Search for $\tau \to 3\mu$ at ATLAS

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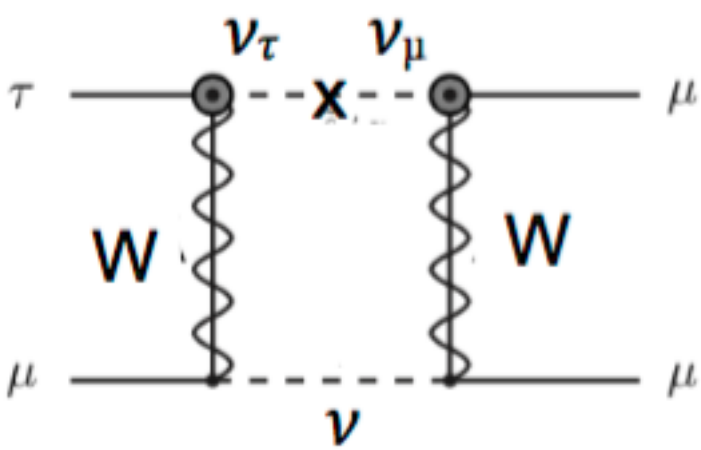
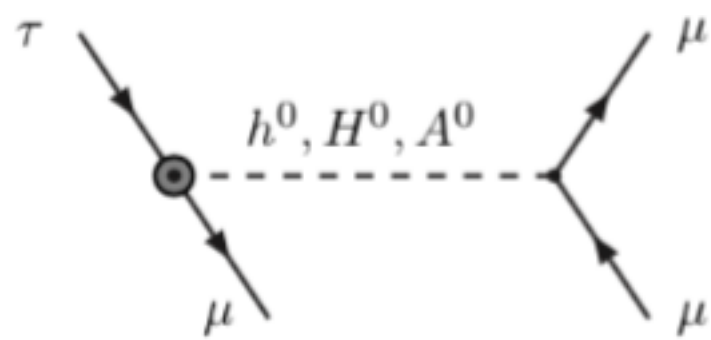
Why searching for $\tau \to 3\mu$

- LFV observed in neutral sector, but not in charged sector → Why?
- No preventing symmetry in SM: **BR($\tau \to 3\mu$) ≤ 10^{-14}**
- Observation of $\tau \to 3\mu$ provides a direct hint for new physics
- Several motivations from e.g. leptogenesis, $(g-2)_\mu$

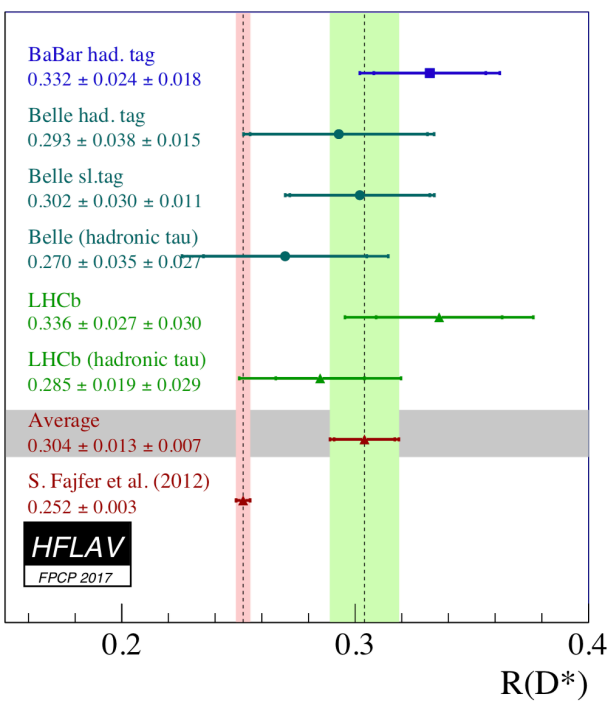
- Though, very challenging channel
  1. Triggering and reconstruction of low-p_T close-by muons
     - High energetic τ's are rare due to low cross-section, while low p_T τ's are difficult to reconstruct and isolation from jets
  2. Vertex reconstruction
  3. Hadronic activity at hadron colliders

