Longitudinal and transverse spin transfer to Λ and $\bar{\Lambda}$ hyperons in p+p collisions at STAR

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for the STAR Collaboration

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What is special with Λ ?

- Λ polarization can be measured in experiment via weak decay:

Λ->pπ^-(Br ~64%), Λ->nπ^0(Br ~36%) ,

-T.D.Lee, C.N.Yang(1957)

$$\frac{dN}{d\Omega} \propto 1 + \alpha\,(\vec{P}_\Lambda \cdot \hat{p}_p^*)$$

Unit vector along proton momentum in Λ's rest frame. $\vec{P}_\Lambda \cdot \vec{p}_p^* = P_\Lambda \cos\theta^*$

decay parameter: 0.642(pπ^-)

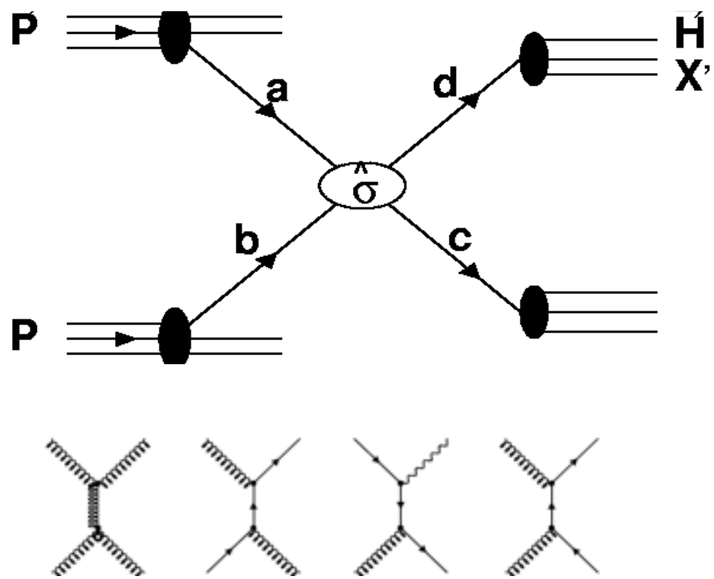
Λ polarization vector

- Λ's contain a strange constitute quark, whose spin is expected to carry most of the Λ spin: $|\Lambda^\uparrow\rangle = (ud)_{00}\, s^\uparrow$

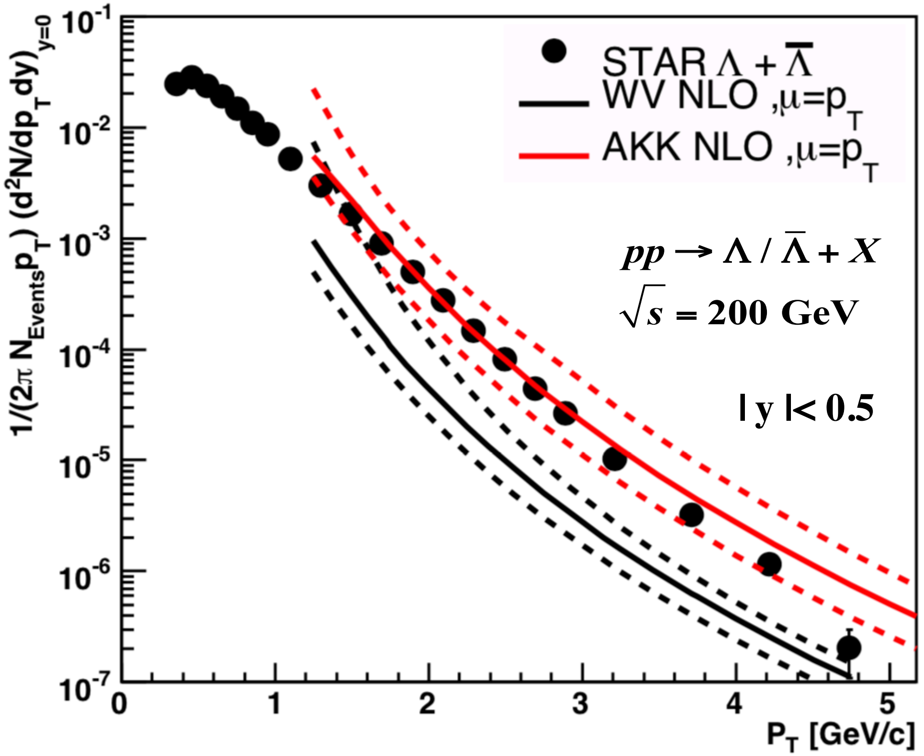
Λ spin ~ *s* quark's spin

Hyperon production in p+p collisions

- Perturbative description of inclusive hyperon production in p+p within factorized framework:



$$d\sigma \propto \int f_a(x_1)\cdot f_b(x_2)\otimes d\hat{\sigma}\otimes D^{\Lambda}(z)$$



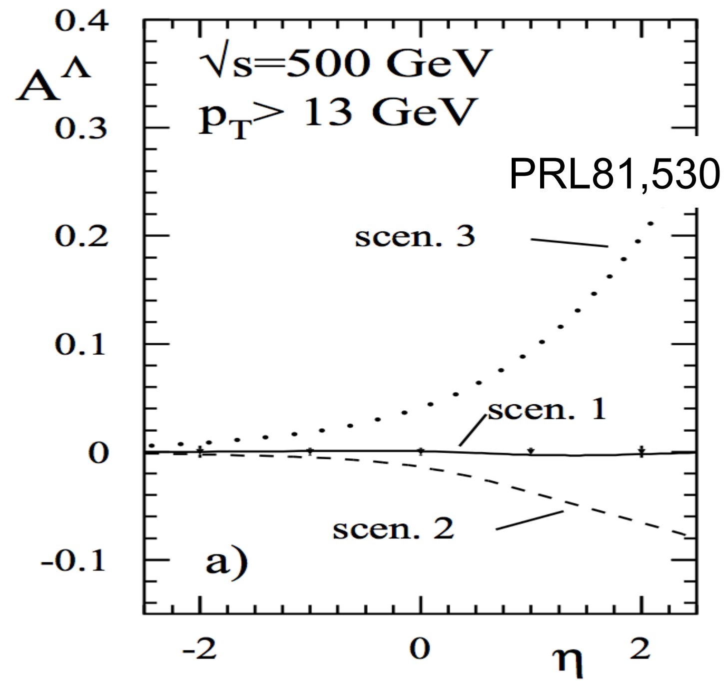
-STAR: PRC 75 (2007) 064901

Longitudinal spin transfer D_{LL} predictions in p+p

- Longitudinal spin transfer D_{LL} provides access to helicity distribution Δf and polarized fragmentation function ΔD:

$$D_{LL} \equiv \frac{\sigma_{p^+ p \to \bar{\Lambda}^+ X} - \sigma_{p^+ p \to \bar{\Lambda}^- X}}{\sigma_{p^+ p \to \bar{\Lambda}^+ X} + \sigma_{p^+ p \to \bar{\Lambda}^- X}} = \frac{d\Delta\sigma}{d\sigma}$$

$$d\Delta\sigma \propto \int \Delta f_a(x_1) \cdot f_b(x_2) \otimes d\Delta\hat{\sigma} \otimes \Delta D^{\Lambda}(z)$$



