Search for the Dark Vector Boson via the Higgs Portal

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On behalf of ATLAS

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Outline

Context and Objectives

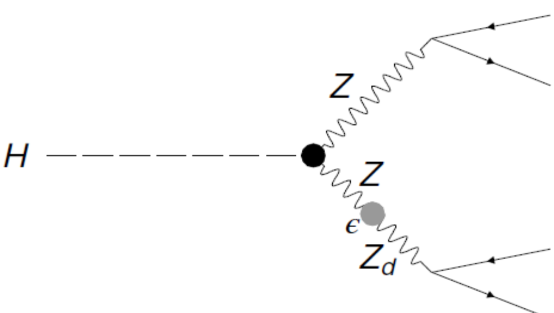
- **Standard Model (SM) deficiencies**
  - → **Many free parameters,(anti)matter paradox,hierarchy problem,strong CP problem, no gravity, no DE or DM...**
  - → **Explanation of astrophysical observations of positron excesses**
- **Hidden (dark) sector states introduced with an additional U(1)d dark gauge symmetry appear in many extensions to the SM, the models are capable of**
  - → **providing a candidate for the dark matter (DM) in the universe**
  - → **explain astrophysical "observations" which may have DM interpretation**
- **This represents an alternative DM scenario to that of Super Symmetry**

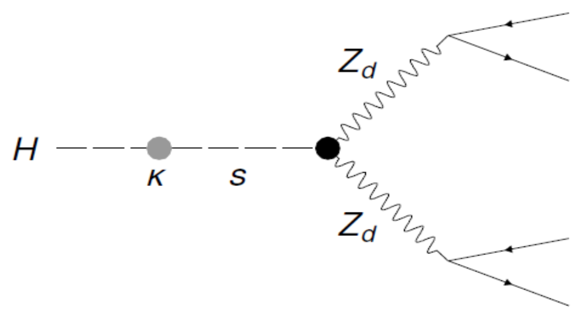
$$\mathcal{L} \subset -\frac{1}{4}\hat{\mathbf{B}}_{\mu\nu}\hat{\mathbf{B}}^{\mu\nu} - \frac{1}{4}\hat{\mathbf{Z}}_{\mathbf{D}\mu\nu}\hat{\mathbf{Z}}_{\mathbf{D}}^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{\mathbf{Z}}_{\mathbf{D}\mu\nu}\hat{\mathbf{B}}^{\mu\nu} + \frac{1}{2}\mathbf{m}^2_{\mathbf{D},0}\hat{\mathbf{Z}}^{\mu}_{\mathbf{D}}\hat{\mathbf{Z}}_{\mathbf{D}\mu}$$

$$\mathbf{V_0}(\mathbf{H},\mathbf{S}) = -\mu^2|\mathbf{H}|^2 + \lambda|\mathbf{H}|^4 - \mu^2_{\mathbf{S}}|\mathbf{S}|^4 + \kappa|\mathbf{S}|^2|\mathbf{H}|^2$$

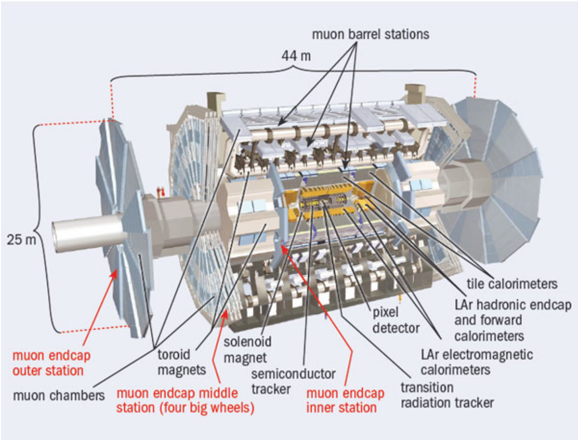
Context and Objectives

- Spontaneously broken dark gauge symmetry, **U(1)d** mediated by a dark gauge boson $\mathbf{Z_d}$
- $\mathbf{Z_d}$ interacts with the SM thru kinetic mixing with hypercharge gauge boson
  - Kinetic mixing parameter ϵ
- Also, a **dark Higgs mechanism** could spontaneously break the **U(1)d** gauge symmetry
  - Mixing between the SM-Higgs and dark higgs boson, mixing parameter κ
- The **U(1)d** kinetic mixing scenario could be generalized to include a mass mixing between the **SM-Z** and $\mathbf{Z_d}$
  - Mass mixing parameter δ





