Search for Soft Unclustered Energy Patterns containing muons in the final state in *pp* collisions at 13TeV with the ATLAS detector

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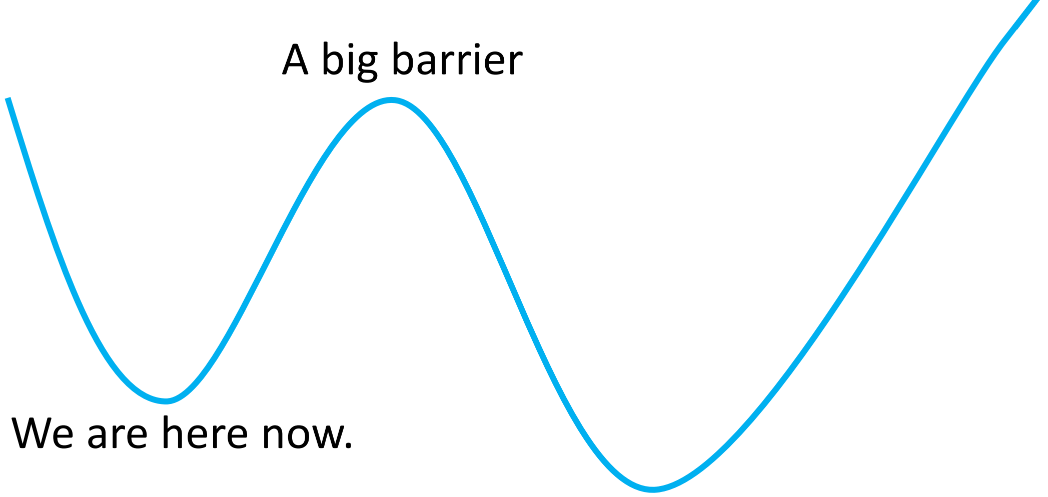
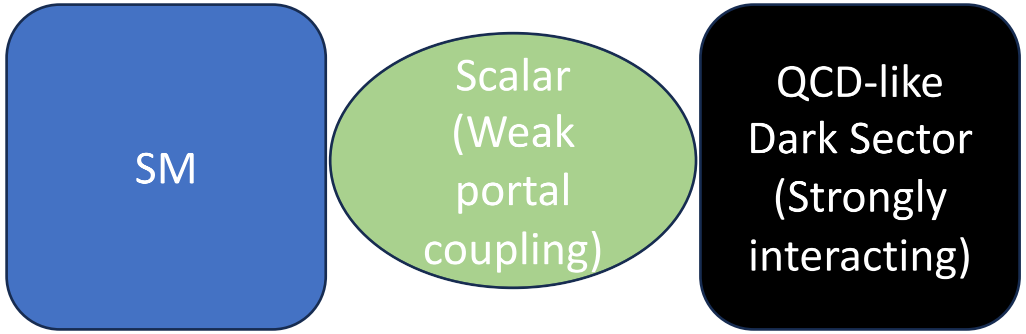
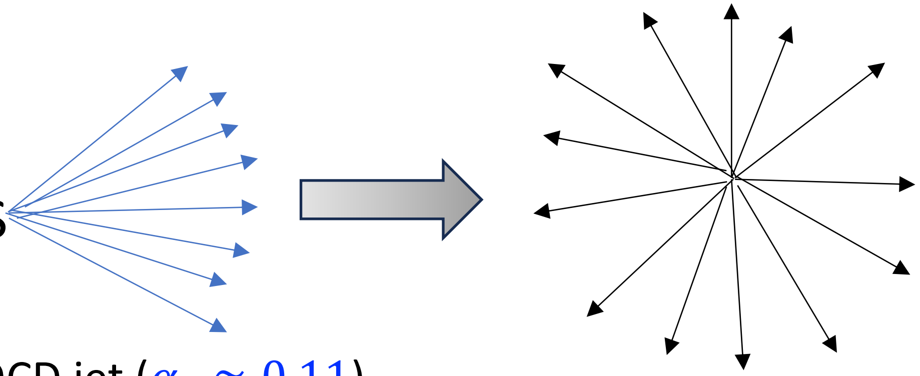
Motivation

- Hidden valley models could explain the hierarchy problem and provide candidates for the dark matter.
- They predict a dark sector in which the interaction is so strong that the dark particle could undergo a QCD-like parton showering.
- The dark sector is weakly coupled to SM via a portal, e.g., a heavy Scalar mediator.
- The main feature is that a dark showering appears as a group of large number of soft particles isotropically distributed, i.e. Soft Unclustered Energy Pattern (SUEP) instead of a jet.
- This unconventional search complements those using jets:
  - Di-jet resonance, semi-visible jets, emerging jets
- The presence of muons also complements previous CMS searches using fully hadronic final state

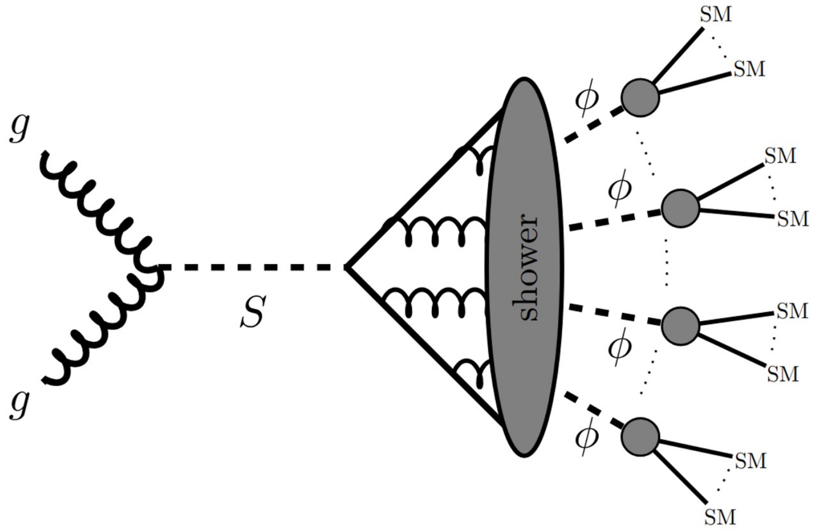


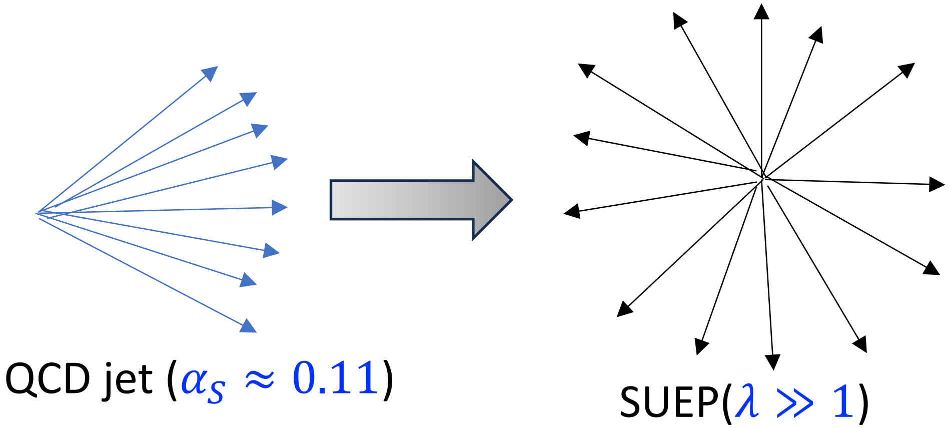




Signal Models

- SUEP features:
  - High multiplicity, Low momentum, Isotropic distribution
- Signal process:
  - a heavy Scalar mediator is produced via the gluon gluon fusion
  - It decays into the dark sector (assuming BF=1) and produces a large number of the lightest dark mesons, ϕ, in the dark showering.
  - The dark mesons' momenta are modeled by a Maxwell-Boltzman distribution with a Temperature parameter, T.
  - The dark meson is assumed to decay to pairs of dark photons, A'.
  - The dark photon A' could decay to SM particles (leptons and hadrons)
  - We have four parameters:
    - Scalar mediator mass (m_S): 125, 400 and 750GeV
    - Dark meson mass (m_ϕ): 1.5, 3 and 5 GeV
    - Temperature parameter (T): $\frac{2}{3}m_\phi, m_\phi, \frac{3}{2}m_\phi$.
    - Dark photon mass ($m_{A'}$): 0.3, 0.5 and 0.7 GeV
  - Key assumption: A' could decay to muons!
  - Only ggF production mode considered



