Correlation measurement of $\boldsymbol{\Lambda\bar{\Lambda}}$, $\boldsymbol{\Lambda\Lambda}$ and $\boldsymbol{\bar{\Lambda}\bar{\Lambda}}$ hyperon pairs at $\sqrt{s} = 7$ TeV at ATLAS

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QCD Discussion Meeting
Feb 1, 2017

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- Motivations
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- Data sample & reconstruction
- Event selection
- Signal & background modeling
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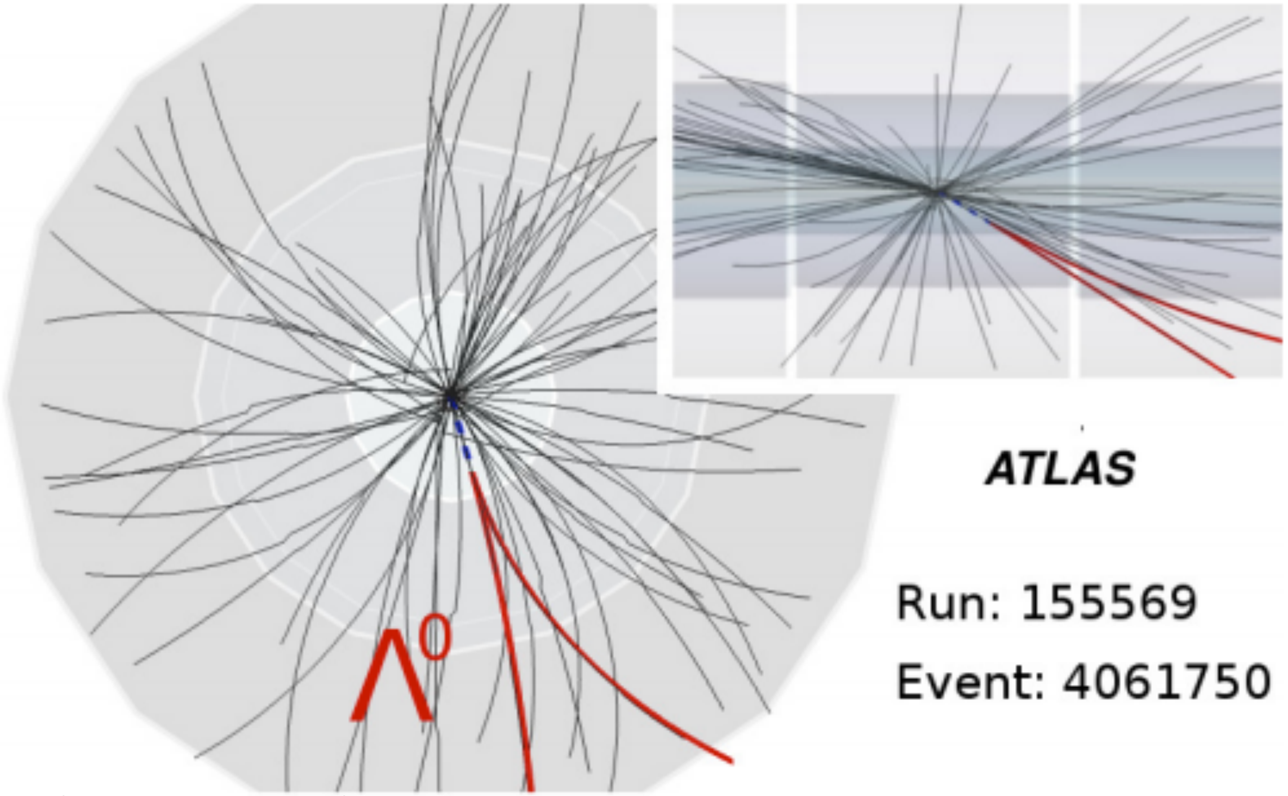
- Summary

$$pp \rightarrow \Lambda^0\overline{\Lambda}^0 + X$$
$$\rightarrow \Lambda^0\Lambda^0 + X$$
$$\rightarrow \overline{\Lambda}^0\overline{\Lambda}^0 + X$$

Scheirich (2013)



Introduction

Lambda hyperon Λ⁰ (uds) – The lightest baryon containing a strange quark

$$m_\Lambda = 1115.683 \pm 0.006 \text{ MeV}$$
$$\tau_\Lambda = (2.632 \pm 0.020) \times 10^{-10} \text{ s}$$

Main decay channels

$$\mathcal{BR}(\Lambda^0 \to p\pi^-) = (63.9 \pm 0.5)\%$$
$$\mathcal{BR}(\Lambda^0 \to n\pi^0) = (35.8 \pm 0.5)\%$$

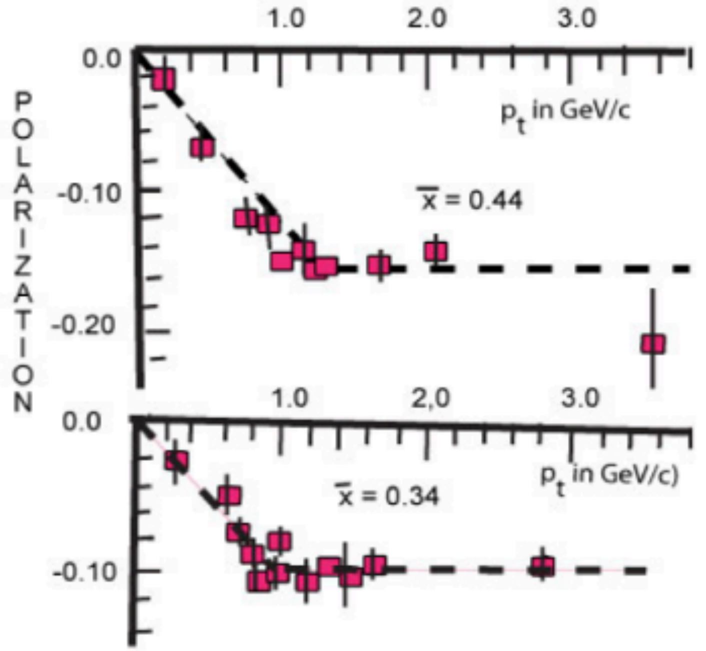
Parity-violating decay parameter

$$\alpha(\Lambda^0 \to p\pi^-) = 0.642 \pm 0.013$$

Some recent Λ^0 hyperon measurements at ATLAS

- Λ^0 and $\overline{\Lambda}^0$ polarization (arXiv:1412.1692)
- K_s and Λ^0 production (arXiv:1111.1297)
- α_b parity-violating asymmetry parameter and helicity amplitude for $\Lambda^0{}_b$ decay (arXiv:1404.1071)

K. Heller (1990)



Unresolved polarization puzzle

Motivations

Physics process $pp \rightarrow \Lambda^0\overline{\Lambda}^0/\Lambda^0\Lambda^0/\overline{\Lambda}^0\overline{\Lambda}^0 + \mathrm{X}$

- To probe $s\bar{s}$ quark-anti-quark pair production
- To measure Fermi-Dirac (FD) correlation between identical fermions
- To test fragmentation and hadronization models, e.g. Lund string model

Methodology

1. Correlation function $\mathrm{C}(\mathrm{p}_1, \mathrm{p}_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}$

   captures dynamical correlations

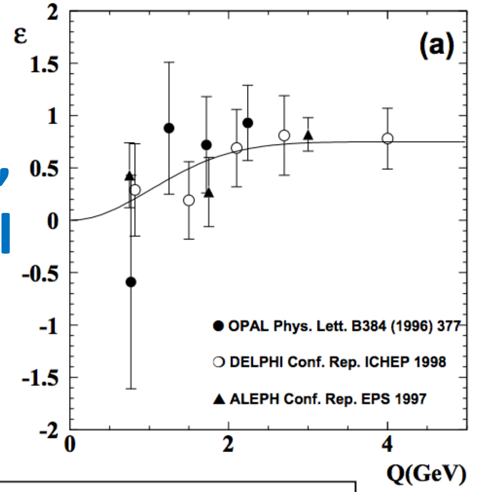
   $N_2(p_1, p_2)$: two-particle density; $N_1(p)$: single-particle density

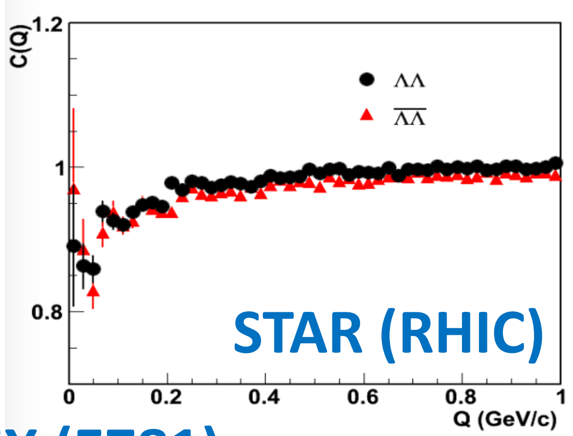
2. Spin composition (spin-0 or spin-1) extracted from relative orientation of decay protons

Past correlation measurements

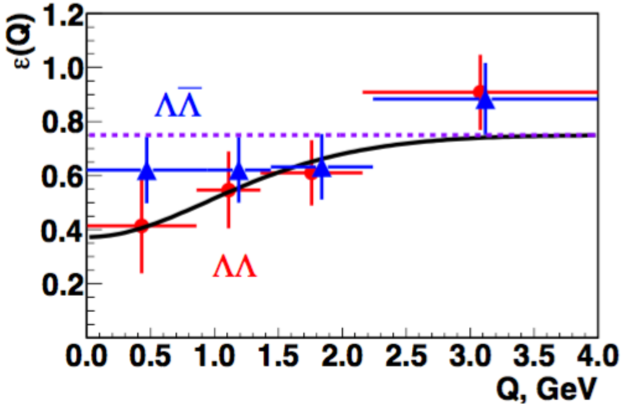
- hadronic Z^0 decays in e^+e^- annihilation at LEP: OPAL, ALPEH, DELPHI
- $Au + Au$ collisions at 200 GeV at STAR in RHIC
- Σ^-A interactions at 600 GeV at SELEX (E781)
- Pb ions collision at 158 A GeV at NA49
- nC collision at 51 GeV at EXCHARM

OPAL, ALPEH, DELPHI

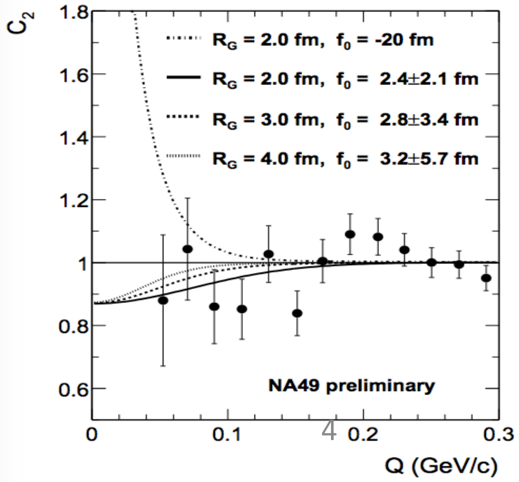




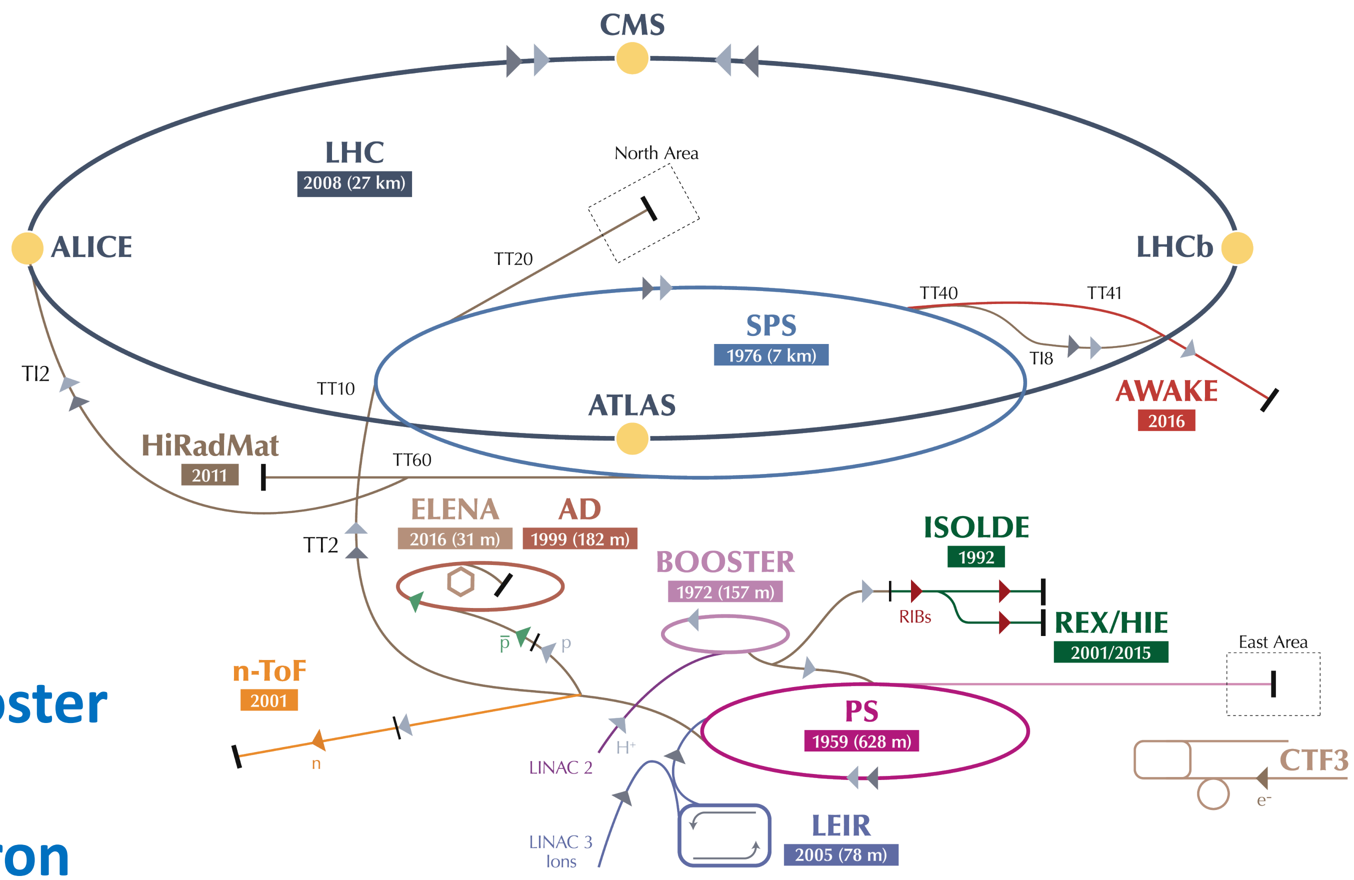
SELEX (E781)



NA49



LHC layout



Beam energy at different part of the accelerator complex:

- **50 MeV - Linac2**
- **1.4 GeV - Proton Synchrotron Booster**
- **25 GeV - Proton Synchrotron**
- **450 GeV - Super Proton Synchrotron**
- **7 TeV - Large Hadron Collider**

