Search for dark photons in rare Z boson decays with the ATLAS detector

CLHCP 2023

Nov. 18th, 2023

Mingyi Liu[1,2]
nh196245@mail.ustc.edu.cn

1. University of Science and Technology of China
2. Brookhaven National Laboratory

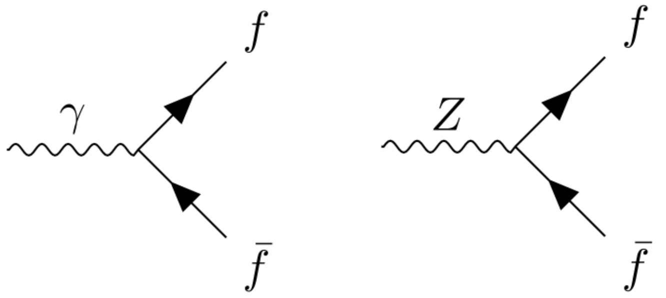
Dark photon: introduction

Motivation

- Important candidate for dark sector: dark photon (A')
- Hidden sector couplings and mass generation mechanisms

Gauge boson from $\mathrm{U(1)_D}$ couples to neutral gauge boson by kinetic mixing $\boldsymbol{\varepsilon}$
Whose mass generated from Dark Higgs $\boldsymbol{h_D}$

$$\mathcal{L}_{int} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{cos\theta_W}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu}$$



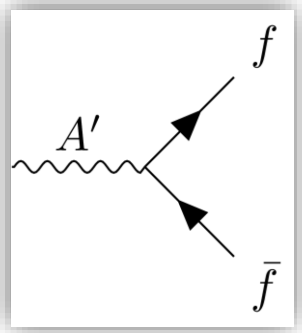
$$\boldsymbol{A'_\mu \rightarrow A'_\mu + \theta_Z Z_\mu}$$

$$\boldsymbol{Z_\mu \rightarrow Z_\mu - (\theta_Z + \varepsilon tan\theta_W)A'_\mu}$$

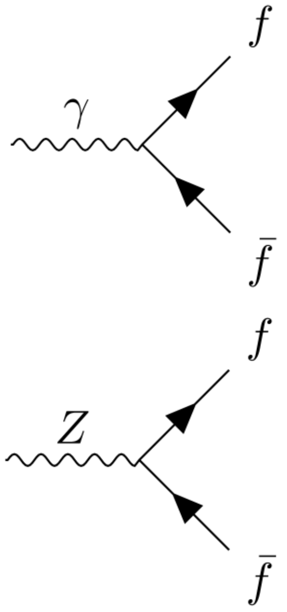
$$\boldsymbol{A_\mu \rightarrow A_\mu + \varepsilon A'_\mu}$$

SM Electroweak couplings

$$\theta_Z = -\frac{\varepsilon tan\theta_W m_Z^2}{m_Z^2 - m_{A'}^2}$$

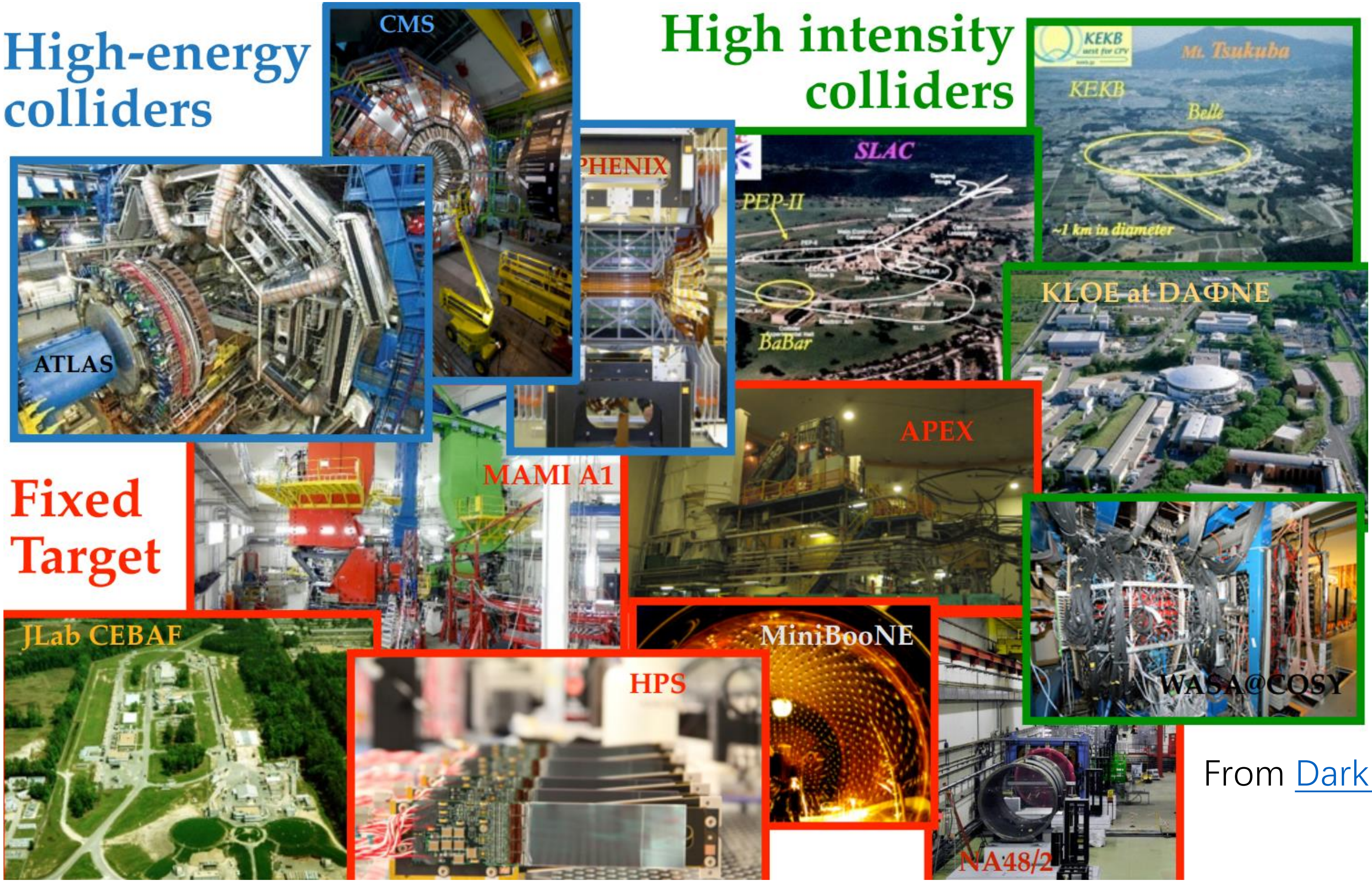


+



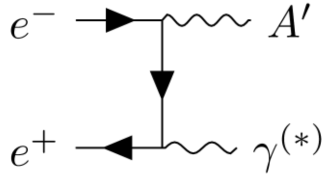
Enable interactions between A' and SM

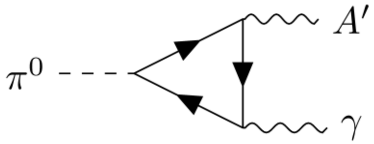
Experiments searching for dark photon

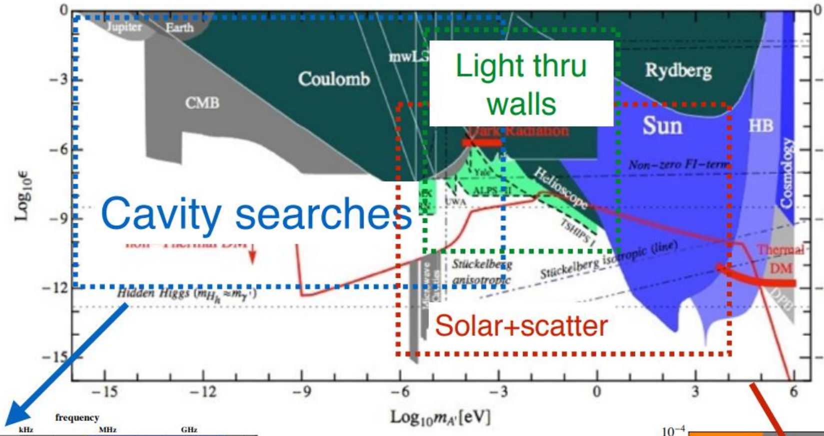


From Dark Sectors 2016

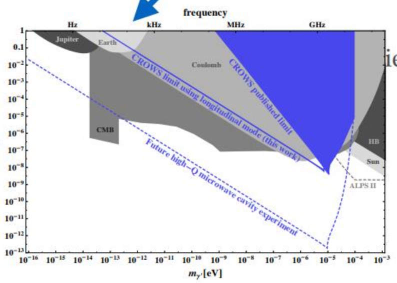
Experiments searching for dark photon



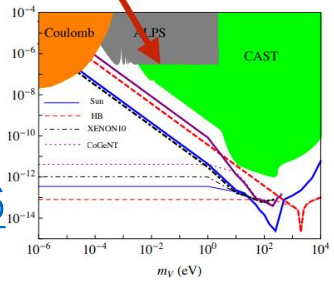




[...ier report – Javier Redondo]

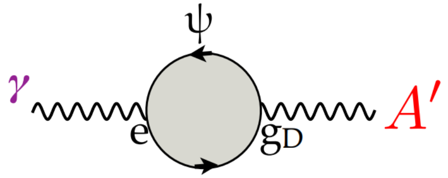


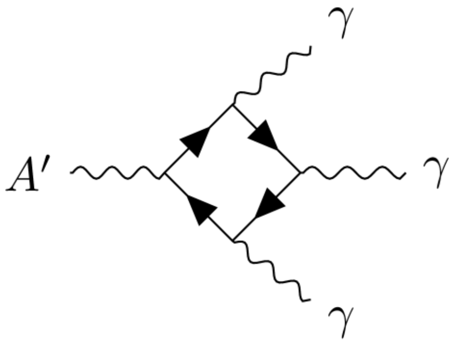
Dark Sectors 2016

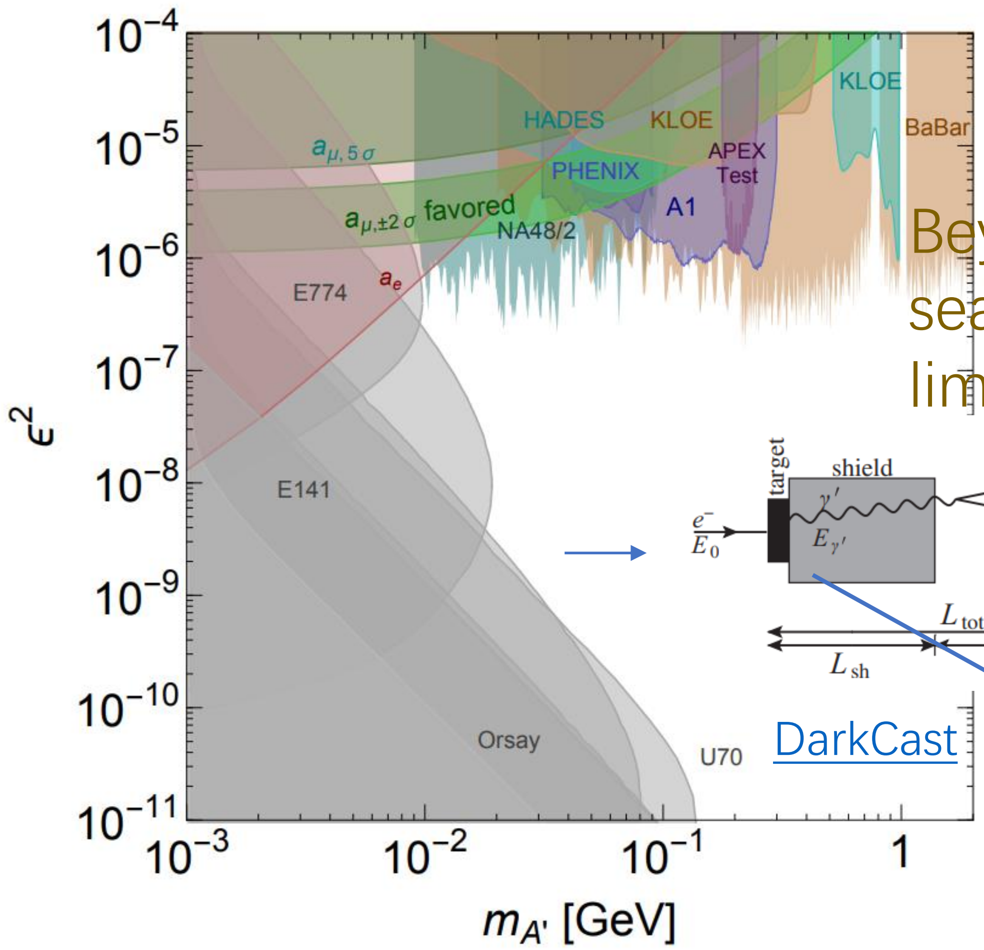


Sub-MeV searches: $m_{A'}$ <~ 1MeV

(Cannot even decay into electron pair)