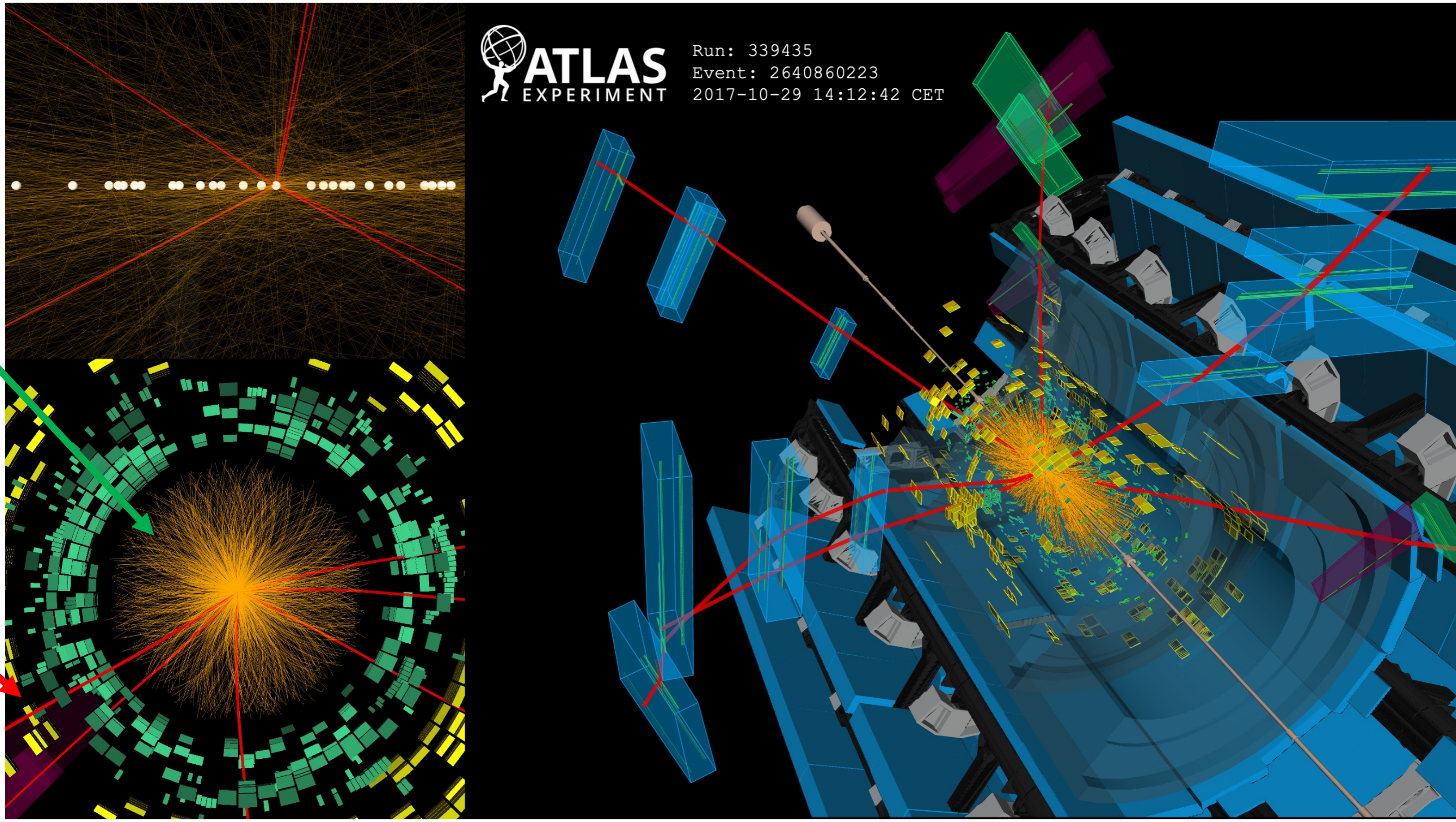


Signal topology

Large number of soft tracks from the same PV

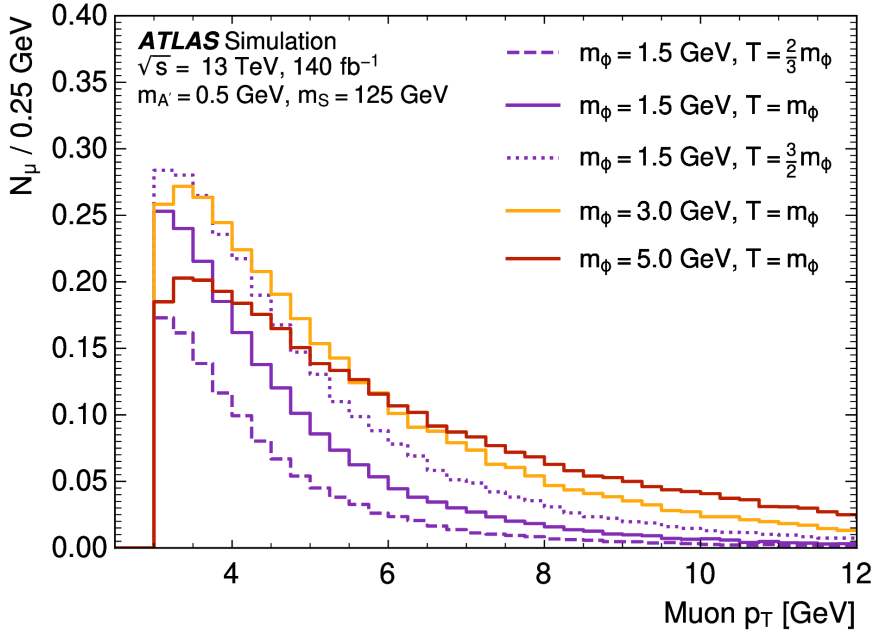
Multiple prompt muons

The tracks and muons distributed isotropically



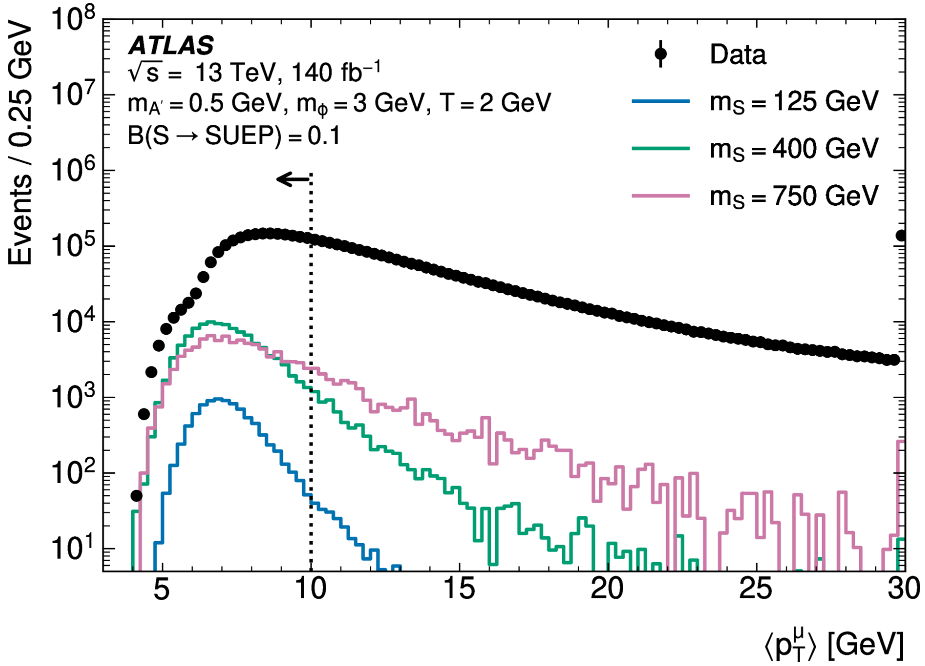
Event reconstruction

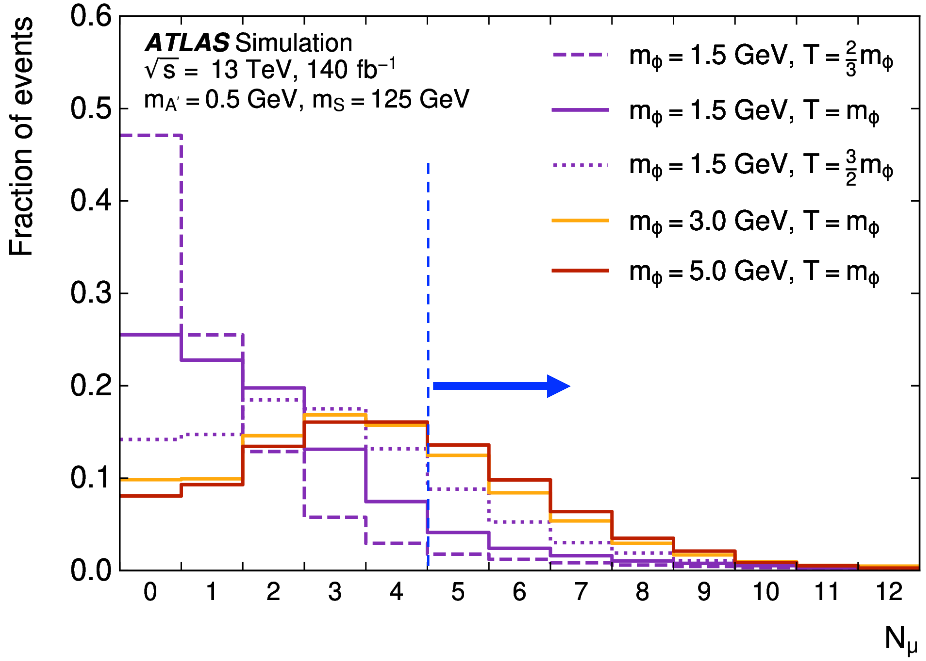
- ID track reconstruction:
  - TightPrimary working point,
  - $p_T > 0.5\text{GeV}, |\eta| < 2.5,$
  - $|\text{d}_0| < 0.5\text{mm}, |\Delta z_0 \sin\theta| < 0.5\text{mm}.$
- Muon reconstruction:
  - combining Inner Detector and Muon Spectrometer
  - satisfying the lowPt working point
  - $p_T > 3GeV, |d_0| < 2\text{mm}$ and $|\Delta z_0 \sin\theta| < 3\text{mm}.$
- Triggers:
  - HLT_3mu6 for 2015/2016: at least 3 muons with pT>6 GeV
  - HLT_4mu4 for 2017/2018: at least 4 muons with pT>4 GeV
  - The single muon trigger efficiencies are measured using $Z \rightarrow \mu^+\mu^-$ events. They are combined to give the multi-muon trigger efficiencies, ranging from 1% for T=1GeV signals to almost 100% for T=5GeV signals.