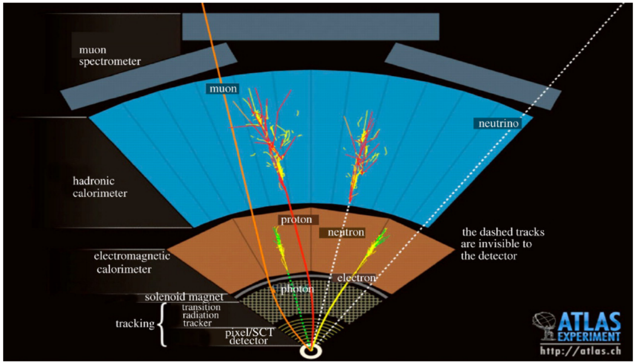
ATLAS Dectector



- muon system
  → designed to identify and reconstruct muons
- trigger system
  → choose either to keep or not events
- hadronic calorimeters
  → measure hadronic energy deposited by hadronic system
- Detector surrounded by Magnetic

- Tracking System
  → reconstruct charged particles trajectories
- Thin superconducting solenoid

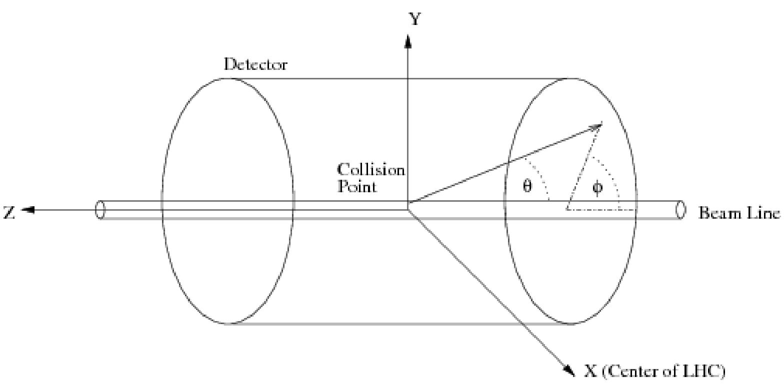
  → to compute particles impulsion
- electromagnetic calorimeter
  → measure electromagnetic energy deposited by e^- and γ



ATLAS Detector

Coordinate System: Centered around the interaction point (ip)

- Cartesian system
  - → x-axis pointing from the ip to the center of the LHC ring
  - → y-axis pointing upward
  - → z-axis defined by the beam direction
- Most commonly used angular coordinates
  - → ϕ (azimuthal angle) measured around the beam axis
  - → θ (polar angle) from the beam axis
  - → y (rapidity) $= \ln[(E + p_z)/(E - p_z)]$
  - → η (pseudo-rapidity) $= -\ln \tan(\theta/2)$
- We define
  - → All transverse physics observables in the (x; y) plane
  - → A commonly used distance in the $(\eta; \phi)$ plane $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$



Signal and background simulation

Signal	*Background*

$H \to Z_d Z_d \to 4l$

Generated by:

- MadGraph5[1]
  $\to$ for ggF mechanism for Higgs boson
- Pythia[2] and Photos[3]
  $\to$ for showering, hadronisation and initial state radiation (ISR)
- Hidden Abelian Higgs Model (HAHM)
  $\to$ as a benchmark signal model

$ZZ^* \to 4l$ (irreducible one)

- PowHeg[4] and Pythia8[2]
  $\to$ for $q\bar{q} \to ZZ^*$ and $gg2ZZ$
- Jimmy[5]
  $\to$ $gg \to ZZ^*$

WZ,ZZ dibosons processes

- Sherpa [6]

J/ψ and Υ

- Pythia8B[2]

Z+jets

- AlpgenB[7]

$t\bar{t}$

- MC@NLO[8]