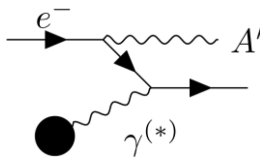






Beyond MeV searches, upper limit at 10 GeV

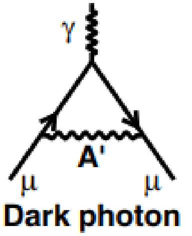
DarkCast



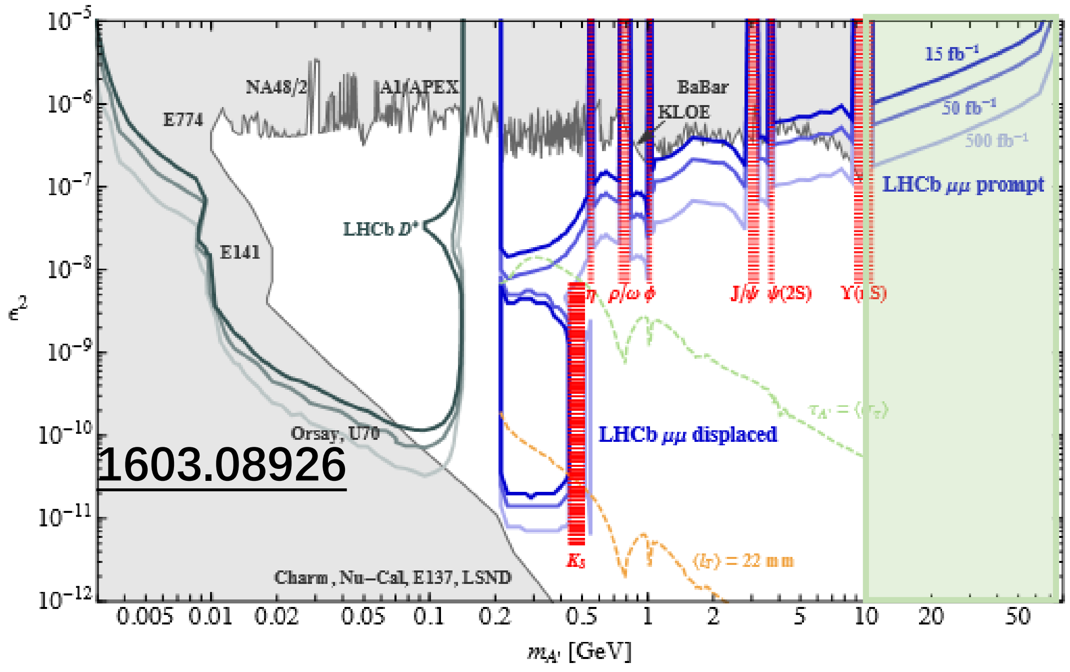
Grey: Beam dump

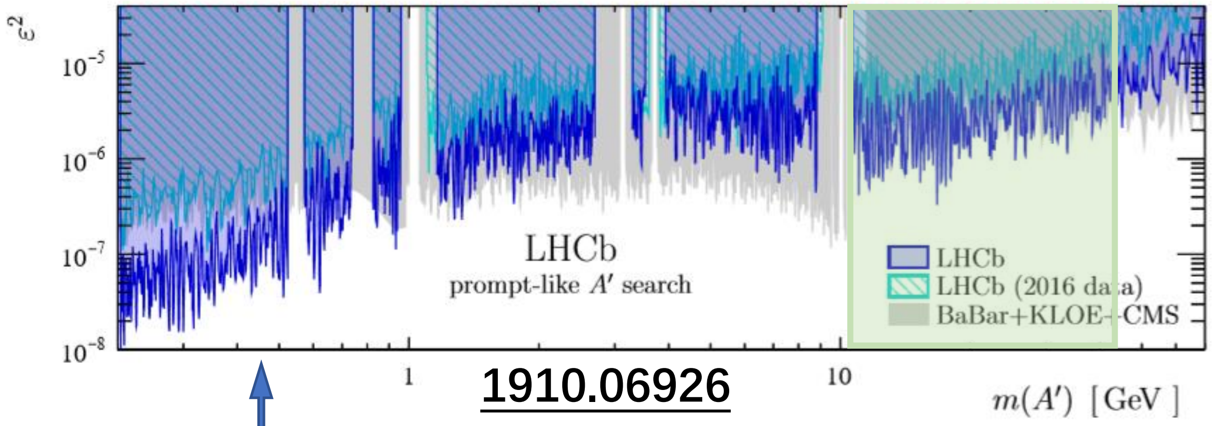
Green/Red: $g-2$ precision measuremen

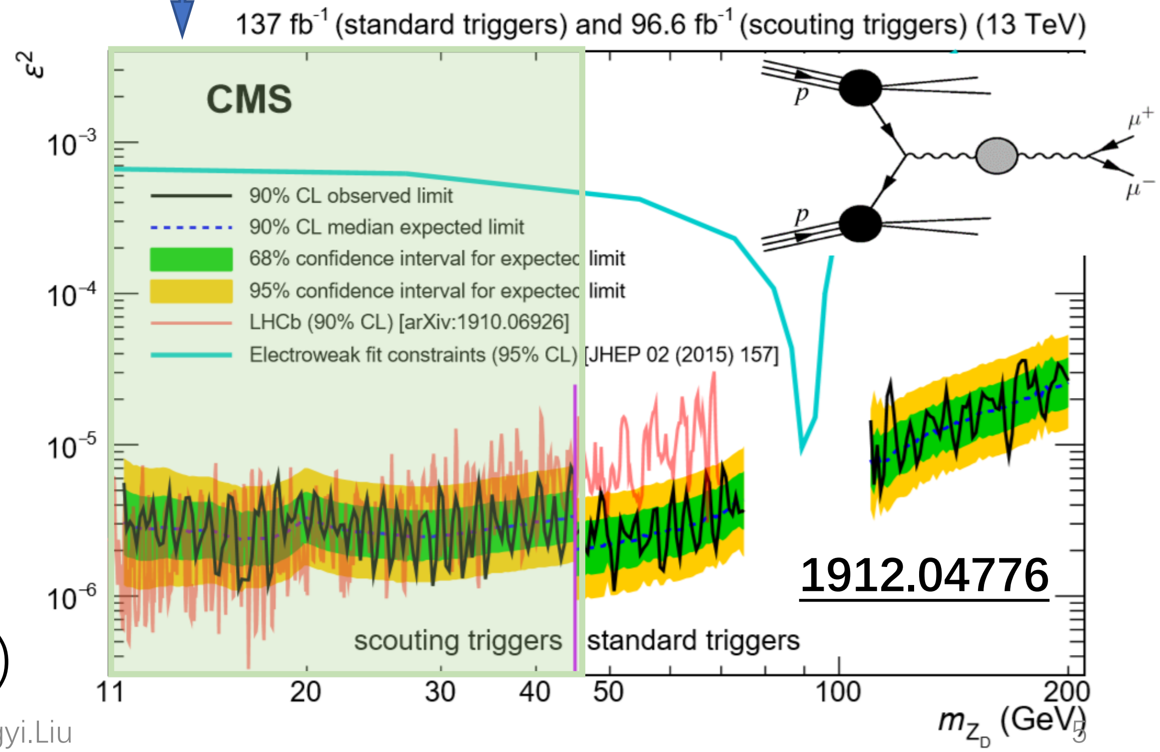
Others: Pair resonance searches



LHC experiments (Set limits on ε vs A' mass)



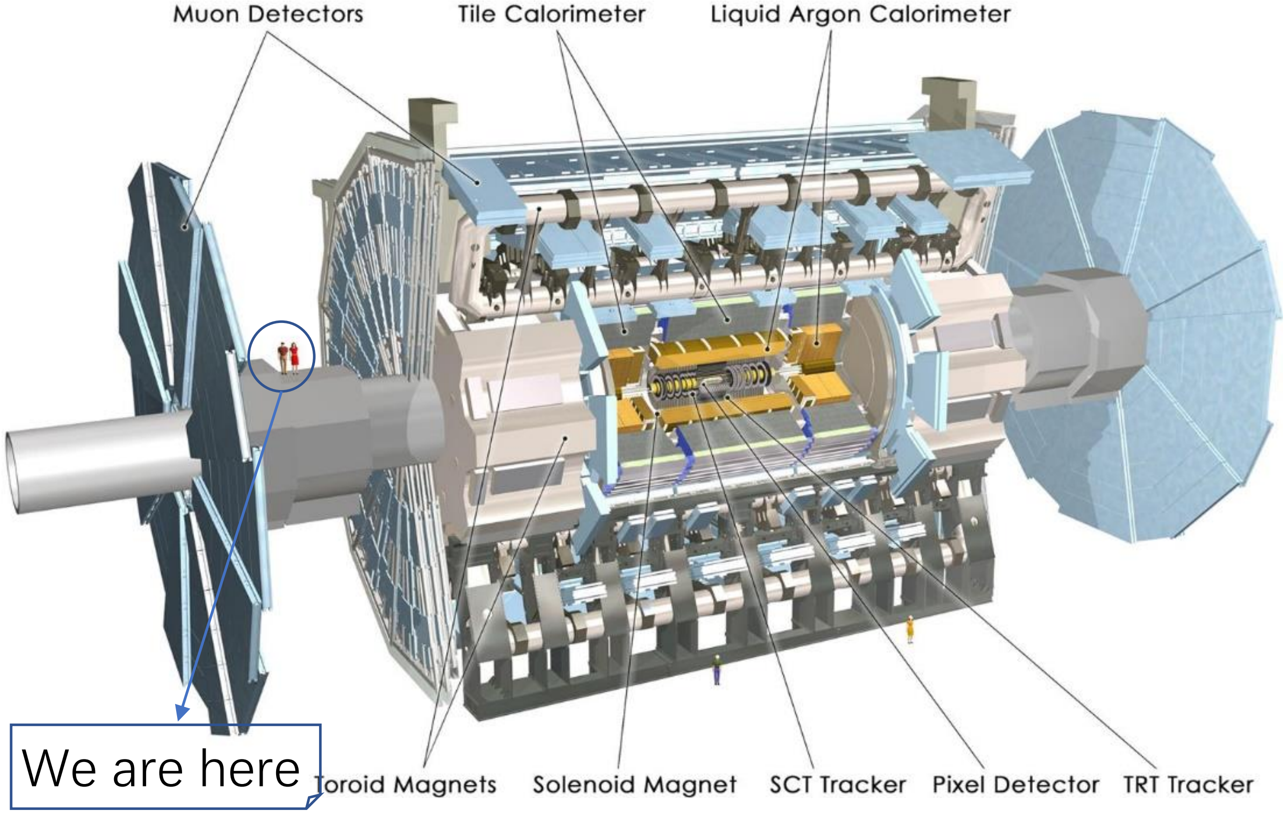




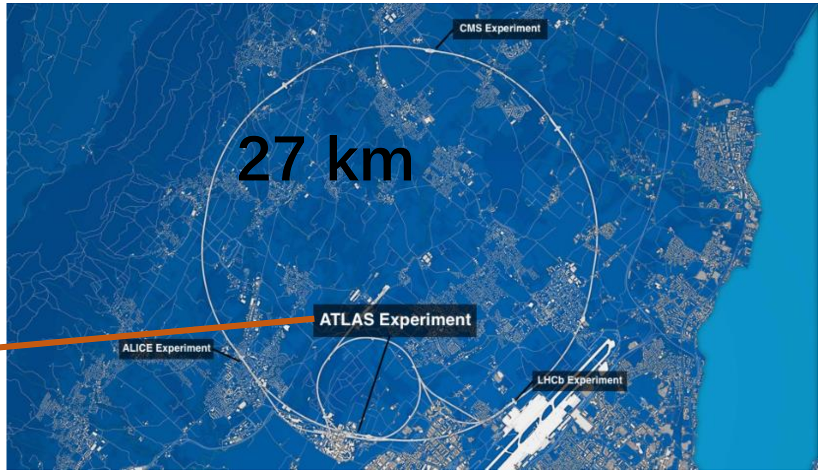
$m_{A'}$ < ~10 GeV:
- → Active region (especially for <~ 1GeV)
- → Not good for ATLAS (resolution)

