LFU & LFV tests at ATLAS

NuFact 2022, Snowbird, Utah

Noam Tal Hod
On behalf of the ATLAS Collaboration

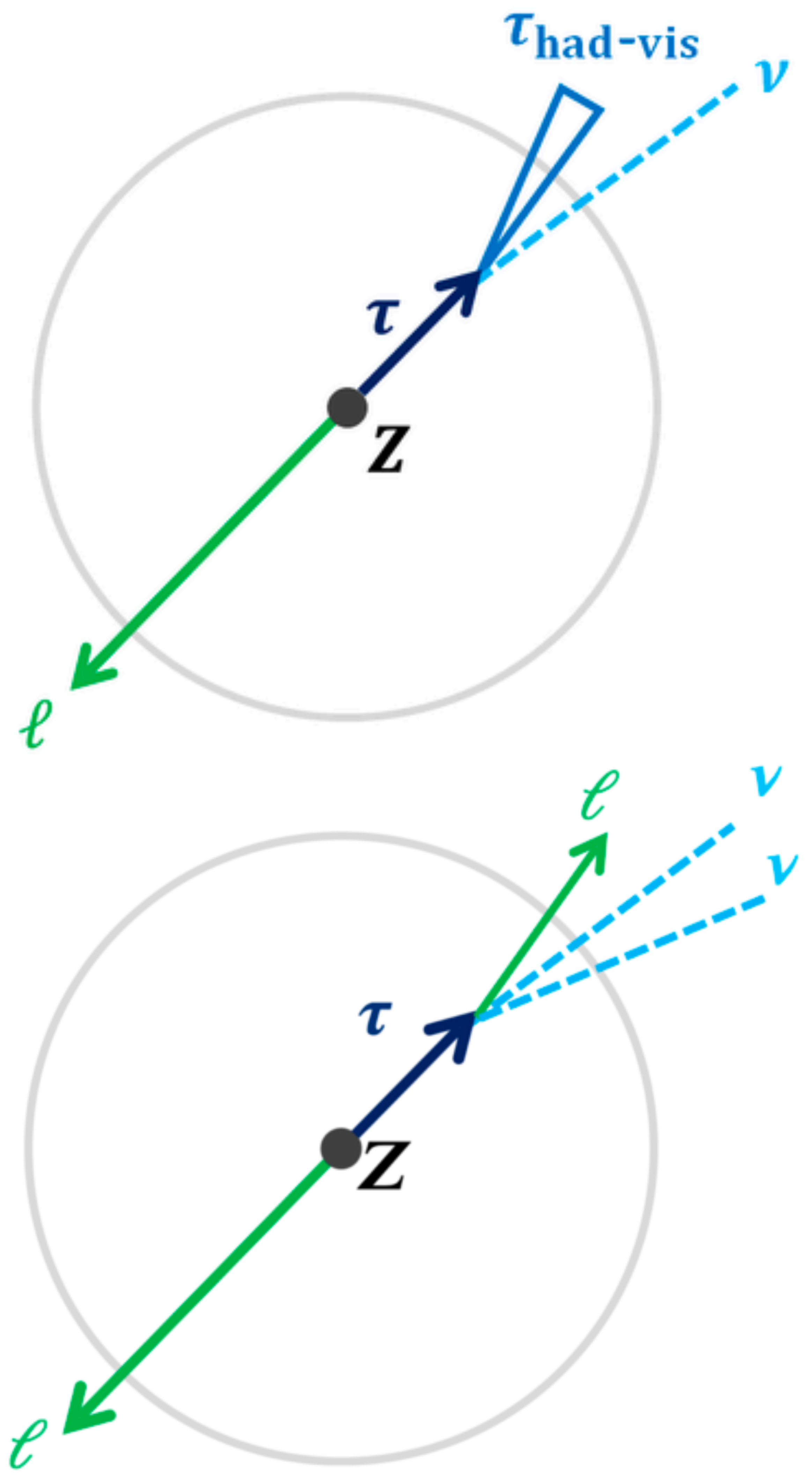
Aug 4 2022

LFV motivations

- Lepton-flavor violation (LFV) is observed in the neutrino sector
  - rate of charged-lepton-flavor (CLF) transitions mediated by neutrino-flavor oscillations is vanishingly small

- Despite the lack of protection from a fundamental symmetry, no CLF-violating (CLFV) decays have been observed so far

- Models with CLFV include SUSY, Composite LQs, Unparticles,…



e.g. LFV in $Z \to \ell\tau$ with τ_{had} and τ_{lep}

arXiv:2010.02566 and arXiv:2105.12491

Anomalies #1

- B-decays: several measurements deviate from SM predictions by $2 - 4\sigma$

- Recent works also consider the $g - 2$ and m_W results in the same fits

- Anomalies in $b \to s\ell\ell$ transitions:
  - angular observables in $B^{(0,+)} \to K^{*(0,+)}\mu\mu$ decays
  - branching ratios of $B \to K/K^*\mu\mu$ and $B_s \to \phi\mu\mu$
  - measurements of LFU ratios $R(K)$ and $R(K^*)$
  - combined measurements of $B_{s,d} \to \mu\mu$

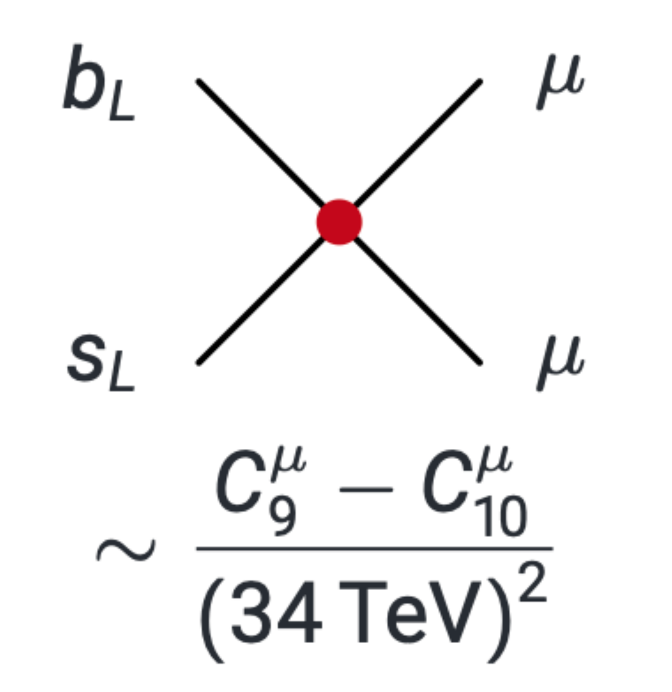
- Anomalies in $b \to c\ell\nu$ transitions:
  - measurements of LFU ratios $R(D)$ and $R(D^*)$

A surely non-exhaustive list:
- 1908.01848, 1705.05802, 2103.11769, 1904.02440
- 2108.09283, 1812.03017, CMS-PAS-BPH-16-004
- 1403.8044, 1606.04731, 2105.14007
- 2012.13241, CMS-PAS-BPH-15-008, 2108.09283

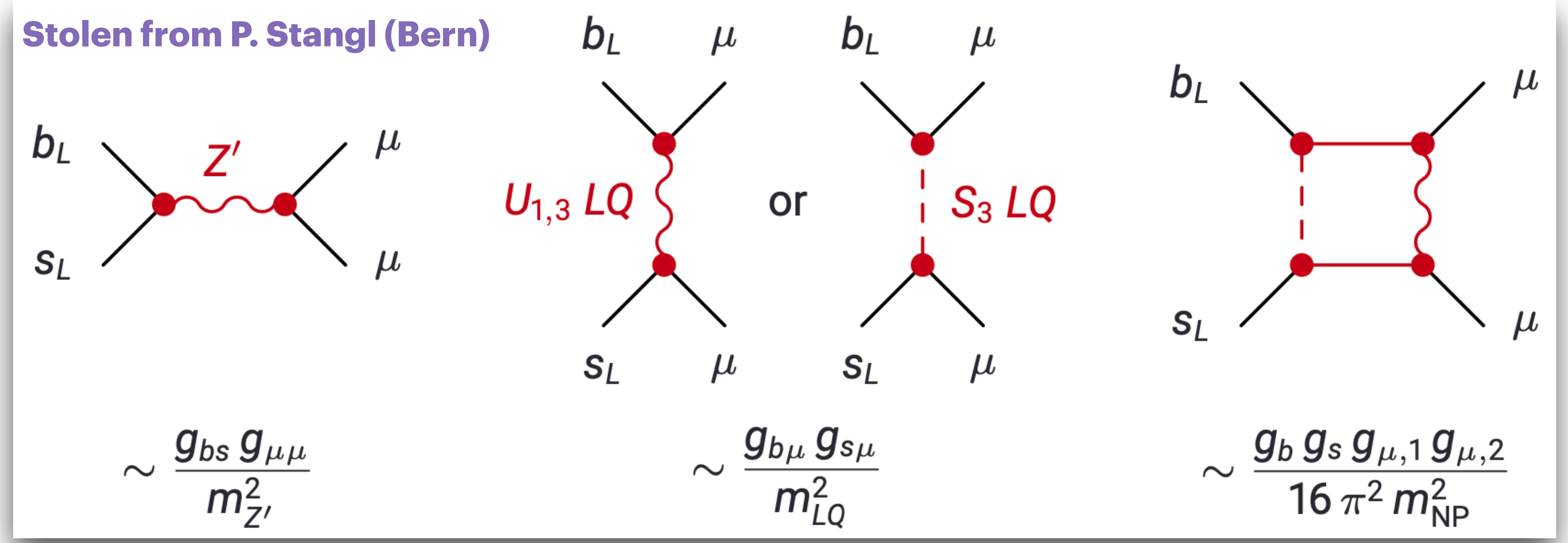
Anomalies #2

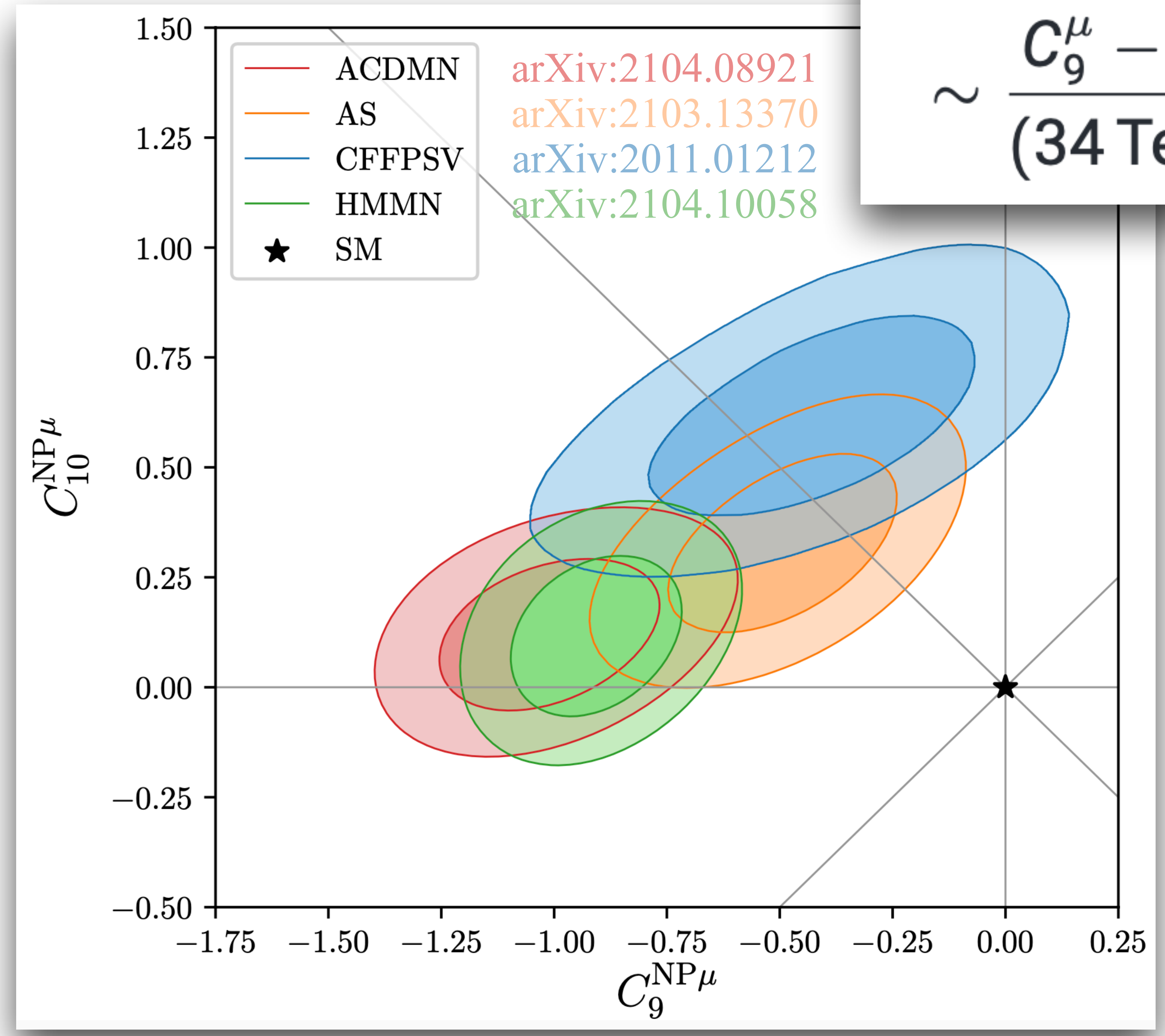
- Usually addressed in a weak EFT with semi-leptonic and hadronic operators and respective Wilson coefficients, $C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}$, which parametrize heavy new physics (NP)
  - focus is on C_9 and C_{10} with operators $O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$ and $O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

- Global fits to the anomalies data are done by several groups and the results are robust
  - suggest that $C_9^\mu - C_{10}^\mu \approx -0.7$ and $0 \gtrsim C_{10}^\mu / C_9^\mu \gtrsim -1$, i.e. far from the SM…



- Typical new physics explanations include Z' models, LQs, etc.





