Measurements of Correlations between Inclusively Produced $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ Hyperon Pairs at $\sqrt{s} = 7$ TeV in the LHC ATLAS Experiment

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Motivations

Main physics goals include:

- **understanding how hadrons are formed from the quark-gluon system**
- **studying the $s\bar{s}$ quark-antiquark pair production through the $\Lambda^0\bar{\Lambda}^0$ system**
- **testing the predictions of jet fragmentation and hadronization models, such as the string model and the "popcorn" mechanism**
- **probing the Fermi-Dirac (FD) correlation between identical fermions, namely $\Lambda^0\Lambda^0$ and $\bar{\Lambda}^0\bar{\Lambda}^0$ pairs**

Motivations

"Very encouraging that you are studying baryon (antibaryon) correlations at LHC. Baryon production is definitely among the most poorly understood aspects of the fragmentation mechanism, and having experimental measurements and constraints is absolutely crucial." – from my email exchange with Prof. Peter Skands, one of the authors of PYTHIA event generator

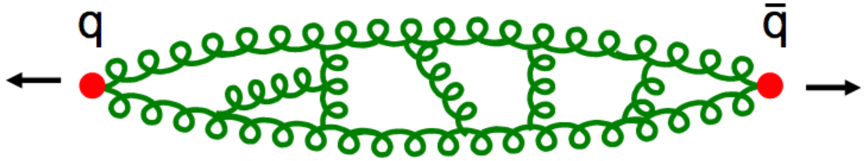
The String Model

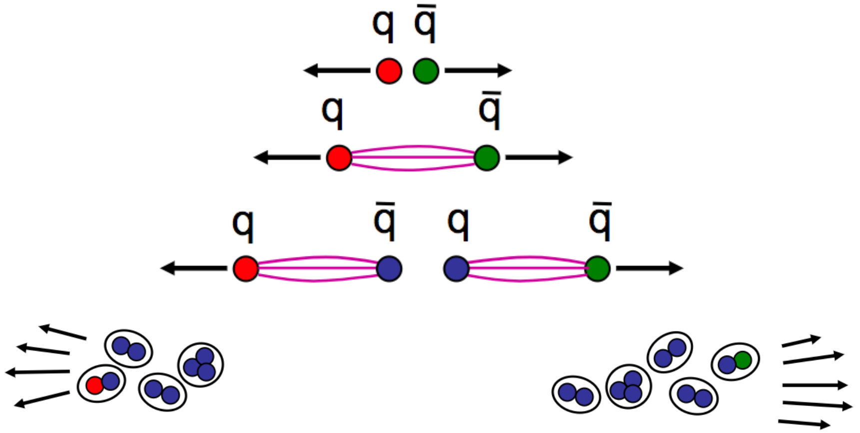
- Hadronization (formation of hadrons from quark-gluon system) is non-perturbative, and not (yet) calculable
- **Phenomenological models are developed to describe the physics processes and give predictions for experimental observables**
- One of the most successful model is the Lund string model:
  - A massless relativistic string with constant tension is used to model the QCD flux tube between colored objects
  - Endpoints are identified as quark and antiquark
  - Lund symmetric fragmentation function

$$f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$$

where z is the fractional momentum of parton/hadron, a and b are tunable parameters

(Thomson, 2011)

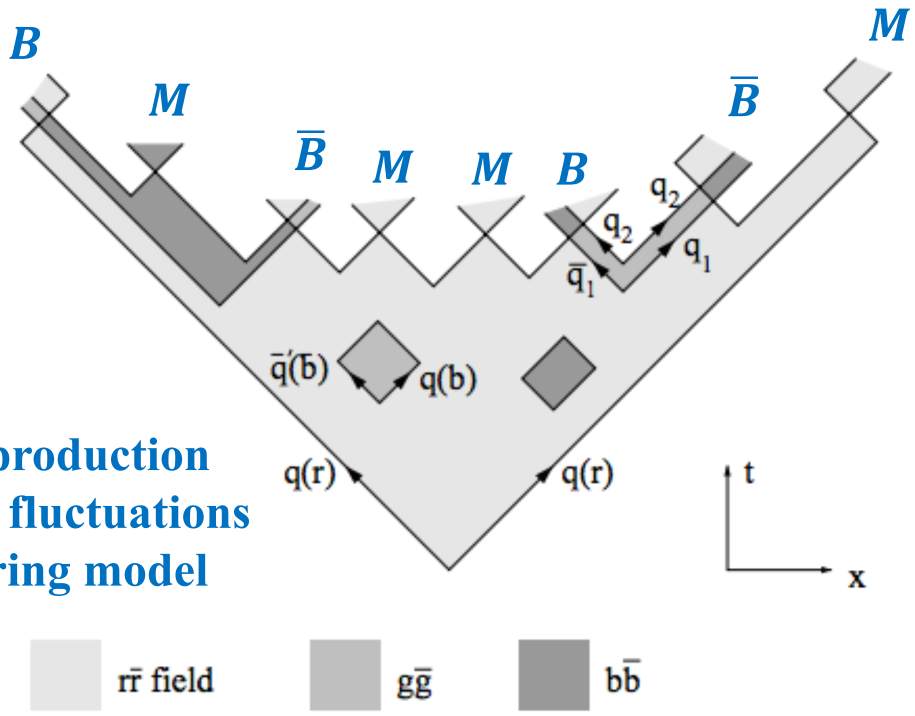




(Thomson, 2011)

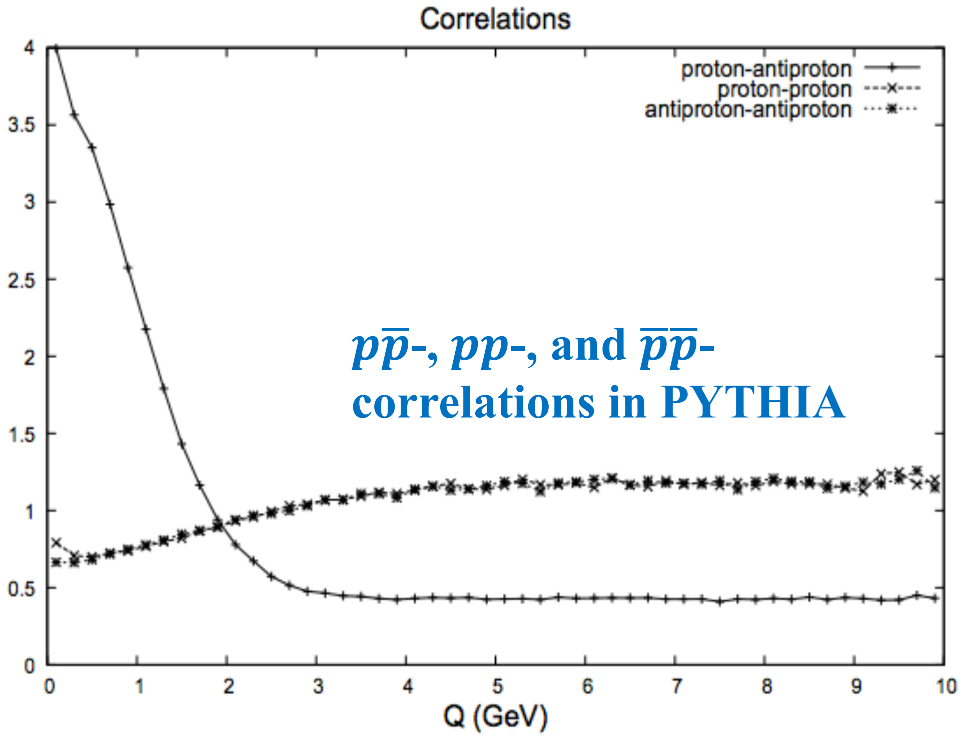
Predictions from the String Model

- Baryon-antibaryon ($B\bar{B}$) pairs are produced closer in rank while baryon-baryon/antibaryon-antibaryon pairs are produced further apart
- Baryon/antibaryon production is heavily suppressed by meson (M) production
- The string model predicts positive correlation between baryon-antibaryon pairs and anti-correlation between baryon-baryon pairs in rapidity and momentum phase space



Baryon production from color fluctuations in the string model

arXiv:0702241 [hep-ph]



$p\bar{p}$-, pp-, and $\bar{p}\bar{p}$-correlations in PYTHIA

arXiv:0702241 [hep-ph]

Correlation Function

Correlation function $C_2(p_1, p_2)$ is defined as

$$C_2(p_1, p_2) = \frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)}$$

where ρ_2 is two-particle density and ρ_1 is single particle density

It measures enhancement/suppression of pair production with respect to single production

Common parameterizations include:

- Relative 4-momenta Q (includes all degrees of freedom, space-time separation, emitter size estimation)
- Relative azimuthal angle $\Delta\phi_{12}$ (study hyperons produced at collinearity ~ 0 and back-to-back $\sim \pi$)