10 GeV < $m_{A'}$:
- → Our sensitive region (Unique!)
- → CMS and LHCb $m(\mu^+\mu^-)$ spectrum (2019)

The ATLAS detector



We are here



- CERN, Geneva, Switzerland
- ATLAS size: 46m×25m, the largest LHC
- Electroweak energy scale
- Full Run2 data (2015~2018), 139 fb^{-1}

Inner detector:

- $|\eta| < 2.5$
- Momentum, electrical charge
- Pixel detector, tracker (semi-conductor), TRT

Calorimeters:

- EM Cal.($|\eta| < 2.5$):

e&γ, lead absorber submerged by LAr

- Hadron Cal.($|\eta| < 4.9$):

LAr with copper/tungsten absorber (forward)
Scintillator tile with steel absorber (central)

Muon spectrometer:

- Tigger($|\eta| < 2.4$): TGC, RPC
- Tracking($|\eta| < 2.7$): MDT, CSC

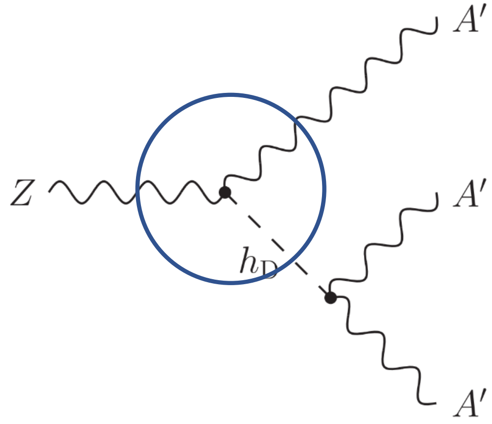
Magnet system:

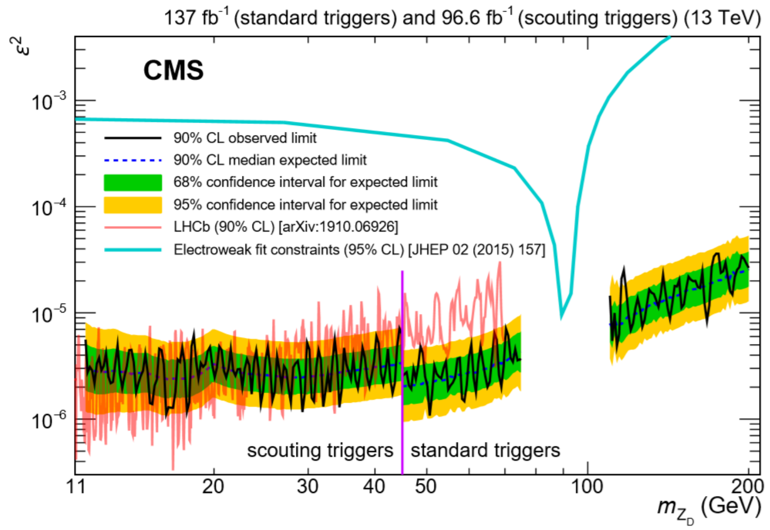
- Solenoid Magnet: 2T
- Toroid Magnets: 4T

Motivation

Search for dark photon A' from BSM rare Z decay: $\boldsymbol{Z \rightarrow A' h_D}$
(h_D is the dark Higgs)

- Important candidate for the dark sector (DS)
- Hidden sector couplings





CMS/LHCb used to set limits on $\boldsymbol{\varepsilon^2}$ from the Drell-Yan production of the A'

Modeling for A'

- ✓ Gauge boson from $\mathrm{U(1)_D}$:

$$D_\mu = \partial_\mu + ie_D A'_\mu$$

$$in\ which:\ e_D = \sqrt{4\pi\boldsymbol{\alpha_D}}$$

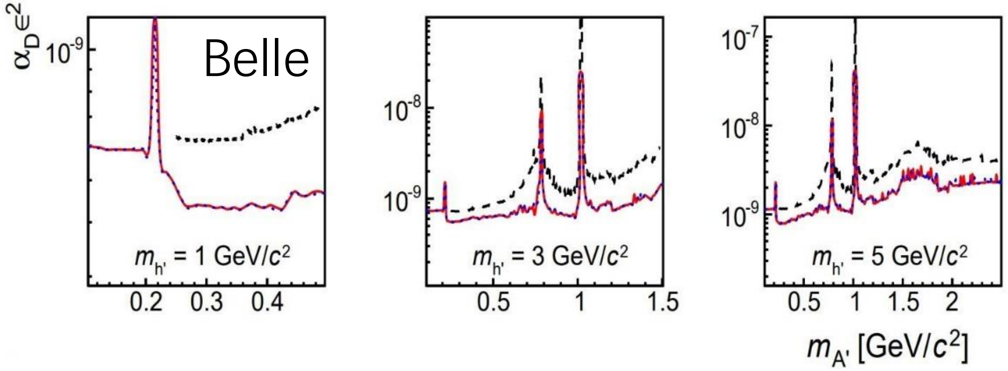
- ✓ Couples to the SM Z boson by kinetic mixing $\boldsymbol{\varepsilon}$:

$$\sim\boldsymbol{\varepsilon} Z^D{}_{\mu\nu}F^{\mu\nu}$$

Decay rate $\propto \boldsymbol{\alpha_D\varepsilon^2}$

Assumptions:
(Minimal kinetically mixed)

- Br $(h_D \rightarrow A'\ A')$ = 100%
- A' is the lightest DS
- Br $(A' \rightarrow SM\ f\ \bar{f})$ = 100%



- The sensitive region on the ATLAS for $\boldsymbol{Z \rightarrow A' h_D}$ is $5\ \mathrm{GeV} < m_{A'} < 40\ GeV$.
- A new mass region for exploring $\boldsymbol{\alpha_D\varepsilon^2}$

B-factories used to set limits on $\boldsymbol{\alpha_D\varepsilon^2}$ with the same dark-Higgs associated process, in the range $m_{A'} < 5\ GeV$

Signal modeling

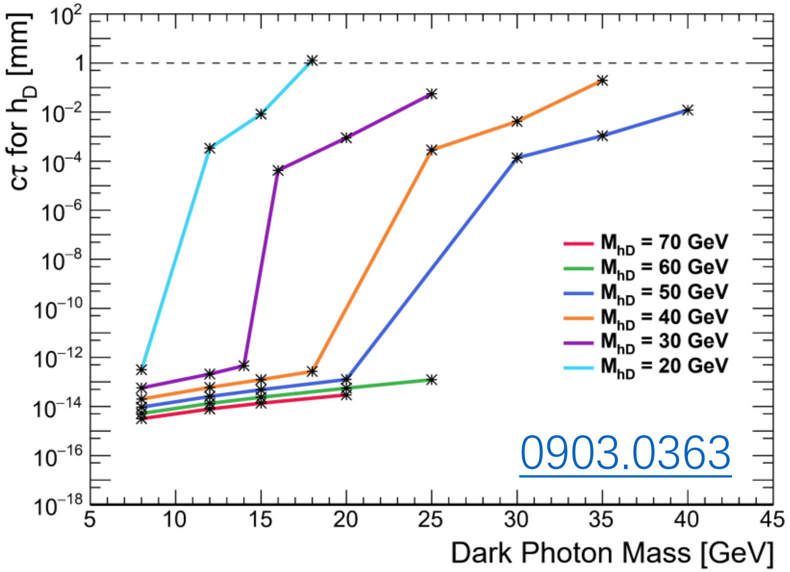
- Focusing on the scenario with $m_{A'} + m_{h_D} < m_Z$ and $m_{A'} < m_{h_D}$

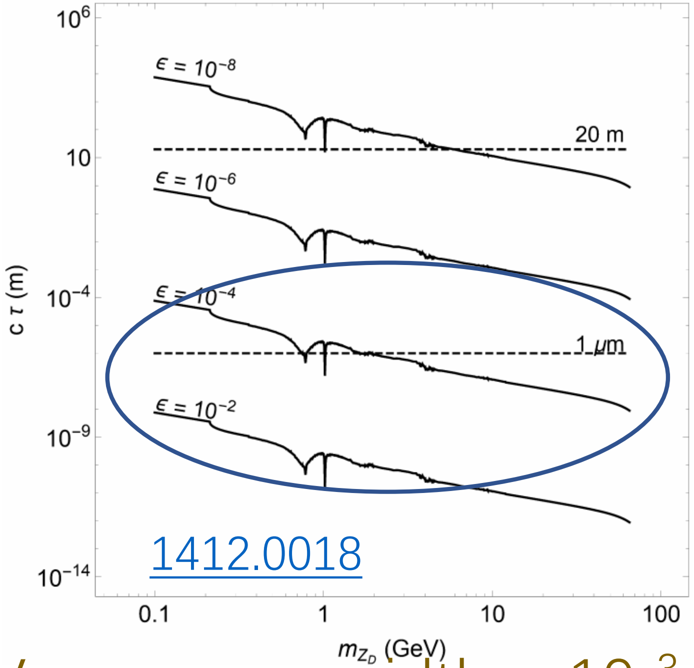
Scenario	$m_{h_D} > 2m_{A'}$	$m_{h_D} \in (m_{A'}, 2m_{A'})$
Dark Higgs decay	$h_D \to A'A'$	$h_D \to A'A'^* \to A' f\bar{f}$ / $h_D^* \to A'A'$
Final state requirement	$Z \to A'\, h_D \to A'A'A'^{(*)} \to 4l + X$	
Monte Carlo (MC) simulation	Madgraph5 (ME) + MadSpin (Decay) + Pythia8 (A14)	

- Benchmark parameter:
  $\alpha_D = 0.1;\ \varepsilon = 10^{-3}$

- Testing mass points

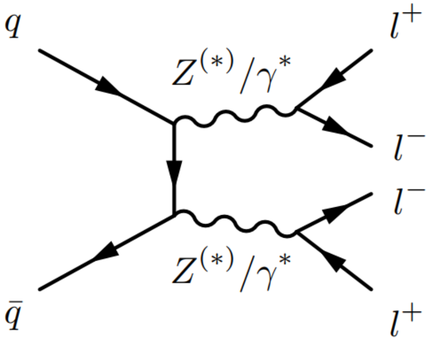
$m_{A'}$ range	5 ~ 40 GeV
m_{h_D} range	20 ~ 70 GeV
$\Delta(m_{A'}, m_{h_D})$	(1, 10) GeV



