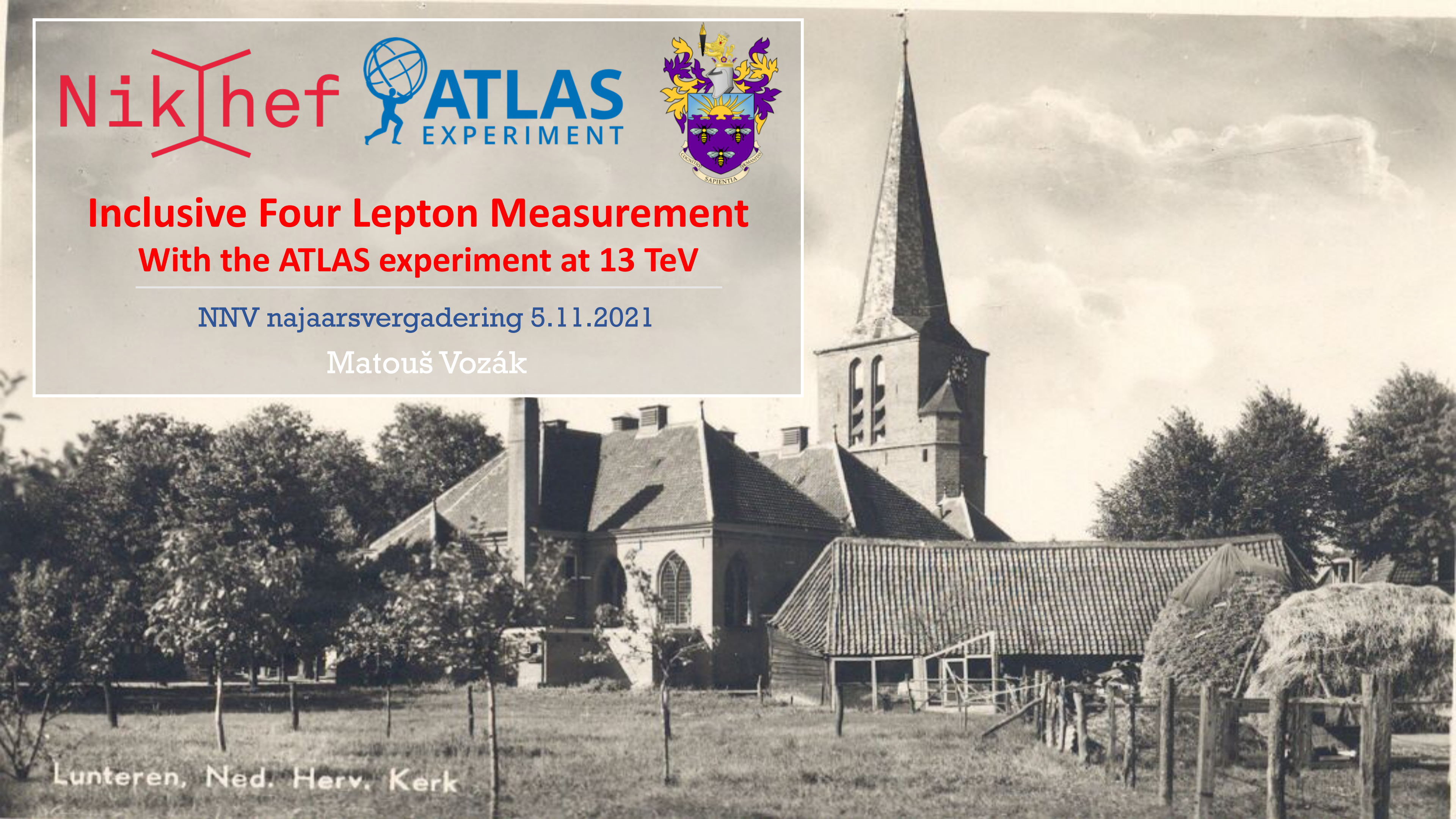
Inclusive Four Lepton Measurement

With the ATLAS experiment at 13 TeV

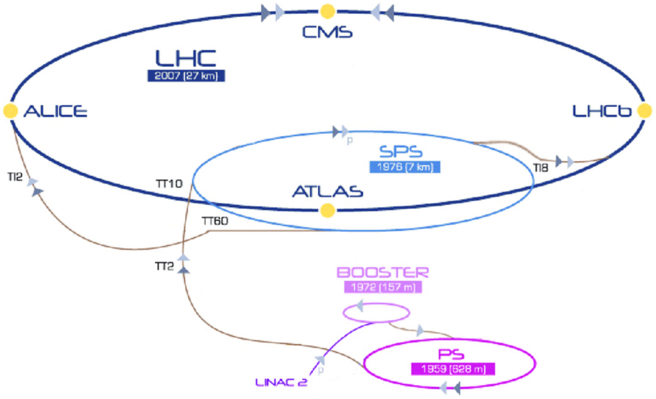
NNV najaarsvergadering 5.11.2021

Matouš Vozák

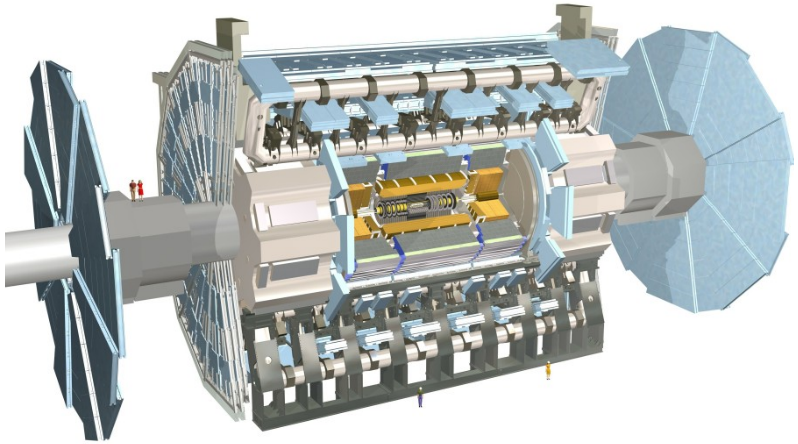


LHC & ATLAS Experiment

CERN **accelerator** complex



ATLAS **detector**

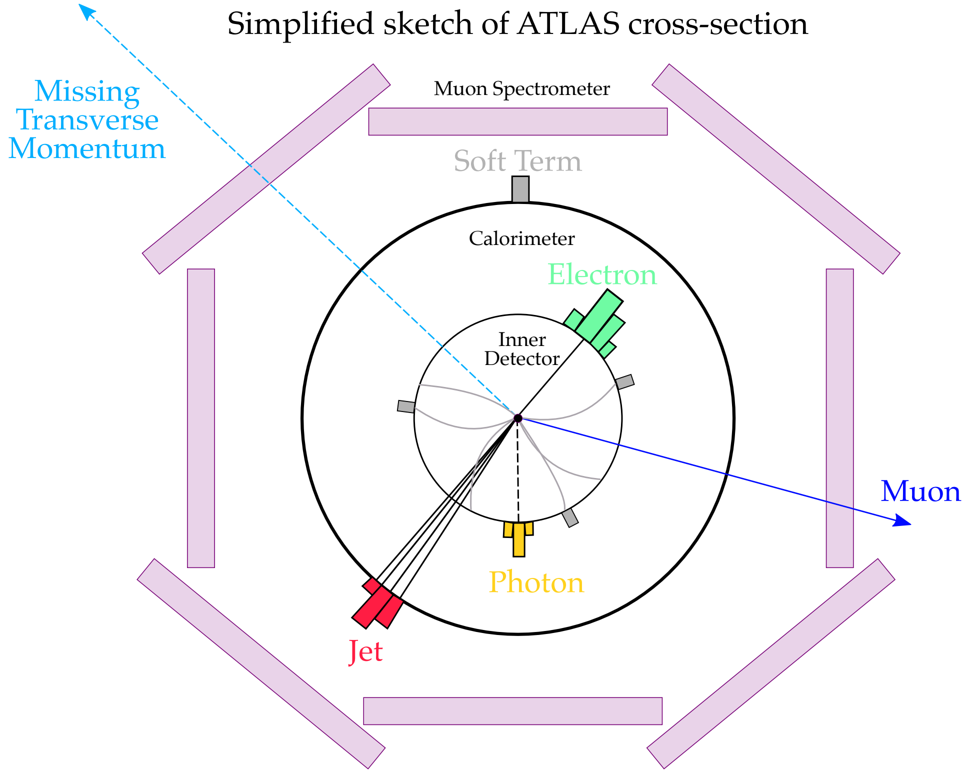


- Accelerating protons from 1 GeV to 6.5 TeV in two directions until brought to collide at four main interaction points

- Built around one of these interaction points in order to study the outcome of proton-proton collisions

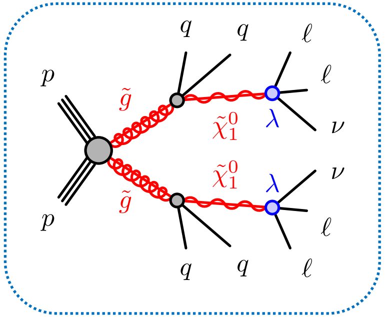
ATLAS Reconstruction

Simplified sketch of ATLAS cross-section

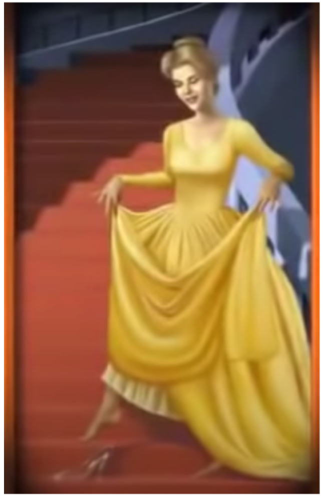


By studying properties of reconstructed objects we infer behaviour of underlying physics

ATLAS Search?

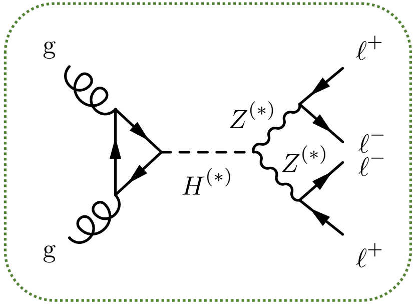


Search



- BSM process driven (sensitive)
- Detector level (no corrections)
- **Many models**
- Difficult to reuse data

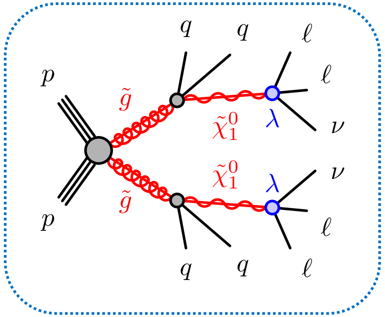
ATLAS Measurement?



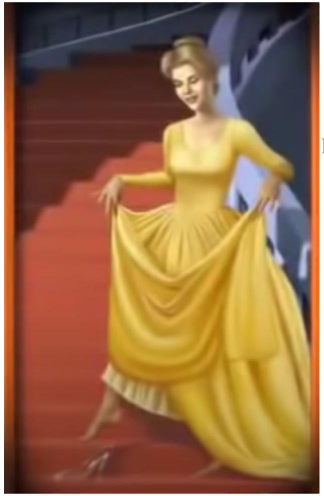
Measurement

- SM process driven
- Particle level (needs detector correction)
- Longevity (future theory improvements)
- **Any SM measurement can help to put limits on BSM**

ATLAS Search or Measurement?



