Search for resonances in light-by-light scattering using the forward proton detectors at the LHC-ATLAS

ATLAS-CONF-2023-002

La Thuile 2023

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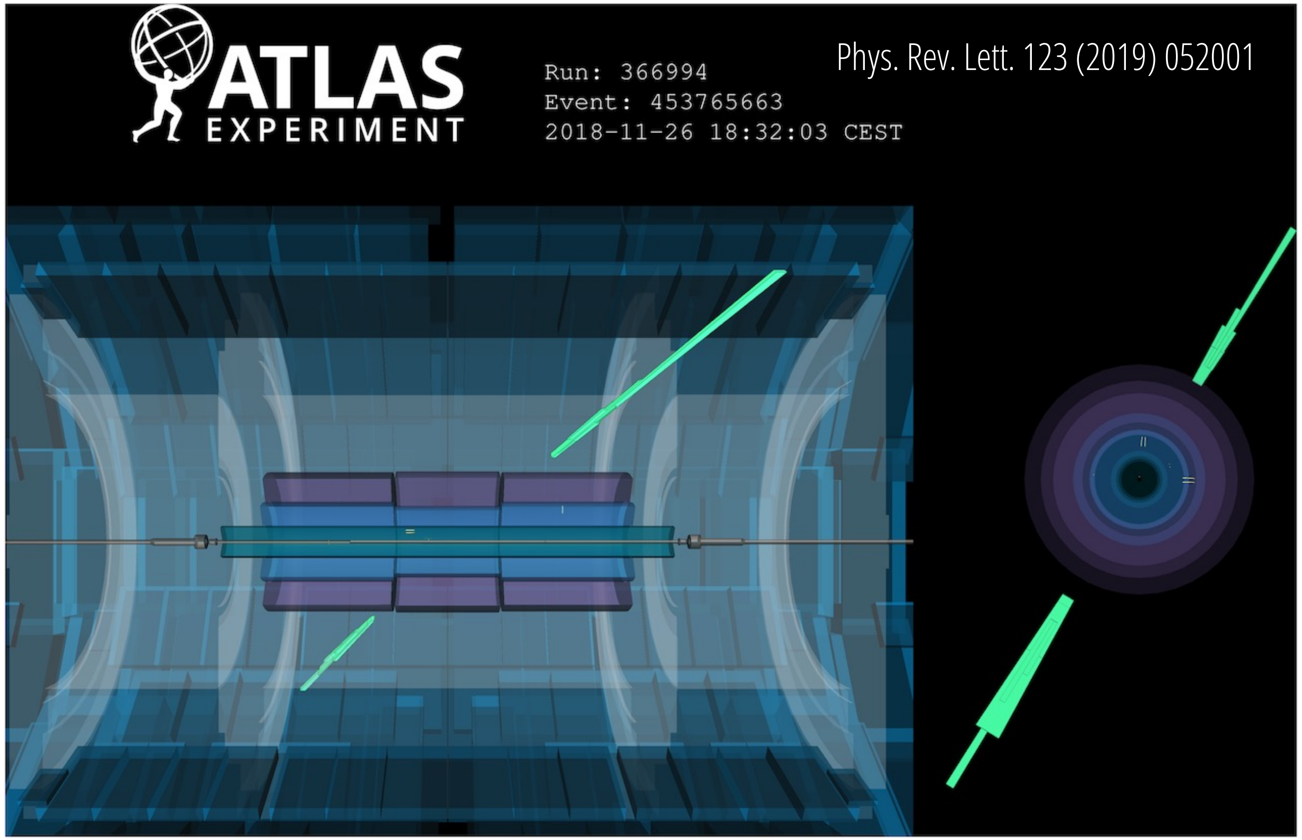
on behalf of the ATLAS Collaboration

Light-by-light scattering @ LHC

Electric field around LHC beam proton is regarded as photons
→ Use LHC as a $\gamma\gamma$ collider

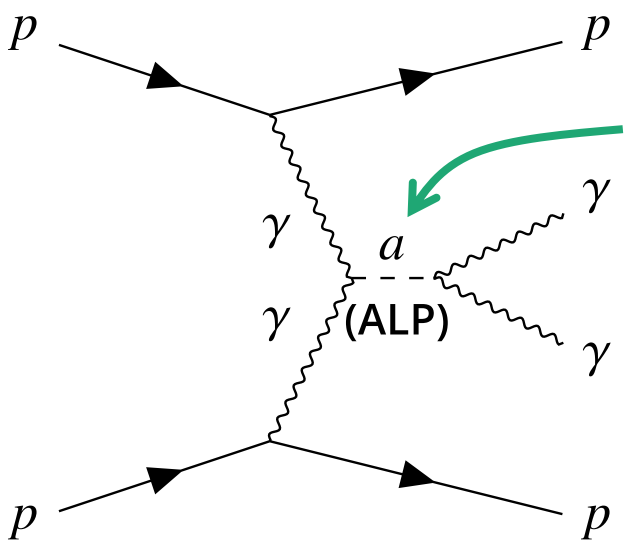
SM $\gamma\gamma \to \gamma\gamma$ observed in lead ion collisions



In pp collisions, SM $\gamma\gamma \to \gamma\gamma$ has too small cross section...

But BSM can enhance it!

e.g. Axion-like particle (ALP) (assumed for signal modeling)

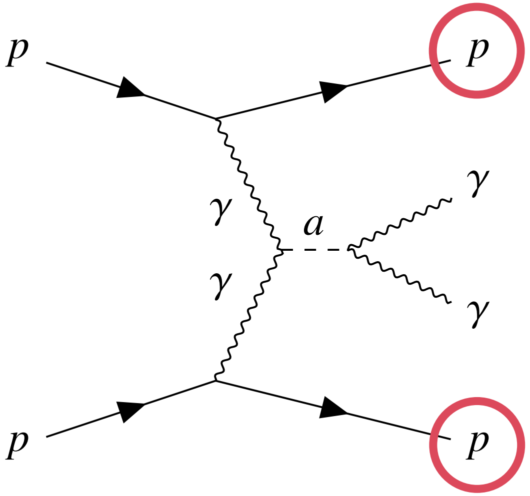


Mass: m_X
Coupling constant: f^{-1}

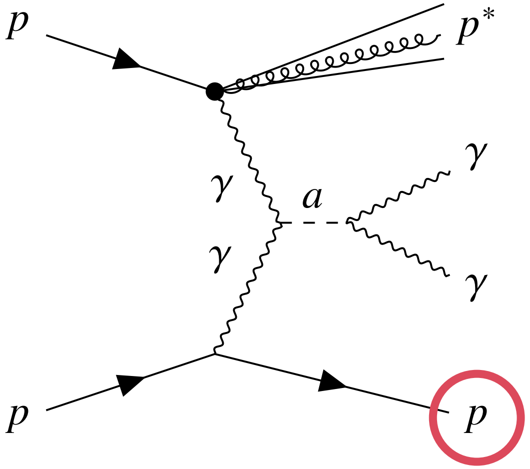
AFP detector

In the $\gamma\gamma \rightarrow \gamma\gamma$ event, final state proton can be intact (not broken)

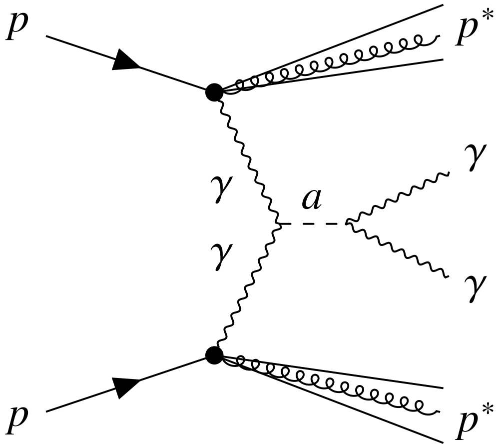
Exclusive event



Single-dissociative (**SD**) event



Double-dissociative (**DD**) event

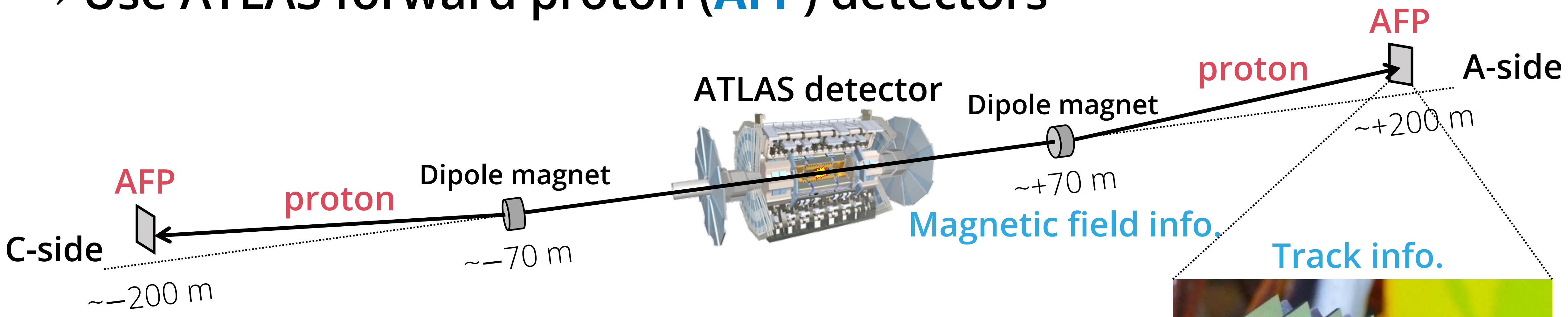


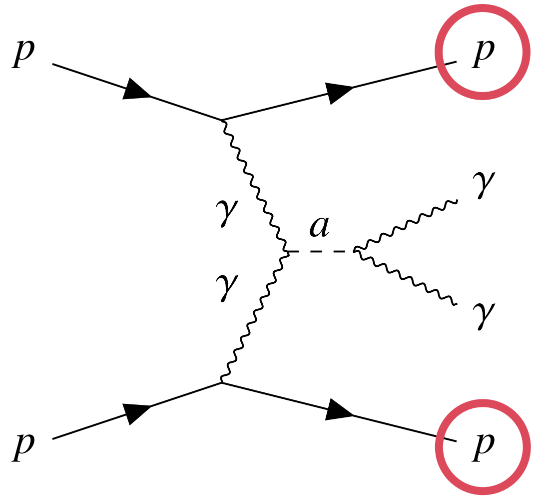
(Re-hadronization into proton may occur)

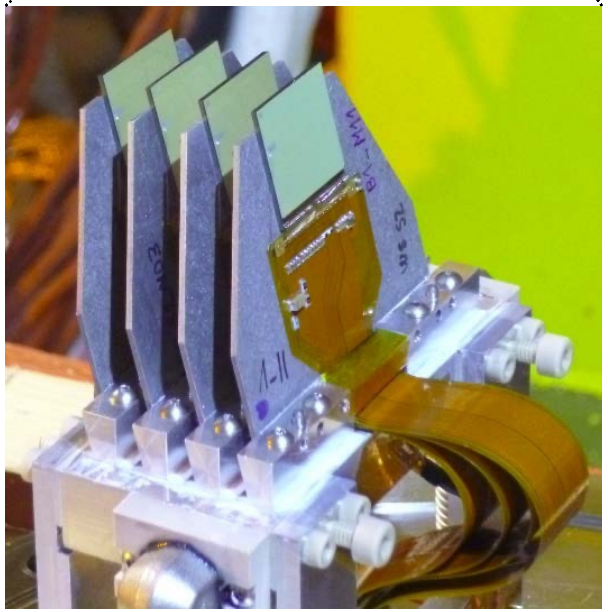
AFP detector

In the $\gamma\gamma \rightarrow \gamma\gamma$ event, final state proton can be intact (not broken)

→ Use ATLAS forward proton (**AFP**) detectors



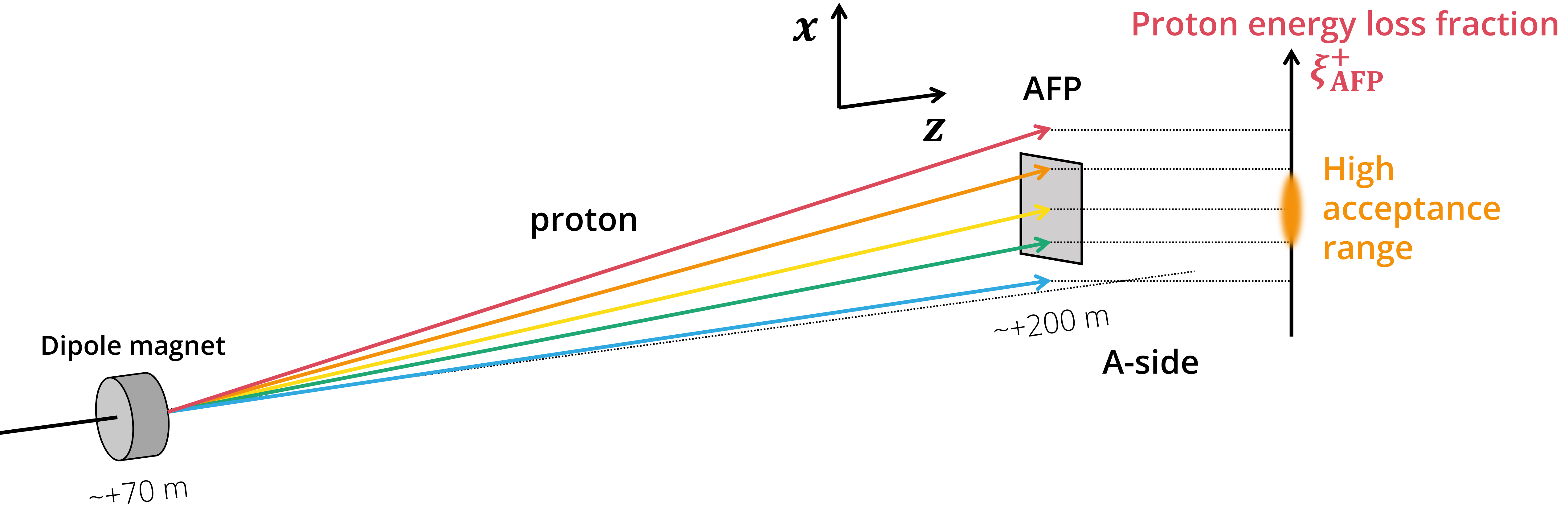




AFP detector

In the $\gamma\gamma \rightarrow \gamma\gamma$ event, final state proton can be intact (not broken)