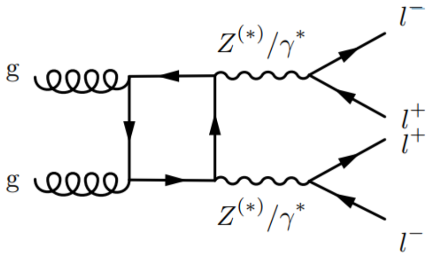


A' and h_D decay promptly; A': Very narrow width ~ 10^{-3} GeV

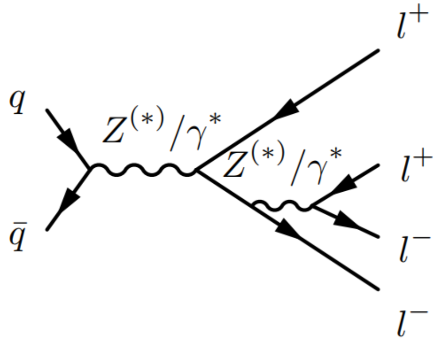
SM Background (BKG) modeling



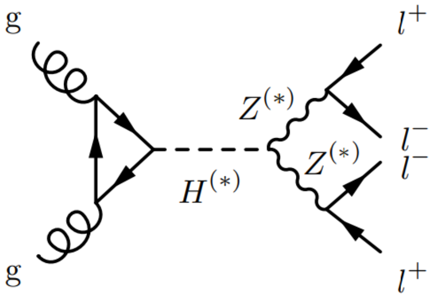
$q\,q \rightarrow ZZ \rightarrow 4l$



$gg \rightarrow ZZ \rightarrow 4l$



$q\,q \rightarrow Z \rightarrow 4l$



$gg \rightarrow H \rightarrow ZZ \rightarrow 4l$

- Prompt BKGs (share the same $4l$ final state as the signal process)

✓ Simulated by MC method ➡

Inclusive $Z/ZZ \rightarrow 4l$	Inclusive $q\,q \rightarrow 4l$	Sherpa
	$ggZZ$ (Non-resonance $ZZ^{(*)}$)	Sherpa
$Higgs \rightarrow ZZ \rightarrow 4l$	ggF, VBF	Powheg + Pythia
tri-Boson (VVV)	WWZ, WZZ, ZZZ	Sherpa
$ttll$	ttZ	Sherpa

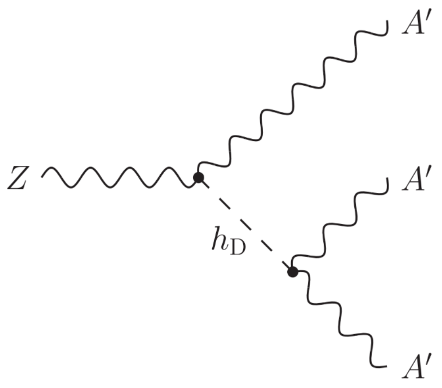
- Non-prompt BKGs (with different final states)

✓ Recognized as $4l$ events by mistake, due to the detector's mis-identification effect

✓ Poor MC modeling, a data-driven fake factor method used

✓ Also called as Fake BKGs

Signal Region (SR)



$Z \rightarrow$ 6 final objects

High multiplicities of soft particles from decay of hidden-sector particles!

Low efficiency for low p_{T} leptons

Soft criteria for object selection

Muon	Electron
p_{T} > 3GeV	p_{T} > 4.5GeV
Loose W.P.s for identification/isolation	

Selections	Description
N_{lepton} >= 4	No less than 4 leptons
From Z	For all OSSF quadruplets, $m_{4l} + 5\mathrm{GeV} < m_Z$
N_{quad} >= 1	At least one OSSF quadruplet (ΔR > 0.1(0.2) between SF (OF) leptons) $\min\lvert m_{l1l2} - m_{l3l4}\rvert$ $(m_{l1l2} > m_{l3l4})$
On Shell	m_{l3l4}/m_{l1l2}>0.85
J/ψ Veto	For all OSSF pairs, $m_{ll} > 5\mathrm{GeV}$
$\Upsilon(b\bar{b})$ Veto	Mass window veto (OSSF pairs): $[m_{\Upsilon(1s)} - 0.7, m_{\Upsilon(3s)} + 0.75]\mathrm{GeV}$

Results

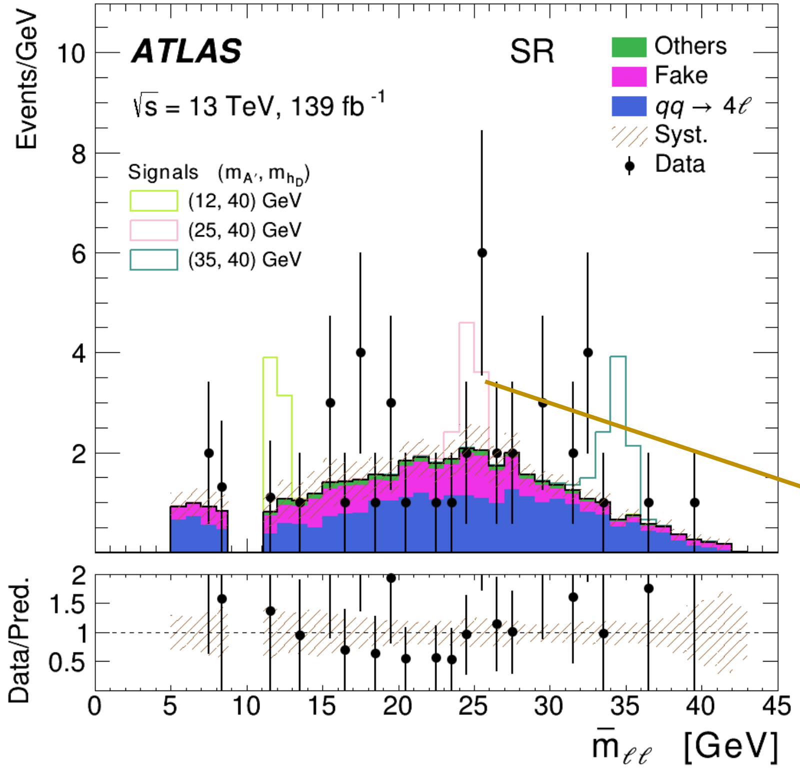
139 fb^{-1}

BKG	Yields (Post-fit)
$qq4l$	25.9 ± 2.4
Fake	13.2 ± 5.6
$ggZZ$	1.9 ± 0.7
Others	<<1
Total	41.4 ± 5.3
Data	44

Dominant backgrounds:
$qqZZ$, Fake

Good agreement between SM prediction and data

BKG modeling has been constrained and validated in CR/VR



- SGN width for $\bar{m}_{ll}$ under different testing points
- Width ranges: 0.2~1.4 GeV
- 1 GeV as the bin width for fitting template

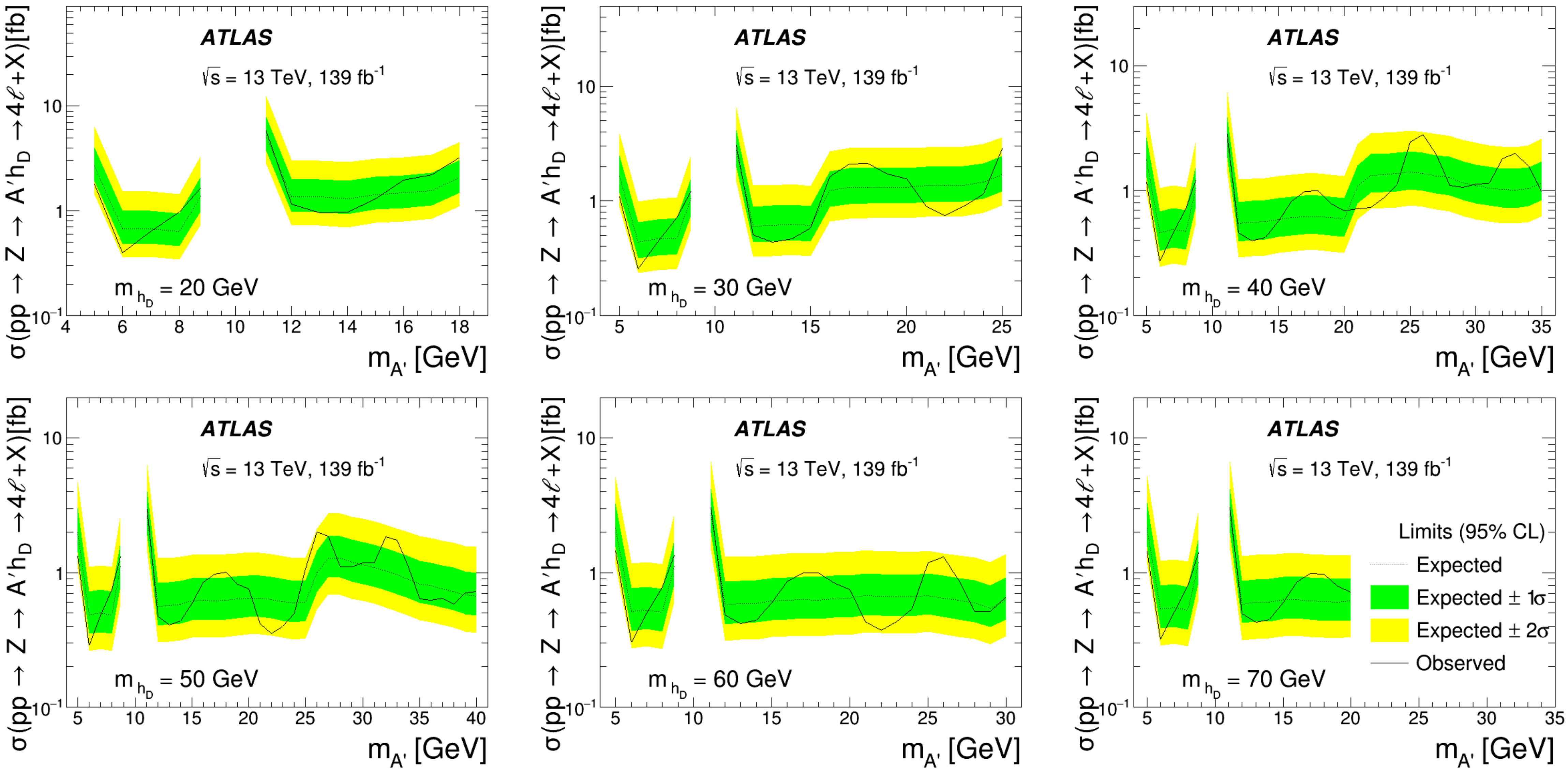
- The best local sensitivity (around 25 GeV): 1.6σ
- No evidence for the SGN

$$\bar{m}_{ll} = \frac{1}{2}(m_{l1l2} + m_{l3l4})$$

✓ Good physics meaning
✓ Best sensitivity for most of the signal points
✓ Chosen as the fitting discriminant

