Scattering Protons & Colliding Photons

Looking at photon-induced WW production

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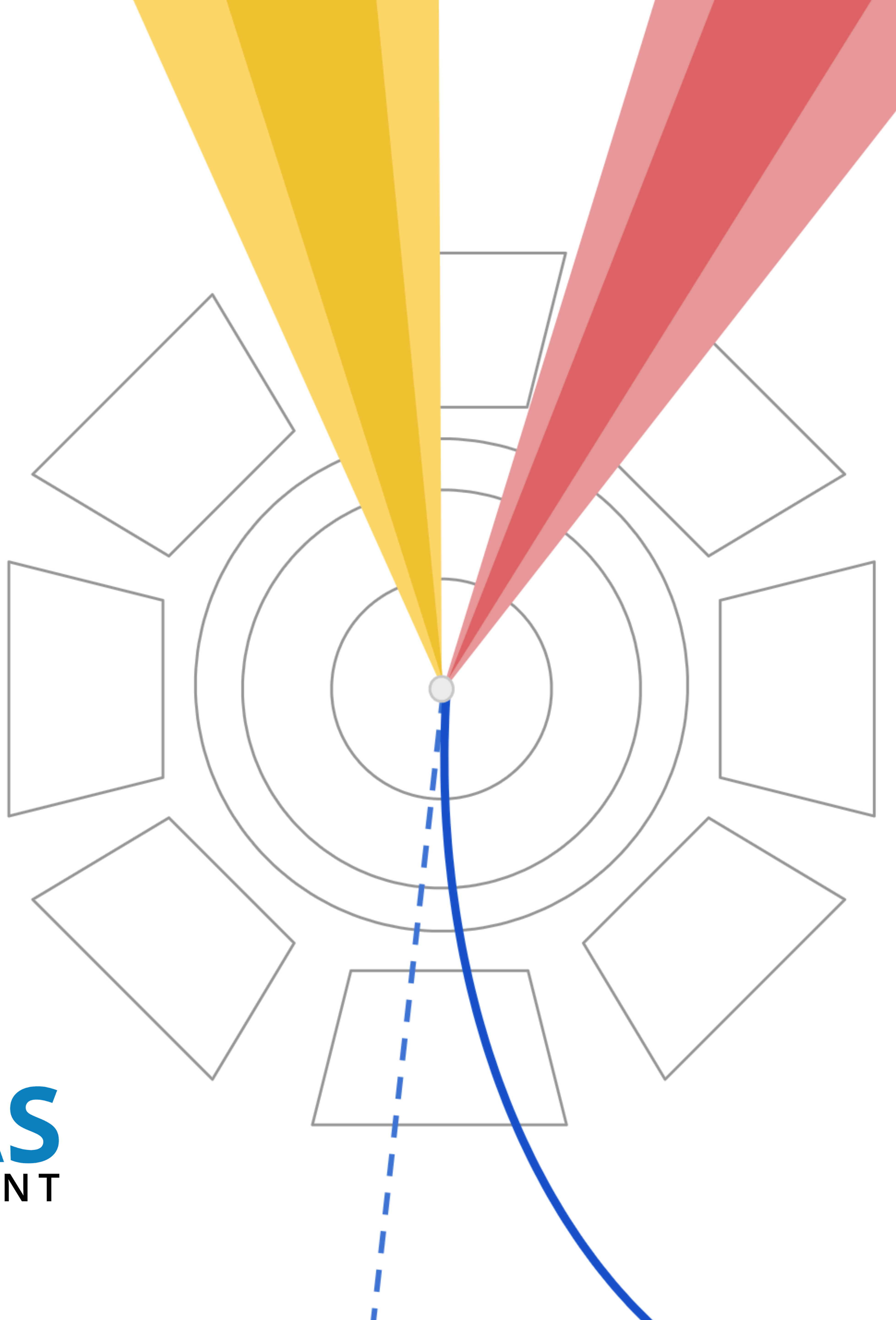
ATLAS-Heidelberg Meeting
Trifels 2024



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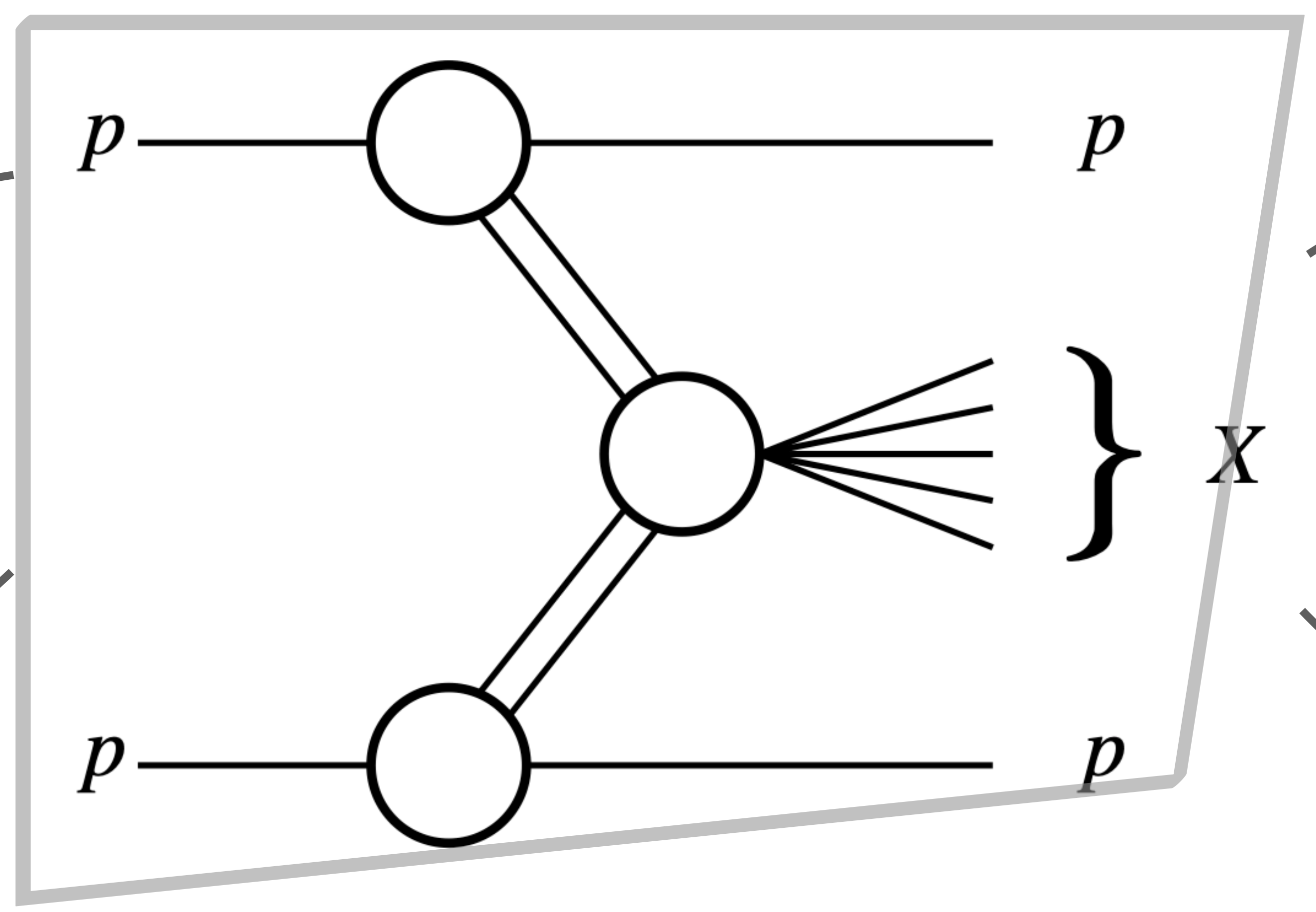
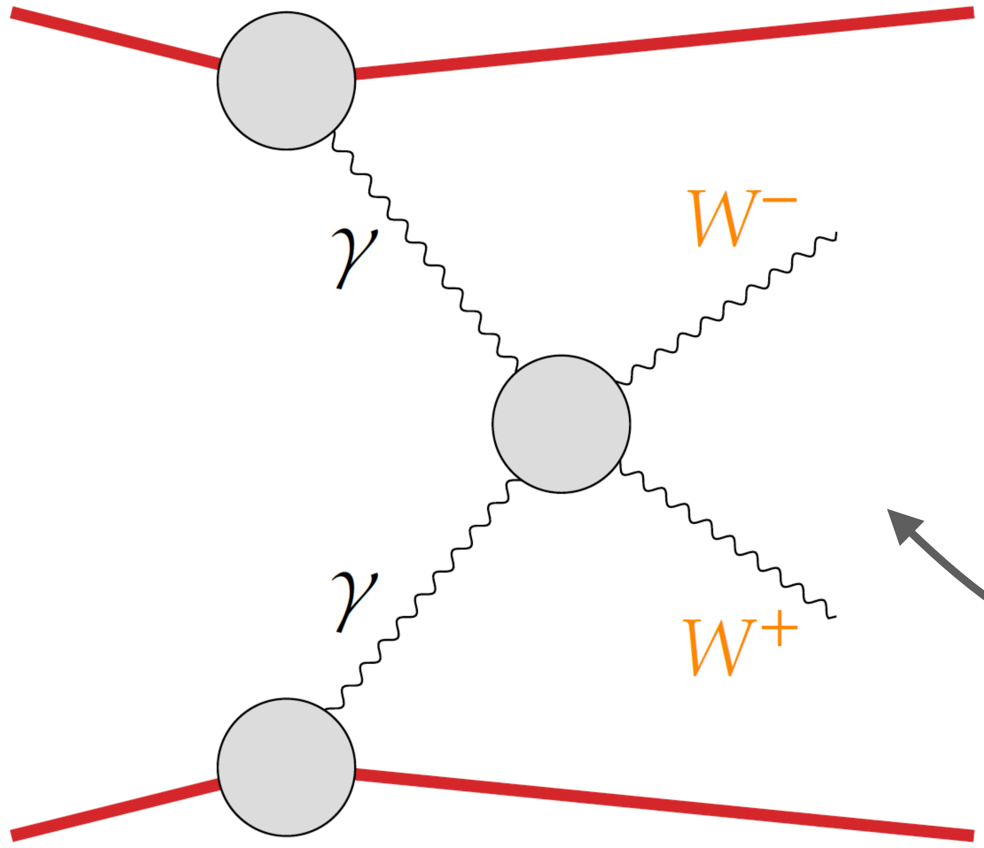
ATLAS
EXPERIMENT