PRL81,530

- D_{LL} predictions in pp with modeling Pol. Frag. Function:

D.de Florian, M.Stratmann, and W.Vogelsang, PRL81, 530(1998)

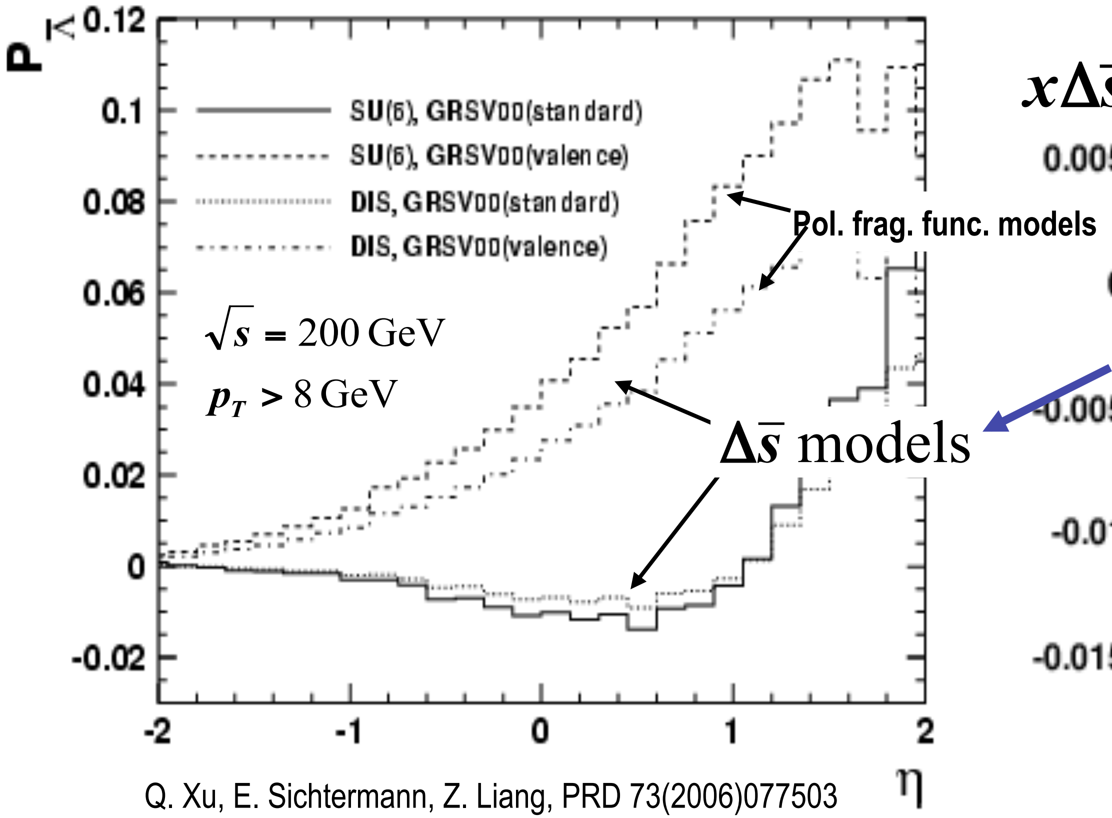
C. Boros, J.T.Londergan, A.W.Thomas, Phys. Rev. D62 (2000)

B.Q. Ma, I.Schmidt, J.Soffer, J.J.Yang, Nucl. Phys. A703 (2002)

Q. Xu, C.X. Liu, Z.T. Liang, Phys. Rev. D65, 114008 (2002).

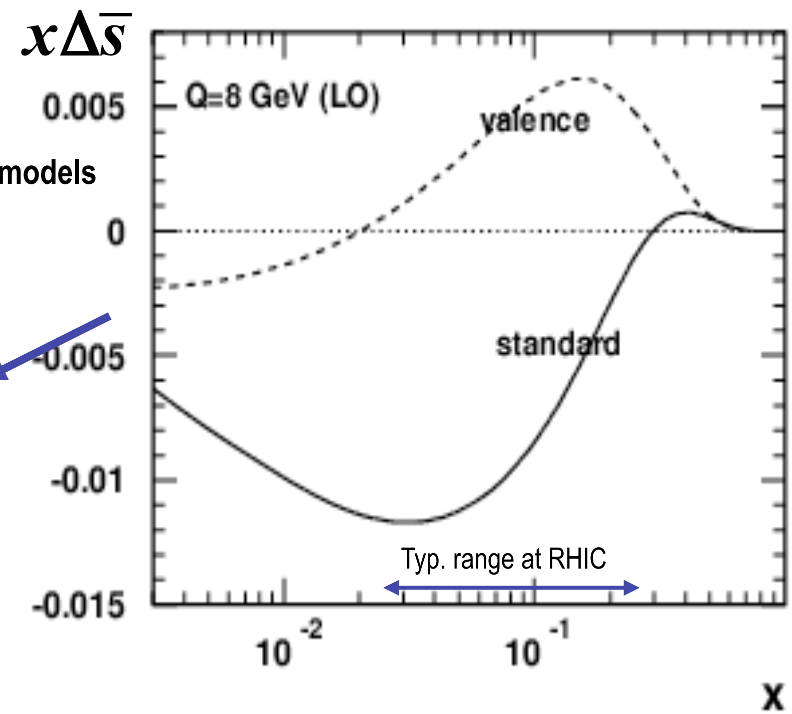
D_{LL}-Longitudinal spin transfer at RHIC

- Expectations at LO show sensitivity of D_{LL} for anti-Lambda to $\Delta\bar{s}$:



Q. Xu, E. Sichtermann, Z. Liang, PRD 73(2006)077503

GRSV00-M.Gluck et al, Phys.Rev.D63(2001)094005

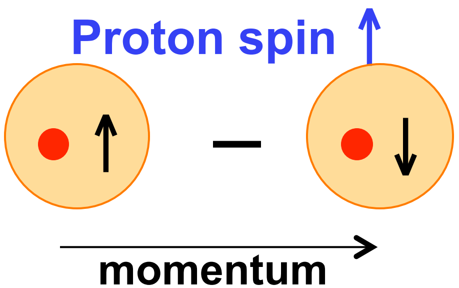


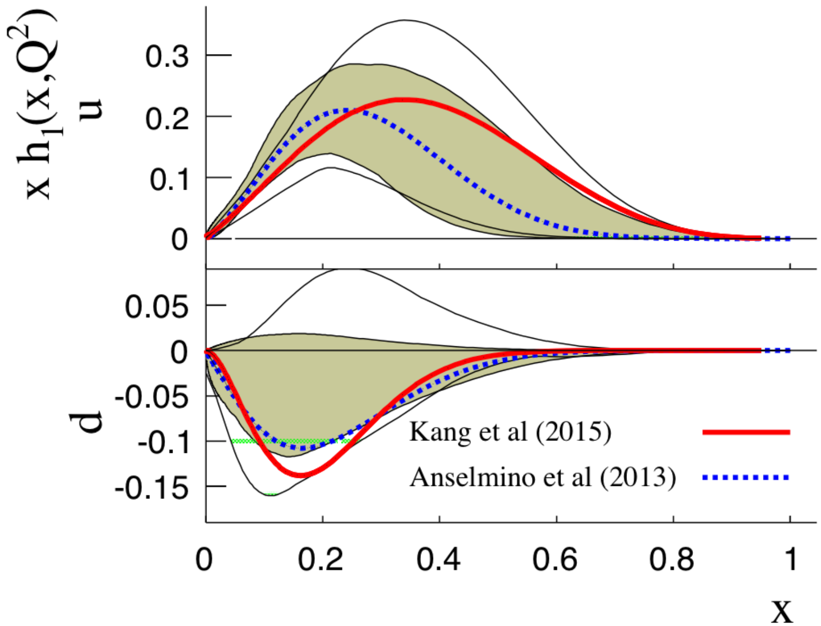
- Λ D_{LL} is less sensitive to Δs, due to large u,d quark fragmentation.
- $\bar{\Lambda}$ Promising measurements for anti-strange quark polarization.

Transverse spin structure of nucleon

- Transversity- least known pdf among 3 leading twist pdfs.

$$\delta q(x,Q^2) = q^{\uparrow}(x,Q^2) - q^{\downarrow}(x,Q^2)$$



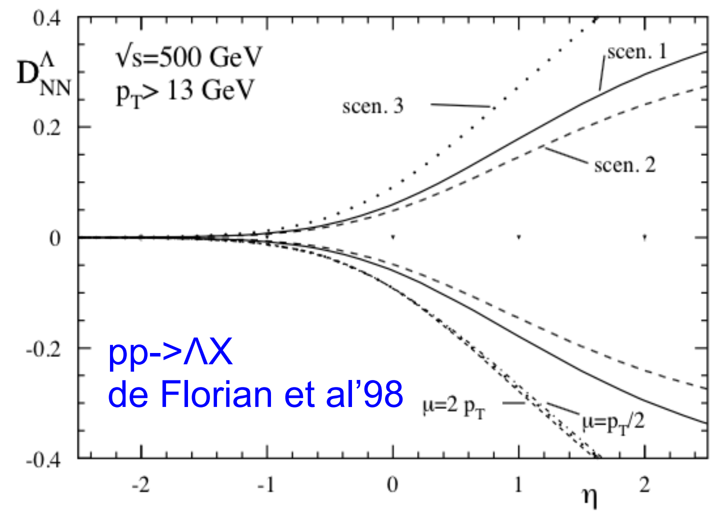


- Transversity involves helicity flip, thus no access in inclusive DIS process.

- Possible experimental measurements on $\delta q(x)$:
  - Via Collins function (SIDIS, p+p), di-hadron production (SIDIS and p+p)
    Several Global fits available: Anselmino et al’13, Kang et al’15, M. Radici et al’18
  - Transversely polarized Drell-Yan process
  - Transverse spin transfer to hyperons (DIS, p+p)

Transverse spin transfer of hyperons and δq(x)

- Transverse spin transfer of hyperons provide access to transversity and transversely pol. frag. function:



$$D_{TT} \equiv \frac{d\sigma^{(p^{\uparrow}p \to H^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p \to H^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p \to H^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p \to H^{\downarrow}X)}} = \frac{d\Delta_T\sigma}{d\sigma}$$

$$d\Delta_T\sigma^{(pp\to HX)} \propto \sum_{abcd} \int dx_a\, dx_b\, dz\, \delta f_a(x_a) f_b(x_b) \Delta_T D_c^H(z) d\Delta_T\hat{\sigma}^{(ab\to cd)}$$

