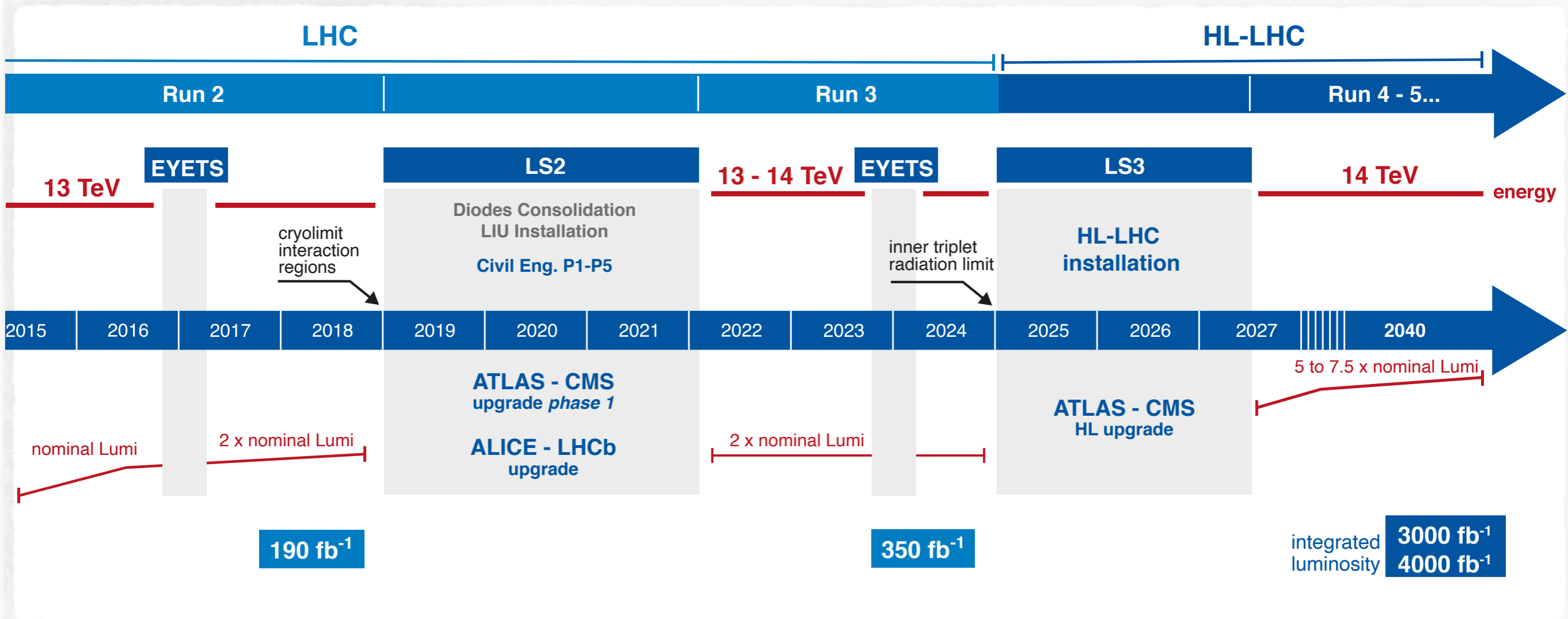




Prospects for BSM at LHC (experimental vision)

Livia Soffi on behalf of ATLAS and CMS Collaboration

Setting the stage



- **Long Shutdown 2** (Phase-1 upgrade) preparing **Run 3**
 - Luminosity at $2 \times 10^{34}/\text{cm}^2/\text{s}$, possible increase to $\sqrt{s}=13.5$ or 14 TeV
- **Long Shutdown 3** (Phase-2 upgrade) preparing **HL-LHC**
 - Luminosity at $7.5 \times 10^{34}/\text{cm}^2/\text{s}$ at $\sqrt{s}=14$ TeV
 - Large data samples and major experimental challenges

Run 2 close out

LHC

Run 2

EYETS

13 TeV

cryolimit
interaction
regions

2015

2016

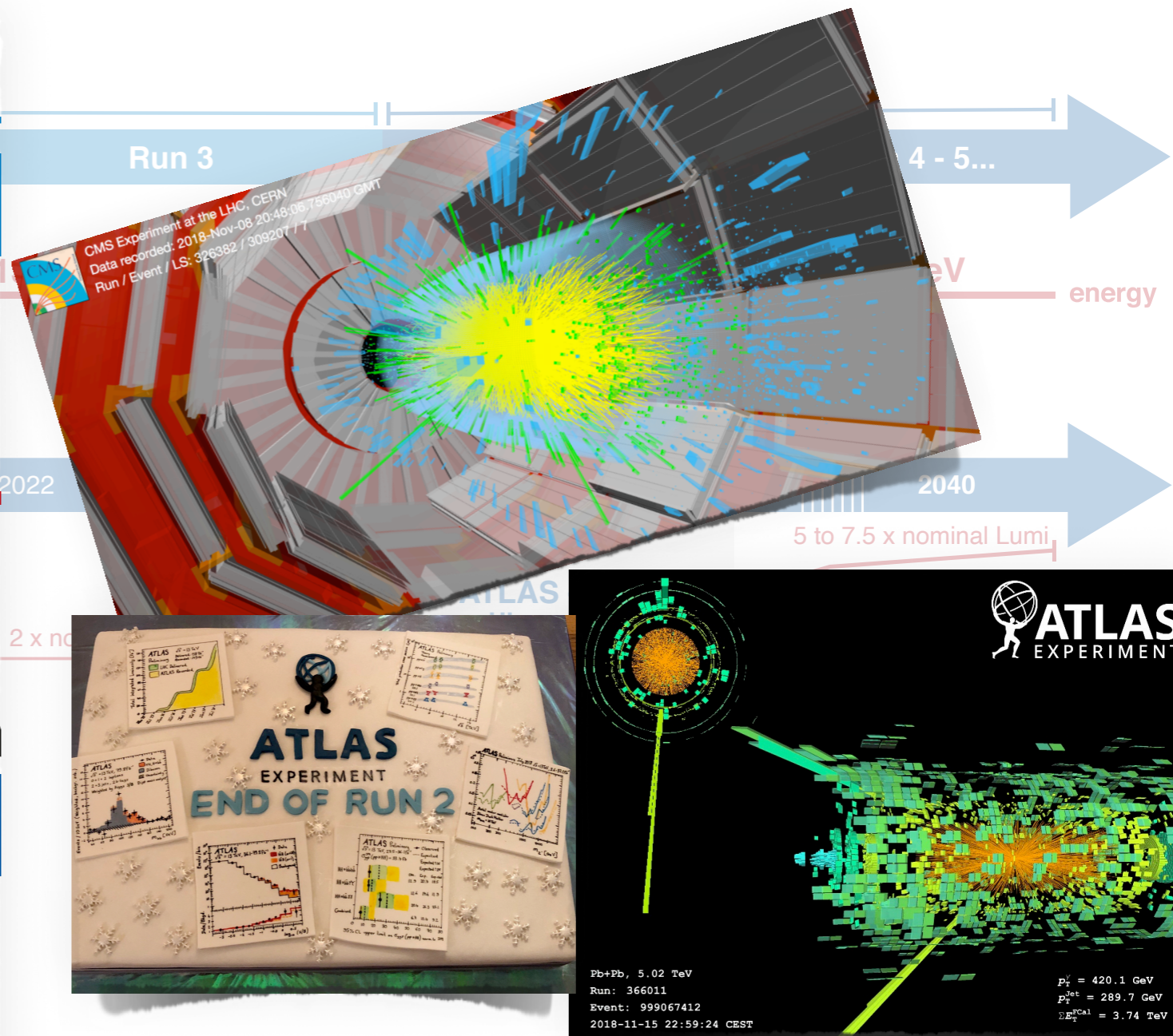
2017

2018

nominal Lumi

2 x nominal Lumi

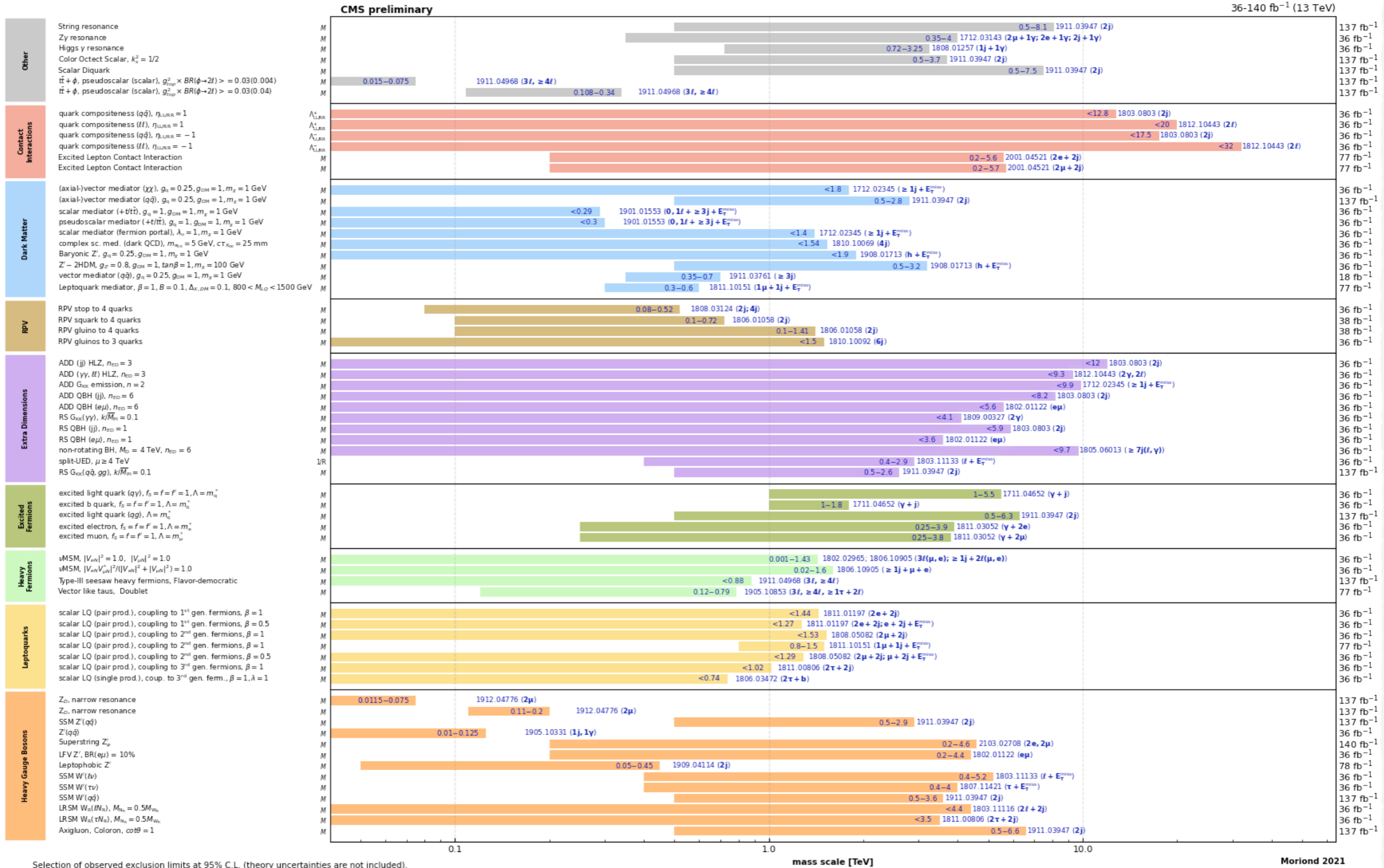
190 fb⁻¹



Run 2 extraordinary exploration of the high-energy frontier!

A New Understanding of Particle Physics

Overview of CMS EXO results



CMS EXOTICA Summary 2021

A New Understanding of Particle Physics

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1 - 4 j$	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	-	$2 j$	-	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{th} 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$	1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 J$	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J / 2 j$	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \rightarrow WV \rightarrow qq qq$ model B	$0 e, \mu$	$2 J$	-	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \rightarrow WH$ model B	$0 e, \mu$	$\geq 1 b, \geq 2 J$	-	139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	W_R mass 3.25 TeV		1807.10473	
LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV	$m(N_R) = 0.5 \text{ TeV, } g_L = g_R$	1904.12679	
CI	CI $qqqq$	-	$2 j$	-	37.0	Λ 21.8 TeV	η_{LL}	1703.09127
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	Λ 35.8 TeV	η_{LL}	CERN-EP-2020-066
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV	$ C_{4t} = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	m_{med} 1.55 TeV	$g_q = 0.25, g_\chi = 1.0, m(\chi) = 1 \text{ GeV}$	1711.03301
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	m_{med} 1.67 TeV	$g = 1.0, m(\chi) = 1 \text{ GeV}$	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	M_s 700 GeV	$m(\chi) < 150 \text{ GeV}$	1608.02372
	Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	$0-1 e, \mu$	$1 b, 0-1 J$	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$	1812.09743
LQ	Scalar LQ 1 st gen	$1, 2 e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2 nd gen	$1, 2 \mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3 rd gen	2τ	$2 b$	-	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	1902.08103
	Scalar LQ 3 rd gen	$0-1 e, \mu$	$2 b$	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	$2(\text{SS})/\geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883	
	VLQ $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	1812.07343
	VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-024
VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV		1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q^* mass 6.7 TeV	only u^* and $d^*, \Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass 5.3 TeV	only u^* and $d^*, \Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	1411.2921
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2μ	$2 j$	-	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1 \text{ TeV, } g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q = 5e$	1812.03673
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g = 1g_D, \text{ spin } 1/2$	1905.10130

