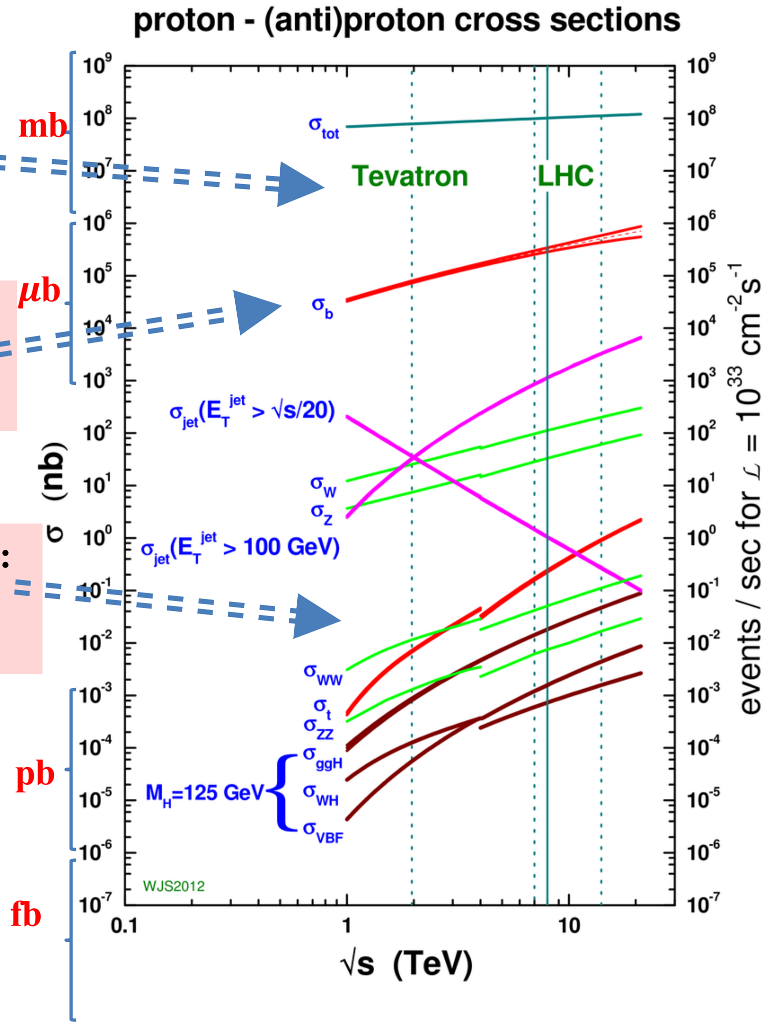
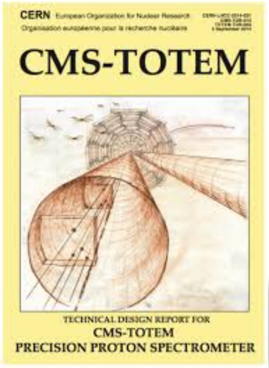


Introduction to CMS-TOTEM Precision Proton Spectrometer

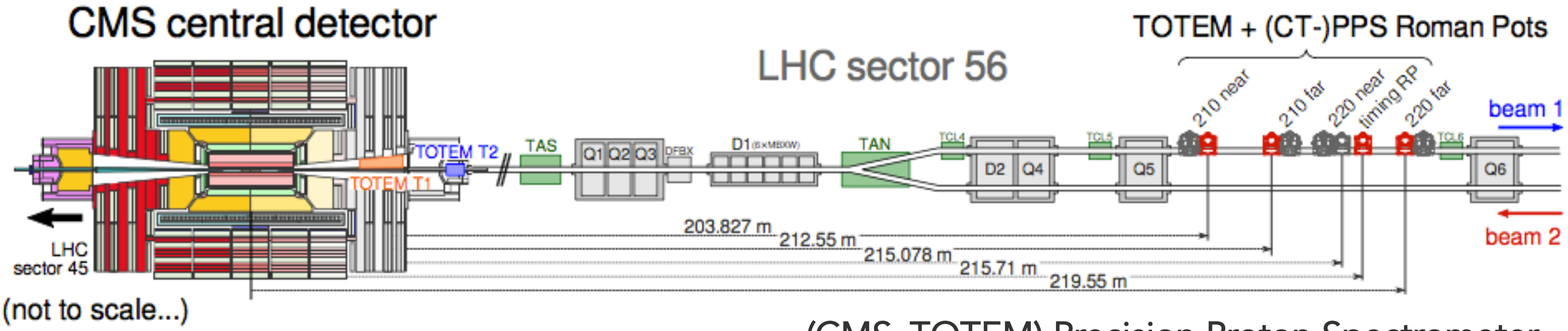


CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CMS-TOTEM

TECHNICAL DESIGN REPORT FOR
CMS-TOTEM
PRECISION PROTON SPECTROMETER

- For **measuring the** kinematics of scattered protons **very close to beam on both sides of CMS.**
- Using LHC magnets to bend the protons.
- In **standard running conditions** (high luminosity**),** Synced with CMS.



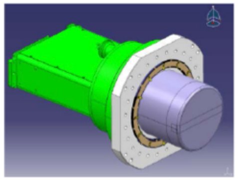
TOTEM in a CMS environment [low-PU]:

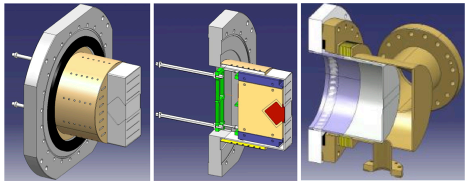
- Tracking telescopes (T1 and T2) for the measurement of inelastic interactions in the $3.2 \leq |\eta| \leq 6.5$ range.
- Horizontal + vertical Roman pots (RPs) for the **detection** of **forward scattered protons,** measurement of $\xi p = 1 - |p_f / p_i|$, and $t=(p_f - p_i)^2$
- So measurement of total, elastic, inelastic cross section of proton.

(CMS–TOTEM) Precision Proton Spectrometer [high-PU]:

- Horizontal Roman pots (RPs), located at > 200 m from CMS interaction point.
- **Tracking** and **timing components** fully integrated in the CMS readout environment.
- designed for **high-luminosity** operation mode
- The total cost is ~1 MCHF

Experimental apparatus and challenge in LHC





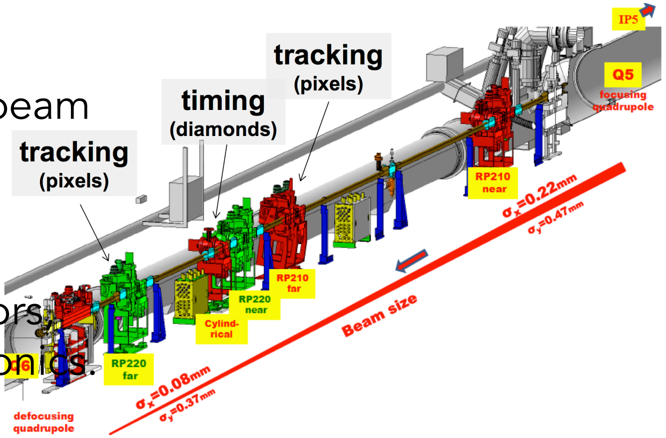
- Roman Pots (RP) need to operate at few mm from the beam (~1.5 mm) to maximize acceptance for low momentum loss (ξ*p*) protons (horizontally and vertically)

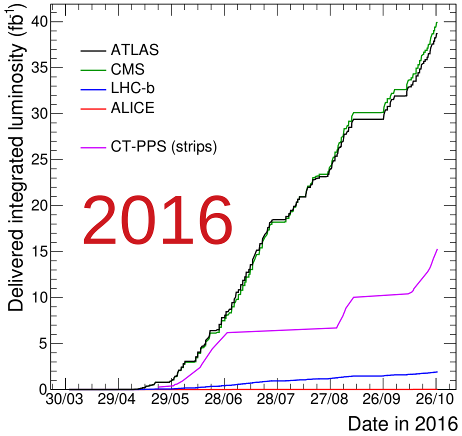
- Moving during each fill of LHC so alignment is crucial.

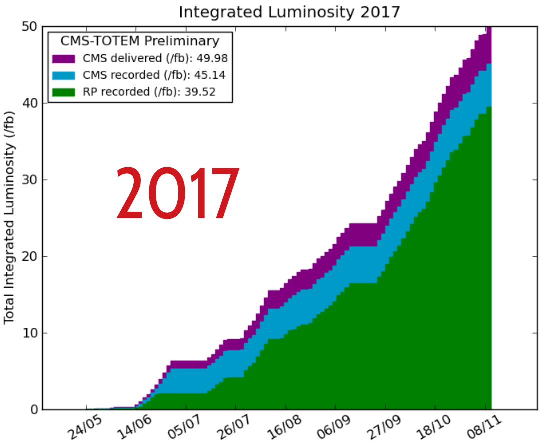
- Limit impedance introduced by beam pockets
  – Monitor beam losses, showers, interplay with collimators, beam impedance (heating, vacuum and beam orbit stability)

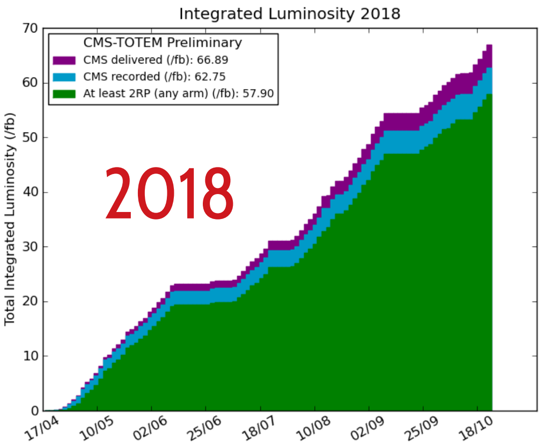
- Sustain high radiation levels
  – For 100/fb, proton flux up to 5×10^{15}cm^{-2} in tracking detectors 10^{12}neq/cm^2 and 100Gy in photosensors and readout electronics.