Search

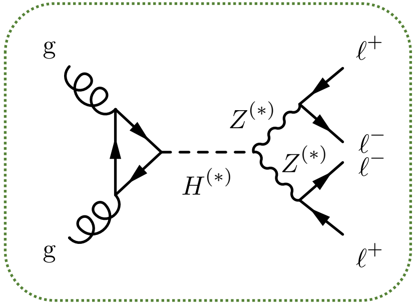


- BSM process driven (sensitive)
- Detector level (no corrections)
- **Many models**
- Difficult to reuse data

Model independence

Reinterpretation

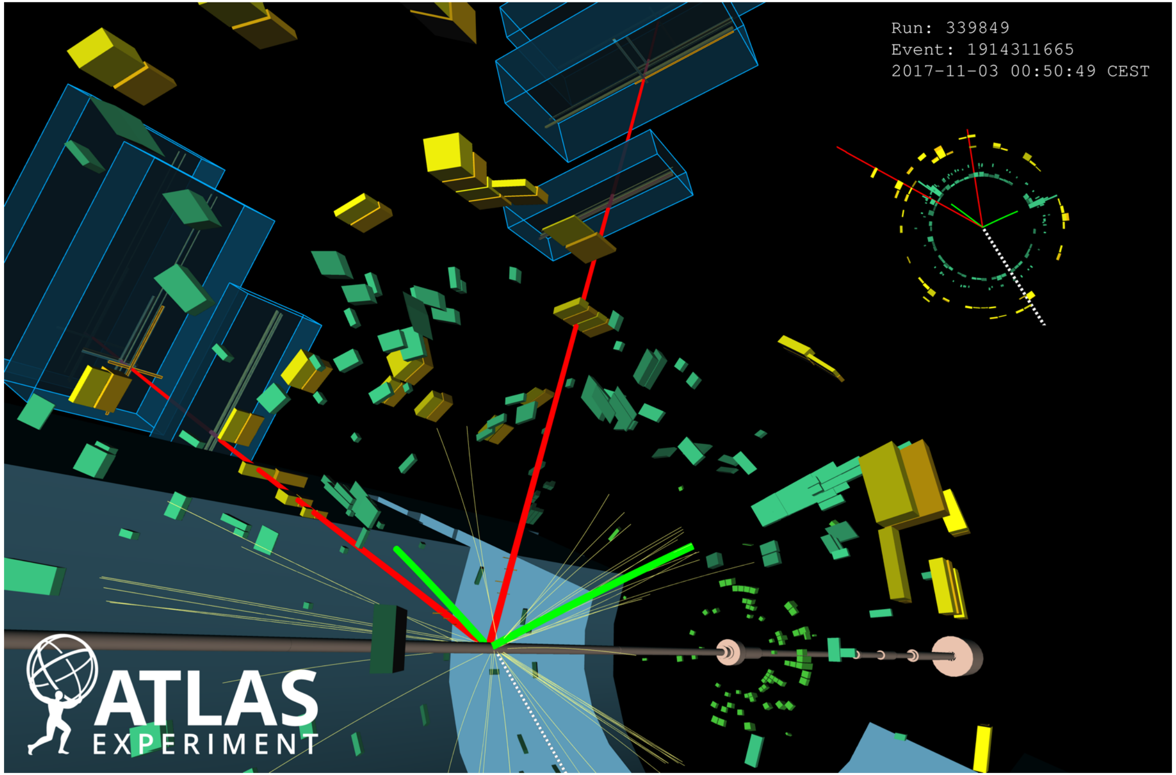
- SM process driven
- Particle level (needs detector correction)
- Longevity (future theory improvements)
- **Any SM measurement can help to put limits on BSM**



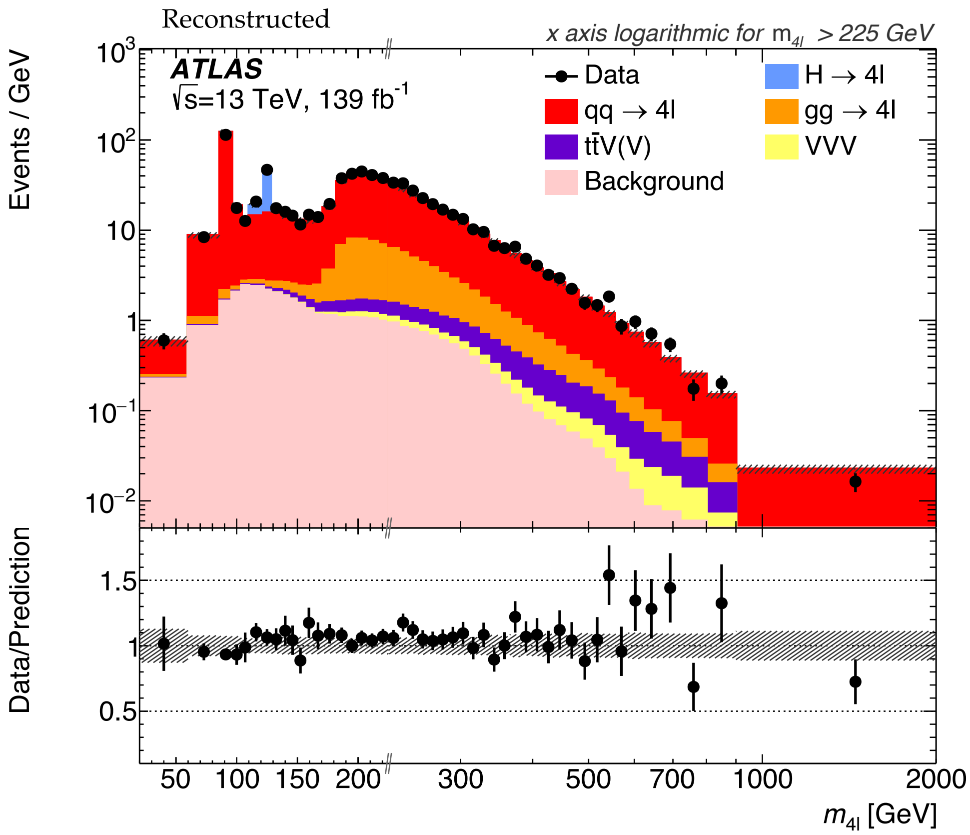
Measurement

Inclusive Four Lepton Measurement

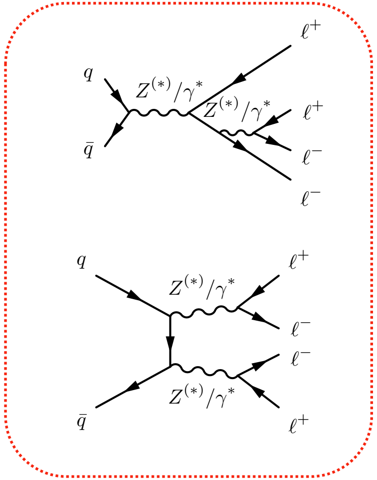
Probing **events** with at least 4 leptons (Quad: 2x SFOS pairs: 4e,4mu, 2e2mu)

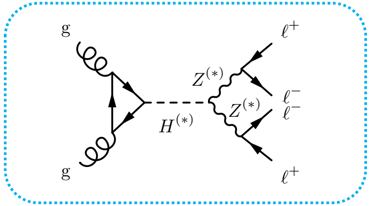


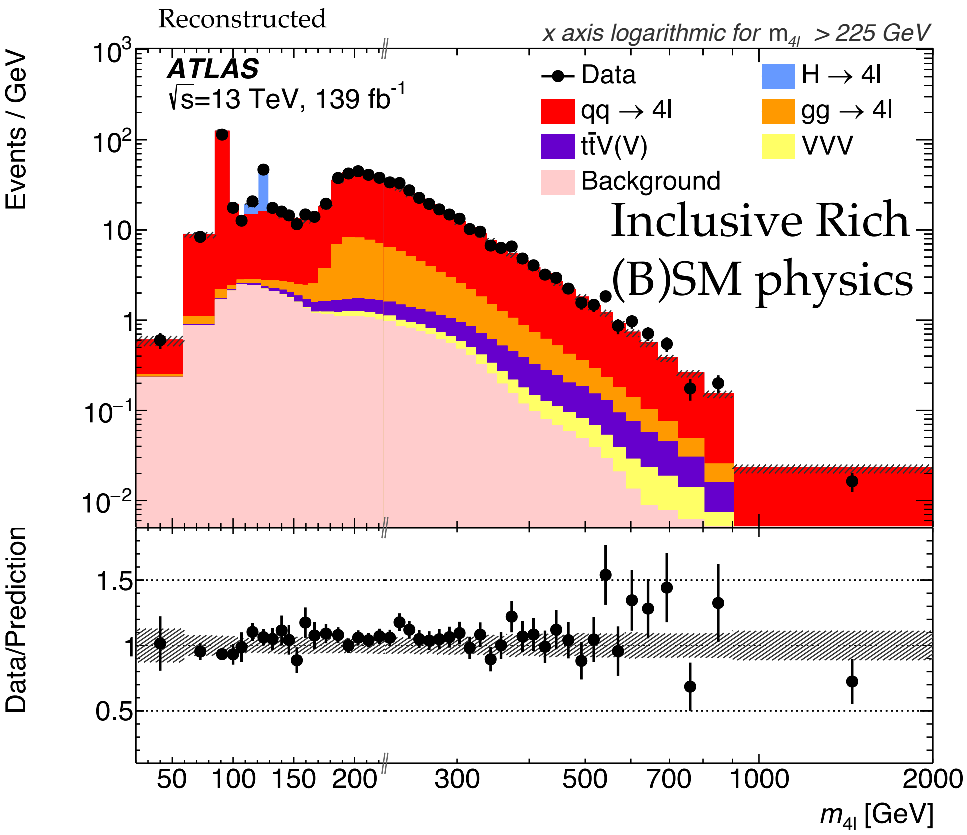
Why Four Lepton Systems?



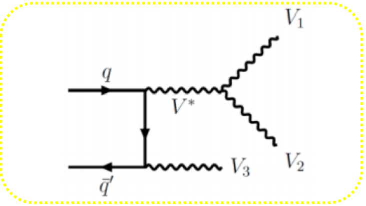
Why Four Lepton Systems?

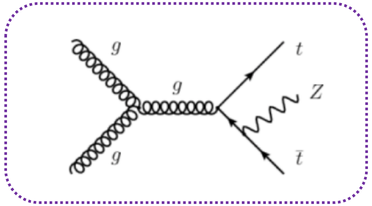


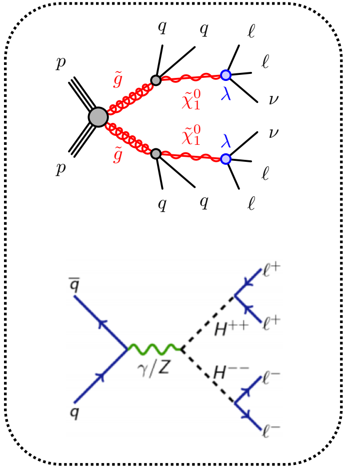




Inclusive Rich (B)SM physics



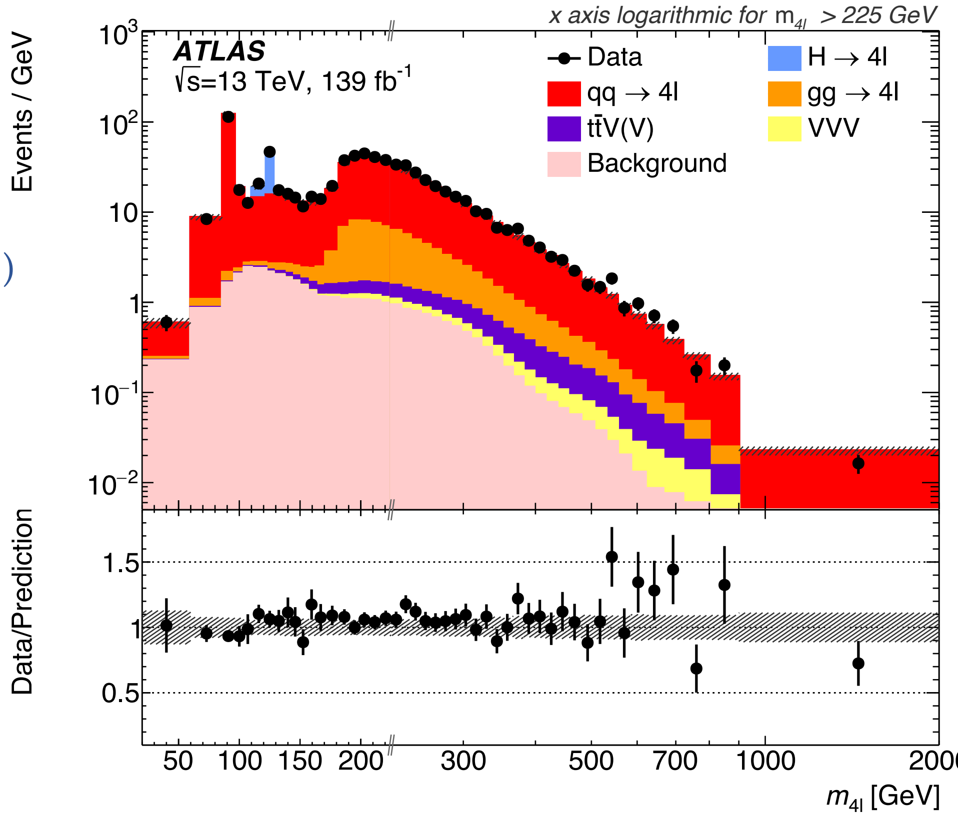




Why Four Lepton Systems?