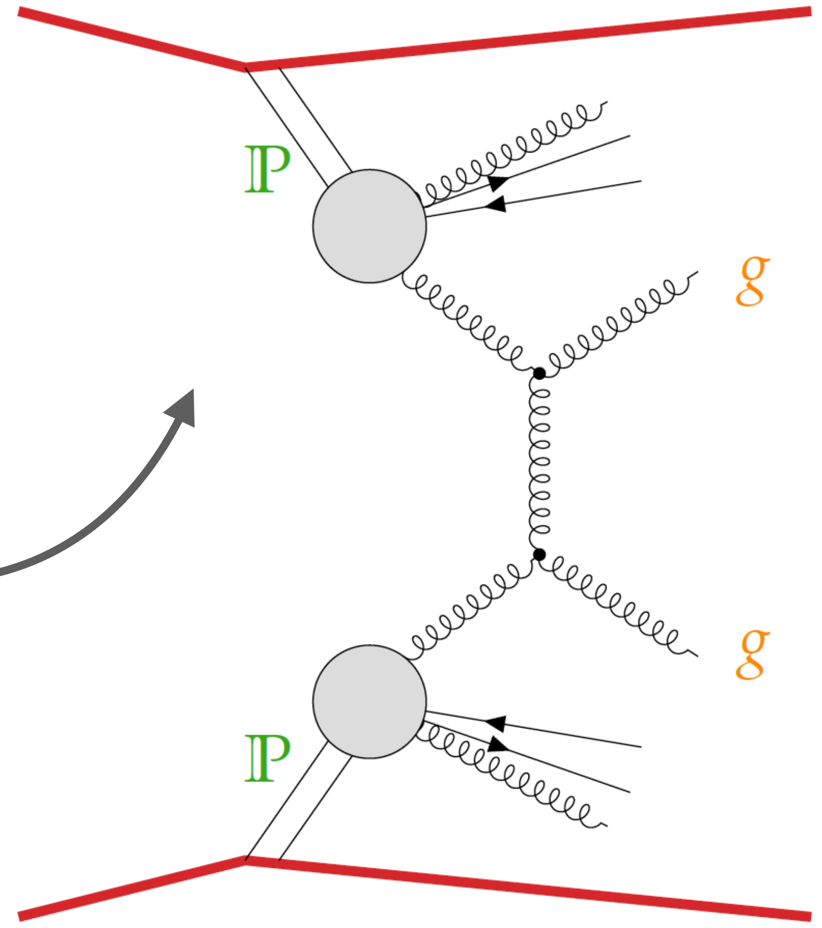
Diffractive Physics

Central Exclusive Production

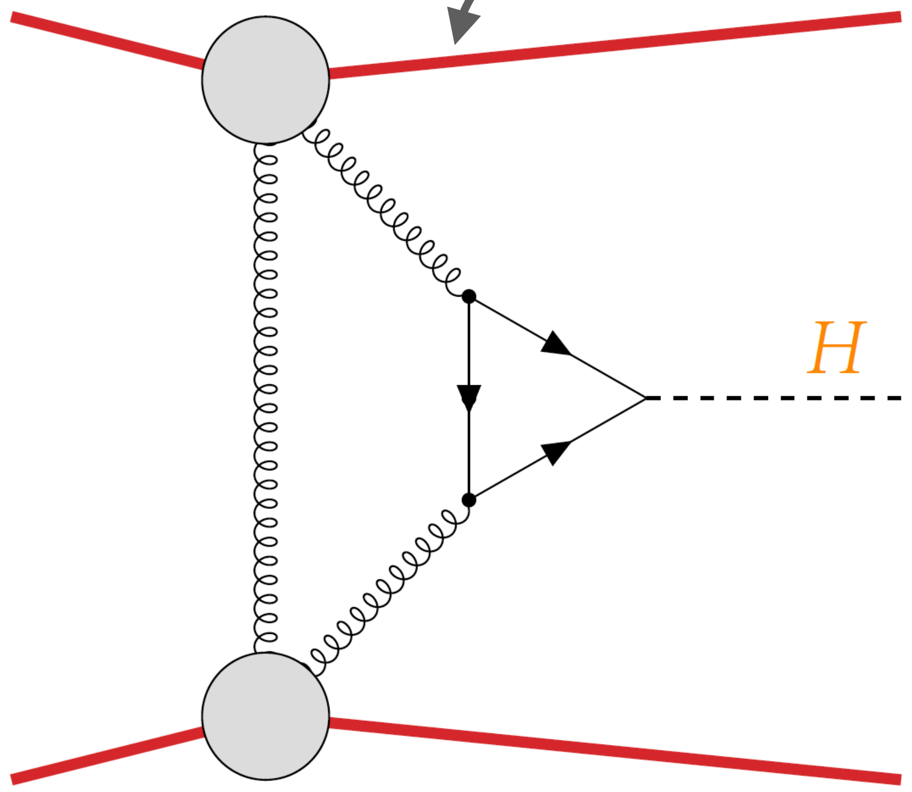




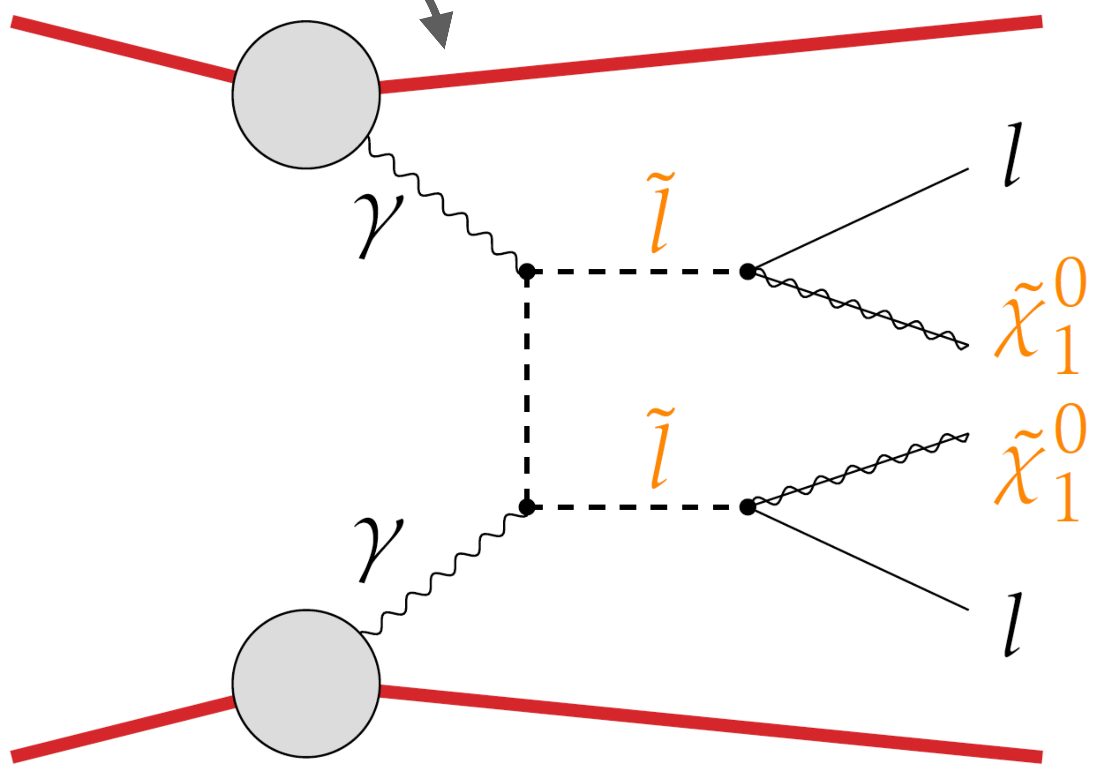
W Bosons



Diffractive Jets

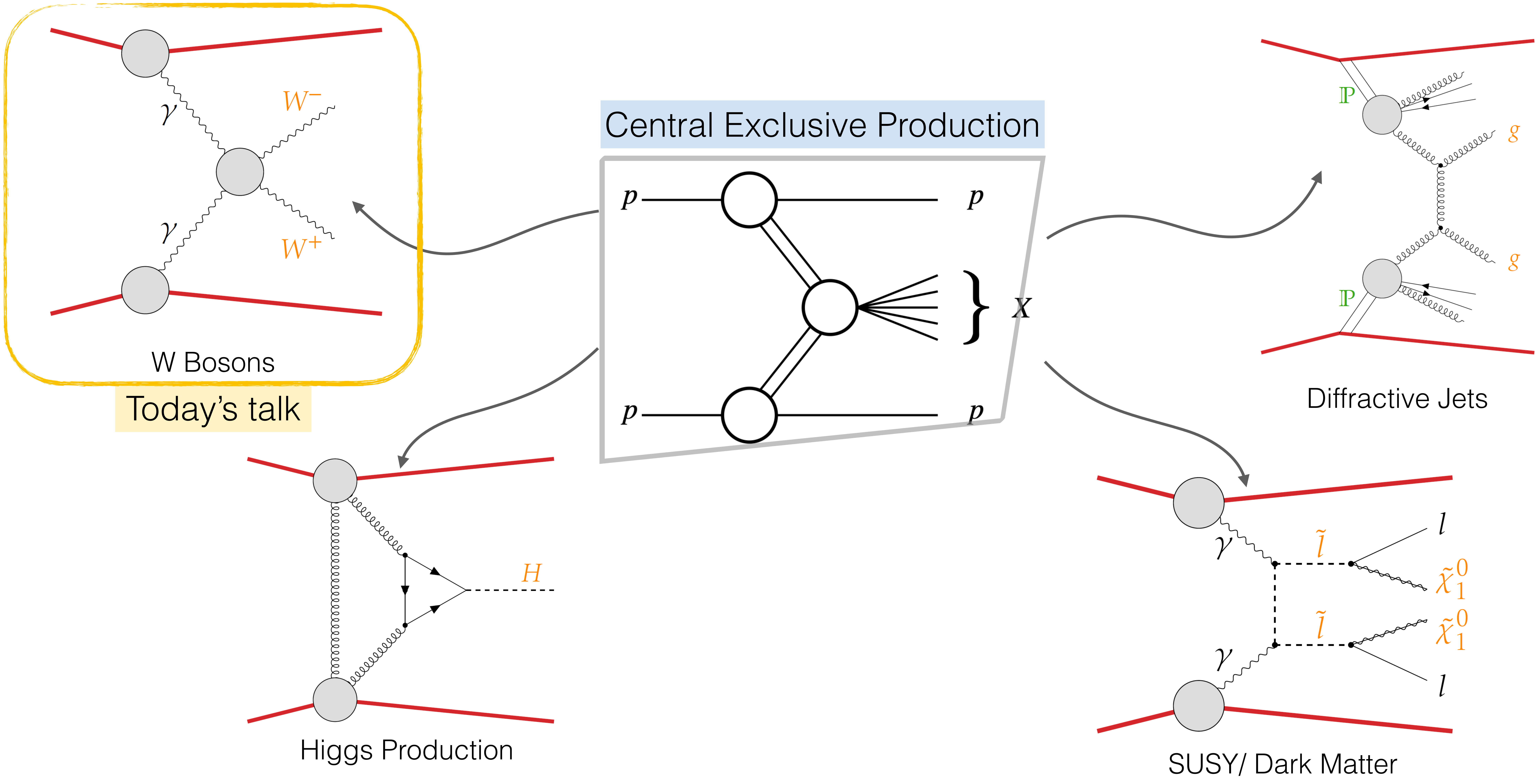


Higgs Production

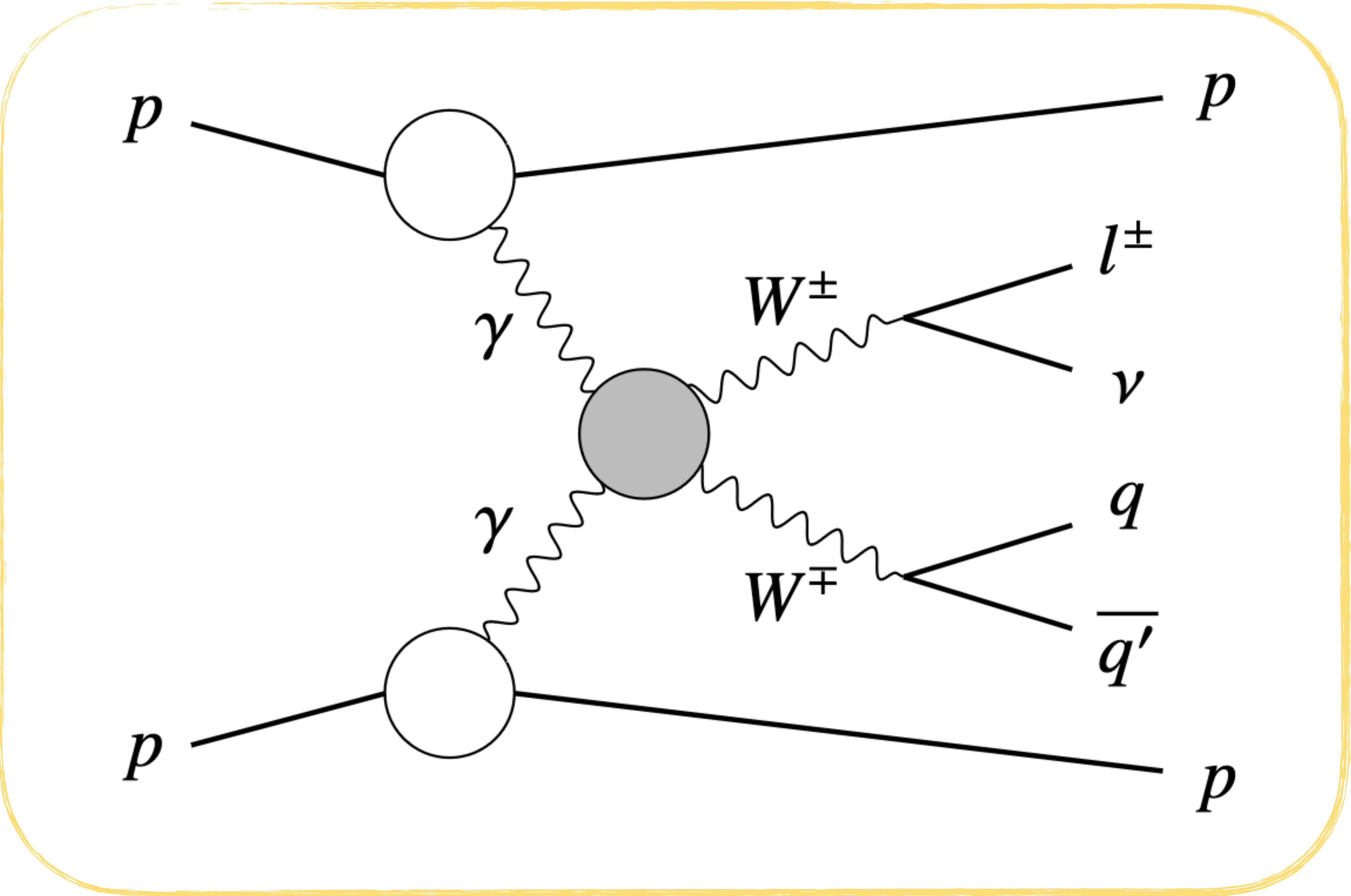


SUSY/ Dark Matter

Diffractive Physics



Photon-Induced WW



Boosted Channel

Photon-induced→ decay products are produced back-to-back

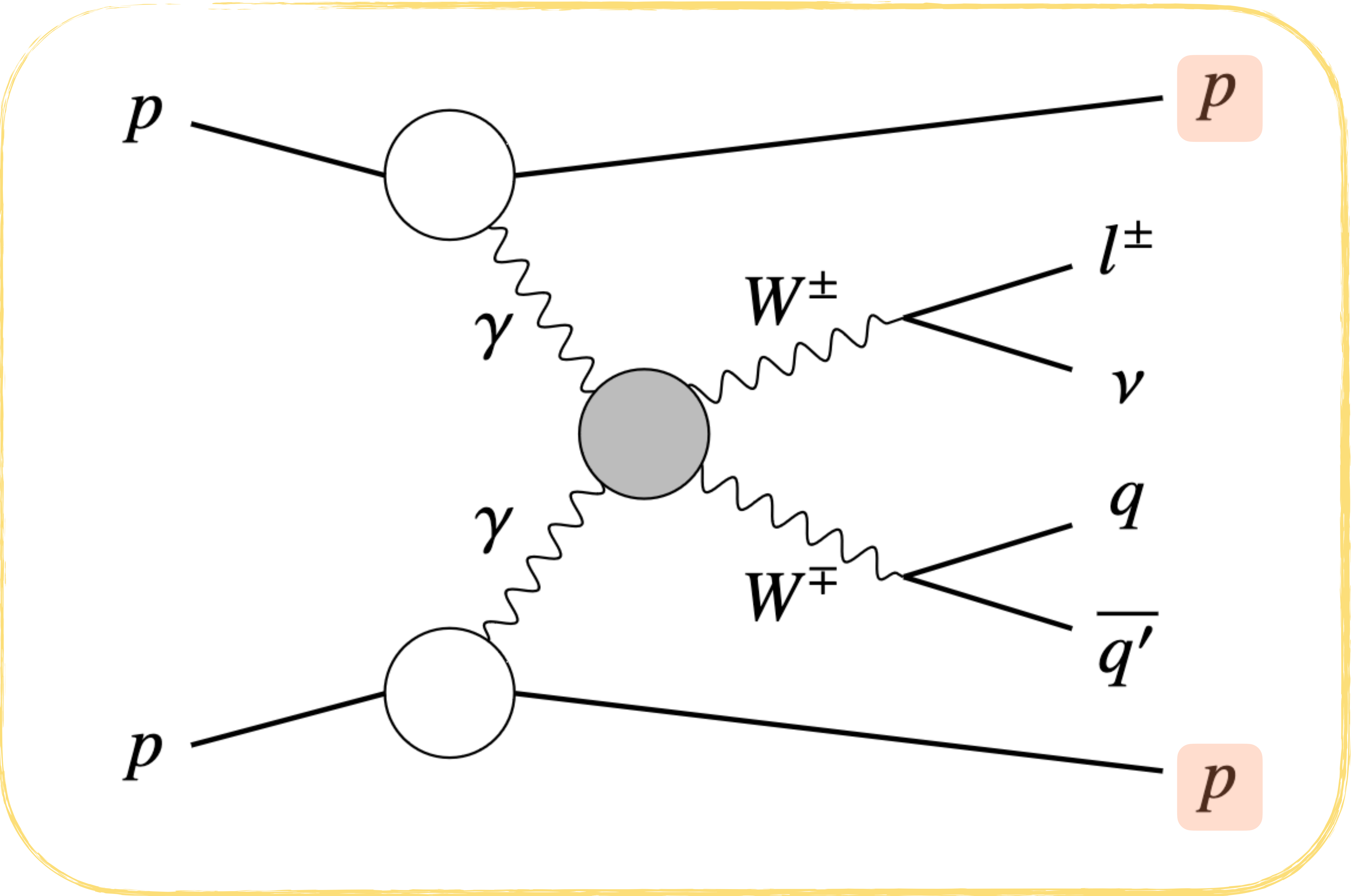
W mass → heavier final state

New Physics

Semileptonic channel → access higher energy regions

Phase space to measure deviations from the Standard Model → SMEFTs, aQGC

Photon-Induced WW



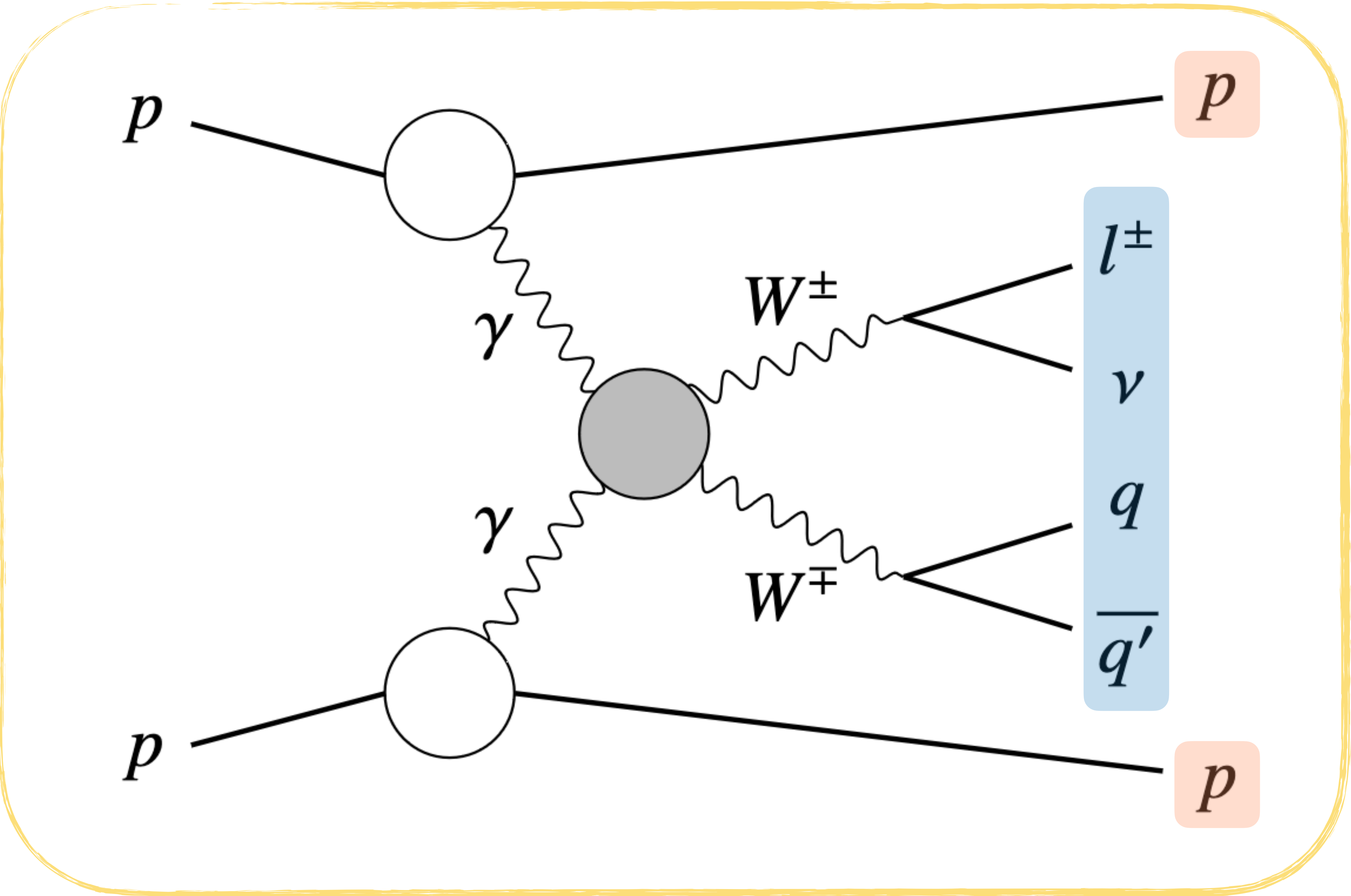
Challenge

Large jet/QCD background @LHC

Solution

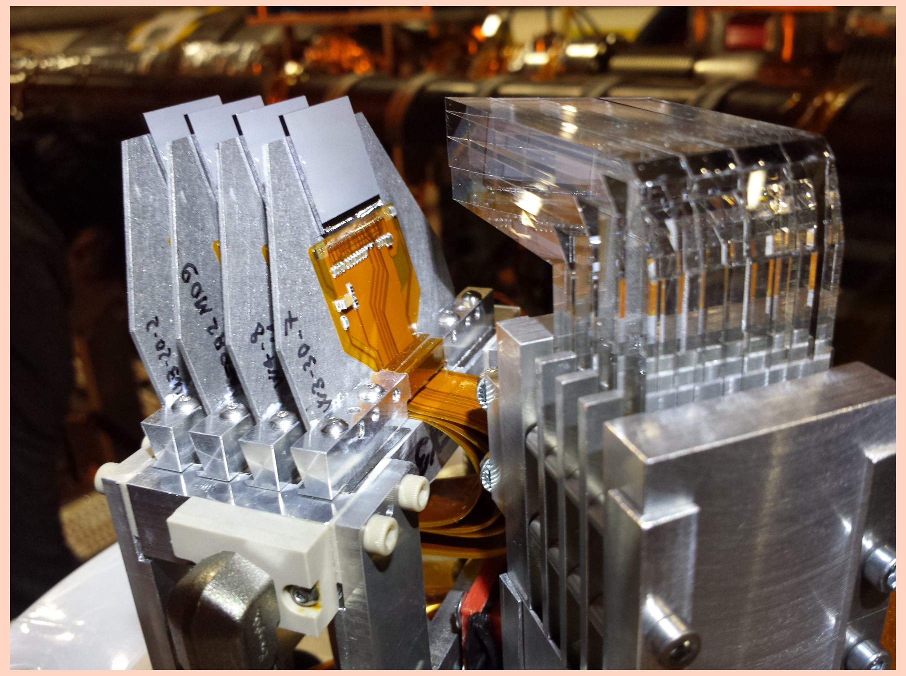
Take advantage of scattered protons to constrain process

