Charged particle and underlying event measurements with the ATLAS detector

ICHEP 2024

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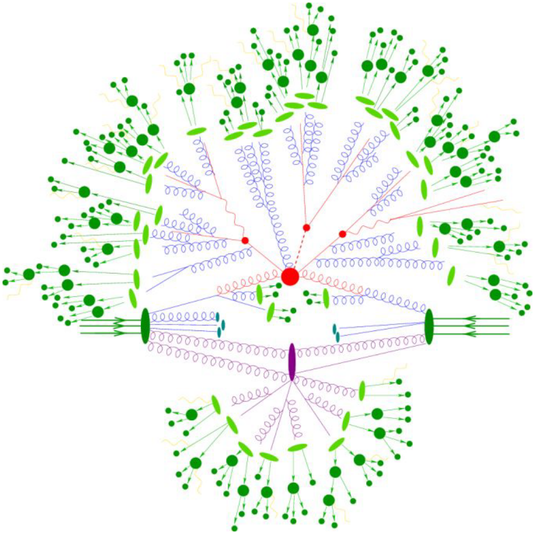
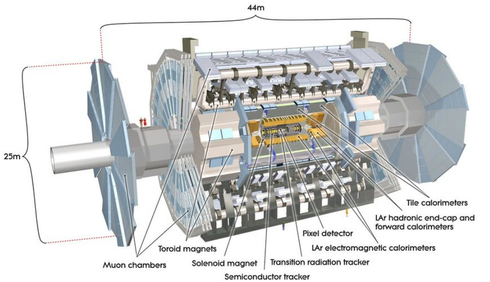
Introduction



- Perturbation physics
  - Large momentum transfer → small coupling constant
  - Hard scattering processes
  - Prompt decays of heavy flavor particles
- Soft physics
  - Small momentum transfer → only model dependent description
  - Underlying event (everything except hard scattering)
  - Diffractive & elastic scattering
  - Hadronization and hadron decays
- No sharp boundaries between hard processes and underlying events

The ATLAS Detector

- ATLAS detector at LHC covers nearly entire solid angle around collision point.
- **Inner Detector (ID)**:
  - Immersed in 2 T axial magnetic field.
  - Provides charged-particle tracking in range $|\eta| < 2.5$
  - Includes high-granularity silicon pixel detector, SemiConductor Tracker (SCT), and Transition Radiation Tracker (TRT)
- **Calorimeters**:
  - Electromagnetic and hadronic calorimeters
  - Used to measure energy of particles
- **Muon Spectrometer**:
  - Incorporates superconducting air-core toroidal magnets
  - Measures muon momentum.
- **Trigger System**:
  - Minimum-bias trigger scintillators (MBTS) provide trigger signal
  - First-level trigger accepts events $\leq$ 100 kHz
  - High-level trigger for further selections to reduce rate to about 1.5 kHz.
- High precision tracking and particle identification critical for study of underlying events



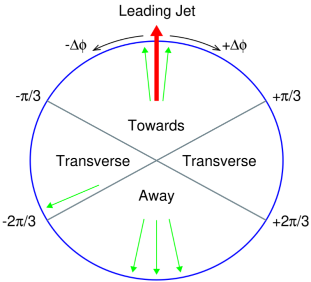
Underlying-event studies with strange hadrons in pp collisions at $s = \sqrt{13}$ TeV with the ATLAS detector

(CERN-EP-2024-105)

https://arxiv.org/abs/2405.05048

Introduction

- Investigating properties of underlying event in *pp* collisions at $\sqrt{s} = 13$ TeV
- Focus on strange hadrons: K_S^0, Λ, and $\overline{\Lambda}$
- Hadron reconsruction: displaced two-particle vertices from decay modes
- Underlying-event observables in azimuthal regions relative to leading charged-particle jet
- Compare data with predictions from various hadronization and underlying-event physics models
- Enhance understanding of hadronization processes and multi-parton interactions (MPI)
- Provide data to improve and tune Monte Carlo (MC) simulation models



Data & Monte-Carlo Samples

Data Samples

- Data collected with ATLAS detector in June 2015 (LHC Run 2)
- Includes 6 LHC runs with up to 29 colliding bunches
- Approximately 110M events recorded with single-hemisphere trigger
- Additional 20M events recorded with two-hemisphere trigger for specific leading jet p_T selection
- Mean number of inelastic interactions per bunch-crossing: $\langle \mu \rangle$ varied between 0.003 and 0.03.

