BSM Higgs & Dark Matter Results from ATLAS and CMS

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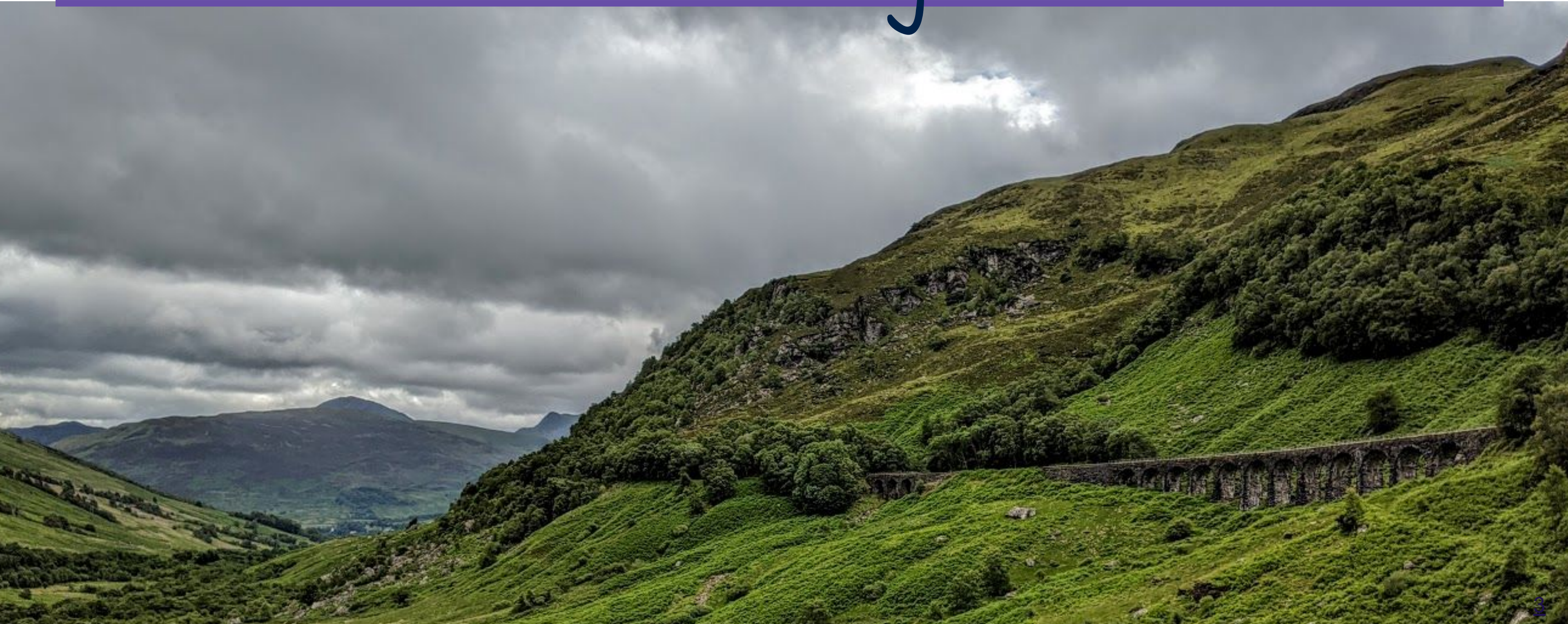
International Conference on the Physics of the Two Infinities
March 2023

Overview

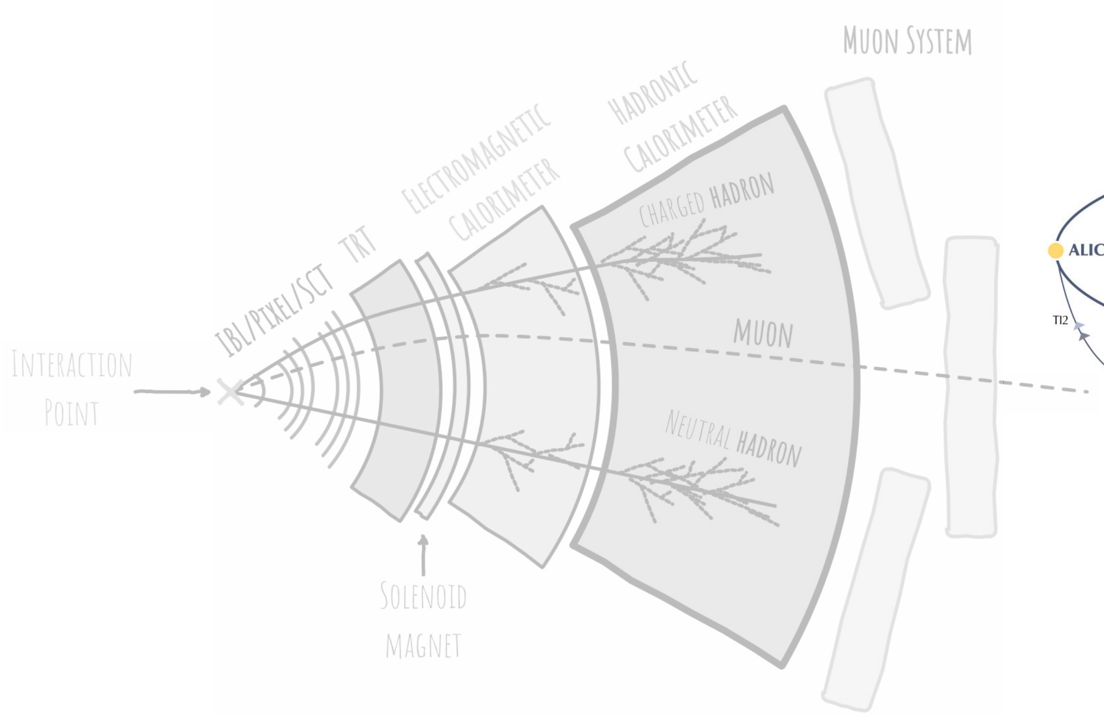
- **New physics** searches @ **LHC**
- Dark **M**atter and **B**eyond **S**tandard **M**odel Higgs @ **LHC**
- Recent results from **ATLAS** and **CMS**
- Summary

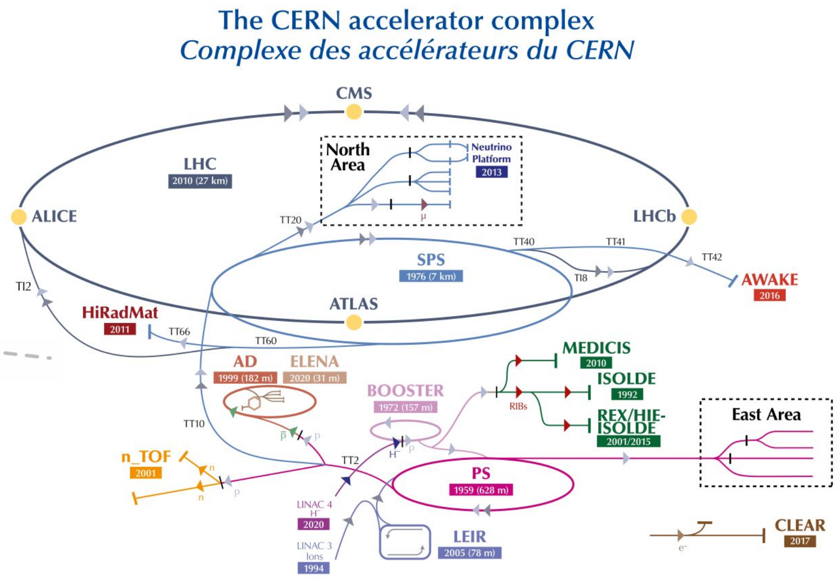
DM and BSM Higgs @ LHC

how? why?



The LHC & collider detectors





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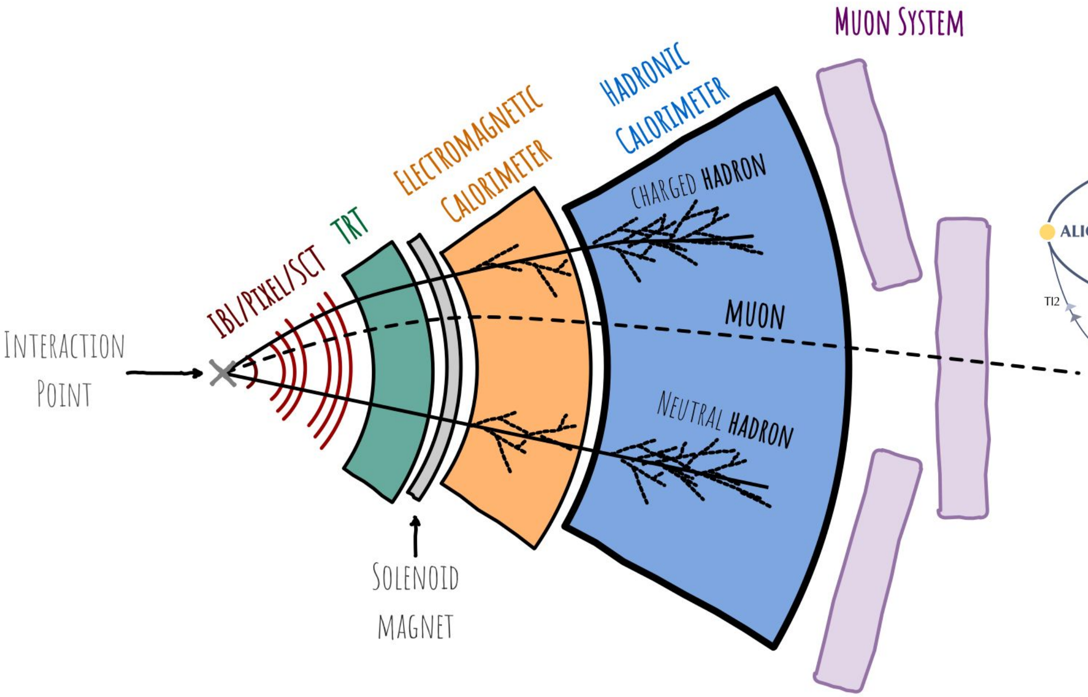
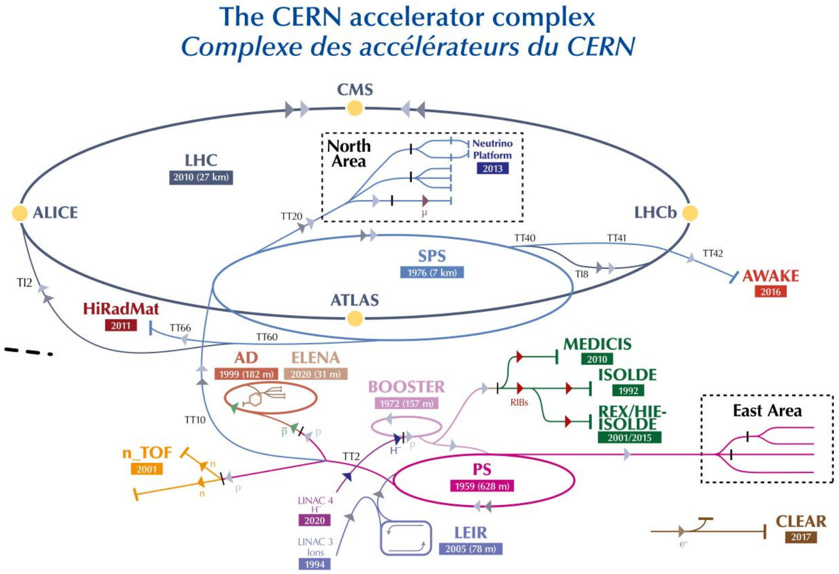
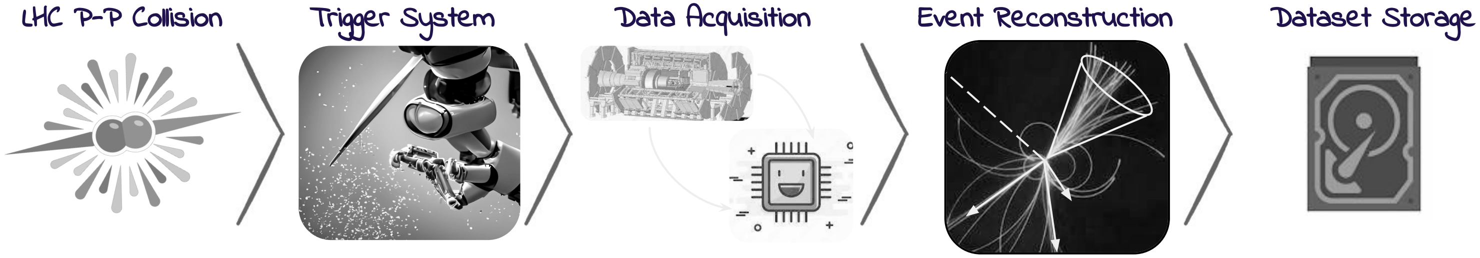