Experimental Search



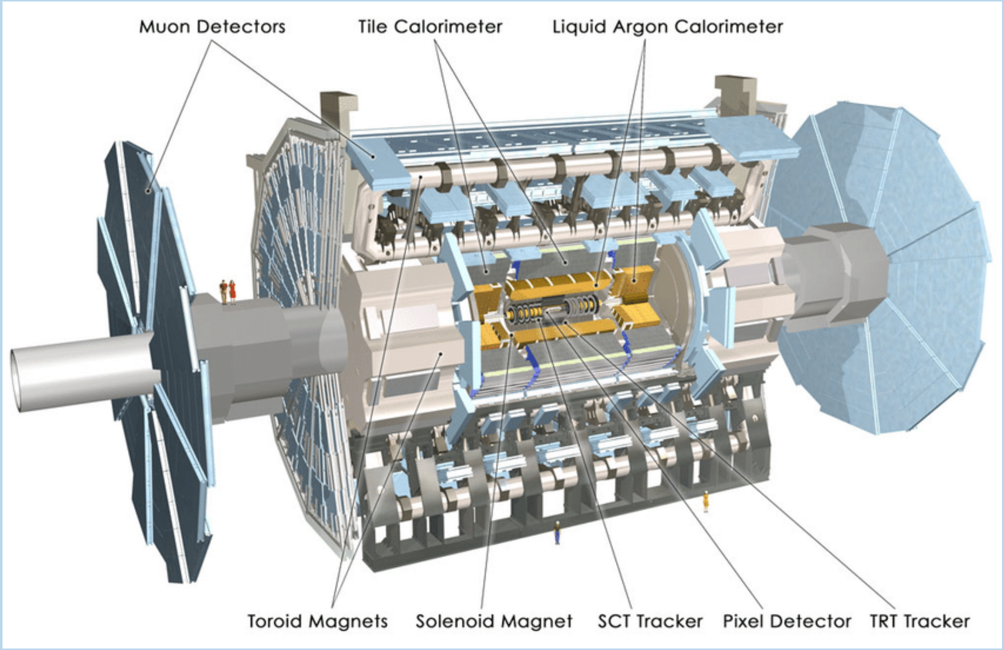
Scattering Protons

Protons tagged using forward detectors

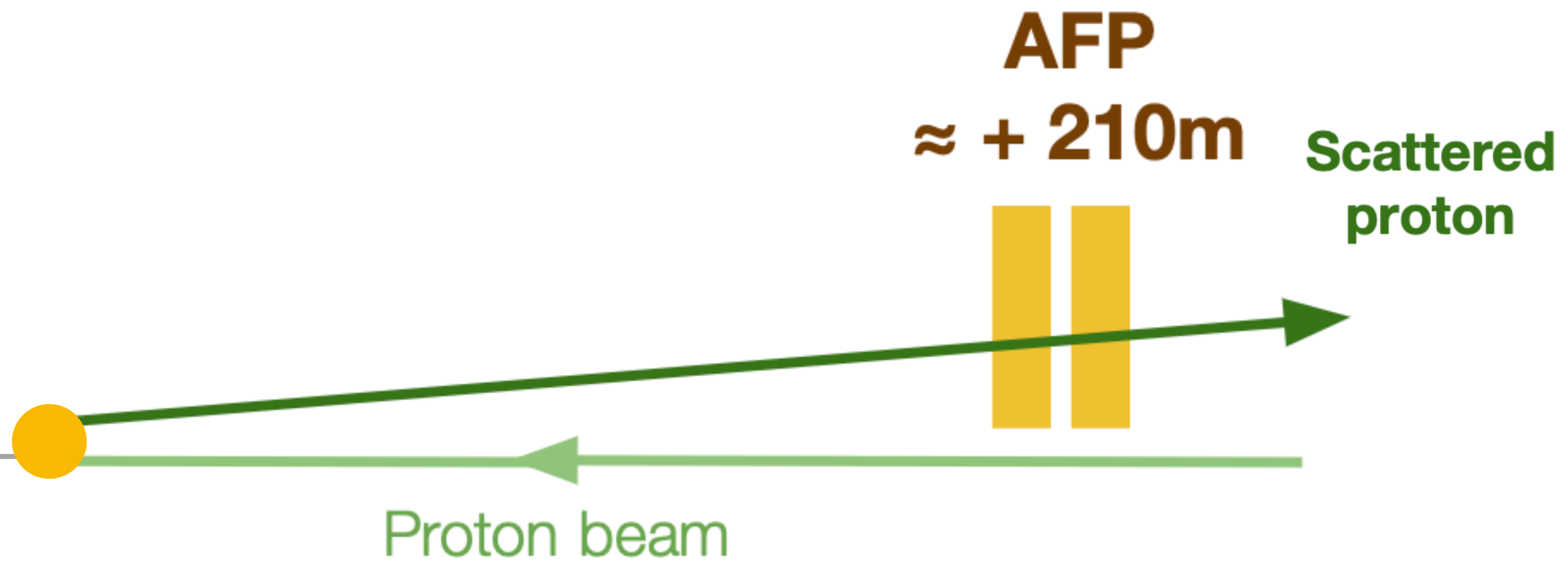


Colliding Photons

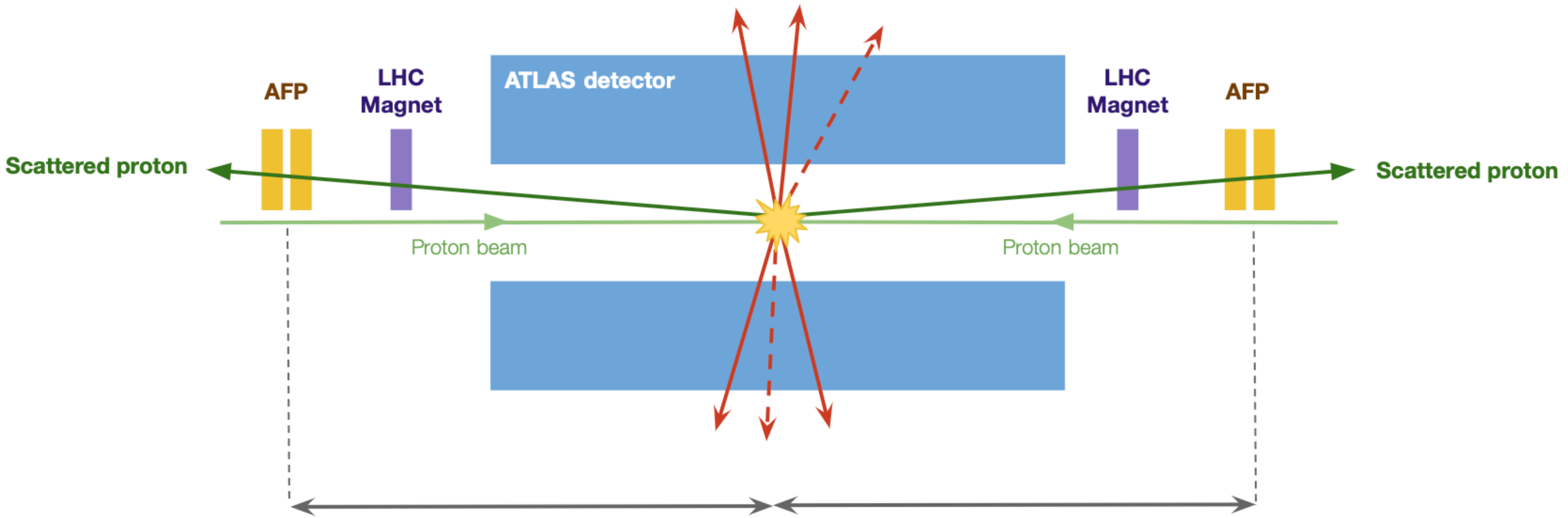
Standard ATLAS search



Scattering Protons

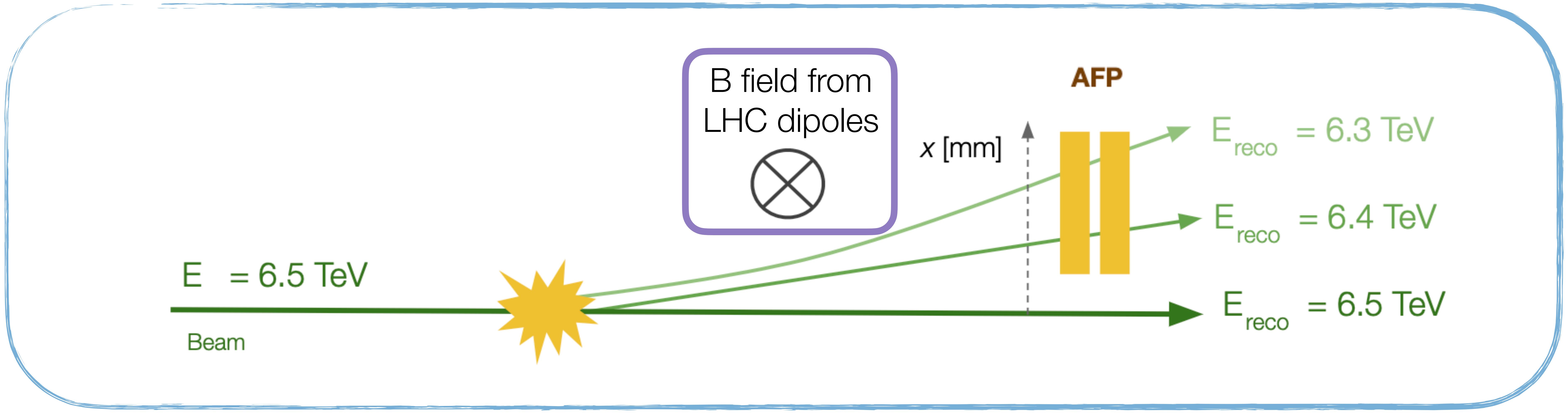


AFP: ATLAS Forward Proton Spectrometer



AFP detectors located ~ 200m either side of the interaction point

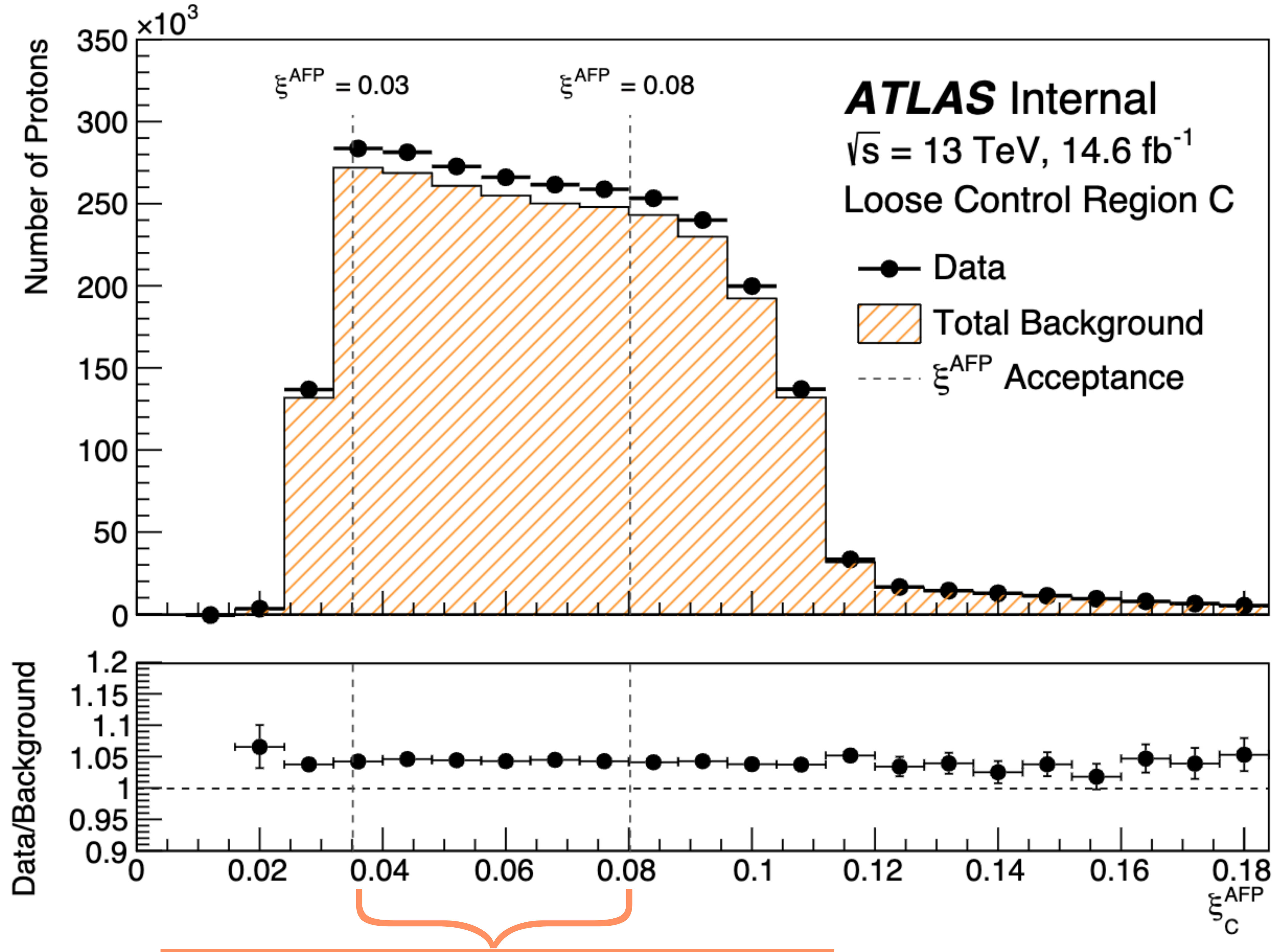
How to detect forward protons



Deflection of proton in x → Infer energy of proton

$$\xi^{A,C}_{AFP} = 1 - E_{\text{reconstructed}} / E_{\text{beam}}$$

Proton Kinematics



Geometric Acceptance of AFP

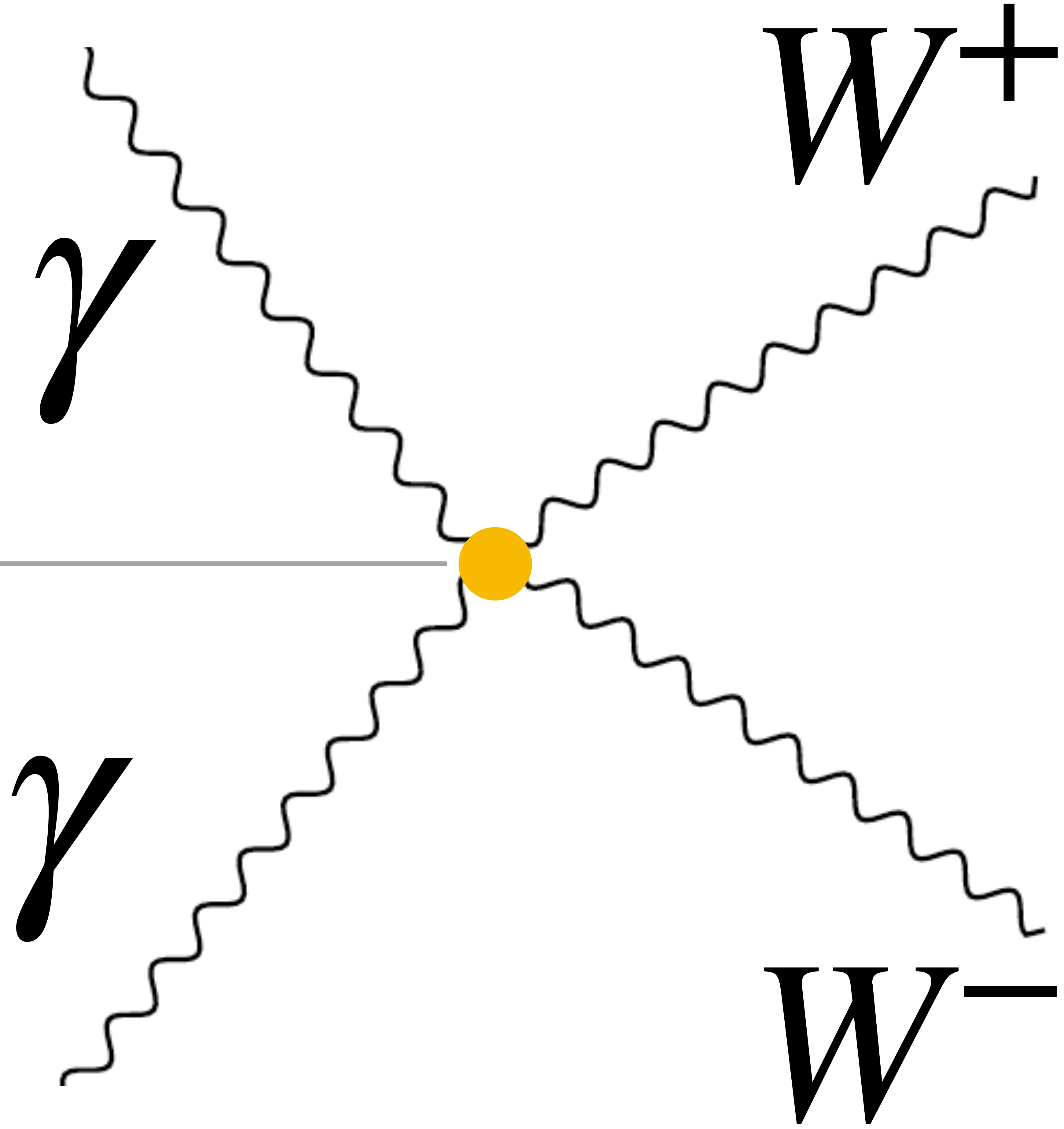
Control Region Distributions

Background well modelled & consistent

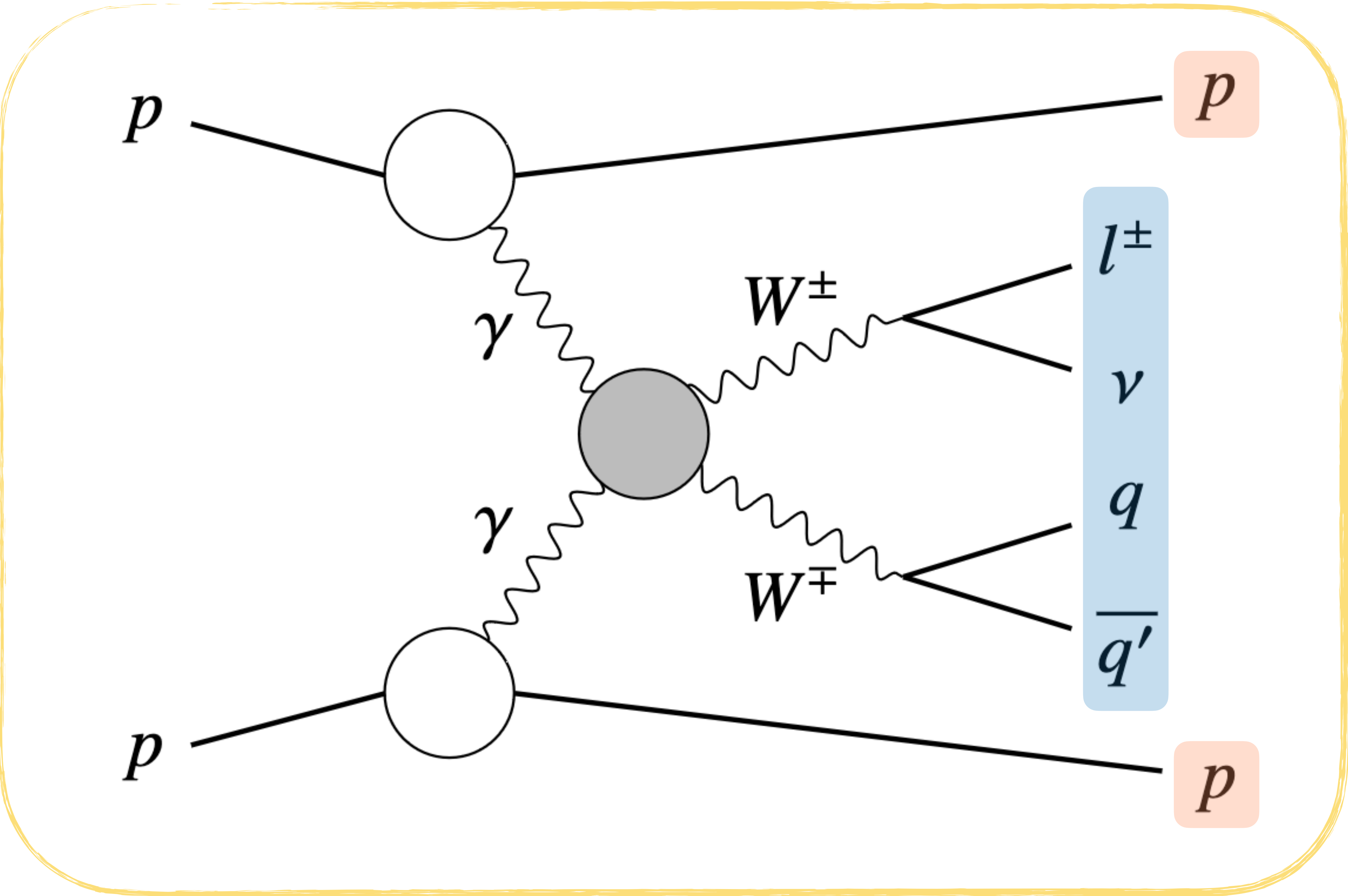
Similarly seen for proton multiplicity

$$\xi^{A,C}_{AFP} = 1 - E_{\text{reconstructed}} / E_{\text{beam}}$$

Colliding Photons



Central Process Kinematics



Search strategy

Comparison of ATLAS ξ_{WW} and ATLAS Forward Proton Detector ξ_{AFP}

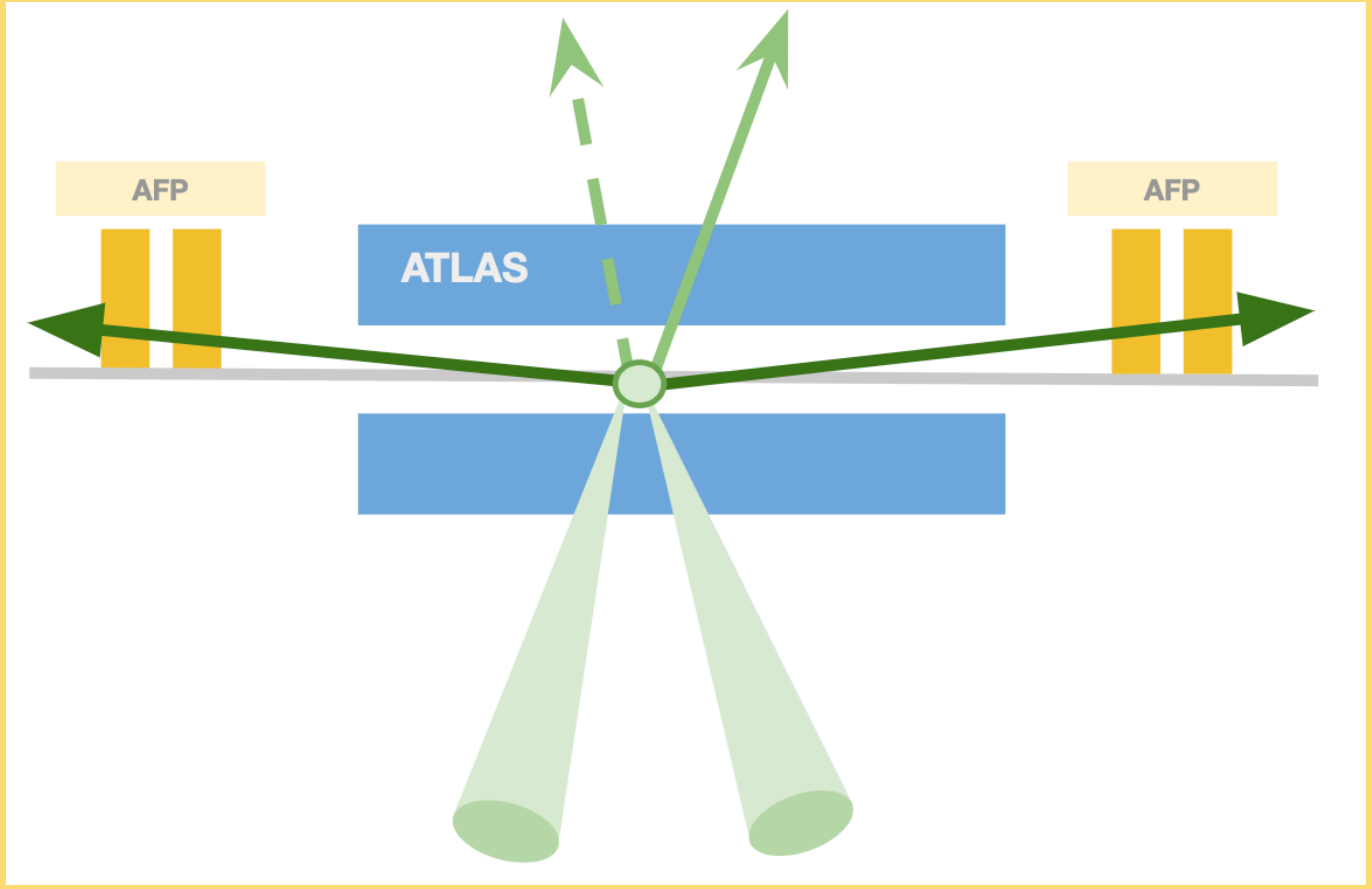
$$\xi_{AFP}^{A,C} = 1 - E_{\mathrm{reconstructed}} / E_{\mathrm{beam}}$$