- For recent reviews, see arXiv:2103.13370, arXiv:2204.03686

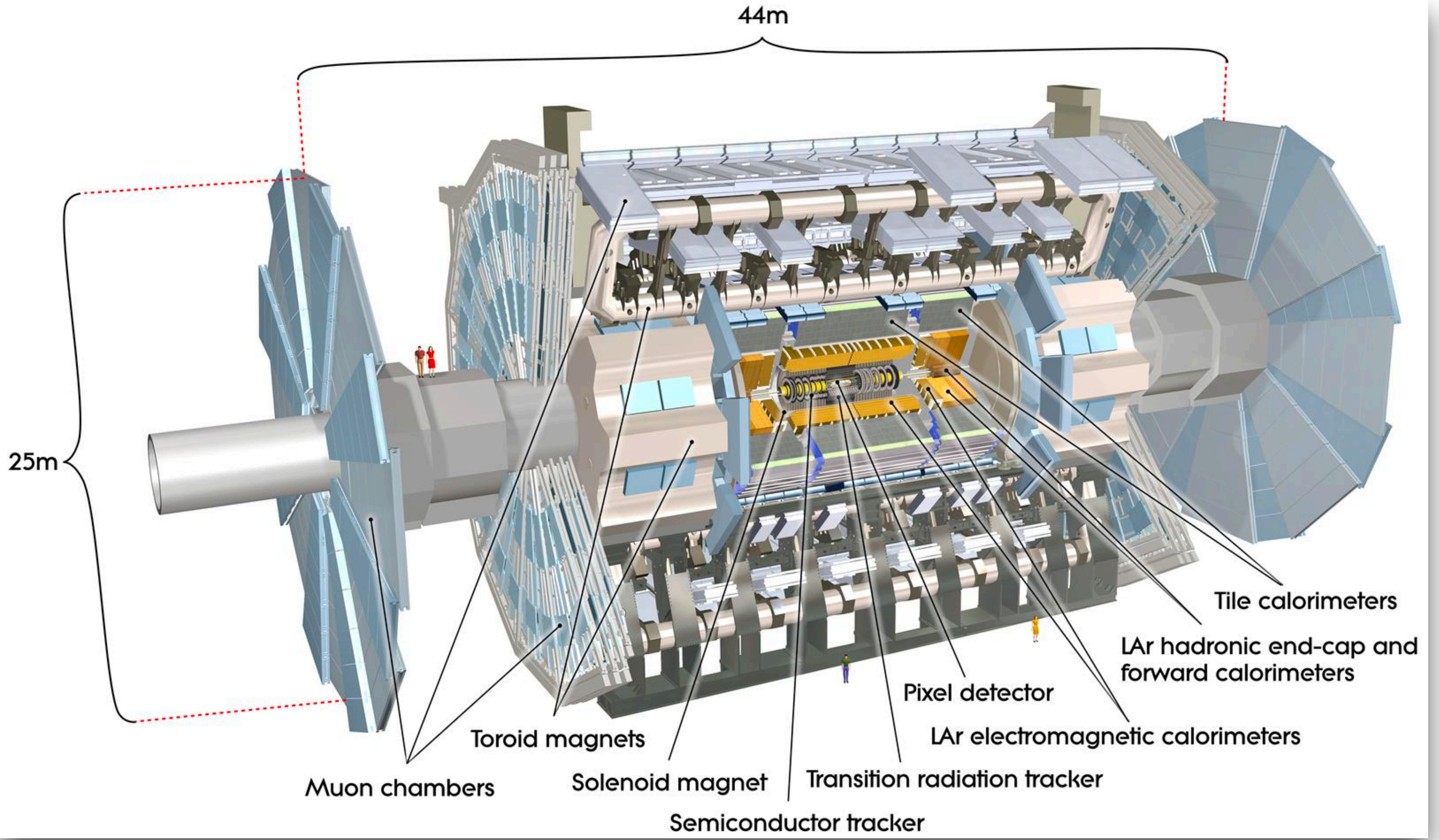
"New" LFU & LFV tests in ATLAS

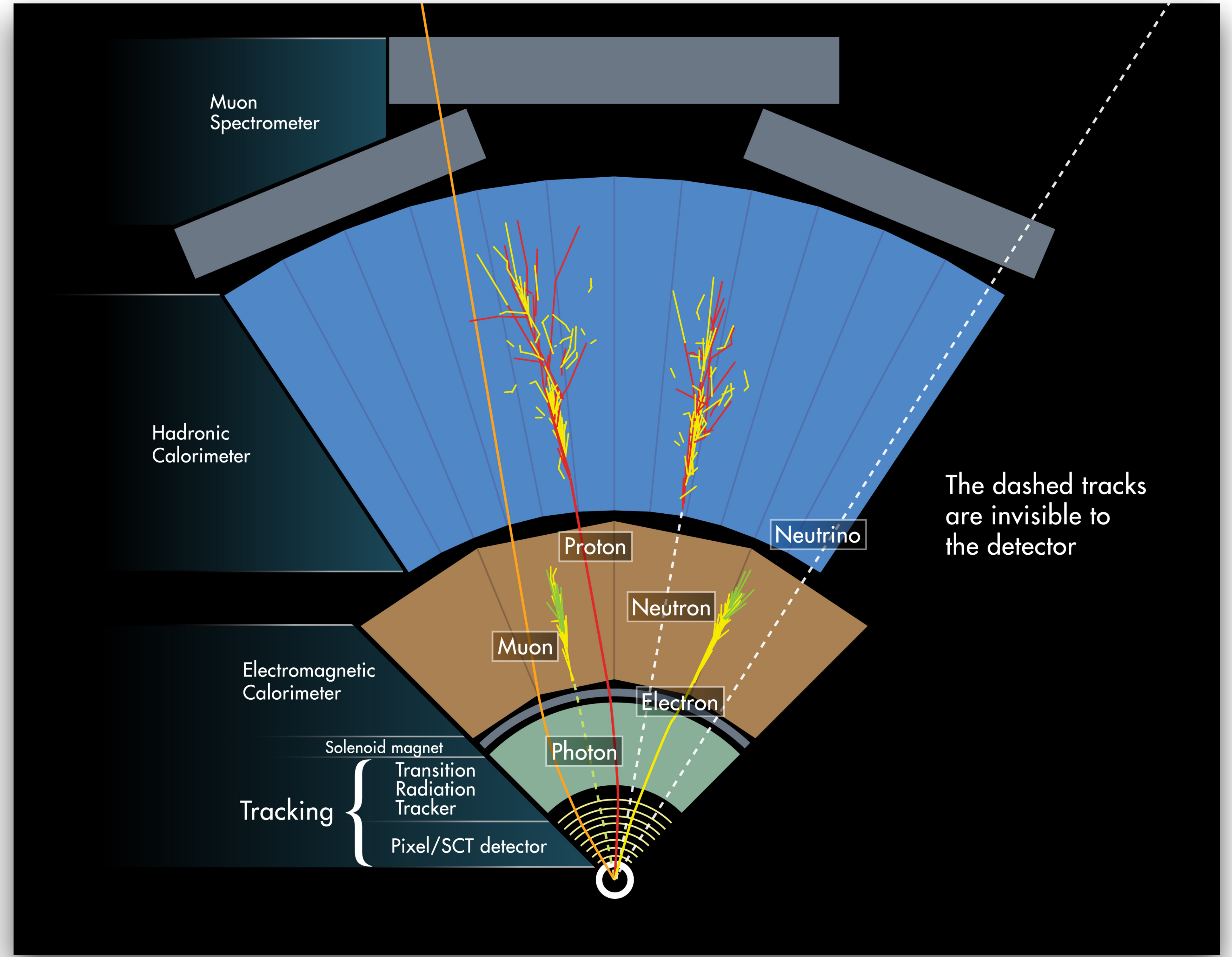
B-physics	SM/Top	Exotics/SUSY/Higgs
Trigger for $R(K^*)$	LFU in $t\bar{t}$ decays	LFV in Z/H decays
		LFV in Z' decays

Today: focus on recent direct probes of LFV/LFU with full Run 2 data

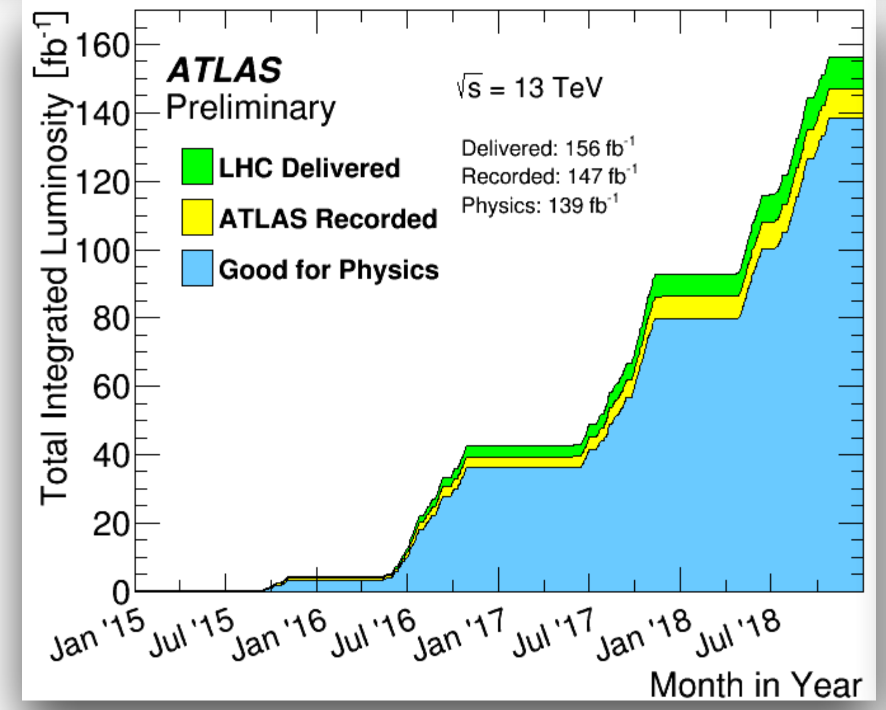
Not today:
- LFV in CI
- Leptoquarks
- Vector-Like Leptons

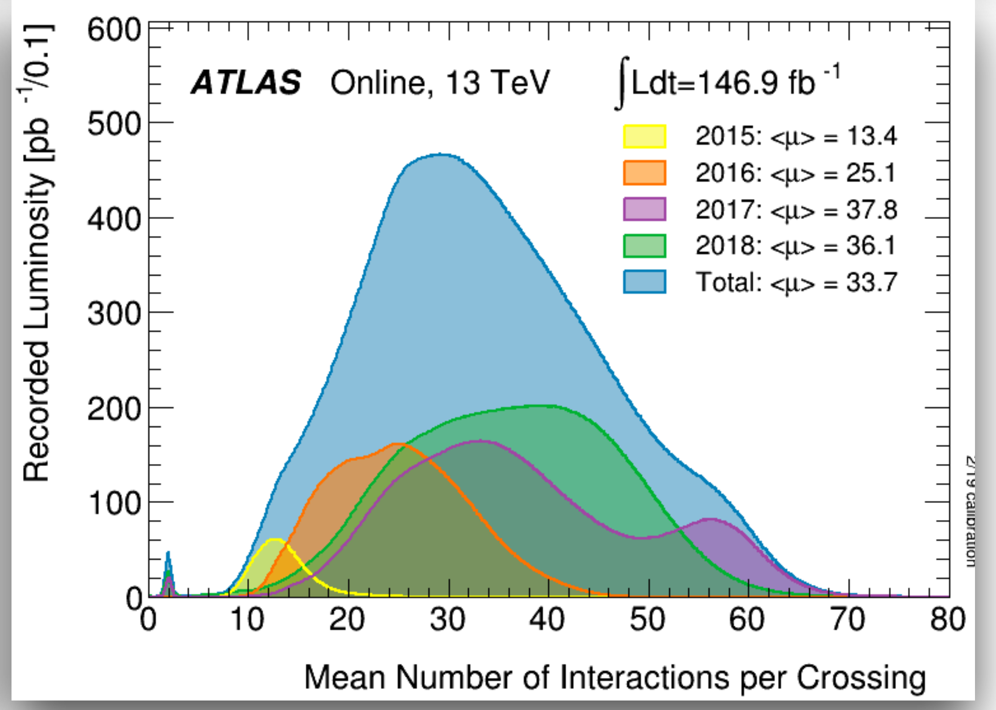
…The ATLAS detector





- Muons: measured by the MS, MS+ID (and sometimes the EMcal)
- Electrons: measured by the EMcal and ID
- Neutrinos: invisible to us! (needless to say, but this is NuFact…)
- Low-p_T leptons are very challenging (trigger, identification, etc.)