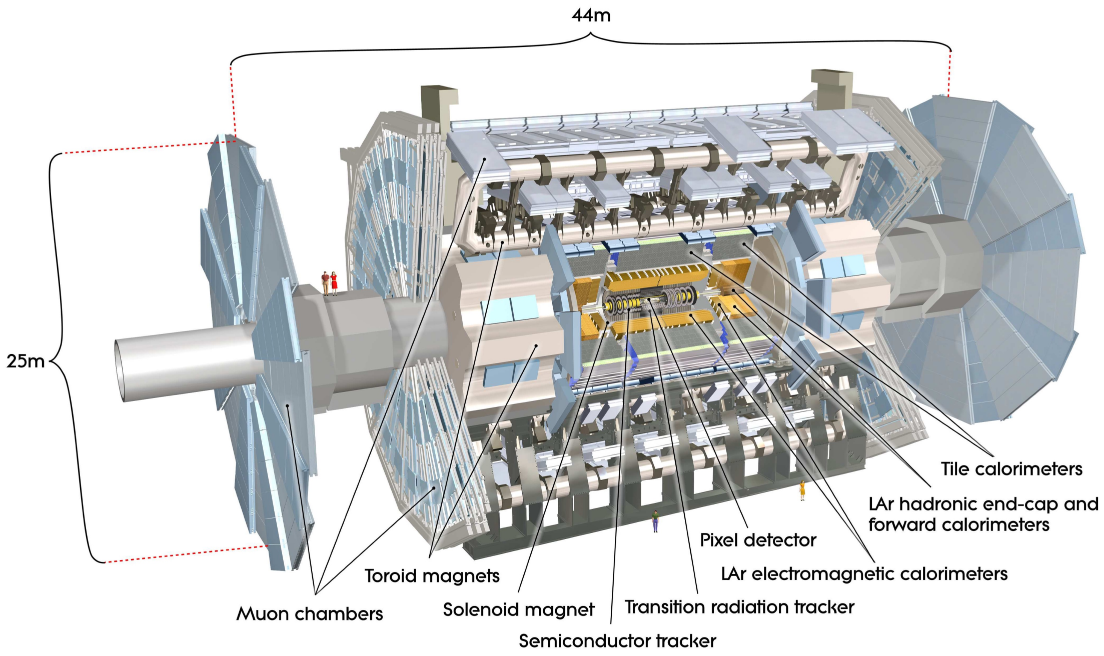
p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e- (electrons) proton/antiproton conversion proton/RIB conversion

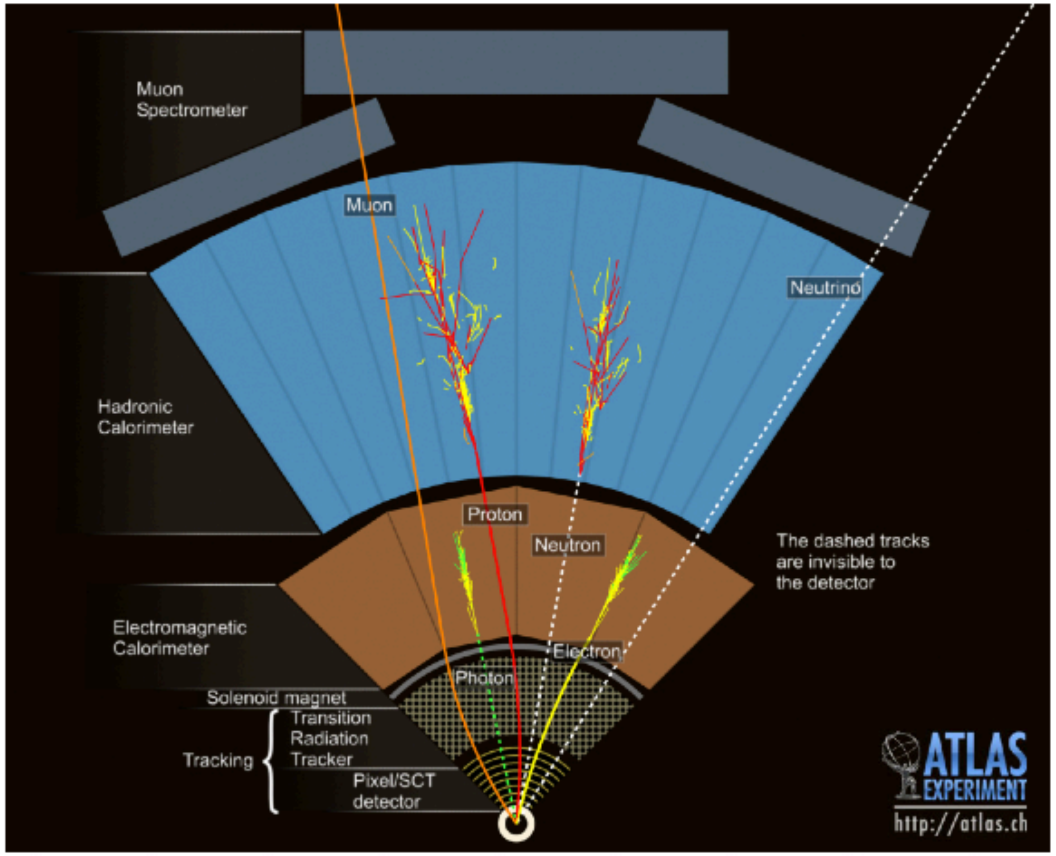
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

ATLAS detector





Muon Spectrometer

Hadronic Calorimeters

EM Calorimeters

Inner 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

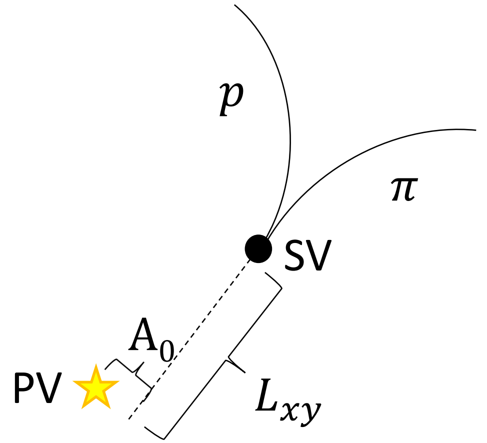
Data sample and reconstruction

Data sample

- Data 2010, $\sqrt{s} = 7$ TeV
- MuonswBeam and Muons stream AOD samples
    - `data10_7TeV.periodA.physics_MuonswBeam.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodB.physics_MuonswBeam.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodC.physics_MuonswBeam.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodD.physics_MuonswBeam.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodE.physics_Muons.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodF.physics_Muons.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodG.physics_Muons.PhysCont.AOD.repro05_v02/`
    - `data10_7TeV.periodH.physics_Muons.PhysCont.AOD.repro05_v02/`
- Trigger selection has been removed to maximize statistics

Reconstruction

- ATLAS `V0Finder` is used to reconstruct secondary vertex with a pair of oppositely charged tracks

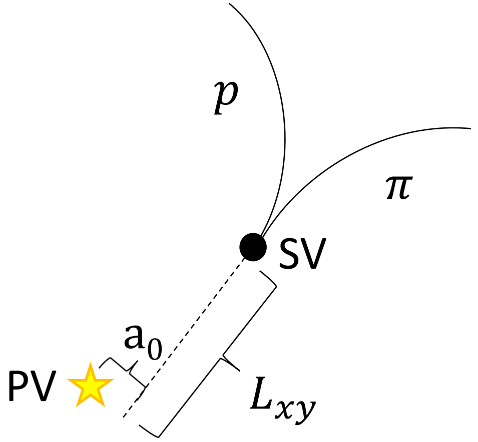


Topology of $\Lambda^0 \to p\pi$ decay

Event selection

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

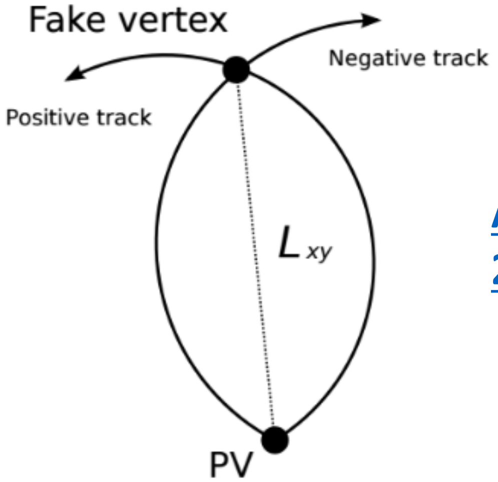
- Invariant mass window: $M_{p\pi} \in [1100,1135]$ MeV
- Cumulative χ^2-probability of V^0 vertex fit > 0.05
- Track quality: $\mathrm{nPixel} + \mathrm{nSCT} > 3$ per track
- Fraction of TRT high threshold hits < 0.14
- $\gamma \to e^+e^-$ conversion removal: $M_{ee} < 75$ MeV
- $K_s \to \pi\pi$ removal: $M_{\pi\pi} \in [480,515]$ MeV
- Fake vertex removal: $L_{xy} > 15$ mm and $L_{xy}/\sigma_{L_{xy}} > 15$
- Impact parameter significance: $A_0 = a_0/\sigma_{a_0} < 3$



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

Event yields

Type of hyperon pairs	$\Lambda^0\,\bar{\Lambda}^0$	$\Lambda^0\Lambda^0$	$\bar{\Lambda}^0\bar{\Lambda}^0$
Data sample	295,202	140,232	113,596
Mixed data sample	2,534,826	2,823,627	2,527,252
MC sample†	2,679	1,005	673
Mixed MC sample†	54,460	67,182	53,439



Fake secondary vertex formed by associated tracks

ATL-COM-PHYS-2011-1672

† Minimum bias MC sample: `mc10_7TeV.105001.pythia_minbias_merge.AOD.e574_s932_s946_r1649_r1700/`

Signal and background modeling

1D invariant mass distribution is fitted with a two-component function

$$M(m) = N_{sig}M_{sig}(m) + N_{bkg}M_{bkg}(m)$$

The signal is modeled by a *double asymmetric Gaussian* function

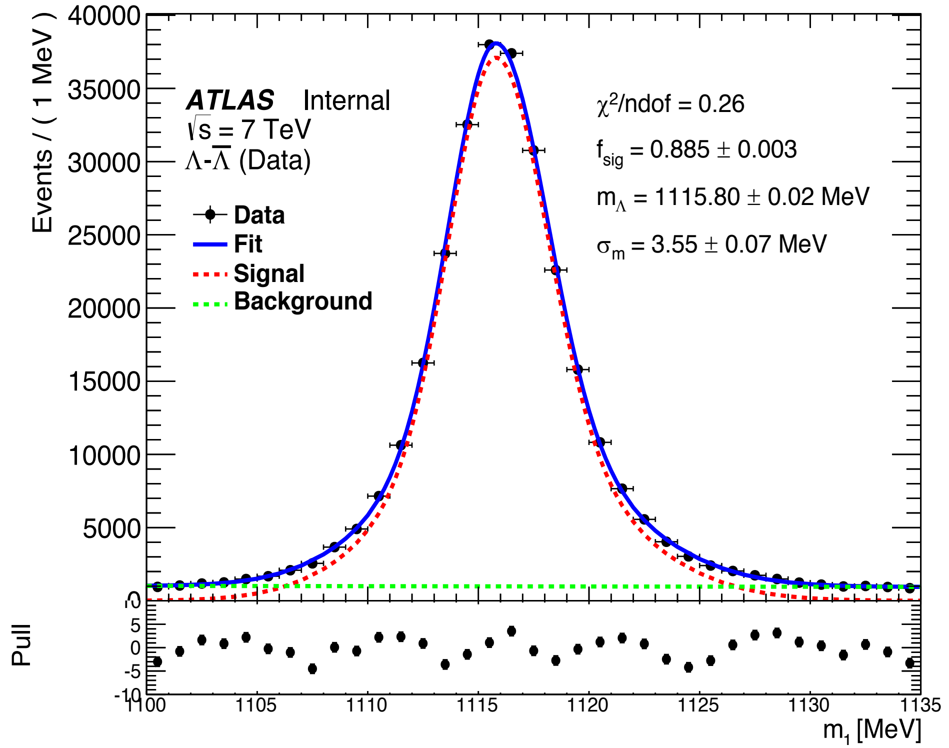
$$M_{sig}(m) = f_1 G(m - m_\Lambda, \sigma_1^L, \sigma_1^R) + (1 - f_1) G(m - m_\Lambda, \sigma_2^L, \sigma_2^R)$$

- $G(m - m_\Lambda, \sigma^L, \sigma^R)$ - asymmetric Gaussian function
- m_Λ - peak of asymmetric Gaussian function
- σ^L and σ^R - widths of asymmetric Gaussian function
- f_1 - fraction of the first Gaussian function

The background is modeled by a linear function

$$M_{bkg}(\mathrm{m}) = \frac{1}{\Delta m}[1 + c_0(m - m_c)]$$

- Δm - width of mass window
- m_c - mid-value of mass window
- c_0 - fit parameter of linear polynomial



Invariant mass distribution fitted w/ sig and bkg models

Signal and background modeling

2D invariant mass distribution

$$M(m_1, m_2) = N_{sig} M_{sig}(m_1) M_{sig}(m_2) + N_{bkg} M_{bkg}(m_1) M_{bkg}(m_2)$$

PDG value:

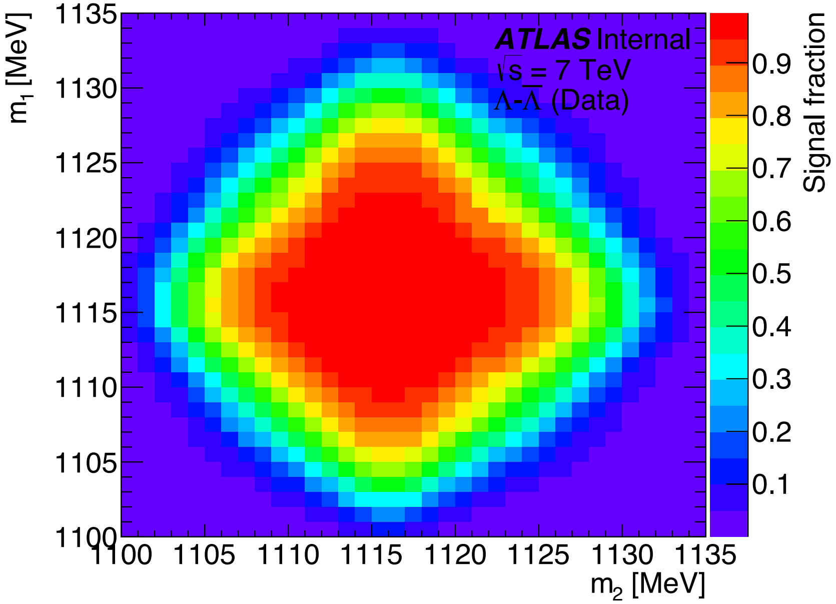
$m_\Lambda = 1115.683 \pm 0.006$ MeV

Fit results

Type of hyperons	$\Lambda^0 \bar{\Lambda}^0$	$\Lambda^0\Lambda^0 + \bar{\Lambda}^0\bar{\Lambda}^0$	$\Lambda^0\Lambda^0$	$\bar{\Lambda}^0\bar{\Lambda}^0$
m_{Λ_1} [MeV]	1115.80 ± 0.02	1115.73 ± 0.02	1115.76 ± 0.03	1115.69 ± 0.03
m_{Λ_2} [MeV]	1115.65 ± 0.02	1115.78 ± 0.03	1115.79 ± 0.04	1115.76 ± 0.04
$\sigma_{m_{\Lambda_1}}$ [MeV]	3.55 ± 0.07	3.56 ± 0.08	3.57 ± 0.11	3.55 ± 0.13
$\sigma_{m_{\Lambda_2}}$ [MeV]	3.57 ± 0.08	3.55 ± 0.09	3.55 ± 0.11	3.56 ± 0.14