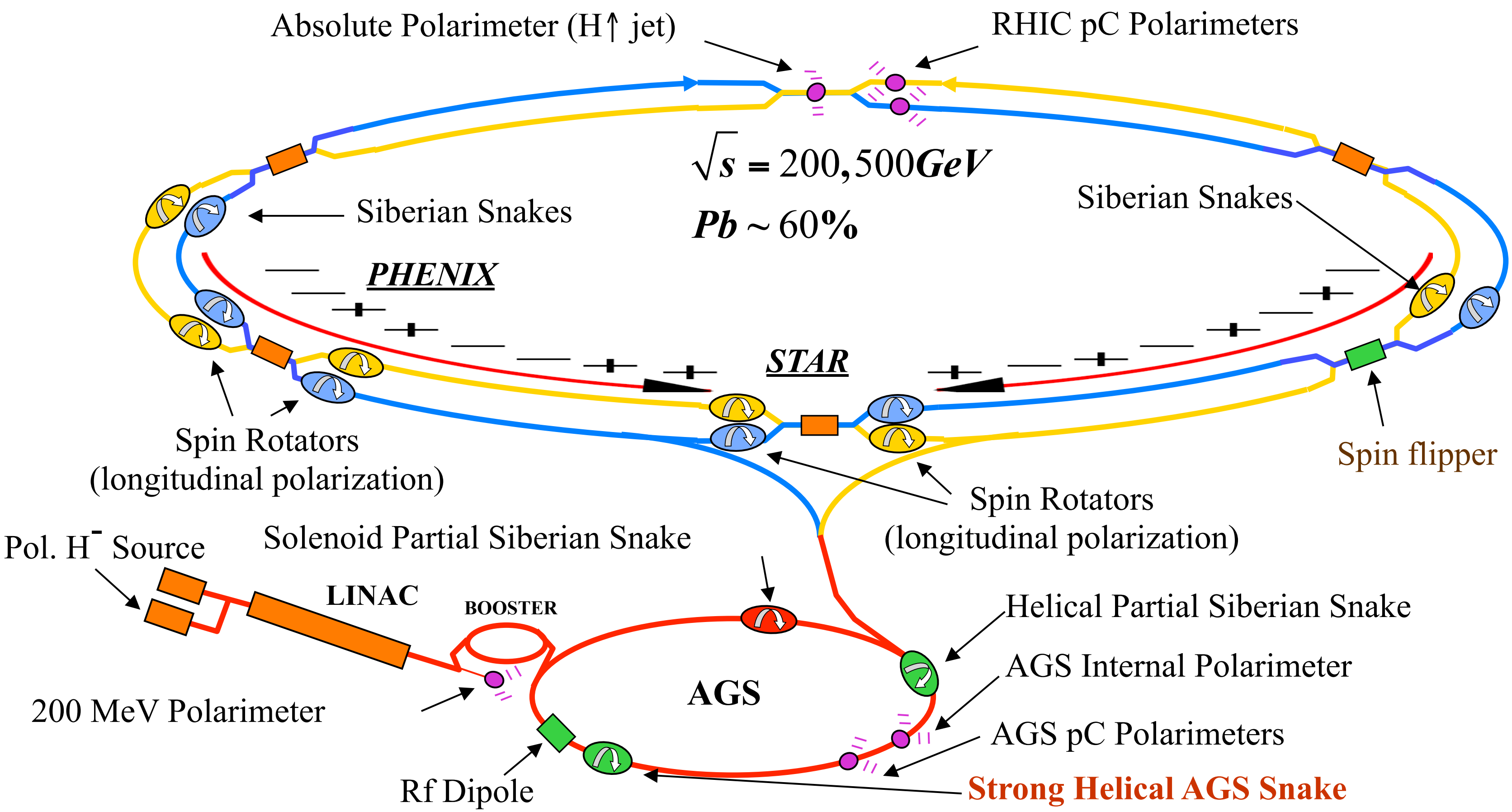
transversity distribution

Transversely polarized fragmentation function

pQCD

- D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB439, 176 (1998).
- Q. Xu , Z. T. Liang, PRD70, 034015 (2004).
- Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

RHIC- a polarized proton+proton collider



- ✓ Data sample I: longitudinally polarized p+p collisions at 200GeV with STAR in 2009, ~19pb^{-1}, beam polarization ~57%. -> D_{LL}
- ✓ Data sample II: transversely polarized p+p collisions at 200GeV with STAR in 2012, ~18pb^{-1}, beam polarization ~61%. -> D_{TT}

STAR - Solenoid Tracker At RHIC

Magnet

- 0.5 T Solenoid

Triggering & Luminosity Monitor

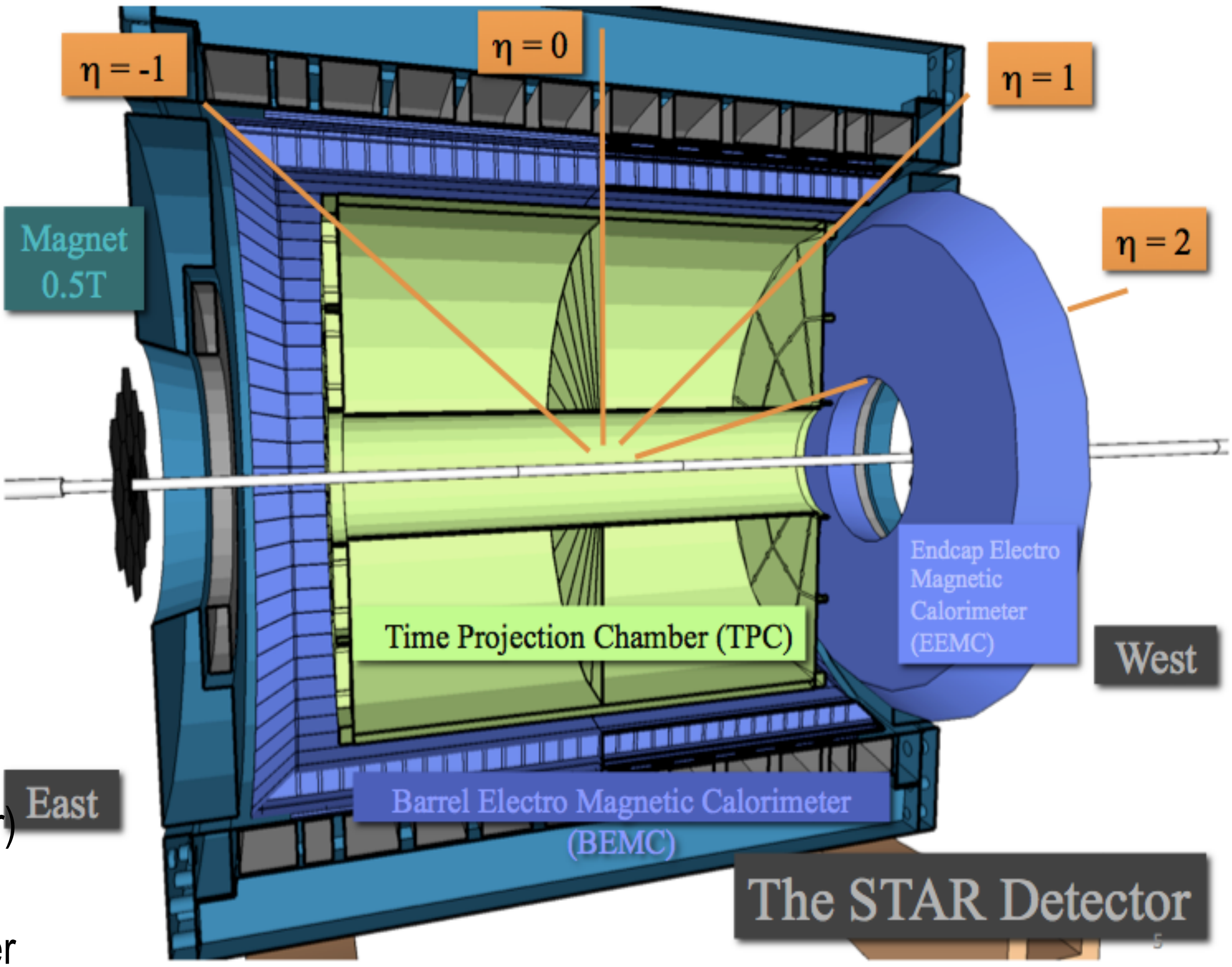
- Beam-Beam Counters
  - $3.4 < |\eta| < 5.0$
- Zero Degree Calorimeters
- Vertex Position Detector