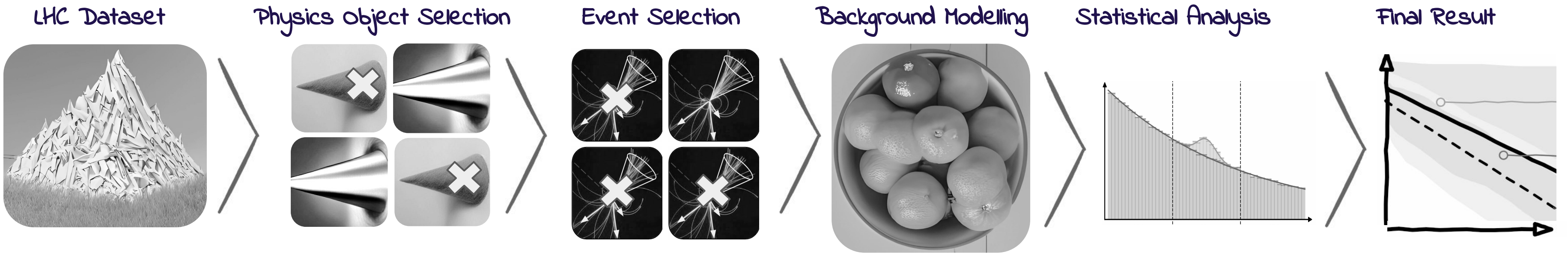


An LHC data analysis in a nutshell

- First: acquire and save the data sets



- Next: interpret the data, define strategies, statistical analysis



➳ ATLAS and CMS apply **different approaches** in **some steps**

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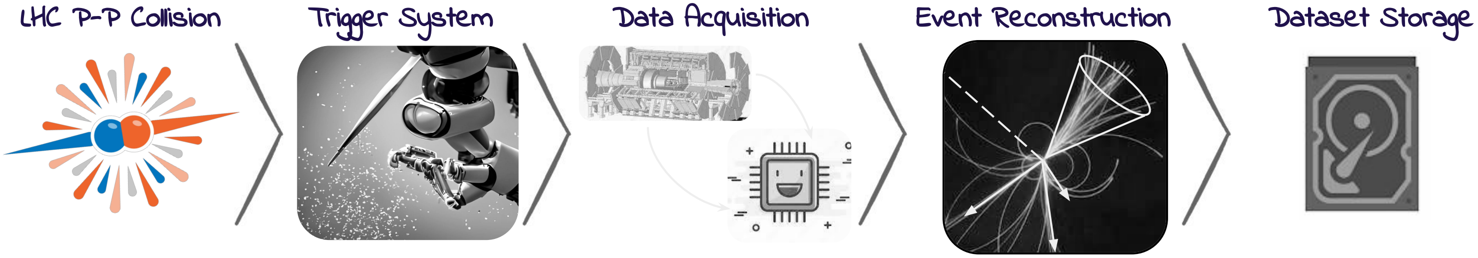

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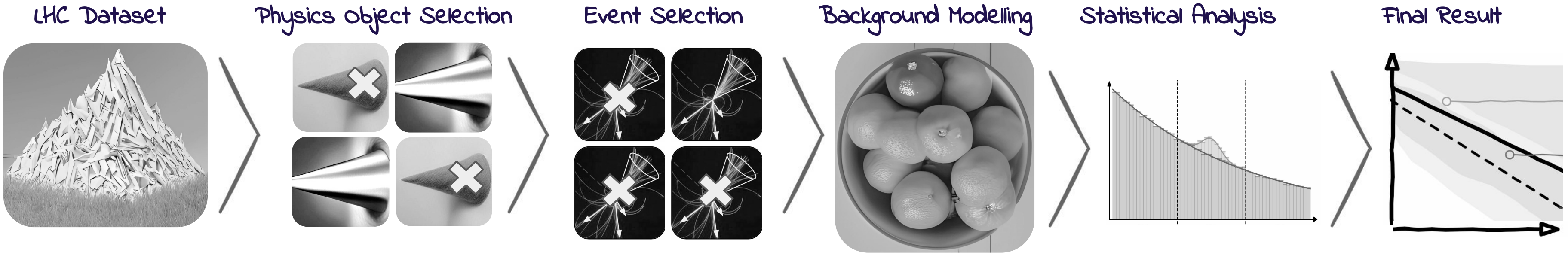

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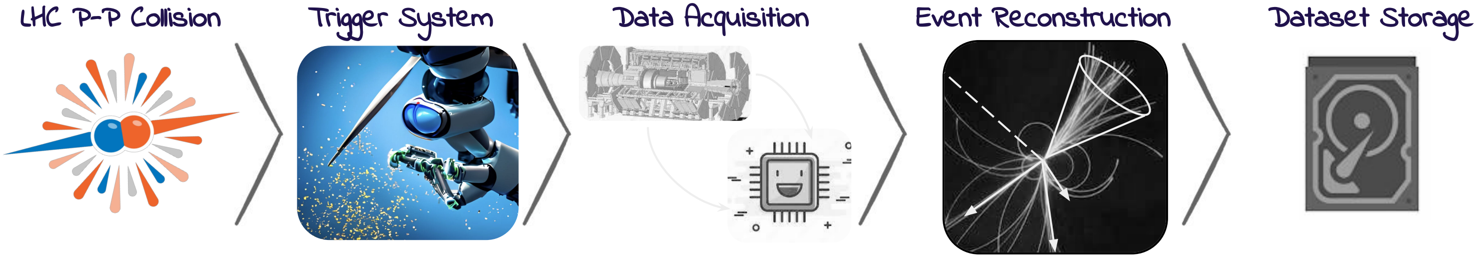

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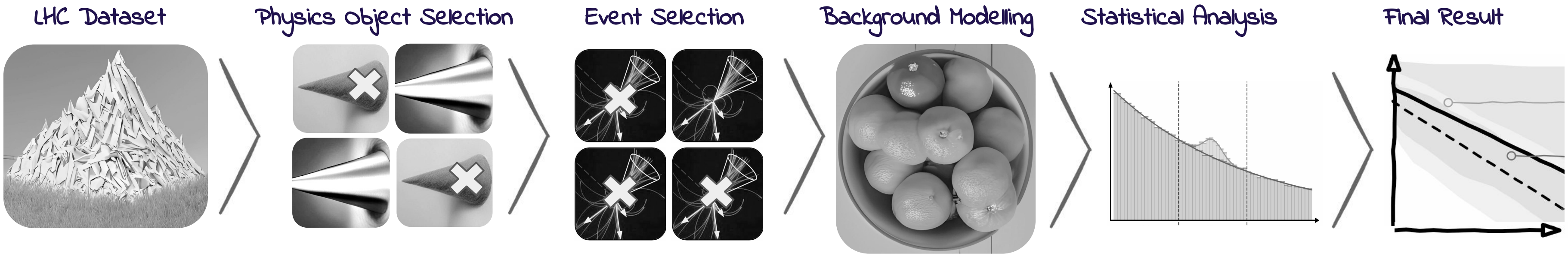

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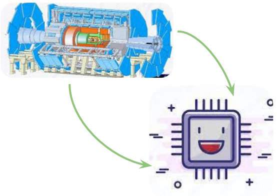
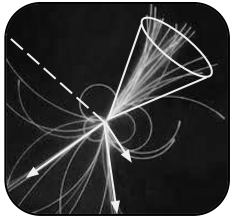
LHC P-P Collision

Trigger System

Data Acquisition



Event Reconstruction

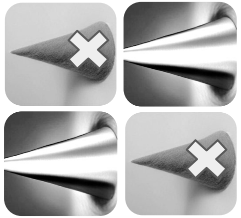


Dataset Storage

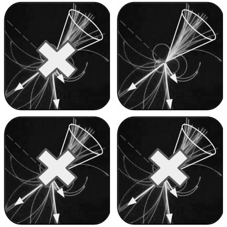
- Next: interpret the data, define strategies, statistical analysis