Signal region

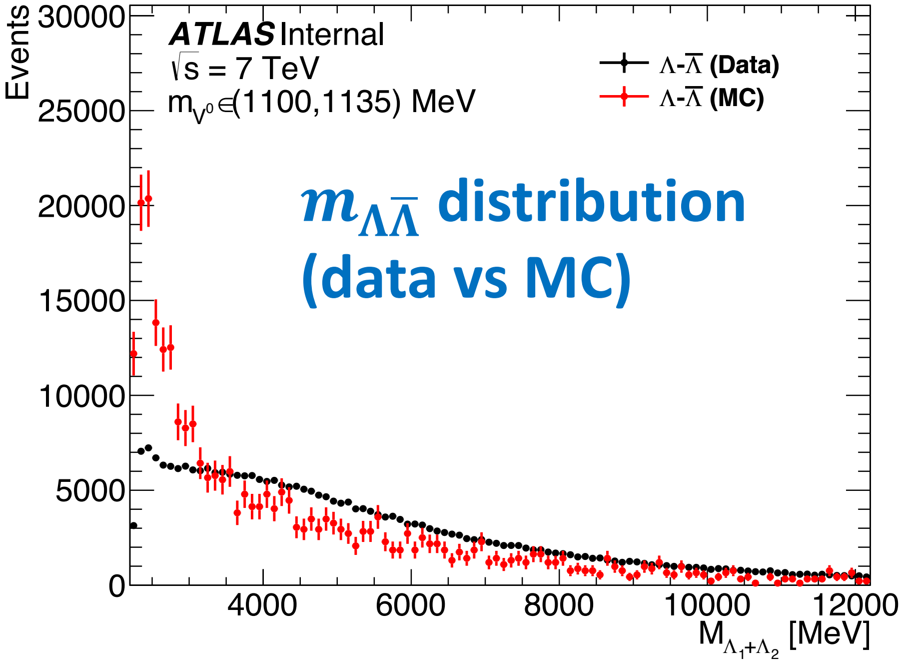
Type of hyperons	$\Lambda^0 \bar{\Lambda}^0$	$\Lambda^0\Lambda^0 + \bar{\Lambda}^0\bar{\Lambda}^0$	$\Lambda^0\Lambda^0$	$\bar{\Lambda}^0\bar{\Lambda}^0$
Signal region [MeV]	$[1112, 1120]$	$[1112, 1120]$	$[1112, 1120]$	$[1112, 1120]$
Signal yield N_{sig}	162990	133653	74374	59275
Background yield N_{bkg}	1881	1861	988	872
Signal fraction f_{sig} [%]	98.85	98.63	98.68	98.55

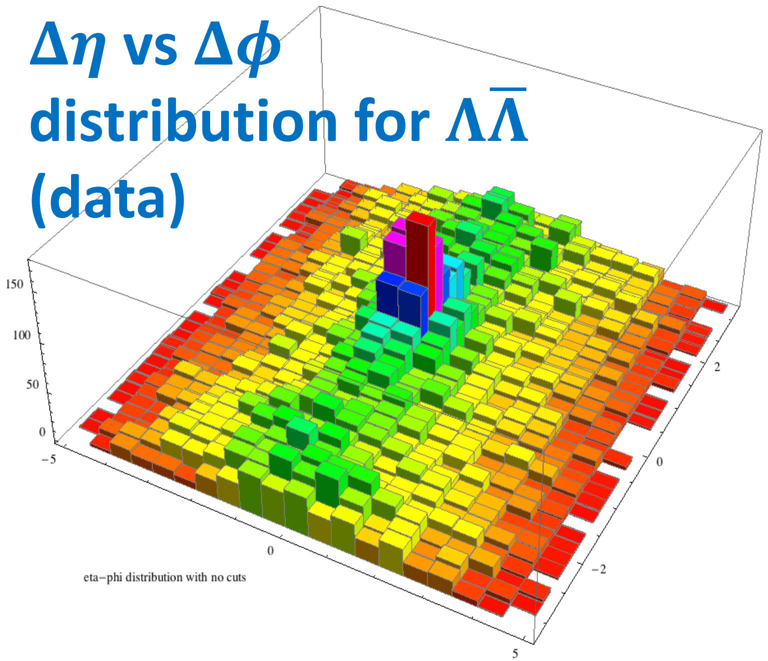


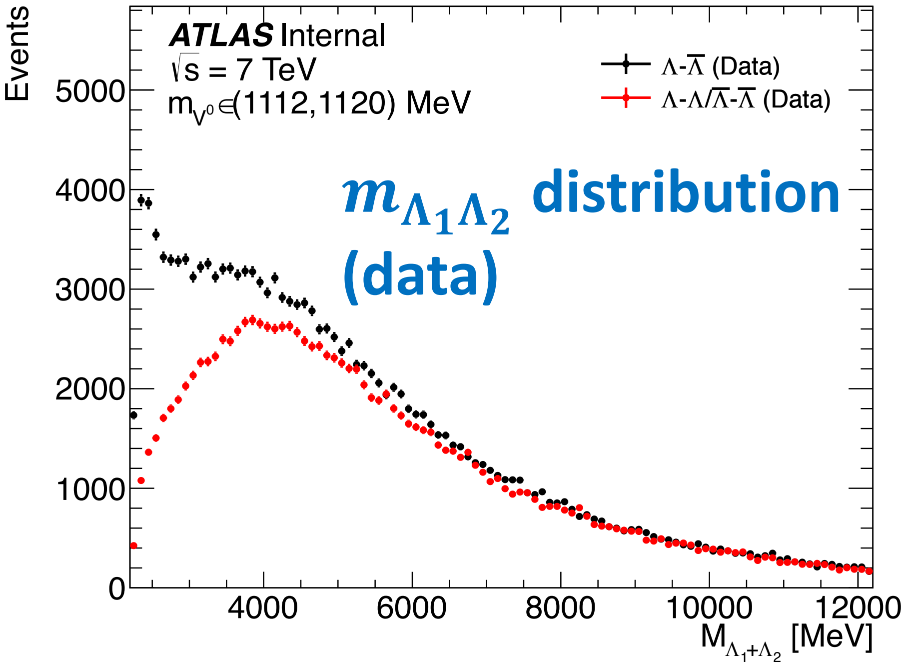
Signal fraction distribution for $\Lambda^0\bar{\Lambda}^0$ events (data)

Dynamical correlations

- Excess $\Lambda^0\overline{\Lambda}^0$ events observed near $(\Lambda\Lambda)$ threshold when compared to $\Lambda^0\Lambda^0$ and $\overline{\Lambda}^0\overline{\Lambda}^0$ events
- The excess is overestimated by MC (PYTHIA) sample when compared to data sample



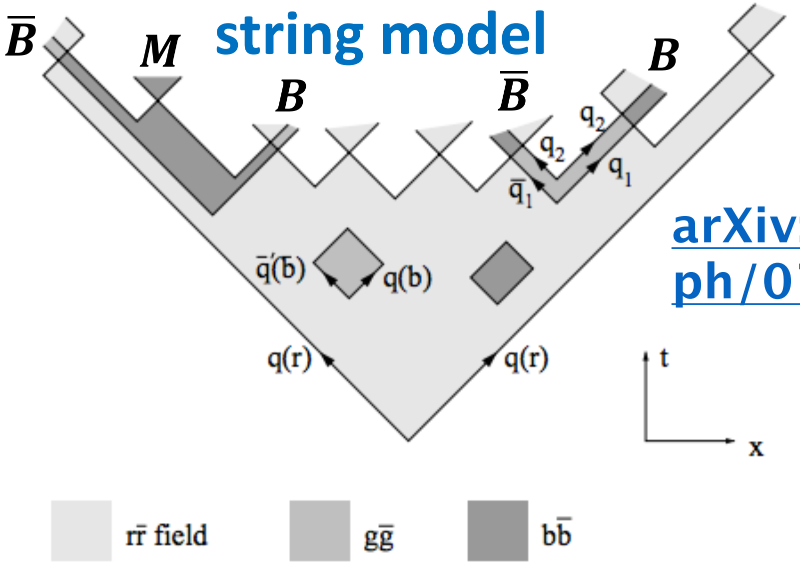




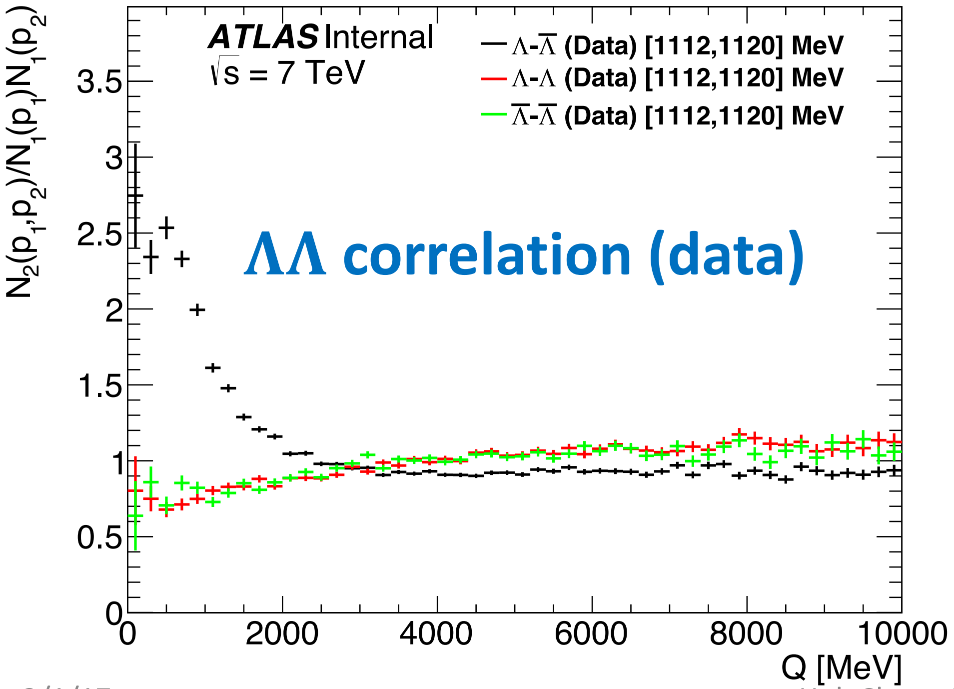
Dynamical correlations

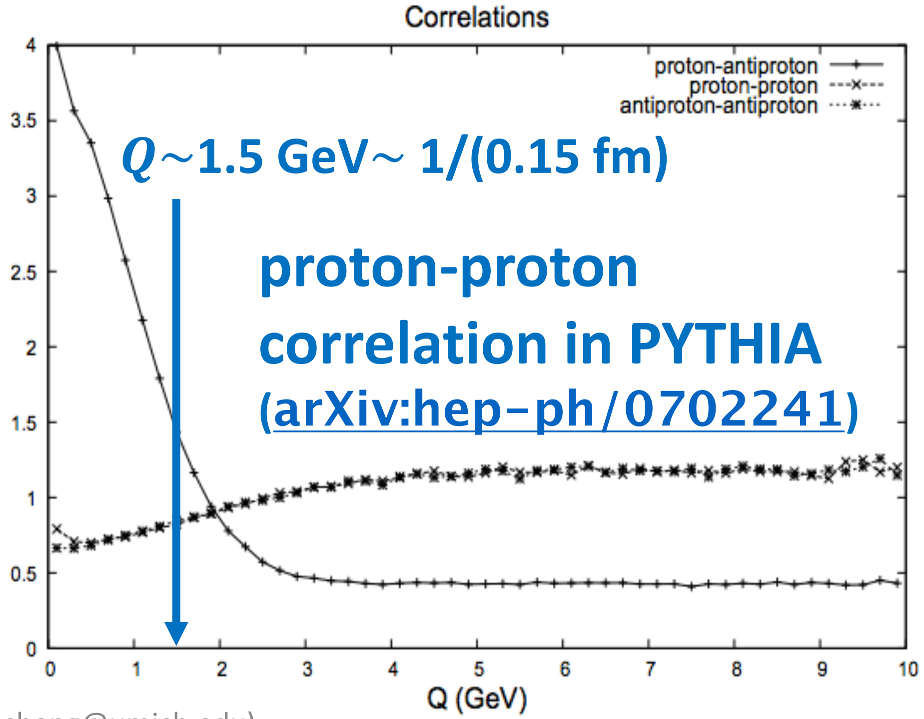
- Lund string model predicts *positive* correlation between *baryon-antibaryon* pairs and *anti-correlation* between *baryon-baryon* pairs in rapidity and momentum phase space
- *Dynamical correlations* captured by correlation function $N_2(p_1, p_2)/N_1(p_1)N_1(p_2)$ resembles baryon-antibaryon and di-baryon productions in the PYTHIA generator