Allow to probe wide range of interesting physics:

- Z -> 4l branching fraction
- Signal strength (gg -> 4l, Off-shell Higgs, …)
- BSM (Exotic Higgs) interpretation
- SMEFT interpretation
- …

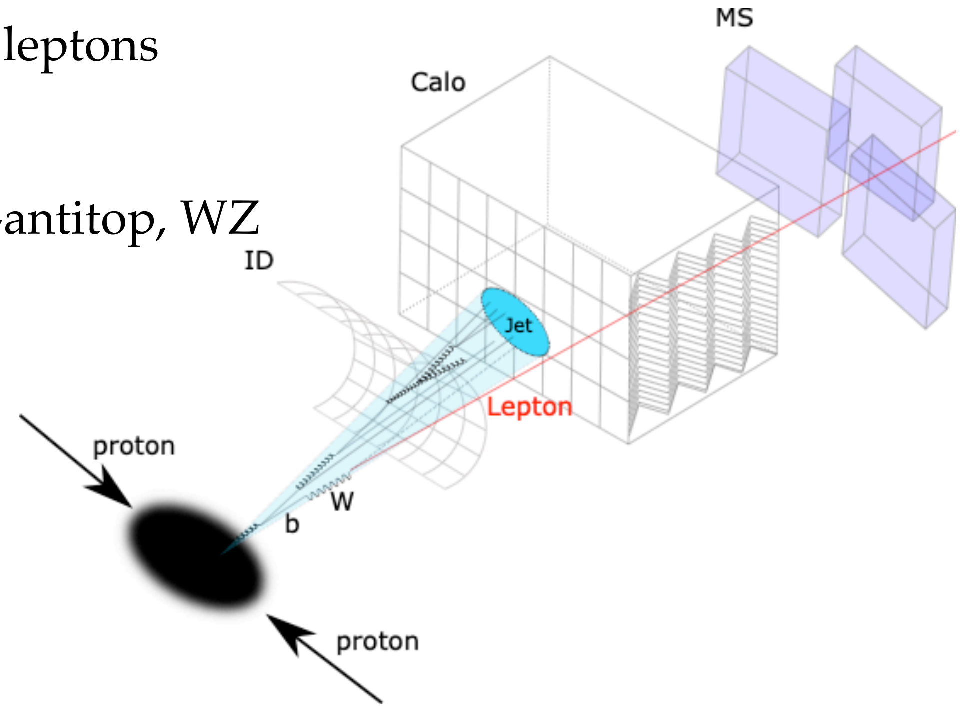


ATLAS analysis with 36 fb^{-1}

ATLAS analysis with 139 fb^{-1}

Fake Lepton Background

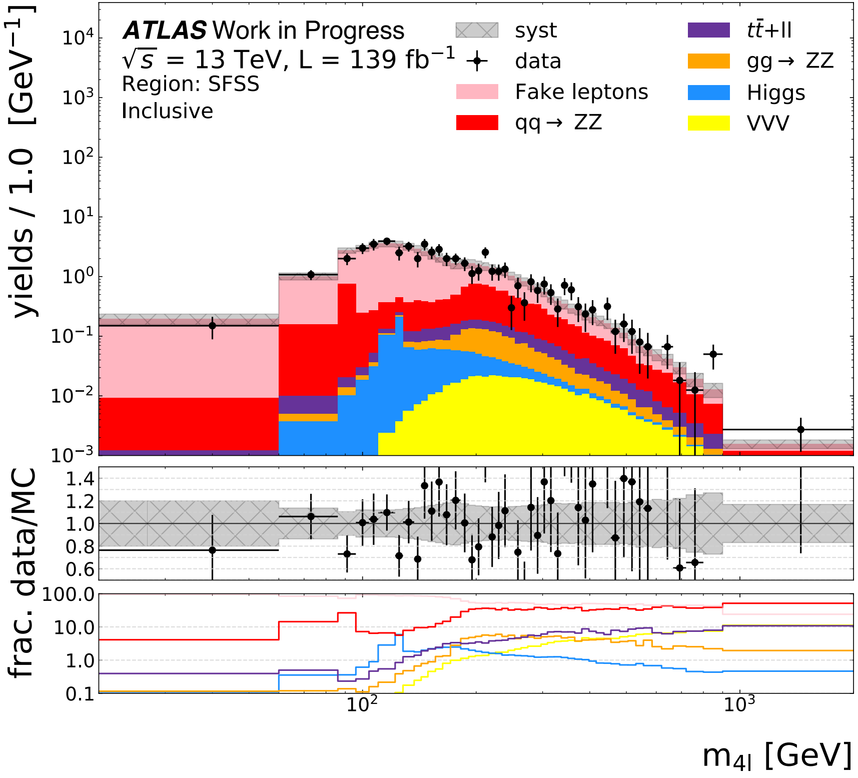
- Main background from non-prompt leptons (heavy, light flavour decays)
- Originating mainly from Z+jets, top-antitop, WZ
- These are not well modelled
- Estimated directly from data (Fake Factor method)



Fake Lepton Background

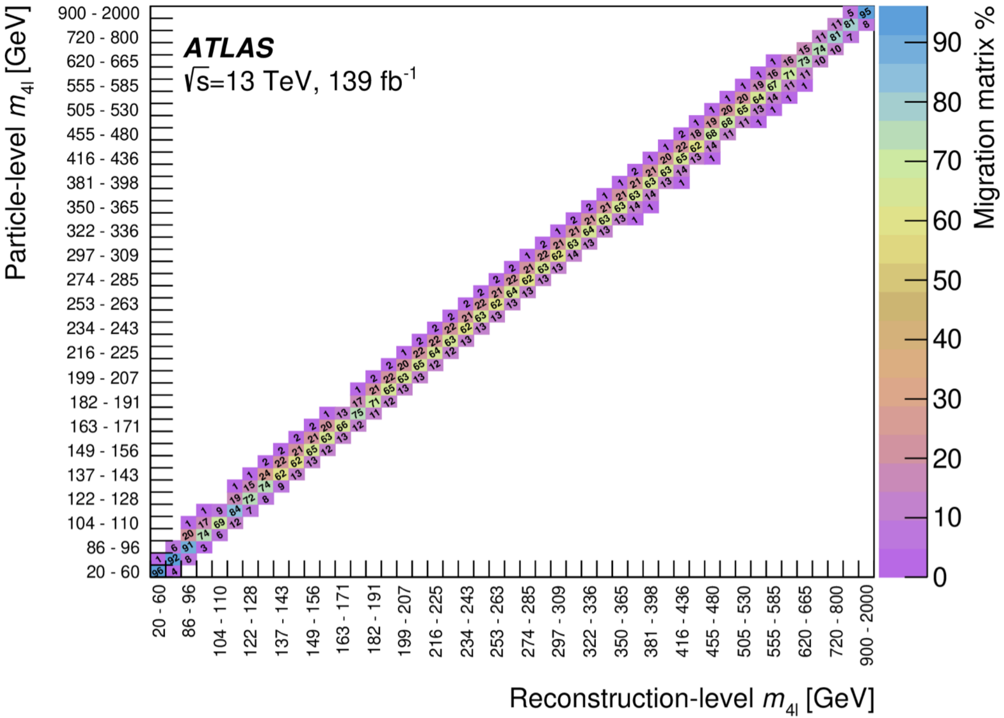
- Main background from non-prompt leptons (heavy, light flavour decays)
- Originating mainly from Z+jets, ttbar, WZ
- These are not well modelled
- Estimated directly from data (Fake Factor method)
- Validated in dedicated regions

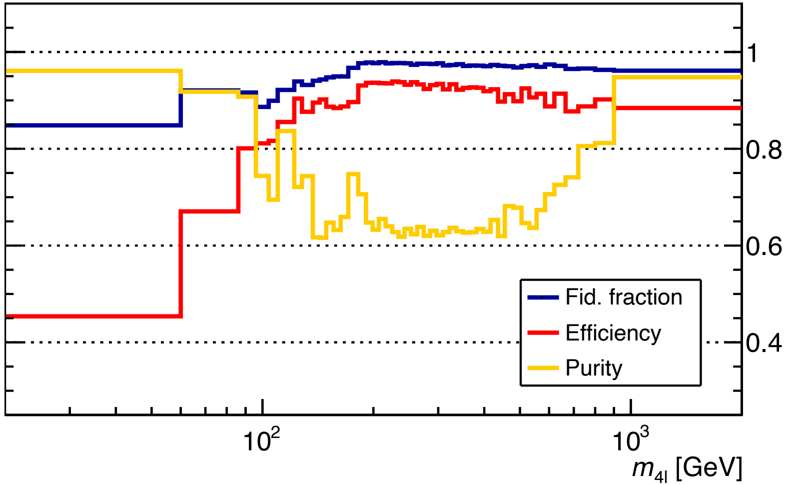
Same-flavor same-sign pair
Different-flavor opposite-sign pair



Correction to Particle-level

Resolution & Efficiency effects





- Chosen Method: Iterative Baysian Unfolding with lepton-based pre-unfolding correction

Results (Cross-sections)