  - Feature: QCD background suppression due to multi-muon triggers



Event selection

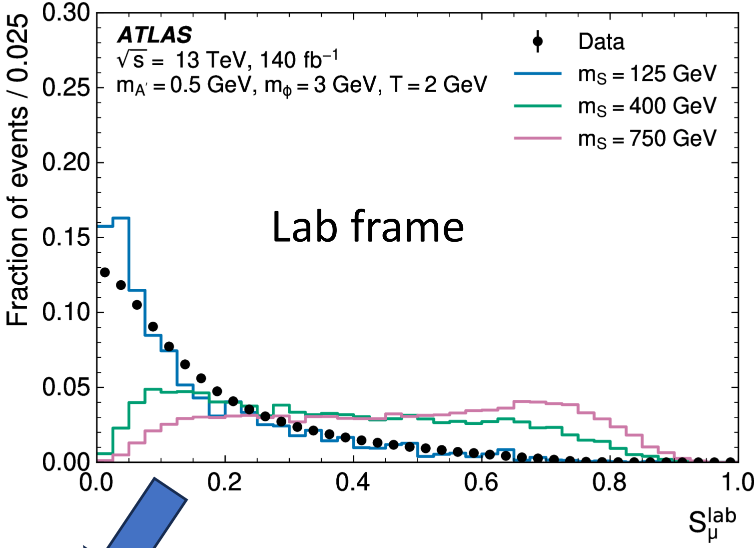
- Pass the trigger selection and matching
- At least one vertex with at least two associated tracks with pT>0.5GeV
- Average muon momentum: $\langle p_T^\mu \rangle < 10\mathrm{GeV}$ to suppress the QCD multijet background
- The leading muon impact-parameter significance: $\frac{\mathrm{d}_0(\mu_1)}{\sigma_{\mathrm{d}_0(\mu_1)}} < 3$ to suppress the heavy-flavour background
- Muon multiplicity: at least 5 muons





Two powerful observables (1)

- Muon sphericity (SUEP features in isotropic distribution)
  - calculated in the CoM system of the selected muons
  - It is 0 for pencil-like configuration and 1 for isotropic configuration
  - Its value is low for background while high for signal.