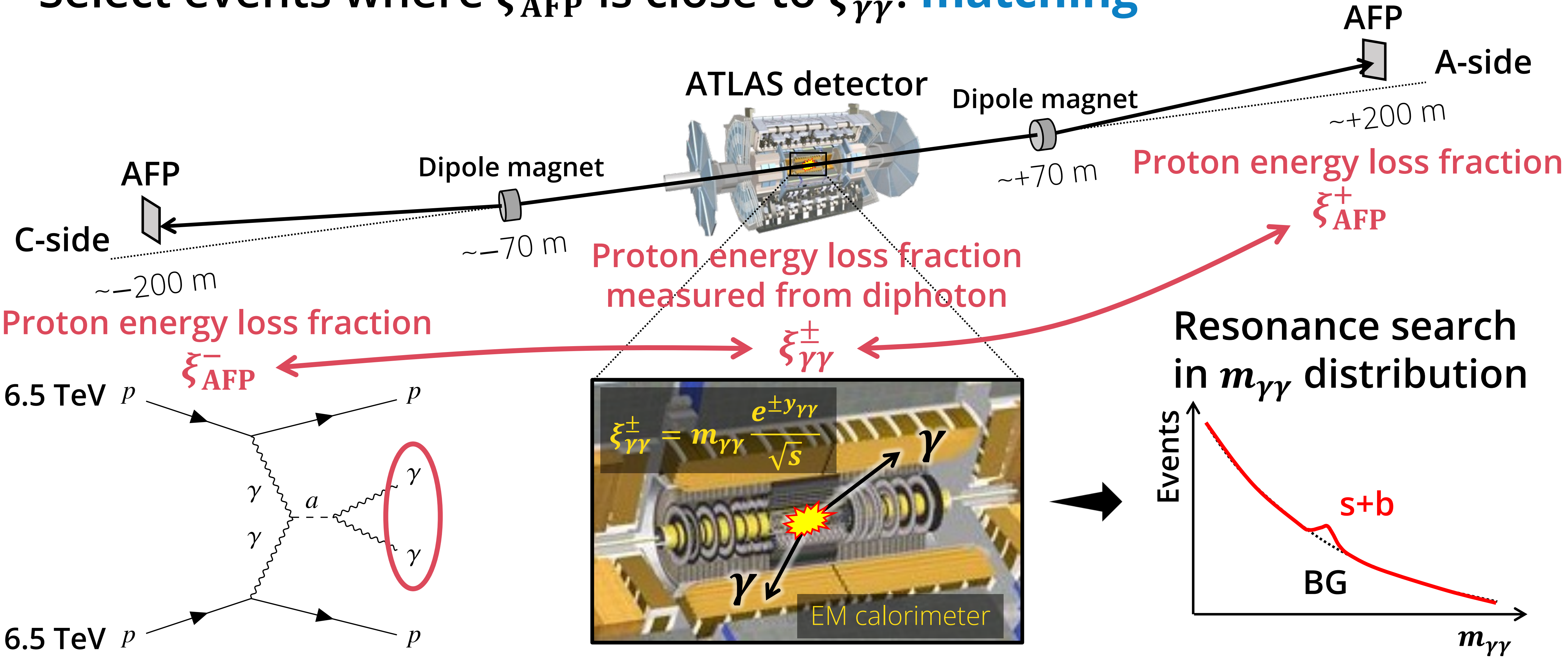
→ Use ATLAS forward proton (**AFP**) detectors



Purpose and main strategy

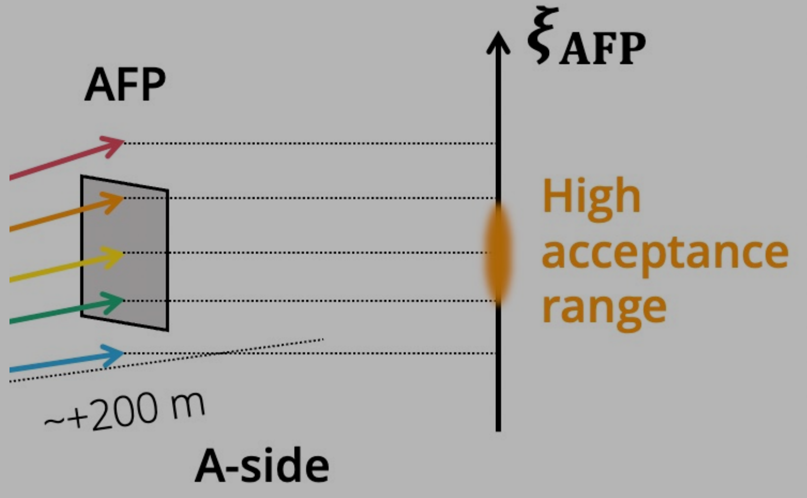
Diphoton resonance search using AFP (Data is 14.6 fb^{-1} from runs in 2017)

Select events where $\xi_{\mathbf{AFP}}$ is close to $\xi_{\gamma\gamma}$: **matching**



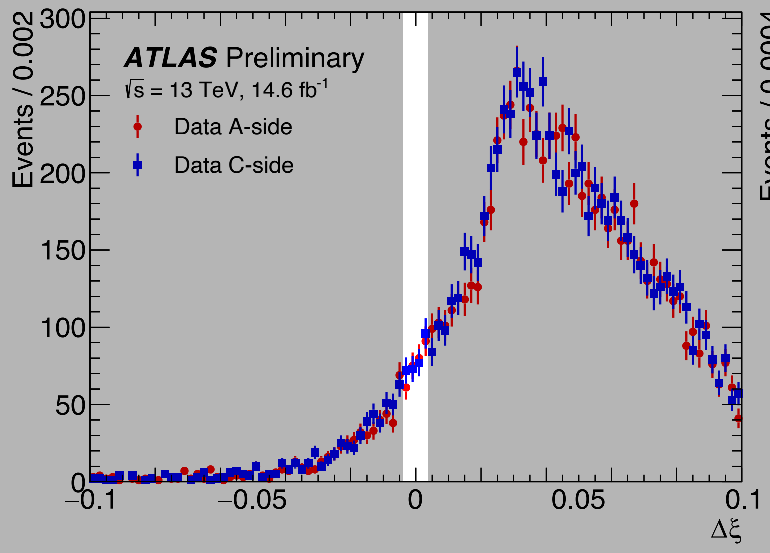
Event selection

1. Require diphoton to be back-to-back
   Acoplanarity $A_{\phi}^{\gamma\gamma} \equiv |\Delta\phi|/\pi < 0.01$
2. Require ξ_{AFP} in the high acceptance range
   $0.035 < \xi_{\mathrm{AFP}} < 0.08 \rightarrow \xi_{\gamma\gamma}$ range is also limited
3. At least one matching
   $|\Delta\xi| \equiv \left|\xi_{\mathrm{AFP}} - \xi_{\gamma\gamma}\right| < 0.004 + 0.1\xi_{\gamma\gamma}$

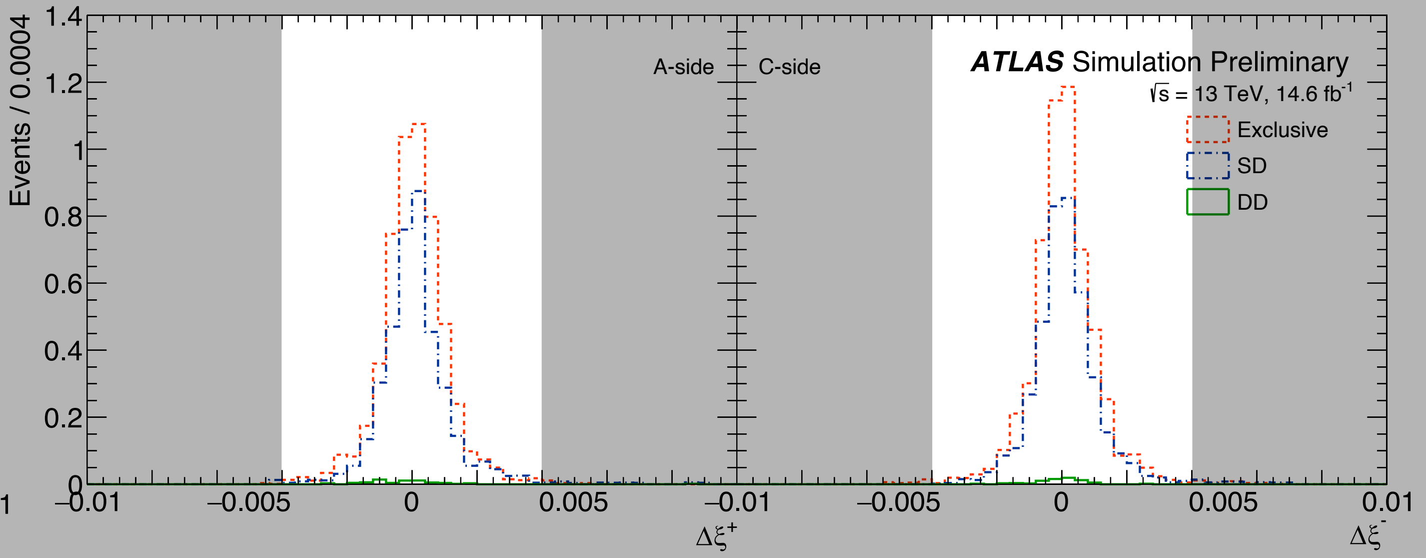


Generated using SuperChic 4

Data



Signal MC ($m_X = 300$ GeV)

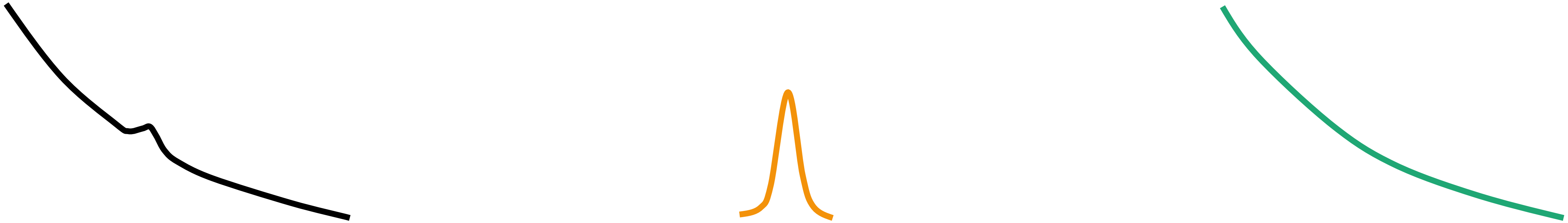


Statistical modeling

s+b unbinned maximum likelihood fit to the $\boldsymbol{m_{\gamma\gamma}}$ distribution

Signal PDF — Signal yield — BG PDF — BG yield

$$\mathcal{F}\left(m_{\gamma\gamma};\boldsymbol{\sigma}_X(\mu),m_X,N_{\mathrm{b}},\boldsymbol{a}\right)=f_X\left(m_{\gamma\gamma};\boldsymbol{x}_X(m_X)\right)N_X(\boldsymbol{\sigma}_X(\mu);m_X)+f_{\mathrm{b}}\left(m_{\gamma\gamma},\boldsymbol{a}\right)N_{\mathrm{b}}$$



Double-sided crystal ball (**DSCB**) function

Natural width neglected

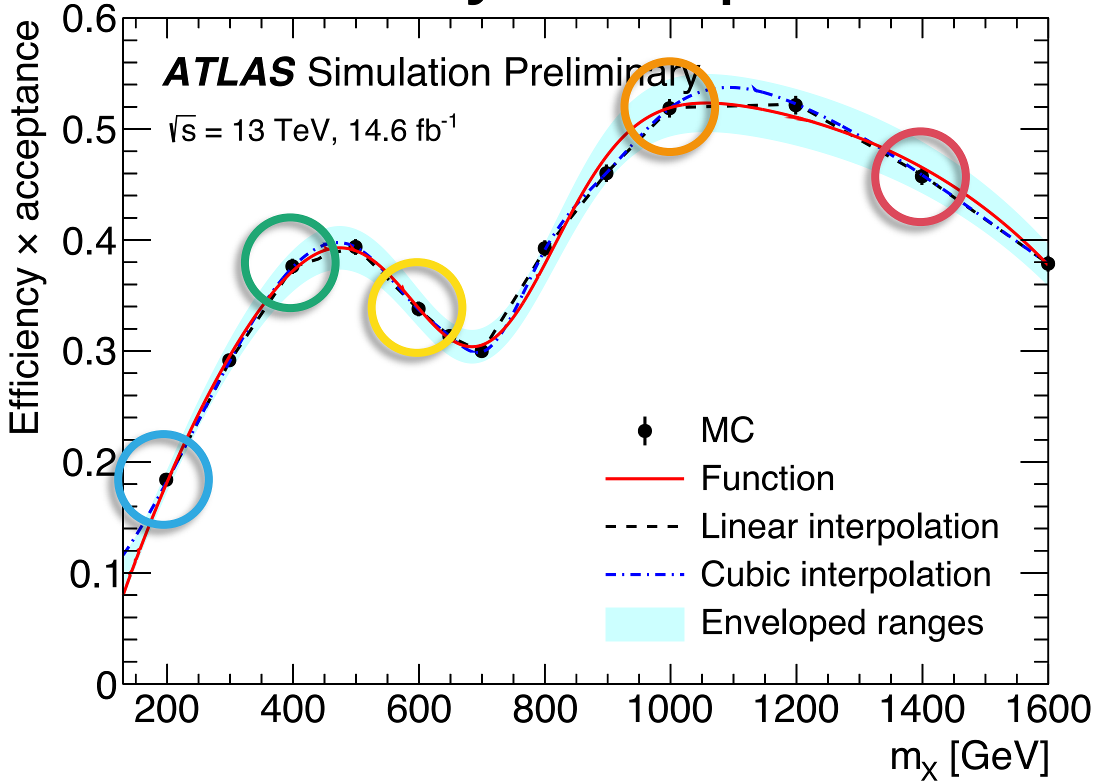
Signal yield modeling

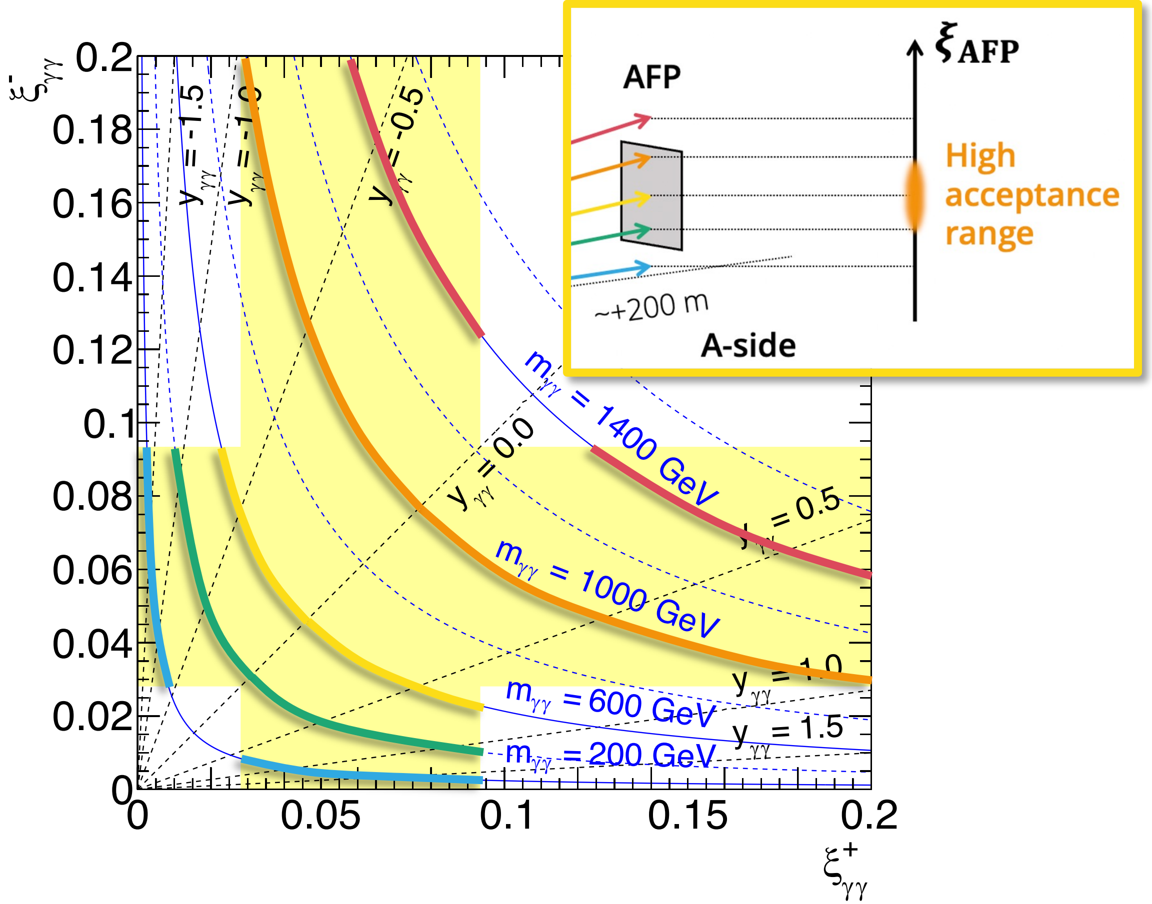
s+b unbinned maximum likelihood fit to the $m_{\gamma\gamma}$ distribution

