**Preprint:** arXiv:2405.05048 (May 8th),
**HepData:** ins2784422 (May 29th), **Rivet:** In Validation

# Strangeness of the Underlying Event with ATLAS

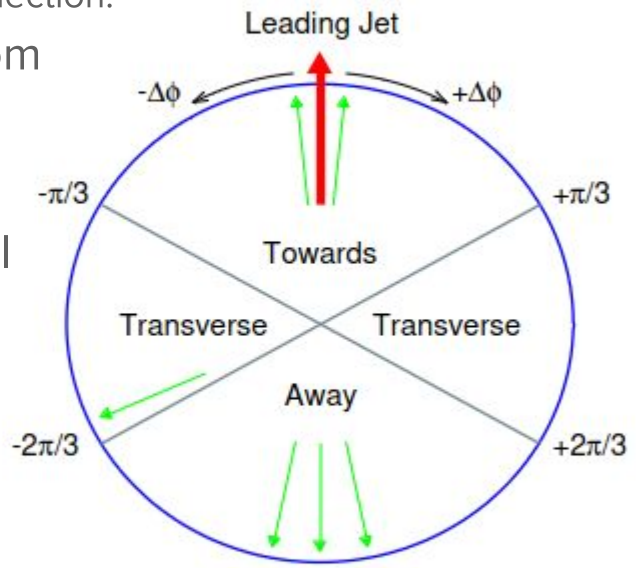

**Tim Martin** (STFC)

30th May 2024
*Non-Perturbative and Topological Aspects of QCD*


Science and Technology Facilities Council

# Analysis Outline

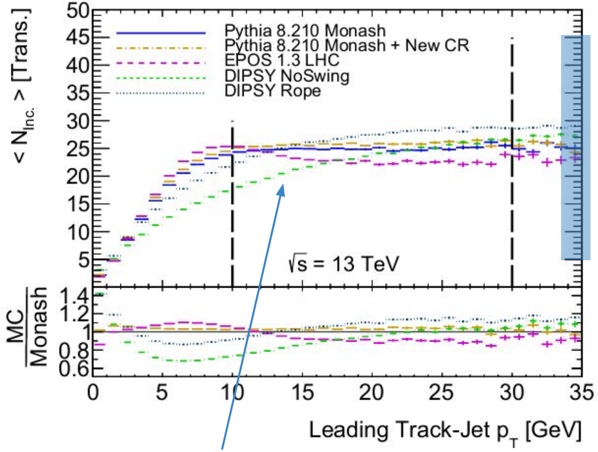
- Use *Underlying Event* style measurements to probe hadronisation with strange particles (Kaon and $\Lambda^0$), making use of their displaced decay vertices.
    - Near $\Lambda_{QCD}$, sensitive to hadronisation.
    - $\Lambda$ baryon production probes three-way colour reconnection.
- Leading charged-particle jet reconstructed from prompt charged particles defines the event axis in the azimuth.
- Single-interaction 13 TeV pp data from “special runs” in 2025 with $\langle\mu\rangle \approx 0.03$
    - 110M events recorded with minimum-bias trigger.
    - 67M events passing analysis’ event selection.
- Look beyond the *mean* activity levels in the underlying event…



# Prior Work

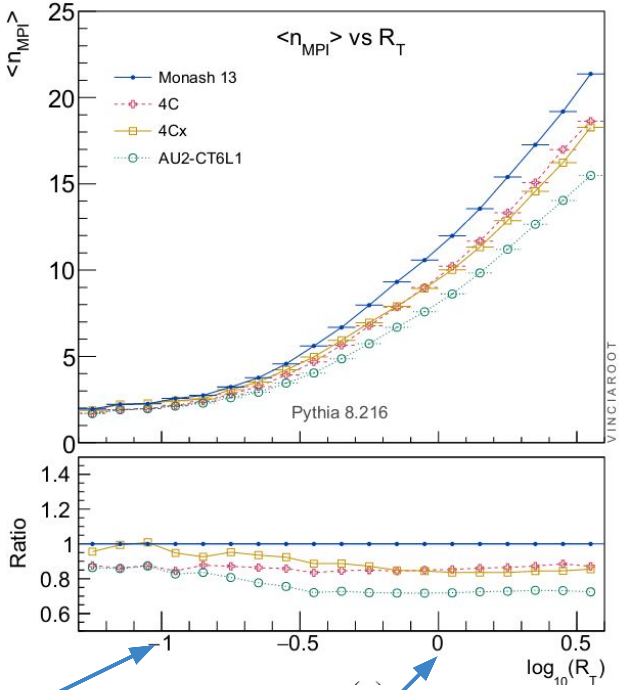
Eur. Phys. J. C (2016) 76 T. Martin, P. Skands, S. Farrington
Warwick-Monash Alliance

- Measure sensitive quantities **as a function of the per-event number of multi-particle interactions**.
  - Except this is not an observable, but there are proxy variables
  - We use the **number of prompt charged particles** in the **transverse region**, for events with **leading anti-$k_t$ charged-particle jet $p_T$ > 10 GeV** as a proxy to the amount of MPI.
  - Measure the strange yield in the different underlying event regions with respect to this.