LHC Dataset

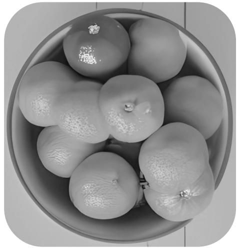
Physics object Selection



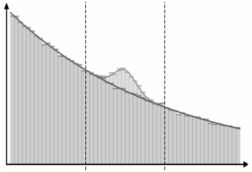
Event Selection



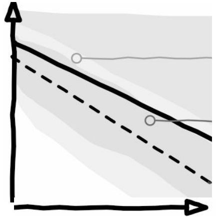
Background Modelling



Statistical Analysis



Final Result



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An LHC data analysis in a nutshell

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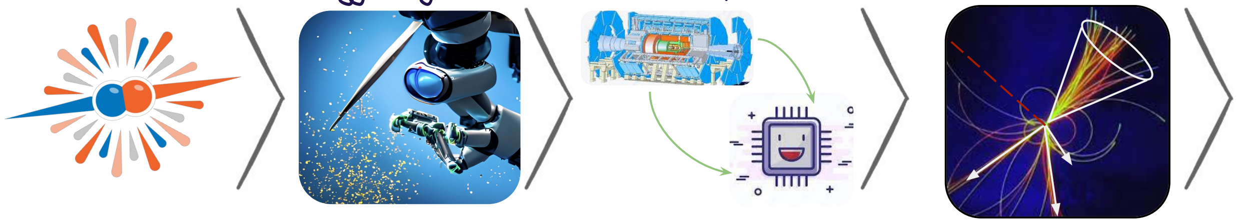
LHC P-P Collision · Trigger System · Data Acquisition · Event Reconstruction · Dataset Storage



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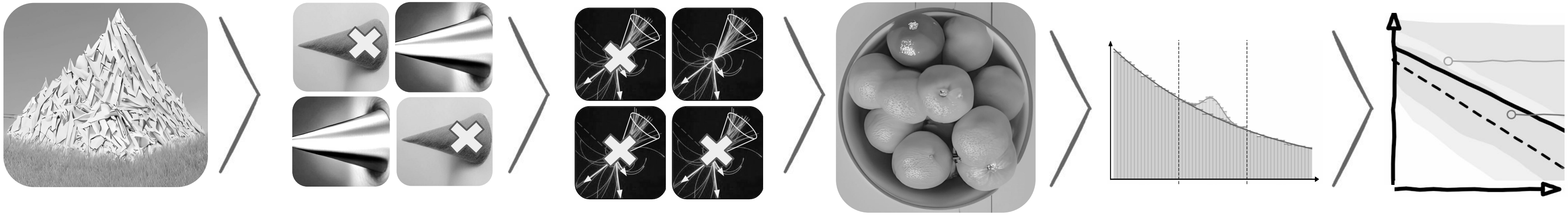
LHC Dataset · Physics object Selection · Event Selection · Background Modelling · Statistical Analysis · Final Result



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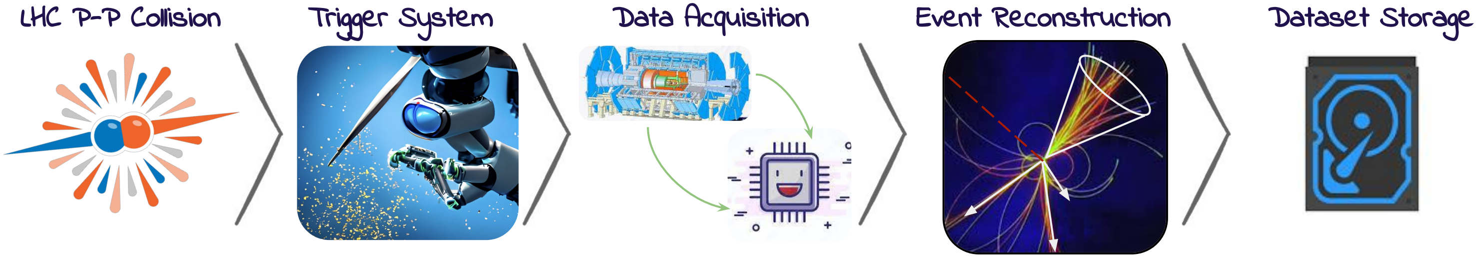

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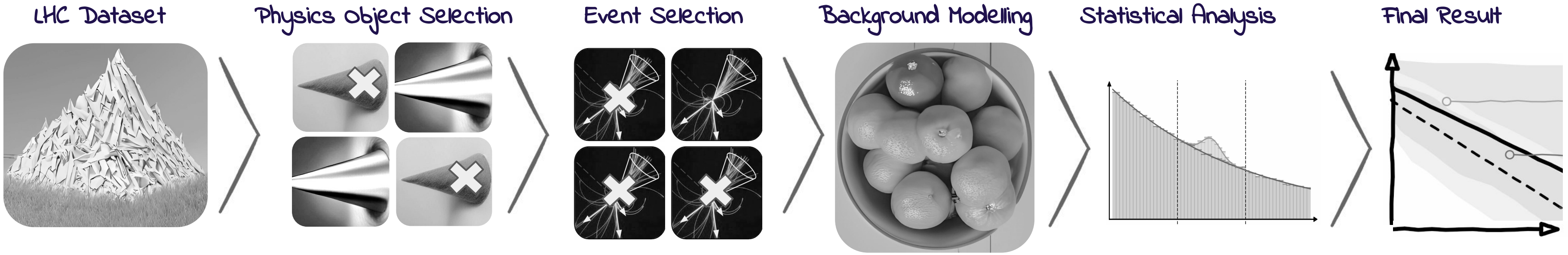

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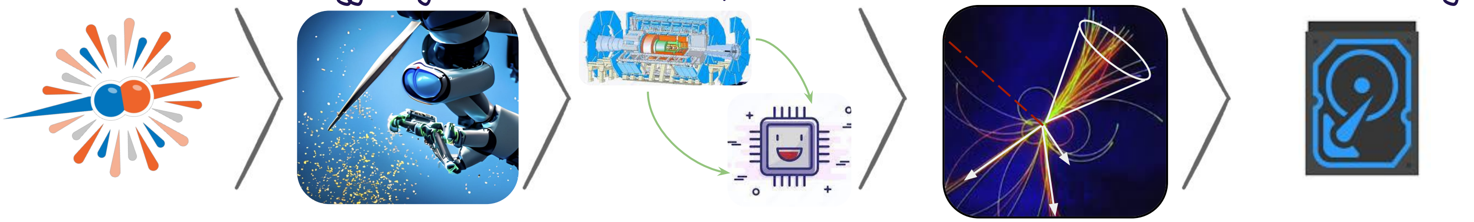

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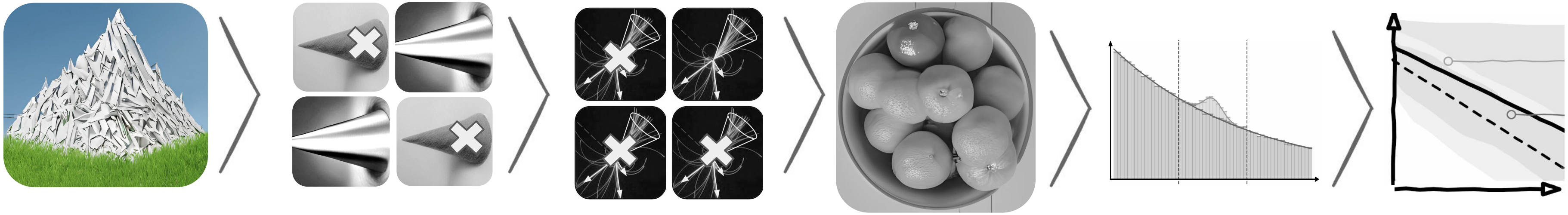

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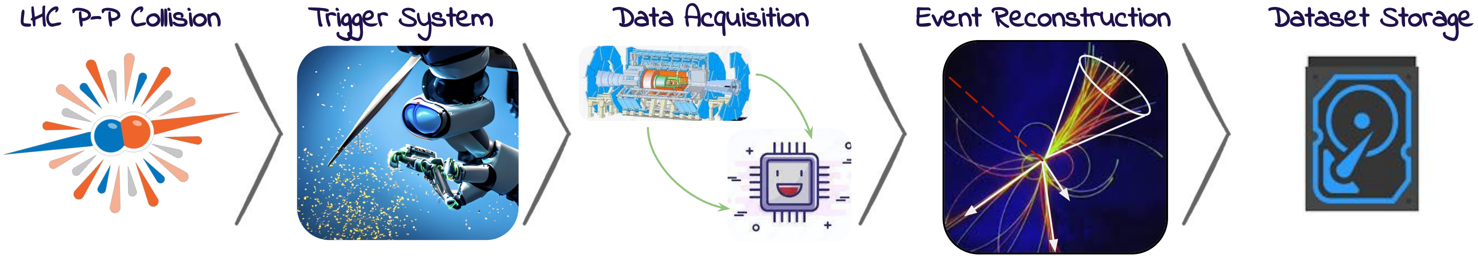

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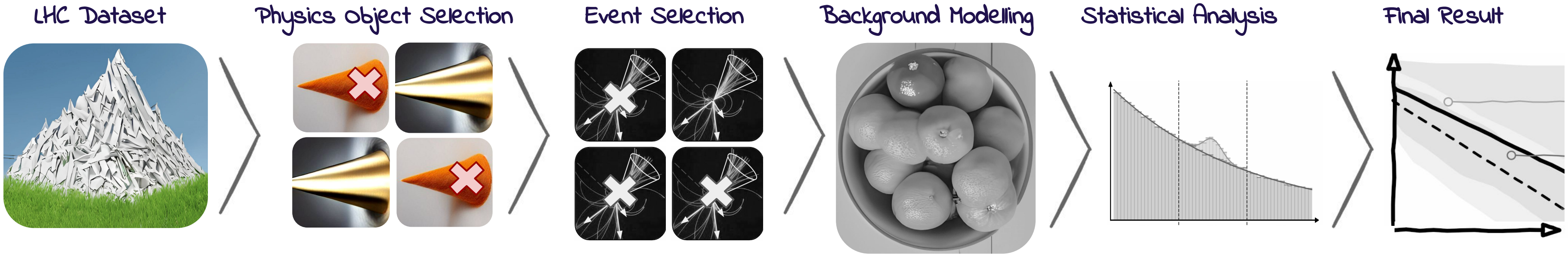

