Forward physics and colliding light at HL-LHC

Photon-induced Processes Workshop

IPPP, Durham University

3 November 2022

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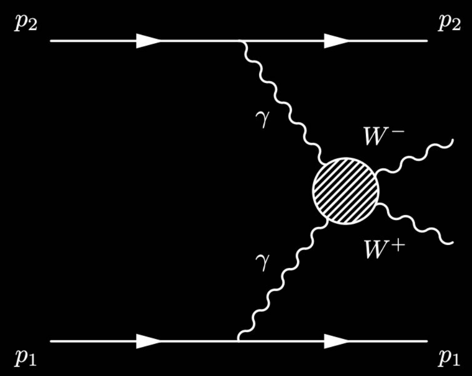
University of Cambridge

TRINITY COLLEGE CAMBRIDGE

UNIVERSITY OF CAMBRIDGE

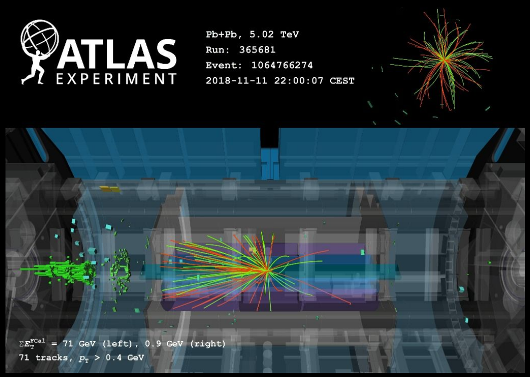


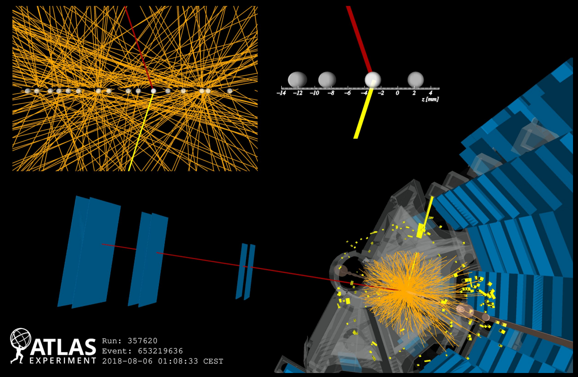
OUTLINE

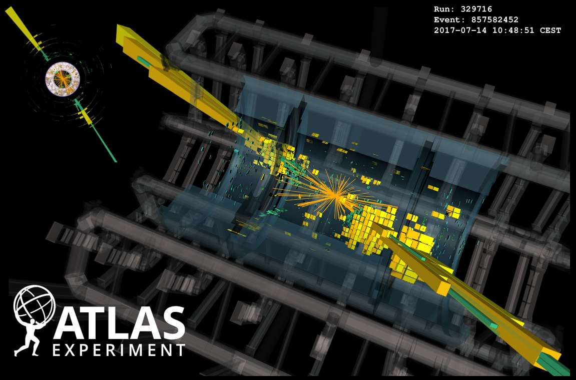
PART 1
General overview

PART 2
Benchmark processes

Program dovetails with HL-LHC science drivers







STRONG INTERACTIONS

Only known confining force still fundamentally mysterious

Nonperturbative dynamics requires data tuning

PRECISION ELECTROWEAK

Electroweak symmetry breaking remains an enduring enigma

Precision powerful indirect probes of new physics

DIRECT BSM SEARCHES

Widespread evidence in lepton flavour & dark matter

Need broad searches in varied production & decay channels

“*The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques*” – European Strategy Update 2020

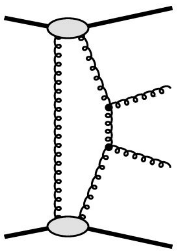
ATLAS Event Displays, ATLAS+CMS Yellow Report [1902.10229], EPPSU Physics Briefing Book [1910.11775]

Vibrant science opportunities

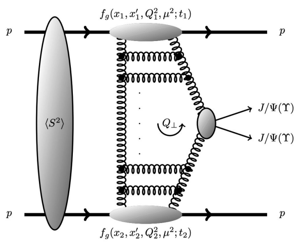
Highlight rare femtobarn processes just being observed

High luminosity vital for precision and search sensitivity

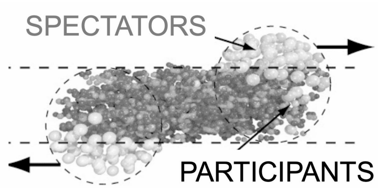
SM JETγ **BPHY** **HION** **TOPQ** **HIGG**



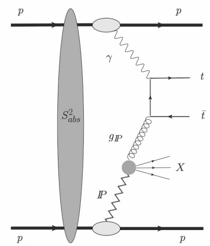
Jets
ATLAS PHYS-PUB-2015-003
CMS 2002.12146



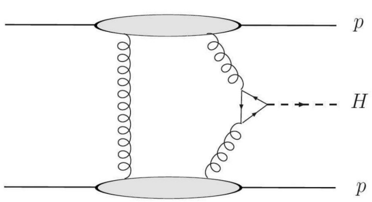
Quarkonia
Harland-Lang et al 1508.02718
Goncalves et al 1912.02720



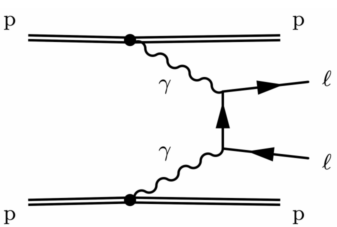
Heavy ions
Oppedisano Elba Wkshp 2016
Chwastowski et al 2011.00872



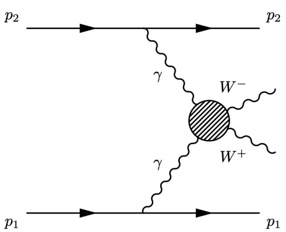
Top quarks
Goncalves et al 2007.04565
Howarth 2008.04249



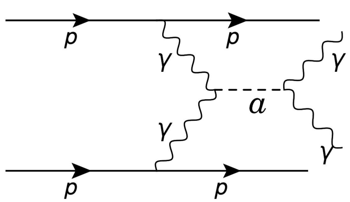
Higgs boson
Cox et al 0709.3035
Heinemeyer et al 0708.3052



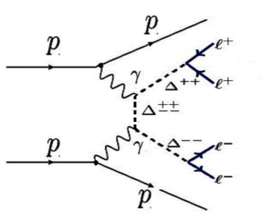
Electrons/muons
CMS+TOTEM 1803.04496
ATLAS 2009.14537



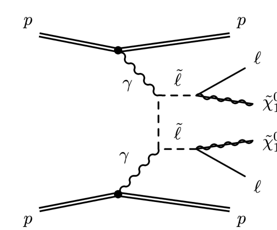
Gauge bosons
Tizchang & Etesami 2004.12203
Baldenegro et al 2009.08331



Axion-like particles
Fichet et al 1312.5153
Baldenegro et al 1803.10835



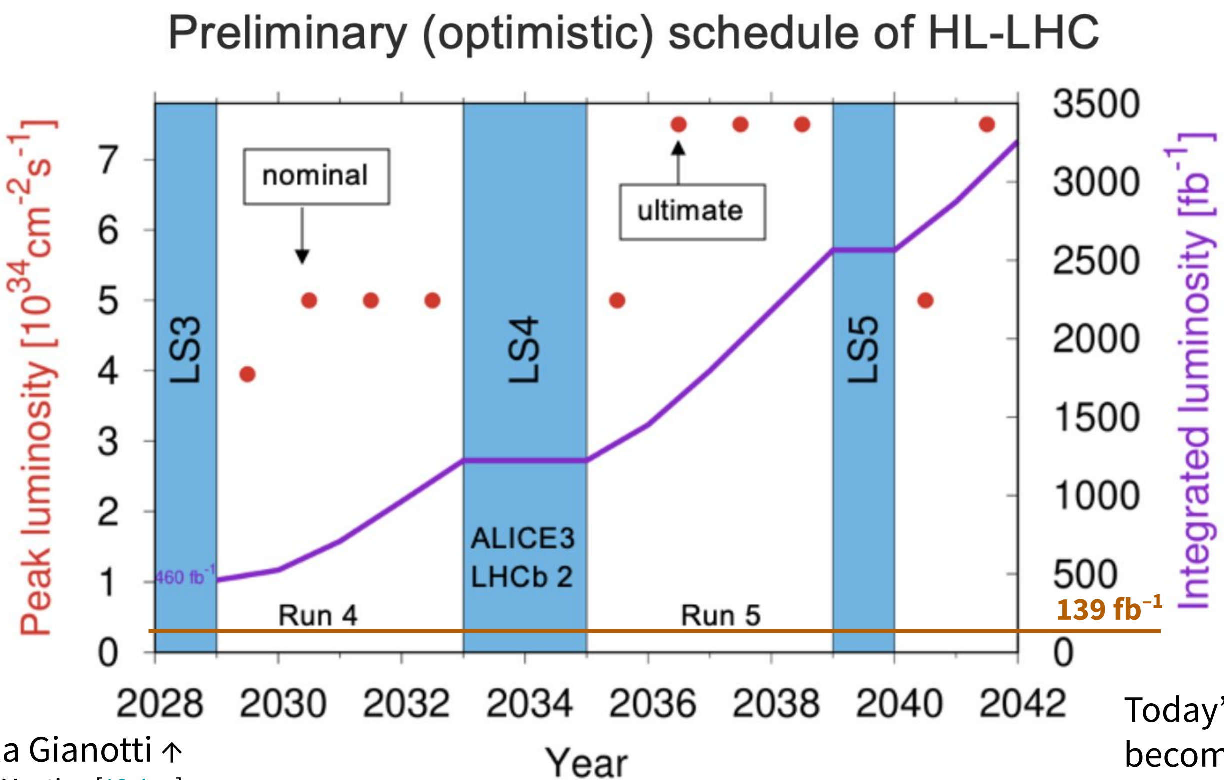
Multicharged Higgs
Babu & Jana 1612.09224
Fuks et al 1912.08975



Sleptons & neutralinos
Beresford & JL 1811.06465
Harland-Lang et al 1812.04886

SM sQCD **SM EWK** **EXOT** **HDBS** **SUSY**

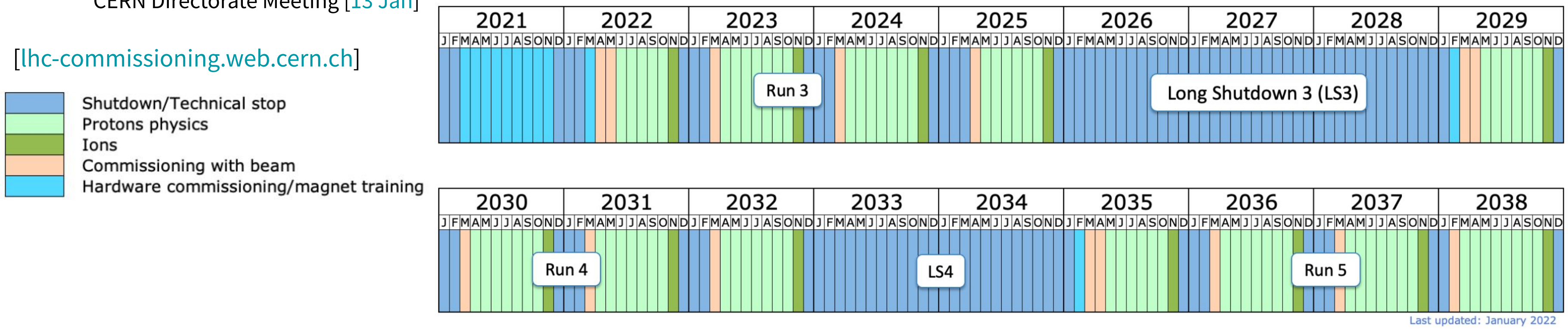
HL-LHC baseline schedule



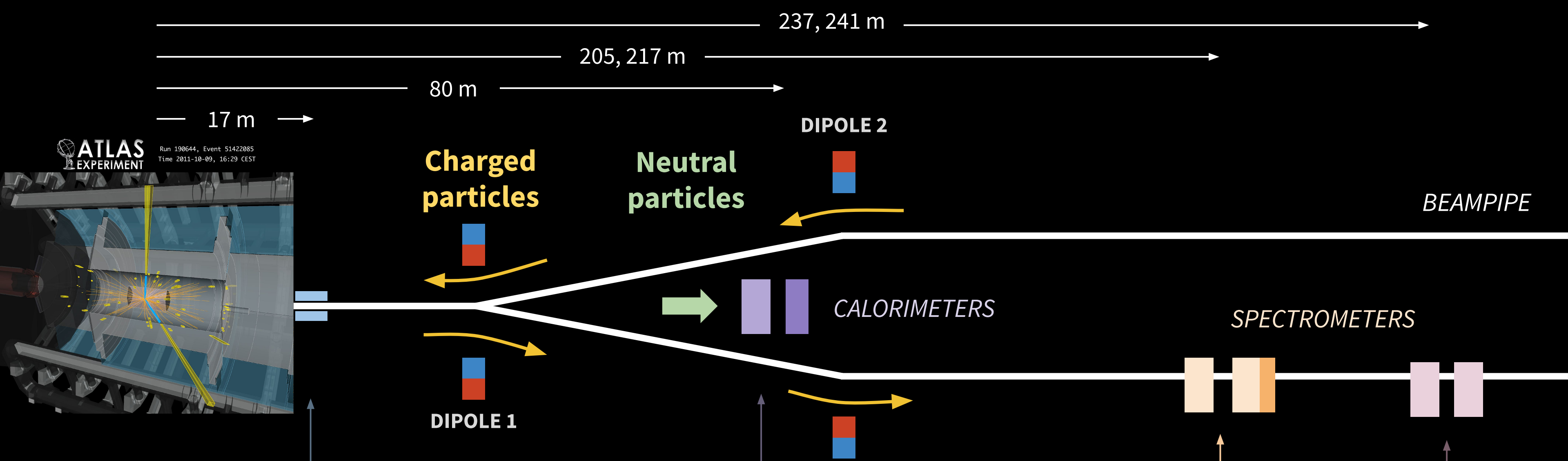
Fabiola Gianotti ↑
CERN Directorate Meeting [13 Jan]

Today's undergrads become postdocs ↓

[lhc-commissioning.web.cern.ch]



FORWARD DETECTORS @ P1



LUCID

Luminosity Cherenkov Integrating Detector

$5.6 < |\eta| < 5.9$

→ Run 4: LUCID-3

LHCf

LHC Forward

→ Run 4: no plans

ZDC

Zero Degree Calorimeter

→ Run 4: HL ZDC

Low-μ, $|\eta| > 8.0$

AFP

ATLAS Forward Proton

Low & high μ, $0.02 < \xi < 0.12$

→ Run 4: Not recommended

ALFA

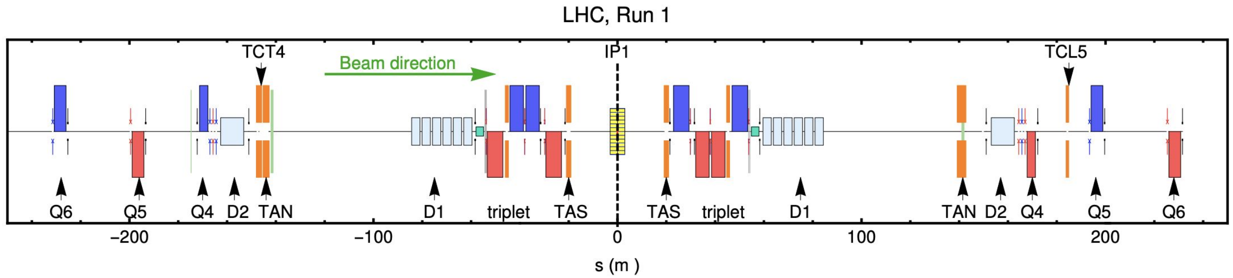
Absolute Luminosity For ATLAS

Low-μ, $0 < \xi < 0.2$, $10.6 < |\eta| < 13.5$

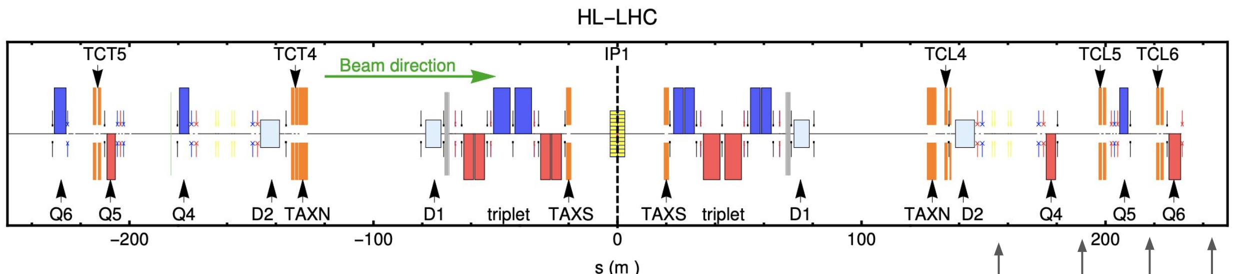
→ Run 4: no plans

Machine upgrades: LHC → HL-LHC

Beamline



2010–13



Start ≳ 2029

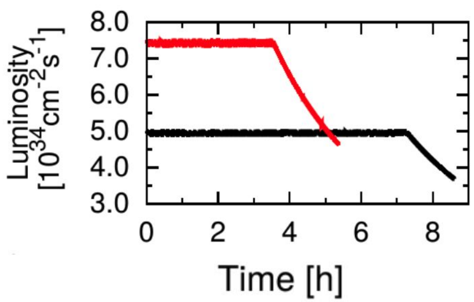
Crab cavities

AFP locations?

