Olga Igonkina (1973 – 2019)
A life in tau leptons, trigger and flavor violation

W. Verkerke (Nikhef)
on behalf of the ATLAS Collaboration

Olga Igonkina – a one-page introduction

Career

- from 2015 – professor at Radboud Universiteit Nijmegen (NL)
- from 2008 – senior researcher at Nikhef/FOM (NL)
- 2002-2007 – postdoc at University of Oregon (USA)
- 1996-2002 – research scientist at ITEP (Moscow, Russia)
- 2002 – PhD in Experimental High Energy Physics (Moscow, Russia)

Coordination roles in ATLAS

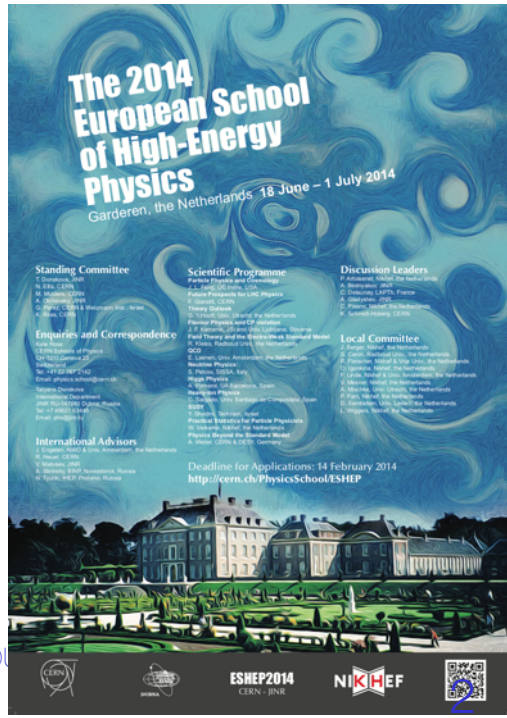
- co-convenor of B-physics trigger group (2016- 2017)
- coordinator of Express stream (2014-)
- co-convenor of Lepton+X Exotics physics group (2013-2014)
- chair of L4 trigger study task force (2013)
- member of trigger workshop panel (2012)
- trigger menu coordinator (2010-2011)
- local organizer of ATLAS trigger workshop in Amsterdam (2010)
- tau trigger coordinator (2007-2010)
- chair/member of TDAQ speaker committee (2007-2009)
- coordinator of trigger validation software validation

Coordination roles in BABAR

- convener of Tau-QED physics working group (2005-2006)
- reconstruction operation manager

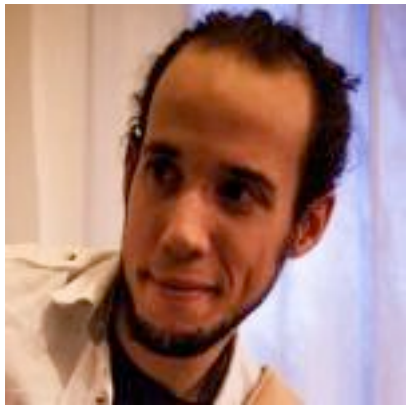
Conference and school organization

- Chair of Local organizing committee TAU2018 conference in Amsterdam, NL
- Local director of CERN physics school in NL (2014)
- Local co-organizer of TIPP 2014 conference in Amsterdam, NL



Olga as supervisor – postdocs and students

Postdocs



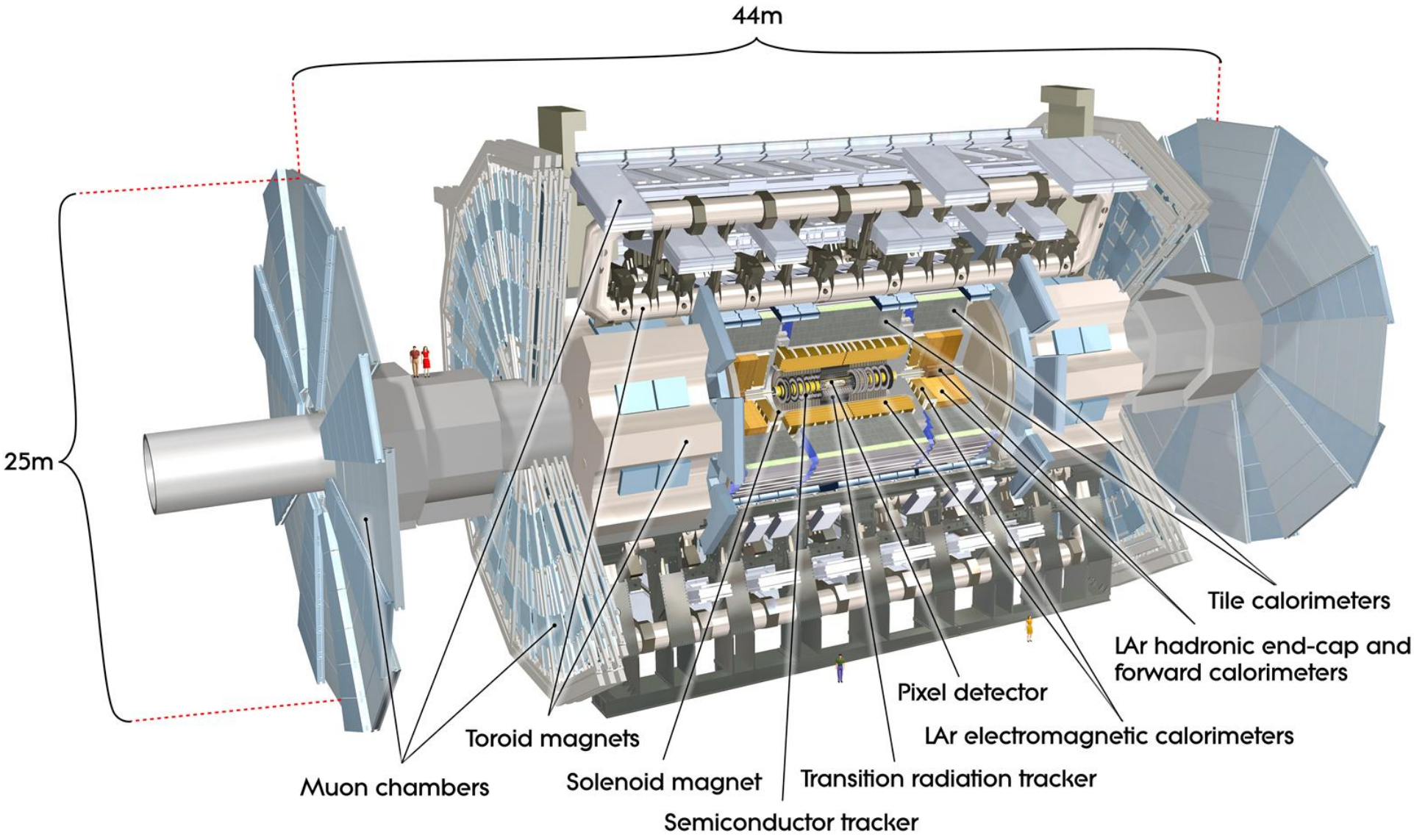
PhD students

Olga's vision – ATLAS as W and τ factory

- ATLAS and the LHC are prolific τ and W/Z factories
- Can be basis of program of charged LFV searches
  - Observation of cLFV = evidence of BSM physics
  - SM rates vanishingly small or absent,
    BSM rates typically in range 10^{-7} to 10^{-10}
- But: the hadronic environment of the LHC
  is *seriously* challenging
  - An ambitious program was set to harness this environment through development of new triggers and data-driven measurement of backgrounds
- I will focus on three areas of Olga's work in the past decade
  1) ATLAS trigger development and organization,
  2) Search for τ→3μ and
  3) Search for Z→τμ

ATLAS and the LHC

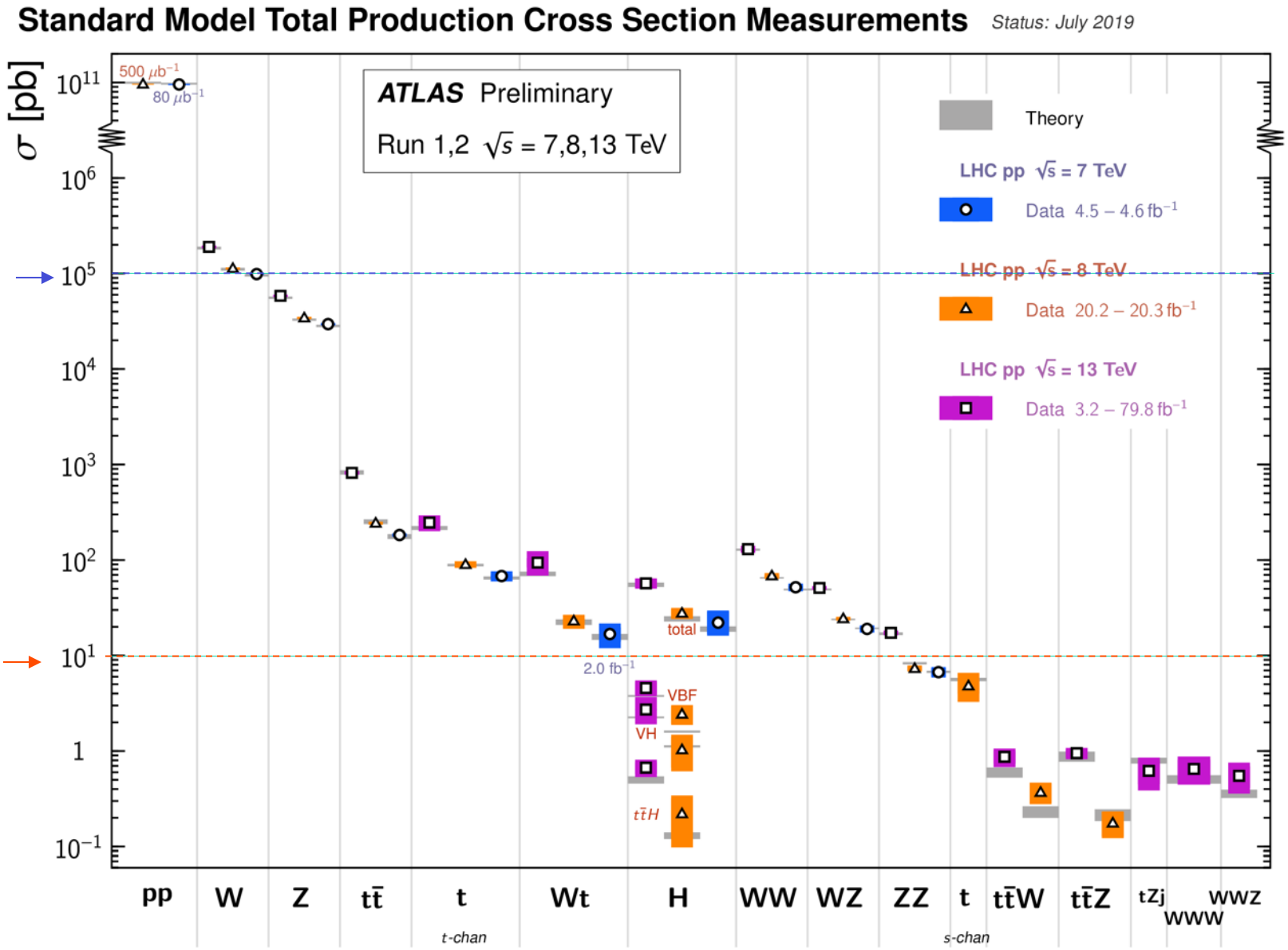
- The LHC collides protons at 7/8 TeV in Run-1, at 13 TeV in Run-2
  → Collisions recorded by general purpose ATLAS detector