Central Tracking

- Large-volume TPC
  - $|\eta| < 1.3$

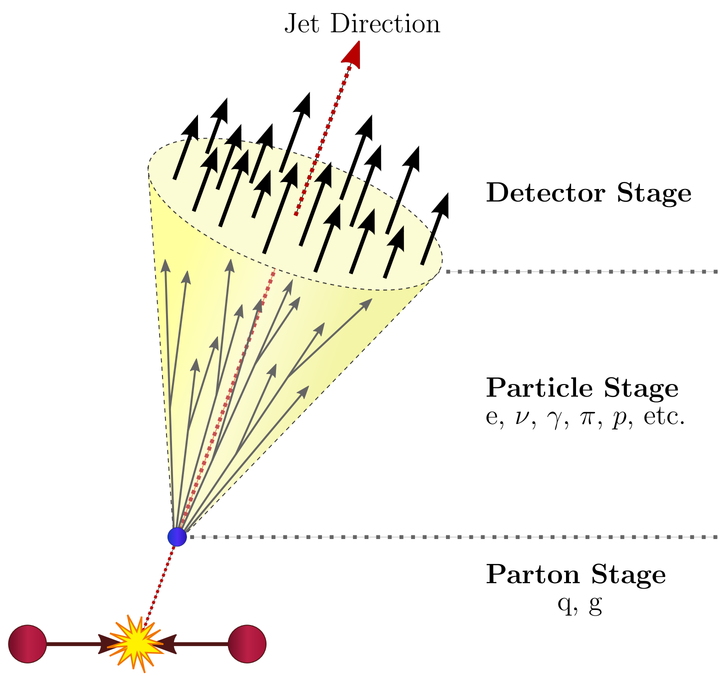
Calorimetry

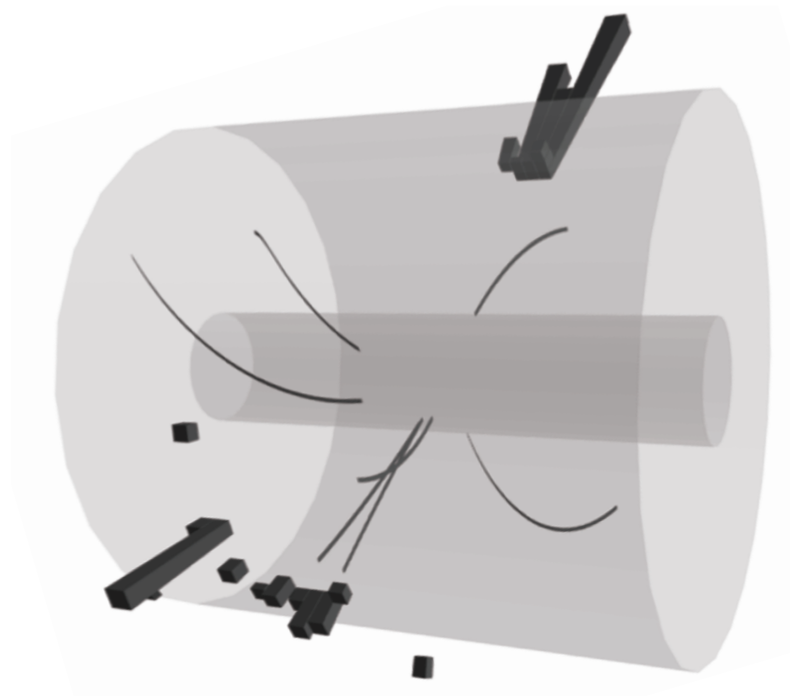
- Barrel EMC (Pb/Scintilator)
  - $|\eta| < 1.0$
- Endcap EMC (Pb/Scintillator)
  - $1.0 < \eta < 2.0$
- Forward Meson Spectrometer
  - $2.5 < \eta < 4.0$



STAR triggered data – 2009 & 2012

- STAR was triggered on energy deposits in jet-patches (JP) of the Barrel EMC



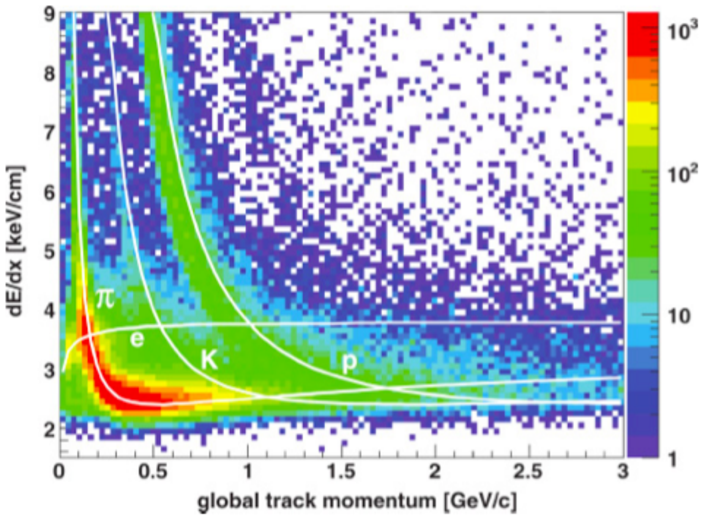


✓ Trigger on high p_T jets → allow to study hard scattering events.

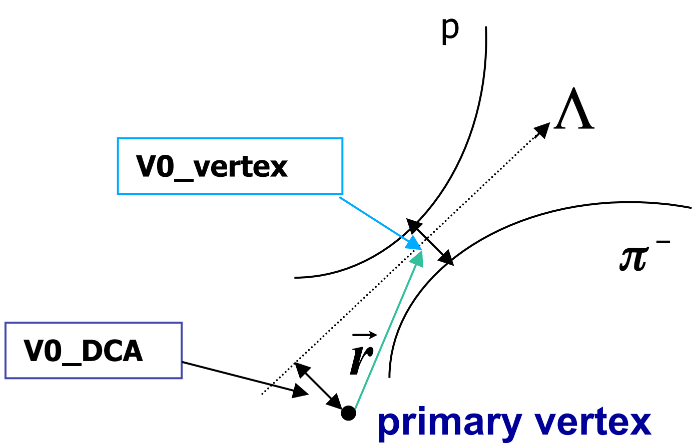
✓ Recorded a (biased) sample of Λ and $\overline{\Lambda}$ candidates with considerably higher p_T, although not directly triggered.