Signal PDF — **Signal yield** — BG PDF — BG yield

$$\mathcal{F}(m_{\gamma\gamma}; \boldsymbol{\sigma}_X(\mu), m_X, N_{\mathrm{b}}, \boldsymbol{a}) = f_X\left(m_{\gamma\gamma}; \boldsymbol{x}_X(m_X)\right) N_X(\boldsymbol{\sigma}_X(\mu); m_X) + f_{\mathrm{b}}(m_{\gamma\gamma}, \boldsymbol{a})\, N_{\mathrm{b}}$$

Efficiency × acceptance





Signal yield modeling

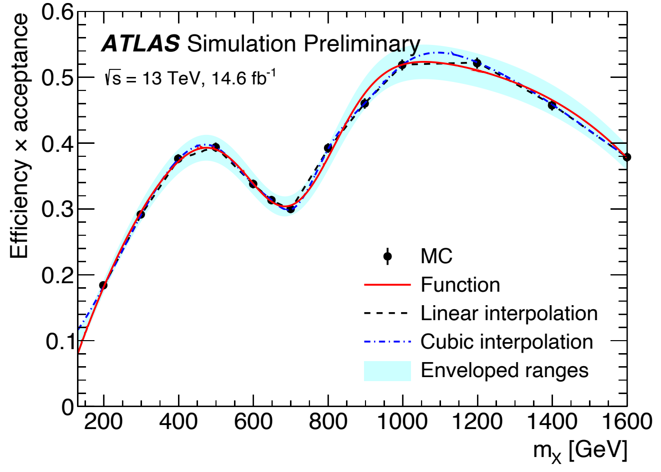
s+b unbinned maximum likelihood fit to the $m_{\gamma\gamma}$ distribution

Signal PDF | Signal yield | BG PDF | BG yield

$$\mathcal{F}\left(m_{\gamma\gamma};\boldsymbol{\sigma}_X(\mu),m_X,N_\mathrm{b},\boldsymbol{a}\right)=f_X\left(m_{\gamma\gamma};\boldsymbol{x}_X(m_X)\right)N_X(\boldsymbol{\sigma}_X(\mu);m_X)+f_\mathrm{b}\left(m_{\gamma\gamma},\boldsymbol{a}\right)N_\mathrm{b}$$

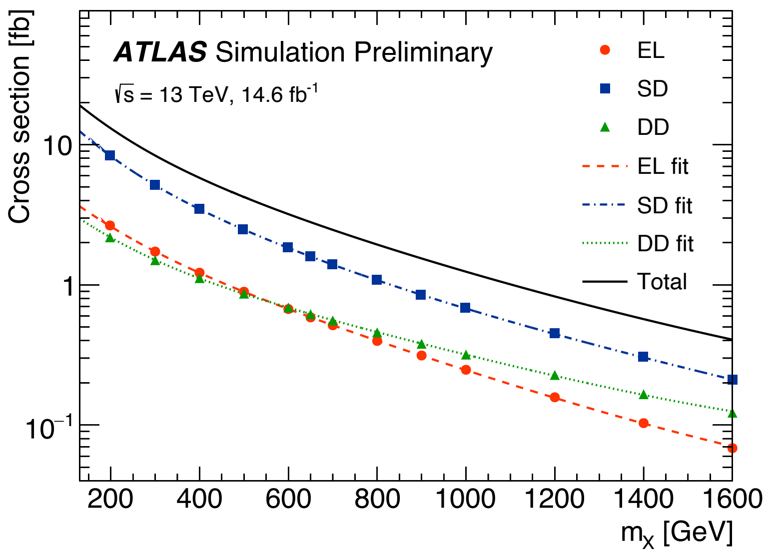
Signal strength $\mu = 1$

Efficiency × acceptance



×

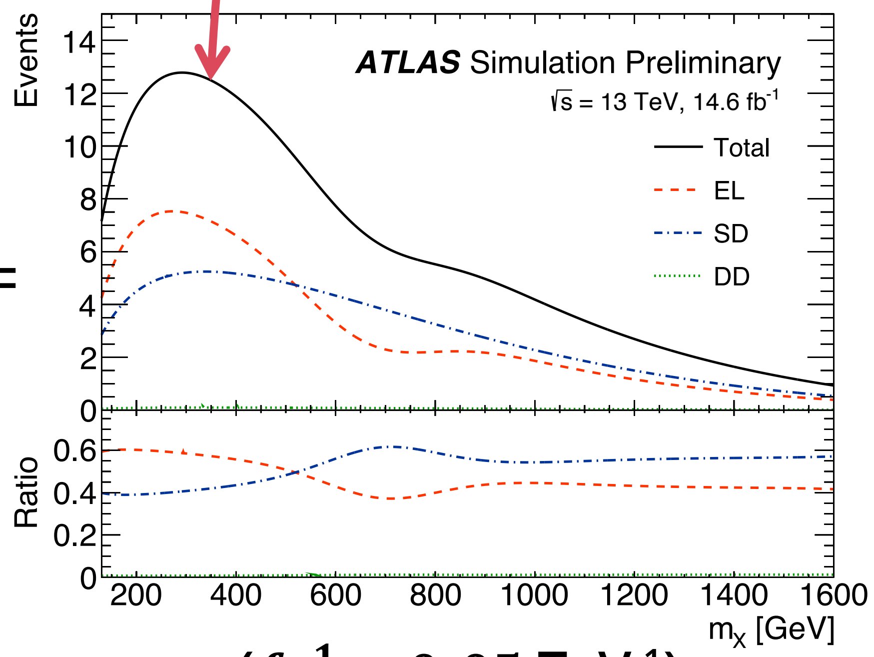
Cross section



$(f^{-1} = 0.05$ TeV-1)

=

Signal yield



$(f^{-1} = 0.05$ TeV-1)

Background modeling

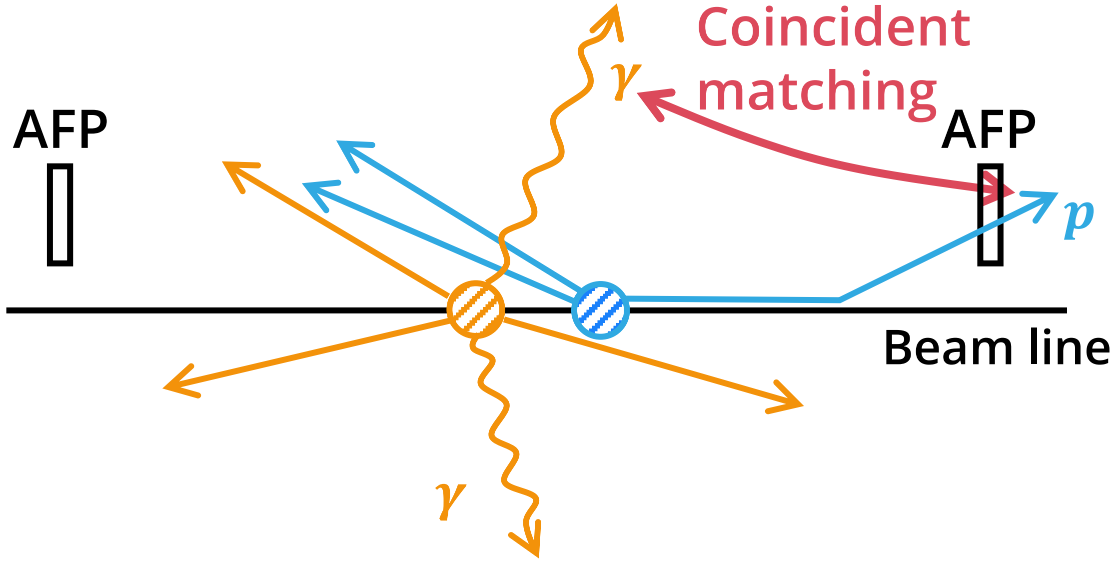
s+b unbinned maximum likelihood fit to the $m_{\gamma\gamma}$ distribution

Signal PDF — Signal yield — **BG PDF** — BG yield

$$\mathcal{F}(m_{\gamma\gamma};\boldsymbol{\sigma}_X(\mu),m_X,N_\mathrm{b},\boldsymbol{a}) = f_X\left(m_{\gamma\gamma};\boldsymbol{x}_X(m_X)\right)N_X(\boldsymbol{\sigma}_X(\mu);m_X) + f_\mathrm{b}(m_{\gamma\gamma},\boldsymbol{a})\,N_\mathrm{b}$$

Combinatorial BG

BG $\gamma\gamma$ (including fake) +
pileup proton from another vertex



Empirical PDF: $f_\mathrm{b}(m_{\gamma\gamma};\boldsymbol{a}) = \left(1-\left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{1/3}\right)^{b}\cdot\left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{a_0}$

$\boldsymbol{a}\equiv(a_0,b)$

To
- determine parameters $\boldsymbol{a}$
- validate this form
- evaluate uncertainty on signal sterngth μ

including
- actual detector response
- fake photons,

Create fully data-driven combinatorial BG sample

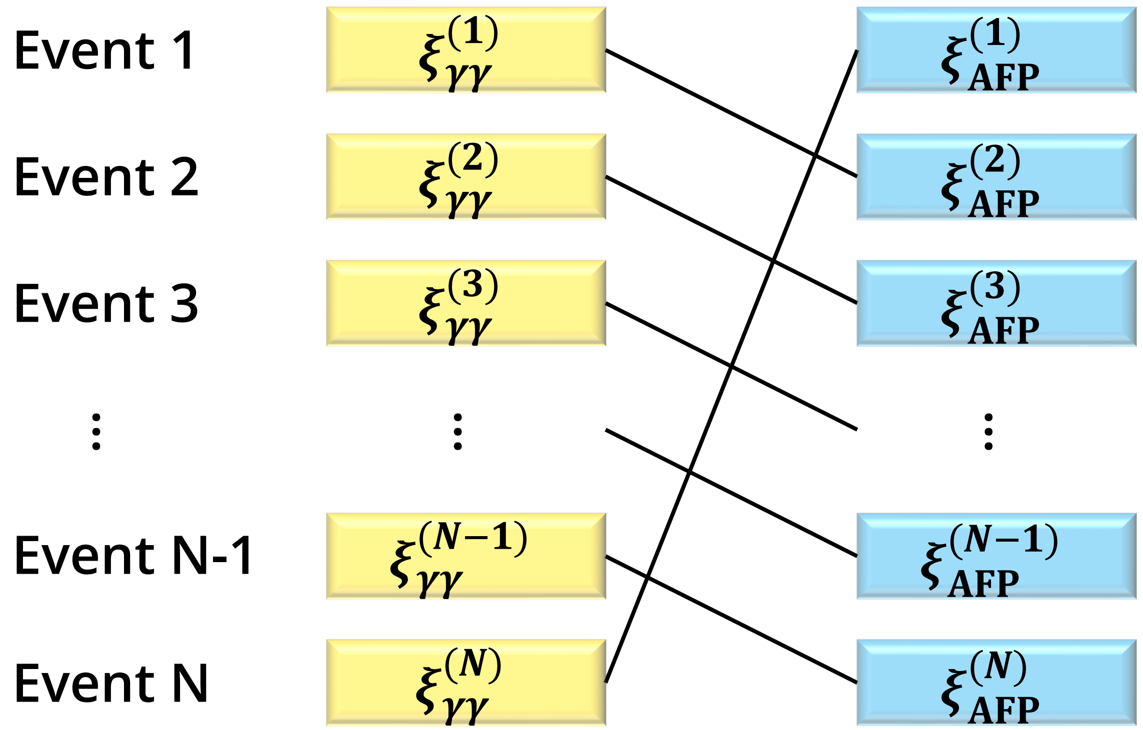
Background sample generation

Photons and protons are recorded for each event

Event 1	$\xi_{\gamma\gamma}^{(1)}$	$\xi_{\mathrm{AFP}}^{(1)}$
Event 2	$\xi_{\gamma\gamma}^{(2)}$	$\xi_{\mathrm{AFP}}^{(2)}$
Event 3	$\xi_{\gamma\gamma}^{(3)}$	$\xi_{\mathrm{AFP}}^{(3)}$
⋮	⋮	⋮
Event N-1	$\xi_{\gamma\gamma}^{(N-1)}$	$\xi_{\mathrm{AFP}}^{(N-1)}$
Event N	$\xi_{\gamma\gamma}^{(N)}$	$\xi_{\mathrm{AFP}}^{(N)}$

Background sample generation

Photons and protons are recorded for each event



Reassignment of protons to diphotons

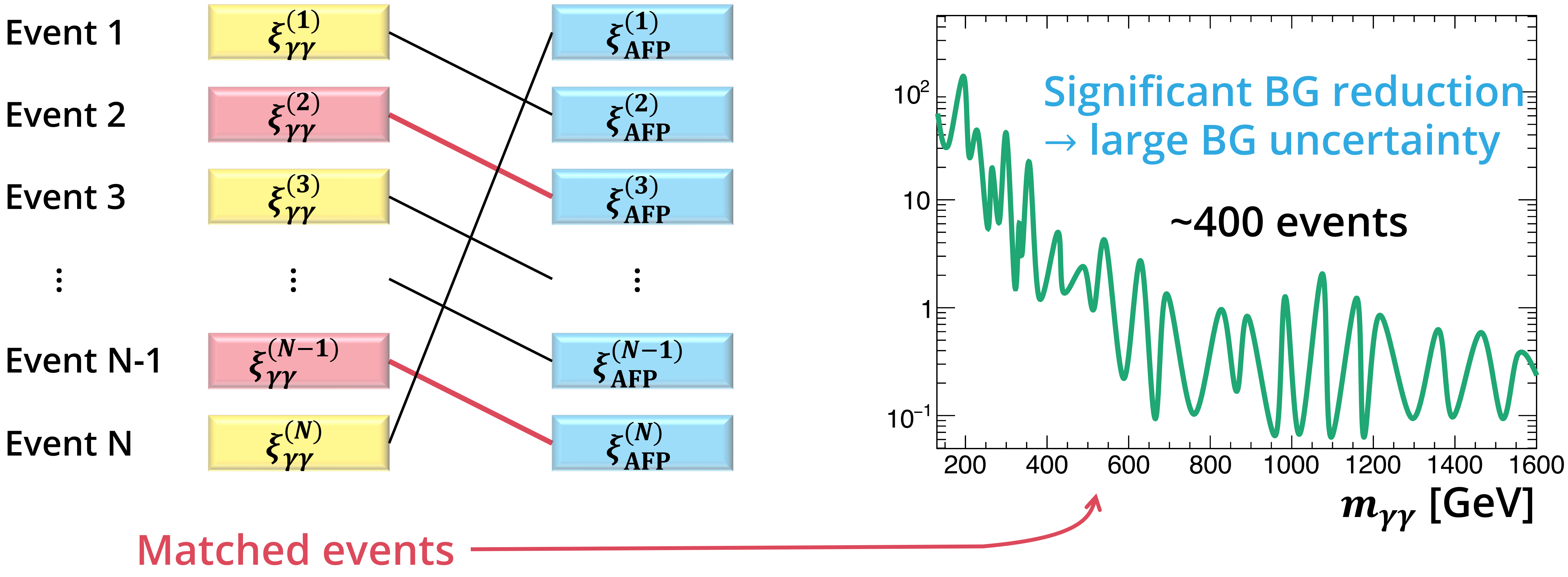
↓

- Reproduce the coincident matching between $\gamma\gamma$ and proton
- Suppress the single-vertex BG and signal-contamination in data