More machine protection (collimators) → constrains beamline

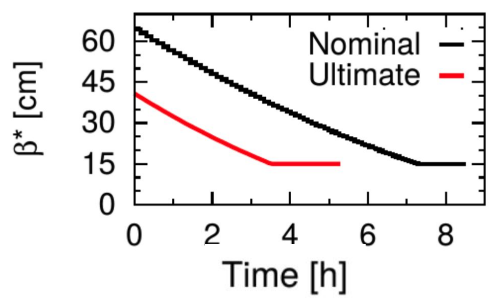
Bruce et al CERN-ACC-2015-0192 ↑ | Revisit with new optics: HLLHCV1.5 (2020)

Parameters

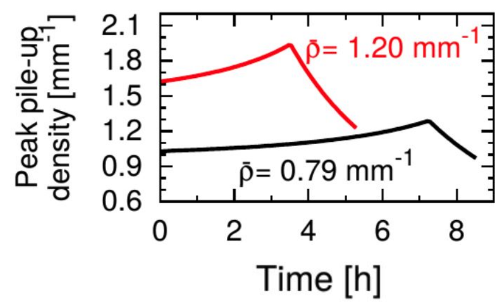


More pileup

Arduini et al [HL-LHC TDR]



Optics changes during fill



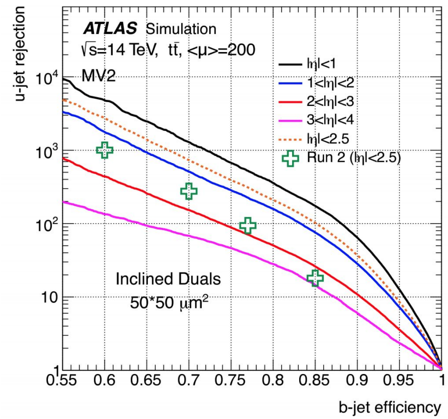
Track exclusivity More difficult

Central detector upgrades

Trigger Selection	Run 1 Offline p_T Threshold [GeV]	Run 2 (2017) Offline p_T Threshold [GeV]	Planned HL-LHC Offline p_T Threshold [GeV]	L0 Rate [kHz]
isolated single e	25	27	22	200
isolated single μ	25	27	20	45
single γ	120	145	120	5
forward e			35	40
di-γ	25	25	25,25	
di-e	15	18	10,10	60
di-μ	15	15	10,10	10
$e-\mu$	17,6	8,25 / 18,15	10,10	45
single τ	100	170	150	3
di-τ	40,30	40,30	40,30	200
single b-jet	200	235	180	25
single jet	370	460	400	
large-R jet	470	500	300	40
four-jet (w/ b-tags)		$45^{\dagger}$(1-tag)	65(2-tags)	100
four-jet	85	125	100	
H_T	700	700	375	50
E_T^{miss}	150	200	210	60

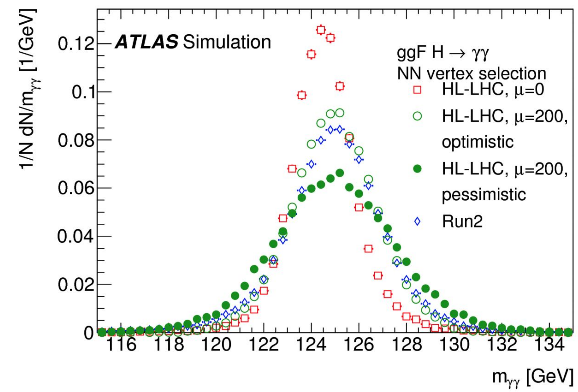
Trigger [TDAQ TDR]

Lower e/μ thresholds & higher muon barrel coverage improves γγ → ℓℓ analysis



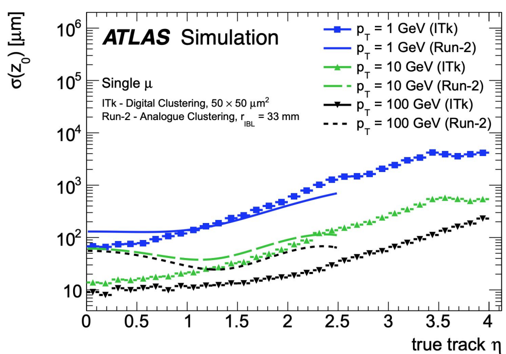
B-tagging [ITk Pixel TDR]

Improved track resolution betters light rejection given b-tag efficiency important for h → bb



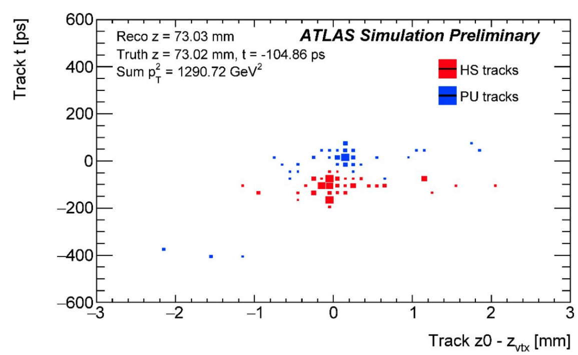
m(γγ) resolution [LAr TDR]

Comparable to Run 2 (driven by LAr)
Important for AFP diphoton analyses



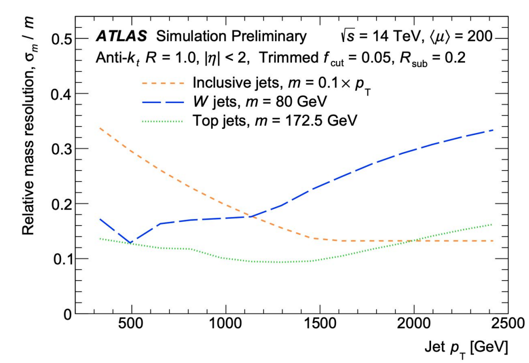
Vertex resolution [ITk Pixel TDR]

Improved z_0 resolution important for exclusive vertex isolation in γγ → WW analysis



Forward track timing [2018]

HGTD enables track timing for 2.4 < $|\eta|$ < 4.0
Impacts CEP decays to $|\eta|$ > 2.4 electrons/jets



W → jj tagger [PHYS-PUB-2019-005]

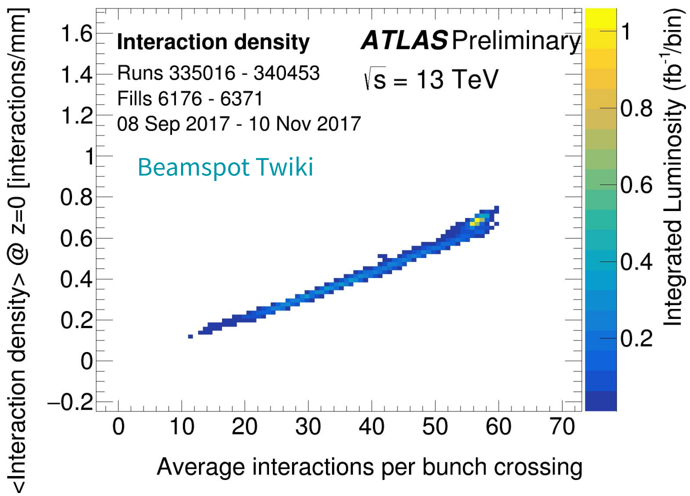
Pileup mitigation important for high-mass boosted hadronic γγ → WW analyses

Practical challenges on program

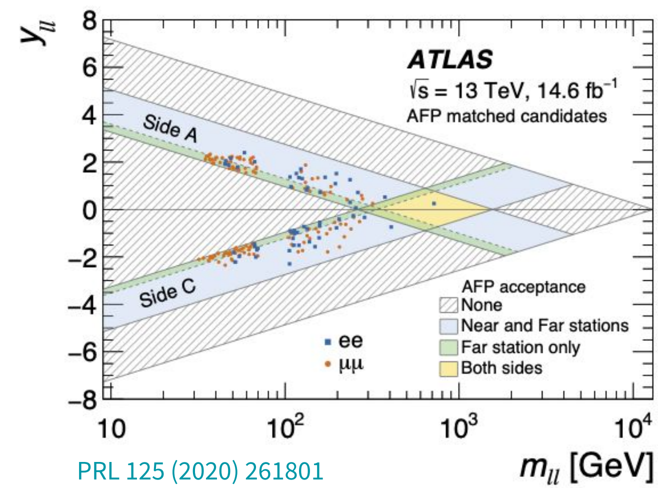
Central detector: pileup density

Forward detector: acceptance

Run 2

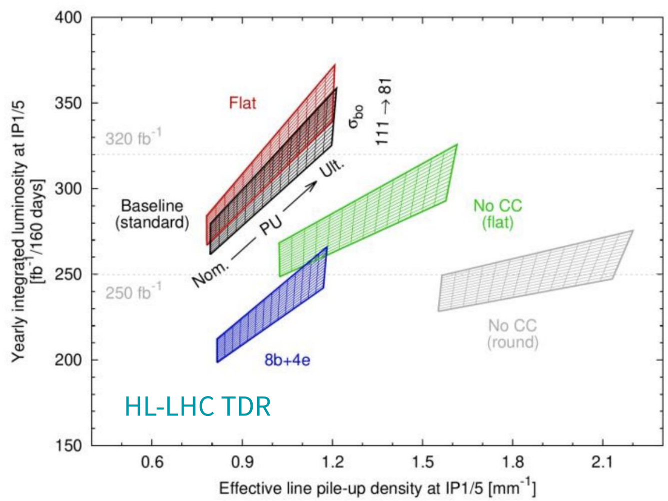


Beamspot Twiki

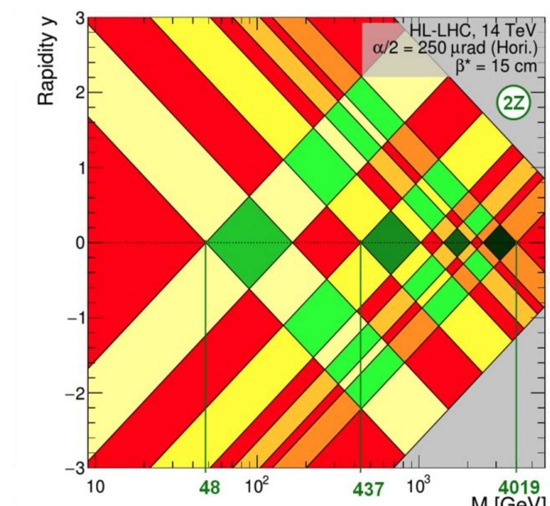


PRL 125 (2020) 261801

Run 4



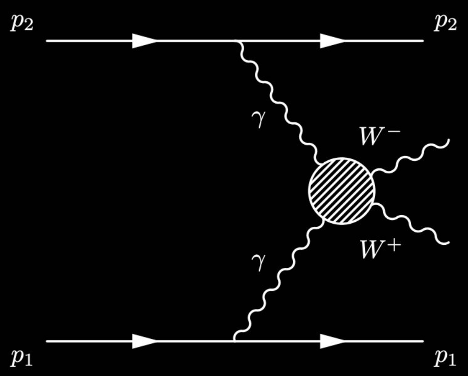
HL-LHC TDR



2103.02752

Up to 0.6 mm^{-1} → up to 1.2 mm^{-1}

Machine protection → discontinuous acceptance

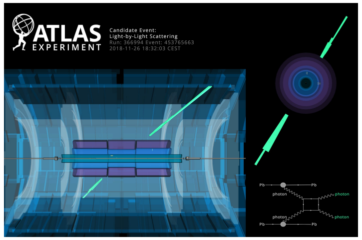


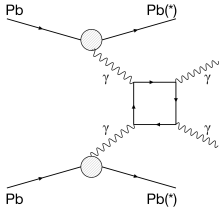
OUTLINE

PART 1
General overview

PART 2
Benchmark processes

Recent experimental breakthroughs key HL-LHC targets

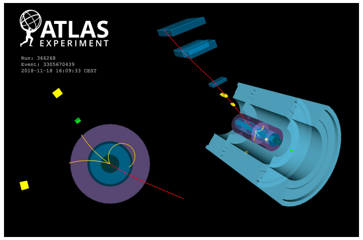


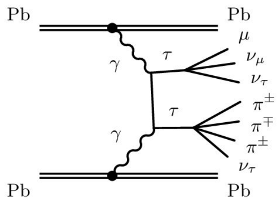


Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector

Probe photon self-coupling & axion-like particles

PRL 123 (2019) 052001

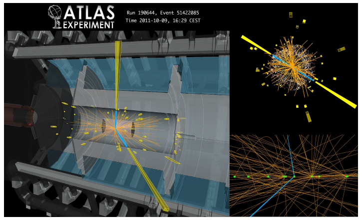


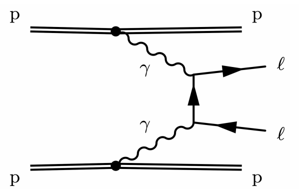


Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector

First tau $g - 2$ measurement in 2 decades

2204.13478 (Accepted PRL)