*Select region where mean quantity is ~flat*

*Event-by-event, N may be far from this mean….*




**N = 0.1 x mean**

**N = 1 x mean**

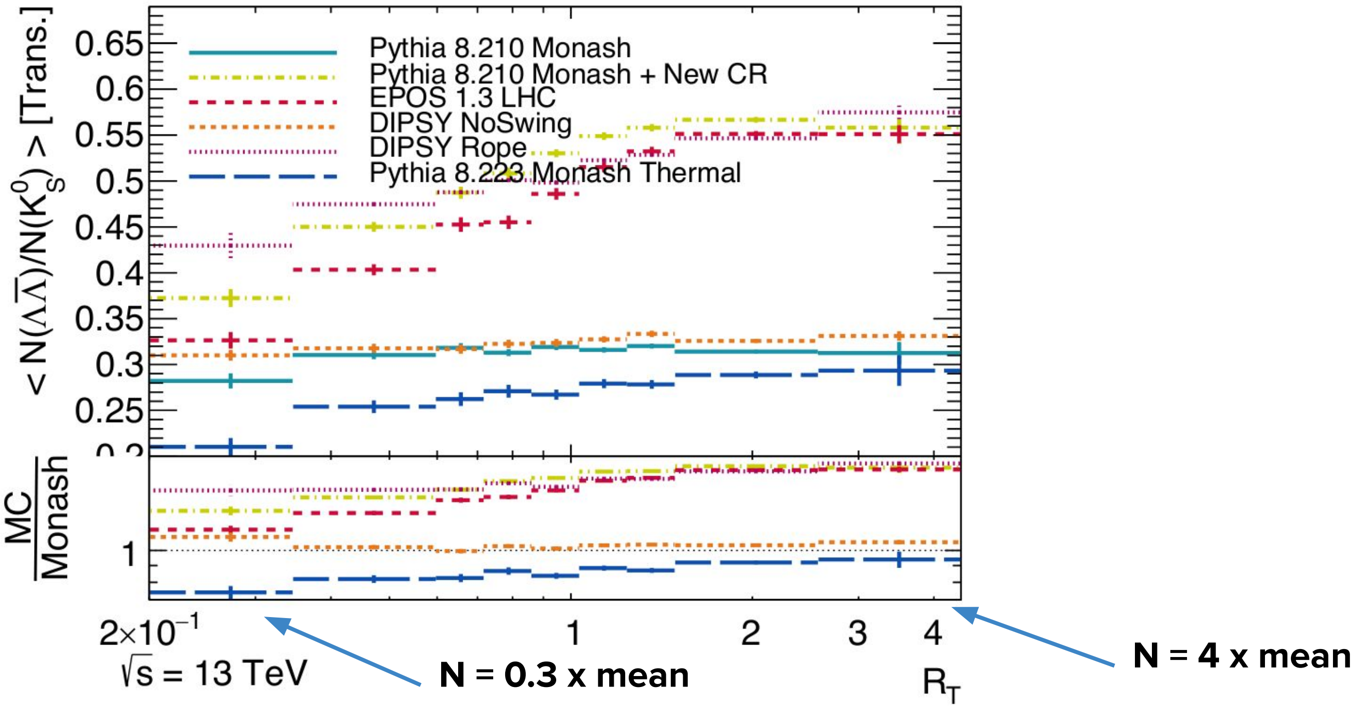
**N = 3.16 x mean**

*The per-event number of particles correlates with the number of soft / semi-hard scatters (at least, it does in Pythia…).*

# Prior Work

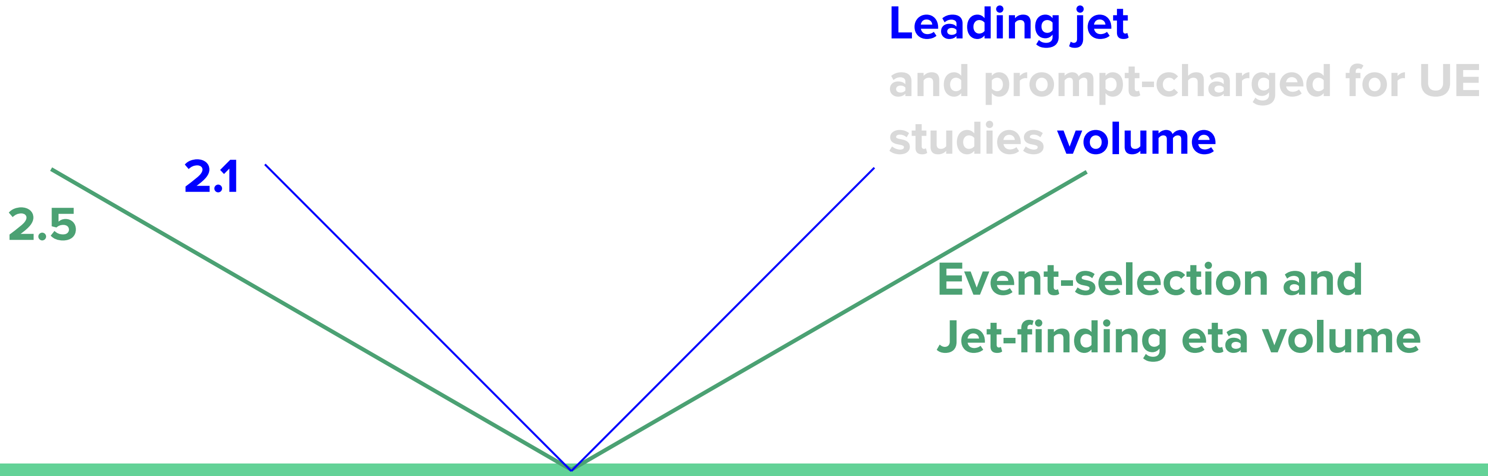
Eur. Phys. J. C (2016) 76 T. Martin, P. Skands, S. Farrington
Warwick-Monash Alliance

- Ratio of **$\Lambda^0$ to $K^0_s$ in the Transverse region** as a function of this proxy
- Discrimination between models.