Color fluctuations in string model



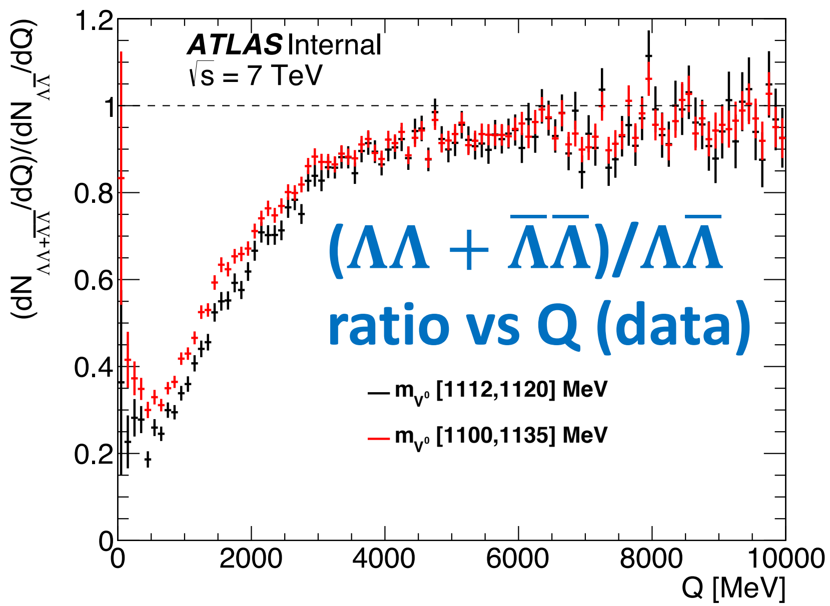
arXiv:hep–ph/0702241



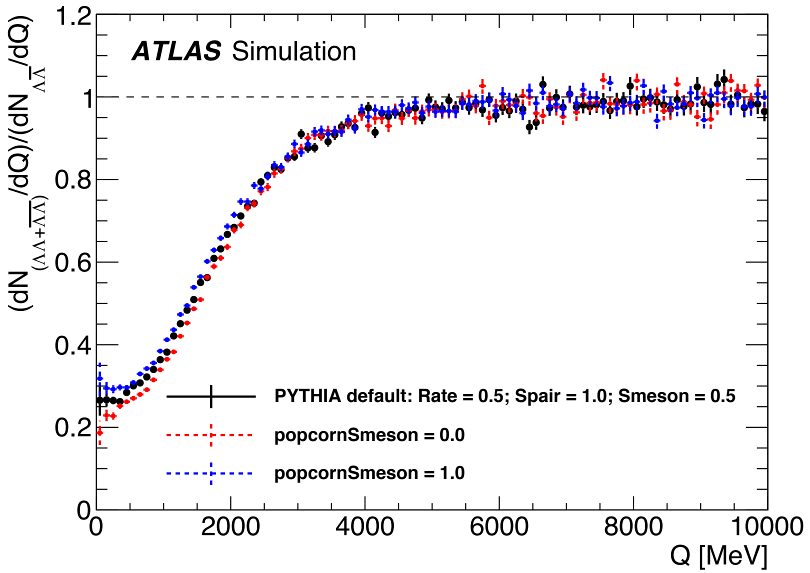


"Popcorn" mechanism in PYTHIA

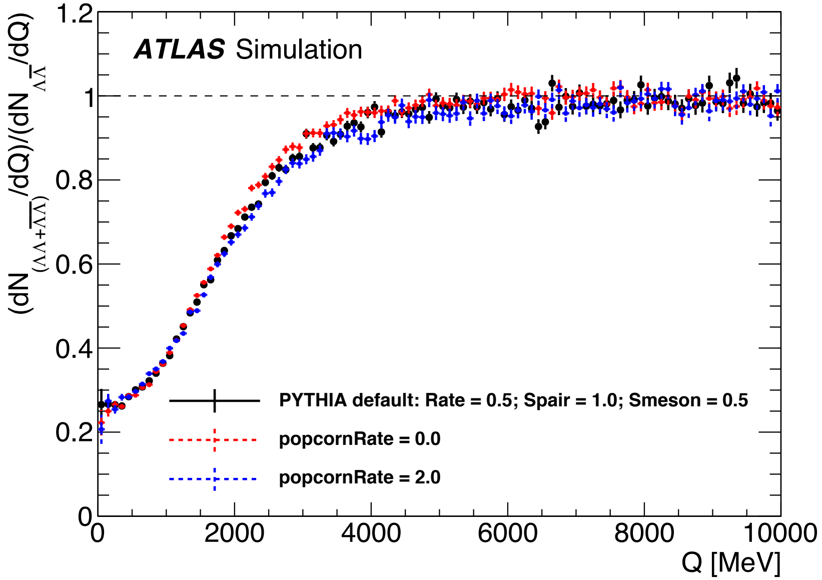
- The popcorn mechanism controls how easily mesons pop up in baryon-antibaryon production in the string model
- Three parameters, namely popcornSmeson, popcornRate and popcornSpair, are implemented and tuned
- $(\Lambda\Lambda + \overline{\Lambda}\overline{\Lambda})/\Lambda\overline{\Lambda}$ ratio is not very sensitive to the three parameters



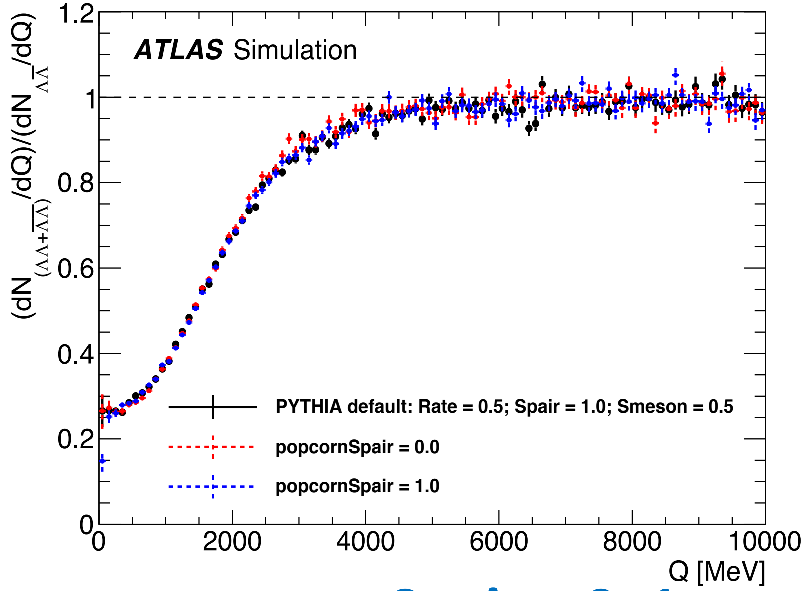
$(\Lambda\Lambda + \overline{\Lambda}\overline{\Lambda})/\Lambda\overline{\Lambda}$ ratio vs Q (data)



popcornSmeson = 0, 0.5, 1



popcornRate = 0, 0.5, 2



popcornSpair = 0, 1

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

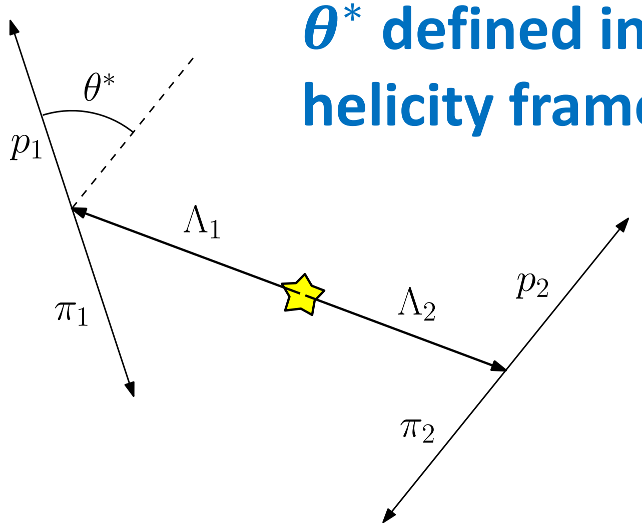
$$\frac{dw(\boldsymbol{n}_1, \boldsymbol{n}_2)}{d\Omega_{\boldsymbol{n}_1} d\Omega_{\boldsymbol{n}_2}} = \frac{1}{16\pi^2}\left(1 + \alpha_\Lambda \boldsymbol{P}_1 \boldsymbol{n}_1 + \alpha_\Lambda \boldsymbol{P}_2 \boldsymbol{n}_2 + \alpha_\Lambda^2 \sum_{i=1}^{3}\sum_{k=1}^{3} T_{ik} \boldsymbol{n}_{1i}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

$\boldsymbol{P}_1$ 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

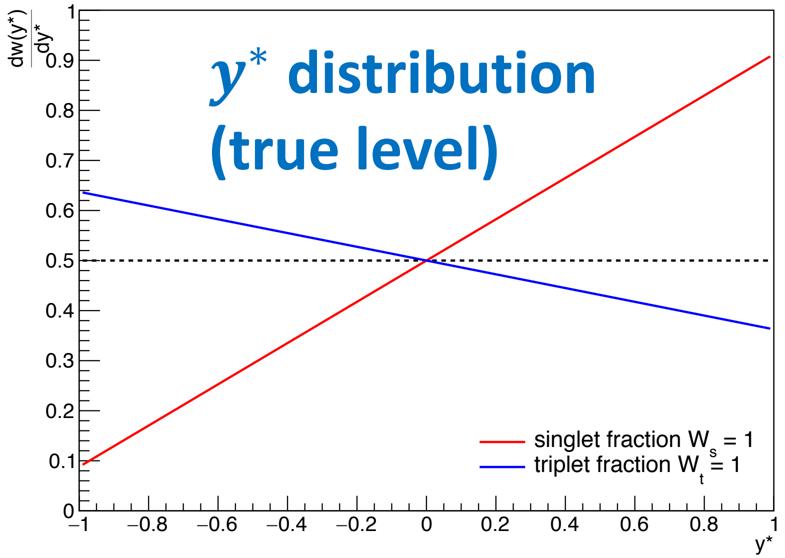
$$\frac{dw(cos\theta^*)}{dcos\theta^*} = \frac{1}{2}\left(1 + \frac{1}{3} T \alpha_\Lambda^2 cos\theta^*\right) = \frac{1}{2}\left(1 + \boldsymbol{A} \alpha_\Lambda^2 cos\theta^*\right)$$

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



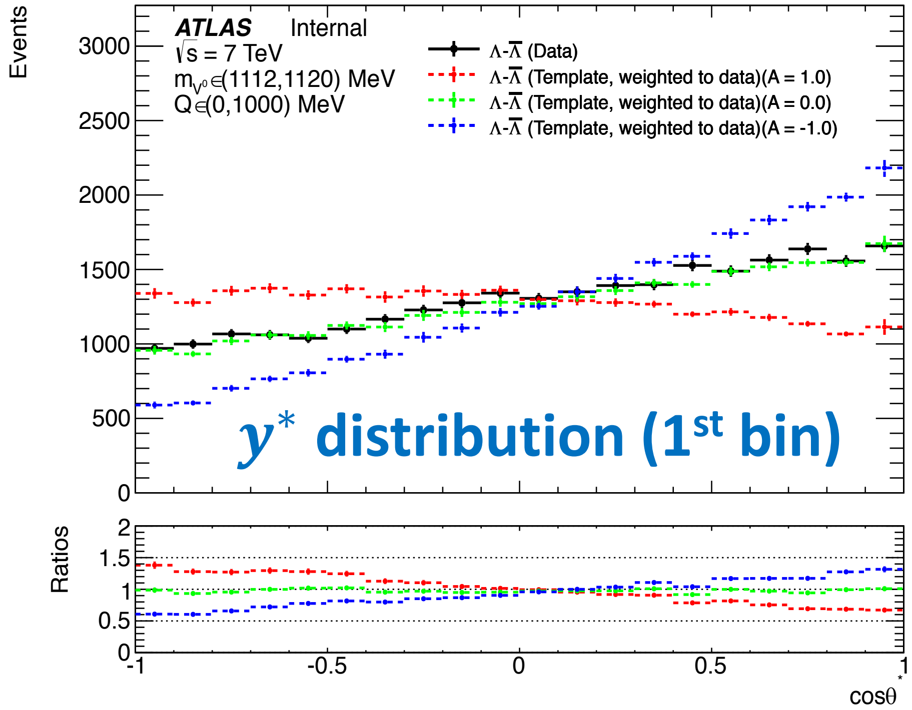
$\boldsymbol{\theta^*}$ defined in the helicity frame

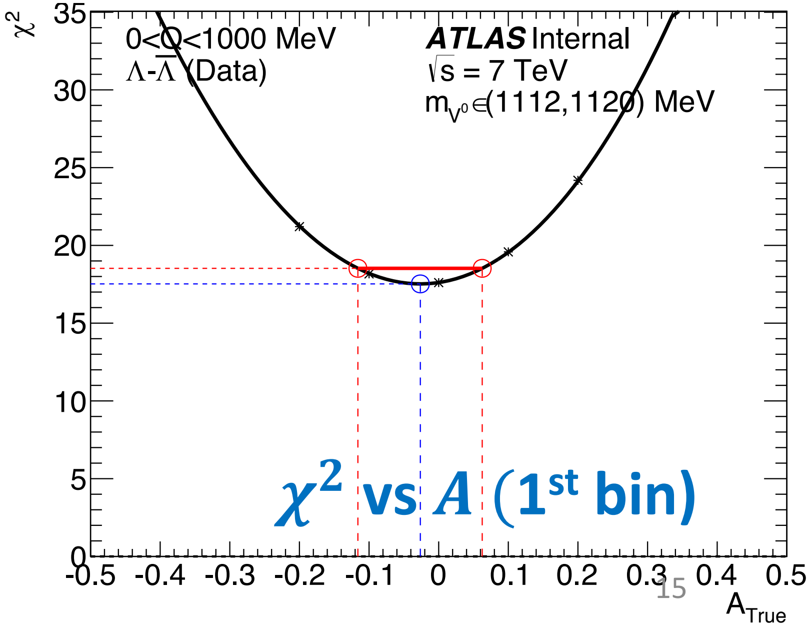
$$y^* = cos\theta^*$$



Extraction of spin correlation

1. Mixed data sample is created by combining Λ^0 and/or $\bar{\Lambda}^0$ candidates from odd and even events
2. The mixed sample is weighted iteratively to data sample to correct for the differences in kinematics
3. 9 reference samples for different spin correlation are created by weighting the mixed sample by a factor of $(1 \pm A\alpha^2 y^*)$ for $A = 0,\ \pm 0.1,\ \pm 0.2,\ \pm 0.5$ and ± 1
4. Pearson's χ^2-value is calculated for each pair of reference sample and data, A_{min} corresponding to the minimum χ^2-value is determined
5. Uncertainty ΔA_{min} is computed at variation $\chi^2_{min} \pm 1$
6. The results are expressed as a function of 4-momentum difference $Q = \sqrt{-(p_1 - p_2)^2}$ of the hyperon pair





Breakdown of systematic uncertainties

- Total uncertainty is calculated by adding all uncertainties in quadrature

$\Lambda\bar{\Lambda}$

Q [GeV]	1	2	3	4	5	6	7	8	Total
0-1	0.58319	0.07705	0.02553	-0.00489	0.00109	-0.00074	0.00275	0.00143	0.58884
1-2	-0.00786	0.02534	0.00429	-0.00683	0.00036	0.00198	-0.00063	0.00053	0.02782
2-3	-0.09420	0.00952	0.00167	0.00272	0.00057	-0.00189	0.00053	0.00201	0.09478
3-4	-0.04528	0.01148	0.00540	-0.00346	-0.00154	0.00064	-0.00084	0.00009	0.04719
4-5	-0.01427	0.01177	0.00731	-0.00978	-0.00052	-0.00043	0.00027	0.00050	0.02218
5-6	-0.00656	0.00958	0.00274	0.00710	0.00282	0.00396	-0.00096	0.00156	0.01483
6-7	-0.00920	0.01477	0.00534	0.00072	-0.00192	-0.00253	-0.00226	0.00103	0.01866
7-8	-0.01418	0.01872	0.00582	0.01503	-0.00078	0.00019	0.00055	0.00160	0.02855
8-9	-0.00745	0.01111	0.00266	0.04021	-0.00009	0.00062	-0.00104	0.00234	0.04254
9-10	-0.01424	0.02549	0.00518	-0.00493	0.00198	-0.00999	0.00147	0.00341	0.03195

