THE UNIVERSITY of EDINBURGH

Search for the exclusive hadronic W boson decays at the ATLAS experiment

Júlia Cardoso Silva

7th February 2024

ATLAS EXPERIMENT

erc

Exclusive Higgs

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

W boson discovery

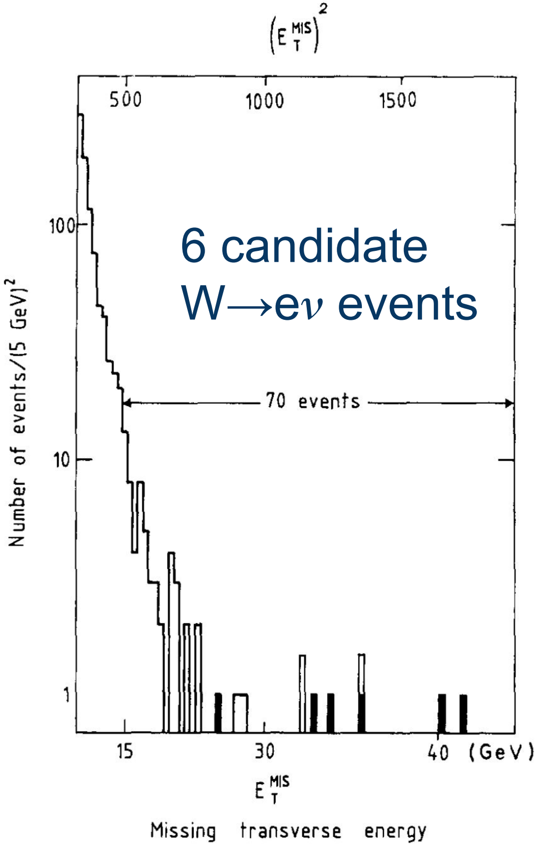
The W boson turned 40 last year!

Carlo Rubbia

Simon van der Meer

Pierre Darriulat

CERN announcement of W boson discovery by UA1 and UA2



6 candidate $W \rightarrow e\nu$ events

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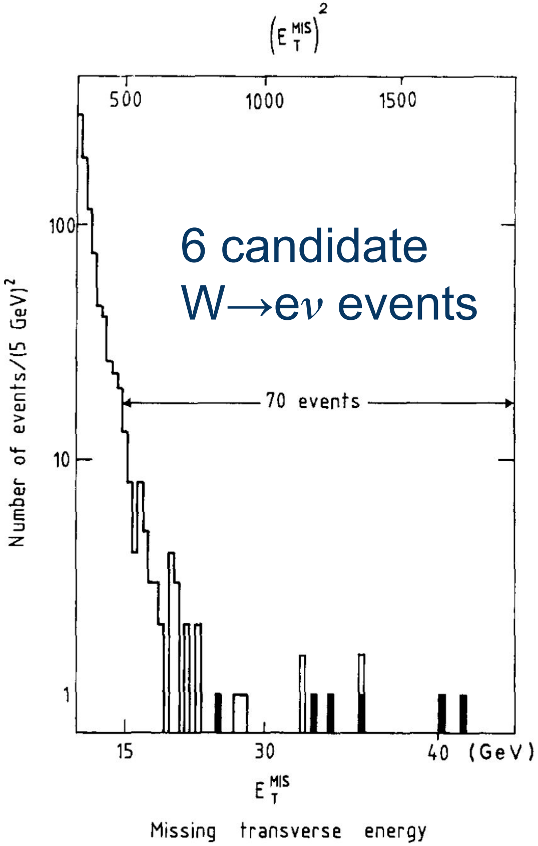

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W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.86 ± 0.09) %	
Γ_2	$e^+\nu$		(10.71 ± 0.16) %	
Γ_3	$\mu^+\nu$		(10.63 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.38 ± 0.21) %	
Γ_5	hadrons		(67.41 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%
Γ_8	cX		(33.3 ± 2.6) %	
Γ_9	$c\bar{s}$		$(31 {}^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	
Γ_{11}	$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$	95%

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-	[a]	(3.3632 ± 0.0042) %	
Γ_2	$\mu^+\mu^-$	[a]	(3.3662 ± 0.0066) %	
Γ_3	$\tau^+\tau^-$	[a]	(3.3696 ± 0.0083) %	
Γ_4	$\ell^+\ell^-$	[a,b]	(3.3658 ± 0.0023) %	
Γ_5	$\ell^+\ell^-\ell^+\ell^-$	[c]	$(3.5 \pm 0.4) \times 10^{-6}$	S=1.7
Γ_6	invisible	[a]	(20.000 ± 0.055) %	
Γ_7	hadrons	[a]	(69.911 ± 0.056) %	
Γ_8	$(u\bar{u}+c\bar{c})/2$		(11.6 ± 0.6) %	
Γ_9	$(d\bar{d}+s\bar{s}+b\bar{b})/3$		(15.6 ± 0.4) %	
Γ_{10}	$c\bar{c}$		(12.03 ± 0.21) %	
Γ_{11}	$b\bar{b}$		(15.12 ± 0.05) %	
Γ_{12}	$b\bar{b}b\bar{b}$		$(3.6 \pm 1.3) \times 10^{-4}$	
Γ_{13}	ggg		< 1.1 %	CL=95%
Γ_{14}	$\pi^0\gamma$		$< 2.01 \times 10^{-5}$	CL=95%
Γ_{15}	$\eta\gamma$		$< 5.1 \times 10^{-5}$	CL=95%
Γ_{16}	$\omega\gamma$		$< 6.5 \times 10^{-4}$	CL=95%
Γ_{17}	$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	CL=95%
Γ_{18}	$\phi\gamma$		$< 8.3 \times 10^{-6}$	CL=95%
Γ_{19}	$\gamma\gamma$		$< 1.46 \times 10^{-5}$	CL=95%
Γ_{20}	$\pi^0\pi^0$		$< 1.52 \times 10^{-5}$	CL=95%
Γ_{21}	$\gamma\gamma\gamma$		$< 2.2 \times 10^{-6}$	CL=95%
Γ_{22}	$\pi^\pm W^\mp$	[d]	$< 7 \times 10^{-5}$	CL=95%
Γ_{23}	$\rho^\pm W^\mp$	[d]	$< 8.3 \times 10^{-5}$	CL=95%
Γ_{24}	$J/\psi(1S)$X		$(3.51 {}^{+0.23}_{-0.25}) \times 10^{-3}$	S=1.1
Γ_{25}	$J/\psi(1S)\gamma$		$< 2.6 \times 10^{-6}$	CL=95%
Γ_{26}	$\psi(2S)$X		$(1.60 \pm 0.29) \times 10^{-3}$	
Γ_{27}	$\chi_{c1}(1P)$X		$(2.9 \pm 0.7) \times 10^{-3}$	
Γ_{28}	$\chi_{c2}(1P)$X		$< 3.2 \times 10^{-3}$	CL=90%
Γ_{29}	$\Upsilon(1S)$ X $+ \Upsilon(2S)$ X $+ \Upsilon(3S)$ X		$(1.0 \pm 0.5) \times 10^{-4}$	
Γ_{30}	$\Upsilon(1S)$X		$< 3.4 \times 10^{-6}$	CL=95%
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Γ_{33}	$(D^0/\overline{D}^0)$ X		(20.7 ± 2.0) %	
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Γ_{35}	$D^*(2010)^\pm$X	[d]	(11.4 ± 1.3) %	
Γ_{36}	$D_{s1}(2536)^\pm$X		$(3.6 \pm 0.8) \times 10^{-3}$	
Γ_{37}	$D_{sJ}(2573)^\pm$X		$(5.8 \pm 2.2) \times 10^{-3}$	
Γ_{38}	$D^{*\prime}(2629)^\pm$X		searched for	
Γ_{39}	BX			
Γ_{40}	B^*X			

etc.

Exclusive hadronic decays of the W boson

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Exclusive hadronic decays of the W boson

- **None of the exclusive hadronic W (or Z) decays predicted by the Standard Model have been observed**
  - Can offer novel precision studies of QCD factorisation
    - Amplitudes written as expansions in terms of Λ_{QCD}/E
      - bound states described by meson LCDAs
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      - Can probe meson LCDAs in a clean way!

Grossman, König & Neubert

Decay Channel	SM Branching Fraction
$W^{\pm} \to \pi^{\pm}\gamma$	$(4.0 \pm 0.8) \times 10^{-9}$
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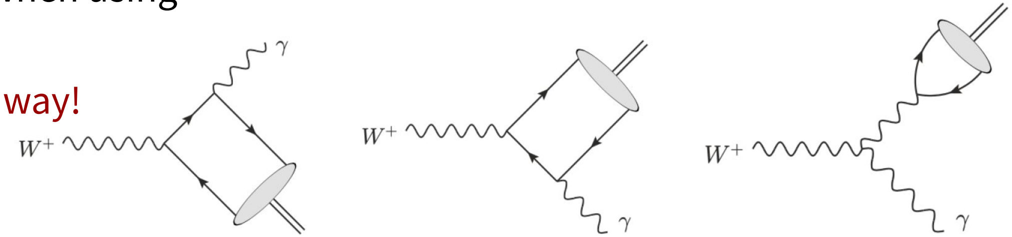

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Very rare! SM predictions ranging from O(10^{-8})-O(10^{-12})

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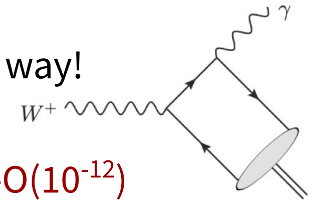

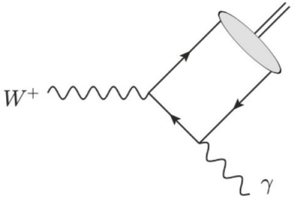

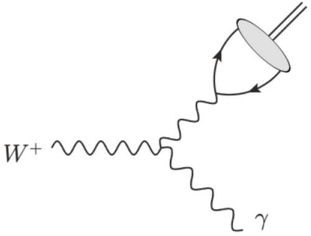

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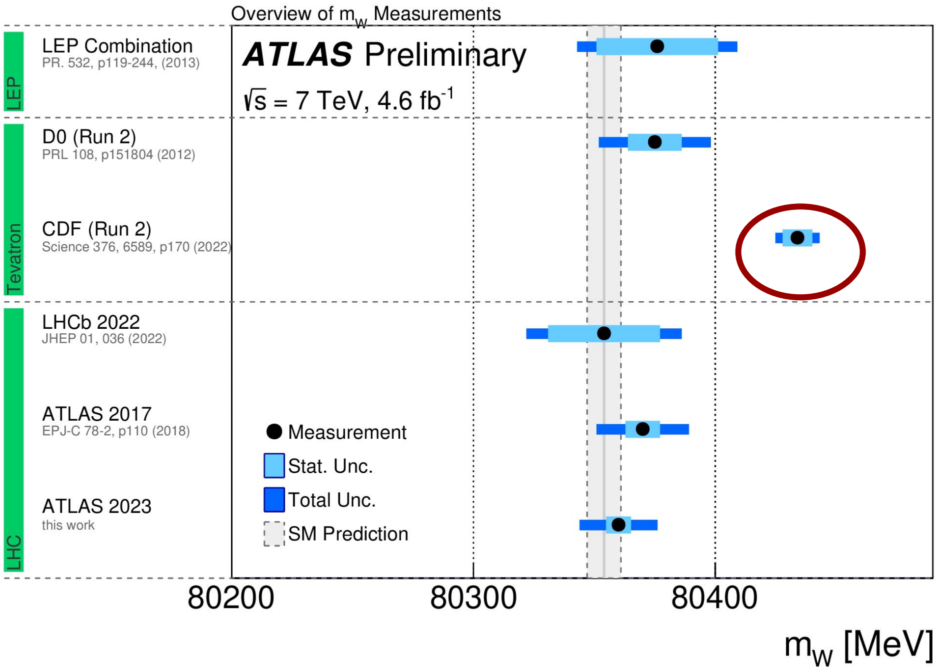

Renewed interest after CDF mass measurement

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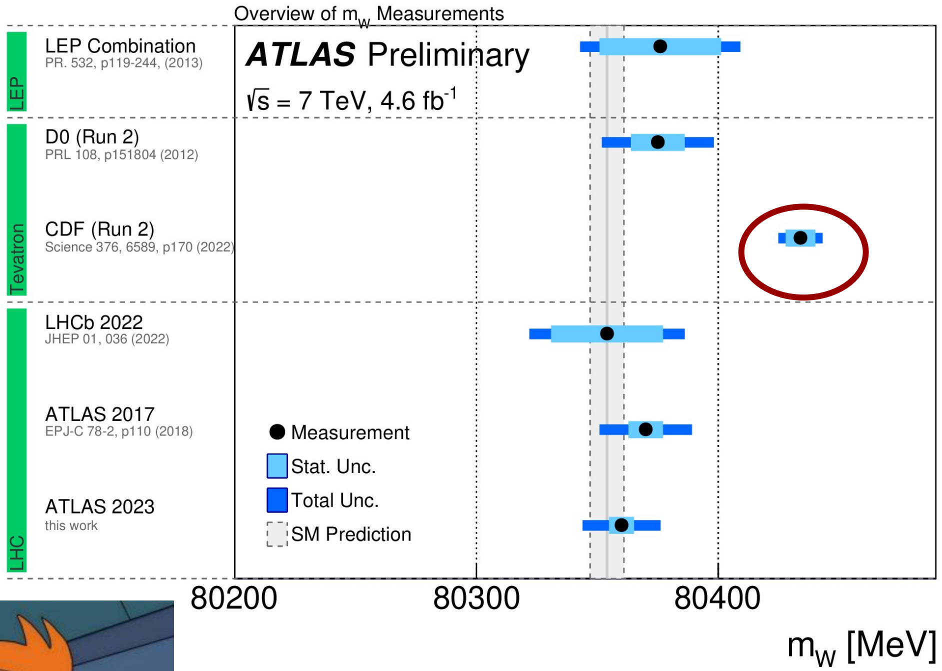

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7σ above expectation?!

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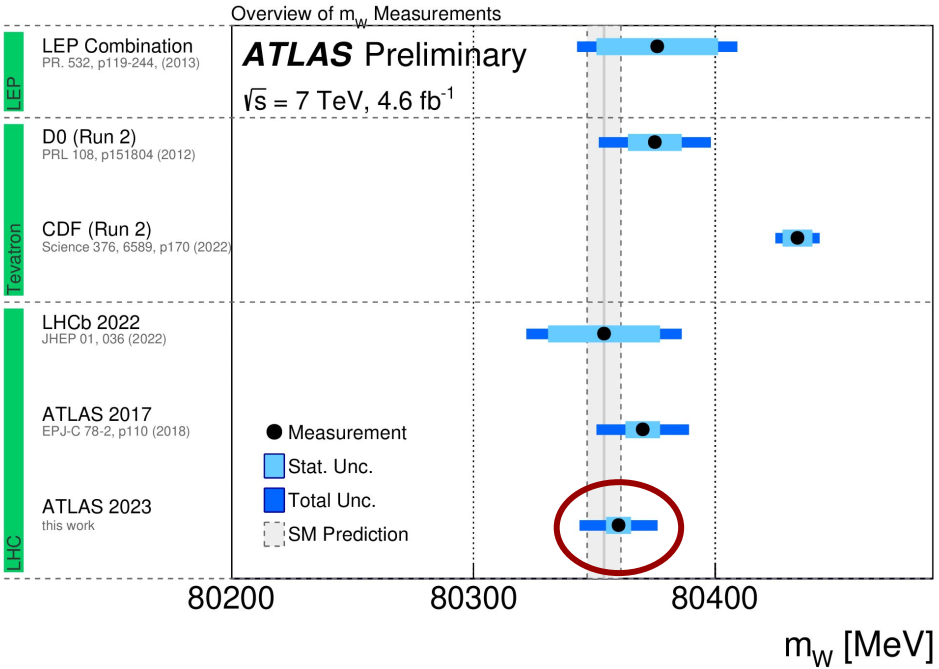

ATLAS W boson mass reanalysis at 7 TeV
15% improvement in precision!!
Closer to SM, further from CDF