Hyperon reconstruction at STAR (2009)

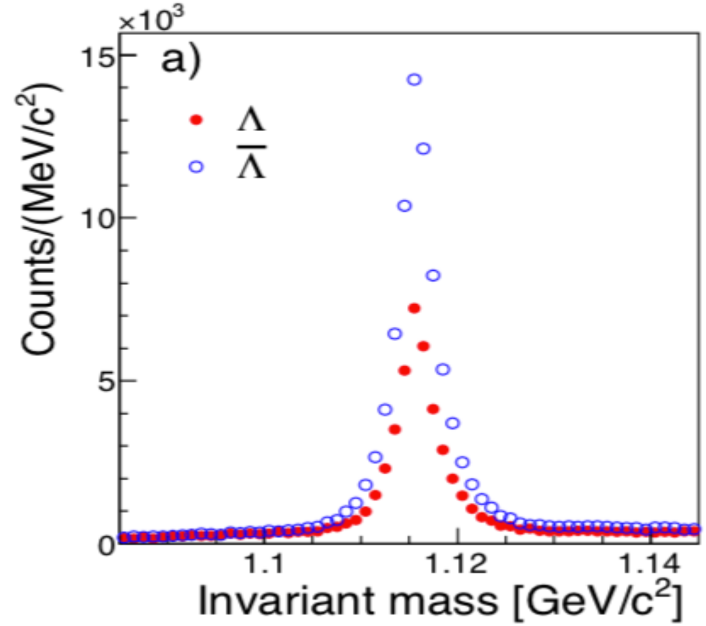
Time Projection Chamber enables PID

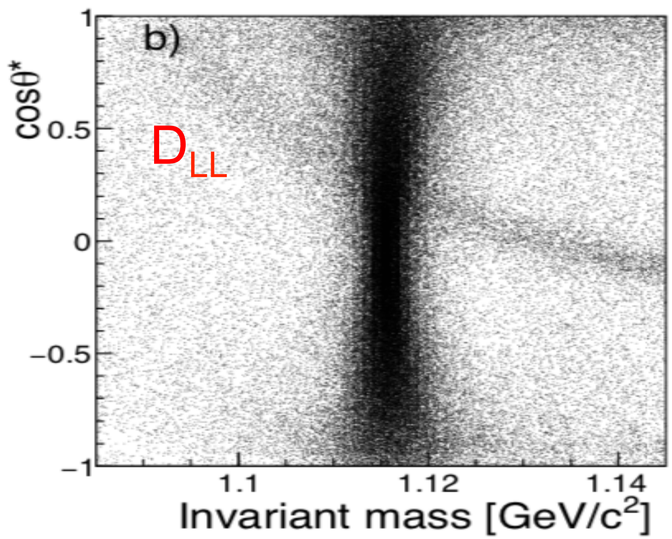


Plus topological reconstruction:



for |η|<~1.2

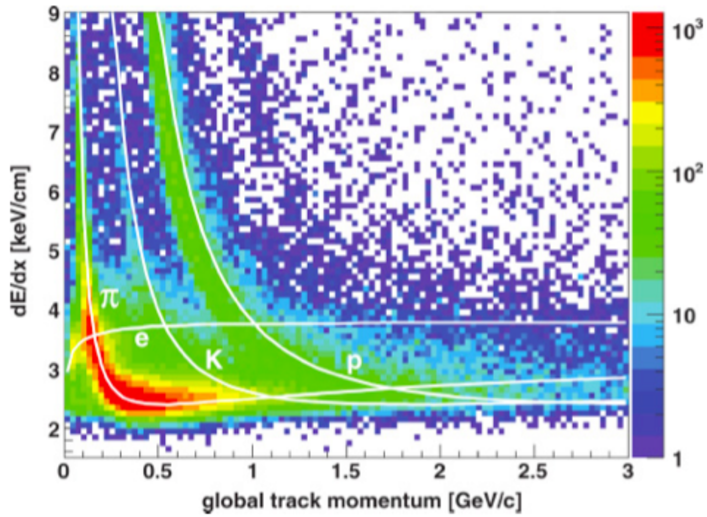


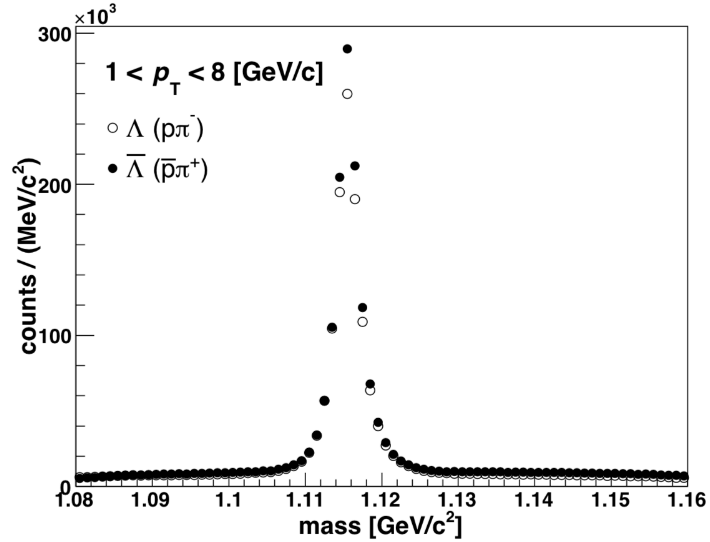


(2<p_T<3 GeV, 2009 data)

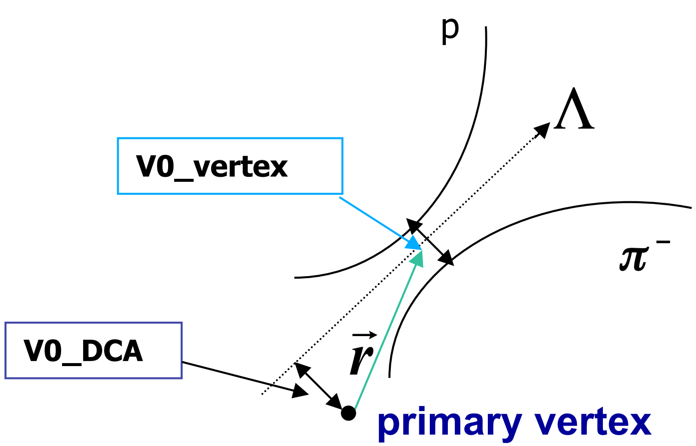
Hyperon reconstruction at STAR (2012)