Reconstruction, Identification and Selection

Baseline lepton cuts ->
(very loose for purposes of reversing subsequent cuts for data-driven background)

	e	μ
ID	Silicon Hit	Loose
IP	$|z0 \sin\theta| < 0.5$	
pT	7 GeV	6 GeV (15 GeV if calotagged)
$|\eta|$	2.47	2.7
OR*	e+μ	e+μ

e must be at least **loose to participate in OR*

Selection

1. Form **all** quadruplets satisfying: "Quadruplet-level cuts"
   - 2 x Same Flavour Opposite Sign pairs ($q_{12}=q_{34}=0$)
   - $p_T^1 > 20$GeV , $p_T^2 > 15$ GeV , $p_T^3 > 10$ GeV } HSG2
   - Trigger matched (see backup for list of triggers)
   - Electrons in leading[1] pair ≥ LooseLH
   - Number of CaloTagged or Standalone muons < 2
   - $\Delta R < 0.1$ same flavour, 0.2 opposite flavour } HSG2
2. Pick "*best*" quadruplet "Quadruplet Ranking"
   - minimum $|m_{12} - m_{34}|$ (1. Pair ranking def.: $|m_{12}-m_Z| < |m_{34}-m_Z|$)
3. Apply further cuts "Event-level Cuts"

c.f. HSG2: lexographic in $|m_{12}-m_Z|$, $|m_{34}-m_Z|$
SMZZ: minimum $|m_{12}-m_Z|+|m_{34}-m_Z|$

Reconstruction, Identification and Selection

- Reject the event if selected quadruplet fails any of these cuts
  - Electron Quality ≥ Loose LH
  - All leptons *FixedCutLoose* isolated
  - Electron (muon) d0 significance < 5 (3)
  - **H Window:** $115 < m_{4l} < 130$ GeV
  - **Quarkonia Veto:** $|m_{xy} - 3\text{ GeV}| > 1$ GeV, $|m_{xy} - 10\text{GeV}| > 1$ GeV (xy = 12, 34, 14, 23)
  - **Z Veto:** $m_{12} < 64$ GeV, $m_{34} < 64$ GeV, $m_{14} < 75$ GeV, $m_{23} < 75$ GeV
    - Optimized Z Veto cuts from dedicated study

Same as HSG2

- Events passing all these cuts define the **loose signal region (LooseSR)**

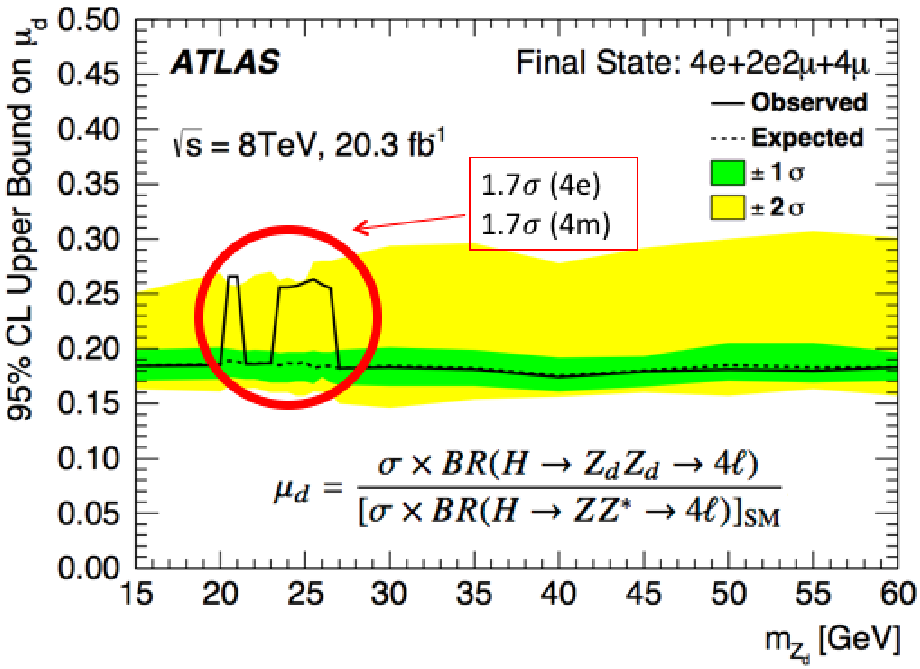
Signal Monte Carlo Cutflow

- Cutflow for $M_{Z_d} = 25$ GeV signal sample. Each channel is determined at truth level. The very last row shows the yield and significance in the Tight SR if all cuts had been placed at quadruplet level.