- Reject background in the high-pileup (μ=50) of normal LHC running









Over 110 fb^{-1} (75%) of collected data during full LHC run 2

Physics Motivation of PPS

- Central exclusive production

$pp \rightarrow p\,X\,p$

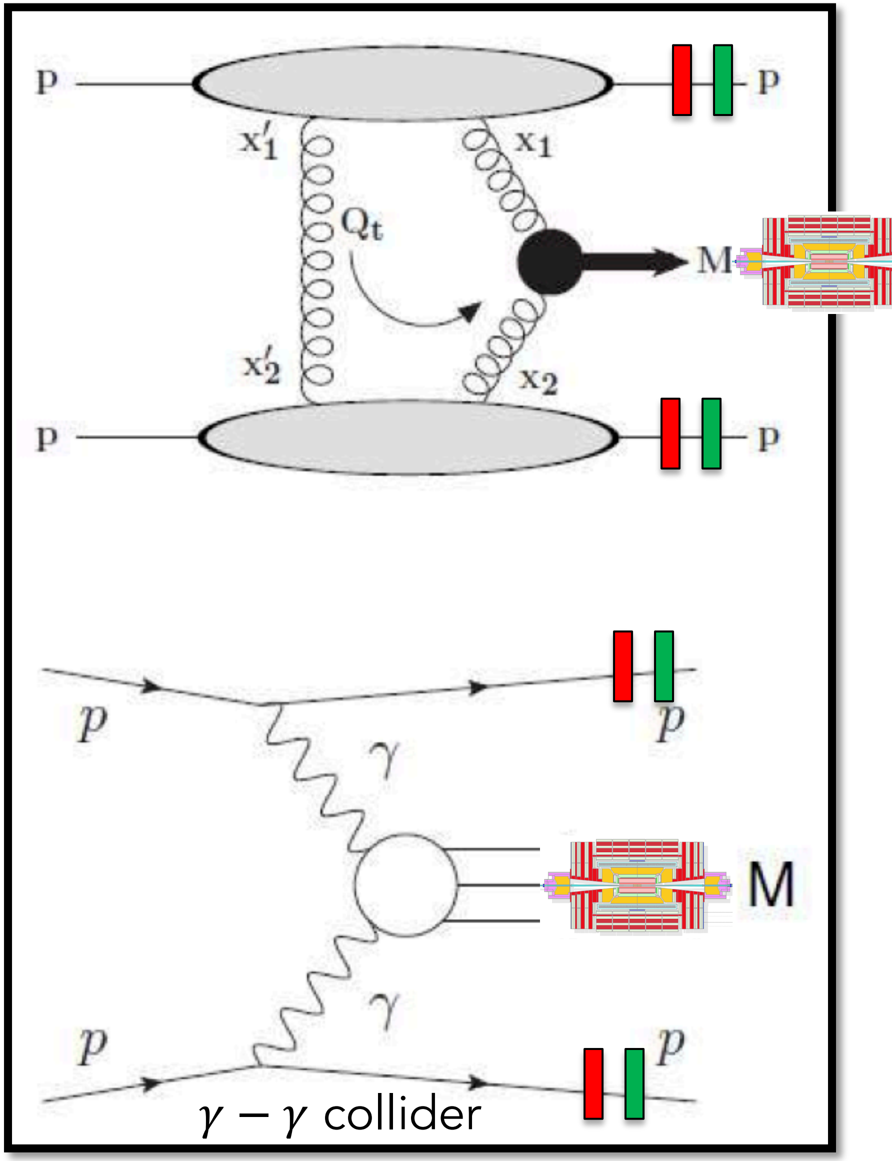
$M(X) = M(pp) \sim \mathrm{sqrt}(\xi_1 \xi_2 s)$.

-photon or colour-singlet exchange in t-channel.

-Varieties of physics such as EW, QCD and BSM can be studied.

Advantages of protons tagging and matching:

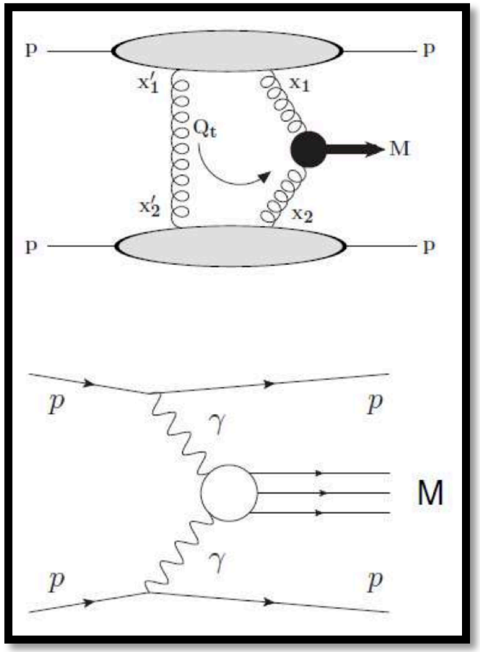
- ✸ Event-by-event constraints on √s of the interaction, independent of final state.
- ✸ Strong background suppression due to simultaneous and precise measurements of the initial and final state kinematics
- ✸ Reduced theory uncertainties related to dissociation of the protons



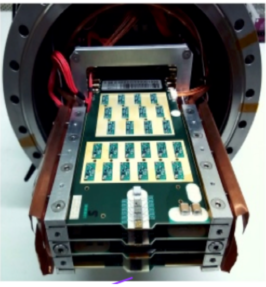
PPS Detectors: Tracking

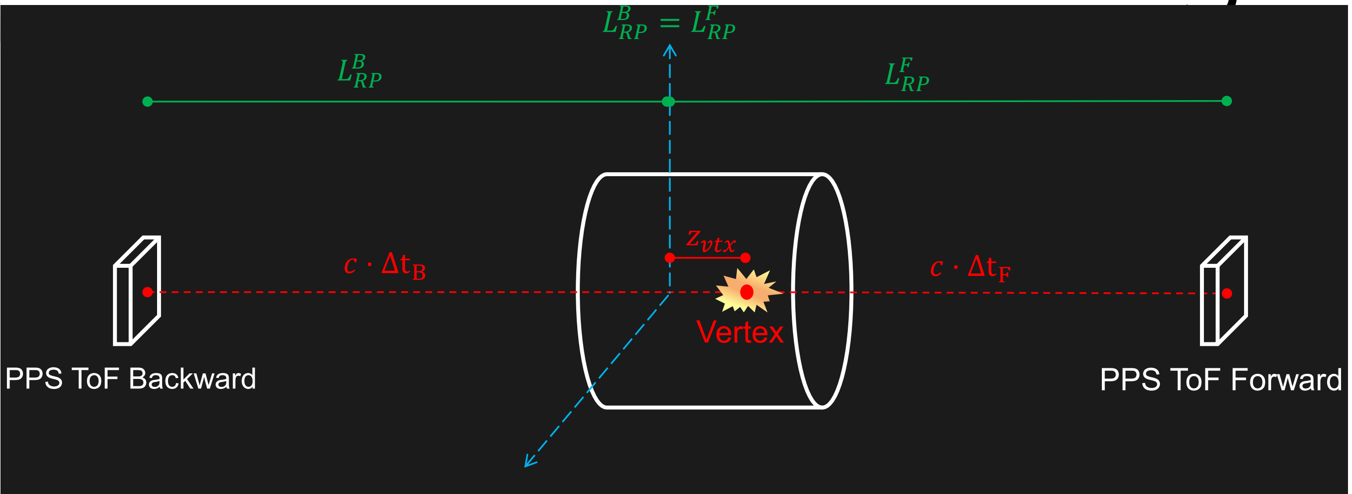
Tracking detectors:

- Goal: measure proton momentum.
- Missing mass of 2 leading protons M(X) = M(pp) .
- Longitudinal momentum balance $p_z(X) = (p_z(p_1)+p_z(p_2))$.
- Transverse momentum balance $p_T(X) = -(p_T(p_1) + p_T(p_2))$.
- Technologies : silicon 3D pixels (6 planes per pot)
- Pixel size 100μm x 150μm; track resolution ~20μm
- Designed for high-lumi running with Multi-track capability



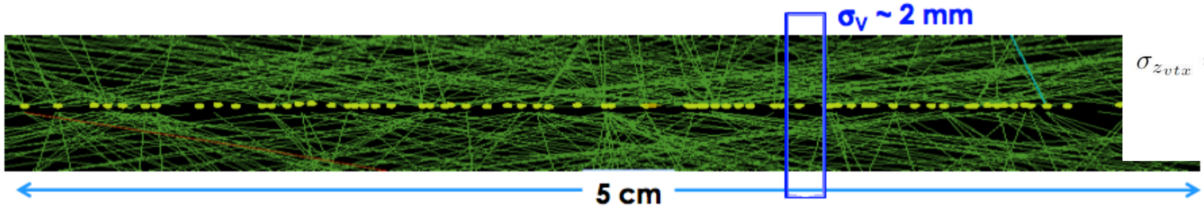
PPS Detectors: Timing





$$c\,\Delta t_B + c\,\Delta t_F = L_{RP}^{B} + L_{RP}^{F}$$

$$z_{vtx} = c\,\Delta t_B - L_{RP}^{B} = L_{RP}^{F} - c\,\Delta t_F = \frac{c}{2}(\Delta t_B - \Delta t_F)$$



$$\sigma_{z_{vtx}} = \frac{c}{2}\sqrt{2\sigma_{\Delta t}^{2}} \overset{\sigma_{\Delta t}=10\text{ps}}{\approx} 2\text{ mm}$$

$$\overset{\sigma_{\Delta t}=30\text{ps}}{\approx} 6\text{ mm}$$

Timing detectors:

- Goal: identify primary vertex, correlate it with the central detectors ,reject pileup.
- $\boldsymbol{\sigma}_{\text{time}}$~10ps ⇒ $\boldsymbol{\sigma}_z$~2mm allowing pileup rejection by a factor of approximately 25.
- Technologies: diamond/silicon

Physics domain of CEP

BSM in the High Mass Region

Upper mass of central system 2 TeV in RunII and 2.7 TeV in HL-LHC

Direct BSM Searches :

-new resonance, new spin 0 or 2 particles like axion, non-SM higgs,..
-new pair productions, Susy, Dark matter, magnetic monopole,….

Indirect BSM Searches and Electroweak Physics:

-Quartic Gauge Couplings with W Bosons, $WW\gamma\gamma$, $WW\gamma$
-Neutral Anomalous Quartic Gauge Couplings, $\gamma\gamma\gamma\gamma$ and $\gamma\gamma ZZ$
-Non-resonant searches, kk gravition.

Standard Model Processes

from tens of pb for di-jet production to a few fb for Higgs boson production.