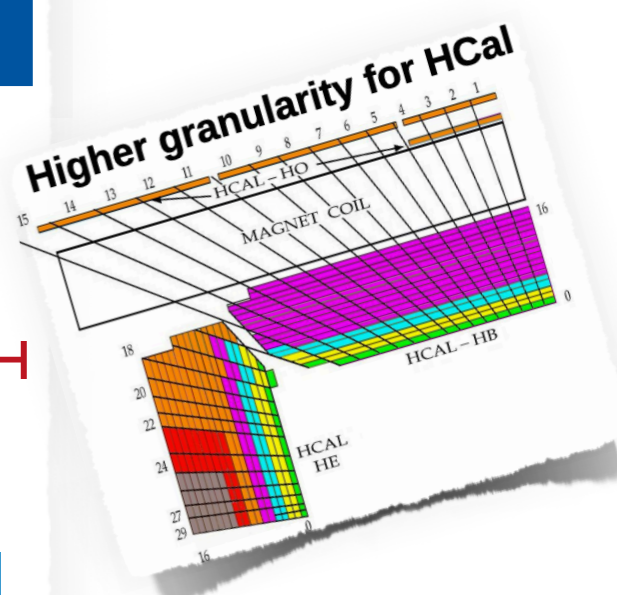
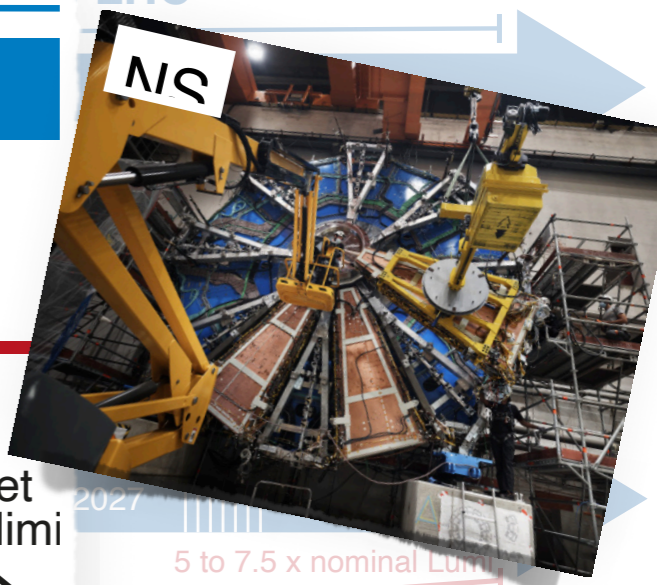
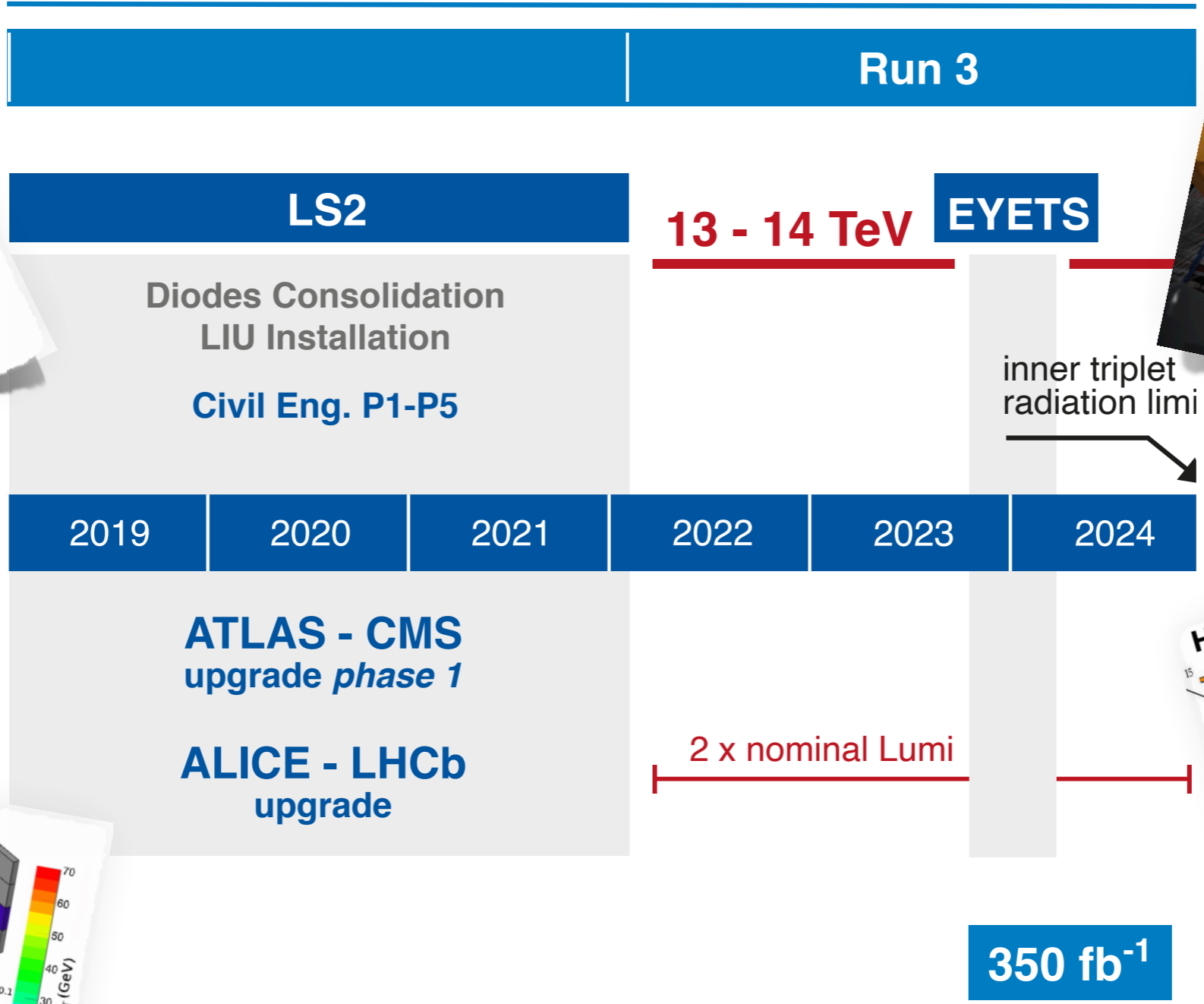
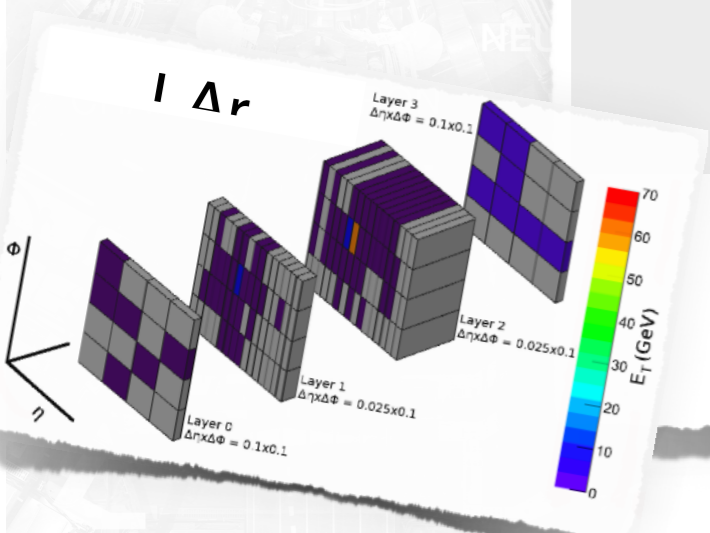
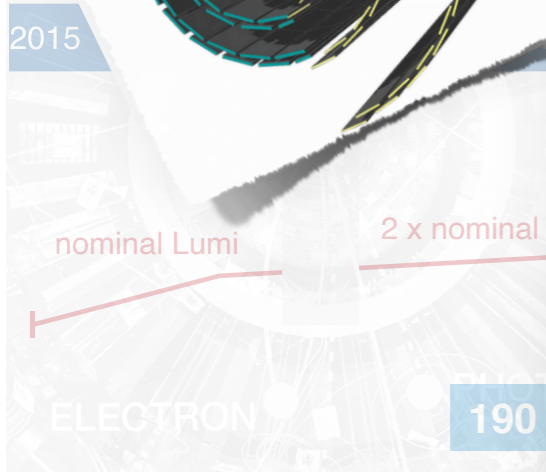
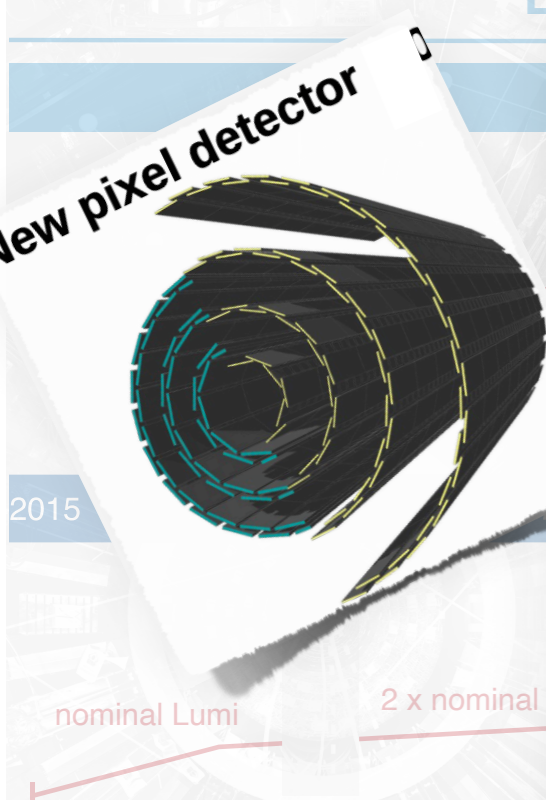
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$ partial data $\sqrt{s} = 13 \text{ TeV}$ full data

ATLAS EXOTICA Summary 2021

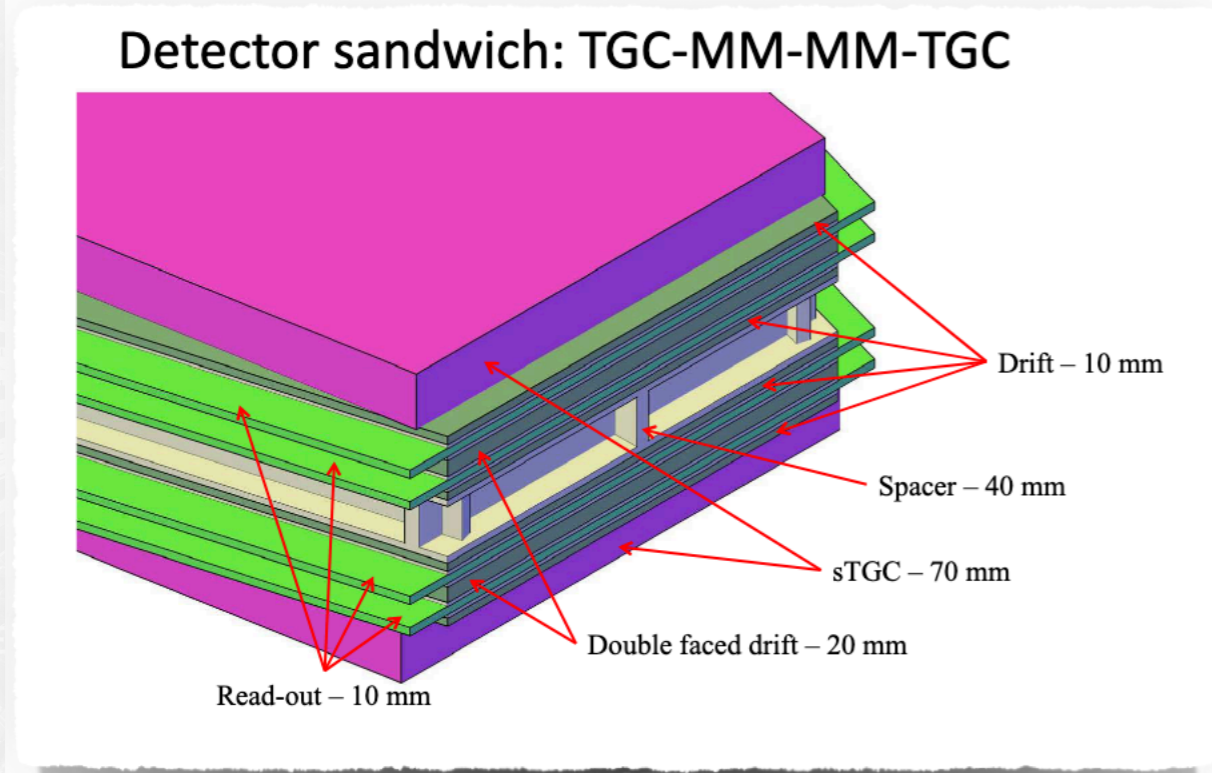
Long Shutdown 2: preparing for Run 3



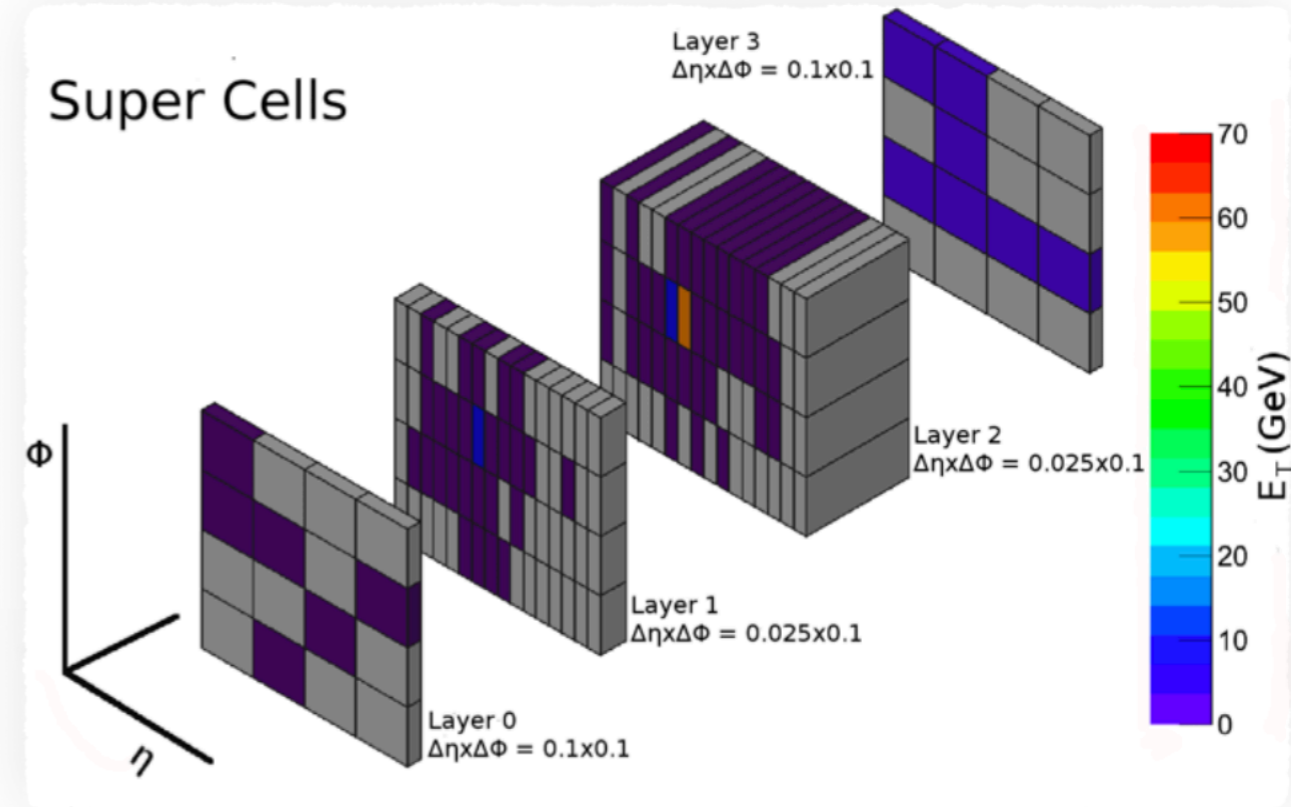
**Run 3 approaching fast..
getting ready!**

Some new opportunities at Run 3

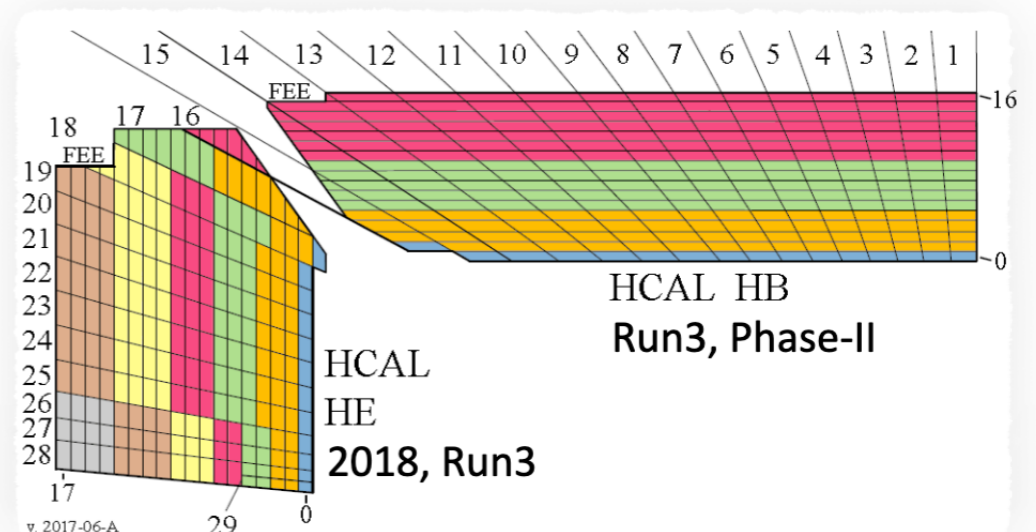
- **ATLAS New Small Wheel:** Fast readout and precision tracking resolution



- **ATLAS LAr L1:** super cells improved energy resolution and identification efficiency