$Z \to e\mu$ search [arXiv:2204.10783, Apr 2022]

- Indirect: $\mu \to 3e$ (SINDRUM) and $\mu \to e\gamma$ (MEG): $\mathscr{B}(Z \to e\mu) < 5 \times 10^{-13}$ at 90% CL
- Direct: the ATLAS search at 8 TeV have yielded $\mathscr{B}(Z \to e\mu) < 7.5 \times 10^{-7}$ at 95% CL

- Backgrounds: $Z \to \tau\tau$, $Z \to \mu\mu$ with muon faking electron (resonant), $t\bar{t}$, WW and jj (non-resonant)

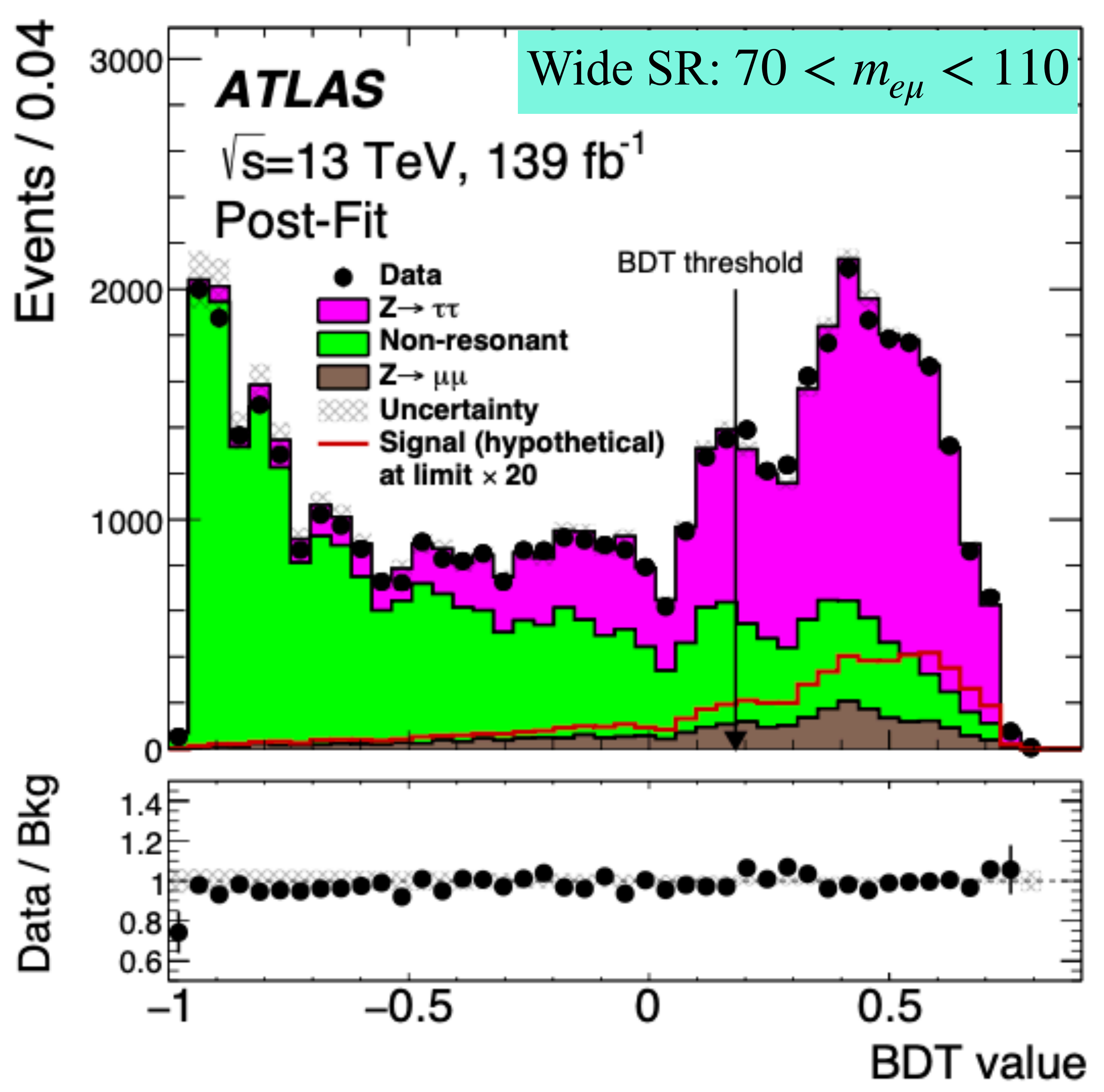
- Selection: two isolated energetic, oppositely charged $e\mu$ within $70 < m_{e\mu} < 110$ GeV with small jet activity and low E_T^{miss}
  - using a a b-jet veto and a BDT (w/leading jet p_T, E_T^{miss} and $p_T^{e\mu}$)
  - two control regions (ee and $\mu\mu$) and two SRs (wide/narrow)

- Likelihood: fit the signal $\mathscr{B}$ simultaneously with the 3 bkg yields

	Best-fit contribution in mass window	
Background	[70, 110] GeV	[85, 95] GeV
$Z \to \tau\tau$	13716 ± 185	951 ± 13
$Z \to \mu\mu$	1557 ± 209	533 ± 72
Non-resonant	4105 ± 259	1075 ± 68

$$\mathscr{B}(Z \to e\mu) = \frac{N_{Z\to e\mu}/(\mathscr{A}\times\epsilon)_{Z\to e\mu}}{N^{avg}_{Z\to X}}$$

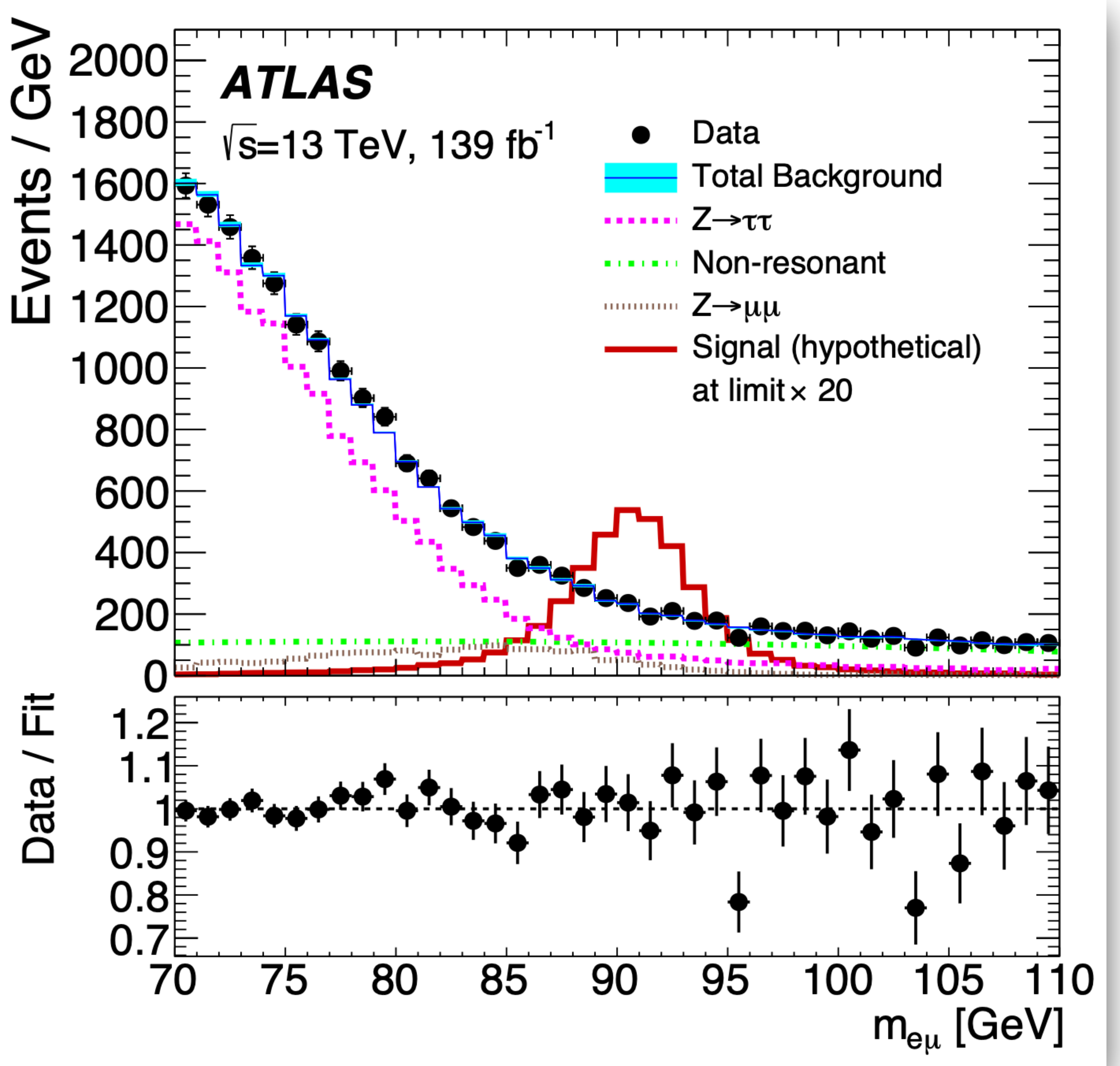
$N^{avg}_{Z\to X}$ is averaged from $Z \to ee/\mu\mu$ data with the same $e\mu$ selection, corrected for $\mathscr{A}\times\epsilon$ and $\mathscr{B}(Z \to \text{lep})$



$Z \to e\mu$ search [arXiv:2204.10783, Apr 2022]

- Signal MC at LO (difference to NLO $Z \to \mu\mu$ is checked)
- Non-resonant bkg is modeled with 2nd order polynomial
- Dominant systematics are due to the statistical uncertainty of the $Z \to \tau\tau/\mu\mu$ in MC
- No signal is found and the best fit is $\mathscr{B}(Z \to e\mu) = (0.3 \pm 1.1_{\text{stat}} + 0.6_{\text{syst}}) \times 10^{-7}$
- Limit: $\boldsymbol{\mathscr{B}(Z \to e\mu) < 2.62_{\text{obs}}\ (2.37_{\text{exp}}) \times 10^{-7}}$ at 95% CL
  - corresponds to approximately 200 $Z \to e\mu$ events
- This is a 3-fold improvement compared to the previous result and the most stringent direct result yet reported

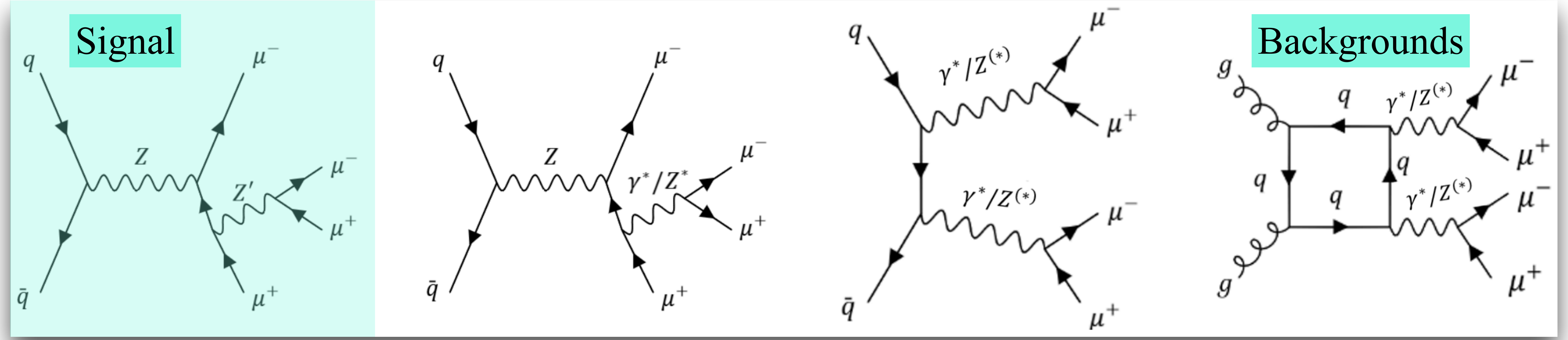
Quantity	Value
$A \times \varepsilon_{Z \to e\mu}$	$(10.3 \pm 0.3)\%$
N_Z^{avg}	$(7.87 \pm 0.19) \times 10^9$



$Z' \rightarrow 4\mu$ search [ATLAS-CONF-2022-041, Jul 2022]

- A new, **low-mass** $Z'\mu\mu \rightarrow 4\mu$ is predicted by $L_\mu - L_\tau$ models
  - couples **only** to 2nd and 3rd gen leptons (w/same $g_{Z'}$): **no** couplings to $ee/q\bar{q}$ so **no** strong precision constraints
  - addresses the observed anomalies in B-decays, $g-2$ puzzle and also questions related to DM and ν-masses
  - relevant four-muon mass range is $80 < m_{4\mu} < 180$ GeV (excluding $110 < m_{4\mu} < 130$)
  - The contribution of signal from the $Z' \rightarrow 4\tau/2\tau2\mu \rightarrow 4\mu$ is negligible

- Search done in the low dimuon mass range of $5 < m_{Z' \rightarrow 2\mu} < 75$ GeV
- Dominant prompt-muon backgrounds are $Z\mu\mu \rightarrow 4\mu$ and ZZ^*



- Standard muon selection besides:
  - Loose quality, with 4 leading muons having: $p_T > 20,15,8,3$ GeV
  - non-combined muon are also used (at most 1, must have p_T>15 GeV):
    - MS stand-alone tracks in the region $2.5 < |\eta| < 2.7$,
    - matching ID tracks w/calorimeter hit information within $|\eta| < 0.1$
    - using ID tracks associated w/at least 1 local track segment in the MS