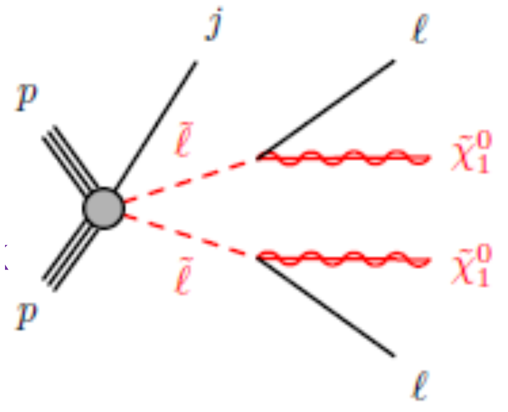
-QCD Physics
-Electroweak Physics
-Higgs Physics
-Top Physics
-Photoproduction

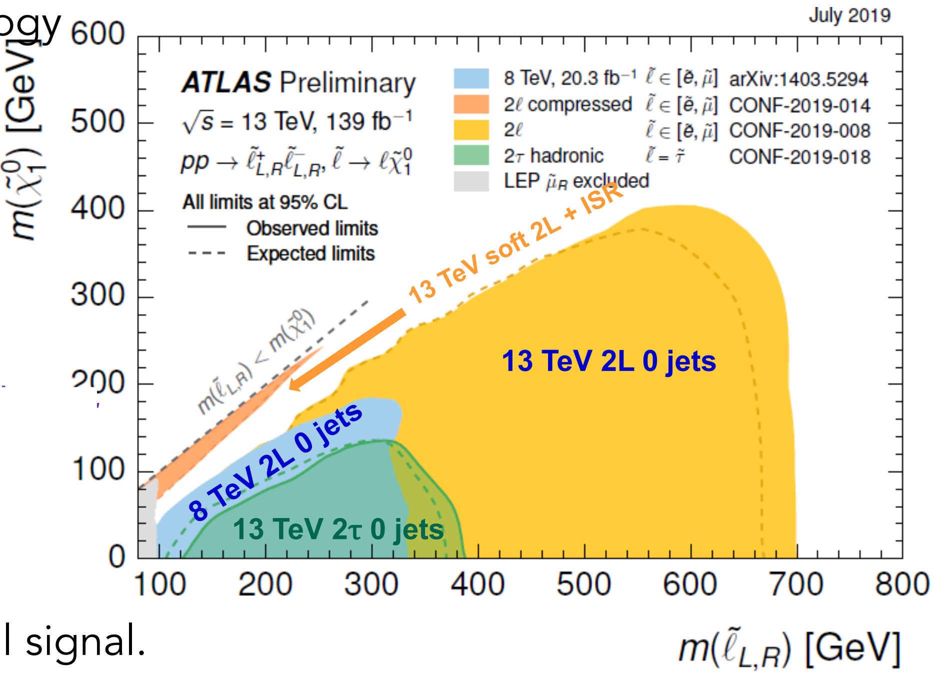
Direct BSM Searches: **Inclusive** slepton searches

MSSM offers natural candidate for cold Dark Matter (DM), the Lightest Supersymmetric Particle (LSP), which is the stable lightest neutralino, $\widetilde{\chi}_1^0$.

The sleptons (spin=0 partner of lepton) direct X-sections at the LHC are quite small so the LHC discovery potential and current experimental bounds are substantially weaker in comparison to other SUSY states.

compressed mass scenario, (ΔM = $M_{\tilde{l}}$ - $M_{\widetilde{\chi}_1^0}$ small) is Motivated by cosmological observations, naturalness considerations, and (g-2) phenomenology ($M_{\tilde{l}}$ =120-300 GeV , ΔM = 10,20 GeV).





Challenges of Inclusive searches:

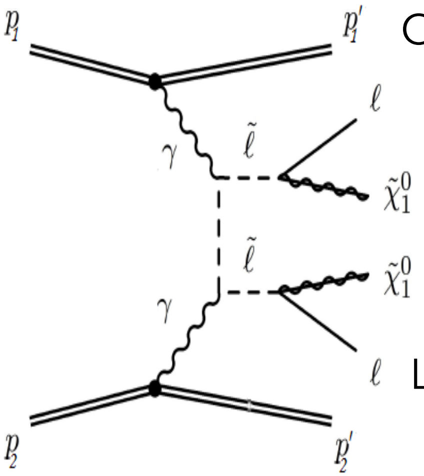
- SM WW background contaminates any potential signal.
- Decay products have low momenta and often do not pass detector acceptance thresholds
- To trigger on such events, generally the presence of an additional jet or photon due to ISR is required, so the final-state particles with a boost in the transverse plane(generating a large missing transverse momentum

Direct BSM Searches: **Excluisve** slepton searches

Search for pair production of slepton in compressed mass scena with decays to fermionic DM + leptons with BR=100% .

JHEP (2019) 2019, 010

Advantage of exclusive search:

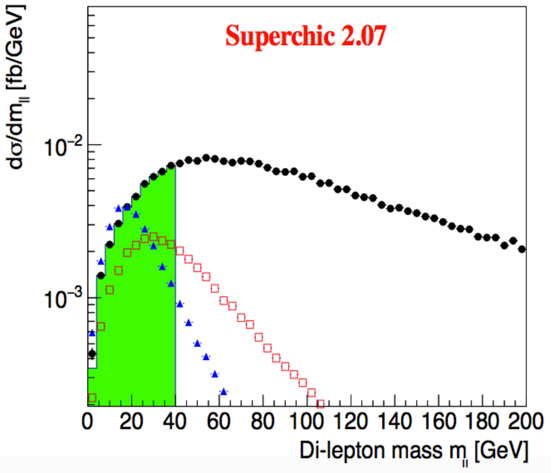


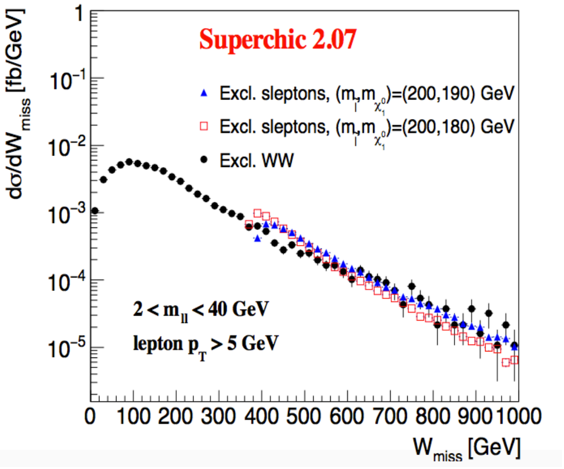
Outgoing proton 4-momentum measured precisely $\xi_i = 1 - \frac{E_{p_i'}}{E_{p_i}}$, $i=1,2$

4-momentum of system of 2 DM particles could be constrained from photons & lepton 4-momenta

Lepton 4-momentum measured in central detector

Proton missing energy can give quite a precise hint about $2m_{DM}$.





Analysis strategy

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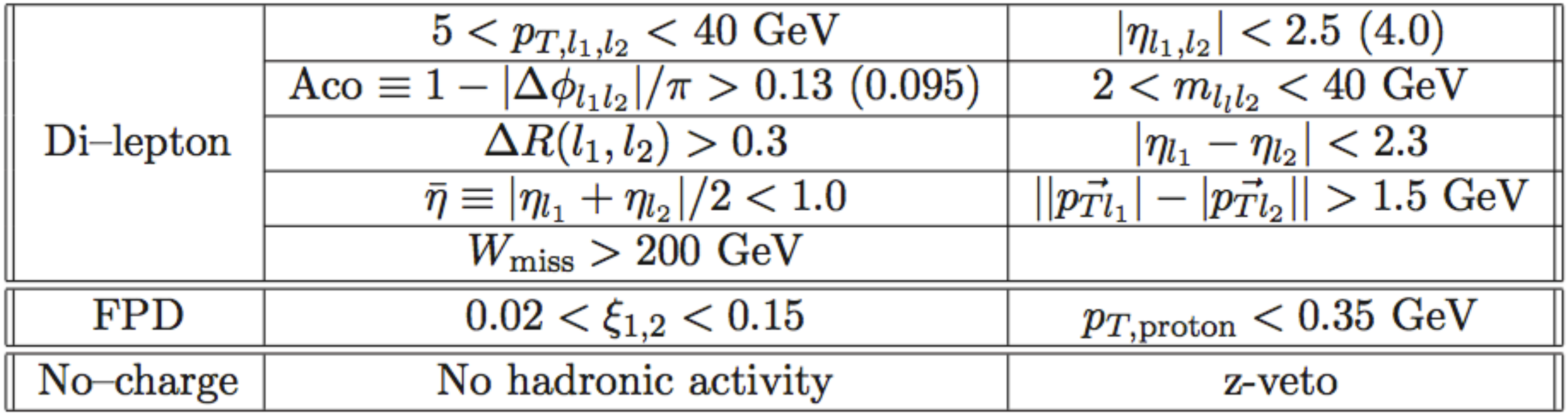
Backgrounds:

1) Exclusive WW

2) Semi-exclusive dilepton production with proton from dissociation giving hit in FPD

3) Pile-up background: overlay of inclusive non-diffractive event in central detector with unrelated soft diffractive protons in FPD acceptance



Di–lepton	$5 < p_{T,l_1,l_2} < 40$ GeV	$\lvert\eta_{l_1,l_2}\rvert < 2.5$ (4.0)
	Aco $\equiv 1 - \lvert\Delta\phi_{l_1 l_2}\rvert/\pi > 0.13$ (0.095)	$2 < m_{l_l l_2} < 40$ GeV
	$\Delta R(l_1, l_2) > 0.3$	$\lvert\eta_{l_1} - \eta_{l_2}\rvert < 2.3$
	$\bar{\eta} \equiv \lvert\eta_{l_1} + \eta_{l_2}\rvert/2 < 1.0$	$\lvert\lvert p_{\vec{T}l_1}\rvert - \lvert p_{\vec{T}l_2}\rvert\rvert > 1.5$ GeV
	$W_{\text{miss}} > 200$ GeV	
FPD	$0.02 < \xi_{1,2} < 0.15$	$p_{T,\text{proton}} < 0.35$ GeV
No–charge	No hadronic activity	z-veto

Excluisve slepton searches: Results

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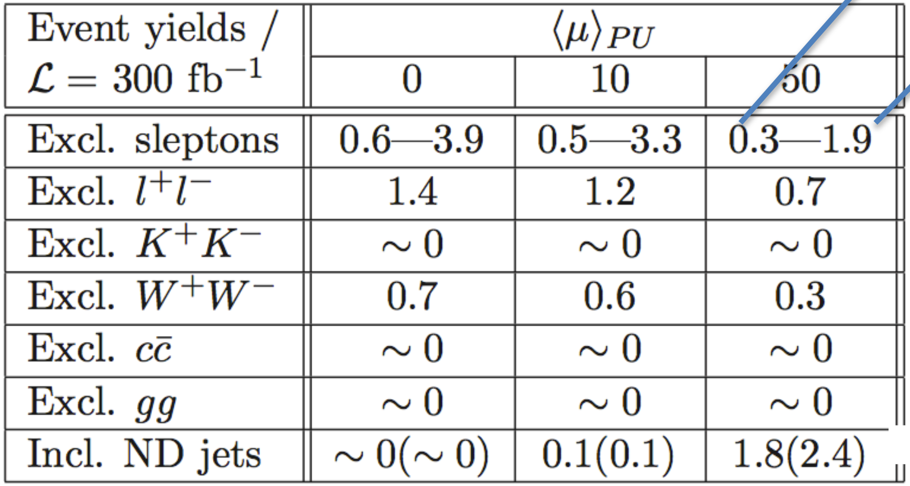
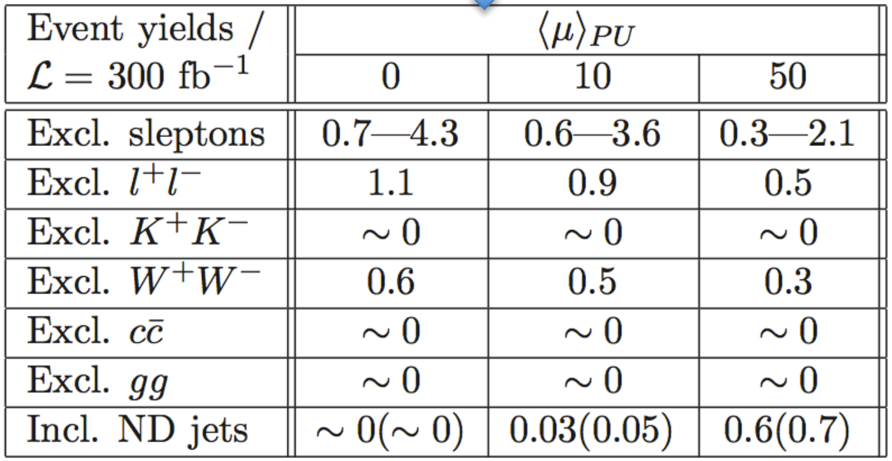


Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.6—3.9	0.5—3.3	0.3—1.9
Excl. l^+l^-	1.4	1.2	0.7
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.1(0.1)	1.8(2.4)

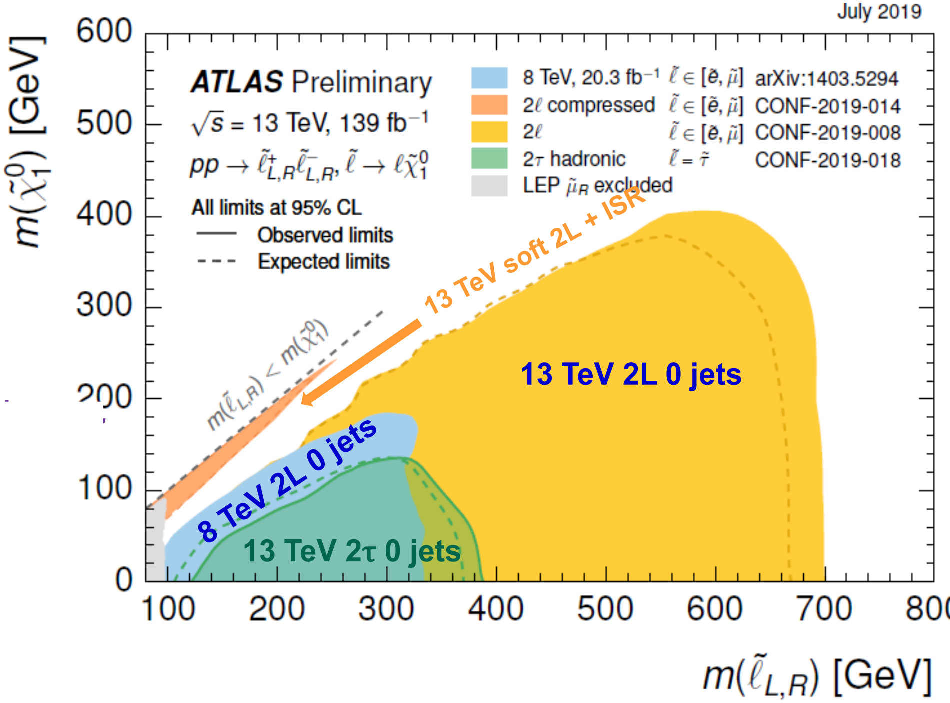
$(M_{\tilde{l}}\ ,\ M_{\widetilde{\chi}_1^0})$ =(300,280)

$(M_{\tilde{l}}\ ,\ M_{\widetilde{\chi}_1^0})$ =(120,110)

Improvemnet of tracker coverage to $|\eta| < 4.0$



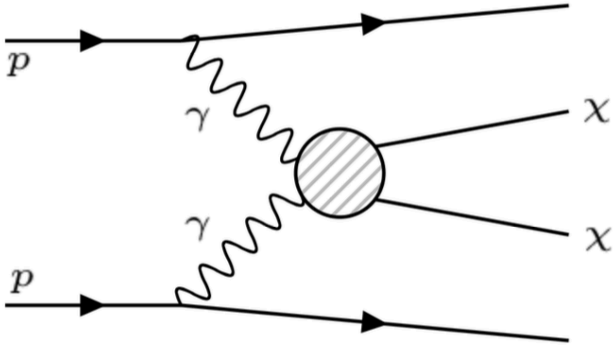
Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.7—4.3	0.6—3.6	0.3—2.1
Excl. l^+l^-	1.1	0.9	0.5
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.6	0.5	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.03(0.05)	0.6(0.7)



ATLAS SUSY Summary plot

Direct BSM Searches: limits on dark matter annihilation

Phys. Rev. D 96, 015027 (2017)



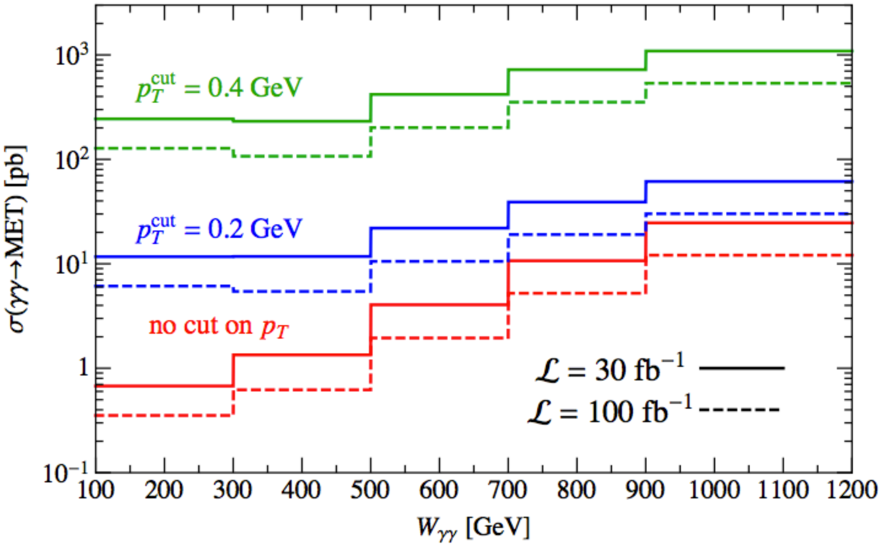
Background processes:

$$pp \to p + \gamma\gamma + p,$$
$$\gamma\gamma \to l^+l^-, \text{ where } l = e, \mu, \tau; \text{ with } |\eta_l| > 2.5.$$
$$pp \to p + \gamma\gamma + p,$$
$$\gamma\gamma \to q\bar{q}, \text{ where } q = u, d, c, s, b; \text{ with } |\eta_q| > 2.5.$$
$$pp \to p + \gamma\gamma + p,$$
$$\gamma\gamma \to W^+W^-, \text{ with } W \to l\nu_l, q\bar{q}; \text{ with } |\eta_{l,q}| > 2.5.$$

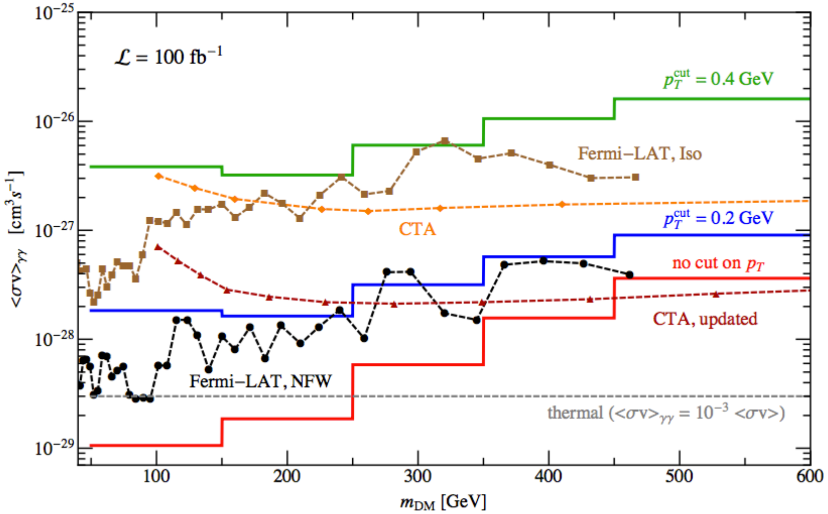
Inclusive (ZZ, WW) +Pile-up events.

Bremsstrahlung of the beam protons pp → pp$\gamma\gamma$

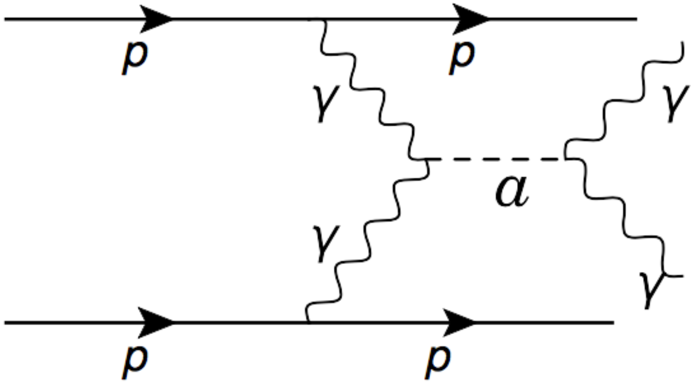
The sensitivity of the LHC on DM production $\sigma(\gamma\gamma \to \chi\tilde{\chi})$



The indirect sensitivity of the LHC $\sigma(\chi\tilde{\chi} \to \gamma\gamma)$



Direct BSM Searches: Axion-like particles with proton tagging



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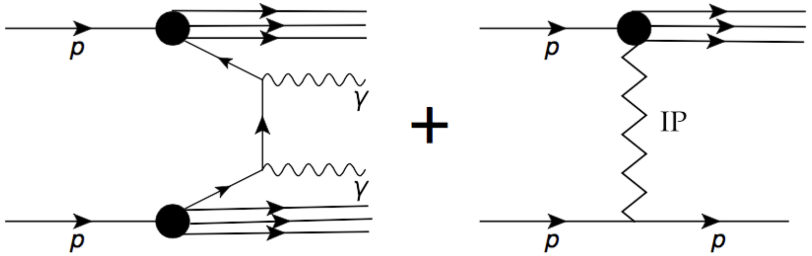
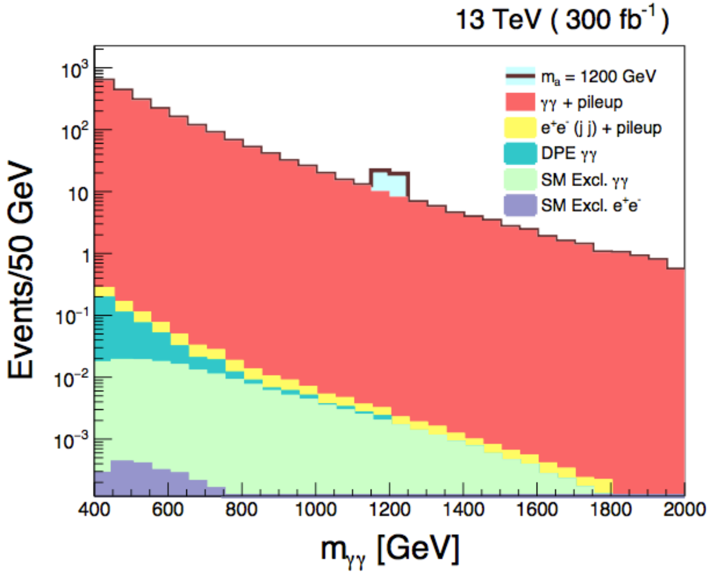
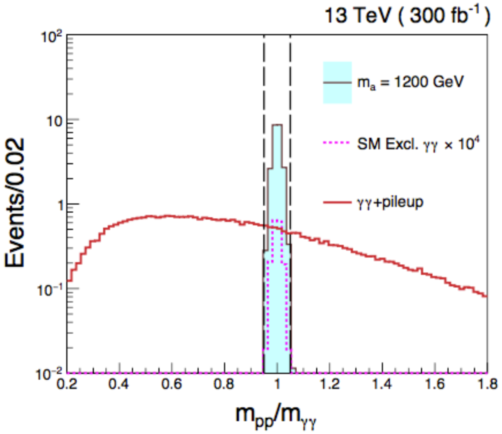
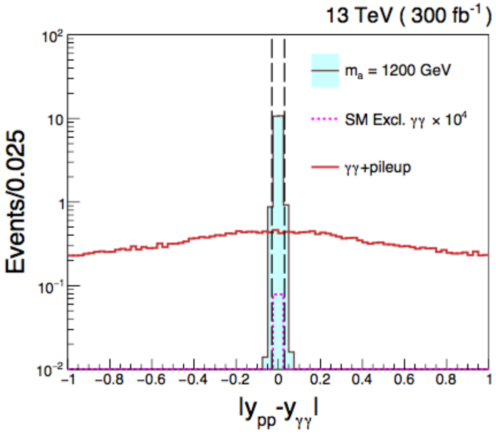


