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Strange Hadrons in Underlying-Events, Measured in Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector

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Importance of Underlying-Events

- In proton-proton collisions, perturbative Quantum Chromo Dynamics (pQCD) computes the partonic hard scattering and, to some extent, parton shower process.
- But pQCD is unable to describe hadronization and underlying-event (UE).
- UE arises from initial and final-state radiation, color reconnection between spectator and final state partons, Multi-Parton Interactions (MPI) and beam remnants for diffractive scattering.
- UE is important for a correct modeling of proton-proton collisions and their (non trivial) extrapolation to hadron-hadron collisions, especially for studies of air-shower triggered by high energy cosmic rays.

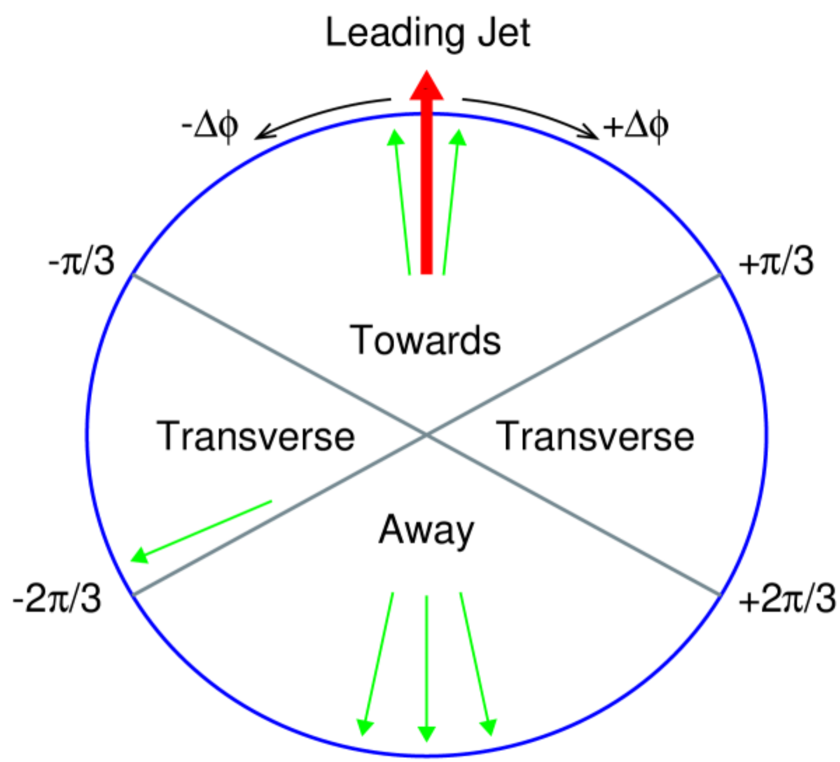
Strange Particles: Another Probe to Study Underlying Events

- $m_s \sim \Lambda_{QCD}$, pQCD does no work. We need measurements to tune models.
- K_S^0 and Λ are the lightest strange meson and baryon: easier to produce.
- Easy to tag: By identifying their displaced decay vertex to two charged particles, called V^0:
  - $K_S^0 \rightarrow \pi^+\pi^-,\ c\tau = 2.7\ cm.$
  - $\Lambda \rightarrow \pi^- p$ and $\overline{\Lambda} \rightarrow \pi^+ \bar{p},\ c\tau = 7.9\ cm.$
- Today: K_S^0 and Λ in UE of p-p collisions at $\sqrt{s}$ = 13 TeV with ATLAS: CERN-EP-2024-105
  - There was a study by CMS at $\sqrt{s}$ = 7 TeV in 2013: Phys. Rev. D 88 (2013)

Where are Underlying Events at LHC proton-proton collisions ?

- Even a simple minimum-bias trigger introduces a bias due to higher than average P_T particle(s) which fired the trigger.
- The leading jet P_T is the scale of the hard process.

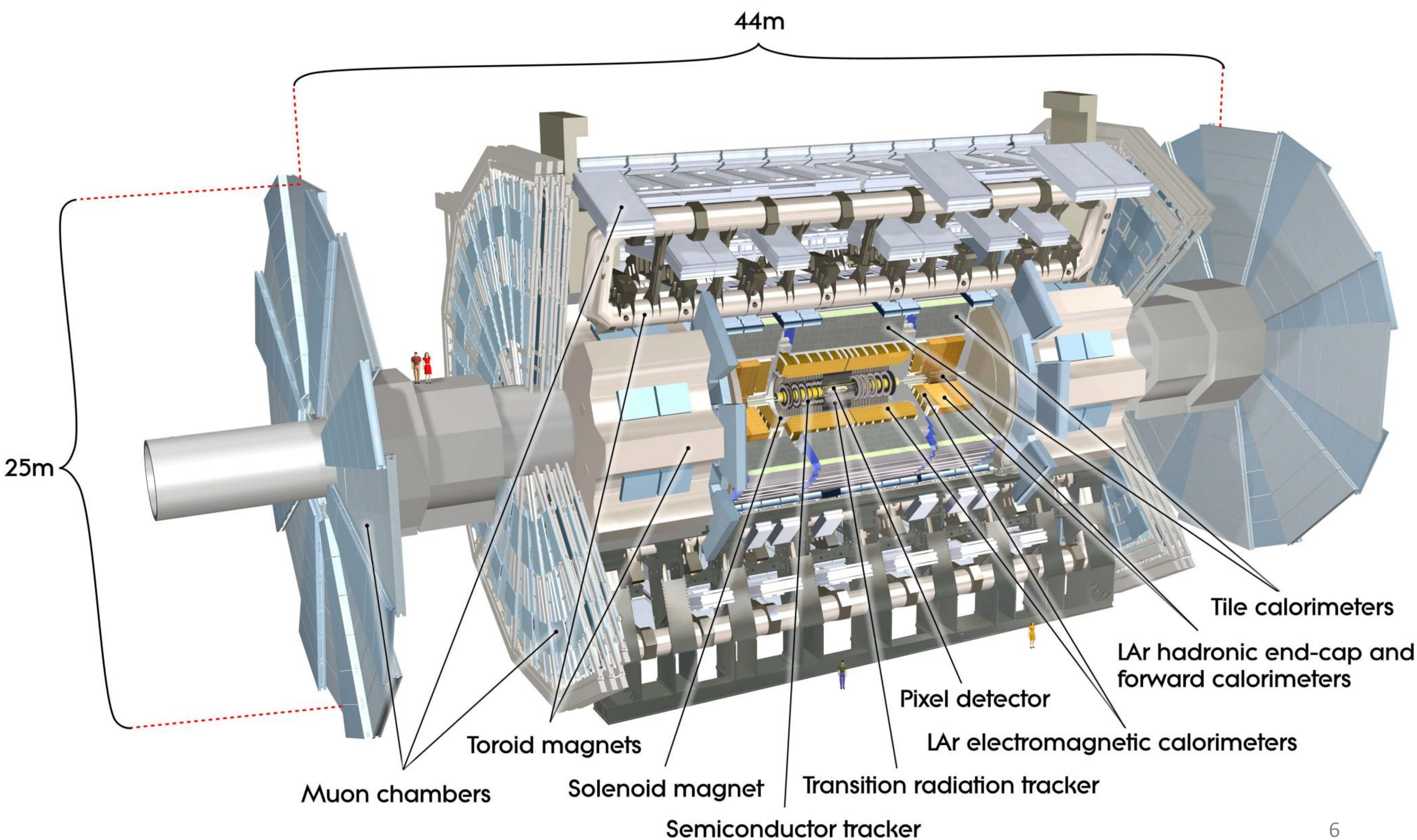
- Divide the azimuth according to the leading jet P_T:
  - The two $2 \times 60°$ cones around the leading jet **(Towards)** and back to back to it **(Away)** are dominated by the hard scattering.
  - The two other regions **(Transverse)** are dominated by UE.