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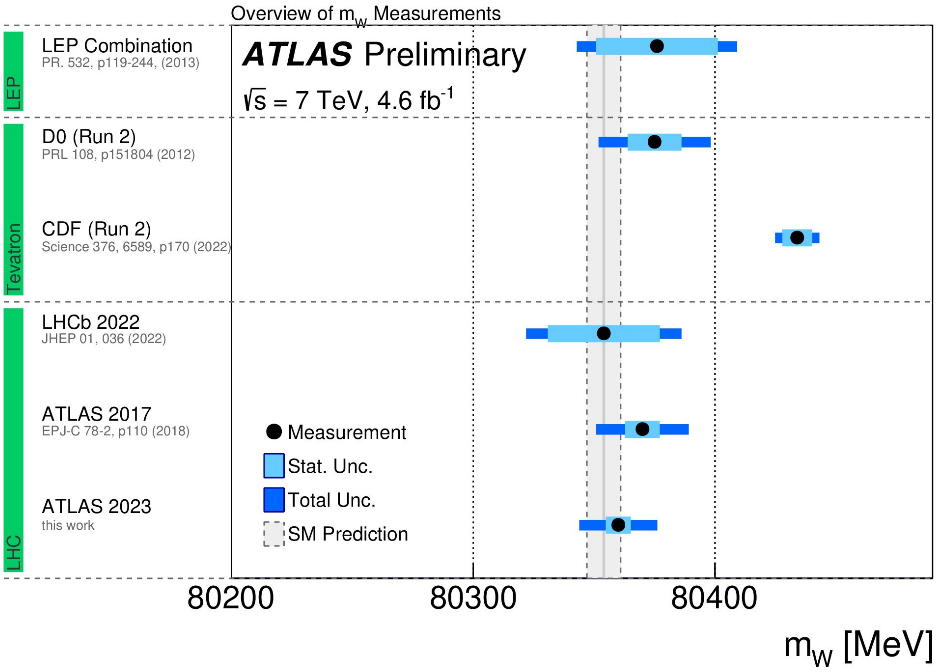

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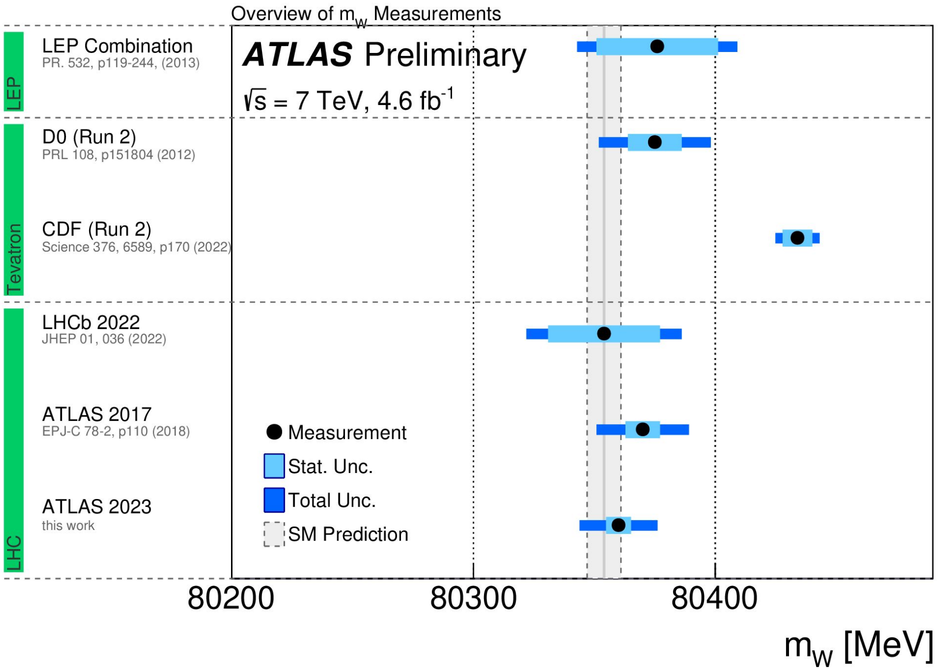

Could take advantage of high mass resolution for decays to charged particles and photons

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Search for $W^{\pm} \rightarrow \pi^{\pm} + \gamma$ at CDF

- **Dataset**: $p\bar{p}$ collisions, 4.3 fb^{-1}, at $\sqrt{s}$ = 1.96 TeV
- **Trigger:** Photon triggers requiring E_T > 25 GeV

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Phys. Rev. D 85, 032001 (2012)

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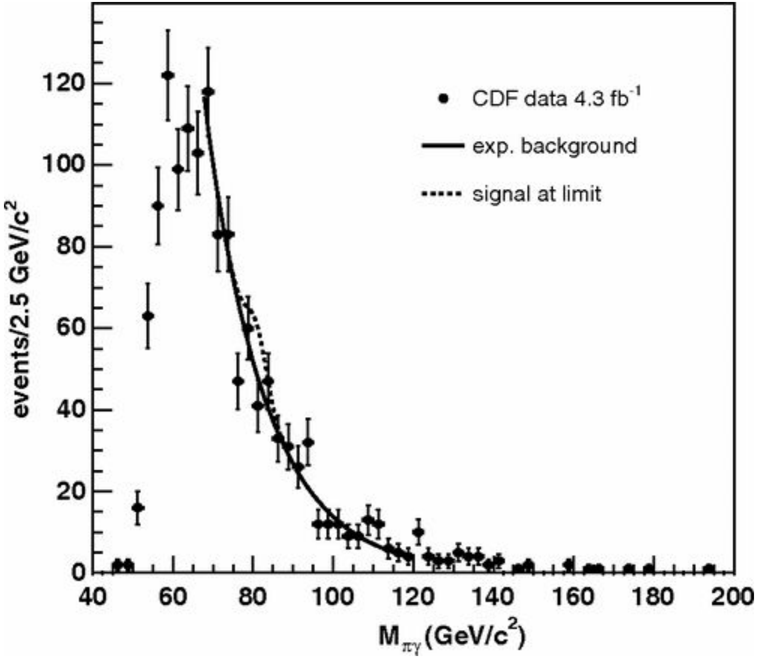
- **Offline selection:** back-to-back isolated photon ($E_T > 25$ GeV) and isolated track ($p_T > 25$ GeV)
- **Background estimation:** Fit to W sidebands, using exponential function
- $W^{\pm} \to e^{\pm}\nu$ used as reference, allowing cancellation of common systematics



Search for $W^{\pm} \rightarrow \pi^{\pm} + \gamma$ at CDF

$B(W \rightarrow \pi\gamma) < 7 \times 10^{-6}$ at 95% CL

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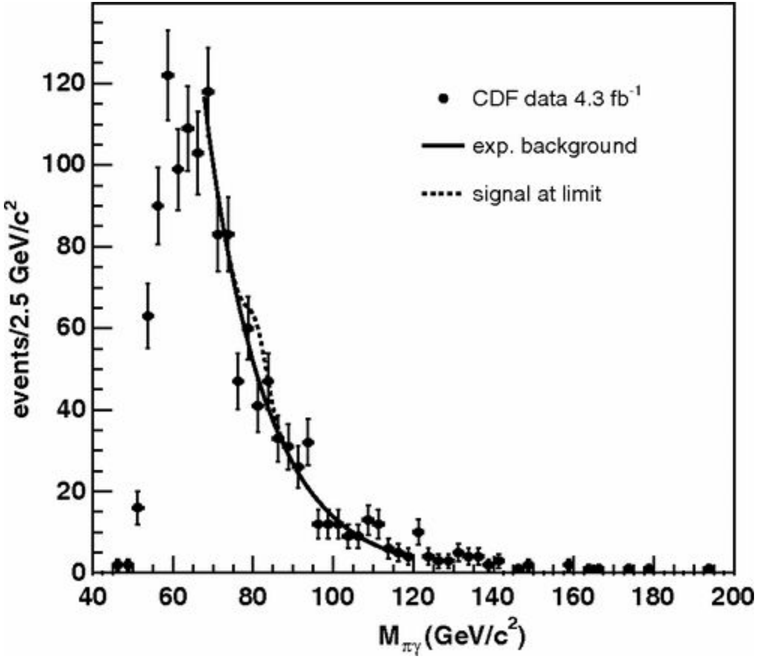

Search for $W^{\pm} \rightarrow \pi^{\pm} + \gamma$ at CMS

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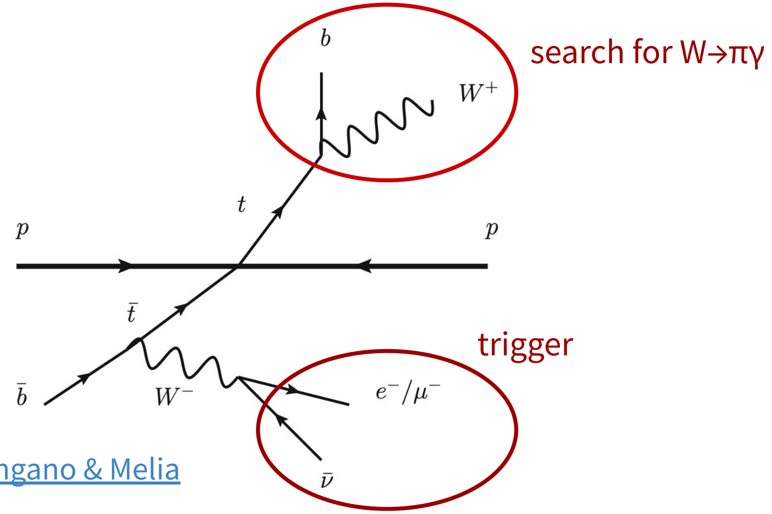
- Targeting W boson production in $t\bar{t}$ events



Mangano & Melia

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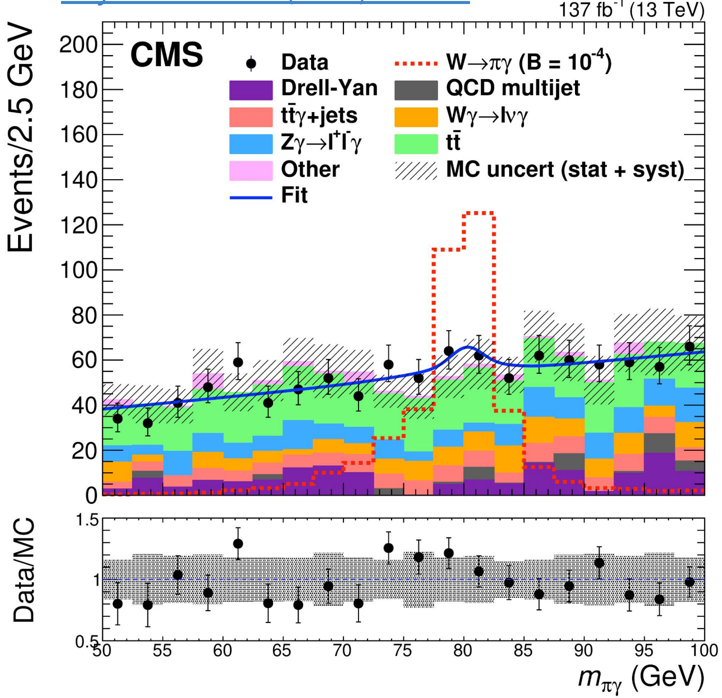
- **Trigger:** Lepton triggers
- Targeting W boson production in $t\bar{t}$ events

- **Offline selection:**
  - 1 muon or electron (p_T > 25 GeV) + one track (p_T > 20 GeV) with opposite charge wrt lepton + one isolated photon (E_T > 25 GeV)
  - BDT for signal/background discrimination
- **Background estimation:** analytic shape defined in fit to data control region (linear polynomial)

Phys. Lett. B 819 (2021) 136409



Search for $W^{\pm} \rightarrow \pi^{\pm} + \gamma$ at CMS

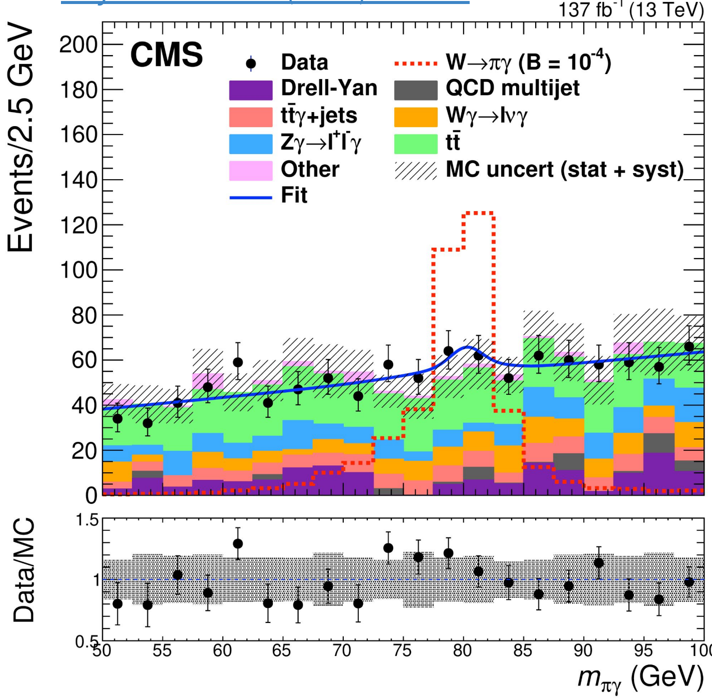
$B(W \rightarrow \pi\gamma) < 1.5 \times 10^{-5}$ at 95% CL

sensitivity limited by $t\bar{t}$ cross section

- **Dataset**: pp collisions, 137 fb^{-1}, at $\sqrt{s}$ = 13 TeV
- **Trigger:** Lepton triggers
- Targeting W boson production in $t\bar{t}$ events

- **Offline selection:**
  - 1 muon or electron (p_T > 25 GeV) + one track (p_T > 20 GeV) with opposite charge wrt lepton + one isolated photon (E_T > 25 GeV)
  - BDT for signal/background discrimination
- **Background estimation:** analytic shape defined in fit to data control region (linear polynomial)

Phys. Lett. B 819 (2021) 136409



Search for $W^{\pm} \rightarrow D^{\pm}_{s} + \gamma$ at LHCb

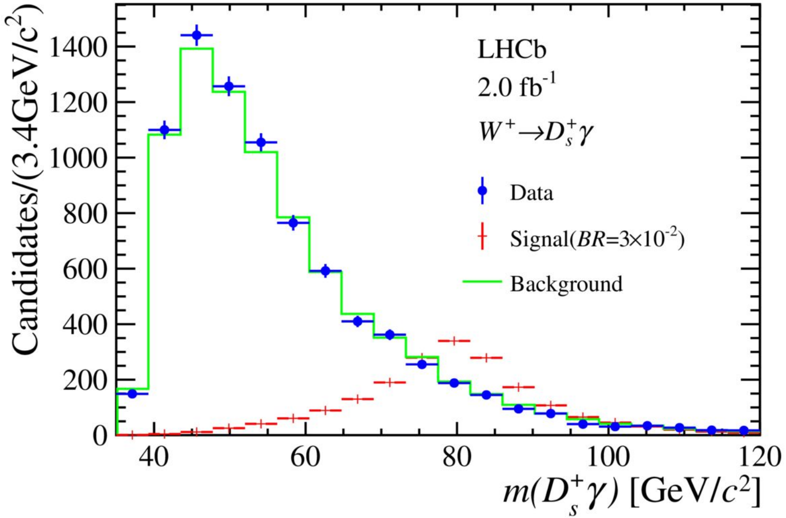
- **Dataset**: pp collisions, 2 fb^{-1}, at $\sqrt{s}$ = 13 TeV
- Targeting W → $\mathbf{D_s}$**(→KKπ)** + γ events (5% BF)
- **Trigger:** Dedicated triggers targeting 3 displaced tracks consistent with D_s + photon

Search for $W^{\pm} \to D^{\pm}_s + \gamma$ at LHCb

- **Dataset**: pp collisions, 2 fb^{-1}, at $\sqrt{s}$ = 13 TeV
- Targeting $W \to$ **D_s($\to$KKπ)** + γ events (5% BF)
- **Trigger:** Dedicated triggers targeting 3 displaced tracks consistent with D_s + photon

- **Offline selection:** photon (E_T > 15 GeV) + D_s candidate (p_T > 20 GeV && 1.92 < m< 2.02 GeV)
- **Background estimation:** Non-parametric data-driven background model
- Fit to W pseudomass and p_T
- $W^{\pm} \to \mu^{\pm}\nu$ used as normalisation channel

Chinese Phys. C **47** 093002 (2023)



$$m(M\gamma) = \sqrt{2p^M p_T^M \frac{p^\gamma}{p_T^\gamma}(1 - \cos\theta)}$$

θ - opening angle between meson and photon

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$B(W \rightarrow D_s\gamma) < 6.5 \times 10^{-4}$ at 95% CL