The LHC as particle factory

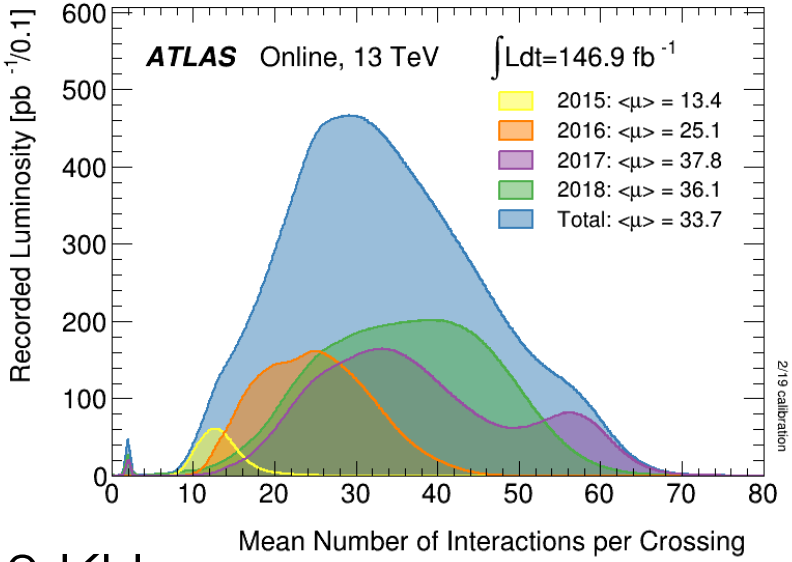
10 billion produced per 100 fb^{-1}

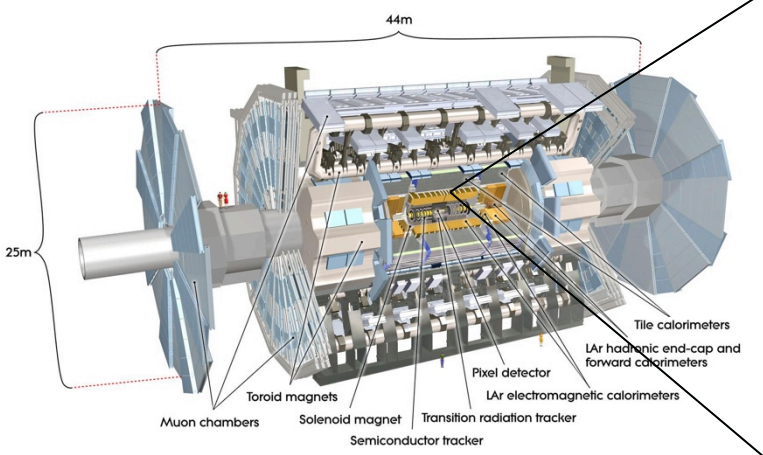
1 million produced per 100 fb^{-1}

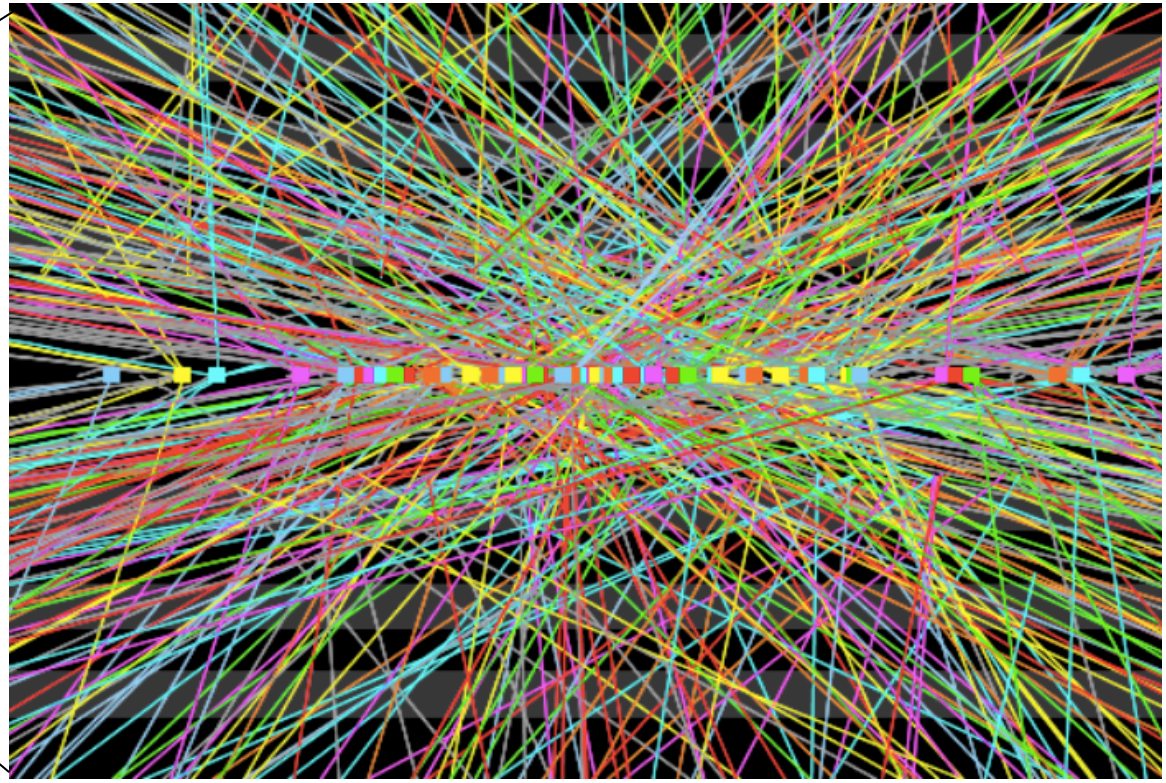


The ATLAS Trigger system

- At a data taking rate of 40 MHz, with up to 80 overlapping collisions per bunch crossing, **a good triggering system is crucial.**
  - Level-1 trigger (HW) reduces rate to 100 KHz,
  - High-Level Trigger (SW) reduces rate further to 1.2 KHz → written to tape



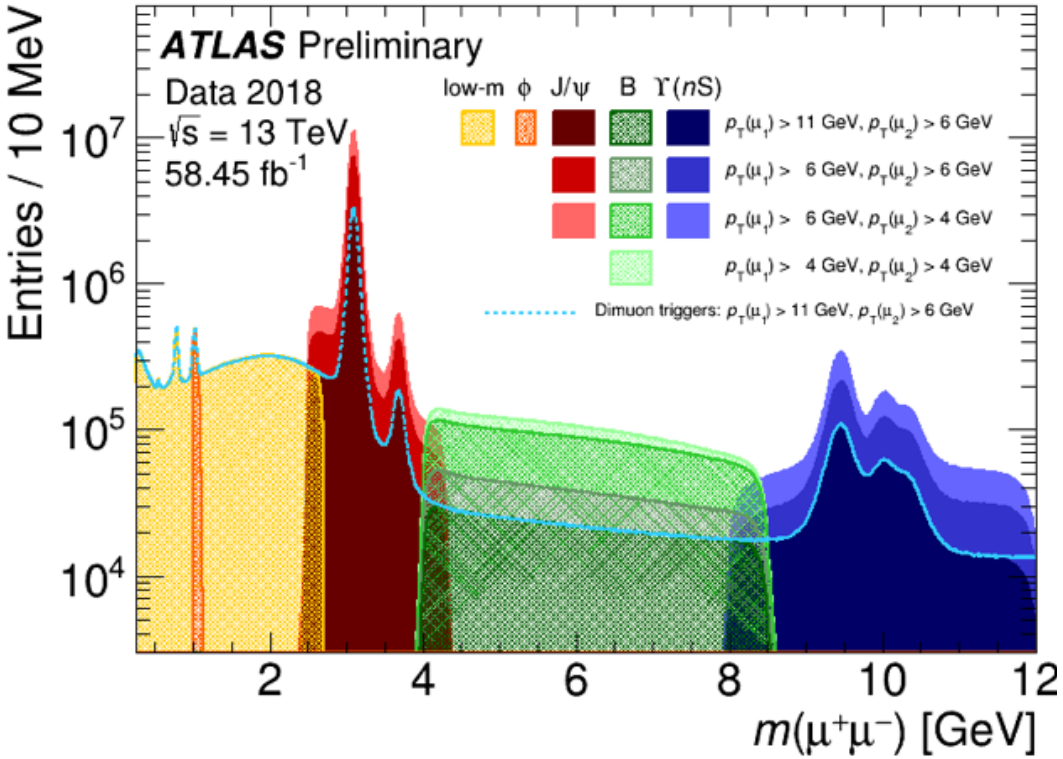




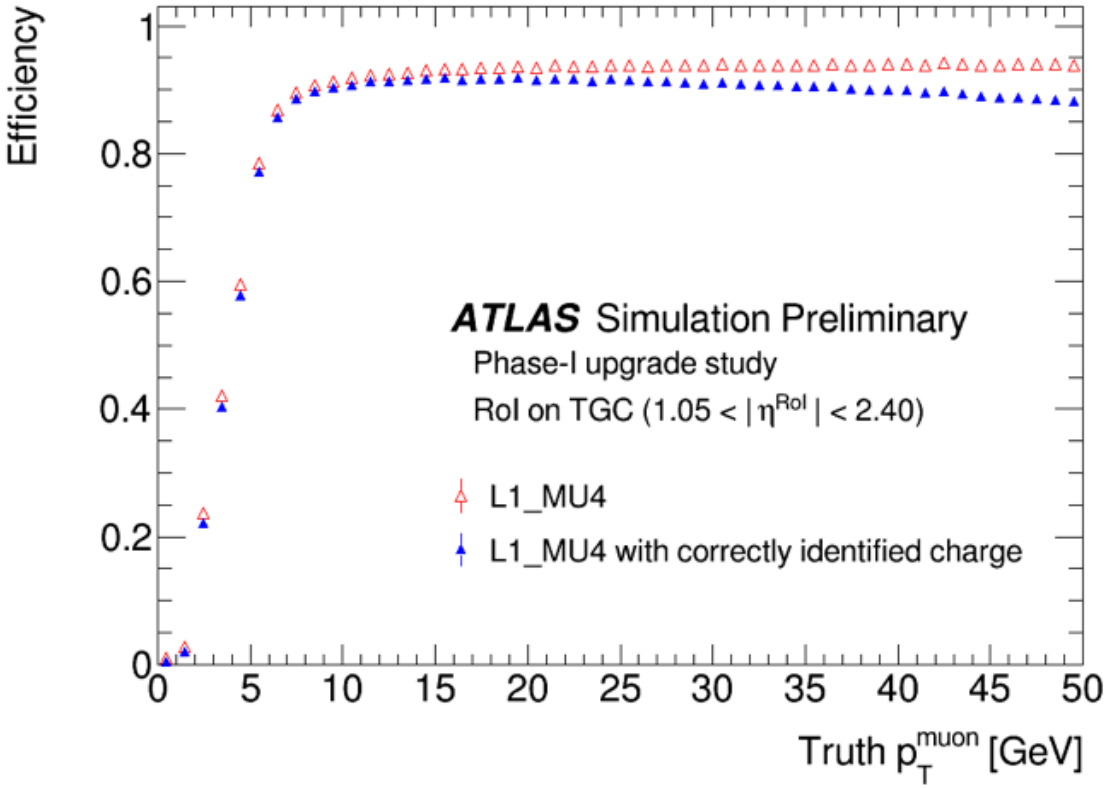
The ATLAS Trigger system

- For signatures with low-p_T particles,
  topological triggers (involving >1 particle and/or detector) **at Level-1**
  essential to control rate

Dimuon mass spectrum 2018 (Run-2)



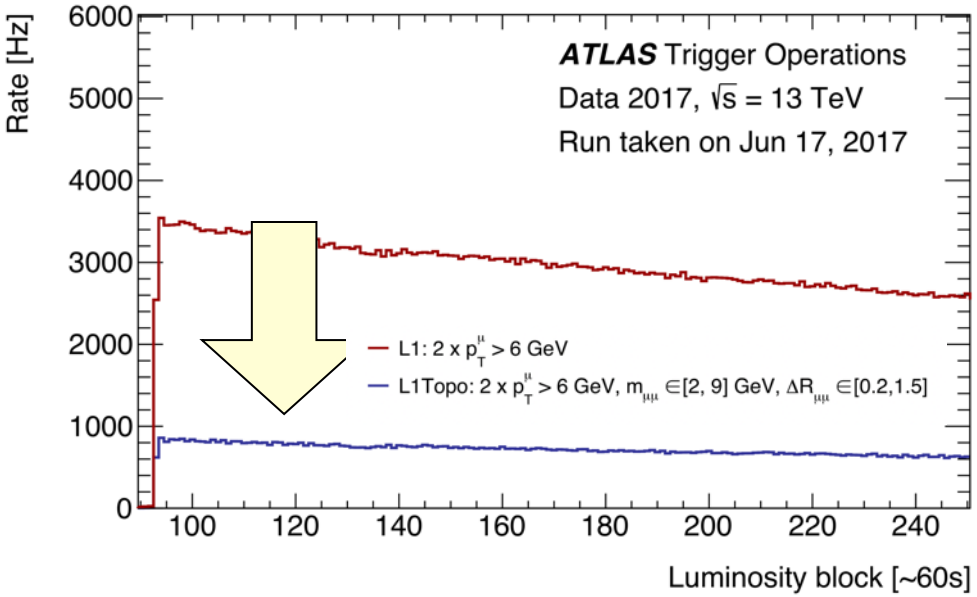
Muon charge ID in Level-1 trigger (Run-3)



Crucial role for Level-1 topological trigger

- ATLAS Outstanding Achievement Award 2018
  "…for their exceptional contributions and dedication in successfully commissioning the Level-1 Topo trigger"