Goldhaber parameterization of emitter size:

$$C_2(Q) = N(1 + \beta e^{-R^2Q^2})$$

where β is a suppression factor and R is the emitter size

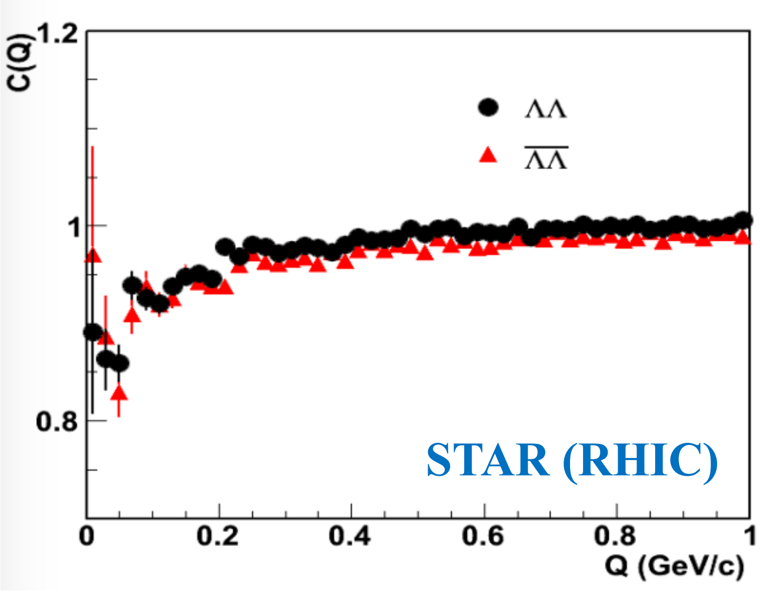
Past Results

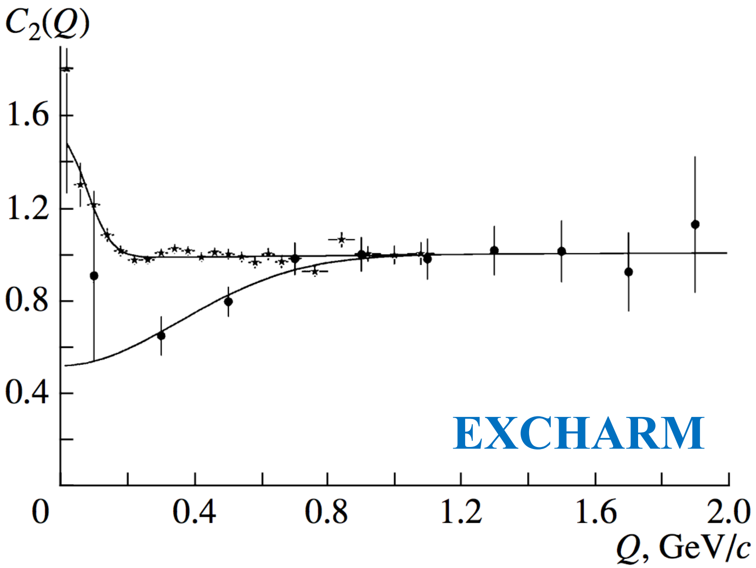
Experiments:

- pp collision at 7 TeV at ALICE
- $Au + Au$ collisions at 200 GeV at STAR
- Pb ions collision at 158 A GeV at NA49
- nC collision at 51 GeV at EXCHARM

Results:

- $R_{\Lambda\Lambda}$ measured ranging from 3.13 fm (STAR) to 4.0 fm (NA49/EXCHARM)
- Positive correlation at $\Delta\phi \sim 0$ for $\Lambda\bar{\Lambda}$ events
- Anti-correlation at Q < 0.4 and $\Delta\phi \sim 0$ for $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ events
- BE correlation for pion pairs at Q ~ 0
- Dependence on baryon mass





Extraction of Spin Composition

The spin composition of a di-hyperon system can be extracted using the decay angular distribution y^* in the helicity frame

$$dN/dy^*|_{S=0} = N(1 \mp \alpha^2 y^*) \quad \text{and} \quad dN/dy^*|_{S=1} = N(1 \pm \frac{\alpha^2}{3} y^*)$$

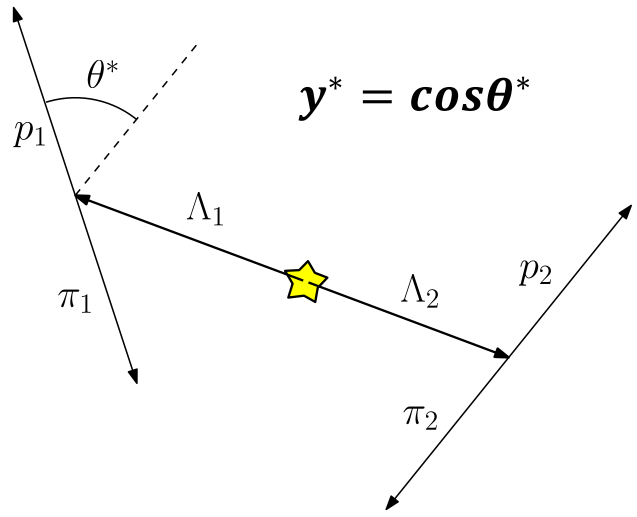
where S is the spin of the di-hyperon system

Adding contribution from S = 0 (singlet) and S = 1 (triplet) states:

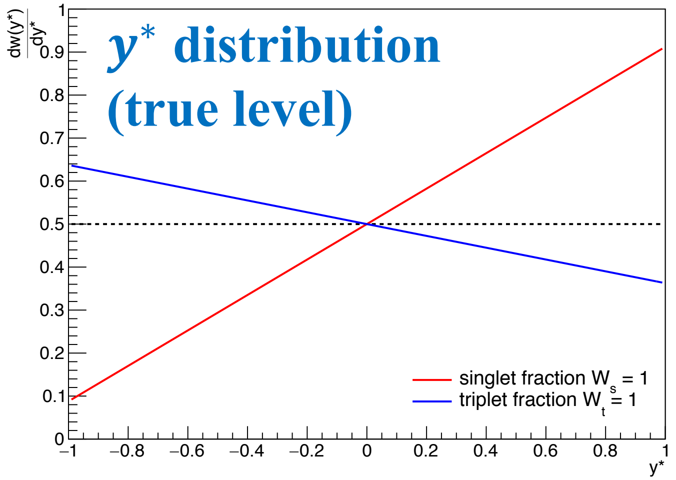
$$\boxed{dN/dy^* = (1-\epsilon) dN/dy^*\Big|_{S=0} + \epsilon dN/dy^*\Big|_{S=1} = N(1 + (\frac{4}{3}\epsilon - 1)\alpha^2 y^*)}$$

where ϵ is the fractional contribution from the $S = 1$ state

Spin composition can be expressed in terms of the fraction of $S = 1$ state ϵ and can be extracted from the slope of the y^* plot



θ^* defined in the helicity frame

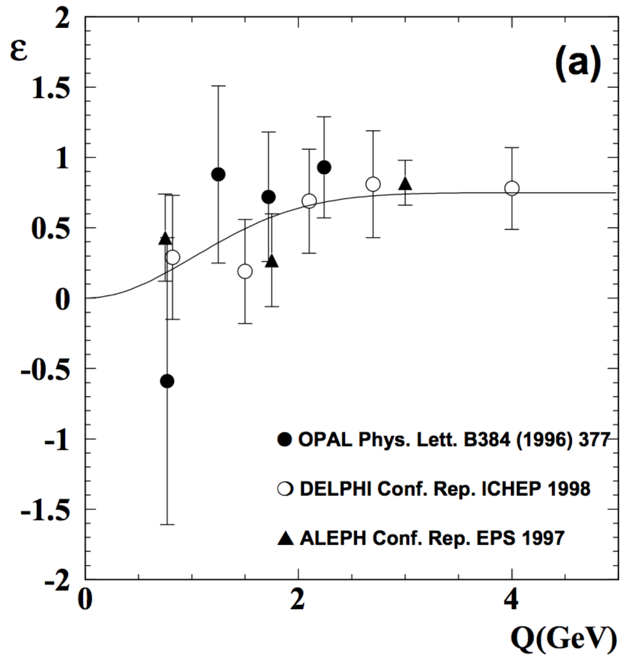


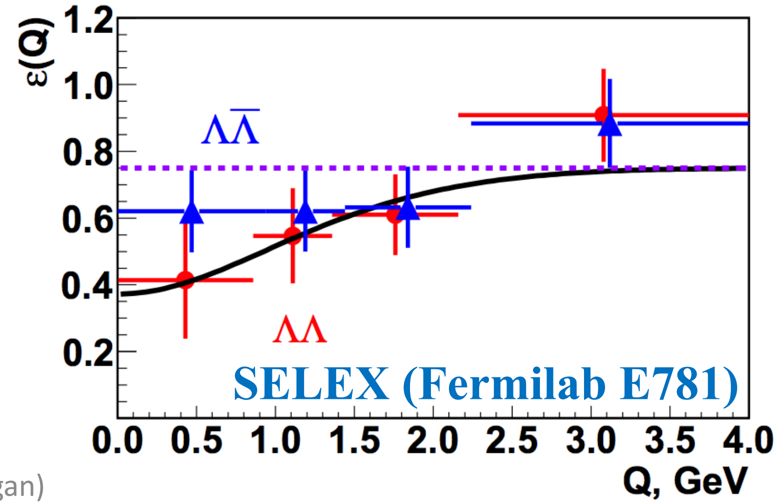
Past Results

Experiments:
- e^+e^- collisions at LEP (OPAL, ALPEH, DELPHI)
- $\Sigma^- A$ interactions at 600 GeV at SELEX (Fermilab E781)

Results:
- Suppression of S = 1 state near Q ~ 0 for $\Lambda^0\Lambda^0/\bar{\Lambda}^0\bar{\Lambda}^0$
- $R_{\Lambda\Lambda}$~0.15 fm for LEP and ~0.3 fm for SELEX
- Data statistics are very limited in both experiments