# Analysis Cuts - Event Selection

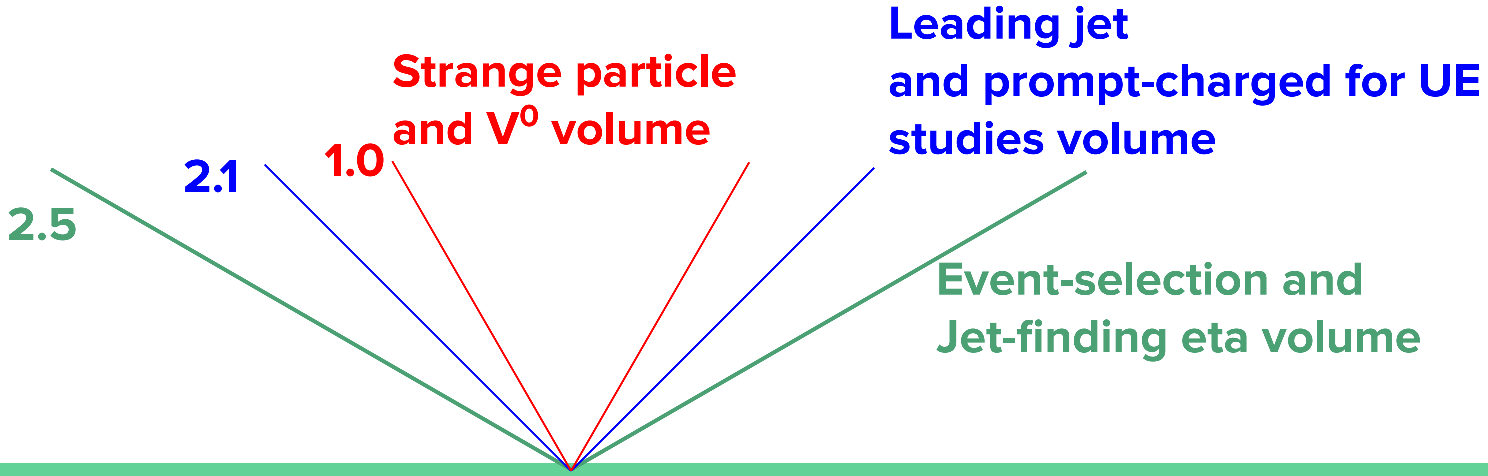
- Two event selections, events failing either of these are **vetoed**
- **Must have** Prompt $\mathbf{N_{Ch}}$ > **0**, with $\mathbf{p_T}$ > **1 GeV** and **|η|** < **2.5**
- Make **R=0.4** $\mathbf{ak_t}$ charged-particle jets with prompt {$\mathbf{p_T}$ > **500 MeV, |η|** < **2.5**}
- The leading jet **within |η|** < **2.1** must be $\mathbf{p_T}$ > **1 GeV**



# Analysis Cuts - Prompt and Strange Selection

- Prompt selection of all stable charged with $\{p_T > 500$ MeV, $|\eta| < 2.1\}$
- $K_S^0$ and $\Lambda^0$ selection - at reco. from two-particle $V^0$ vertices.
  - $K_S$, $\Lambda$: $|\eta| <$ **1.0**
  - $K_S$: $p_T >$ **400 MeV**, $\Lambda^0$: $p_T >$ **750 MeV**
  - $K_S$: $\cos(\Theta) >$ **0.9990**, $\Lambda^0$: $\cos(\Theta) >$ **0.9998** (3D pointing angle of $V^0$ momentum vector from primary vertex)
  - $K_S$: Decay radius **4 < $R_{xy}$ < 300 mm**, $\Lambda^0$: Decay radius **17 < $R_{xy}$ < 300 mm**
  - $K_S$: Decay mode **$\pi^+ \pi^-$**, $\Lambda^0$: Decay mode **p $\pi^-$** or **pbar $\pi^+$**
  - $K_S$: Mass window **20 MeV** and max mass error **15 MeV**. $\Lambda^0$: Mass win. **7 MeV**, max mass err **5 MeV**
  - $K_S$, $\Lambda^0$: Decay children $|\eta| <$ **2.5**
  - **Veto**: Any pair of K or pair of $\Lambda$ at $\Delta R < 0.1$ (motivated on the reconstruction side of things)

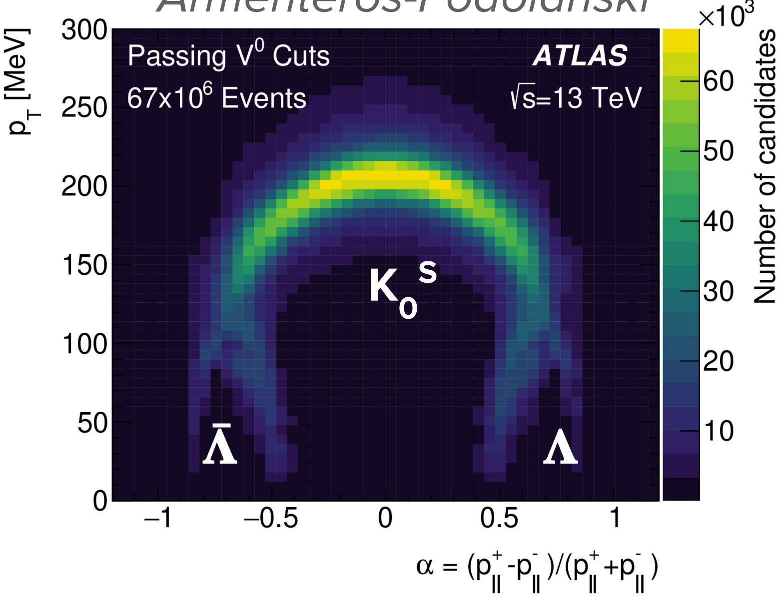
**Special "low pT (~100 MeV, large d0 tracking pass.**