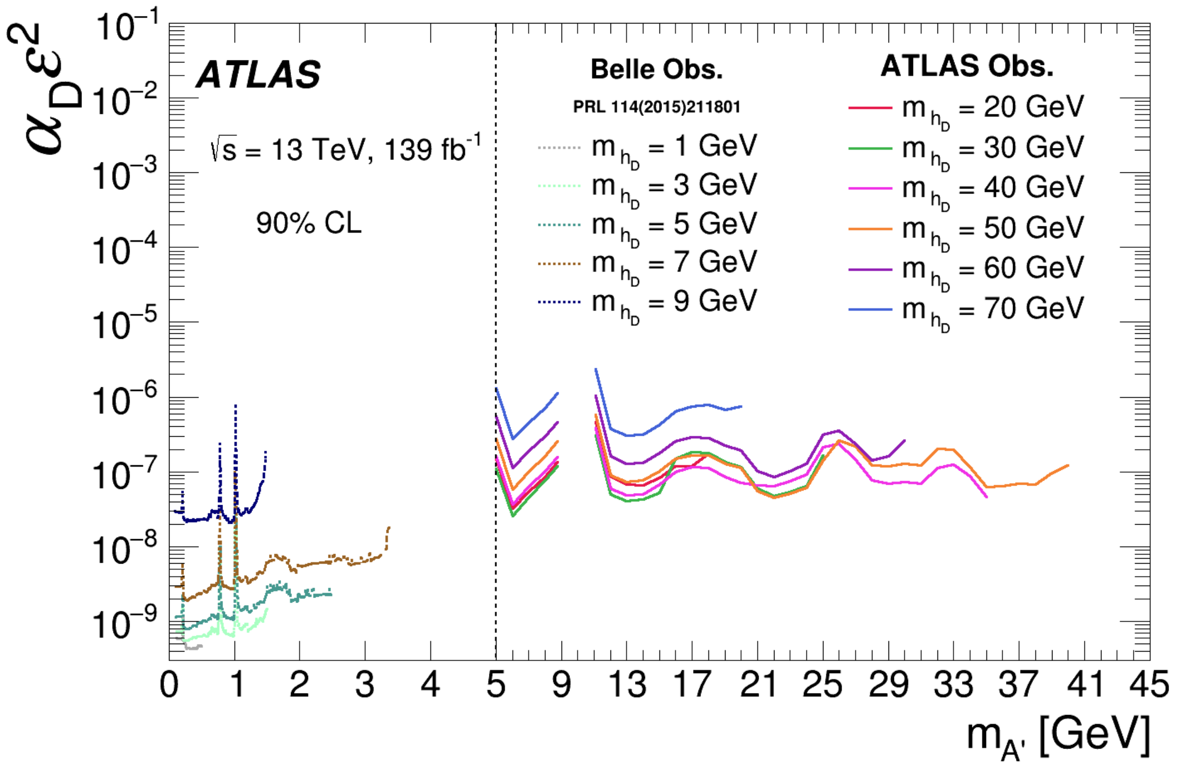
Systematics (prompt): theoretical/experimental uncertainties; uncertainties from the data-driven approach

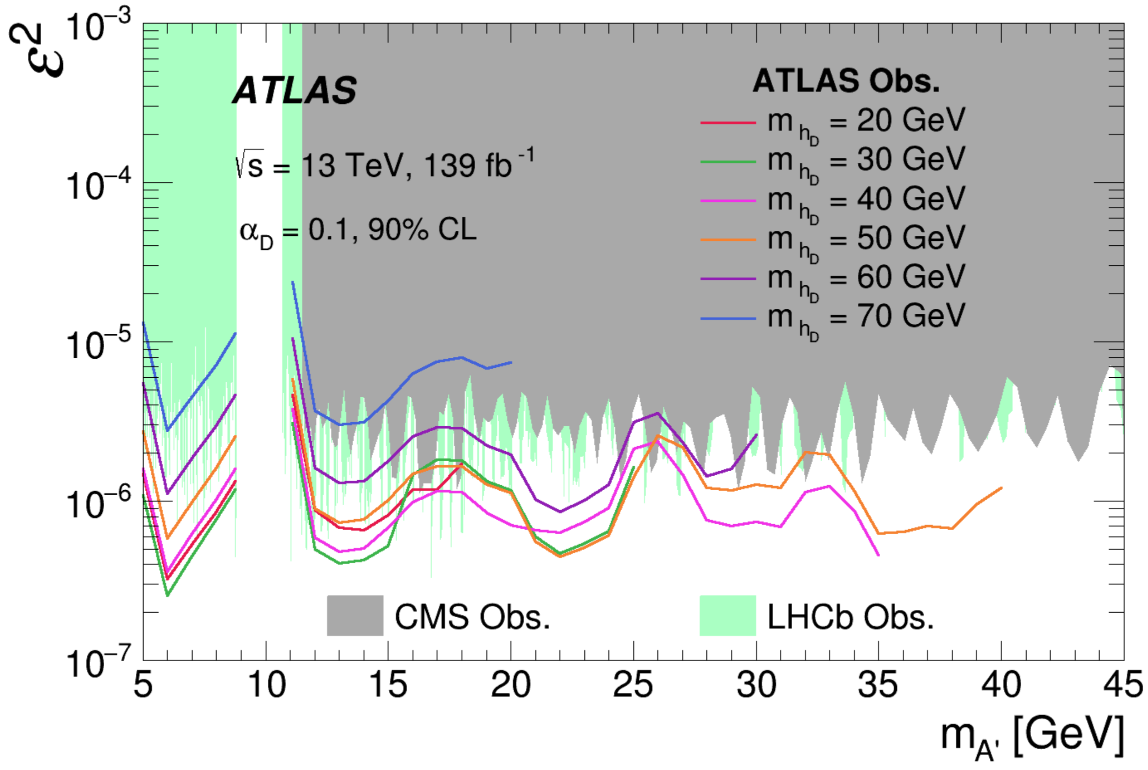
Limits on $\sigma(pp \to Z \to A'\,h_D \to 4l + X)$



Limits on $\alpha_D\varepsilon^2$

Decay rate (cross-section) $\propto \alpha_D\varepsilon^2$





Setting limits on $\alpha_D\varepsilon^2$:

✓ Previous range (Belle): $m_{A'} < 5\text{GeV}$

✓ Extended significantly to 40 GeV

Compare with CMS/LHCb (limits on ε^2):

✓ Some assumptions on α_D (set it as 0.1)

✓ Comparable (even better)

Summary

- The first search for the dark-Higgs-strahlung process on the LHC.
- No evidence for A' signal, setting limits on the signal cross section.
- Setting limits on $\alpha_D \varepsilon^2$ in a significantly extended A' mass region.
- Reference: Search for dark photons in rare Z boson decays with the ATLAS detector, arXiv:2306.07413, accepted by Physical Review Letters.

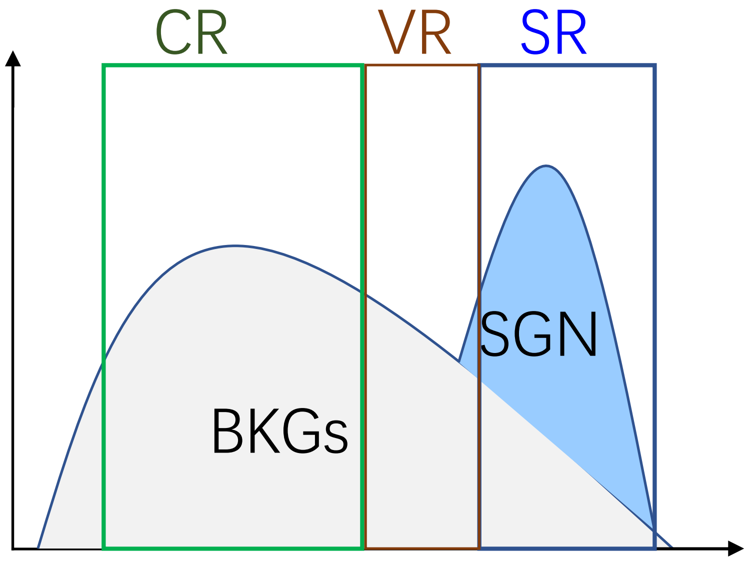
Thanks!

Backup

Analysis strategy

- Signal Region (SR): optimize a region rich of signals, with the best S/B sensitivity
- Control Region (CR): a region rich of BKGs, poor of signals, for constraining the major background
- Fitting: simultaneous fit in the SR and CR for background constrain, before estimating significance/setting limits.
- Validation Region(s) (VR): rich of BKGs, but more similar to the SR, to validate the background modeling
- Systematics: theoretical/experimental uncertainties; uncertainties from the data-driven approach

Only for schematically usage



Control Region (ZCR)

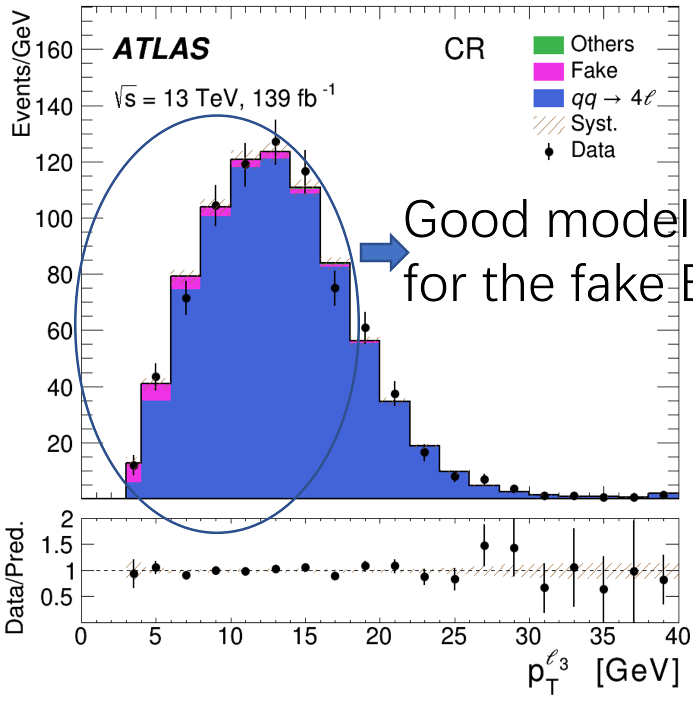
Selections	Description
N_{lepton} >= 4	No less than 4 leptons
CR Z Peak	For all OSSF Quadruplets, $m_Z - 5\text{GeV} < m_{4l} < m_Z + 5\text{GeV}$
N_{quad} >= 1	At least one OSSF quadruplet (ΔR > 0.1(0.2) between SF (OF) leptons) Pairing: $\min|m_{l1l2} - m_{l3l4}|$ $(m_{l1l2} > m_{l3l4})$
J/ψ Veto	For all OSSF pairs, $m_{ll} > 5$ GeV

Fitting discriminant:

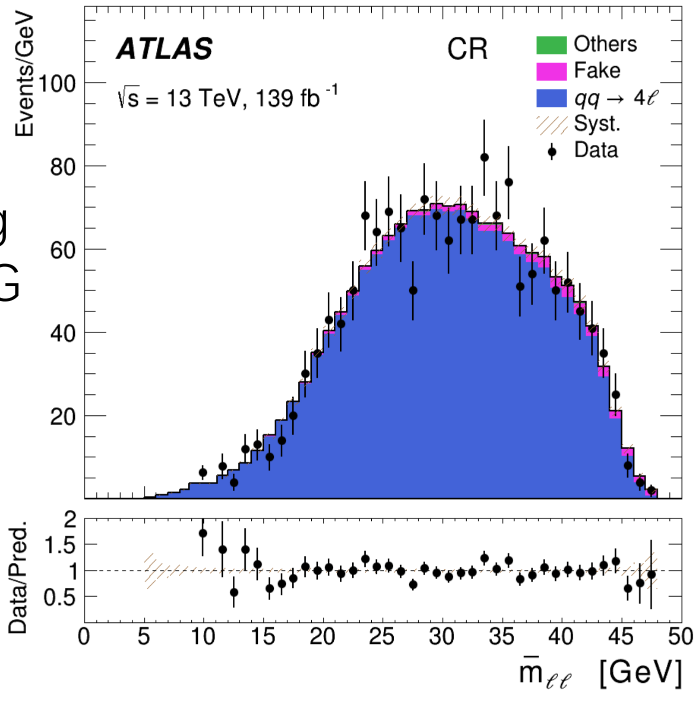
$$\bar{m}_{ll} = \frac{1}{2}(m_{l1l2} + m_{l3l4})$$