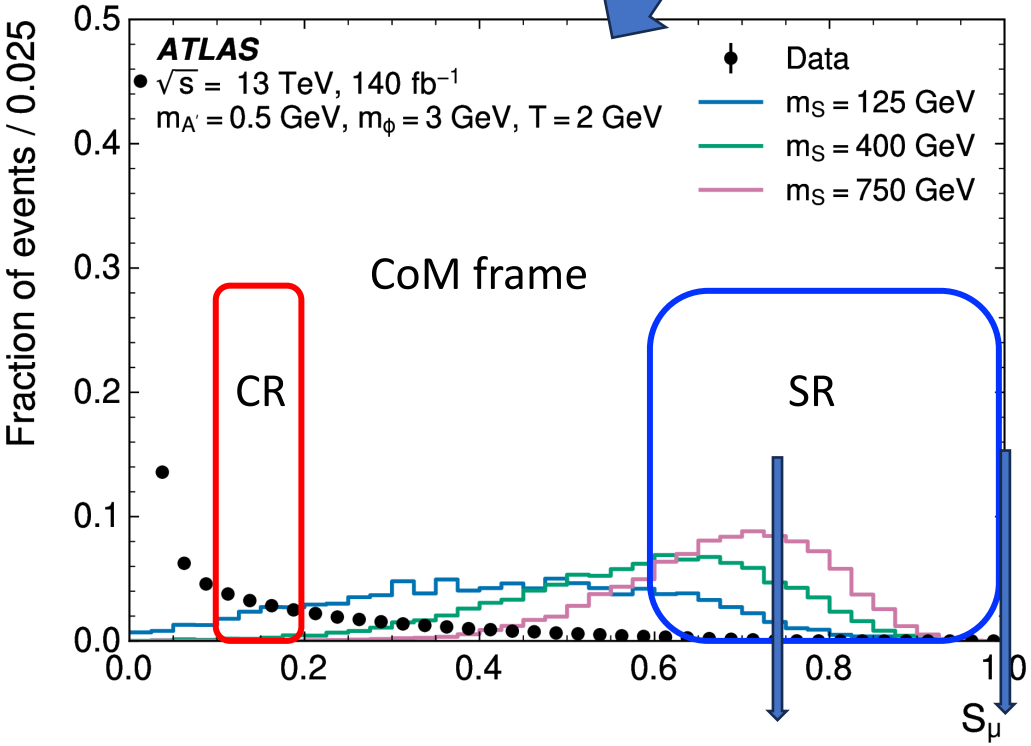


$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

α, β: spatial indices

$$S_\mu = \frac{3}{2}(\lambda_2 + \lambda_3)$$

λ: eigenvalues

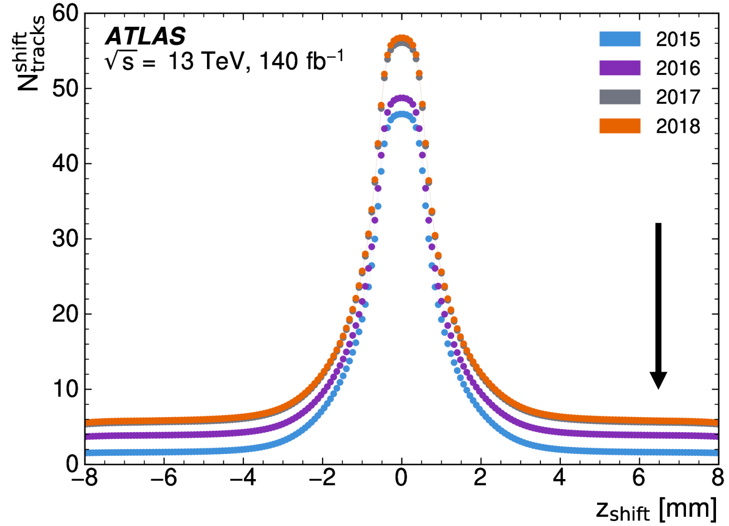


Background estimation:

- $0.1 < S_\mu < 0.2$: used for background estimation
- $0.6 < S_\mu < 1$: used for signal searching (signal region)

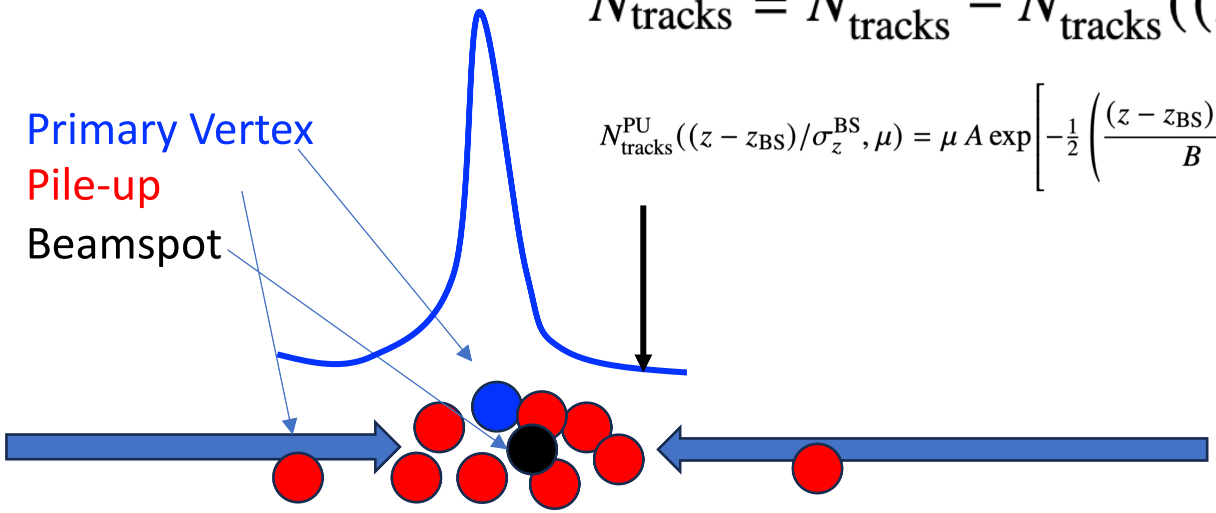
Two powerful observables (2)

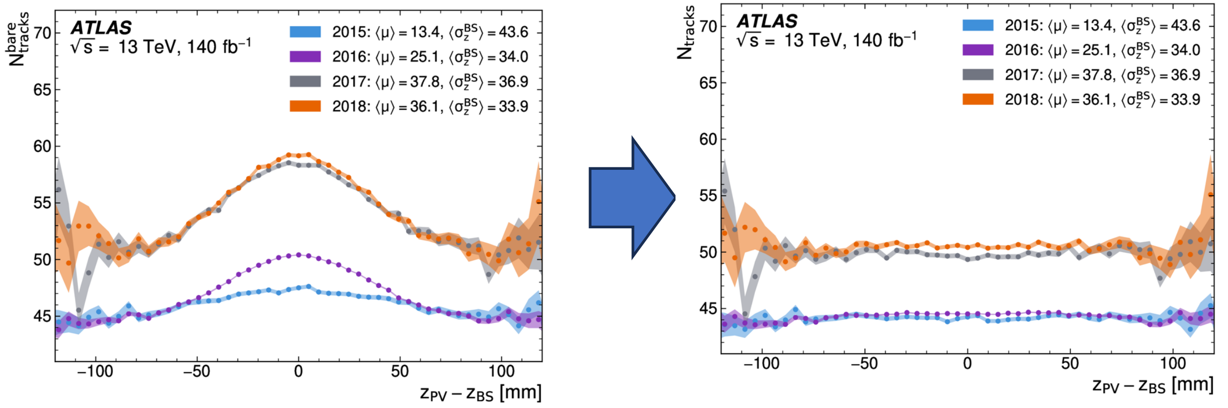
- Track multiplicity (SUEP features in large number of soft tracks):
  - tight requirement $|\Delta z_0 \sin\theta| < 0.5\mathrm{mm}$ to suppress pile-up tracks
  - Perform the pile-up correction in a data-driven way
    - Manually shift Z_{PV} and count the number of tracks
    - Fit using a Gaussian + a constant
    - The tail part (z=6.5mm) gives the estimation of the pileup contribution.
    - Uncertainty estimated using the $Z \to \mu^+\mu^-$ events



$$N_{\text{tracks}} = N_{\text{tracks}}^{\text{bare}} - N_{\text{tracks}}^{\text{PU}}((z_{\text{PV}} - z_{\text{BS}})/\sigma_z^{\text{BS}}, \mu)$$

$$N_{\text{tracks}}^{\text{PU}}((z - z_{\text{BS}})/\sigma_z^{\text{BS}}, \mu) = \mu\, A \exp\left[-\frac{1}{2}\left(\frac{(z - z_{\text{BS}})/\sigma_z^{\text{BS}}}{B}\right)^2\right] + N_0$$