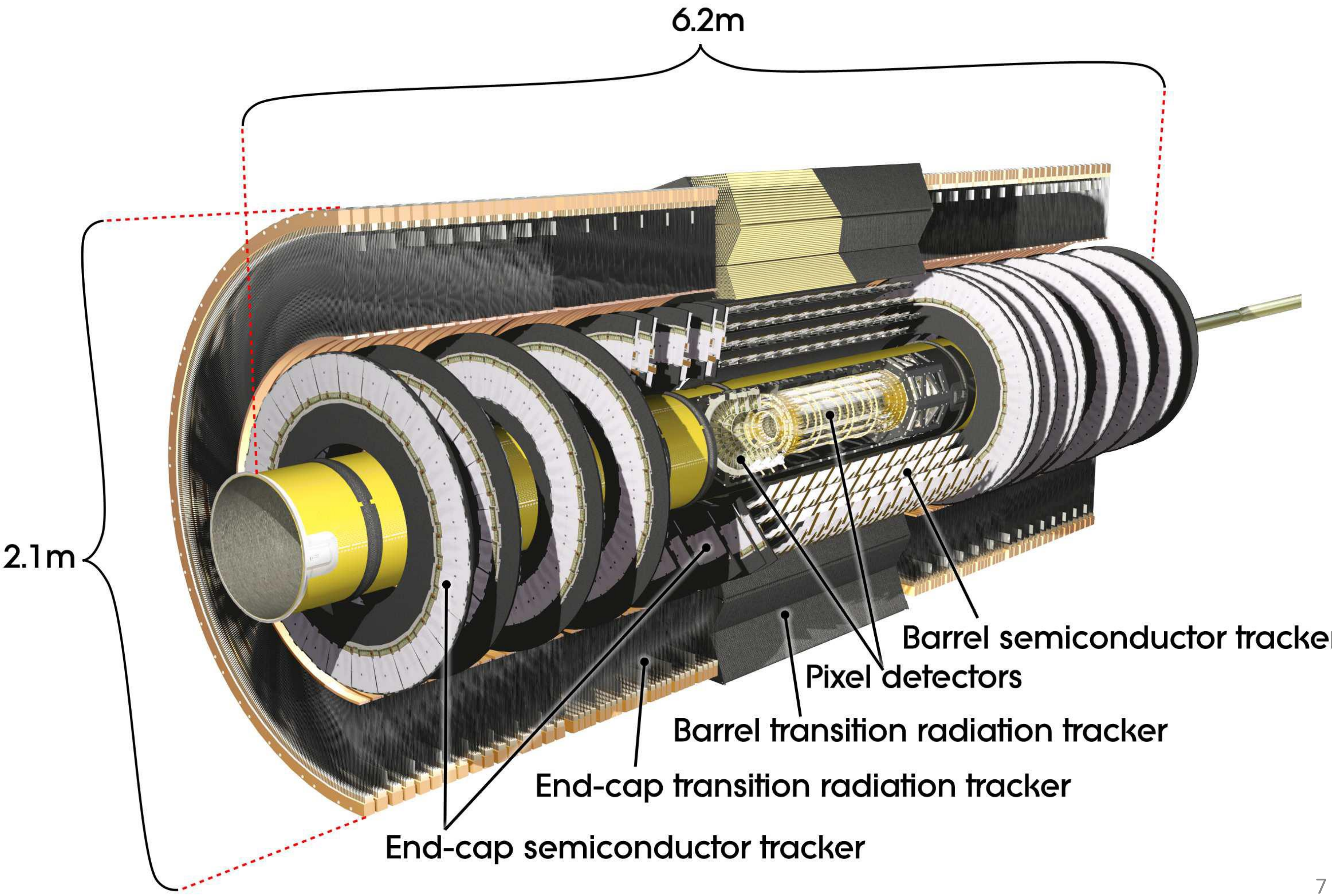
What Do We Need to Perform the Study ?

- Acquire events representatives of hadronic interactions:
  - Minimum-bias trigger.
- Get rid of pile-up:
  - Operate LHC at very low luminosity.
- Identify K_S^0 and Λ by their decay vertices and invariant masses:
  - Precise tracking and vertexing.
  - Good momentum resolution.
- Reconstruct relatively low P_T jets,
- and reconstruct charged particles with a large efficiency:
  - Large tracking volume.
- The ATLAS experiment fulfils these requirements.

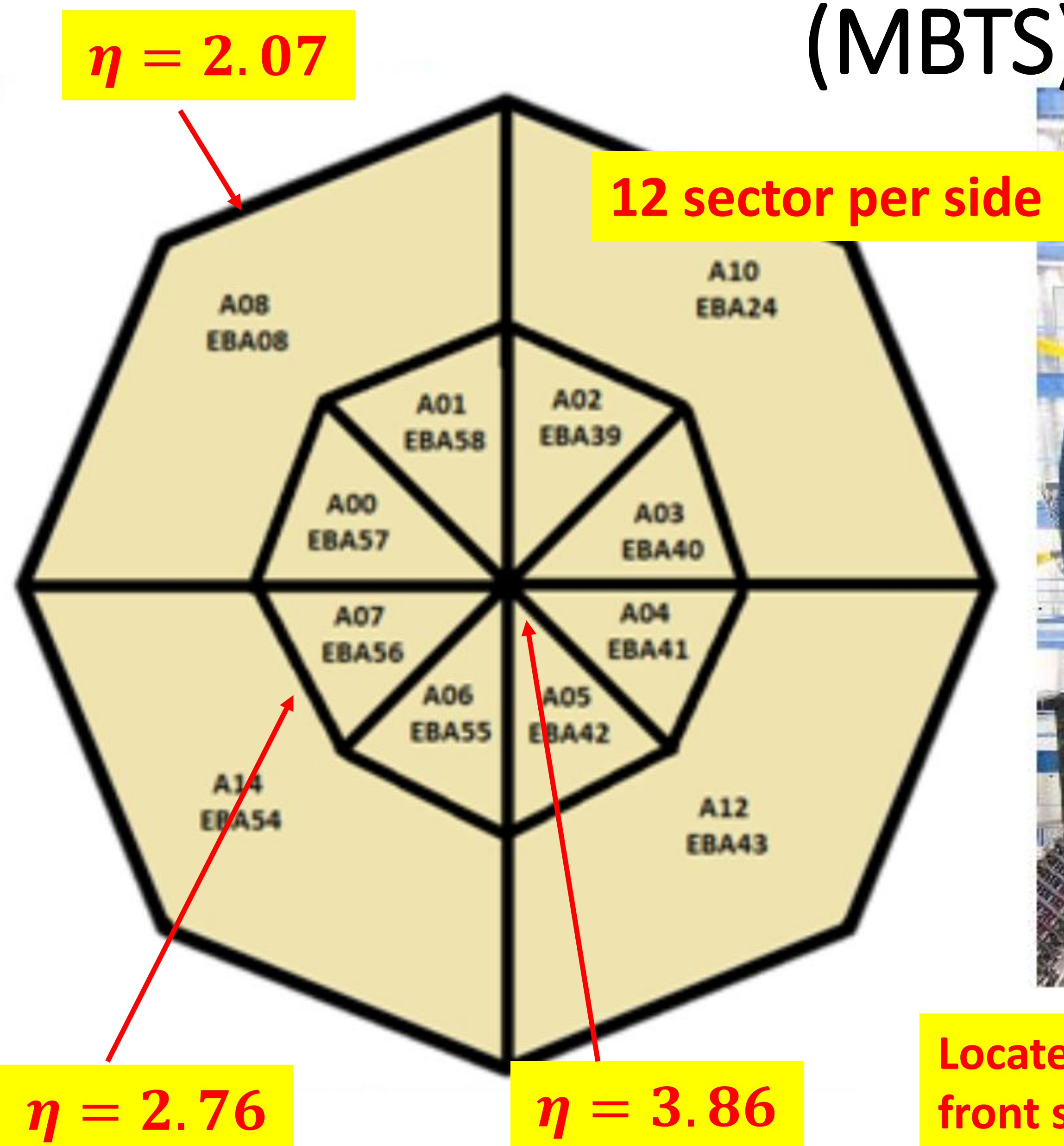
The ATLAS Detector



The ATLAS Inner Tracker



The ATLAS Minimum Bias Trigger Scintillators (MBTS)