Monte Carlo Samples

- **EPOS 3.4**: EPOS-LHC tune including parton-based Gribov-Regge theory
- **Pythia 8**:
  - A2 tune: Based on MSTW2008 LO PDF set, tuned using ATLAS minimum-bias data at 7 TeV.
  - Monash+CR tune: Includes alternate color-reconnection model for improved baryon production.
- All MC samples simulated using Geant4 for detector response.
- Comparison of MC predictions with data to evaluate underlying event models.

Objects Selections

Prompt Tracks:

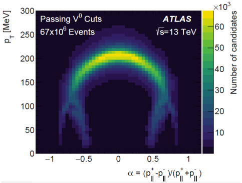
- Reconstructed with a maximum transverse impact parameter of 10 mm
- $p_T > 500$ MeV and $|\eta| < 2.5$.
- Minimum hits required in pixel and SCT detectors
- Tracks both transverse and longitudinal impact parameters relative to primary vertex ≤ 1.5 mm

Jets:

- Reconstructed using anti-k_t algorithm with a radius parameter $R = 0.4$
- Leading jet highest-p_T jet within $|\eta| < 2.1$

Large-radius Tracks:

- Secondary tracking step to improve efficiency for low-p_T particles
- Looser requirements on impact parameters and no pixel hit requirement



Kaon and Lambda Selection:

- K_S^0, Λ, and $\overline{\Lambda}$ candidates identified via V0-finder algorithm
- Selection criteria include p_T thresholds, decay lengths, and mass window constraints

Vertex Reconstruction:

- Primary vertex reconstructed from two or more tracks with $p_T > 100$ MeV.
- Events with multiple vertices (pile-up) are removed

Event Selections

Trigger Requirements:

- Five of six runs events recorded by a single-hemisphere primary trigger requiring at least one MBTS sector above threshold
- Sixth run used a two-hemisphere trigger selection introducing a slight bias towards events with a larger number of charged particles

Vertex Requirements:

- Events must contain a primary vertex reconstructed from two or more tracks with $p_T > 100$ MeV.
- Pile-up events including two or more reconstructed primary vertices with four or more associated tracks each are removed

Jet Requirements:

- Events with leading jet $10 < p_T \leq 40$ GeV satisfy restricted leading-jet selection.

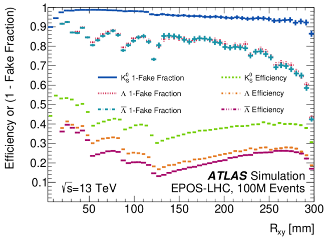
Track Requirements:

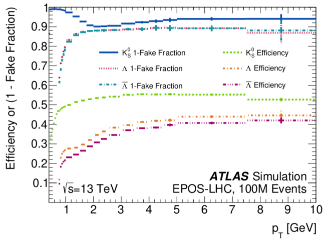
- Events must have at least one track with $p_T > 1$ GeV passing prompt tracking selection
- Particle-level events require at least one selected charged particle with $p_T > 1$ GeV

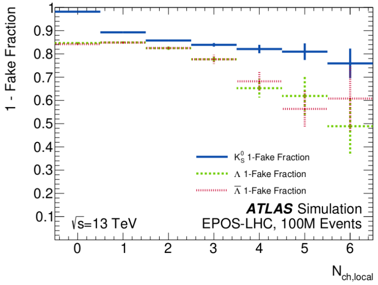
Statistics:

- Total of 67 million events satisfy event selections in data
- A subset of 1.4 million events satisfies restricted leading-jet selection
- Available EPOS-LHC and Pythia 8 Monash+CR MC statistics are comparable in size to data
- Pythia 8 A2 sample is only around 25% of data size