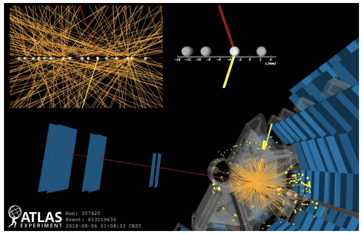


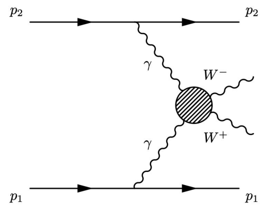


Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

Pioneer ATLAS Forward Proton at weak scale

PRL 125 (2020) 261801

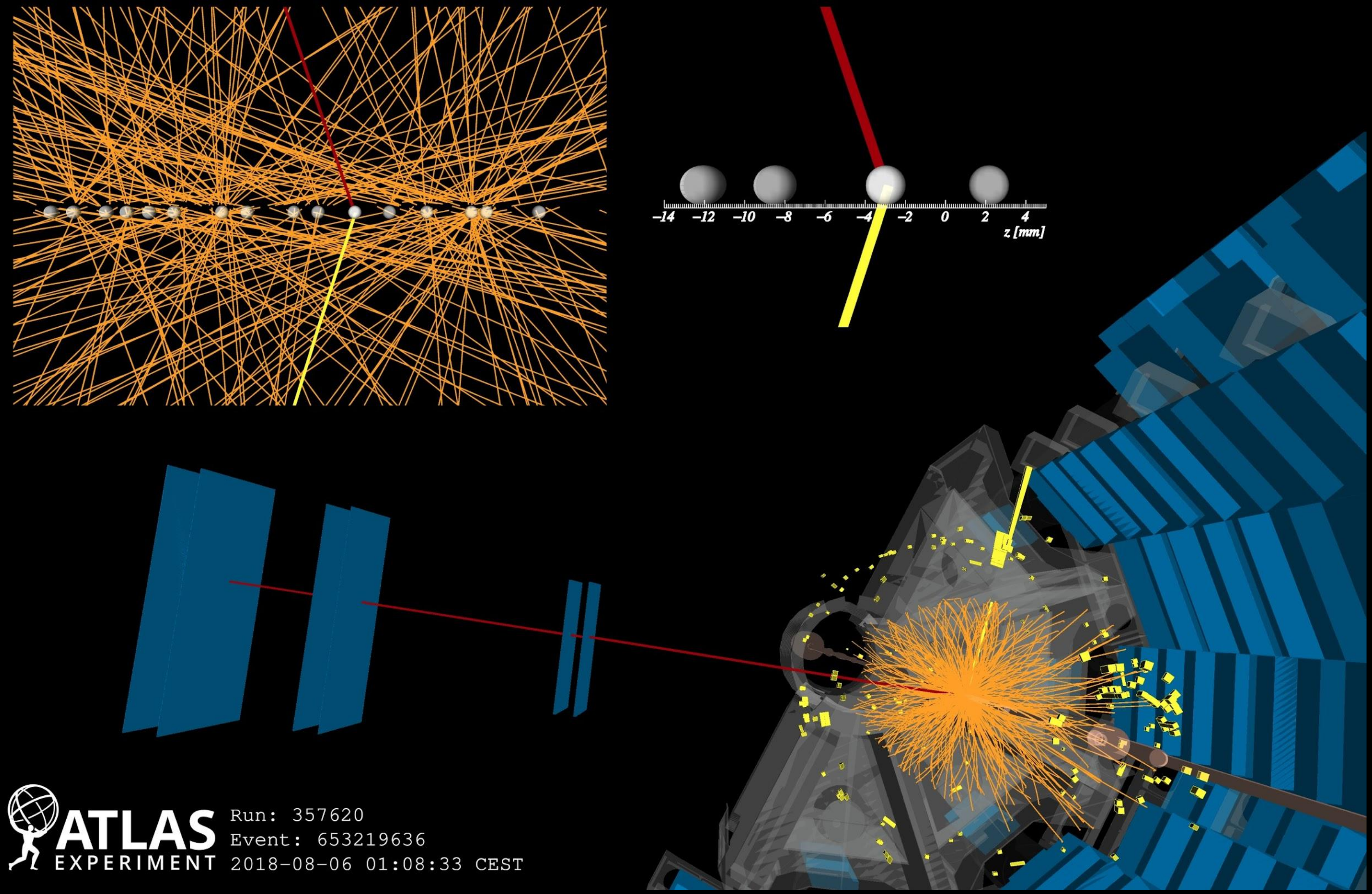




Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector

Create electroweak mass states via photon fusion

PLB 816 (2021) 136190



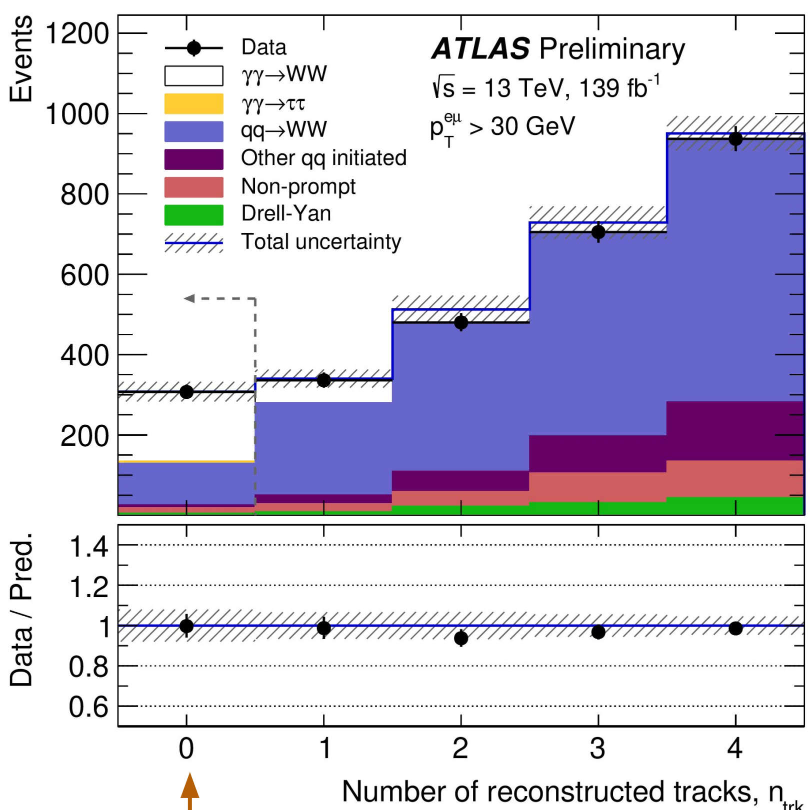
Run 1: ATLAS [1607.03745], CMS [1305.5596, 1604.04464]
Run 2: ATLAS [2010.04019]

Observation of γγ → WW → e$\nu\mu\nu$

$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

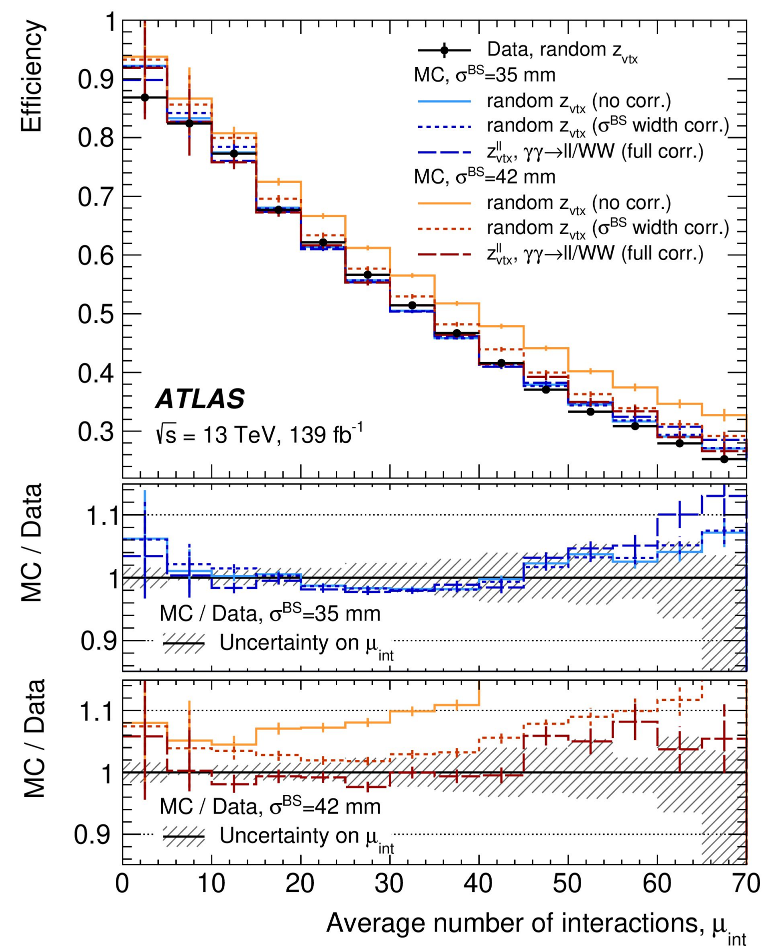
Run 2 pileup already more challenging than Run 1

8.4σ (6.6σ) obs (exp) significance



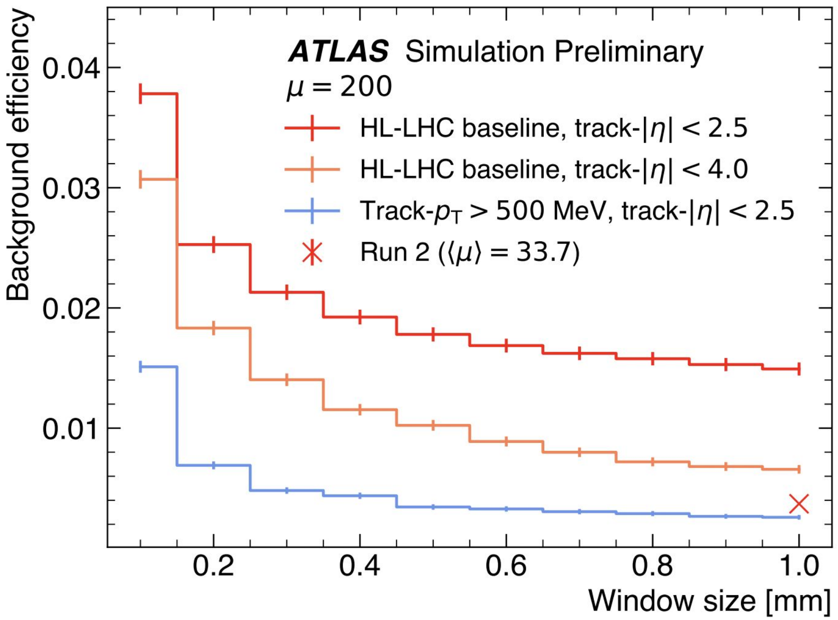
Discriminant: photon collisions leave no additional tracks near eμ vertex

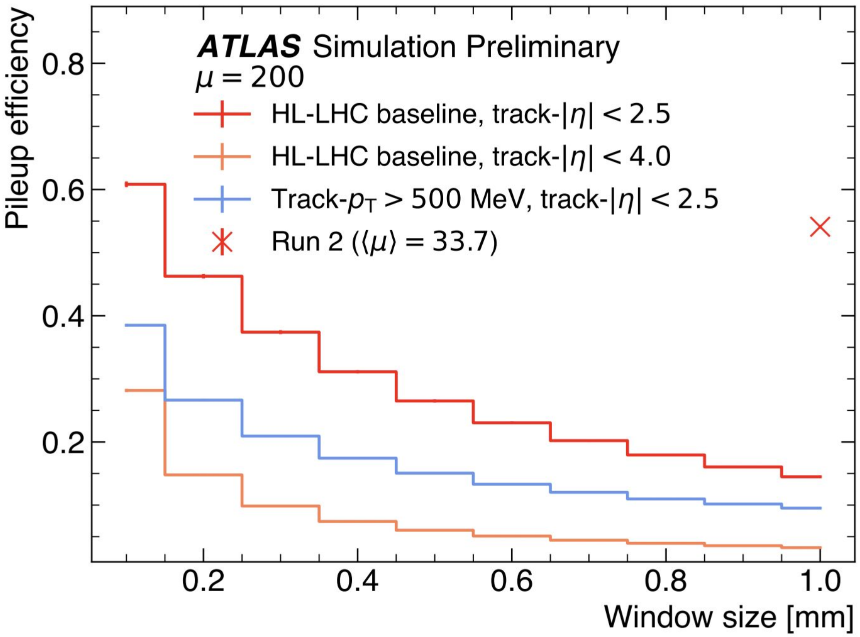
Signal efficiency vs pileup of $n_{trk} = 0$



ATLAS [2010.04019] (PLB)

Background & pileup efficiency with Phase II tracker





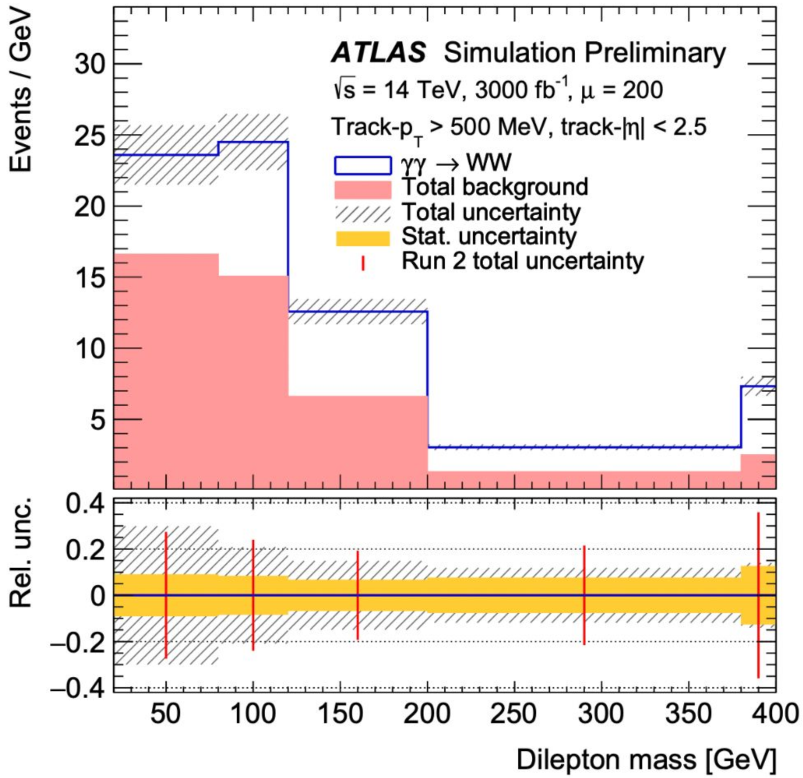
$$N_{\text{signal}}^{\text{HL-LHC}} = N_{\text{signal}}^{\text{Run 2}} \times \frac{\mathcal{L}_{\text{HL-LHC}}}{\mathcal{L}_{\text{Run 2}}} \times \frac{\varepsilon_{\text{pileup}}^{\text{HL-LHC}}}{\varepsilon_{\text{pileup}}^{\text{Run 2}}} \times \frac{\varepsilon_{\gamma\gamma WW}^{\text{HL-LHC}}}{\varepsilon_{\gamma\gamma WW}^{\text{Run 2}}}$$

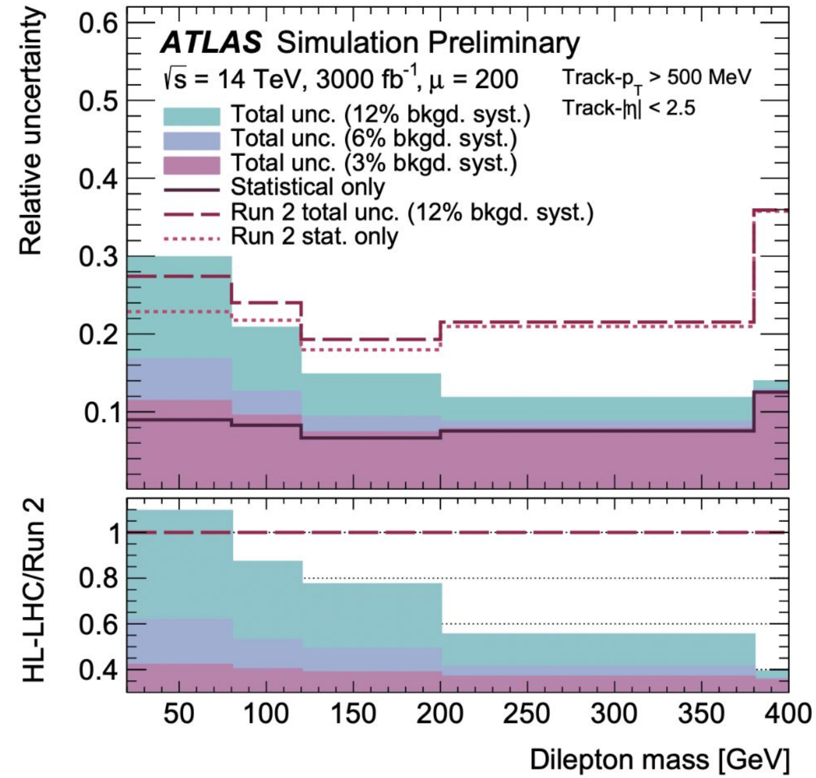
$$N_{\text{bkgd.}}^{\text{HL-LHC}} = N_{\text{bkgd.}}^{\text{Run 2}} \times \frac{\mathcal{L}_{\text{HL-LHC}}}{\mathcal{L}_{\text{Run 2}}} \times \frac{\varepsilon_{\text{pileup}}^{\text{HL-LHC}}}{\varepsilon_{\text{pileup}}^{\text{Run 2}}} \times \frac{\varepsilon_{qqWW}^{\text{HL-LHC}}}{\varepsilon_{qqWW}^{\text{Run 2}}}$$

Studies led by Savannah Clawson!

ATL-PHYS-PUB-2021-026

Extrapolation to HL-LHC: statistics to furnish high-mass tails



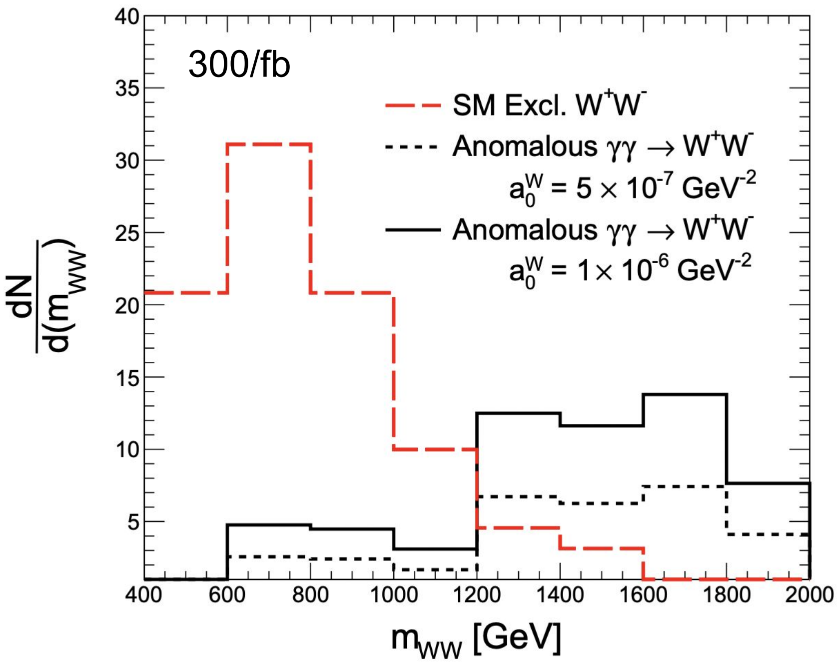


	Dilepton mass [GeV]				
	20–80	80–120	120–200	200–380	380+
Signal					
Run 2	43	39	49	32	10
HL-LHC	419	377	477	310	97
Background					
Run 2	54	33	29	13	3
HL-LHC	997	603	529	236	50

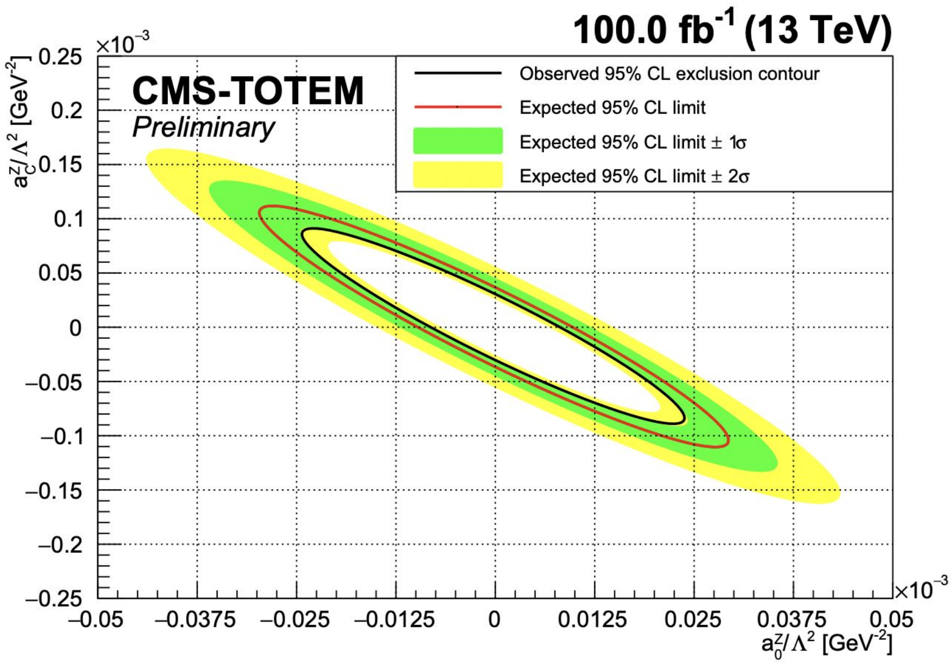
Studies led by Savannah Clawson!
ATL-PHYS-PUB-2021-026