$\Lambda\Lambda + \bar{\Lambda}\bar{\Lambda}$

Q [GeV]	1	2	3	4	5	6	7	8	Total
0-1	-0.15302	0.03267	0.04350	-0.01018	-0.00208	0.00117	0.00531	0.00019	0.16282
1-2	-0.01619	0.00402	0.00289	0.00382	-0.00599	0.00108	0.00019	0.00194	0.01850
2-3	0.04219	0.00346	0.00472	-0.00146	-0.00091	-0.00347	0.00017	0.00440	0.04299
3-4	0.00345	0.00597	0.00190	0.00404	-0.00037	0.00354	0.00063	0.00044	0.00899
4-5	-0.00435	0.00965	0.00328	0.00490	-0.00192	-0.00490	0.00057	0.00209	0.01338
5-6	-0.00426	0.00432	0.00229	0.00685	0.00018	0.00598	0.00158	0.00168	0.01141
6-7	-0.00548	0.00706	0.00268	0.02368	0.00051	-0.00686	0.00054	0.00019	0.02637
7-8	-0.00206	0.01658	0.00201	-0.01473	0.00297	0.00437	0.00037	0.00308	0.02319
8-9	-0.00783	0.01327	0.00133	0.00902	-0.00044	0.00773	0.00030	0.00339	0.01980
9-10	-0.00539	0.02582	0.00631	-0.01790	-0.00498	-0.00989	-0.00040	0.00061	0.03434

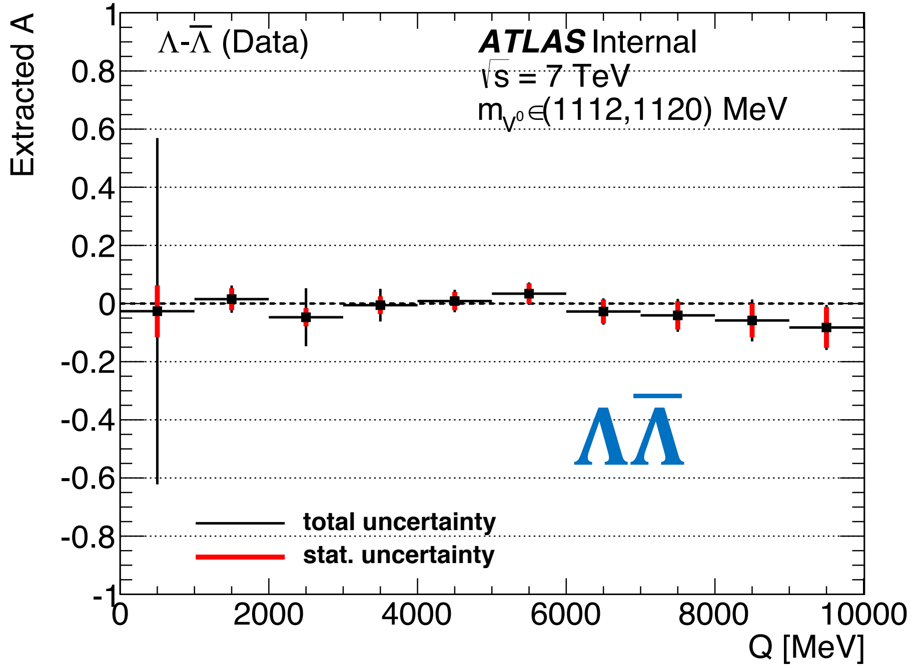
1. Kinematic weighting
2. Template statistics
3. Binning
4. Width of signal region
5. Background
6. Event migration
7. Decay angle resolution
8. Uncertainty of α parameter

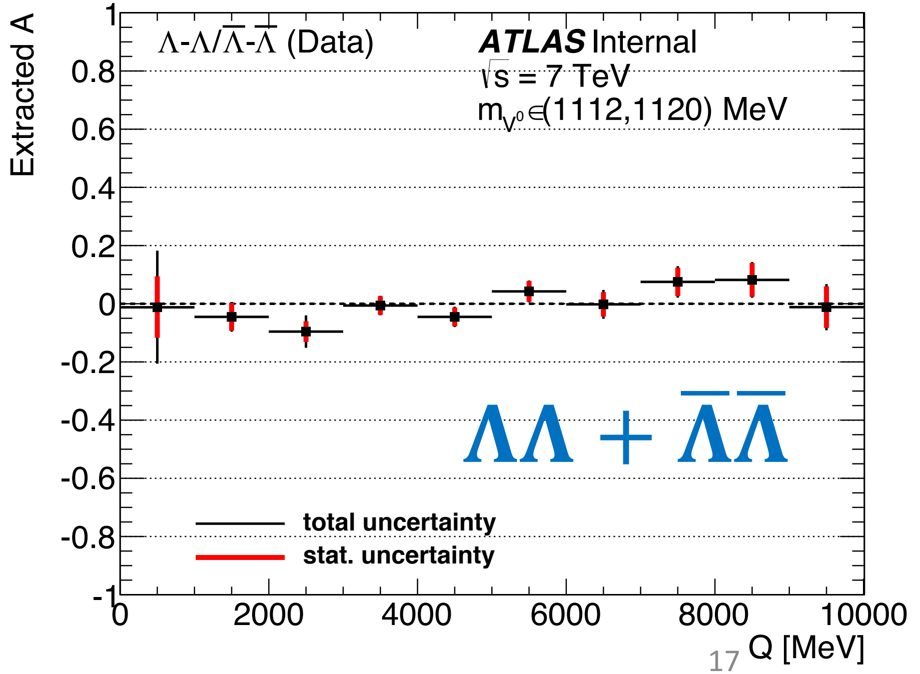
(See backup for details of treatment for each uncertainty)

Results

- Total uncertainty ~0.1 for Q = [1,10] GeV
- A-values consistent with zero for Q = [1,10] GeV
- Large systematics for Q = [0,1] GeV dominated by kinematic weighting
- **Very challenging to find an appropriate reference sample which captures the correct kinematics w/o any FD effect**

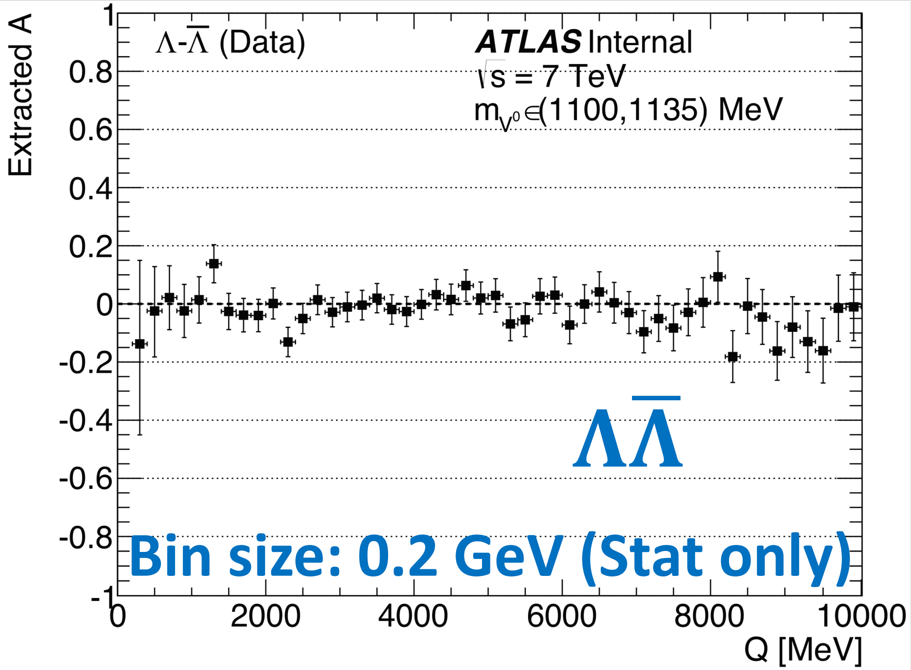
Q [GeV]	A for $\Lambda^0\bar{\Lambda}^0$	A for $\Lambda^0\Lambda^0+\bar{\Lambda}^0\bar{\Lambda}^0$
0-1	$-0.026^{+0.089}_{-0.090}$ (stat) $\boxed{\pm 0.589 \text{ (syst)}}$	$-0.012^{+0.107}_{-0.105}$ (stat) $\boxed{\pm 0.163 \text{ (syst)}}$
1-2	0.015 ± 0.038 (stat) ± 0.028 (syst)	-0.045 ± 0.048 (stat) ± 0.019 (syst)
2-3	-0.047 ± 0.031 (stat) ± 0.095 (syst)	-0.096 ± 0.036 (stat) ± 0.043 (syst)
3-4	-0.006 ± 0.030 (stat) ± 0.047 (syst)	-0.006 ± 0.032 (stat) ± 0.009 (syst)
4-5	0.009 ± 0.032 (stat) ± 0.022 (syst)	-0.045 ± 0.032 (stat) ± 0.013 (syst)
5-6	0.034 ± 0.035 (stat) ± 0.015 (syst)	0.042 ± 0.036 (stat) ± 0.011 (syst)
6-7	-0.027 ± 0.041 (stat) ± 0.019 (syst)	-0.002 ± 0.042 (stat) ± 0.026 (syst)
7-8	-0.041 ± 0.049 (stat) ± 0.029 (syst)	0.075 ± 0.049 (stat) ± 0.023 (syst)
8-9	-0.058 ± 0.058 (stat) ± 0.043 (syst)	0.082 ± 0.058 (stat) ± 0.020 (syst)
9-10	$-0.082^{+0.071}_{-0.070}$ (stat) ± 0.032 (syst)	$-0.012^{+0.071}_{-0.072}$ (stat) ± 0.034 (syst)

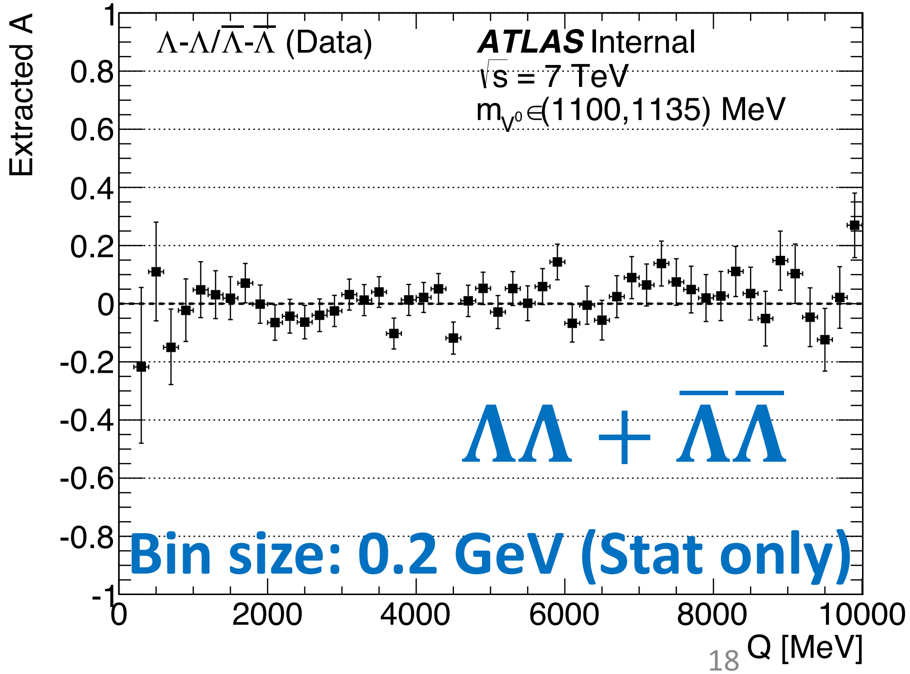




Results

- Results for bin size of 0.2 GeV are shown with full mass window to increase statistics
- Results are consistent with zero for $Q = [1{,}10]$ GeV
- Very low statistics in $Q = [0{,}1]$ GeV
- LEP results ($R \sim 0.15$ fm & $Q \sim 1.5$ GeV) is inconsistent with most hadronization models as it is much smaller than the baryon radius (See backup for comment by Lund group)
- FD effect is expected to show up in $Q \sim 0.5$ GeV for emitter size $\mathrm{R} \sim 1$ fm
- Attempt to set a lower limit on the emitter size R for FD effects (Work in progress)



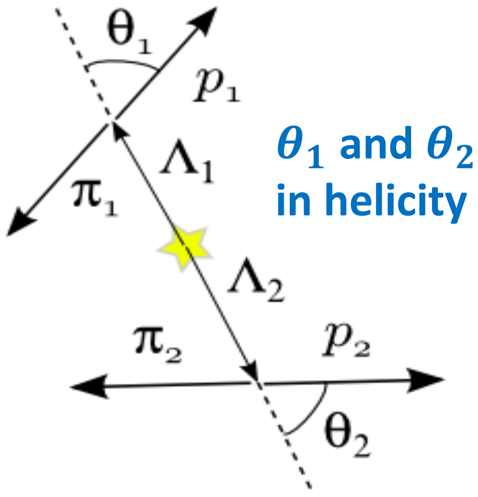


Alternative definition for decay angles

2D decay angular distribution

$$\frac{d^2w(cos\theta_1,cos\theta_2)}{dcos\theta_1 dcos\theta_2} = \frac{1}{4}(1 + P_1\alpha_\Lambda cos\theta_1)(1 - P_2\alpha_\Lambda cos\theta_2) \text{ for } \Lambda^0\overline{\Lambda}^0$$

where P_1 and P_2 are the polarization vectors for $\Lambda_1\Lambda_2$



θ_1 and θ_2 defined in helicity frame

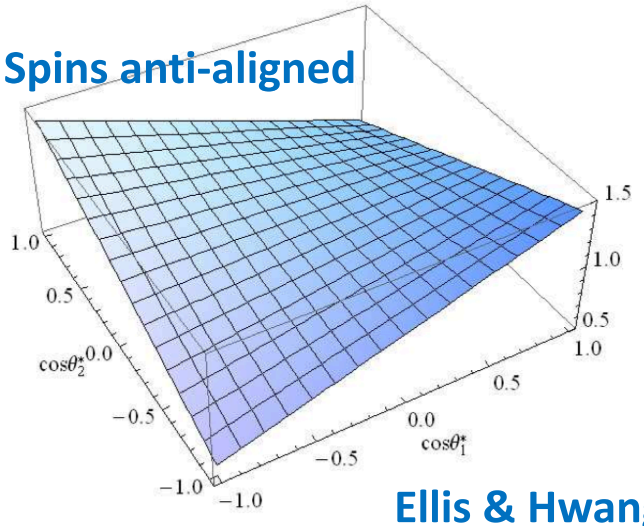
Spins anti-aligned

$(P_1, P_2) = (+1, +1)$ or $(-1, -1) \rightarrow w(cos\theta_1, cos\theta_2) \propto (1 - \alpha_\Lambda^2 cos\theta_1 cos\theta_2)$

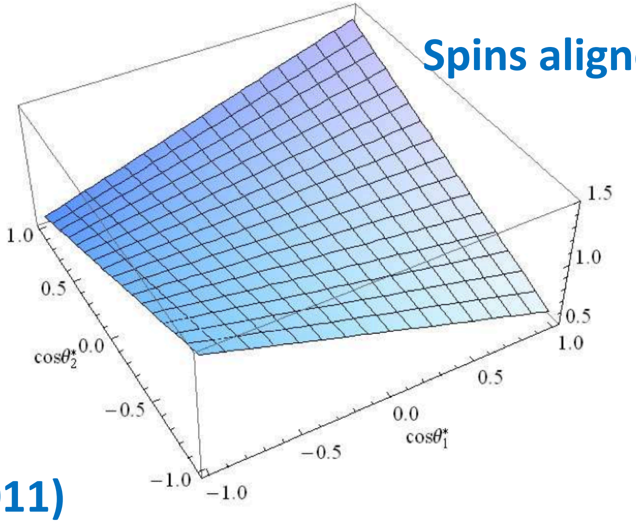
Spins aligned

$(P_1, P_2) = (+1, -1)$ or $(-1, +1) \rightarrow w(cos\theta_1, cos\theta_2) \propto (1 + \alpha_\Lambda^2 cos\theta_1 cos\theta_2)$