Sequential selection	ALP	Excl. SM	DPE $\gamma\gamma$	e^+e^- / dijet +pileup	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{\mathrm{T}1,(2)} > 200, (100)$ GeV]	23.1	0.1	0.1	1.2	1246
$m_{\gamma\gamma} > 600$ GeV	23.1	0.06	0	0.1	440
$[p_{\mathrm{T}2}/p_{\mathrm{T}1} > 0.95$, $\lvert\Delta\phi^{\gamma\gamma} - \pi\rvert < 0.01]$	23.1	0.06	0	0	35
$\lvert m_{pp}/m_{\gamma\gamma} - 1\rvert < 0.03$	21.8	0.06	0	0	1.2
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	21	0.06	0	0	0.2







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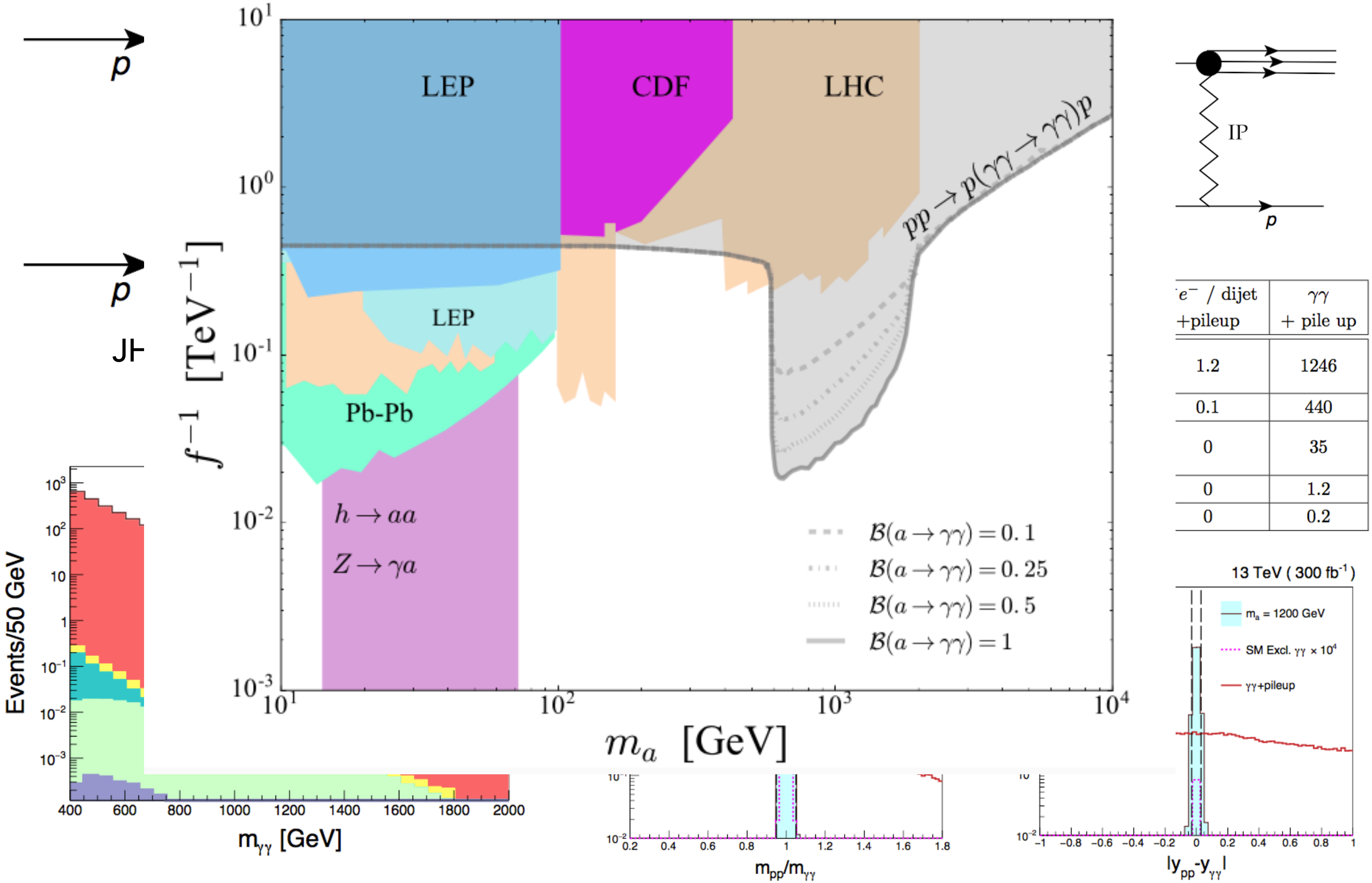

e$^-$ / dijet +pileup	$\gamma\gamma$ + pile up
1.2	1246
0.1	440
0	35
0	1.2
0	0.2

Quartic Gauge Couplings with W Bosons without proton tagging

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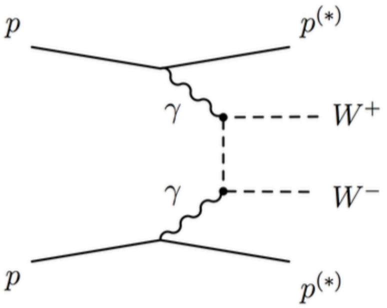
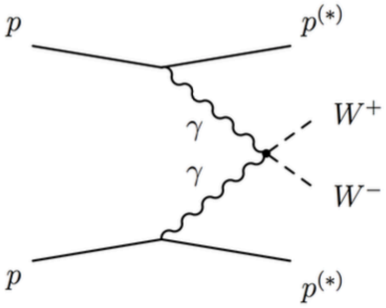
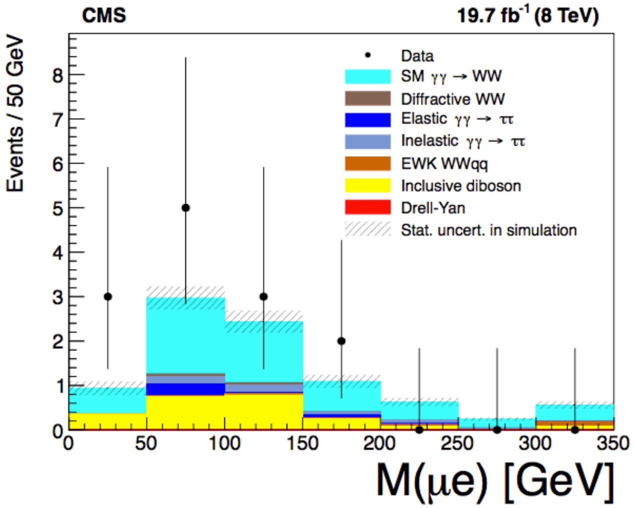






- In Run 1 of the LHC, investigated by CMS and ATLAS without proton tagging but only track restriction.

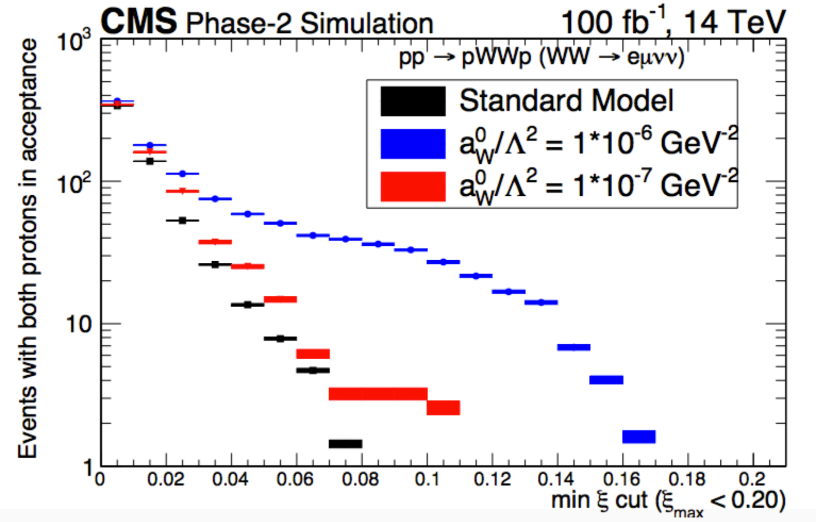
- Large backgrounds so only $e\mu\,\nu_\mu\,\nu_e$ (≈ 2% of total BR)considered.

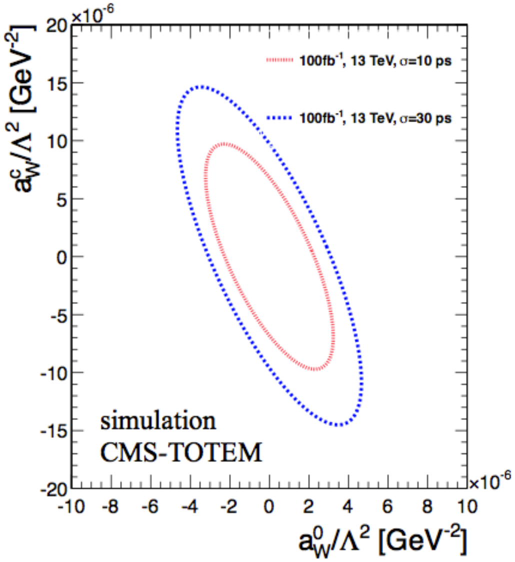
- Large correction factors and systematic uncertainties needed for modelling of the central track multiplicity.