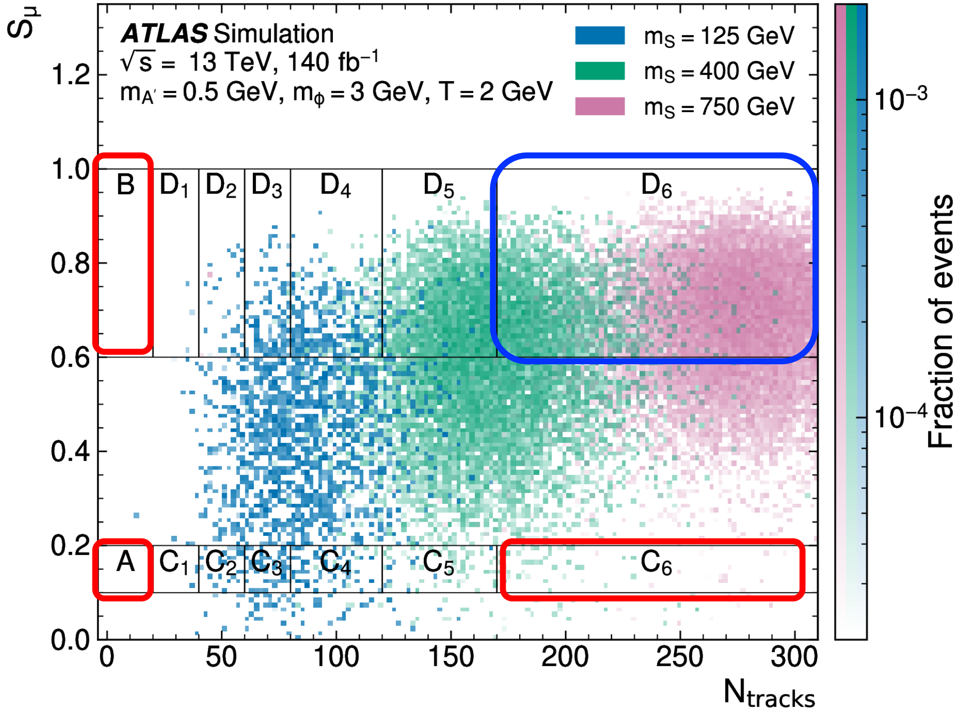


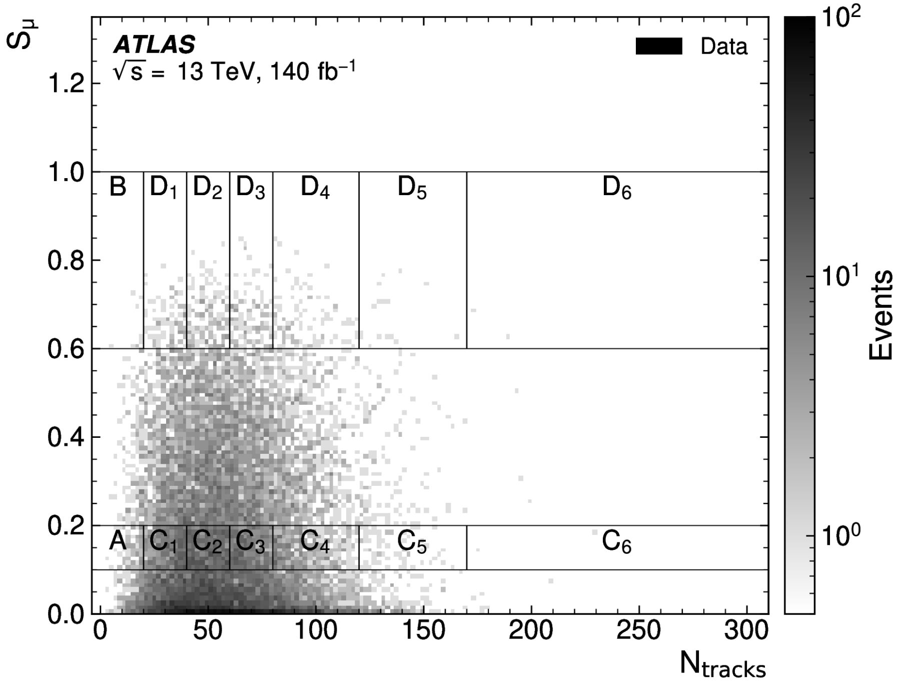


Background modeling strategy

- ABCD method:
  - muon sphericity V.S. track multiplicity
  - Signal: high muon sphericity and high track multiplicity (D1-D6)
    - 6 bins to probe different signal models and maximize the sensitivity
  - Background: low muon sphericity or low track multiplicity (A,B, C1-C6)
- Background prediction in Signal regions: $B \times \frac{C_i}{A}$
- Key assumption of the method: no significant correlation for the background