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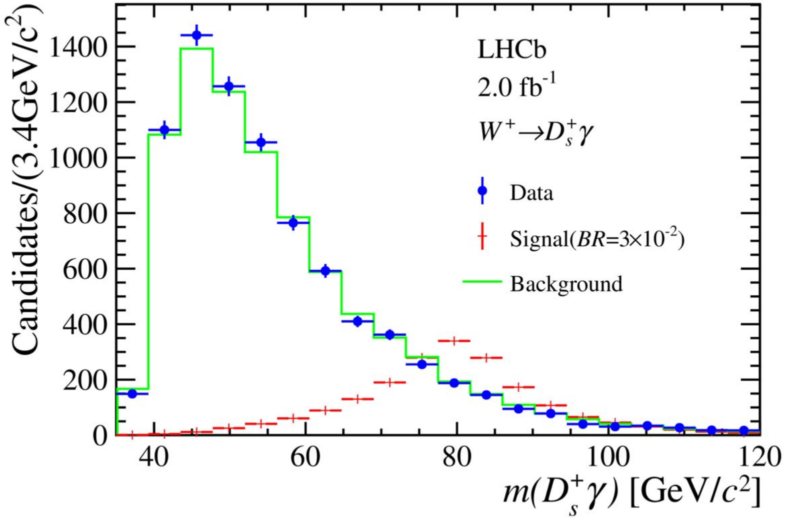

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Search for $W^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$ at CMS

- **Dataset**: pp collisions, 77.3 fb^{-1}, at $\sqrt{s}$ = 13 TeV
- **Trigger:** Di-tau triggers (p_T > 35/40 GeV)

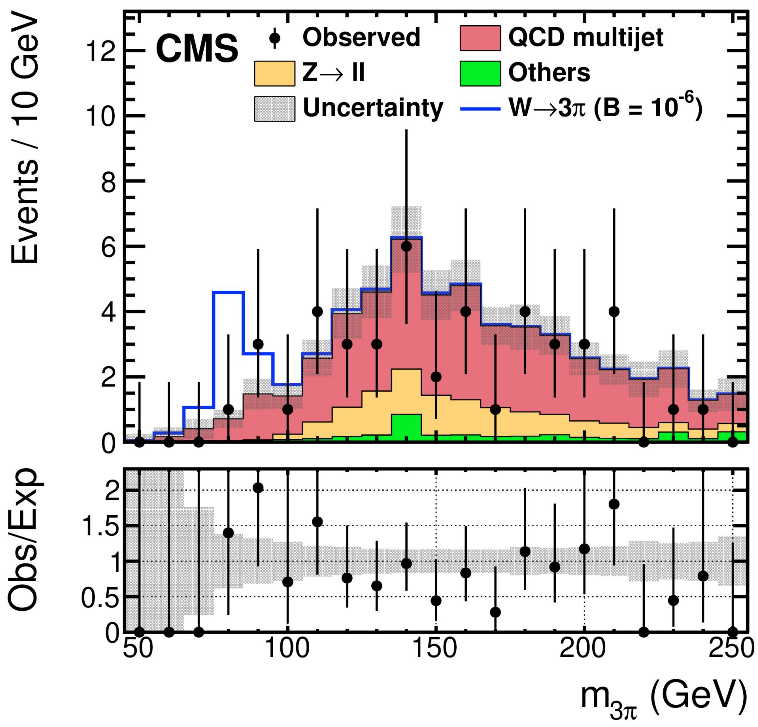
No precise theoretical calculation for this BF, but expected to be $O(10^{-7})$-$O(10^{-9})$

Search for $W^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}$ at CMS

- **Dataset**: pp collisions, 77.3 fb^{-1}, at $\sqrt{s}$ = 13 TeV
- **Trigger:** Di-tau triggers (p_T > 35/40 GeV)

- **Offline selection:**
  - 3 isolated charged pion candidates reconstructed as 1-prong taus (2 matched to trigger object)
  - Hadronic tau discrimination algorithms are leveraged
  - $p_T(W)$ > 40 GeV
- **Background estimation:**
  - Template derived using anti-isolated, and $p_T(W)$ < 40 GeV data CRs

Phys. Rev. Lett. 122, 151802 (2019)



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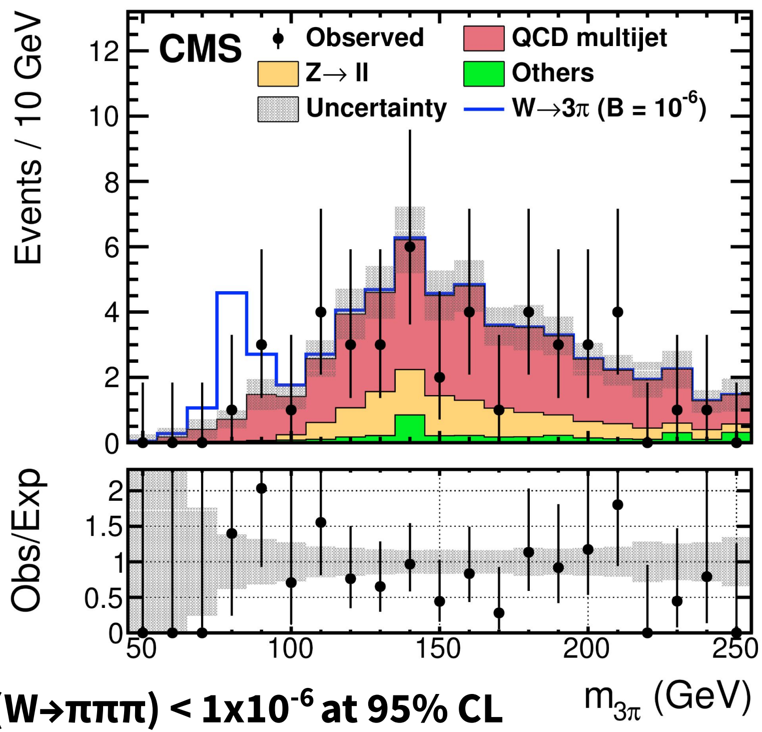
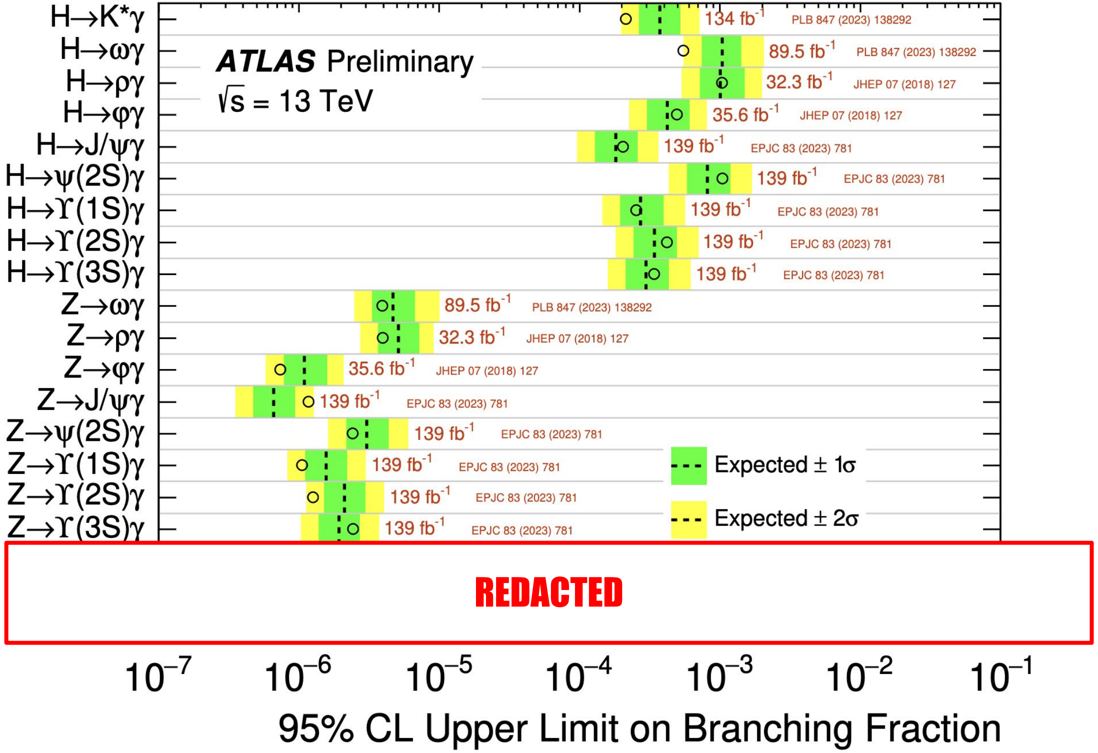
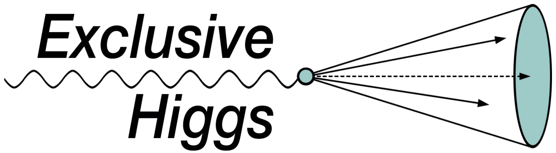


B(W→πππ) < 1x10^{-6} at 95% CL

Searches for H/Z→Mγ at ATLAS





- **Several ATLAS publications on exclusive Higgs/Z decays**
  - Potential to probes light quark Yukawa couplings
- **Many of the same techniques are used in the searches being discussed**

Searches for W→Mγ decays at ATLAS

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence
Γ_1	$\ell^+\nu$	[a]	(10.86 ± 0.09) %	
Γ_2	$e^+\nu$		(10.71 ± 0.16) %	
Γ_3	$\mu^+\nu$		(10.63 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.38 ± 0.21) %	
Γ_5	hadrons		(67.41 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	95%
Γ_7	$D_s^+\gamma$		$< 6.5 \times 10^{-4}$	95%
Γ_8	cX		(33.3 ± 2.6) %	
Γ_9	$c\bar{s}$		$(31 ^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	
Γ_{11}	$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$	95%

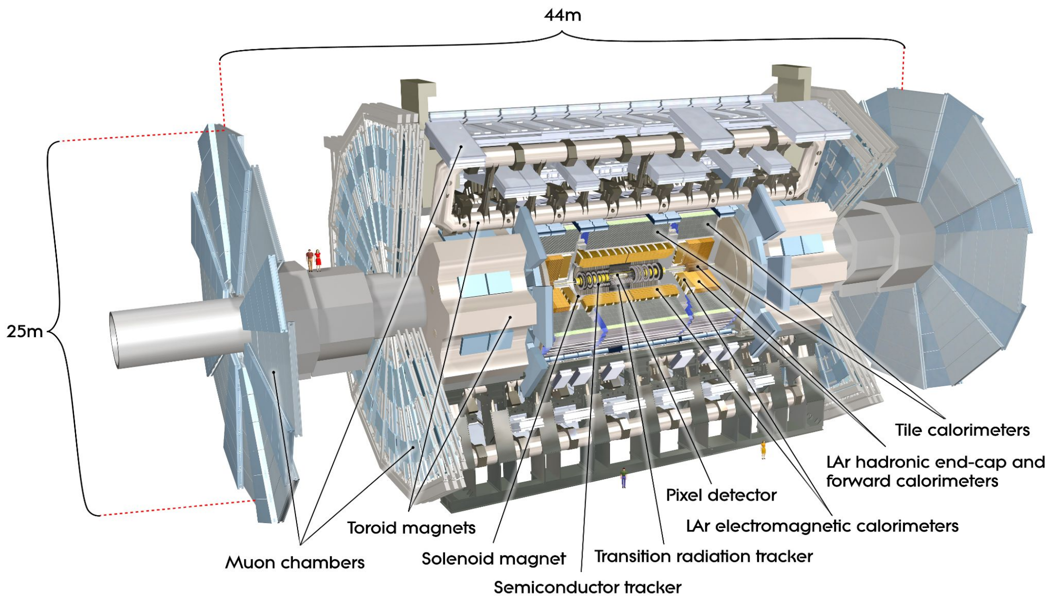
Introducing 2 decays to this list!

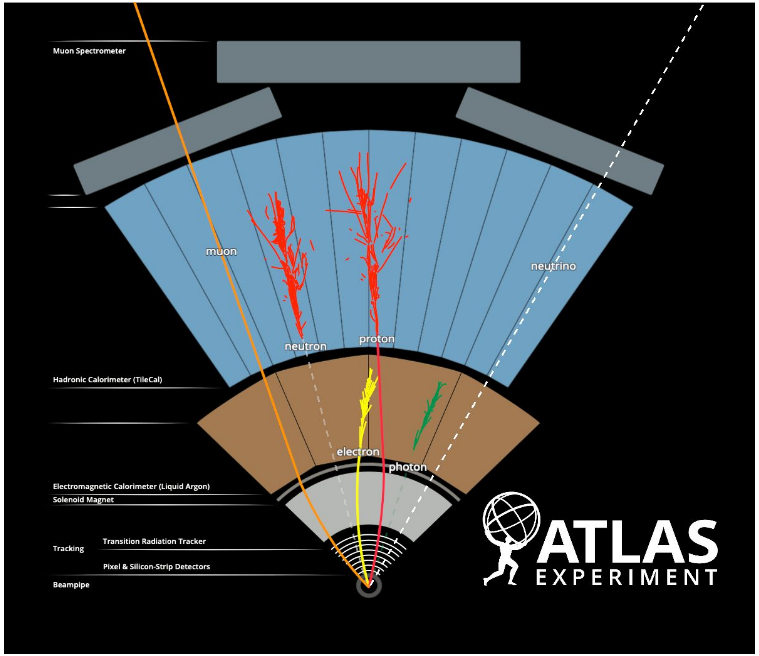
Decay Channel	SM Branching Fraction
$W^\pm \to \pi^\pm\gamma$	$(4.0 \pm 0.8) \times 10^{-9}$
$W^\pm \to \rho^\pm\gamma$	$(8.7 \pm 1.9) \times 10^{-9}$
$W^\pm \to K^\pm\gamma$	$(3.3 \pm 0.7) \times 10^{-10}$

Searches for $W^\pm \to \pi^\pm\gamma$, $W^\pm \to \rho^\pm\gamma$ and $W^\pm \to K^\pm\gamma$, using ATLAS Run-2 data

The ATLAS Experiment (in Run 2)

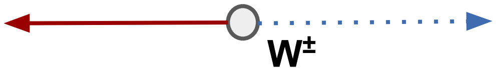
- **Inner Detector:** Silicon pixels and strips (SCT) with Transition Radiation Tracker (TRT)
- **LAr EM calorimeter:** high granularity + longitudinally segmented
- **Two level trigger:** L1 Hardwarwe Trigger (40 MHz → 100 kHz) + HLT Software Trigger (100 kHz → 1 kHz)

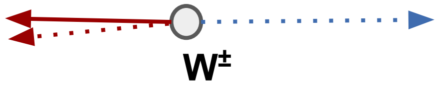




Analysis Final States

- **$W^{\pm}\rightarrow \pi^{\pm}/K^{\pm} + \gamma$**: **Isolated high p_T track** recoiling against **isolated high p_T photon**
- **$W^{\pm}\rightarrow \rho^{\pm} (\rightarrow\pi^{\pm} + \pi^0) + \gamma$:** extra **electromagnetic energy deposition** coming from π^0





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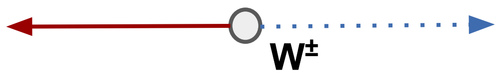
- Analysis performed through **track + photon** and the **tau+photon** final states:
  - Different strategies employed

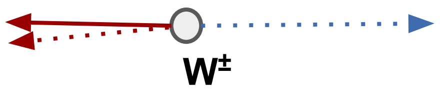
track + photon

- Sensitive to **$W^{\pm} \to \pi^{\pm}/K^{\pm}/\rho^{\pm} + \gamma$** decays
- No attempt to reconstruct **π^0**
- **Dedicated triggers**: track (p_T > 30 GeV) + photon (p_T > 25 GeV)



tau + photon

- Sensitive to **$W^{\pm} \to \rho^{\pm} (\to \pi^{\pm}\pi^{0}) \gamma$** decay
- ρ-candidate reconstructed as 1-prong τ-lepton
- No dedicated triggers, using **di-photon triggers**



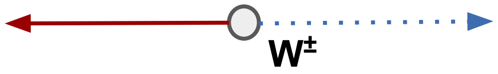
Trigger Strategy

track + photon

- **Dedicated triggers allow us to identify specific event topologies**
  - Using modified tau-lepton trigger algorithms
- **Collected 137 fb^{-1} from 2016 to 2018**
  - With **58% signal efficiency** wrt offline selection (for $W^{\pm} \rightarrow \pi^{\pm}\gamma$ signal)

Requirements:

- **single track** (p_T > 30 GeV)
- **single photon** (p_T > 25/35 GeV)
- m(trk+γ) > 50 GeV
- $0.4 < E_T/p_T(trk) < 0.85$



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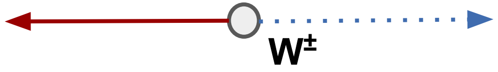
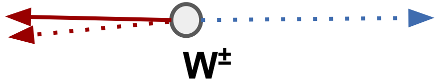


tau + photon

- Lower acceptance for this final state from dedicated $W \rightarrow \pi\gamma$ triggers:
  - Mostly due to $0.4 < E_T/p_T < 0.85$ requirement
- **Diphoton** triggers are used instead
  - taking advantage of **$\pi^0 \rightarrow \gamma\gamma$ decays**
  - p_T > 35 GeV, p_T>25 GeV
  - with **43% efficiency** wrt offline SR selection