139 fb^{-1}

BKG	CR Yields (Post-fit)
$qq4l$	1554.8 ± 47.6
Fake	43.1 ± 25.0
$ggZZ$	4.2 ± 1.7
Others	~1
Total	1603.7 ± 40.0
Data	1602



Good modeling for the fake BKG



Validation Region (VR)

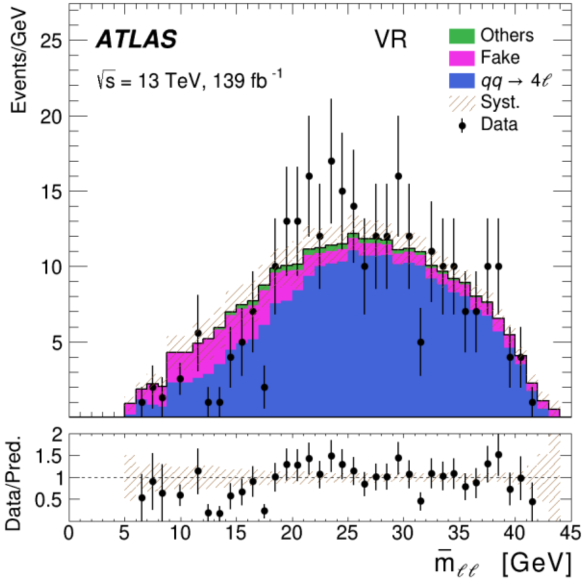
SR: m_{l3l4}/m_{l1l2}>0.85

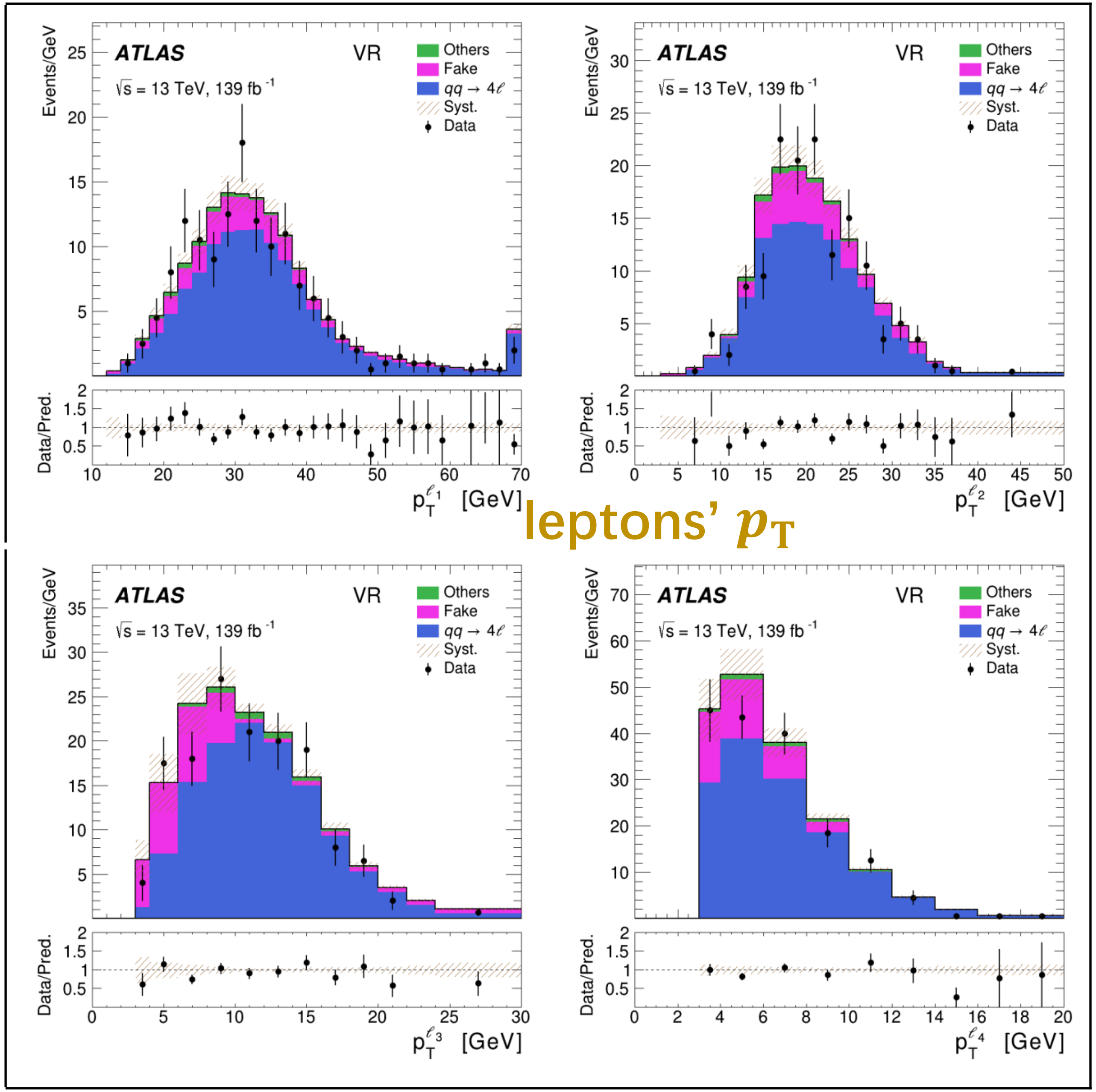
→

VR: m_{l3l4}/m_{l1l2}<0.85

Fitting discriminant:

$$\bar{m}_{ll} = \frac{1}{2}(m_{l1l2} + m_{l3l4})$$





leptons' p_T

139 fb^{-1}

BKG	Yields (Post-fit)
$qq4l$	238.8 ± 15.2
Fake	47.3 ± 26.1
$ggZZ$	5.4 ± 1.9
Others	~1
Total	292.8 ± 27.7
Data	286

Fake plays an important role in the soft region.

Good BKG modeling in the VR!

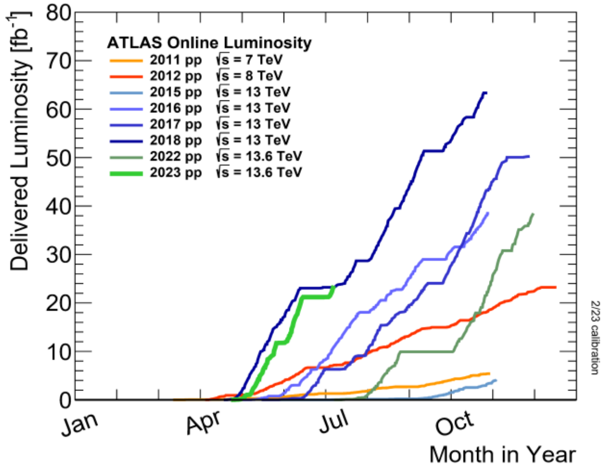
Data collected by the ATLAS

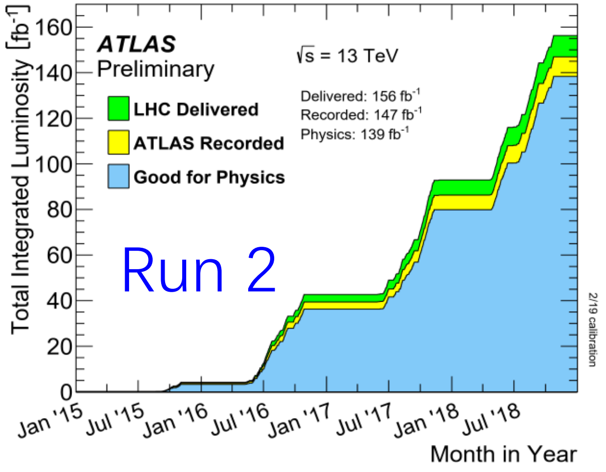
Integrated luminosity for describing the accumulated data: $\mathcal{L} = \int L \, dt$

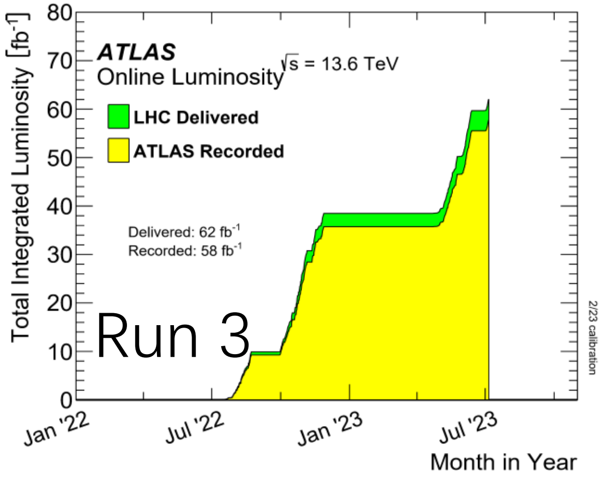
Run 1 (2011~2012)
- 7~8 TeV, ~30 fb^{-1}

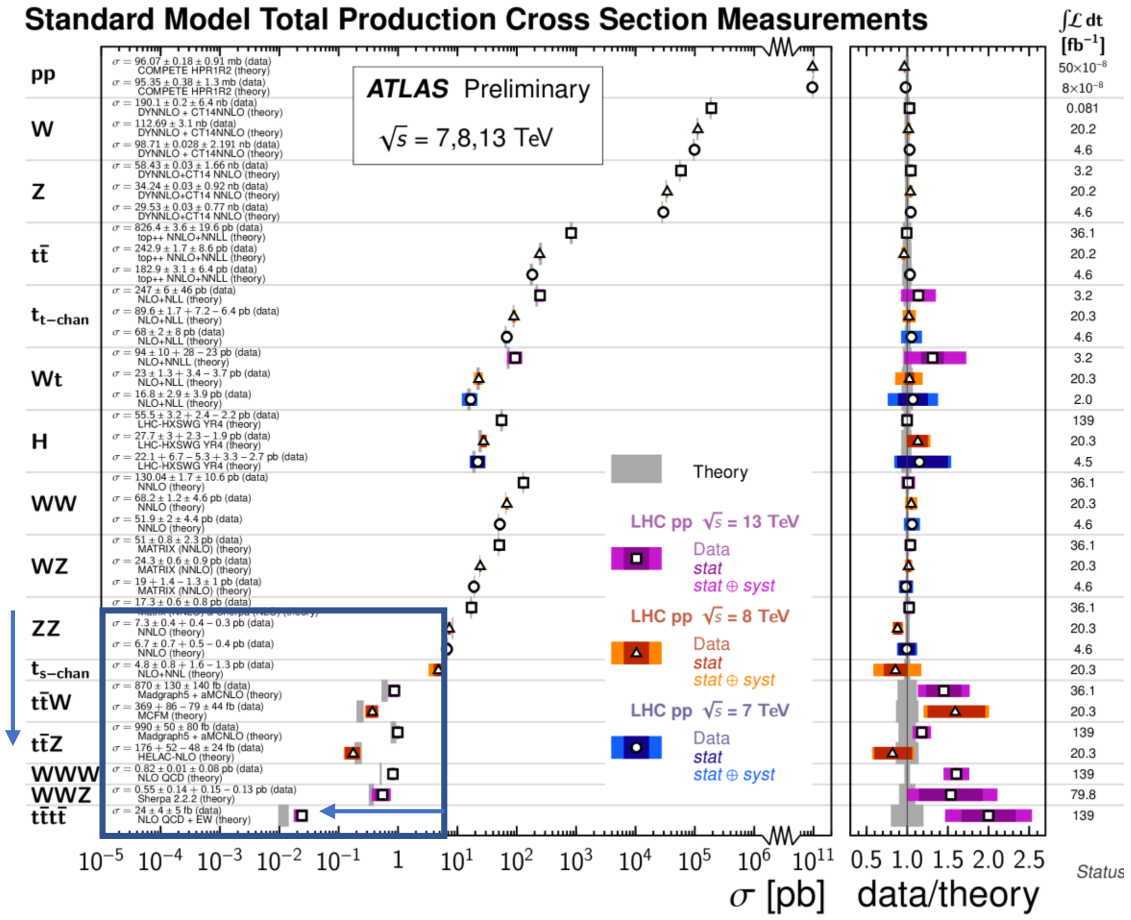
Run 2 (2015~2018)
- 13 TeV, 139 fb^{-1}

Run 3 (2022~Now)
- 13.6 TeV, ~60 fb^{-1}









✓ SM processes with $4l$ final state have small cross-sections!