Signal MC



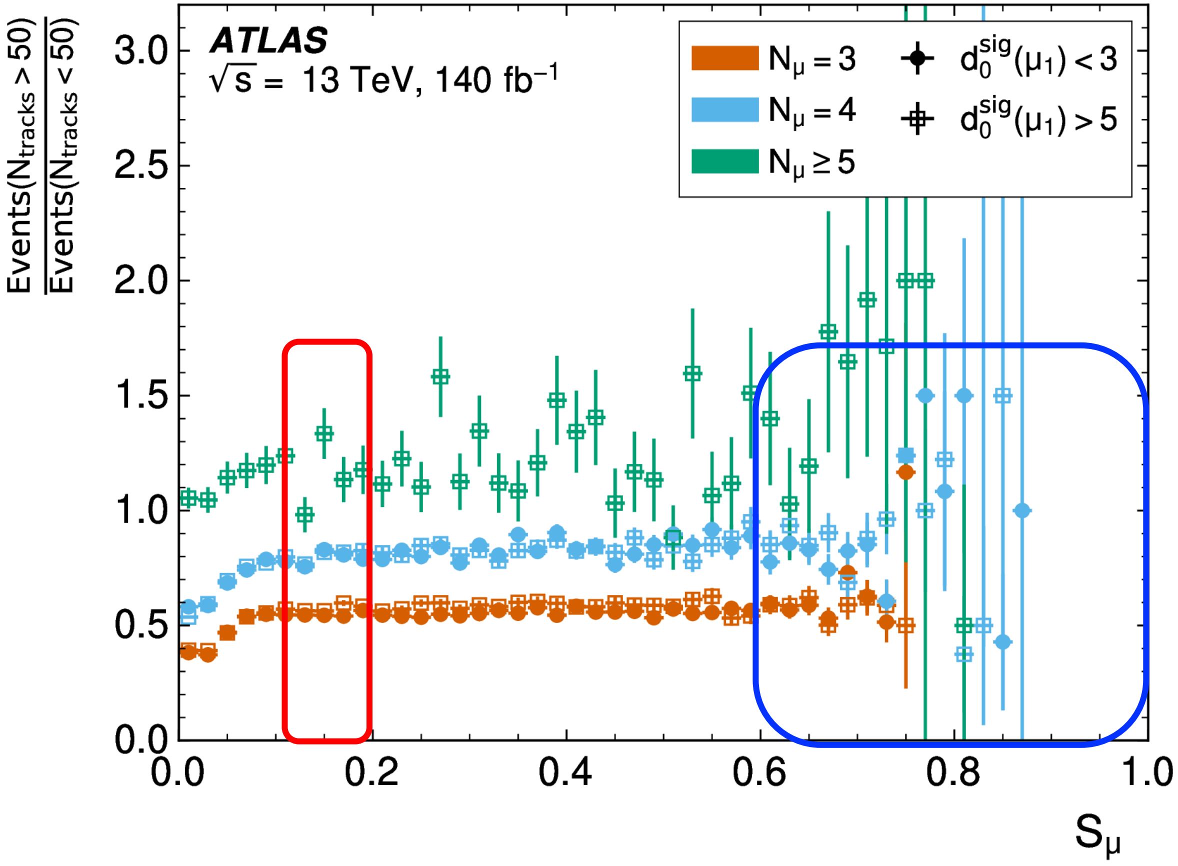


Data

Background modeling in the validation regions

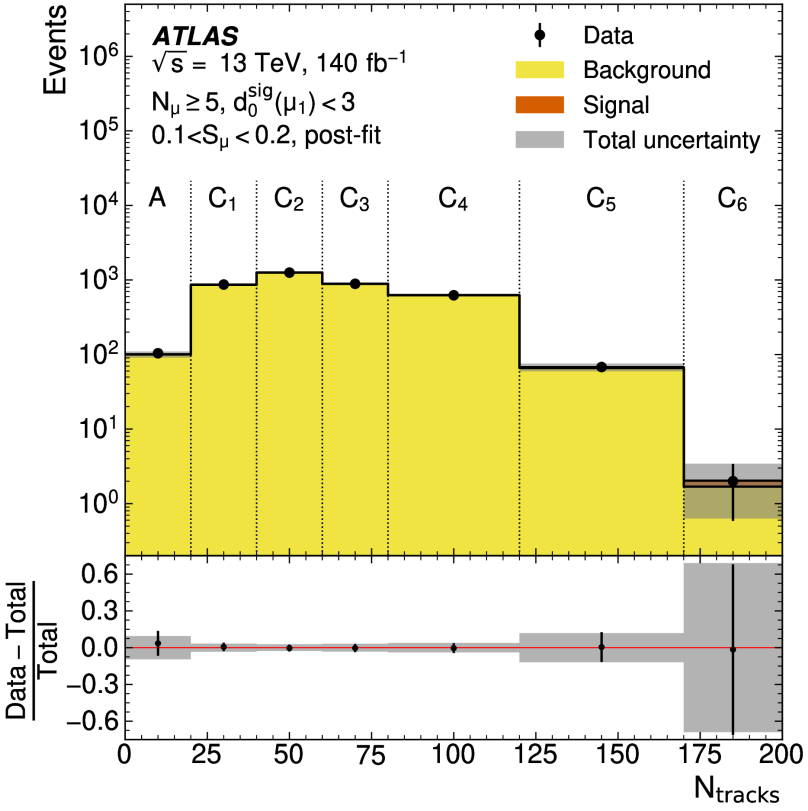
Requirements		Region purpose
$N_\mu = 3$	$d_0^{\text{sig}}(\mu_1) > 5$	validation
	$d_0^{\text{sig}}(\mu_1) < 3$	validation
$N_\mu = 4$	$d_0^{\text{sig}}(\mu_1) > 5$	validation
	$d_0^{\text{sig}}(\mu_1) < 3$	validation
$N_\mu \geq 5$	$d_0^{\text{sig}}(\mu_1) > 5$	validation
	$d_0^{\text{sig}}(\mu_1) < 3$	search

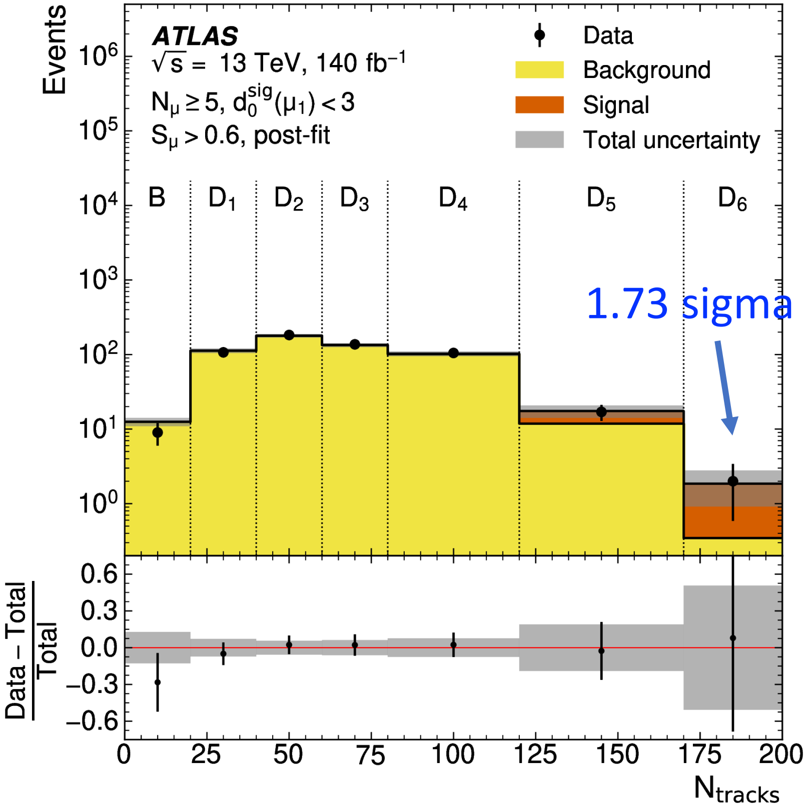
- Check the correlation between S_μ and N_{tracks}.
- No significant correlation for $S_\mu > 0.1$.
- For events with $S_\mu < 0.1$, the muons are found to be mostly in two jet-like structures with aligned axes.
- Therefore, we exclude $S_\mu < 0.1$. The signal region $S_\mu > 0.6$ is optimized for maximal sensitivity.
- The data-bkg agreement is good in most of the VRs. The remaining mismodeling is considered as a systematic uncertainty.



Statistical analysis in the signal regions

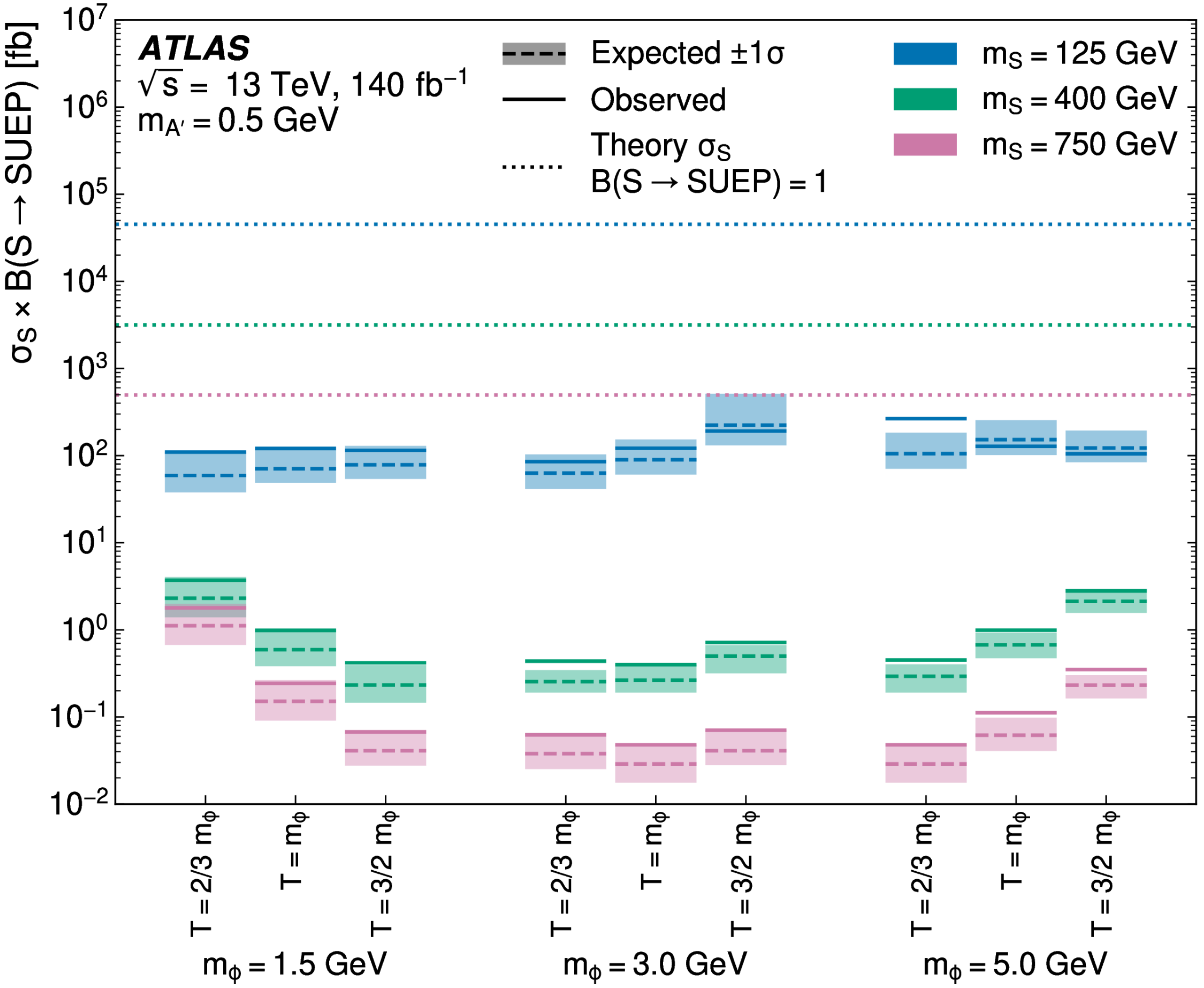
- No significant deviation seen from the background prediction
- Largest excess is seen for the signal with $m_S = 400GeV, m_\phi = 3GeV, T = 3GeV, m_A' = 0.7\ GeV$ with a local significance of 1.73 sigma.