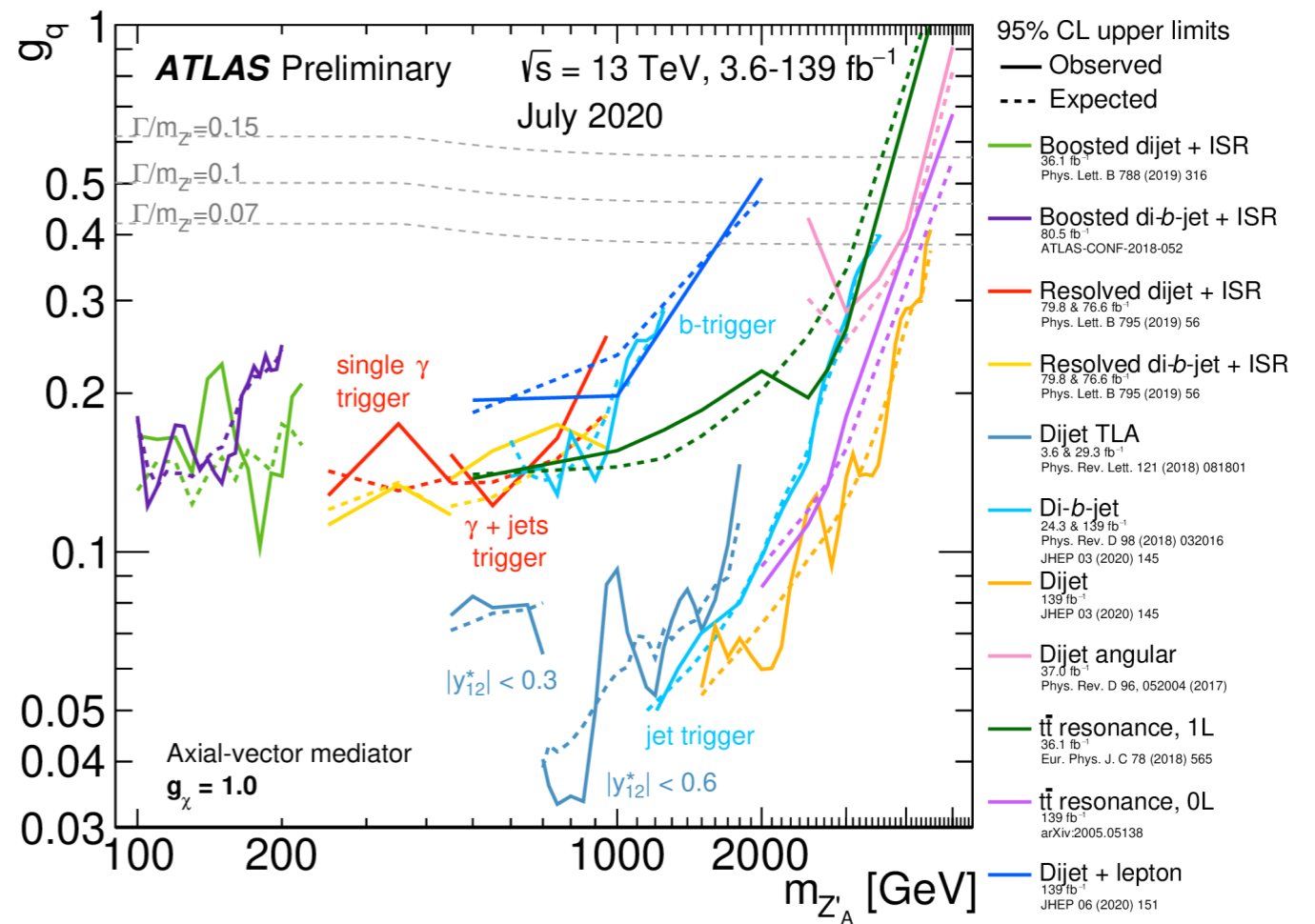
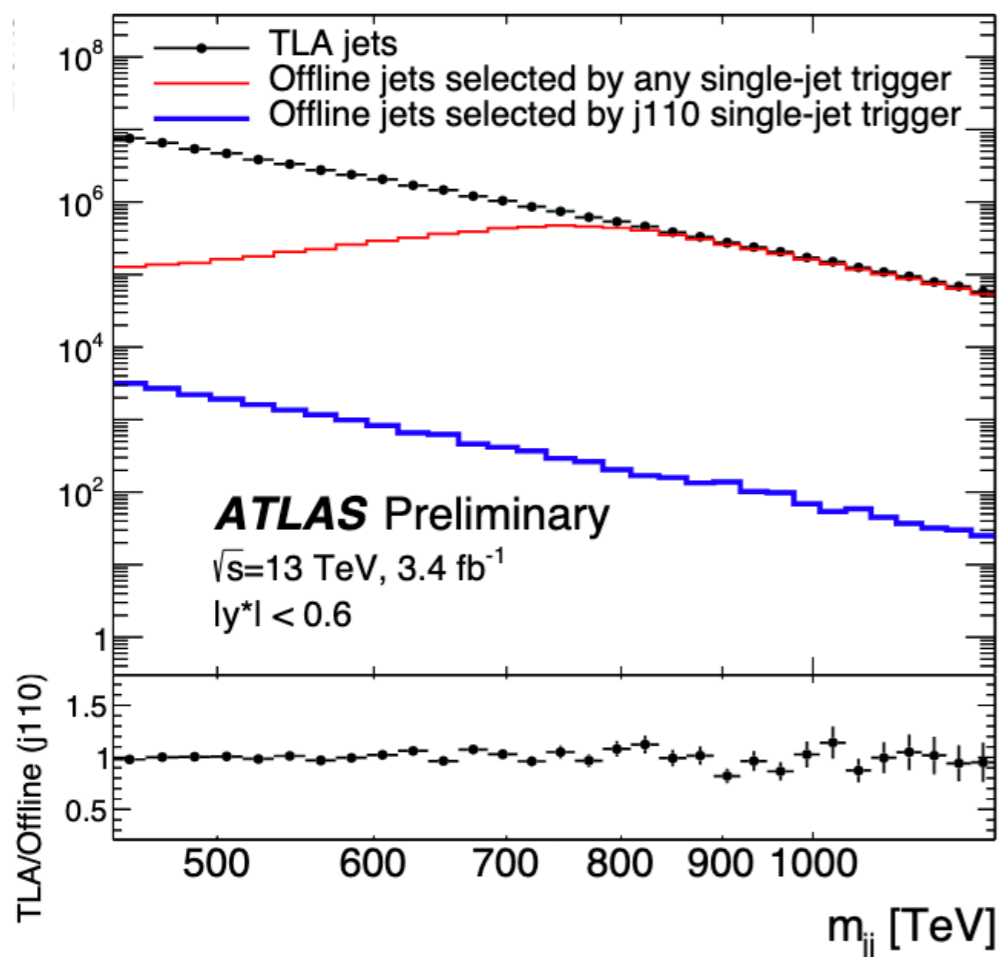


- **CMS HCAL** electronics upgraded now read out in 4-7 depths



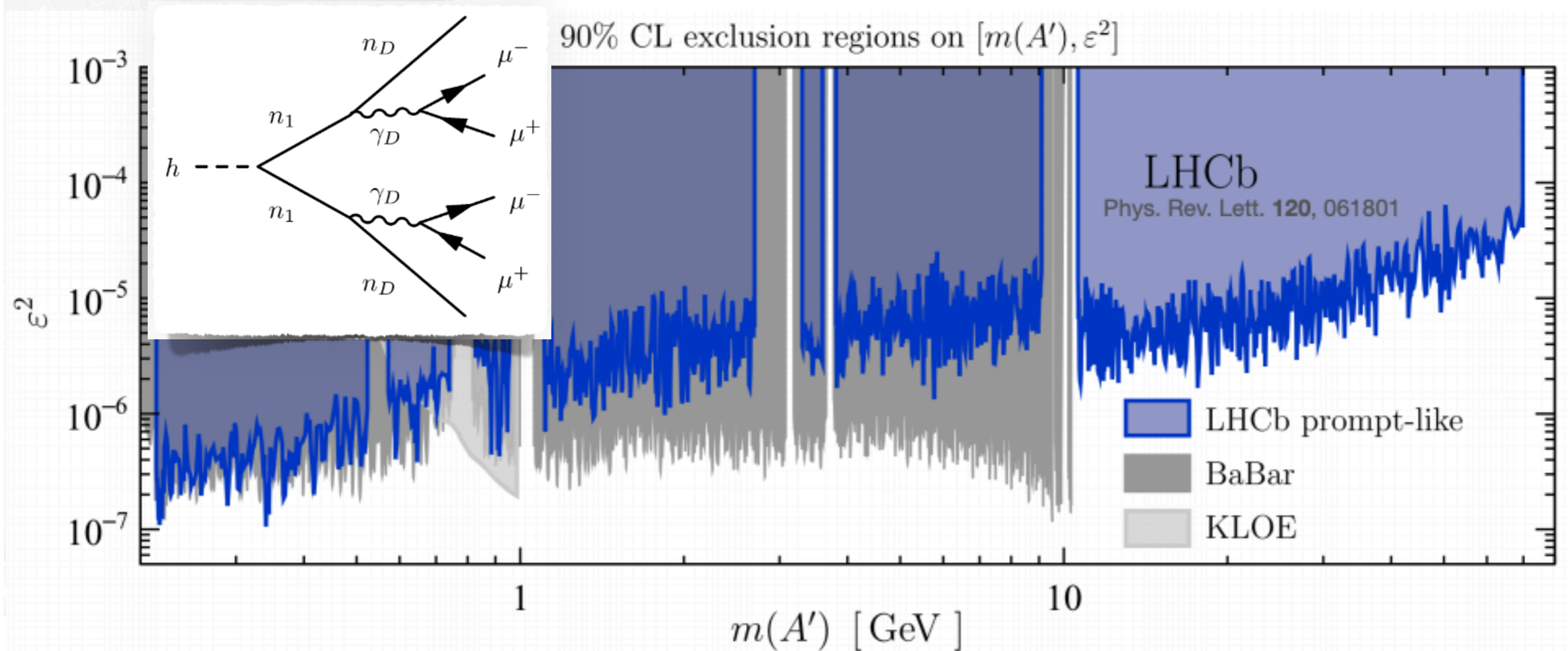
Unconventional Data Taking

- Novel idea to **circumvent bandwidth limitation w/ partial event building**
- Going beyond the 1-kHz limit in two ways:
 - **“data parking”** → offline reconstruction is delayed.
 - **“data scouting”** → saving only objects reco'd at trigger level



Keep an eye on the other side of the ring

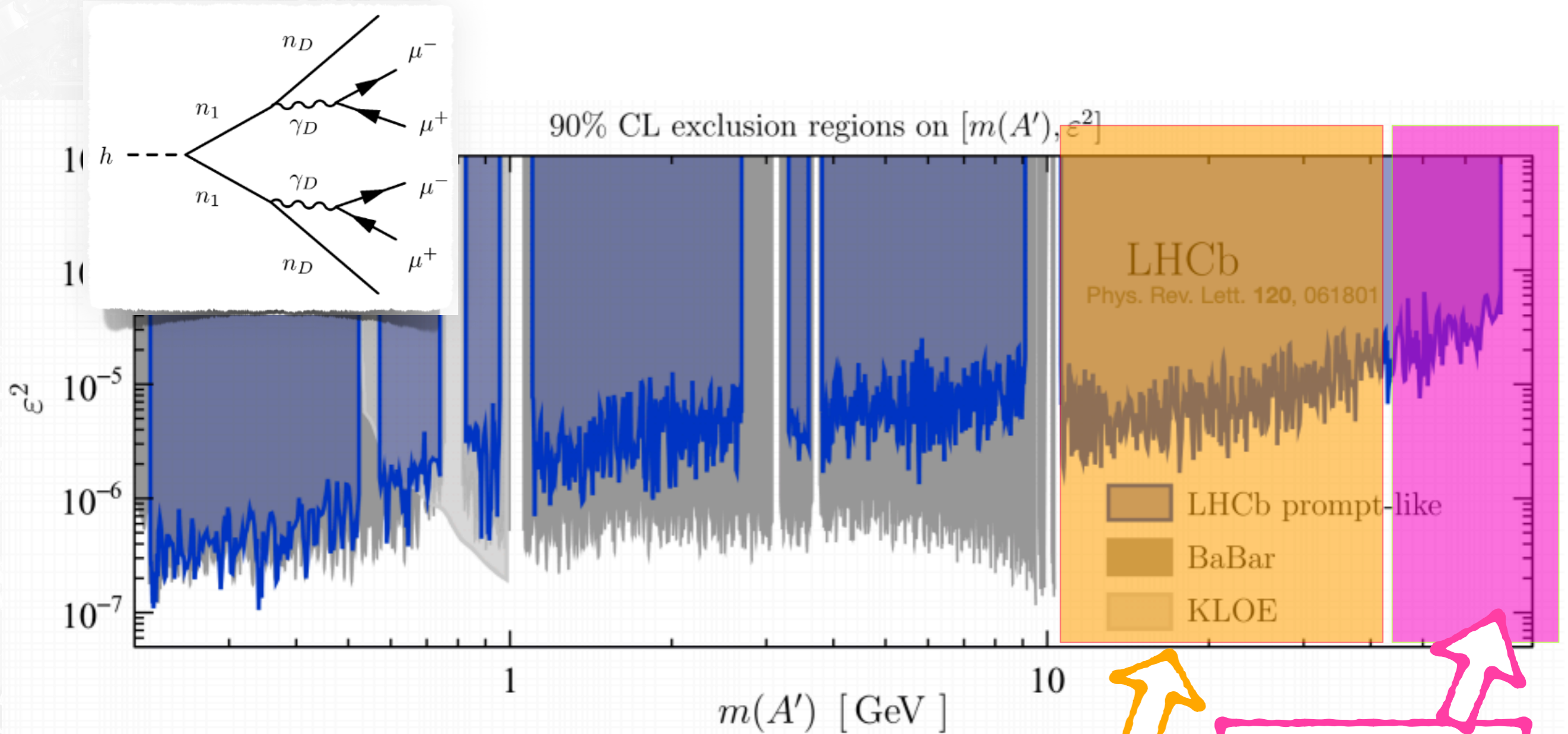
- Most spectacular example of vector portal address SM problems: dark photon



[PhysRevLett.120.061801](https://arxiv.org/abs/120.061801)

- If $\epsilon < 10^{-5}$ A' can be longlived
- Main **challenge for ATLAS/CMS is triggering** and discriminating backgrounds

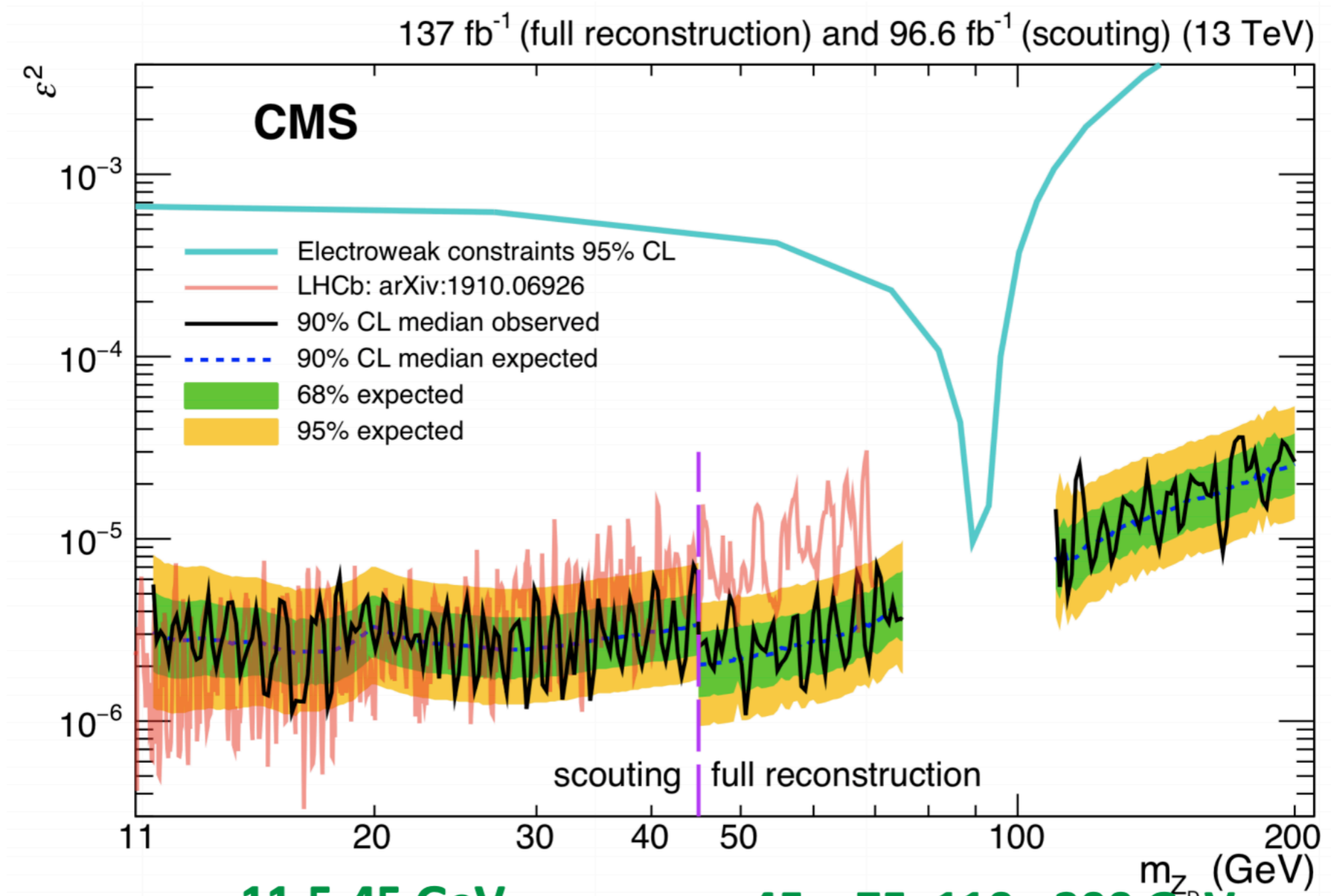
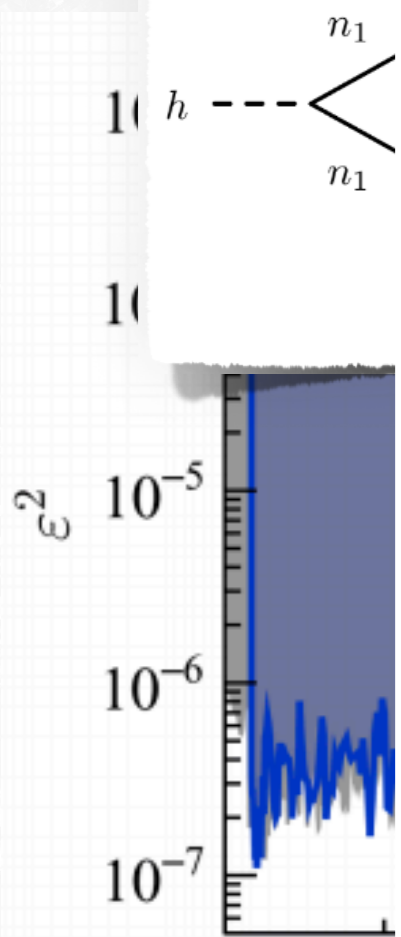
Scouting Dark Photons at CMS