Spins anti-aligned

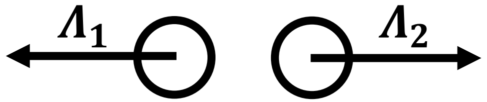


Spins aligned



Ellis & Hwang (2011) arXiv:1108.5319

(P_1, P_2)	S_1	S_2
$(+1, +1)$	←	→
$(-1, -1)$	→	←



$(+1, -1)$	←	←
$(-1, +1)$	→	→

Polarization vectors and spin alignments in the helicity frame

Cross-checks: correlation function

- Four quadrants (TR, BL, TL, BR) of $cos\theta_2$ vs $cos\theta_1$ distribution are used to define a ***correlation function*** $f(x)$ Ellis & Hwang (2011)

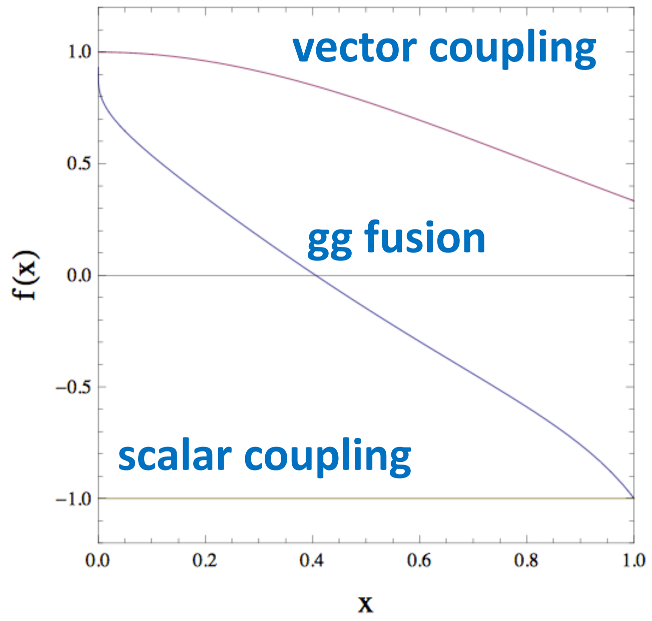
$$\frac{\alpha^2}{4} f(x) = \frac{N(TR+BL)-N(TL+BR)}{N(TR+BL)+N(TL+BR)} =$$

- Efficiency difference is corrected by a correction factor E

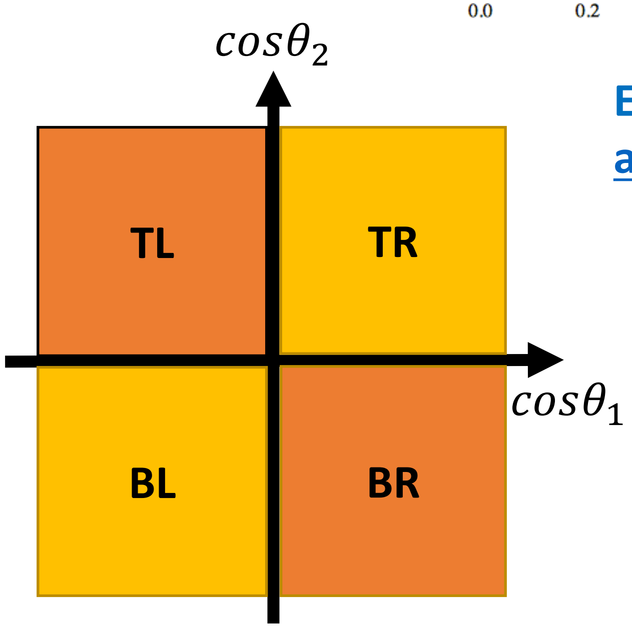
$$\frac{\alpha^2}{4} f(x) = \frac{N(TR+BL)^{reco}_{data} - E \times N(TL+BR)^{reco}_{data}}{N(TR+BL)^{reco}_{data} + E \times N(TL+BR)^{reco}_{data}}$$

where $E = \frac{\epsilon(TR+BL)}{\epsilon(TL+BR)} = \frac{N(TR+BL)^{reco}_{mixed}}{N(TL+BR)^{reco}_{mixed}} =$

$f(x)$ vs x $(= 2m_s/\sqrt{s})$

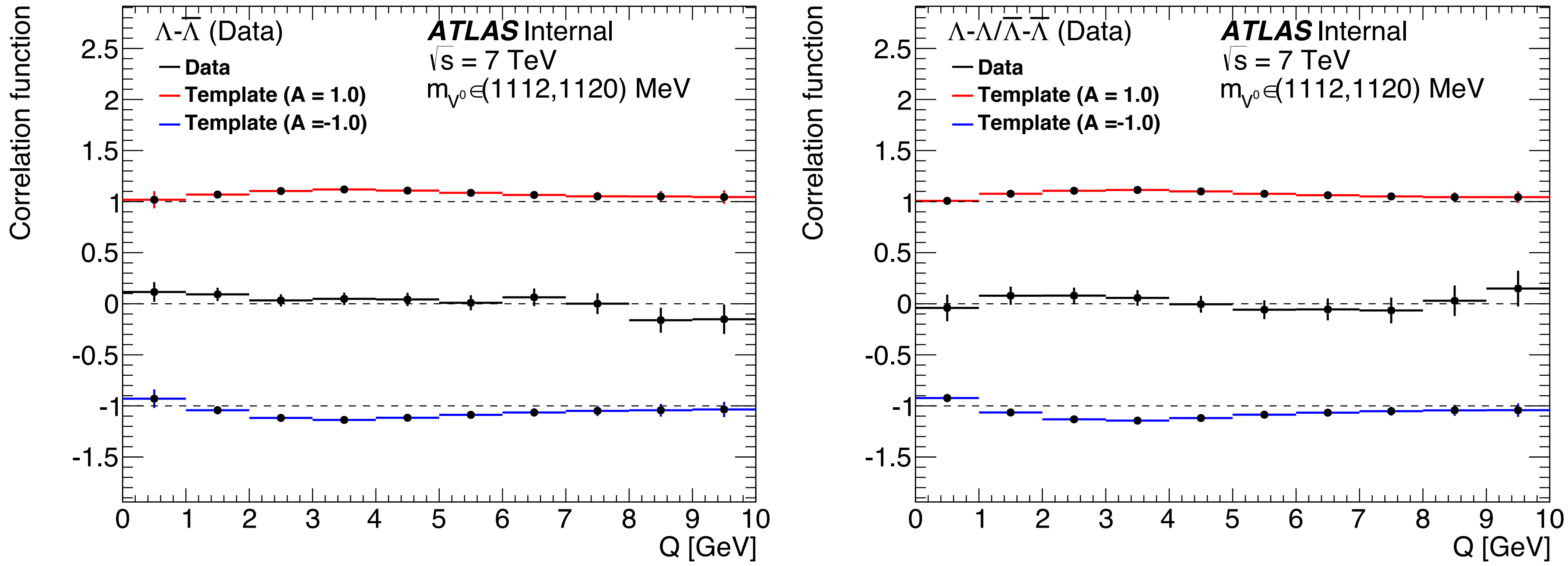


Ellis & Hwang (2011)
arXiv:1108.5319



Cross-checks: correlation function

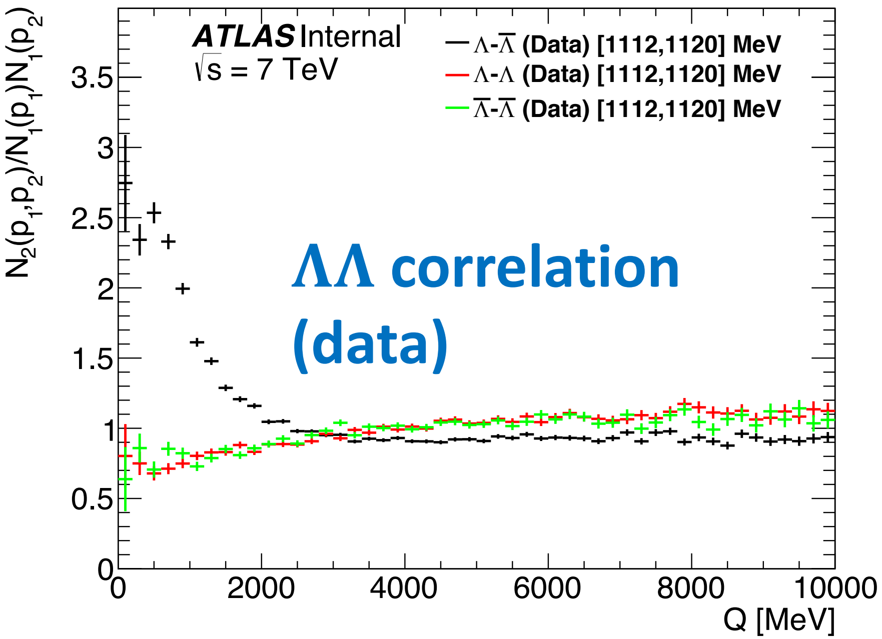
- $f(x)$ is consistent with zero in all bins (bin size: 1 GeV)
- $f(x)$ of control samples ($A = \pm 1$) give value consistent with expected value

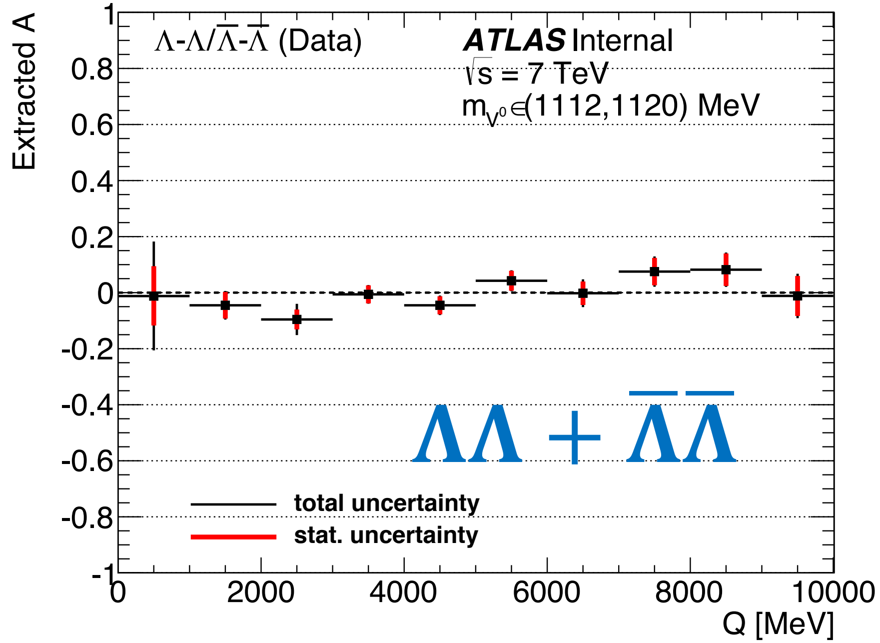


$\Lambda\bar{\Lambda}$ **Statistical uncertainty only** $\Lambda\Lambda + \bar{\Lambda}\bar{\Lambda}$

Summary

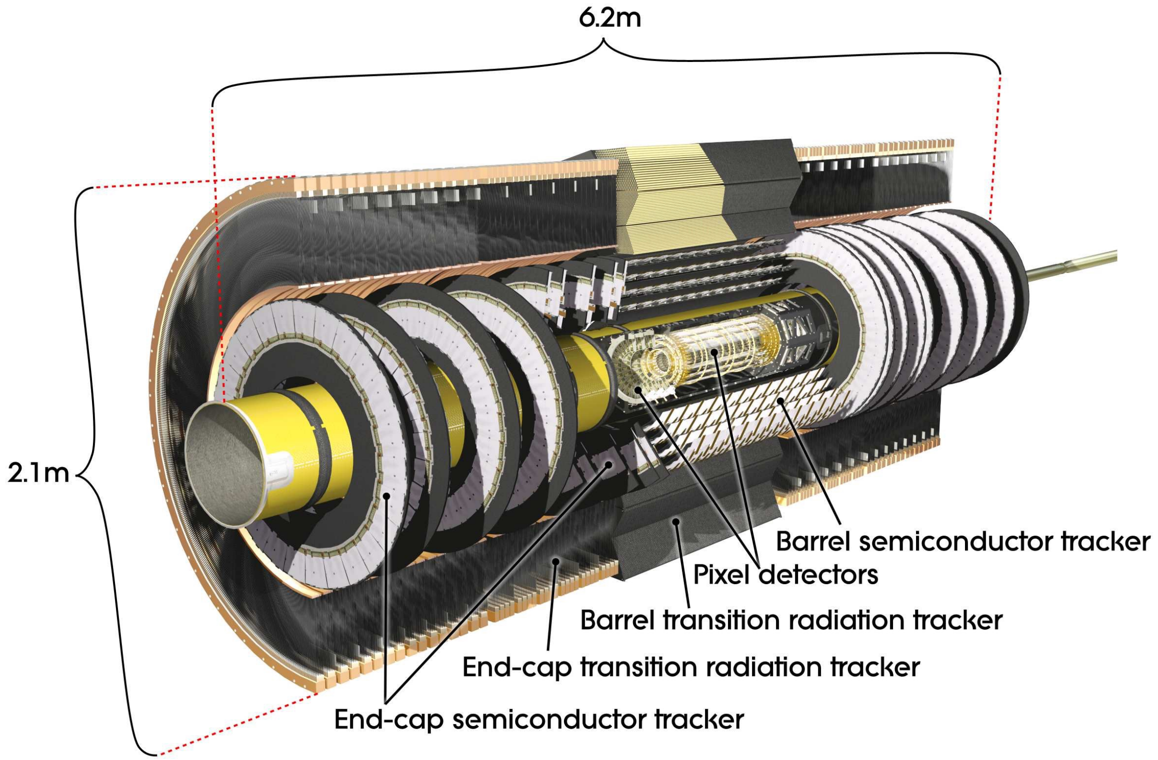
- $\Lambda\Lambda$ dynamical correlations in data resemble baryon-baryon (pp) production in PYTHIA
- Spin correlation is consistent with zero for $Q \in [1,10]$ GeV
- Cross-checks gave consistent results
- FD effect is expected in smaller range $Q \in [0,1]$ GeV where statistics is very limited
- Attempt to set a lower limit for the FD emitter size R