Obtained with E_{reco} inferred from WW decay products

$$\xi_{WW}^{\pm} = \left(\frac{M_{WW}}{\sqrt{s}}\right)e^{\pm y_{WW}}$$

AFP and ATLAS correlations

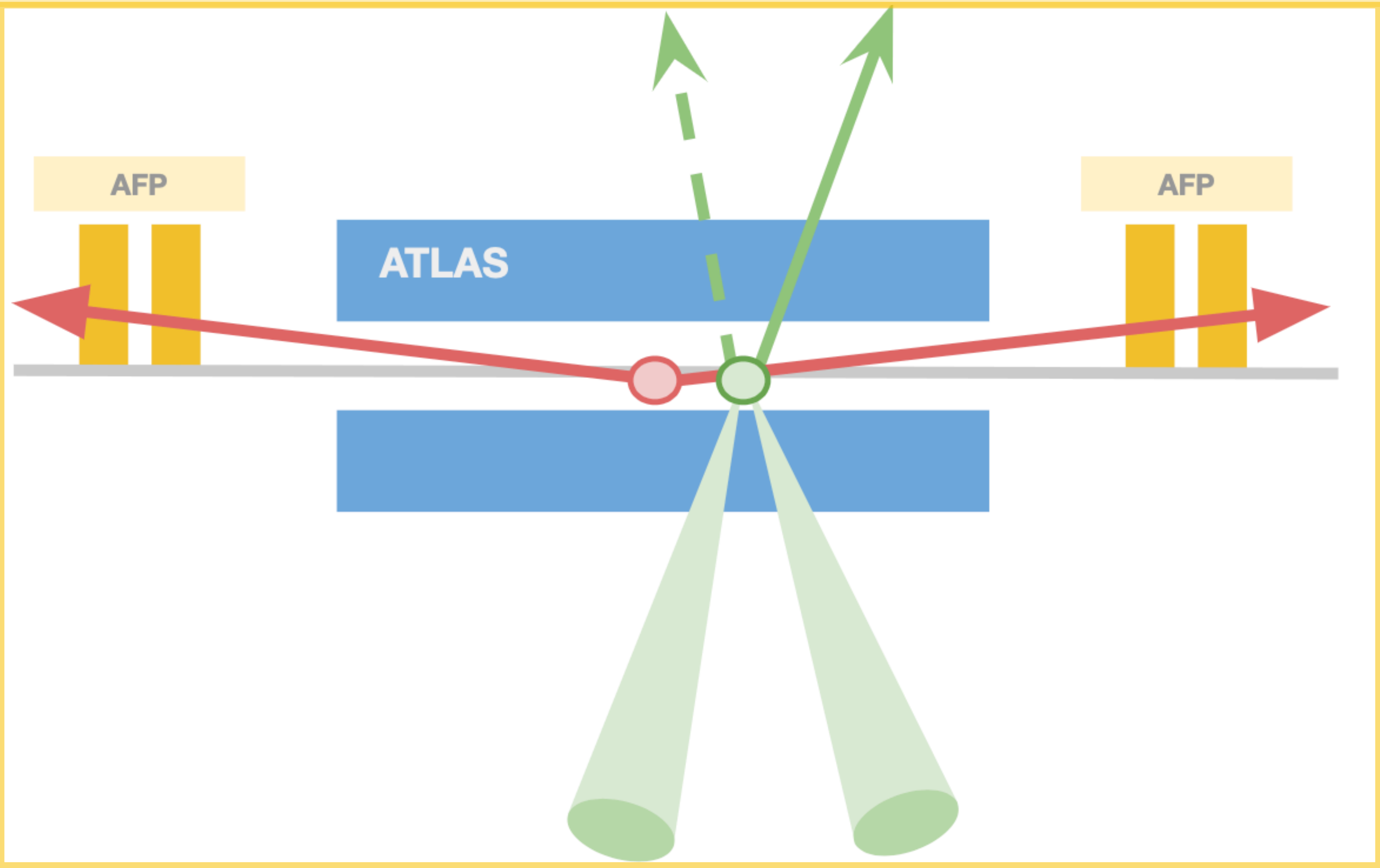
Signal



ξ_{WW} & ξ_{AFP}

Kinematically **correlated**

Background



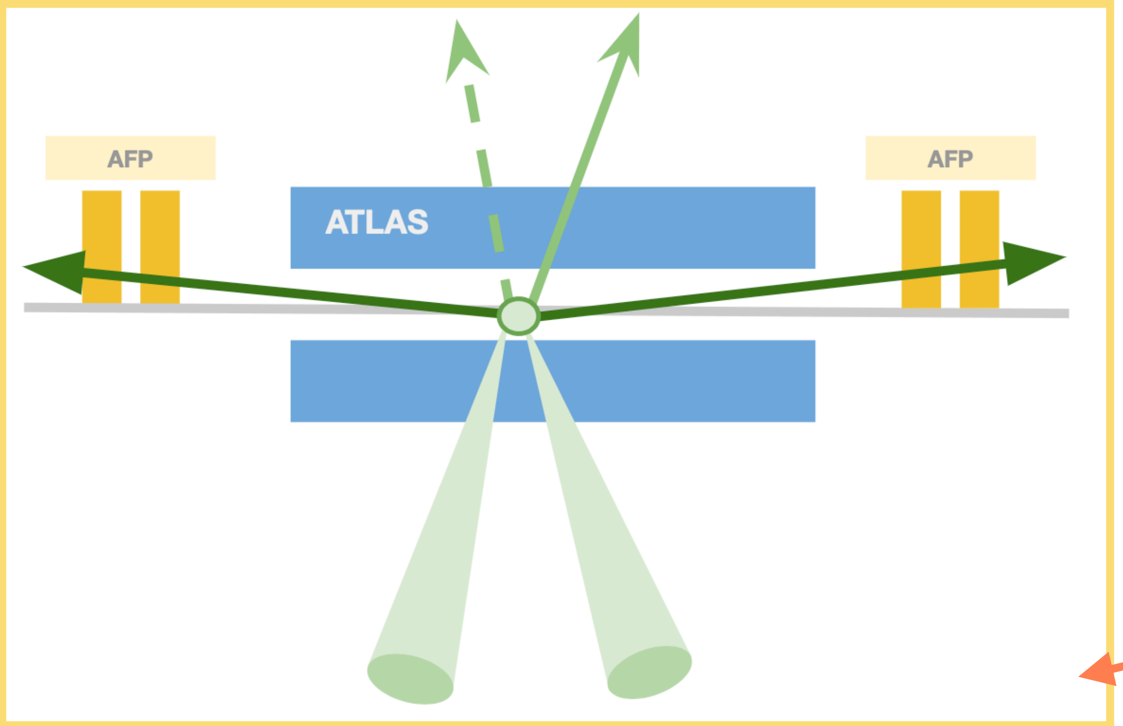
ξ_{WW} & ξ_{AFP}

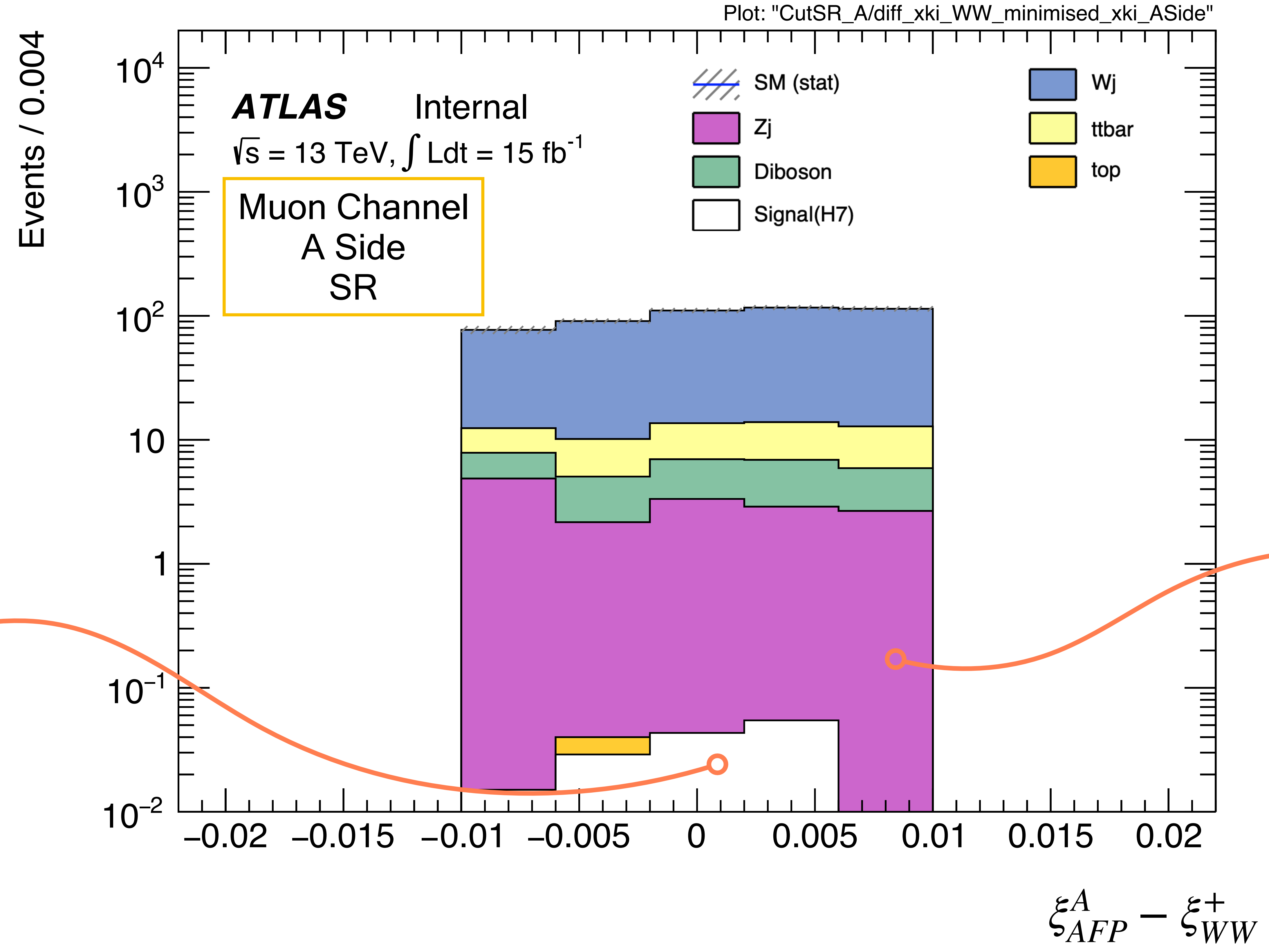
Kinematically **uncorrelated**

Combinatorial Background

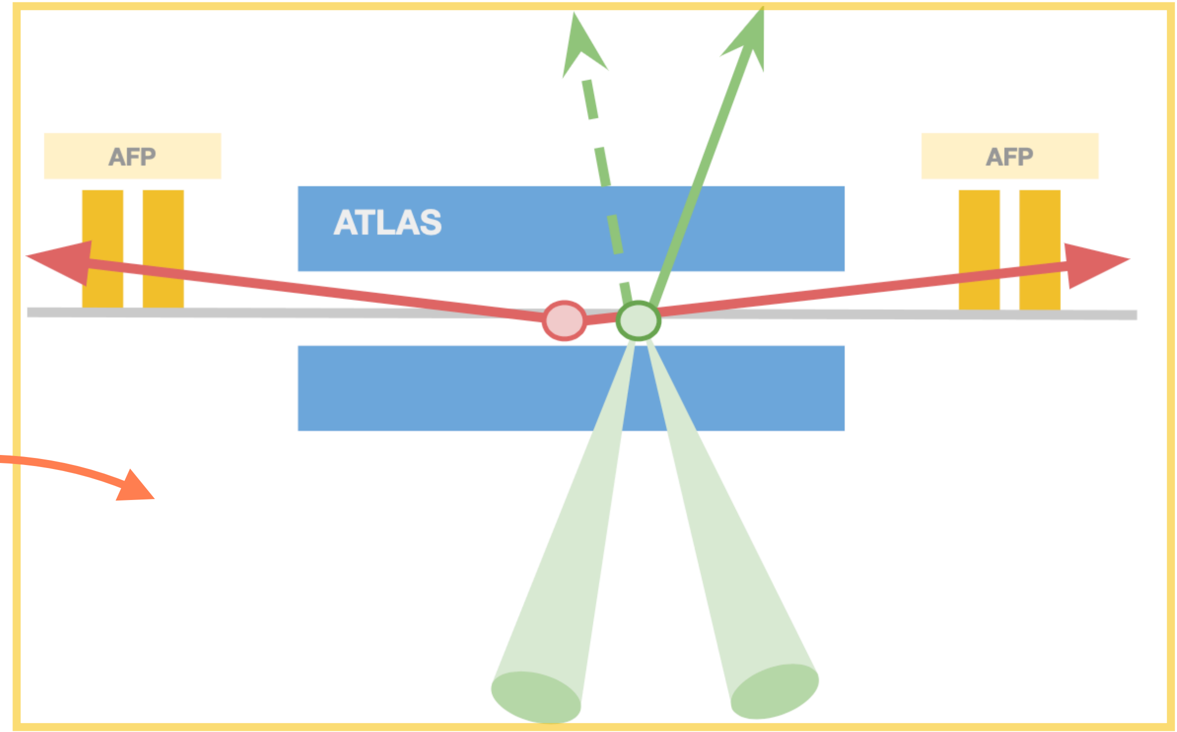
Event yields in simulation

Signal





Background



Null-hypothesis: Background only → dominated by combinatorial background

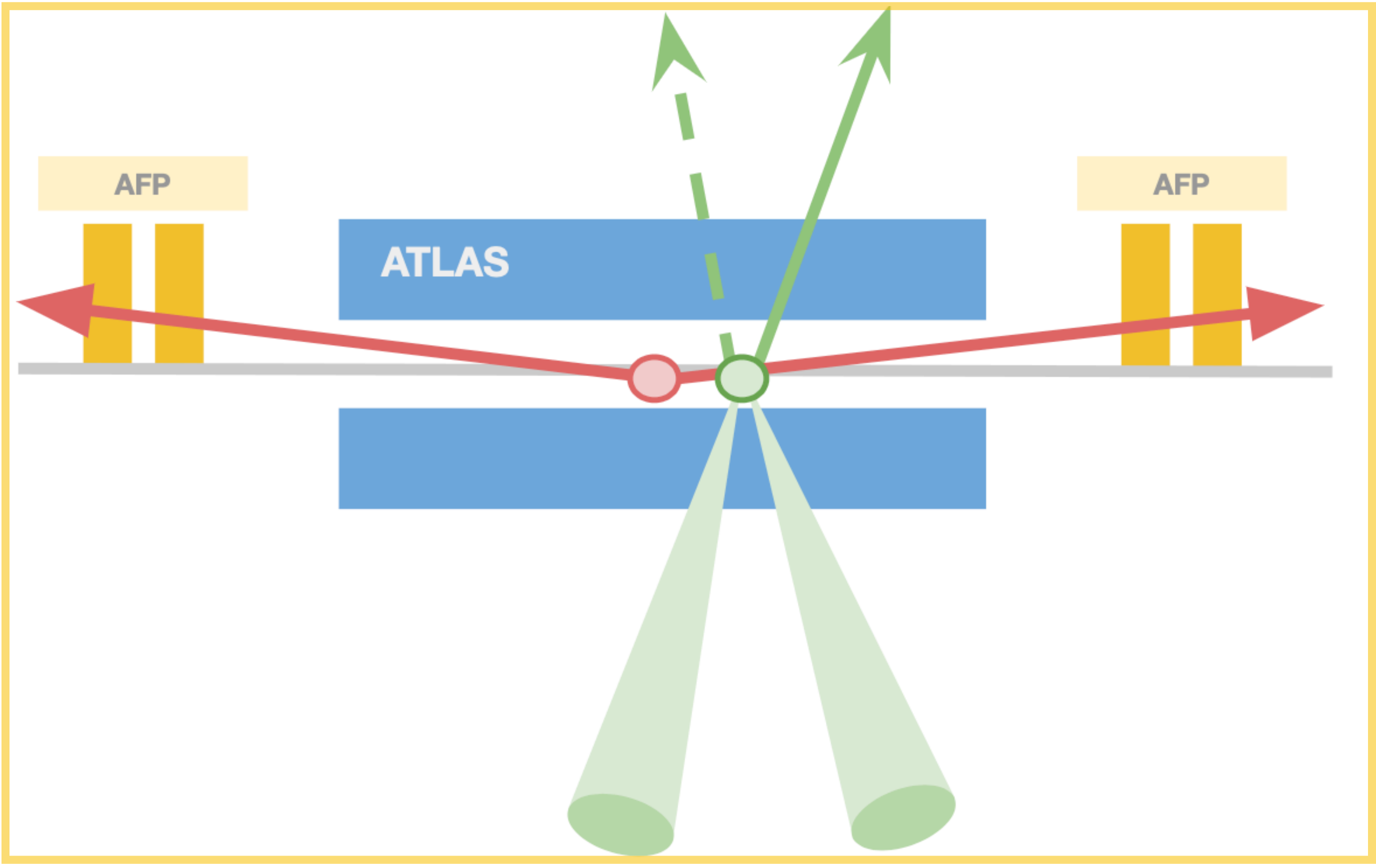
Background Modelling

Null hypothesis: Background only

Accurate **estimate for combinatorial background** in Signal Region required

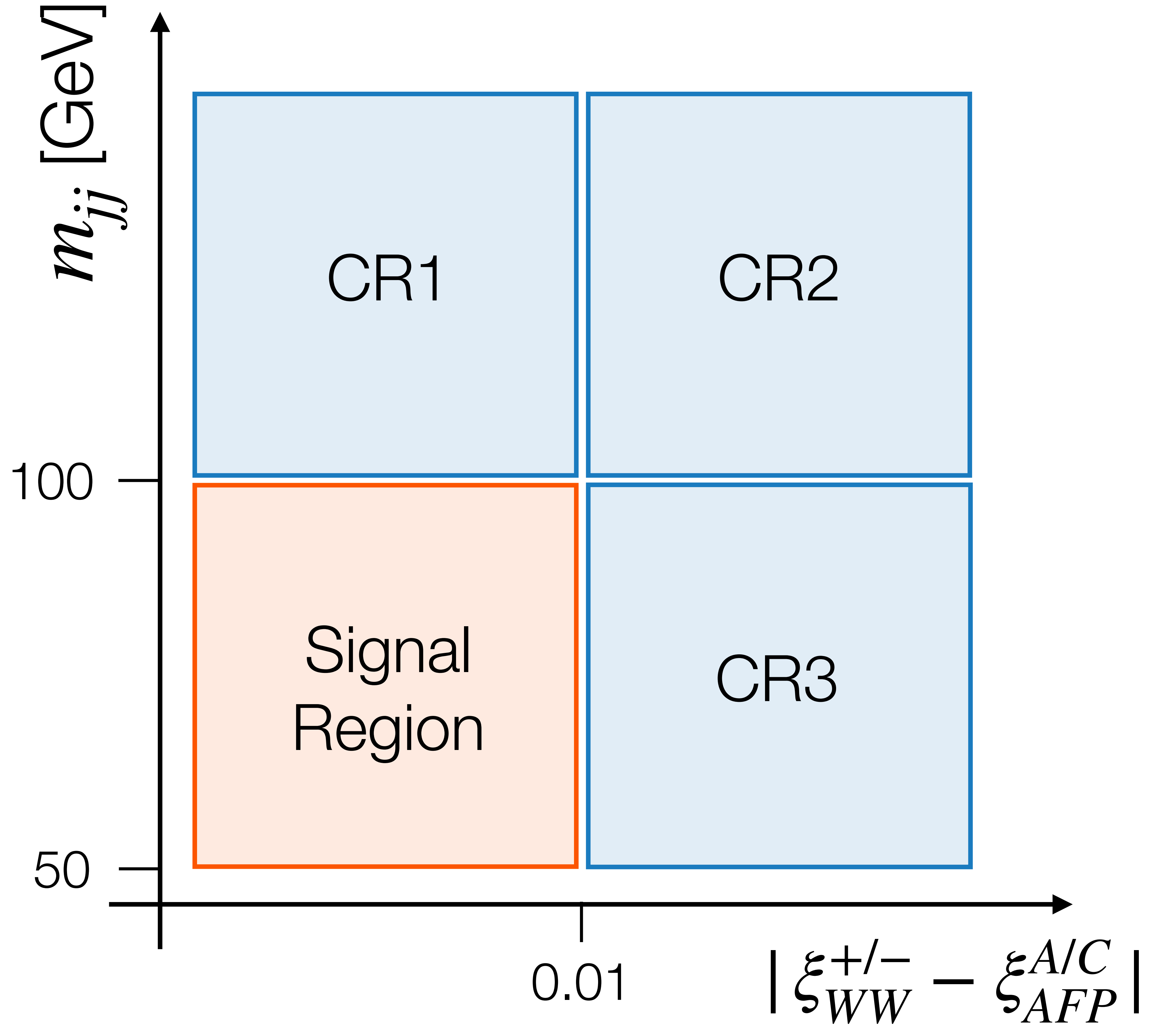
At unblinding:
See if data follows background only model

Background



Essential when setting limits on New Physics models!

Signal & Control Region Definitions



Regions defined by m_{jj} and $|\xi_{WW}^{+/-} - \xi_{AFP}^{A/C}|$ cuts

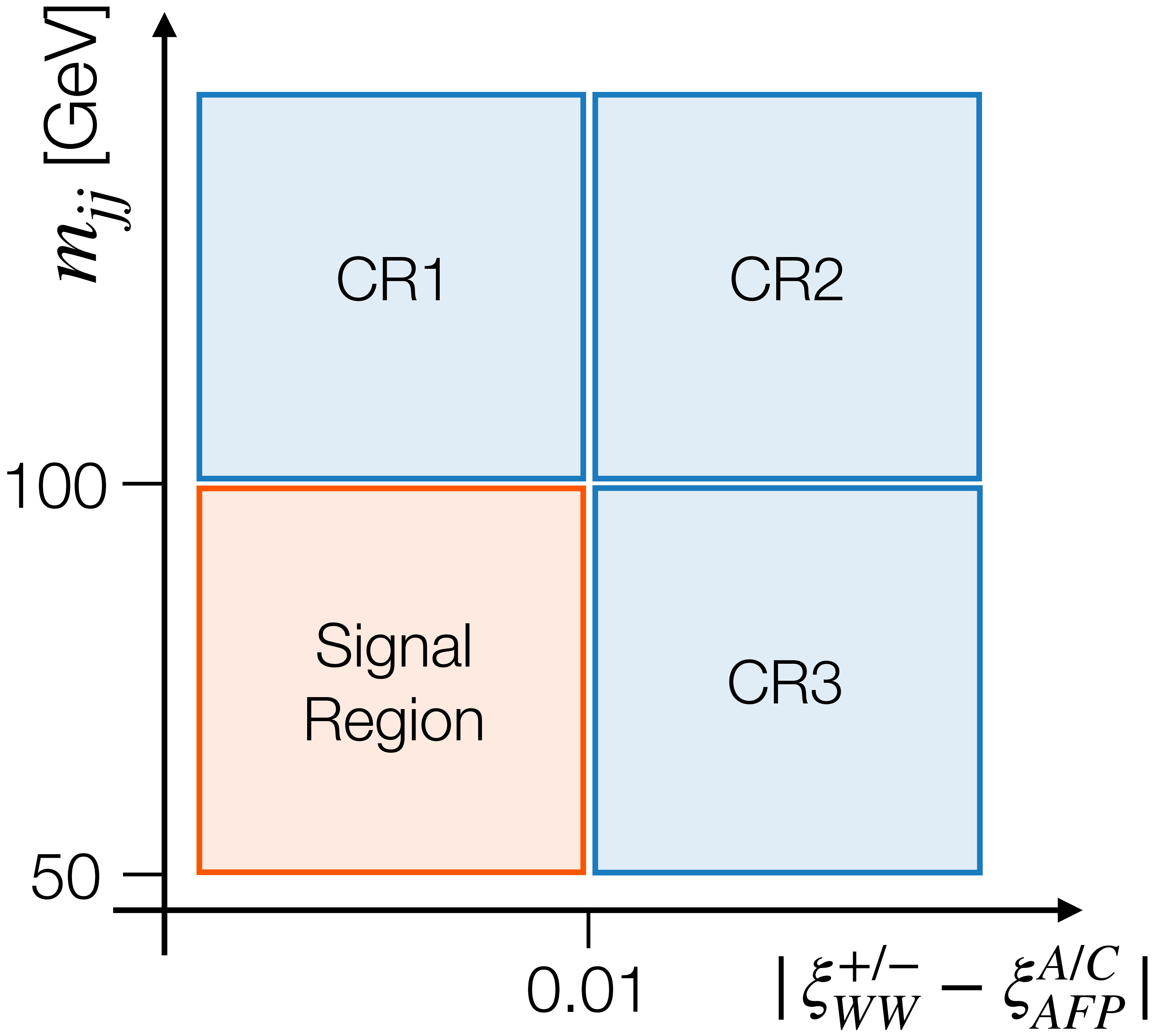
Two signal regions:

A Side: $|\xi_{WW}^{+} - \xi_{AFP}^{A}|$

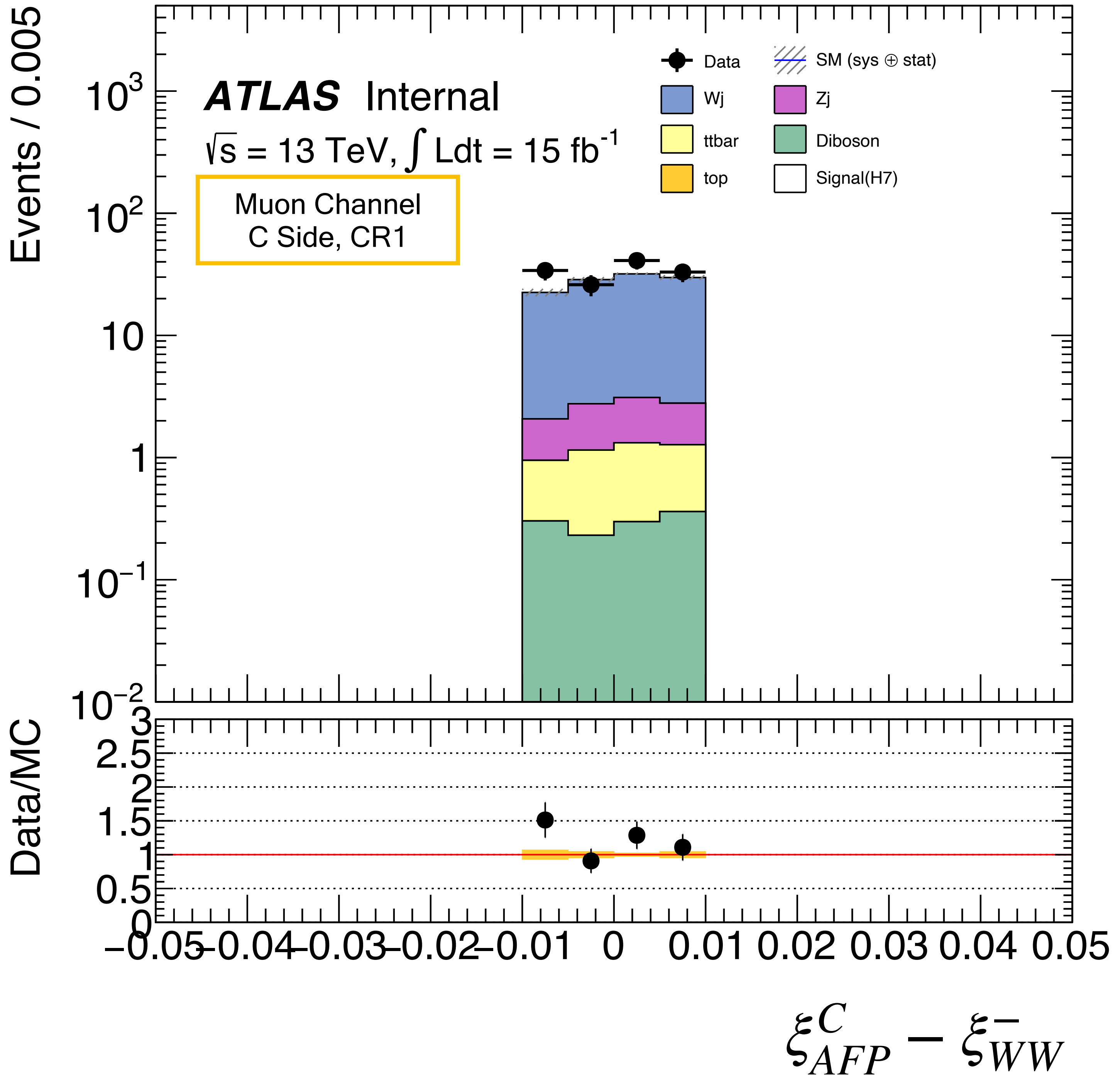
C Side: $|\xi_{WW}^{-} - \xi_{AFP}^{C}|$

Which can further be divided by lepton flavour (e, μ)

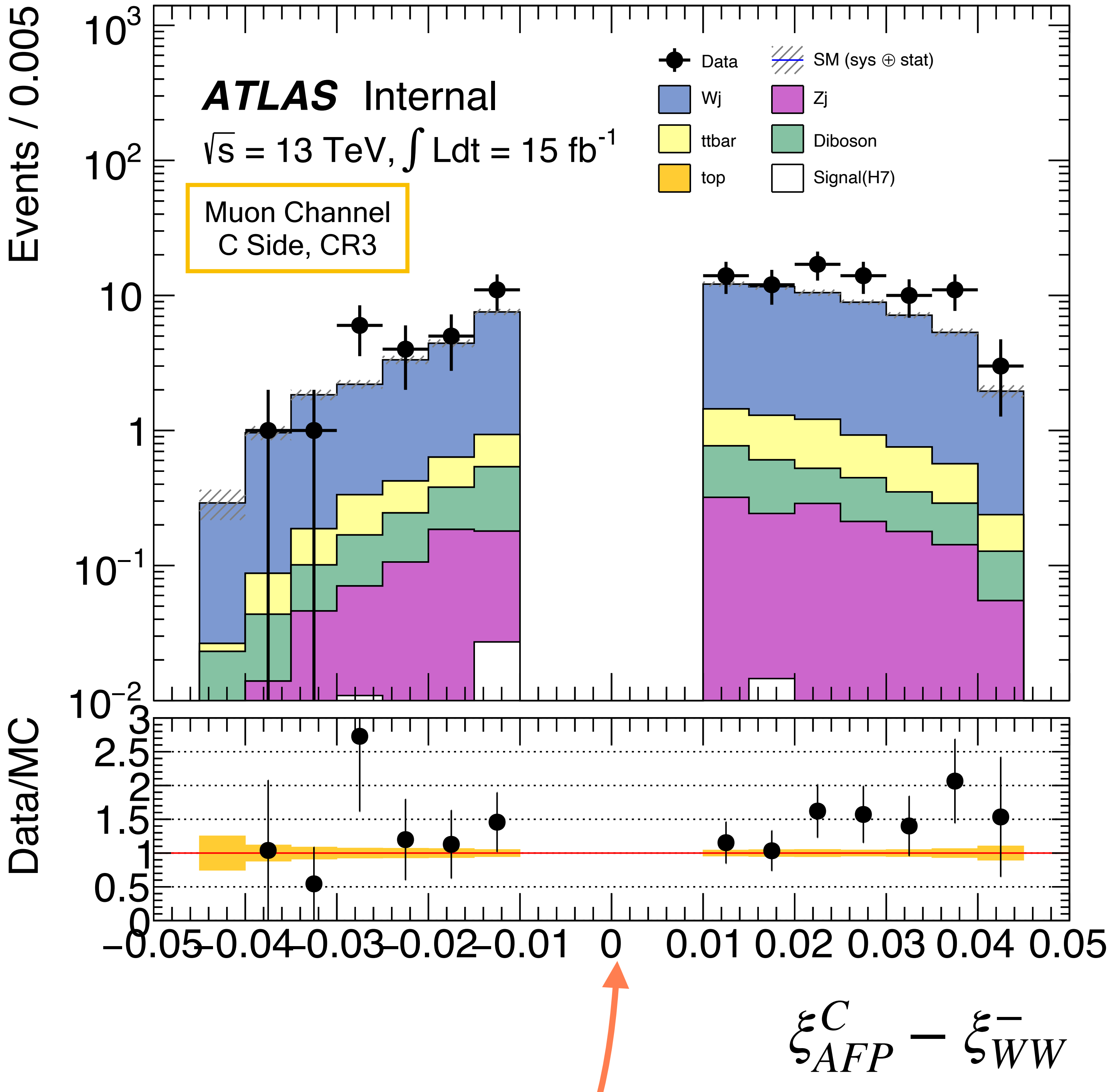
Control Region Modelling



Control Region 1

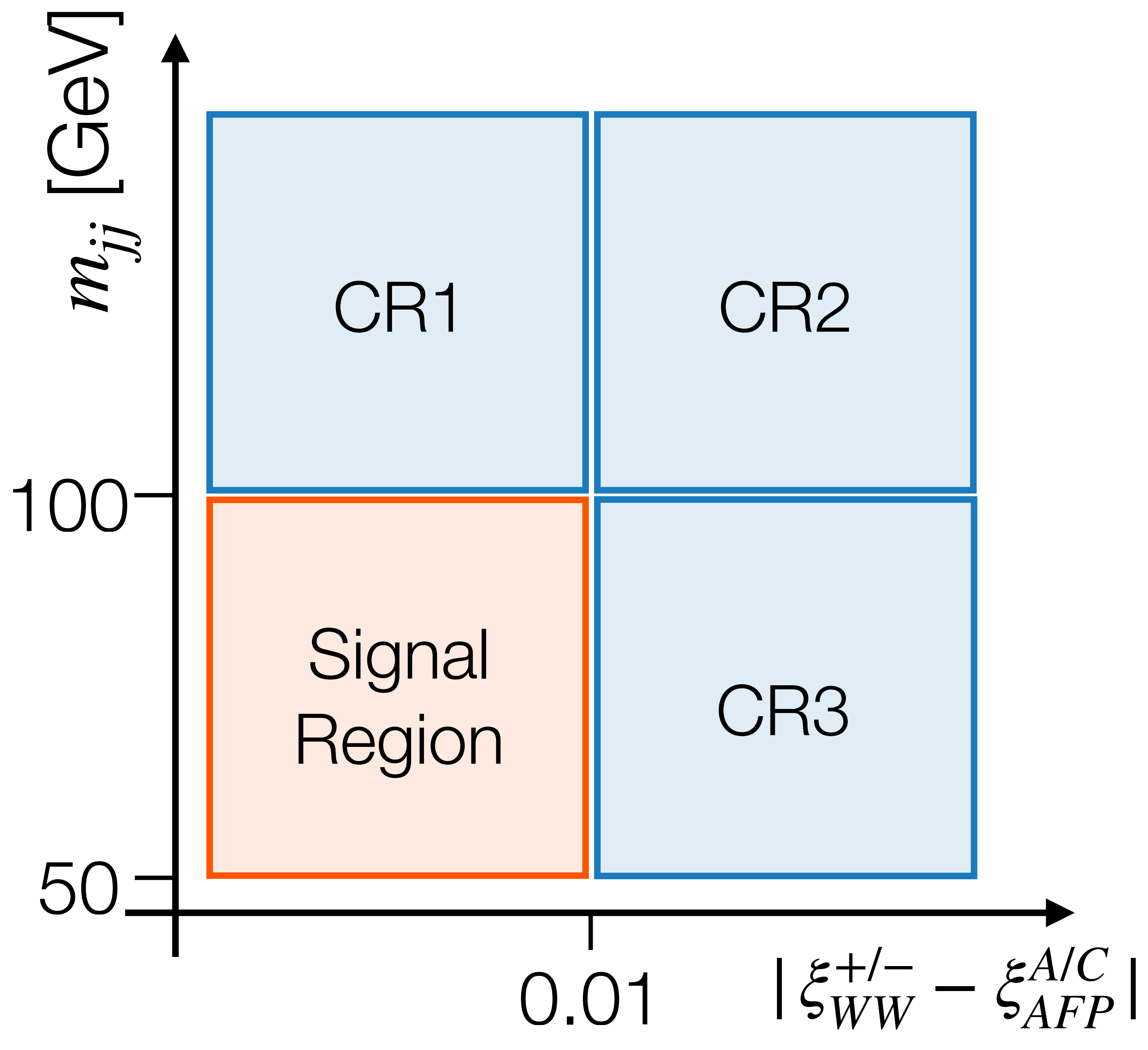


Control Region 3



Blinded Signal Region

Total Background Modelling



Estimate using ABCD Method

Using MC, calculate correlation factor:

$$R^{MC}_{e/\mu} = \frac{N(SR) \cdot N(CR2)}{N(CR1) \cdot N(CR3)}$$

Using data, calculate N(SR):