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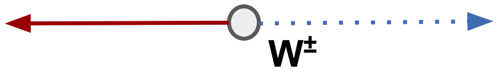

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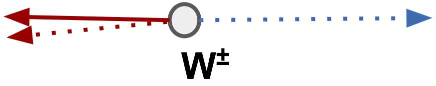


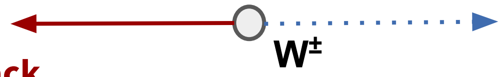
Dedicated triggers and diphoton triggers are orthogonal

Can combine two final states in a simultaneous fit

track + photon

Event Selection

$\Delta\Phi(\text{track},\gamma) > \pi/2$



Track

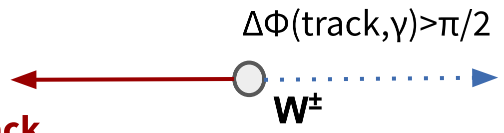
p_T > 33 GeV
Tight ID
Isolated

Photon

p_T > 30/35 GeV (depending on trigger)
Tight ID
Isolated

W candidate = highest p_T track + highest p_T photon

Event Selection



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Isolated

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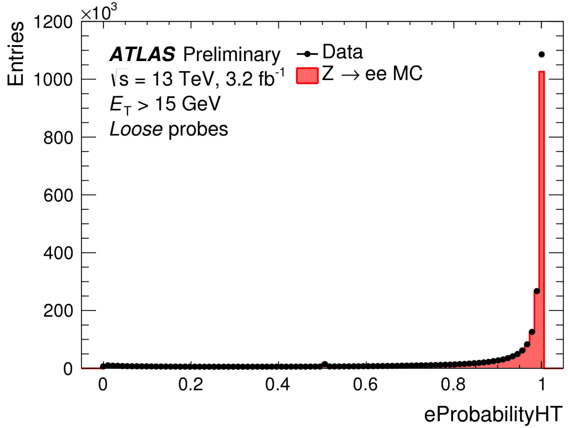
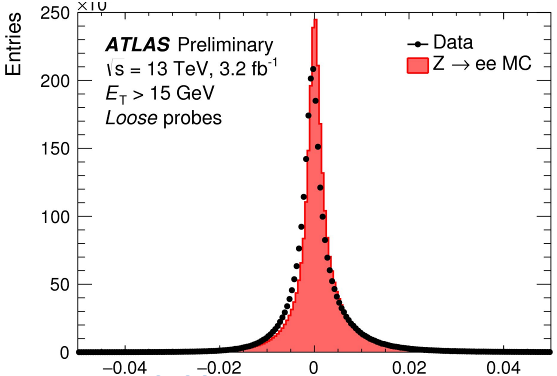
Z → ee rejection

- Resonant background arising from **Z → ee events**
  - not modelled by inclusive background modelling method - **modelled with MC** in final fit
- Exploit differences between electrons and charged hadrons:
  - hadronic leakage and transition radiation
- Reject if **Rhad(e) < 0.03 and eProbabilityHT(trk) > 0.1**

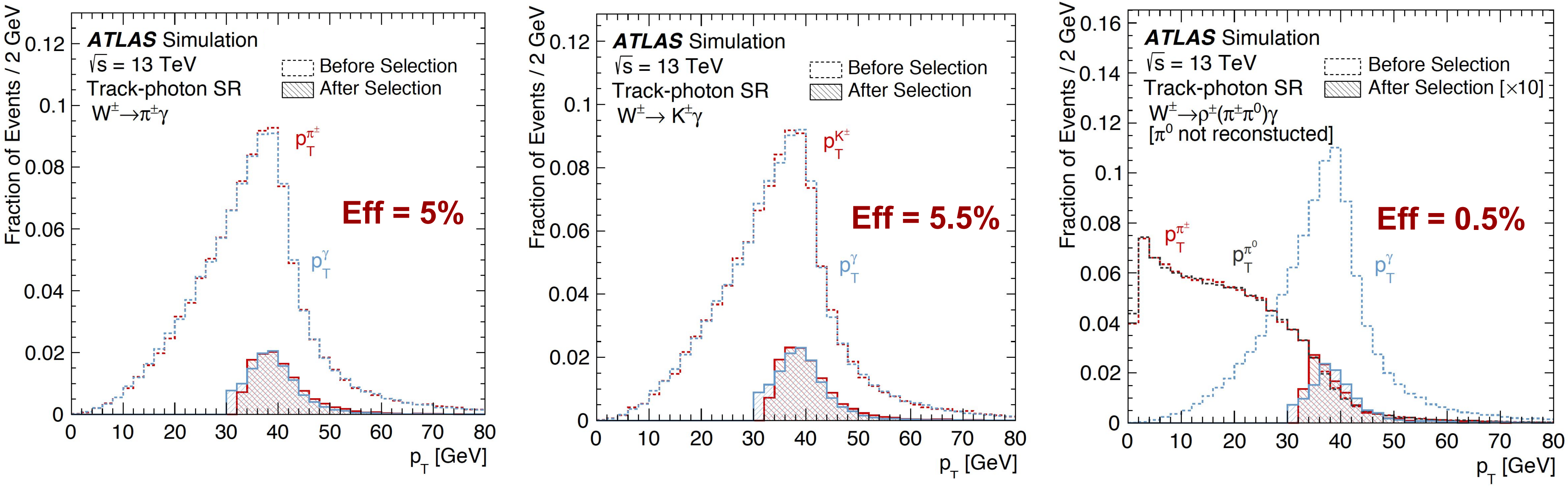




ATLAS-CONF-2016-024

Event Selection

- Signal efficiencies mainly driven by trigger p_T thresholds
- **~10% efficiency difference between $W^{\pm} \rightarrow \pi^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$**
  - originating from differences between E_T/p_T(trk) and $Z \rightarrow ee$ rejection variables



Background modelling

- Main background arising from **dijet** and **jet + photon** processes
    - neither shape or normalisation reliably modelled by MC - use **data-driven** method instead

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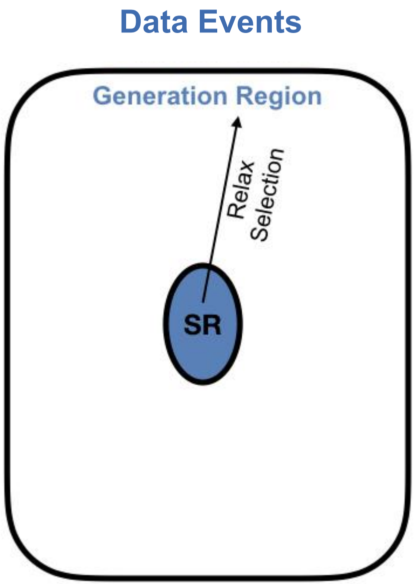

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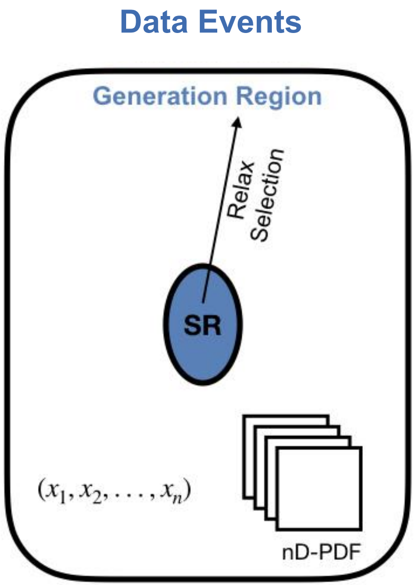

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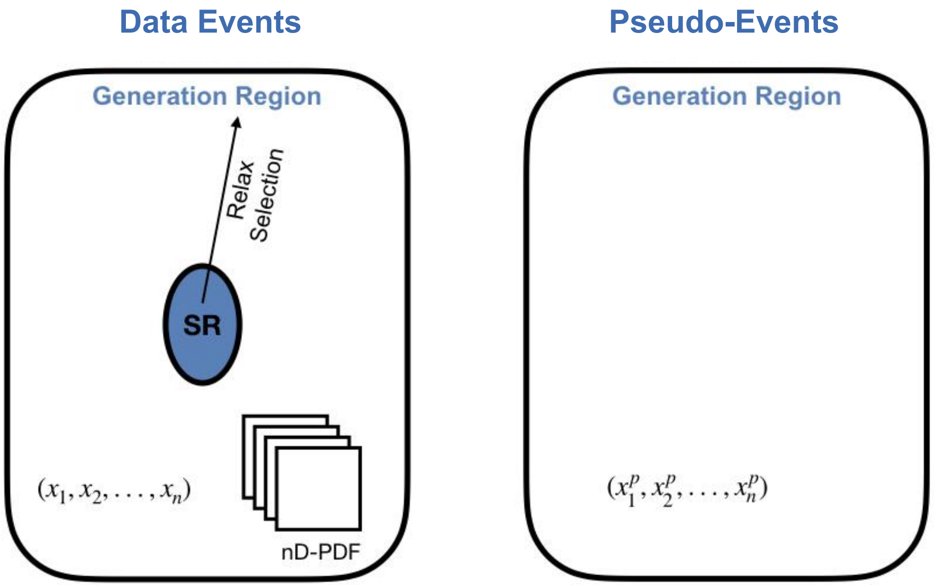

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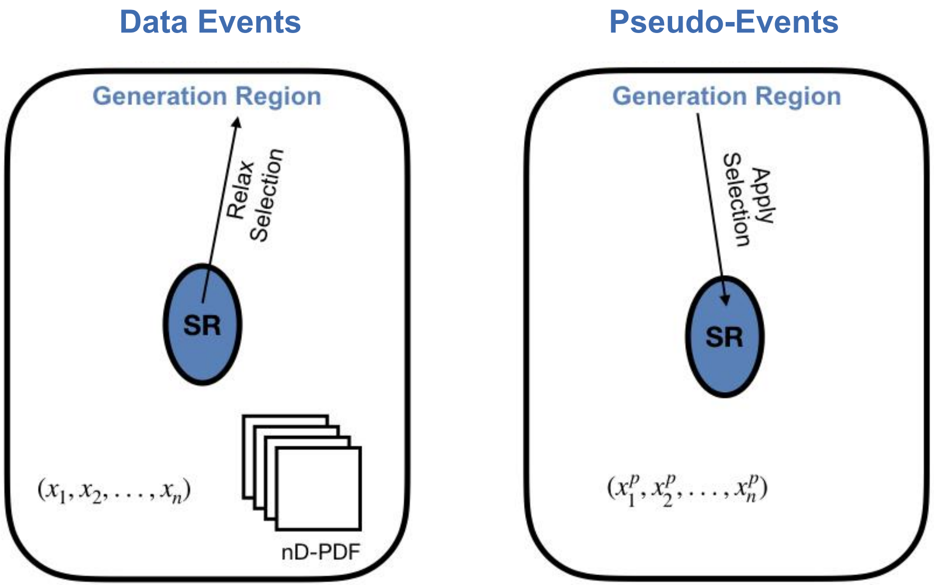

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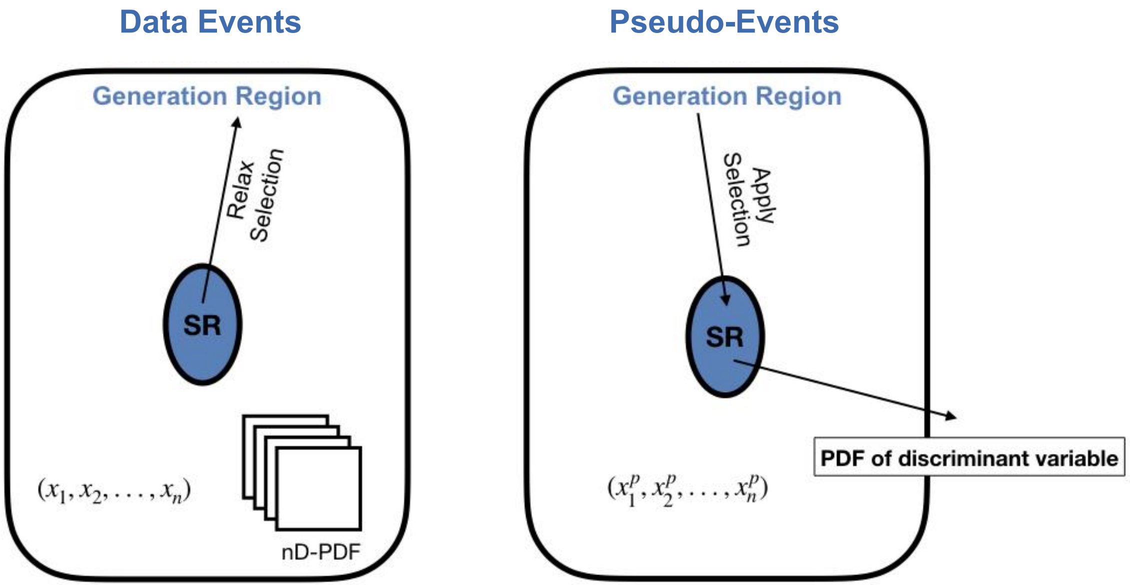

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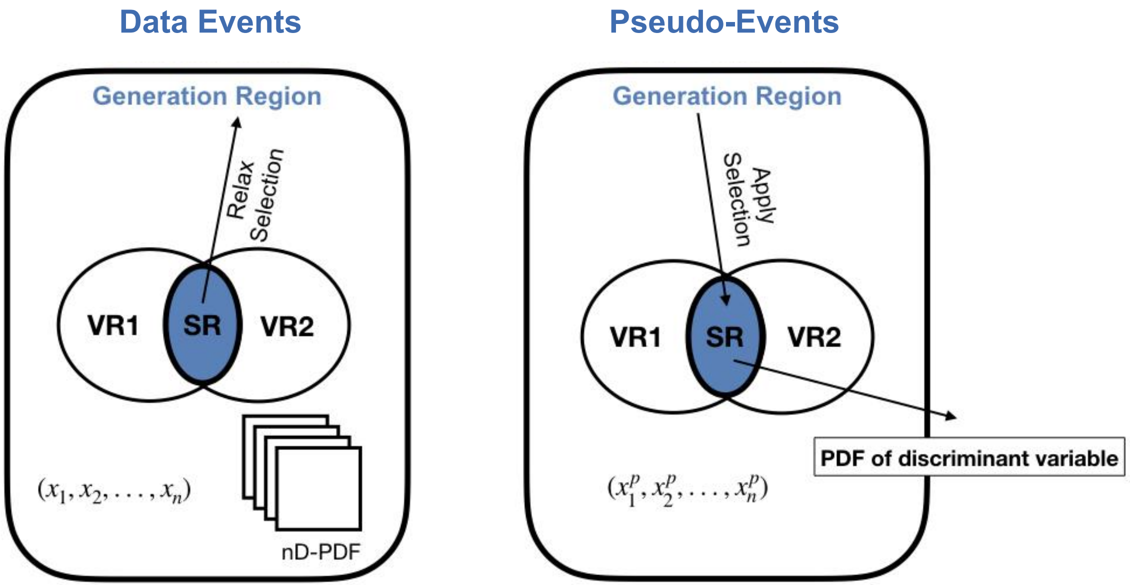