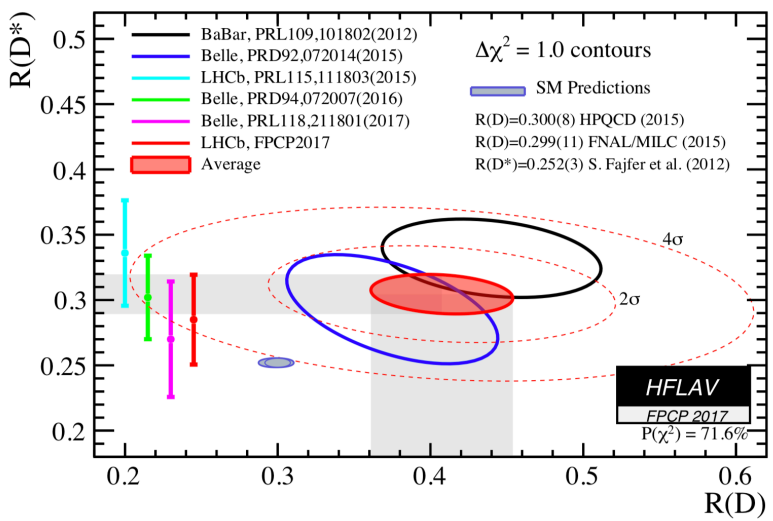




Experimental landscape

- Several searches performed previously without any hint for $\tau \to 3\mu$, thus placed upper limits on BR($\tau \to 3\mu$)
  - ATLAS: 3.7 * 10^{-7} (EPJC 76, 232 (2016))
  - Belle/BaBar: 2.1 * 10^{-8} (arxiv:1012.3733v2)
  - LHCb: 4.6 * 10^{-8} (arxiv:1409.8548)
- Other relevant results:
  - Belle $\tau \to \mu\gamma$: 4.5 * 10^{-8} (arxiv:0705.0650v2)
  - SINDRUM $\mu \to 3e$: 1.0 * 10^{-12} (Nucl.Phys.B299(1988)1)
  - Recent measurement on R(K*) and R(D)/R(D*) by LHCb indicate LFV might be realised in nature

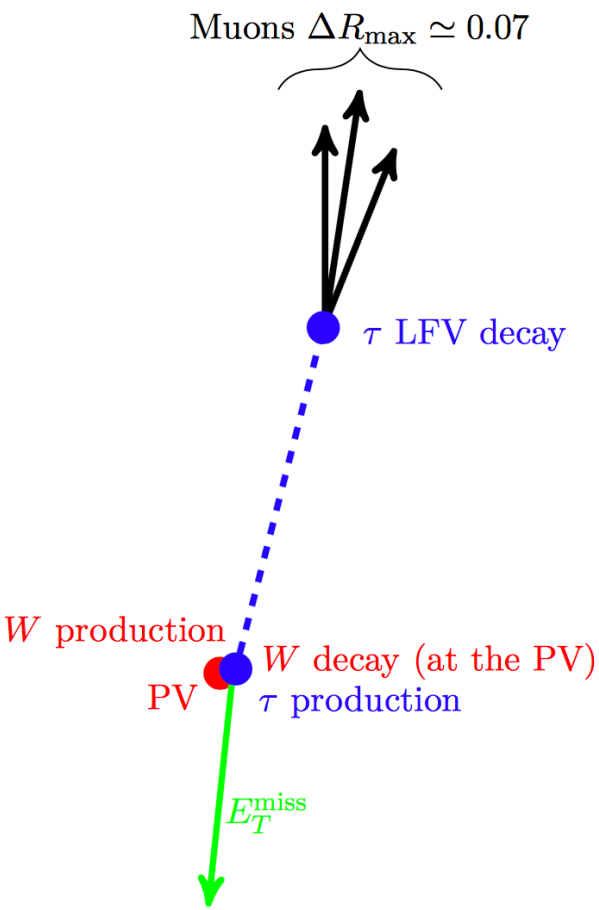




$$R(D^*) = \frac{BR(B^0 \to D^* \tau \nu_\tau)}{BR(B^0 \to D^* \mu \nu_\mu)}$$

How to search for $\tau \to 3\mu$ @ LHC

- Different sources of τ lepton at pp collisions
- Run-1 analysis used τ's originating from $W \to \tau\nu$ decays exploiting the full dataset of 20.3 fb^{-1} of 8 TeV data