Event & Particle Correction Factors

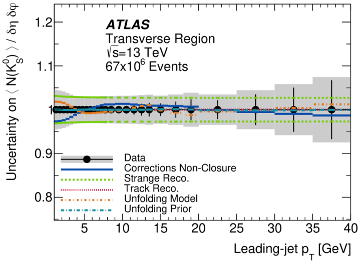


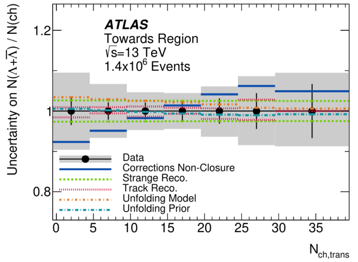




- Correction mitigates for detector effects.
- Trigger correction applied for single-hemisphere MBTS trigger
- Per-track and per-V^0 weights applied to correct for detector efficiency and fake rates
- Mean correction factors provided for K_S^0, Λ, and $\overline{\Lambda}$

Uncertainties





Unfolding Uncertainties:

- Reweighting method: Ratio between MC and data
- Deviation of unfolded EPOS-LHC pseudo-data as uncertainty
- Unfolding with Pythia 8 A2 response matrices.
- Percentage difference with EPOS-LHC considered

Correction Systematics:

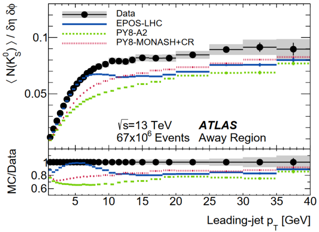
- Fake V^0 probability from line-shape fits.
- Material budget uncertainty included
- Inner-detector material and χ^2 requirements
- Additional 0.5% systematic uncertainties

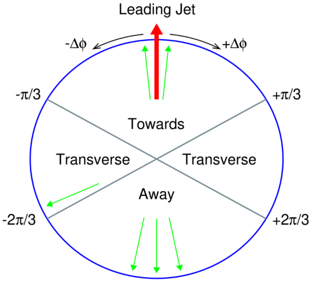
Non-closure:

- Differences between corrected reconstruction-level MC and particle-level distributions
- Statistical uncertainty from bootstrap method (500 pseudo-runs)

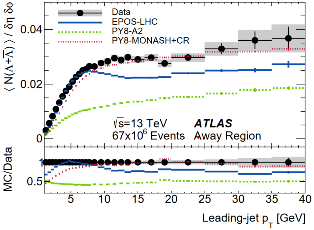
Soft Regime (Leading-jet $p_T < 10$ GeV):

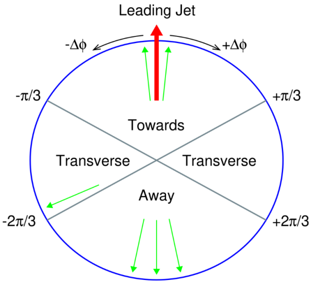
- EPOS-LHC model provides best overall performance for both K_S^0 and $\Lambda + \overline{\Lambda}$ mean multiplicities.
- At very low leading-jet p_T, EPOS-LHC tends to underestimate relative baryon yields.
- Pythia 8 A2 model significantly underestimates all distributions (up to 40% for K_S^0 and up to 60% for $\Lambda + \overline{\Lambda}$).
- Pythia 8 Monash+CR model performs better than A2 model, especially in towards region for K_S^0 and $\Lambda + \overline{\Lambda}$ relative yields.





Results for $\Lambda+\bar{\Lambda}$





Hard Regime (Leading-jet $p_T > 10$ GeV):

- Weaker dependence on leading-jet p_T
- Non-diffractive *pp* interactions at low impact parameter drive observed activity
- Towards and away regions show a tendency for event-normalized mean multiplicity to rise with increasing leading-jet p_T
- Transverse region shows predominantly flat behavior over hard regime, minimally affected by leading partonic scattering
- EPOS-LHC model less accurate in hard regime due to lack of hard-scattering model

Study of ordered hadron chains in proton-proton, proton-lead and lead-lead collisions with the ATLAS detector

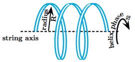
(ATLAS-CONF-2022-055)

https://cds.cern.ch/record/2819852

Introduction and Motivation

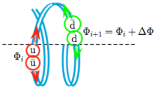
Introduction

- Hadronization studies crucial for understanding high-energy collision dynamics
- ATLAS unique for momentum difference measurement between charged hadrons in different collision systems: pp, p+Pb, Pb+Pb



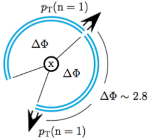
Motivation

- Traditional models like Lund string fragmentation model offer insights (discrepancies with experimental data require refined models)
- Identifying universal patterns in hadronization across different collision systems → deeper understanding of particle production mechanisms
- Recent advancements: propose helical string model for hadronization