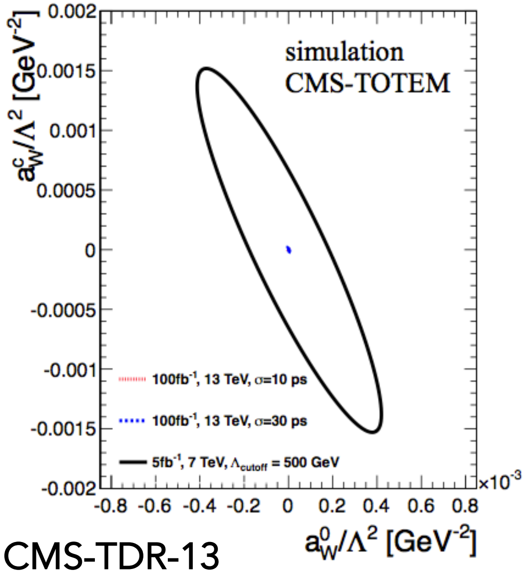
- without the constraints on the photon-photon collision energy provided by the protons, these analyses required the introduction of form factors to avoid unitarity-violating effects at very large masses, complicating the theory interpretation.

Quartic Gauge Couplings with W Bosons
with proton tagging

- Only a few SM events are expected within the Run 2/3 PPS acceptance in this channel.
- the Run 1 limits on unitarized AQGCs could be exceeded by almost 2 orders of magnitude.
- Due to high background rejection(kinematic constraints on protons) in high mass semi-leptonic, full hadronic channels are allowed(opens 70% of BF).
- preliminary Run-2 analyses using PPS of are in progress.
- limited by statistics in Runs 2 and 3.

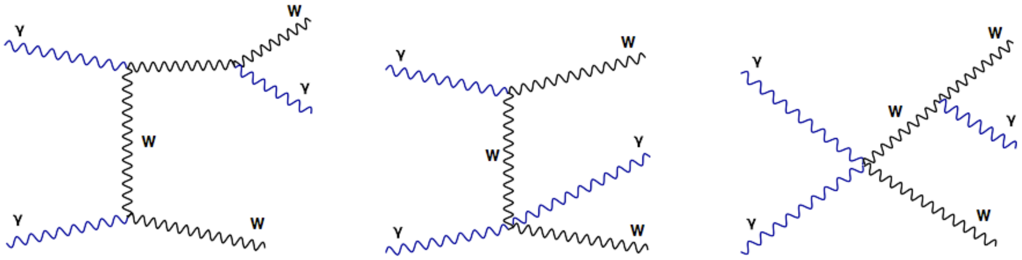






CMS-TDR-13

Indirect BSM Searches :Triple\quartic gauge boson couplings in wwγ production



(a) (b) (c)

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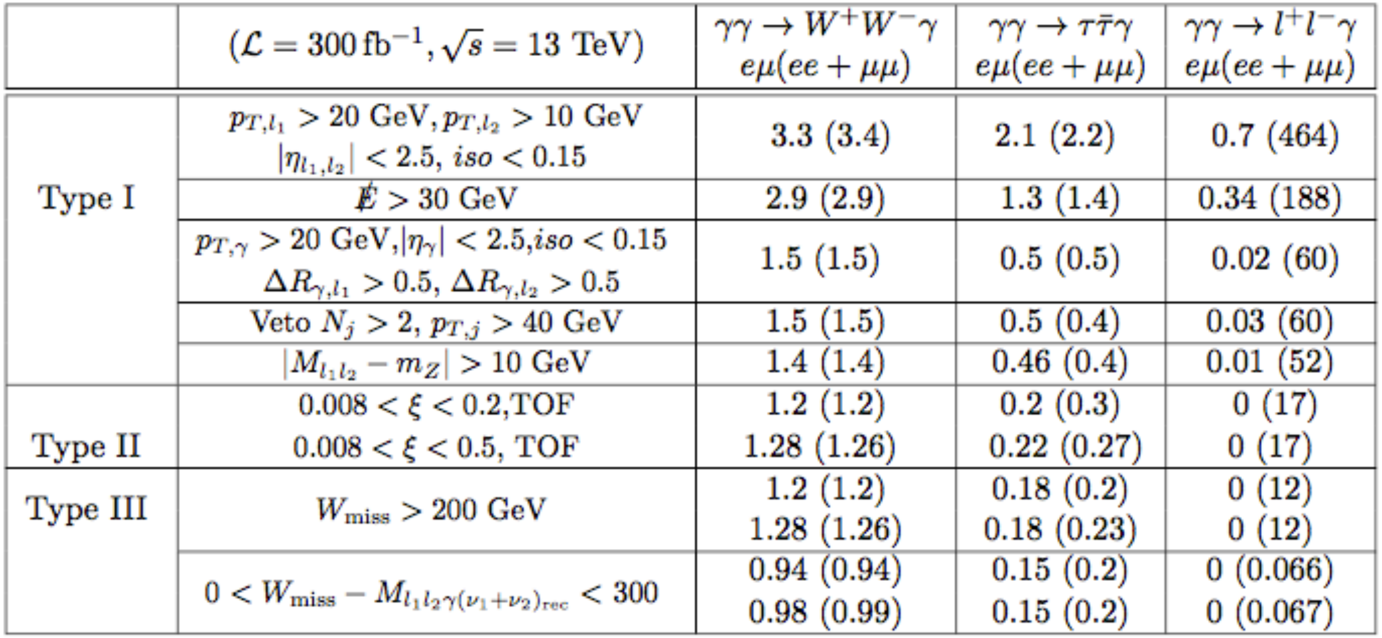
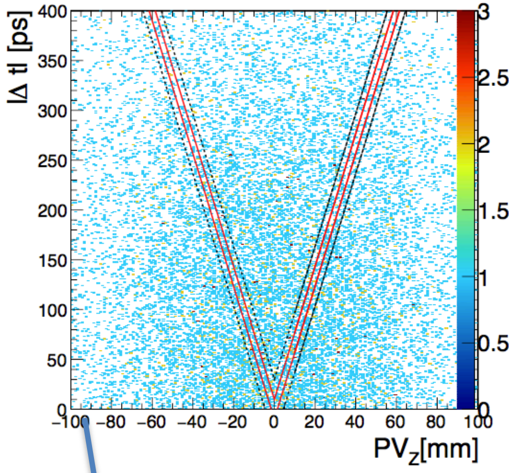
Photon-photon initiated backgrounds($\tau\tau\gamma$, llγ)

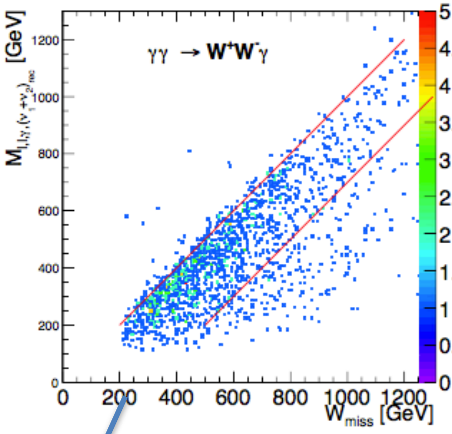
Inclusive backgrounds with pile-up protons ($\tau\tau\gamma$,llγ,ttγ,WZγ,WZγ)

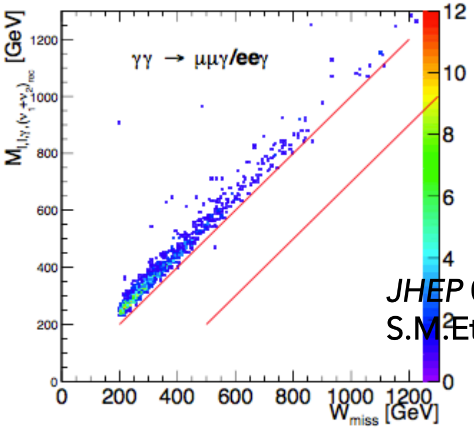


	$(\mathcal{L} = 300\,\mathrm{fb}^{-1}, \sqrt{s} = 13$ TeV$)$	$\gamma\gamma \to W^+W^-\gamma$ $e\mu(ee+\mu\mu)$	$\gamma\gamma \to \tau\bar{\tau}\gamma$ $e\mu(ee+\mu\mu)$	$\gamma\gamma \to l^+l^-\gamma$ $e\mu(ee+\mu\mu)$
Type I	$p_{T,l_1} > 20$ GeV, $p_{T,l_2} > 10$ GeV $\lvert\eta_{l_1,l_2}\rvert < 2.5$, $iso < 0.15$	3.3 (3.4)	2.1 (2.2)	0.7 (464)
	$\not{E} > 30$ GeV	2.9 (2.9)	1.3 (1.4)	0.34 (188)
	$p_{T,\gamma} > 20$ GeV,$\lvert\eta_\gamma\rvert < 2.5$,$iso < 0.15$ $\Delta R_{\gamma,l_1} > 0.5$, $\Delta R_{\gamma,l_2} > 0.5$	1.5 (1.5)	0.5 (0.5)	0.02 (60)
	Veto $N_j > 2$, $p_{T,j} > 40$ GeV	1.5 (1.5)	0.5 (0.4)	0.03 (60)
	$\lvert M_{l_1 l_2} - m_Z\rvert > 10$ GeV	1.4 (1.4)	0.46 (0.4)	0.01 (52)
Type II	$0.008 < \xi < 0.2$,TOF $0.008 < \xi < 0.5$, TOF	1.2 (1.2) 1.28 (1.26)	0.2 (0.3) 0.22 (0.27)	0 (17) 0 (17)
Type III	$W_{\mathrm{miss}} > 200$ GeV	1.2 (1.2) 1.28 (1.26)	0.18 (0.2) 0.18 (0.23)	0 (12) 0 (12)
	$0 < W_{\mathrm{miss}} - M_{l_1 l_2 \gamma(\nu_1+\nu_2)_{\mathrm{rec}}} < 300$	0.94 (0.94) 0.98 (0.99)	0.15 (0.2) 0.15 (0.2)	0 (0.066) 0 (0.067)