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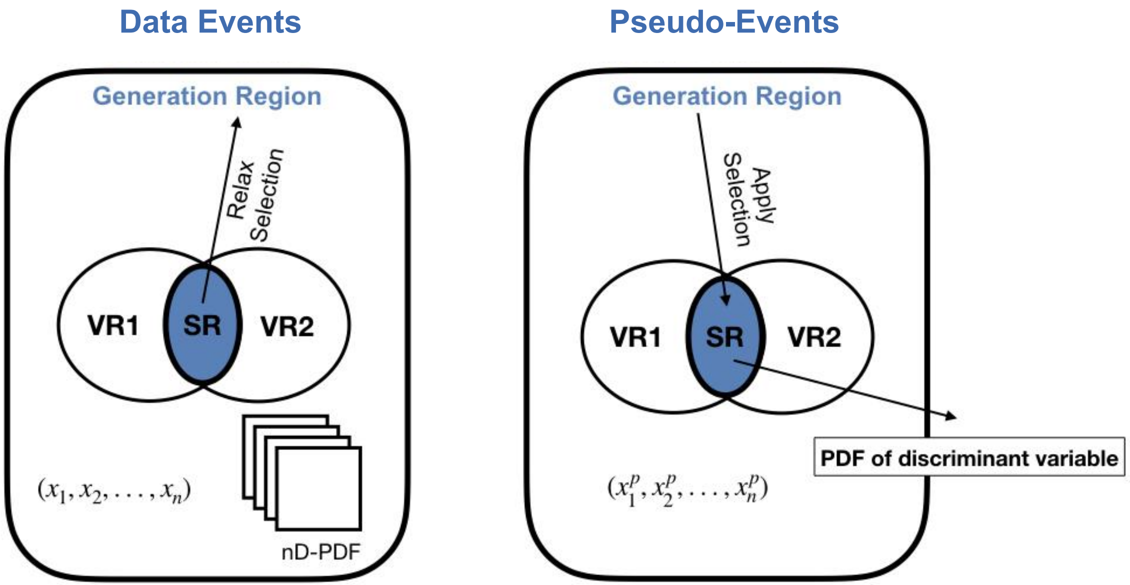
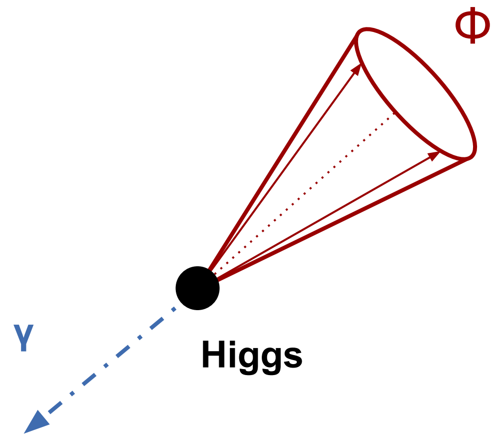
- Method described in [JHEP10 (2022) 001]



- Let's take a $H \to \phi(K^+K^-)\gamma$ case study
  - **Similar signature**: pair of collimated high-p_T isolated tracks recoiling against isolated photon
  - Main background : **photon + jet** and **dijet**
  - **photon + jet MC** sample as data

JHEP10 (2022) 001



$H \to \phi(K^+K^-)\gamma$
case study for background model

Non-parametric data-driven background modelling

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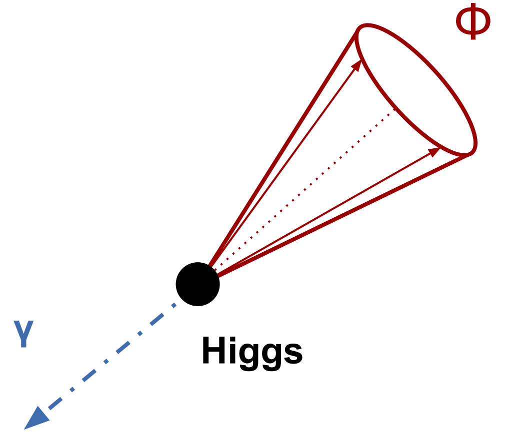
JHEP10 (2022) 001

Which variables do we need to include in the model?

ϕ and γ 4-momentum vectors to ultimately obtain **m(ϕγ)**
+ extra variables which define Signal Region

pT(Φ), pT(γ), ΔΦ(ϕ,γ), Δη(ϕ,γ), Iso(Φ)



$H \to \phi(K^+K^-)\gamma$
case study for background model

Non-parametric data-driven background modelling

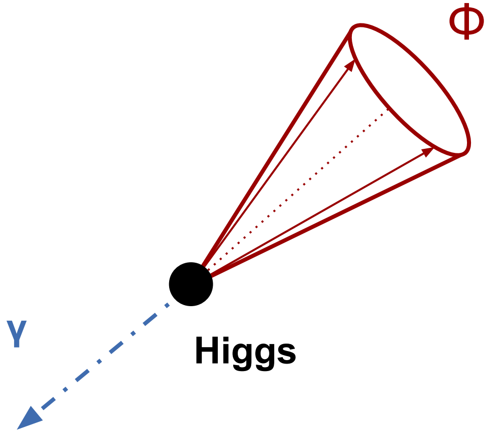
- Let's take a $H \to \phi(K^+K^-)\gamma$ case study
  - **Similar signature**: pair of collimated high-p_T isolated tracks recoiling against isolated photon
  - Main background : **photon + jet** and **dijet**
  - **photon + jet MC** sample as data

[JHEP10 (2022) 001](#)

Which variables do we need to include in the model?

ϕ and γ 4-momentum vectors to ultimately obtain **m(ϕγ)**
+ extra variables which define Signal Region

pT(Φ), pT(γ), ΔΦ(ϕ,γ), Δη(ϕ,γ), Iso(Φ)

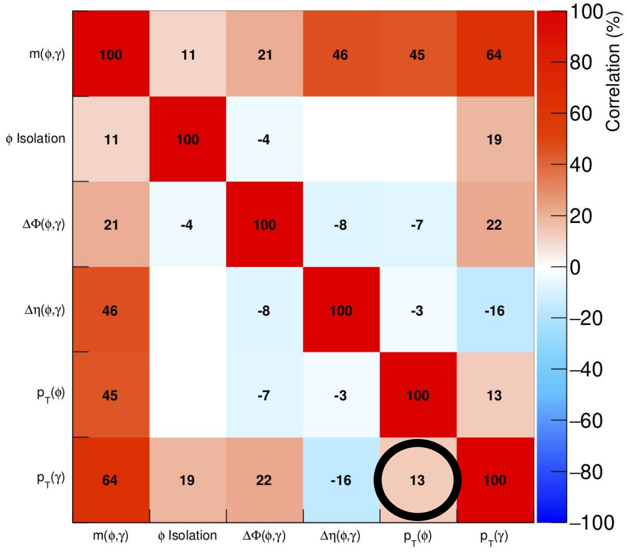


$H \to \phi(K^+K^-)\gamma$
case study for background model

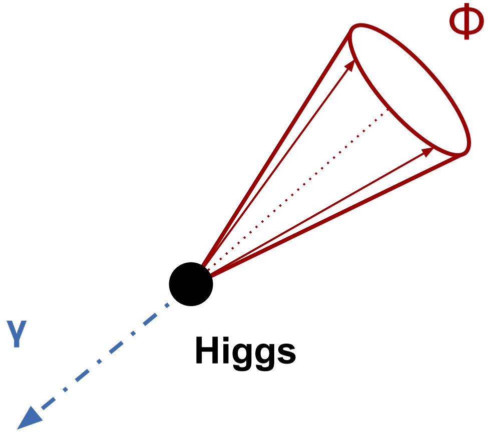
ATLAS EXPERIMENT

JHEP10 (2022) 001

- Build PDFs of relevant variables following most important correlations in **Generation Region**
  - 1D, 2D and 3D histograms to be sampled from in generation step



$p_T(\phi)$	$p_T(\gamma)$



H→ϕ(K^+K^-)γ
case study for background model

Non-parametric data-driven background modelling

[JHEP10 (2022) 001]

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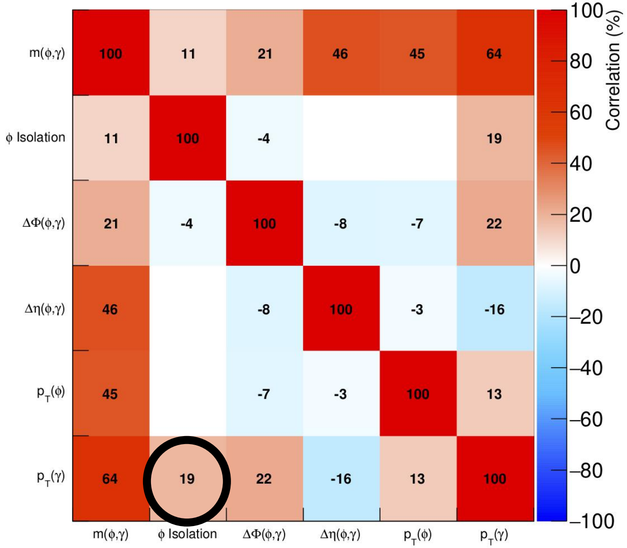
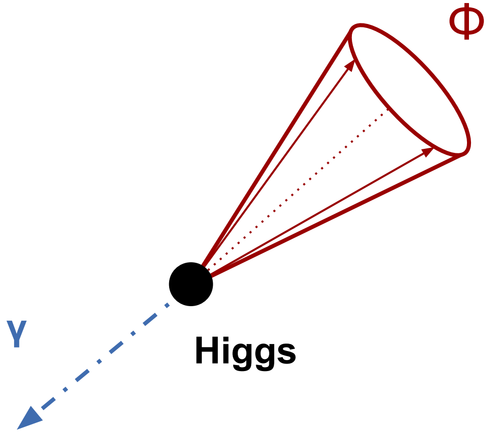


$p_T(\phi)$	$p_T(\gamma)$

$p_T(\gamma)$	ϕ Iso



$H \to \phi(K^+K^-)\gamma$
case study for background model

Non-parametric data-driven background modelling

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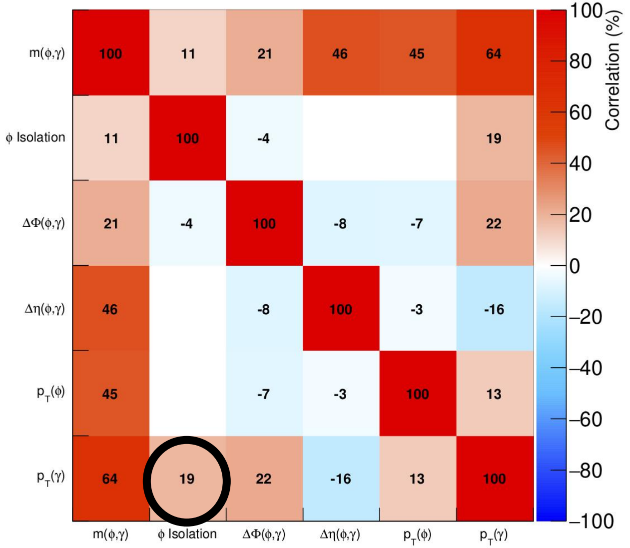
  - 1D, 2D and 3D histograms to be sampled from in generation step

[JHEP10 (2022) 001]

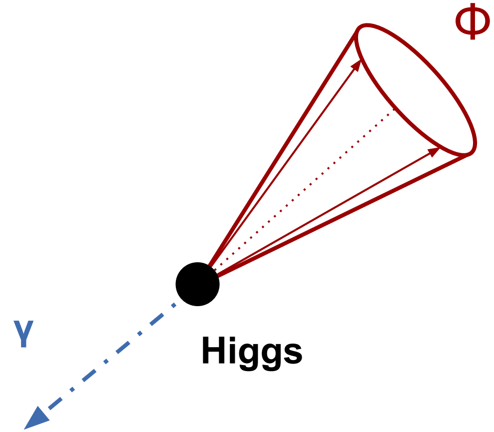


$p_T(\phi)$	$p_T(\gamma)$

$p_T(\gamma)$	ϕ Iso

$p_T(\phi)$	$p_T(\gamma)$	$\Delta\Phi(\phi,\gamma)$

$\Delta\Phi(\phi,\gamma)$	$\Delta\eta(\phi,\gamma)$



$H \rightarrow \phi(K^+K^-)\gamma$
case study for background model

ATLAS EXPERIMENT

- **Sample** from PDFs and construct pseudo-candidates
  - each pseudo-candidate is defined by the ϕ and γ 4-momentum vectors, and an associated Φ isolation variable

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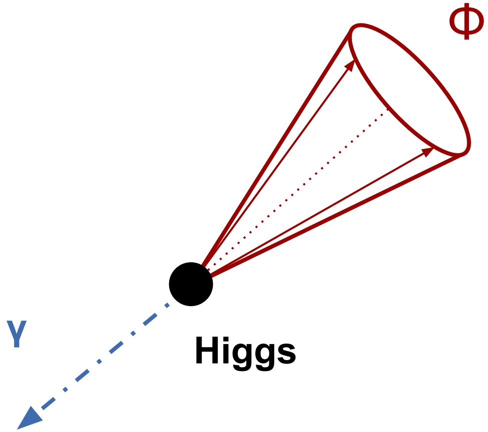
$p_T(\phi)$	$p_T(\gamma)$

$\phi = (\mathbf{p_T}, \eta, \Phi, m)$

$\gamma = (\mathbf{p_T}, \eta, \Phi, m)$

$Iso(\phi)$



$H \rightarrow \phi(K^+K^-)\gamma$
case study for background model

Non-parametric data-driven background modelling

JHEP10 (2022) 001

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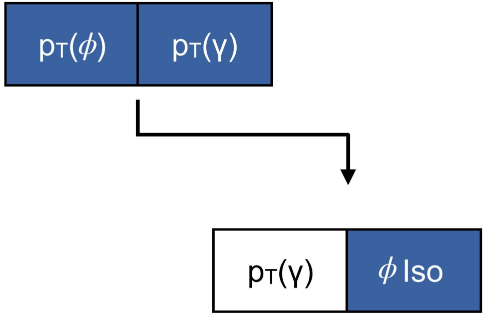
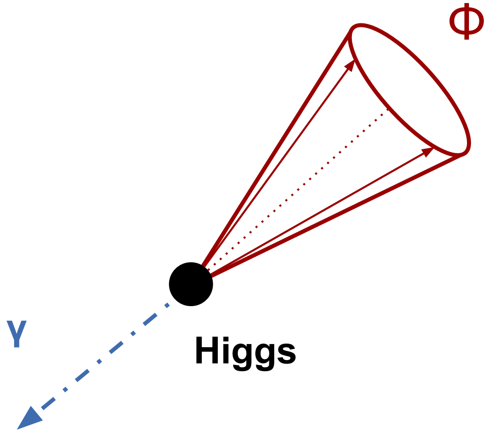
$\phi = (\mathbf{p_T}, \eta, \Phi, m)$

$\gamma = (\mathbf{p_T}, \eta, \Phi, m)$

Iso(ϕ)





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- **Sample** from PDFs and construct pseudo-candidates
  - each pseudo-candidate is defined by the ϕ and γ 4-momentum vectors, and an associated Φ isolation variable

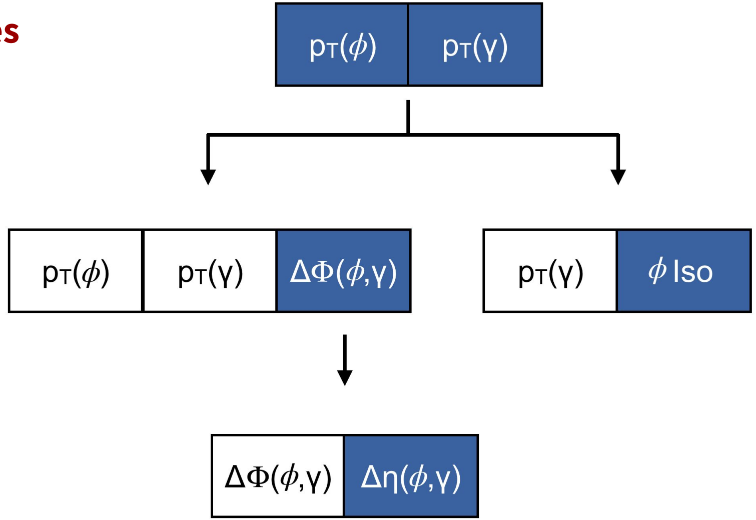
[JHEP10 (2022) 001]