Methodology

- pp, p+Pb, Pb+Pb at different energies
- Extracting spectra of pair adjacent in color flow with difference hadron pair yield with like-sign and opposite-sign charge



Inclusive Pair Measurements

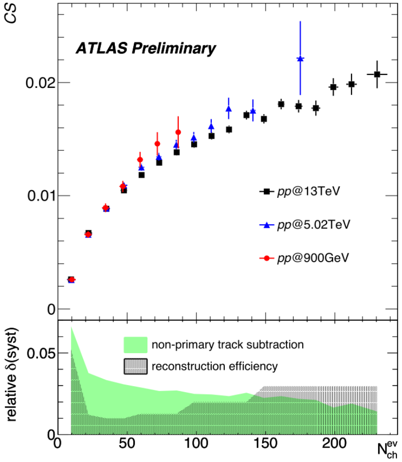
- Differential charge distribution;

$$\Delta(Q) = \frac{1}{N_{ch}}[N^{OS}(Q) - N^{LS}(Q)]$$

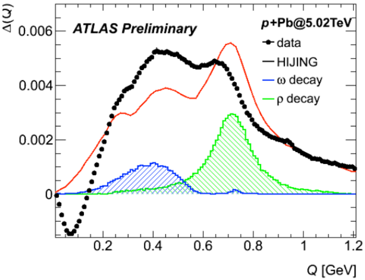
- Correlation strength (CS) and chain correlation strength (CCS):

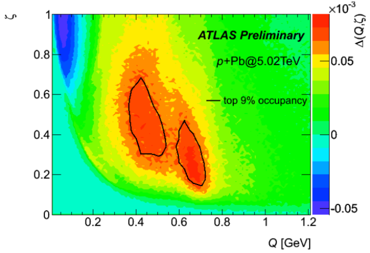
$$\text{CS} = -\int_{\Delta<0} \Delta(Q)\,\mathrm{d}Q, \quad \text{CS} = -\int_{\Delta_{3h}<0} \Delta_{3h}(Q)\,\mathrm{d}Q$$

- Studies showed independence of $\Delta(Q)$ from collision energy
- Consequence: Universality of multiplicity dependent on enhanced production rate of close LS pairs
- First LS pair production measurement in model-independent way $\rightarrow$ forecast of future minimum bias measurements



Universality of Hadron Productions





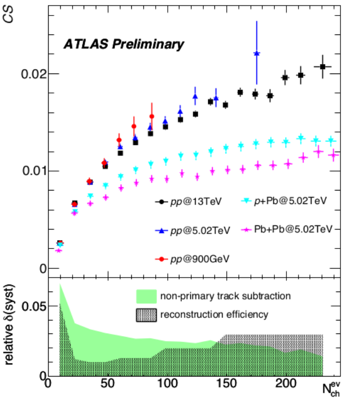
- $\Delta(Q)$ distributions for p+Pb and Pb+Pb collisions
- Insights into hadronization process and identifying discrepancies in current models
- Ratio of absolute momenta

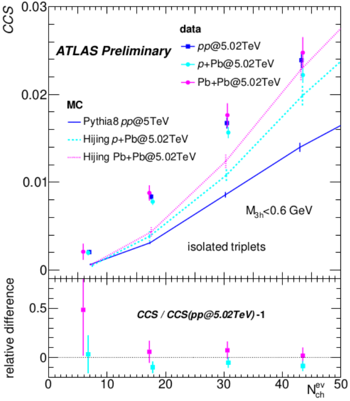
$$\zeta = \min\left(\frac{|p_j|}{|p_i|}, \frac{|p_j|}{|p_i|}\right)$$

- (Q, ζ) dependence of Δ for p+Pb and Pb+Pb (dominant running contributions)
- Comparing Hijing model predictions for $\Delta(Q, \zeta)$ with experimental data
- Indicating areas for potential improvement in hadronization modeling

Universality of Hadron Productions

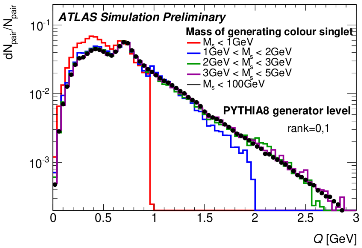
- Rising trend of CS with multiplicity for all collision systems
- Good agreement between HI and pp samples regarding chain properties → universality in hadronization process
- Correlated systematic uncertainties below
- Significant difference between Hijing and Pythia8