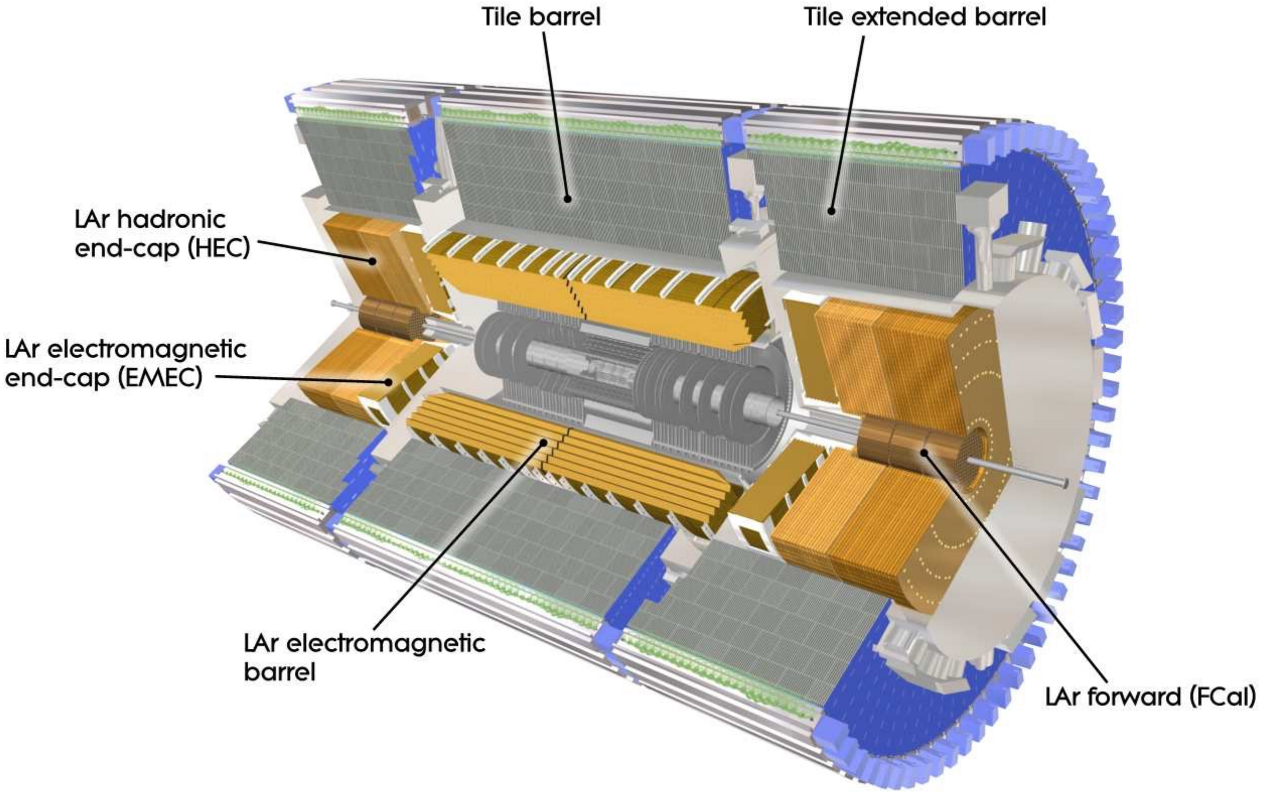


Backup

Backup: Inner detector and calorimeters

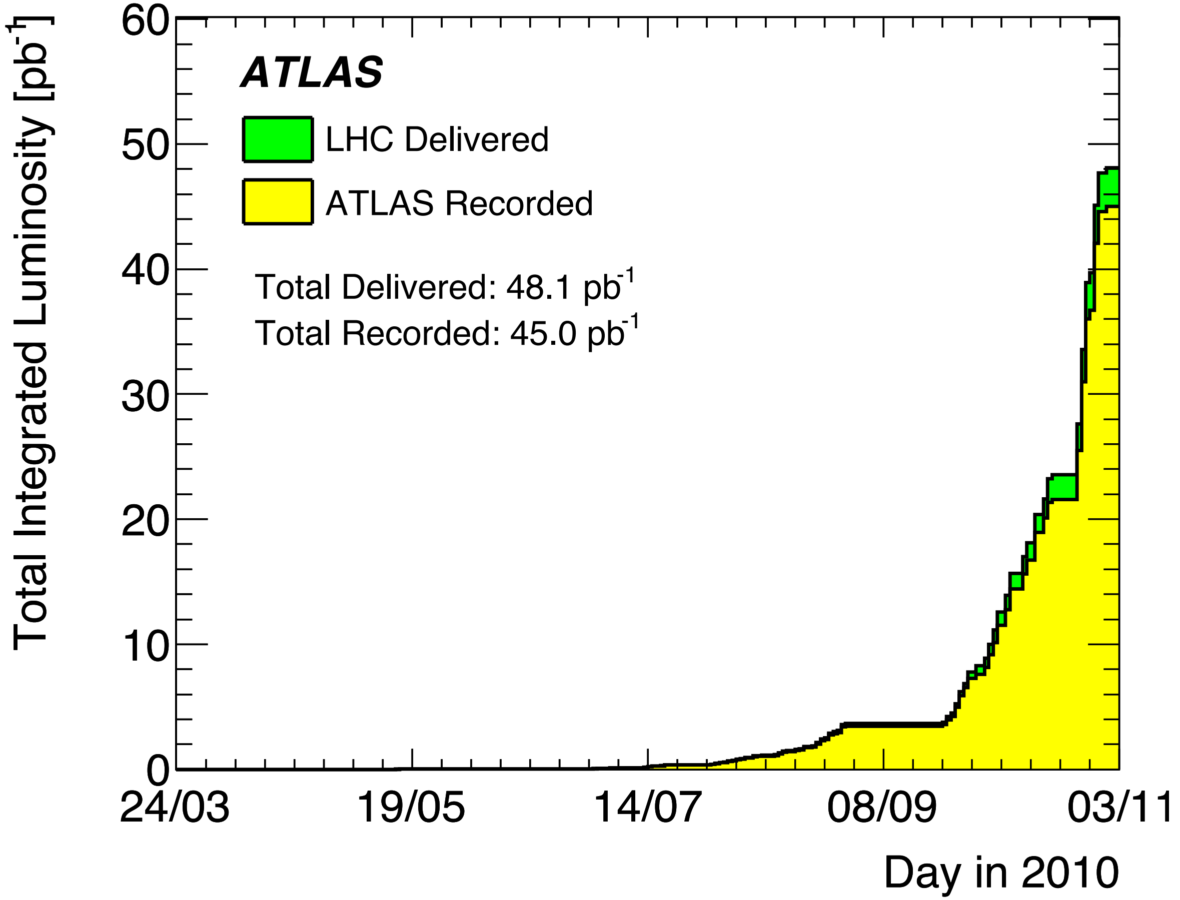


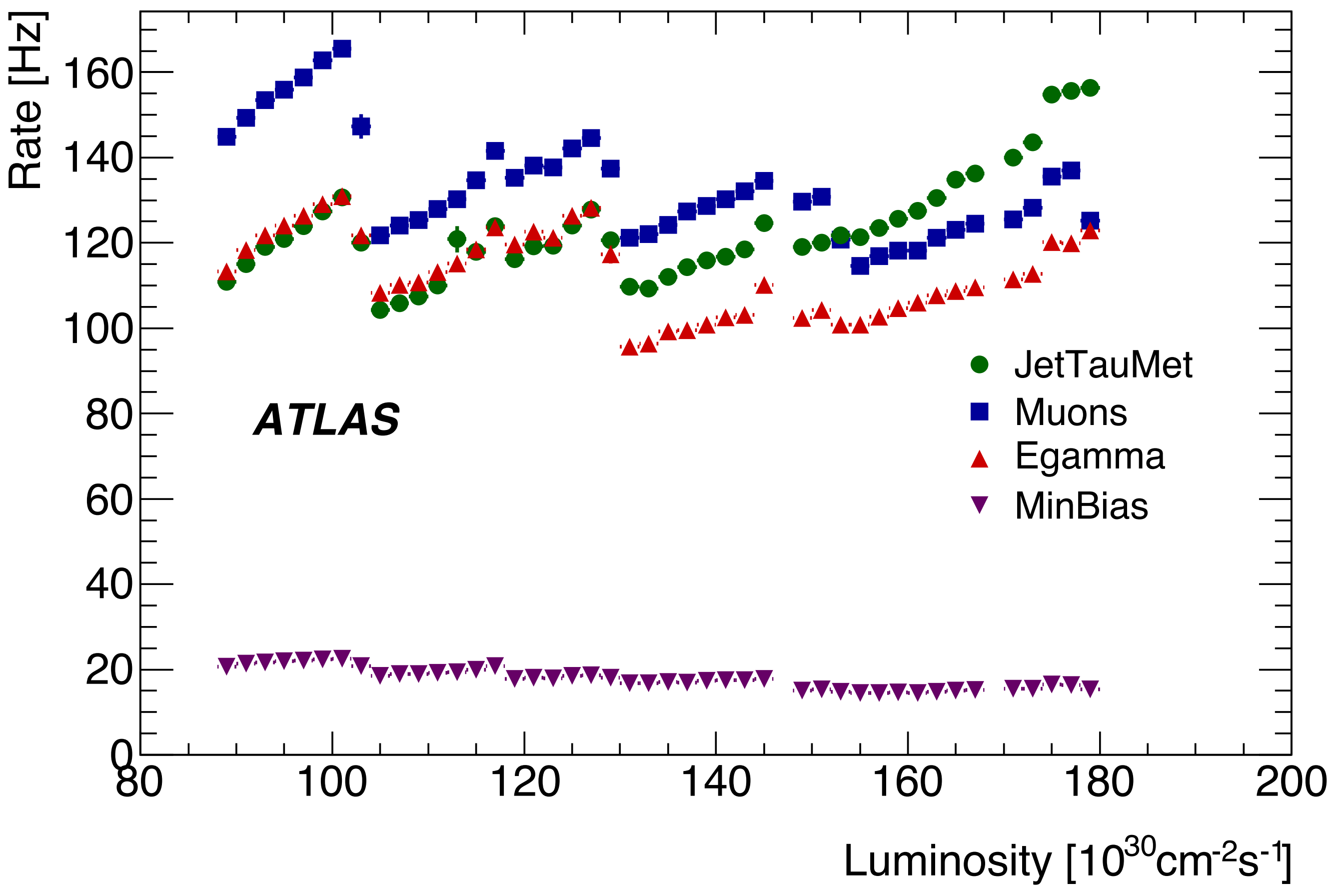
Inner detector



Calorimeters

Backup: Luminosity and trigger rates in 2010





Backup: LEP results

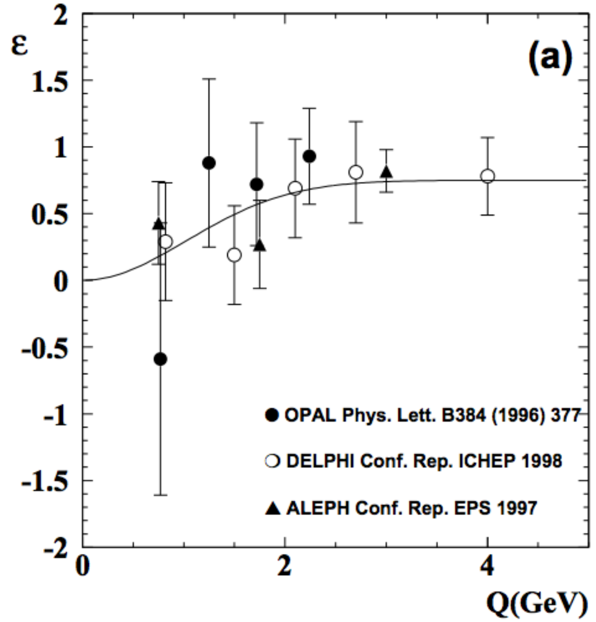
- "Double ratio" method for FD effects:

$$C(Q) = \left(\frac{N^{exp}(Q)}{N^{exp}_{ref}(Q)}\right) \Big/ \left(\frac{N^{MC}(Q)}{N^{MC}_{ref}(Q)}\right)$$

- Drawback: The results are very sensitive to the description of correlation in the MC sample

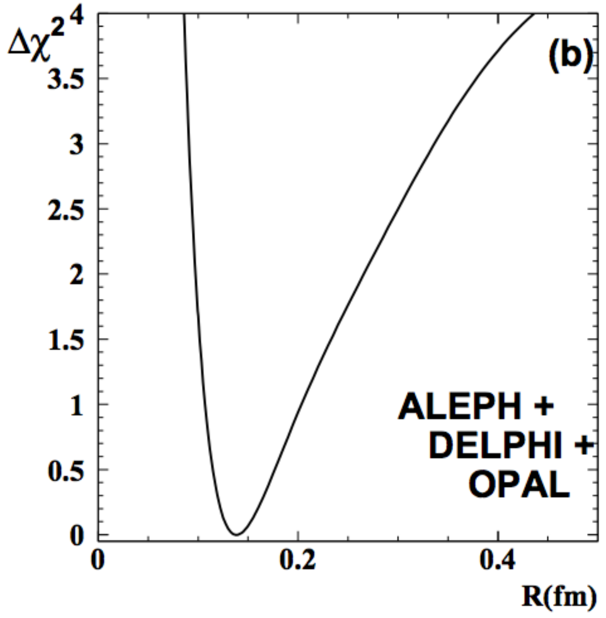
	$R\,(fm)$	λ	Experiment	
$\bar{p}\bar{p}$	0.14 ± 0.06	0.76 ± 0.33	OPAL[1]	[10]
	0.11 ± 0.01	0.49 ± 0.09	ALEPH	[11]
	0.16 ± 0.05	0.67 ± 0.25	DELPHI	[12, 13]
$\Lambda\Lambda$	0.11 ± 0.02	0.59 ± 0.10	ALEPH	[14]
	0.17 ± 0.14	Spin Analysis	ALEPH	[14]
	$0.19^{+0.37}_{-0.07}$	Spin Analysis	OPAL	[15]
	$0.11^{+0.05}_{-0.03}$	Spin Analysis	DELPHI[1]	[16]

arXiv:hep-ph/0702241



$\epsilon(Q) = 0.75[1 - e^{(-R^2Q^2)}]$

Fraction of $S = 1$ state ϵ vs Q



χ^2 fit for emitter radius R

Backup: Comment on LEP results by Lund group

“The reported results on the production radius for baryon pairs is clearly not consistent with the conventional picture of string fragmentation. In fact, **a production radius of 0.15 fm, which is smaller than the size of the baryons themselves seems difficult to reconcile with any conceivable hadronization model. There are principal problems in the construction of a reference sample which contains all dynamical baryon–baryon correlations but not the effects of Fermi–Dirac statistics.** […]

[…] **In particular we noted that the strong dynamical correlation between baryons in the model appears in the same range of Q as the claimed FD correlations in the data**, and that the model uncertainties for these correlations are large and have not been independently constrained by data.