E.g :Factor 4 reduction in dimuon rate when topological criteria applied

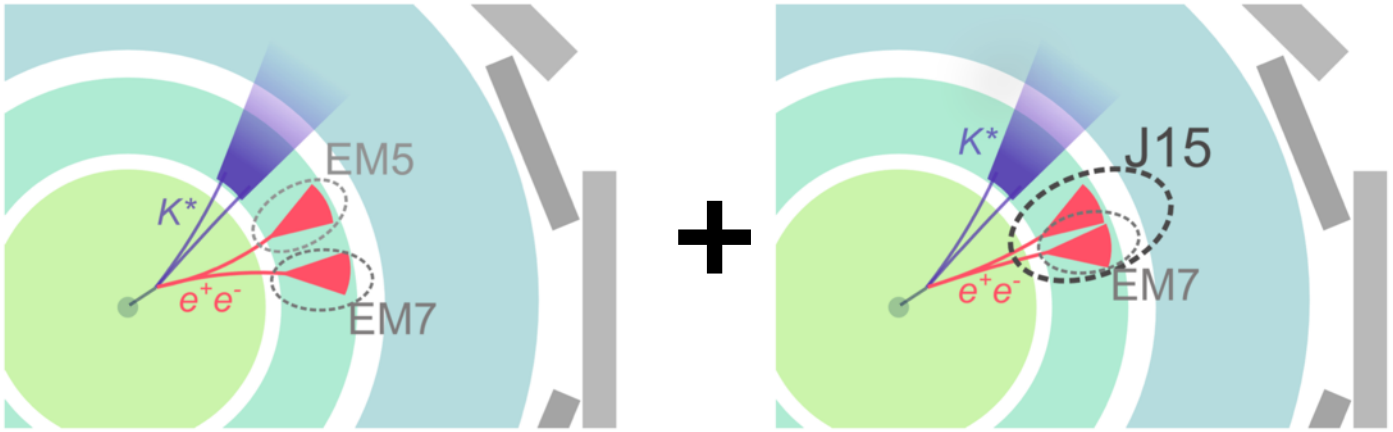


Custom L1 Trigger hardware

Designing new advanced triggers for Run-3

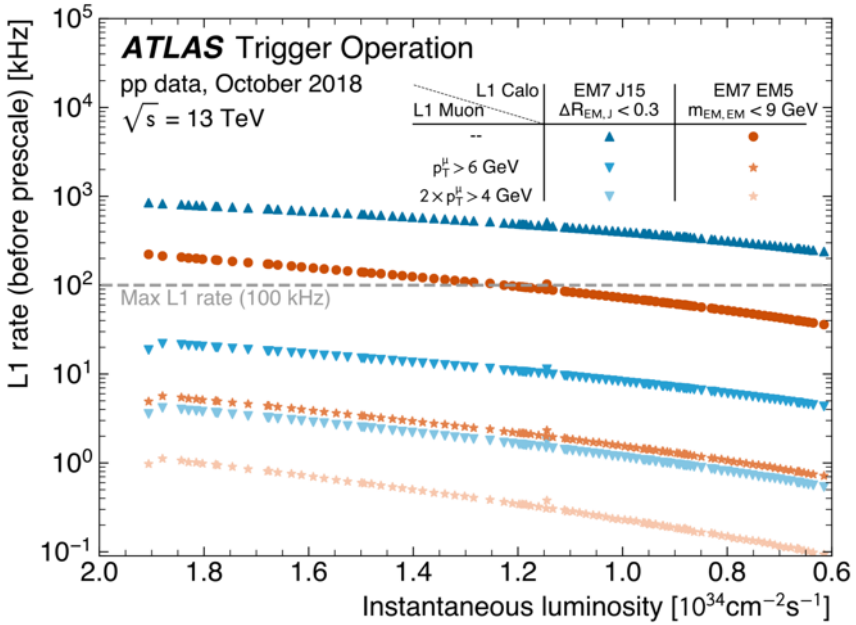
ATL-DAQ-PUB-2019-001

- New $K^*e^+e^-$ trigger in 2018 menu – as proposed by Olga

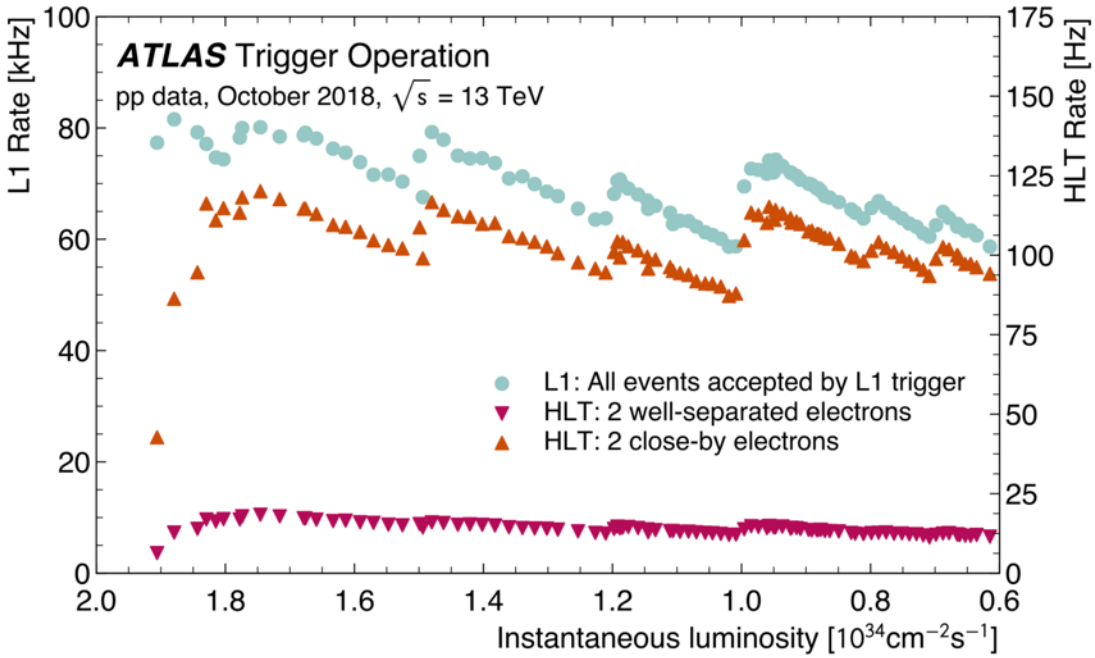


Trigger on two close-by soft EM clusters that may overlap

L1 rates when combined with muon



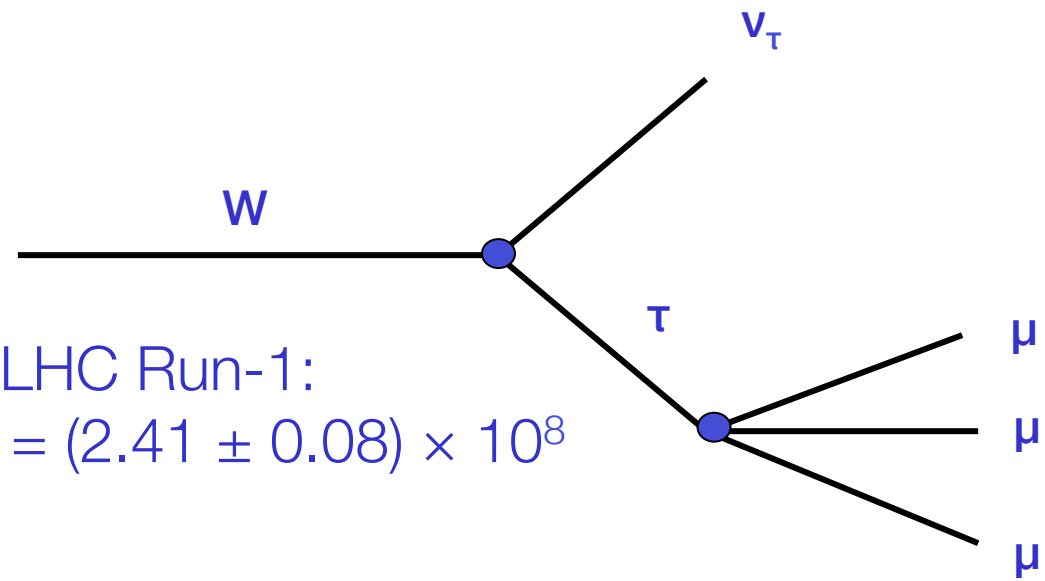
Rates w/o muon, trigger contingent on L1 accept



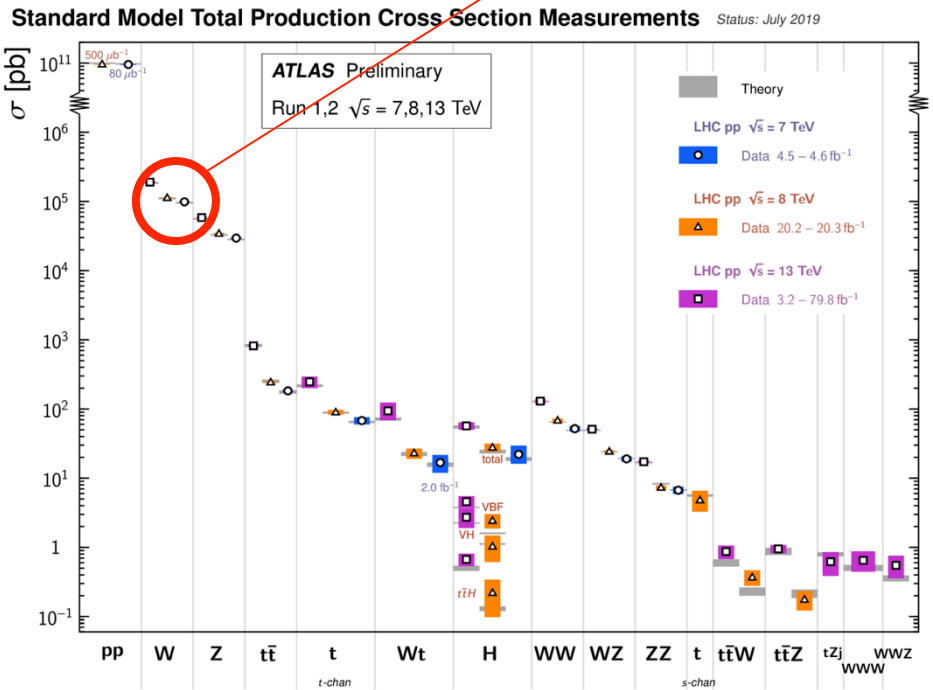
Searching for τ→3μ in ATLAS

Eur. Phys. J. C (2016) 76:232

- Idea: exploit copious production of *W* bosons at LHC as source of τ leptons

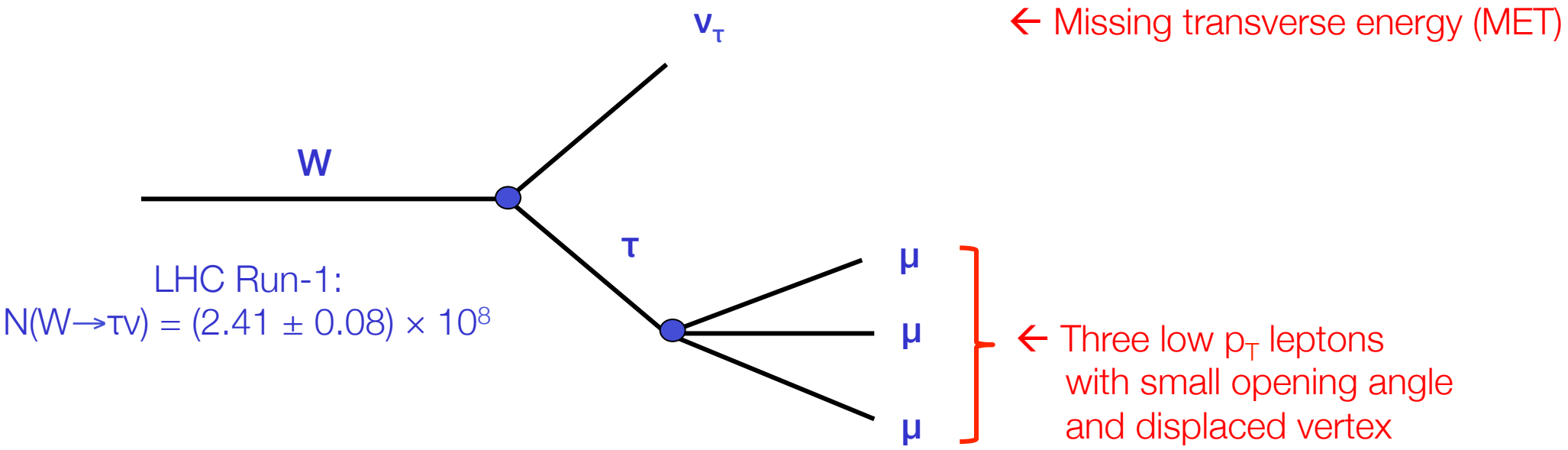


LHC Run-1:
$N(W \to \tau\nu) = (2.41 \pm 0.08) \times 10^8$



Triggering τ→3μ in ATLAS

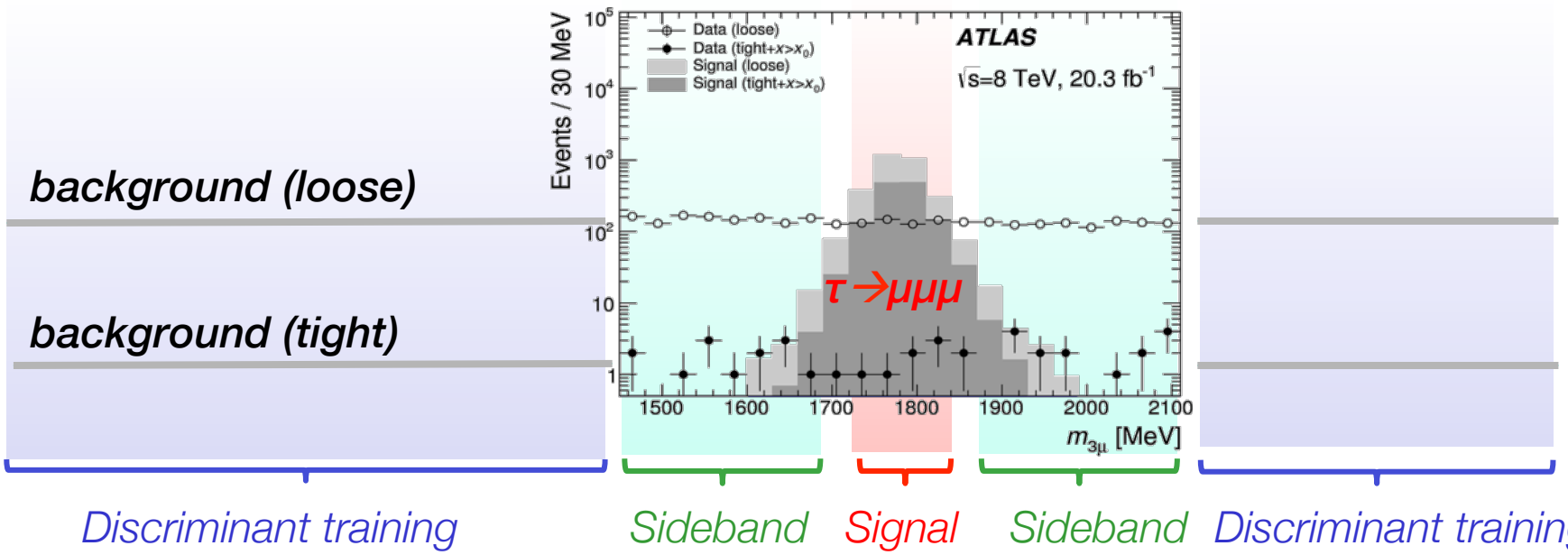
- First challenge: triggering on the W→ν(τ→3μ) signature



- Require one of 7 triggers: 6 multi-muon triggers, 1 di-muon+MET
  - Muon p_T thresholds ranging from 4-18 GeV, MET threshold 30 GeV
  - **Trigger signal efficiency** for muons in acceptance (p_T>2.5,|η|<2.4) **is 31%**

Analysis strategy for τ→3μ

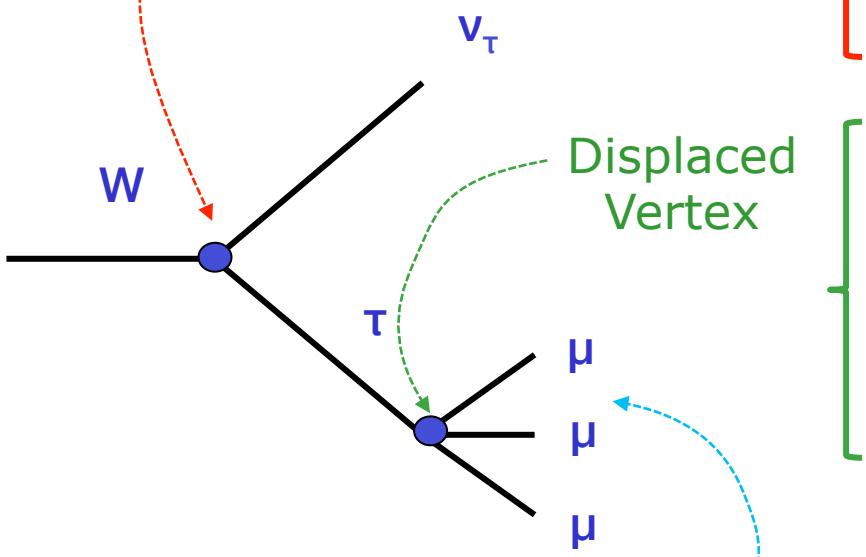
- Reconstruct μμμ invariant mass, **signal will peak at m(τ)**
- **No simulation samples for background used (or needed)!**