Scouting

Standard Trigger

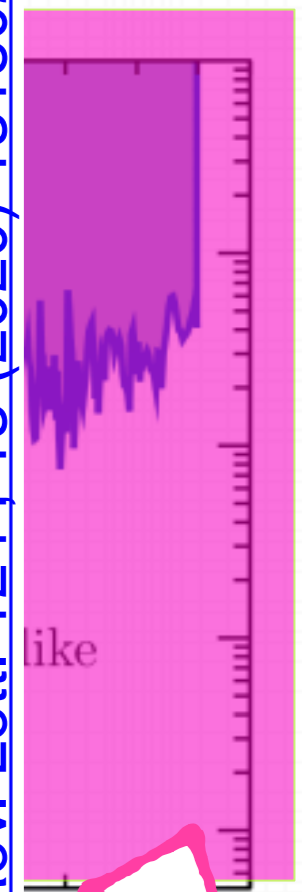
Scouting Dark Photons at CMS



**11.5-45 GeV
scouting**

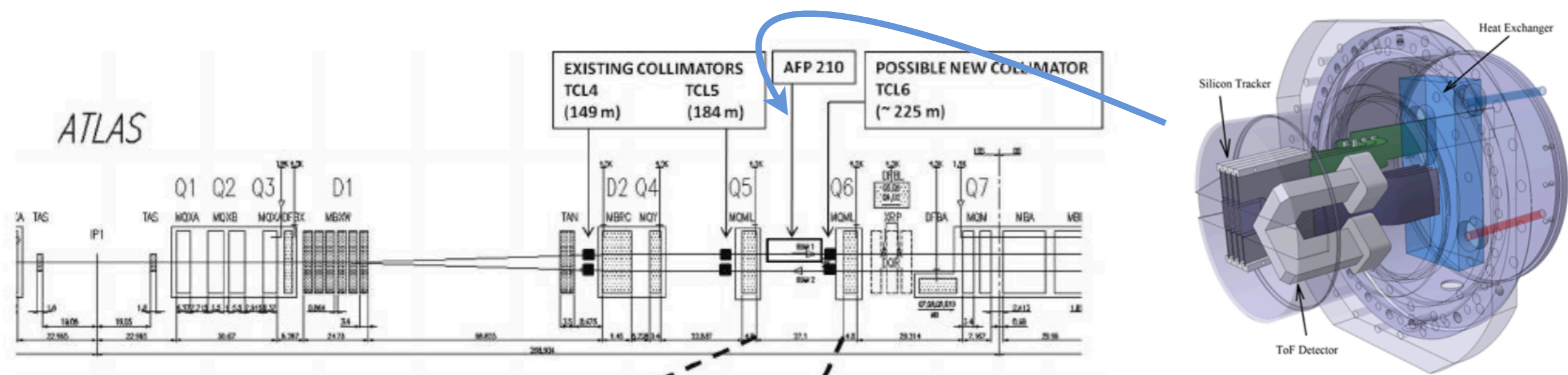
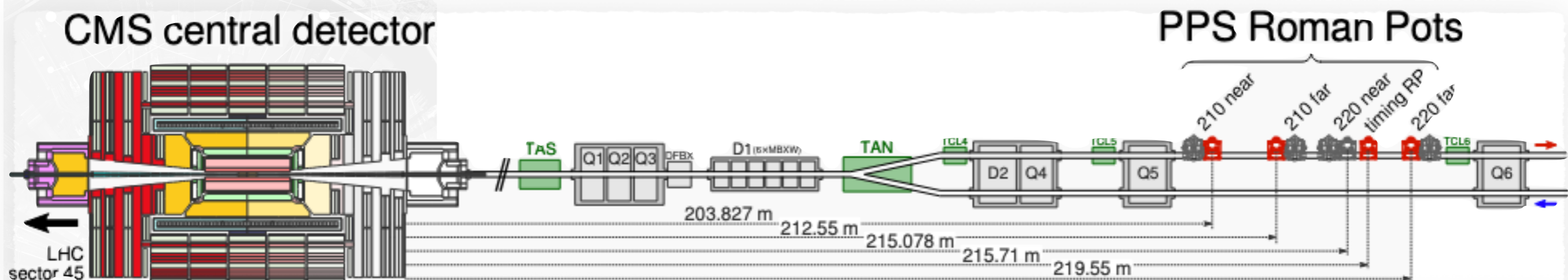
**45 – 75, 110 - 200 GeV:
full reconstruction**

[Phys. Rev. Lett. 124, 13 \(2020\) 131802](#)



Standard
Model
+
Dark
Photon

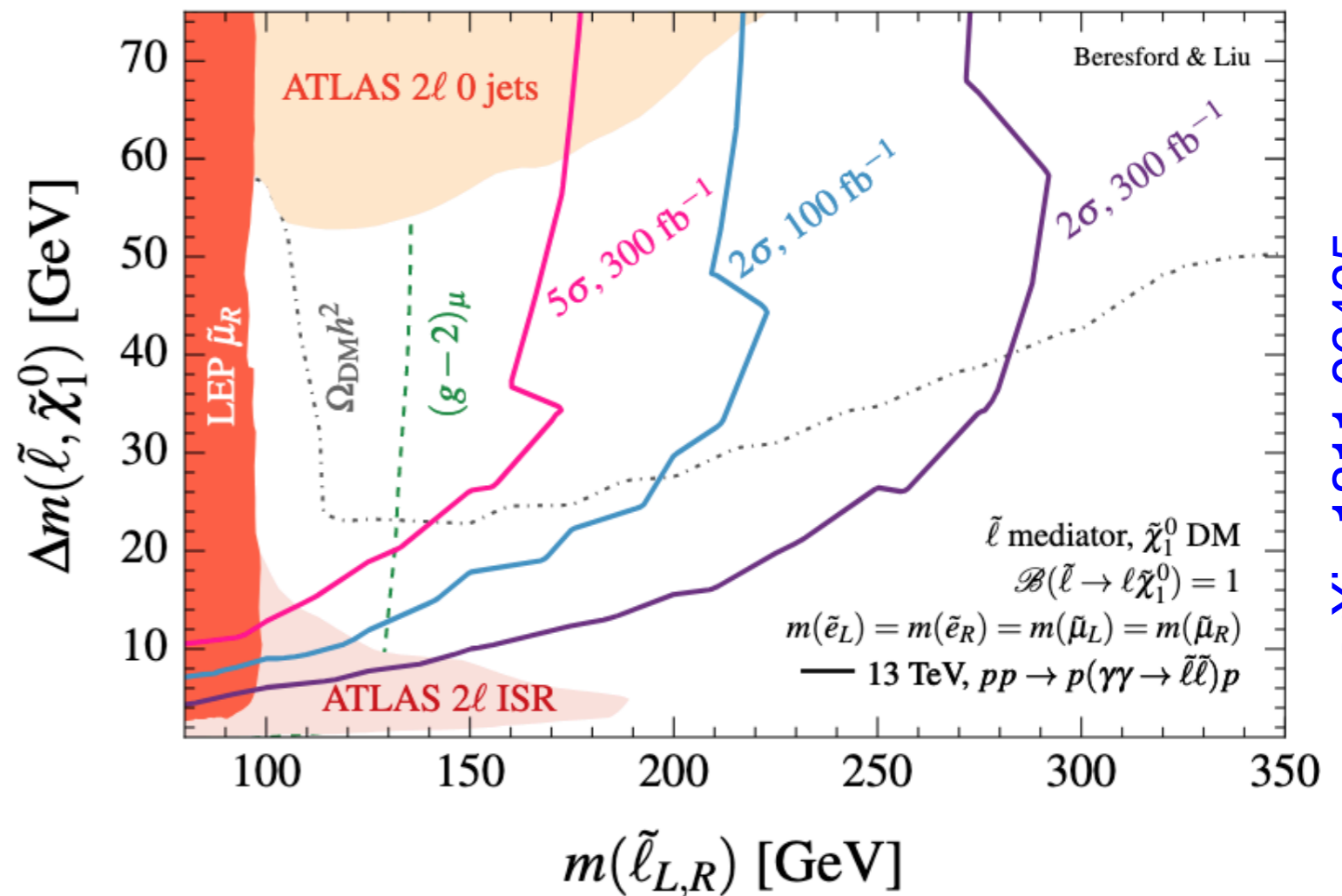
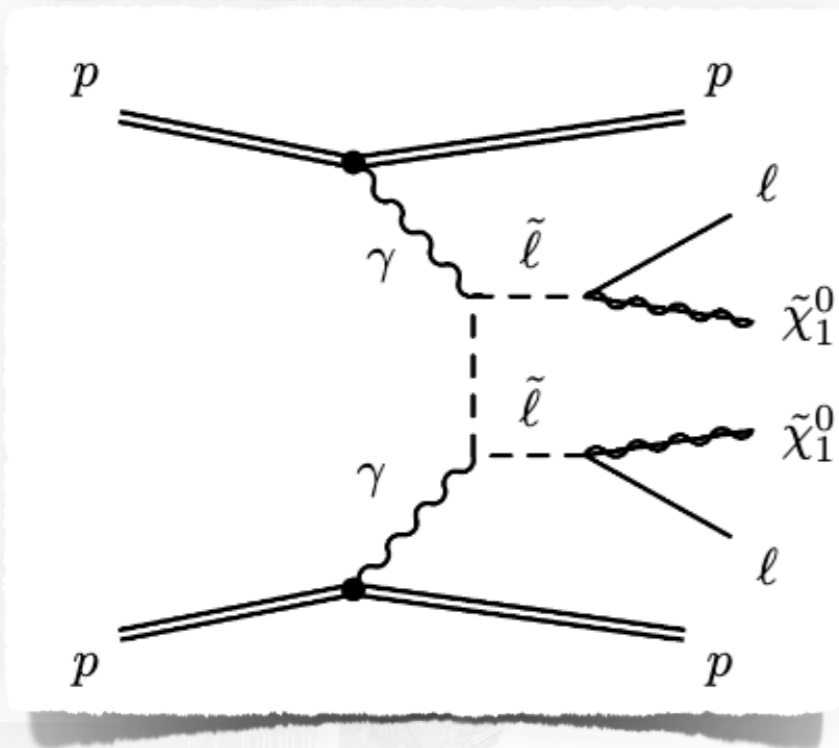
New forward detectors have their say