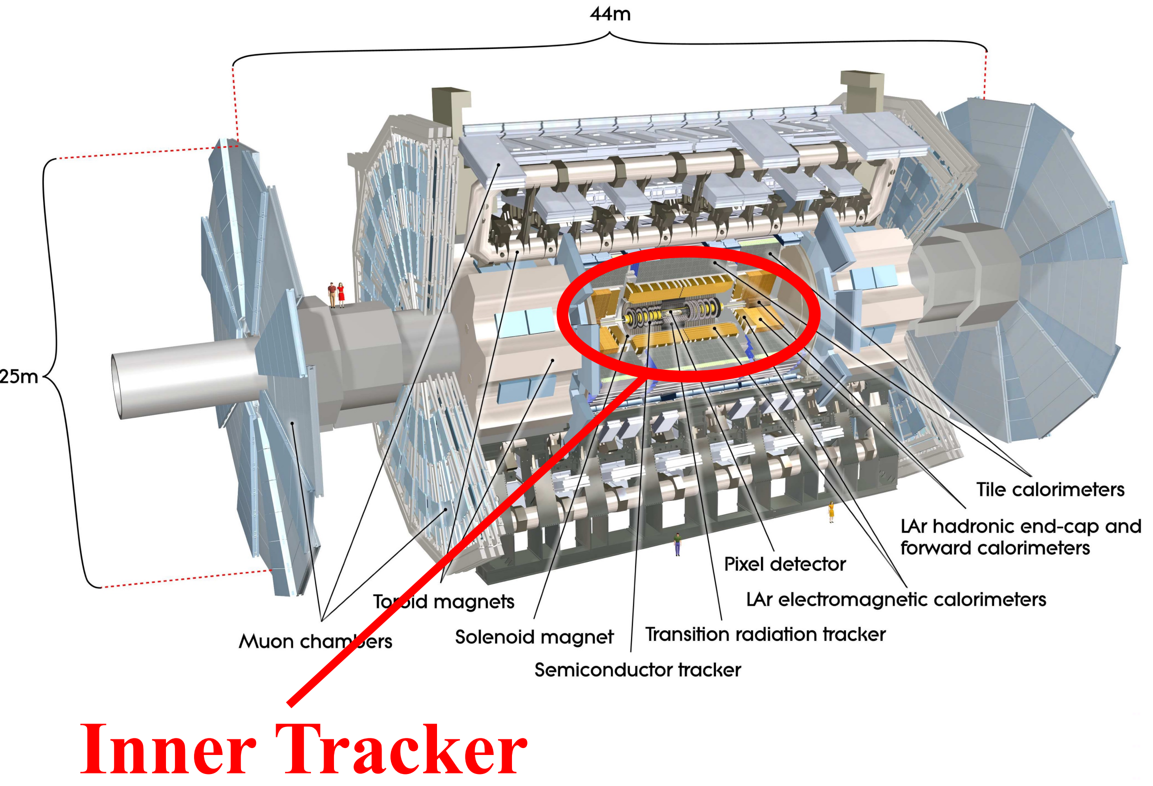
OPAL, ALPEH, DELPHI in LEP

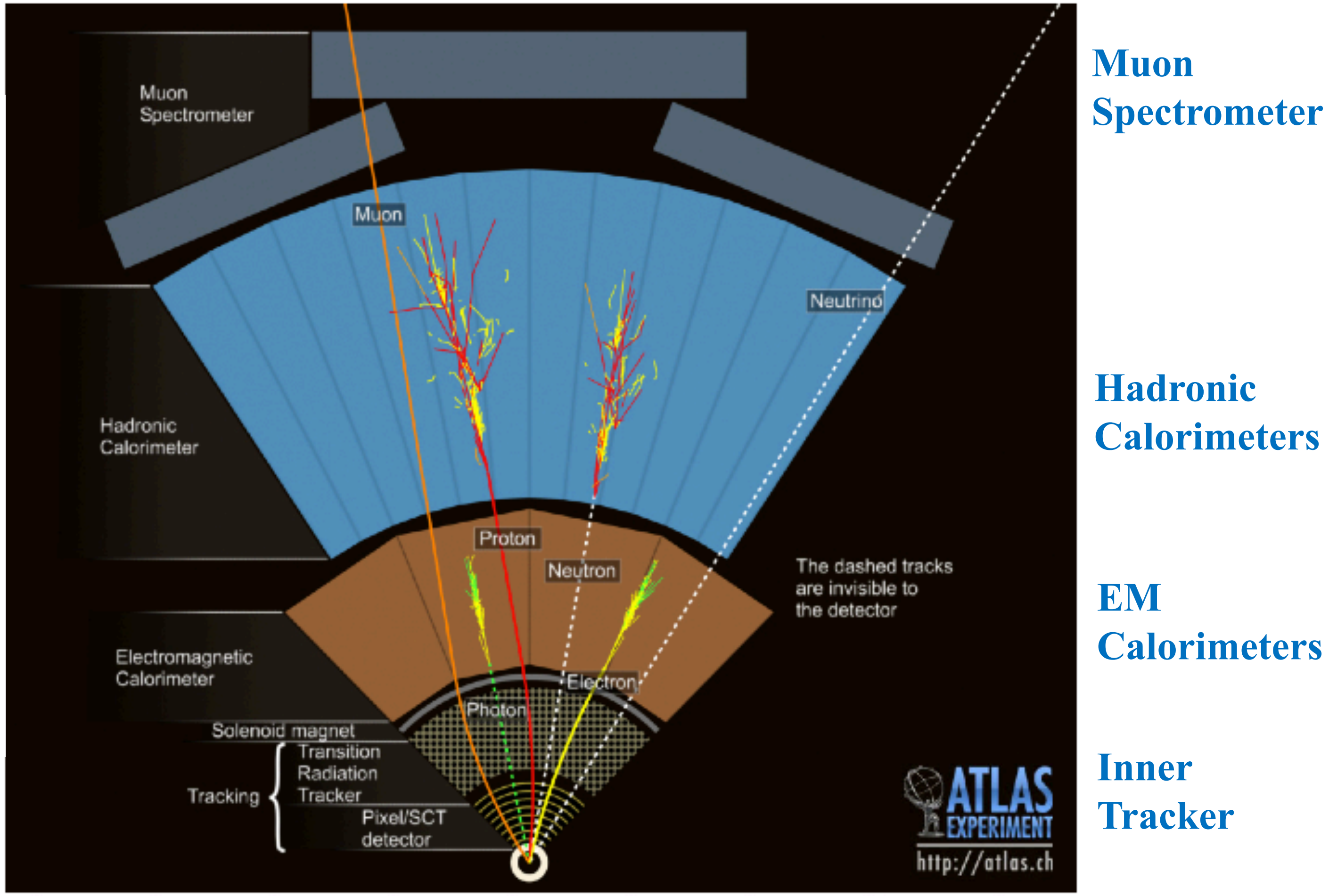




ATLAS Detector

All-purpose detector





- **Tracking system (Pixel, SCT & TRT)** reconstruct trajectories and momenta of charged particles
- **EM/hadronic calorimeters** energy deposition of particles and missing energy
- **Muon spectrometer** precise tracking and momentum measurement of muons

Data and Event Selection

Data sample

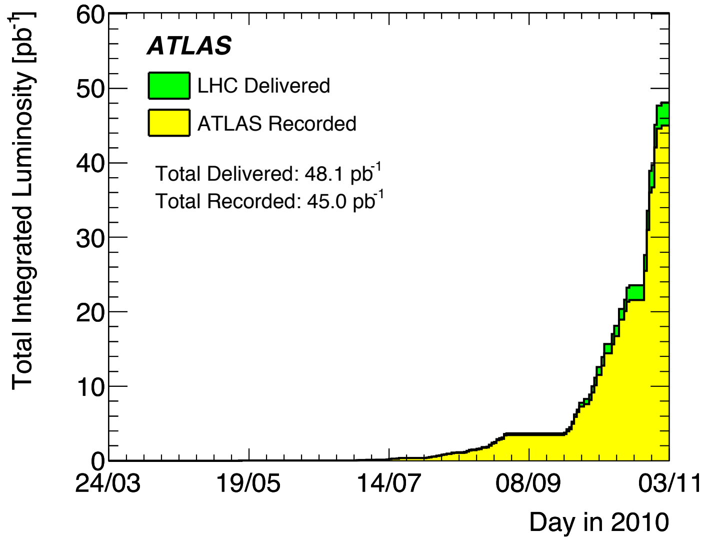
- 2010 run period A-H, $\sqrt{s} = 7$ TeV, $\int L = 22.12$ pb^{-1}
- Minimum bias (for minimum trigger bias) and Muon (for the largest data statistics) stream samples

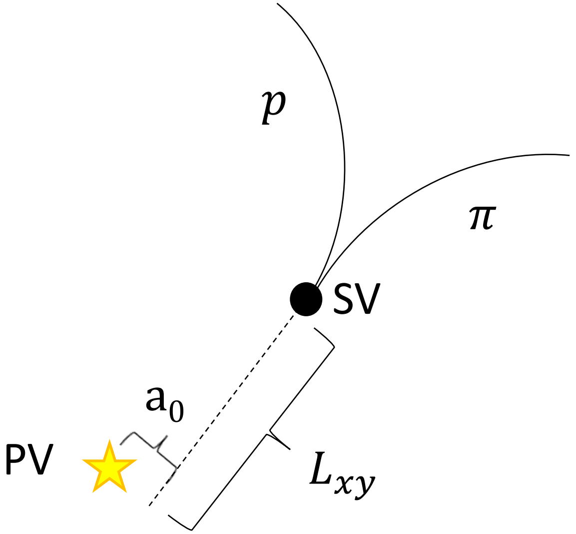
Reconstruction

- ATLAS V0Finder is used to reconstruct secondary vertex formed by a pair of oppositely charged tracks in the inner detector

$\Lambda^0/\bar{\Lambda}^0$ candidate selection

- Invariant mass window: $M_{p\pi} \in [1100,1135]$ MeV
- Cumulative χ^2-probability of V^0 vertex fit > 0.05
- Track quality: nPixel + nSCT > 3 per track
- Fraction of TRT high threshold hits < 0.14
- $\gamma \rightarrow e^+e^-$ conversion removal: $M_{ee} < 75$ MeV
- $K_s \rightarrow \pi\pi$ removal: $M_{\pi\pi} \in [480,515]$ MeV
- Fake vertex removal: $L_{xy} > 15$ mm and $L_{xy}/\sigma_{L_{xy}} > 15$
- Impact parameter significance: $a_0/\sigma_{a_0} < 3$