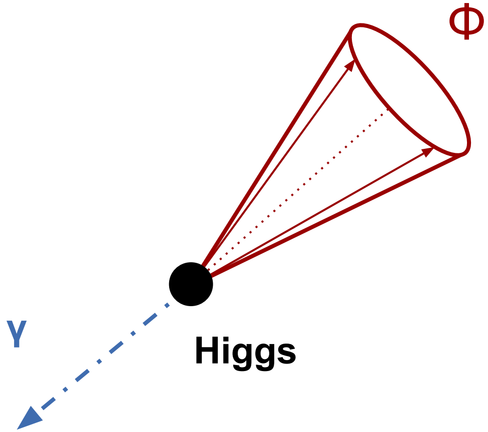
Higgs pseudo-candidates

$\phi = (p_T, \eta, \Phi, m)$

$\gamma = (p_T, \eta, \Phi, m)$

$Iso(\phi)$





$H \to \phi(K^+K^-)\gamma$
case study for background model

Non-parametric data-driven background modelling

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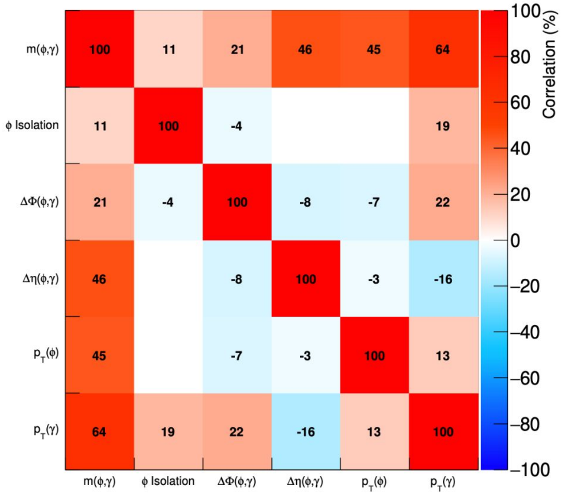
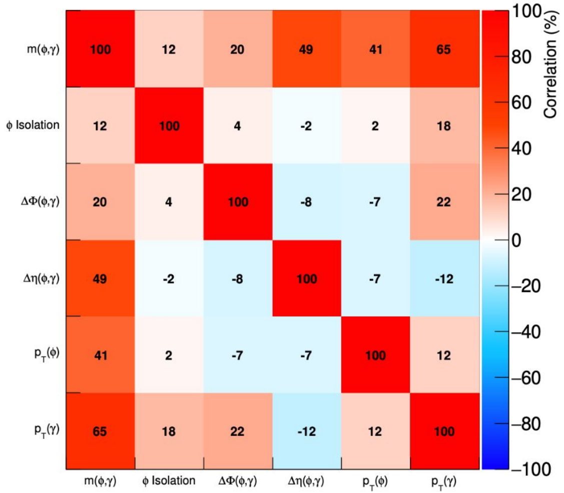
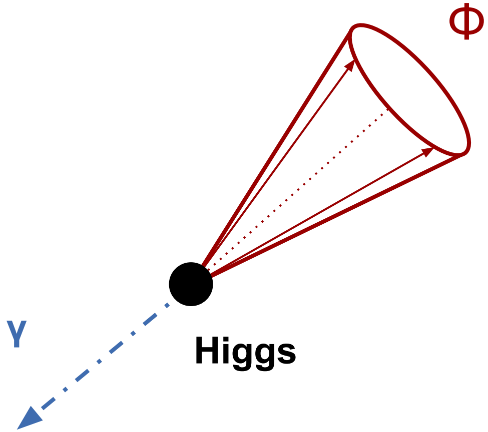
γ+jet MC



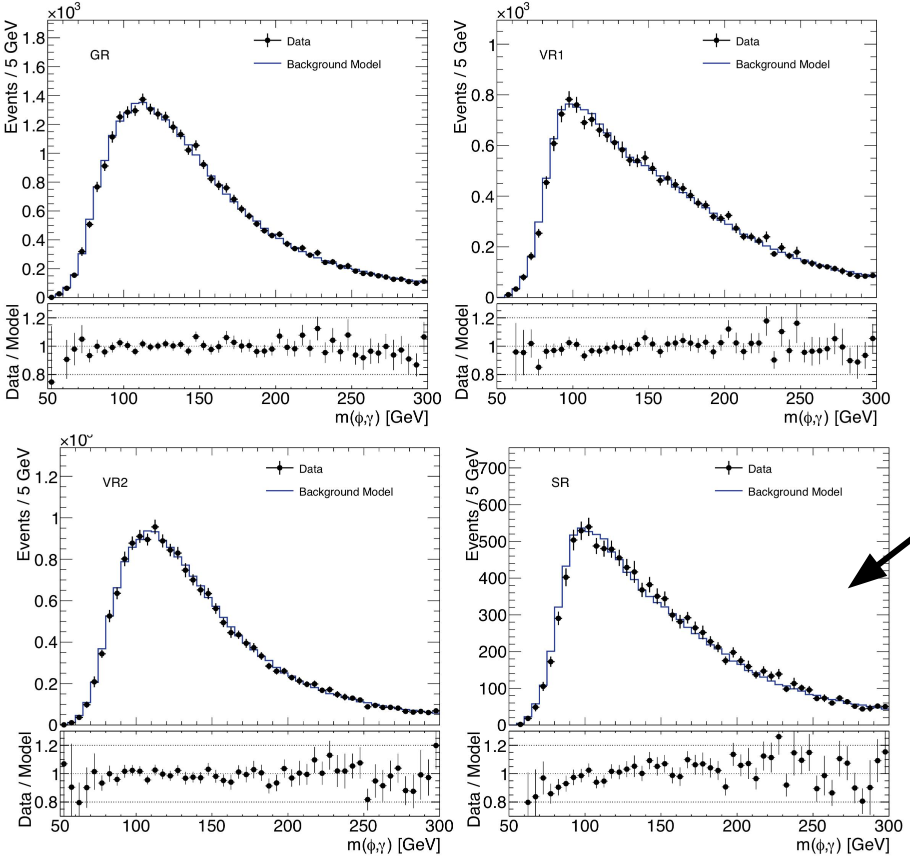
Model





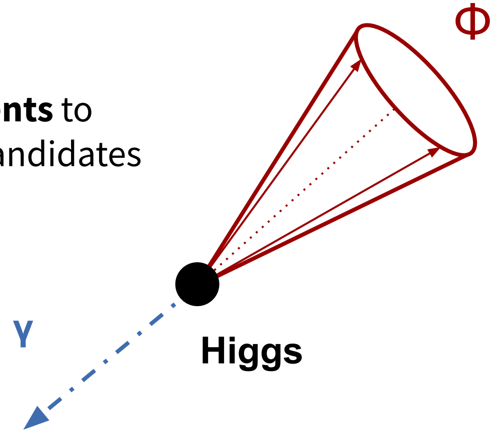
$H \rightarrow \phi(K^+K^-)\gamma$
case study for background model

Non-parametric data-driven background modelling



[JHEP10 (2022) 001]

Apply **SR requirements** to sample of pseudo-candidates



$H \to \phi(K^+K^-)\gamma$

case study for background model

Non-parametric data-driven background modelling

- **Systematic uncertainties** provided through variations of the nominal PDFs
  - selected to capture different modes of potential deformations of the background shape

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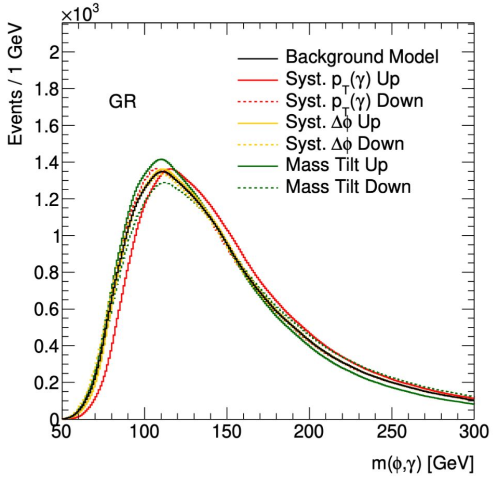
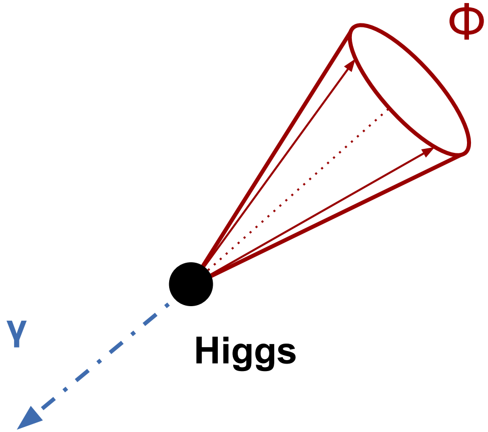


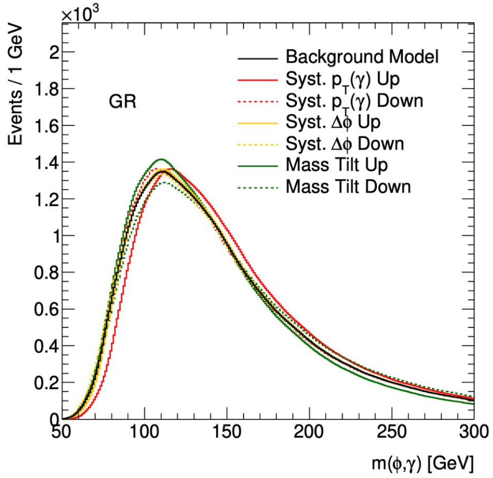


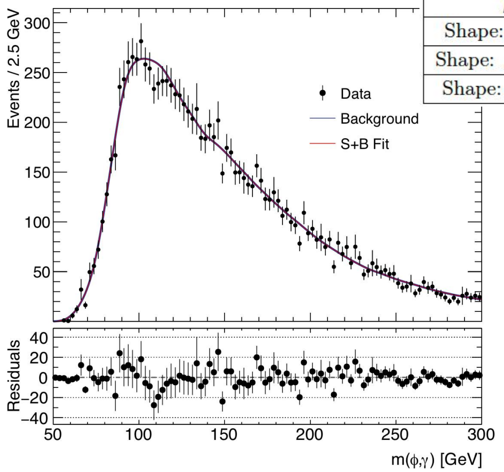
$H \to \phi(K^+K^-)\gamma$
case study for background model

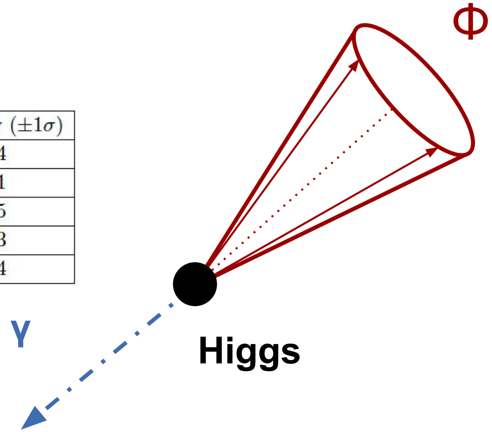
[JHEP10 (2022) 001]

- **Systematic uncertainties** provided through variations of the nominal PDFs
  - selected to capture different modes of potential deformations of the background shape
  - each variation controlled by a nuisance parameter - directly constrained by data in fit

Parameter	Value	Uncertainty ($\pm 1\sigma$)
μ_{signal}	-0.07	± 0.54
μ_{bkgd}	1.01	± 0.01
Shape: $p_T(\gamma)$ shift	0.26	± 0.15
Shape: $\Delta\Phi(\phi,\gamma)$ tilt	0.30	± 0.43
Shape: $m(\phi,\gamma)$ tilt	0.10	± 0.24







H→ϕ(K⁺K⁻)γ
case study for background model

Non-parametric data-driven background modelling

- **Model is robust** under signal contamination:
  - Features of resonant contributions are diluted in the process of factorising the background PDF

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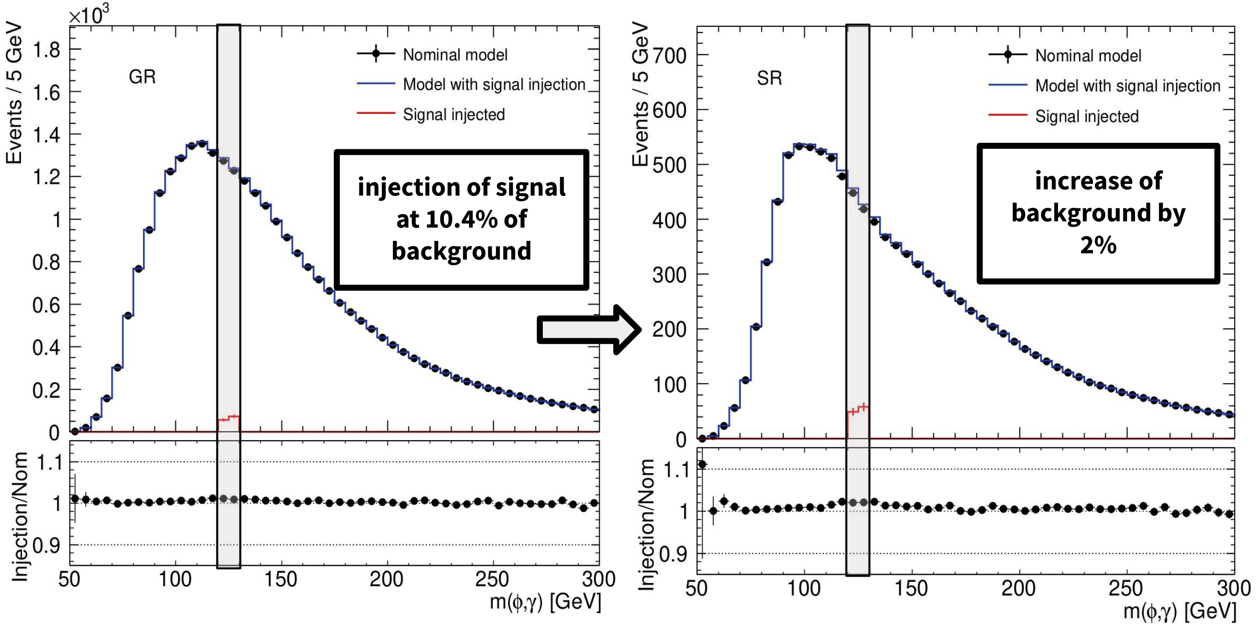

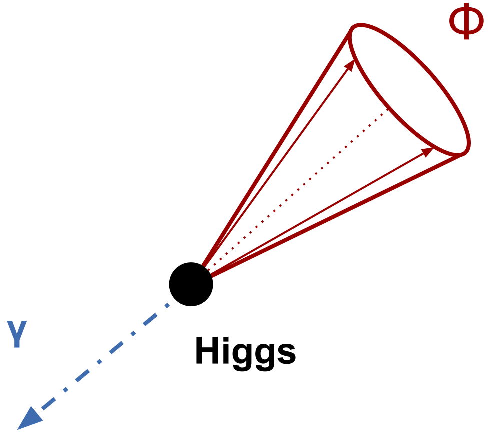

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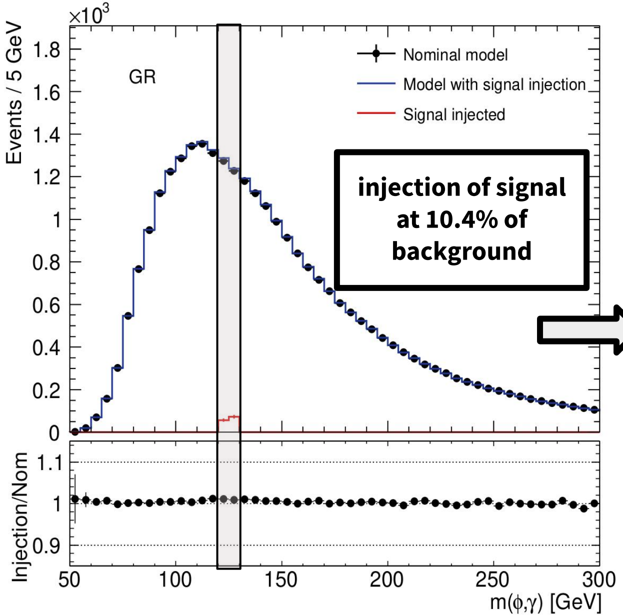