Located at $z = \pm$ 3.56 m, on end-cap cryostats front side

Data Samples and Triggers

- Six LHC fills recorded by ATLAS in June 2015:
  - To get rid of pile-up, only up to 29 colliding bunches, larger betatronic function and smaller bunches.
  - Mean number of inelastic collisions by bunch crossing $0.003 < \langle \mu \rangle < 0.03$.
- Trigger for five fills: At least one MBTS sector above threshold.
- Trigger for the sixth fill: At least one MBTS sector above threshold on both sides (positive and negative *z*).
- 110 M and 20 M minimum bias events recorded with each trigger respectively.

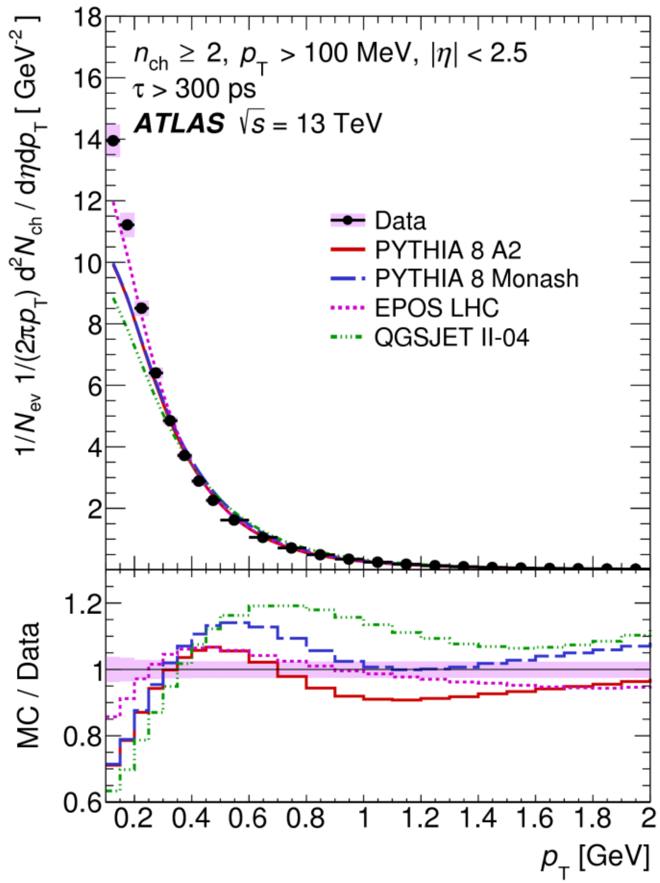
Simulation: Three Monte Carlo Samples

- EPOS 3.4 with EPOS-LHC tune:
  - Gribov-Regge theory.
  - MPI included.
  - Nuclear effects included.
- PYTHIA 8:
  - t-channel gluon and Pomeron exchange.
  - MPI included with impact-parameter approach
  - PYTHIA 8 A2 tune: MSTW2008 LO pdf and MPI tuned on ATLAS minimum bias data at 7 TeV.
  - PYTHIA 8 Monash tune: NNPDF 2.3 LO pdf, tuned on LHC, SPS and Tevatron data.
    - + an alternative color reconnection (CR) model.

Prompt Track Selection and Jet Reconstruction

Prompt Track Selection

- Tracks selected from low P_t tracks (see figure).
- $P_T > 500$ MeV
- $|\eta| < 2.5$
- $|d_0| < 1.5$ mm
- $|z_0 \sin\theta| < 1.5$ mm
- Minimal hits requirements in silicon detectors.
- χ^2 requirement.



Eur. Phys. J. C **76** (2016) 502

Jet Reconstruction

- Uses prompt tracks as input.
- Jets reconstructed using anti-k_t algorithm.
- $R = 0.4$.
- Leading jet: Highest P_T jet in $|\eta| < 2.1$.

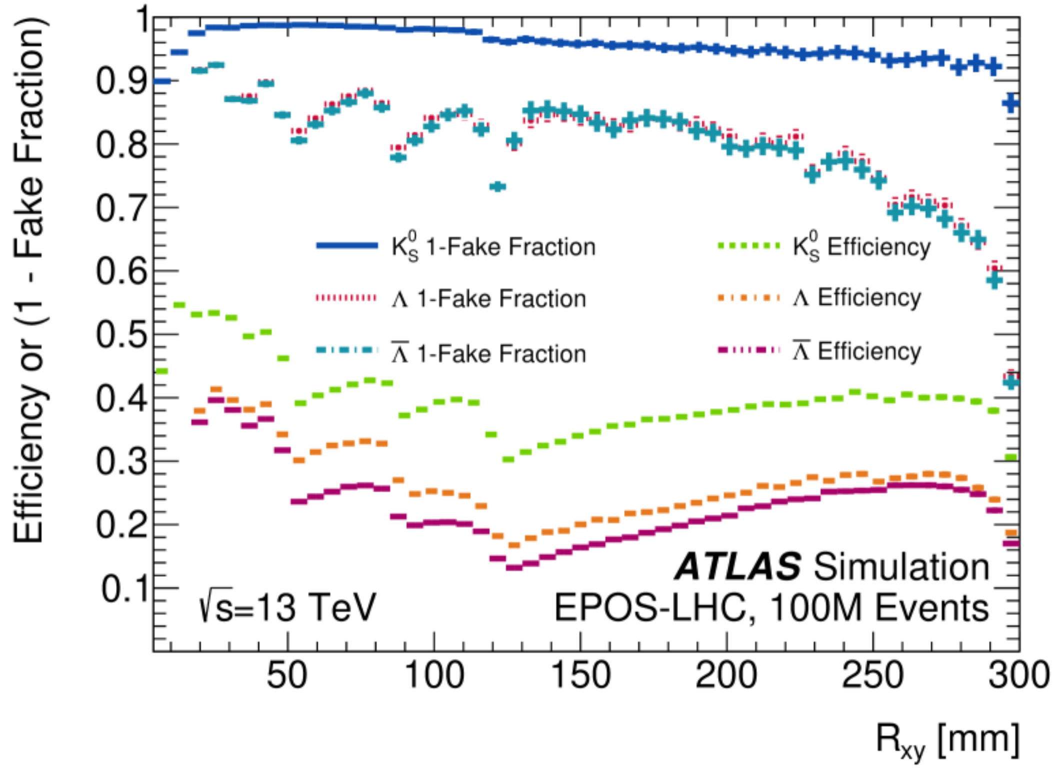
K_S^0 and Λ identification

- Allow and reconstruct large radius tracks:
  - Use only unused space points by prompt tracks.
  - Impact parameters requirements loosened.
- V^0 finder algorithm:
  - Iterates over all possible pairs of oppositely charged tracks using both prompt and large radius tracks.
  - Each V^0 candidate is fitted with each of the 3 hypothesis: $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow \pi^- p$ and $\bar{\Lambda} \rightarrow \pi^+ \bar{p}$.
- K_S^0 and Λ:
  - Selected vertices must have their invariant mass in agreement with one hypothesis: $\left|M_{V^0} - M_{K_S^0}\right| < 20$ MeV or $|M_{V^0} - M_\Lambda| < 7$ MeV.
  - A few other quality cuts on η, P_T, direction, decay length, mass uncertainty, minimal distance between same species V^0.
  - V^0 must satisfy one and only one hypothesis.