- Cut on quantities uncorrelated to m(3μ) to suppress backgrounds.
  1. Define set of **loose/tight** selection criteria (used for training and final selection resp.)
  2. **Train** signal classier (Boosted Decision Tree) in training region on loose selection
  3. **Measure** residual background in sideband region, extrapolate to 'tight' criteria
  4. **Interpolate** to signal region, extract limit

Background reduction strategy

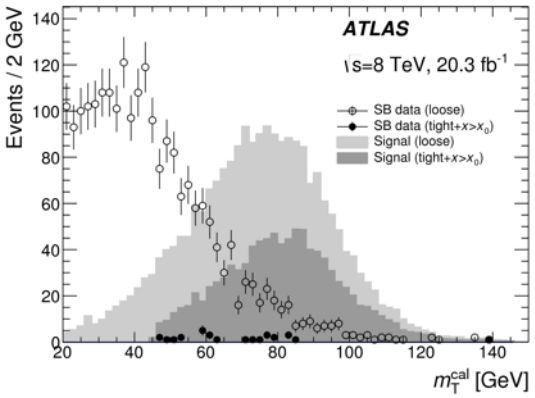
- Exploit multiple quantities related to signal kinematics

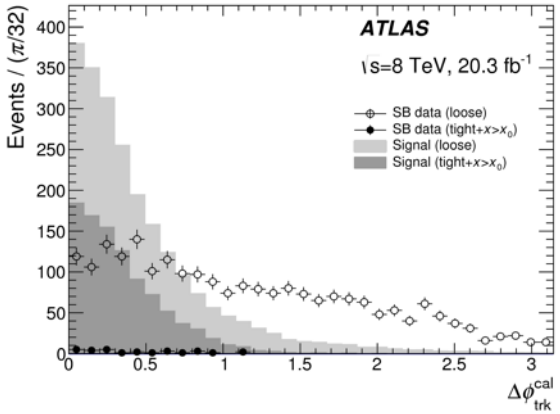


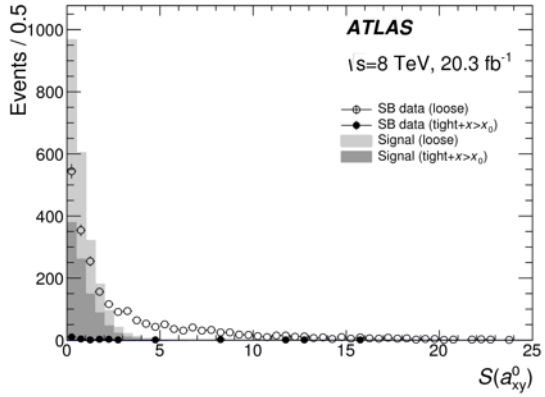
W decay topology
ν,τ back-to-back with
large p_T ($\sim m_W/2$)

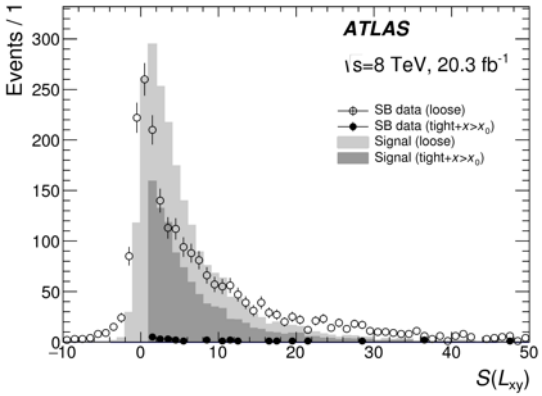
Displaced Vertex

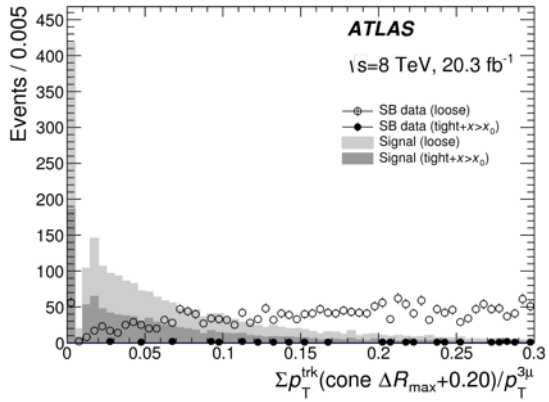
Collimated muons

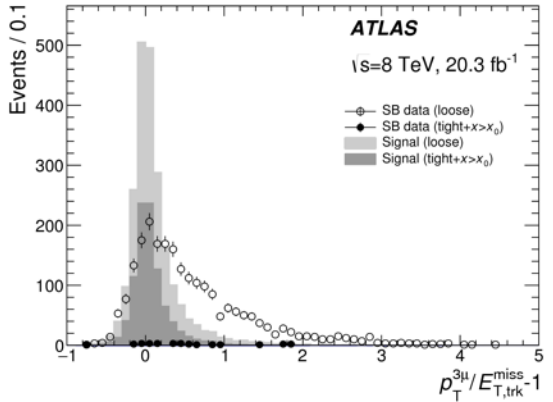






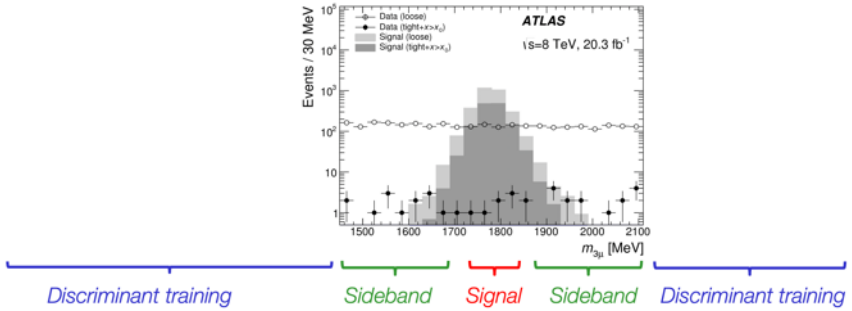




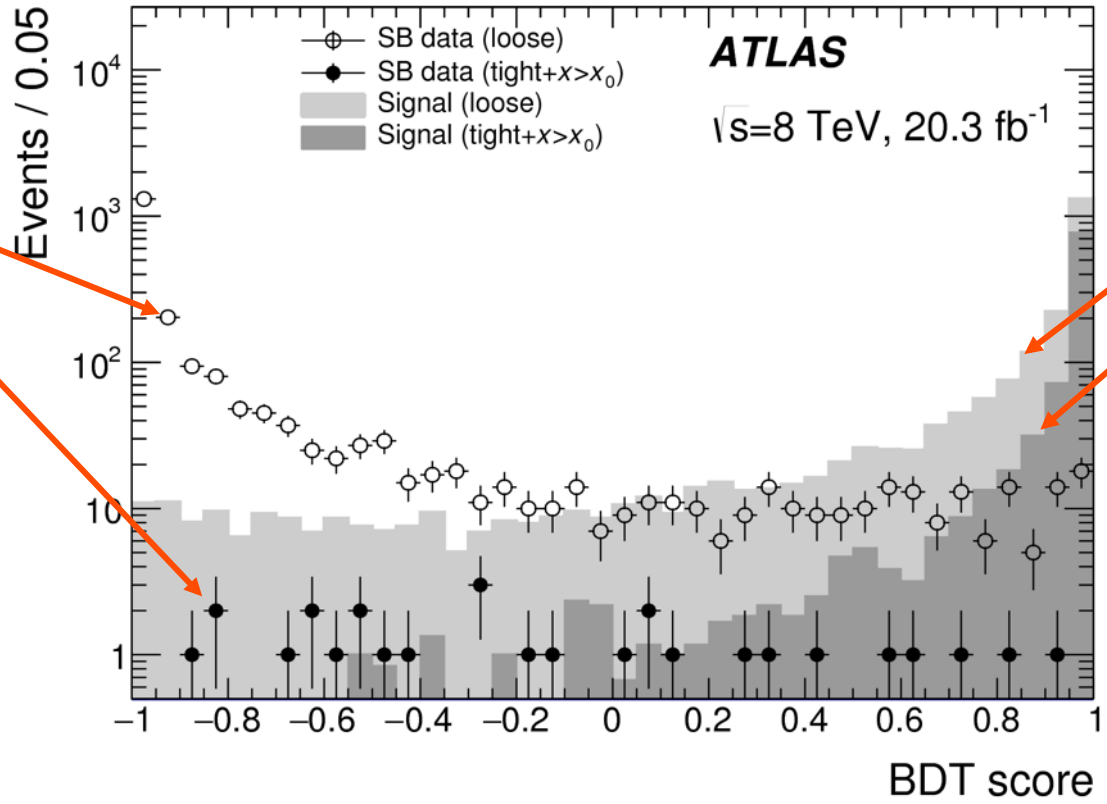


Optimization of selection criteria

- Train BDT classifier in training region, measure performance in sideband region



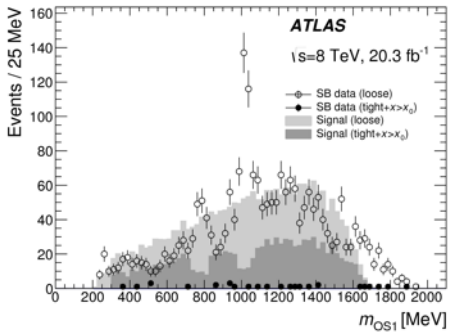
Sideband Sig+Bkg score ***on data*** *(Loose selection) (Tight selection)*



Sideband Signal score ***from simulation*** *(Loose selection) (Tight selection)*

Essence of tight vs loose selection:

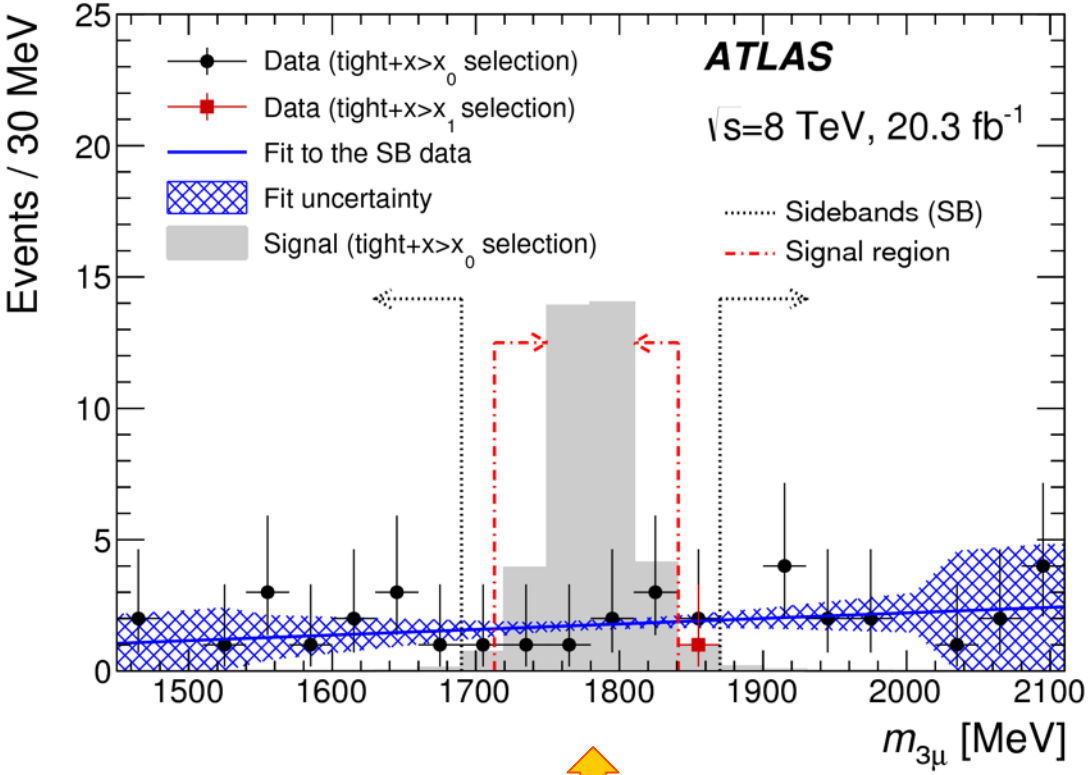
- *Tightened criteria on selected BDT input observables*
- *Criteria to reject jet-like activity close to μμμ*
- *Criteria to reject (ω,ρ,ϕ)+track ,D_s→π(ϕ→μμ) in SR.*

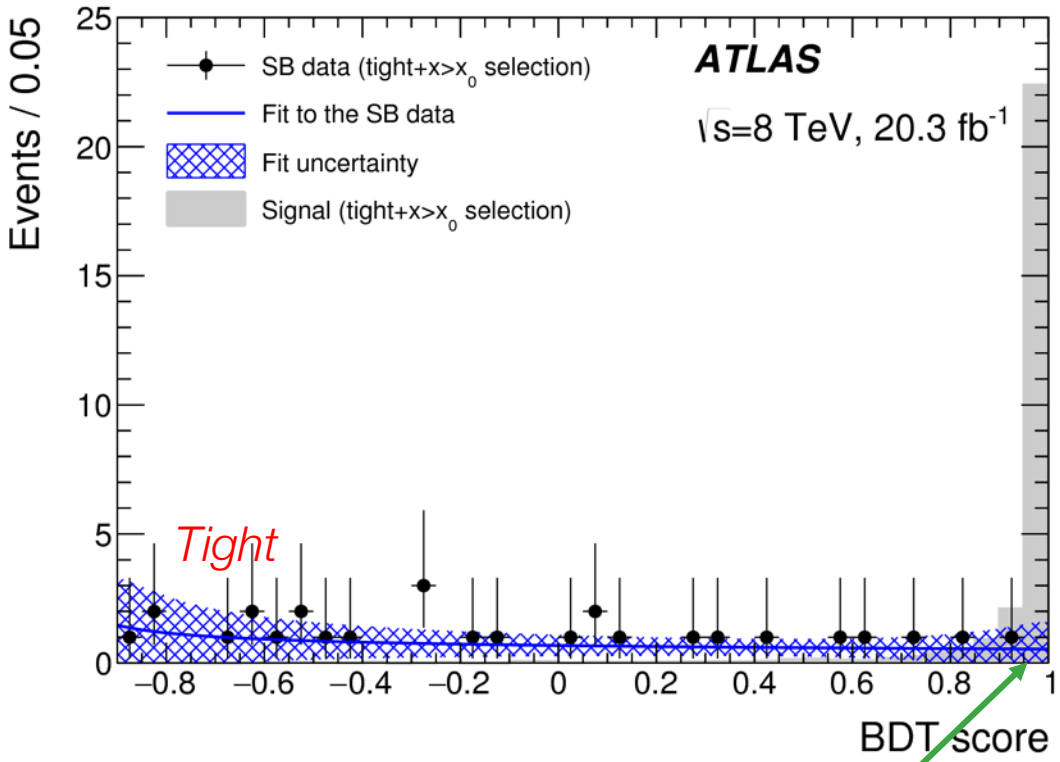


Optimization, background estimation

- On loose selection, fit m(3μ) to functional form, estimate background in signal window