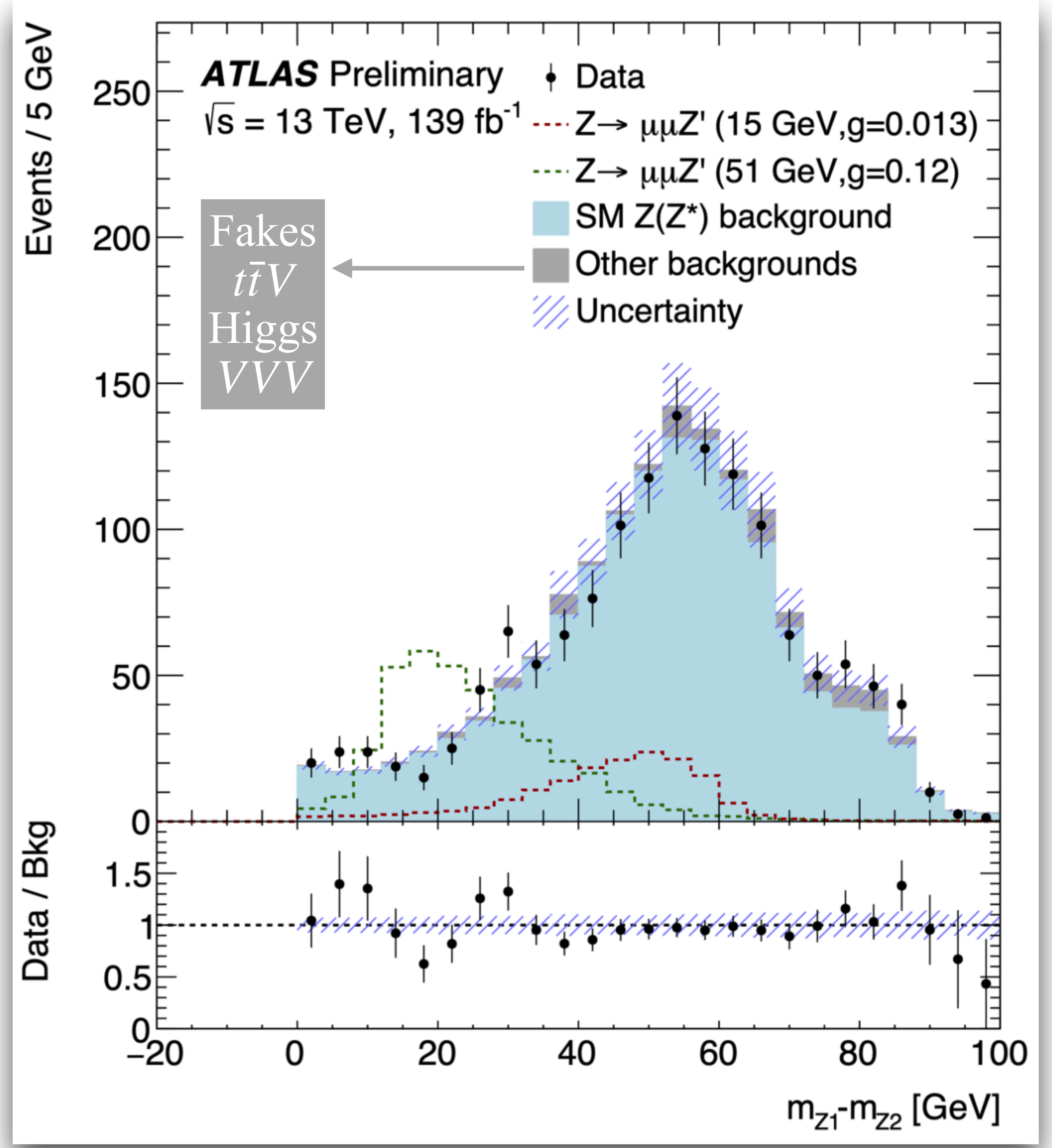
$m_{Z'}$ [GeV]	5	42	63	72
MC simulation filter efficiency	32.8%	57.7%	61.0%	64.7%
Number of identified muons ≥ 4	47.3%	74.1%	70.8%	72.4%
$p_T^i (i = 1,4) > 20,\ 15,\ 8,\ 3$ GeV	60.0%	82.6%,	90.3%	93.6%
$\Delta R(\mu_i, \mu_j) > 0.2$ & vertex requirement	87.2%	95.4%	96.2%	96.6%
Isolation	54.2%	76.9%	79.2%	84.1%
$m_{4\mu}$ within [80, 110] or [130, 180] GeV	91.9%	88.8%	58.9%	33.5%
Combined event selection efficiency	12.3%	39.9%	28.7%	18.4%
Overall 4μ signal efficiency	4.1%	23.0%	17.5%	11.9%

$Z' \to 4\mu$ search [ATLAS-CONF-2022-041, Jul 2022]

- $Z+$jets, $t\bar{t}$ and WZ bkgs are estimated with fake-factor method with two prompt and two **non-prompt** muons (failing the isolation and impact parameter cuts)

- Using a parametrized deep neutral network (pDNN):
  - train a single classifier for multiple signal mass hypotheses in the search range
  - pDNN input features: $p_T(\mu)$, $\eta(\mu)$, $p_T(Z_i)$, $m_{Z_1} - m_{Z_2}$, $\Delta R(\mu\mu\,|\,Z_i)$, $\Delta\eta(\mu\mu\,|\,Z_i)$ and $p_T(4\mu)$
  - the pDNN cut is optimized to max the sensitivity

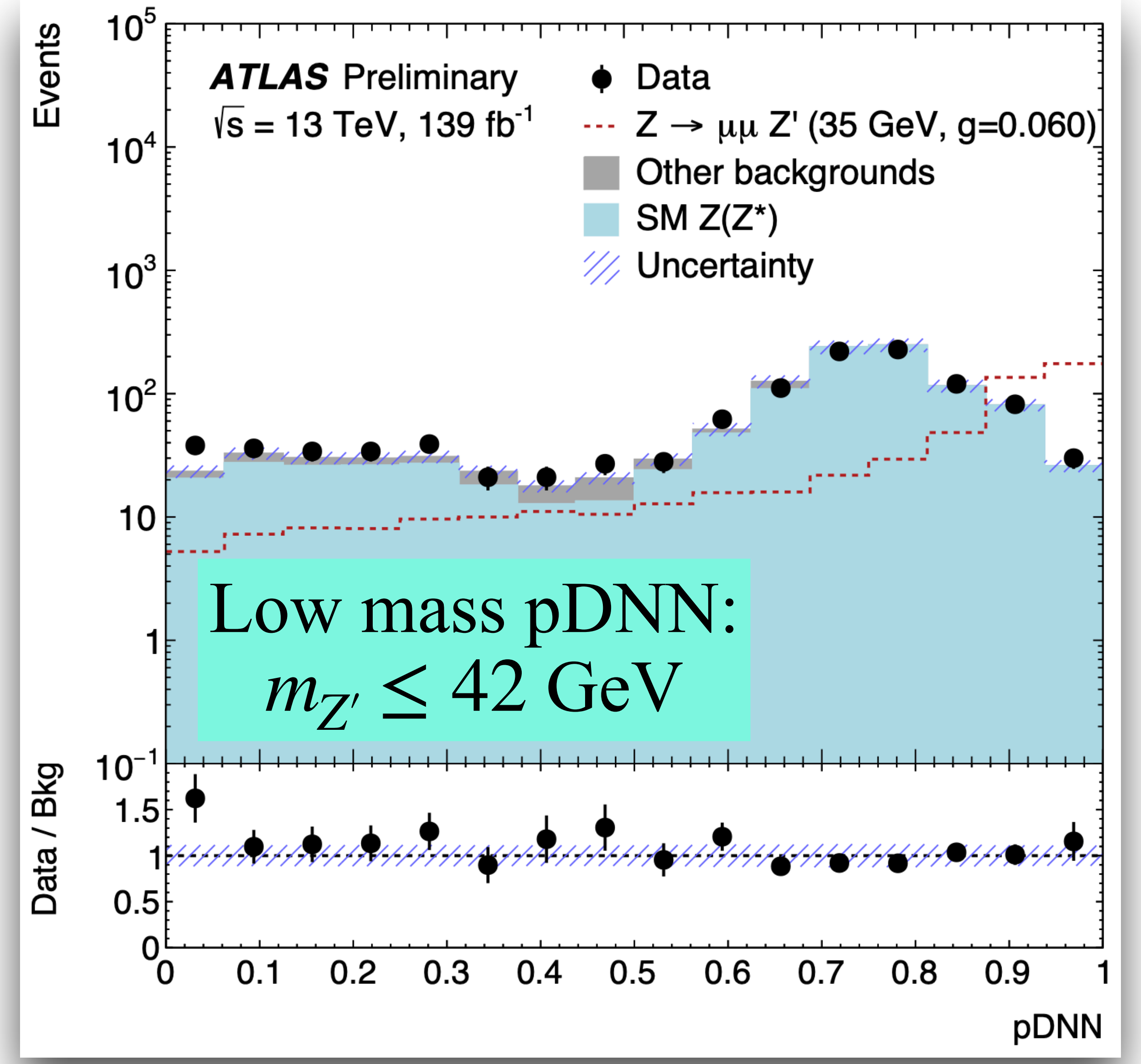
- The analysis is statistical dominant.
- Dominant systematic is due to the selection efficiency: this varies from 8.3% to 3.9%, depending on $m_{Z'}$

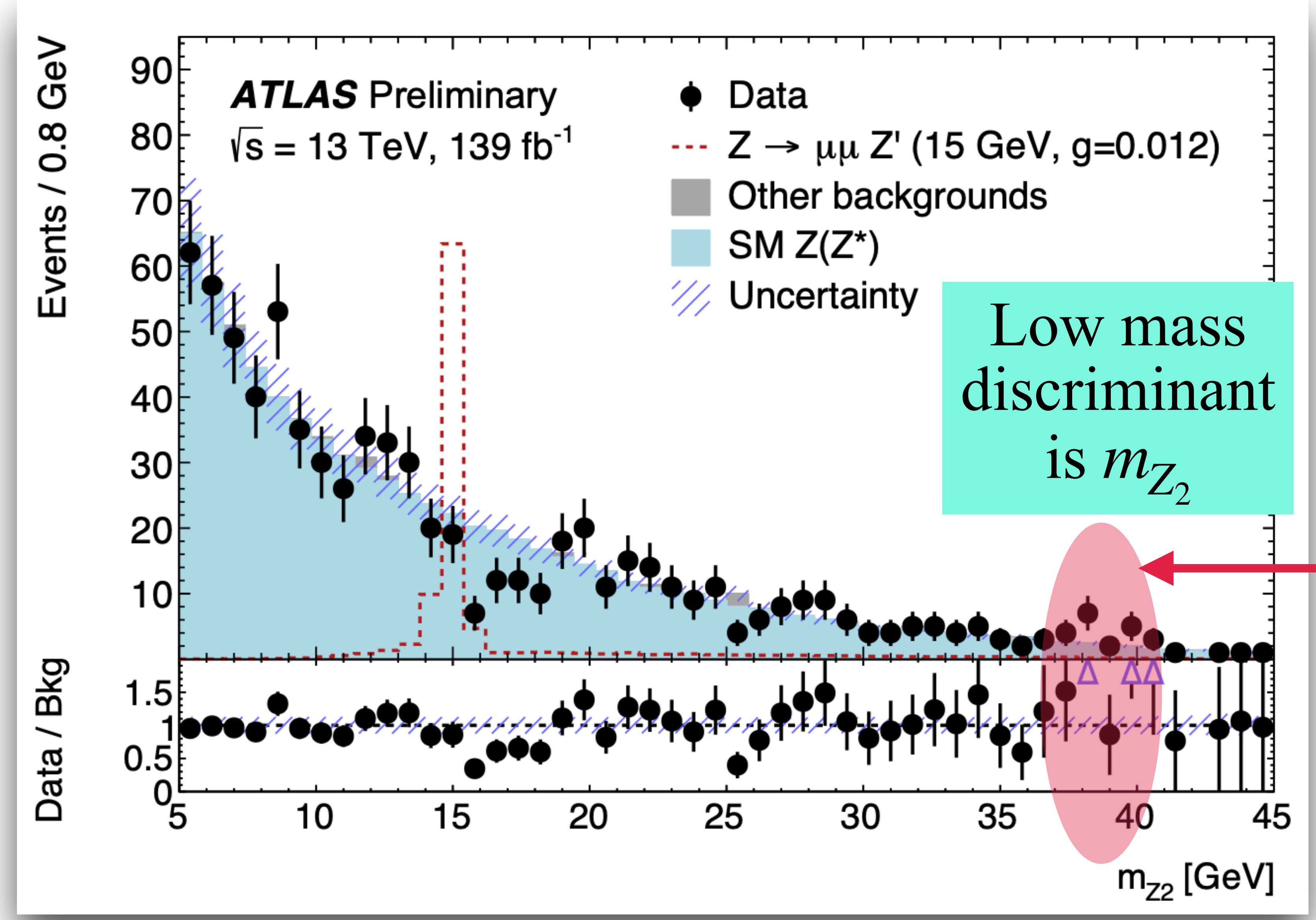


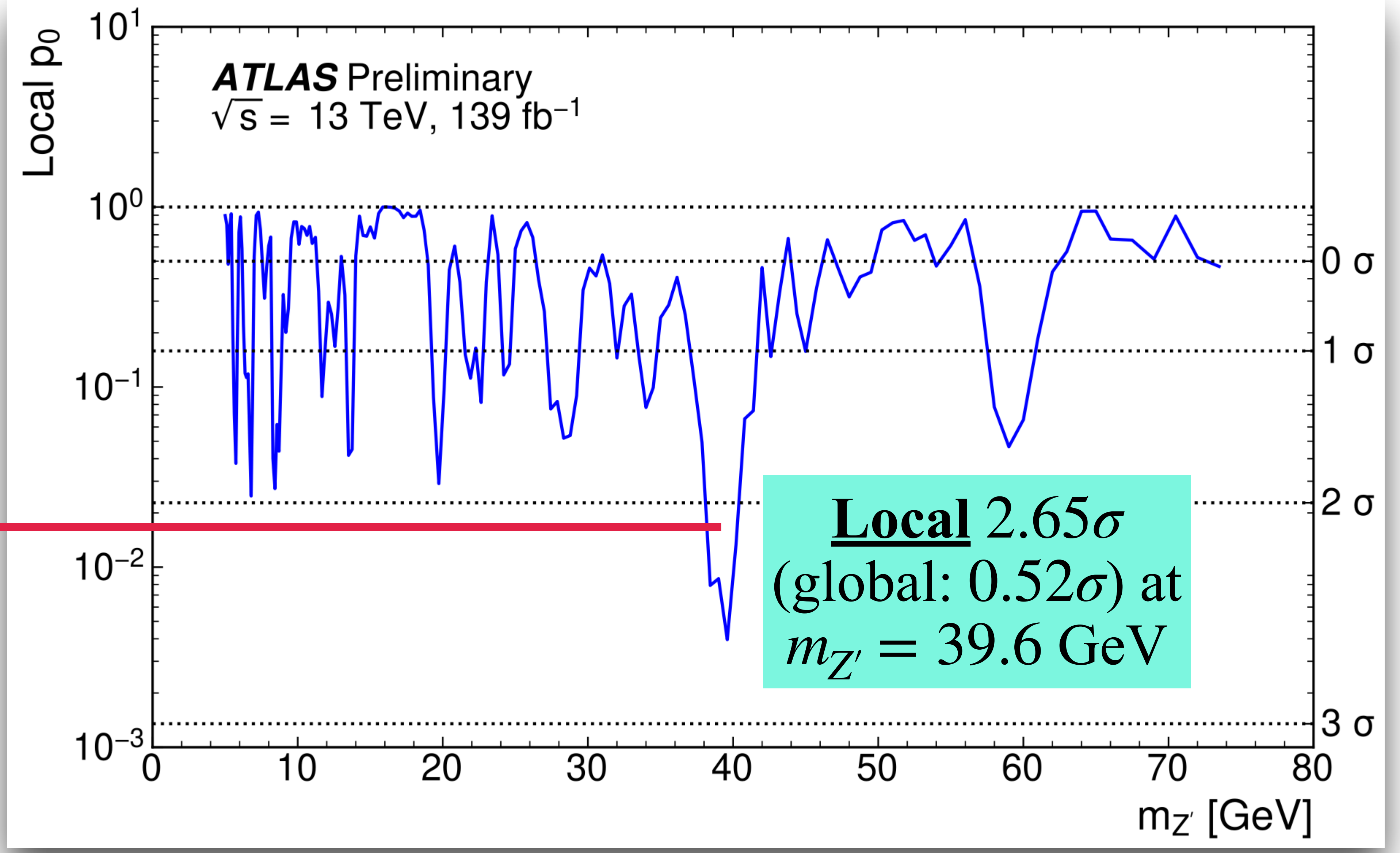
First pair (Z_1) : $\min(|m_{\mu_1\mu_2} - m_Z|)$