γγ → WW/ZZ: hadronic channel furnishes high-mass tails

Search for exclusive $\gamma\gamma \to$ WW and $\gamma\gamma \to$ ZZ production
in final states with jets and forward protons



Baldenegro et al [2009.08331]

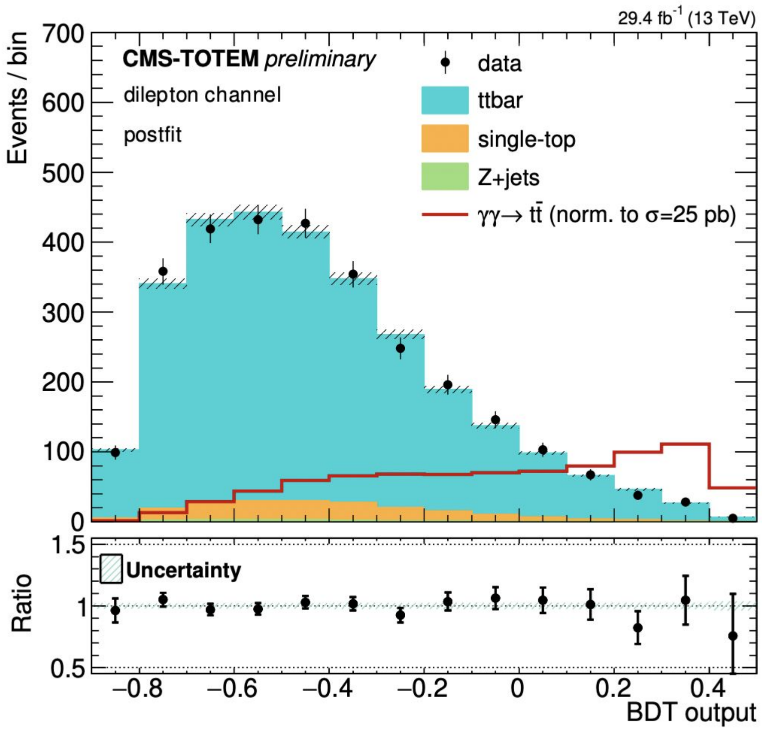


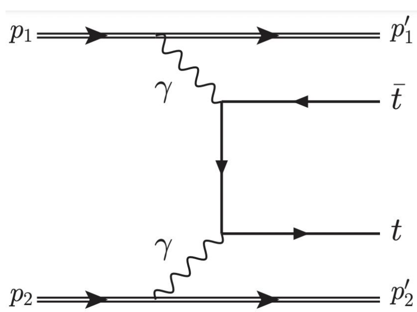
CMS-PAS-SMP-21-014

$$\sigma(pp \to p\mathrm{WW}p)_{0.04<\xi<0.20, m>1000\ \mathrm{GeV}} < 67(53^{+34}_{-19})\ \mathrm{fb},$$

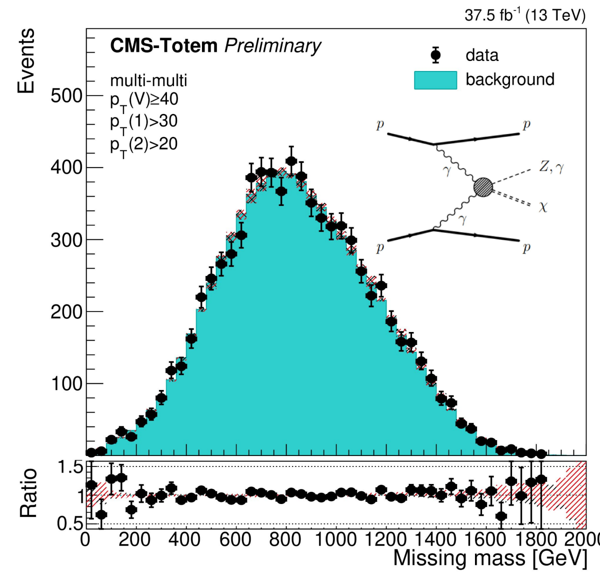
$$\sigma(pp \to p\mathrm{ZZ}p)_{0.04<\xi<0.20, m>1000\ \mathrm{GeV}} < 43(62^{+33}_{-20})\ \mathrm{fb},$$

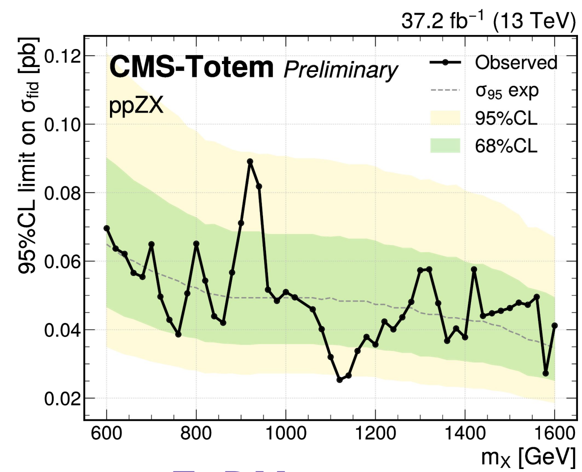
CMS opening novel searches: prime HL-LHC targets





γγ → tt [CMS-PAS-TOP-21-007]



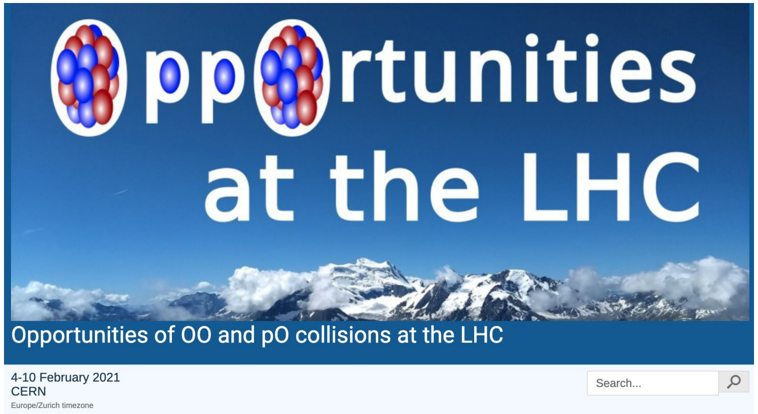


γγ → Z+DM [PAS-EXO-19-009]

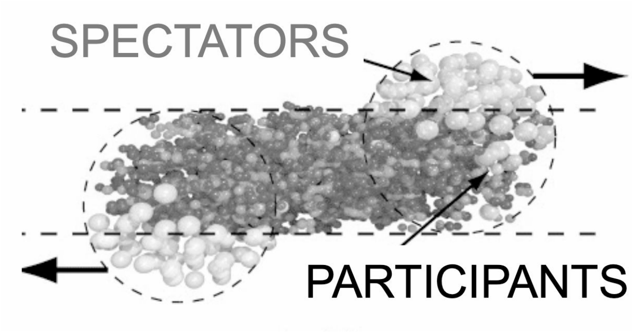
Heavy ion opportunities: strong interactions

Year	Systems, $\sqrt{s_{NN}}$	Time
2021	Pb–Pb 5.5 TeV	3 weeks
	pp 5.5 TeV	1 week
2022	Pb–Pb 5.5 TeV	5 weeks
	O–O, p–O	1 week
2023	p–Pb 8.8 TeV	3 weeks
	pp 8.8 TeV	few days
2027	Pb–Pb 5.5 TeV	5 weeks
	pp 5.5 TeV	1 week
2028	p–Pb 8.8 TeV	3 weeks
	pp 8.8 TeV	few days
2029	Pb–Pb 5.5 TeV	4 weeks
Run-5	Intermediate AA	11 weeks
	pp reference	1 week

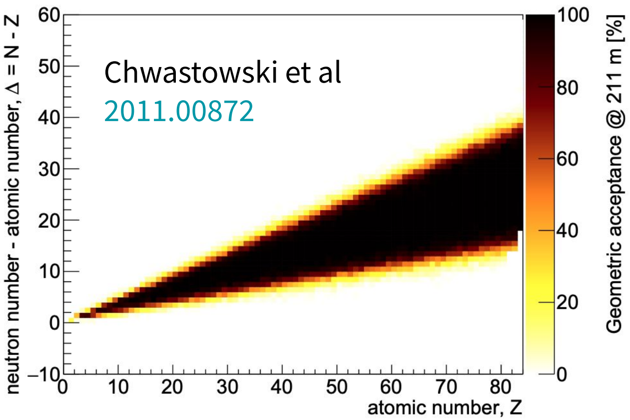
HION YR [1812.06772]



Workshop for pO/OO (in Run 3)



Oppedisano Elba Wkshp 2016

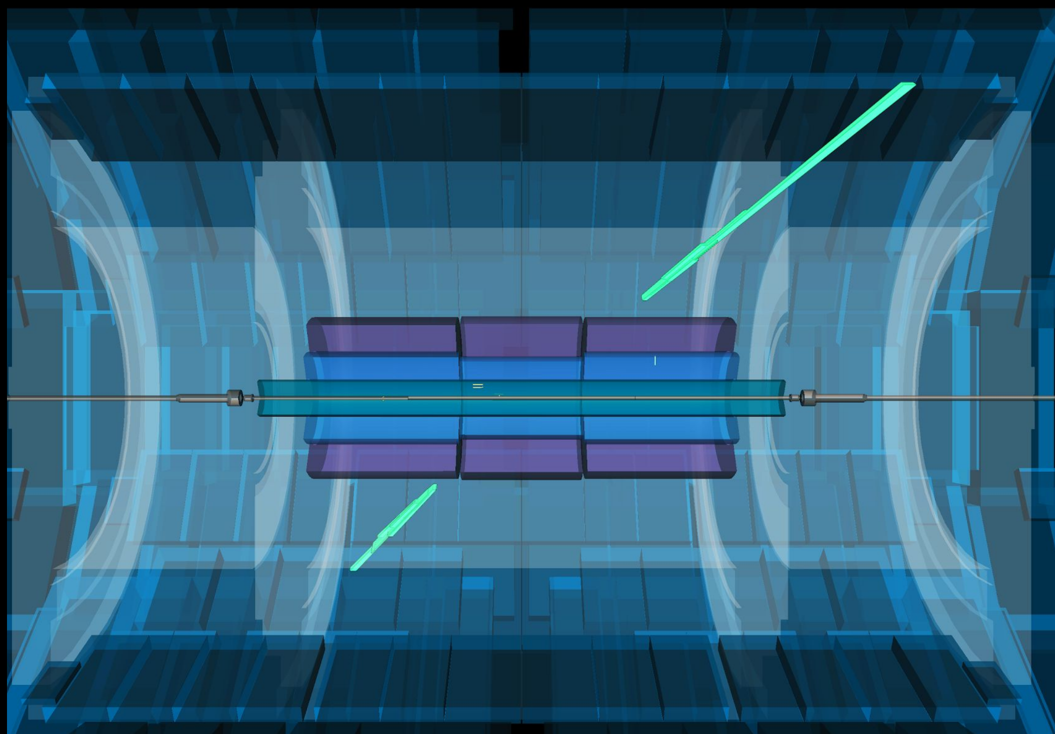


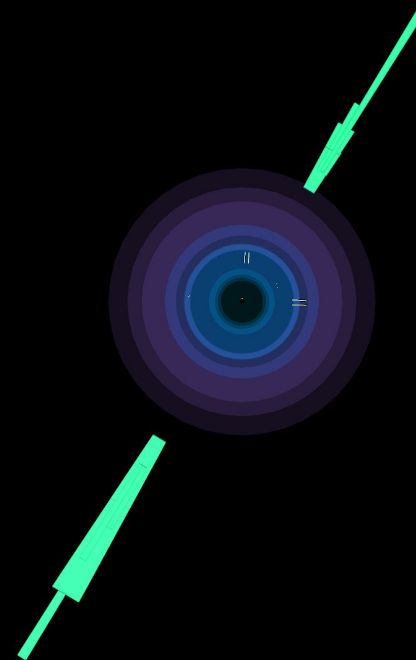
AFP **charged** spectator spectrometry to probe forward nuclei fragment scattering in low/mid-centrality pA/AA collisions

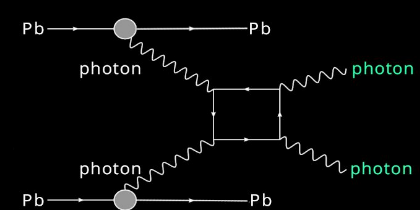
*Current HION data only has ZDC for **neutral** spectator tagging*
*HL-LHC plan **intermediate AA** to study evolution with mass*

ATLAS EXPERIMENT

Candidate Event:
Light-by-Light Scattering
Run: 366994 Event: 453765663
2018-11-26 18:32:03 CEST







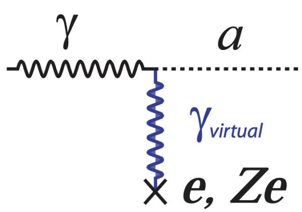
“All charged-particle tracks with p_T > 100 MeV are shown”

Observation of light-by-light scattering $\gamma\gamma \to \gamma\gamma$

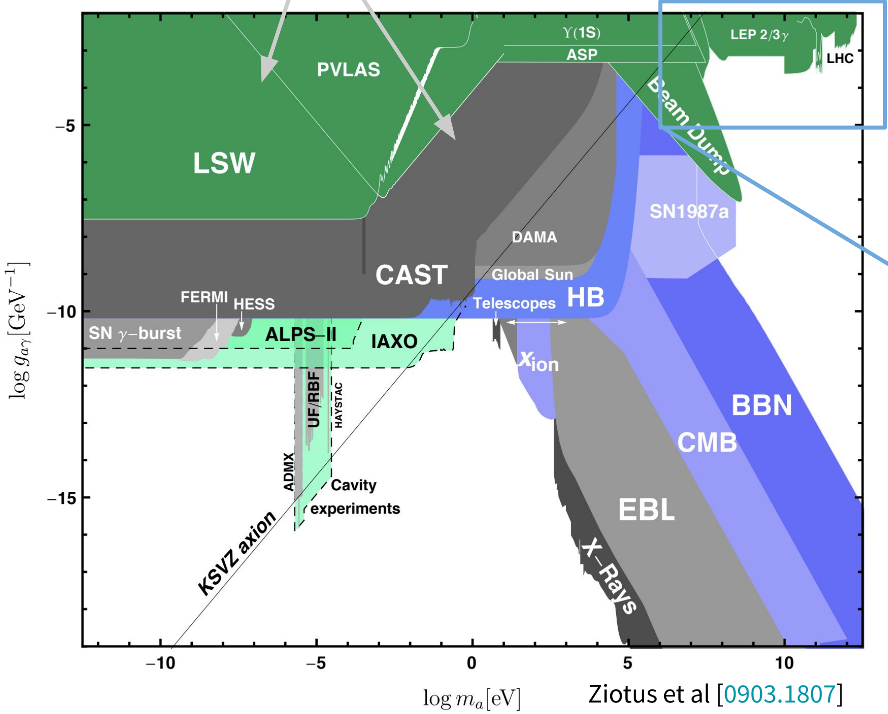
8.2σ (6.2σ) obs (exp) significance

ATLAS [1904.03536]; see also d'Enterria & da Silveira [1305.7142], ATLAS [1702.01625, 2008.05355], CMS [1810.04602]

GeV-scale axion-like particles: sensitivity

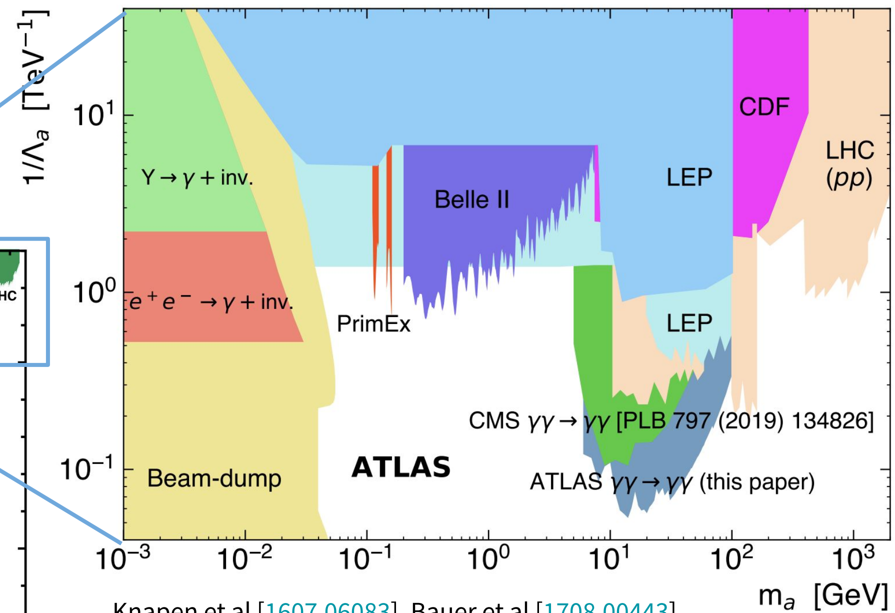


Primakoff production is a photon collision

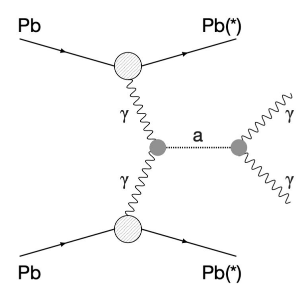


Ziotus et al [0903.1807]
MADMAX [1901.07401]