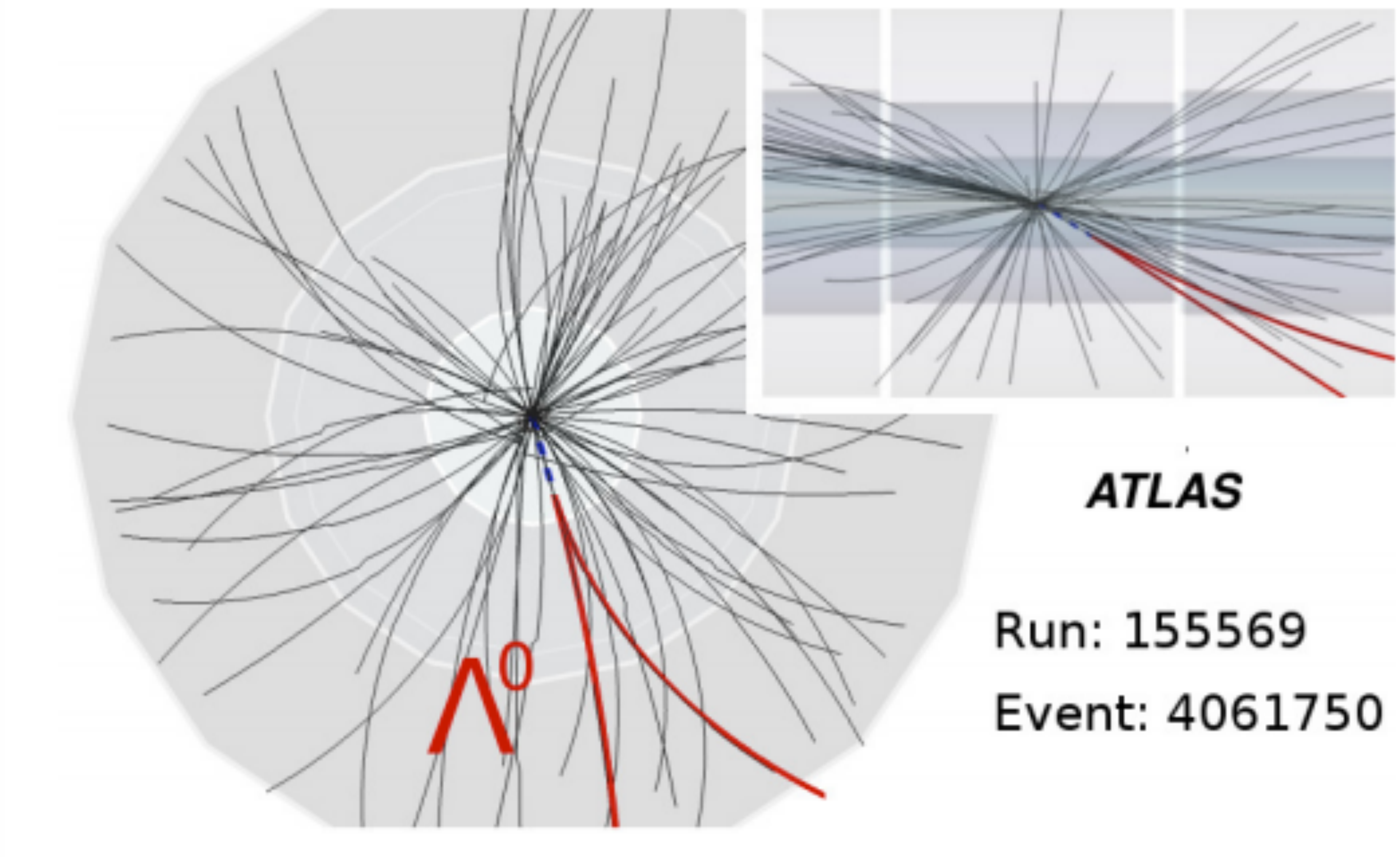




Topology of $\Lambda^0 \rightarrow p\pi$ decay

Event Display of Λ^0 Candidate in Inner Tracker

(Scheirich, 2013)



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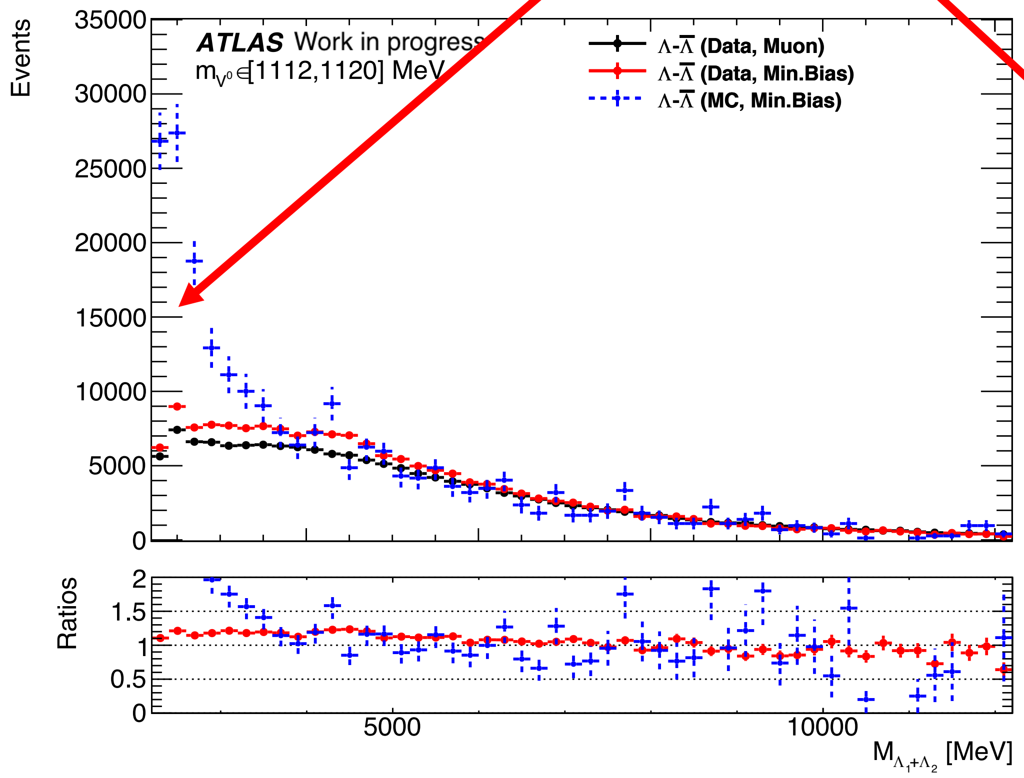
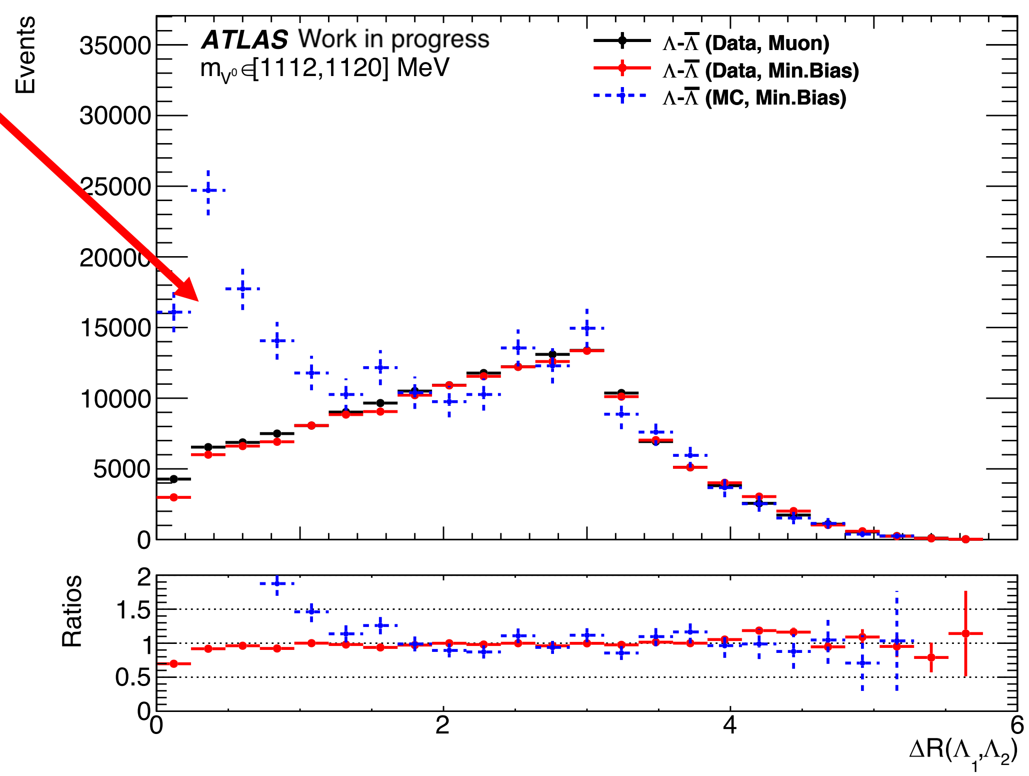
Excess $\Lambda^0\overline{\Lambda}^0$ Event near $\Lambda^0\Lambda^0$ Threshold

- Excess events are observed in $\Lambda^0\overline{\Lambda}^0$ events near production threshold

Excess overestimated by PYTHIA generator



Invariant mass of di-hyperon



Opening angle of di-hyperon

Definition of Correlation Function

Correlation function $C_2(p_1, p_2)$ is defined as

$$C_2(p_1, p_2) = \frac{\rho_2(p_1, p_2)}{\rho_1(p_1)\rho_1(p_2)}$$

where ρ_2 is two-particle density and ρ_1 is single particle density

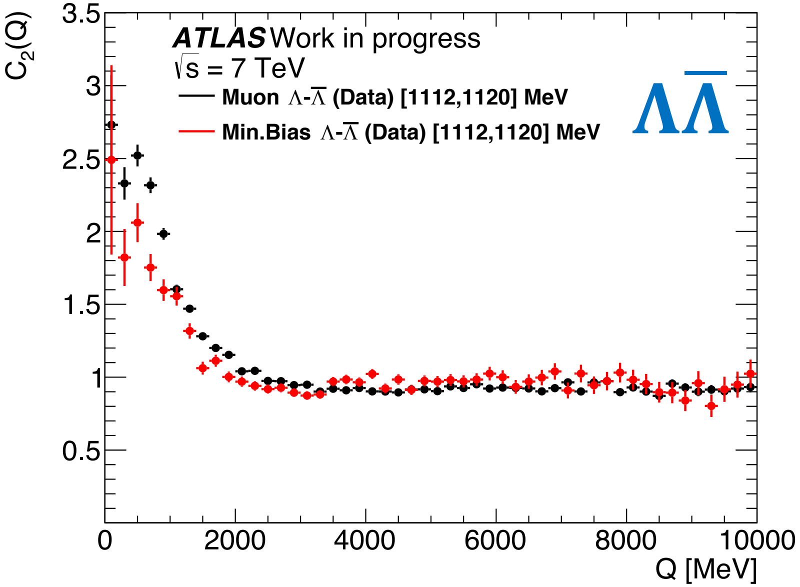
Experimentally, one measures the differential cross section ratio