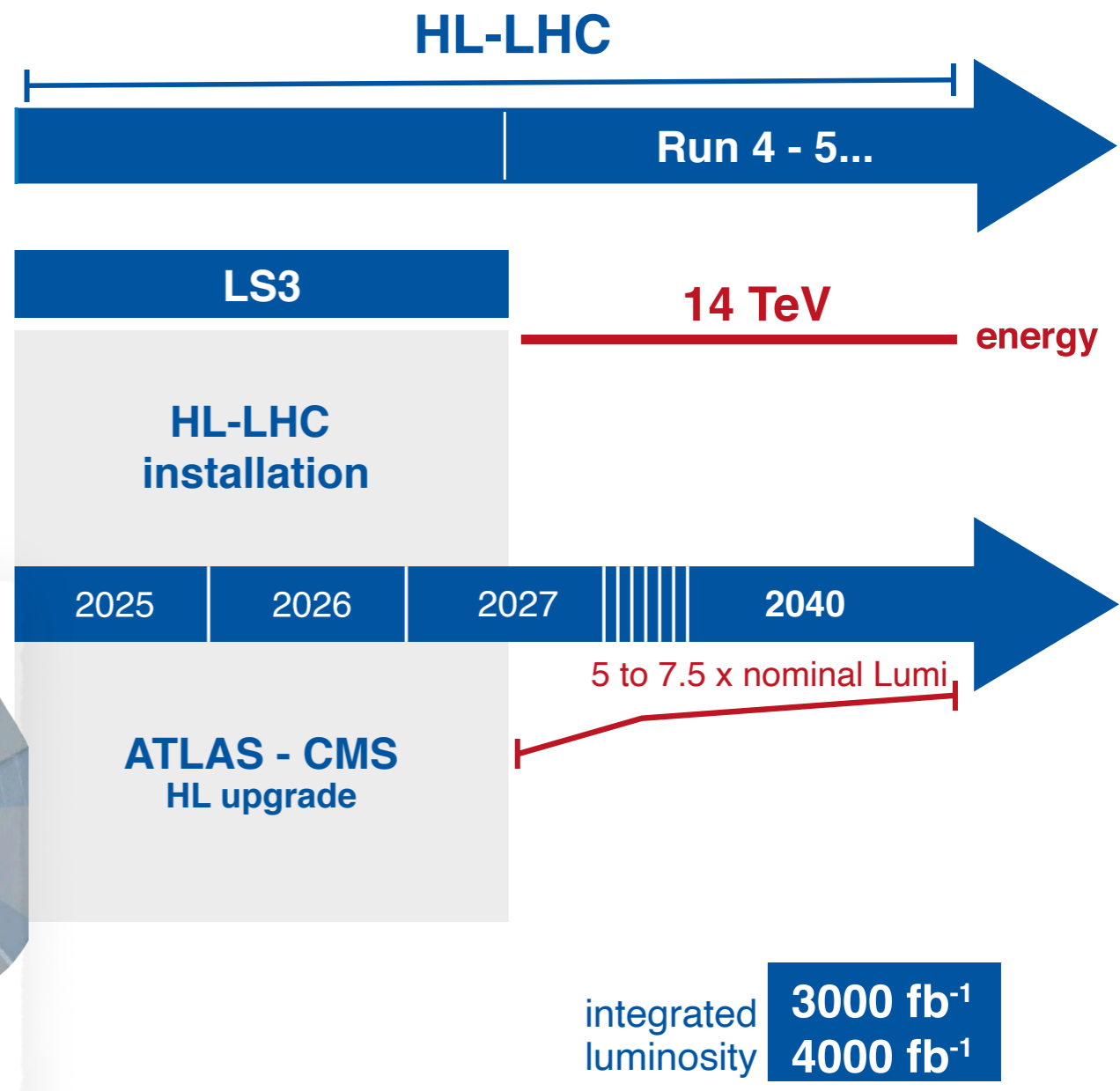
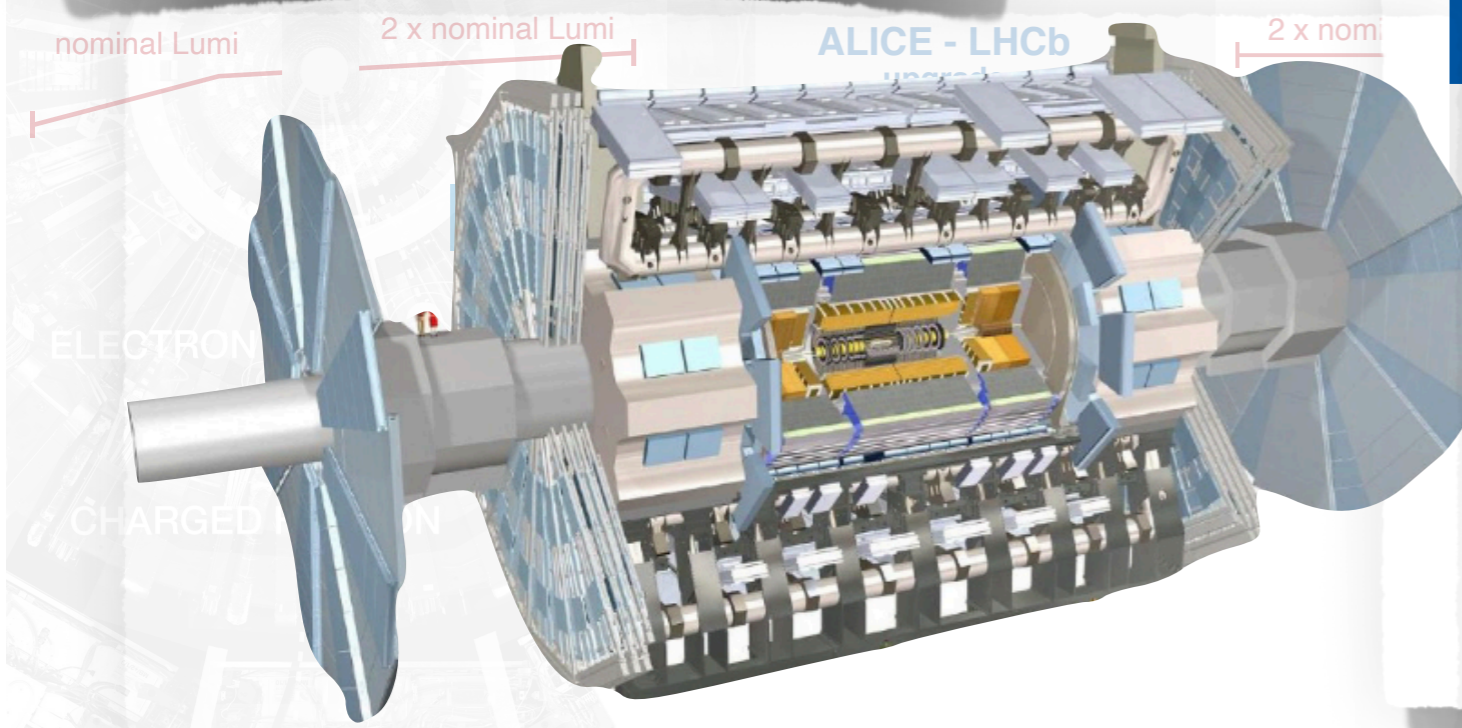
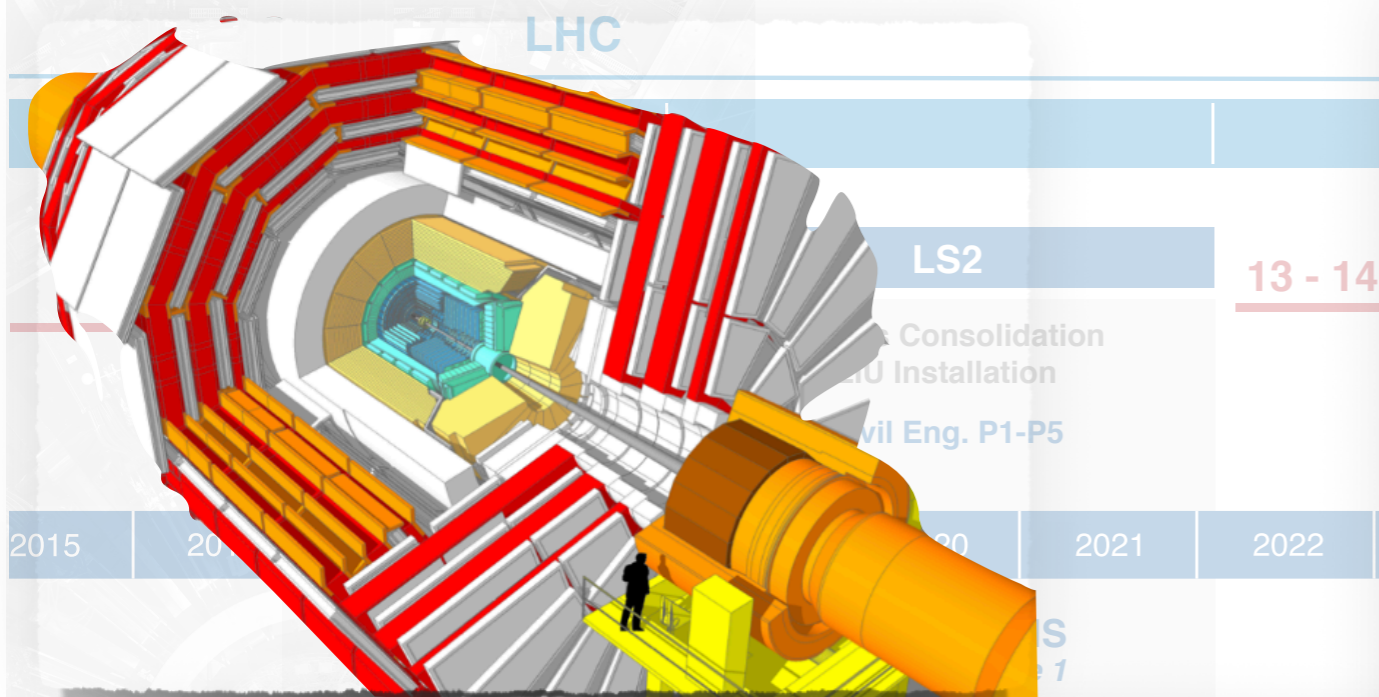
- Significant **extension to the physics reach** by tagging and measuring momentum and emission angle of very forward protons

Exploring Squeezed Mass Spectra

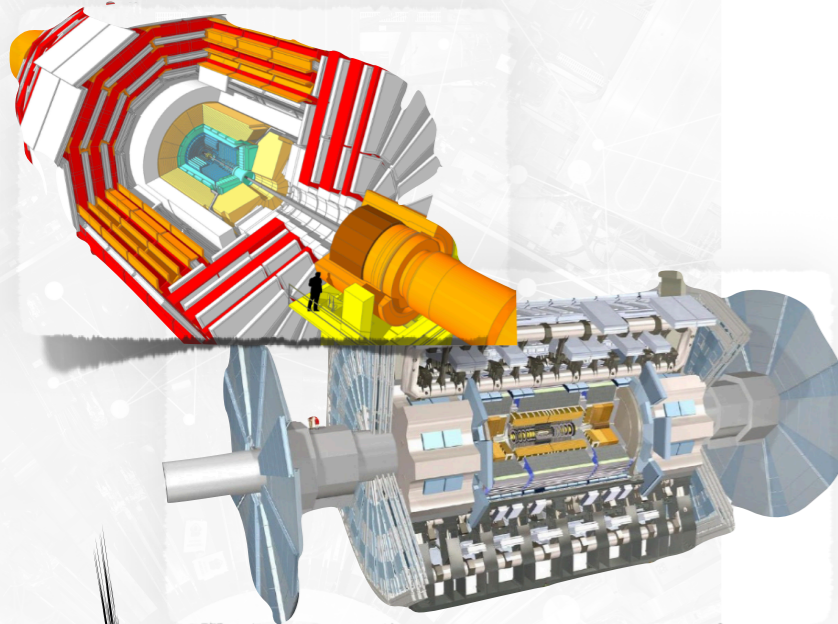
- Forward detectors offer a **unique opportunity to probe $\gamma\gamma$ and gluon-gluon collisions**
- **Complete measurement of the final state**
- Example: Inelastic Dark Matter or Split SUSY



Looking forward for High Lumi



HL LHC Physics Opportunities



- **Large data sample:**
 - Lower experimental uncertainties

- **New tools for searches:**
 - timing information
 - extended tracking for forward boosted physics
 - new trigger strategies

- **Common Effort**

[CERN-LPCC-2018-05](#)

[European Strategy](#)

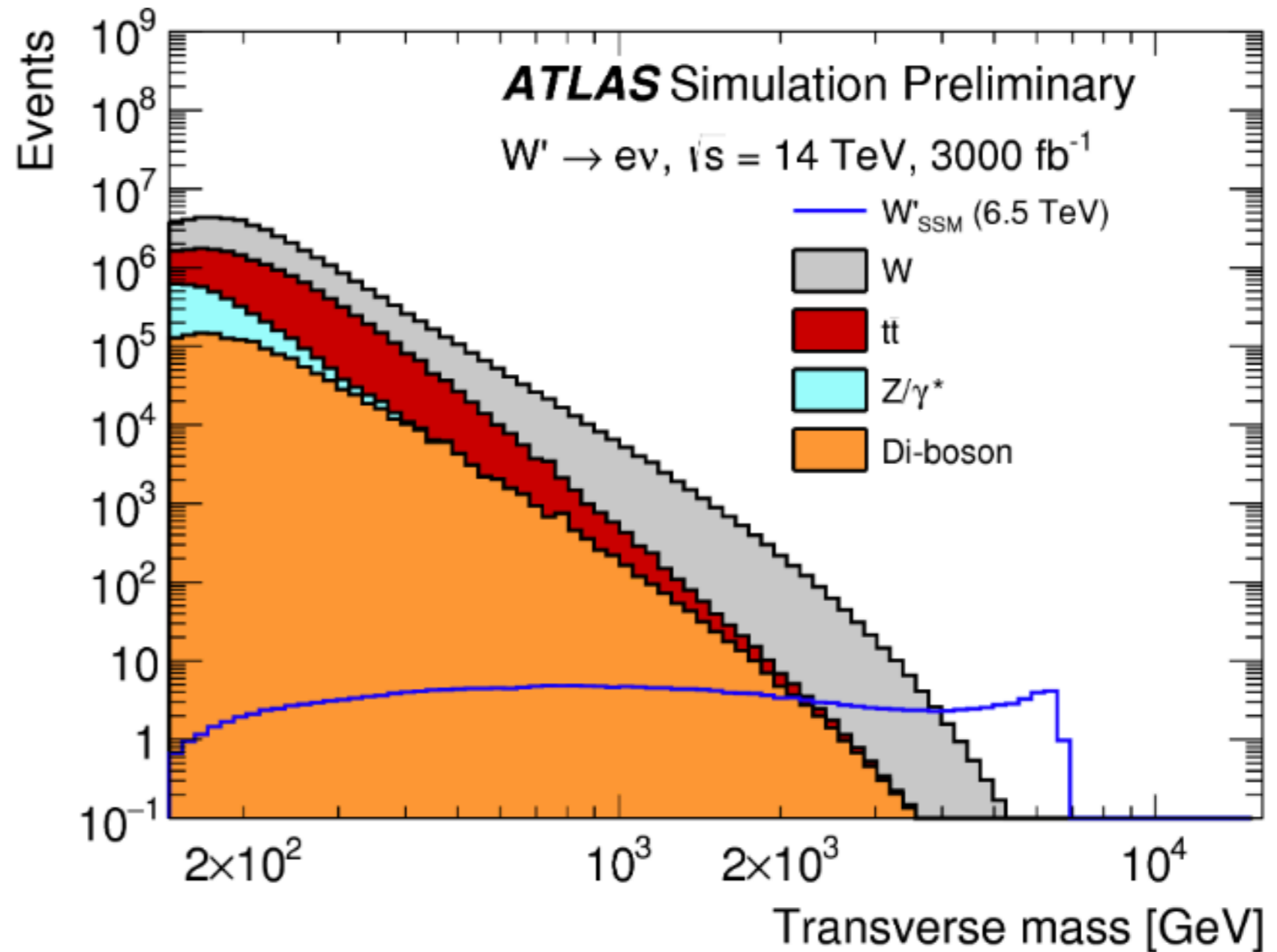
[SnowMass2021](#)

Accumulating data

- **High mass sensitivity** dominated by statistics and object performance at high energy

- **Leptonic channels** (Z'/W') reach 6-8 TeV mass sensitivity

- **1-2.5 TeV better than Run 2**



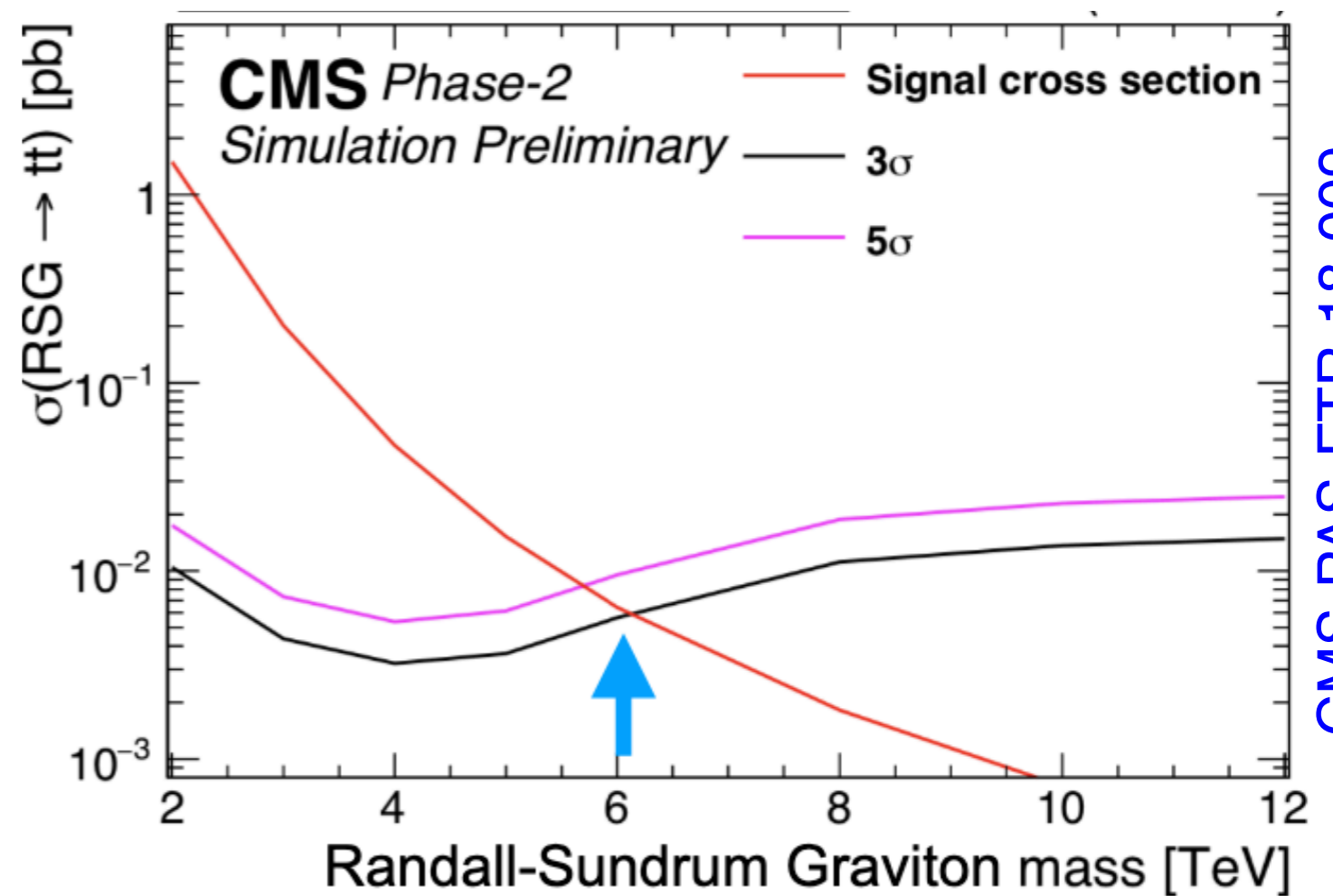
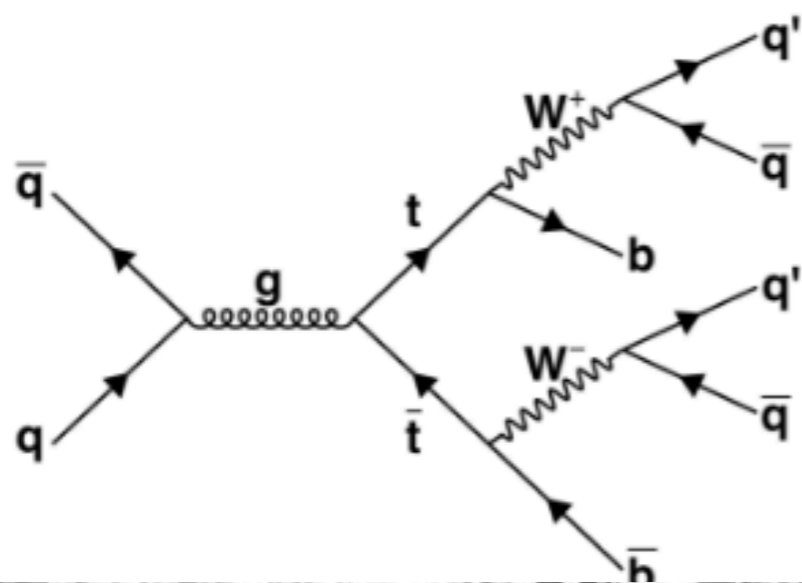
[ATL-PHYS-PUB-2018-044](#)