Time Projection Chamber enables PID

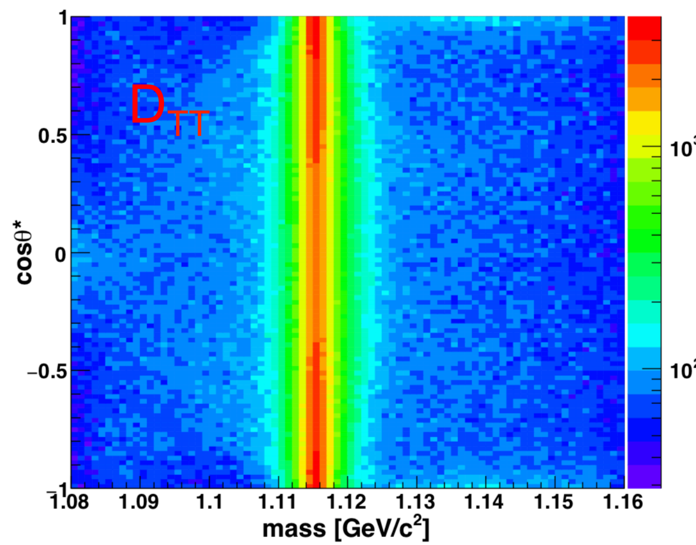




Plus topological reconstruction:



for |η|<~1.2



(1<p_T<8 GeV, 2012 data)

Extraction of spin transfer D_{LL}

- Λ polarization is usually extracted from the angular distribution of its weak decay ($\Lambda \to p\pi^-$):

$$dN = \frac{N_{tot}}{2} A(\cos\theta^*)(1+\alpha P_\Lambda \cos\theta^*)$$

$$\cos\theta^* \propto \vec{P}_\Lambda \cdot \vec{p}_p^{\,*}$$

α: decay parameter: 0.642
A(cosθ*): detector acceptance

- D_{LL} has been extracted from Λ counts with opposite beam polarization within a small interval of cosθ*:

-STAR, hep-ex/0512058

$$D_{LL} = \frac{1}{\alpha \cdot P_{beam} < \cos\theta^* >} \cdot \frac{N^+ - N^-}{N^+ + N^-}$$

, where the acceptance cancels.

$$N_\Lambda^+ = N^{++} \frac{L_{--}}{L_{++}} + N^{+-} \frac{L_{--}}{L_{+-}}$$

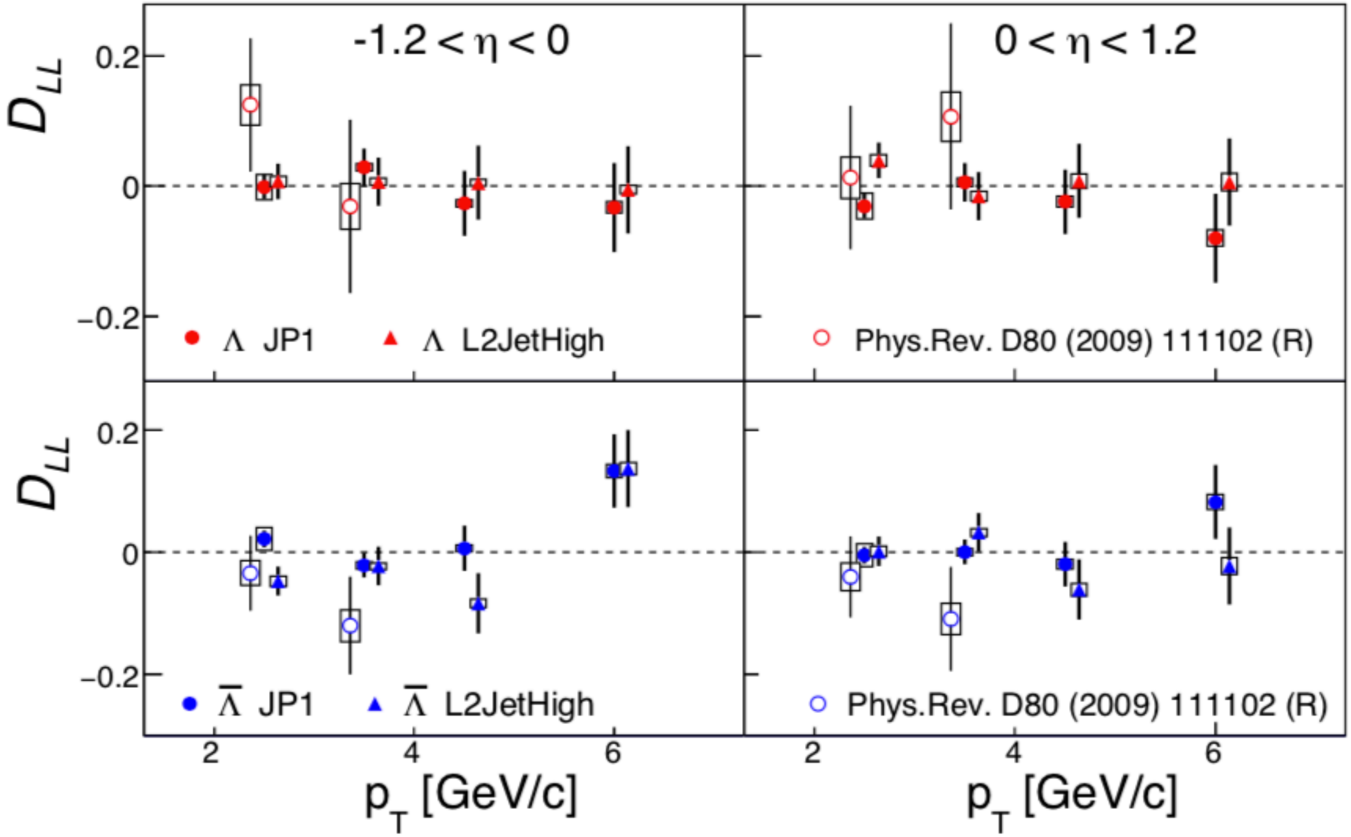
$$N_\Lambda^- = N^{-+} \frac{L_{--}}{L_{-+}} + N^{--}$$

Relative luminosity ratio measured with BBC, and P_{beam} in RHIC.