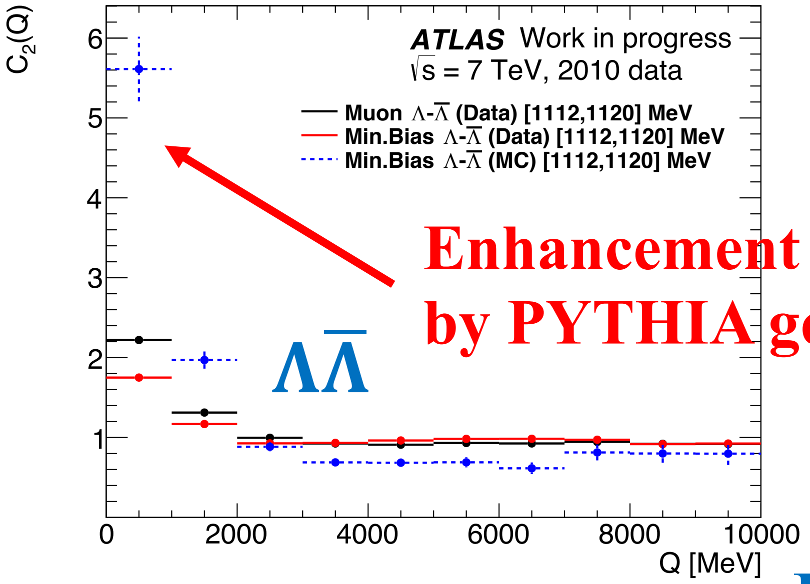
$$\boxed{C_2(Q) = \frac{N_{ref}}{N_{exp}} \frac{dN_{exp}/dQ}{dN_{ref}/dQ}}$$

where N_{exp} and N_{ref} are the numbers of di-hyperon pairs in the experimental and reference (event mixing) samples

Correlation Function vs Q

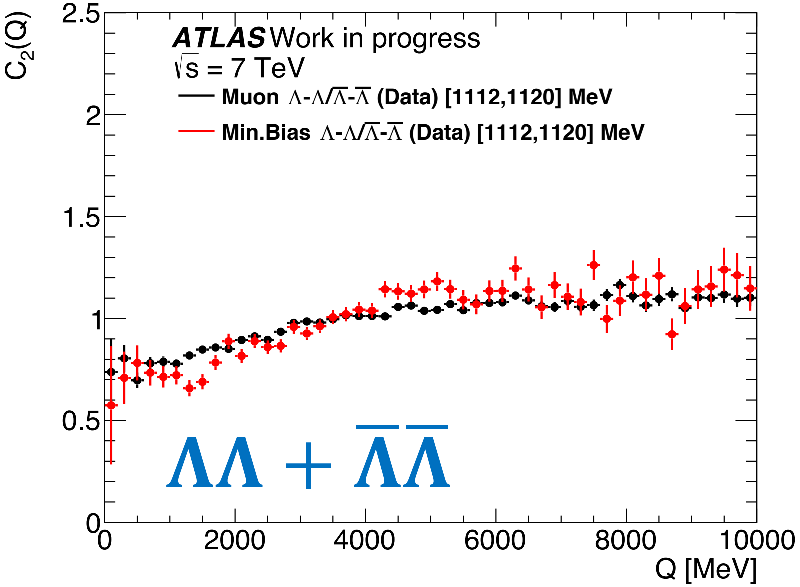
Muon vs Min. Bias

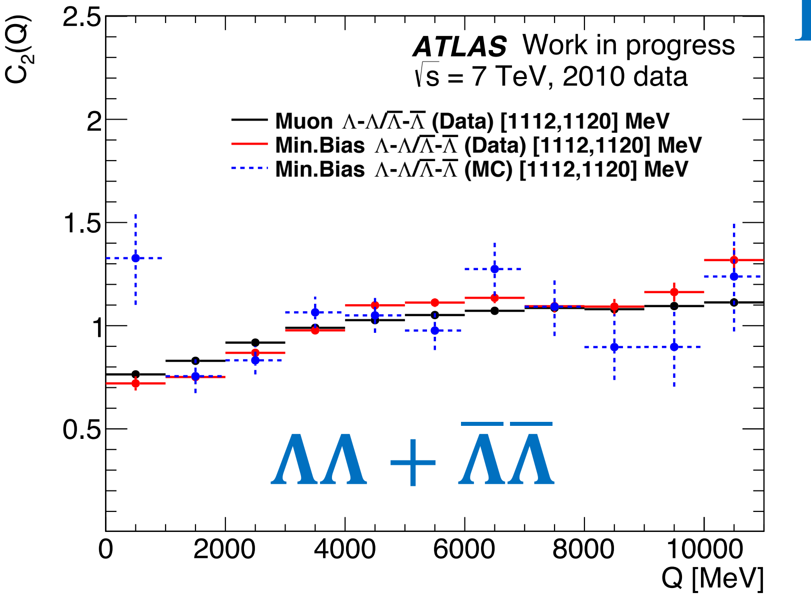




Enhancement overestimated by PYTHIA generator

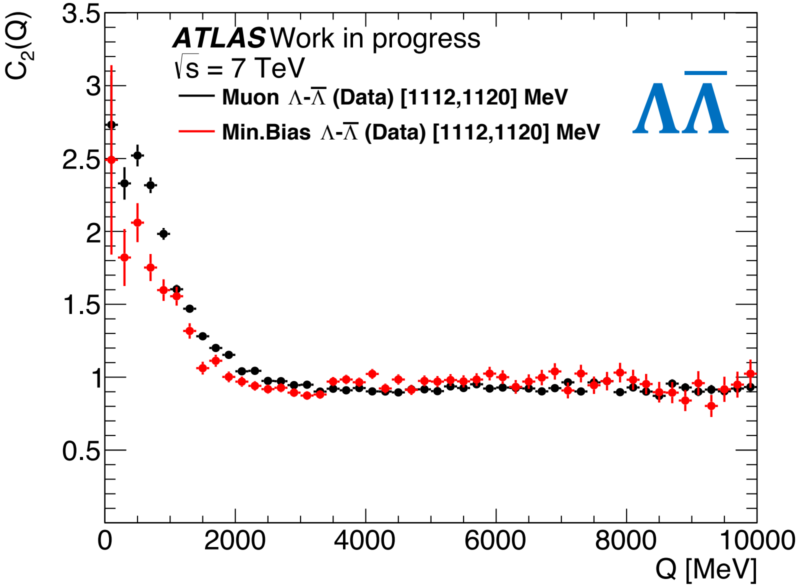
Data vs MC

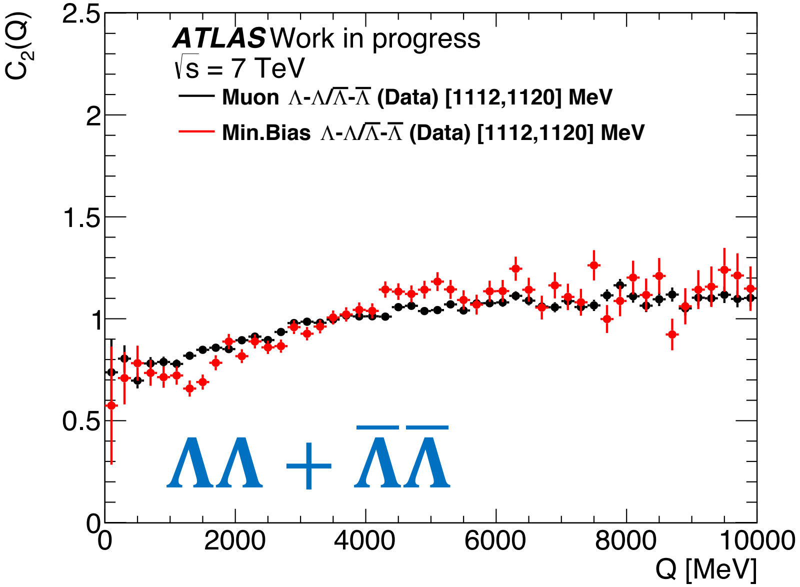




Correlation Function vs Q

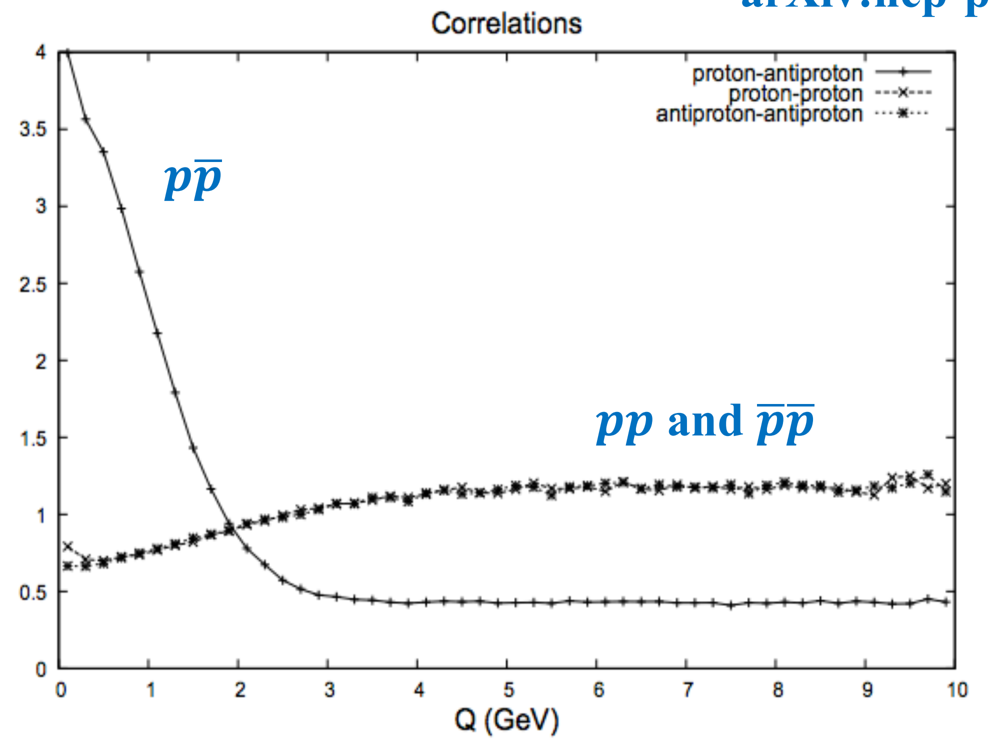
Muon vs Min. Bias





- **Consistent with string model predictions**
- **Similar results for di-hyperon and di-proton systems**