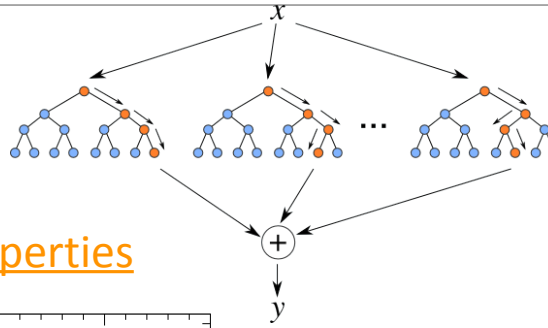
Event selection strategy

1. Loose pre-selection selecting W topology
   - MET, m_T
   - Vertexing
2. Three close-by muons
3. BDT (see following slides)
4. Tight selection
   - Tighten vertex selection
   - Remove low mass resonances (ω, ϕ, D_s)

$$\mathrm{Br}(\tau \to 3\mu) = \frac{N_{\mathrm{s}}^{\mathrm{UL}} / \mathcal{A}_{\mathrm{s}} \times \epsilon_{\mathrm{s}}}{N_{W \to \nu\tau}}$$

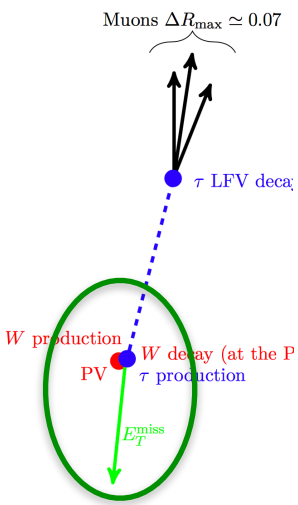
Analysis strategy (I)

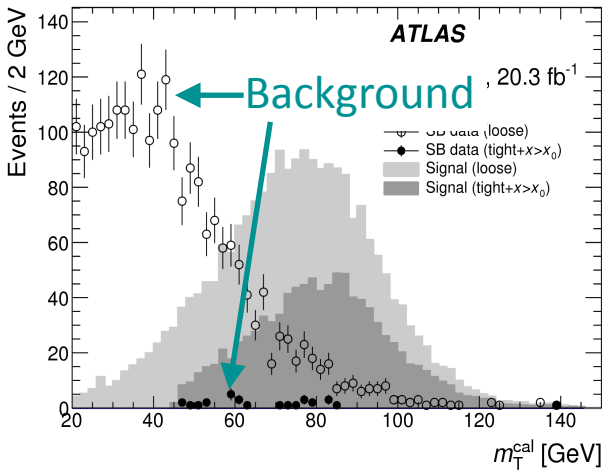
- Train BDT on sideband data (background) and MC signal
- Exploit full event topology