Fit N_{bkg} on tight selection no BDT cut → *Fit N(data) vs BDT on Tight*



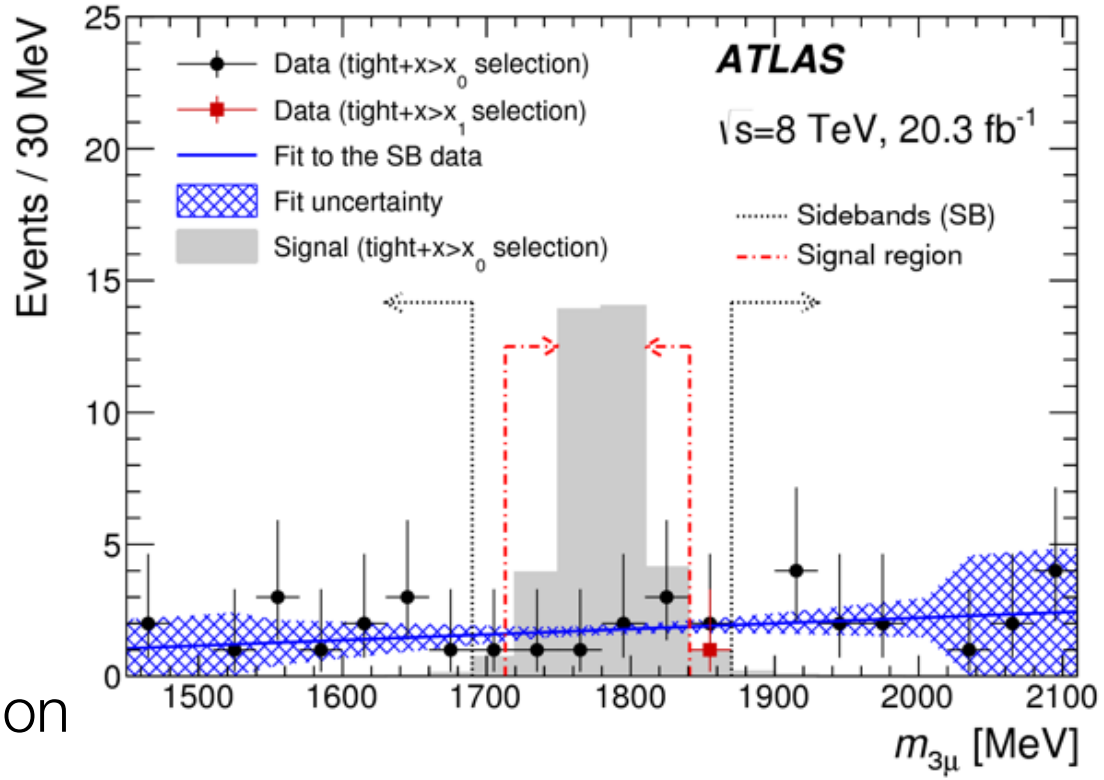


Extrapolate N_{bkg} with BDT cut from fitted BDT distribution

Expected *optimal sensitivity BDT>0.931*

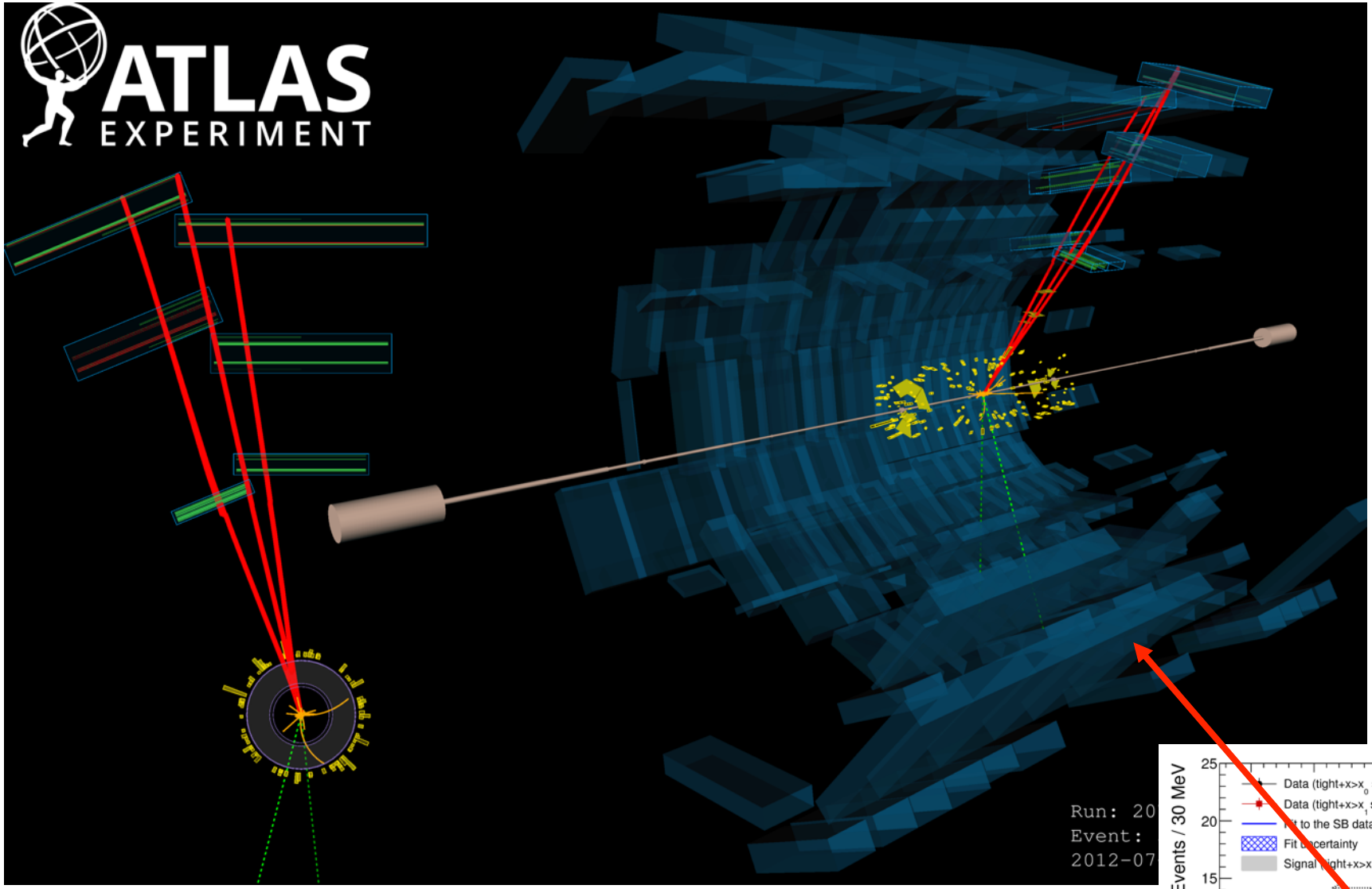
Result, limit

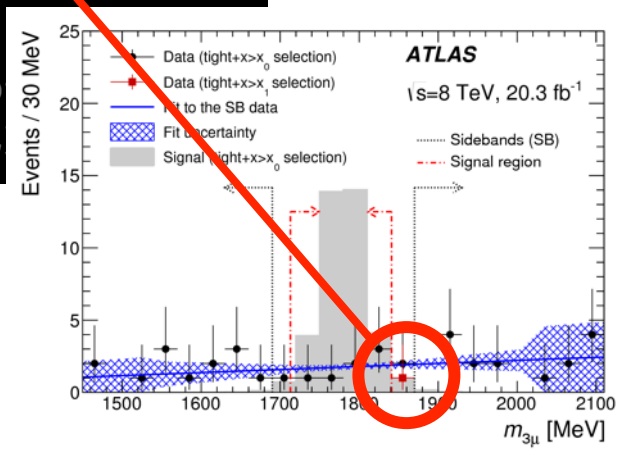
- **Zero events observed** in the signal region → set limit
  - Perform limit calculation using Poisson counting model
  - Describe (systematic uncertainties) with nuisance parameters



- Data-driven background estimation
  - $N_b = 0.193 \pm 0.131_{syst} \pm 0.037_{stat.}$
  - Systematic uncertainty from loose→tight extrapolation
- Acceptance times efficiency from simulation is 2.31%
  - $A_s \times \varepsilon_s = 0.0231 \pm 0.0005_{jet/E^{miss}} \pm 0.0009_{modelling} \pm 0.0025_{trig} \pm 0.0030_{reco}$
  - Uncertainties dominated by trigger and reconstruction
- Result: $Br(\tau \rightarrow 3\mu) < 3.76\times10^{-7}$ at 90% C.L. (3.94×10^{-7} expected)
  using 20.3 fb^{-1} of Run-1 data

Event display of only event passing the tight selection

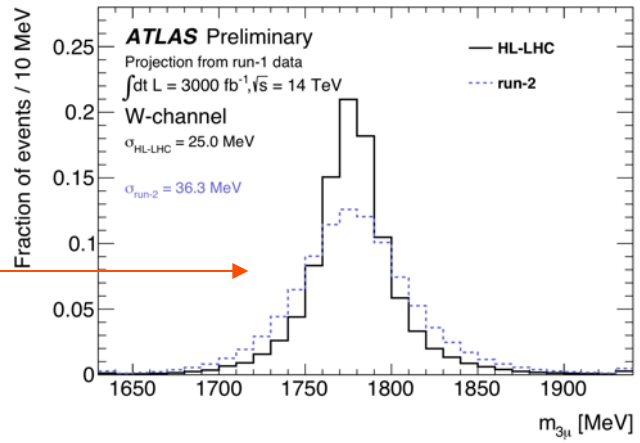




ATL-PHYS-PUB-2018-032

Future projections for τ→3μ in ATLAS

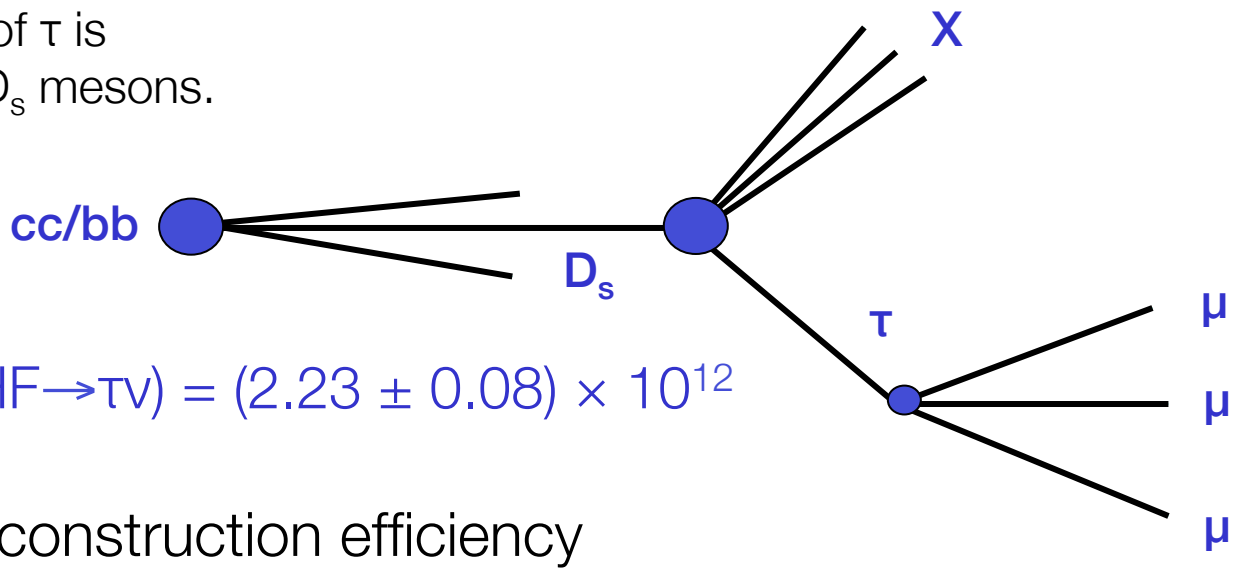
- What is ultimate reach of a W→ν(τ→3μ) analysis at the High-Luminosity LHC, assuming a data sample of 3000 fb^{-1}?
  - I. Substantially 260-fold increased data volume $N(W \to \tau\nu) = 6.50 \times 10^{10}$
  - II. Improvement in acceptance by factor 2.2 due to improved triggering and reconstruction of low-p_T muons (based on Run-2 simulation)
  - III. New all-silicon tracker in ATLAS for HL-LHC running will *improve* mass resolution by about 20%



Scenario	$\mathcal{A} \times \epsilon$ [%]	N_{bkg}^{exp}	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
Run 1 result	2.31	0.19	276
Using I Non-improved	2.31	50.71	13.52
Using I+II Intermediate	5.01	50.71	6.23
Using I+II+III Improved	5.01	40.06	5.36

Future projections for τ→3μ in ATLAS – inclusive HF

- A further more ambitious improvement is to look at **inclusive Heavy Flavor** decays as τ production process
  - Cross-section HF→ τν is 745±150 nb for $p_T(\tau)>10$ GeV, $|\eta(\tau)|<2.5$. (40x larger than W mode)
  - Inclusive HF production of τ is dominated by decay of D_s mesons.