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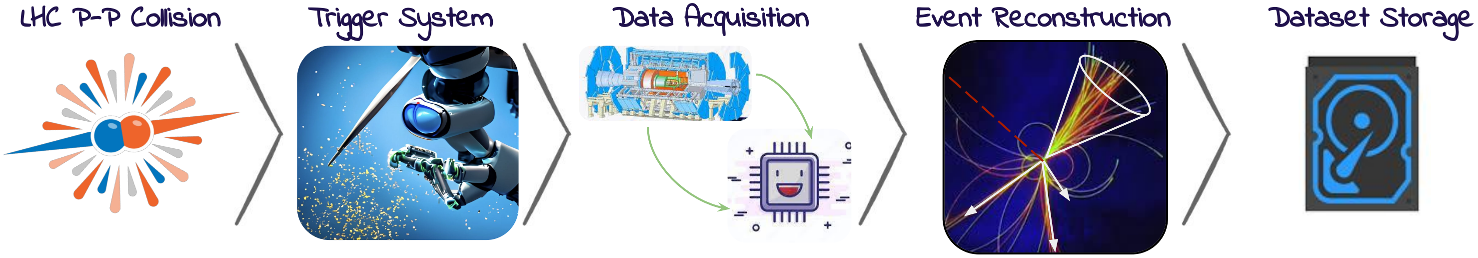

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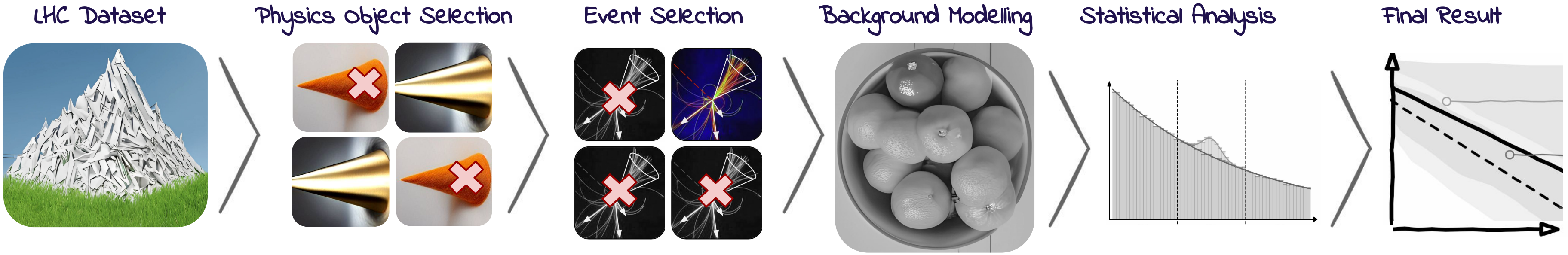

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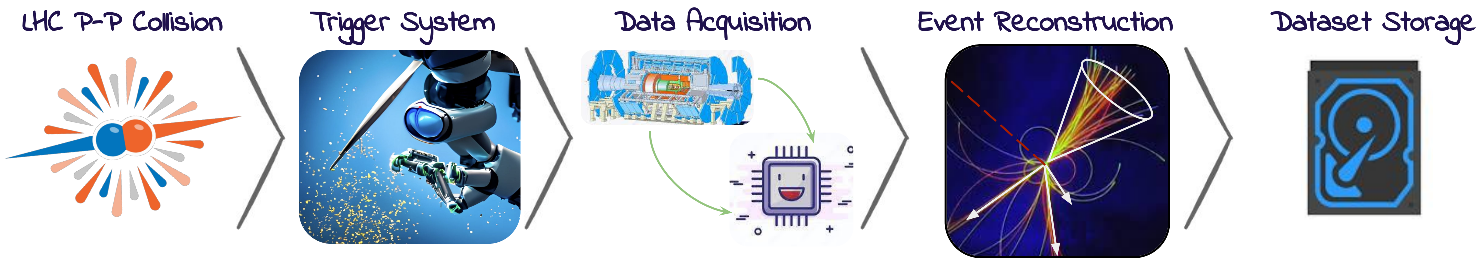

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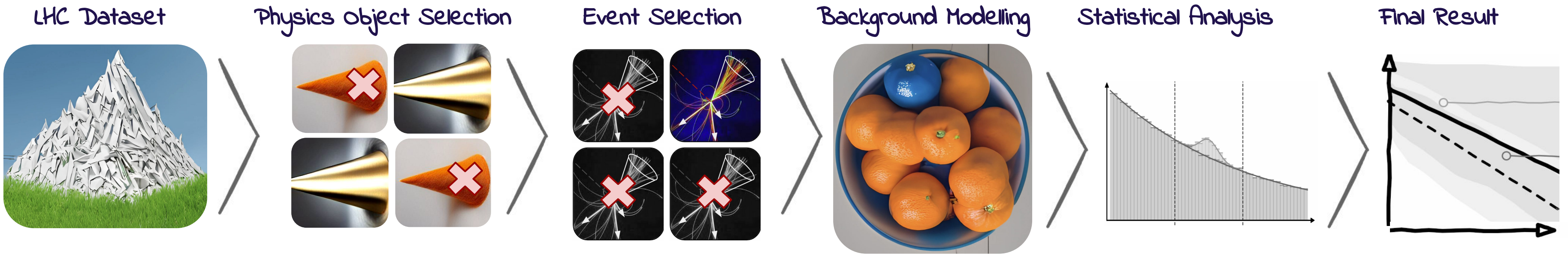

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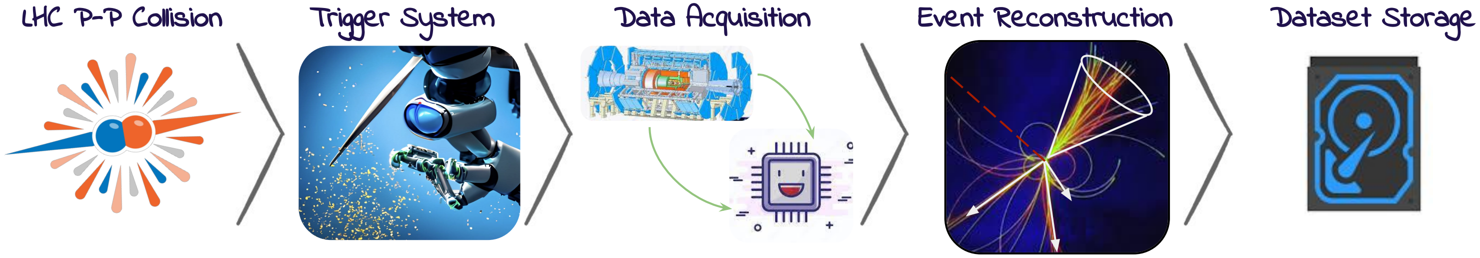

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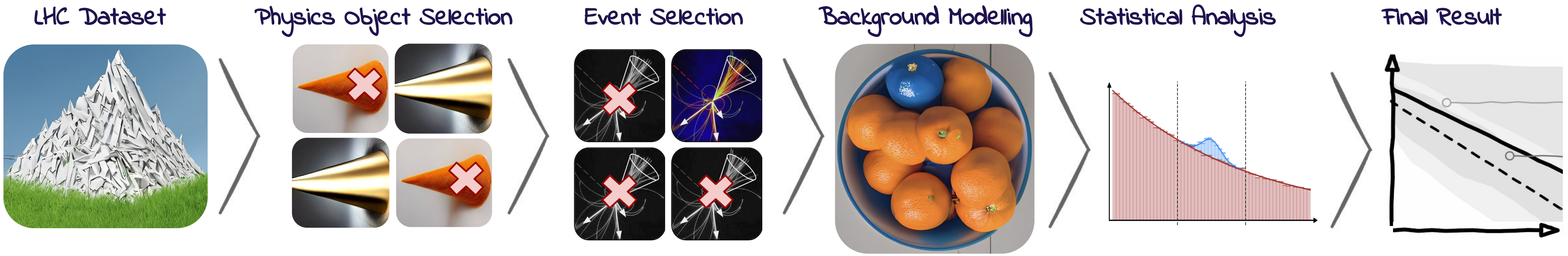

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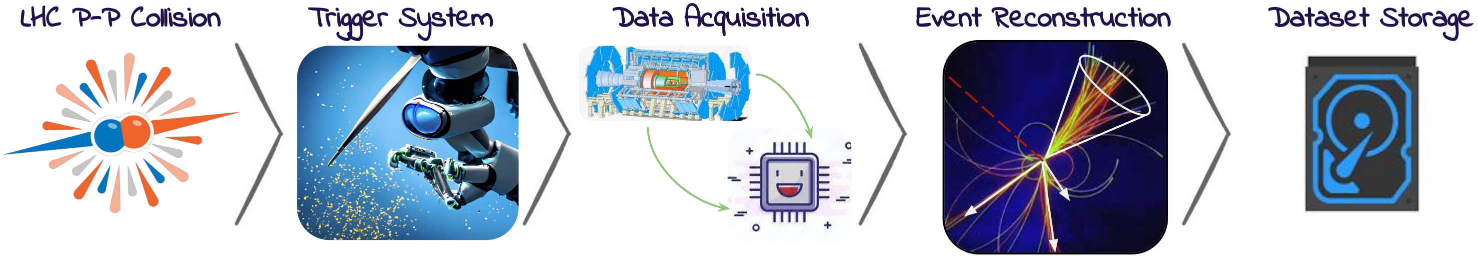

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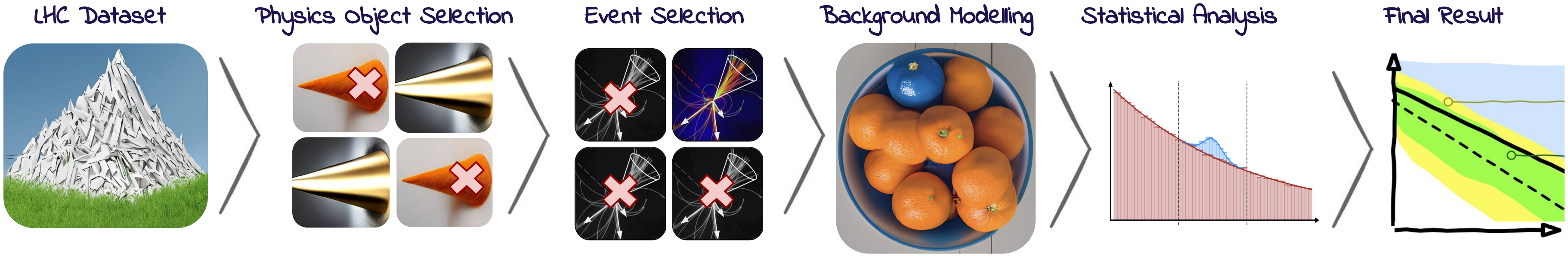