Indirect BSM Searches Triple\quartic gauge boson couplings in wwγ production







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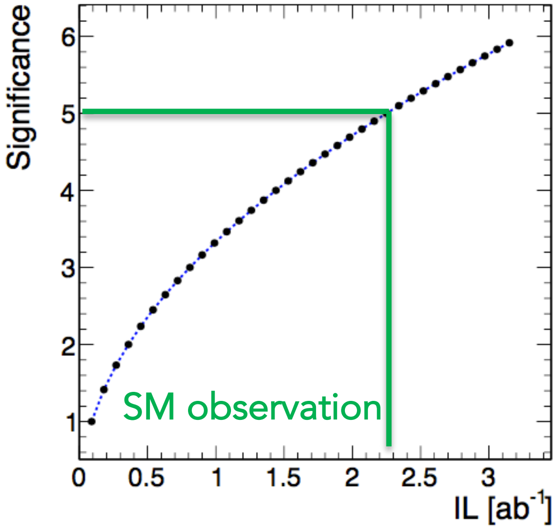
	($\mathcal{L} = 300\,\mathrm{fb}^{-1}, \sqrt{s} = 13$ TeV)	pp $\to \tau\bar{\tau}\gamma$ $e\mu(ee+\mu\mu)$	pp $\to t\bar{t}\gamma$ $e\mu(ee+\mu\mu)$	pp $\to W^+W^-\gamma$ $e\mu(ee+\mu\mu)$	pp $\to ZZ\gamma$ $e\mu(ee+\mu\mu)$	pp $\to W^\pm Z\gamma$ $e\mu(ee+\mu\mu)$	pp $\to l\bar{l}\gamma$ $e\mu(ee+\mu\mu)$
Type I	$p_{T,l_1} > 20$ GeV, $p_{T,l_2} > 10$ GeV $\lvert\eta_{l_1,l_2}\rvert < 2.5$, $iso < 0.15$	8519 (8411)	6106(6089)	560 (588)	0.07 (4)	23 (114)	949 (418763)
	$\not{E} > 30$ GeV	4106 (4191)	5447(5409)	447 (469)	0.05 (2.2)	18 (92)	501 (171067)
	$p_{T,\gamma} > 20$ GeV, $\lvert\eta_\gamma\rvert < 2.5$, $iso < 0.15$ $\Delta R_{\gamma,l_1} > 0.5$, $\Delta R_{\gamma,l_2} > 0.5$	1141 (1124)	2709(2516)	204 (210)	0.02 (1)	8 (41)	43 (60093)
	Veto $N_j > 2$, $p_{T,j} > 40$ GeV	1124(1119)	1101(1034)	201(205)	0.02(0.82)	7.77(39)	33(59649)
	$\lvert M_{l_1l_2} - m_Z\rvert > 10$ GeV	1090 (1107)	282 (266)	609 (622)	0.015(0.07)	6.9 (8.8)	5(4446)
Type II	$0.008 < \xi < 0.2$ $0.008 < \xi < 0.5$	182(187) 858(772)	207(197) 219(202)	38(39) 137(140)	0.005(0.01) 0.01 (0.06)	1.2(1.8) 5.3 (7)	0(1035) 19(3396)
	TOF	0 (0) 23(23)	5.4(3.4) 17(24)	0.88(0.75) 3.3 (4)	0(0) 0(0.0009)	0.03 (0.006) 0.14(0.2)	0(19) 0 (100)
Type III	$W_{\mathrm{miss}} > 200$ GeV	0(0) 23(23)	5.4(2.75) 17 (24)	0.76 (0.75) 3.3(4)	0 (0) 0(0.0009)	0.03(0.006) 0.14(0.2)	0(19) 0 (100)
	$0 < W_{\mathrm{miss}} - M_{l_1l_2\gamma(\nu_1+\nu_2)_{\mathrm{rec}}} < 300$	0 (0) 0 (0)	0(0) 1.36(0)	0.13 (0.06) 0.126 (0.126)	0 (0) 0(0.0009)	0(0) 0.006(0.006)	0(0) 0(0)

SM observation and constraints on the AQGCs



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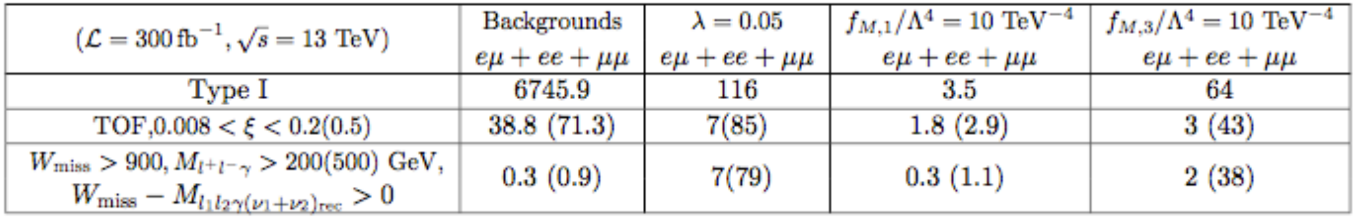
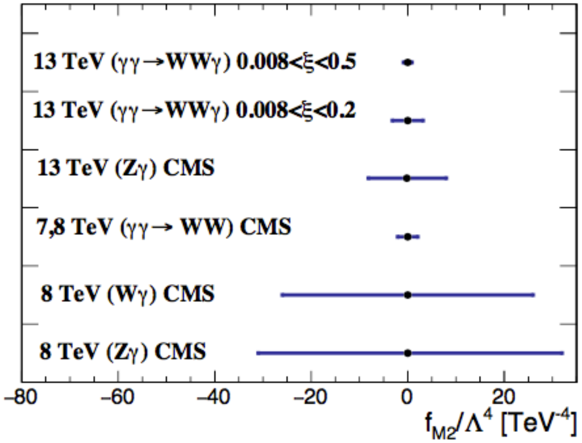
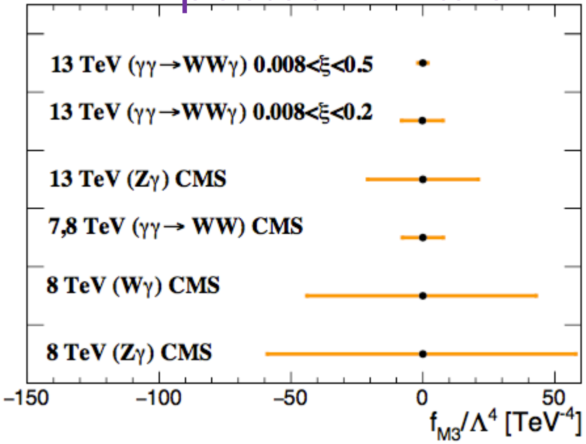
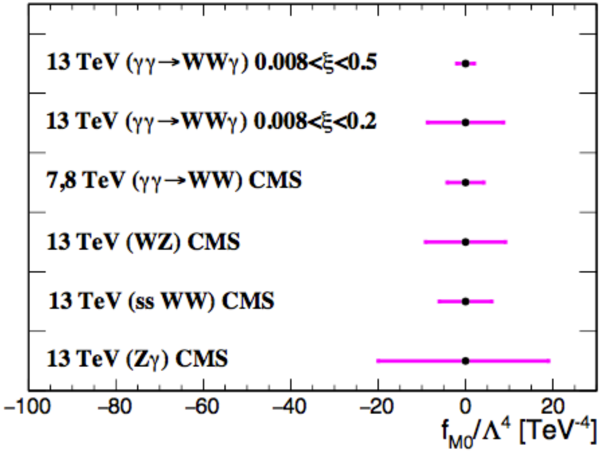


($\mathcal{L} = 300\,\mathrm{fb}^{-1}$, $\sqrt{s} = 13$ TeV)	Backgrounds $e\mu + ee + \mu\mu$	$\lambda = 0.05$ $e\mu + ee + \mu\mu$	$f_{M,1}/\Lambda^4 = 10$ TeV^{-4} $e\mu + ee + \mu\mu$	$f_{M,3}/\Lambda^4 = 10$ TeV^{-4} $e\mu + ee + \mu\mu$
Type I	6745.9	116	3.5	64
TOF,$0.008 < \xi < 0.2(0.5)$	38.8 (71.3)	7(85)	1.8 (2.9)	3 (43)
$W_{\mathrm{miss}} > 900$, $M_{l^+l^-\gamma} > 200(500)$ GeV, $W_{\mathrm{miss}} - M_{l_1 l_2 \gamma(\nu_1+\nu_2)_{\mathrm{rec}}} > 0$	0.3 (0.9)	7(79)	0.3 (1.1)	2 (38)