Accumulating data

- **High mass sensitivity** dominated by statistics and object performance at high energy

- **Hadronic channels** dominated by top final states

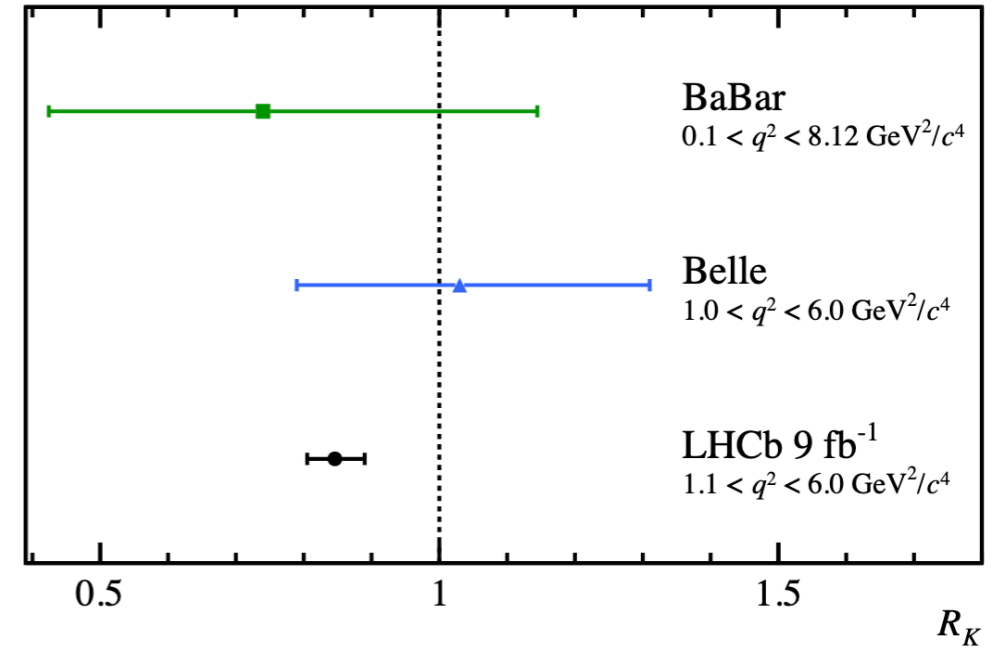
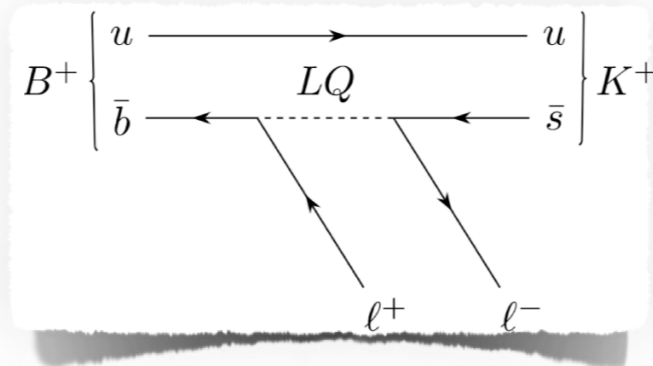
- Good **b-tagging** efficiency
- Phase2 **high granularity and timing/New trigger**



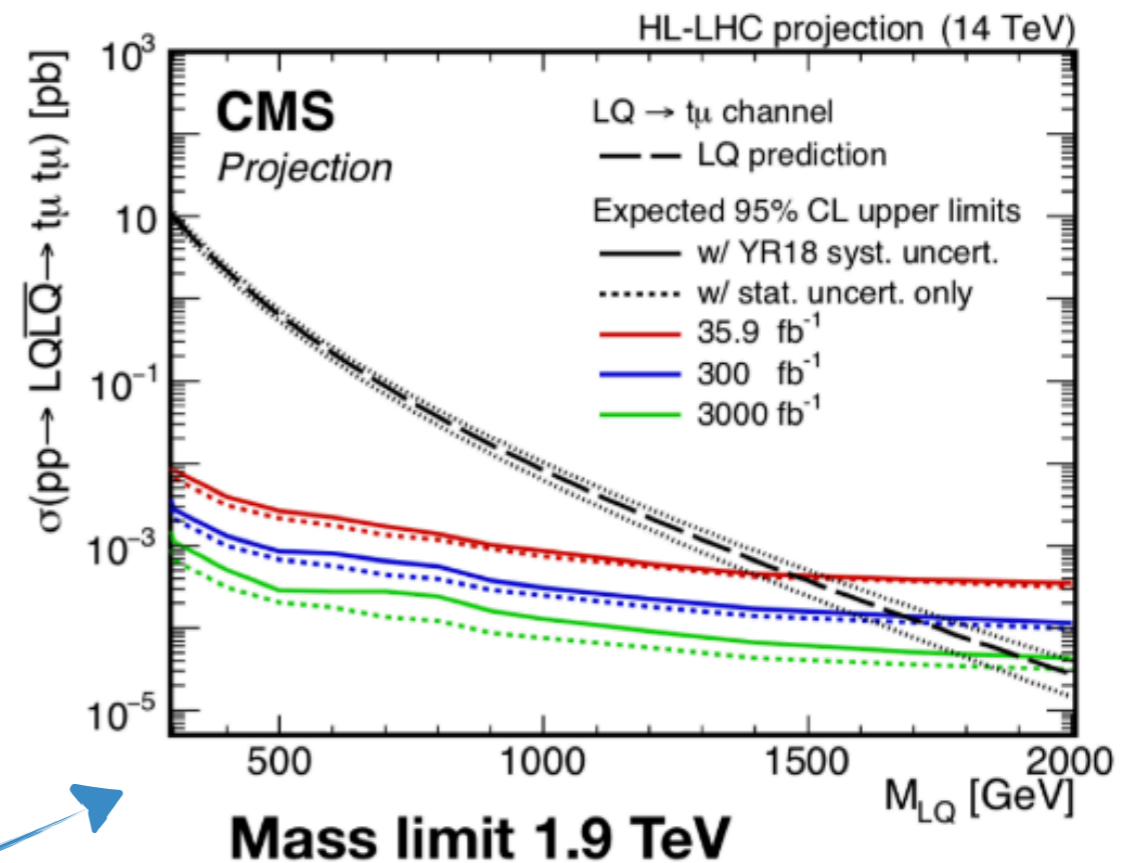
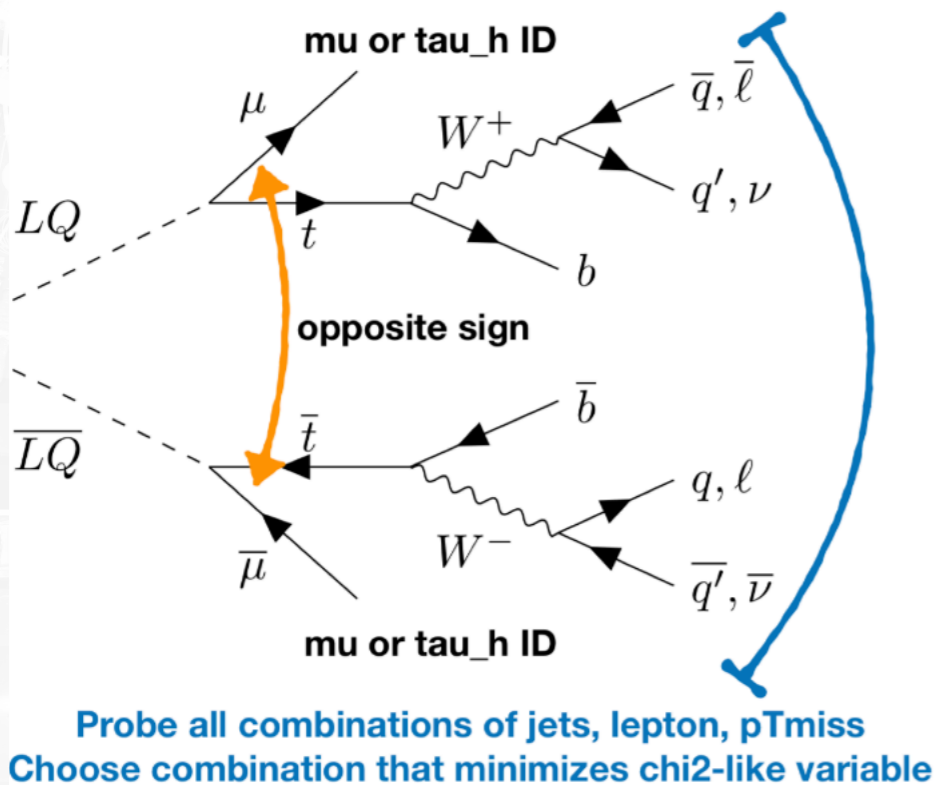
CMS-PAS-FTR-18-009

Being inspired by Run 2

- Pattern of **interlinked anomalies** emerged in experimental studies of **LFU**

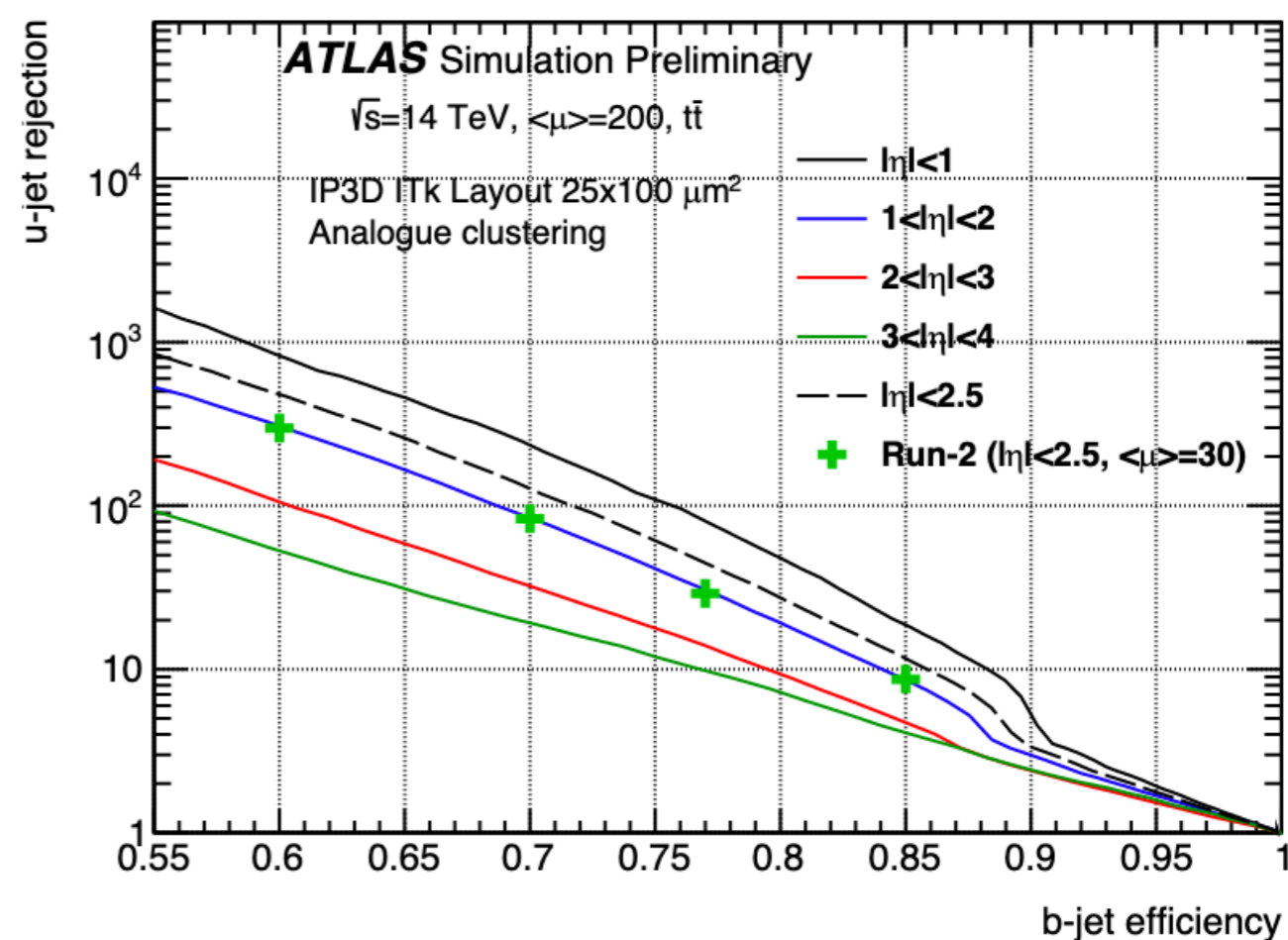
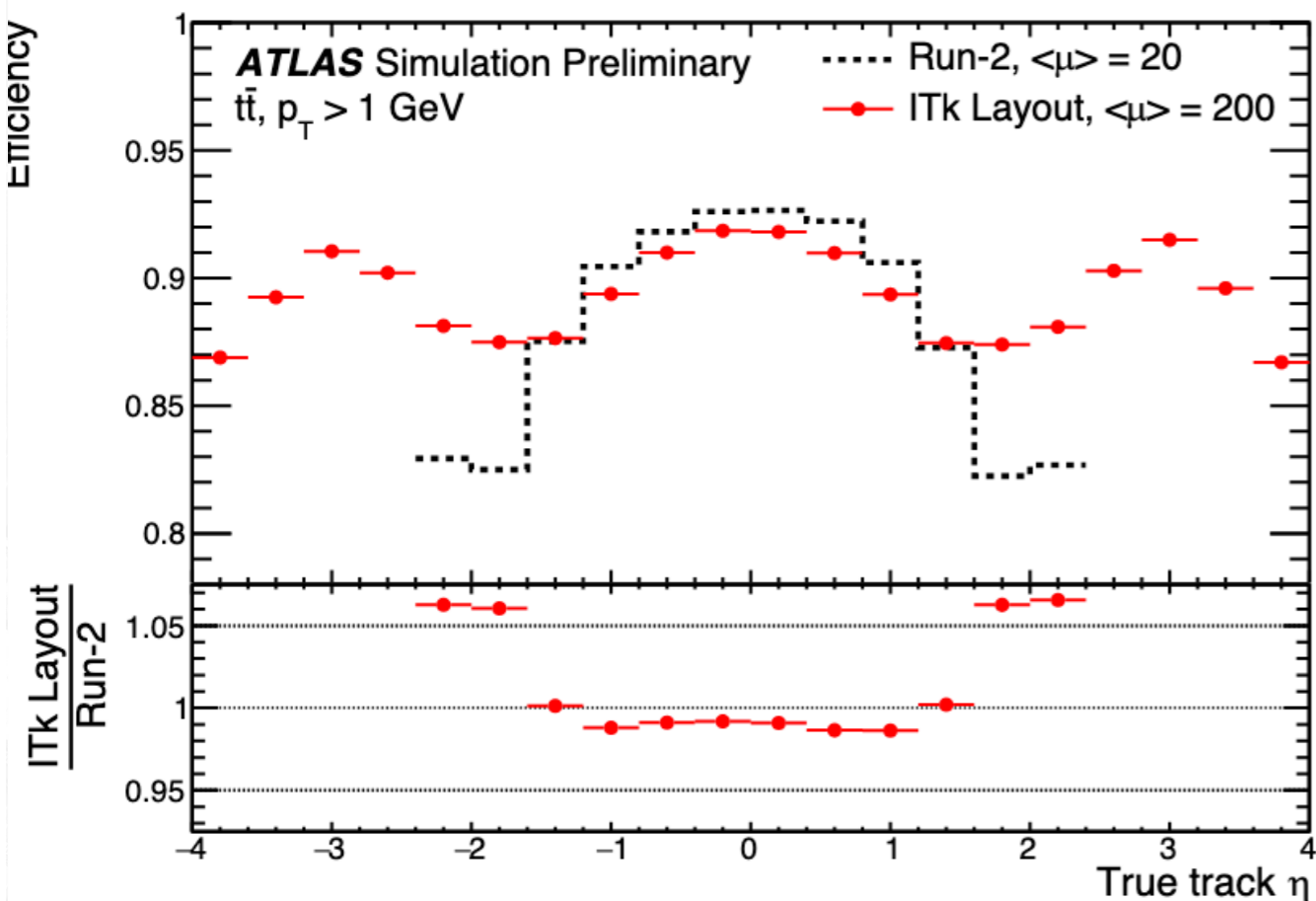