✓ $4l$: very clean channel for rare process hunting

Object definition

	Muon	Electron
Baseline leptons	p_T > 3GeV p_T > 15GeV if Calo-tagged	p_T > 4.5GeV $\|\eta\|$ < 2.47
	$\|\eta\|$ < 2.7	Pass object quality (isGoodOQ)
	$z_0 sin\theta < 0.5$ mm if μ isn't SA	$z_0 sin\theta < 0.5$ mm
	ID: Loose working point	ID: Loose working point
	Overlap removal between μ/e	Overlap removal between μ/e & e/e

Signal leptons (Tight leptons)	**Fulfill Baseline requirements**	
	$\|d_0/\sigma_{d_0}\|$ < 3 if μ isn't SA	$\|d_0/\sigma_{d_0}\|$ < 5
	ID: the same as baseline	ID: LooseAndBLayerLLH W.P.
	Isolation: PflowLoose_VarRad W.P.	Isolation: FCLoose W.P.

Loose leptons	**Baseline leptons fail the signal-lepton requirements**

Data and triggers

- Data: Full Run 2 data, 13 TeV, 139 fb^{-1}
- Trigger list (single lepton, di-lepton, tri-lepton soft triggers)

2015	HLT_mu20_iloose_L1MU15 HLT_mu50 HLT_mu18_mu8noL1 HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose HLT_2e12_lhloose_L12EM10VH
2016~2018	HLT_mu26_ivarmedium HLT_2mu14 HLT_mu22_mu8noL1 HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_2e17_lhvloose_nod0_L12EM15VHI HLT_e17_lhloose_nod0_mu14 HLT_e12_lhloose_nod0_2mu10 HLT_2e12_lhloose_nod0_mu10

Trigger efficiency only ~70%
→ Global trigger scale factor implemented (Pseudo-experimental method)

Fake BKG: Fake enriched region and fake factor

- Fake leptons from $Z + jets$ / tt / WZ, poor modeling: Data-driven **fake factor** method
- Fake enriched region defined to calculate fake factor (F.F.)

N $_{\text{Baseline lepton}}$ ⩾ 3
N $_{\text{OSSF signal lepton pair}}$ ⩾ 1
$|m_{\text{Signal lepton pair}} - m_Z| < 15$ GeV

- F.F. is calculated by the baseline leptons aside from the Z-decayed pair
- Parametrized by $(p_{\mathrm{T}}, \eta, lepton\ flavor)$
- MC contaminant judged by MC information

$$F.F. = \frac{N_{Data}^{Tight} - N_{Prompt\ MC}^{Tight}}{N_{Data}^{Loose} - N_{Prompt\ MC}^{Loose}}$$

- Apply fake factors to $4l$ events with loose leptons that can enter the SR (FFAR):

$$N_{fake} = \sum_i^{N_{oneLoose}} w_i F_i - \sum_i^{N_{twoLoose}} w_i F_i F_i' + \sum_i^{N_{threeLoose}} w_i F_i F_i' F_i'' - \sum_i^{N_{fourLoose}} w_i F_i F_i' F_i'' F_i''' - \left(\sum_i^{N_{oneLoose}^{MC}} w_i F_i - \sum_i^{N_{twoLoose}^{MC}} w_i F_i F_i' + \sum_i^{N_{threeLoose}^{MC}} w_i F_i F_i' F_i'' - \sum_i^{N_{fourLoose}^{MC}} w_i F_i F_i' F_i'' F_i''' \right)$$

Systematics for fake BKG

- **Fake source uncertainty (Impact on the F.F. from the b-jet sources, dominant)**

- Uncertainty of fake factor
  - ✓ MC subtraction uncertainty (uncertainties of the subtracted prompt BKGs)
  - ✓ Statistical uncertainty in the Fake enriched region when calculating the F.F.s

- From the F.F. application region (FFAR) when calculating fake yields
  - ✓ MC subtraction uncertainty
  - ✓ **Statistical uncertainty (Dominant, due to low statistics)**

The secondary dominant background

Fake yield (SR)	9.45
A.R. Stat.	41.38%
A.R. Theo.	4.45%
F.F. Stat.	3.07%
F.F. Theo.	4.87%
Fake source	50.32%
Total	66.21%

Statistical analysis

- Simultaneous fit of the SR and CR, with floating normalization factor μ_b for the dominant SM $4l$ background.

  [POI: $\boldsymbol{\mu_s}$ (signal strength); NPs: Systematics θ_j, normalization factor μ_b for BKG]

$$L(\mu\,;\,\sigma) = \prod_{j}^{syst.num} L_{gauss}(\theta_j) \prod_{i}^{bins} L_{poiss}\,(N_{data}\,|\,\mu_s s(\theta_j)\, + \mu_b b(\theta_j))_i$$

- Discriminant: $\bar{m}_{ll} = \frac{1}{2}(m_{l1l2} + m_{l3l4})$

- Binning (GeV): $\Upsilon(b\bar{b})$ window

1 GeV Bin width

[0,5,6,7,8,8.76,11.105,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50]

Systematics for prompt processes

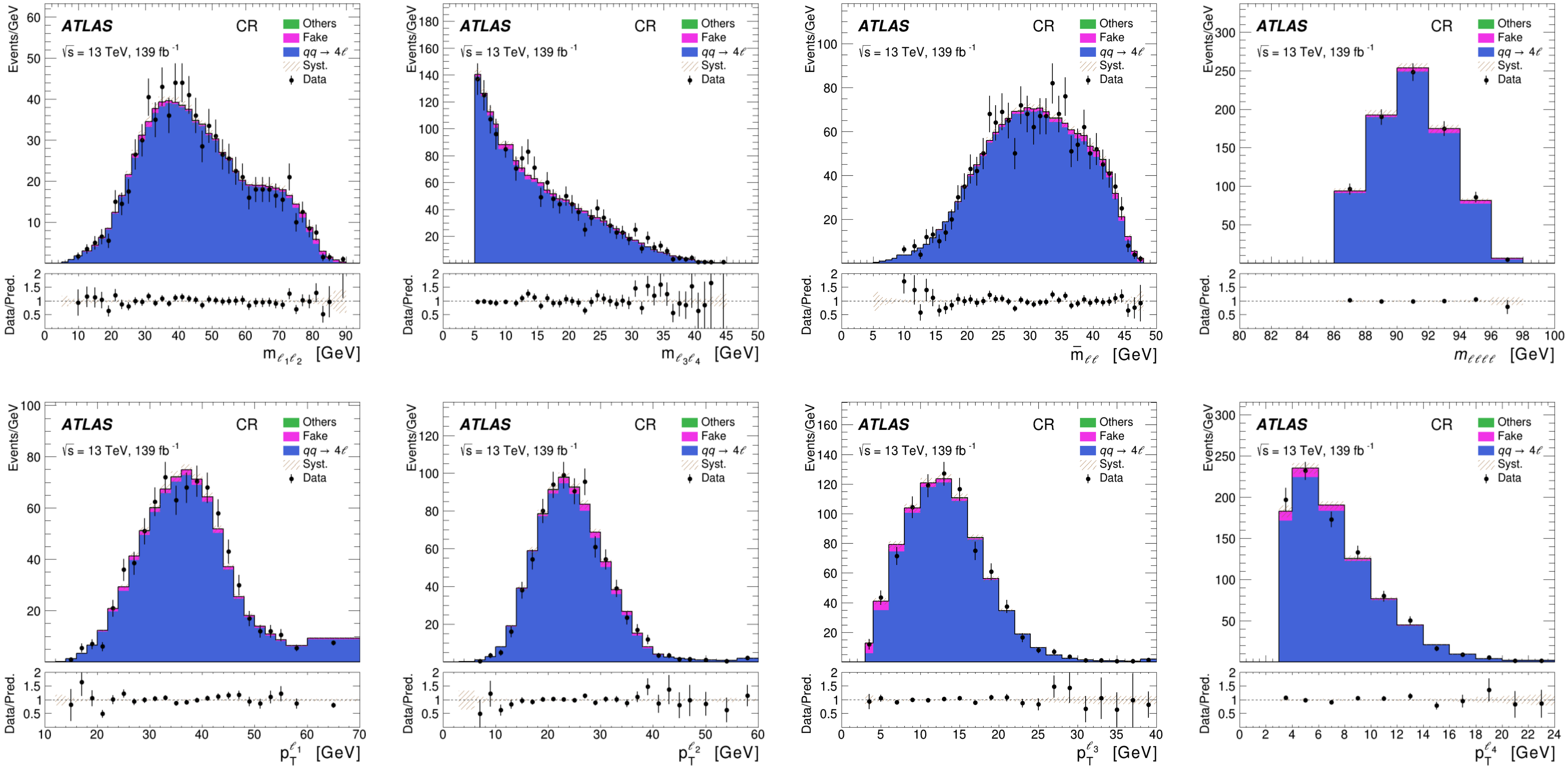
Experimental Uncertainties

- Detecting uncertainties for electrons and muons (Identification, energy resolution ⋯)
- Trigger S.F. uncertainties
- Pileup, luminosity uncertainties
- Total Exp. uncertainty ~ 7% (5%) for SGNs (BKGs) in the SR.