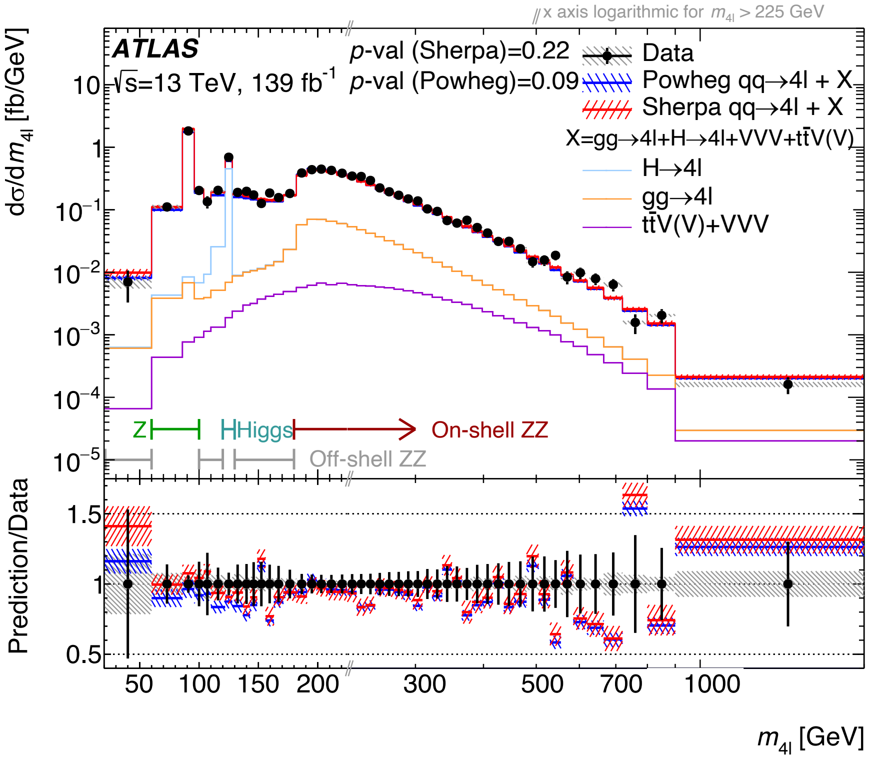
Integrated cross sections

	Full	$Z \to 4\ell$	Region $H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
Sherpa	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
Powheg + Pythia8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

Used to extract (most precise) Z -> 4l BF

$$B_{Z\to 4l} = (4.41 \pm 0.30) \times 10^{-6}$$

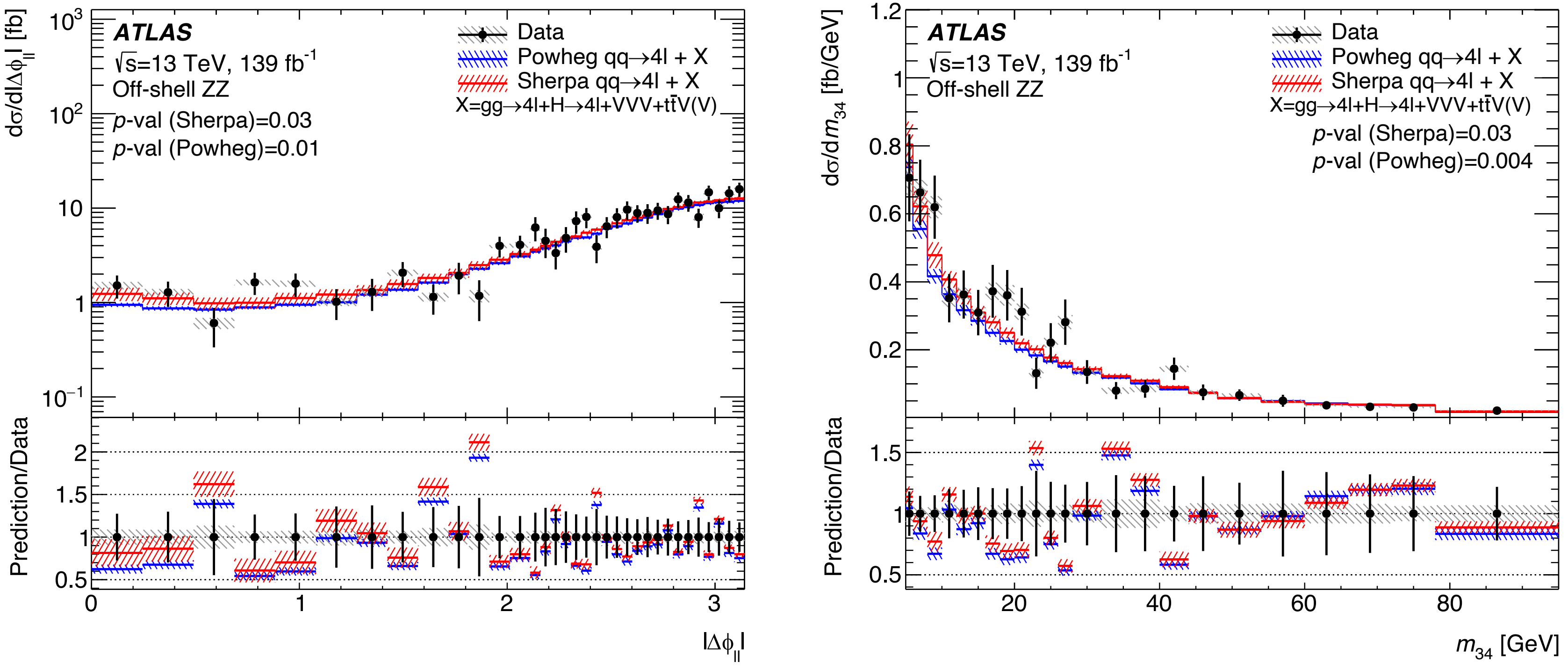
Differential cross sections:



Results (Cross-sections)

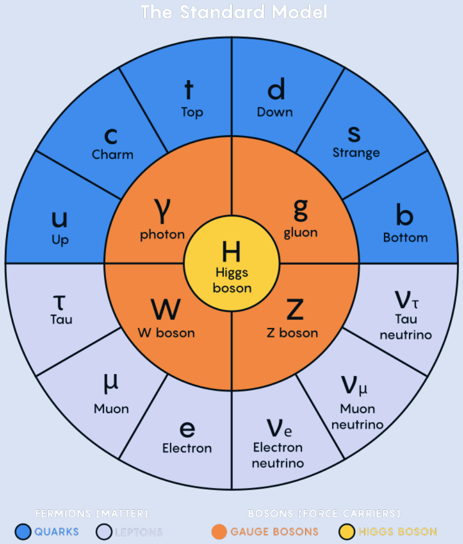
Double Differential cross sections:

(m4l (inc., p_T4l, y4l, flavour), Δy_{pairs}, $\Delta\phi_{pairs}$, $\Delta\phi_{ll}$, m_{z1}, m_{z2}, p_{Tz1}, p_{Tz2}, polarisation variables)



SM Effective Field Theory (SMEFT)

Low energy limit



High energy limit

Sensitivity in the m4l analysis

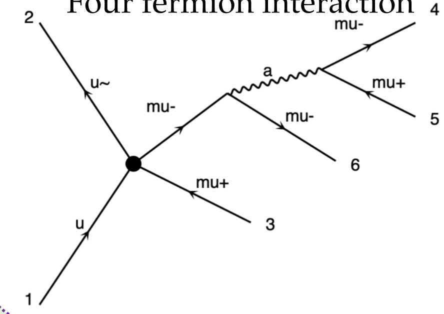
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_j C_j^{(6)}\mathcal{O}_j^{(6)} + \dots$$

Wilson coefficients

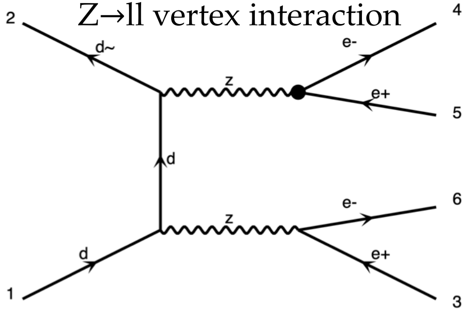
Scale of the new physics

Operators

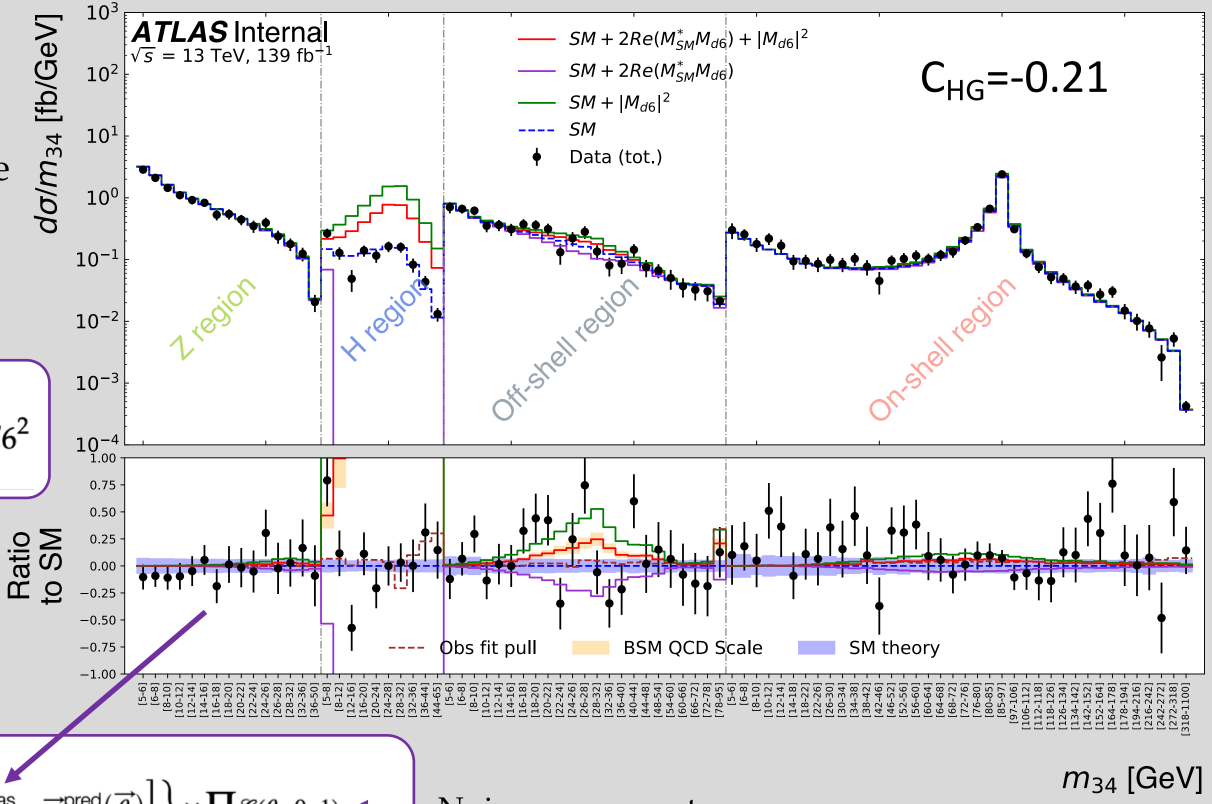
Four fermion interaction



Z→ll vertex interaction



SMEFT Interpretation Model



Choosing the most sensitive observable for each Wilson coefficient

Model parametrization

$$\sigma_{SMEFT}(c) = \sigma_{SM} + c \cdot \sigma_{Int} + c^2 \cdot \sigma_{d6^2}$$