- Renewed interest in Models with **third generation LeptoQuarks**



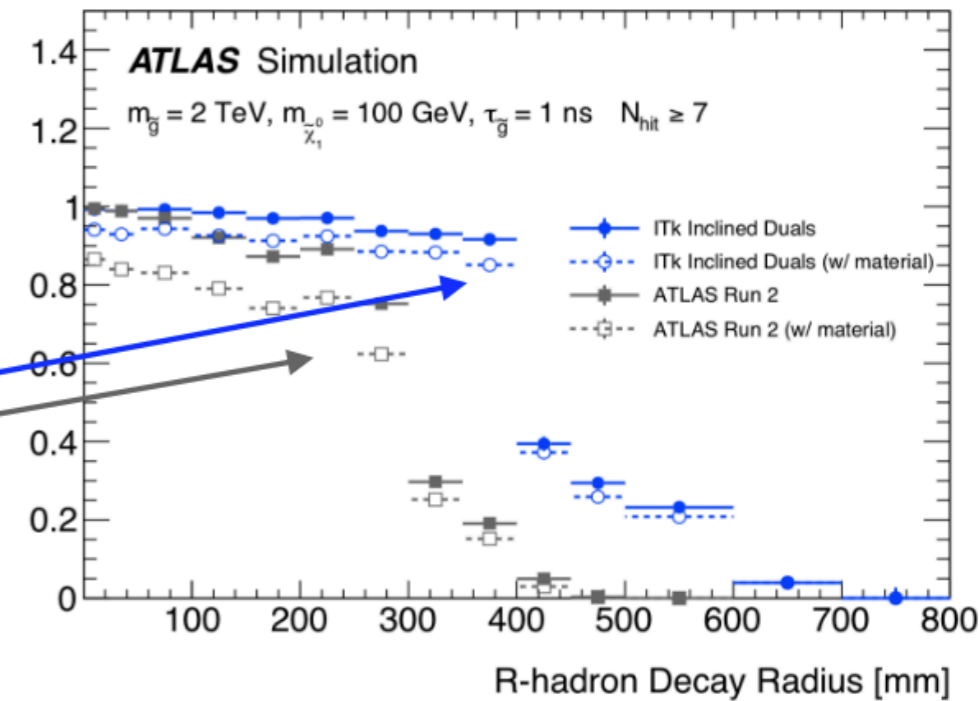
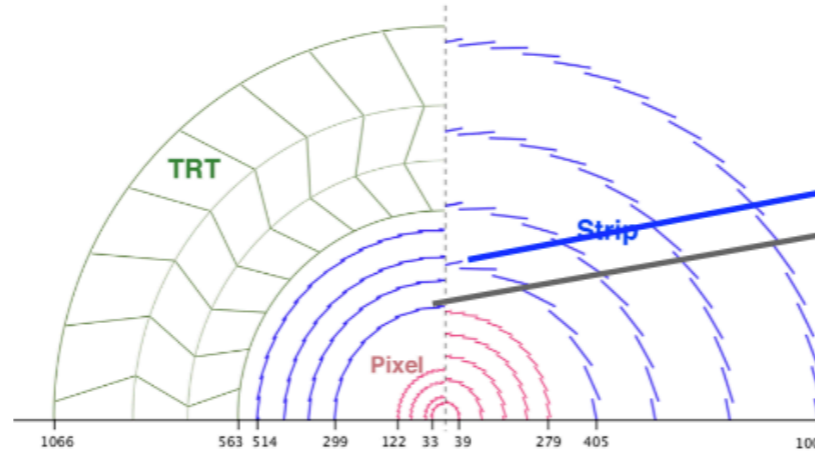
ATLAS ITk Silicon Tracker upgrade

- Nearly 13 m² of pills and 165 m² of strips with **improved coverage and novel readout electronics**
- Improves **tracking and b-tagging** performance compared to Run 2

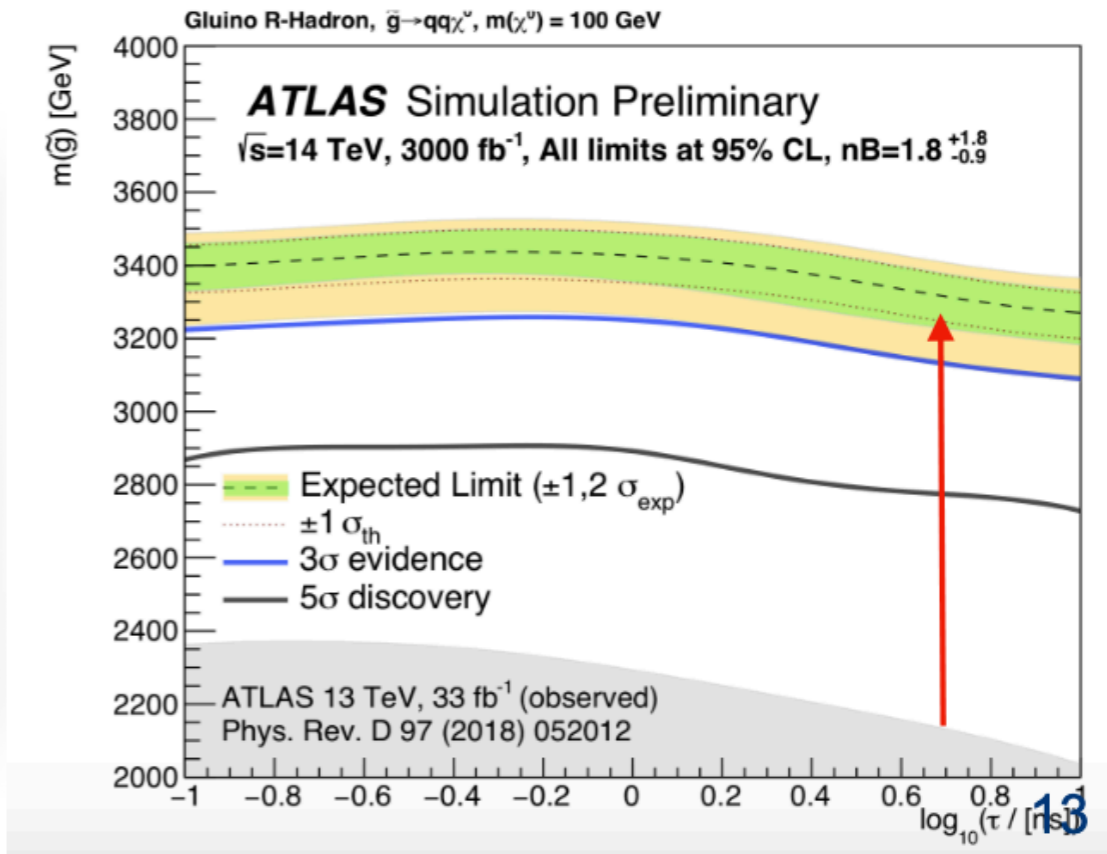
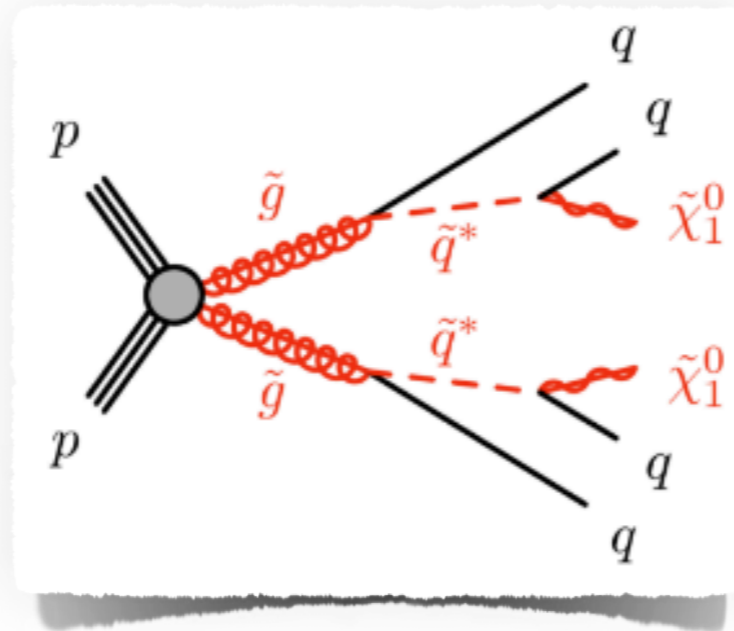


Displaced Tracks at HL-LHC

- Higher **reco efficiency** with ITk detector
- Improved geometry and **larger volume w/ lower material budget**



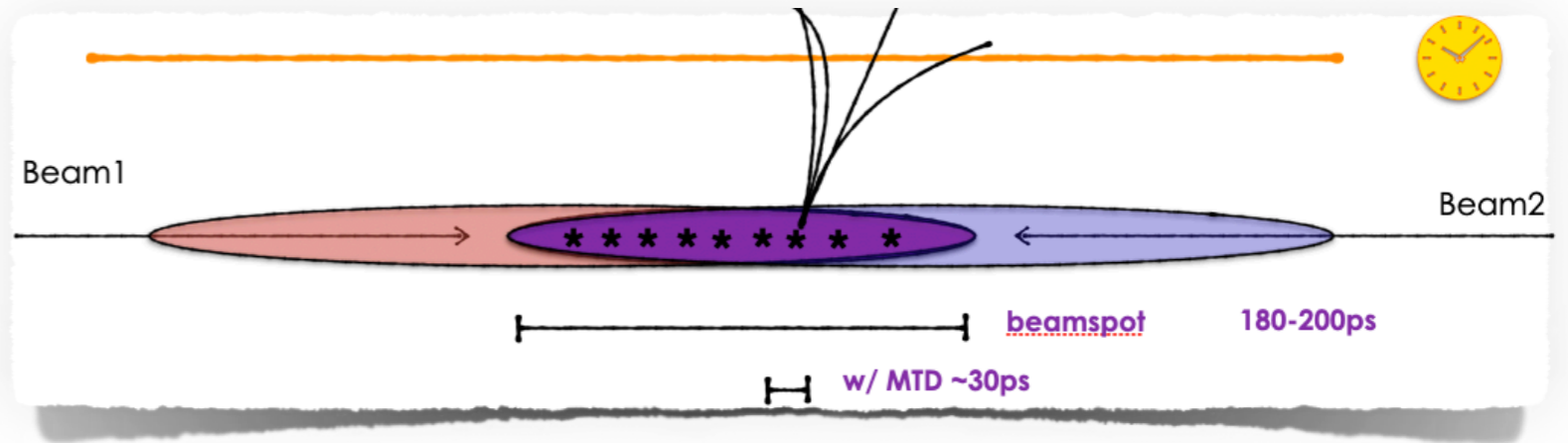
- Sensitive to **long-lived particles with $\tau \sim 10 \text{ ps} - 10 \text{ ns}$** decaying to multiple charged particles



ATL-PHYS-PUB-2018-033

CMS New MIP Timing Detector

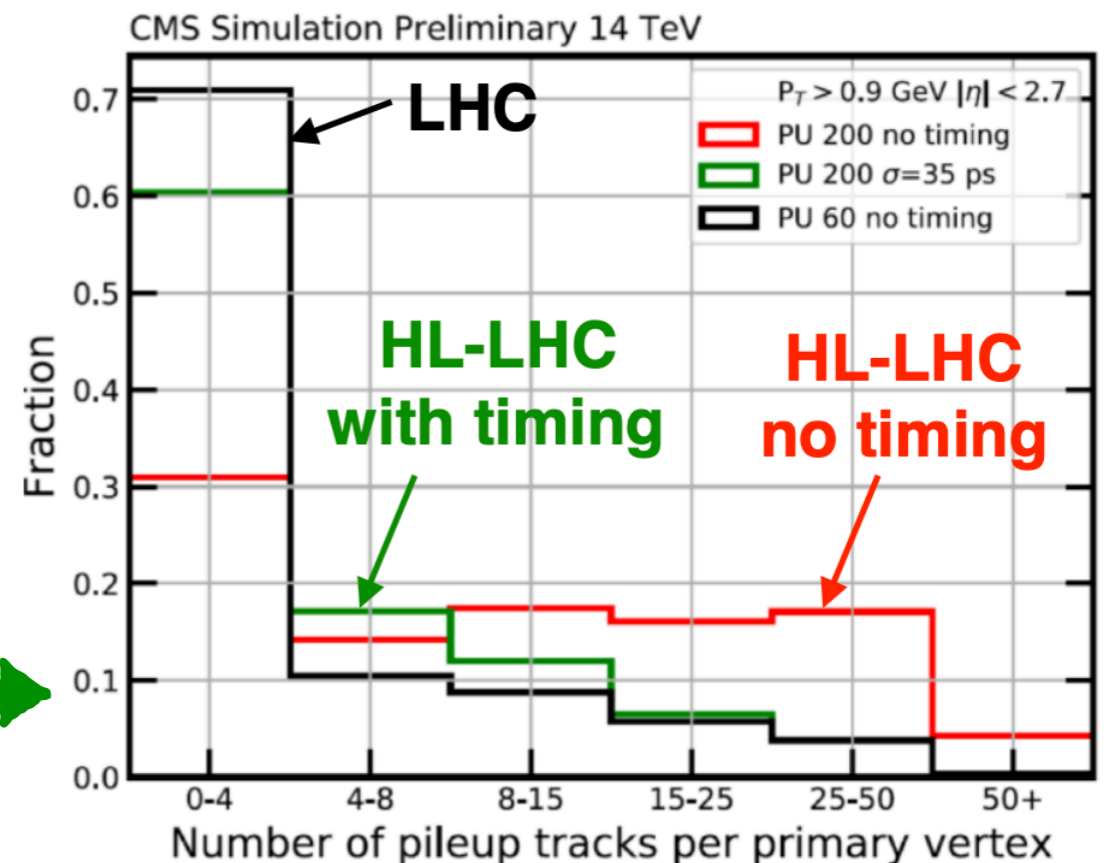
- Significant **PU contamination** and whole **event reconstruction degradation** at HL-LHC