Event Selection, Event and Particle corrections

CERN-EP-2024-105
All following figures are taken from this reference

- Event Selection:
  - Data and MC events required to have a primary vertex from at least two tracks with $P_T > 100$ MeV. Pile-up events rejected.
  - Events required to have at least one prompt track with $P_T > 1$ GeV.
- Events are corrected for trigger efficiency.
- Prompt tracks are corrected for reconstruction efficiency.
- V^0s are corrected for reconstruction efficiency and fakes (see figure).
- Migrations between P_T bins of reconstructed jets corrected by unfolding.
- Corrections and unfolding derived from the EPOS LHC simulation.

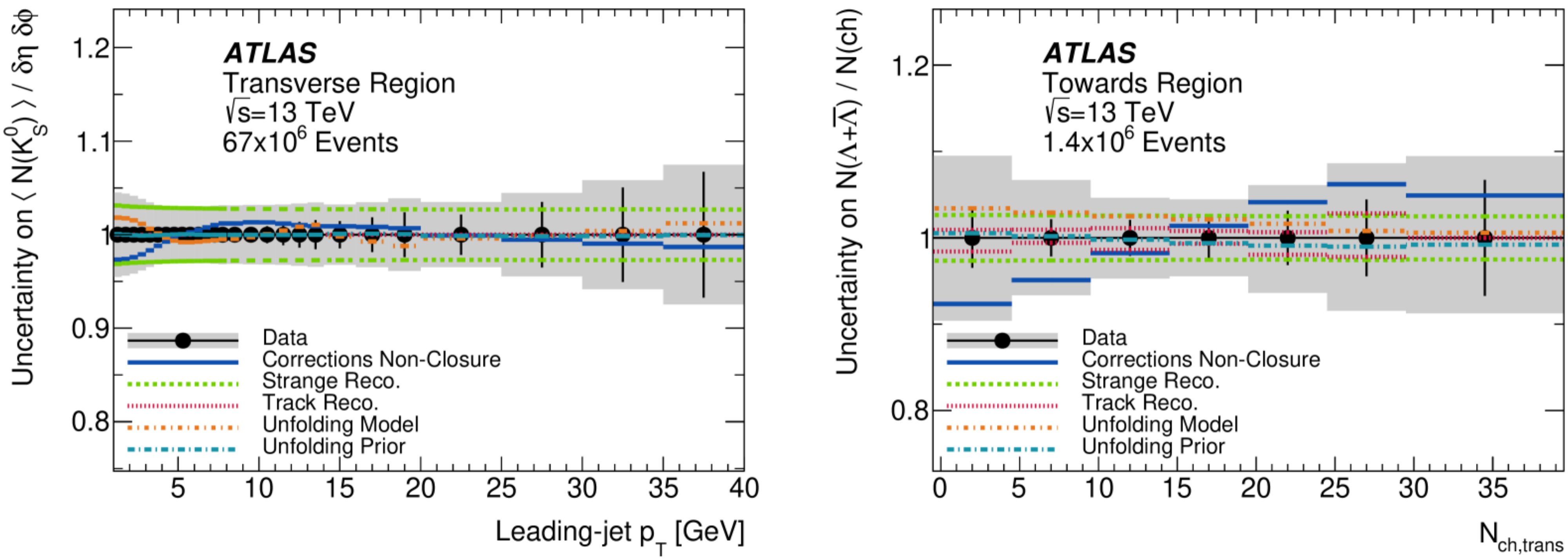


R_{xy} is the projection of the decay length of reconstructed strange hadron on the transverse plane.

Systematic Uncertainties

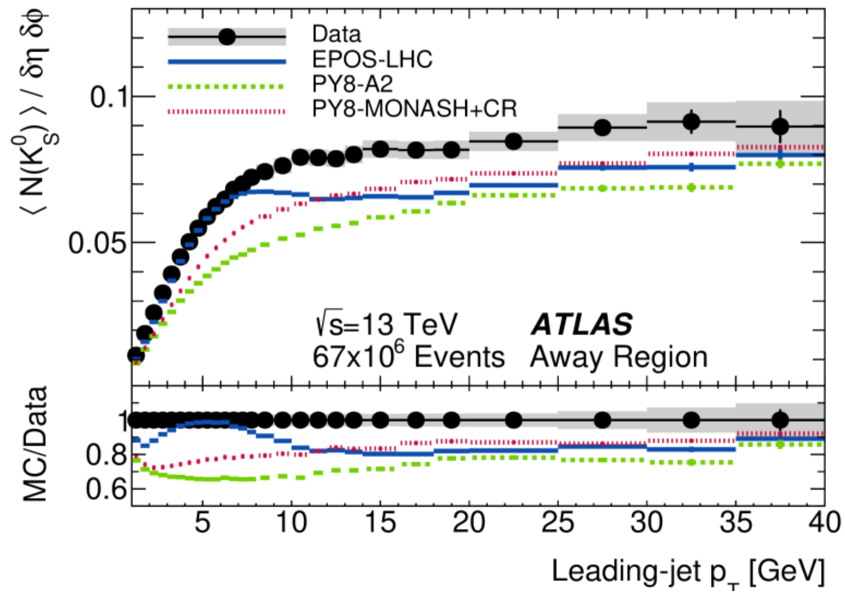
- Unfolding prior: Use EPOS LHC simulated events as pseudo-data after reweighting them to real data.
- Unfolding model: Unfold data with PYTHIA A2 and compare with the nominal EPOS LHC unfolded data.
- Strange hadron uncertainties: Difference in fake estimation between data and EPOS LHC, material budget, statistical errors on efficiency and fake fraction.
- Prompt tracks uncertainty: Material budget, track selection.
- Non-closure correction: Residual non-matching between reconstruction and particle level after unfolding, V^0 efficiency correction estimated at particle level and applied on reconstructed data.