Cut	$4e$ channel	$2e2\mu$ channel	4μ channel	All	$S/\sqrt{B}$
No Cut	27.0 (100.0%)	60.8 (100.0%)	33.7 (100.0%)	121.6 (100.0%)	0.1
Trigger+PV	26.1 (96.7%)	58.0 (95.3%)	32.9 (97.3%)	116.9 (96.2%)	0.1
SFOS	19.8 (73.2%)	44.6 (73.4%)	26.2 (77.5%)	90.6 (74.5%)	0.1
OR	19.8 (73.2%)	44.6 (73.4%)	26.2 (77.5%)	90.6 (74.5%)	0.1
Kinematic	19.2 (71.1%)	43.5 (71.5%)	25.0 (74.2%)	87.7 (72.1%)	0.1
Trigger Matched	19.2 (71.1%)	43.5 (71.4%)	25.0 (74.2%)	87.7 (72.1%)	0.1
Delta R	19.2 (71.1%)	43.4 (71.3%)	25.0 (74.1%)	87.6 (72.0%)	0.1
Muon Quality	19.2 (71.1%)	43.4 (71.3%)	25.0 (74.0%)	87.6 (72.0%)	0.1
CBC Isolation	14.8 (54.8%)	35.5 (58.4%)	21.3 (63.0%)	71.6 (58.9%)	0.9
Electron ID	11.6 (42.9%)	31.2 (51.4%)	21.3 (63.0%)	64.1 (52.7%)	1.4
Impact Parameter	11.5 (42.5%)	30.9 (50.8%)	20.9 (62.1%)	63.3 (52.1%)	1.5
Quarkonia Veto	11.5 (42.5%)	30.9 (50.7%)	20.9 (61.9%)	63.2 (52.0%)	1.5
Low Mass Veto	11.5 (42.5%)	30.9 (50.7%)	20.9 (61.9%)	63.2 (52.0%)	1.6
H Window	10.7 (39.7%)	29.4 (48.3%)	20.2 (59.7%)	60.3 (49.6%)	6.0
Z Veto	7.3 (26.9%)	29.4 (48.3%)	13.0 (38.6%)	49.7 (40.9%)	14.2
Loose SR	7.3 (26.9%)	29.4 (48.3%)	13.0 (38.6%)	49.7 (40.9%)	14.9
Medium SR	7.1 (26.4%)	28.9 (47.5%)	12.9 (38.2%)	49.0 (40.3%)	24.2
All as quadruplet cuts	7.5 (27.8%)	29.7 (48.9%)	13.2 (39.2%)	50.5 (41.5%)	23.8

Result Run 1

See paper http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.092001



Excess seen at local 2s level is not significant.
Within Statistics, consistent with the SM

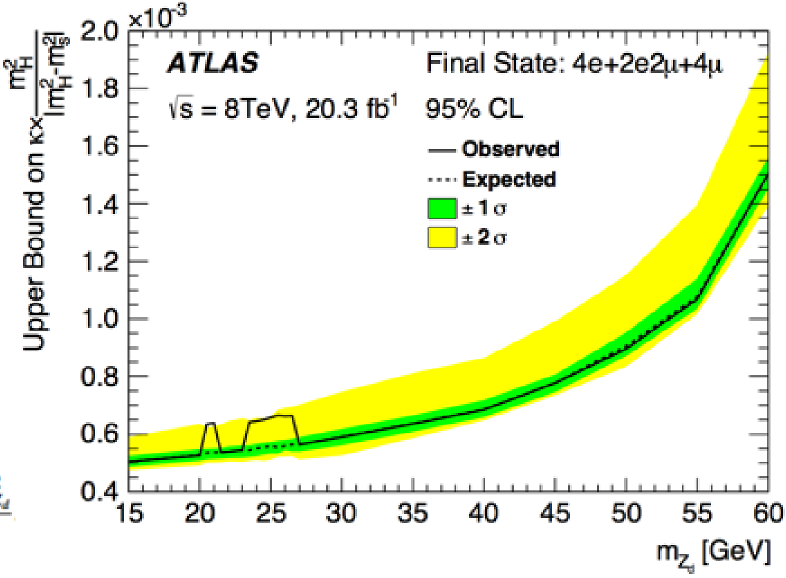
Interpretation in term of Higgs mixing

See paper http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.092001

model dependent interpretation Curtin et al in ArXiv 1412.0018v2.pdf

$$\kappa^2 = \frac{\Gamma_{SM}}{f(m_{Z_d})} \frac{BR(H \to Z_d Z_d)}{1 - BR(H \to Z_d Z_d)},$$