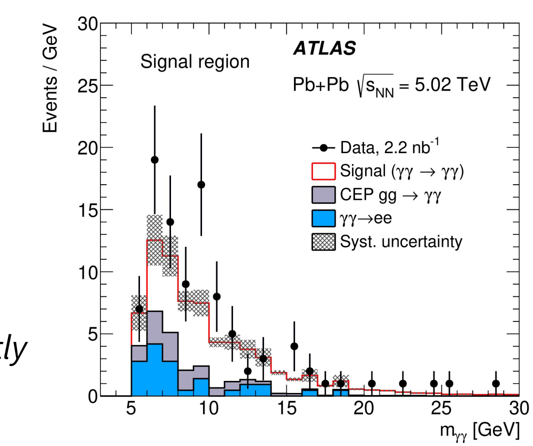
Existing constraints from JHEP 12 (2017) 044



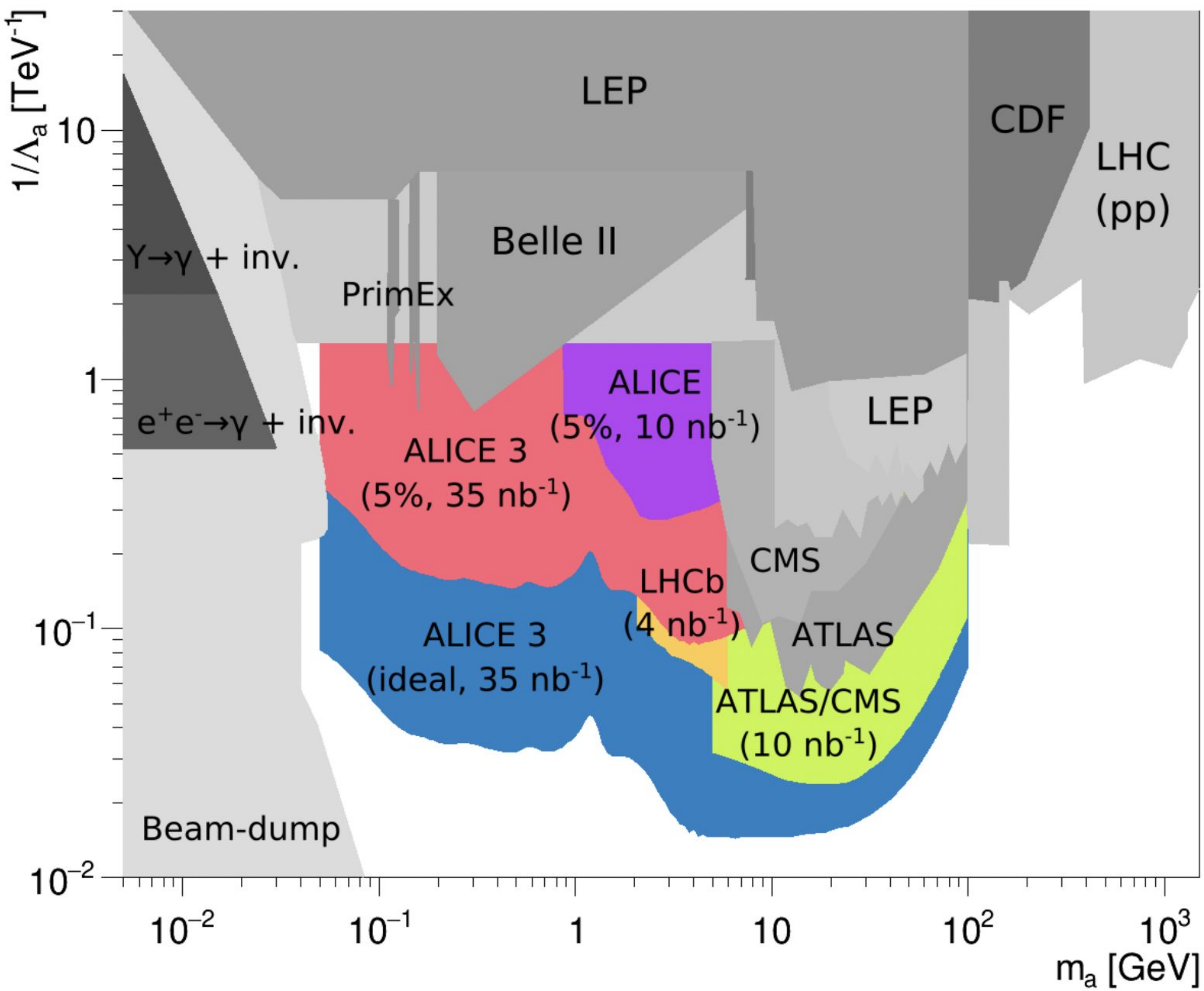
Knapen et al [1607.06083], Bauer et al [1708.00443]
CMS [1810.04602], ATLAS [1904.03536, 2008.05355]



Photon self-coupling resonantly enhanced ⇒ bumphunt

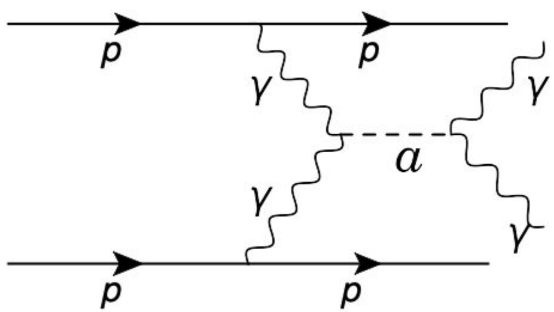


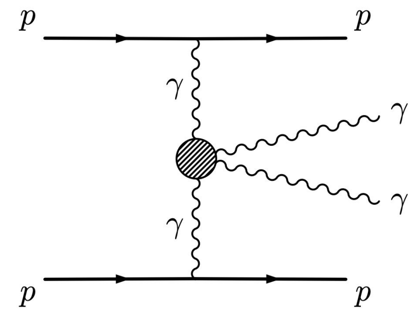
GeV-scale axion-like particles: extrapolation

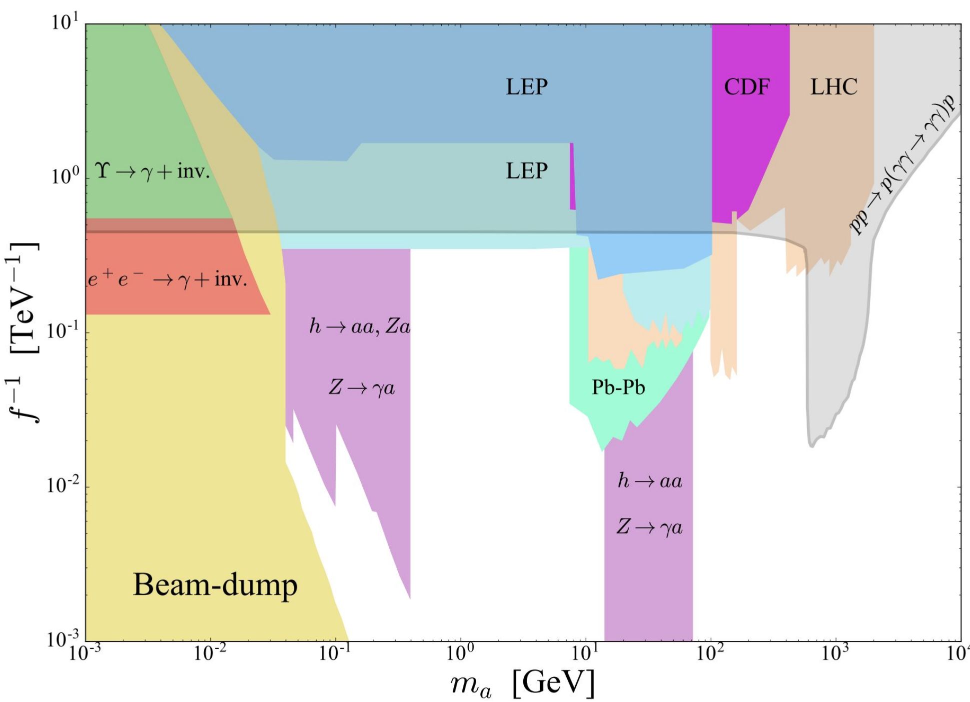


d'Enterria et al (Snowmass whitepaper) [2203.05939]

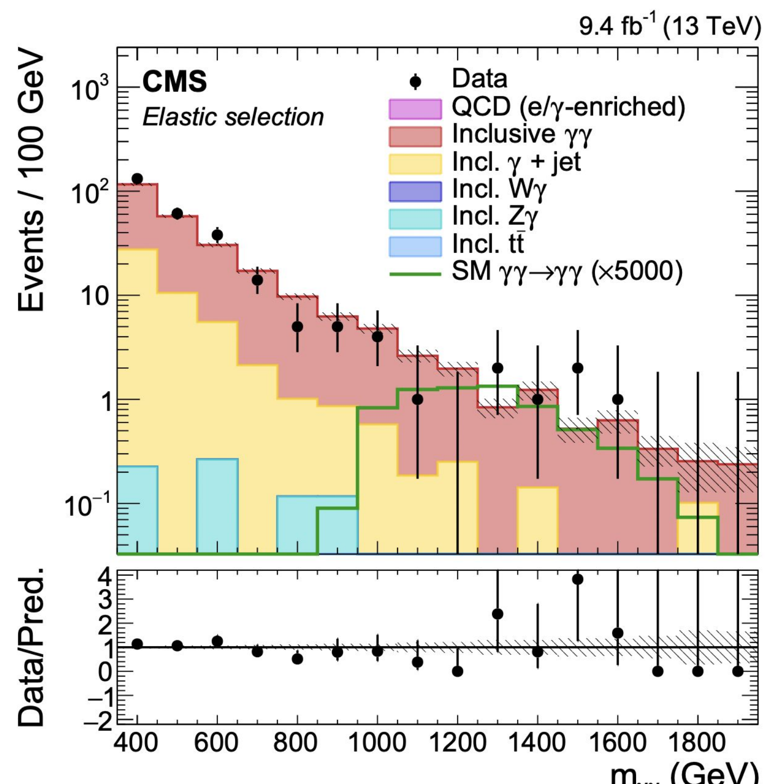
Future: TeV-scale axion-like particles via pp data





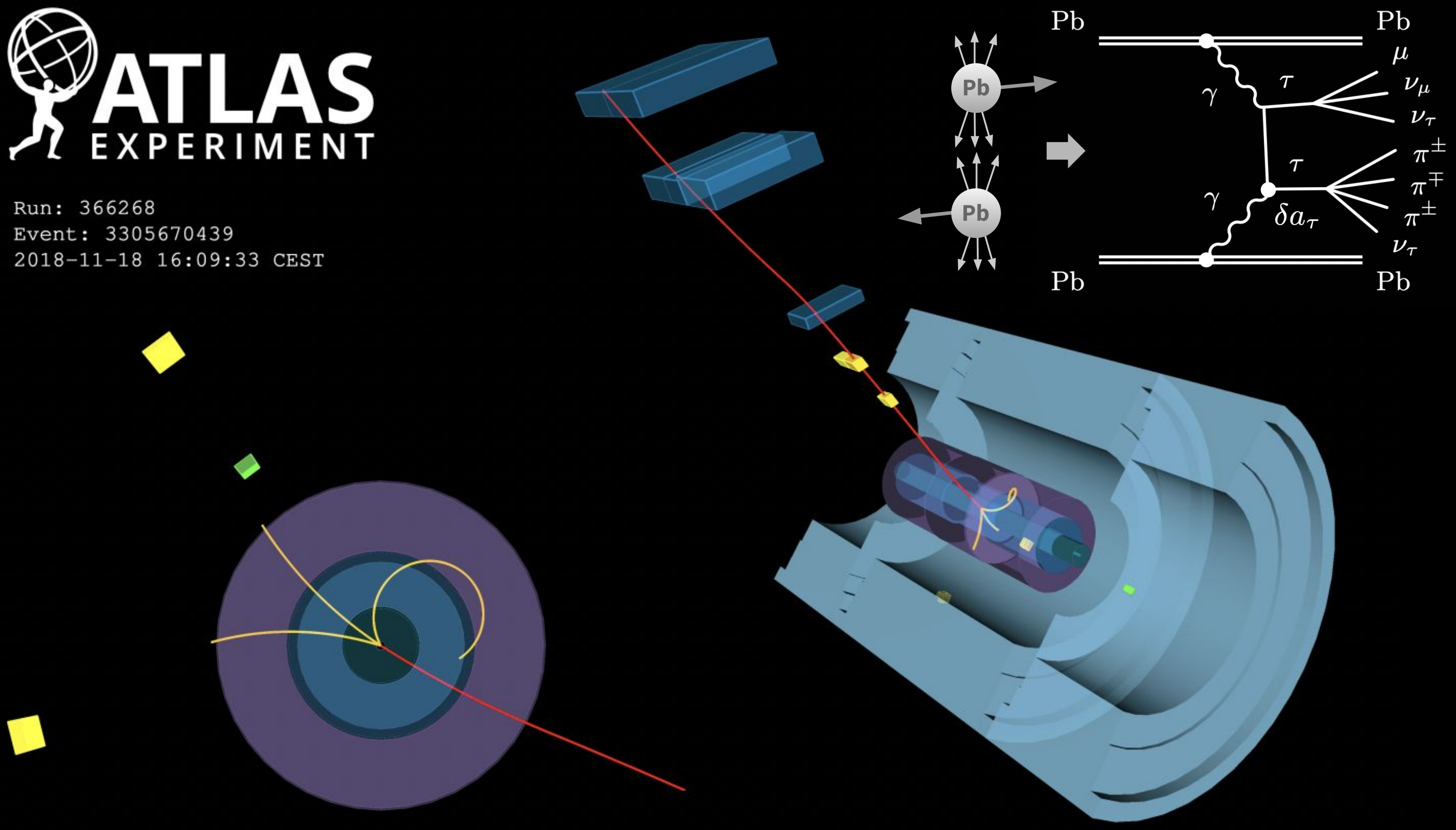


Baldenegro et al [1803.10835] (JHEP)



CMS [2110.05916] (PRL)

Observation of Pb+Pb → Pb ($\gamma\gamma \rightarrow \tau\tau$) Pb

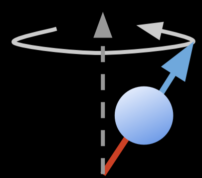


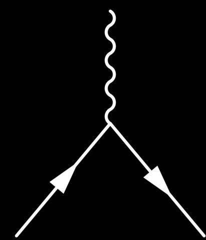
↑ *All charged-particle tracks above 100 MeV are shown*

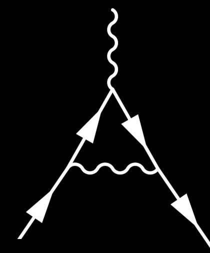
1 month to double dataset | Pileup μ ~ 0.003 | $p_T(\mu)$ > 4 GeV trigger

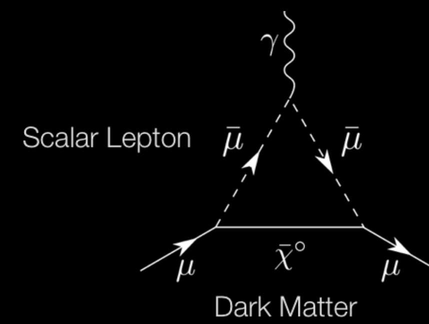
ATLAS 2204.13478 (Accepted PRL), CMS [2206.05192]

$g_\ell - 2$: cracks at the heart of the Standard Model?







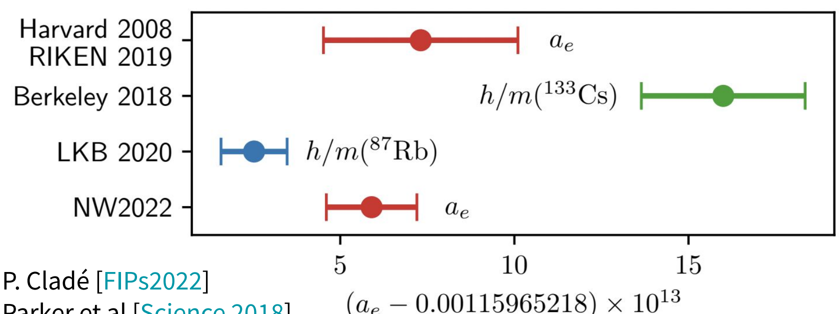


$$g = 2 + \frac{\alpha}{\pi}$$

$$\boldsymbol{\mu}_f \cdot \mathbf{B} = \frac{g_f e}{2m_f} \mathbf{S} \cdot \mathbf{B}$$

Dirac (1928) **Schwinger (1948)** **Dark matter?**

Electron $g - 2$ (-2.5σ?)