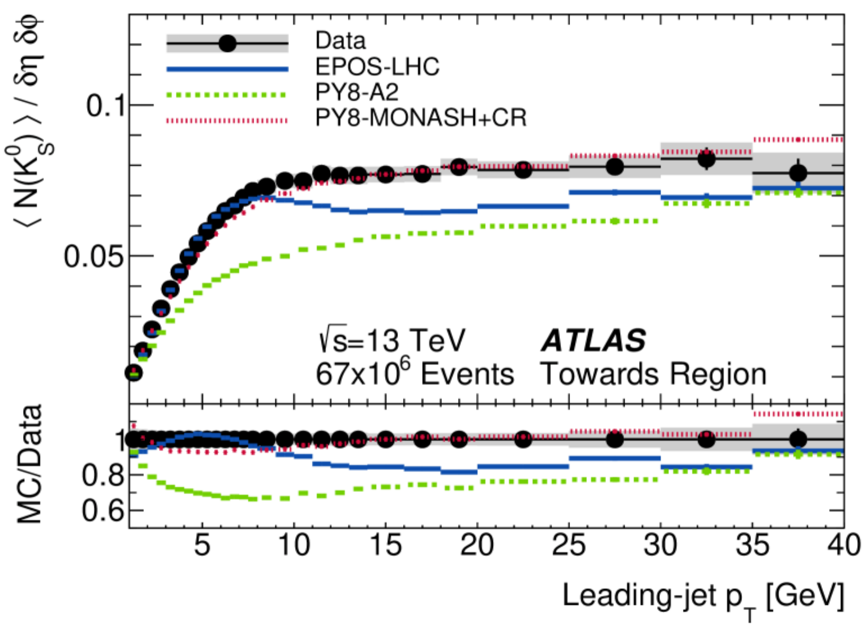
Systematic Uncertainties Breakdown

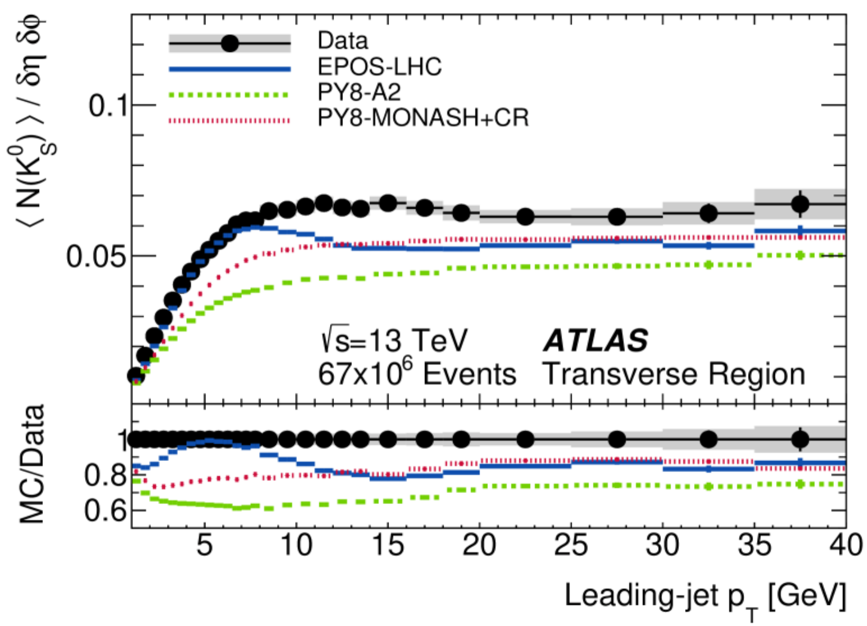


Results: K_S^0 per event

- Data: Soft and hard regime. Transition around leading jet P_T of 10 GeV.
- Soft regime:
  - EPOS LHC closest to data.
  - PYTHIA Monash + CR is better in the Towards region.
- Hard regime:
  - EPOS LHC shows a dip absent from data and other models.
  - PYTHIA A2 models well the data shape.
  - PYTHIA Monash + CR models well the Towards region.

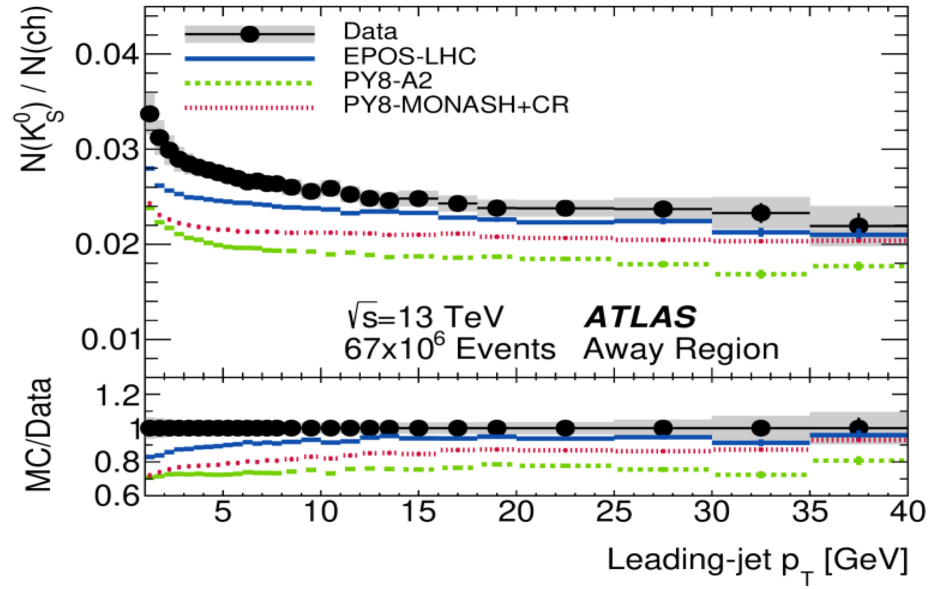


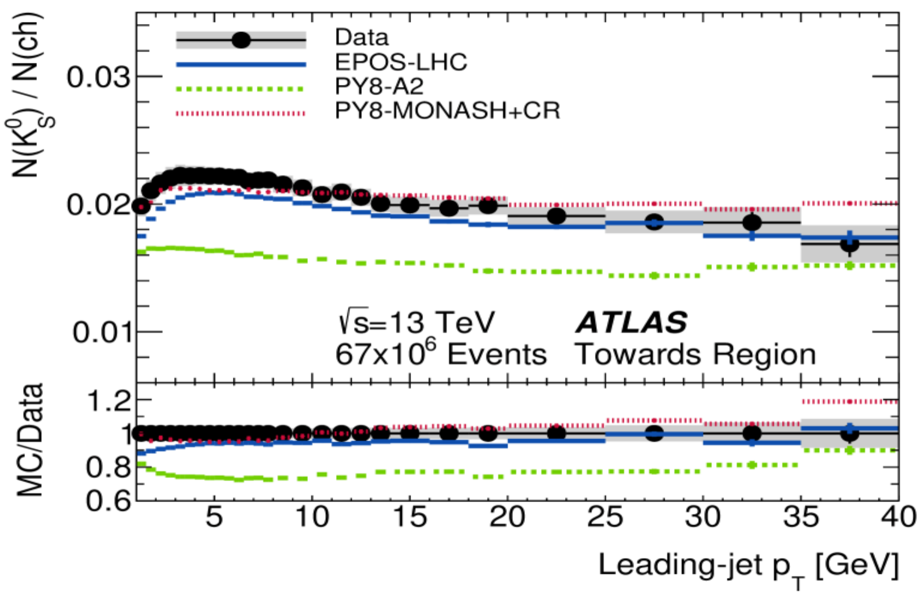


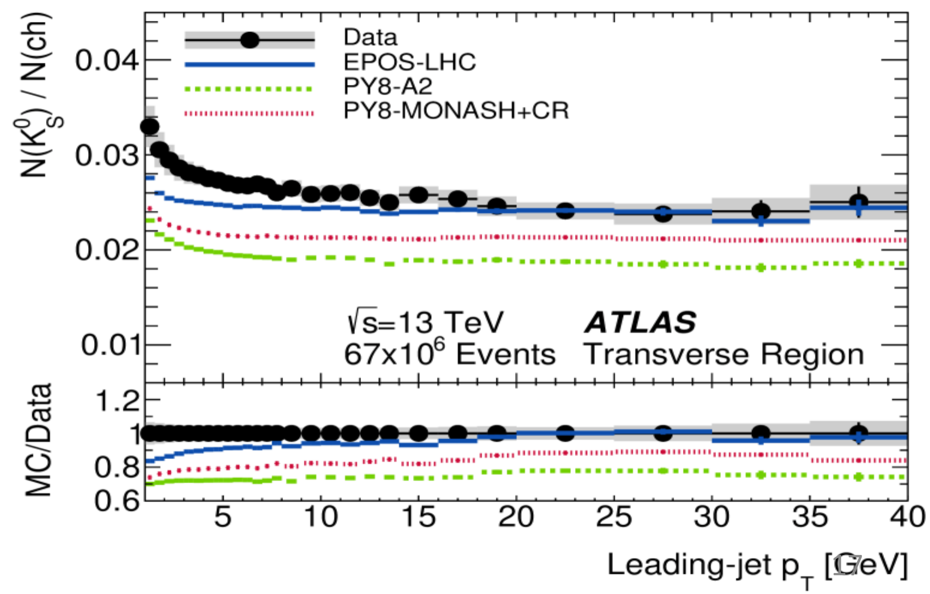


Results: K_S^0 per prompt charged particle

- Data: Soft to hard transition less distinct.
- Soft regime:
  - EPOS LHC agreement not as good as event-normalisation.
  - PYTHIA Monash + CR is again better in the Towards region.
- Hard regime:
  - PYTHIA Monash + CR reproduces data in the Towards region.
  - All models reproduce data shape.