→ Pure combinatorial BG sample

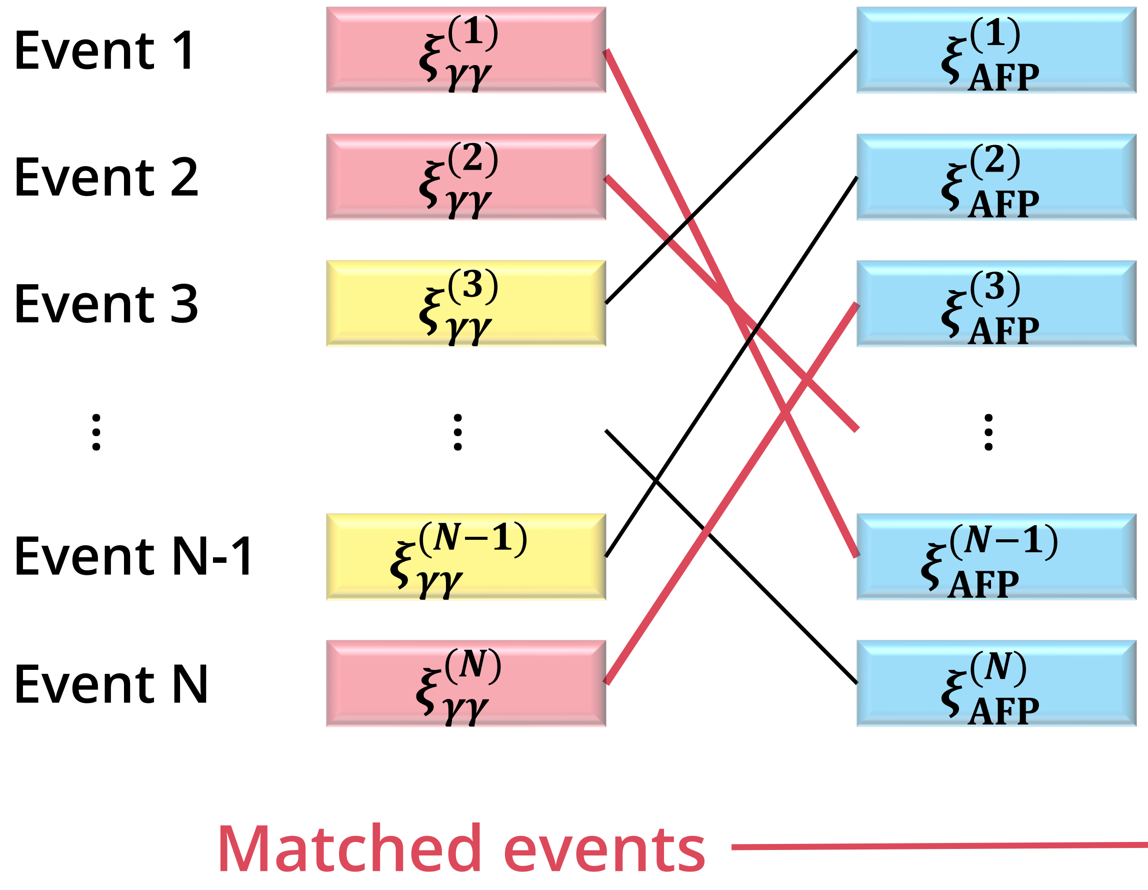
Background sample generation

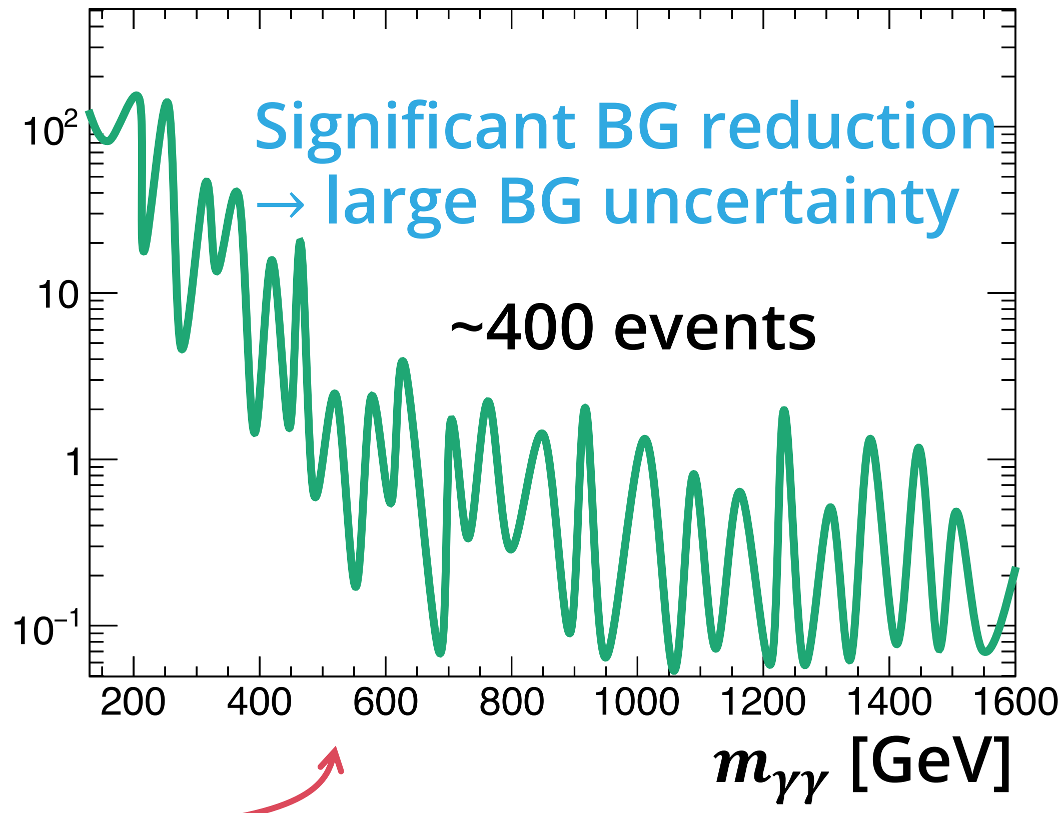
Photons and protons are recorded for each event



Background sample generation

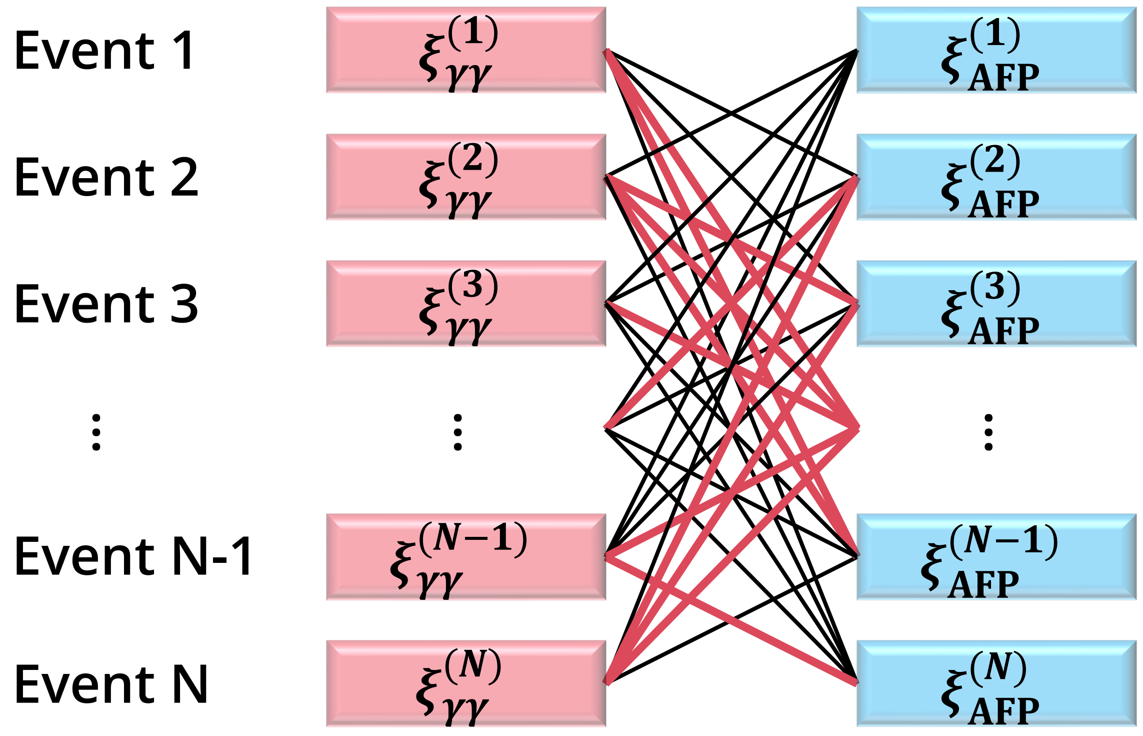
Try other combination of the reassignment