arXiv:hep-ph/0702241

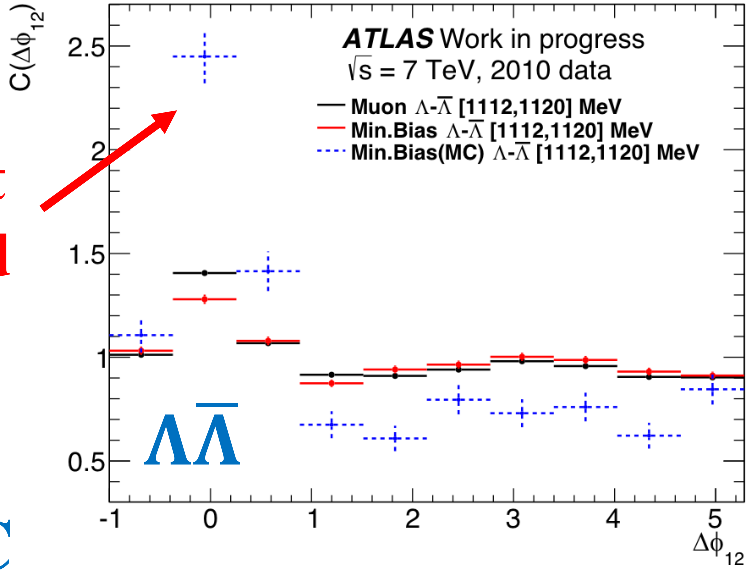


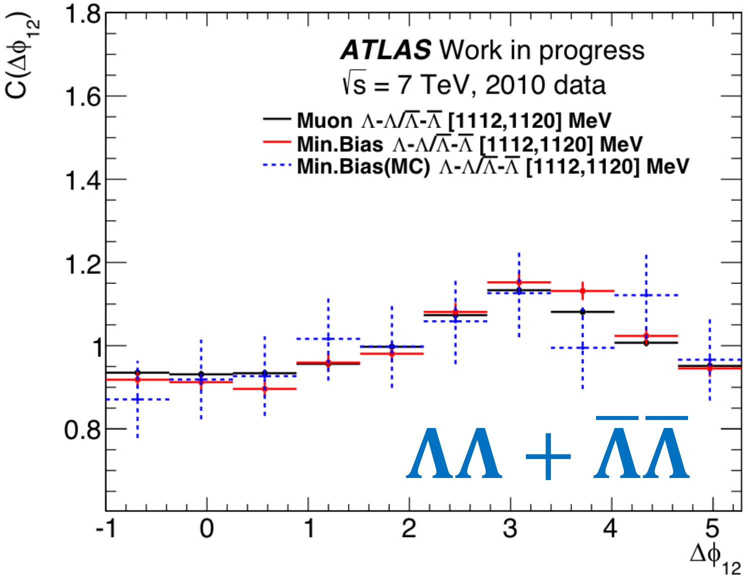
$p\bar{p}$-, pp-, and $\bar{p}\bar{p}$-correlations in PYTHIA

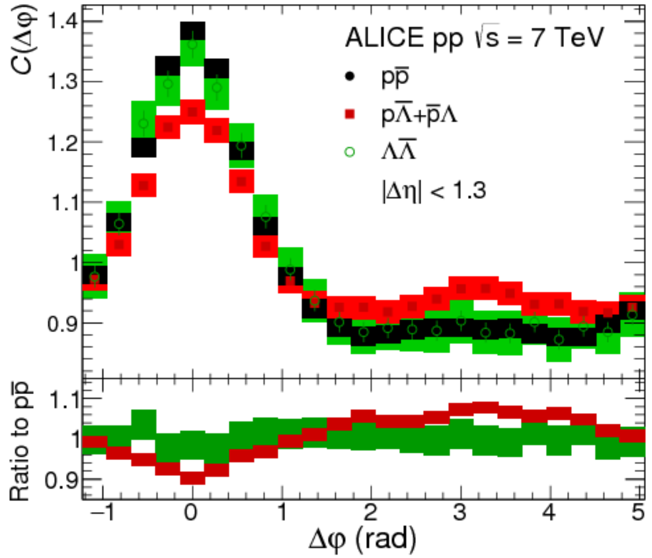
Correlation Function vs $\Delta\phi_{12}$

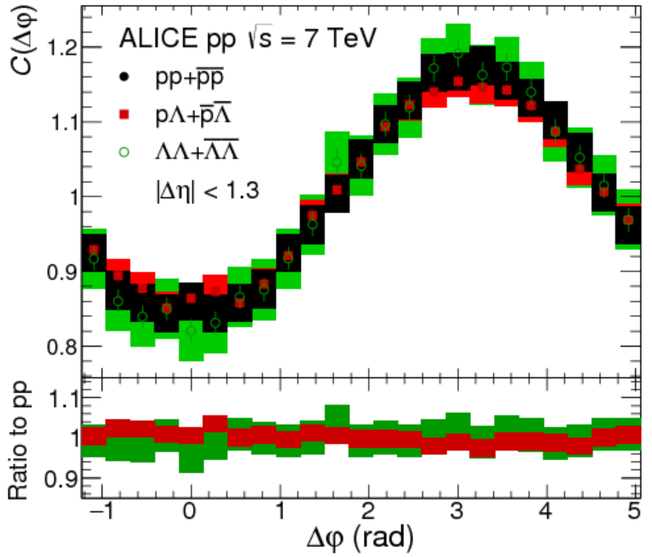
Enhancement overestimated by PYTHIA generator

Data vs MC





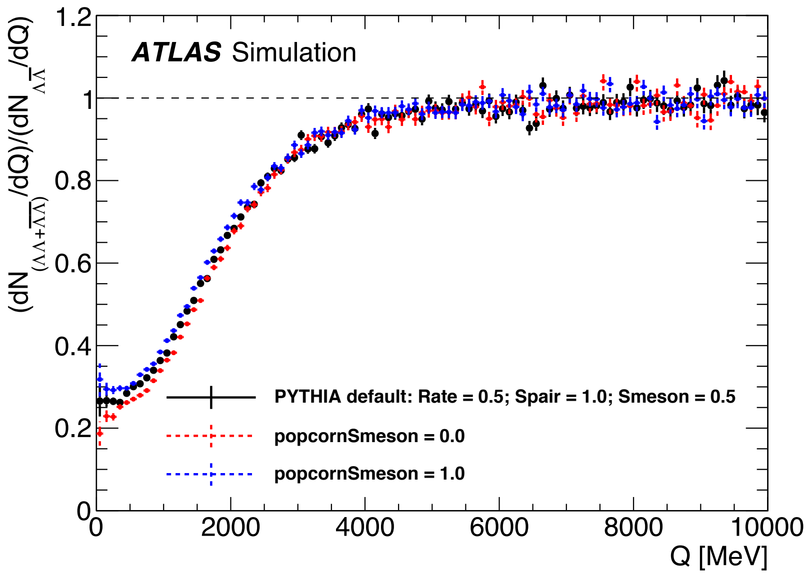




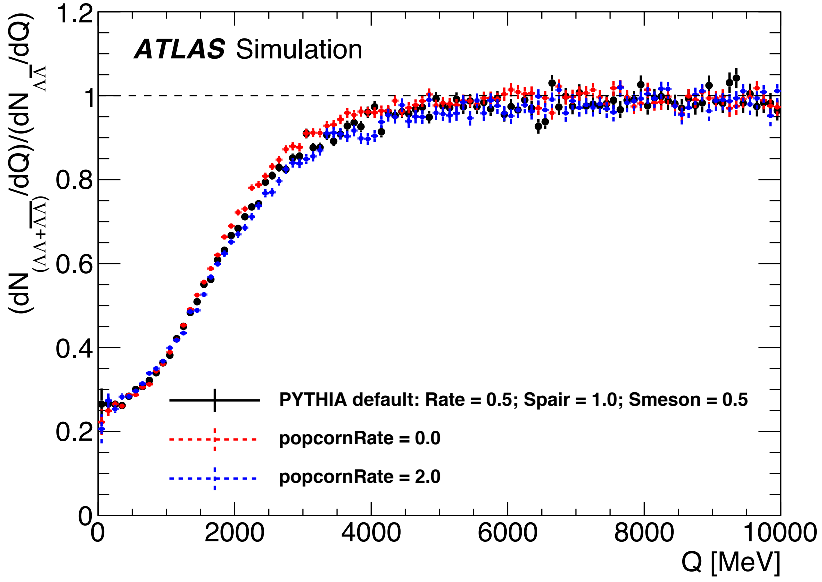
Similar results from *pp* collisions at ALICE including *pp* and *p*Λ correlations