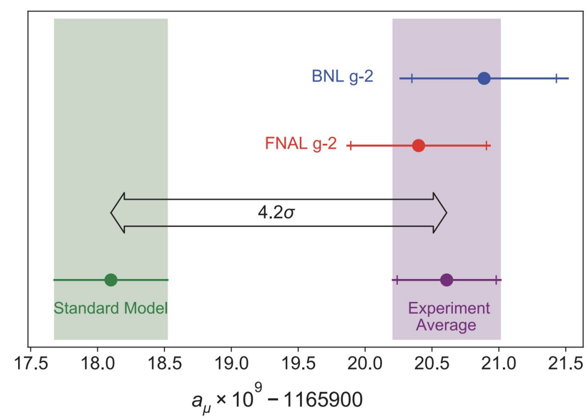


P. Cladé [FIPs2022]
Parker et al [Science 2018]
Morel et al [Nature 2022], Fan et al [2209.13084]

0.2 parts per billion

"Triumph of quantum electrodynamics"

Muon $g - 2$ ($+4.2\sigma$?)



0.5 parts per million

"Hadronic ignorance or harbinger of new physics?"

Muon g–2 Experiment [2104.03281] (PRL)

What about tau *g* – 2?

SHOCKING EXPERIMENTAL IGNORANCE!

Pressing problem: barely measured

$$a_\tau^{\mathrm{exp}} = -0.018\,(17)$$

DELPHI [hep-ex/0406010]

$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

Not even testing 70 year old 1-loop QED

$$\alpha/2\pi = 0.001162$$

Schwinger [1948]

But 280× more sensitive to SUSY than muon

$$\delta a_\ell \sim m_\ell^2/M_{\mathrm{SUSY}}^2 \qquad m_\tau^2/m_\mu^2 \sim 280$$

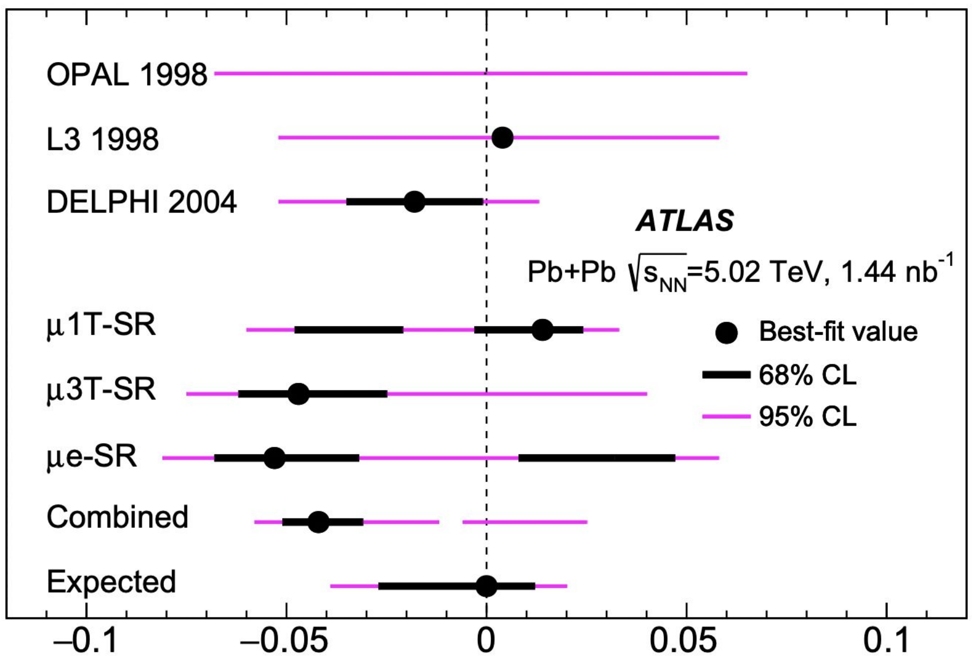
Martin, Wells [hep-ph/0103067]

Groundbreaking results competitive with LEP

First lab measurement of tau $g - 2$ in 2 decades

First time tau pairs observed in heavy ion data

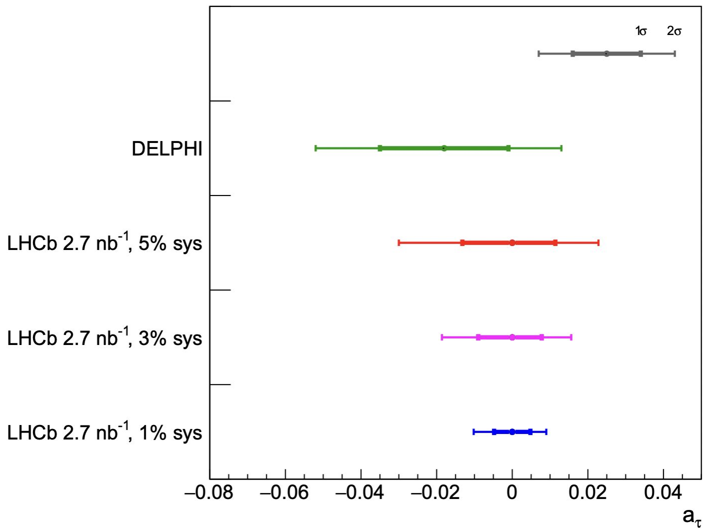
Heavy ions enabled 5% measurement of QED g_τ

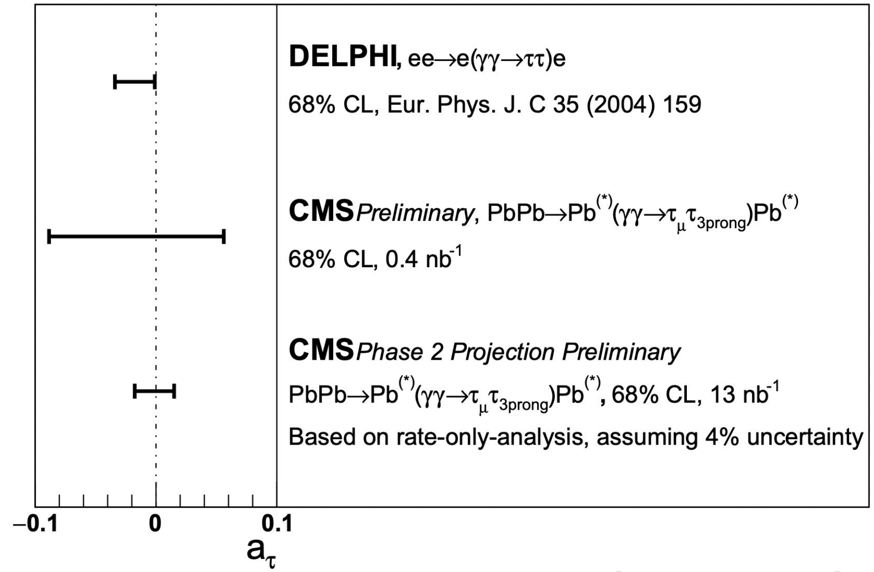


$a_\tau = (g_\tau - 2)/2$

ATLAS 2204.13478 (Accepted PRL)

CMS (& ALICE+LHCb) tau *g*–2 Phase II extrapolations





LHCb+ALICE too: Burmasov et al [2203.00990]

CMS [PAS-HIN-21-009]

Table 1: Projected integrated luminosity at each LHC experiment during a typical future 1-month run with Pb-Pb or p-Pb operation [71]. Assuming five 1-month runs with Pb-Pb and two with p-Pb, the total integrated luminosity projected until the end of Run 4 in the present baseline scenario is also listed. An operational efficiency of 50% is assumed, as well as 24 days available for physics operation after the initial commissioning.

	runtime	ATLAS/CMS	ALICE	LHCb
Pb-Pb	1 month	2.1–2.5 nb^{-1}	2.5–2.8 nb^{-1}	$<$ 0.5 nb^{-1}
	5 months	10.5–12.5 nb^{-1}	12.5–14.0 nb^{-1}	$<$ 2.5 nb^{-1}
p-Pb	1 month	470–630 nb^{-1}	310–330 nb^{-1}	$<$ 170 nb^{-1}
	2 months	940–1260 nb^{-1}	620–660 nb^{-1}	$<$ 340 nb^{-1}

d'Enterria et al (Snowmass whitepaper) [2203.05939]

EPILOGUE

Neutron magnetic moment

When Nature laughed in our 1930s faces

***Theory*: zero as it's neutral & pointlike**

***Nature*: large *AND* negative haha (g – 2 = –5.8)**

Chadwick (1932), Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)

Completely confounded expectation!

TRANSFORMATIVE

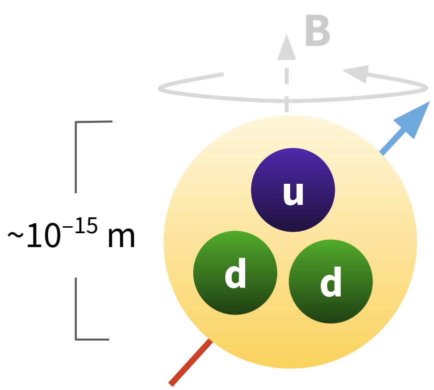
Neutron magnetic moment

When Nature laughed in our 1930s faces

Theory: zero as it's neutral & pointlike

Nature: large *AND* negative haha ($g - 2 = -5.8$)

Chadwick (1932), Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)



NUCLEAR SUBSTRUCTURE

New confining strong force

hopkinsmedicine.org

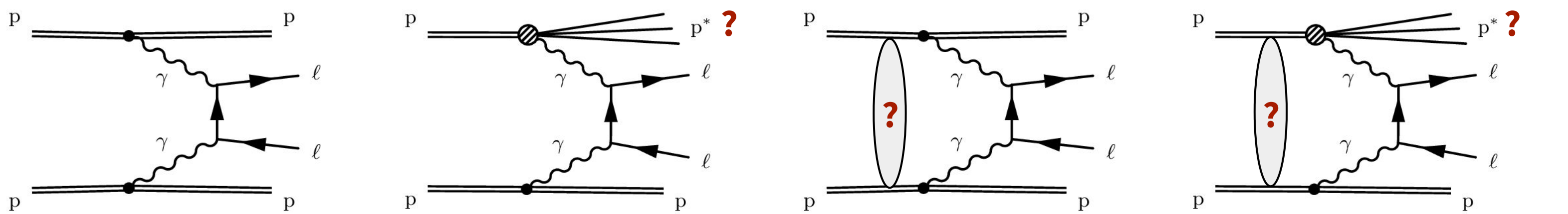
Today nuclear moments save lives with MRI medical imaging

Nobel prize in Physiology or Medicine 2003

EXTRAS

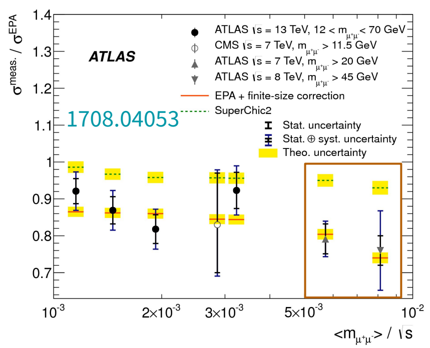
Probe proton breakup for precision EWK

Exclusive | Single dissociation | Exclusive + rescattering | Single dissociation + rescattering

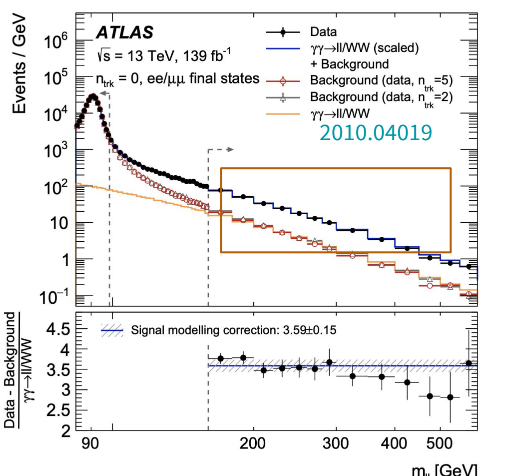


Problem: soft-survival/dissociation (mis)modelling obstructs reliable+precise (< 10%) EWK predictions
Solution: measure 2 vs 1 protons for model-independent excl vs SD separation in uncharted regimes

$\sigma_{\text{Herwig+Lpair}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [31,30]	10.9 ± 0.8	9.4 ± 0.7
SuperChic 4 [94]	12.2 ± 0.9	10.4 ± 0.7
Measurement 2009.14537	11.0 ± 2.9	7.2 ± 1.8

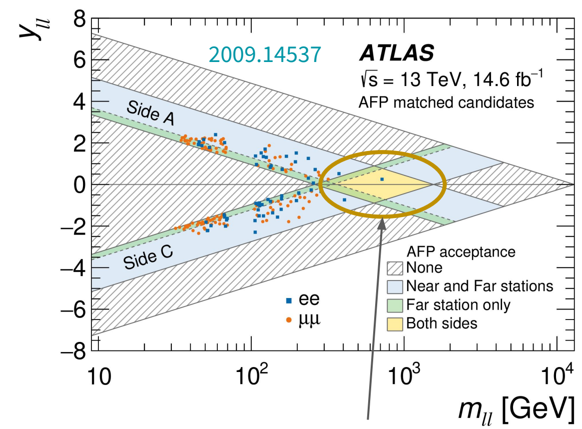


Persistent ~10% overprediction
Likely soft survival models used in MCs



$\sigma_{\text{theo}} \times 3.59 \pm 0.15\ \text{(exp.)} \pm 0.39\ \text{(trans.)} = 2.34 \pm 0.27$ fb

sQCD leading γγ → WW uncertainty
Precision crucial to probe BSM couplings



HL-LHC goal: $\dfrac{\sigma(pp \to p + (\gamma\gamma \to \ell\ell) + p)}{\sigma(pp \to p + (\gamma\gamma \to \ell\ell))}$

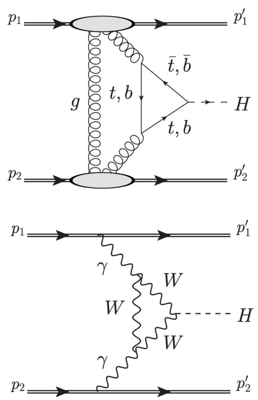
AFP directly measures 2 vs 1 proton
Without, *indirectly* infer via central kinematics

Problem & impact | **AFP solution**

Analogous measurements in hadronic final states (e.g. dijets) also desirable

Higgs: final-state independent measurements

Excl ggF ~ 0.4–2.3 fb
Harland-Lang et al [1405.0018]



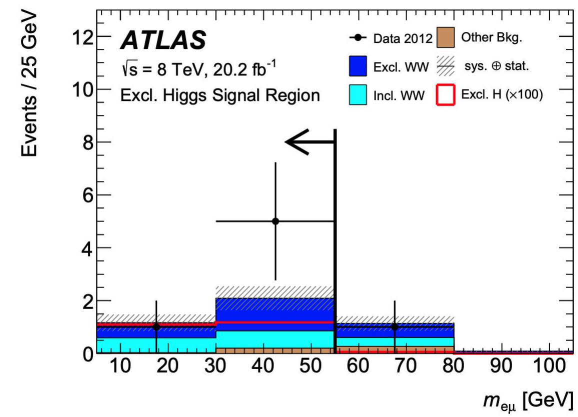
Photon fusion ~ 0.2 fb

← Problem: factor of 5 spread in predictions
due to poor theoretical control of soft-survival
Goal: observe/upper-limit on exclusive Higgs
to directly constrain cross-section predictions
Pre-cut 1000-5000 h → bb, 300-2000 h → WW* events @ 4/ab
[0709.3035, 0708.3052, 0806.0302, 1407.8332]

↓ Table assumes proton detection in both sides at 420 m

Cut	Cross section (fb)						
	↓ MSSM CEP			DPE	[p][X][p]	[p][pX]	[pp][X]
	$h \to bb$	bb	gg	bb	bb	bb	bb
E_T, ξ_1, ξ_2, M	1.011	1.390	2.145	0.666	5.42×10^6	8.98×10^3	1.16×10^6
TOF (2σ,10 ps)	0.960	1.320	2.038	0.633	3.91×10^5	7.33×10^2	6.29×10^4
R_j	0.919	1.182	1.905	0.218	4.73×10^4	85.2	7.59×10^3
Δy	0.774	1.036	1.397	0.063	2.16×10^3	1.38	3.50×10^2
$\Delta\Phi$	0.724	0.996	1.229	0.058	6.66×10^2	0.77	1.07×10^2
$N_C, N_C^\perp$	0.652	0.923	0.932	0.044	6.49	0.45	1.35
ΔM	0.539	0.152	0.191	0.009	1.28	0.06	0.28

AFP: unique bkg rejection + decay-independent mass/width & $J^{CP} = 0^{++}$ constraint



Current world limit is Run 1 eμ search
95% CL upper limit 1.2 pb: 400 × SM
[1607.03745]

Towards a measurement of the two-photon decay width of the Higgs boson at a Photon Collider