In conclusion we feel that it is premature to claim that the observed discrepancy between data and Monte Carlo is really only due to Fermi–Dirac effects, which would indicate a new kind of production mechanism. […]” **– R. Delgado, G. Gustafson, L. Lonnblad (2007) arXiv:hep-ph/0702241**

Backup: Splitting function

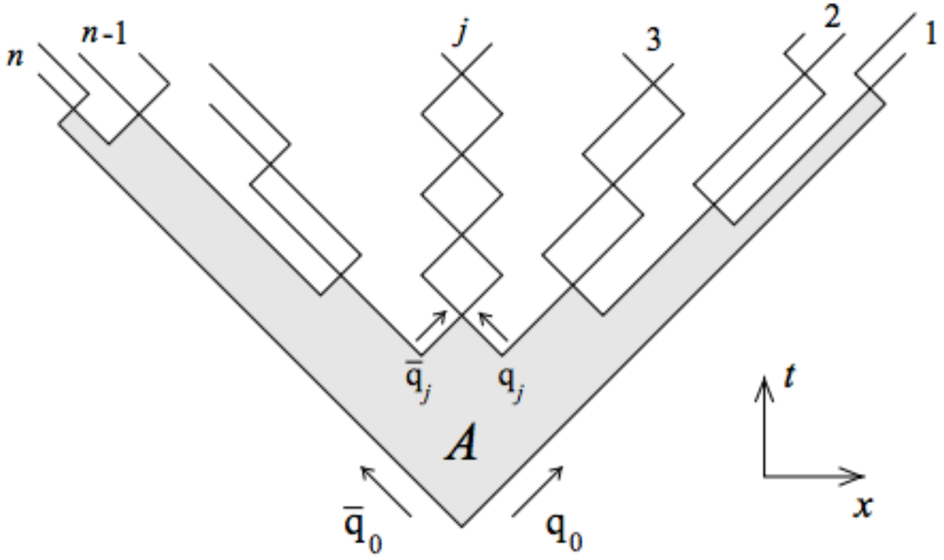
- Probability for a final state with n mesons with mass m and momenta p_i is given by

$$dP \propto \prod_{i}^{n}\left[N d^2 p_i \delta\left(p_i^2 - m^2\right)\right]\delta\left(\sum p_i - P_{tot}\right)\times\exp(-bA)$$

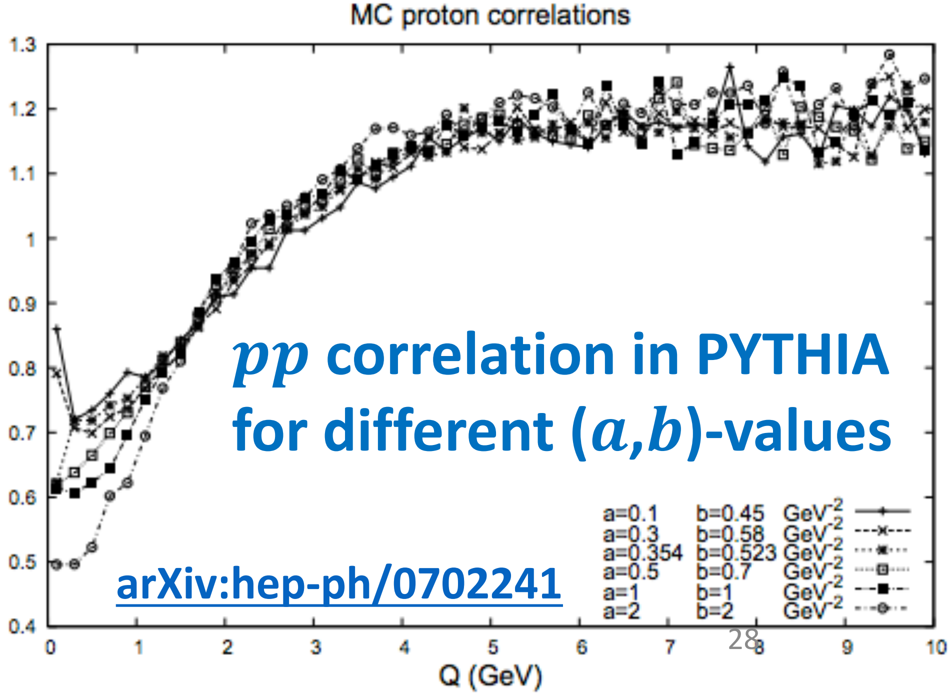
- Fraction of momentum z_i taken by each meson can be determined by the "splitting function" iteratively

$$f(z_i) = N\frac{(1-z_i)^a}{z_i}\exp\left(-\frac{bm^2}{z_i}\right)$$

- Larger (a, b)-values correspond to stronger correlation and a deeper dip for small Q for the correlation function



Production of n mesons in the Lund string model



pp correlation in PYTHIA for different (a,b)-values

arXiv:hep-ph/0702241

Backup: Systematic uncertainties

Kinematic weighting

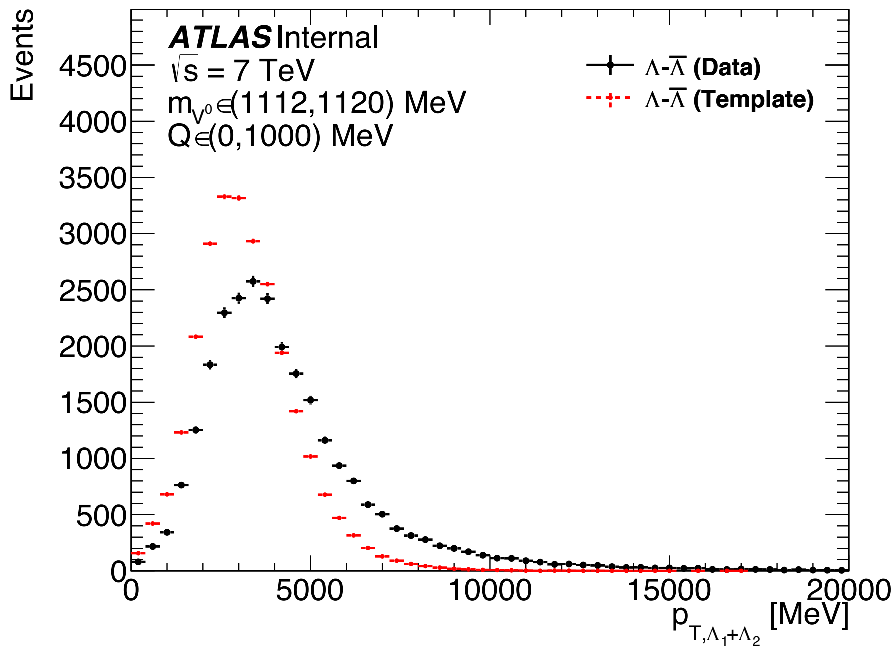
- Kinematic weighting may alter input A-value
- Difference between results obtained w/ and w/o kinematic weighting is taken as systematic uncertainty
- Dynamical correlations of data and template are very different in the 1st bin, esp. for $\Lambda\bar{\Lambda}$, resulting in a very large uncertainty

Template statistics

- Mixed sample is split into 4 statistically-independent subsets
- $\sigma/\sqrt{3}$ is taken as the systematic uncertainty, where σ is the standard derivation of $\Delta A_{i=\{1,2,3,4\}} = A_{i=\{1,2,3,4\}} - A_{default}$

Binning

- 2-times finer and coarser bin sizes are used for y^* distribution



$p_{T,\Lambda\bar{\Lambda}}$ **distribution (1st bin) (data vs template)**

Width of signal region

- Width of mass window of signal region is varied up and down by 2 MeV

Backup: Systematic uncertainties

Decay angle resolution

- Mixed MC sample is weighted to reference sample
- True decay angle is used instead of reconstructed one to build templates
- $A_{new} - A_{default}$ is taken as the systematic uncertainty

Background

- A-value is extracted in signal region (SR) $[1112,1120]$ and background region (BG) $[1100,1107]\cup[1125,1135]$
- Signal fractions f_{SR} and f_{BG} are used to correct the A-value

$$A_{sig} = \frac{1}{f_{SR} - f_{BG}}\left[(1 - f_{BG})A_{SR} - (1 - f_{SR})A_{BG}\right]$$

Event migration

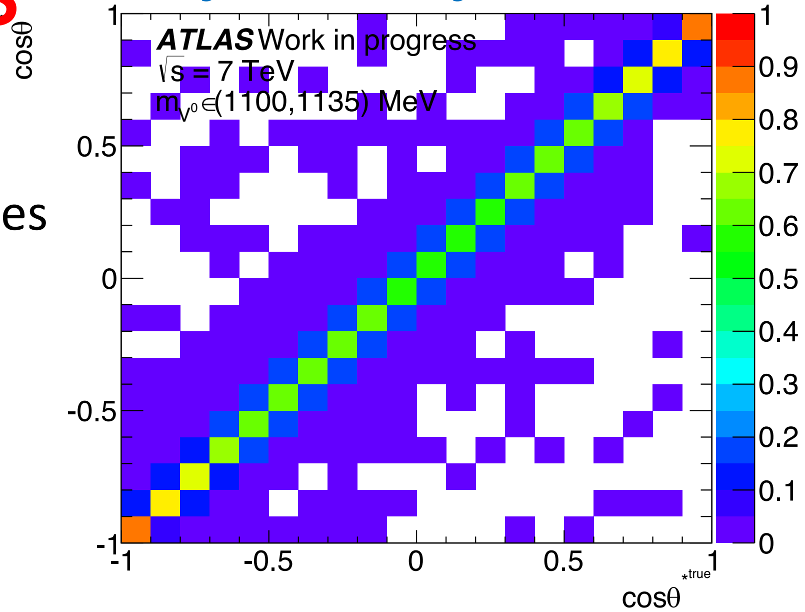
- Migration matrix is computed using the MC mixed sample
- A_{new} is computed bin-by-bin using the migration matrix M

$$(A_{new})_i = \sum_j M_{ij}\,(A_{def})_j$$

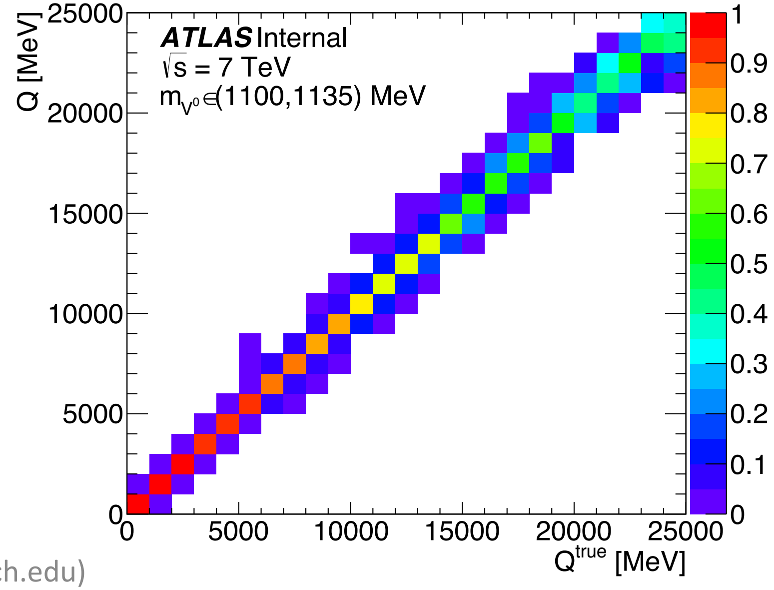
Uncertainty of α parameter

- The value of α is varied up and down by $\sigma_\alpha = 0.013$

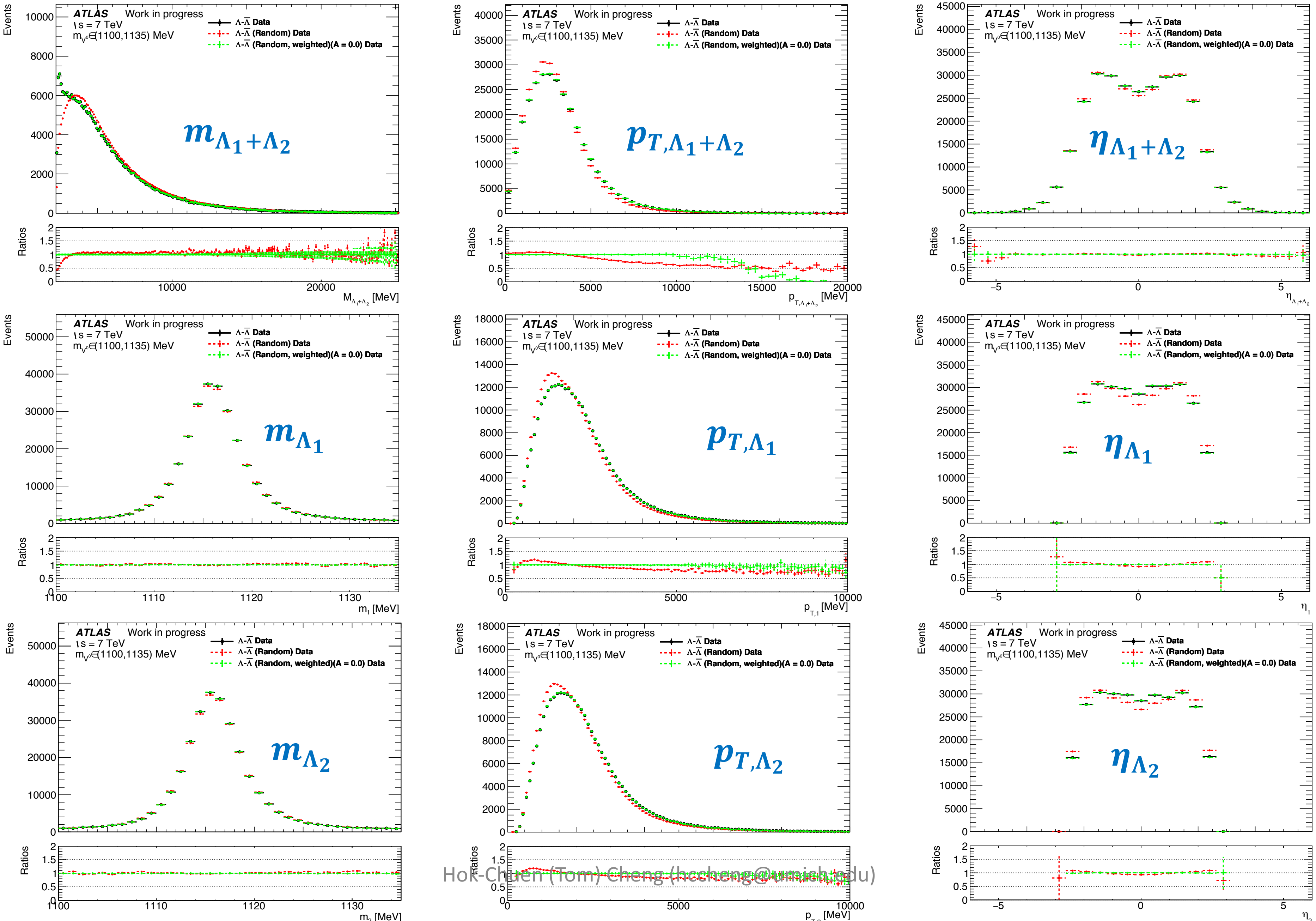
y^{*true} vs y^* (MC)



Q^{true} vs Q (MC)



Backup: Kinematics of $\Lambda\bar{\Lambda}$ (before vs after KW)



Backup: Kinematics of $\Lambda\Lambda+\bar{\Lambda}\bar{\Lambda}$ (before vs after KW)