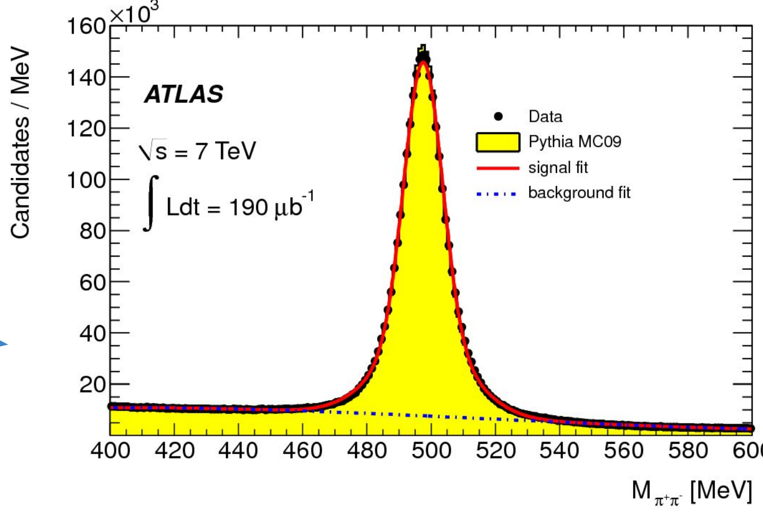


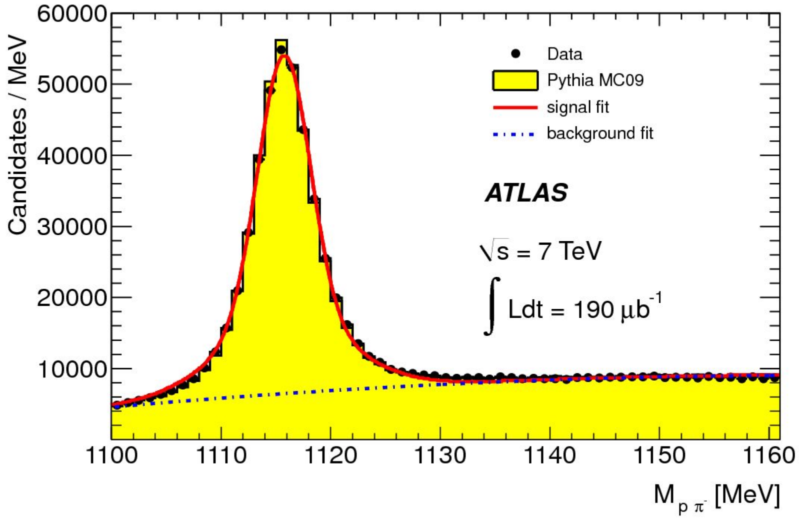
# Strange Selection

- Strange particle reconstruction in ATLAS here is similar to [Phys. Rev. D 85 (2012) 012001]

*Armenteros-Podolanski*

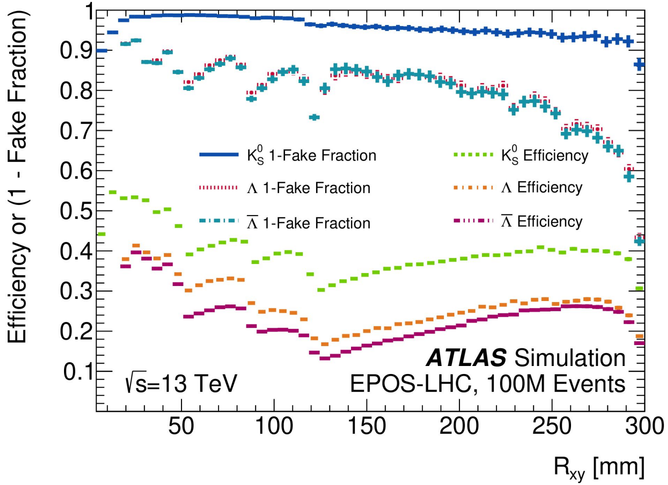


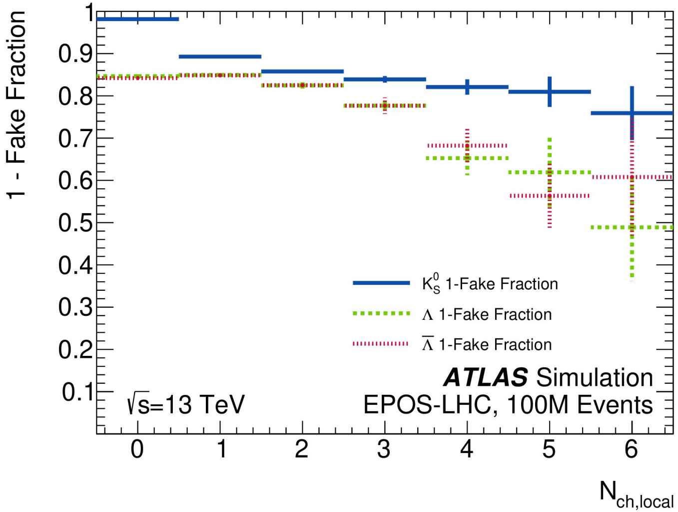



# Efficiencies and Fakes

- Reconstructed selected $K_S^0$ and $\Lambda^0$ are corrected up for detector inefficiencies and down for fakes (combinatorial background) via per-$V^0$ weight.
- MC-driven, with a data-driven check on fakes.
- 2D Efficiency in $V^0$ decay radius & $p_T$
- 3D for fakes - include "*am I in a jet?*"