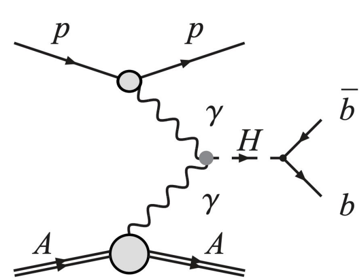
K. Mönig[1] and A. Rosca[2] 0705.1259

[1] DESY, Zeuthen, D 15738, Germany
[2] West University of Timisoara, Timisoara, RO 300223, Roumania

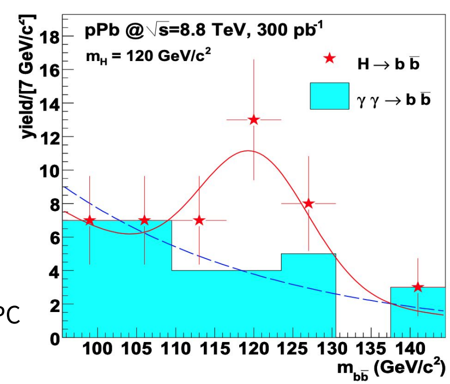
Very challenging but measuring γγ → h → bb gives

$$\Gamma_h = \frac{[\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})]}{[\mathrm{BR}(h \to \gamma\gamma)][\mathrm{BR}(h \to b\bar{b})]}$$

Denominator now known via ggF and VH production
Won't compete with ee250 but important independent test



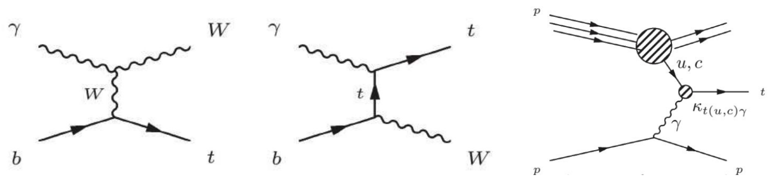
As aside (unless AFP tags proton) UPC heavy ion also interesting window
d'Enterria, Lansberg
[hep-ph/0909.3047]

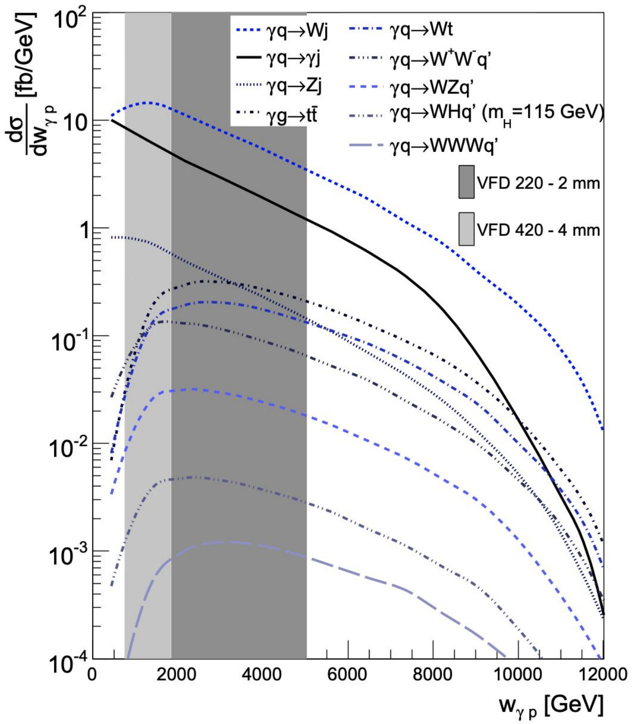


But 3 years of low-μ p+Pb unlikely

Top quark: physics like lepton colliders

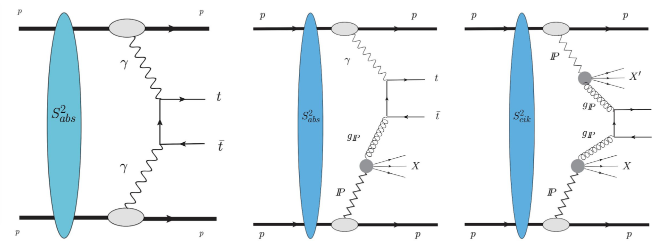
Single top photoproduction (γp → X)



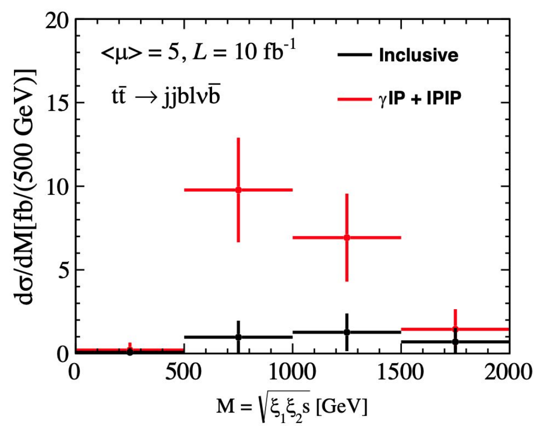


Anomalous FCNC single-top production including charm
HERA-like physics at unprecedented energy regimes

Top pairs and mass threshold



Potentially sensitive to BSM couplings (to be studied)



Goal: observe semi-exclusive ttbar & first LHC cross-section measurement

Direct threshold measurement unprobed for top quark
Important experimentally-independent test of SM
ee350 collider still decades away (ee250 prioritised)

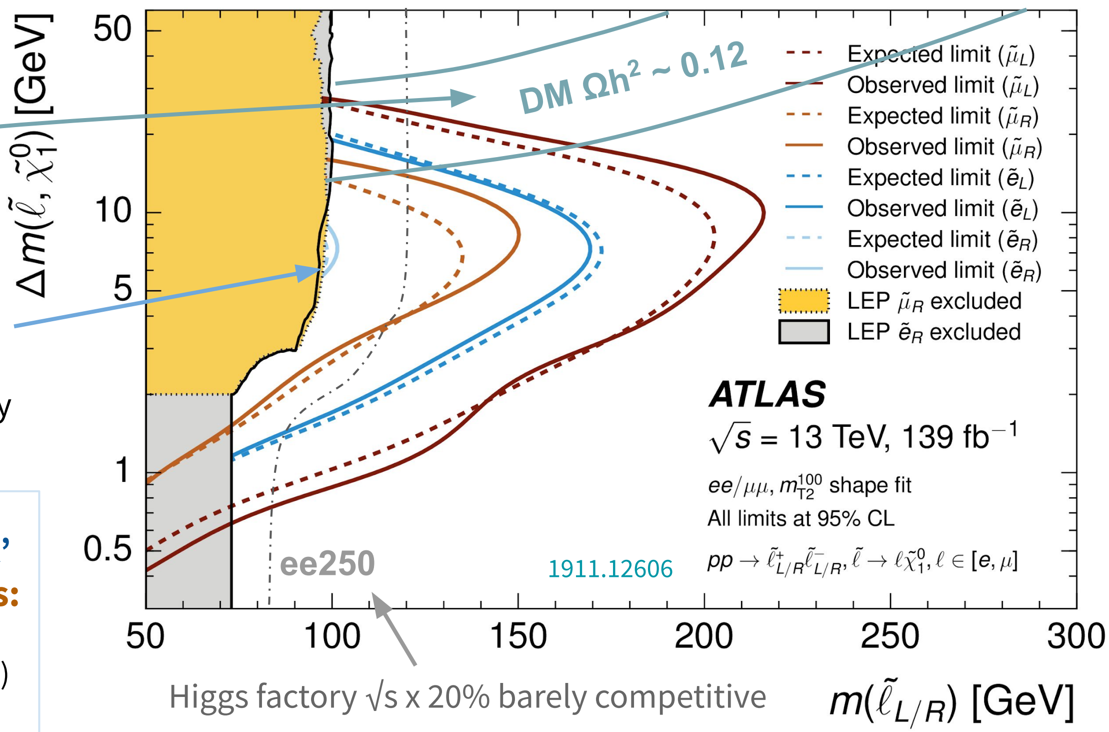
H1 [hep-ex/0310032]
de Favereau de Jeneret et al [0908.2020]
Goncalves et al [2007.04565], Howarth [2008.04249]

SUSY dark matter: striking low-mass targets

→ Pressing problems
revealed by world-leading ATLAS searches

DM coannihilation corridor highly motivated but poorly probed
$10 \lesssim \Delta m \lesssim 80$ GeV key AFP targets

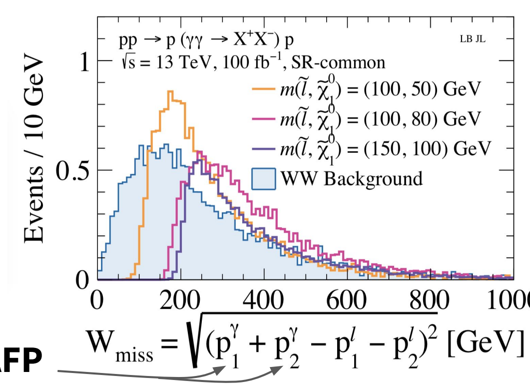
Run 2 expected $\tilde{e}_R$ sensitivity does not surpass LEP despite $\sigma(\tilde{e}_R) \sim 100$ fb
HL-LHC makes 400k events but discovery not guaranteed without innovation



Reason: LHC DM searches are 'MET+X'
Large WW → ℓνℓν bkg but AFP opens:

1) Directly reconstruct parent mass ($p^2_{\rm init}$)
2) Directly reconstruct invisible mass ($p^2_{\rm miss}$)

Slepton MC with Phase II sim done [ATLMCPROD-8977]
Harland-Lang et al 1110.4320, Beresford & JL 1811.06465



AFP

Harland-Lang et al 1812.04886 studied Run 2/3 pileup in detail & challenging $\Delta m \lesssim 20$ GeV signals

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{\rm PU}$ 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	∼ 0(∼ 0)	0.1(0.1)	1.8(2.4)

$|\eta| < 2.5$

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{\rm PU}$ 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	∼ 0(∼ 0)	0.03(0.05)	0.6(0.7)

$|\eta| < 4$ (ITk @ Run 4)

Glossary

Experiment	
AFP	ATLAS Forward Proton spectrometer
PPS	CMS-TOTEM Precision Proton Spectrometer
RP	Roman Pot (Pot = Proton on target)
SiT	AFP Silicon Tracker
ToF	AFP Time of Flight
Side A (C)	Side +z "*A*éroport" (–z "*C*arrefour")
Diffraction	Proton stays intact in strong interaction
Dissociation	Proton fragments from EM excitation
Exclusive	Production without associated particles

Machine	
IP/IR	Interaction Point/Region
TAN	Target Absorber Neutral (outgoing neutrals)
TCS/L	Target Collimator Short/Long (near/far)
TCT	Target Collimator Tertiary (ingoing beam)
β*	Length when beam width halves at IP
D1/2, Q1-6	Dipole one/two, first six quadrupole magnets
S12 (S81)	Machine sector towards ALICE (LHCb)
CC	Crab Cavity (rotate bunches pre/post collision)
MAD-X	Methodical Accelerator Design v10 software

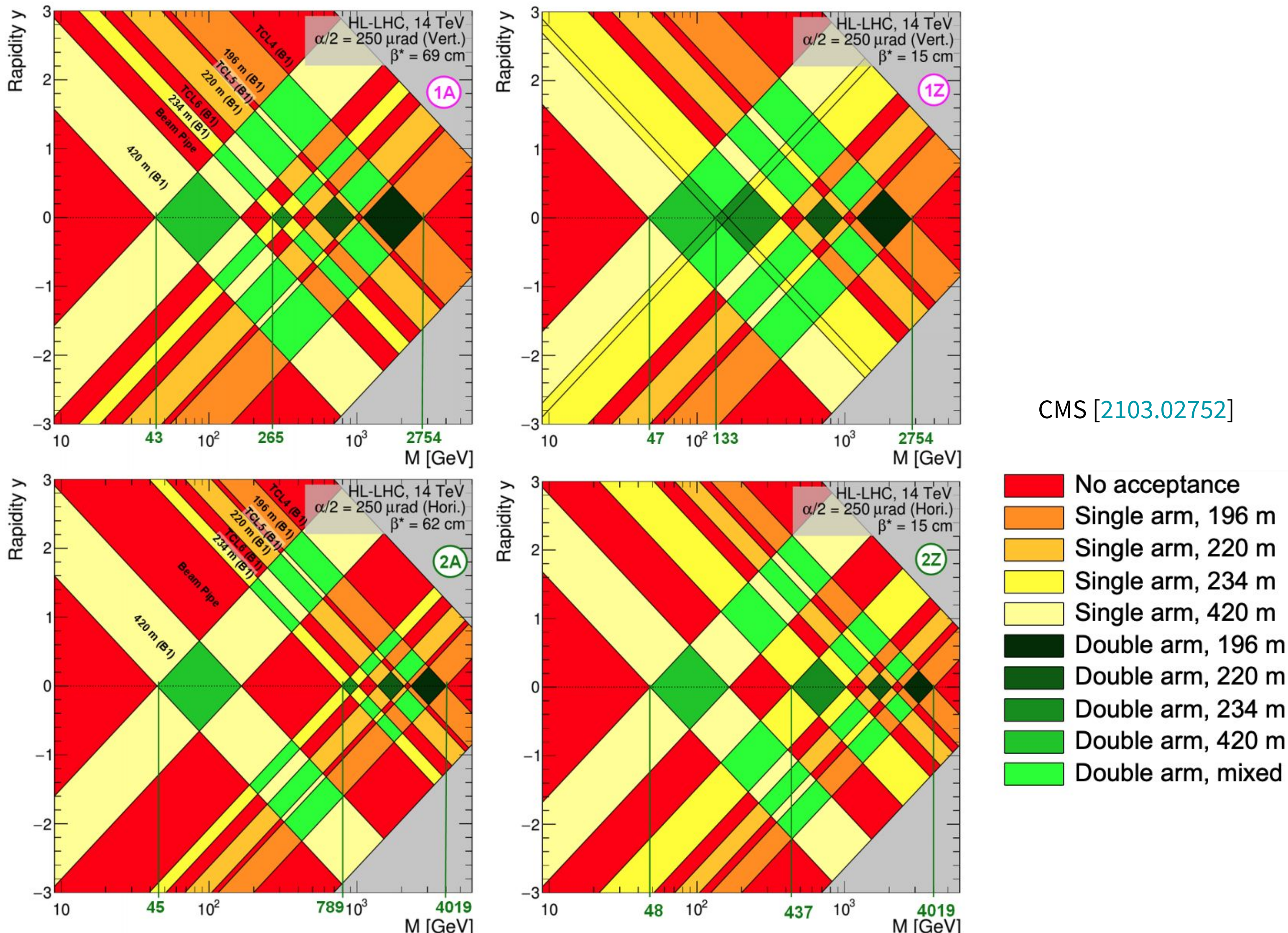
Forward physics = creative community bridging physics, detector & accelerator science

Snapshot of CMS PPS EoI: proton acceptance

Start of fill **End of fill**

Vertical crossing

Horizontal crossing



CMS [2103.02752]

Snapshot of CMS PPS EoI: proton acceptance

Table 4: Lower and upper ξ limits, and minimum and maximum central mass accepted by each station at rapidity y = 0. The top and bottom blocks represent vertical (officially chosen for implementation) and horizontal crossing (for comparison), respectively. The ranges in the minimum values indicate the beginning and the end of the levelling trajectories, (1A) to (1Z) and (2A) to (2Z).