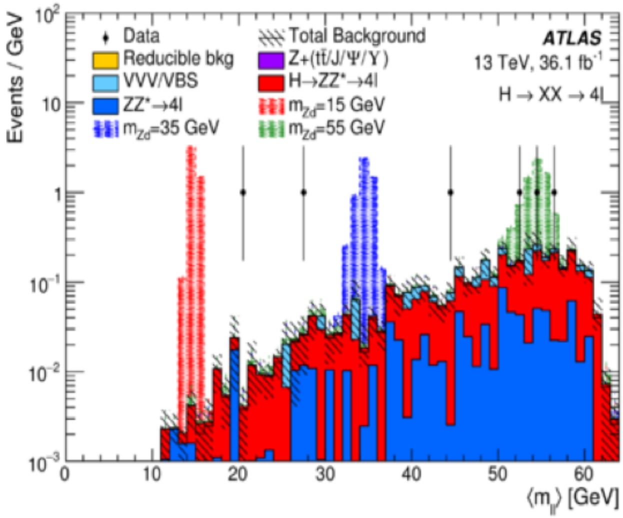
$$f(m_{Z_d}) = \frac{v^2}{32\pi m_H} \times \sqrt{1 - \frac{4m_{Z_d}^2}{m_H^2}} \times \frac{\left(m_H^2 + 2m_{Z_d}^2\right)^2 - 8\left(m_H^2 - m_{Z_d}^2\right) m_{Z_d}^2}{\left(m_H^2 - m_S^2\right)^2}$$



Run1 $\longrightarrow$ Run2

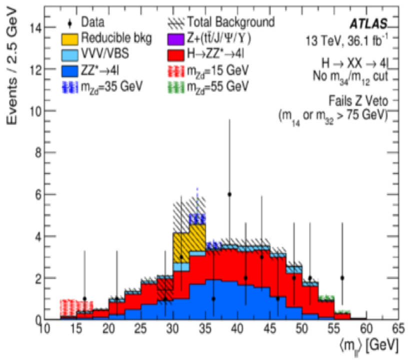
- **Factors that are expected to lead to an improvement in the Run 2 result**
  - **The Higgs production cross section in Run 2 (14 TeV) > Run 1 (8 TeV) 43.92 pb vs 19.3 pb**
  - **The Luminosity in Run 2 > Run 1 36.1 vs 20.3**
  - **Improvement in the Analysis code, various levels**
  - **Overall factor of 4 improvement expected in the limit.**

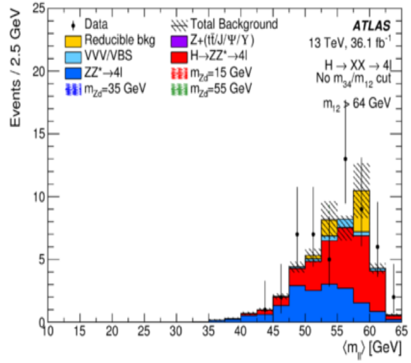
MC-Data distribution

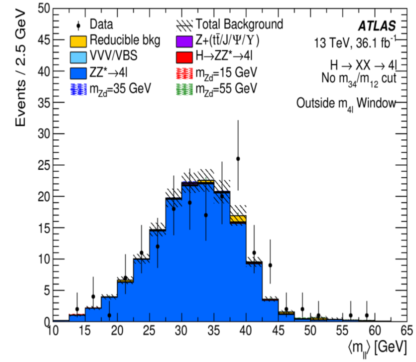


Process	Yield
$ZZ^* \to 4\ell$	0.8 ± 0.1
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
VVV/VBS	0.51 ± 0.18
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

- Distribution of $< m_{ll} >= \frac{1}{2}(m_{12} + m_{34})$
- Events selected in the $H \to XX \to 4l$ $(15 < m_X < 60 GeV)$ analysis