"Popcorn" Mechanism

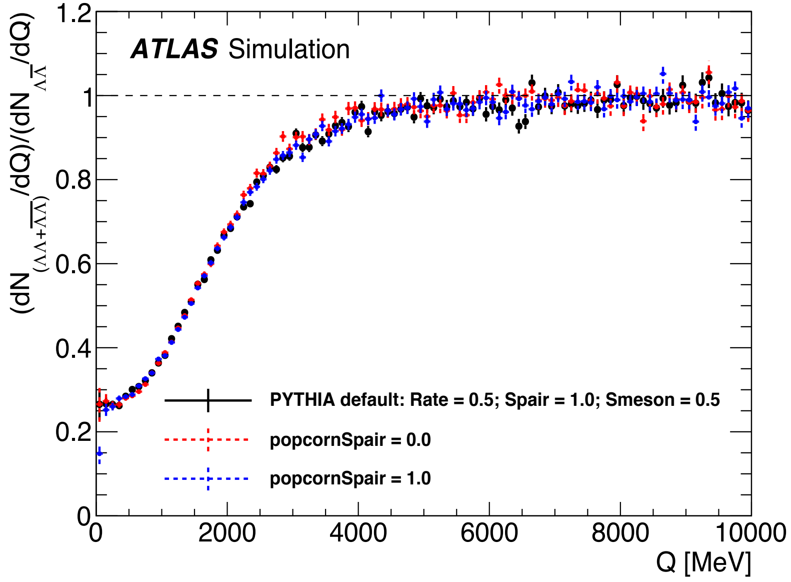
- "Popcorn" mechanism controls how easily mesons pop up in $B\bar{B}$ production in the string model
- Three parameters:
  - popcornSmeson: extra suppression for having a strange meson M in a $BM\bar{B}$ configuration
  - popcornRate: relative rates of $B\bar{B}$ and $BM\bar{B}$ production
  - popcornSpair: extra suppression for having a $s\bar{s}$-pair shared between B and $\bar{B}$ in a $BM\bar{B}$ configuration
- **($\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$) to $\Lambda\bar{\Lambda}$ differential cross section (XS) ratio** is not very sensitive to the "popcorn" mechanism



popcornSmeson = 0, 0.5, 1



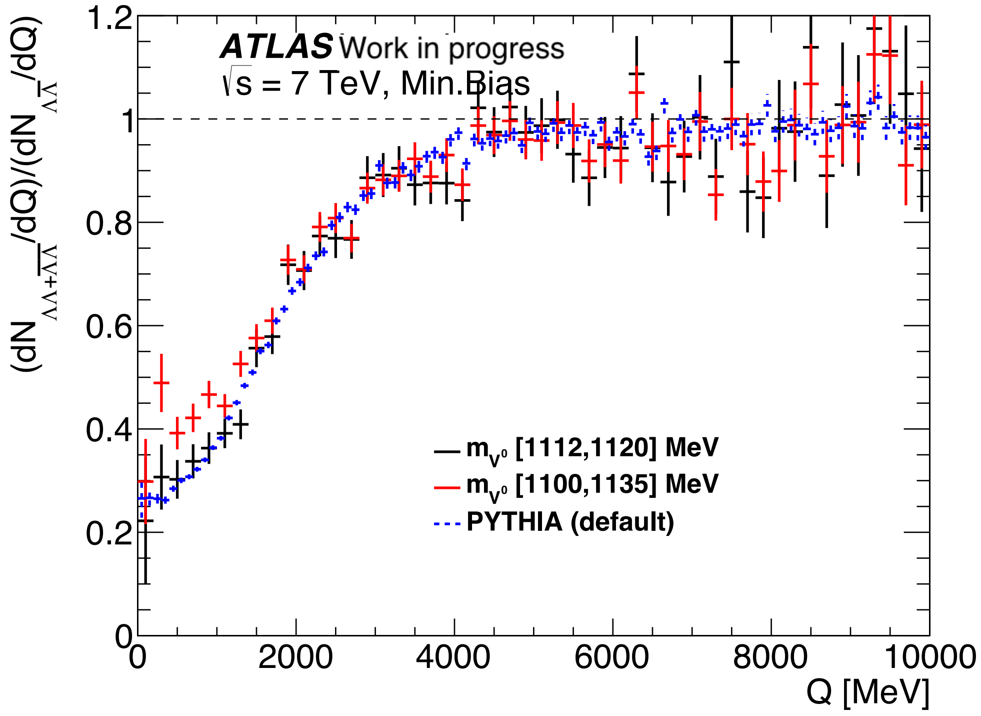
popcornRate = 0, 0.5, 2



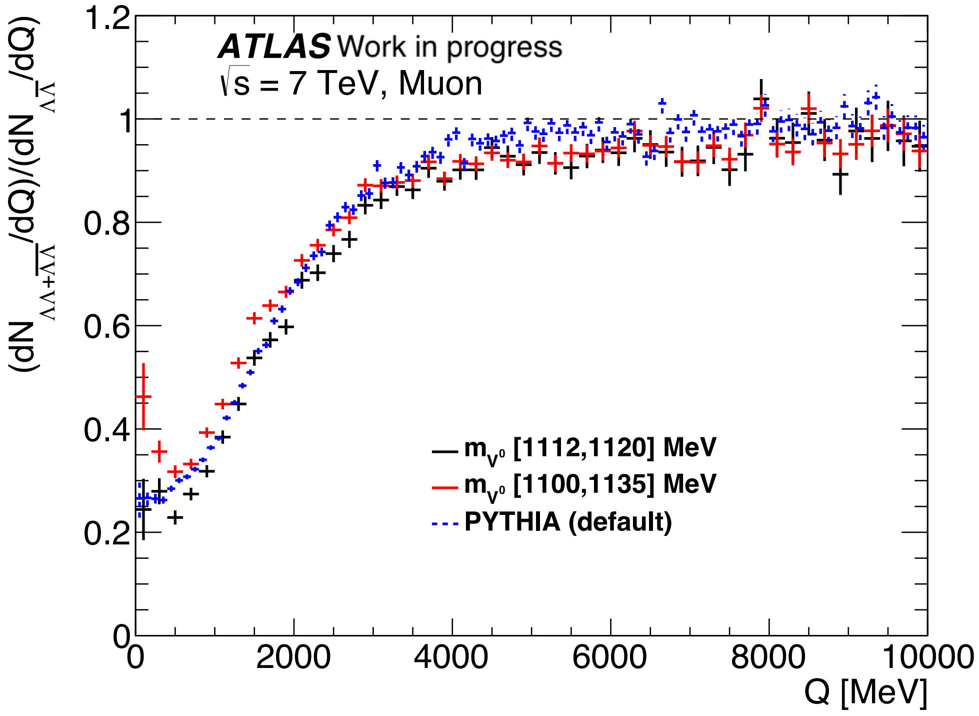
popcornSpair = 0, 1

“Popcorn” Mechanism

- **($\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$) to $\Lambda\bar{\Lambda}$ diff. XS ratio** agrees surprisingly well between data in the signal region and PYTHIA generator
- “Popcorn” mechanism somehow affects $B\bar{B}$ and $BB/\bar{B}\bar{B}$ production at the same rate
- Can it be an important signature feature for $B/\bar{B}$ production in the string model?



Minimum Bias sample vs PYTHIA



Muon sample vs PYTHIA

Spin Correlation and Decay Angles

Normalized angular distribution for a spin-$\frac{1}{2}$ fermion

$$\frac{dw(\boldsymbol{n})}{d\Omega_{\boldsymbol{n}}} = \frac{1}{4\pi}(1 + \alpha_\Lambda \boldsymbol{P}_\Lambda \boldsymbol{n}_\Lambda)$$

$\boldsymbol{P}_\Lambda$ - polarization vector of Λ^0
$\boldsymbol{n}_\Lambda$ - unit vector along proton in the rest frame of Λ^0

Two-particle angular distribution

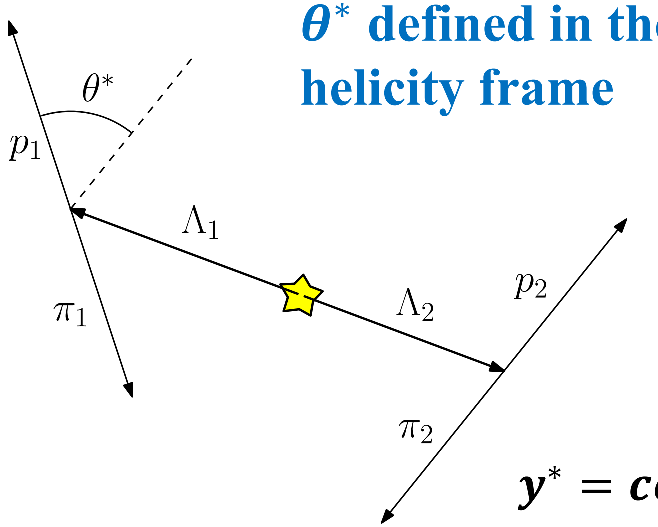
$$\frac{dw(\boldsymbol{n}_1, \boldsymbol{n}_2)}{d\Omega_{\boldsymbol{n}_1} d\Omega_{\boldsymbol{n}_2}} = \frac{1}{16\pi^2}\left(1 + \alpha_\Lambda \boldsymbol{P}_1 \boldsymbol{n}_1 + \alpha_\Lambda \boldsymbol{P}_2 \boldsymbol{n}_2 + \alpha_\Lambda^2 \sum_{i=1}^{3}\sum_{k=1}^{3} T_{ik} \boldsymbol{n}_{1i} \boldsymbol{n}_{2k}\right)$$

$\boldsymbol{P}_1$ and $\boldsymbol{P}_2$ - the polarization vectors of Λ_1 and Λ_2
$\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ - unit vectors along protons in the rest frame of Λ_1 and Λ_2
T_{ik} - correlation tensor components

Integrating over all angles except angle between protons

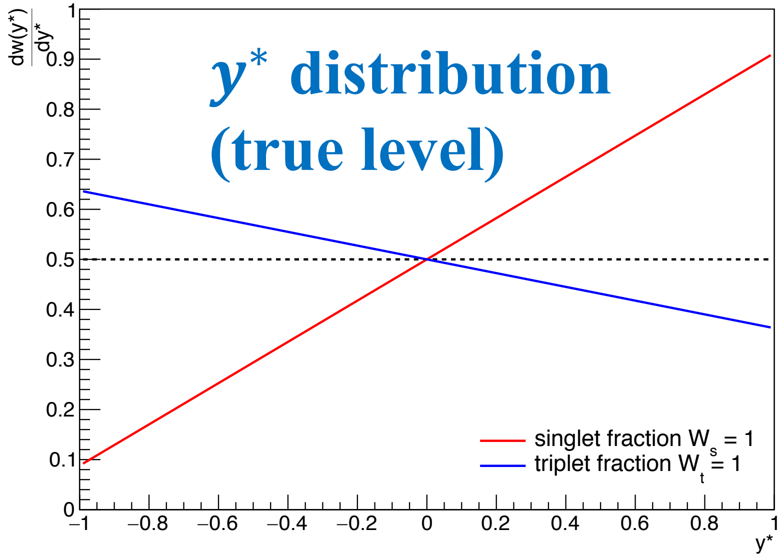
$$\boxed{\frac{dw(\cos\theta^*)}{d\cos\theta^*} = \frac{1}{2}\left(1 + \frac{1}{3}T\alpha_\Lambda^2 \cos\theta^*\right) = \frac{1}{2}\left(1 + \boldsymbol{A}\alpha_\Lambda^2 \cos\theta^*\right)}$$