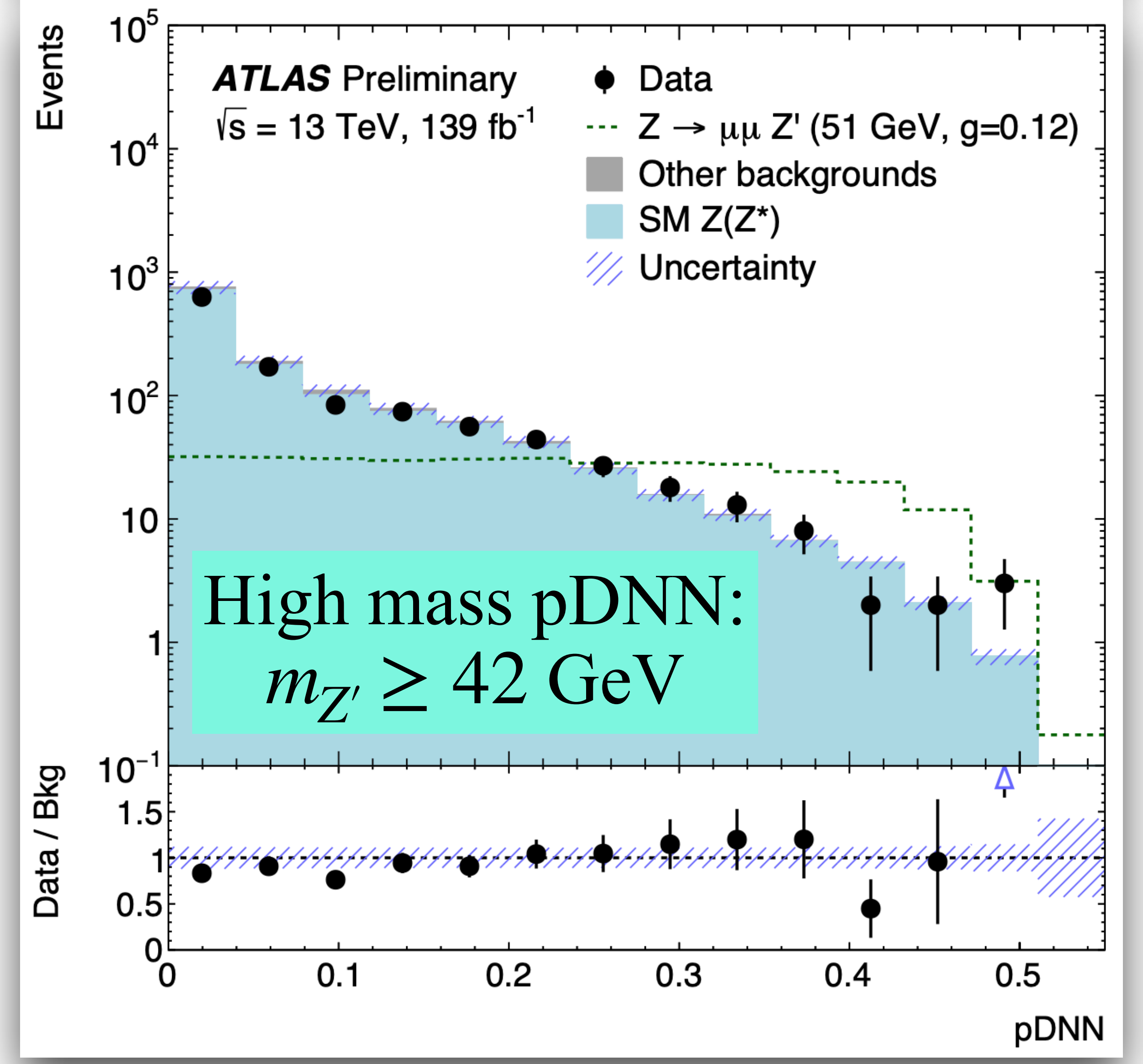
Second pair (Z_2) : $\max(m_{\mu_3\mu_4})$

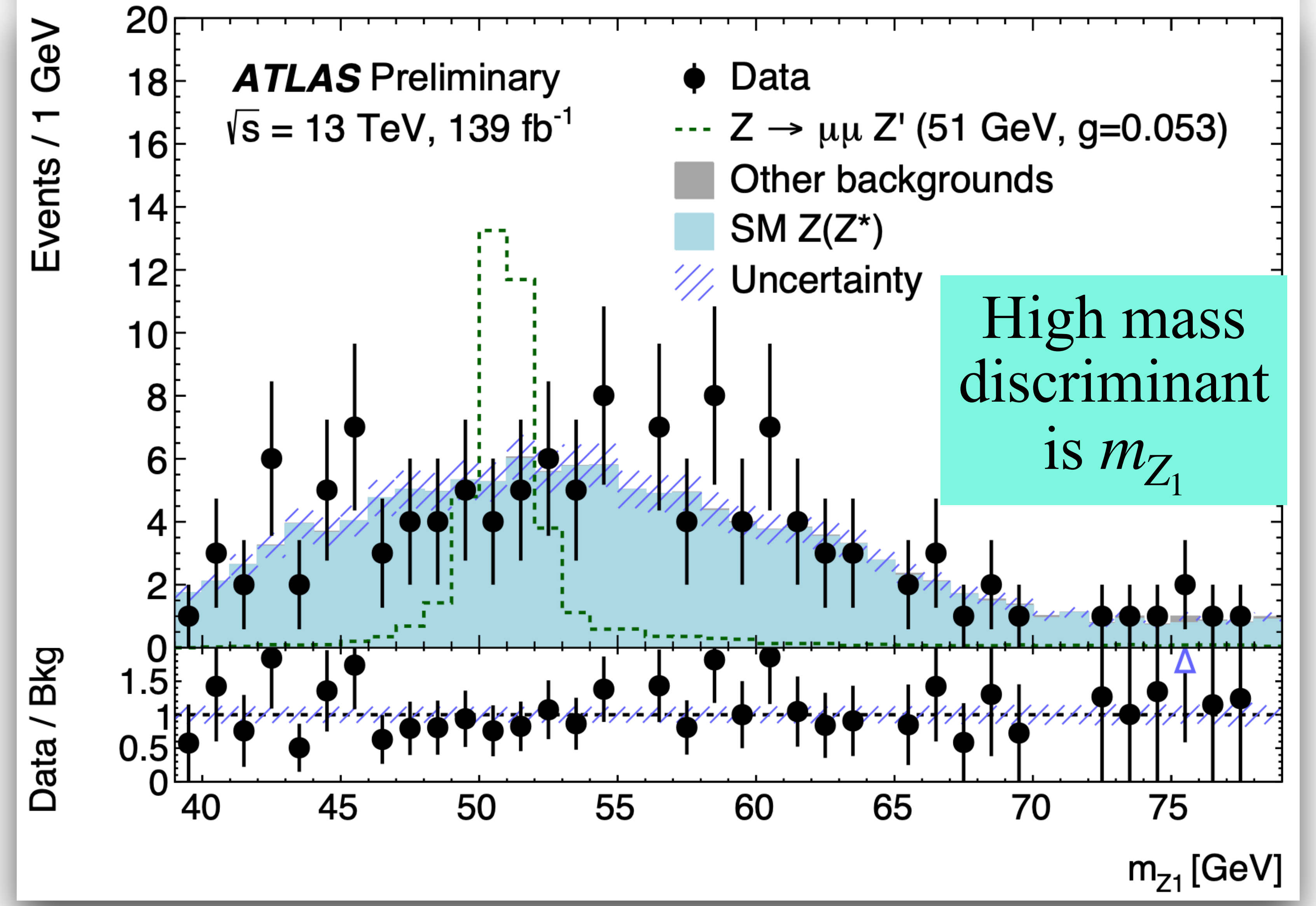
$Z' \rightarrow 4\mu$ search [ATLAS-CONF-2022-041, Jul 2022]