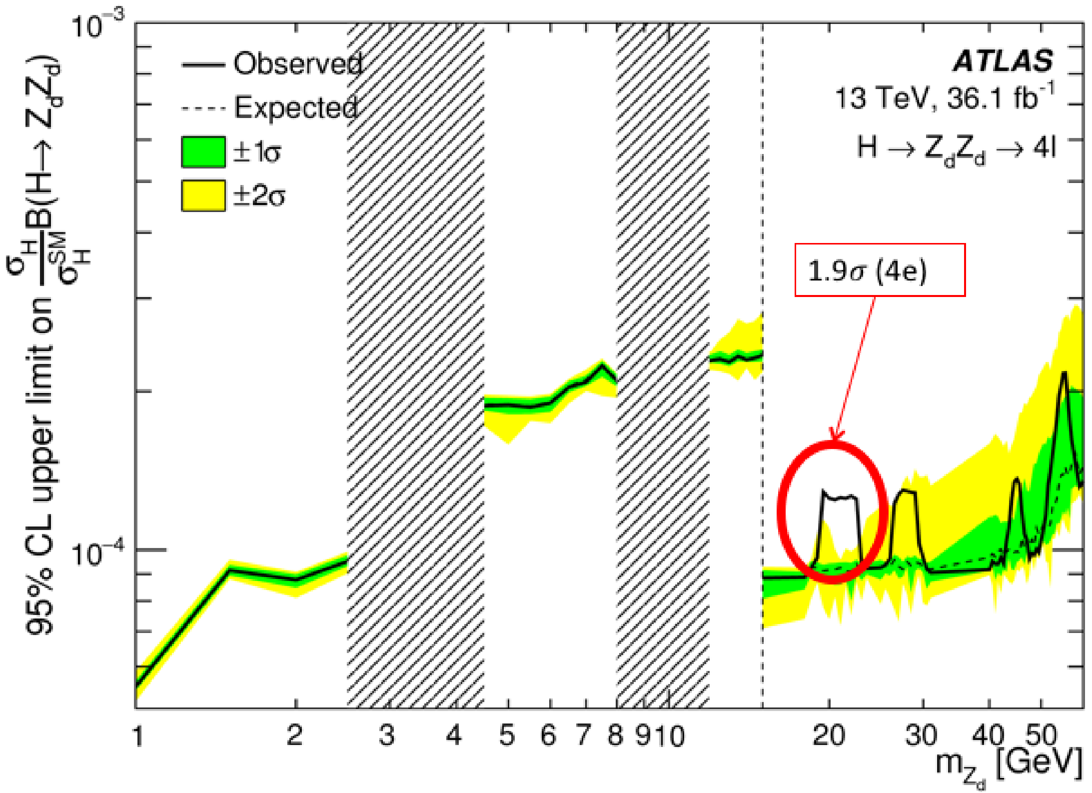






- 3 Validations Regions:
  - ☞ Events failing the Z Veto
  - ☞ Events where $m_{12} > 64GeV$
  - ☞ Events outside of the $115 < m_{4l} < 130GeV$ window
- These distributions validated the $H \to ZZ^* \to 4l$ and $ZZ^* \to 4l$ (Main backgrounds) process

Result Run2



Observed
Expected
±1σ
±2σ
ATLAS
13 TeV, 36.1 fb-1
H → ZdZd → 4l
1.9σ (4e)
95% CL upper limit on σH/σH^SM B(H→ ZdZd)
10-3
10-4
1
2
3
4
5
6
7
8
9
10
20
30
40
50
mZd [GeV]

Reducible backgrounds

- **Data-driven estimate for processes with fake leptons**
  - WZ, $t\bar{t}$ and $Z + Jets < 4l +$ (incorrect id for l ... eg jet faking l)
- **MC estimation $\rightarrow$ shows very low contribution**
- **Data Driven cross check (ABCD Method)**
  - Inverting isolation, impact parameter, or ID requirements on the leptons
  - Define a control region rich in misidentified leptons.
  - Transfer factors are measured in orthogonal control regions, also rich in misidentified leptons
  - Extrapolate from the events measured in the inverted cut control region into the signal region
  - The data-driven method < 0.1 events

Conclusion

- **Run 2 Analysis in Open Review**
- **Extension to Run 1 with higher stats**
- **Improved analysis procedure.**
  - → Soon to be published ......
- **Research on High scalar particle is on going...**

Systematics

In the case of a signal, we will determine the significance, and in the case of exclusion, we will set limits. Presented here are the relative uncertainties on the high-mass fiducial efficiency for three mass points. All uncertainties were estimated using the ZdZd signal samples