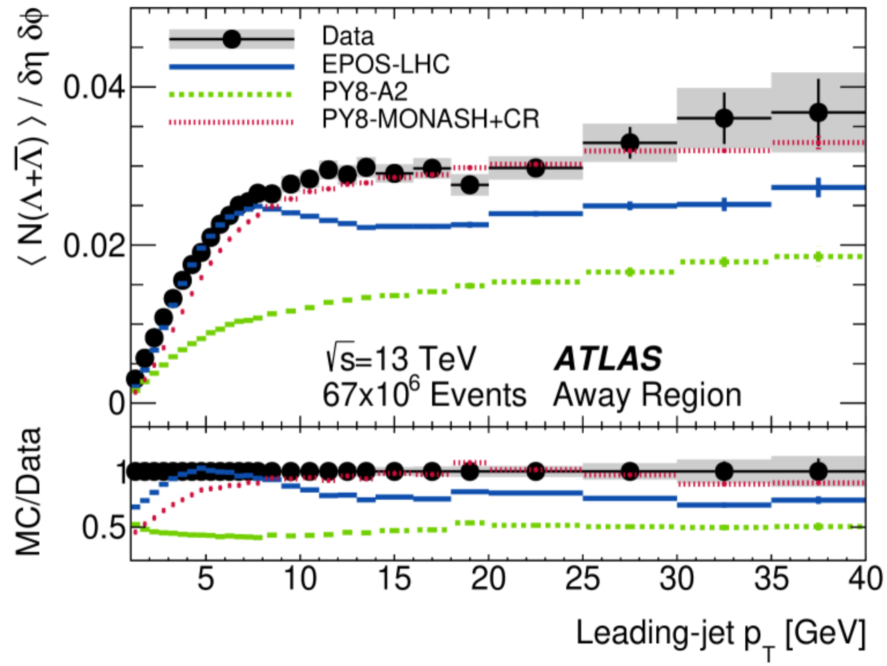


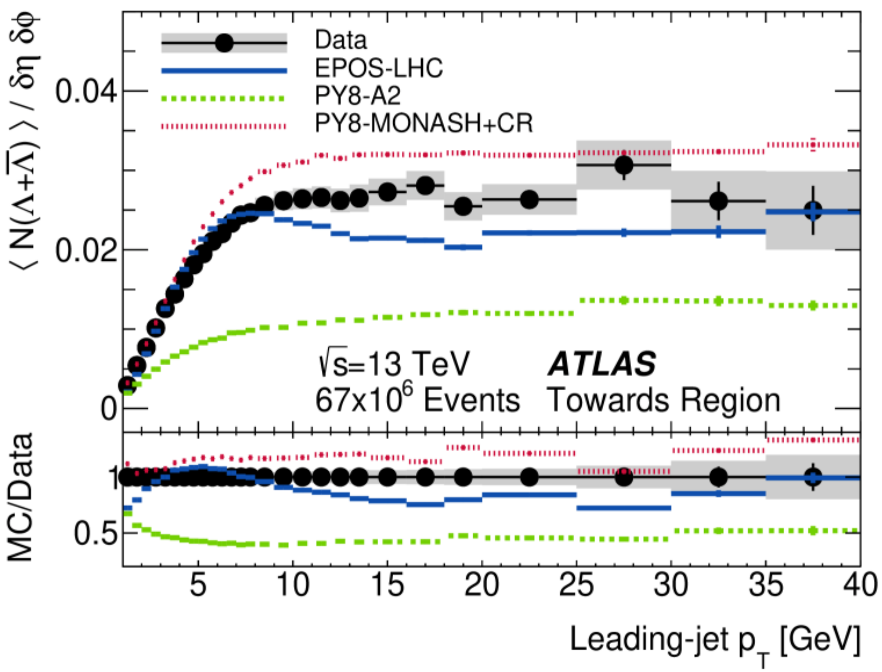


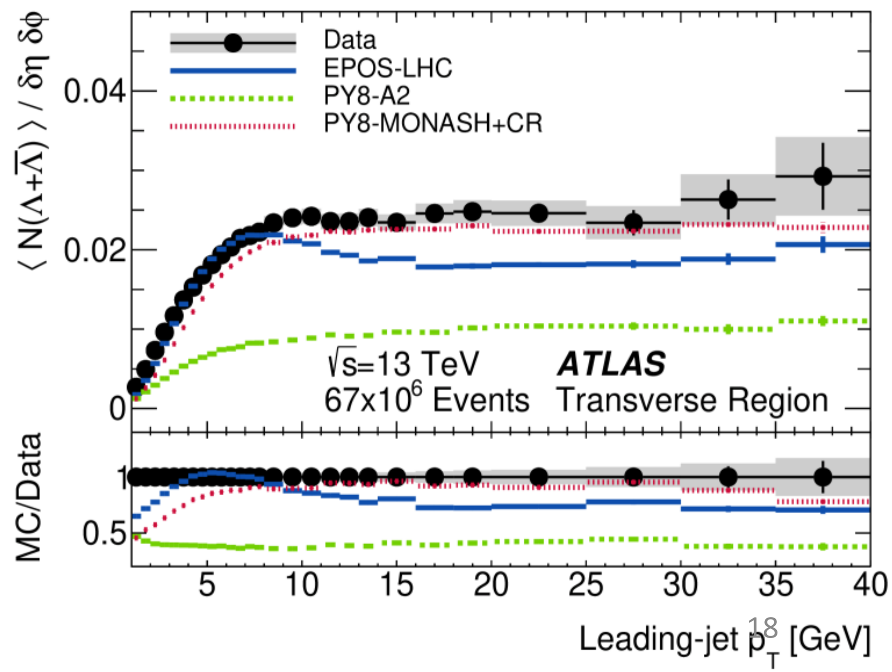


Results: Λ per event

- Data: Soft and hard regime. Transition around leading jet P_T of 10 GeV.
- Soft regime:
    - EPOS LHC is the closest to data.
    - PYTHIA Monash + CR is better in the Towards region.
- Hard regime:
    - EPOS LHC shows a dip absent from data and other models.
    - PYTHIA A2 models well the data shape.
    - PYTHIA Monash + CR models well the Away and Transverse regions.