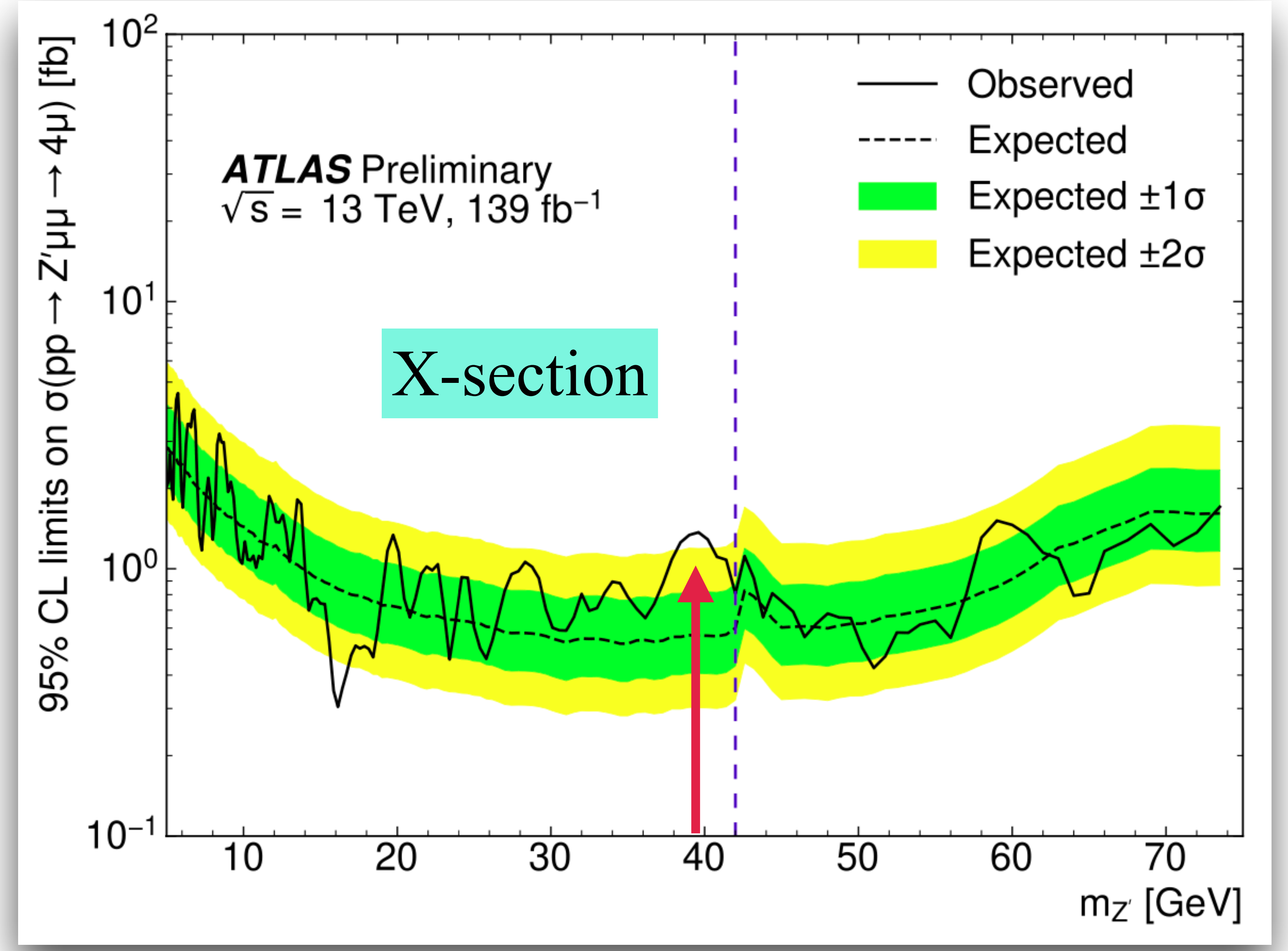


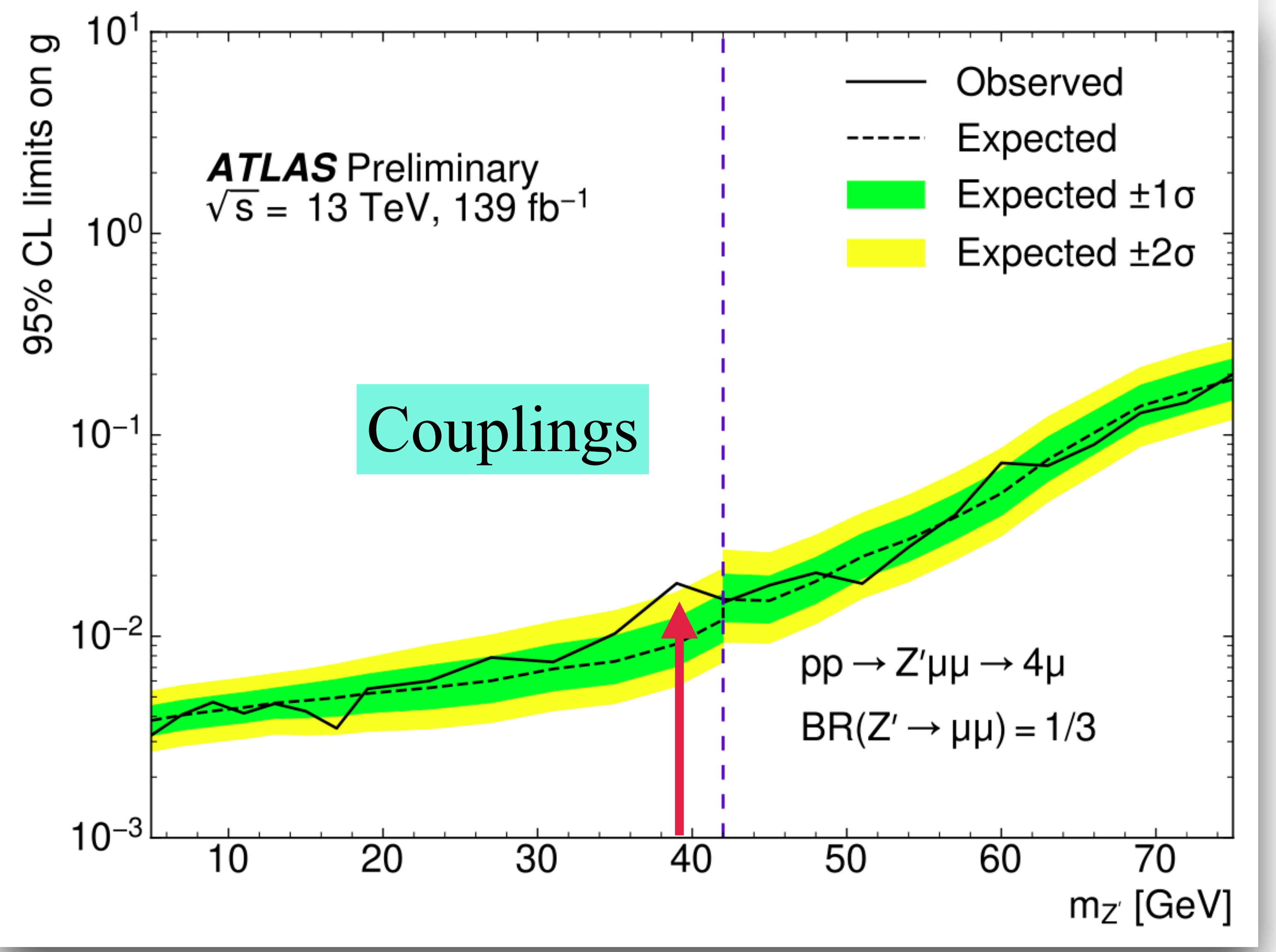


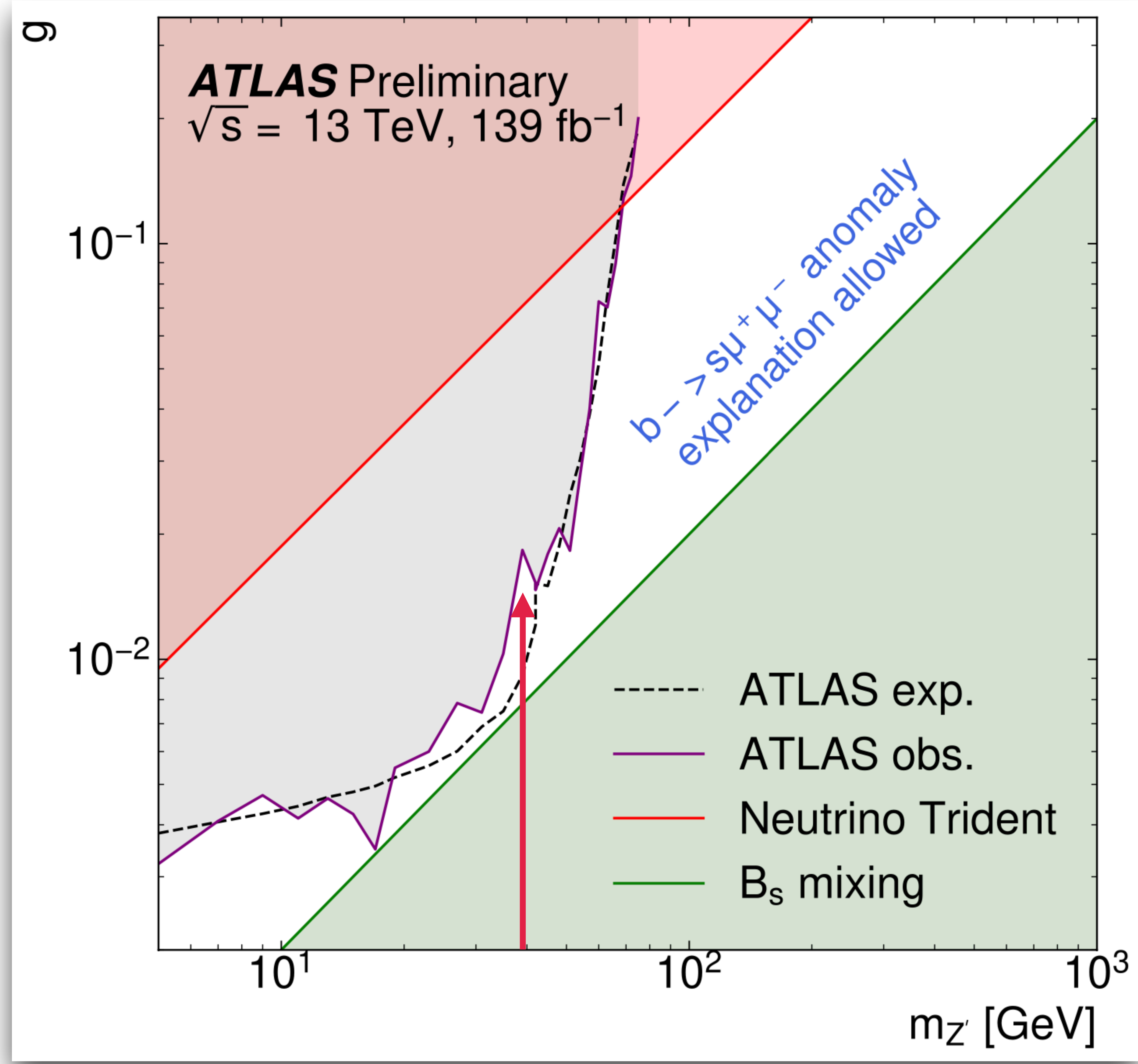
- The final discriminant is m_{Z_1} for $m_{Z'} > 42$ GeV, or m_{Z_2} for $m_{Z'} \leq 42$ GeV
- For each $m_{Z'}$ point the SR is:
  - mass window is sliding
  - $0.1 < \sigma(m_{\mu\mu}) < 2.1$ GeV
- The sidebands are defined as the CR: constrains the overall normalization for the bkg in the SR

$Z' \to 4\mu$ search [ATLAS-CONF-2022-041, Jul 2022]

- Limits on the coupling are in the range of 0.003 (for $m_{Z'} = 5$ GeV) to 0.2 (for $m_{Z'} = 75$ GeV)
- The gap left (for the $L_\mu - L_\tau$ model) in the $g - m_{Z'}$ space by the LHCb B_s mixing global fit and the Neutrino Trident experiment is now partially excluded

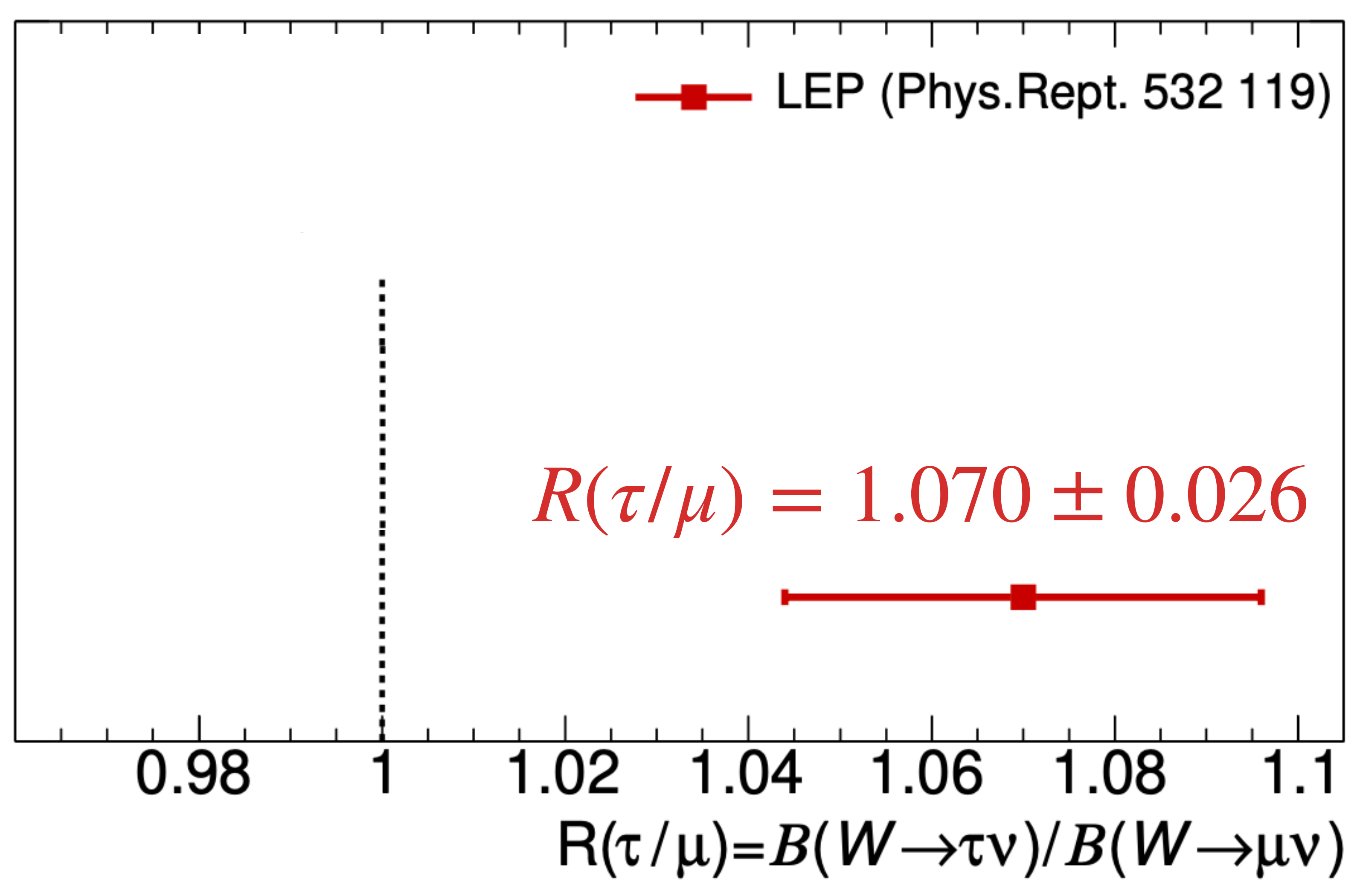


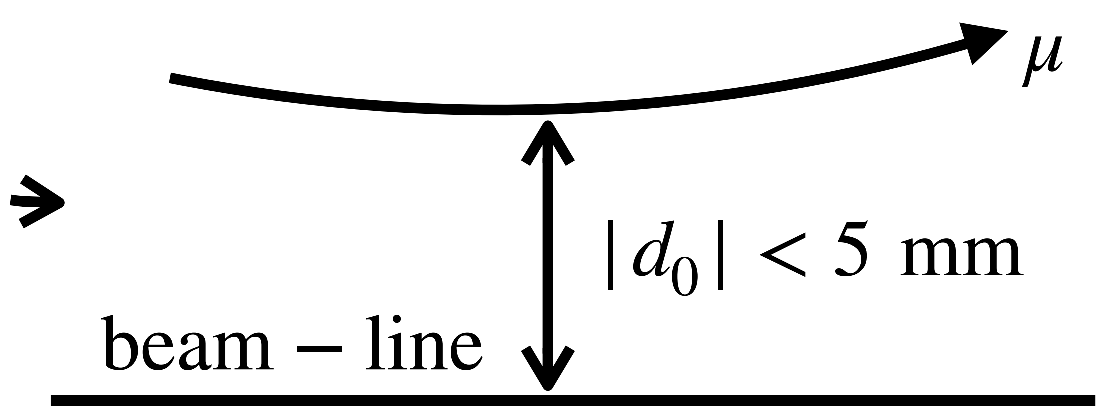




LFU test in $W\tau/\mu$ [Nat. Phys. 17 (2021) 813]

- $R(\tau/\mu) = \frac{\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu)}$ from $t\bar{t} \to \ell_1\ell_2$ events (with on-shell W's)
  - large, clean and unbiased sample (~0.5M events)
  - $R(\tau/\mu) = 1$ in the SM (neglecting phase-space effects)
  - $R(\mu/e)$ from LEP, LHCb, ATLAS is consistent with the SM within 1%
- **The τ-leptons are identified through their decay to muons only**
  - $\mathcal{B}(\tau \to \nu\mu\nu) = (17.39 \pm 0.04)\,\%$ from LEP
  - muons from taus have a relatively lower p_T and a displaced vertex
- SRs: opposite charge $e\mu$ (with electron trigger) or $\mu\mu$ (with muon trigger)
- The W of the trigger lepton is the "tag" object (in $\mu\mu$ it may be swapped)
  - the "probe" muons have no trigger bias
- Reject events with >2 leptons, or <2 b-jets, or with $m_{\ell_1\ell_2} < 15$ GeV, or $\mu\mu$ events around the Z mass ($85 < m_{\mu\mu} < 95$ GeV)
- Dominant backgrounds: $Z(\mu\mu)$ + jets (normalized from data: 1.36±0.01) and events where the probe muon does not originate from a W (mostly semi-leptonic $t\bar{t}$, normalized in same-sign CR)