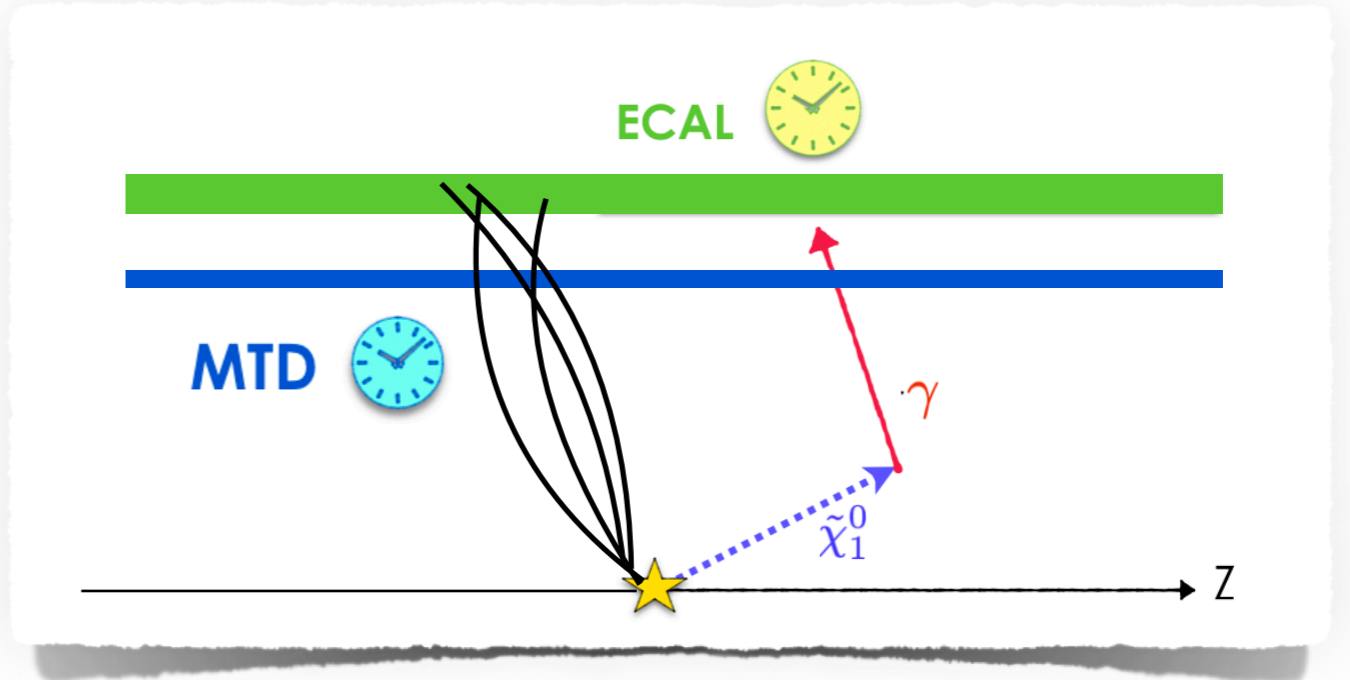
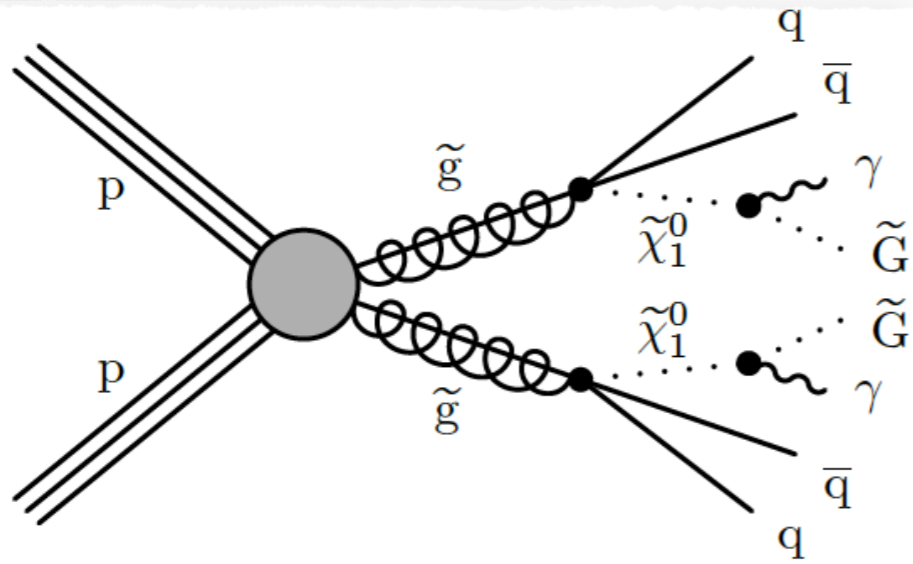
- New **Hermetic timing detector** with various technologies optimized for different radiation levels

- Require time compatibility within $O(30\text{ps})$ for **track vertex association**

- Effectively **reduce actual pileup** to level of the current LHC well handled by CMS detector

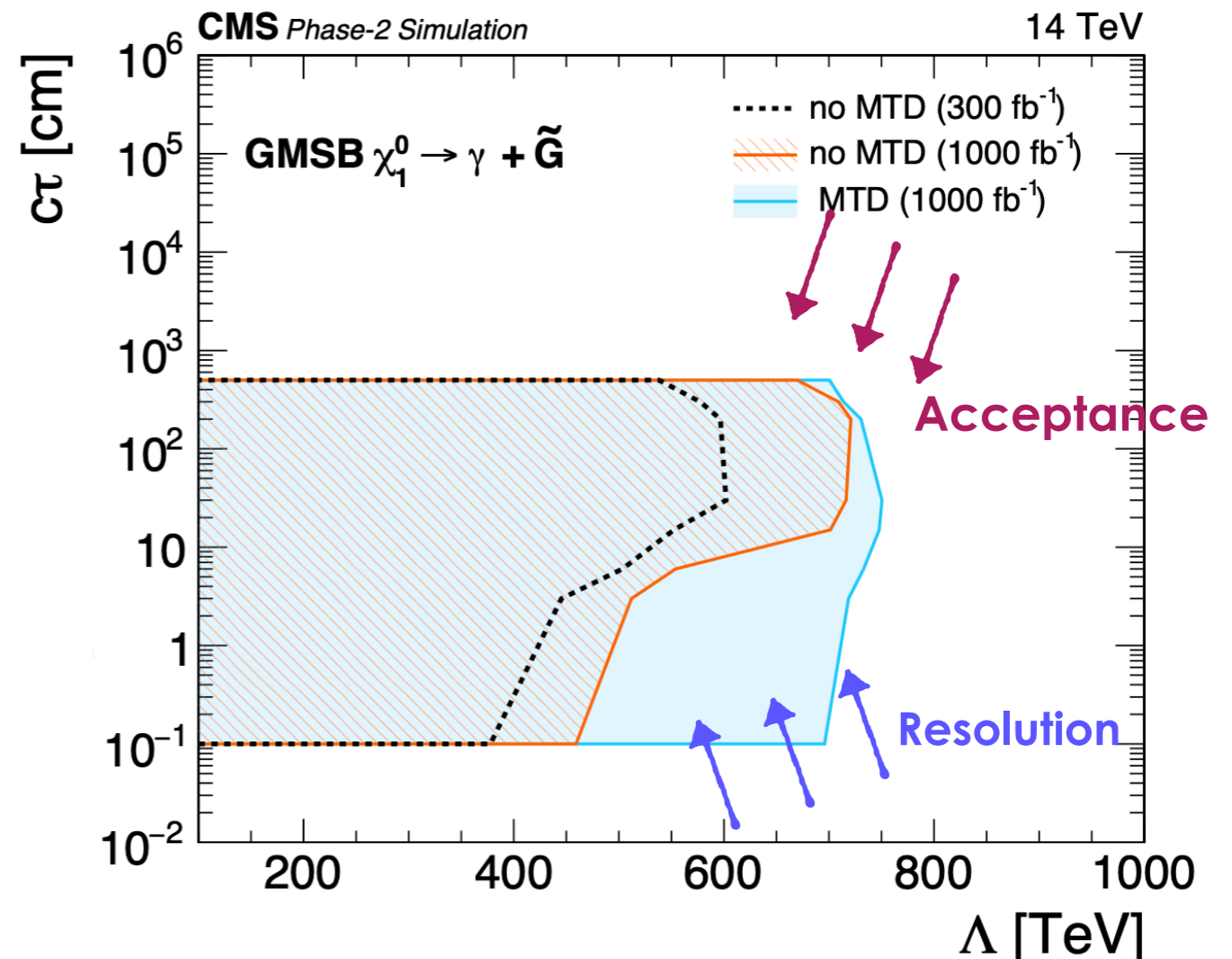


Displaced Photons w/ MTD



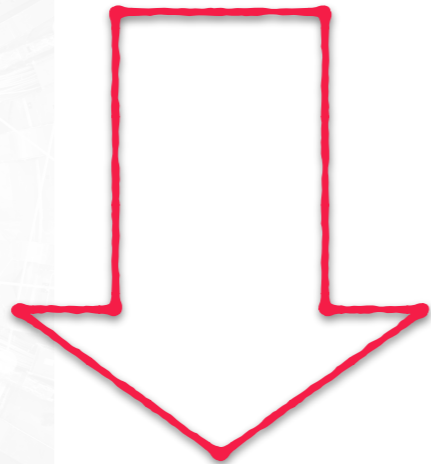
- Exploit **MTD to reduce BS timing information** crucial to **evaluate photons TOF w/ ECAL**

- Sensitivity of the analysis is explored requiring **at least one displaced photon** and making a **0 background assumption**.

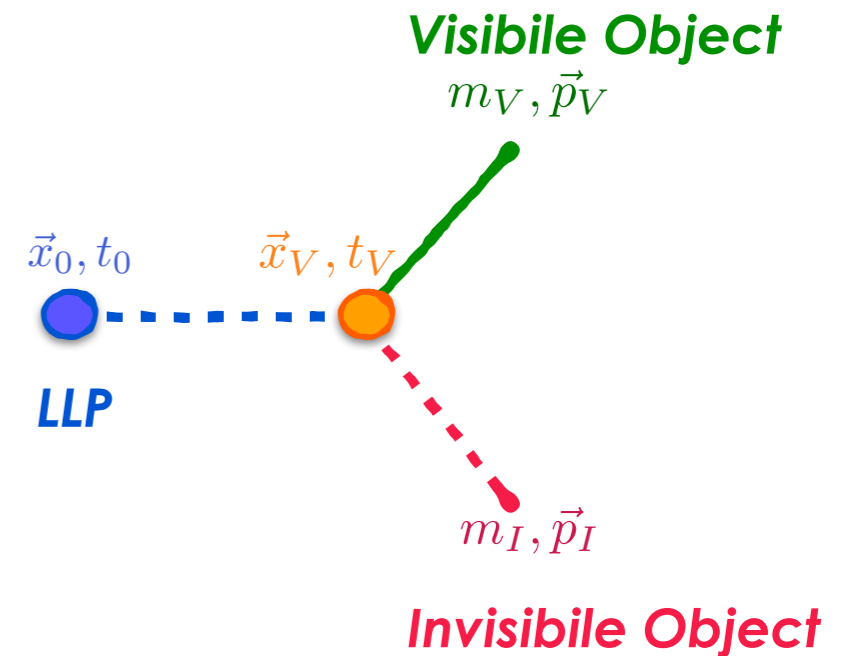


Being creative with timing

- **Reconstructed vertex to measure the TOF of LLPs**

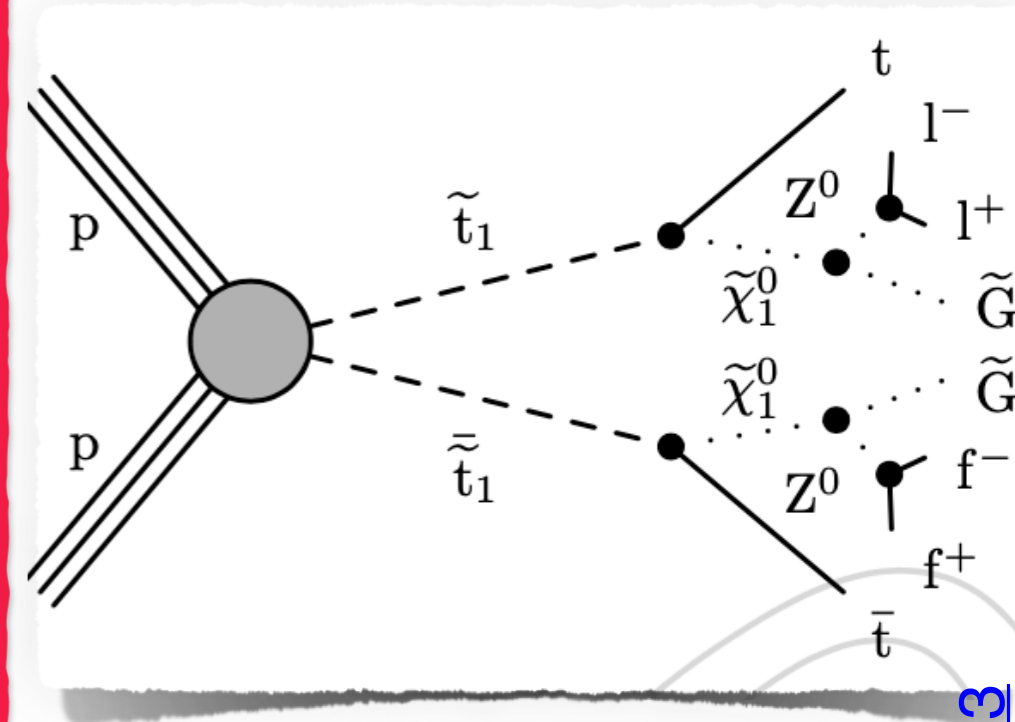
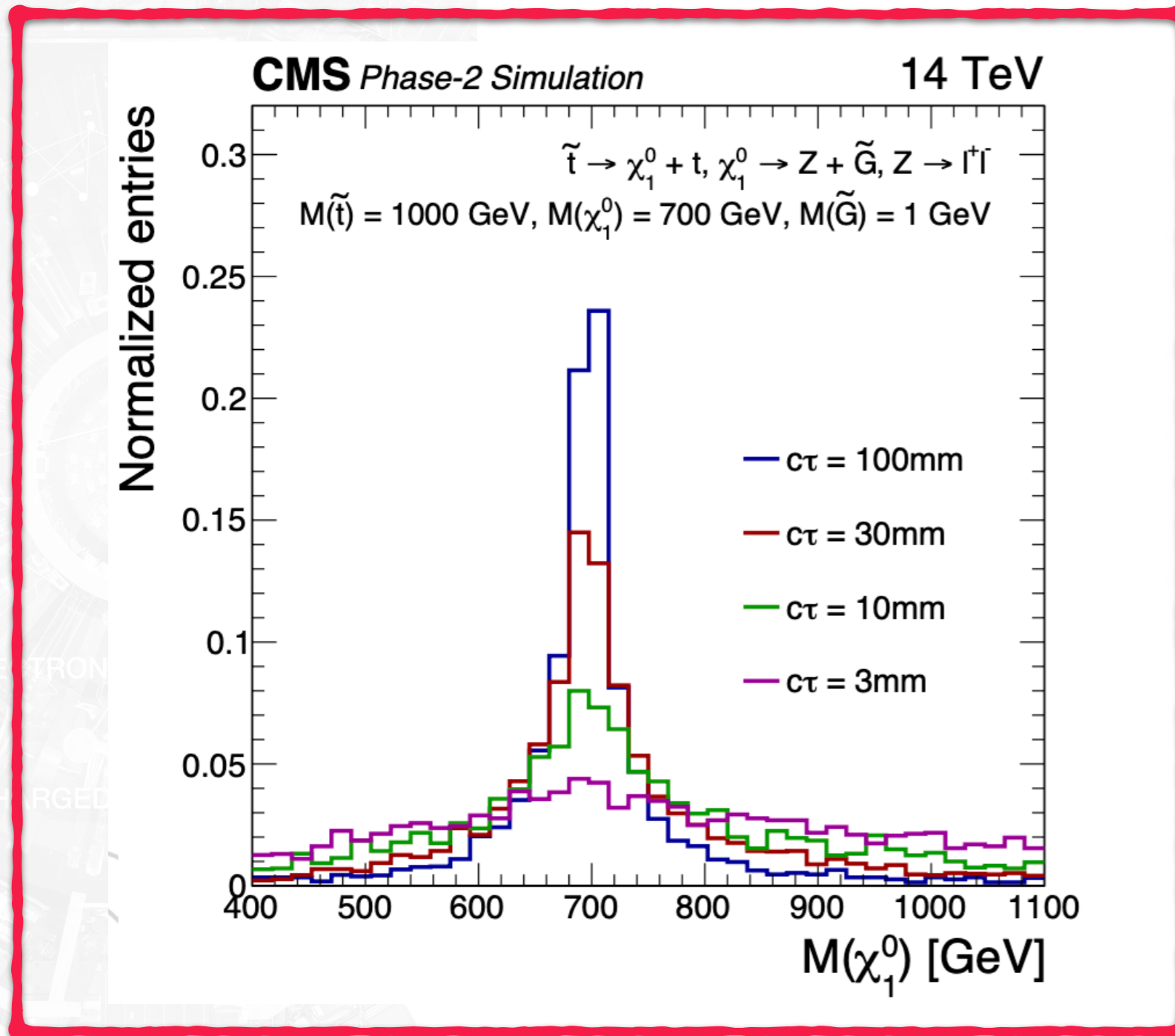


- **Kinematic closure: direct measurement of the LLP mass**



Neutralino mass reconstruction

- Stop production with LL neutralino decaying into Z and Gravitino



Conclusions

- Direct searches for **BSM signatures important part of the (HL) LHC programme**
- These signatures could have been missed or thrown away as noise:
Important to **check all our blind spots!**

Conclusions

**Non
Conventional
Signatures**

**Dedicated
trigger
algorithms**

**Unique object
reconstruction,
discriminating
variables, or data
processing**

**Re-defined
analyses strategies
w/ atypical
backgrounds**

Conclusions

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**Non
Convention
Sign**

**Dedicated
trigger
algorithms**

Uni-

**Looking for Forward for Run 3 Pilot
Run in October!**

processing

**Re-defined
analyses strategies
w/ atypical
backgrounds**