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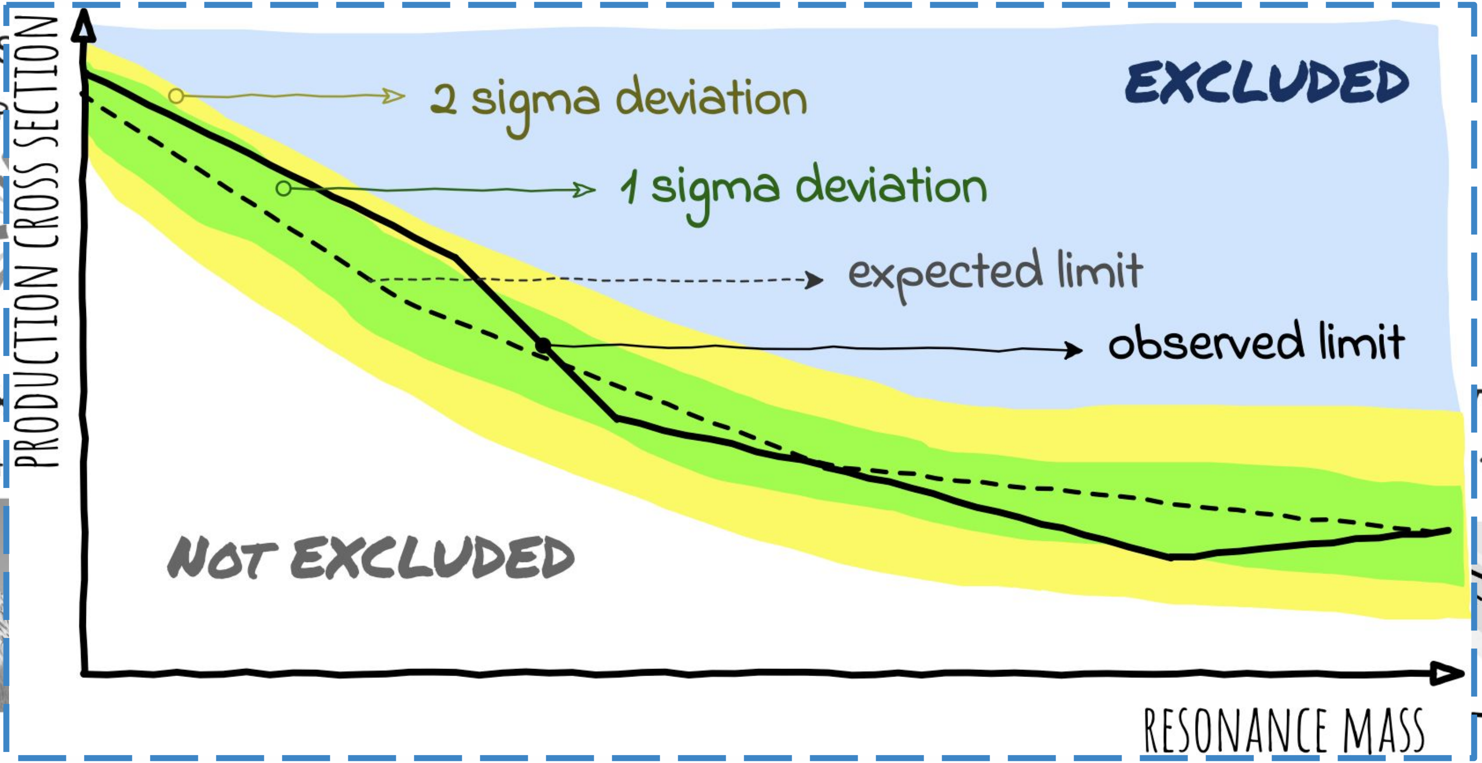
An LHC data analysis in a nutshell

- Firs

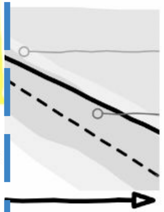
LHC P

- Nex ... rsis

LHC Dataset



Result



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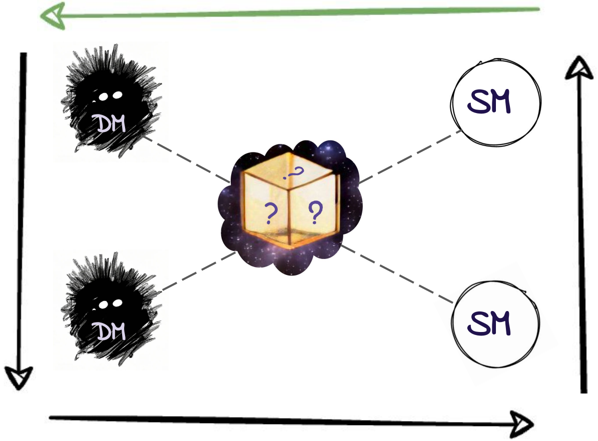
DM searches @ LHC

- Several ways to look for Dark matter
  - Colliders play an important role!



By Danyer Perez Adan

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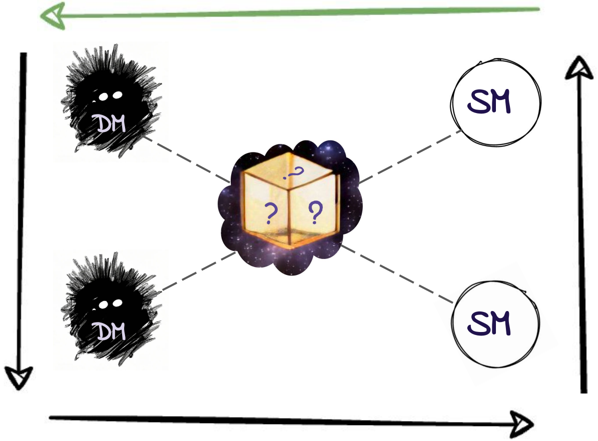

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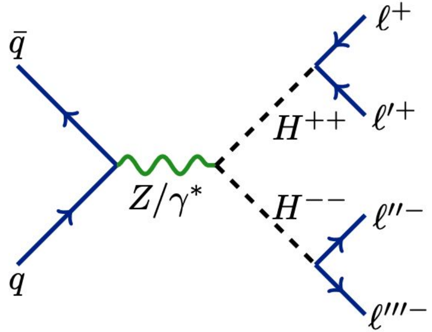
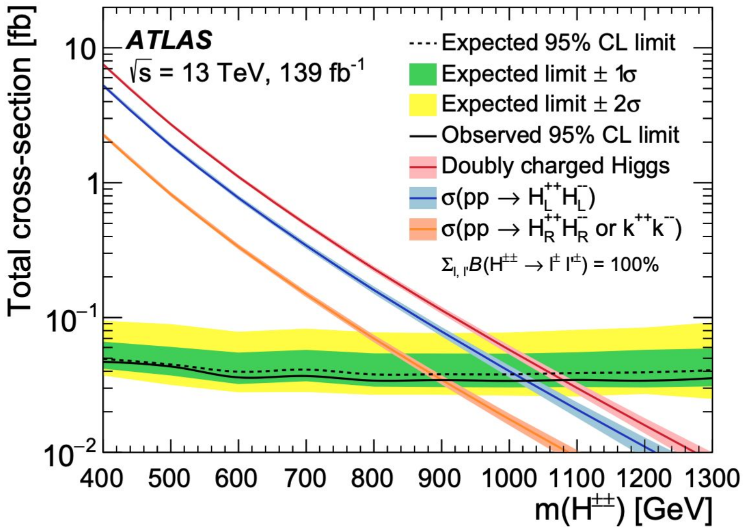
Recent results from ATLAS & CMS

ATLAS H++H-- search

EXOT-2018-34

- Search for doubly-charged Higgs bosons
  - Motivated in **extended Higgs** sector models, **ν-mass** models (type-2 seesaw models), others.
  - **e/μ** channels
  - **Same sign** lepton pairs
- Strategy
  - **Same-sign** requirement ⇒ **virtually background-free** analysis!
  - Use **invariant mass** of same sign pair as **discriminant***

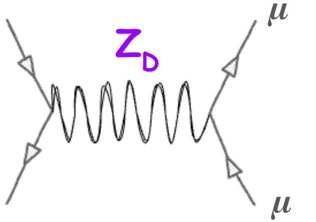


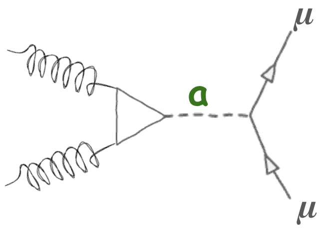


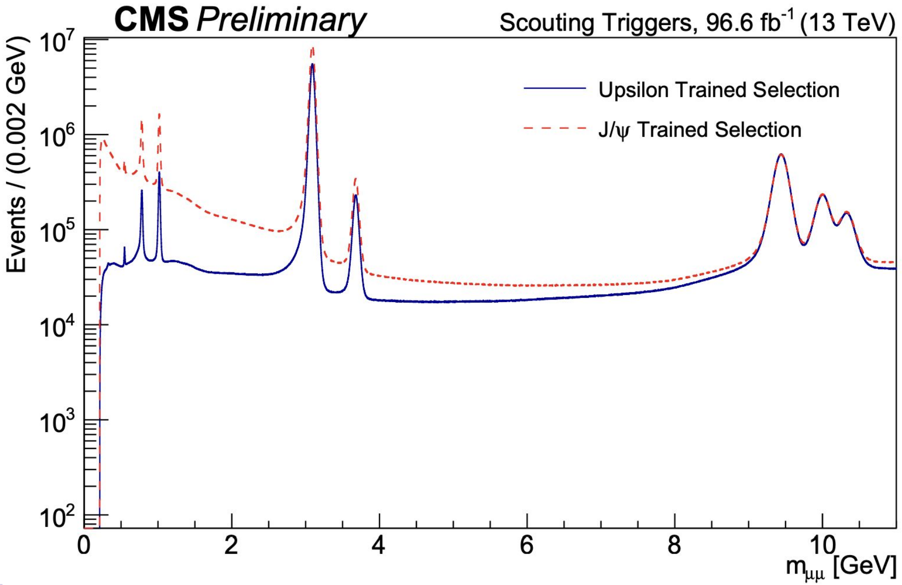
CMS GeV scale resonance search

CMS-PAS-EXO-21-005

- Low mass resonance → $\mu\mu$
  - Resonance searches are a **powerful tool** for searches for **new physics**
  - Interpretation in **dark-photon** and **extended Higgs** sector models
- Strategy
  - **Trigger-level "scouting"** analysis
  - **Dedicated** triggers and μ **identification** for low mass
  - Search range: around the J/Ψ and Υ resonances