HL-LHC 3 ab^{-1}: N(HF→τν) = (2.23 ± 0.08) × 10^{12}

- Projection of trigger, reconstruction efficiency
  - Study samples of bb/cc→D_s→(τ→3μ)+X
  - Trigger: $p_T(\mu)>3.5$ GeV (all) OR $p_T(\mu)>10.5,5.5,2$ GeV (respectively) Efficiency of trigger is 14% as estimated on Run-2 simulation,
  - Acceptance x Efficiency of reco+trigger is 3.1% before BDT. Assuming* same BDT efficiency as in Run-1 (28%), total $A_s \times \varepsilon_s$ is 0.87%

*) *No simulation sample is available for HL-HLC to re-estimate this*

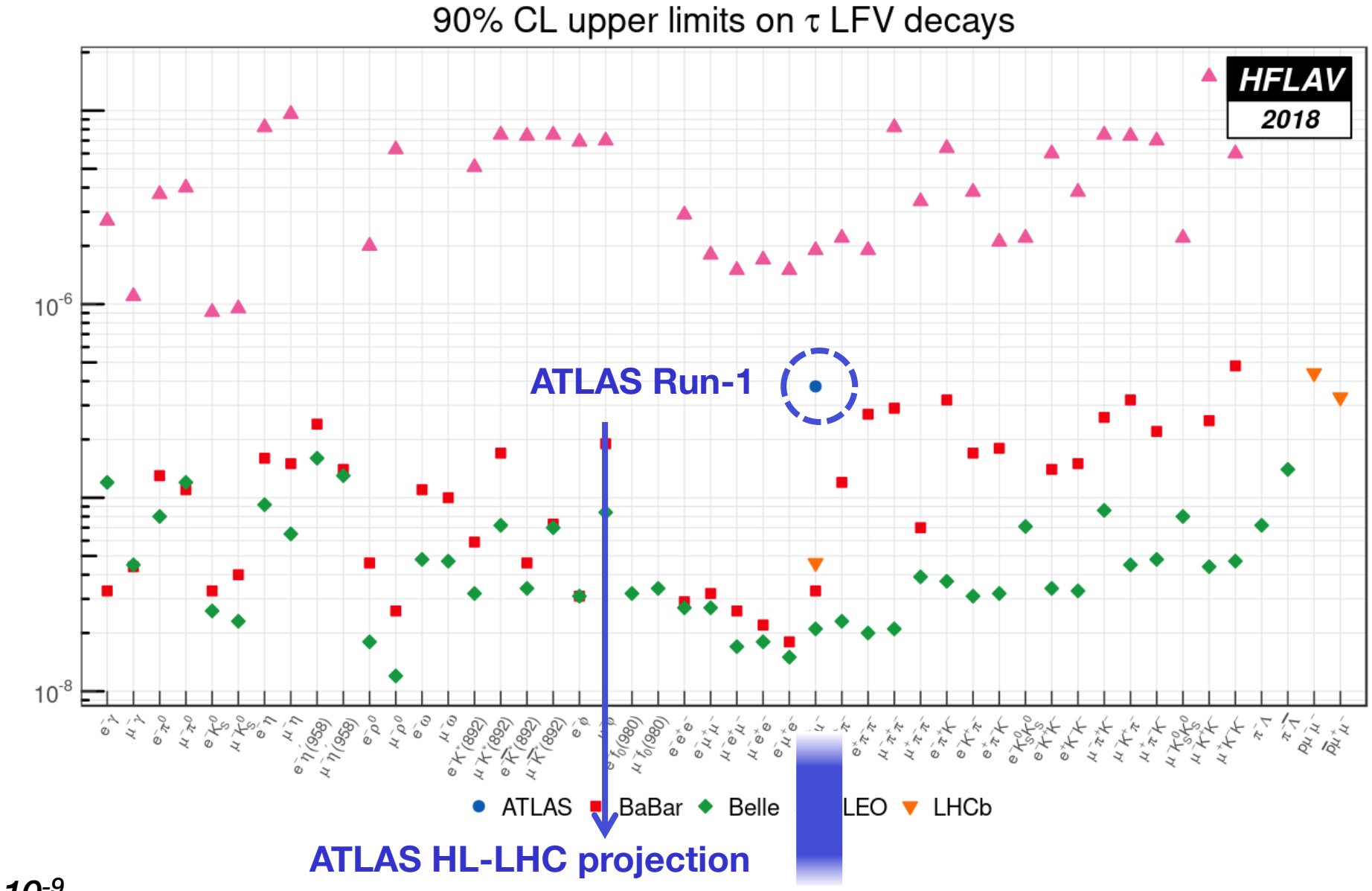
Future projections for τ→3μ in ATLAS – inclusive HF

- **Major uncertainty** in projections for τ→3μ in HF mode is **expected background** rate relative to W mode.
  - Project reach under three assumptions: 10x, 3x, same background as W mode analysis of Run-1, always with a 260-fold increase of luminosity

	Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\text{bkg}}^{\text{exp}}$	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
bkg x10	High background	0.88	507.05	6.40
bkg x3	Medium background	0.88	152.12	2.31
bkg x1	Low background	0.88	50.71	1.03

- Summary: Exclusion limits at 90% CL on the τ → 3μ branching fraction below 10^{-8} in the W-channel and a few 10^{-9} in the HF-channel are foreseen.

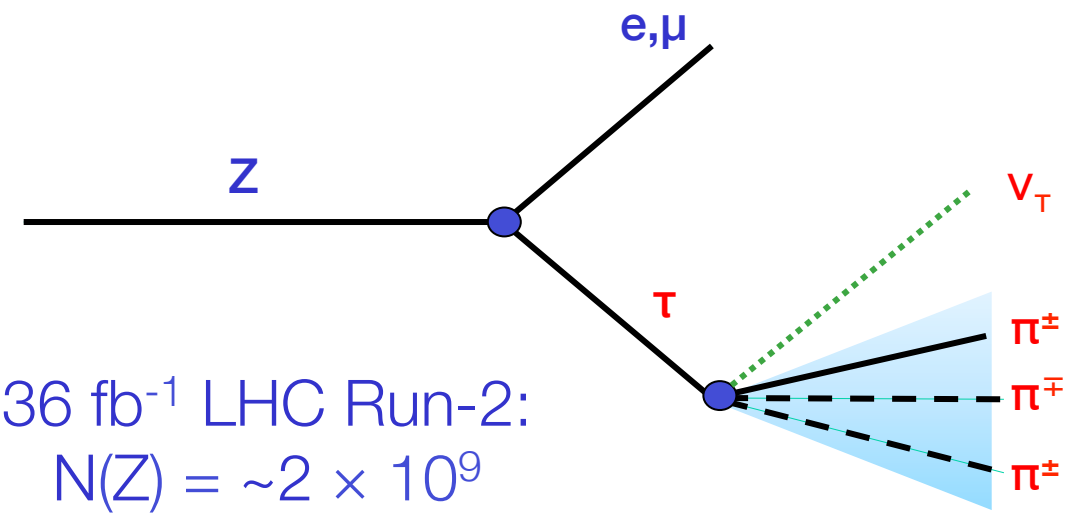
Future projections for τ→3μ in ATLAS – inclusive HF



Searching for Z→τμ/e in ATLAS

Phys. Rev. D 98 (2018) 092010

- Cross-section of inclusive Z production at 13 TeV is ~60nb
  → about 2.2 billion Z bosons produced in 36 fb^{-1} of Run-2 data
  → *A priori very competitive with existing LEP-era limits*
- Look for rare flavor-violating decays Z→τ(e,μ) in this sample
  - Only considering hadronic tau decays in this analysis



36 fb^{-1} LHC Run-2:
N(Z) = ~2 × 10^9

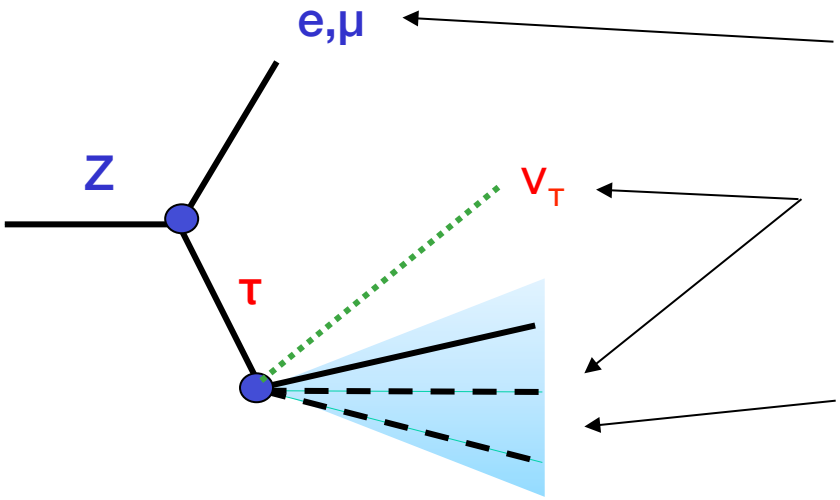
In event, look for

- High-p_T isolated lepton

*- Neutrino (observed as **missing transverse energy**)*

*- Hadronic τ **jet**, containing 1 or 3 charged particles plus neutrals (calorimeter)*

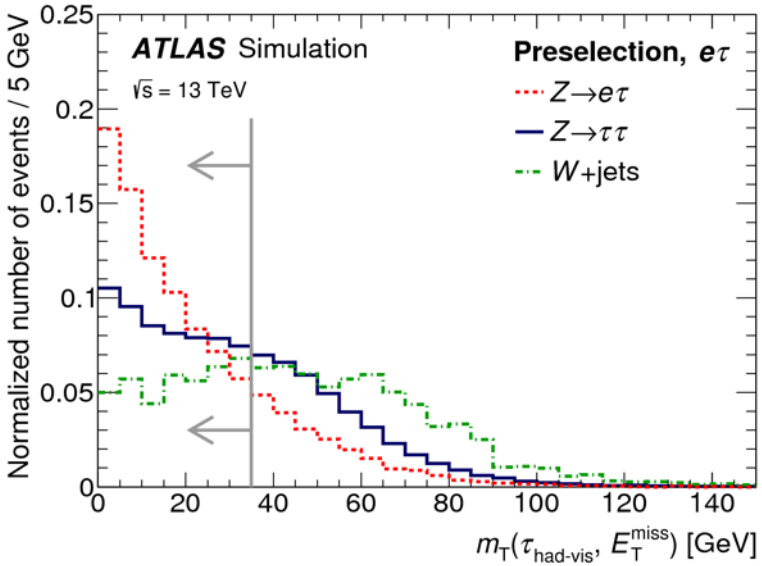
Basic selection of Z→ τμ/e events



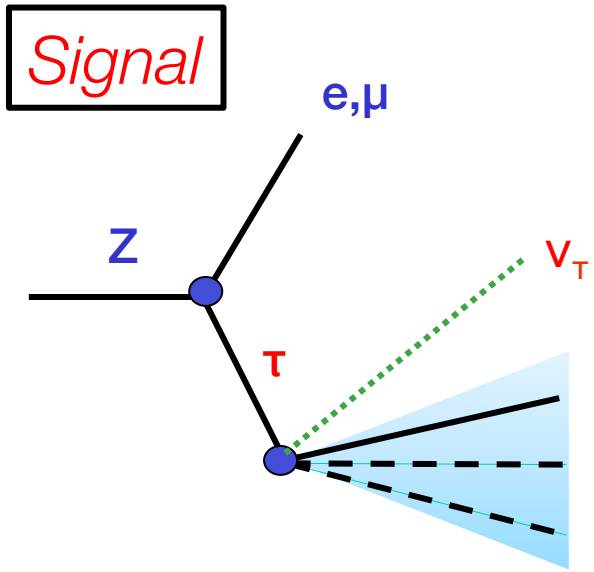
- Select events with
  - **Isolated lepton candidate** (e,μ)
    - p_T>30 GeV, |η|<2.47/2.5, q opposite to q(τ_{had})
  - A **transverse mass < 35(30) GeV**

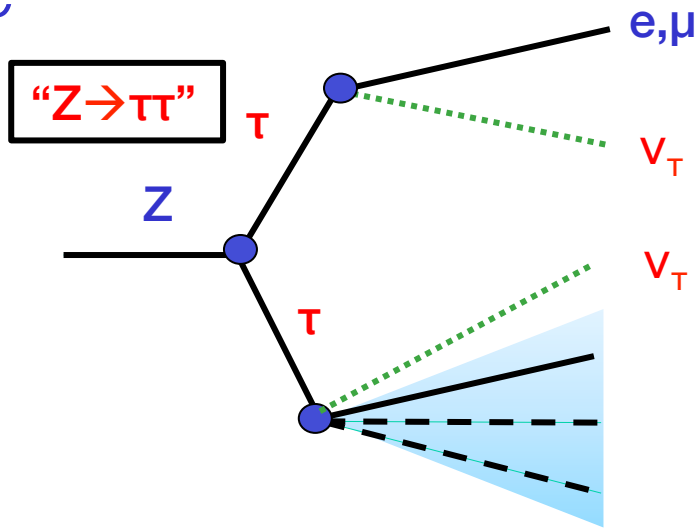
$$m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}}) \equiv \sqrt{2 p_{\mathrm{T}}(\tau_{\text{had-vis}}) E_{\mathrm{T}}^{\text{miss}} \left[1 - \cos\left(\Delta\phi(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}})\right)\right]},$$

  - **Hadronic τ candidate** (1p or 3p)
    - p_T>20 GeV, tracks p_T>1 GeV, |η|<2.5, |q|=1 plus quality cuts through MV discriminant
  - No b-flavor tagged jets
    - To suppress background with top quark decays
  - Some further cuts to avoid detector regions with poor performance
    - E.g exclude $|\eta(\tau_{\text{had-vis}})| < 0.1$ for 1-prong in Z→μτ