LH formula

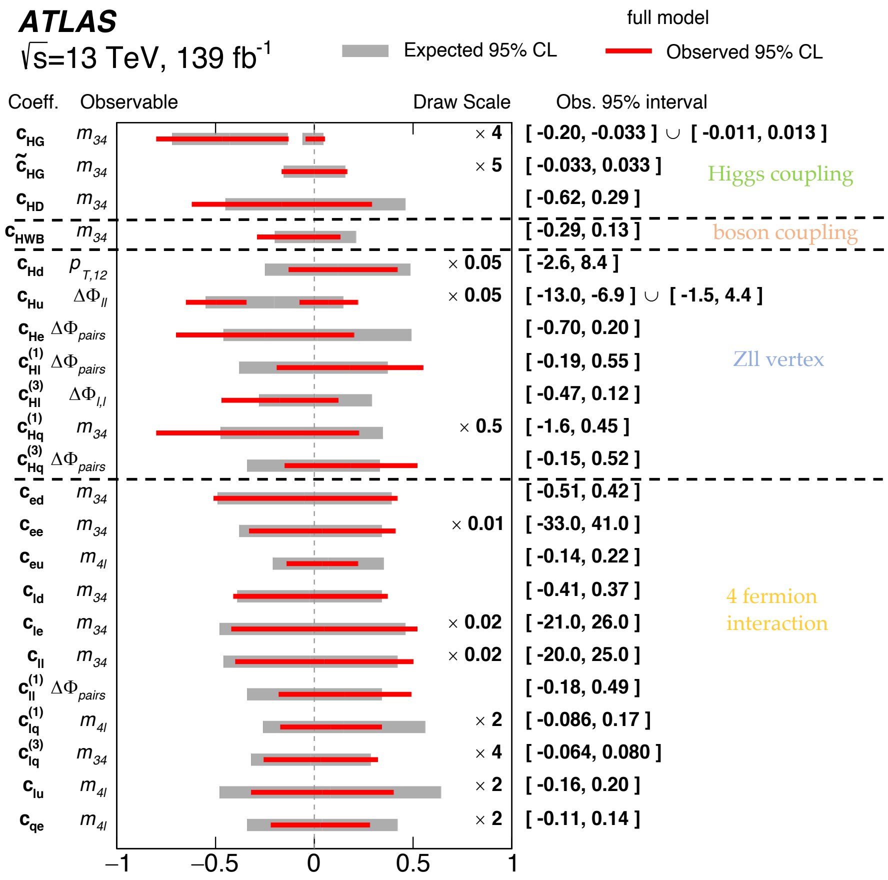
$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left\{ -\frac{1}{2} \left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}(\vec{\theta}) \right]^T C^{-1} \left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}(\vec{\theta}) \right] \right\} \times \prod_i \mathcal{G}(\theta_i, 0, 1)$$

Covariance matrix

Nuisance parameter term

SMEFT Interpretation Results

- Individual limits on 22 Wilson coefficients
- Higgs coefficients more constrained by dedicated Higgs measurements
- C_{HWB} 5 x more constrained by m4l (global fit currently the best)
- Zll best constraints currently from the combination of LEP and LHC data
- Limits provided for full model but also linear only -> test of missing dim8 EFT
- The results can be used in combination with other measurements to perform global fit



For gif scans see: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-30/animated_01.gif

What to carry away?

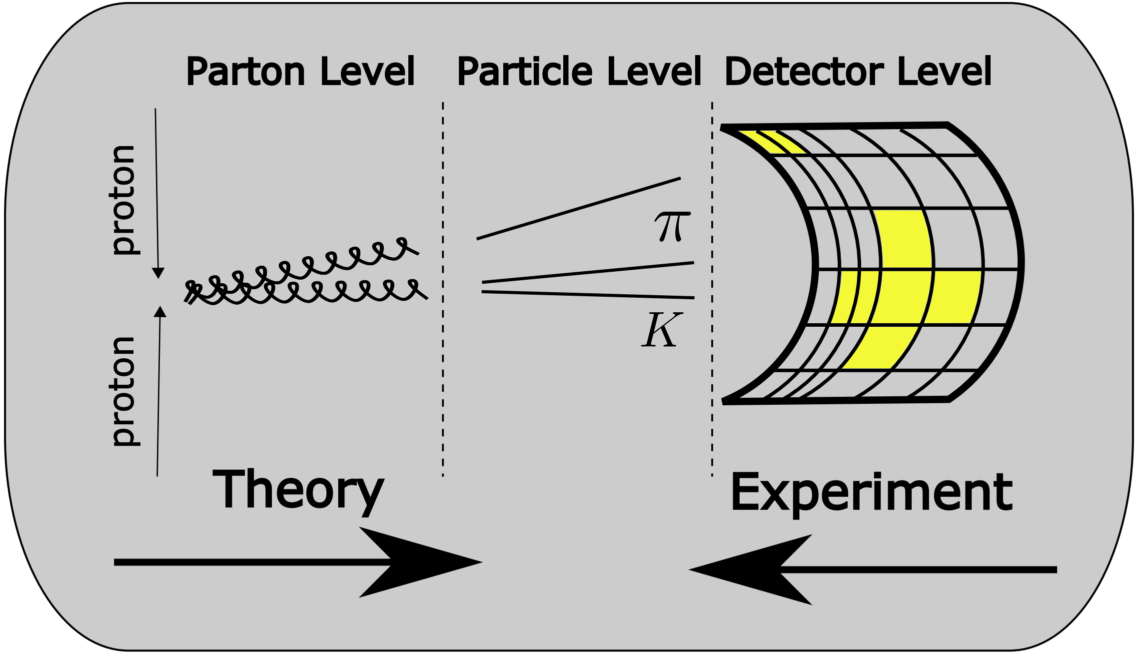
- Elusive nature of new physics leads to vast mapping of parameter phase space of BSM models
- SM measurements (such as inclusive four lepton analysis), and their combinations, can help to constrain BSM physics in a systematic way (Example: SMEFT)

Thank you for your attention

Additional Material

Correction to Particle-level

- Reconstructed distribution has to be corrected for detector effects

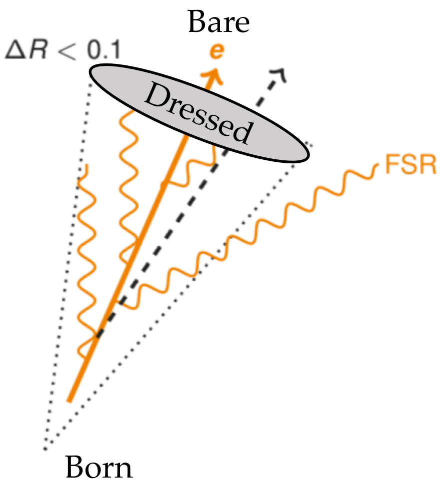


Measurement Defined by Final State Objects

- Loosened selection to allow for **maximal inclusivity**
- Lepton selection defined by ATLAS acceptance
- Relaxed lepton separation allowing for boosted topologies
- **Less extrapolation (and model dependence)** from measured quantities:
  - Lepton type (bare vs dressed)
  - Isolation (mimic reco isolation)
- Tau decay leptons included (to allow for BSM with taus)

Table 1: Definition of the fiducial region.

	Lepton selection
Muon selection	Bare, $p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electron selection	Dressed, $p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
	Event selection
Four-lepton signature	At least 4 leptons, with 2 Same-Flavour, Opposite-Sign pairs
Lepton kinematics	$p_T > 20/10$ GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Truth isolation	ptcone30/p_T < 0.16



M4L Reco Selections

Overlap Removal

Reject	Against	Overlap Criteria
electron	electron	shared track, $p_T^1 < p_T^2$
calo muon	electron	shared ID track
electron	muon	shared ID track
jet	electron	ΔR <0.2
jet	muon	NumTrack < 3 and ghost-associated/ΔR <0.2

Jet selection

Table 17: Definition of the jet selection.

Collection:	AntiKt4EMPFlow
Kinematics:	$\lvert\eta\rvert < 4.5$
	$p_{\mathrm{T}} > 30$ GeV
Signal jet (after overlap removal):	pass JVT

Reco Selection

Table 20: Definition of the reconstruction-level selection.

Category	Requirement
Event Preselection	Fire at least one lepton trigger
	$\geq$1 vertex with 2 or more tracks
Four-lepton signature	At least 4 leptons (e, μ)
Lepton kinematics	$p_{\mathrm{T}} > 20/10$ GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any two leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Trigger matching	Baseline leptons matched to at least one lepton trigger
Quadruplet formation	At least one quadruplet with 2 Same-Flavour, Opposite-Sign (SFOS) pairs
Quadruplet categorisation	4 signal, 0 non-signal: signal region
	$\leq$ 3 signal, $\geq$ 1 non-signal: background control region

Inclusive 4l: Results (integrated fid. x-sec, BR)

1] Integrated fiducial cross-sections

	Full	$Z \to 4\ell$	Region $H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
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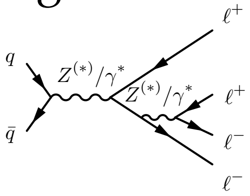
2] Branching fraction of Z->4l



Subtraction of predicted
Non qqZZ processes

Fraction of single Z
(rather than T channel)

$$B_{Z\to 4l} = \frac{\left(\sigma^{\rm meas} - \sigma^{\rm pred}_{{\rm non}-q\bar{q}\to 4l}\right) \times f_Z \times f_{{\rm non}-\tau}}{\sigma_Z \times A_{\rm fid}}$$

Fraction of leptons
Not originating from taus

Total cross-section for a single Z production
Phys. Lett. B 759 (2016) 601

Extrapolate to extend phase space
80 < m4l < 100, mll > 4, no kin. req on leptons

Most precise results up to date!

$$B_{Z\to 4l} = (4.41 \pm 0.13({\rm stat}) \pm 0.23({\rm syst}) \pm 0.09({\rm theory}) \pm 0.12({\rm lumi})) \times 10^{-6} = (4.41 \pm 0.30) \times 10^{-6}$$

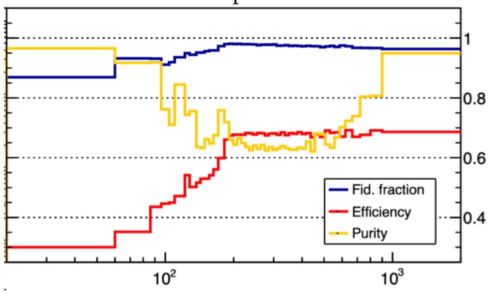
Powheg: $B_{Z\to 4l} = (4.50 \pm 0.01) \times 10^{-6}$ Phys. Rev. Lett. 112, 231806 (2014)

Impact of pre-unfolding

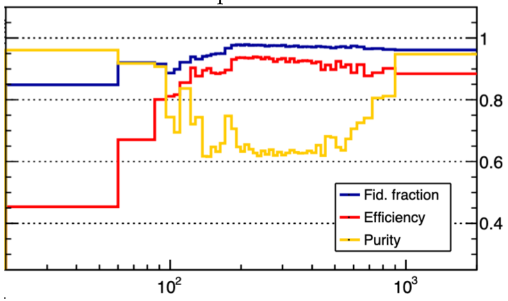
- Reduced size of efficiency correction in the unfolding
- Robustness tested with various BSM signal injections

Unfolding inputs

No pre-unf

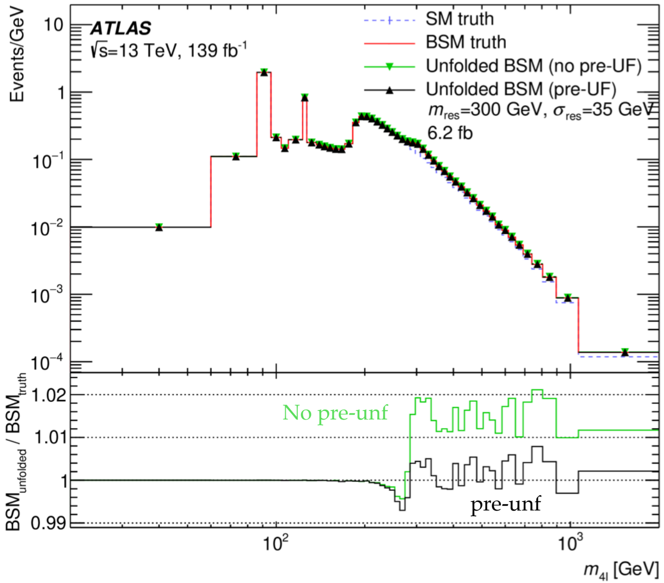


pre-unf



$$\text{Efficiency} = \frac{\text{N events passing reco}}{\text{N events passing truth}}$$