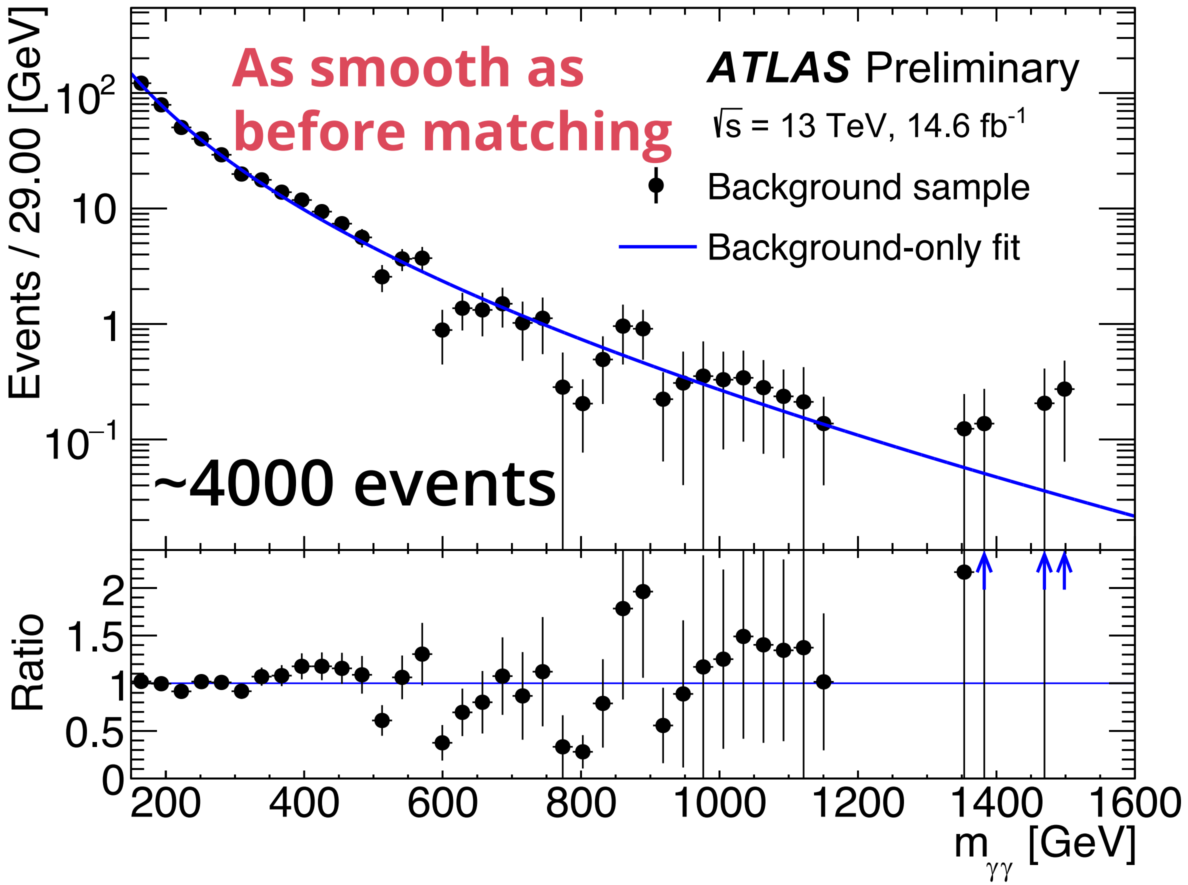
Background sample generation

Use all possible combinations of reassignment



Matched events

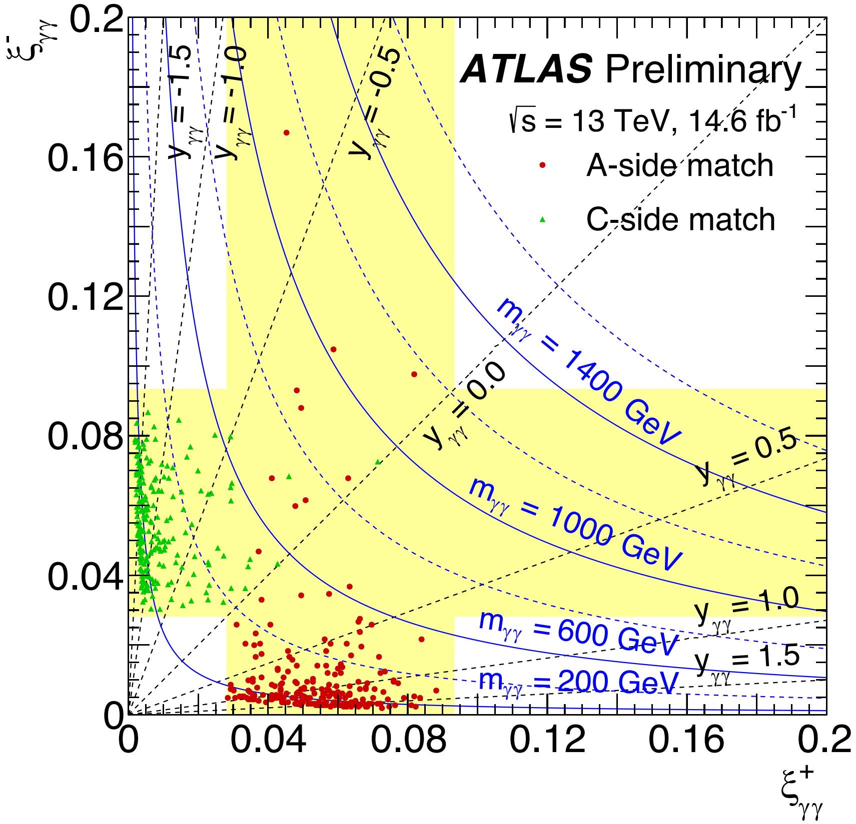
Sample size enhanced

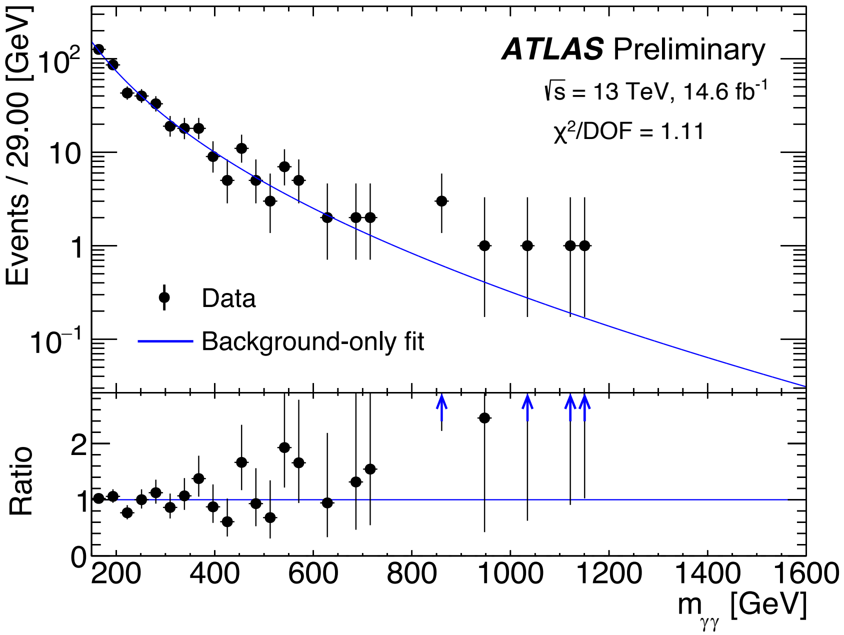


BG PDF initial parameters are determined

Search results

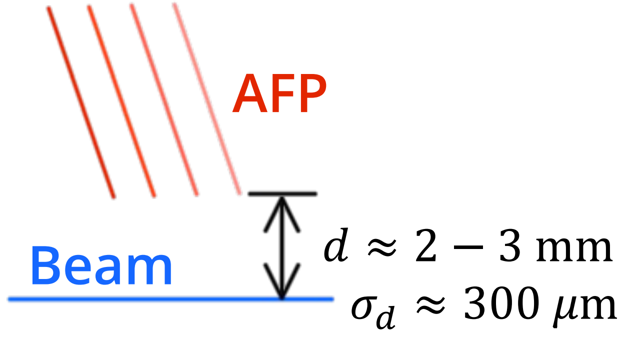
441 events observed

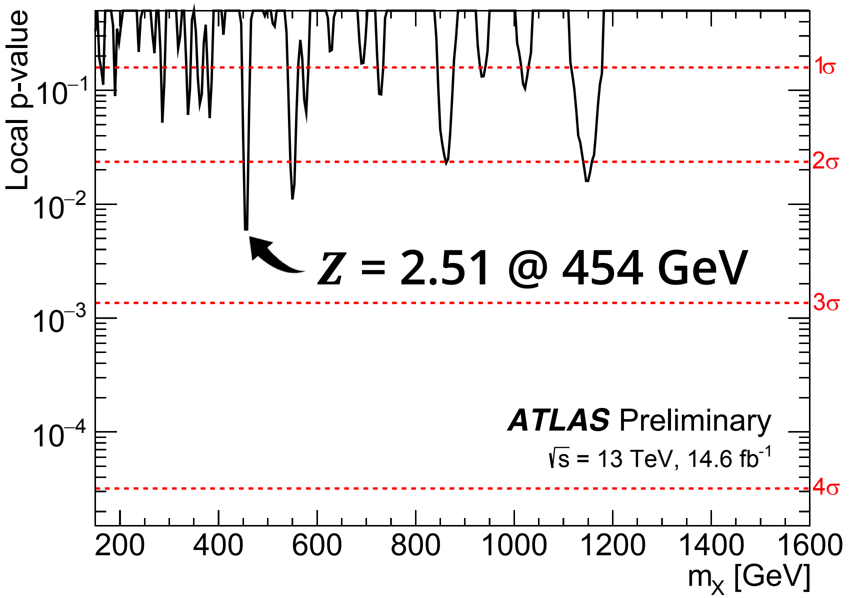




No double matching

Dominant sys. unc.: AFP global alignment





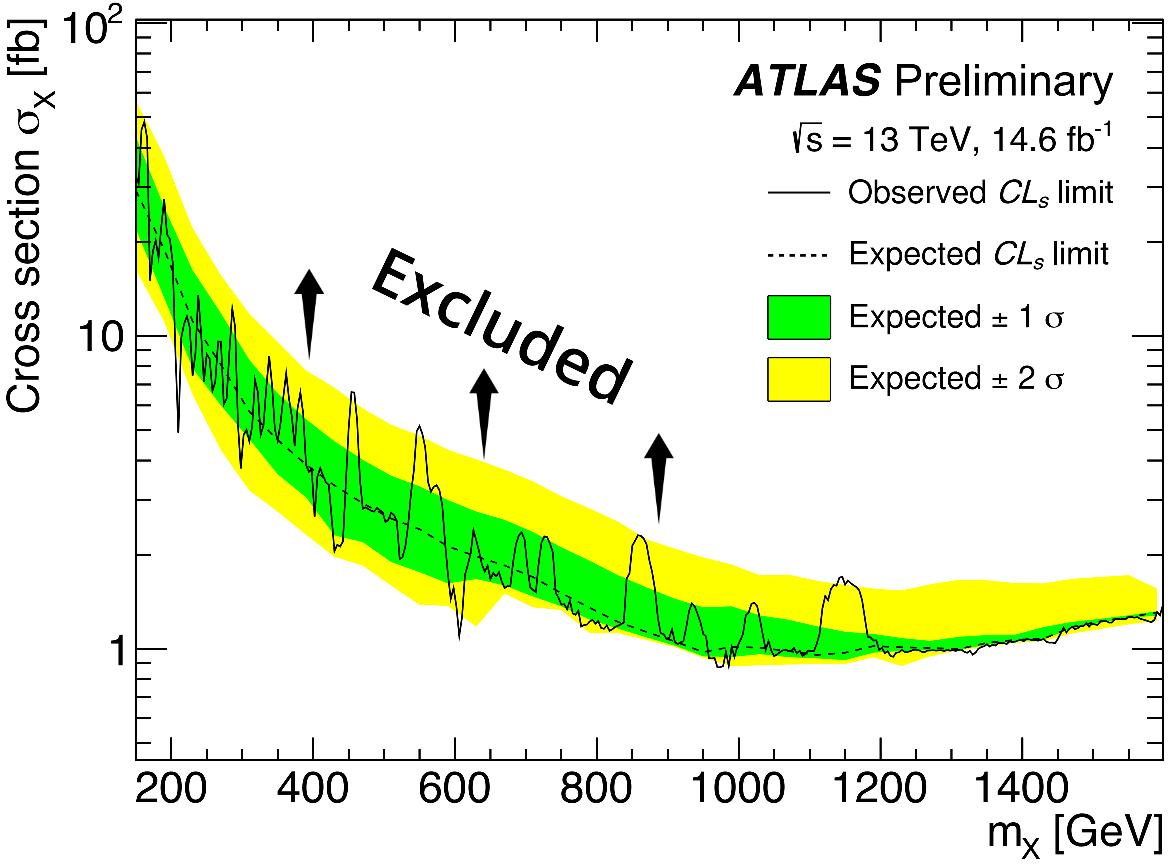
No excess from the BG-only hypothesis

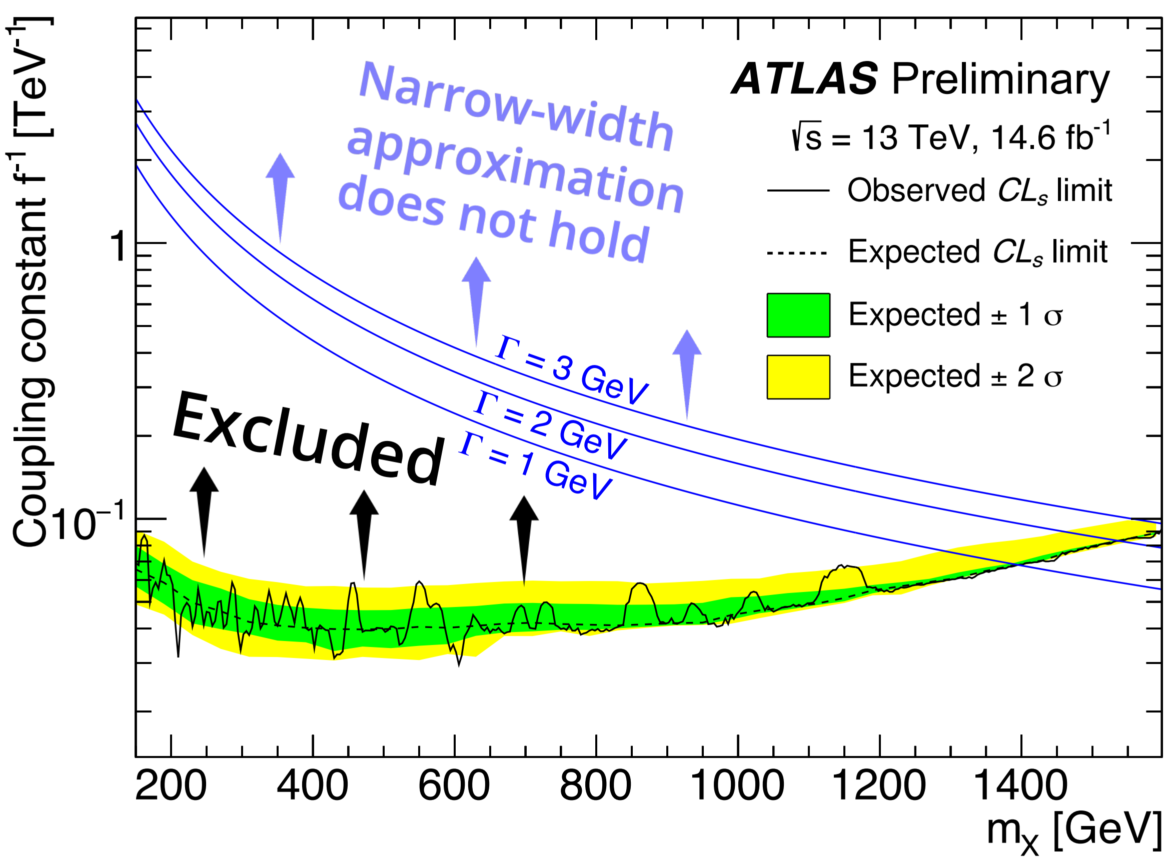
Statistical uncetainty is dominant

Exclusion limit

CL_s limit @ 95% CL

100% ALP → $\gamma\gamma$ branching ratio is assumed

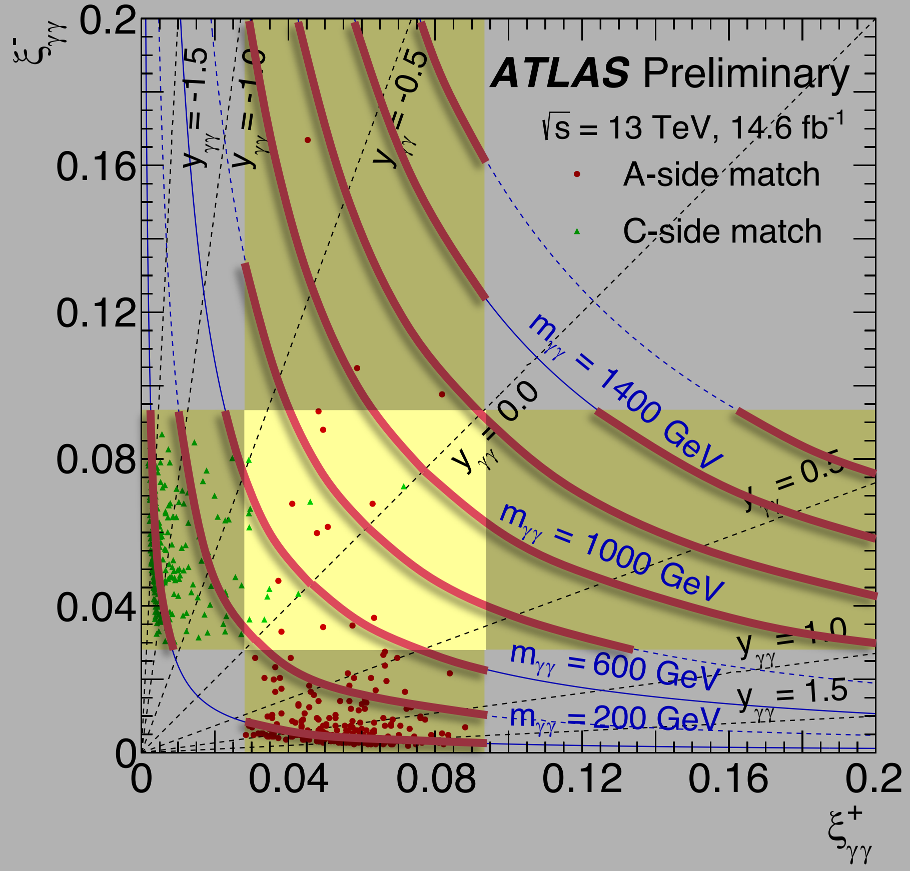


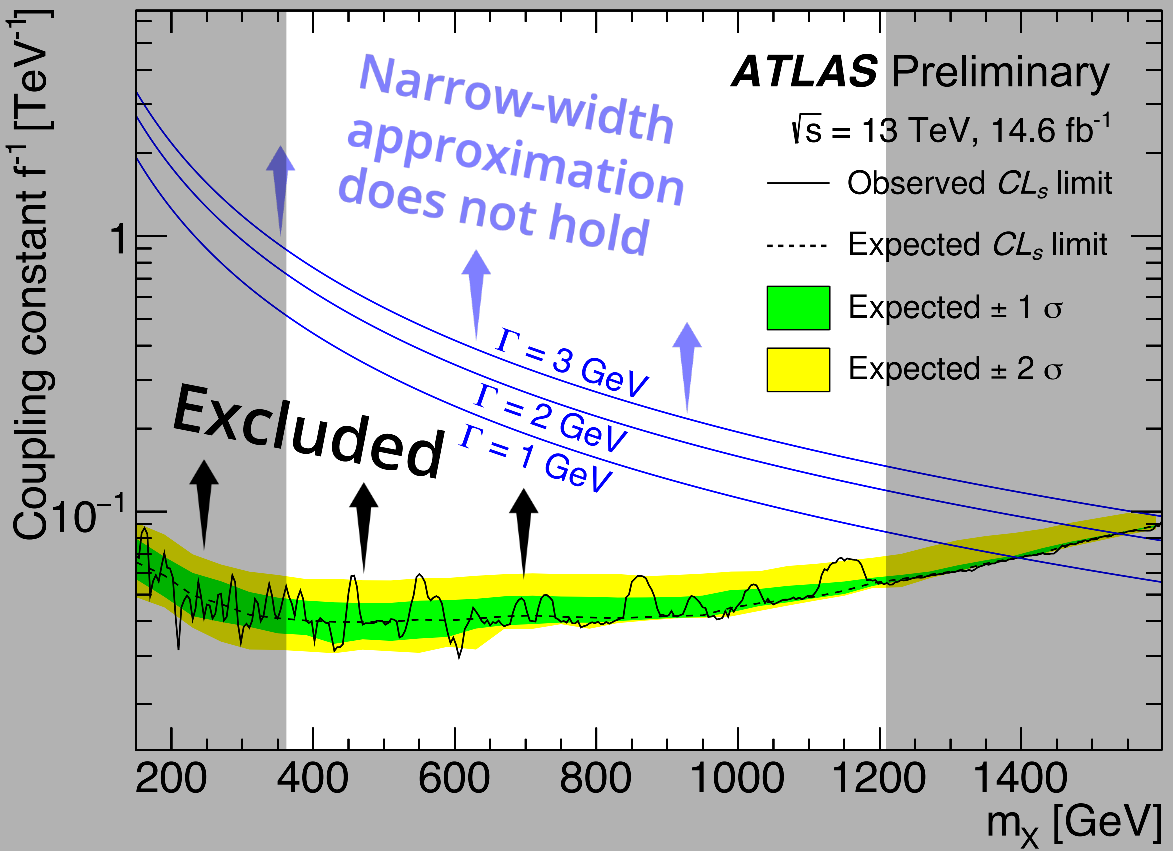


Exclusion limit