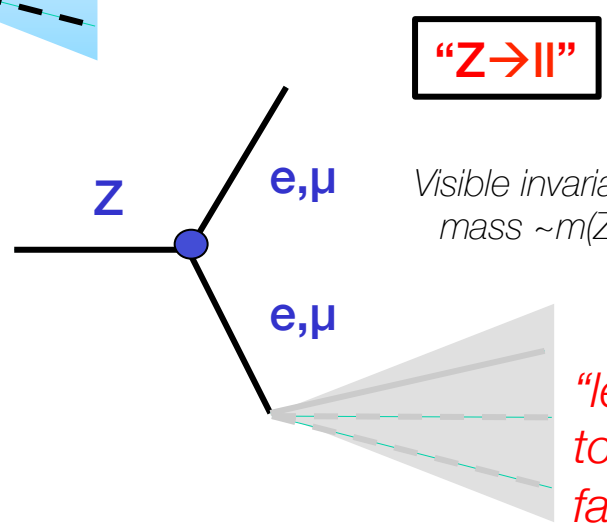


Backgrounds in Z→ τμ/e



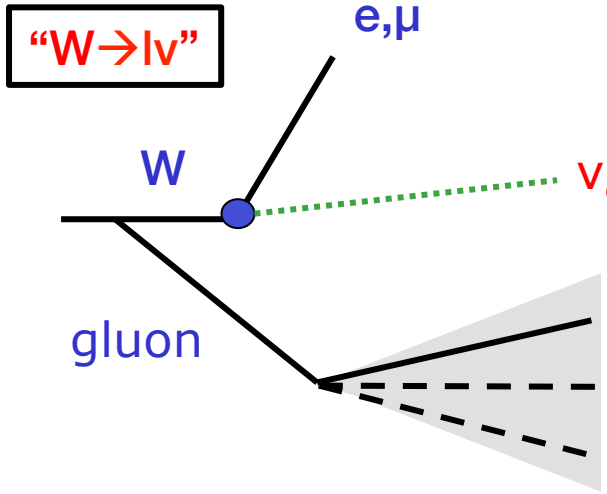


Large transverse mass



Visible invariant mass ~m(Z)

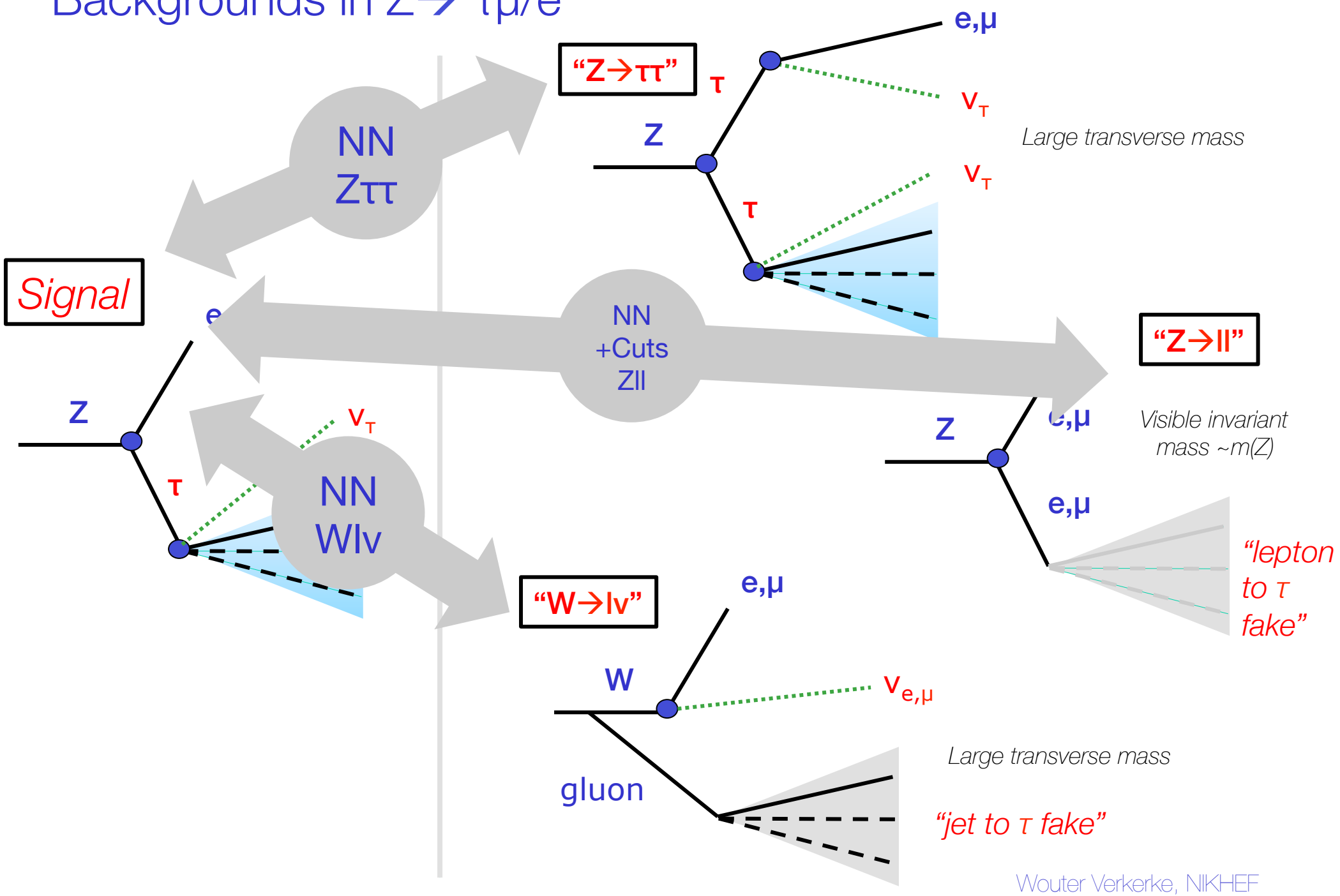
"lepton to τ fake"



Large transverse mass

"jet to τ fake"

Backgrounds in Z→ τμ/e



NN classifiers to discriminate Z→eτ/μτ from background

- For each background and each signature (τe/τμ) **a separate NN is trained** (6 in total)
  - Input to each NN are **particle kinematics and invariants**

Training with TensorFlow

Topology:
2 hidden layers
with 16 nodes each

Variable	Description	Z NN	Zll NN	W NN	
$\hat{E}^{\text{lep}}$	light-lepton energy	✓	✓	✓	*lepton energy*
$\hat{p}_x^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_x	✓	✓	✓	*τ kinematics*
$\hat{p}_z^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_z	✓	✓	✓	
$\hat{E}^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ energy	✓	✓	✓	
$\hat{p}_z^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$ component along z-axis	✓	✓	✓	*ν kinematics*
$\hat{E}^{\text{miss}}$	magnitude of $E_{\text{T}}^{\text{miss}}$	✓	✓	✓	
$p_{\text{T}}^{\text{tot}}$	transverse component of total momentum	✓	✓	✓	*other kinematics (invariants etc)*
m_{coll}	collinear mass	✓	✓	✓	
$\Delta\alpha$	see Eq. (1) [48]	✓	✓	✓	
$m(\ell, \tau_{\text{had-vis}})$	invariant mass of light lepton and $\tau_{\text{had-vis}}$		✓		

- **Outputs of classifiers combined with simple quadrature formula**
  - I.e. all discriminants carry equal weight
  - For 3p only "Zττ" and "Wlν" NNs are used, for 1p all three NNs are used

Z→eτ output for all discriminant pairs

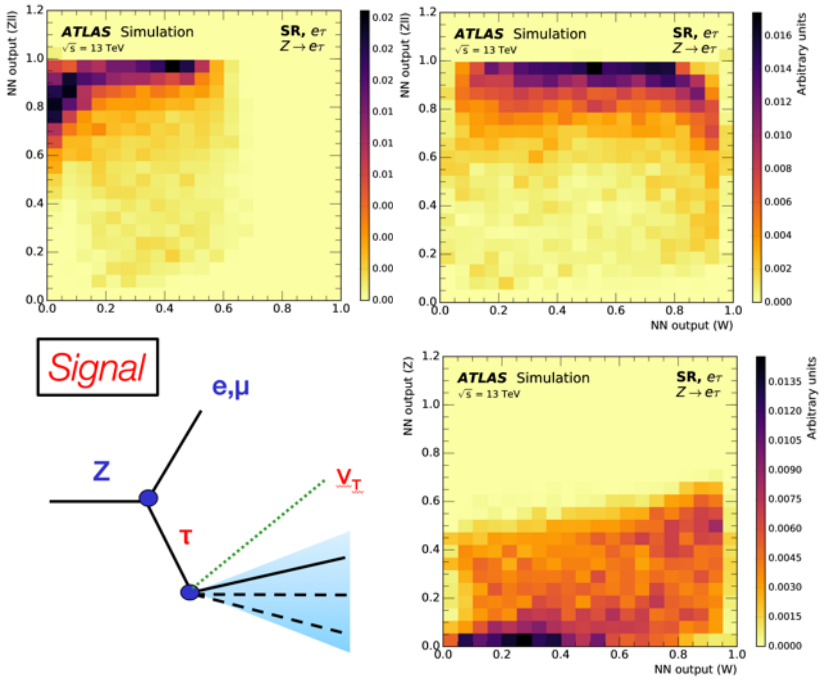
Zττ vs sig

Wlv τ vs sig

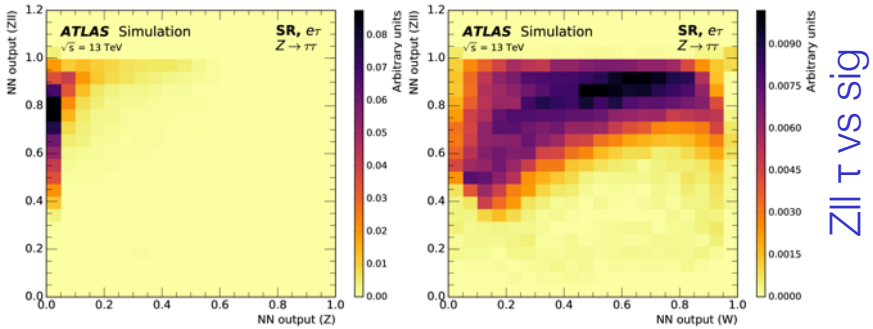
Zll τ vs sig

Zll τ vs sig

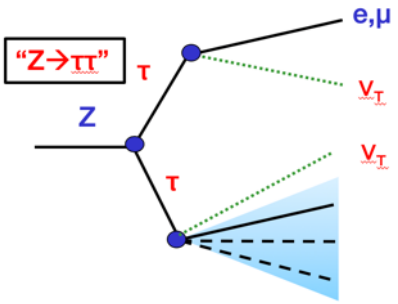
Zττ τ vs sig

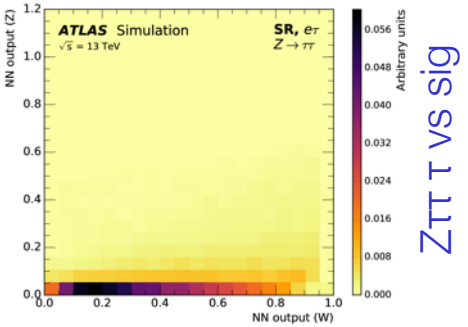


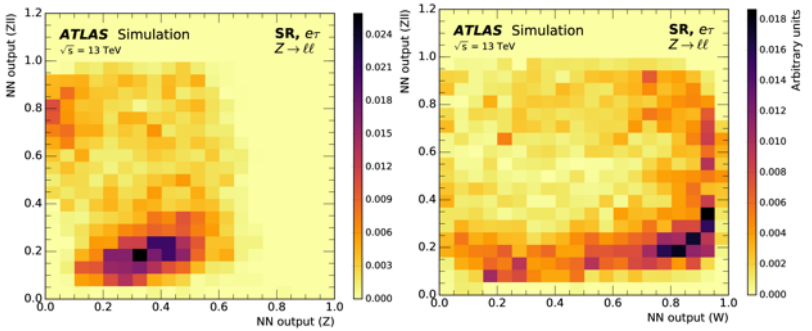
Signal



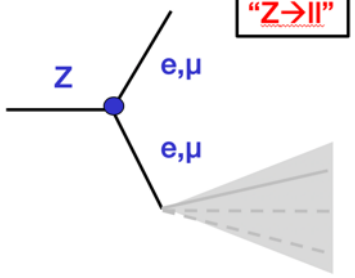
"Z→ττ"

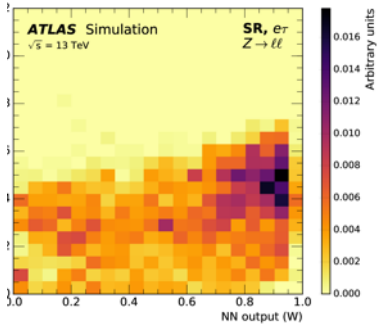


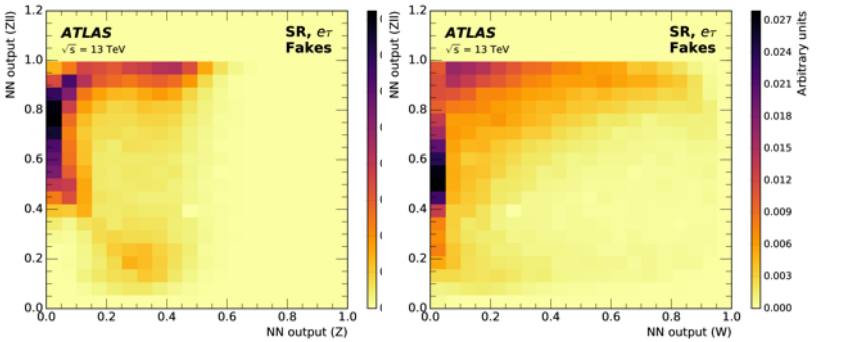




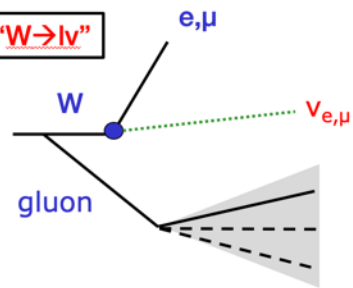
"Z→ll"