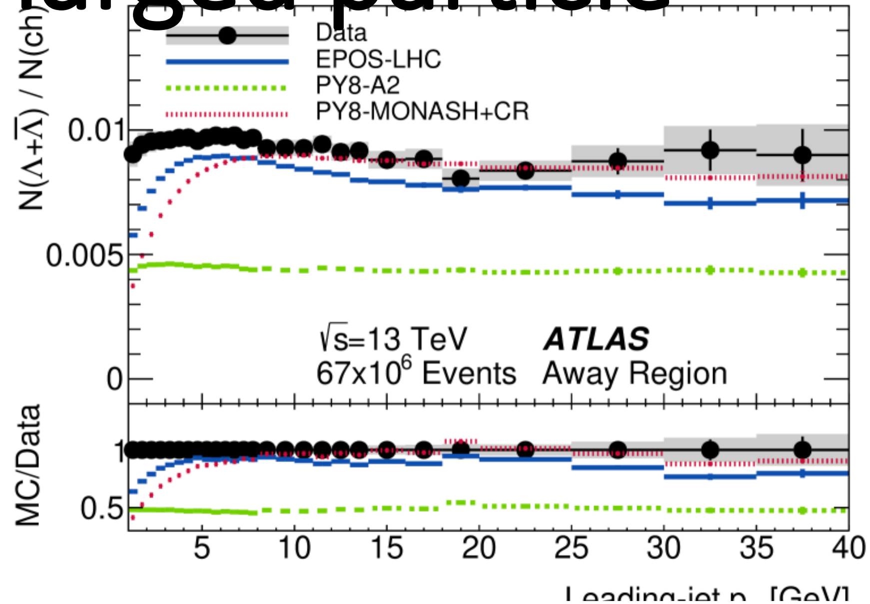


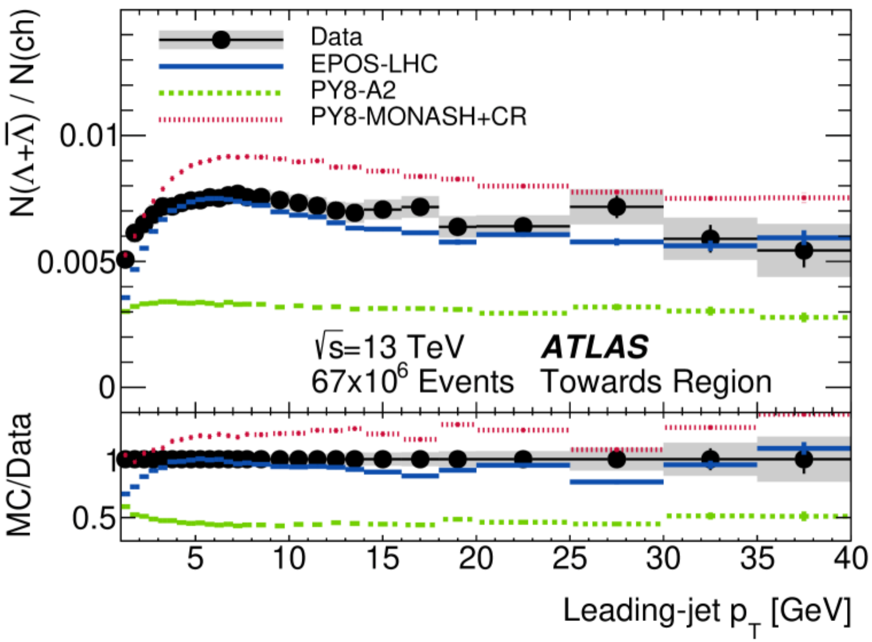


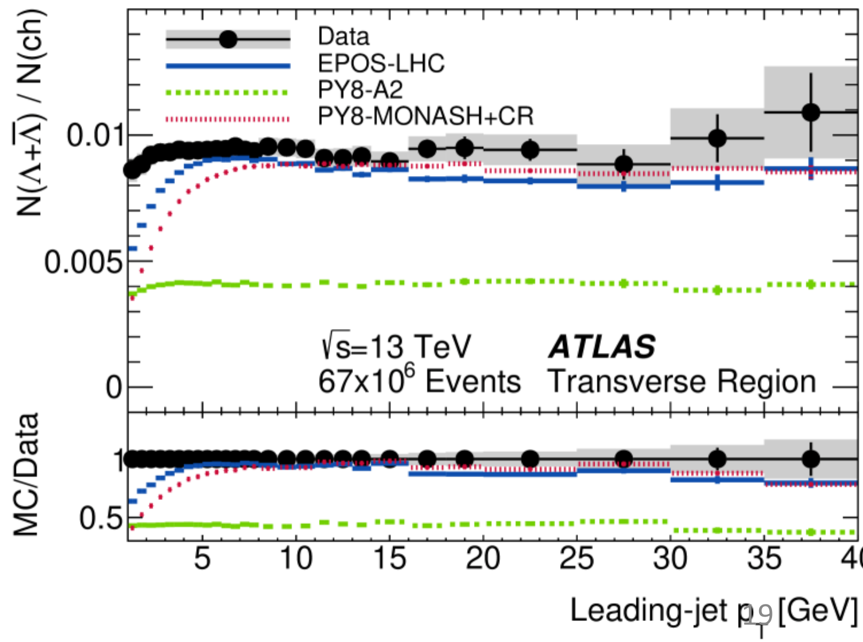


Results: Λ per prompt charged particle

- Data: Soft to hard transition less distinct.
- Soft regime:
  - EPOS LHC is closer to data
  - PYTHIA Monash + CR is better in the Towards region.
- Hard regime:
  - EPOS LHC is close to data.
  - PYTHIA Monash + CR is closer to data except for Towards region.
- General remark: Except PYTHIA Monash+CR in Towards region, all models underestimate strange particle yield.





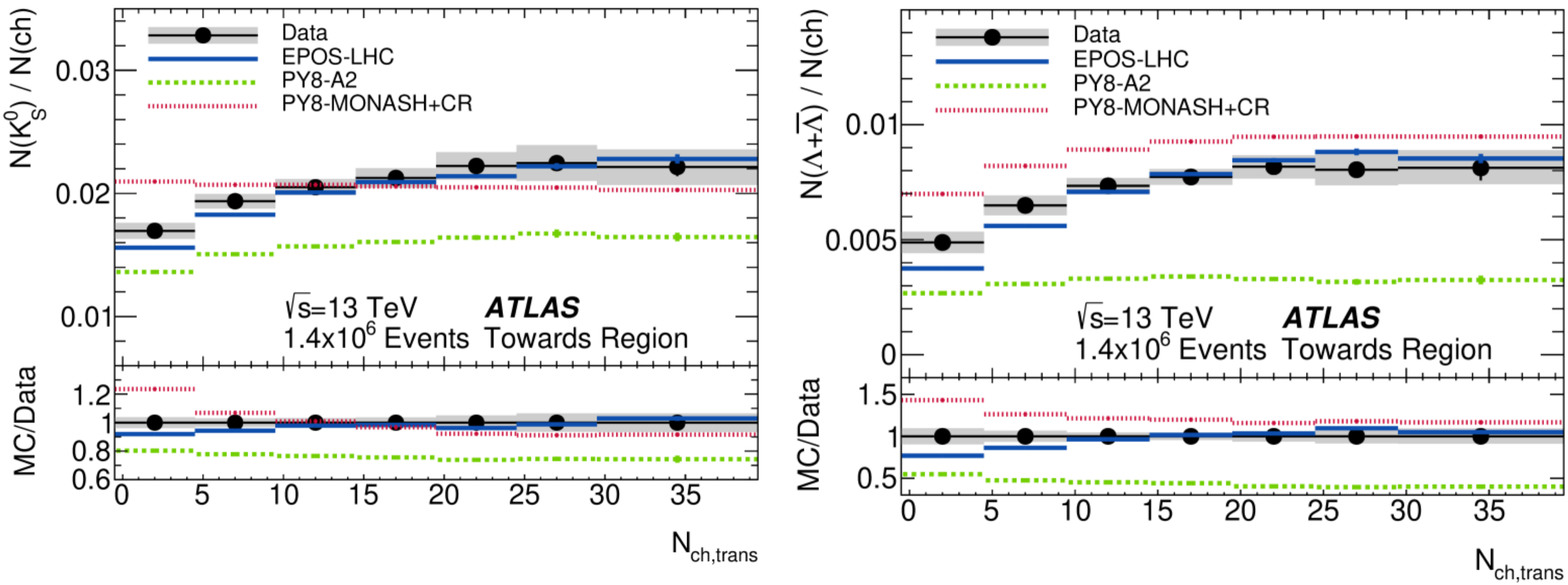


Interpretation

- The increasing of strange hadrons yield in the soft regime: Confirms the impact parameter b picture of MPI: Higher P_T leading jet means smaller b, and so larger MPI.
- The yield then saturates for totally «central collisions».
- Strange hadrons yield normalised by prompt charged particles varies much less with P_T than when normalised by event: MPI independent from hadronisation.
- EPOS LHC better at soft than at hard regime: It needs a better modeling for hard processes.