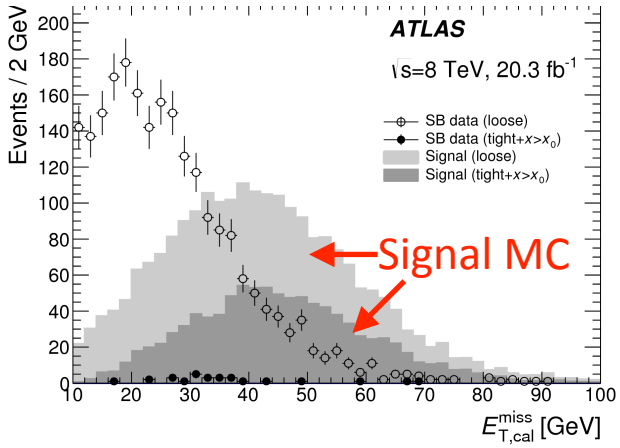


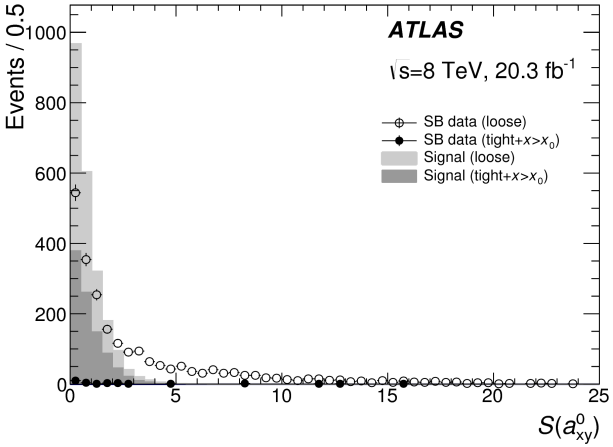
W decay properties

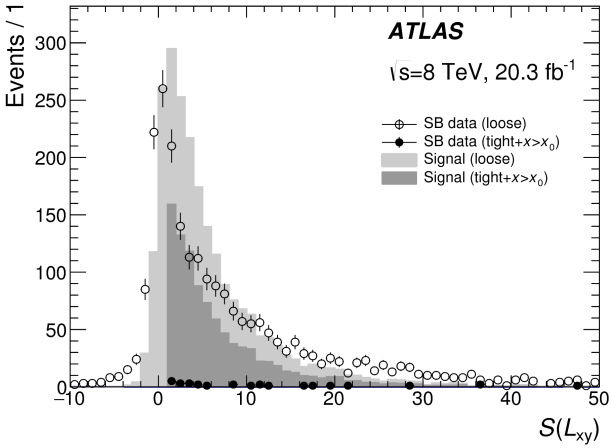
Tau decay properties

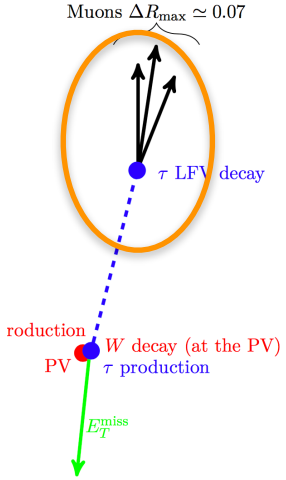






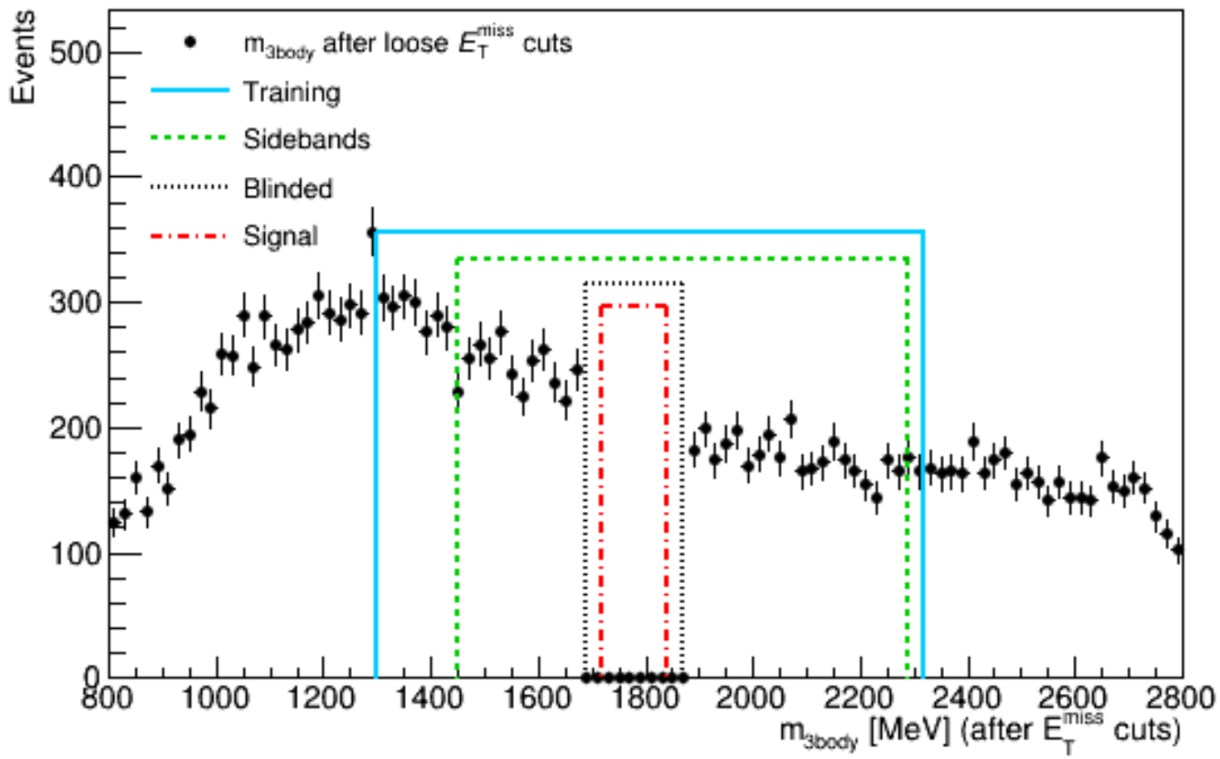






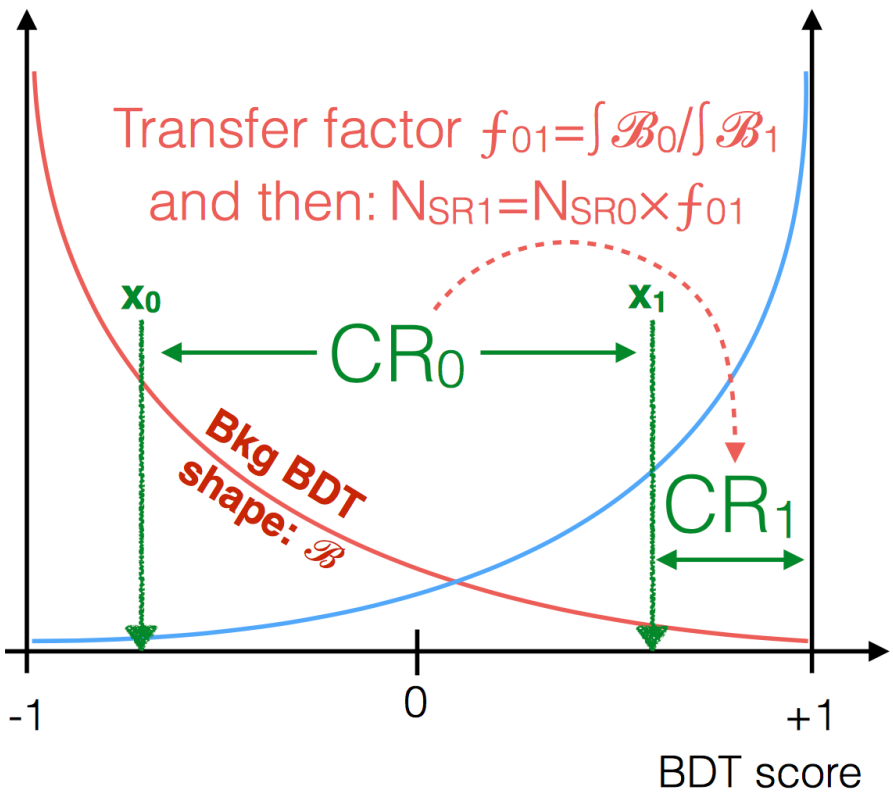
Analysis strategy (II)

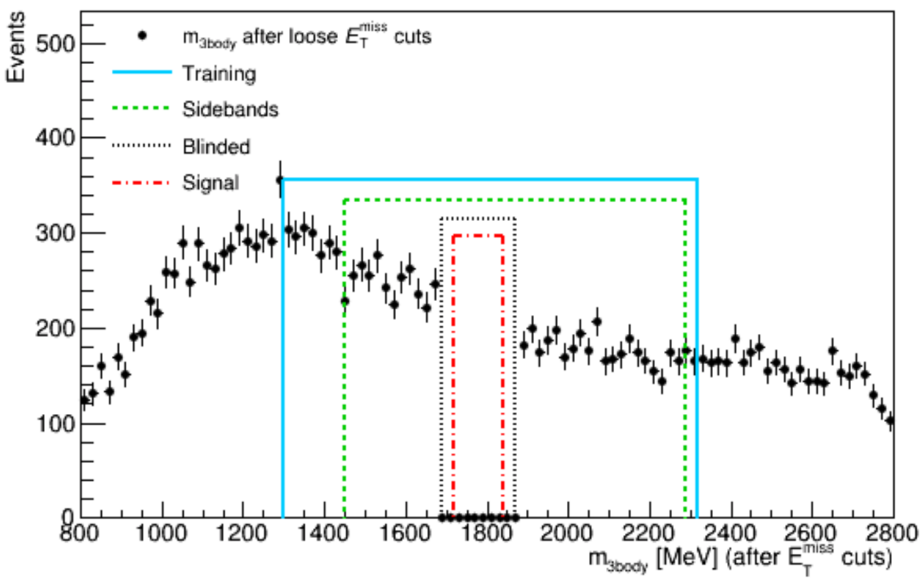
- Chose different sidebands in data
  - Training region: increased mass window around signal region designed to have sufficient statistics for training while remaining as close as possible to signal region, i.e. proper description of background in SR
  - Sidebands: Tighter than training selection, used to estimate background in SR via extrapolation (see next slide)
  - Blinded region: blind extended signal region in data to avoid any potential bias in BDT training



Analysis strategy (III)

- Given performance of BDT expectation of background events in signal and sideband region close to 0
- Thus, need
  1. Fit background BDT shape before applying BDT selection
  2. Fit 3-muon mass in sidebands in control region (CR0)
  3. Derive transfer factor between control (CR0) and signal region (CR1)
  4. Scale sideband mass fit after by transfer factor