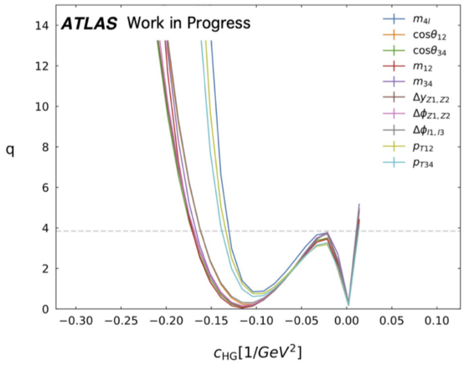
Injection tests



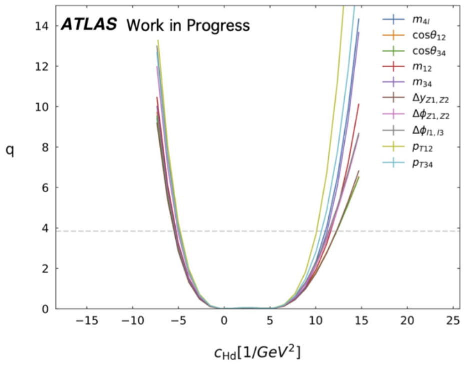
Dimension 6 operators

	X^3		H^6 and H^4D^2		$\psi^2 H^3$
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
	X^2H^2		$\psi^2 XH$		$\psi^2 H^2 D$
$\mathcal{O}_{HG}$	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$
	$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

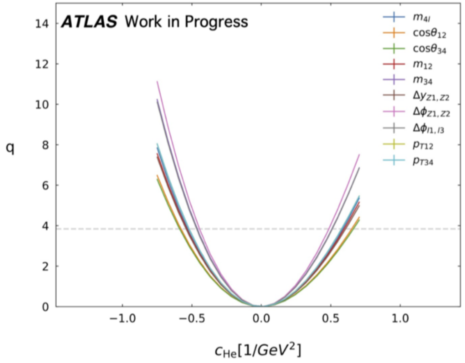
Q-scans



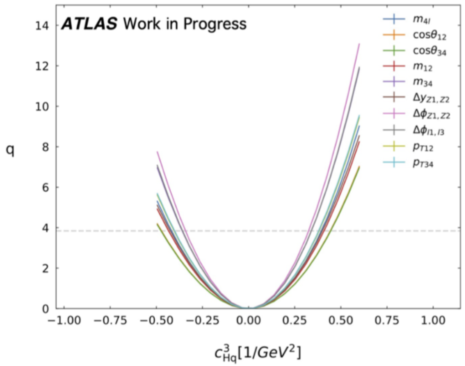
(a) c_{HG}



(b) c_{Hd}



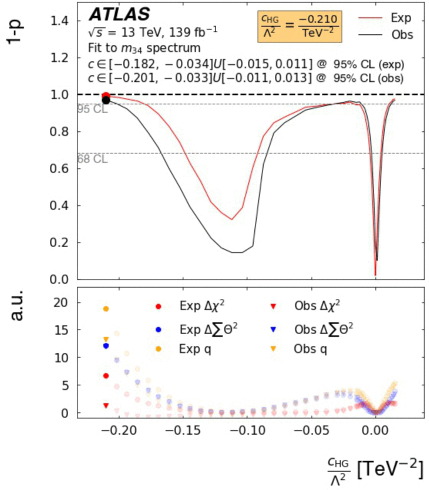
(c) c_{He}

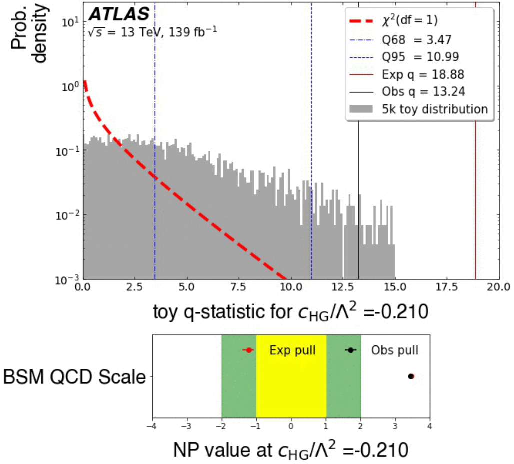


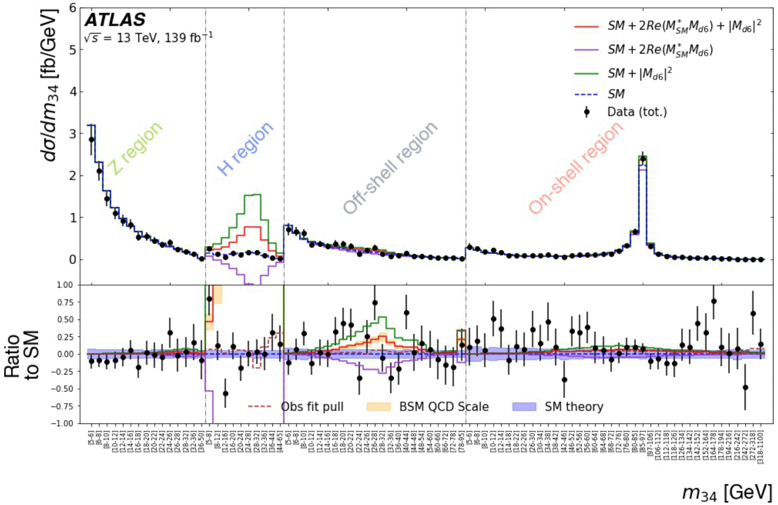
(d) $c_{Hq}^{(3)}$

EFT Limit Setting

$$q(c) = -2\log\left(\frac{\mathrm{argmax}_{\theta}\mathcal{L}\left(\vec{x}|c,\theta\right)}{\mathrm{argmax}_{c',\theta}\mathcal{L}\left(\vec{x}|c',\theta\right)}\right)$$







https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-30/animated_01.gif

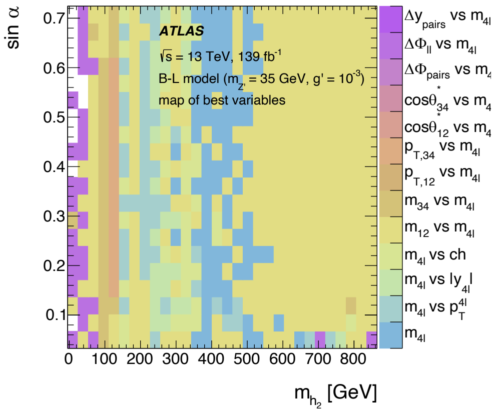
Inclusive 4l: Results (interpretation)

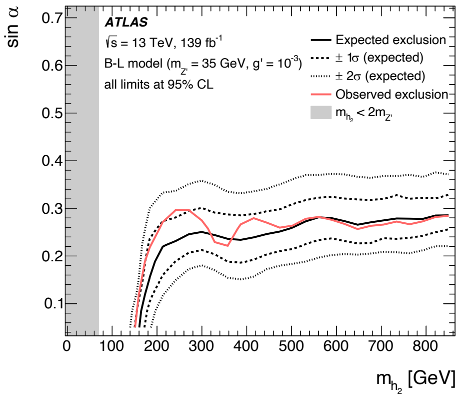
Used LH formula for the interpretation

$$\mathscr{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left\{ -\frac{1}{2}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}(\vec{\theta})\right]^T C^{-1} \left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}(\vec{\theta})\right] \right\} \times \prod_i \mathscr{G}(\theta_i, 0, 1)$$

Baryon – Lepton number gauge model

- Spontaneously broken local gauge B-L symmetry
- Predicts Z′ and exotic Higgs h2 mixing with SM Higgs via α, possible decays of both Higgs to ZZ and Z′Z′
- Model generated with Herwig 7.2

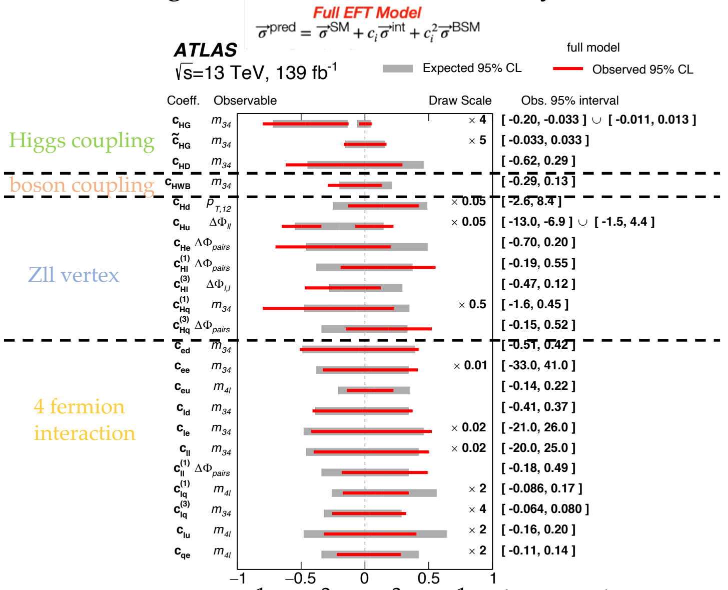




Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \boxed{\mathcal{L}_{\text{SM}} + \sum_{\forall i} \frac{C_i \mathcal{O}^{(6)}}{\Lambda^2}} + \sum_{\forall j} \frac{C_j \mathcal{O}^{(8)}}{\Lambda^4} + \sum_{\forall k, n=5,7,9\cdots} \frac{C_k \mathcal{O}^{(n)}}{\Lambda^{n-4}}$$

- Limits on 22 Wilson coefficient dim6
- EFT terms generated (Mg5@NLO + Py8) individually



- c_{HD}, c_{HWB}, c_{He}, c^1_{Hl}, c^3_{Hq}, c^3_{Hl}, c^1_{ll}, linear dominant

EFT Interpretation Results

- c_{HD}, c_{HWB}, c_{He}, c^1_{Hl}, c^3_{Hq}, c^3_{Hl}, c^1_{ll}, linear dominant

Only interference term

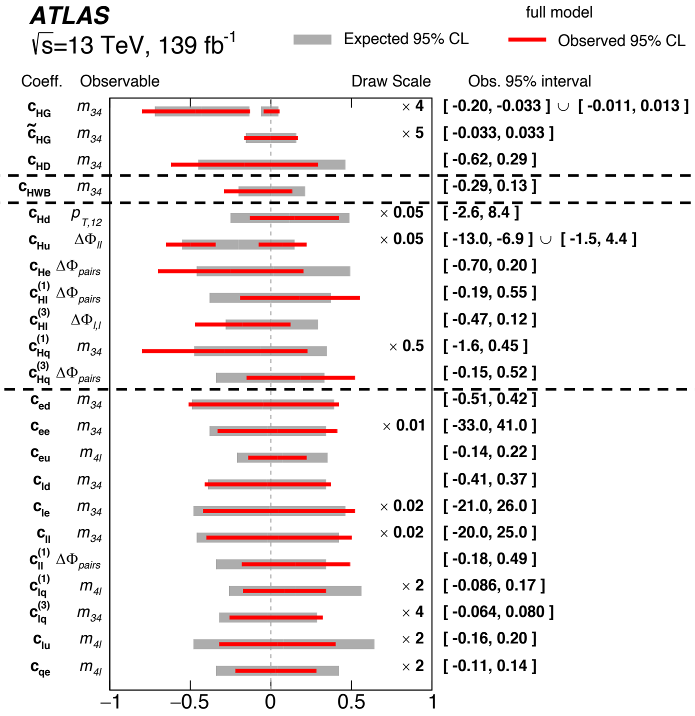
$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}}/\vec{\sigma}^{\text{LO SM}} + \cancel{c_i^2 \cdot \vec{\sigma}^{\text{BSM}}/\vec{\sigma}^{\text{LO SM}}}\right)$$