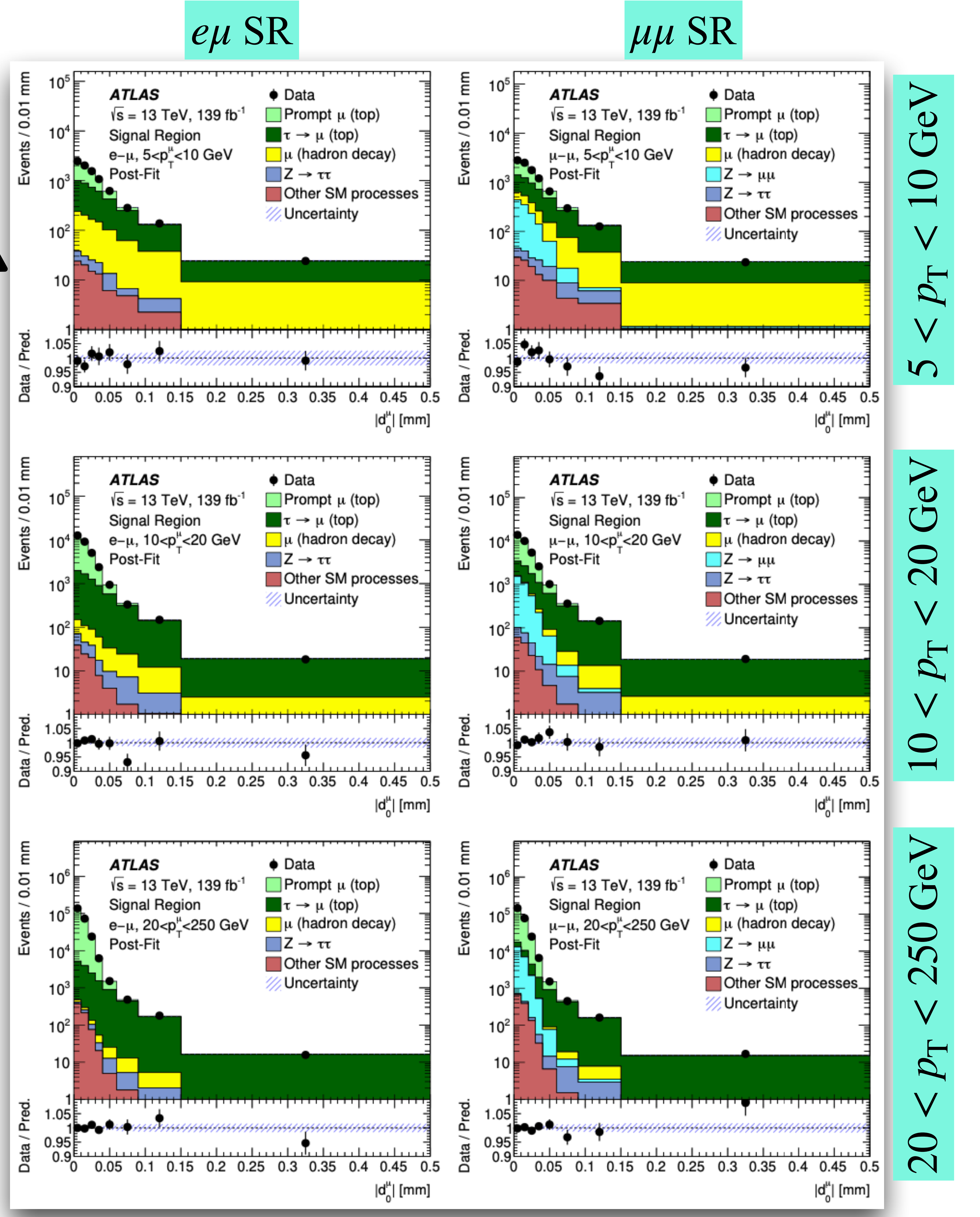
The muon's transverse impact parameter $|d_0|$ has particular importance for this analysis (calibrated with $Z \to \mu\mu$ events).

$\mu_{\text{from}\,\tau}$: large $|d_0|$, small p_T

μ_{prompt}: small $|d_0|$, large p_T

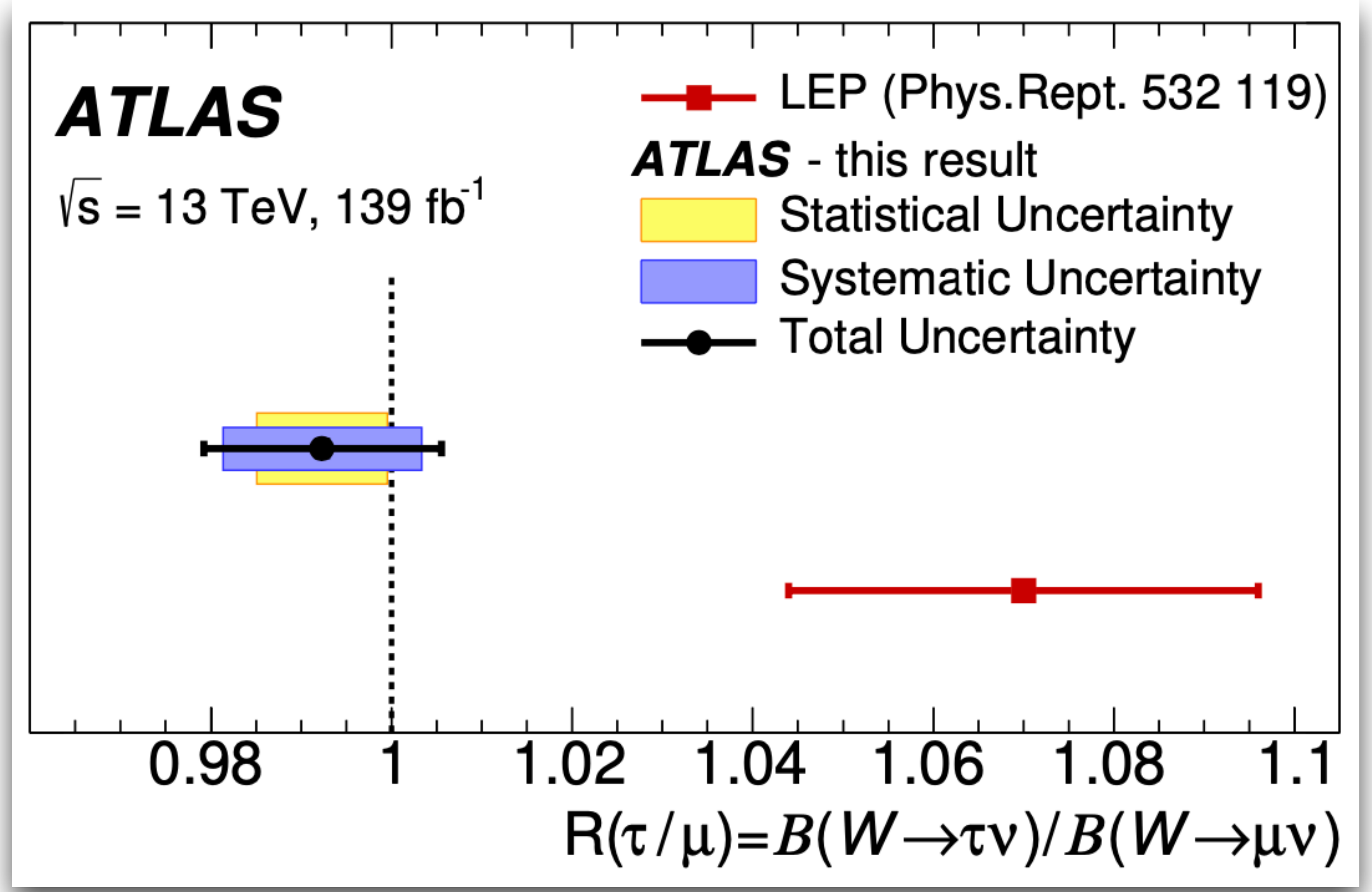
LFU test in $W\tau/\mu$ [Nat. Phys. 17 (2021) 813]

- A 2D profile likelihood fit is performed in the probe muon's $|d_0|$ and p_T distributions
- Fit $R = \frac{N(\mu_{\text{from }\tau})}{N(\mu_{\text{prompt}})}$ with >100 nuisance parameters
  - some systematics are correlated between the $\mu_{\text{from }\tau}$ and μ_{prompt} templates (e.g. jets rec., flavor tag., trigger eff., etc.) $\Longrightarrow$ cancel in R
  - the dominant uncertainties are in the data-driven methods and the theoretical modeling
- $R = 0.992 \pm 0.013\ [\pm 0.007_{\text{stat}} \pm 0.011_{\text{syst}}]$



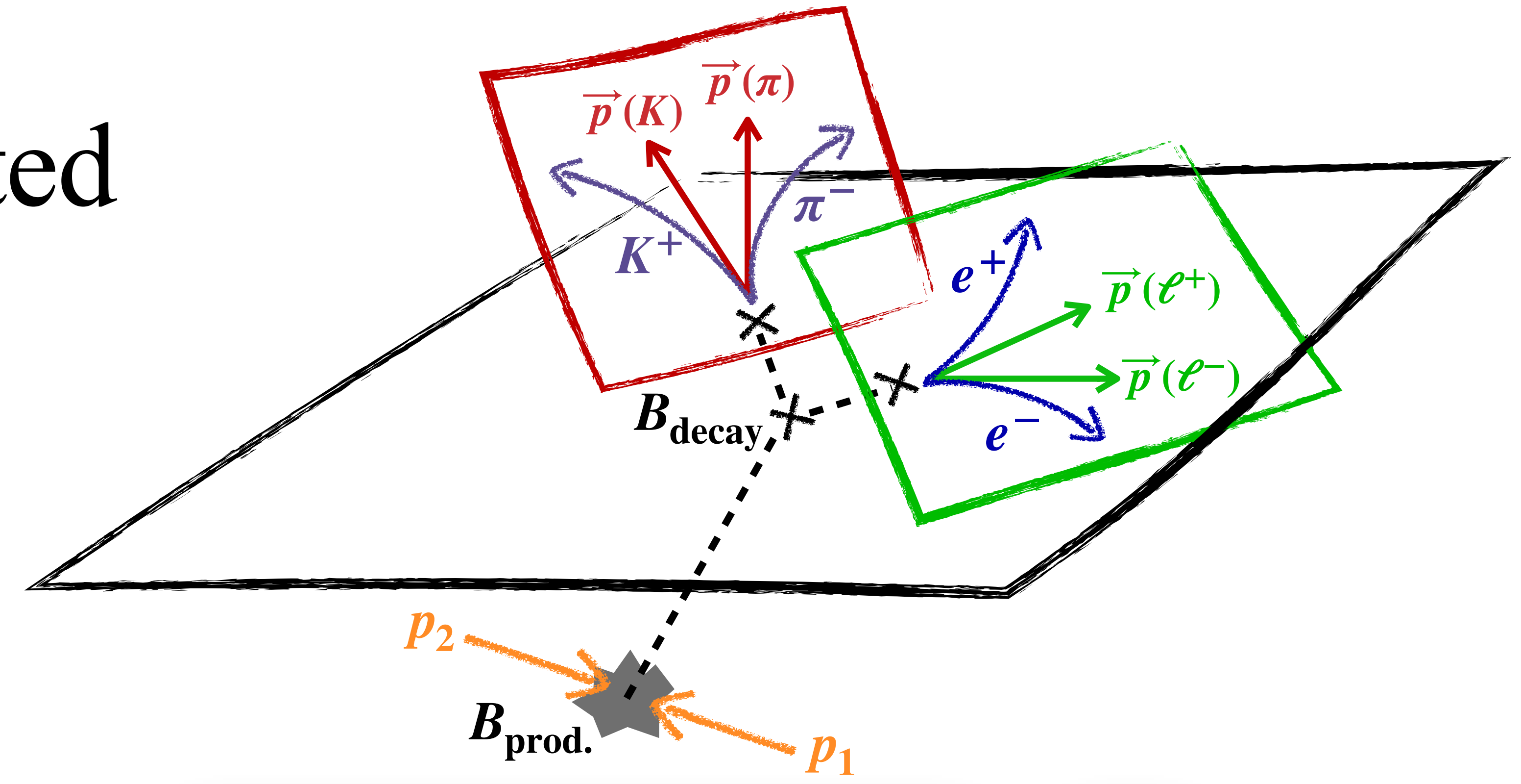
LFU test in $W\tau/\mu$ [Nat. Phys. 17 (2021) 813]

Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^{μ} templates	0.0038
μ_{prompt} and $\mu_{\tau(\rightarrow\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_{T} spectum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\rightarrow\mu)}$ and μ_{had} d_0^{μ} shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \rightarrow \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**



This result surpasses the precision of the previous LEP result and resolves the tension they observed with the SM prediction of LFU

Trigger for $R(K^*)$ [ATL-DAQ-PUB-2019-001]