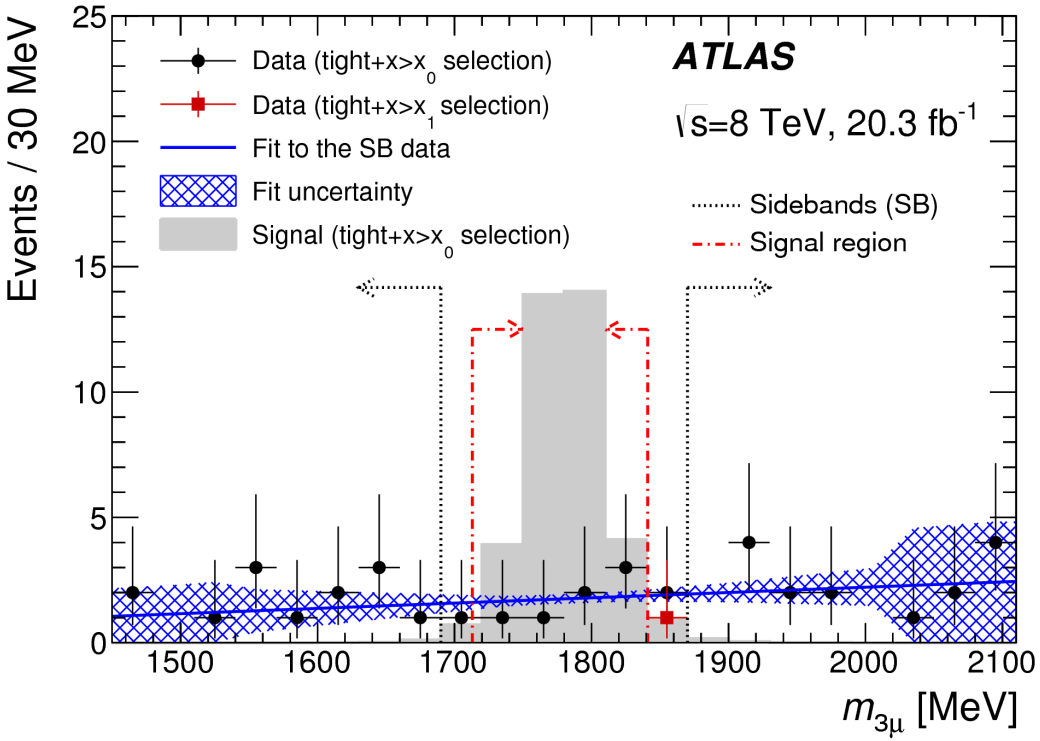




Search for $\tau \to 3\mu$ in W decays

- after applying tight BDT selection expect 0.193 background events, observe none in signal region and 1 event outside of signal region
- Dominant uncertainty from systematics
  - Mainly from background estimation from sideband region
- Place 90% CLs upper limit on branching ratio

BR($\tau \to 3\mu$) = 3.7×10^{-7}



$$\mathrm{Br}(\tau \to 3\mu) = \frac{N_s^{UL} / \mathcal{A}_s \times \epsilon_s}{N_{W \to \nu\tau}}$$