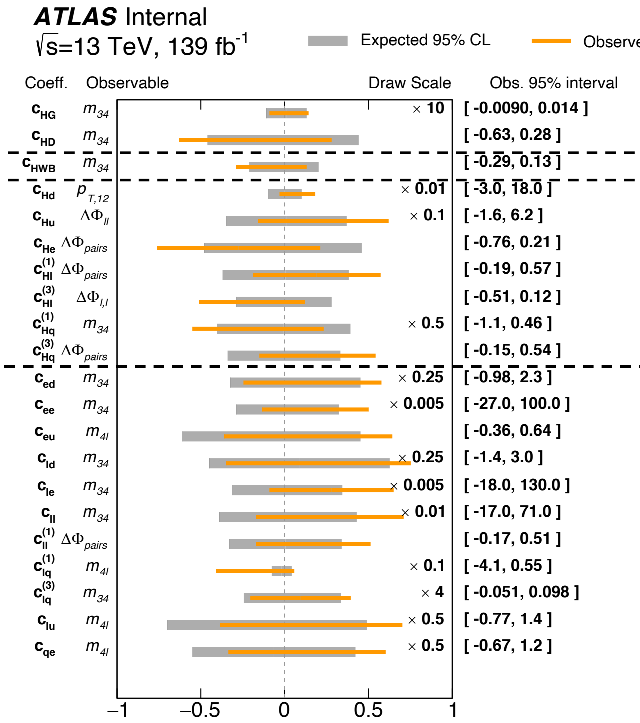
Higgs coupling

boson coupling

Zll vertex

4 fermion interaction





Further Reinterpretation?

arXiv:2105.08494v1 [hep-ph] 18 May 2021

New sensitivity of LHC measurements to Composite Dark Matter Models

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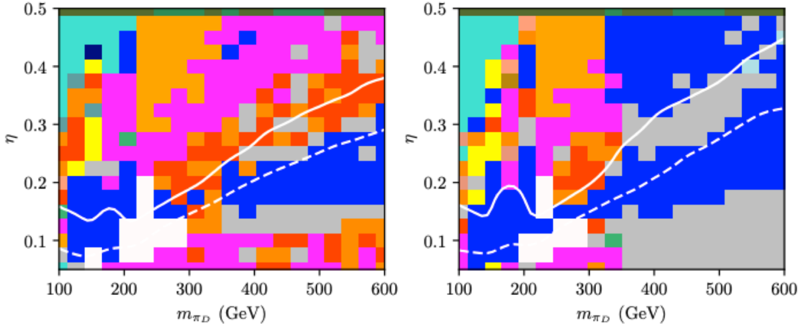
(Dated: May 19, 2021)

Abstract

We present sensitivity of LHC differential cross-section measurements to so-called "stealth dark matter" scenarios occurring in an SU(N_D) dark gauge group, where constituents are charged under the Standard Model and N_D =2 or 4. The low-energy theory contains mesons which can be produced at the LHC, and a scalar baryon dark matter (DM) candidate which cannot. We evaluate the impact of LHC measurements on the dark meson masses. Using existing lattice results, we then connect the LHC explorations to DM phenomenology, in particular considering direct-detection experiments. We show that current LHC measurements constrain DM masses in the region of 10 TeV. We discuss potential pathways to explore these models further at the LHC.



(a) (b)

FIG. 5: Scans in $\eta - m_{\pi_D}$ for two sub-models, focussing on the $\eta < 0.5$ region and excluding the ATLAS dilepton search. (a) Gaugephilic SU(2)$_L$, (b) Gaugephobic SU(2)$_L$. The colours indicate the dominant signature pool giving the sensitivity. The white solid line is the 95% exclusion and the white dashed line is the 68% exclusion.

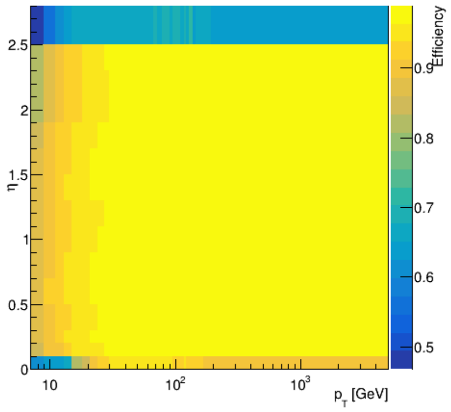
- CMS ee+jet
- CMS $\mu\mu$+jet
- ATLAS ee+jet
- ATLAS $\ell\ell$+jet
- ATLAS $\mu\mu$+jet
- ATLAS $\ell+E_T^{\rm miss}$+jet
- ATLAS $\mu+E_T^{\rm miss}$+jet
- ATLAS $e+E_T^{\rm miss}$+jet
- CMS $\ell+E_T^{\rm miss}$+jet
- ATLAS Hadronic $t\bar{t}$
- ATLAS $\ell_1\ell_2+E_T^{\rm miss}$+jet
- ATLAS high-mass Drell-Yan $\ell\ell$
- CMS high-mass Drell-Yan $\ell\ell$
- ATLAS 4ℓ
- ATLAS γ
- ATLAS $\ell\ell\gamma$
- ATLAS $\gamma+E_T^{\rm miss}$
- ATLAS jets

Pre-unfolding correction

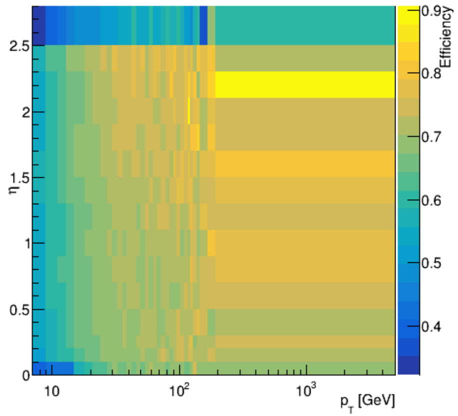
- Lepton pre-unfolding correction applied before common Iterative Baysian Unfolding
- Reduce dependency of SM lepton kinematics, by applying per event efficiency corrections on both data and MC

$$w = \frac{1}{\prod_{i=1}^{4} \epsilon_i[p_T^i, \eta^i]}$$

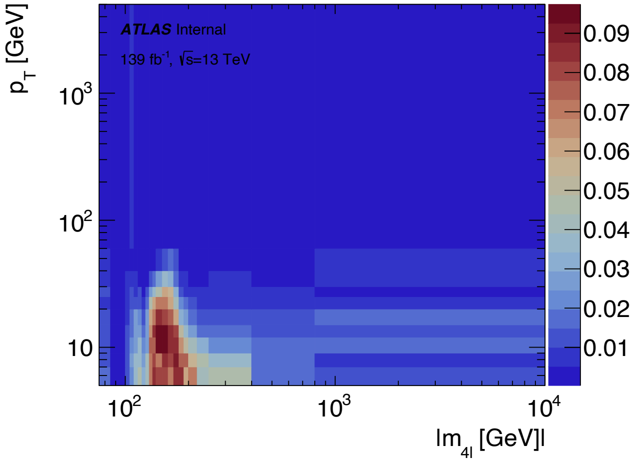
Efficiency of muons



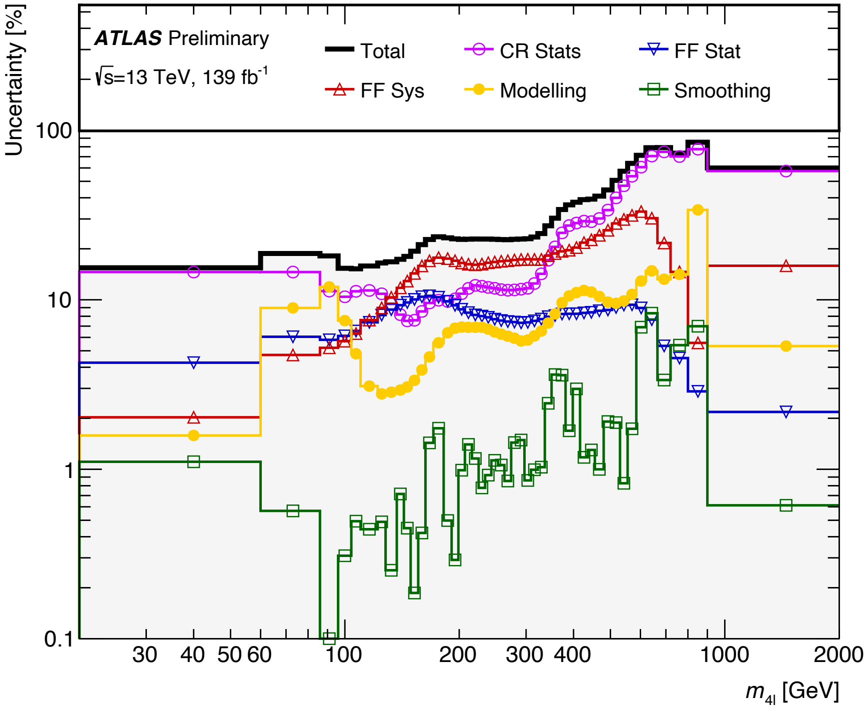
Efficiency of muons from taus



Tau fraction map

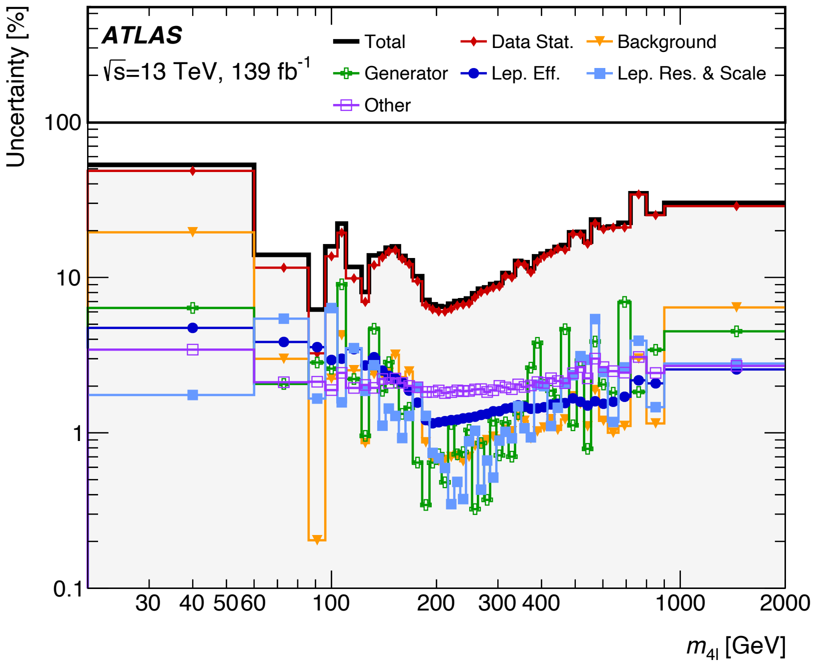


Inclusive 4l: Fake Lepton Systematics



Inclusive 4l: Systematics

- Uncertainty dominated by data statistics (estimated with bootstrap method)
- Lepton efficiency, resolution, scale from data-driven measurements, propagated as scale factors
- Comparison of qq->ZZ generator prediction by Sherpa and Powheg+Py8
- Theoretical syst. of processes treated as uncorrelated, qqZZ uncorrelated across m4l slices