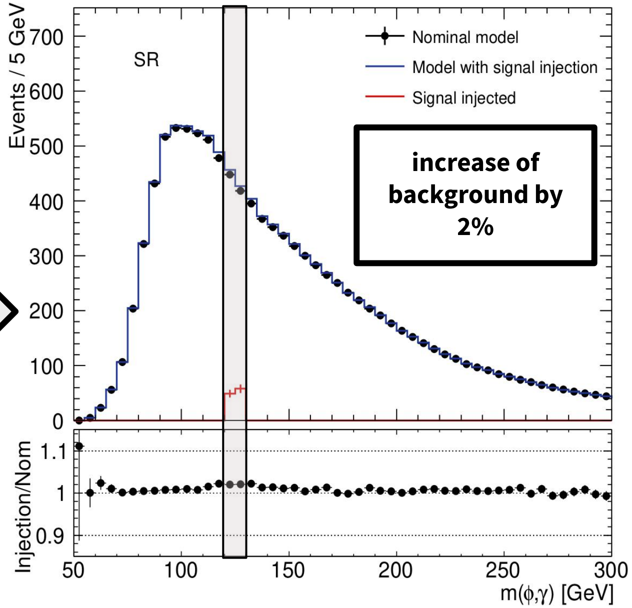

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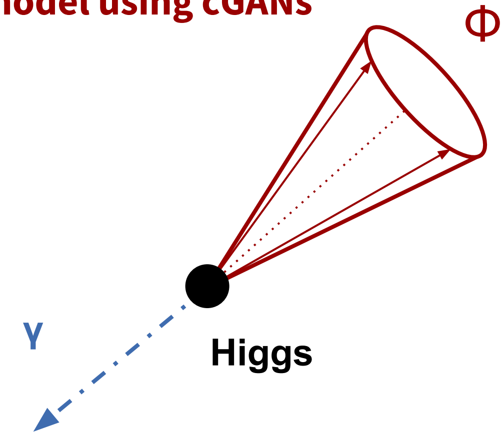
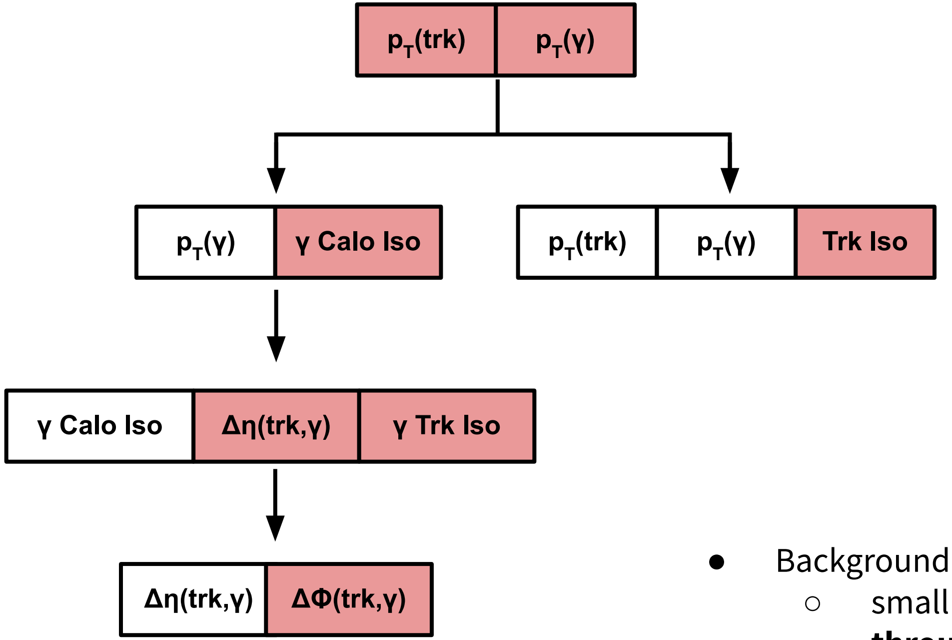
Bonus: generalisation of the model using cGANs



$H \to \phi(K^+K^-)\gamma$
case study for background model

Background modelling

Sampling sequence for track + photon final state



Validation Regions

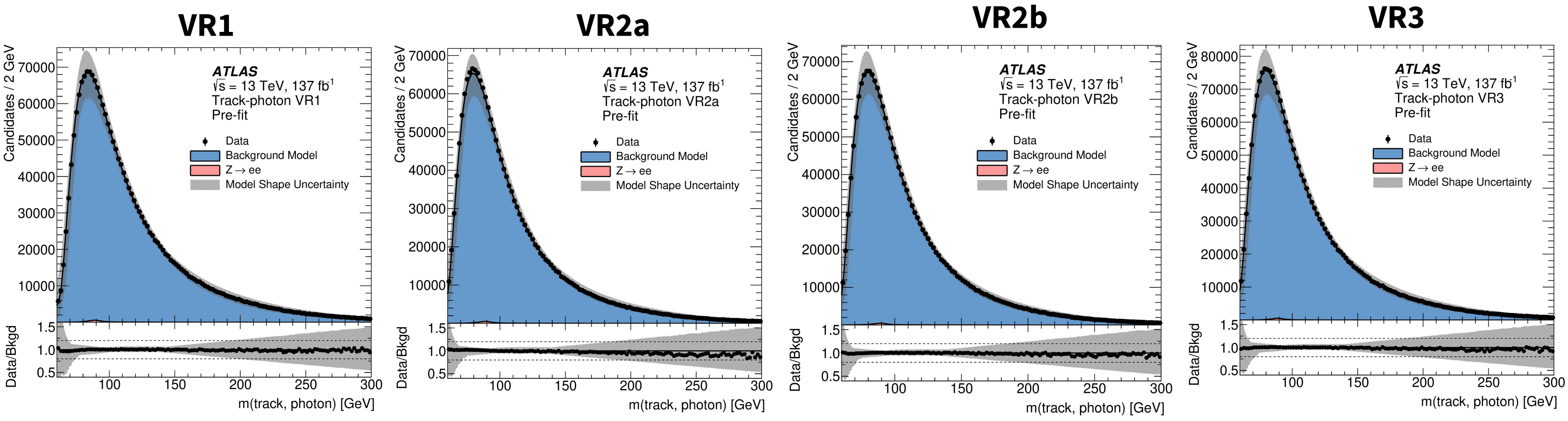
Region	Selection
VR1	GR + $p_T(\pi)$ > 33 GeV
VR2a	GR + Photon Calo Iso
VR2b	GR + Photon Track Iso
VR3	GR + Track Isolation
SR	GR + all of the above

- Background modelling method **does not model resonant processes**:
  - small remaining contribution from **Z → ee background modelled through MC**

Background modelling

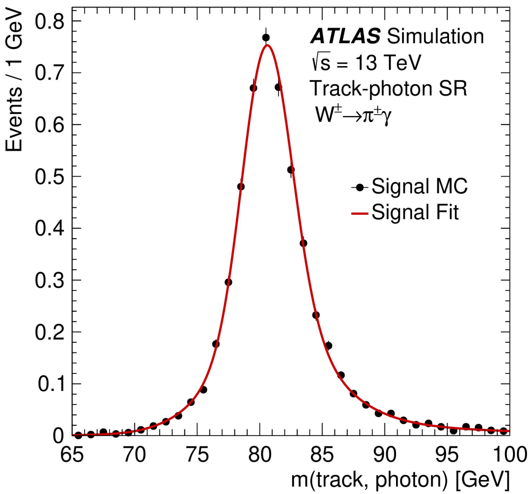
Background Shape Systematics

- Alternative pairs of m(track,γ) shapes are derived and implemented in the fit using **interpolation technique**
  - $p_T(\gamma)$ shifted
  - distortions to ΔΦ(trk, γ)
  - linear re-weighting of m(trk, γ)



Signal Modelling

- Signals simulated using **Powheg + Pythia**
  - decays simulated isotropically and re-weighted to theoretical polarisation
- Modelled in fit using:
  - **$W^{\pm} \rightarrow \pi^{\pm}/K^{\pm}\gamma$:** double voigtian x efficiency function (parameters fixed to MC)



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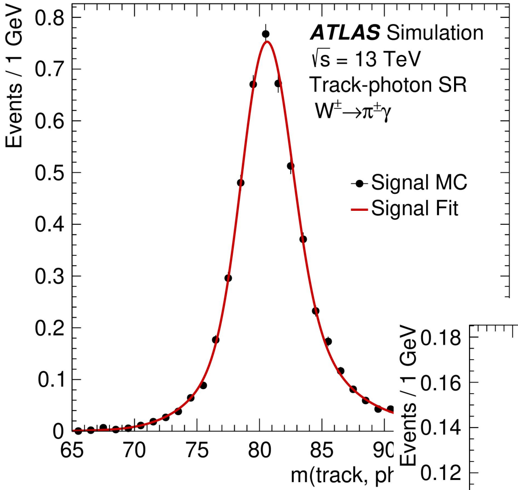
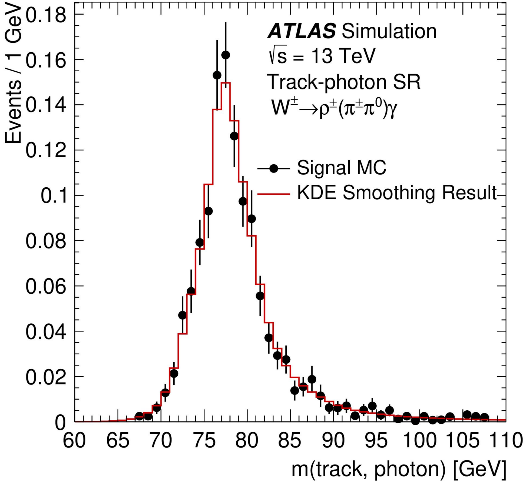
  - **$W^{\pm} \rightarrow \rho^{\pm}\gamma$:** MC distribution smoothed through KDE





Signal modelling & uncertainties

Signal Modelling

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  - decays simulated isotropically and re-weighted to theoretical polarisation
- Modelled in fit using:
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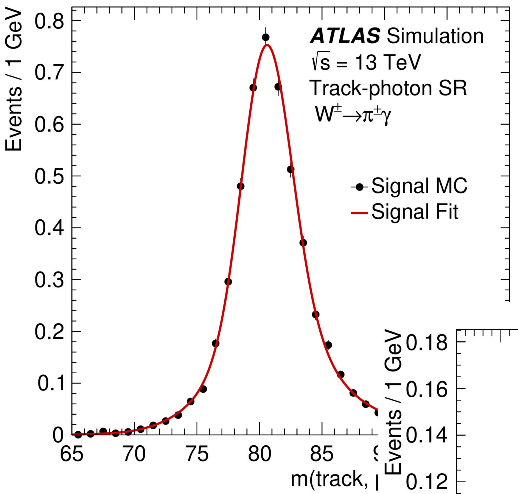
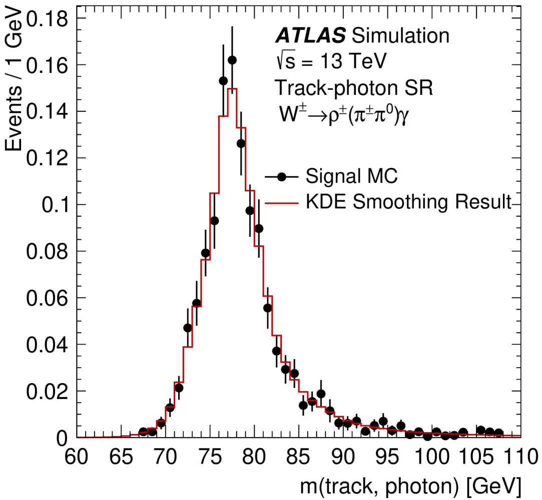
  - **$W^{\pm} \to \rho^{\pm}\gamma$:** MC distribution smoothed through KDE



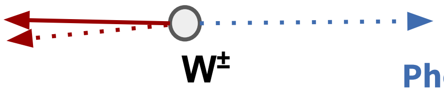


Signal Uncertainties (1% effect on upper limit)

- Theory scale variations - 6.2%
- Trigger Efficiency - 3.6%
- Cross Section - 3.3 %
- Luminosity - 0.83%
- Pileup - 2.2%
- Photon ID & Isolation - 2.1%
- Tracking Efficiency - 1.2%

tau + photon

Event Selection



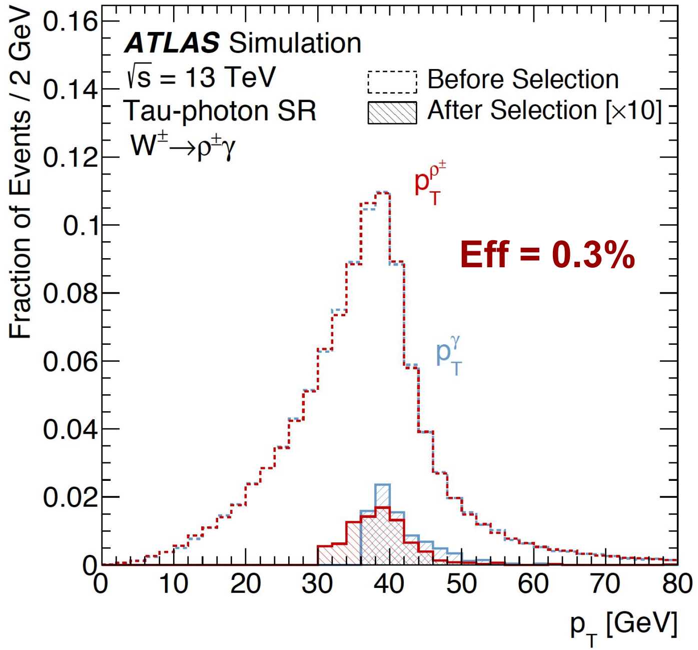
ρ candidate
1-prong tau
$p_T > 30$ GeV
$h^{\pm}\pi^0$ decay mode

Photon
$p_T > 36$ GeV
Tight ID
Tight Iso

- SR defined by simultaneous cut optimisation on $\mathbf{p_T(\tau), \Delta R_{\tau}^{max}}$ and **τ impact parameter d_0**
- Signal efficiency is ~½ of track-photon SR, but with **higher background rejection**

	Tau-photon
VR1	$p_{\mathrm{T}}(M) > 30\,GeV$
VR2	$\Delta R_{\tau_{\mathrm{had}}} < 0.065$
VR3	$\log\lvert d_0\rvert < -1.2$

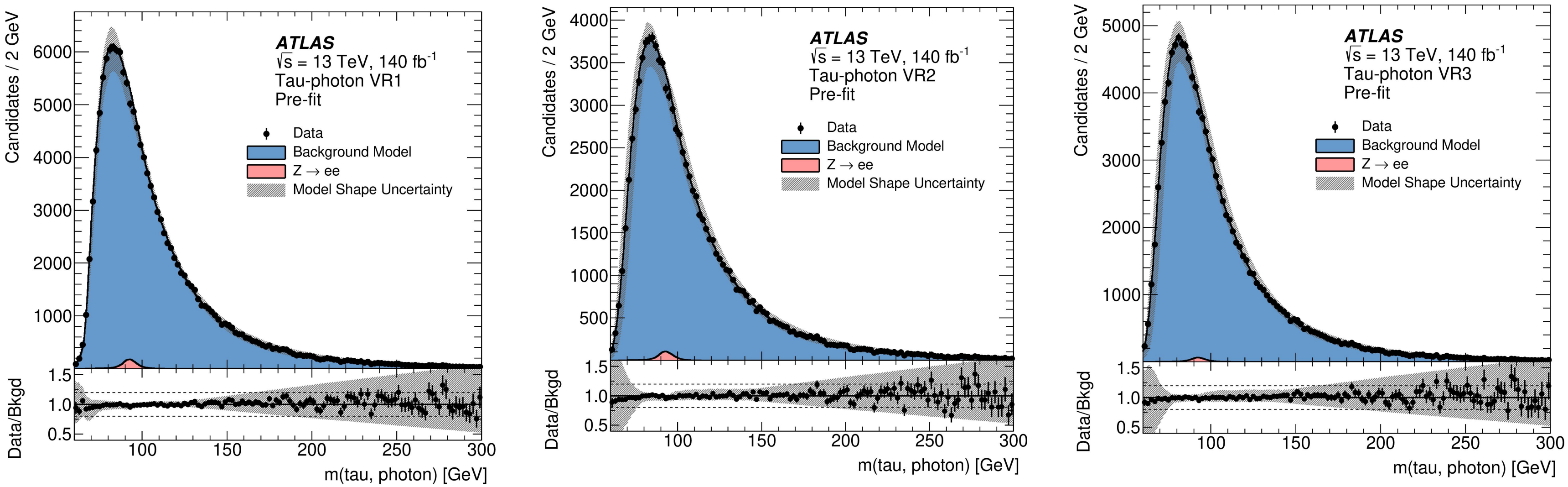
ρ meson reconstructed as tau with exactly one associated charged hadron



Background Modelling

- Main background arising from **dijet** and **jet + photon** processes
- The same **non-parametric data-driven background modelling method** used
  - γ and τ variables used in the modelling
- Background shape systematics derived and implemented in the same way as for track+photon

Tau-photon	
VR1	$p_{\mathrm{T}}(M) > 30\, GeV$
VR2	$\Delta R_{\tau_{\mathrm{had}}} < 0.065$
VR3	$\log \lvert d_0 \rvert < -1.2$



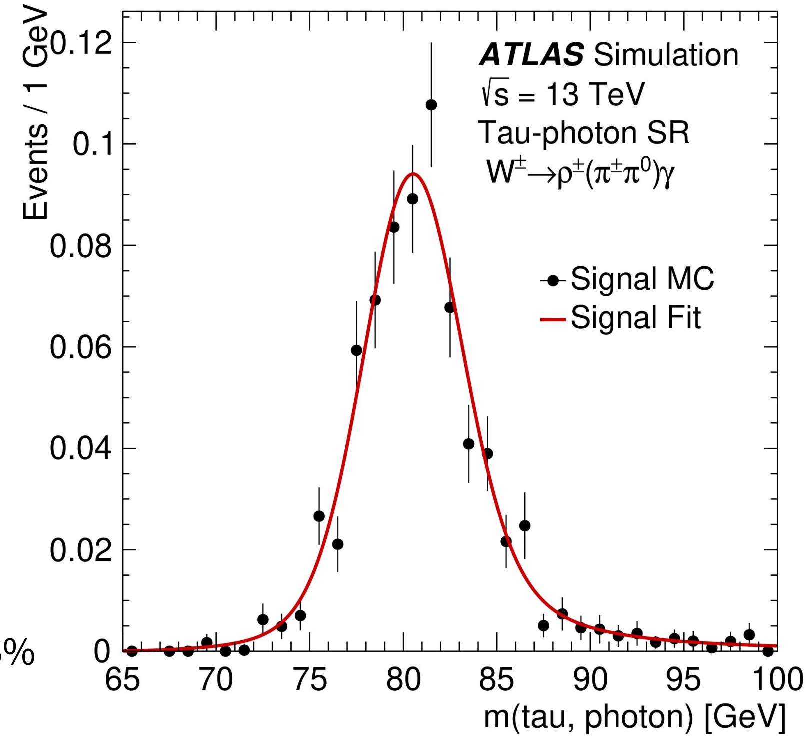
Signal modelling & uncertainties

Signal Modelling

- **$W^{\pm} \rightarrow \rho^{\pm}\gamma$** signal simulated using **Powheg + Pythia**
  - decays simulated isotropically and re-weighted to theoretical polarisation
- Modelled in fit using voigtian x efficiency function (parameters fixed to MC)