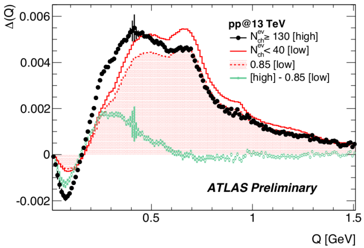




Correlation strength measured in pp, p+Pb and Pb+Pb samples for CS and CCS measurements

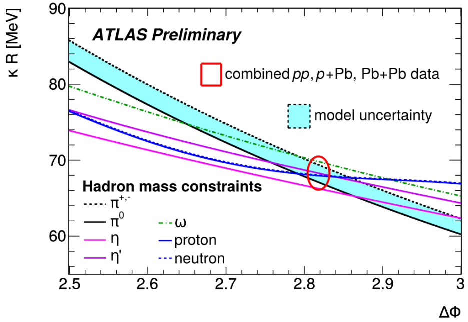
Multiplicity Dependence & Quantum Effects

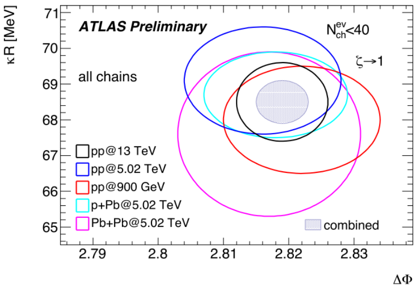


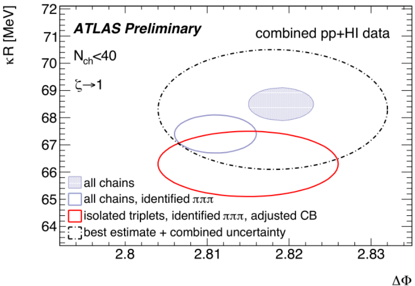


- Density of pairs of color-adjacent hadrons as function of parent color singlet mass
- $\Delta(Q)$ distributions for events with high and low multiplicity of charged particles (Both distributions agrees for $Q > 0.7$ GeV $\rightarrow$ low multiplicity regions template for *hard* component)
- Shape of $\Delta(Q)$ distribution stabilizes with increasing mass of parton system
- High multiplicity samples (85%) resemble *hard* component of low multiplicity samples with remaining 15% additional soft activity carried by low-mass color singlets
- Further studies required for relation between soft hadronization component and dissociating proton

Fit of Δ_{3h} (3 Body Decay)







Combined Results incl. Syst. Uncertainties:

- $m_{3h}^{thr} = (567^{+16}_{-19})$ MeV (hadron threshold)
- $\kappa r = (66.5^{+2.0}_{-2.2})$ MeV (κ: string tension, R: helix radius)
- $\Delta\Phi = (2.819^{+0.013}_{-0.014})$ (quantized helix phase)

$$E_T(n) = \sqrt{m_n^2 + p_T(n)^2} = n\kappa R\Delta\Phi$$

Thank you very much for your attention!

Backup Slides

Results

Soft Regime (Leading-jet $p_T < 10$ GeV):

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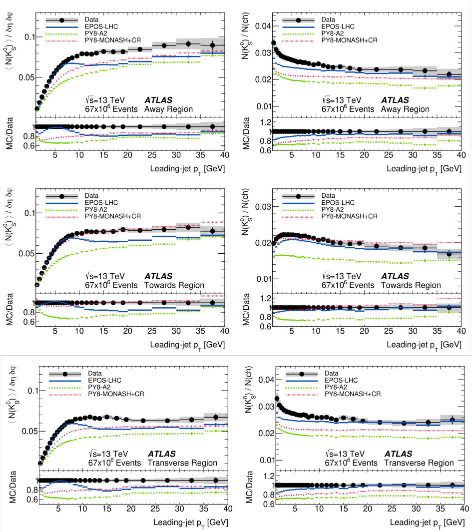