CL_s limit @ 95% CL

100% ALP → $\gamma\gamma$ branching ratio is assumed



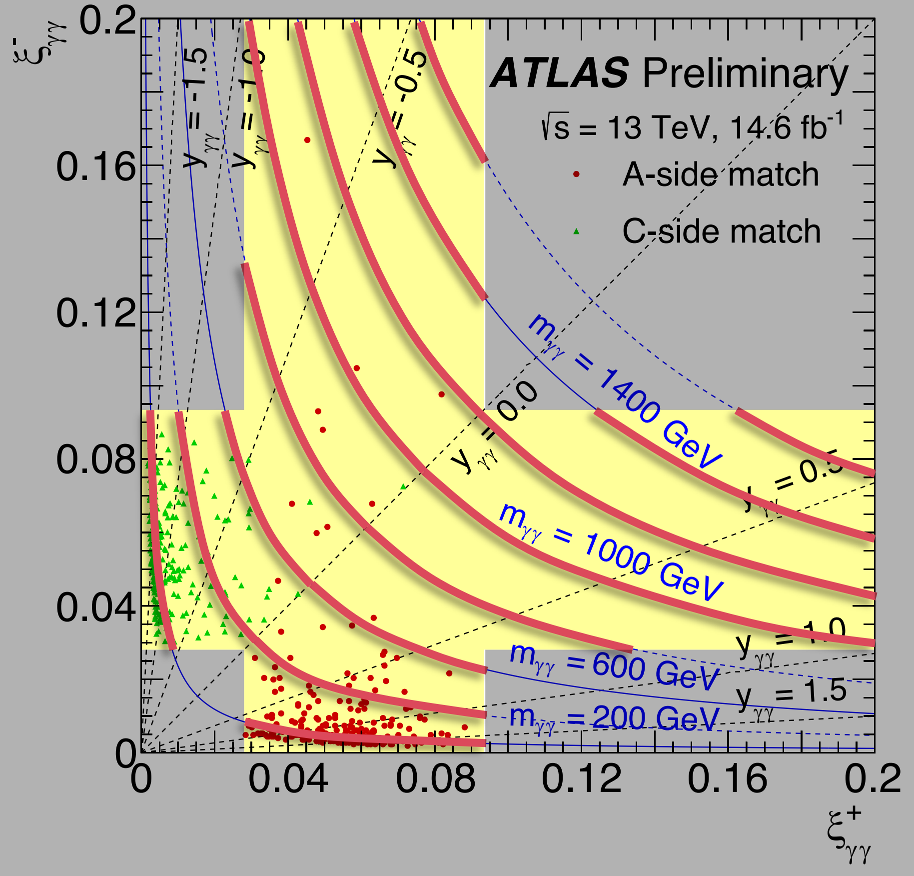


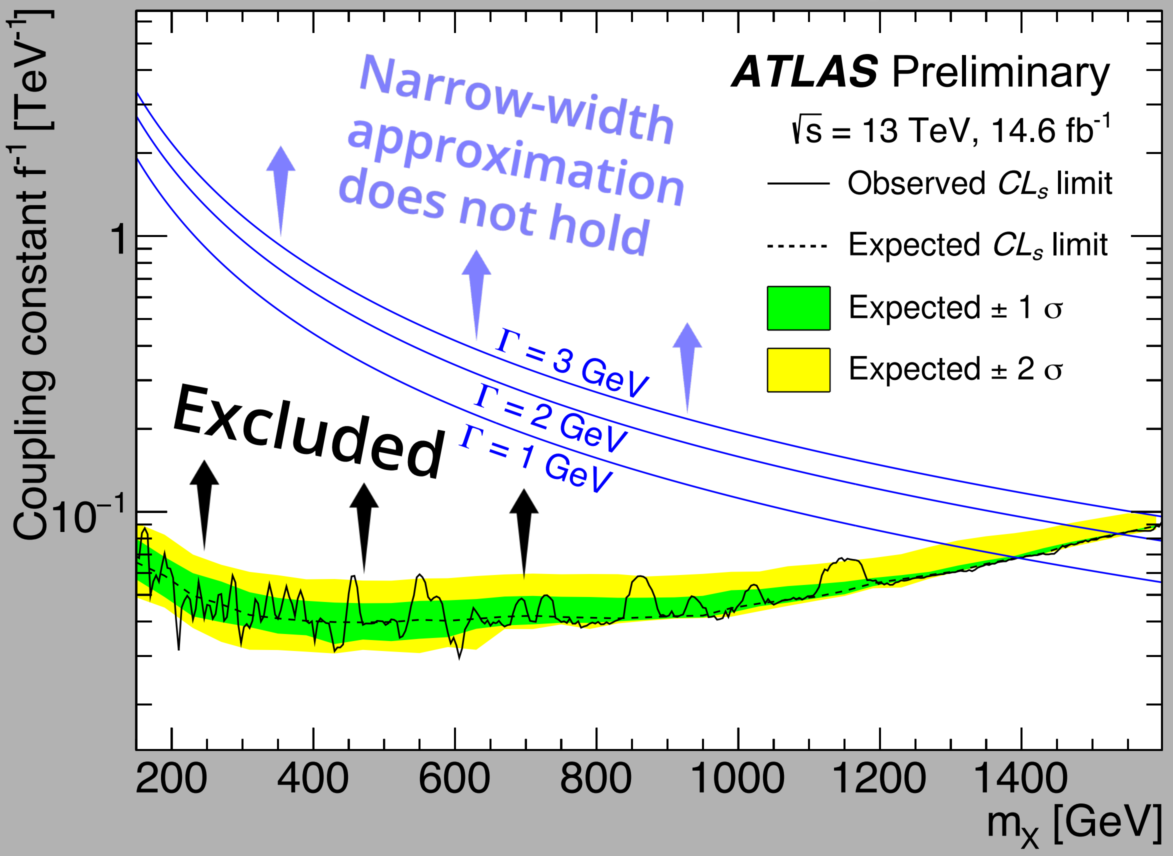
Exclusion limit

CL_s limit @ 95% CL

100% ALP $\rightarrow \gamma\gamma$ branching ratio is assumed

"At least one" matching enhances the mass acceptance





Summary

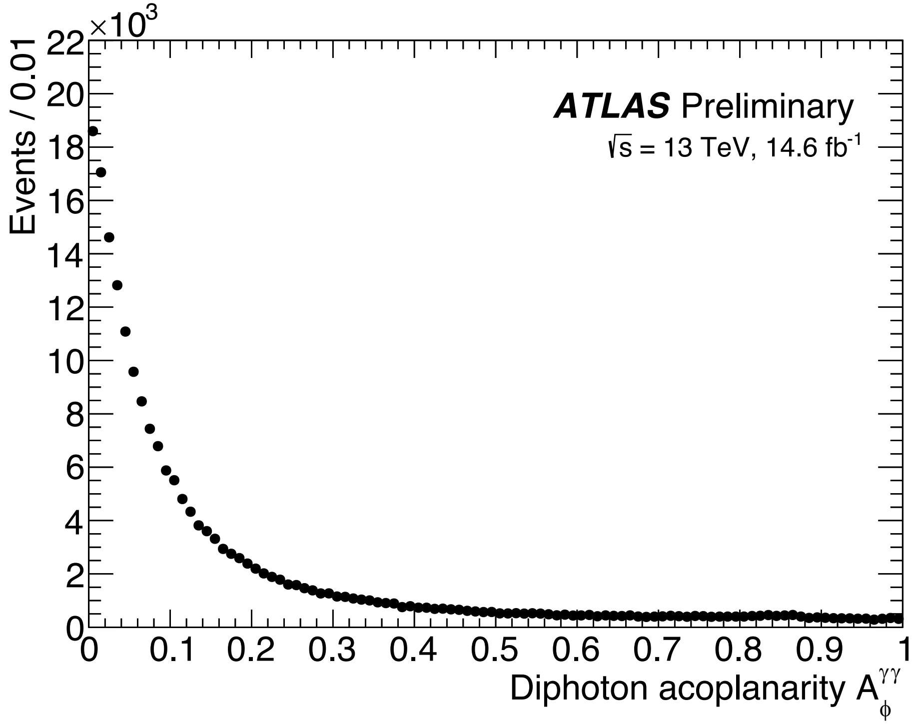
- Search for diphoton resonance in light-by-light scattering
- ATLAS Run 2 experiment (14.6 fb^{-1}) with AFP detector
  First search for BSM with AFP
- Matching between $\gamma\gamma$ and proton
- "At least one" matching requirement enhances the acceptance
- No excess was observed
- Exclusion limits are set on cross section and coupling constant
- CONF note: ATLAS-CONF-2023-002

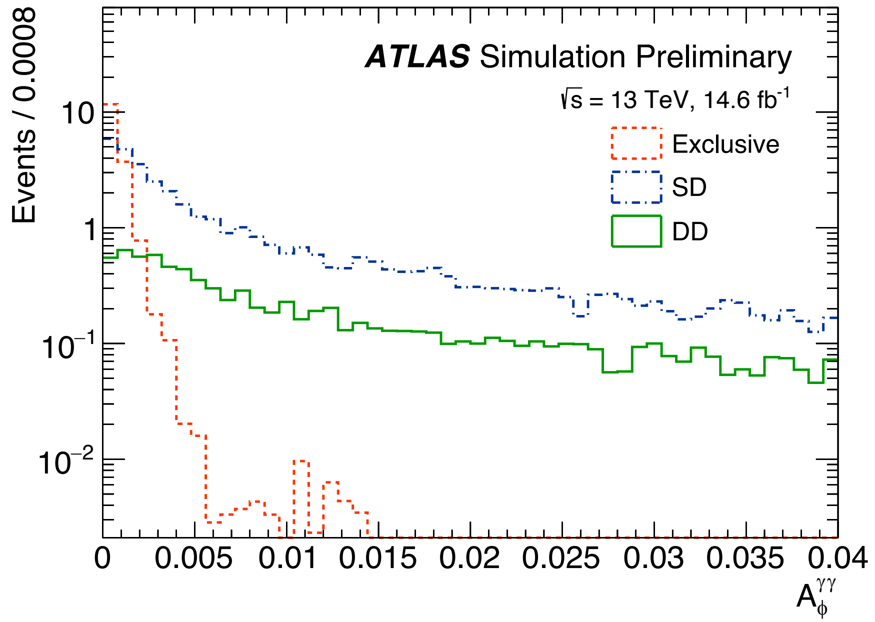
Thank you for listening!