Signal Systematics
(very small effect on upper limit - 1%)

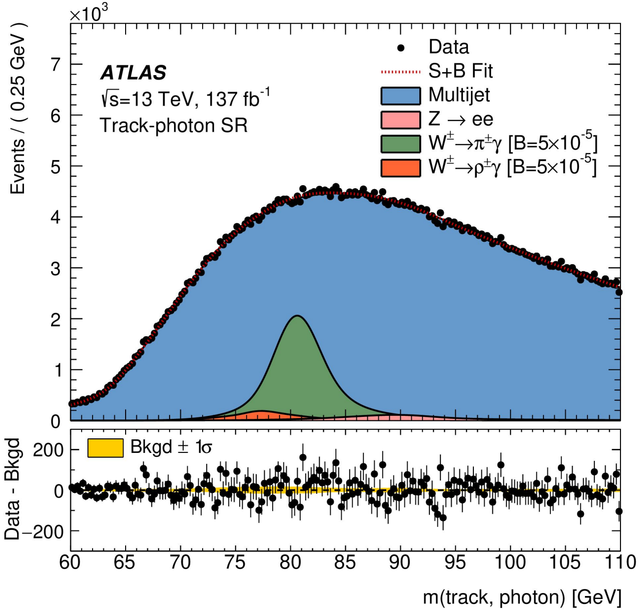
- Theory scale variations - 6.5%
- Trigger Efficiency - 10 %
- Cross Section - 3.3 %
- Luminosity - 0.83%
- Pileup - 5.5%
- EG Scale - 3.0%
- EG Resolution - 4.9%
- Photon ID - 1.1%
- Photon Isolation - 1.6%
- Tau Efficiency - 13%



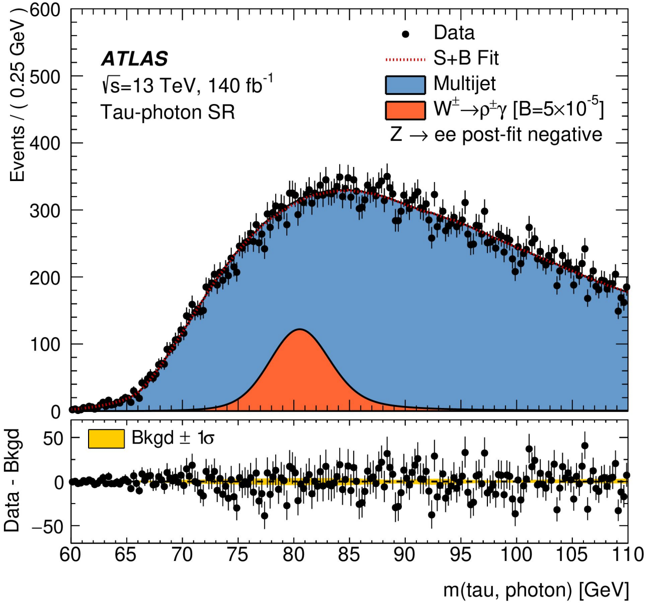
Results

- **Maximum Likelihood Fit in track + photon and tau + photon mass**
  - single fit in two categories, with correlated **μ(W→ ργ)**
  - systematic uncertainties are treated in an uncorrelated matter, except x-section and luminosity systematics

Track+photon



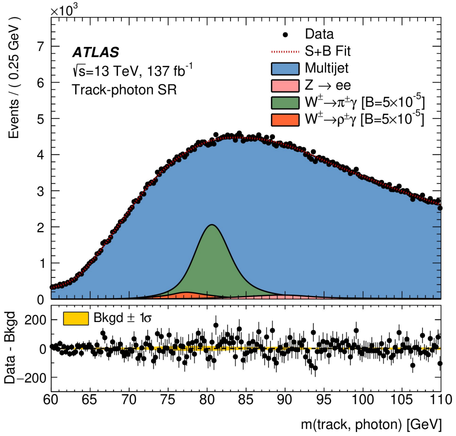
Tau+photon

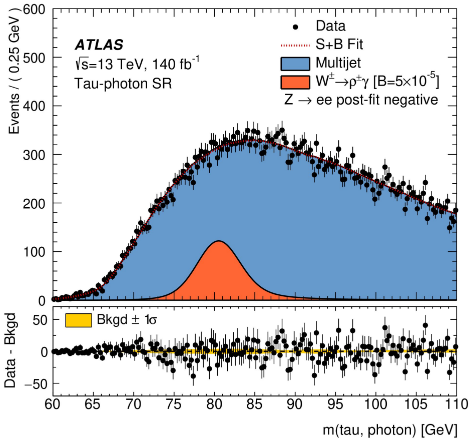


No significant excess with respect to the background prediction is found in data

Results

- **Asymptotic CL_s** with profile likelihood as test statistic
  - **Cannot disentangle W→π+γ and W→K+γ** - only one considered at a time (other signal assumed to be 0)
  - **W→π/K+γ and W→ρ+γ have distinct shapes** - other signal is profiled
  - B(W→ ργ) expected upper limit improves by **7%** wrt fit in tau+photon final state
  - **18%** improvement observed





	Expected branching fraction $\times 10^{-6}$	Observed branching fraction $\times 10^{-6}$
$W^{\pm} \to \pi^{\pm}\gamma$	$1.2^{+0.5}_{-0.3}$	1.9
$W^{\pm} \to K^{\pm}\gamma$	$1.1^{+0.4}_{-0.3}$	1.7
$W^{\pm} \to \rho^{\pm}\gamma$	$6.0^{+2.3}_{-1.7}$	5.2

Results

- **Asymptotic CL$_s$** with profile likelihood as test statistic
  - **Cannot disentangle W→π+γ and W→K+γ** - only one considered at a time (other signal assumed to be 0)
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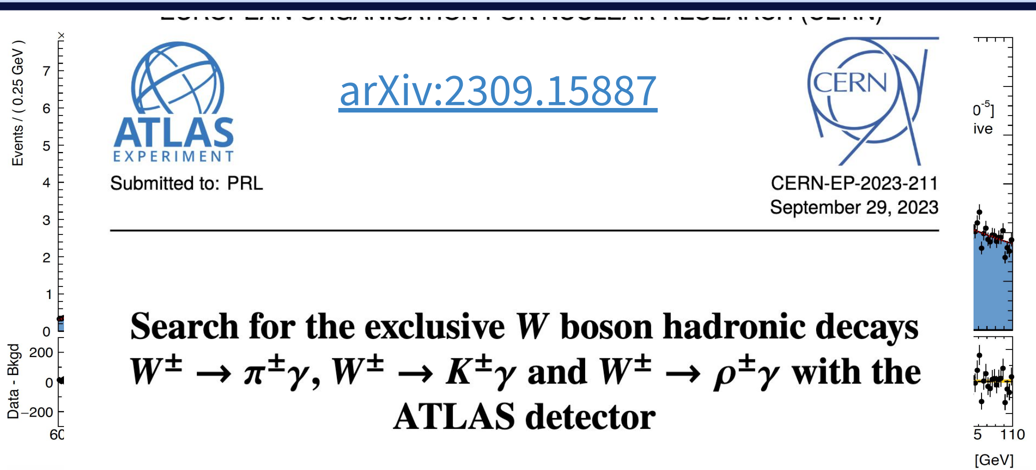


ATLAS EXPERIMENT

arXiv:2309.15887

Submitted to: PRL

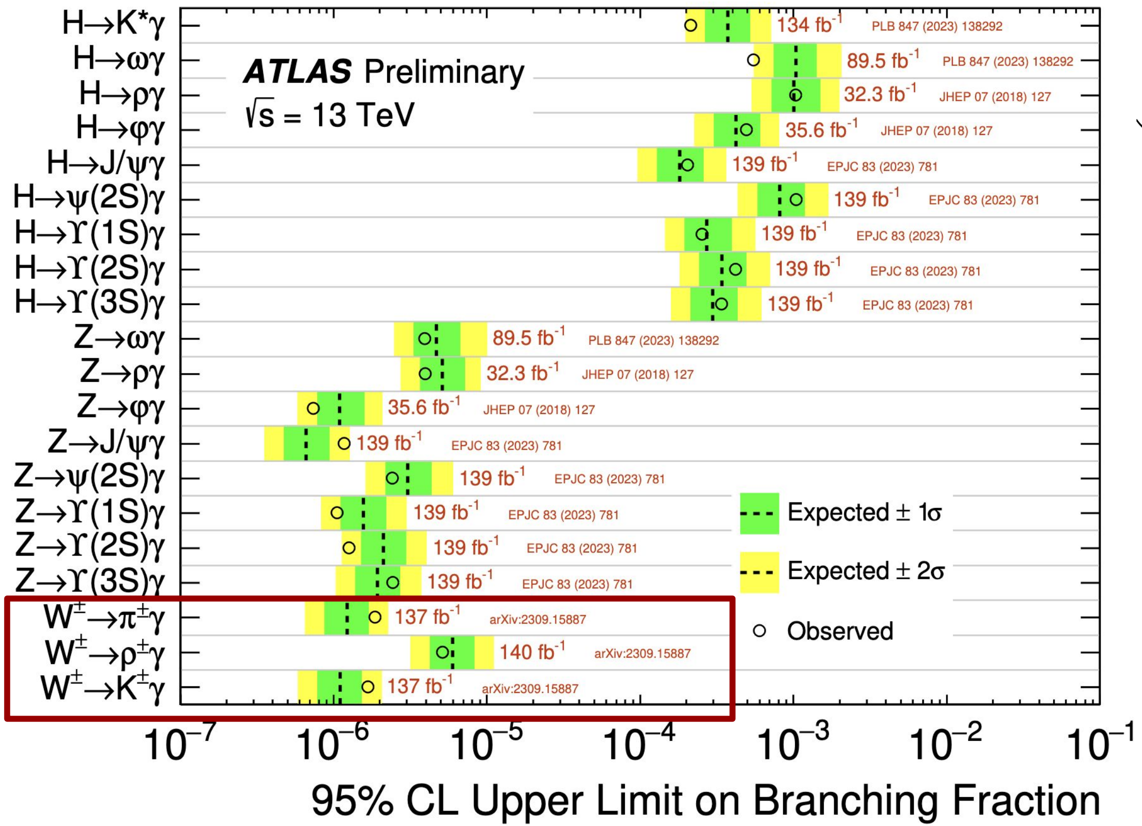
CERN-EP-2023-211

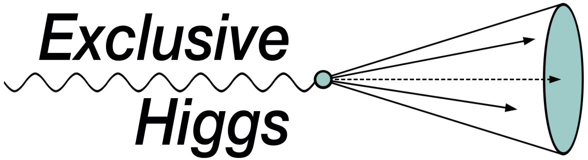
September 29, 2023

Search for the exclusive *W* boson hadronic decays $W^\pm \to \pi^\pm\gamma$, $W^\pm \to K^\pm\gamma$ and $W^\pm \to \rho^\pm\gamma$ with the ATLAS detector

	Expected branching fraction $\times 10^{-6}$	Observed branching fraction $\times 10^{-6}$
$W^\pm \to \pi^\pm\gamma$	$1.2^{+0.5}_{-0.3}$	1.9
$W^\pm \to K^\pm\gamma$	$1.1^{+0.4}_{-0.3}$	1.7
$W^\pm \to \rho^\pm\gamma$	$6.0^{+2.3}_{-1.7}$	5.2

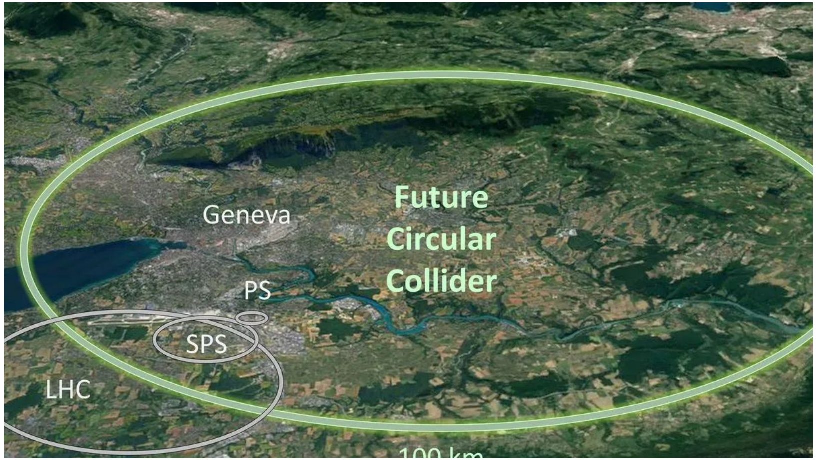
Searches for H/Z→Mγ at ATLAS





What does the future hold?

- 3000 fb^{-1} **HL-LHC**:
  - could be just enough to observe **W→πππ**
  - would require further analysis improvements to observe **W→Mγ**
- Future collider facilities currently being designed
  - **FCC-ee** projected to produce **clean sample** of $O(10^8)$ W^+W^- events
    - Enough to observe **W→D_sγ** and **W→πππ** according to current expectations
  - **FCC-hh** projected to deliver $O(10^{12})$ W bosons from inclusive production
    - $O(10^3)$ **W→πγ** and **W→ργ**



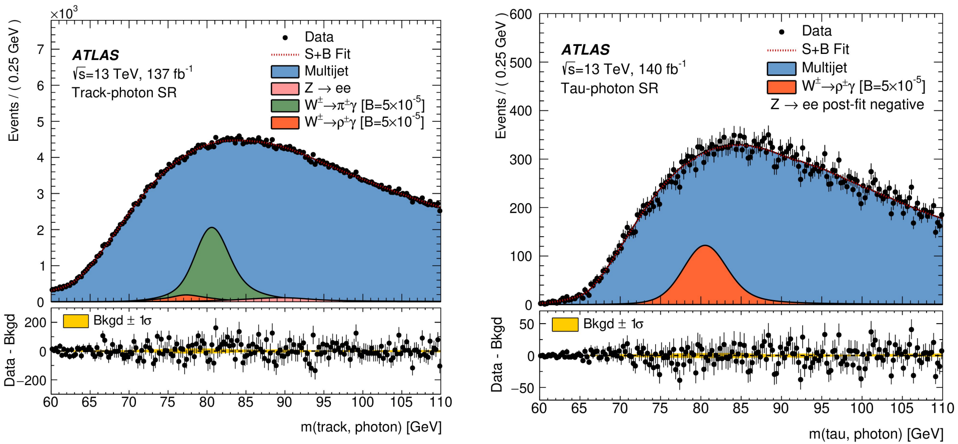
Long road ahead, but these analyses and the developed techniques are fundamental first steps towards observation of these decays

Summary

- **To date none of the exclusive hadronic decays of the W boson have been observed**
  - Weak or no experimental constraints available
- **Searches for these decays enabled by:**
  - Dedicated meson + photon triggers
  - Data-driven non-parametric background modelling method
  - “Inverse” analysis techniques:
    - photon trigger for $W^{\pm} \to \rho^{\pm}\gamma$
    - taus to target $\rho^{\pm} \to \pi^{\pm} + \pi^{0}$ decay

Best UL on $B(W^{\pm} \to \pi^{\pm}\gamma)$

First limits on $B(W^{\pm} \to \rho^{\pm}\gamma)$ and $B(W^{\pm} \to K^{\pm}\gamma)$



	Expected branching fraction $\times 10^{-6}$	Observed branching fraction $\times 10^{-6}$
$W^{\pm} \to \pi^{\pm}\gamma$	$1.2^{+0.5}_{-0.3}$	1.9
$W^{\pm} \to K^{\pm}\gamma$	$1.1^{+0.4}_{-0.3}$	1.7
$W^{\pm} \to \rho^{\pm}\gamma$	$6.0^{+2.3}_{-1.7}$	5.2

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THANK YOU FOR LISTENING!