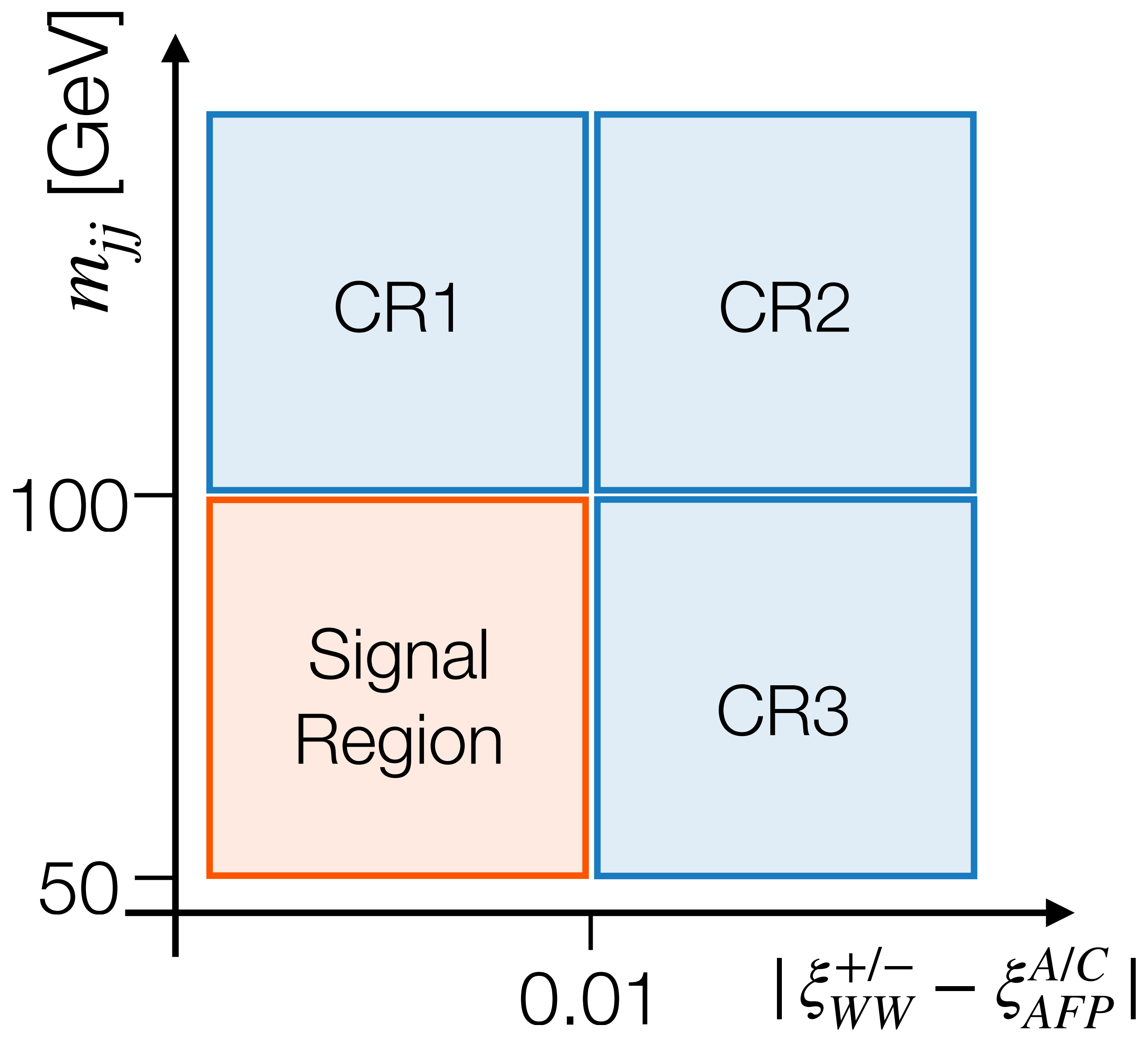
$$N(SR) = N(CR1) \cdot \frac{N(CR3)}{N(CR2)}$$

$$N(SR)^{ABCD}_{Predicted} = R^{MC}_{e/\mu} \cdot N(SR)^{ABCD}_{Data}$$

Require:

- Low signal efficiency in CRs ✓
- m_{jj} and $|\xi_{WW}^{+/-} - \xi_{AFP}^{A/C}|$ to be uncorrelated

Total Background Modelling



Using MC,
calculate correlation factor:

$$R_{e/\mu}^{MC} = \frac{N(SR)\cdot N(CR2)}{N(CR1)\cdot N(CR3)}$$

$R_{e,A} = 1.06 \pm 0.05$

$R_{\mu,A} = 0.94 \pm 0.07$

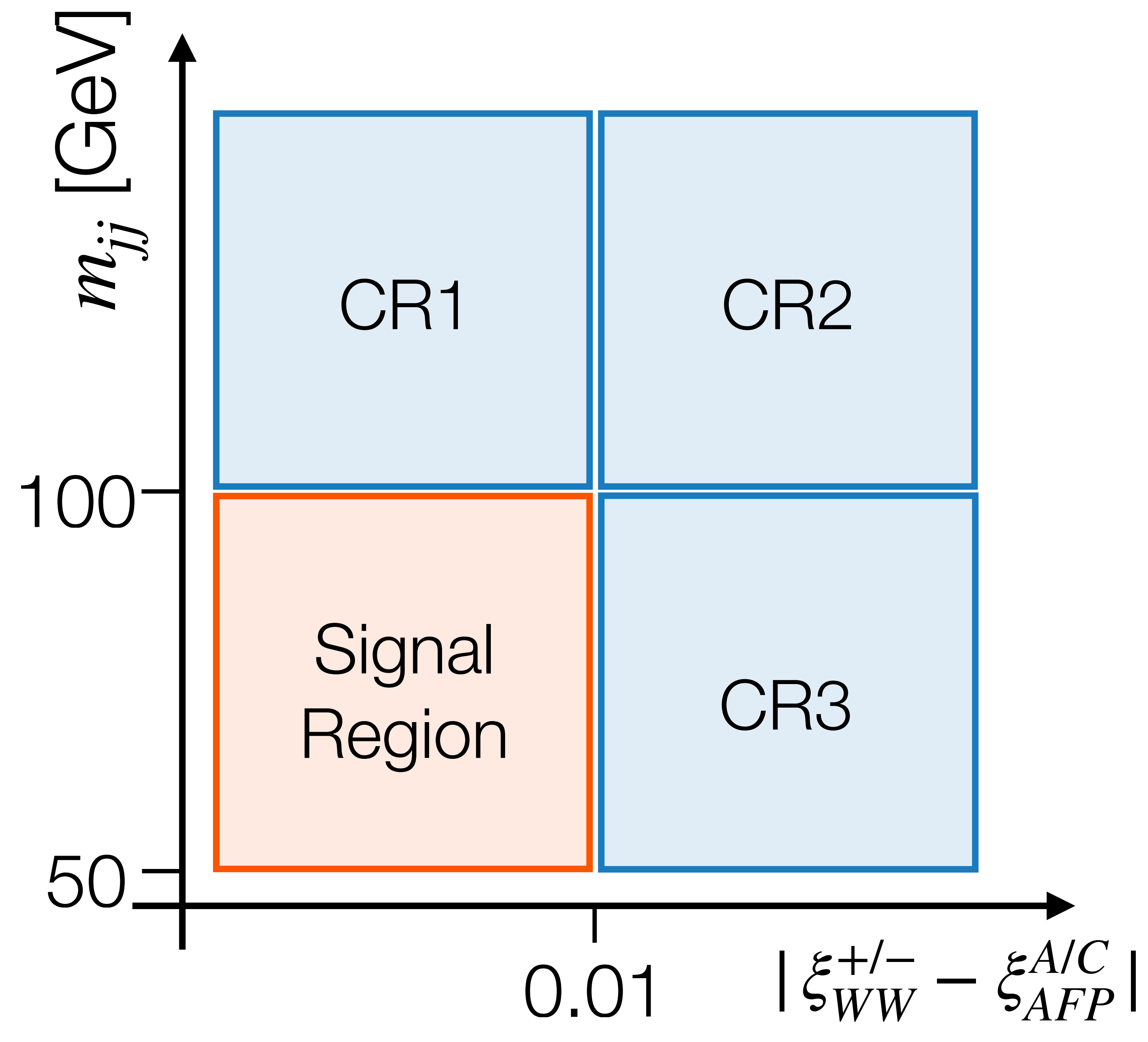
$R_{e,C} = 1.02 \pm 0.05$

$R_{\mu,C} = 0.98 \pm 0.06$

Require:

- Low signal efficiency in CRs ✓
- m_{jj} and $|\xi_{WW}^{+/-} - \xi_{AFP}^{A/C}|$ to be uncorrelated ✓

Total Background Modelling



Obtain final estimate of combinatorial background in Signal Regions

$$N(SR)^{ABCD}_{Predicted} = R^{MC}_{e/\mu} \cdot N(SR)^{ABCD}_{Data}$$

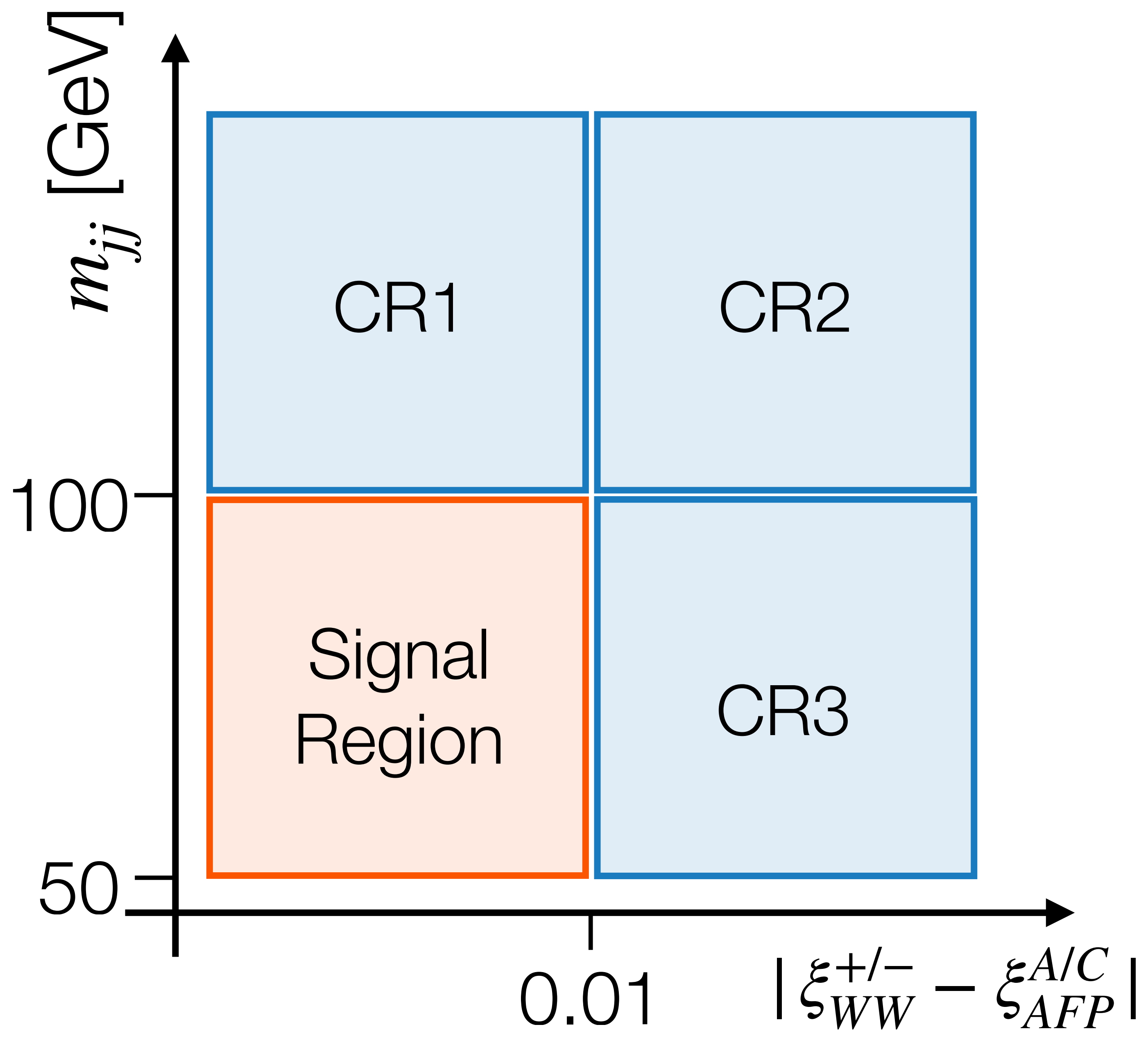
$$N(SR)^{ABCD}_{e,A} = 113.83 \pm 15.25$$

$$N(SR)^{ABCD}_{\mu,A} = 59.66 \pm 10.04$$

$$N(SR)^{ABCD}_{e,C} = 97.96 \pm 13.21$$

$$N(SR)^{ABCD}_{\mu,C} = 65.77 \pm 10.75$$

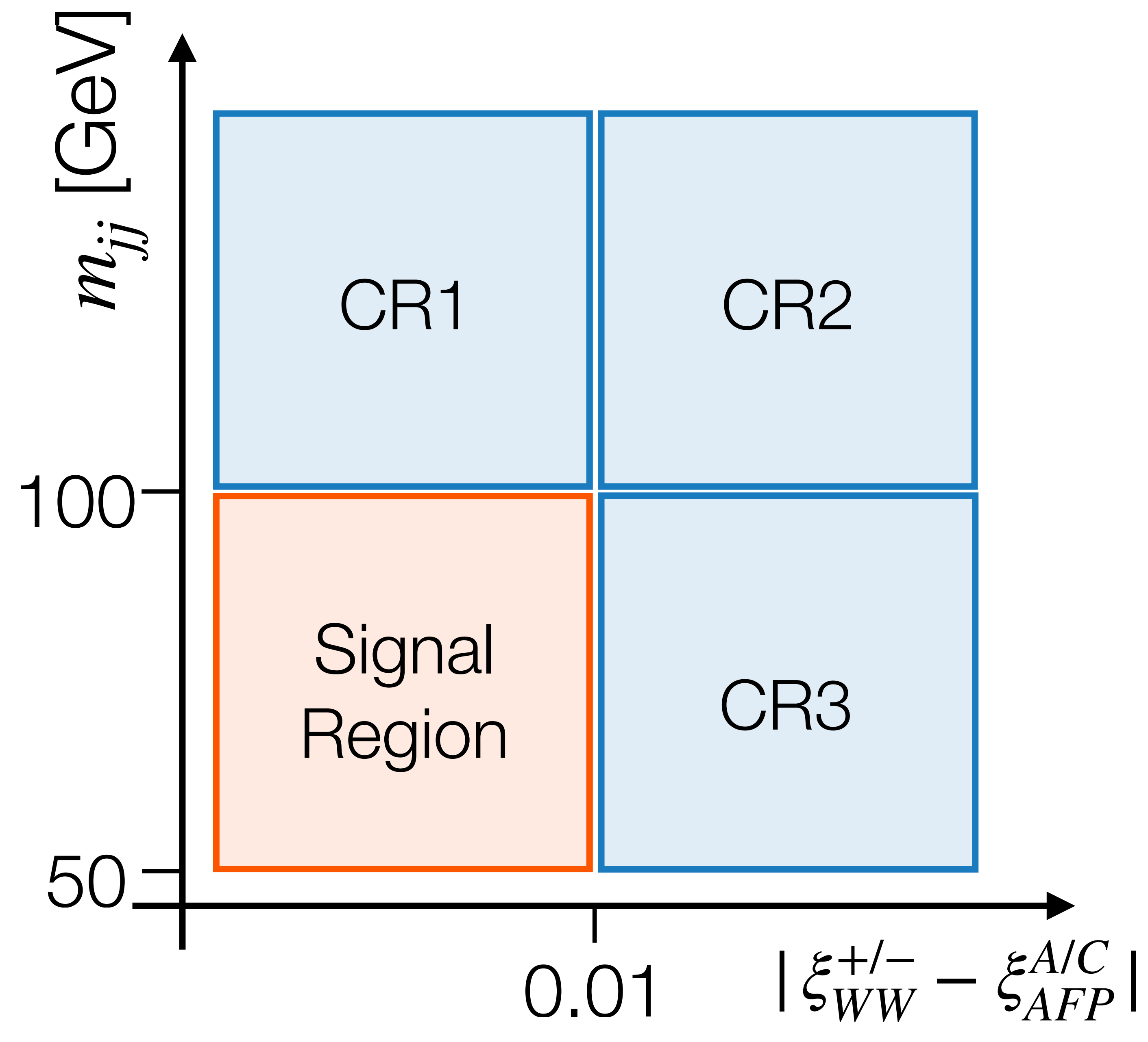
Total Background Modelling



Obtain final estimate of combinatorial background in Signal Regions

$N(SR)^{ABCD}_{Predicted} = R^{MC}_{e/\mu} \cdot N(SR)^{ABCD}_{Data}$	$N(SR)^{Data}_{Unblinded}$
$N(SR)^{ABCD}_{e,A} = 113.83 \pm 15.25$	?
$N(SR)^{ABCD}_{\mu,A} = 59.66 \pm 10.04$	?
$N(SR)^{ABCD}_{e,C} = 97.96 \pm 13.21$	?
$N(SR)^{ABCD}_{\mu,C} = 65.77 \pm 10.75$	?