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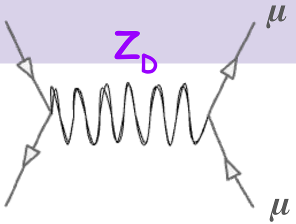

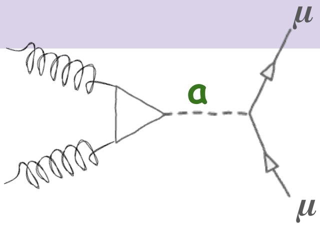

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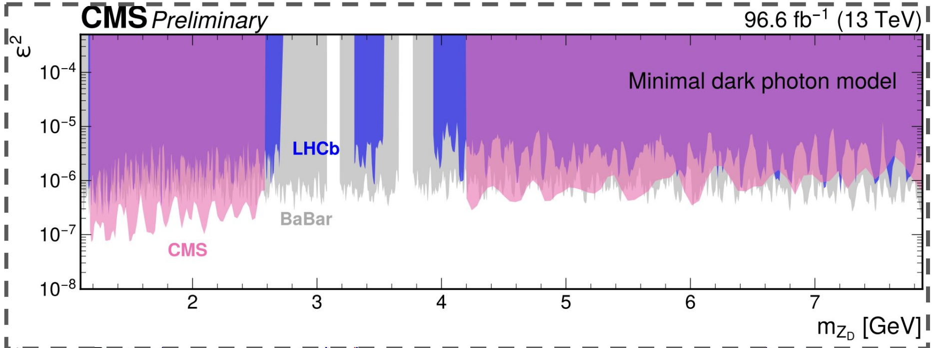
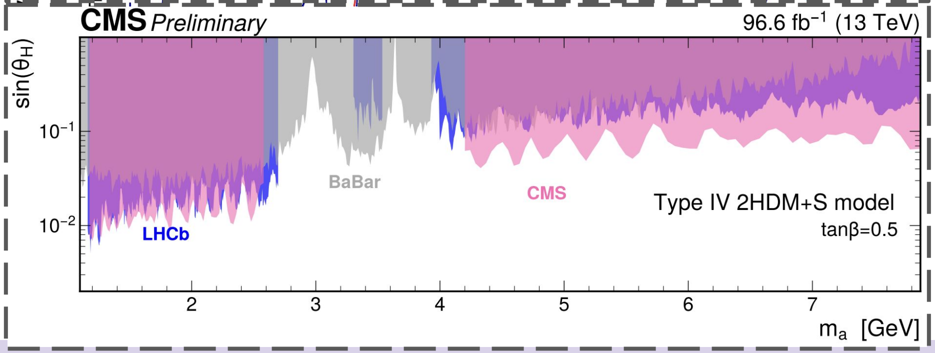
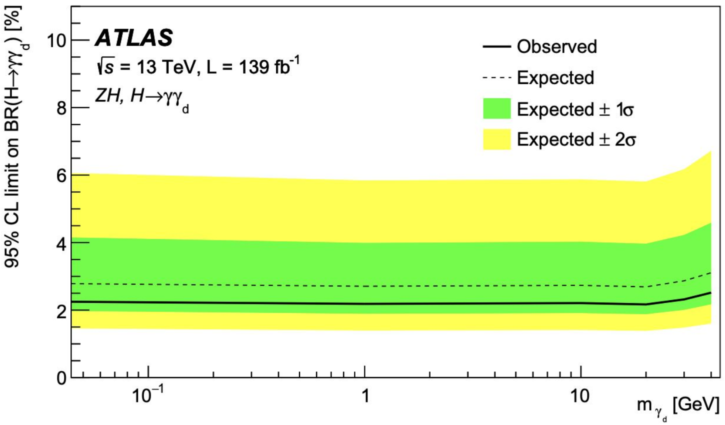


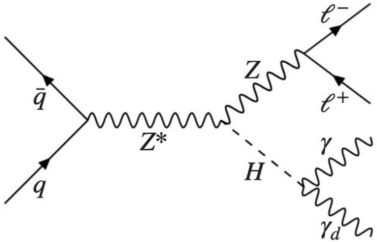


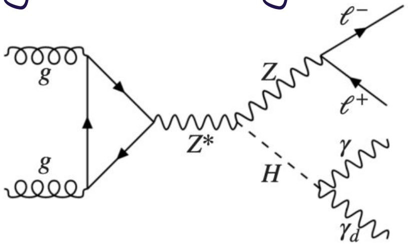
ATLAS dark photon search via ZH

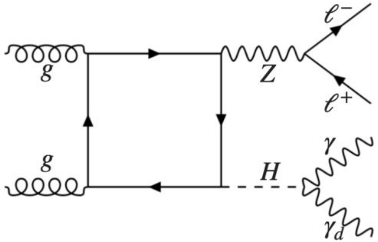
HDBS-2019-13

- Dark photons search in $H \rightarrow \gamma\gamma_d$
  - Here H is m(H) = 125 GeV
  - γ_d can be massive or massless
- Strategy
  - Select events with $Z \rightarrow e^-e^+/\mu^-\mu^+$ and γ
  - use MET + γ to calculate **transverse mass**
  - use **BDT** to classify signal vs background



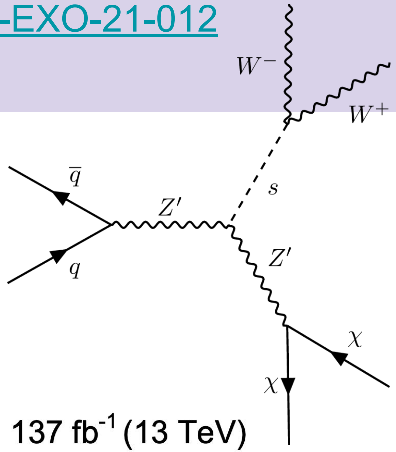




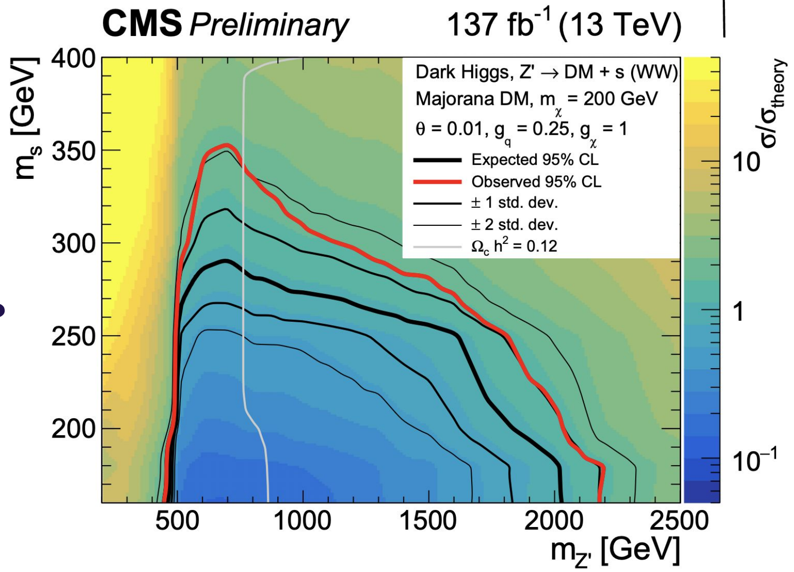


CMS search for DM particles in WW

CMS-PAS-EXO-21-012



- Search for DM particles in events with W^+W^- + MET
  - Interpretation in the context of a **dark Higgs** model



- Strategy
  - DM **recoil** against **WW system**
  - use MET + ℓ to calculate **transverse mass**
  - use **BDT** to classify signal VS background

Summary

Summary

- Showed a select few **new results** from **ATLAS and CMS** on searches for **BSM Higgs** and **Dark Matter**
  - **More exciting results** on plenary and parallel talks!
- **Collider searches** for DM are a **key piece of the puzzle**
  - Higgs boson is a powerful tool for searching for new physics
- **Results** shown here use datasets from **Run 2 of the LHC**
  - **Stay tuned** for results based on the **ongoing Run 3**!

Thanks!

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March 2023

[Backup Slides]

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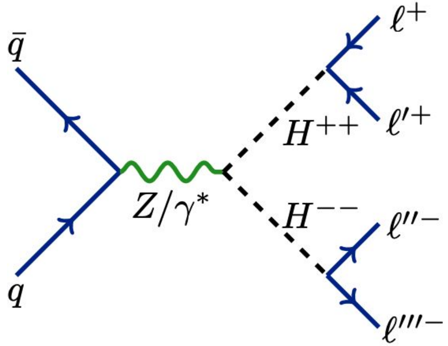
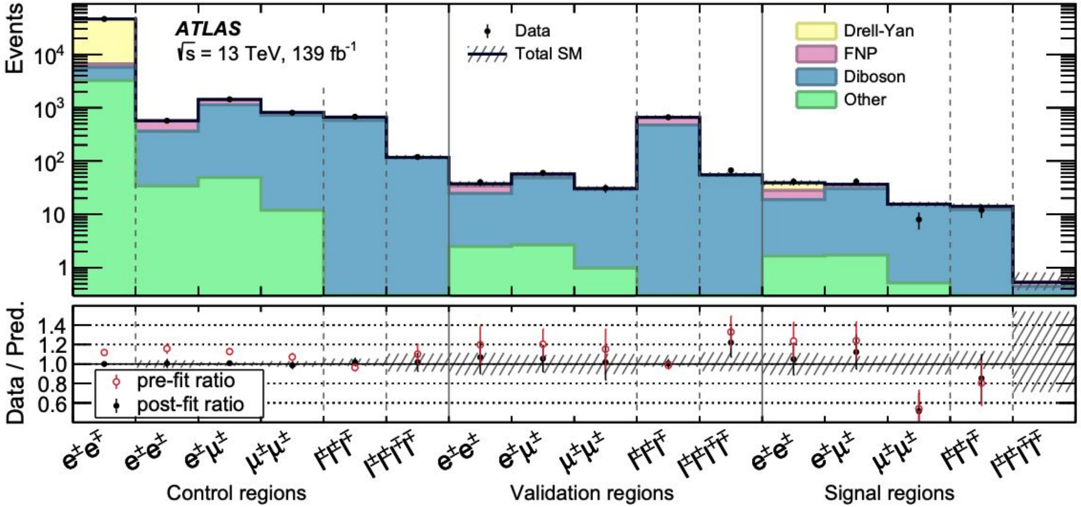
ATLAS H++H-- search