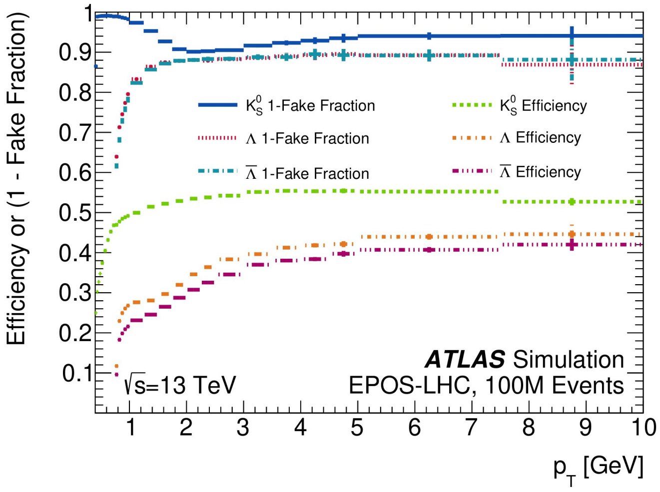




**Mean efficiency:**

$K_S^0$: 46.07 ∓ 0.01%

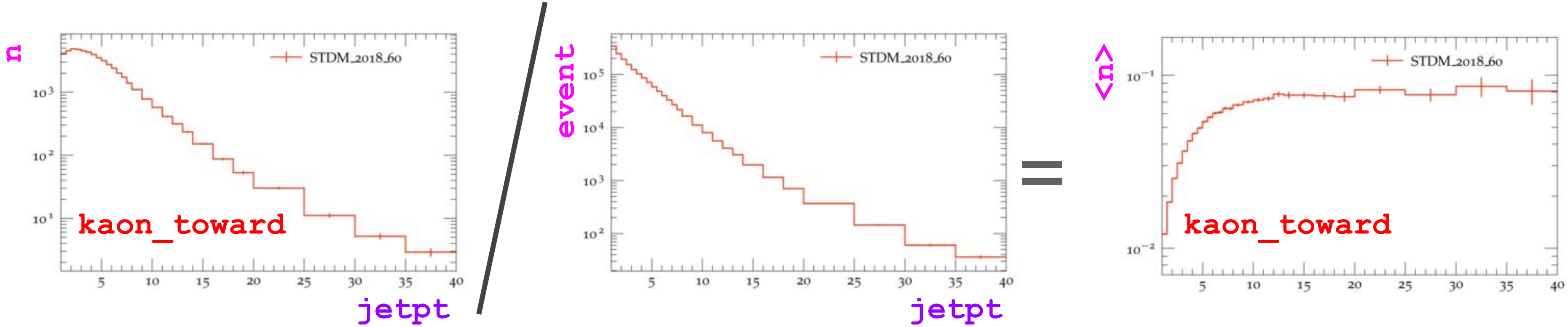
$\Lambda^0$: 30.00 ∓ 0.02%

$\bar{\Lambda}^0$: 26.20 ∓ 0.02%



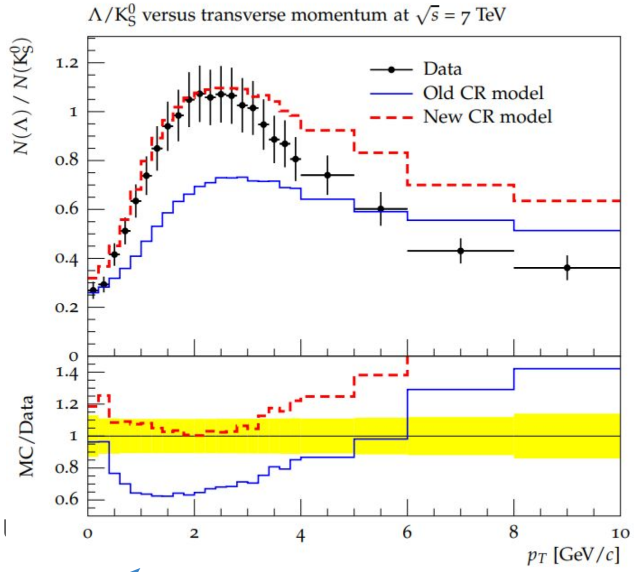
# Analysis Strategy

- Distributions of observables are built up from all 67M events in the data sample.
  - Example of observable: **“Number”** of **“$K^0_S$”** in the **“towards”** region vs. **lead-jet $p_T$**
  - Example of observable: **“Sum-$p_T$”** of **“$\Lambda^0$”** in the **“away”** region vs. **lead-jet $p_T$**
    - Note: sum-$p_T$ in HepData
  - Example of observable: **“Number”** of **“Events”** vs. **lead-jet $p_T$**
- Each of these distributions is **unfolded** via an iterative method with four iterations.
- All final figures are formed by taking the **ratio between a pair** of the distributions.
- Statistical error propagated via a **bootstrap** technique.
- `(n_kaon_toward_vs_jetpt_ / event_vs_jetpt)`