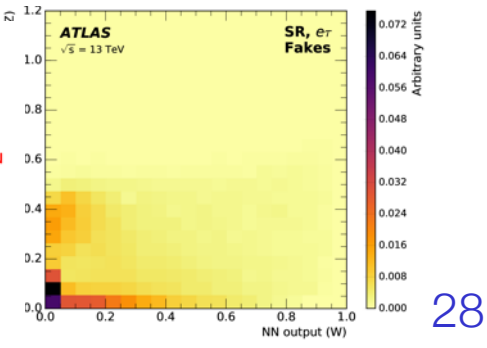




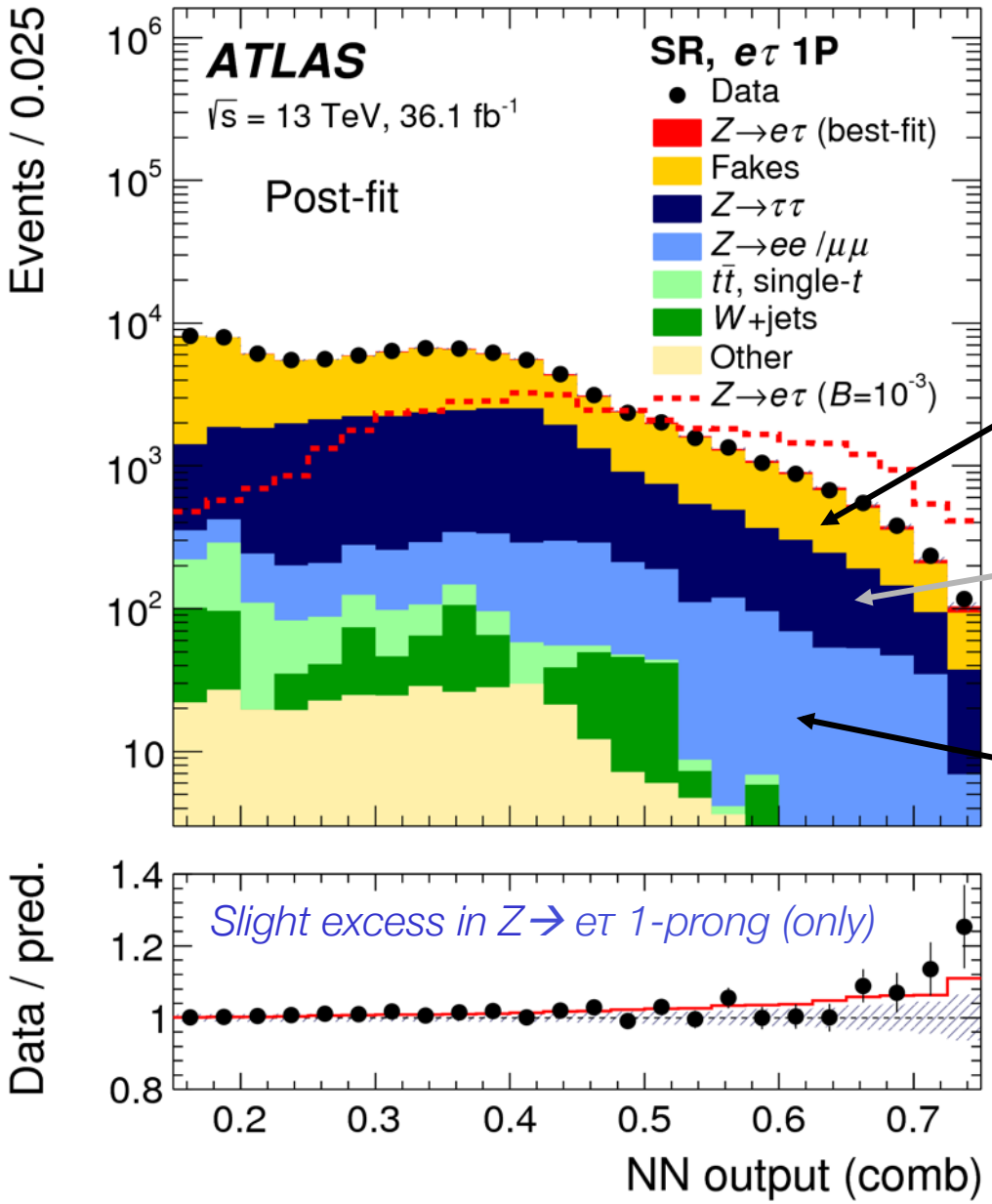


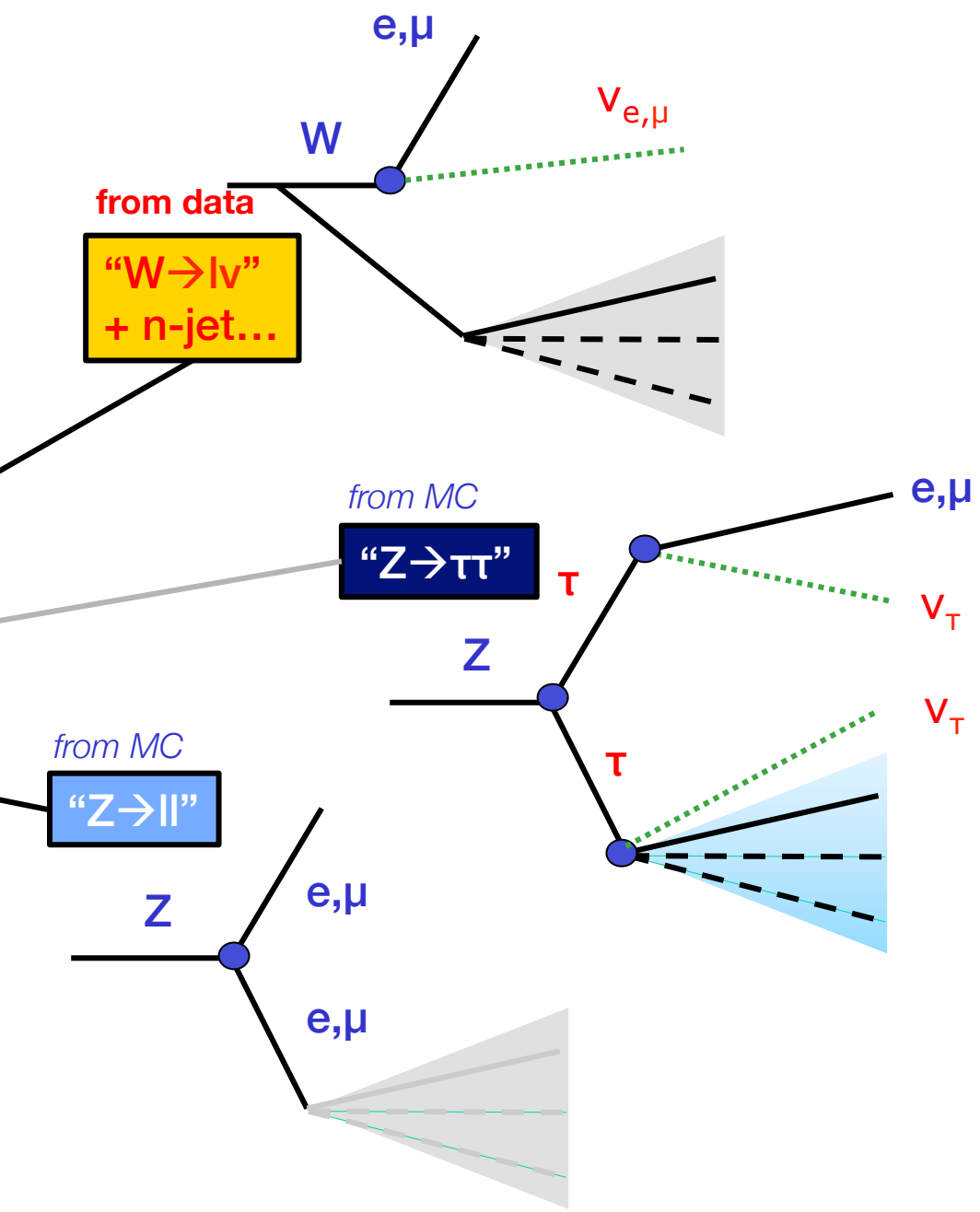
"W→lν"



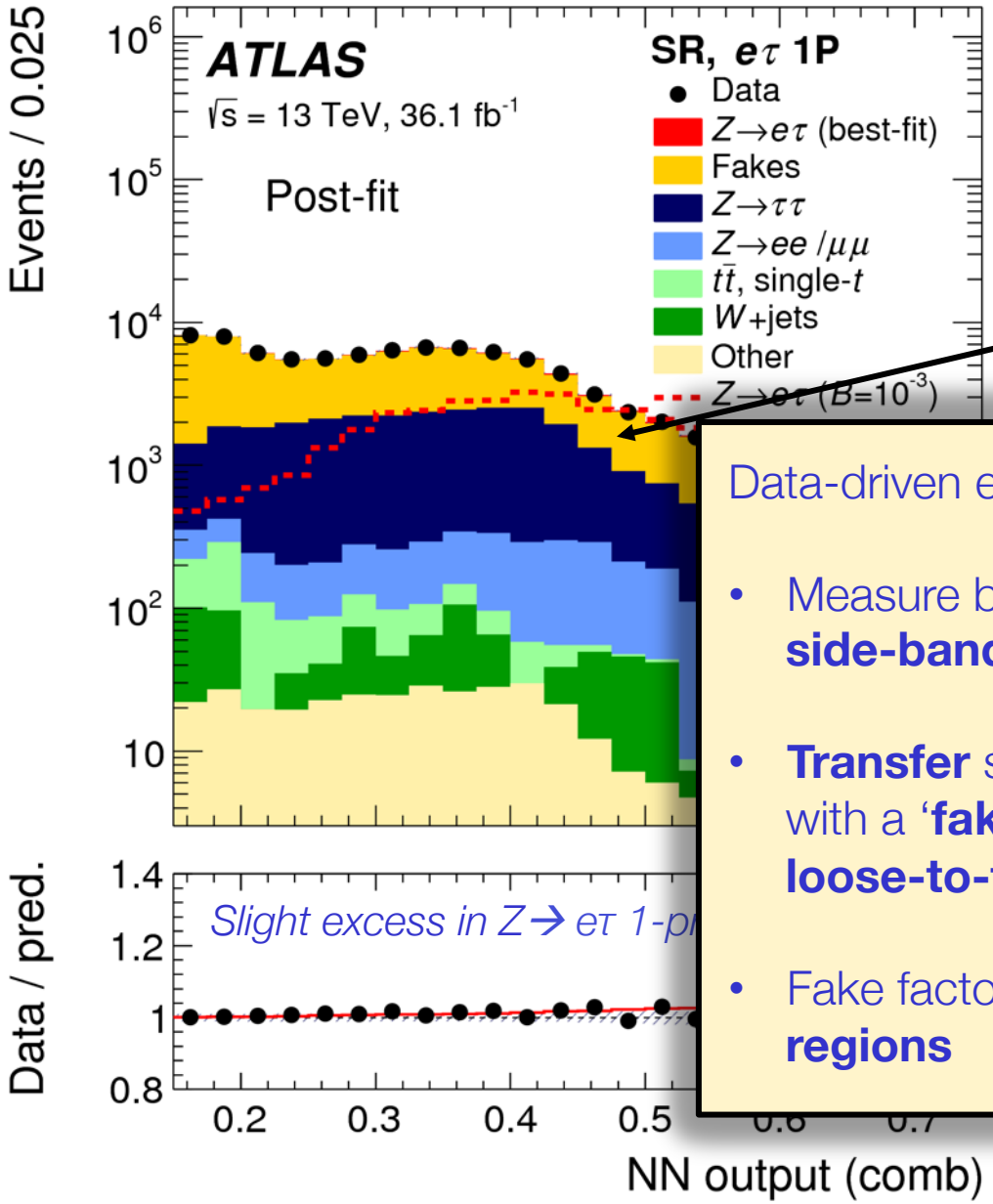


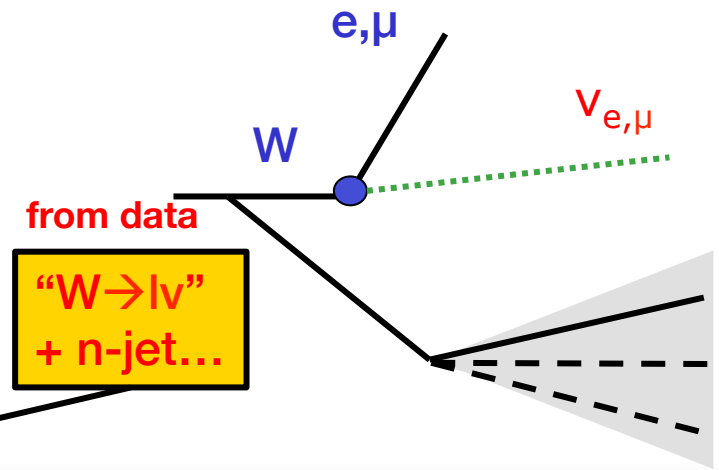
Z→τ/μe yield fits to combined 1D discriminant





Z→τ/μe yield fits to combined discriminant





Data-driven estimates of fake-τ background

- Measure bkg. rate in data in a fake-enhanced **side-band** where τ candidate fails 'tight' criteria.
- **Transfer** side-band prediction to signal region with a '**fake-factor**' correction accounting for **loose-to-tight efficiency ratio**
- Fake factor is measured in **dedicated calibration regions**

Z→τ/μe results

- Result of joint fit in (1p,3p) x (τe,τμ) channels to 36 fb^{-1} of Run-2 data
  - Impact theory systematics negligible – only small background estimated from MC
  - Systematics from fake factors and Wlν calibration region (up to 6%) are leading

significance of observed excess Z→eτ is 2.3σ

	$e\tau$	$\mu\tau$
$\mathcal{B}(Z \to \ell\tau)$	$(3.3^{+1.5}_{-1.4}) \times 10^{-5}$	$(-0.1^{+1.2}_{-1.2}) \times 10^{-5}$
$\mu(Z)$	$0.83^{+0.09}_{-0.07}$	$0.87^{+0.09}_{-0.08}$
μ(fakes_1P)	$1.18^{+0.06}_{-0.06}$	$1.12^{+0.09}_{-0.08}$
μ(fakes_3P)	$1.01^{+0.06}_{-0.05}$	$1.09^{+0.13}_{-0.14}$
Observed (expected) upper limit at 95% CL	$5.8(2.8) \times 10^{-5}$	$2.4(2.4) \times 10^{-5}$

fitted scale factor for σ(Z)

fitted scale factors for fake rates

Combined with ATLAS Run-1 (20.3 fb^{-1}) — **1.3 x 10^{-5}**

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LEP limits — 0.98 x 10^{-5} — 1.2 x 10^{-5}

Sensitivity on 36 fb^{-1} of data approaching LEP limits

Summary

- Olga's vision and pioneering efforts in trigger and analysis have been crucial to make the cLFV program in ATLAS a reality
- Olga has inspired many of her students, postdocs and collegues in her LFV work in ATLAS and most many still working on LFV to prepare the next generation of results
  - In particular her work on the ATLAS trigger will benefit many more analyses than the one I have shown today
  - Future LHC data samples (Run-2,3, HL) can bring improvements of orders of magnitude to Run-1 results
- As colleagues and friends of Olga we will miss her enormously