Upper limits

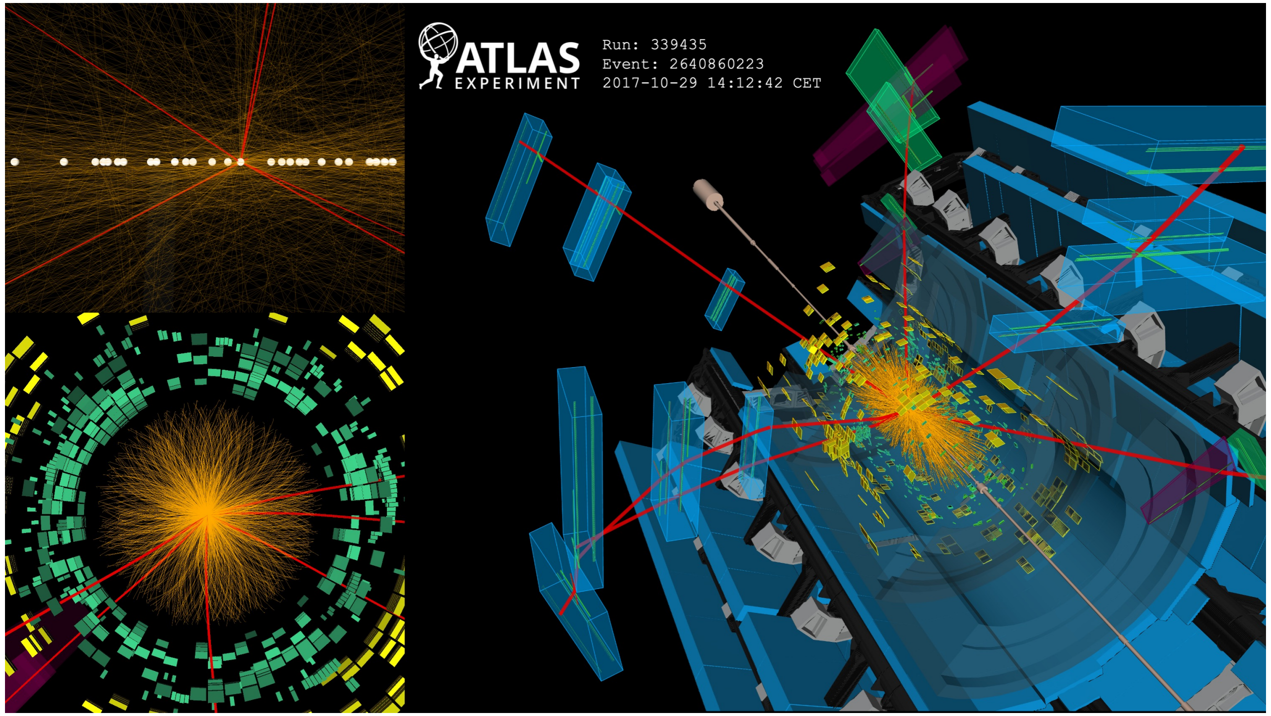
Lephad (mA'=0.5GeV)



- Limits are provided on the production cross section at 95% Confidence Level (assuming 100% branching fraction of the mediator going to SUEP) .
    - 0.05 fb for 750 GeV
    - 0.4 fb for 400 GeV
    - 70 fb for 125 GeV (corresponding to B(H->SUEP)~0.2%)

Summary

- Based on the Run2 data (2015-2018), the SUEPs are searched with the multi-muon final state.
- It is complementary to CMS searches with hadronic final state.
- No significant excess over the background is observed. Stringent upper limits on the SUEP production cross section are provided.
- Assuming the 125GeV mediator to be the Higgs, BR(H→SUEP) is ~0.2%.
- Stay tuned for more wonderful results on dark QCD in the near future.



- BACK UP

Sphericity examples

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}, \qquad S_\mu = \frac{3}{2}(\lambda_2 + \lambda_3)$$

- Example 1: one particle with momentum P=(1,0,0)
  - S_{11}=1, other S_{ij}=0; the eigenvalues are 1, 0, 0. ➔ S=0
- Example 2: two particles with momentum P=(1,0,0,), (-1, 0, 0)
  - S_{11}=1, other S_{ij}=0; the eigenvalues are 1, 0, 0. ➔ S=0
- Example 3: three particles with momentum P=(1,0,0), (-0.5, sqrt(3)/2,0), (-0.5, -sqrt(3)/2,0). ➔ S=0.75

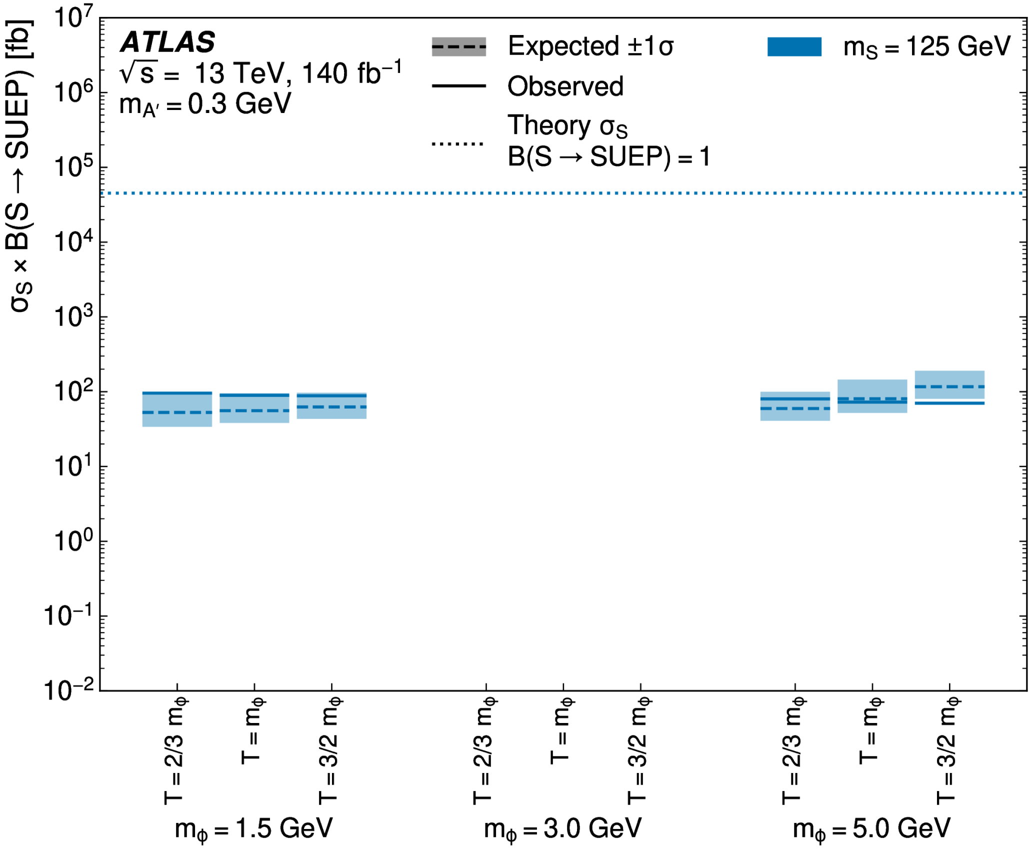
$$\begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- Example 4: four particles with momentum P=(1,0,0),(0,1,0), (-1,0,0),(0,-1, 0). ➔ S=0.75
- Example 5: six particles ➔ S= 1