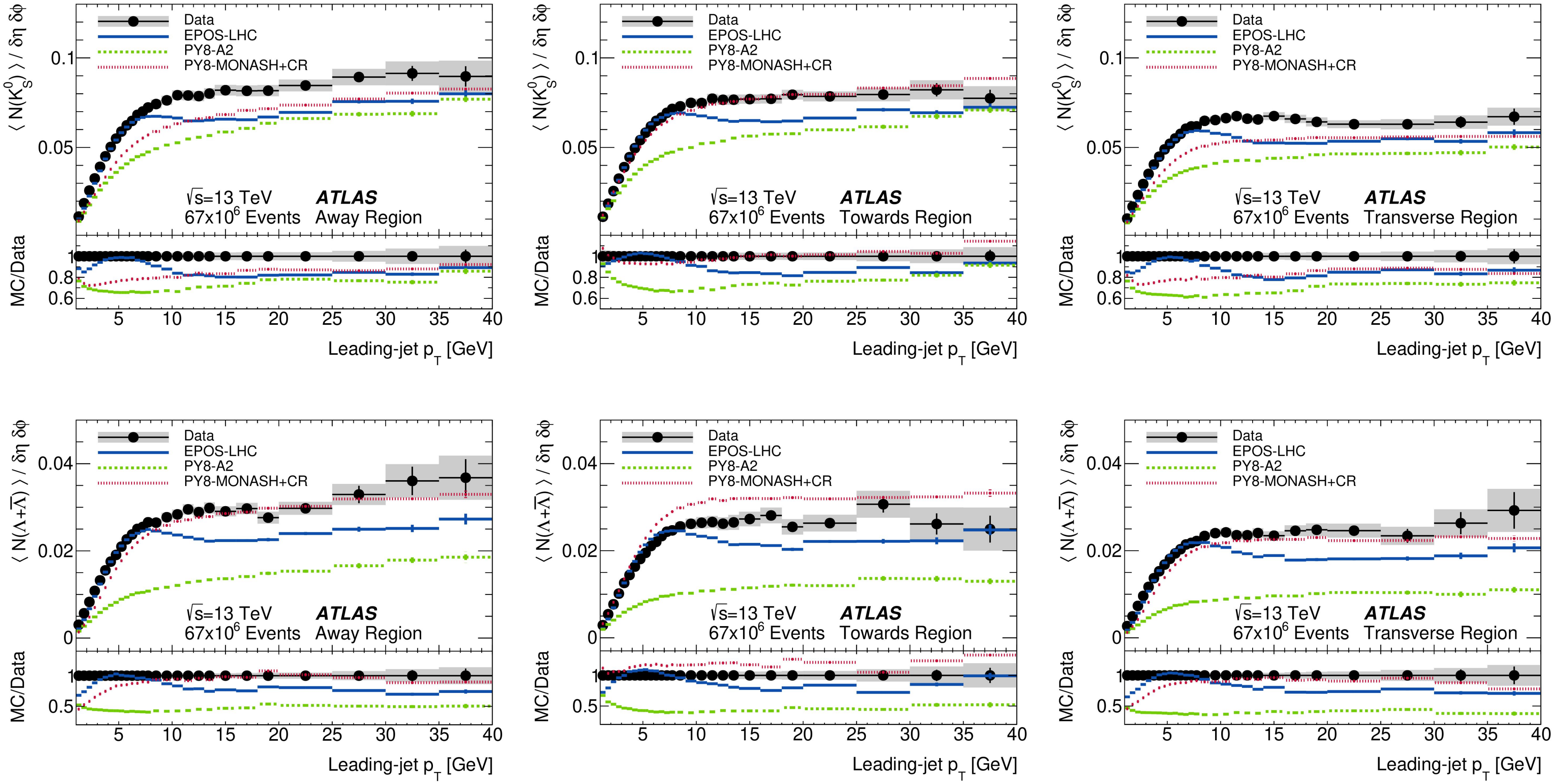
# MC Models

- **EPOS-LHC**: Primary correction MC.
  - Used to compute correction factors for $V^0$
  - Used as the nominal MC when unfolding the data.
  - Full ATLAS simulation, including material variation systematics.
  - Used at particle level to compare against the unfolded data.
- **Pythia8-A2**: Secondary correction MC.
  - Used as cross-check of $V^0$ efficiency measurement.
  - Not used for $V^0$ fake estimation, data-driven lineshape method u
  - Used to unfold the data as a source of systematic uncertainty.
  - Full ATLAS simulation, including material variation systematics.
  - Used at particle level to compare against the unfolded data.
- **Pythia8-Monash + New CR**
  - [JHEP 08 (2015) 003](), J. Christiansen & P. Skands
    - *String formation beyond leading colour*
  - Particle level only.
  - Used at particle level to compare against the unfolded data.