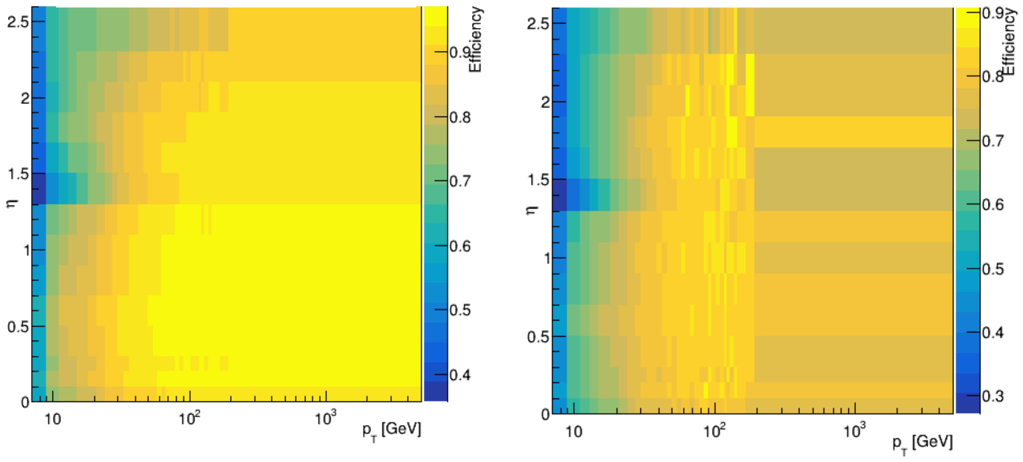


Electron pre-unfolding corrections

$$\mathrm{Eff}_{\mathrm{total}} = \frac{N_{\mathrm{sig}}}{N_{\mathrm{tru}}} \approx \mathrm{Eff}_{\mathrm{reco}} \times \mathrm{Eff}_{\mathrm{isoTTVA}} = \frac{N_{\mathrm{base}}}{N_{\mathrm{tru}}} \times \frac{N_{\mathrm{sig}}}{N_{\mathrm{base}}}$$

Efficiency of electrons

Efficiency of electrons from taus



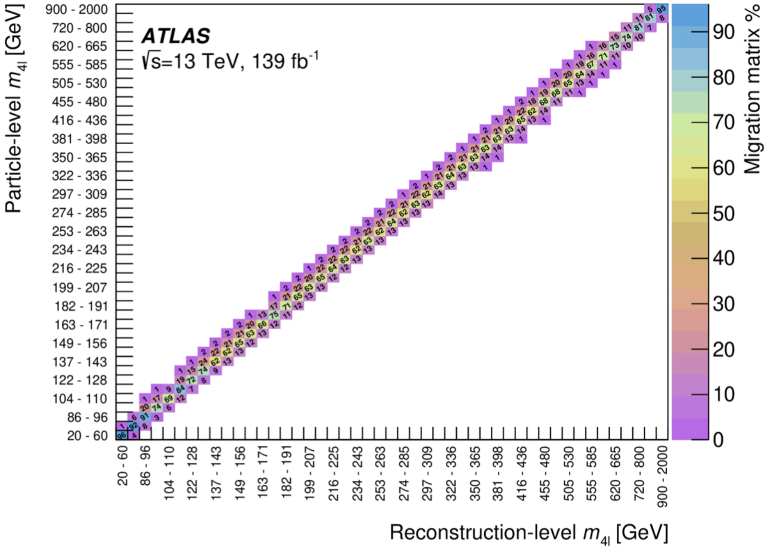
Unfolding correction

$$U_i^l = \sum_j^{reco\ bins} \left((R_j - F_j) \cdot f_j \cdot \frac{1}{\epsilon_j^{pre-unf}} \right) \cdot \frac{\boxed{M_{ji}} U_i^{l-1}}{\sum_k^{tru\ bins} \boxed{M_{jk}} U_k^{l-1}} \cdot \frac{1}{\epsilon_i}$$

Term Description

M= Unfolding matrix
T= Predicted particle level yield
P= Predicted reconstructed yield

- Binning optimized for number of reconstructed events in a bin and purity (amount of migration to neighbouring bins)



Inclusive 4l: HepData

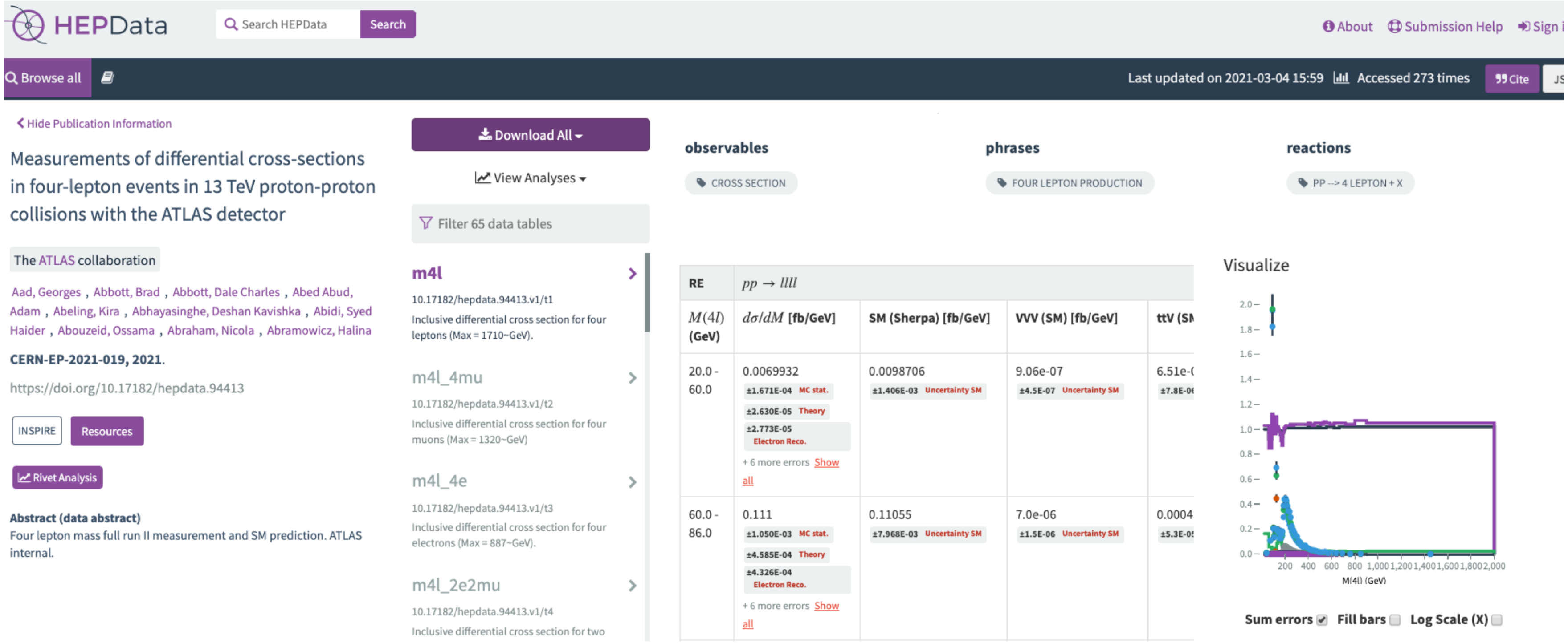


Table 16: Definition of the baseline lepton selection.

Category	Requirement	
Kinematics	Muons :	$p_{\mathrm{T}} > 5$ GeV If CaloTag: >15 GeV $\lvert\eta\rvert < 2.7$
	Electrons:	$p_{\mathrm{T}} > 7$ GeV $\lvert\eta\rvert < 2.47$
Vertex association	Both :	$\lvert z_0 \sin\theta\rvert$ <0.5 mm
Identification:	Muons:	Loose ID
	Electrons:	LooseLH ID
Overlap removal: Lepton-favoured		

Loosened selection
(For additional leptons
and fake estimation)

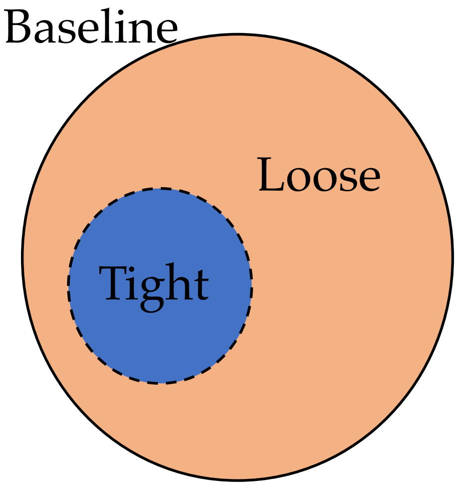
$$N = N^{\mathrm{l}} + N^{\mathrm{t}}$$

Table 19: Definition of the signal lepton selection.

Input objects	Baseline electrons and muons that are part of the quadruplet
Isolation	FixedCutPflowLoose working point *Contribution from all other baseline leptons is subtracted*
Cosmic muon veto	Muons: $\lvert d_0\rvert$ <1 mm
Impact Parameter	Muons: d_0/σ_{d_0} <3 Electrons: d_0/σ_{d_0} <5
Stricter Electron ID	Electrons: LooseBLayerLH ID

Selection for leptons
In the quadruplet

Lepton Selection



Fake Lepton Background

- Simple example: measuring events with 1 lepton

Number of
events with real lepton

Number of
events with fake lepton

Number of measured
events with tight/signal
lepton

$$N^{\mathrm{t}} = rN_{\mathrm{r}} + \boxed{fN_{\mathrm{f}}}$$

Probability of real lepton
To be reconstructed as tight/signal

Probability of fake lepton
To be reconstructed as tight/signal

Fake Lepton Background

- Simple example: measuring events with 1 lepton

Number of events with real lepton

Number of events with fake lepton

Number of measured events with tight/signal lepton

$$N^{\mathrm{t}} = rN_{\mathrm{r}} + \boxed{fN_{\mathrm{f}}}$$

Probability of real lepton
To be reconstructed as tight/signal

Probability of fake lepton
To be reconstructed as tight/signal

- Same applies for our non-signal leptons

$$N^{\mathrm{l}} = (1 - r)N_{\mathrm{r}} + (1 - f)N_{\mathrm{f}}$$

Fake Factor

Detector

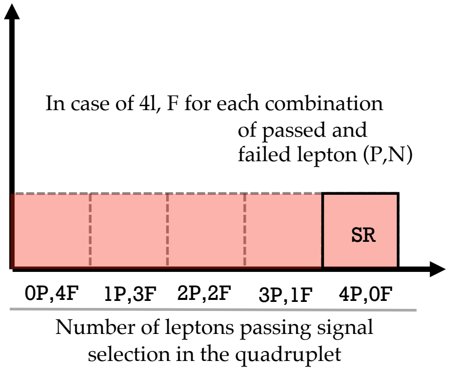
What we measure

$$\begin{pmatrix} N^{\mathrm{t}} \\ N^{\mathrm{l}} \end{pmatrix} = \begin{pmatrix} r & f \\ 1-r & 1-f \end{pmatrix} \begin{pmatrix} N_{\mathrm{r}} \\ N_{\mathrm{f}} \end{pmatrix}$$

Nature

$$N_{\mathrm{f}}^{\mathrm{t}} = \frac{f}{1-f}(N^{\mathrm{l}} - N_{\mathrm{r}}^{\mathrm{l}}) = F(N^{\mathrm{l}} - N_{\mathrm{r}}^{\mathrm{l}}),$$

$$\boxed{N_{\mathrm{f}}^{\mathrm{t}} = F \cdot N_{\mathrm{f}}^{\mathrm{l}}}$$



Conversion factor between SR and background enriched region

Fake Efficiencies

- Measured in Z(ll) + jets + **leptons** region

Creating pure fake region

Probability that baseline fake leptons will pass signal lepton selection

$$f(p_T, njet) = \frac{N^t_{data}(p_T, njet) - N^t_{real\ MC}(p_T, njet)}{N_{data}(p_T, njet) - N_{real\ MC}(p_T, njet)}$$