Conf. Note in CERN Document Server

- Search for doubly-charged Higgs bosons
  - Motivated in **extended Higgs** sector models, **ν-mass** models (type-2 seesaw models), others.
  - **e/μ** channels
  - **Same sign** lepton pairs
- Strategy
  - **Separate** analysis depending on **number of leptons** reconstructed
  - Use **invariant mass** of same sign pair as **discriminant***





H++H-- : selection cuts

	Control regions				Signal regions			Validation regions		
	DYCR	DBCR2L	DBCR3L	CR4L	SR2L	SR3L	SR4L	VR2L	VR3L	VR4L
Channel	e^+e^-	$e^\pm e^\pm$ $e^\pm \mu^\pm$ $\mu^\pm \mu^\pm$	$\ell^\pm \ell^\pm \ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$e^\pm e^\pm$ $e^\pm \mu^\pm$ $\mu^\pm \mu^\pm$	$\ell^\pm \ell^\pm \ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$e^\pm e^\pm$ $e^\pm \mu^\pm$ $\mu^\pm \mu^\pm$	$\ell^\pm \ell^\pm \ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$
Number of leptons	2	2	3	4	2	3	4	2	3	4
$m(\ell^\pm, \ell'^\mp)_{\text{lead}}$ [GeV]	≥ 300	-	-	-	-	-	-	-	-	-
$m(\ell^\pm, \ell'^\pm)_{\text{lead}}$ [GeV]	-	[200, 300)	≥ 300	[100, 200)	≥ 300	≥ 300	≥ 300	≥ 300	[100, 300)	[200, 300)
$p_{\text{T}}(\ell^\pm, \ell'^\pm)_{\text{lead}}$ [GeV]	-	-	-	-	≥ 300	≥ 300	-	[200, 300)	-	-
$\Delta R(\ell^\pm, \ell'^\pm)_{\text{lead}}$	-	-	-	-	< 3.5	-	-	< 3.5	-	-
$\overline{m}$ [GeV]	-	-	-	-	-	-	≥ 300	-	-	-
$E_{\text{T}}^{\text{miss}}$ [GeV]	-	> 30 -	-	-	-	-	-	> 30 -	-	-
$\lvert\eta(\ell, \ell')\rvert$	-	< 3.0 -	-	-	-	-	-	< 3.0 -	-	-
Z-veto	-	-	inverted	-	-	✓	✓	-	✓	-

H++H-- : Fake and non prompt selection

Muon channel	Electron channel
p_{T} variable binning	
b-jet veto	
Single-muon trigger	Single-electron trigger
Exactly one muon	Exactly one electron
Five η bins, two $E_{\mathrm{T}}^{\mathrm{miss}}$ bins	Four η bins, two $E_{\mathrm{T}}^{\mathrm{miss}}$ bins
$p_{\mathrm{T}}(\mathrm{jet}) > 35\,\mathrm{GeV}$	
$\Delta\phi(\mu, \mathrm{jet}) > 2.7$	
$E_{\mathrm{T}}^{\mathrm{miss}} < 40\,\mathrm{GeV}$	

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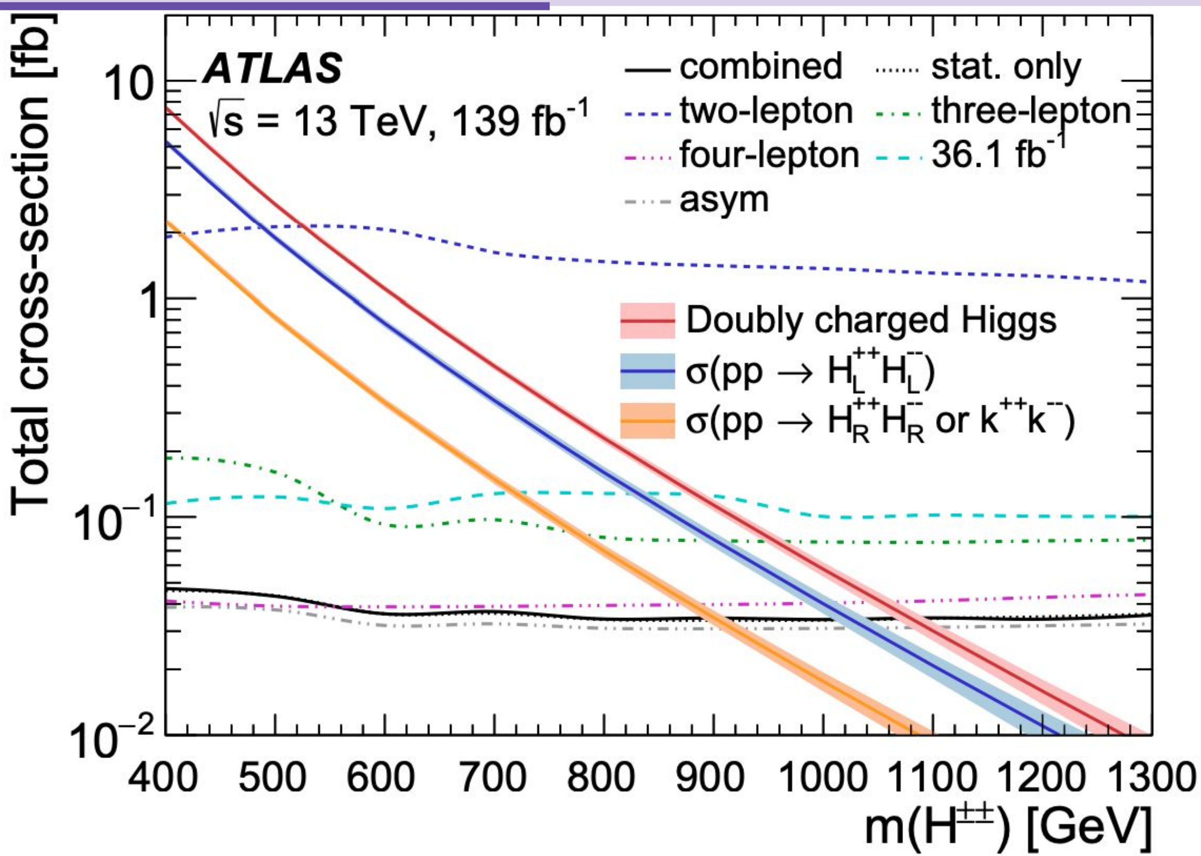
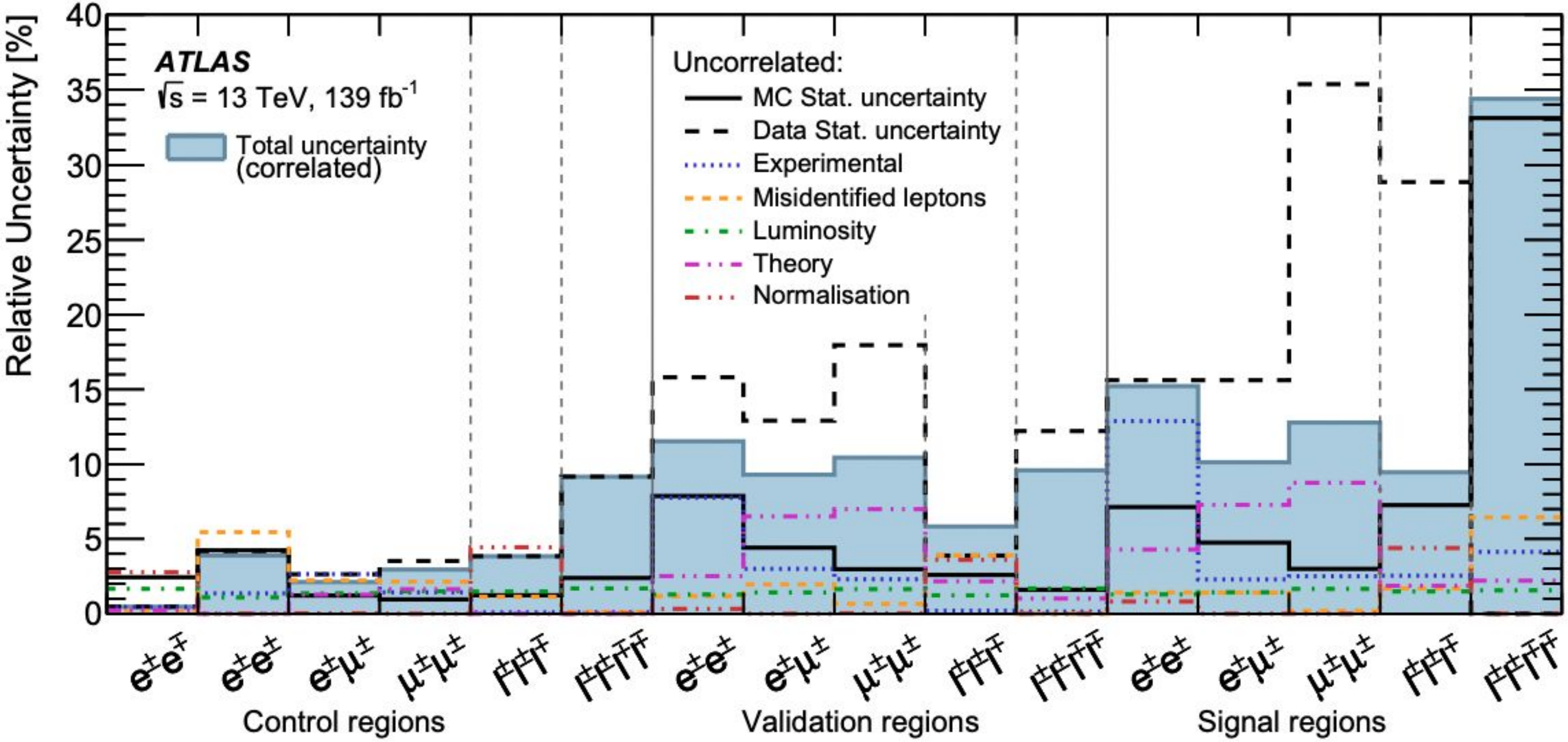
H++H-- : Limits per channel