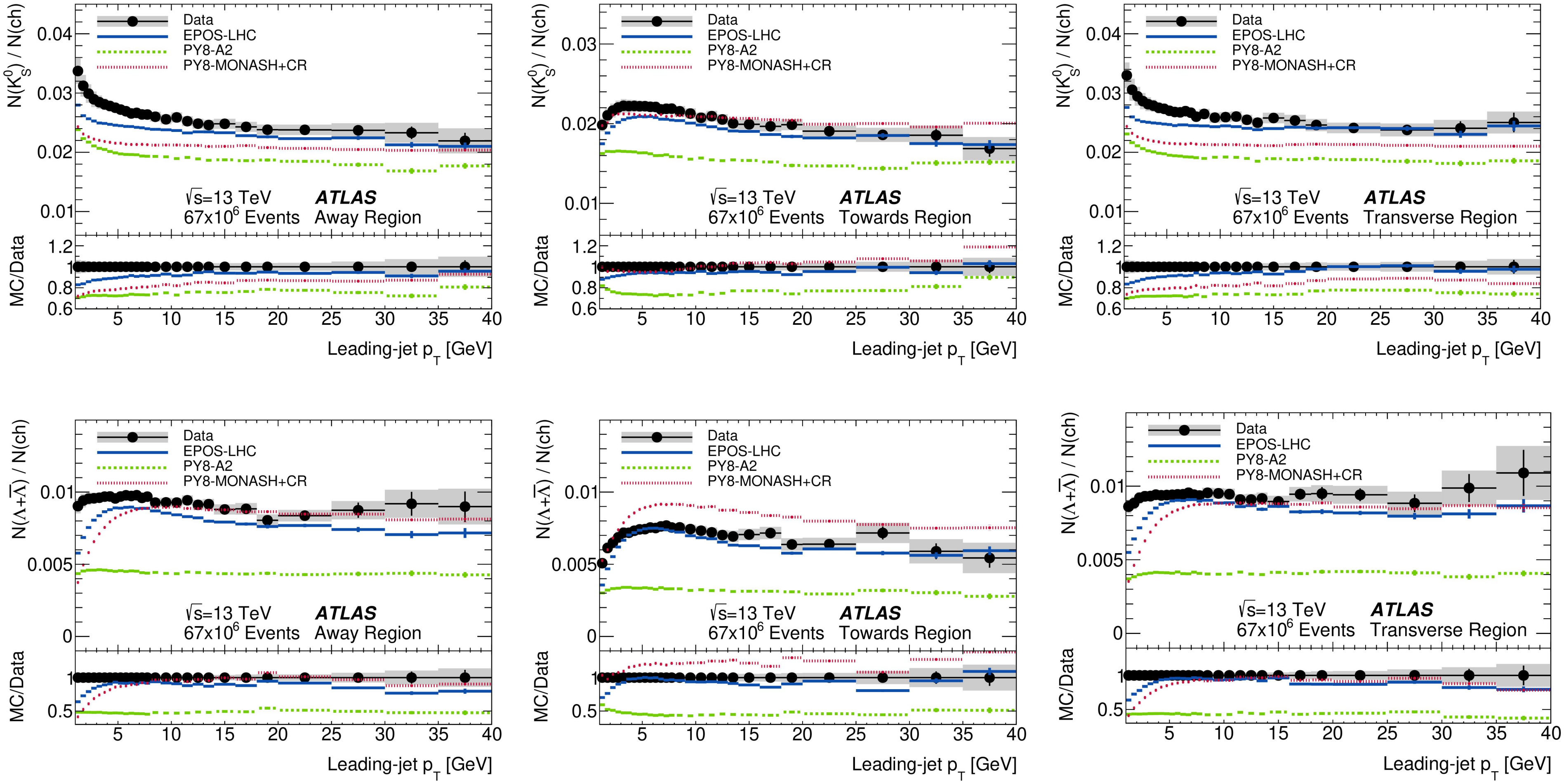



***Will aim to compare against more models with the public HepData***

# Results - Event Normalised

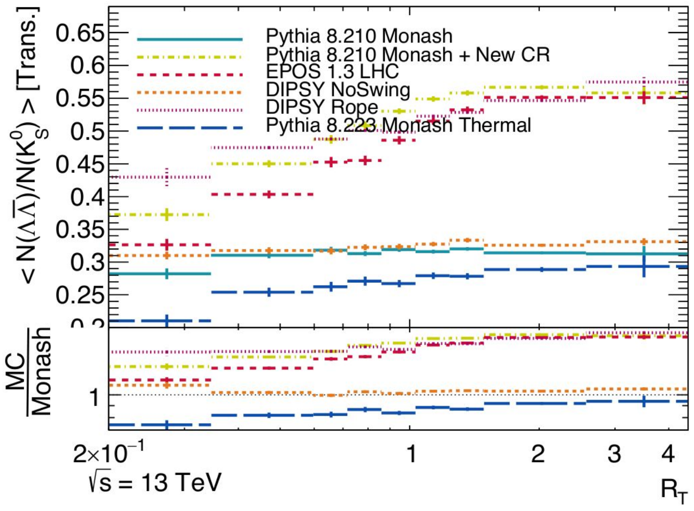


# Results - Prompt-Charged Normalised

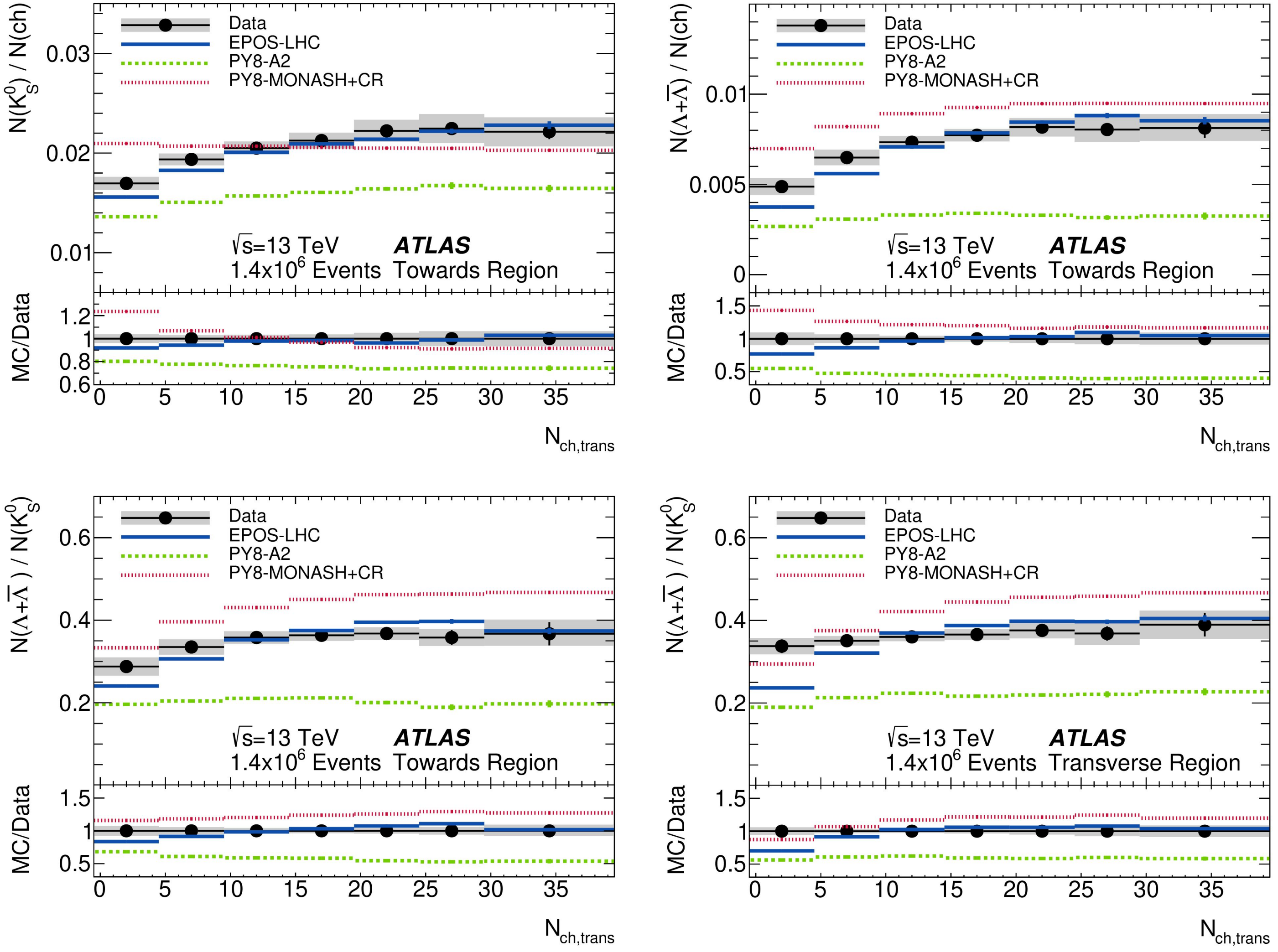


# Results vs. $N_{ch,trans}$

- Only considering the subset of events where the leading charged-particle jet lies in the range **10 < $p_T$ < 40 GeV**. Where **1.4M** events in data pass this selection.
- Use the **number of prompt charged particles in the transverse region** as an alternate **event quantity to use on the x-axis**, instead of jet $p_T$.



# Results vs. $N_{ch,trans}$



# Additional Datapoints

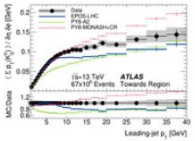
- Additional ratios are available in HepData [ins2784422](#).
- 72 ratios, including per-particle mean-$p_T$
- With bin-bin statistical covariance, uncertainty breakdowns.

**Table 5**

Auxiliary Figure 8(c)

Resources https://www.hepdata.net/re JSON

Mean scalar sum-$p_T$ of $K_S^0$ per unit $(\eta, \phi)$ in the towards region vs. leading-jet $p_T$




**cmenergies**: 13000.0

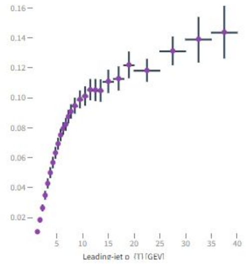
**observables**: RATIO

**phrases**: Inclusive, Proton-Proton Scattering, Underlying Event, Low Pileup, Kaon, Lambda, Hyperon

**reactions**: P P --> X

| | |
|---|---|
| **REGION** | toward |
| **NUMERATOR_SPECIES** | kaon |
| **DENOMINATOR_SPECIES** | events |
| **NUMERATOR_VARIABLE** | sumpt |
| **DENOMINATOR_VARIABLE** | |
| **SQRT(S)** | 13000 GEV |
| **Leading-jet $p_T$ [GEV]** | $\langle \Sigma p_T(K_S^0) \rangle / \delta\eta\,\delta\phi$ [GEV] |
| 1 - 1.5 | 0.0105716 ±0.413169% stat ∓9.13466% sys,nonclosure ±1.71007% sys,unfmodel + 3 more errors Show all |
| 1.5 - 2 | 0.0184603 ±0.364872% stat ∓8.81314% sys,nonclosure ±1.37531% sys,unfmodel + 3 more |

Visualize




**# Kaon / Event - Lead pT**
- kaon_towards_leadpt_n / leadpt_event
- kaon_towards_leadpt_sumpt / leadpt_event
- kaon_transverse_leadpt_n / leadpt_event
- kaon_transverse_leadpt_sumpt / leadpt_event
- kaon_away_leadpt_n / leadpt_event
- kaon_away_leadpt_sumpt / leadpt_event