High-mass Selection	m_X = 15 GeV			m_X = 35 GeV			m_X = 55 GeV		
	$4e$	$2e2\mu$	4μ	$4e$	$2e2\mu$	4μ	$4e$	$2e2\mu$	4μ
STAT	±3.5	±1.7	±2.9	±3.3	±1.8	$^{+2.7}_{-2.6}$	±2.9	±1.7	±2.3
EL_EFF_ID_TOTAL	$^{+7.6}_{-7.3}$	±3.7	--	$^{+8.3}_{-7.9}$	±4.1	--	$^{+7.8}_{-7.4}$	$^{+3.9}_{-3.8}$	--
EL_EFF_ISO_TOTAL	$^{+1.3}_{-1.2}$	±0.7	--	±1.4	±0.7	--	±1.1	±0.6	--
EL_EFF_RECO_TOTAL	±3.1	$^{+1.6}_{-1.5}$	--	$^{+3.4}_{-3.3}$	±1.7	--	$^{+3.1}_{-3.0}$	±1.5	--
MUON_EFF_STAT	--	±0.4	±0.7	--	±0.4	±0.7	--	±0.4	±0.8
MUON_EFF_STAT_LOWPT	--	±0.1	±0.2	--	±0.1	±0.2	--	±0.1	±0.2
MUON_EFF_SYS	--	±1.1	$^{+2.4}_{-2.3}$	--	±1.1	$^{+2.3}_{-2.2}$	--	±1.2	±2.4
MUON_EFF_SYS_LOWPT	--	±0.2	±0.3	--	±0.2	±0.3	--	±0.1	±0.2
MUON_ISO_STAT	--	±0.2	±0.4	--	±0.3	±0.5	--	±0.2	±0.4
MUON_ISO_SYS	--	±0.6	±1.1	--	±0.6	±1.1	--	±0.5	±1.1
MUON_TTVA_STAT	--	±0.5	±0.9	--	±0.5	±0.9	--	±0.4	$^{+0.9}_{-0.8}$
MUON_TTVA_SYS	--	±0.8	±1.2	--	±0.8	±1.4	--	±0.5	±1.1
PRW_DATASF	$^{+2.5}_{-3.0}$	$^{+2.5}_{-2.8}$	$^{+1.6}_{-1.1}$	$^{+0.8}_{-1.2}$	$^{+1.6}_{-1.3}$	$^{+0.8}_{-1.4}$	$^{+3.0}_{-2.4}$	$^{+1.8}_{-2.0}$	$^{+1.3}_{-1.0}$
EG_RESOLUTION_ALL	$^{+0.6}_{-0.4}$	$^{+0.2}_{-0.1}$	--	$^{+0.0}_{-0.4}$	--	--	$^{+0.5}_{-0.6}$	$^{+0.0}_{-0.1}$	--
EG_SCALE_ALL	$^{+0.4}_{-0.5}$	±0.1	--	$^{+0.0}_{-0.6}$	$^{+0.2}_{-0.3}$	$^{+0.0}_{-0.1}$	$^{+0.3}_{-0.6}$	$^{+0.1}_{-0.3}$	--
MUONS_ID	--	±0.1	$^{+0.3}_{-0.0}$	--	±0.1	$^{+0.3}_{-0.1}$	--	$^{+0.0}_{-0.2}$	$^{+0.1}_{-0.2}$
MUONS_MS	--	$^{+0.0}_{-0.1}$	$^{+0.5}_{-0.2}$	--	--	$^{+0.3}_{-0.1}$	--	$^{+0.2}_{-0.1}$	$^{+0.0}_{-0.2}$
MUONS_SCALE	--	--	$^{+0.4}_{-0.1}$	--	$^{+0.0}_{-0.1}$	$^{+0.2}_{-0.0}$	--	$^{+0.0}_{-0.1}$	$^{+0.0}_{-0.1}$
MUONS_SAGITTA_RESBIAS	--	--	--	--	--	--	--	--	--
MUONS_SAGITTA_RHO	--	--	--	--	--	--	--	--	--

trigger

HLT_e24_lhmedium_L1EM20VH
HLT_e60_lhmedium
HLT_mu20_iloose_L1MU15
HLT_mu40
HLT_2e12_lhloose_L12EM10VH
HLT_mu18_mu8noL1
HLT_2mu10
HLT_e17_lhloose_mu14
HLT_e17_lhloose_2e9_lhloose
HLT_3mu6
HLT_e26_lhtight_nod0_ivarloose
HLT_e60_lhmedium_nod0
HLT_mu50
HLT_2e17_lhvloose_nod0
HLT_mu22_mu8noL1 14
HLT_e17_lhloose_nod0_mu14 15
HLT_e17_lhloose_nod0_2e9_lhloose_nod0 16
HLT_mu20_mu8noL1 17
HLT_2mu14 18