Backup slides

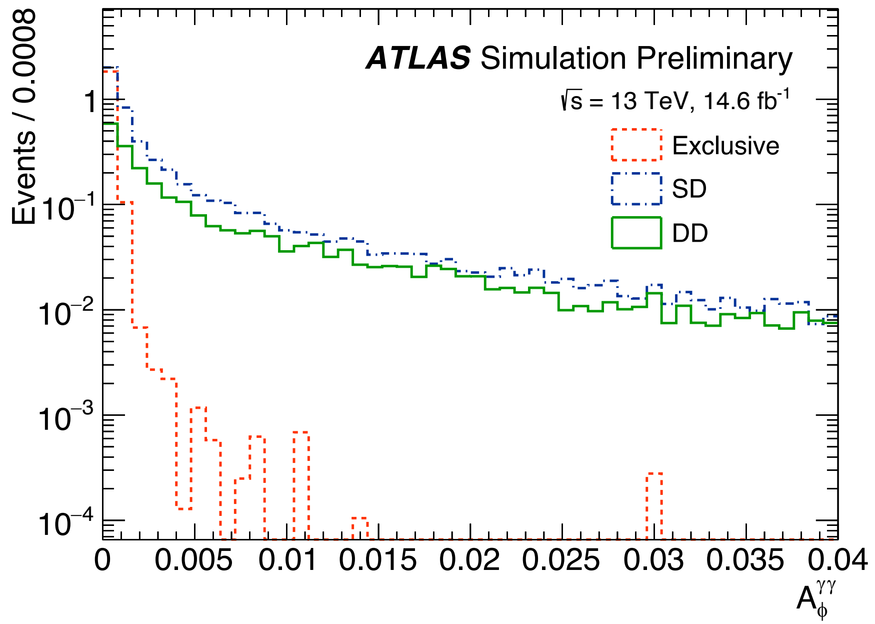
Acoplanarity distribution

Data





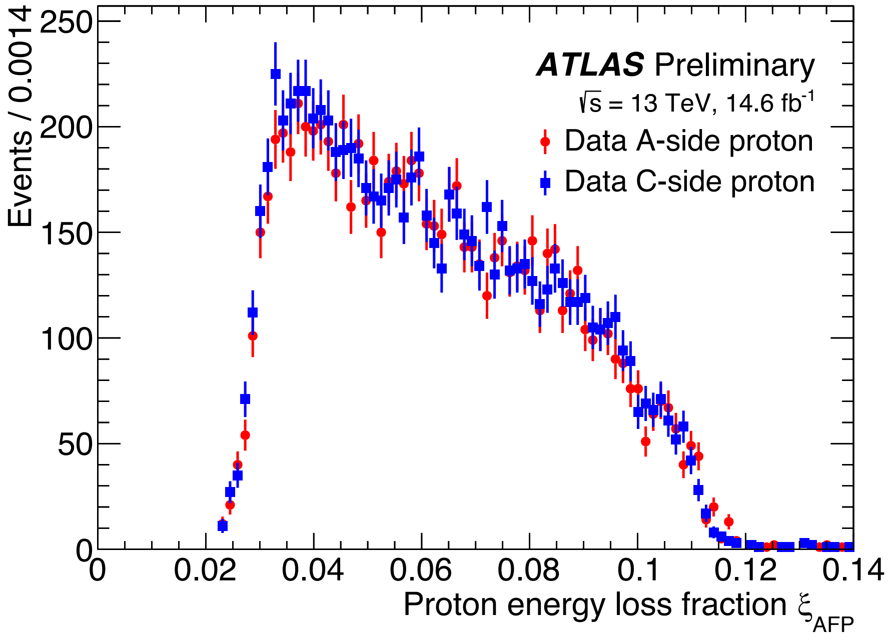
ALP $m_X = 300$ GeV



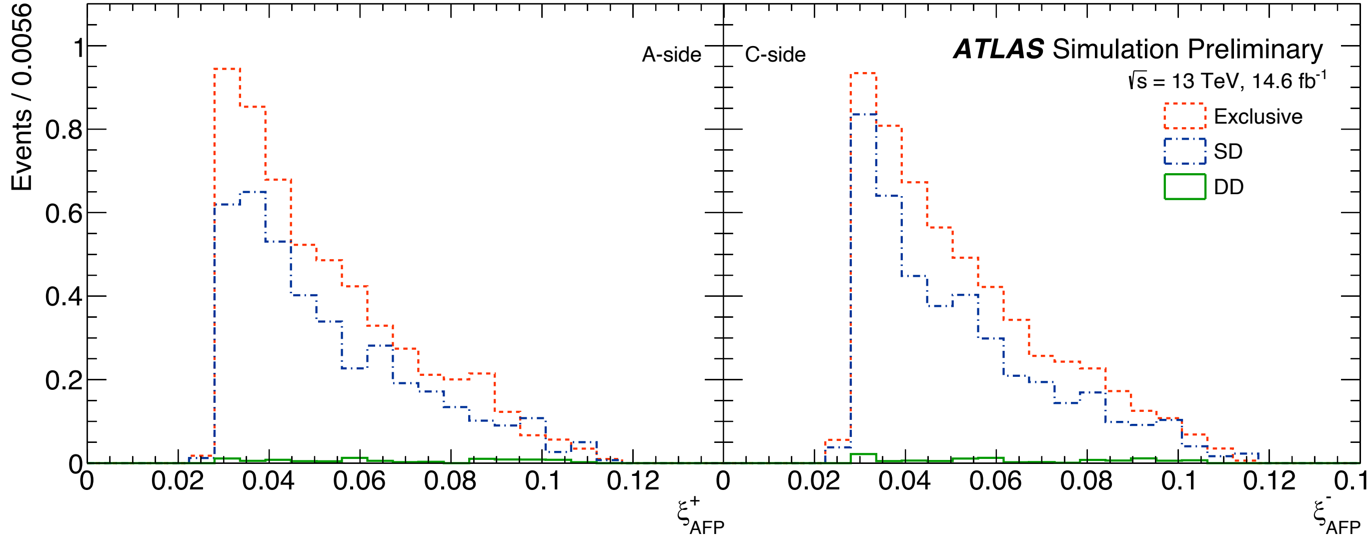
ALP $m_X = 1200$ GeV

ξ_{AFP} distribution

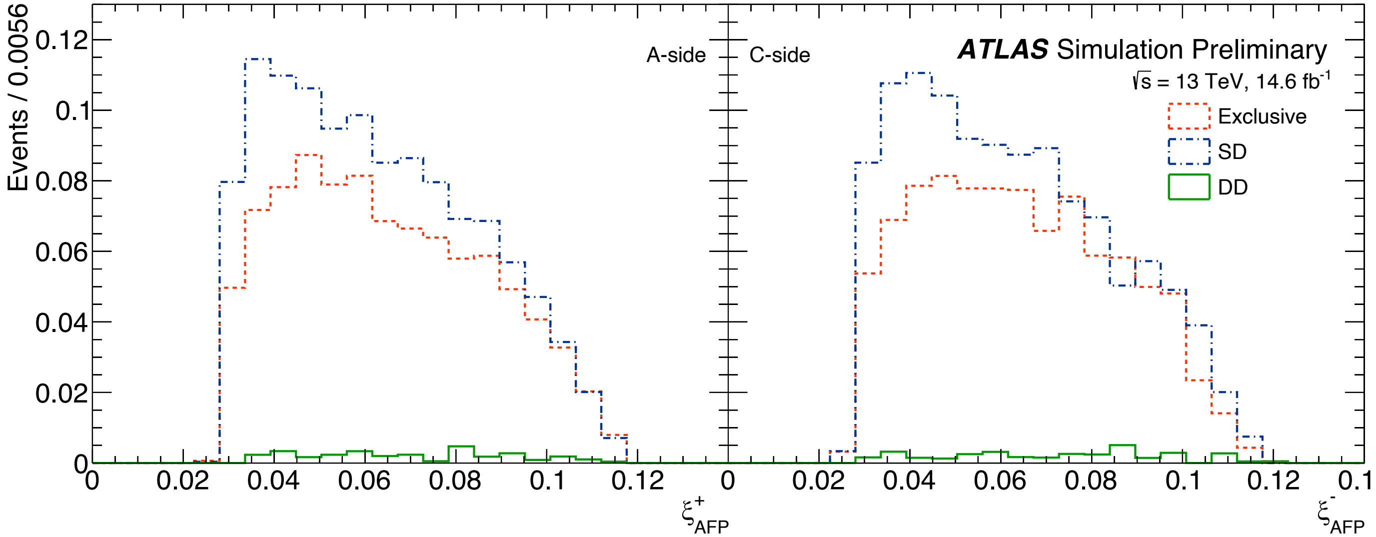
Data



ALP $m_X = 300$ GeV

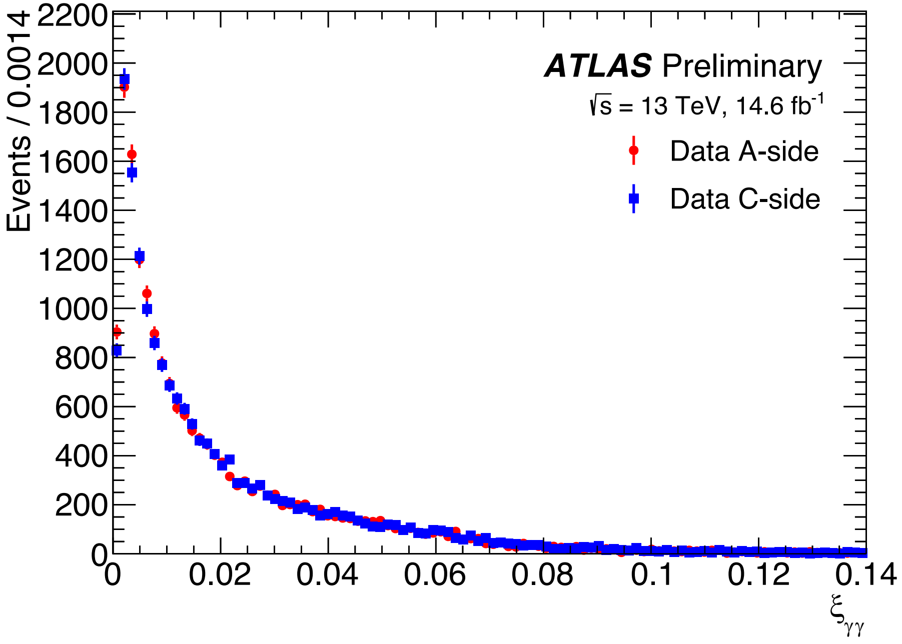


ALP $m_X = 1200$ GeV

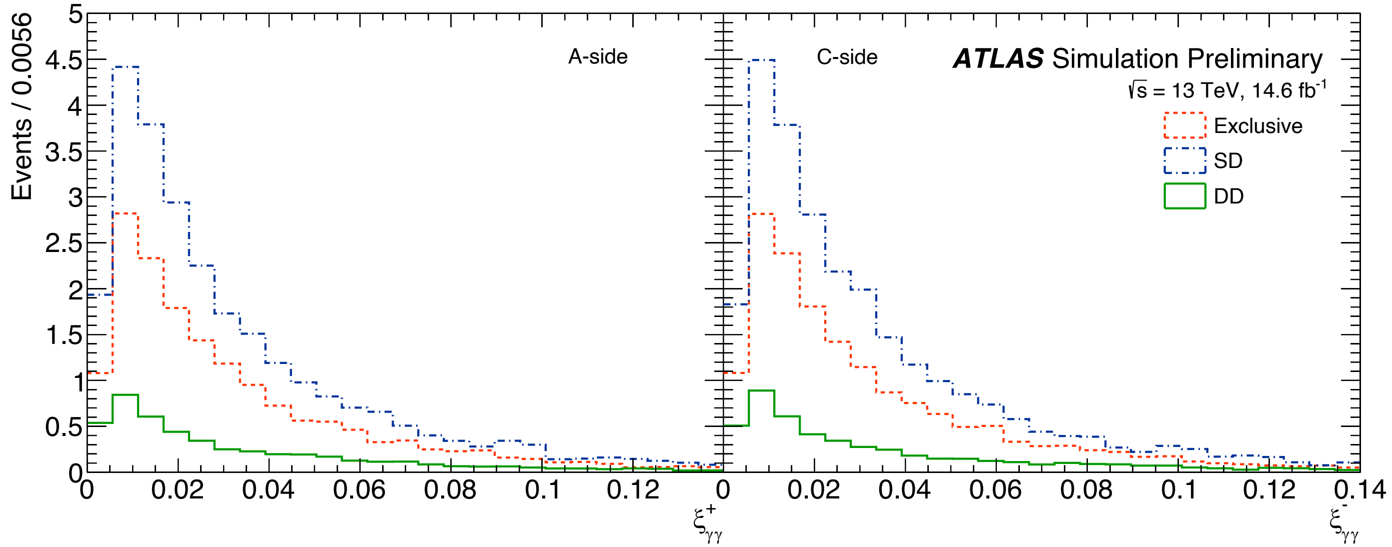


$\xi_{\gamma\gamma}$ distribution

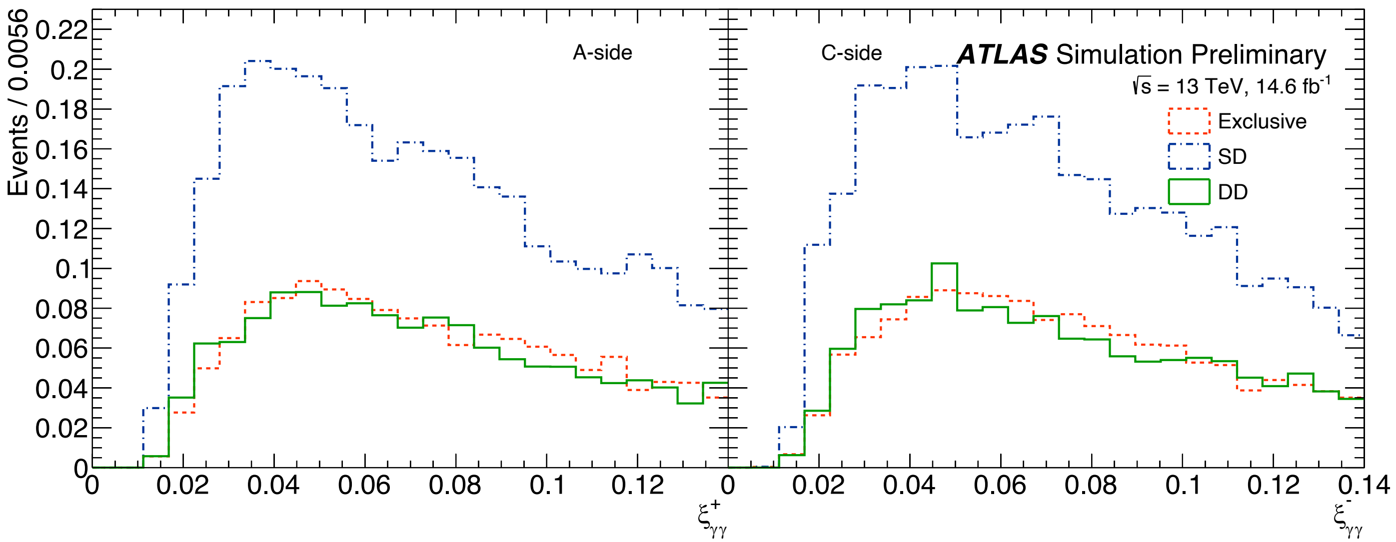
Data



ALP m_X = 300 GeV



ALP m_X = 1200 GeV



Statistical modeling

- **Likelihood**

$$L(\mu, \boldsymbol{\nu}; m_X, \underbrace{\{m_{\gamma\gamma,i}\}}_{\text{Data}}) = \overbrace{e^{-(N_X(\mu)+N_\mathrm{b})}}^{\text{Extended}} \left[\prod_{i=1}^{M} \overbrace{\mathcal{F}(m_{\gamma\gamma,i}; \boldsymbol{\sigma}_X(\mu), m_X, N_\mathrm{b}, \boldsymbol{a}, \boldsymbol{\theta})}^{\text{PDF}}\right] \overbrace{\prod_{\vartheta\in\boldsymbol{\theta}} e^{-\vartheta^2/2}}^{\text{Systematics}}$$

- **PDF**

$$\mathcal{F}(m_{\gamma\gamma}; \boldsymbol{\sigma}_X(\mu), m_X, N_\mathrm{b}, \boldsymbol{a}, \boldsymbol{\theta})$$
$$= \underbrace{f_X\left(m_{\gamma\gamma}; \boldsymbol{x}_X(m_X, \boldsymbol{\theta}_\mathrm{CB})\right)}_{\text{Signal PDF}} \underbrace{N_X(\boldsymbol{\sigma}_X(\mu); m_X, \boldsymbol{\theta}_{N_X})}_{\text{Signal yield}} + \underbrace{f_\mathrm{b}(m_{\gamma\gamma}, \boldsymbol{a})}_{\text{BG PDF}} \underbrace{N_\mathrm{b}}_{\text{BG yield}}$$

- **Signal yield**

$$N_X(\boldsymbol{\sigma}_X(\mu); m_X, \boldsymbol{\theta}_{N_X})$$
$$= L_\mathrm{int} \sum_{i\in\{\mathrm{EL,SD,DD}\}} \left(\mu\sigma^i_\mathrm{std}(m_X)\varepsilon_i(m_X)K_{\varepsilon i}(m_X, \theta_{\varepsilon i})K_{S^2 i}(\theta_{S^2 i})\right) \prod_{k\in S_1} K_k(\theta_k) + \delta_\mathrm{BG}(m_X)\theta_\mathrm{BG}$$

- μ: **Signal strength (unit:** $f^{-1} = 0.05\ \mathrm{TeV}^{-1}$**)**
- $\boldsymbol{\theta}$: **nuisance parameter (NP)**

Signal PDF modeling

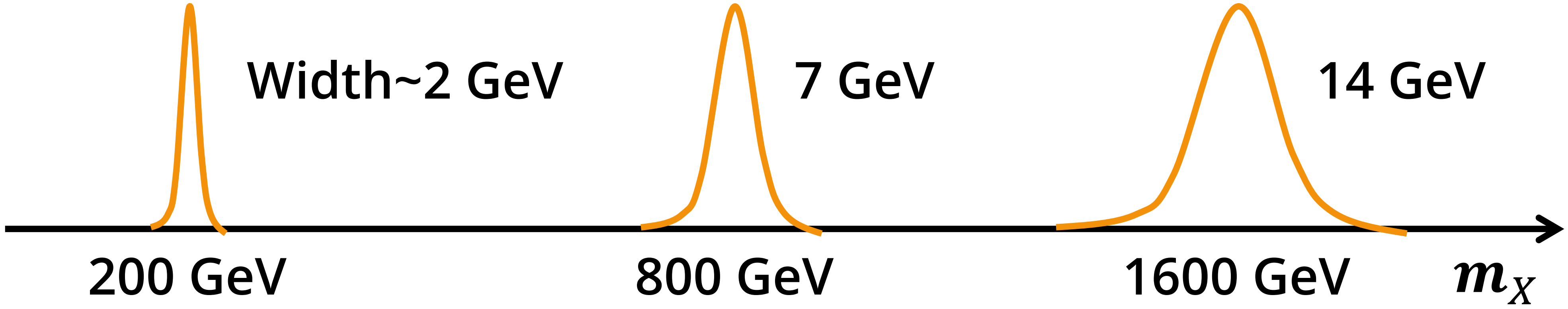
s+b unbinned maximum likelihood fit to the $\boldsymbol{m_{\gamma\gamma}}$ distribution

Signal PDF Signal yield BG PDF BG yield

$$\mathcal{F}\left(m_{\gamma\gamma}; \boldsymbol{\sigma}_X(\mu), m_X, N_\mathrm{b}, \boldsymbol{a}\right) = f_X\left(m_{\gamma\gamma}; \boldsymbol{x}_X(m_X)\right) N_X(\boldsymbol{\sigma}_X(\mu); m_X) + f_\mathrm{b}\left(m_{\gamma\gamma}, \boldsymbol{a}\right) N_\mathrm{b}$$

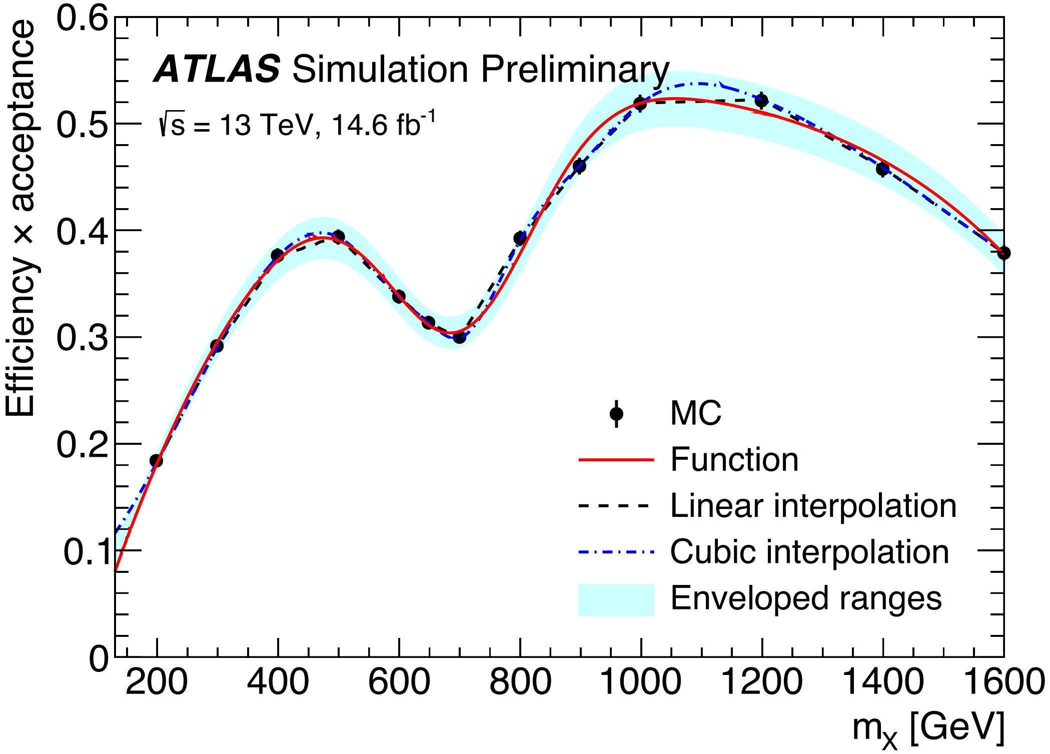
Double-sided crystal ball (DSCB) function