**# Kaon / Event - N Ch Trans**
- kaon_towards_nchtrans_n / nchtrans_event
- kaon_towards_nchtrans_sumpt / nchtrans_event
- kaon_transverse_nchtrans_n / nchtrans_event
- kaon_transverse_nchtrans_sumpt / nchtrans_event
- kaon_away_nchtrans_n / nchtrans_event
- kaon_away_nchtrans_sumpt / nchtrans_event

**# Lambda / Event - Lead pT**
- lambda_towards_leadpt_n / leadpt_event
- lambda_towards_leadpt_sumpt / leadpt_event
- lambda_transverse_leadpt_n / leadpt_event
- lambda_transverse_leadpt_sumpt / leadpt_event
- lambda_away_leadpt_n / leadpt_event
- lambda_away_leadpt_sumpt / leadpt_event

**# Lambda / Event - N Ch Trans**
- lambda_towards_nchtrans_n / nchtrans_event
- lambda_towards_nchtrans_sumpt / nchtrans_event
- lambda_transverse_nchtrans_n / nchtrans_event
- lambda_transverse_nchtrans_sumpt / nchtrans_event
- lambda_away_nchtrans_n / nchtrans_event
- lambda_away_nchtrans_sumpt / nchtrans_event

**# Kaon / Prompt - Lead pT**
- kaon_towards_leadpt_n / prompt_towards_leadpt_n
- kaon_towards_leadpt_sumpt / prompt_towards_leadpt_sumpt
- kaon_transverse_leadpt_n / prompt_transverse_leadpt_n
- kaon_transverse_leadpt_sumpt / prompt_transverse_leadpt_sumpt
- kaon_away_leadpt_n / prompt_away_leadpt_n
- kaon_away_leadpt_sumpt / prompt_away_leadpt_sumpt

**# Kaon / Prompt - N Ch Trans**
- kaon_towards_nchtrans_n / prompt_towards_nchtrans_n
- kaon_towards_nchtrans_sumpt / prompt_towards_nchtrans_sumpt
- kaon_transverse_nchtrans_n / prompt_transverse_nchtrans_n
- kaon_transverse_nchtrans_sumpt / prompt_transverse_nchtrans_sumpt
- kaon_away_nchtrans_n / prompt_away_nchtrans_n
- kaon_away_nchtrans_sumpt / prompt_away_nchtrans_sumpt

**# Lambda / Prompt - Lead pT**
- lambda_towards_leadpt_n / prompt_towards_leadpt_n
- lambda_towards_leadpt_sumpt / prompt_towards_leadpt_sumpt
- lambda_transverse_leadpt_n / prompt_transverse_leadpt_n
- lambda_transverse_leadpt_sumpt / prompt_transverse_leadpt_sumpt
- lambda_away_leadpt_n / prompt_away_leadpt_n
- lambda_away_leadpt_sumpt / prompt_away_leadpt_sumpt

**# Lambda / Prompt - N Ch Trans**
- lambda_towards_nchtrans_n / prompt_towards_nchtrans_n
- lambda_towards_nchtrans_sumpt / prompt_towards_nchtrans_sumpt
- lambda_transverse_nchtrans_n / prompt_transverse_nchtrans_n
- lambda_transverse_nchtrans_sumpt / prompt_transverse_nchtrans_sumpt
- lambda_away_nchtrans_n / prompt_away_nchtrans_n
- lambda_away_nchtrans_sumpt / prompt_away_nchtrans_sumpt

**# Kaon / Kaon - Lead pT**
- kaon_towards_leadpt_sumpt / kaon_towards_leadpt_n
- kaon_transverse_leadpt_sumpt / kaon_transverse_leadpt_n
- kaon_away_leadpt_sumpt / kaon_away_leadpt_n

**# Kaon / Kaon - N Ch Trans**
- kaon_towards_nchtrans_sumpt / kaon_towards_nchtrans_n
- kaon_transverse_nchtrans_sumpt / kaon_transverse_nchtrans_n
- kaon_away_nchtrans_sumpt / kaon_away_nchtrans_n

**# Lambda / Lambda - Lead pT**
- lambda_towards_leadpt_sumpt / lambda_towards_leadpt_n
- lambda_transverse_leadpt_sumpt / lambda_transverse_leadpt_n
- lambda_away_leadpt_sumpt / lambda_away_leadpt_n

**# Lambda / Lambda - N Ch Trans**
- lambda_towards_nchtrans_sumpt / lambda_towards_nchtrans_n
- lambda_transverse_nchtrans_sumpt / lambda_transverse_nchtrans_n
- lambda_away_nchtrans_sumpt / lambda_away_nchtrans_n

**# Lambda / Kaon - Lead pT**
- lambda_towards_leadpt_n / kaon_towards_leadpt_n
- lambda_towards_leadpt_sumpt / kaon_towards_leadpt_sumpt
- lambda_transverse_leadpt_n / kaon_transverse_leadpt_n
- lambda_transverse_leadpt_sumpt / kaon_transverse_leadpt_sumpt
- lambda_away_leadpt_n / kaon_away_leadpt_n
- lambda_away_leadpt_sumpt / kaon_away_leadpt_sumpt

**# Lambda / Kaon N Ch Trans**
- lambda_towards_nchtrans_n / kaon_towards_nchtrans_n
- lambda_towards_nchtrans_sumpt / kaon_towards_nchtrans_sumpt
- lambda_transverse_nchtrans_n / kaon_transverse_nchtrans_n
- lambda_transverse_nchtrans_sumpt / kaon_transverse_nchtrans_sumpt
- lambda_away_nchtrans_n / kaon_away_nchtrans_n
- lambda_away_nchtrans_sumpt / kaon_away_nchtrans_sumpt

# Conclusion

- Underlying Event style analysis using ATLAS data with long-lives strange particles as the primary probes.
- Significantly better modelling agreement observed with EPOS or Pythia’s SU(3) based colour reconnection scheme vs.Pythia’s default colour reconnection model.
    - But still some areas where the models are falling short.
- Data points in HepData, Rivet to follow shortly.

# BACKUP - Systematics