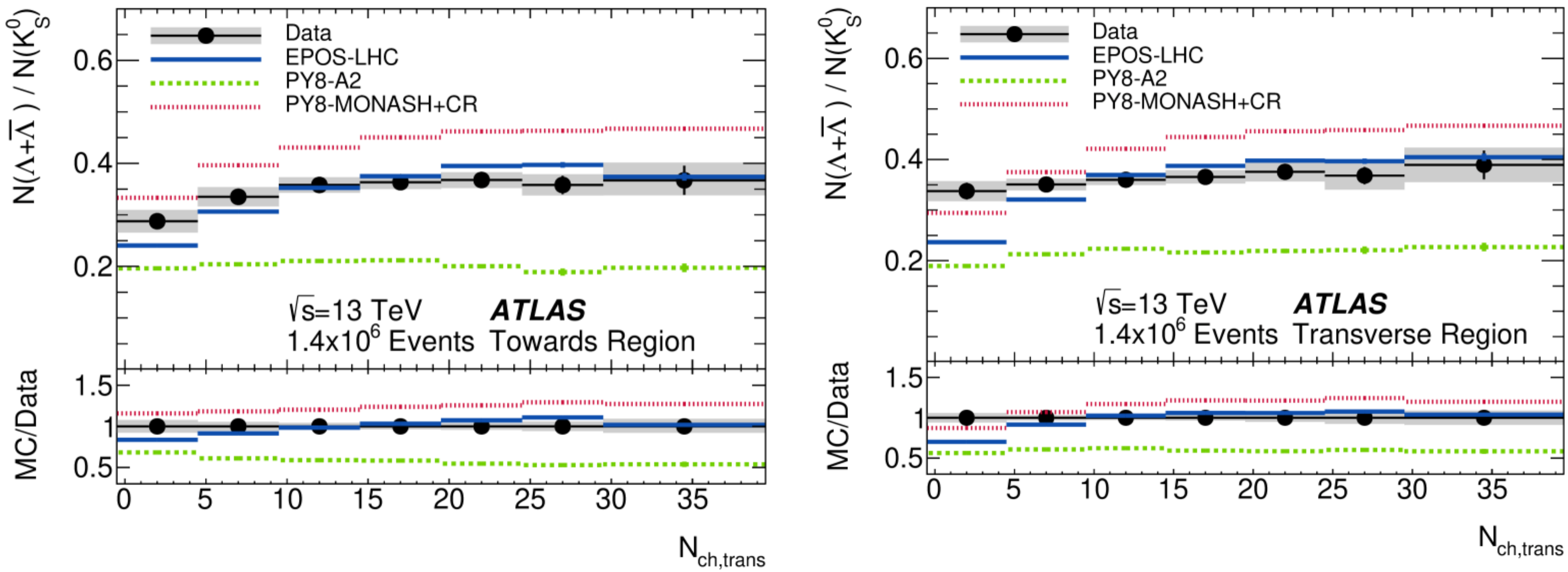
Results for events with leading jets 10 GeV $< P_T \leq$ 40 GeV (1)

- Events acquired with the double hemisphere trigger.
- Number of prompt charged particle in Transverse region used as MPI proxy.



EPOS LHC is the closest to data.

Results for event with leading jets 10 GeV < $P_T \leq$ 40 GeV (2)



PYTHIA A2 reproduces the shape of the data.

Conclusions

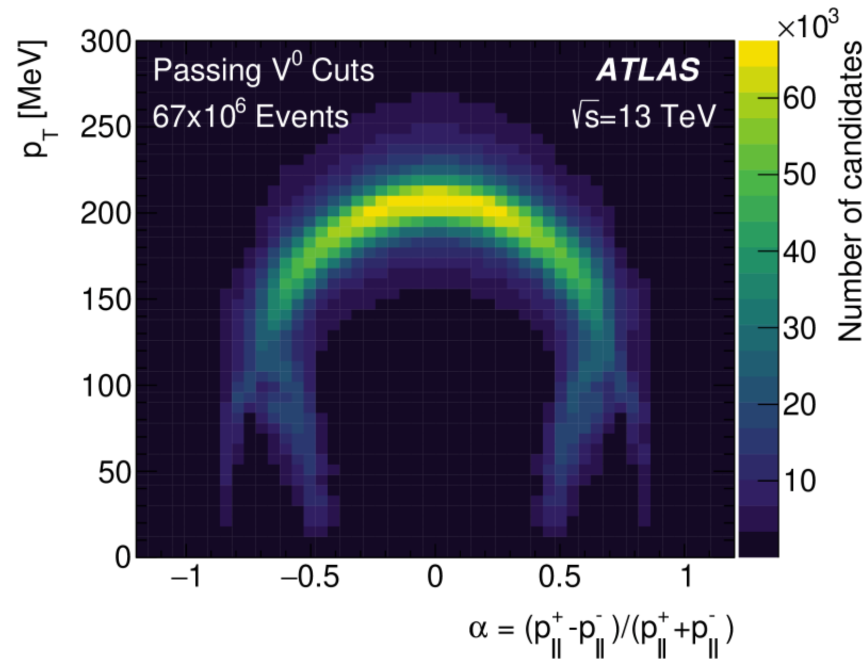
- Properties of underlying-event investigated with the strange hadrons K_S^0, Λ and $\bar{\Lambda}$ in proton-proton collisions at $\sqrt{s} = 13$ TeV.
- Strange hadrons identified via their decay secondary vertices.
- Strange hadrons multiplicities and multiplicity ratios were compared to different Monte Carlo Simulation.
- PYTHIA 8 A2 underestimates the strange hadron yields by 40 to 50 %.
- PYTHIA 8 Monash + CR much closer to data.
- EPOS LHC is the best at soft regime and underestimates the yields at higher P_T.
- EPOS LHC is in best agreement for yields variations with the number of prompt charged particle in the Transverse region.
- These data may be used to improve the modeling of non-perturbative effects in simulations.
- More results to come on hadronic interactions from ATLAS.

Backup

K_S^0 and Λ Selection

Table 1: K_S^0, Λ and $\bar{\Lambda}$ selection criteria.

	K_S^0	Λ, $\bar{\Lambda}$
$\lvert\eta\rvert$	< 1.0	< 1.0
p_T	> 400 MeV	> 750 MeV
$\cos\theta$	> 0.9990	> 0.9998
R_{xy}	4 mm $< R_{xy} \leq 300$ mm	15 mm $< R_{xy} \leq 300$ mm
$M_{V^0}^{err}$	< 15 MeV	< 5 MeV
M_{V^0}	$\lvert M_{V^0} - M_{K_S^0}\rvert < 20$ MeV	$\lvert M_{V^0} - M_{\Lambda}\rvert < 7$ MeV



Efficiency and Fake Fraction of K_S^0 and Λ Vertices