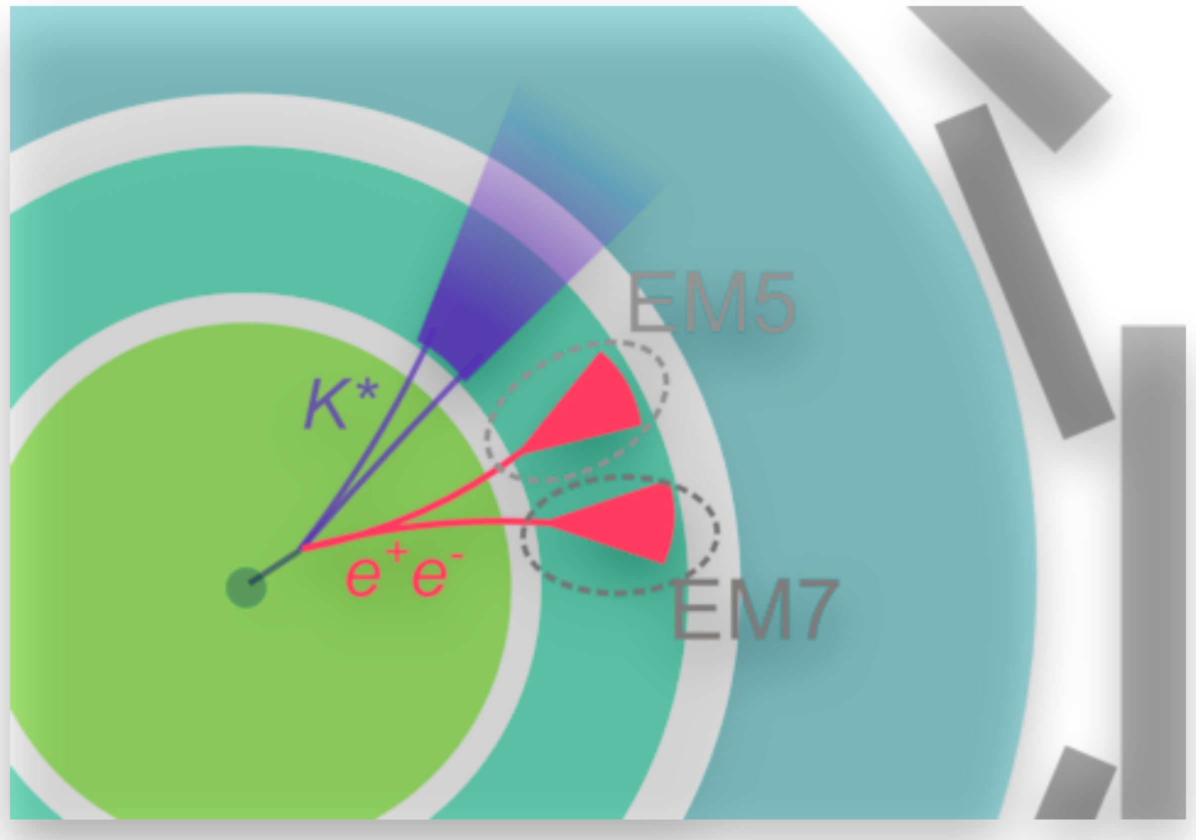


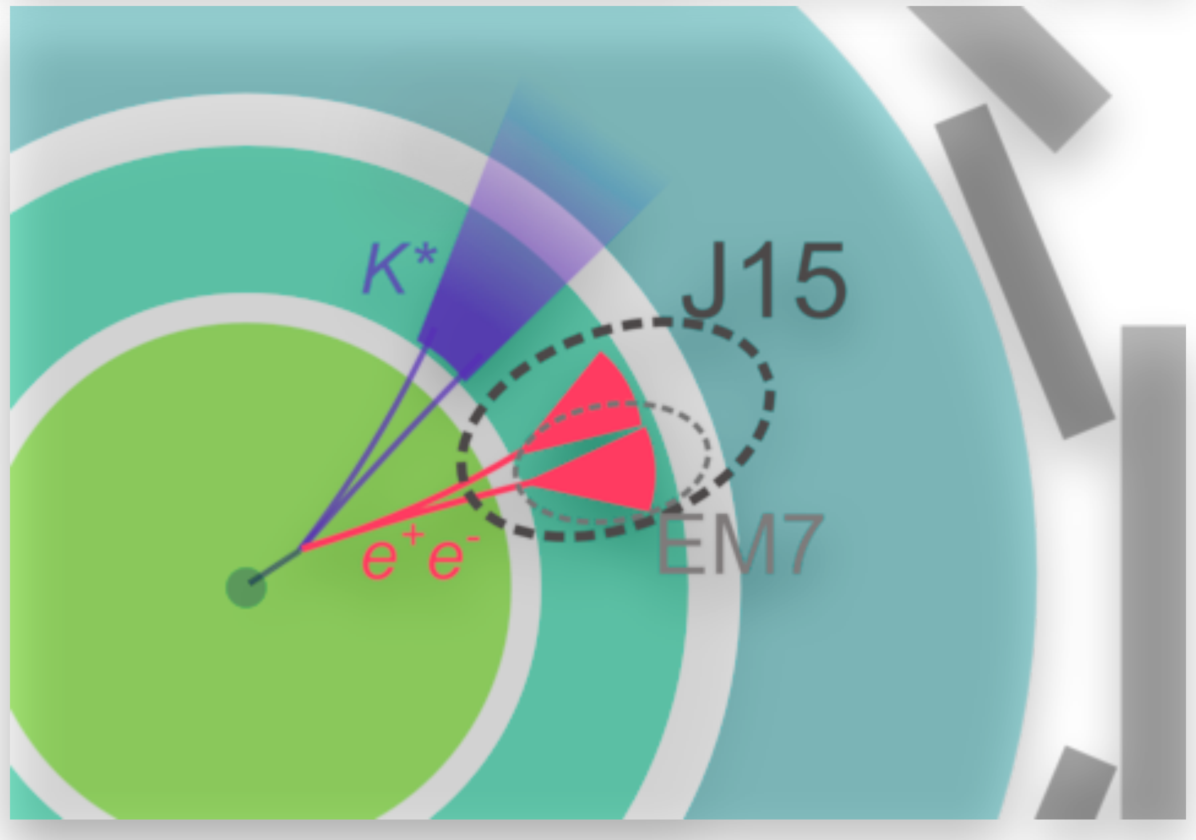
- ATLAS has several dedicated low-p_T two-electron triggers implemented towards the end of Run 2 (in 2018) to allow the $R(K^*)$ measurement

- Vey clean measurement: $R(K^*) = \dfrac{\mathcal{B}(B \to K^*\mu\mu)/\mathcal{B}(B \to K^*(J/\psi \to)\mu\mu)}{\mathcal{B}(B \to K^*ee)/\mathcal{B}(B \to K^*(J/\psi \to)ee)}$

- The non-resonant electron channel is completely driving the measurement precision, solely due to low stats

- **<u>“Unseeded” trigger</u>**: fire the HLT alg on <u>every L1-accept</u> (@100 kHz!)
  - huge bandwidth if turned on indefinitely
  - unprescaled only in the beginning/end of fills
  - agnostic to additional tracks, so also sensitive to e.g. $B^+ \to K^+ee$
  - very loose ID at HLT w/o transverse impact parameter requirements
  - common dielectron vertex with $\chi^2 < 20$ and mass in 0.1-6 GeV (this is inclusive of all relevant B-hadron decays)

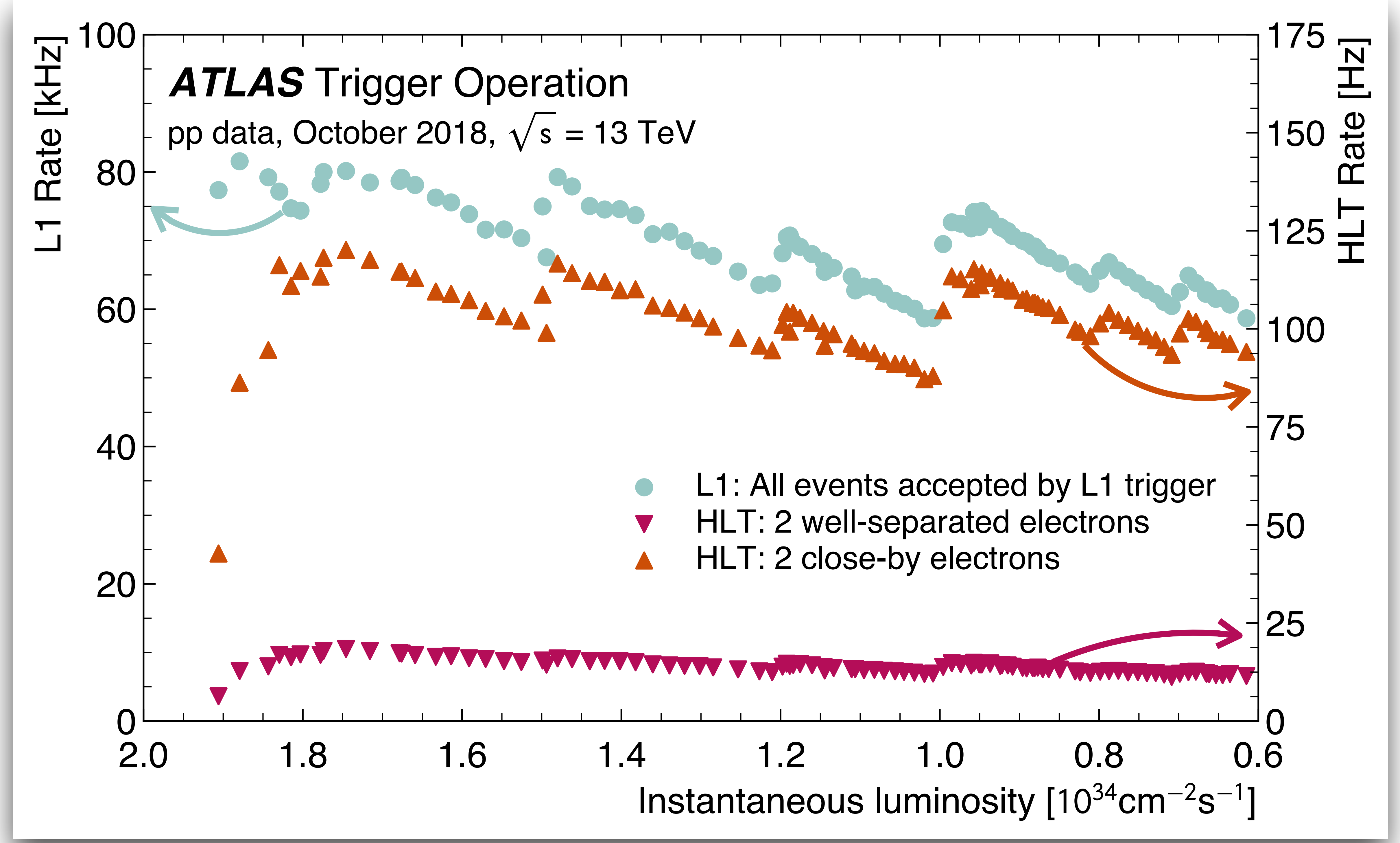




Trigger for $R(K^*)$ [ATL-DAQ-PUB-2019-001]

- Unseeded chains were running w/o HLT prescales below luminosities of $1.85 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Above this, small prescales were applied to reduce the excessive pressure on the RO system (required to run low-p_T electron reco. for every L1 accept:
  - 5 above $2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
  - 2.5 in $[1.95 - 2] \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
  - 1.5 in $[1.85 - 1.95] \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- These HLT prescales were adjusted online until the optimal scenario was achieved
- These chains were improved since then and are actually already online since day one in Run 3!

L1 & HLT trigger rates as a function of instantaneous luminosity for the two unseeded triggers for $R(K^*)$

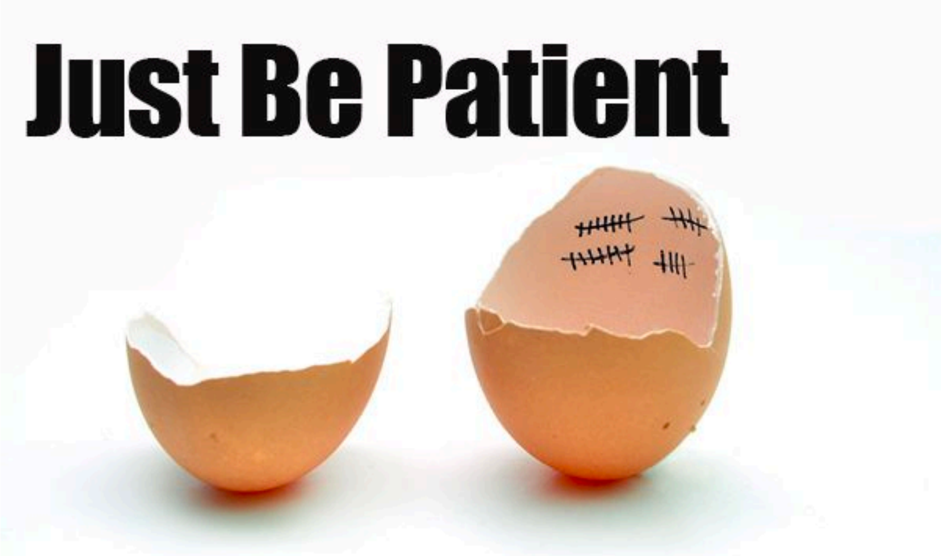


Outlook

- ATLAS has a broad program for direct and indirect LFV/LFUV tests

- So far in ATLAS
  - our direct searches for LFV/LFUV have shown no deviation from the SM
    - **but**, this has been mostly done at high and medium lepton p_{T}
  - the LHC precision is now surpassing LEP, e.g. in $R(\tau/\mu)$ and $Z \to \tau\ell$
    - see backup for the latter
  - our indirect searches (heavy Z', LQs, etc) have also shown no sign of NP yet

- With the introduction of the unseeded triggers concept, ATLAS is now in an era, where e.g. $B \to K^{*}ee$ and possibly $B^{+} \to K^{+}ee$ can be measured
  - these analyses are very very complicated…




THANK YOU

Backup

Inventory

- Exotics Z/Z':
  - Search for the charged-lepton-flavor-violating decay $Z \rightarrow e\mu$ in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector: link
  - Search for Lepton-Flavor Violation in Z-Boson Decays with τ Leptons with the ATLAS Detector: link
  - Search for charged-lepton-flavor violation in Z-boson decays with the ATLAS detector: link
  - Search for new non-resonant phenomena in high-mass dilepton final states with the ATLAS detector: link
  - Plethora of Leptoquark and Vector-like-leptons results

- Top:
  - Test of the universality of τ and μ lepton couplings in W-boson decays from $t\bar{t}$ events with the ATLAS detector: link

- Higgs:
  - Searches for lepton-favor-violating decays of the Higgs boson in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector: link
  - Search for the decays of the Higgs boson $H \rightarrow ee$ and $H \rightarrow e\mu$ in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector: link
  - HDBS-2018-57 (in preparation)

$Z \to e\mu$ search [arXiv:2204.10783, Apr 2022]

Table 3: Effect of various sources of systematic uncertainty on the expected upper limit on the branching fraction $\mathcal{B}(Z \to e\mu)$, measured by comparing the expected limits obtained with and without a given source of uncertainty. Uncertainties due to the statistical uncertainty of the samples of simulated events used to form the histograms which describe the $Z \to \tau\tau$ and $Z \to \mu\mu$ background processes are treated as systematic uncertainties.

Source of uncertainty	Degradation of $\mathcal{B}^{95\%\mathrm{CL}}(Z \to e\mu)$
Statistical uncertainty in MC samples	9.5%
$Z \to \tau\tau$	4.7%
$Z \to \mu\mu$	6.1%
All other sources	2.4%
Jet energy scale and resolution	1.2%
Pileup	1.2%
Electron energy scale and resolution	0.8%
Lepton efficiency	0.7%
b-tagging	0.6%
Muon resolution and bias correction	0.6%