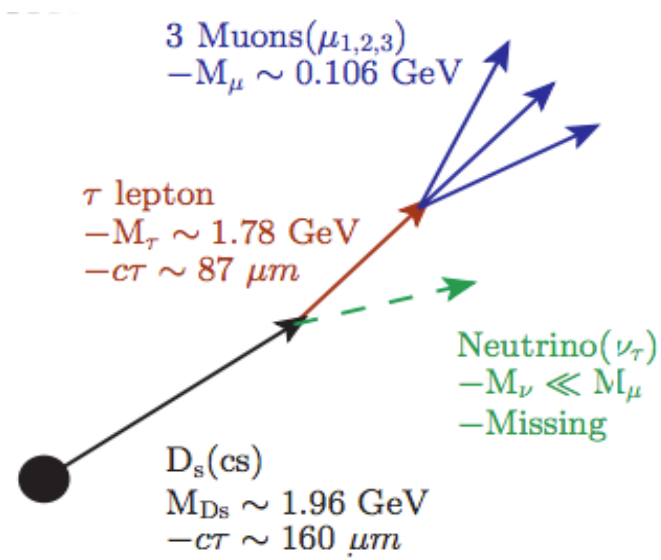
From signal MC

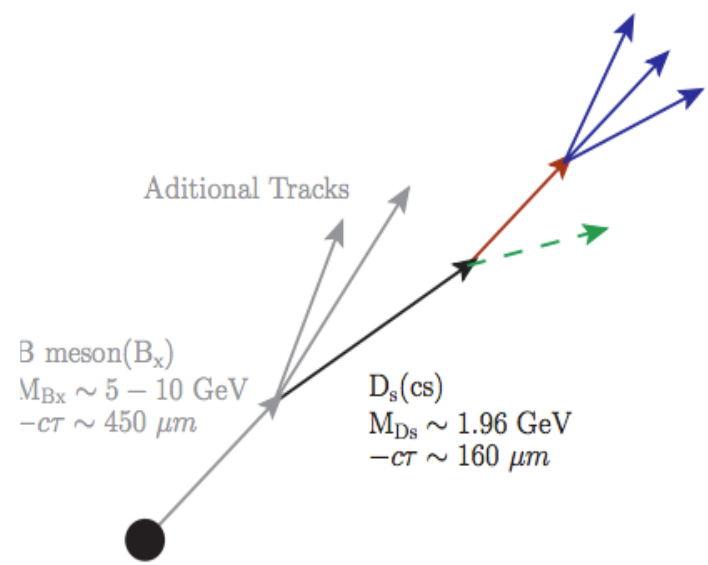
Rescaled 7 TeV measurement

How to search for $\tau \to 3\mu$ - run-2

- At pp collider τ's from heavy flavour decays provide an even better source, e.g. τ's from D_s decays, but also increased challenges to reconstruct 3 close-by muons within jets

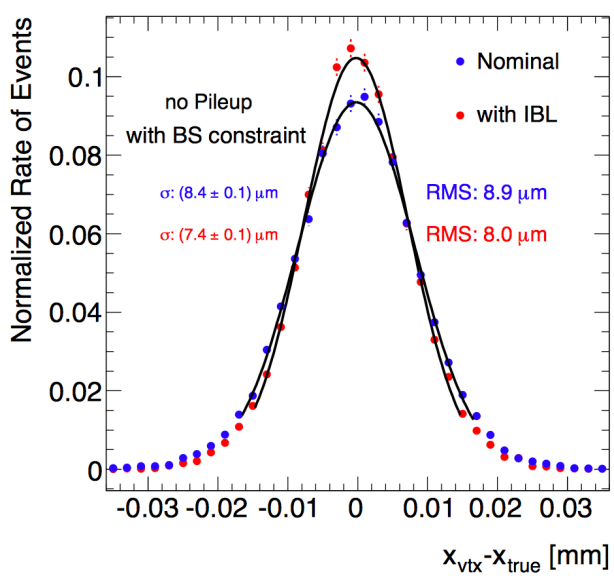
- Production cross section for D_s about one order of magnitude larger than W; BR($D_s \to \tau\nu$) = 5%
  - Expect ~ 10^{11} $D_s \to \tau$ events in 100 fb^{-1} with ~ 10^8 events including acceptance cuts
- W production cross section increased by ~factor 2 between 8 and 13 TeV
  - Expect ~10 times more signal events at end of run-2
  - But also background is expected to increase by factor 10