Total Background Modelling



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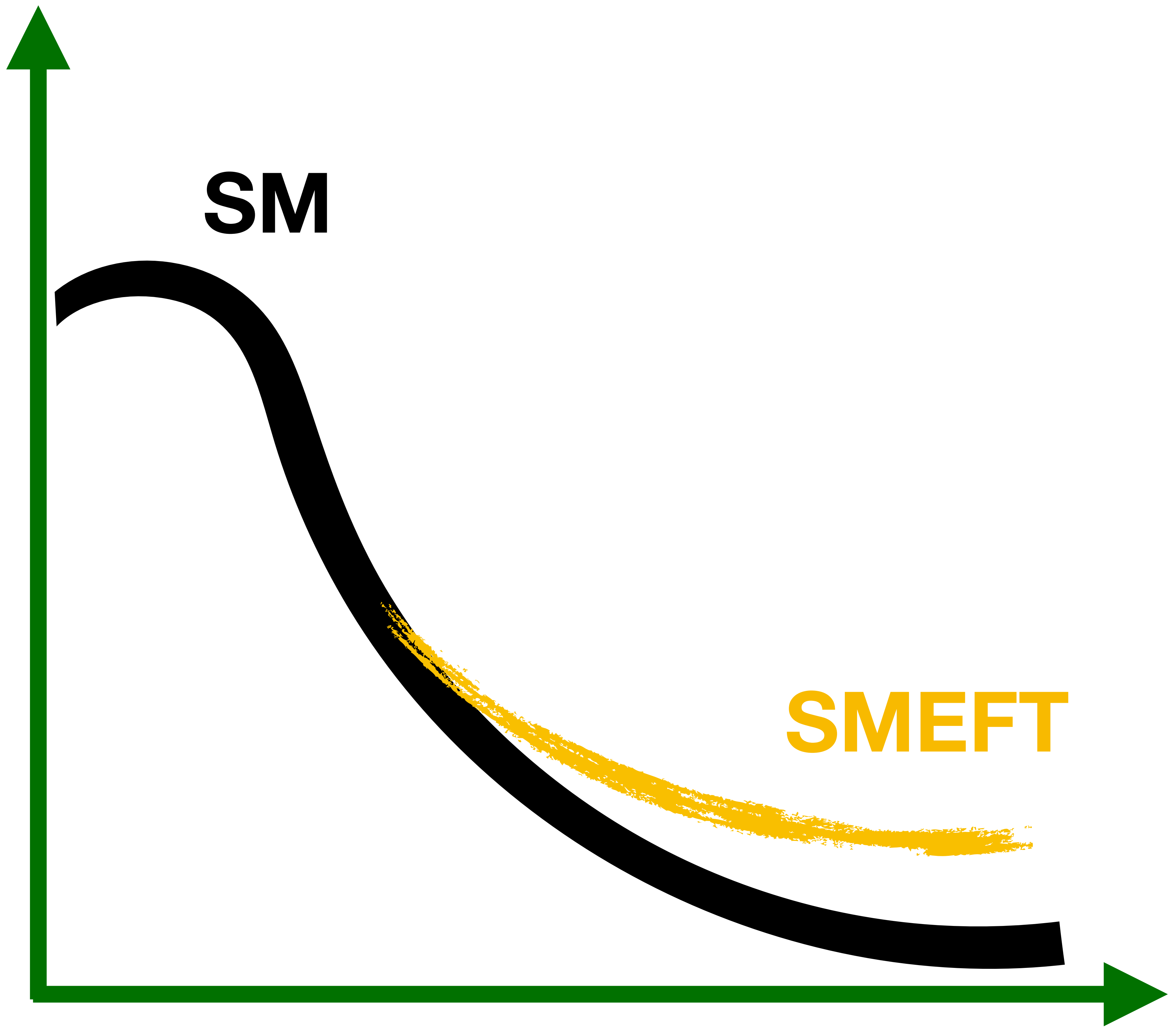
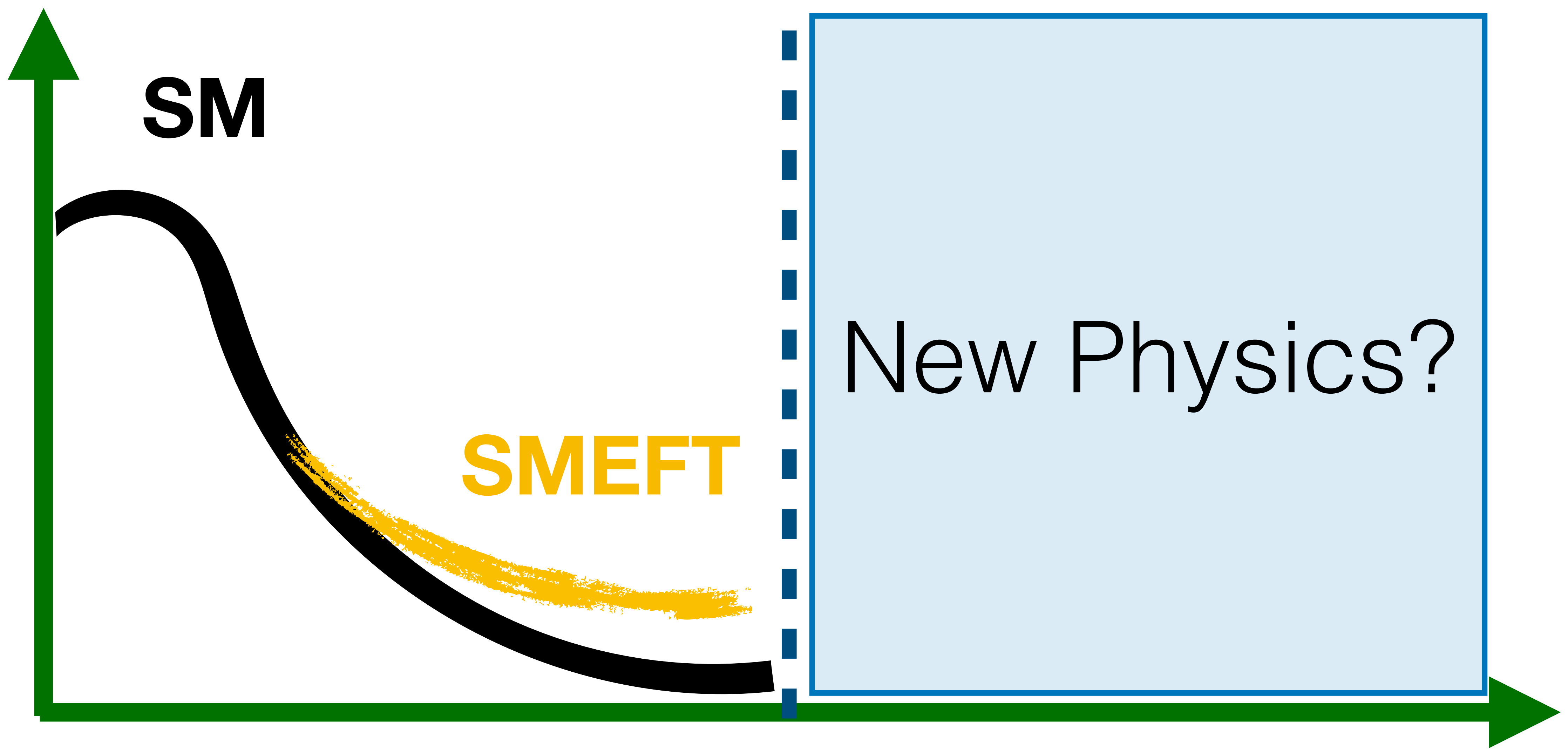
This is what we expect from the SM…

What can we expect for New Physics models?

EFT Interpretation



Effective Field Theory of the Standard Model



Look at sensitivity to low energy effects of UV theories

Model-Independent search with uses the SM measurement to constrain New Physics

EFT Lagrangian

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i^6 + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j^8 + \ldots$$

Λ : Energy scale of New Physics

$\mathcal{O}_i^d$: Operator at dimension d, effective coupling

f_i : Wilson Coefficients

Modify Standard Model Lagrangian with additional fields

Odd dimension operators violate baryon/lepton conservation

Dimension-6 includes triple and quartic gauge coupling

Dimension-8 only quartic gauge couplings

EFT Lagrangian

Dimension-8

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i^6 + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j^8 + \dots$$

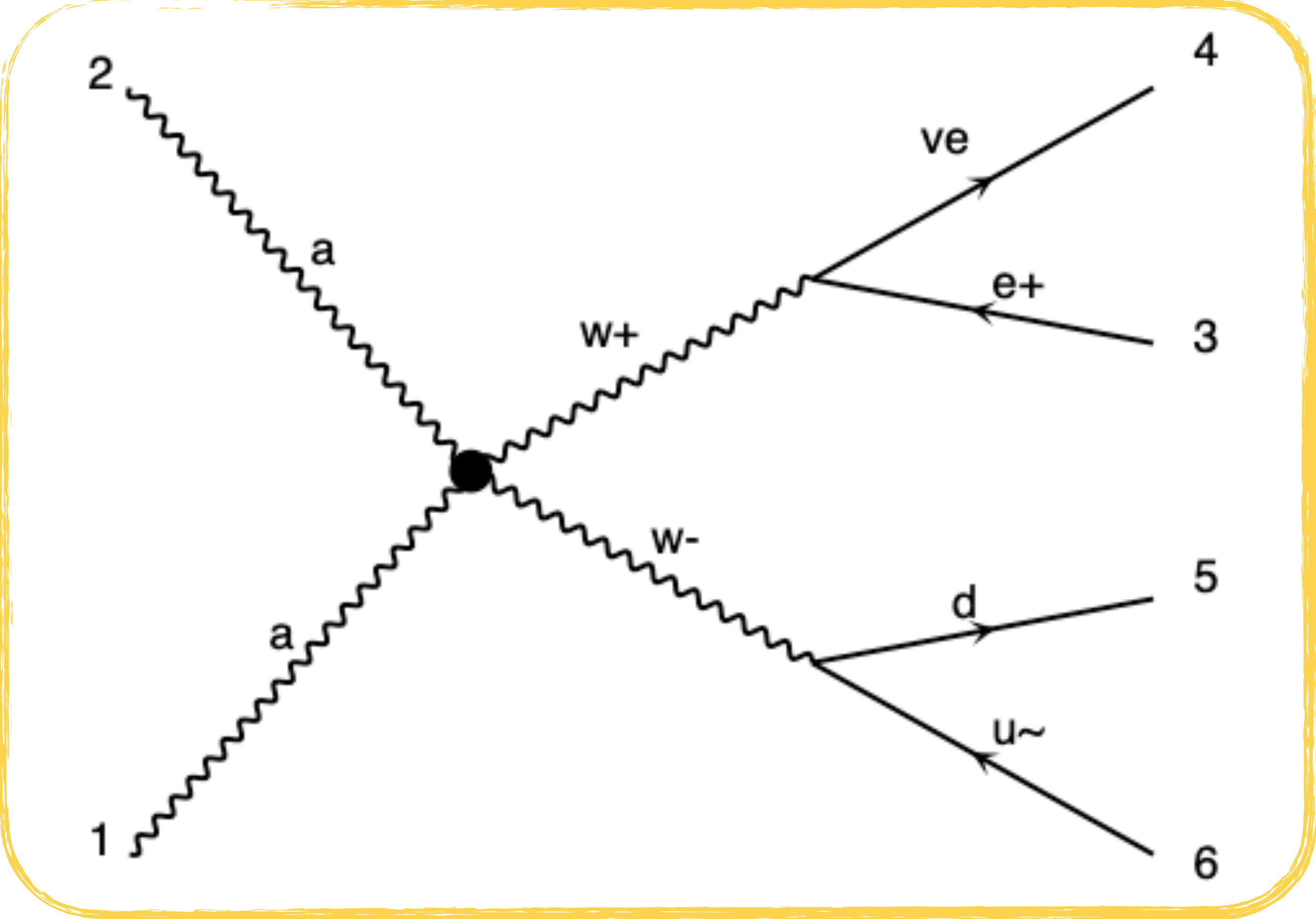
Dimension-8 production cross sections dominate in the $\gamma\gamma \to WW$

Λ : Energy scale of New Physics

$\mathcal{O}_i^d$: Operator at dimension d, effective coupling

f_i : Wilson Coefficients

$\gamma\gamma \to WW$ aQGC Process



EFT Interpretation: Dim-8 Operators

$$\mathscr{L}^8_{EFT} = \sum_j \frac{f_j}{\Lambda^4} \mathscr{O}^8_j$$

Constructing Dimension-8 electroweak fields

Field strength tensors: W^i_μ of SU(2) & B_μ of U(1)

Covariant derivative D_μ of the Higgs field ϕ

Transverse Fields $\mathscr{O}_{T,i}$

Constructed from 4 field strength tensors with no mass limitations

8 operators

Mixed Fields $\mathscr{O}_{M,i}$

Constructed from 2 field strength tensors and 2 Higgs derivatives

7 operators

Longitudinal Fields $\mathscr{O}_{S,i}$

Constructed from 4 Higgs derivatives

3 operators

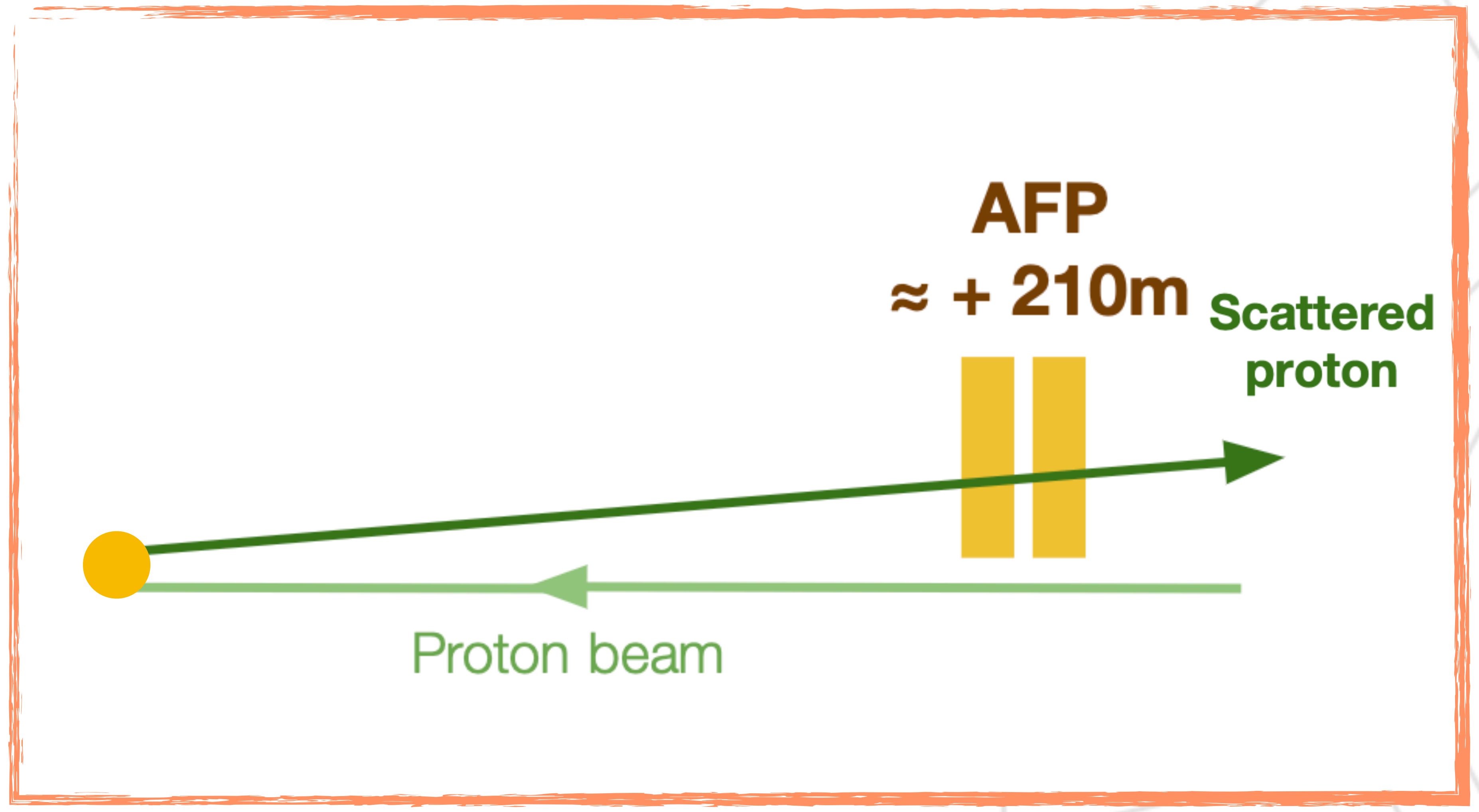
EFT Interpretation: Expected Limits

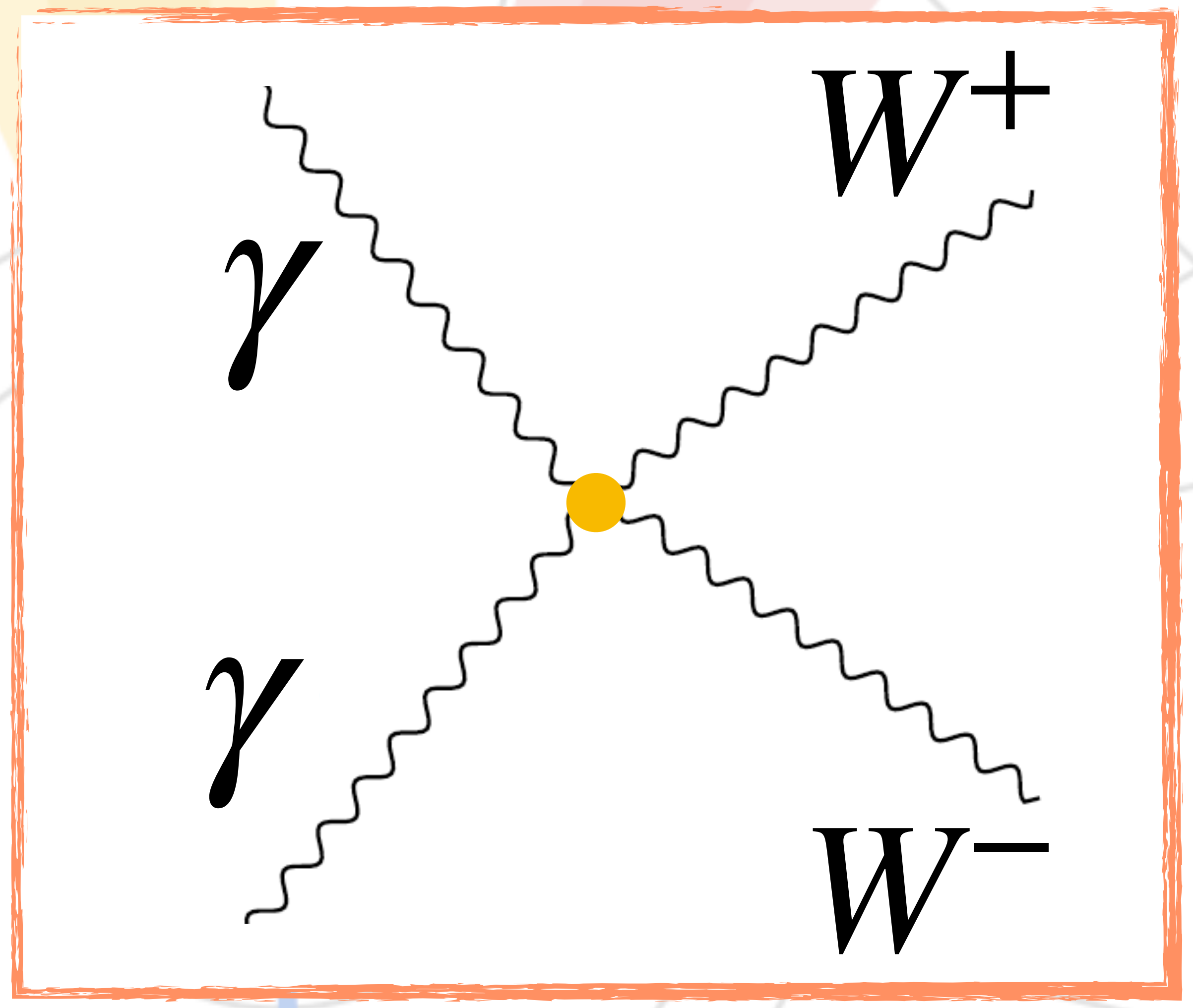
- Expected limits for $\gamma\gamma \rightarrow WW$ semileptonic process at 95% confidence level
- Values calculated likelihood estimation of expected number of events on truth level.
- Non-unitarised limits on EFT parameters