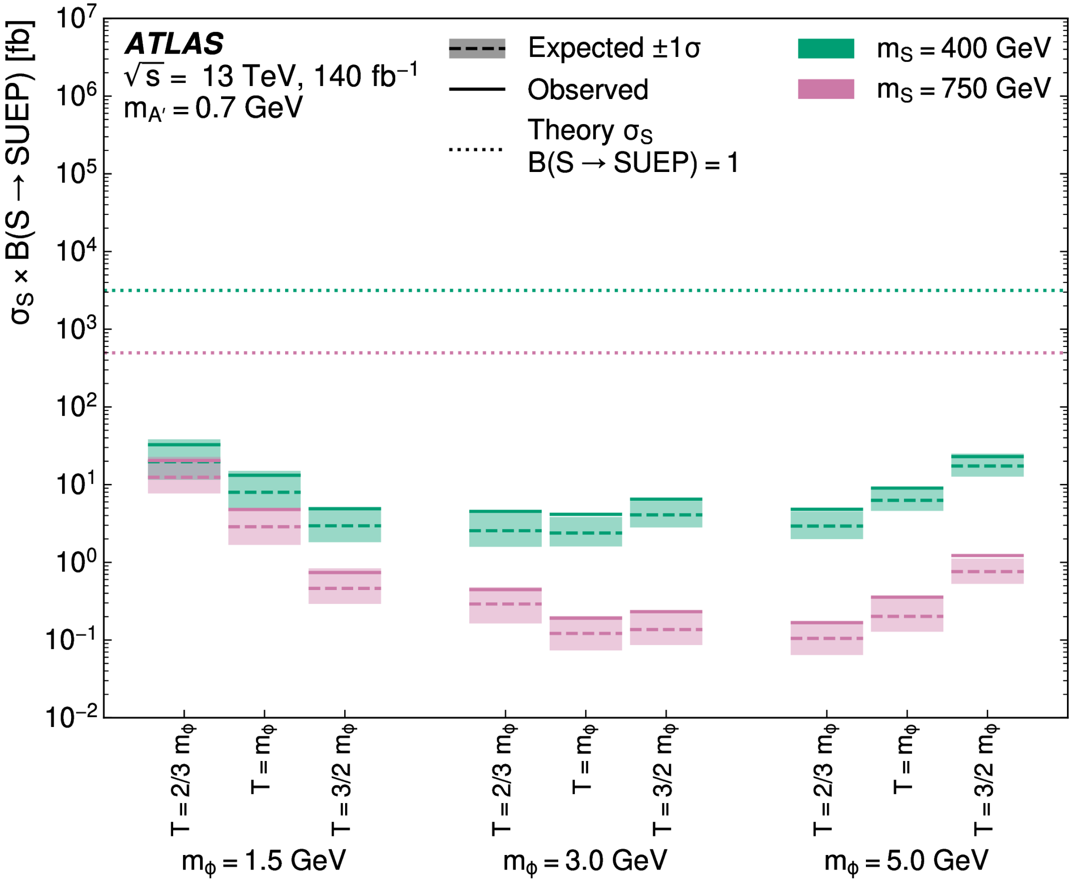
$$\begin{bmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{bmatrix}$$

Limits for the leplep and hadhad mode

Leplep
(mA'=0.3GeV)

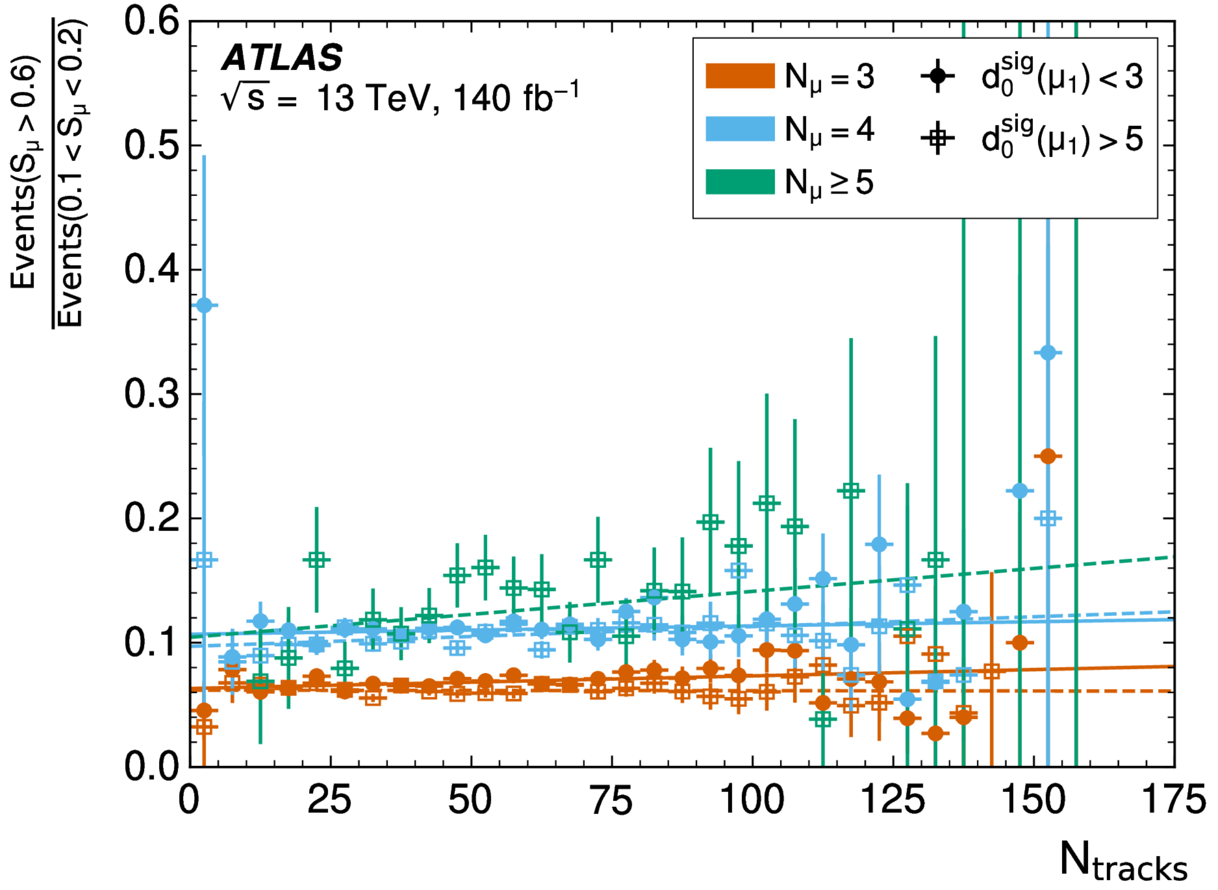


Hadhad
(mA'=0.7GeV)



Background modeling in the validation regions

- Check the correlation between S_μ and N_{tracks}.
- Y axis: Ratio of Yield of $S_\mu > 0.6$ to that of $S_\mu < 0.2$.
- Small correlation is seen for $N_\mu = 3{,}4$ and seems bigger for $N_\mu \geq 5$.
- Based on the largest slope in the validation, a dedicated systematic uncertainty is included to account for the correlation (see next slide).



Systematic uncertainties

- Luminosity uncertainty
- ID Track reconstruction:
  - CP recommendation
  - 1% -5% depending on the signal models mainly due to
- Muon reconstruction:
  - CP recommendation
  - 0.5% - 5% depending on the signal models mainly due to reconstruction efficiency
- Trigger efficiency uncertainty:
  - 0.1% - 4% depending on the signal models
- Pileup uncertainties:
  - Pileup reweighting uncertainty: 1-3% on Ntracks
  - Pileup track correction(comparing a shift at 6.5, -6.5 and 7 mm): 0.5% on Ntracks

Systematic uncertainties

- Higgs mediator signal sample reweighting:
  - These signal MC samples are reweighting according to the SM Higgs NLO simulation with NNLO cross section.
  - The reweighting is parameterized as a function of the Higgs pT.
  - A conservation uncertainty of 20% is used to cover the variation due to α_S, scales, PDF and NNLO cross section calculation.
- Control region definition uncertainty:
  - Change the S_μ bounds by +/- 0.01 for the A and C regions: 5%-10% in background prediction
  - Uncorrelated in all signal bins.
- ABCD correlation uncertainty
  - Introduce a slope to account for the deviation from the ABCD assumption