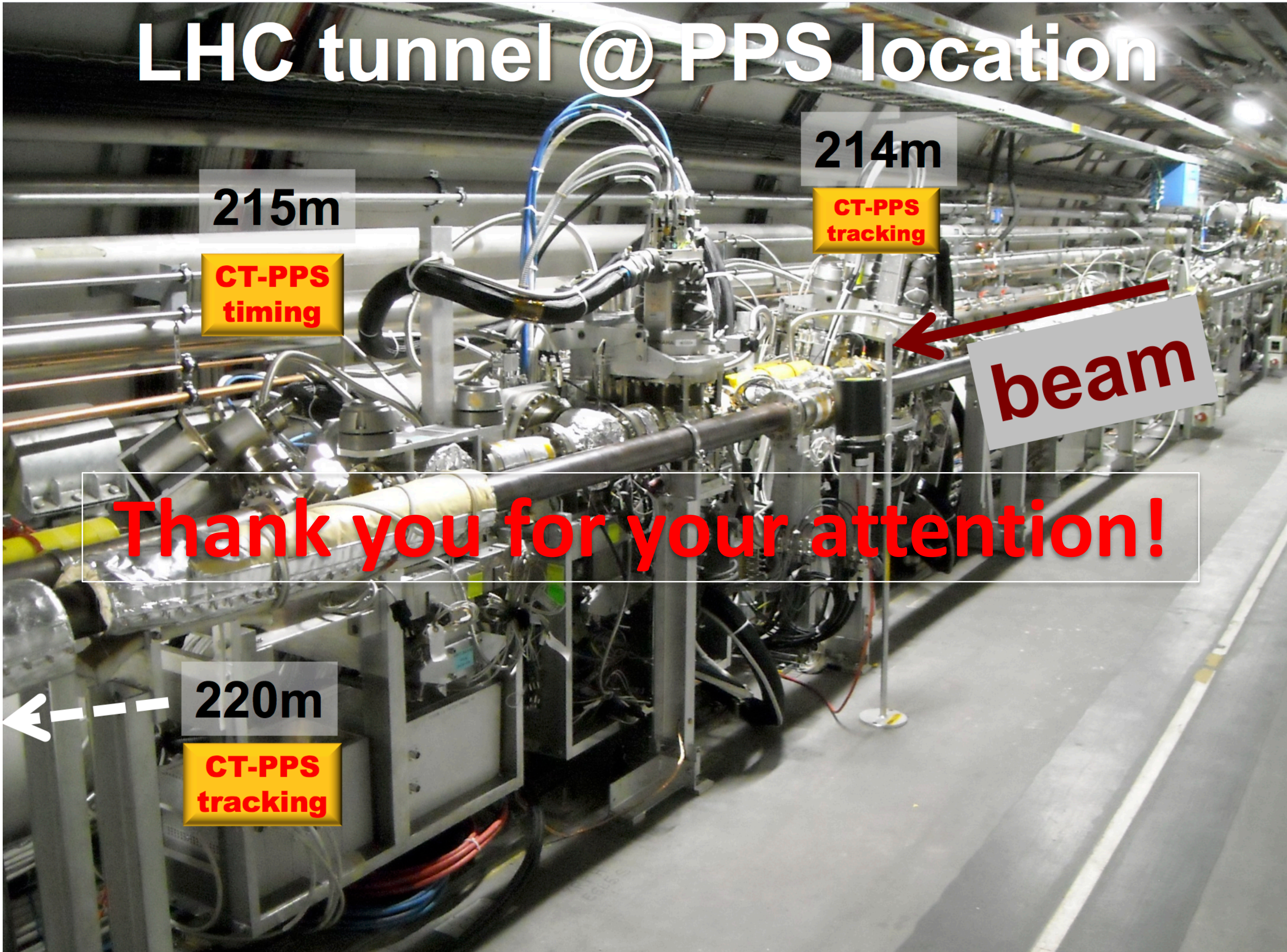
Expected Limits on AQGc







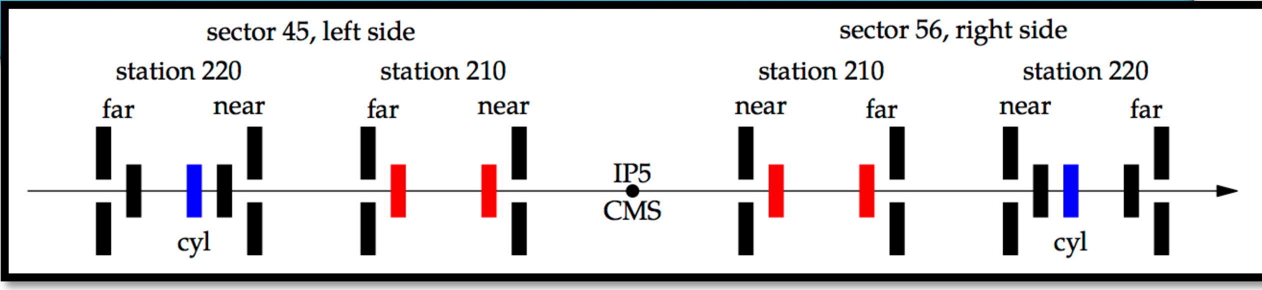
LHC tunnel @ PPS location

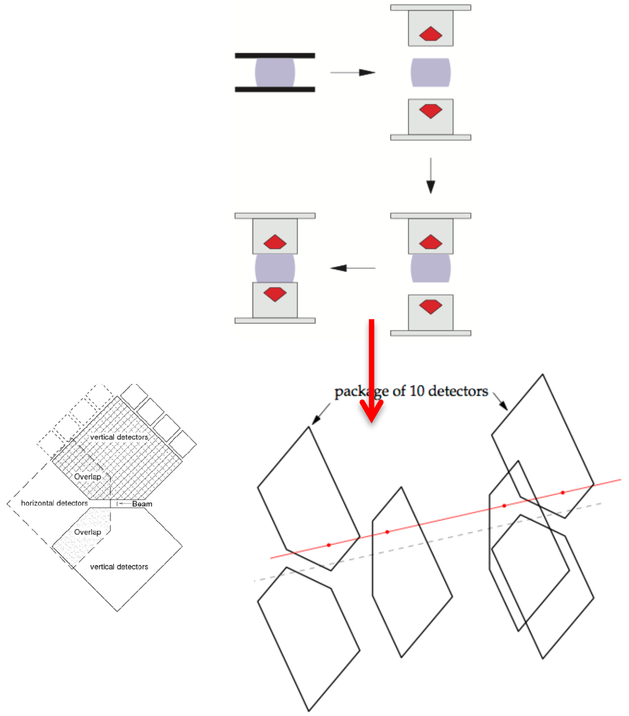


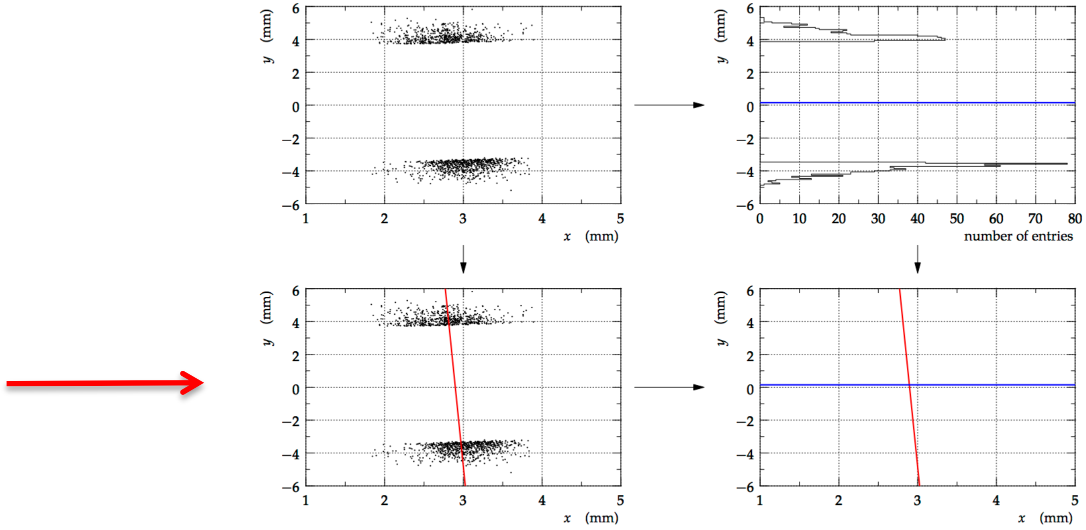
Thank you for your attention!

PPS Alignment (In calibration fill)

- ✸ Alignment is of primary importance as it directly contributes to the reconstruction of proton momentum loss (ξ).
- ✸ Assume 5% uncertainty, $Dx \approx 8$ cm and $\xi \approx 0.05$ yields a horizontal hit position uncertainty of 200 μ m.
- ✸ This stage is performed with a special LHC fill.
- ✸ Consists of three steps, Beam-based alignment, Relative alignment among RPs, Absolute alignment by pp→pp processes.
- ✸ 1h time slices of the data, to examine time variation and to control systematic effects.

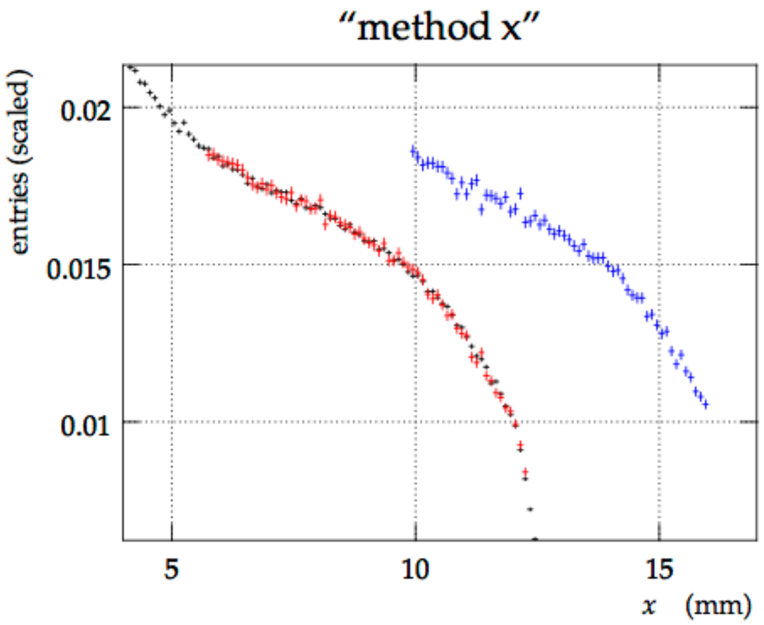




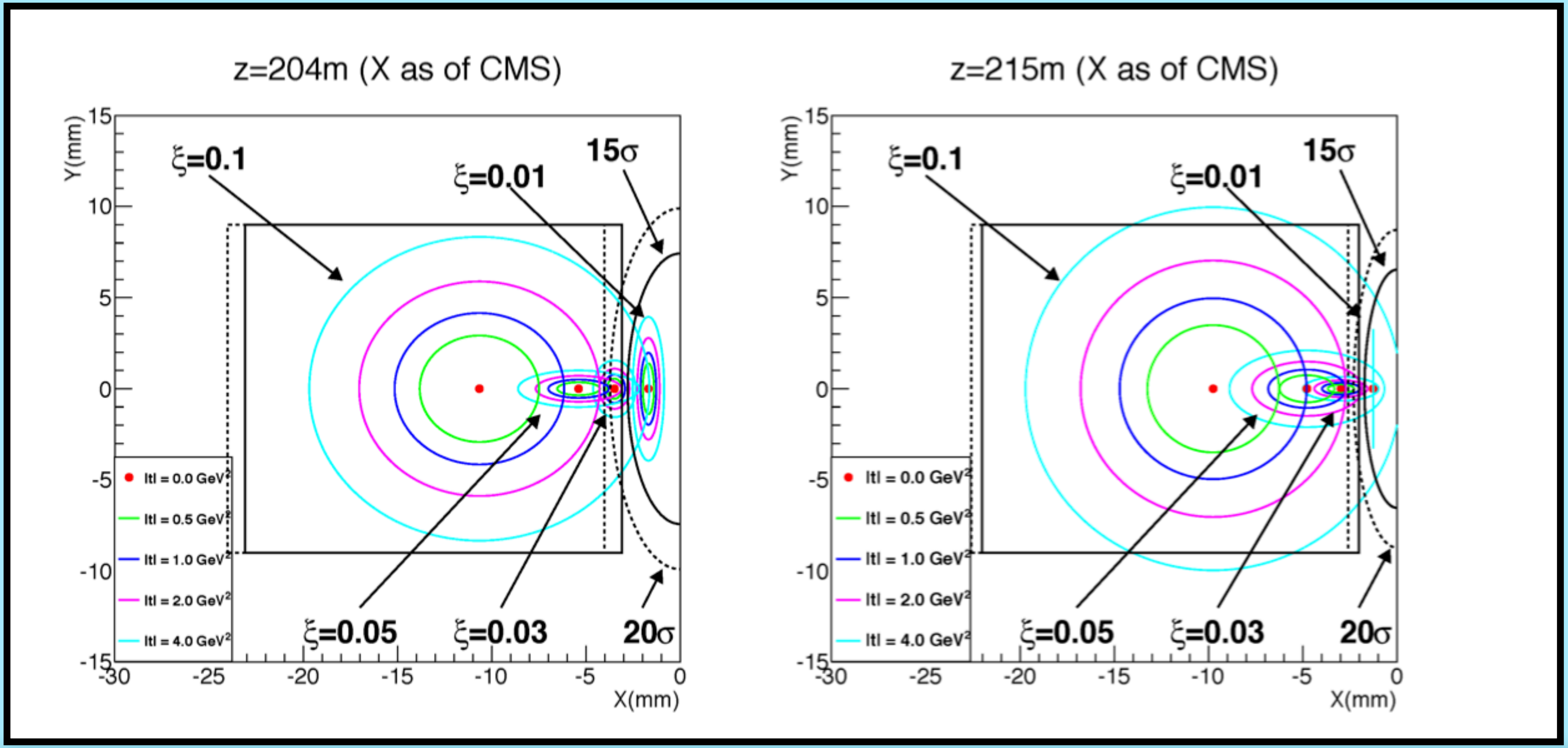


PPS Alignment (In physics fill)

- The physics fills can be characterized by high intensity and only horizontal RPs inserted.
- The procedure is data-driven for both horizontal and vertical alignment and therefore it is important to verify the stability of the LHC conditions (beam orbit, position of collimators, etc.)
- It is based on the fact that the physics is the same in all fills. If the LHC conditions were stable, the same is true for the hit distributions observed in the RPs.
- Therefore, the alignment can be achieved by matching the hit distributions from a physics fill to the previously aligned hit distributions.
- For this method, it is obviously important to suppress non-physical background.



Detector Acceptance(simulation)



TOTEM-TDR-003, CMS-TDR-013