Vertical Crossing-Angle				
Station	$\|\xi_{\text{min}}\|$	$\|\xi_{\text{max}}\|$	M_{min} [GeV] @ y = 0	M_{max} [GeV] @ y = 0
196 m	0.0786−0.0856	0.1967	1100.87−1197.80	2754.27
220 m	0.0371−0.0381	0.0688	519.89−533.18	962.70
234 m	0.0189−0.0095	0.0263	264.96−132.80	368.11
420 m	0.0031−0.0034	0.0116	43.38−47.04	162.66

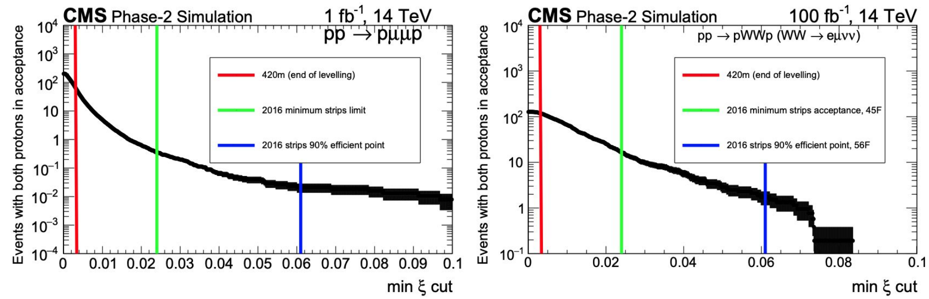
Horizontal Crossing-Angle				
Station	$\|\xi_{\text{min}}\|$	$\|\xi_{\text{max}}\|$	M_{min} [GeV] @ y = 0	M_{max} [GeV] @ y = 0
196 m	0.1654−0.1779	0.2871	2316.15−2490.07	4018.94
220 m	0.0984−0.1014	0.1488	1377.48−1419.13	2083.04
234 m	0.0564−0.0312	0.0732	789.48−437.07	1024.60
420 m	0.0032−0.0034	0.0118	44.55−48.20	165.28

CMS [2103.02752]

Snapshot of CMS PPS EoI: physics perspectives

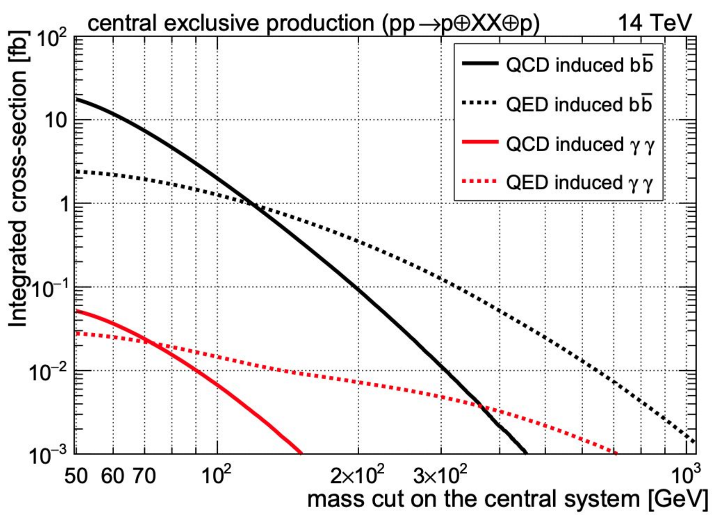
Process	fiducial cross section [fb] all stations		fiducial cross section [fb] w/o 420	
	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$
jj	$\mathcal{O}\left(10^6\right)$	60	$\mathcal{O}\left(10^4\right)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

Cross-sections

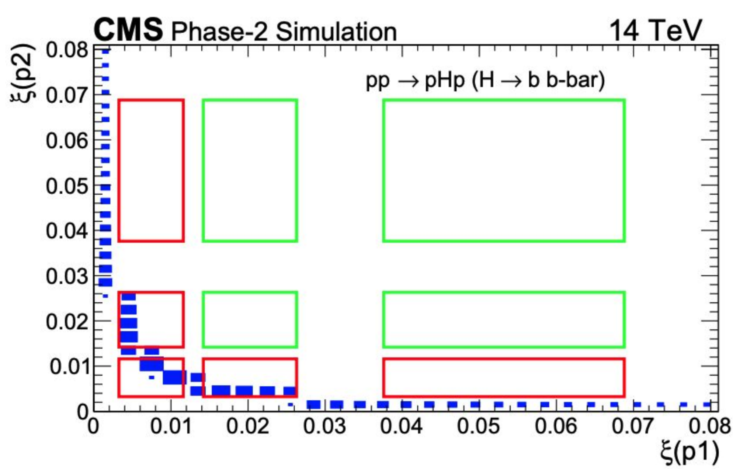


Process	Central detector acceptance cuts	2-arm events
$\gamma\gamma \to \mu\mu$ (SM)	$p_{\mathrm{T}}(\mu) > 20\,\mathrm{GeV}$, $\lvert\eta(\mu)\rvert < 2.4$, $m(\mu\mu) > 40\,\mathrm{GeV}$	$47\ /\ \mathrm{fb}^{-1}$
$\gamma\gamma \to \mathrm{WW} \to \mu e$ (SM)	$p_{\mathrm{T}}(\mu, e) > 20\,\mathrm{GeV}$, $\lvert\eta(\mu, e)\rvert < 2.4$	$72\ /\ 100\,\mathrm{fb}^{-1}$

Dilepton/diboson



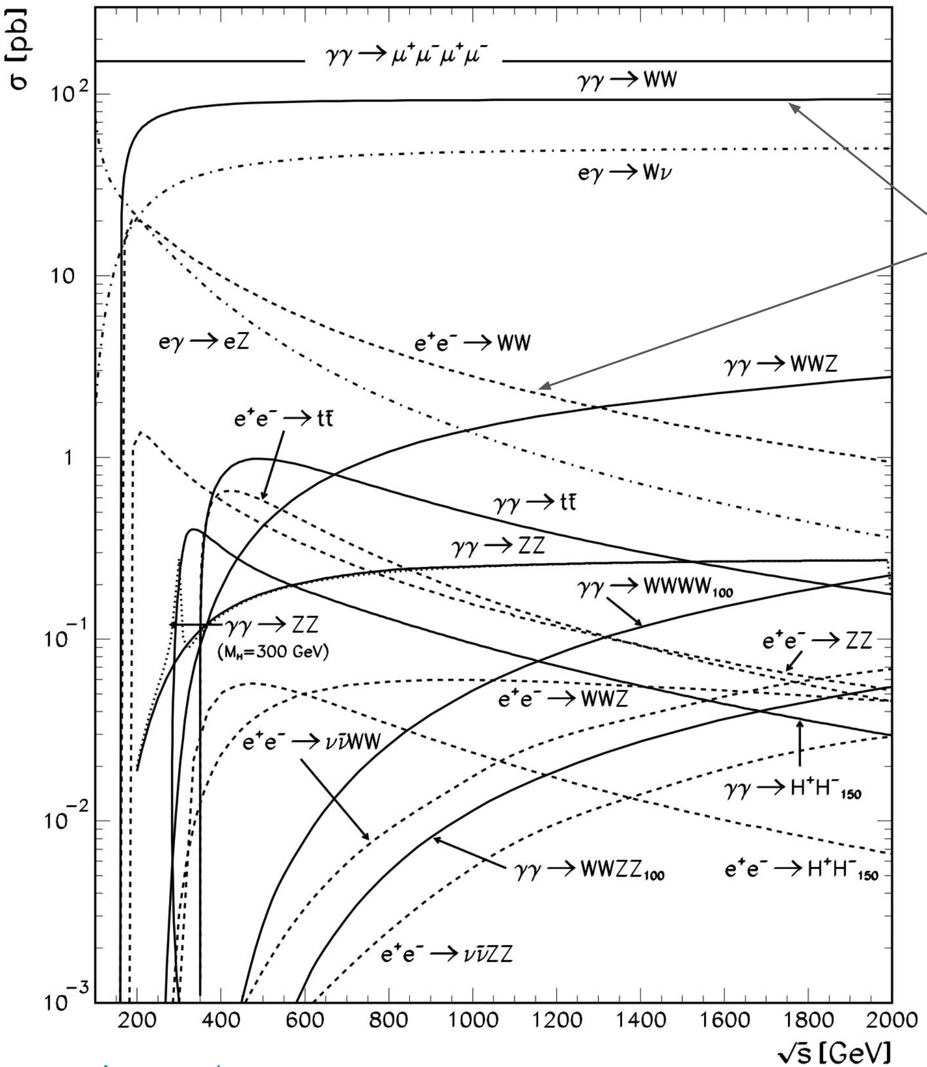
Dijets



Higgs

CMS [2103.02752]

Future e^+e^- (/$\mu^+\mu^-$?) machines as photon colliders

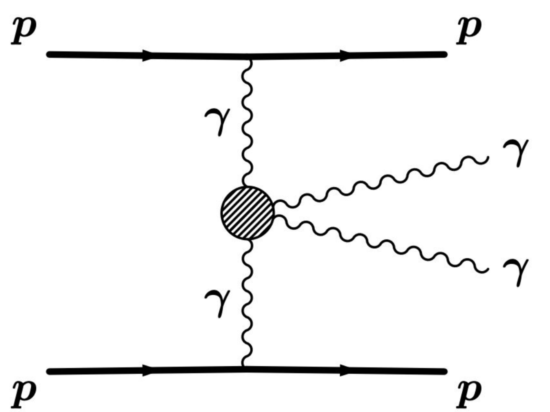


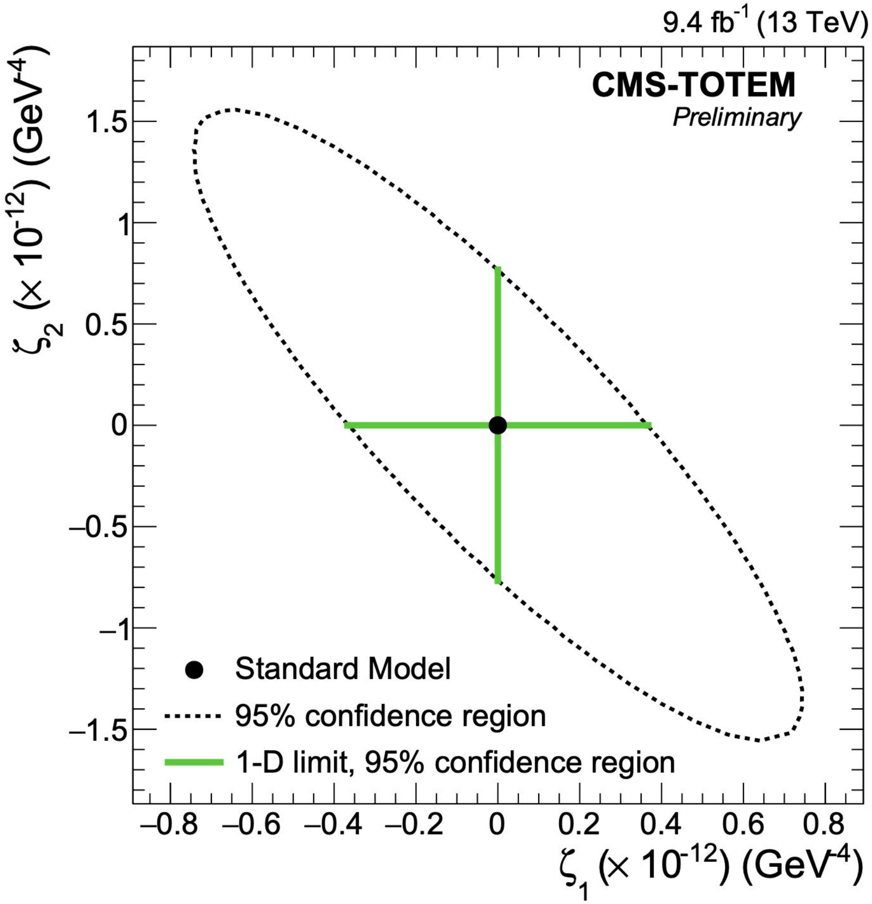
hep-ex/0108012

Photon fusion production becomes significant at high energy ee (and μμ) colliders

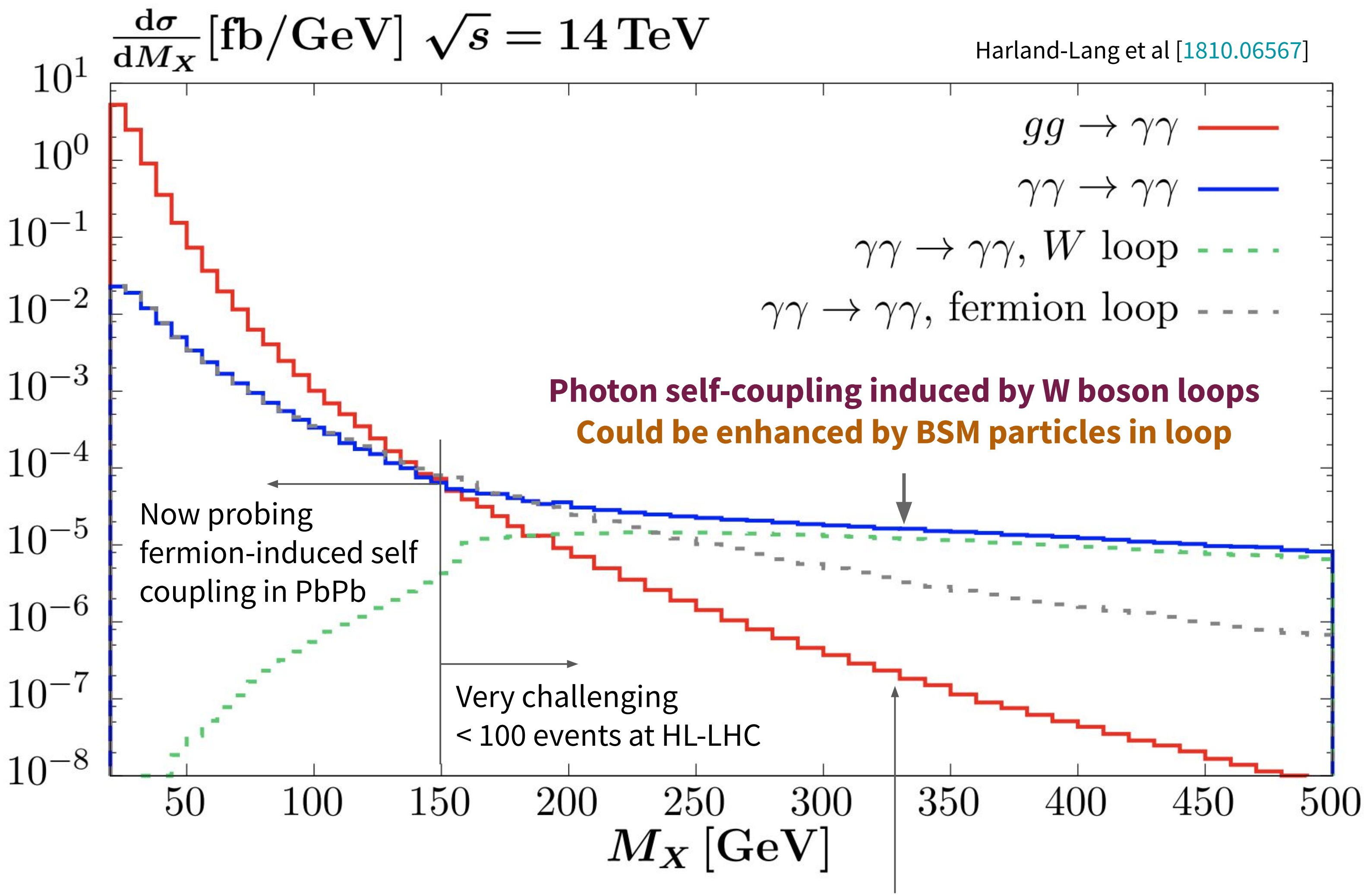
HL-LHC provides a unique window to study these processes in nature in nearer term

CMS-TOTEM: anomalous γ self-couplings



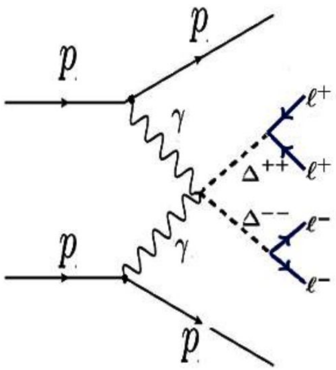


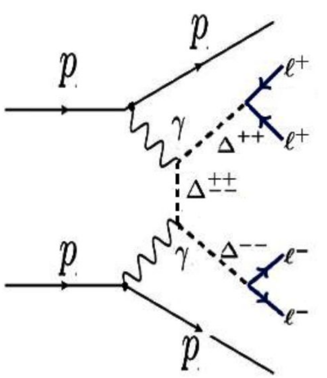
QCD → EWK: boson-induced photon self-coupling



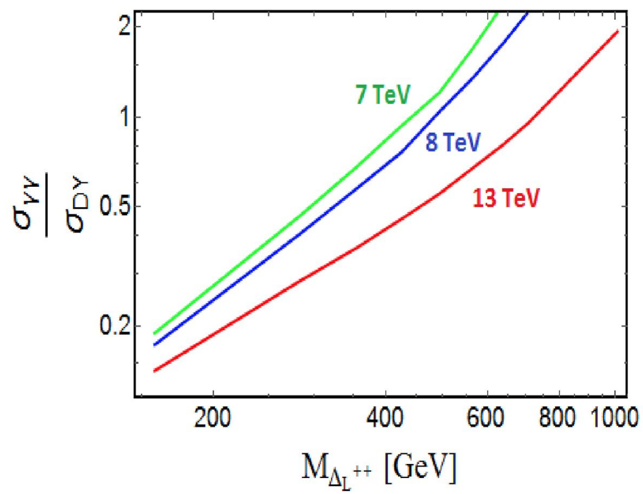
Gluon-induced exclusive production sub-dominant above weak scale due to softer flux vs photons

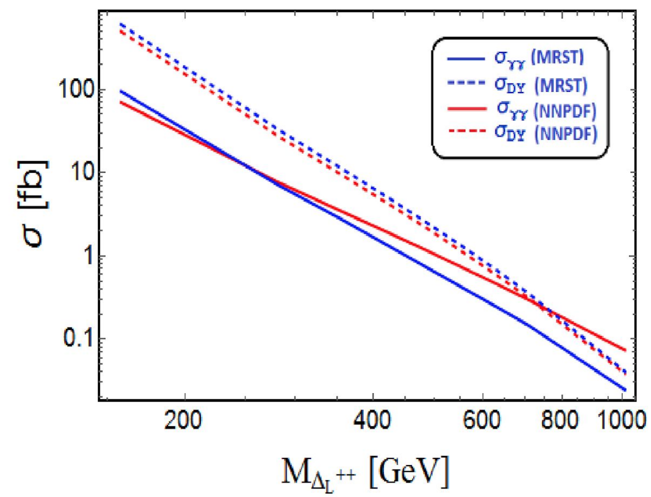
Doubly-charged Higgs boson





Motivation: origin of neutrino masses motivates extended Higgs sector
Type II Seesaw scenario has doubly charged scalar from triplet of SU(2)
Endow neutrinos with mass without a right-handed neutrino (Type I Seesaw)





Babu & Jana 1612.09224
Fuks, Nemevšek, Ruiz 1912.08975

Triply charged Higgs also possible
Pan et al 1909.07254