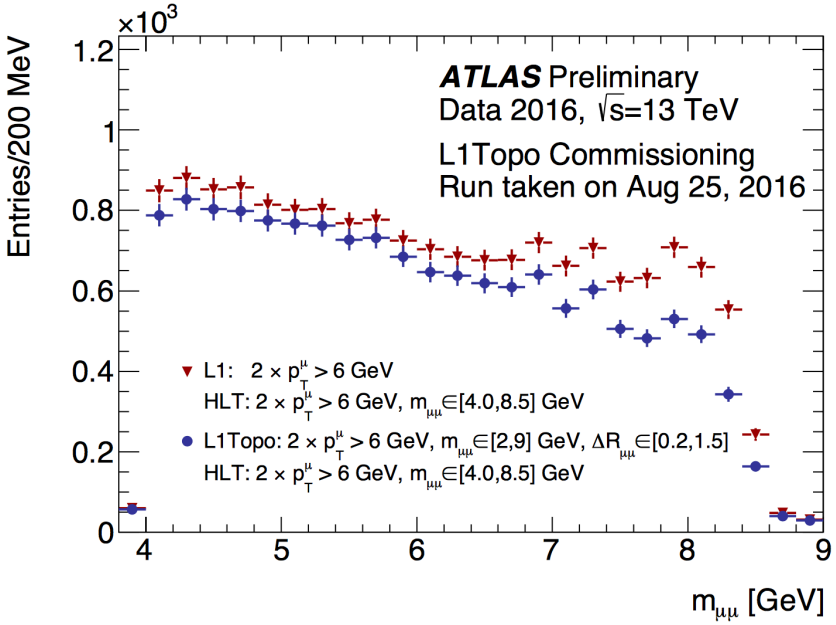




Prospects for run-2

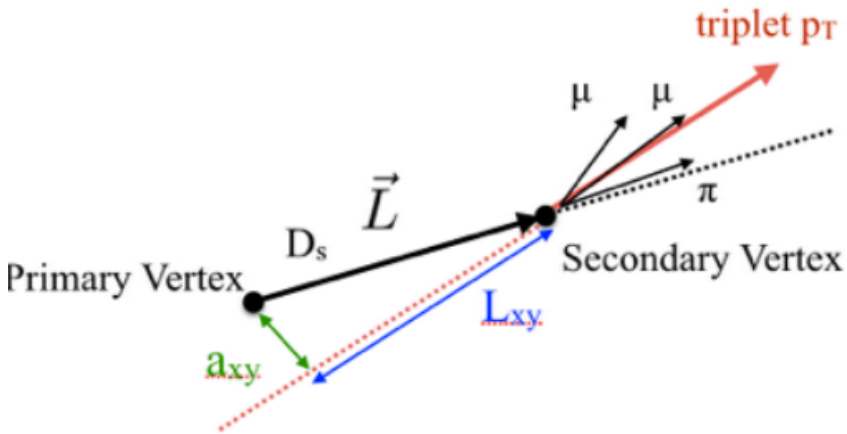
- Many improvements from lessons learned in run-1
- Improved reconstruction efficiency for close-by low p_T muons
- Improved trigger acceptance by more efficiency algorithms and topological selection at level-1 (L1Topo)
- New methods for jet flavour tagging (c-tagging) became available
    - Provide potential to separate signal and background





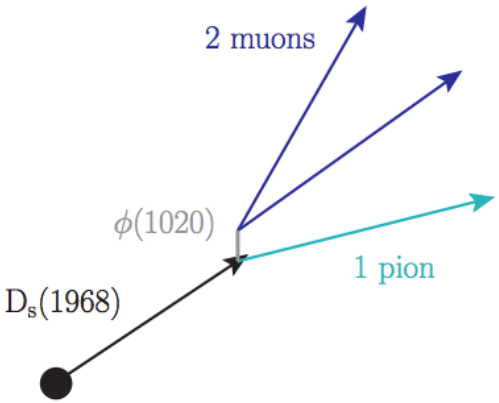
How to search for $\tau \to 3\mu$ - run-2

- Follow similar strategy as in run-1
  - Increase sensitivity by exploiting advanced machine learning techniques including BDTs and neural networks
  - Gain from increased statistics and improvements (see previous slide)
  - But muons have lower momenta compared to W channel which makes it even more challenging for trigger and reconstruction



Validation and normalisation channel $D_s \to \phi(\to \mu\mu) + \pi$

- Use $D_s \to \phi(\to \mu\mu) + \pi$ events as normalisation and validation channel
  - Similar kinematics to LFV signal channel
- Event selection based on vertexing and kinematic criteria
- Unbinned maximum likelihood mass fit using Gaussian for signal and exponential for background
  - Simultaneously fit D and D_s
  - Observe good agreement with PDG mass values
- Cross section measurement will provide D_s yields, i.e. won't rely on MC
- Planned to measure c- and b-fractions



Prospects for HL/HE

- Expect 3000 fb^{-1} after HL LHC upgrade
- D_s cross section increase by 8 % going to 14 TeV centre-of-mass energy and expect 30 times more luminosity
  - Increase statistics by more than a factor of 30
  - Assuming we can keep acceptance×efficiency can be maintained at similar level we could probe branching ratios up to $\mathcal{O}(8)\times10^{-9}$
- Critical component will be trigger
  - Need to ensure sufficiently low threshold triggers
- Optimised jet flavour tagging algorithms for low-p_T jets could improve sensitivity

Conclusion

- Analysis of W channel in run-1 proved that ATLAS can search for LFV decays of τ leptons
  - No events observed in data, thus set upper limits on BR($\tau \to 3\mu$)
  - Not competitive with Belle exclusion, yet
- Efforts on search for $\tau \to 3\mu$ decays continue in run-2
  - Extend search towards τ decays in heavy flavour jets
  - Several improvements on both, the detector and the analysis
    - More efficient triggers and reconstruction
    - Expected improved resolution due to additional b-layer installed in LS1
  - Aim to repeat W channel search and combine with heavy flavour channel
  - Expect limit competitive with most stringent bounds from Belle, i.e. aim for sensitivity of BR($\tau \to 3\mu$) ~ few 10^{-8} on the full run-2 dataset
- Prospect studies towards HL/HE have been started
  - full picture will become available in next few months aiming to be included in Yellow report