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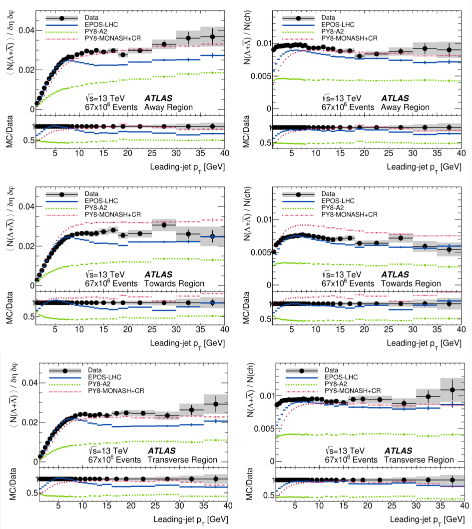

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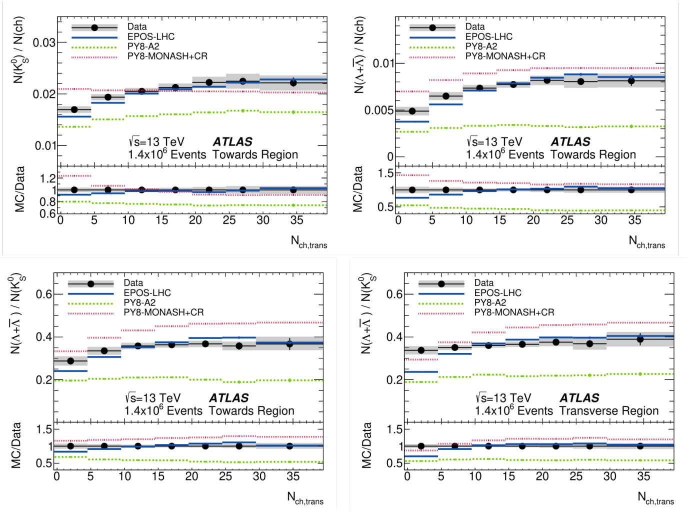
- EPOS-LHC model less accurate in hard regime due to lack of hard-scattering model

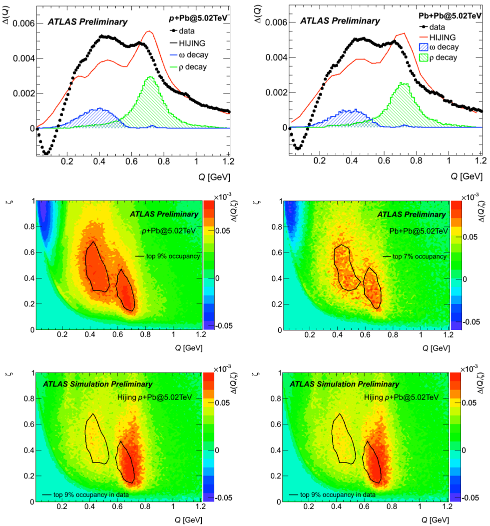
Results

General Observations:

- No model perfectly describes data
- Data could be used to improve future simulations.
- Further studies needed to enhance understanding of underlying-event properties.



Universality of Hadron Productions



- $\Delta(Q)$ distributions for p+Pb and Pb+Pb collisions
- Insights into hadronization process and identifying discrepancies in current models
- (Q, ζ) dependence of Δ for p+Pb and Pb+Pb (dominant running contributions)
- Comparing Hijing model predictions for $\Delta(Q, \zeta)$ with experimental data (contours for better visualization of differences)
- Indicating areas for potential improvement in hadronization modeling

Analysis Strategy

- **Region Definition:**
  - Leading jet defines towards, transverse, and away regions
- **Multiplicity Computation:**
  - Separate for K_S^0, $\Lambda + \overline{\Lambda}$, and prompt charged-particles.
  - Use per-candidate correction weights
- **Unfolding:**
  - Iterative method with four iterations.
  - EPOS-LHC used for response matrix
- **Normalization:**
  - Ratios of multiplicity observables.
  - Event-normalized figures formed
- **Observables:**
  - K_S^0 and $\Lambda + \overline{\Lambda}$ multiplicities vs. leading-jet p_T.
  - Normalize to prompt charged-particle yield or event count
- **Restricted Leading-Jet Selection:**
  - Events with $10 < p_T \leq 40$ GeV.
  - Plot abscissa changed to multiplicity of prompt charged-particles in transverse region
- **Statistical Error:**
  - Bootstrap method with 500 pseudo-runs.
  - Root mean square used for error