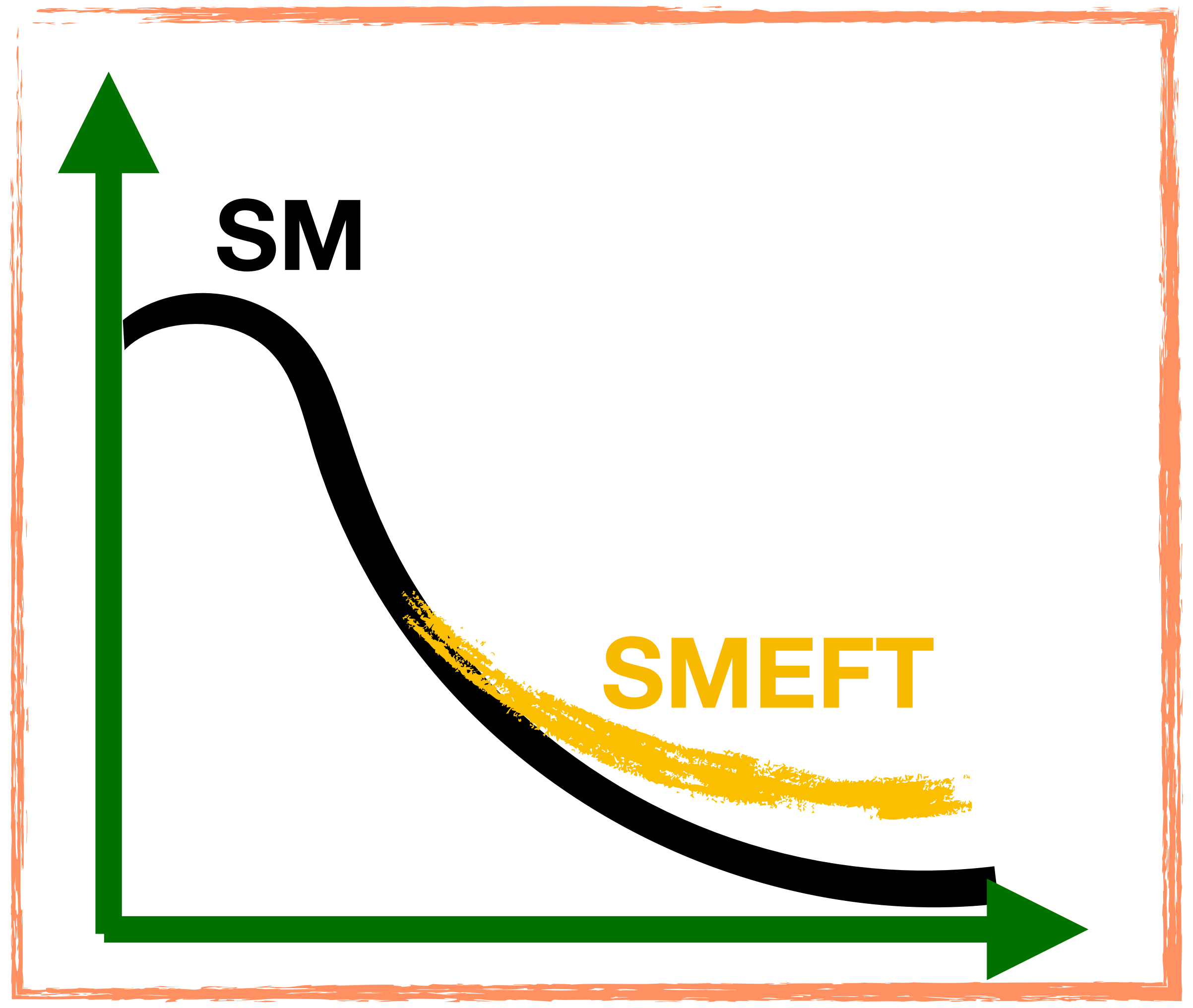
ATLAS Work in Progress

	Operator	Upper Limit (TeV^{-4})	
		Linear	Quadratic
Mixed Fields	$f_{M,0}/\Lambda^4$	163.11	12.07
	$f_{M,1}/\Lambda^4$	276.18	46.70
	$f_{M,2}/\Lambda^4$	23.86	2.13
	$f_{M,3}/\Lambda^4$	43.08	7.20
	$f_{M,4}/\Lambda^4$	89.52	6.73
	$f_{M,5}/\Lambda^4$	75.19	12.94
	$f_{M,7}/\Lambda^4$	548.76	93.39
Transverse Fields	$f_{T,0}/\Lambda^4$	3.95	1.66
	$f_{T,1}/\Lambda^4$	8.97	3.45
	$f_{T,2}/\Lambda^4$	8.00	4.66
	$f_{T,3}/\Lambda^4$	7.83	5.71
	$f_{T,4}/\Lambda^4$	3.19	2.02
	$f_{T,5}/\Lambda^4$	2.00	1.13
	$f_{T,6}/\Lambda^4$	3.54	1.47
	$f_{T,7}/\Lambda^4$	3.24	1.75

Summary





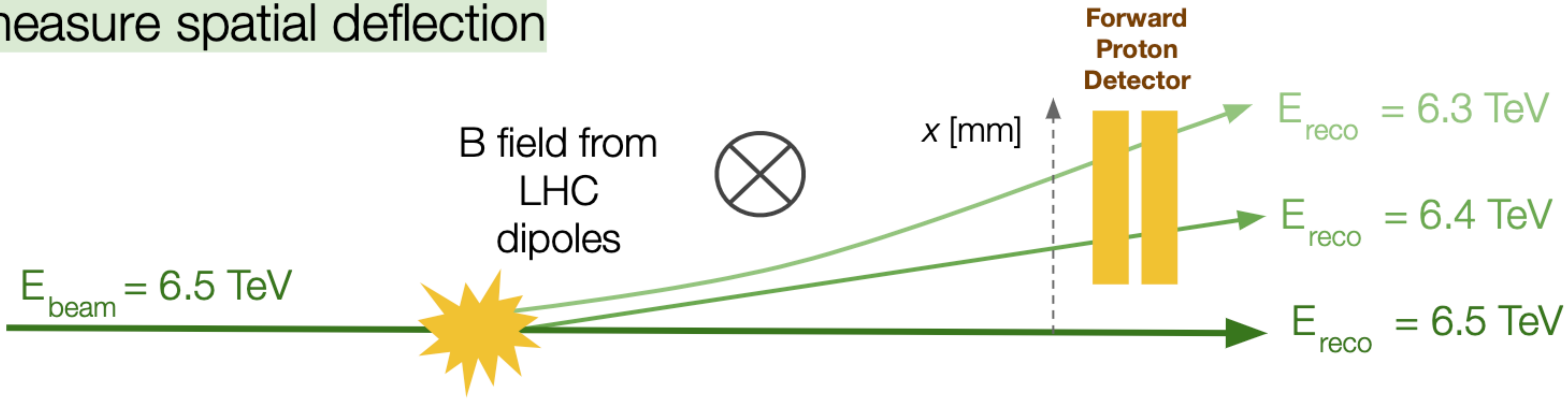


Thank you!

Backup Slides

Use of Forward Detector

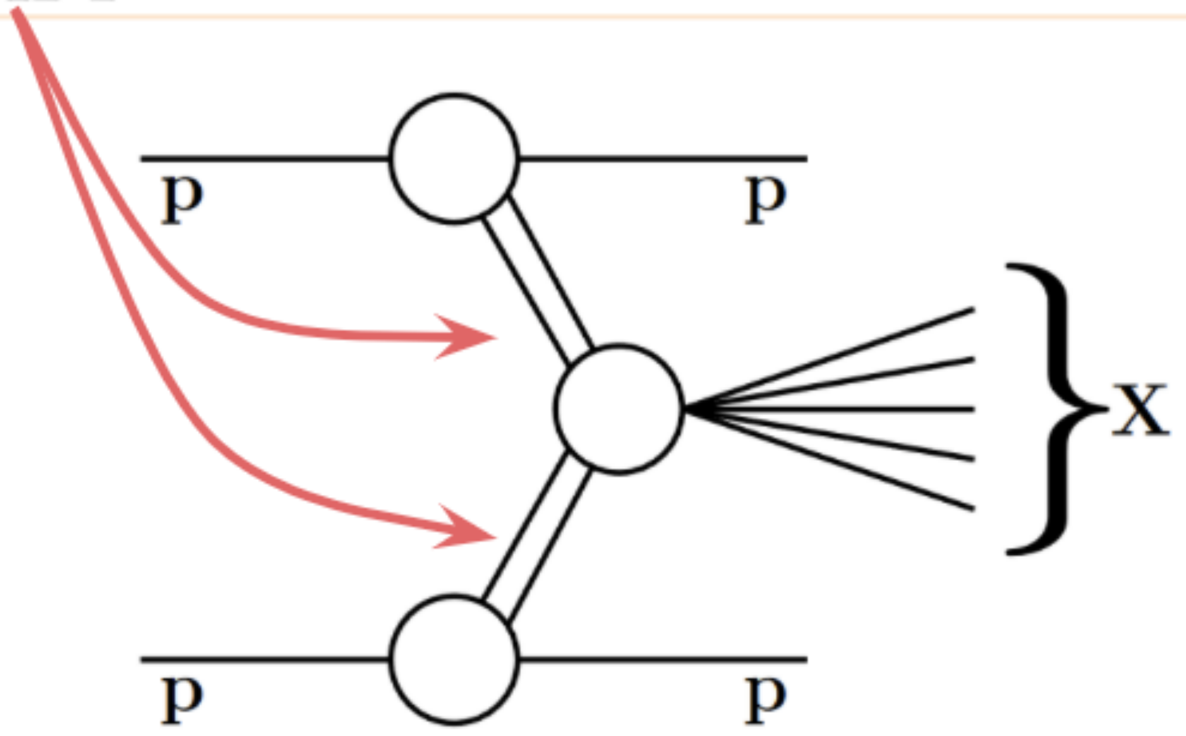
Step 1: measure spatial deflection



Step 2: infer proton energy

$$\xi_{AFP}^{A,C} = 1 - E_{\mathrm{reconstructed}} / E_{\mathrm{beam}}$$

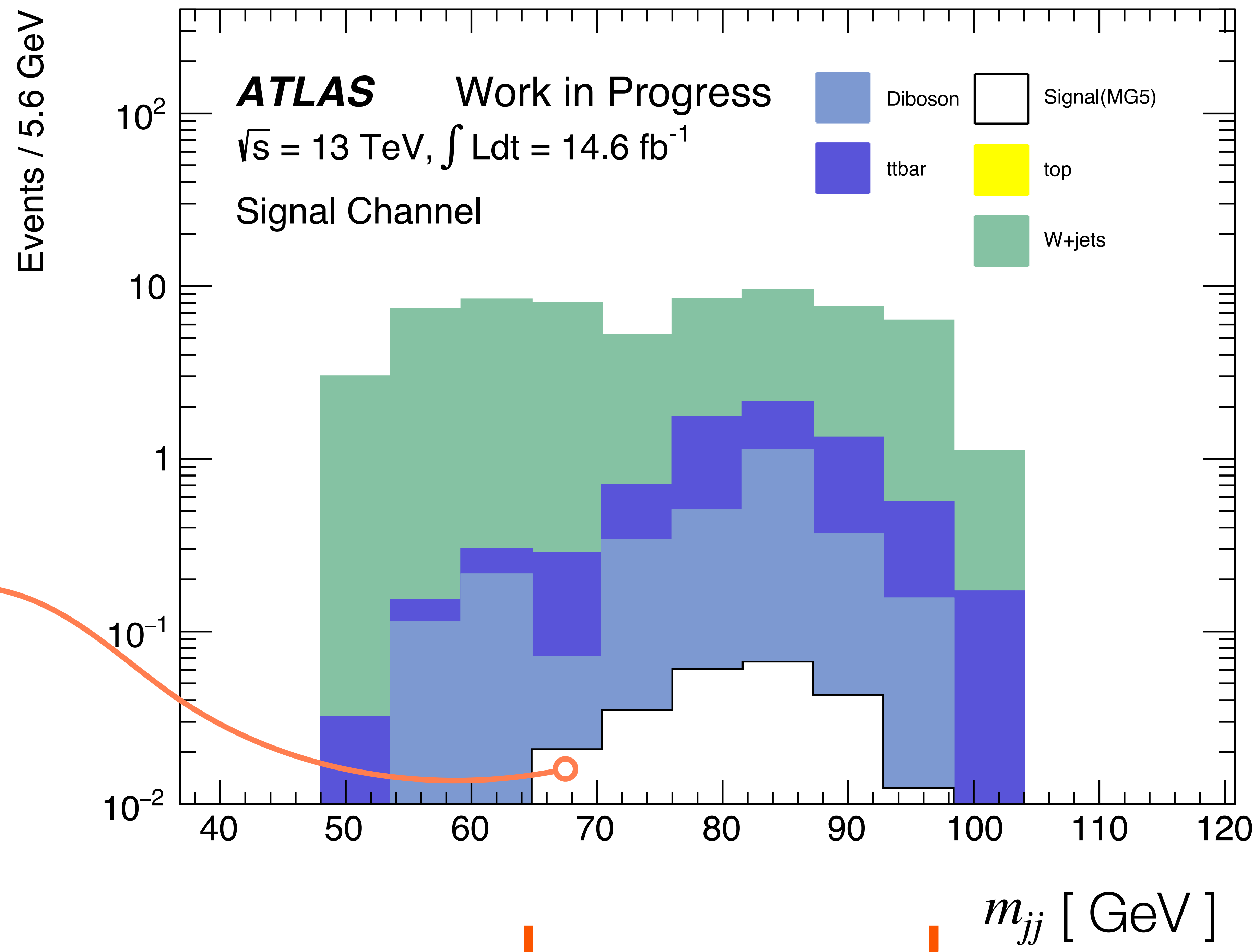
Step 3: know energy of central system



Novelty: reconstruct central process without central ATLAS detector

Event yields in simulation

Background distribution broader than signal



m_W range

Signal expected in certain *phase space where aQGC* may appear

EFT Interpretation

Transverse Fields $\mathcal{O}_{T,i}$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right] \quad , \quad \mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right] \quad , \quad \mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad , \quad \mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad , \quad \mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \; .$$

Mixed Fields $\mathcal{O}_{M,i}$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} \quad , \quad \mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} + \mathrm{h.c.}$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right] \quad .$$

Longitudinal Fields $\mathcal{O}_{S,i}$

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

EFT Interpretation

Estimate expected number of EFT events

$$N_{EFT} = \sigma_{EFT} \cdot \mathscr{L}$$

Expected number of SM events

Nuisance parameter $f(\theta)$ Gaussian distribution of predicted SM events

$$L(N_{obs}; \mu\theta) = \frac{(\mu N_{EFT} + N_{SM})^{N_{obs}}}{N_{obs}!} e^{-(\mu N_{EFT} + N_{SM})} \cdot f(\theta)$$

$L(N_{obs}; \mu\theta)$ used to set limits to a 95% C.L

Done separately for *linear* and *quadratic* terms

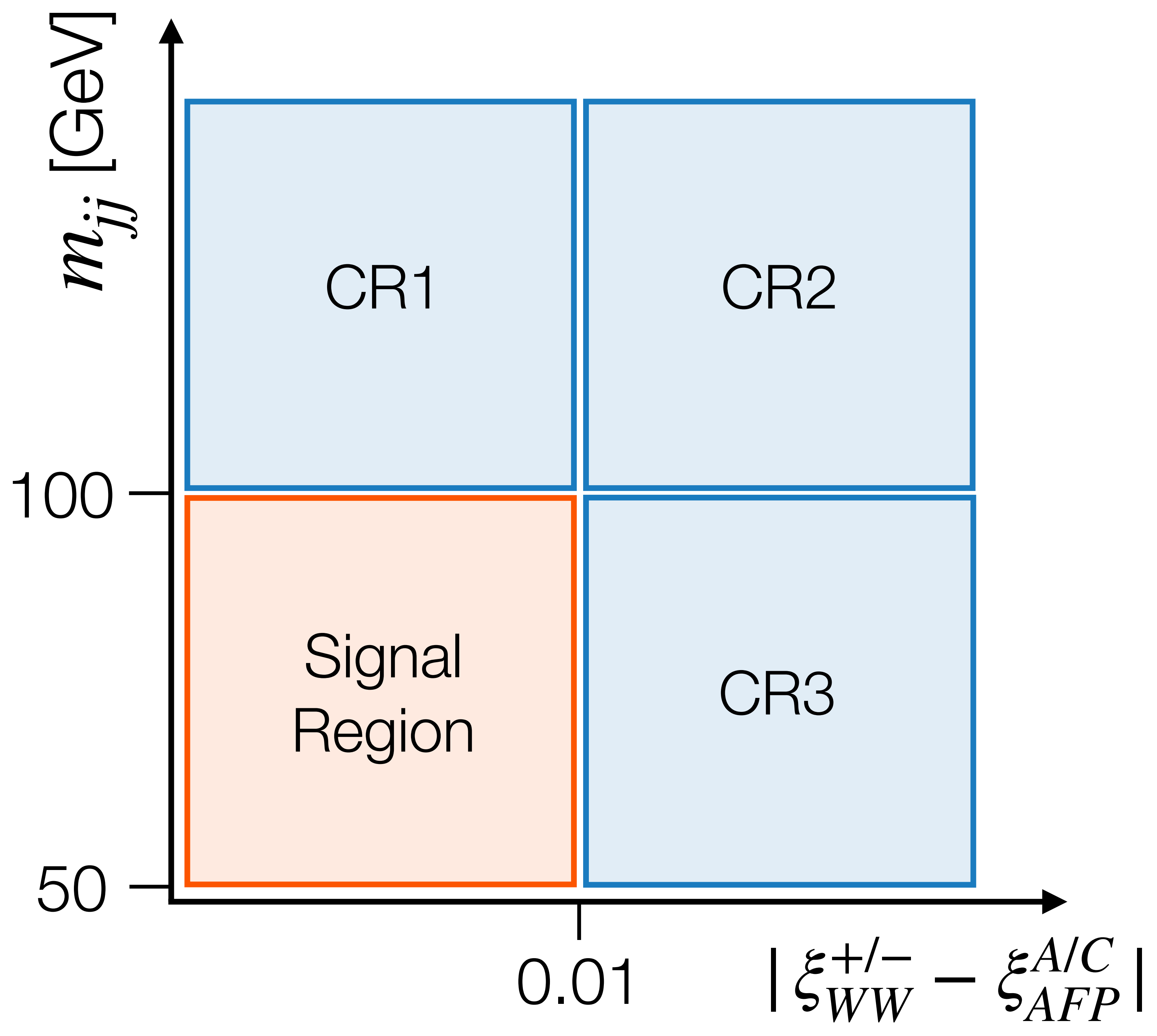
Decomposition Method

Samples generated in independent components where the total EFT amplitude is:

	Standard Model	Linear Term: Interference of SM-aQGC	Quadratic Term: Pure aQGC	Cross Term: Interference between QGC operators

$$|A_{SM} + f_i A_i|^2 = |A_{SM}|^2 + f_i \cdot 2Re(A_{SM} \cdot A_i) + f_i^2 |A_i|^2 + f_i f_j \cdot 2Re(A_i^* \cdot A_j)$$

Total Background Modelling



$$N(SR) = N(CR1) \cdot \frac{N(CR3)}{N(CR2)}$$

Validation Check 1

Test for consistency between different predictions

Normalisation Test:

- Calculate N(SR) using MC values in CRs
- Then correct with normalisation factor of CR1 and CR3 regions to data.

$$f_{CR1} \cdot N(SR)$$

$$f_{CR3} \cdot N(SR)$$

Total Background Modelling

Validation Check 1

Test for consistency between different predictions

	$f_{CR1} \cdot N(SR)$	$f_{CR3} \cdot N(SR)$	$N(SR) = \frac{N(CR3)^{Data}}{N(CR2)^{Data}} \cdot N(CR1)^{Data}$
Electron Channel A Side	94.7 ± 8.99	95.24 ± 8.93	$N_{e,A}^{ABCD} = 107.43 \pm 13.56$
Muon Channel A Side	60.74 ± 6.80	72.24 ± 7.78	$N_{\mu,A}^{ABCD} = 63.17 \pm 9.51$
Electron Channel C Side	90.18 ± 9.09	97.01 ± 9.10	$N_{e,C}^{ABCD} = 96.12 \pm 12.21$
Muon Channel C Side	61.42 ± 6.76	72.24 ± 7.78	$N_{\mu,C}^{ABCD} = 66.95 \pm 10.05$