H++H-- : Systematics



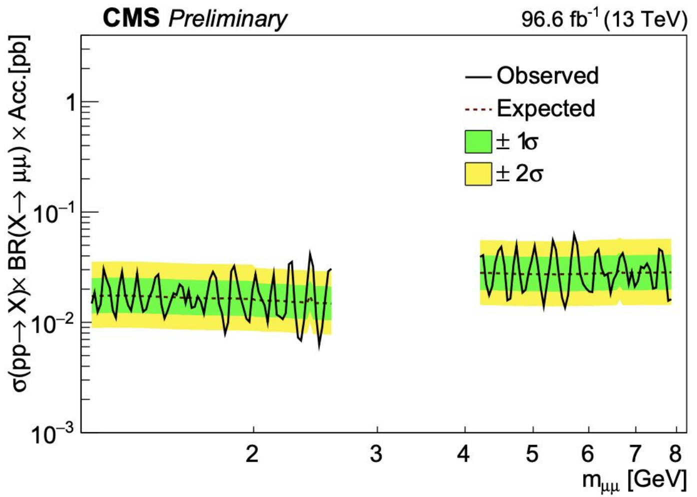
CMS scouting search: systematics

Effect	$m_{\mu\mu} < 2.6$ GeV	$m_{\mu\mu} > 4.2$ GeV
Integrated luminosity	2.3–2.5%	
Mass resolution	20%	
Trigger efficiency	1–20%	
Muon ID efficiency	4–9%	12–20%
Vertex selection	—	3%
Efficiency application	8%	4%
D meson normalization TFs	20–25%	—

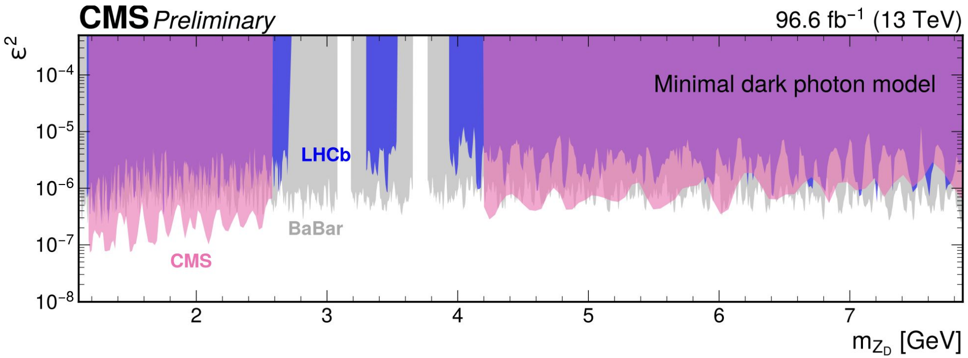
CMS GeV scale resonance search

PAS in CERN Document Server

- Low mass resonance → $\mu\mu$
  - Resonance searches are a **powerful tool** for searches for **new physics**
  - **Generic** search → assume only **narrow resonance**
  - Interpretation in **dark-photon** and **extended Higgs** sector models



- Strategy
  - **Trigger-level "scouting"** analysis
  - **Dedicated** triggers and μ **identification** for low mass
  - Search range: around the J/Ψ and Υ resonances



CMS DM search in WW events: preselection, m_T

Di-leptonic

Quantity	Selection
Number of leptons	2
Lepton flavors	$e\mu$, μe
Lepton charges	Opposite
Additional leptons	0
$p_T^{\ell\,\max}$	> 25 GeV
$p_T^{\ell\,\min}$	> 20 GeV
$m_{\ell\ell}$	> 12 GeV
$p_T^{\ell\ell}$	> 30 GeV
p_T^{miss}	> 20 GeV
$min(p_T^{\text{miss,PF proj}}, p_T^{\text{miss,track proj}})$	> 20 GeV
$m_T^{\ell\ell,p_T^{\text{miss}}}$	> 50 GeV
$\Delta R_{\ell\ell}$	< 2.5
Number of b-tagged jets	0

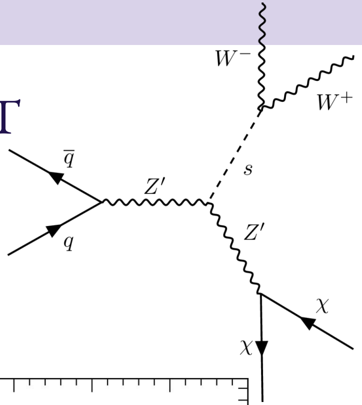
Semi-leptonic

Quantity	Selection
Number of leptons	1
Additional leptons	0
Number of jets	≥ 2
Non W-candidate b-tagged jets	0
m_{jj}	> 65 GeV, < 105 GeV
p_T^{miss}	> 60 GeV
$p_T^{\ell\text{jj}}$	> 60 GeV
$m_T^{\ell,p_T^{\text{miss}}}$	> 80 GeV
$\Delta R_{\ell,\text{jj}}$	< 3
$\Delta\phi_{\ell,\text{jj}}$	< 1.8
$\Delta\phi_{\ell\text{jj},p_T^{\text{miss}}}$	> 2

$$m_T^{\ell\,\min,p_T^{\text{miss}}} = \sqrt{2p_T^{\ell\,\min} p_T^{\text{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\,\min}, \vec{p}_T^{\,\text{miss}})\right]},$$

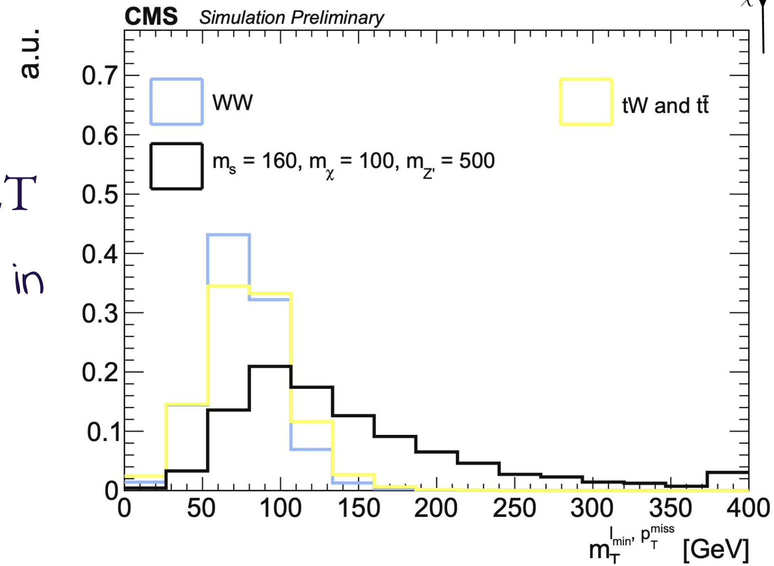
[PAS in CERN Document Server](#)

CMS search for DM particles in WW



- Search for DM particles in events with W^+W^- and MET
  - Interpretation in the context of a **dark Higgs** model
  - Analysis of full Run 2 data set

- Strategy
  - Select 1 or 2 **e/μ** (semi/di-leptonic)
  - Calculate **transverse mass** from ℓ and MET
  - Use **BDT** to classify signal VS background in semi-leptonic channel



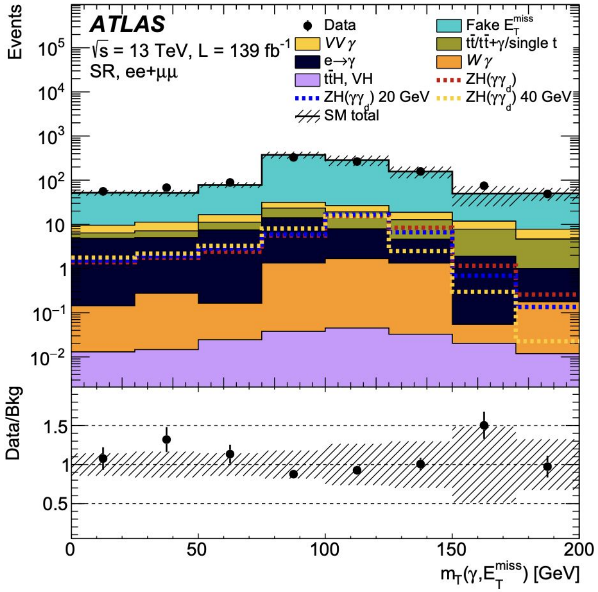
ATLAS dark photon search in ZH: event selection

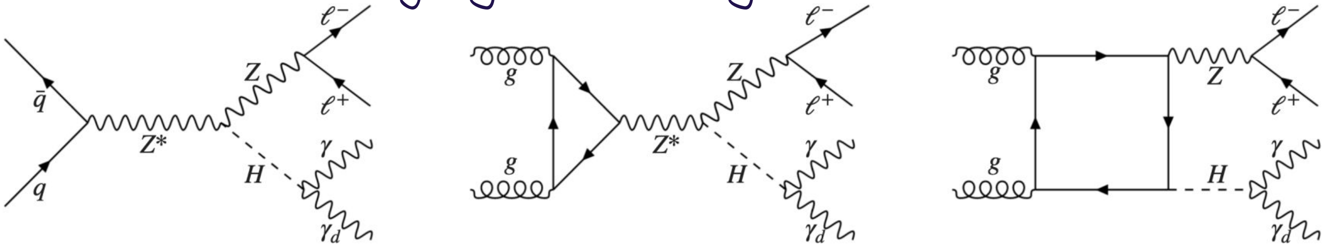
Two same flavour, opposite sign, medium ID and loose isolated leptons, with leading $p_{\mathrm{T}} > 27$ GeV, sub-leading $p_{\mathrm{T}} > 20$ GeV
Veto events with additional lepton(s) with loose ID and $p_{\mathrm{T}} > 10$ GeV
76 GeV $< m_{\ell\ell} <$ 116 GeV
Only one tight ID, tight isolation photon with $E_{\mathrm{T}}^{\gamma} > 25$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV with $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,\ell\ell\gamma}) > 2.4$ rad
$m_{\ell\ell\gamma} > 100$ GeV
$\mathrm{N_{jet}} \leq 2$, with $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Veto events with b-jet(s)

ATLAS dark photon search via ZH

[Article in CERN Document Server]

- Dark photons searched in $H \to \gamma\gamma_d$
  - γ_d motivated in both particle physics and cosmological models
  - Analysis uses **full Run 2** dataset
- Strategy
  - Find events with $Z \to e^-e^+/\mu^-\mu^+$ and γ
  - Calculate **transverse mass** from γ and MET ~ m_H
  - Use **BDT** to classify signal vs background





ATLAS dark photon search via ZH

Article in CERN Document Server

- Dark photons searched in $H \rightarrow \gamma\gamma_d$
  - γ_d motivated in both particle physics and cosmological models
  - Analysis uses **full Run 2** dataset
- Strategy
  - Select events with $Z \rightarrow e^-e^+/\mu^-\mu^+$ and γ
  - use MET to calculate **transverse mass**
  - use **BDT** to classify signal vs background