- ALP natural width is negligible
- 6 parameters ($\boldsymbol{x}_X$)
- Each of them is parametrized as a function of $\boldsymbol{m_X}$ using signal MC
  → Modelled signal shape continuously varies with $\boldsymbol{m_X}$

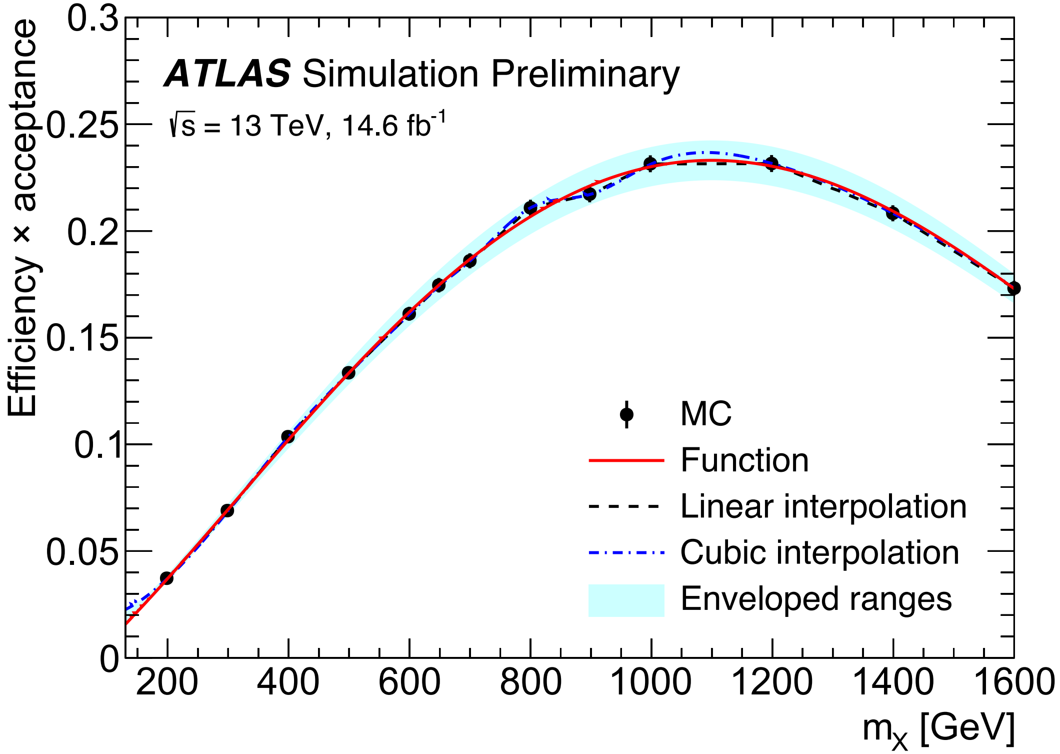


Signal efficiency × acceptance

Exclusive



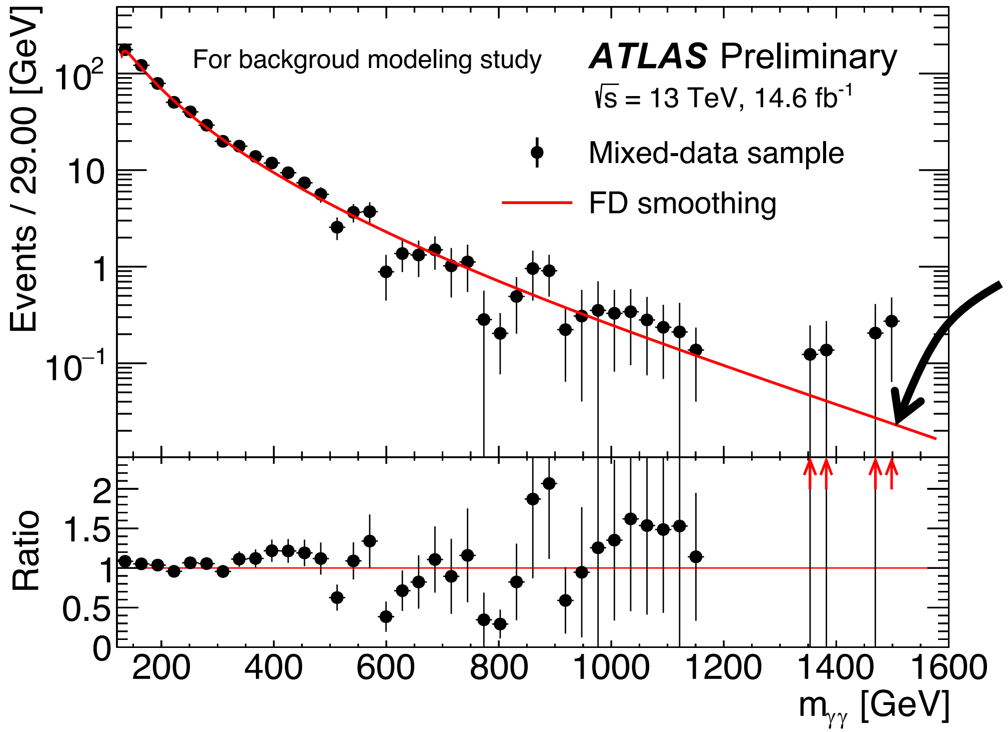
SD



Background modeling uncertainty

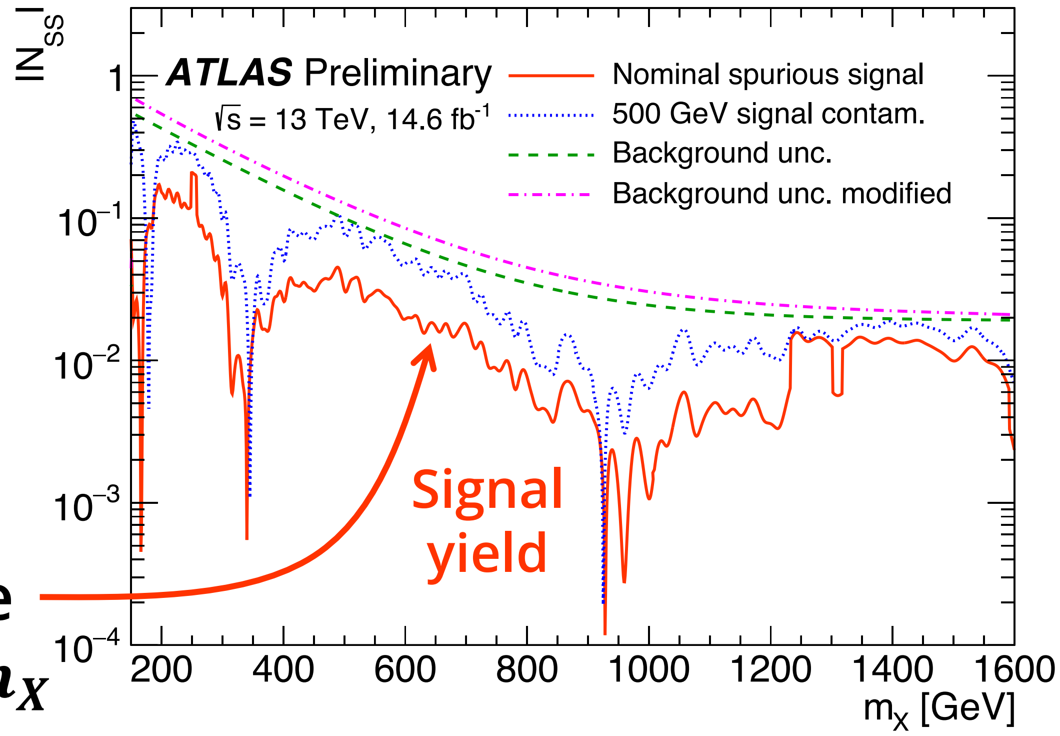
Evaluate the flexibility of BG function

Smooth the BG sample by functional decomposition (**FD**)



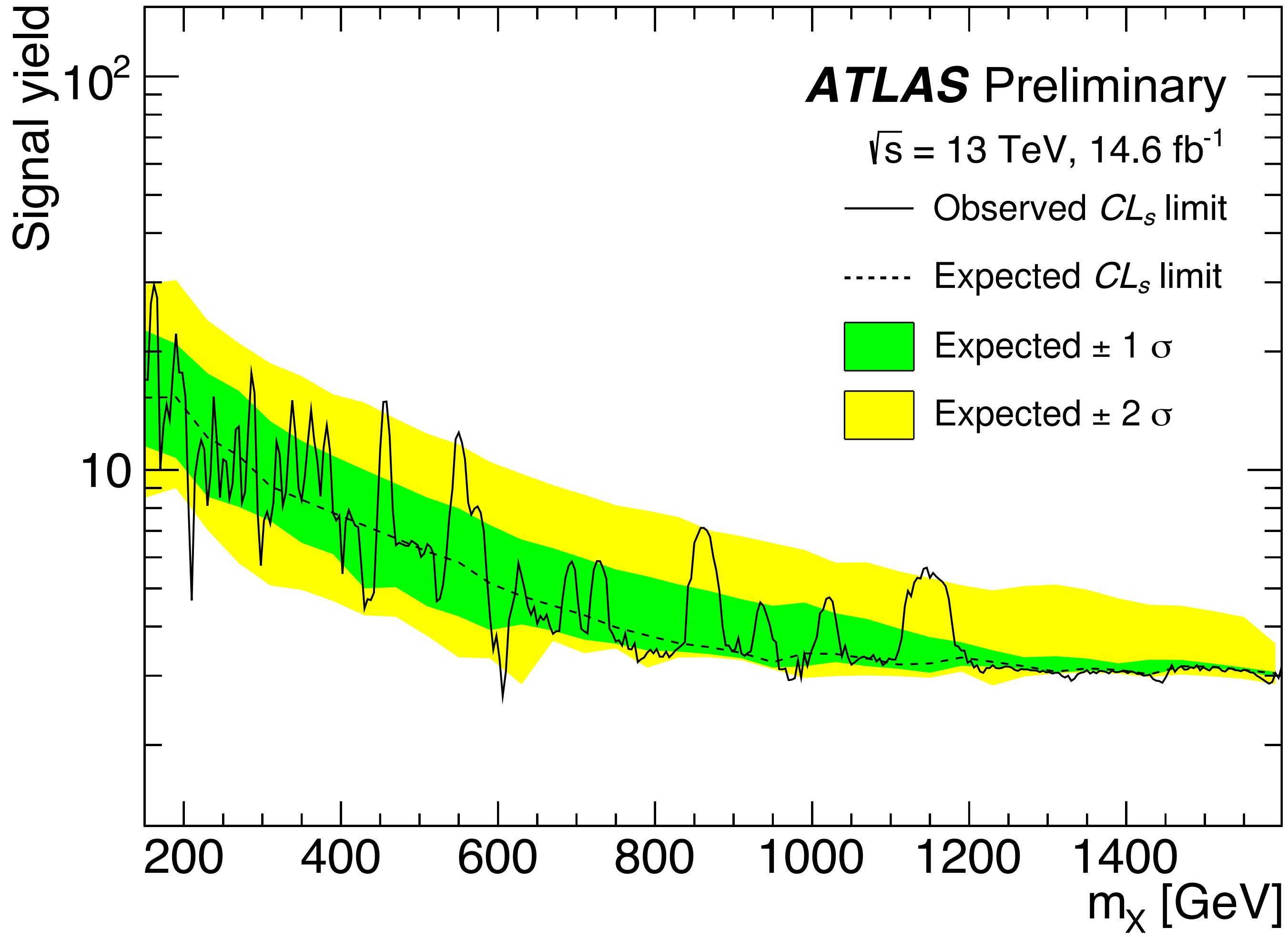
Regard as true BG distribution

s+b fit to this line for each m_X



Ideally 0, but actually non-zero (**spurious signal**)
→ Its envelope is taken as BG modeling uncertainty

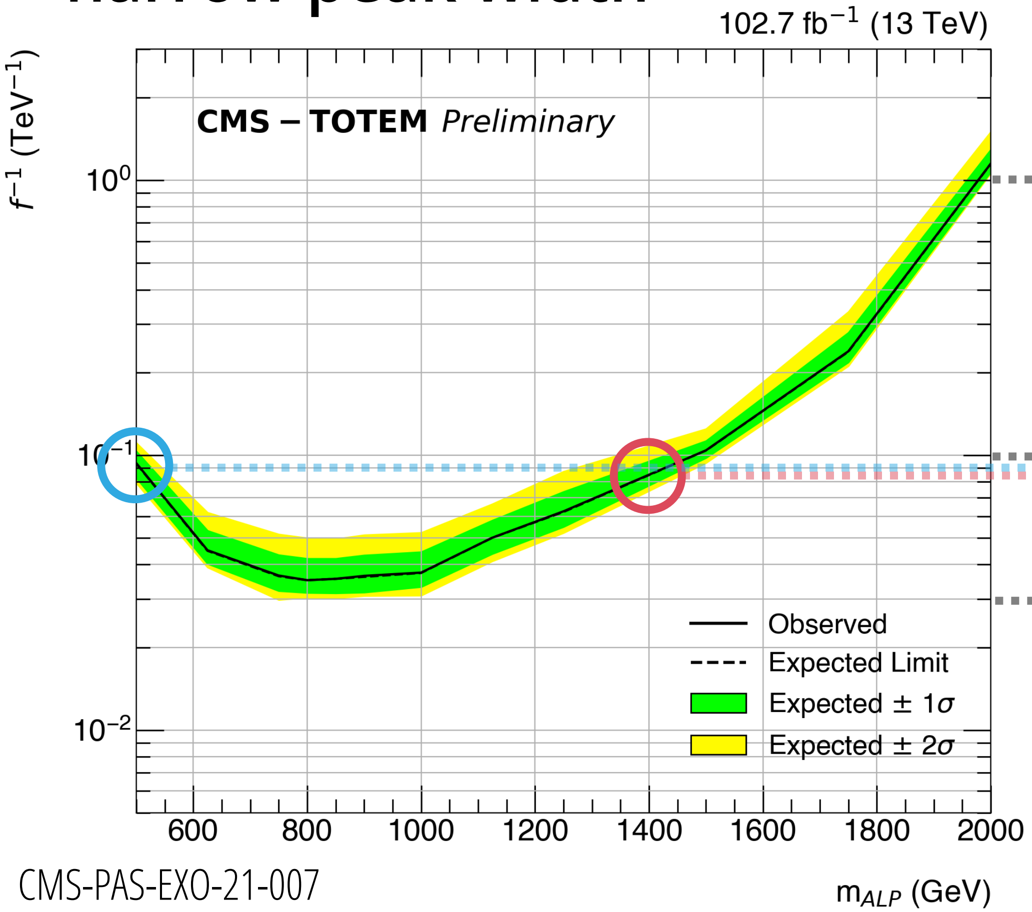
Signal yield limit



Exclusion limit

Stronger limits than CMS-TOTEM in wide range of mass though ATLAS has 7 times lower luminosity – difference is:

- "at least one" matching
- narrow peak width



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