$T = W_t - 3W_s$ where W_t and W_s are the **triplet** and **singlet** fractions



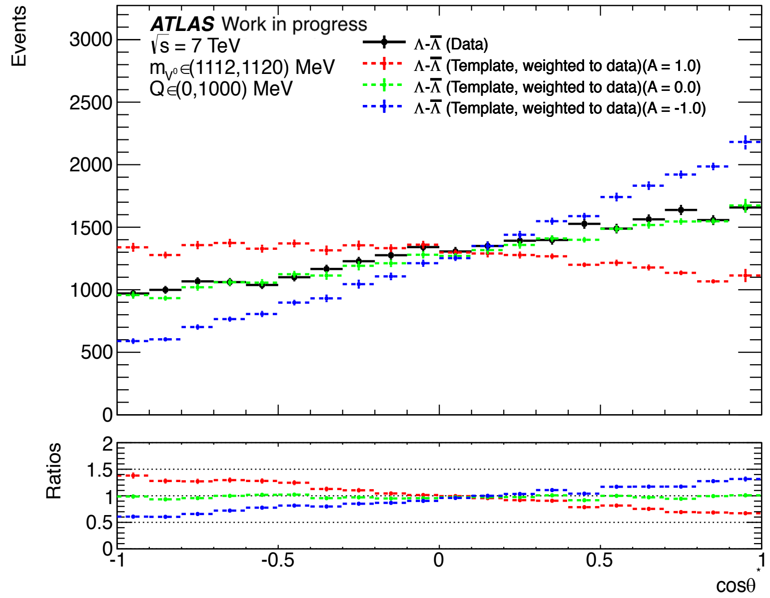
***θ^** defined in the helicity frame**

$y^* = \cos\theta^*$

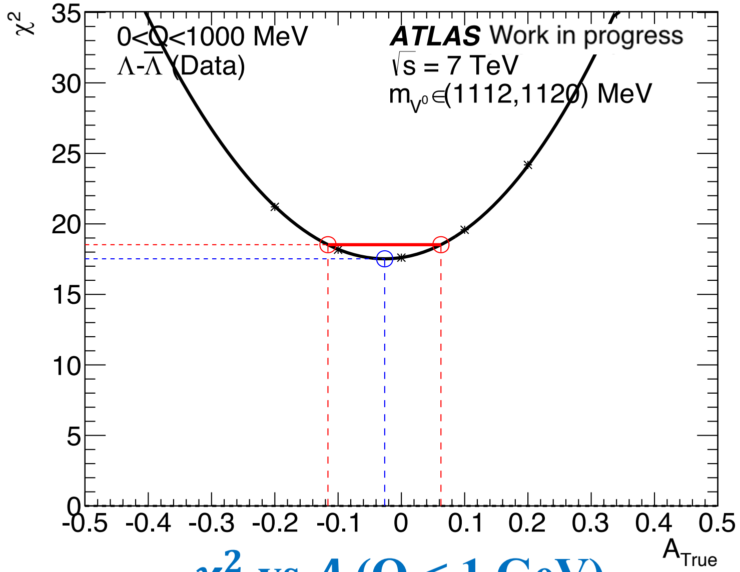


Extraction of Spin Correlation

- Mixed data sample is weighted to data sample and is used to estimate the distortion due to detector effects
- 9 reference samples are created by injecting spin correlation by weighting the sample with a factor of $(1 + A\alpha^2 cos\theta^*)$ for $A = 0,\ \pm0.1,\ \pm0.2,\ \pm0.5$ and ±1
- Pearson's χ^2-value is computed to determine the best fit A_{min}
- Uncertainty ΔA_{min} is computed at variation $\chi^2_{min} \pm 1$
- The results are measured as a function of Q and $\Delta\phi_{12}$



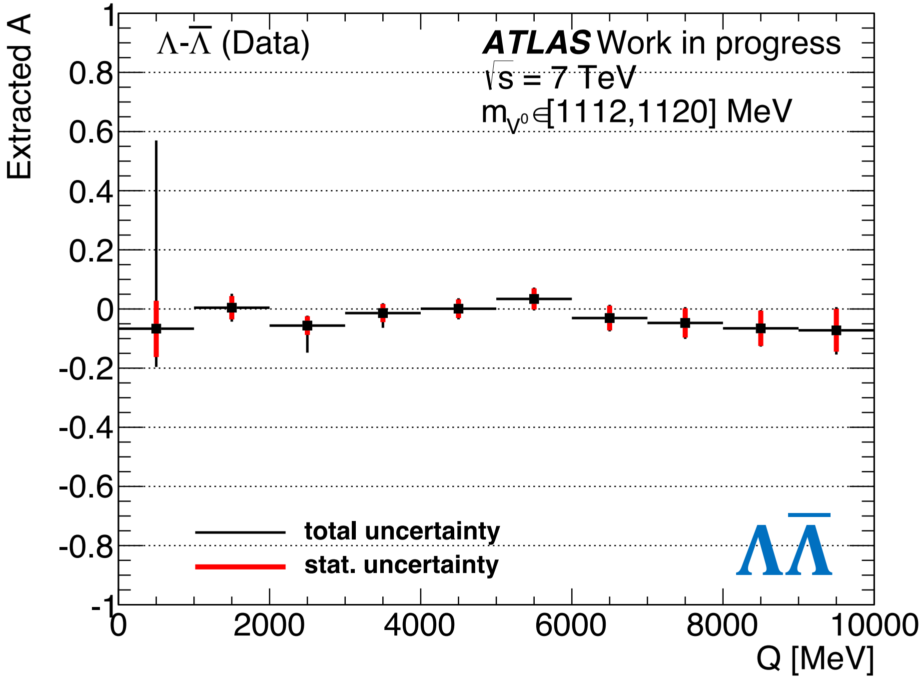
$cos\theta^*$ distribution (Q < 1 GeV)

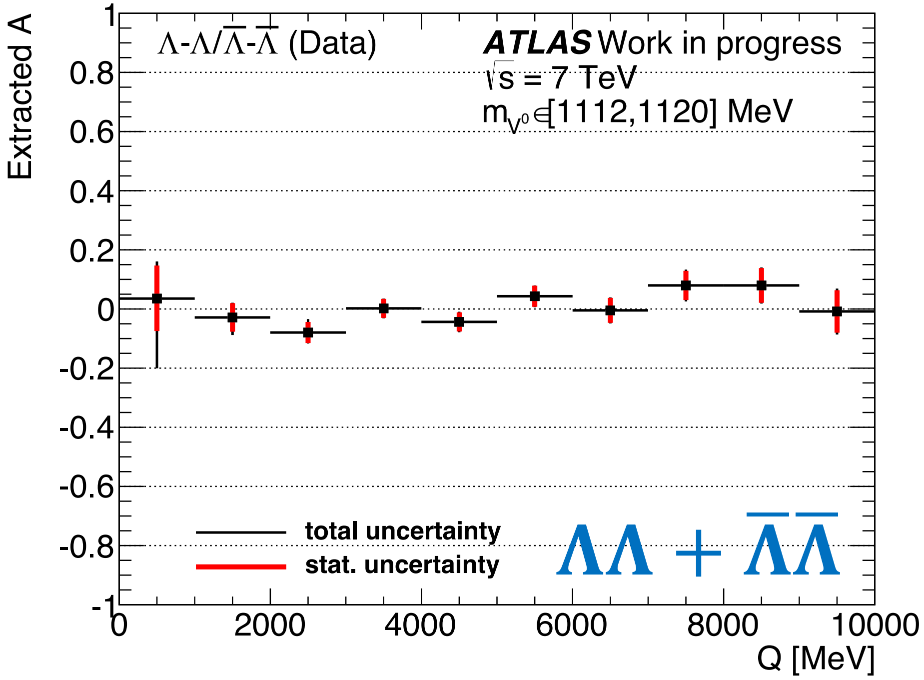


χ^2 vs A (Q < 1 GeV)

Extracted A vs Q (Muon, 1 GeV bin size)

- Extracted A vs Q with bin size of 1 GeV for $\Lambda^0\overline{\Lambda}^0$ and $\Lambda^0\Lambda^0 \oplus \overline{\Lambda}^0\overline{\Lambda}^0$ in the muon sample





- Consistent with zero for $0 < Q < 10$ GeV for both type of events

Total uncertainty < 0.1 (except $0 < Q < 1$ GeV for $\Lambda^0\overline{\Lambda}^0$ total uncertainty ~0.58)

Conclusions

- This analysis demonstrated that correlation measurements of hyperon pairs are feasible at the ATLAS detector despite many limitations, e.g. lack of particle ID and high track p_T threshold
- Excess of $\Lambda^0\overline{\Lambda}^0$ events has been observed near production threshold and is overestimated in PYTHIA, MC studies showed that the excess is originated from parton system in the string model
- Dynamical correlations are consistent with the predictions from the string model implemented in PYTHIA and results from recent experiments such as ALICE at the LHC
- "Popcorn" mechanism is found to have little effect on the $(\Lambda^0\Lambda^0 \oplus \overline{\Lambda}^0\overline{\Lambda}^0)$ to $\Lambda^0\overline{\Lambda}^0$ diff. XS ratio and the MC sample models data shape surprisingly well
- Spin correlation results are consistent with zero in $0 < Q < 10$ GeV with large systematic uncertainty in the range $0 < Q < 1$ GeV for $\Lambda^0\overline{\Lambda}^0$ due to kinematic weighting
- The correlations measured are qualitatively consistent with the predictions from the string model
- Data statistics is too low in $0 < Q < 0.5$ GeV for $\Lambda^0\Lambda^0/\overline{\Lambda}^0\overline{\Lambda}^0$ emitter size estimation where FD effects are expected

Thank you!

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