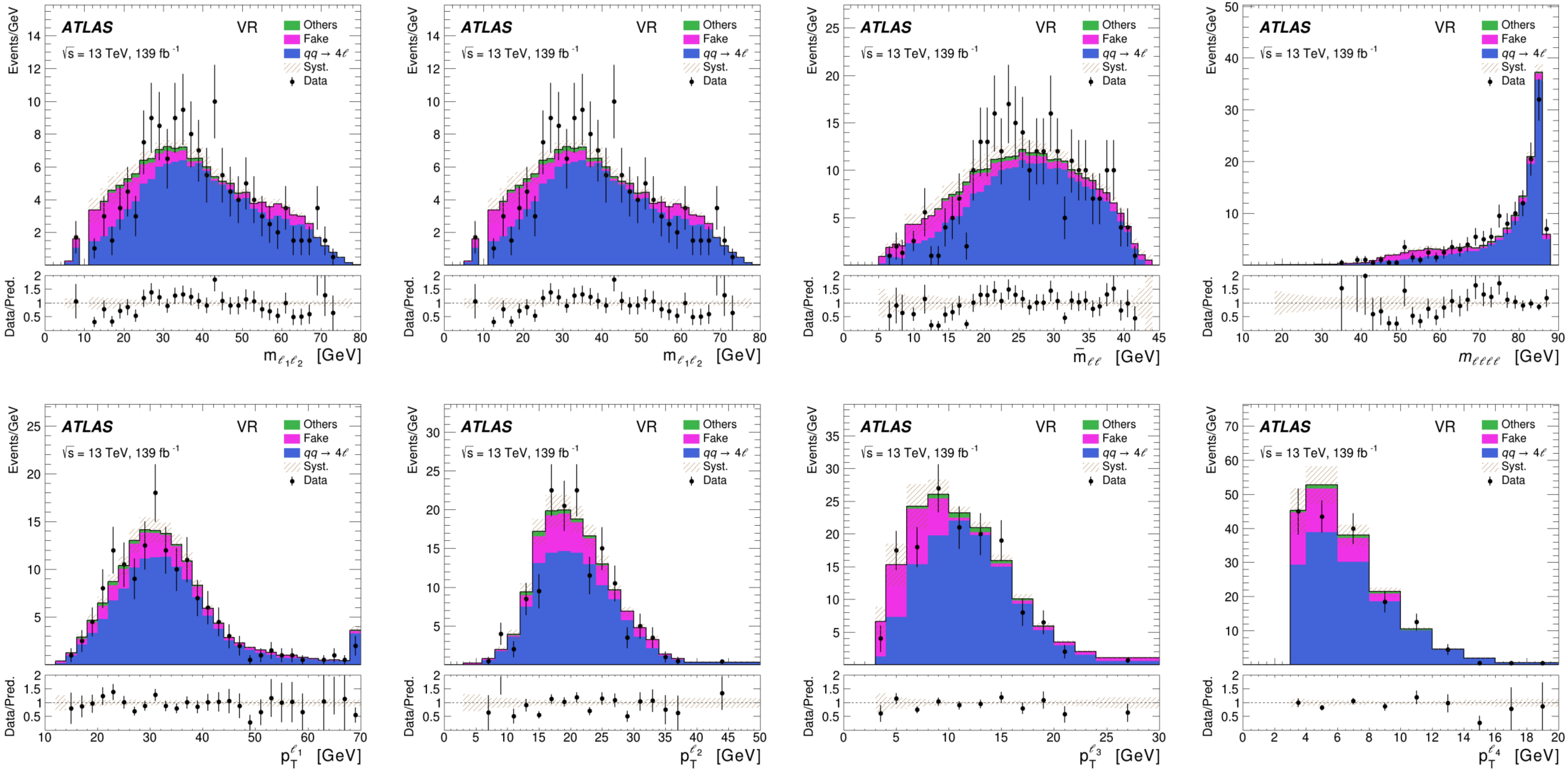
Theoretical Uncertainties

- PDF + α_S Unc.
  - Envelope: NNPDF3.0 (100 internal variations, standard deviation) and CT14 (Nominal)
  - ~2% for both SGNs and BKGs
- QCD scale Unc.
  - Envelope: $\{\mu_R, \mu_F\}$ = {0.5, 0.5}, {0.5, 1.0}, {1.0, 0.5}, {1.0, 2.0}, {2.0, 1.0}, {2.0, 2.0}
  - ~14% for SGNs, ~8% (5%) for $qqZZ$ in the SR (CR)
- Parton showering uncertainty
  - For SGNs: Pythia8 (A14) vs Herwig7 (UE-MMHT) (Truth level), very tiny, ~ 1%
  - For $qqZZ$: Shape comparison between the Sherpa sample and the Powheg+Pythia8 sample (conservative), ~10% (2%) in the SR (CR)

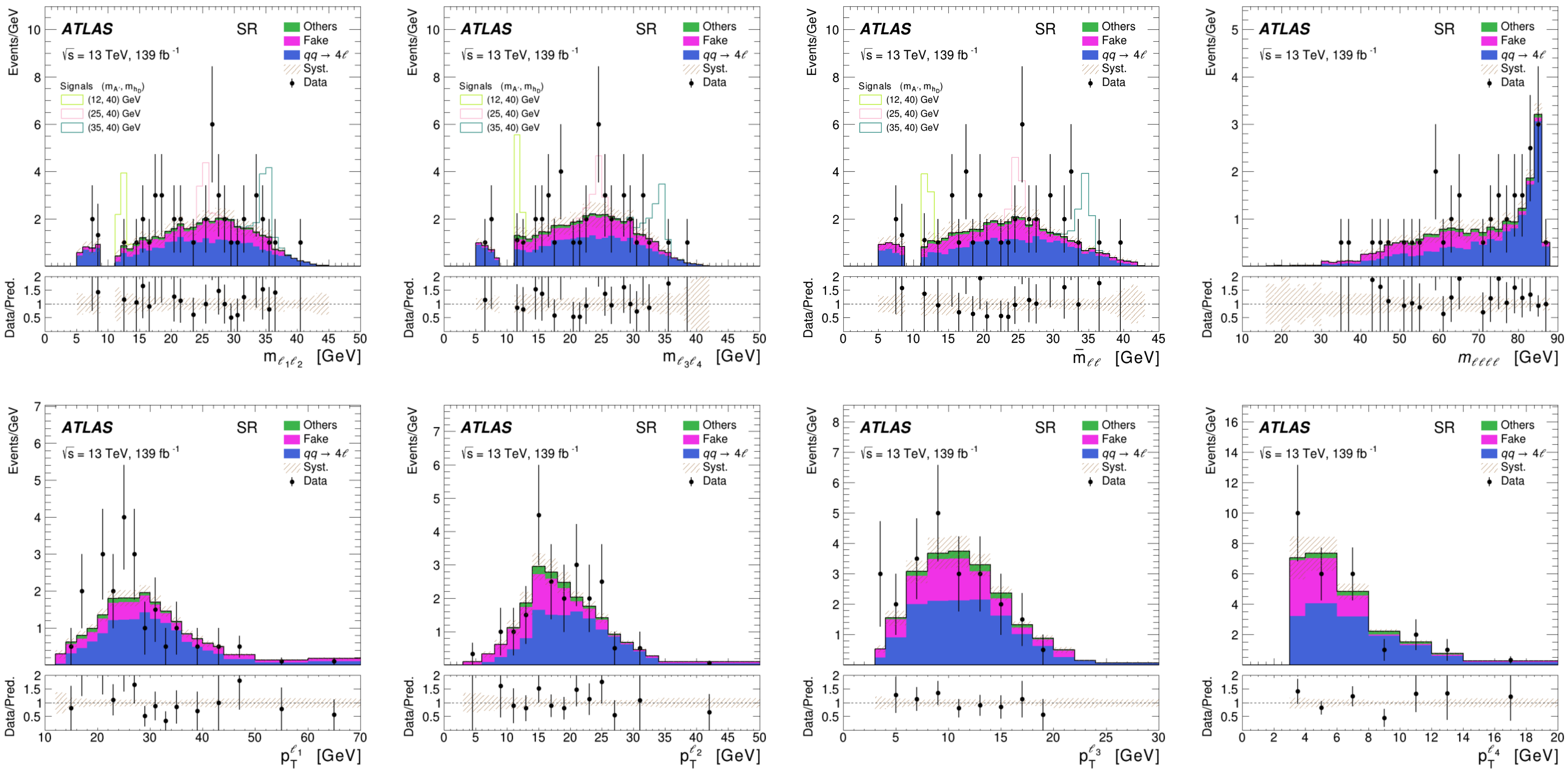
Dark photon: CR distributions



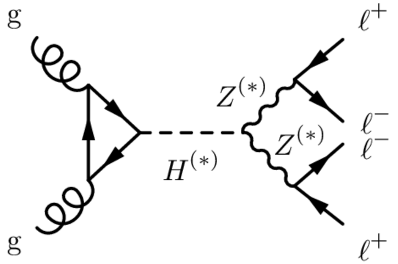
Dark photon: VR distributions

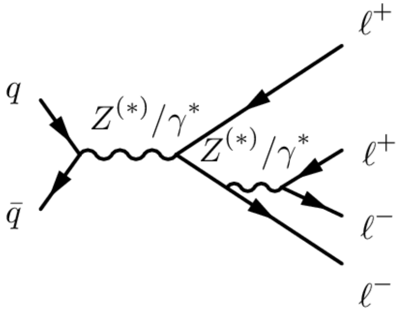


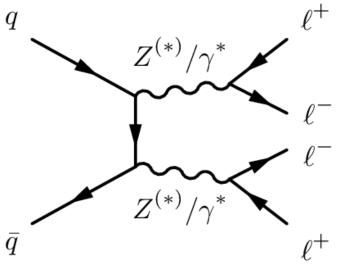
Dark photon: SR distributions

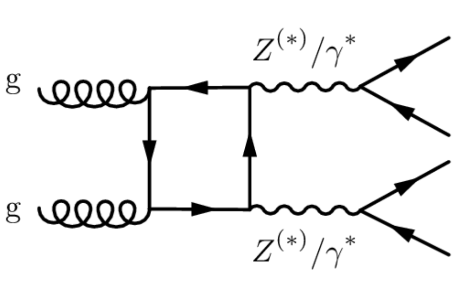


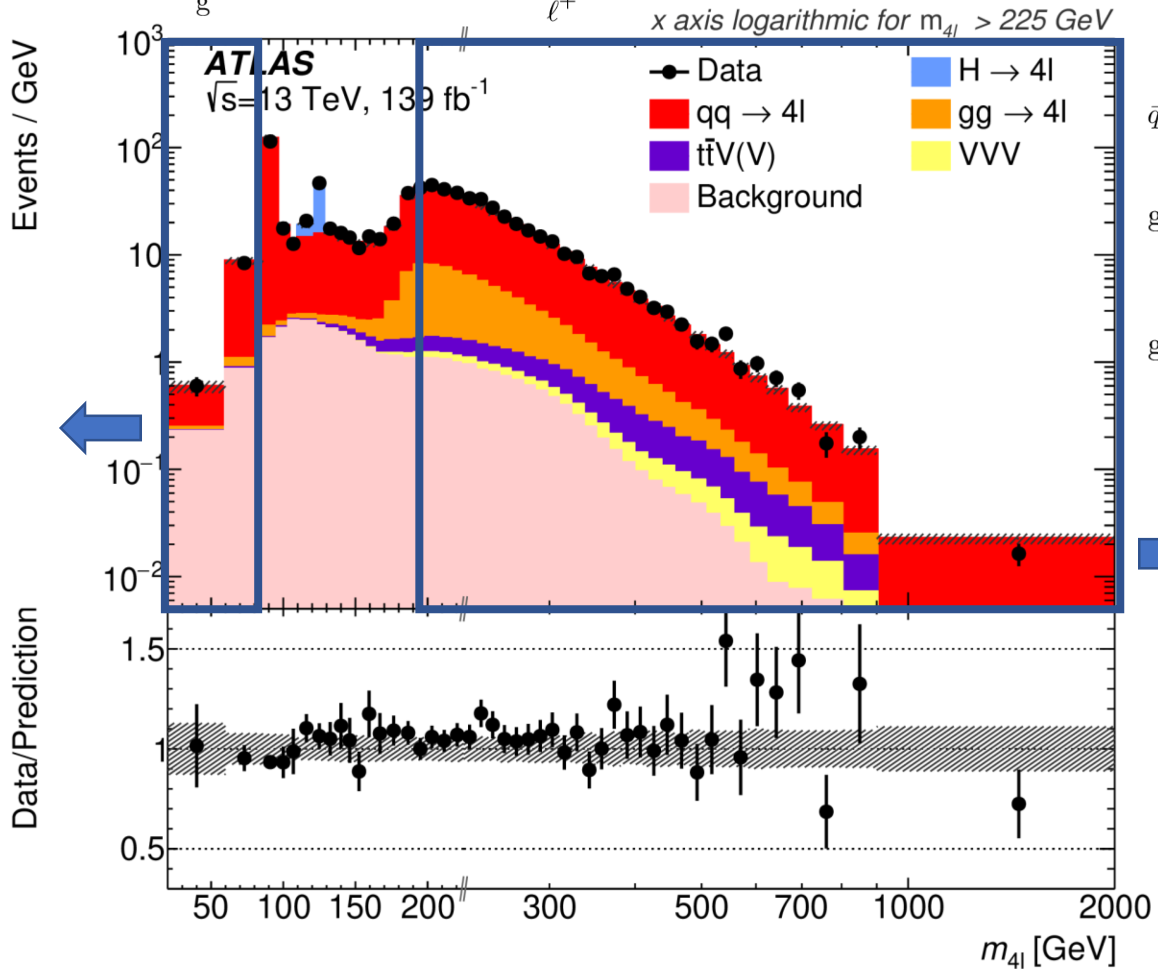
$4l$ mass spectrum by the ATLAS











Mass range related to the dark photon analysis

Mass range related to the VBSZZ analysis