D_{LL} Results of STAR with Data-2009

- Improved D_{LL} measurements from STAR 2009 data:

  -STAR, arXiv: 1808.07634

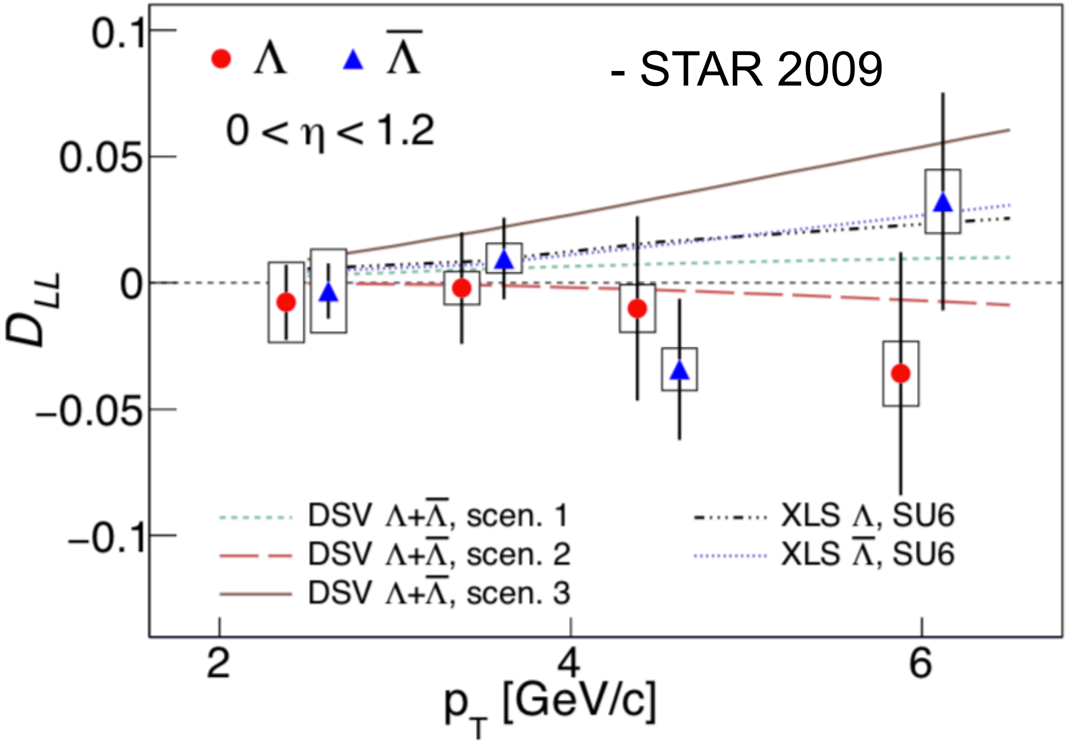


- D_{LL} extended to p_T ~5.9 GeV with ~4% precision, compared to 8% at 3.7 GeV for 2005 data.

D_{LL} Results of STAR with Data-2009

- Improved D_{LL} measurements from STAR 2009 data:

  -STAR, arXiv: 1808.07634



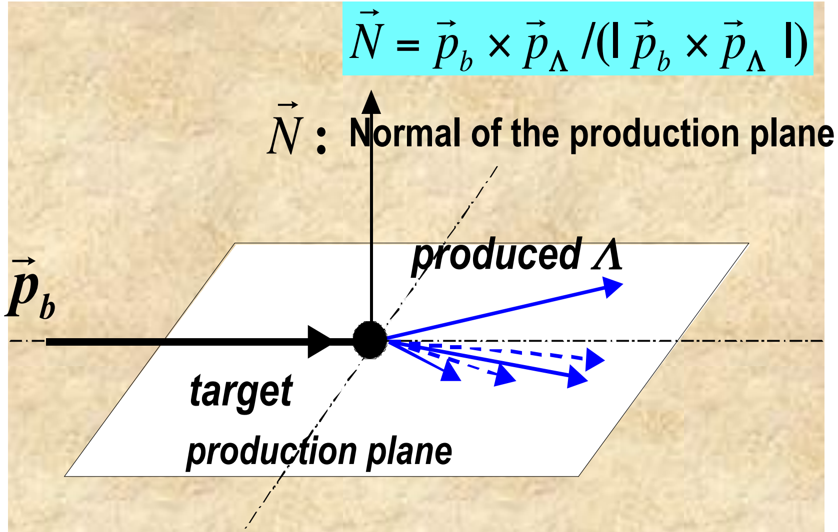
- D.de Florian, M.Stratmann, and W.Vogelsang, PRL81 (1998)530
- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73(2006)077503

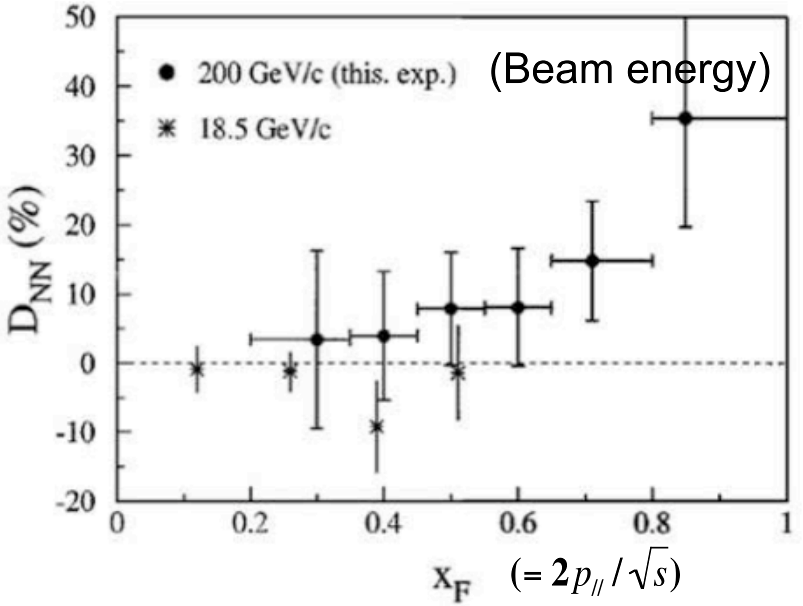
✓ D_{LL} results are still consistent with zero within the uncertainties.

✓ The statistics are similar to the spread of different models.

How to measure transverse spin transfer ?

- Possible measurements on transverse spin transfer:
  - D_{TT} : final state polarization along the pol. of outgoing hard quark (considering the rotation in scattering plane)--- jet correlation
  - D_{NN} : spin transfer w.r.t. production plane
    - precision reduced ~ one half (beam pol. projected to N.)
    - production plane close to hard scattering plane at high p_T
    - in principle D_{TT}=D_{NN}





E704, PRL78, 4003(1997)

Direction of transverse polarization

- Transverse polarization direction - azimuthal angle determination

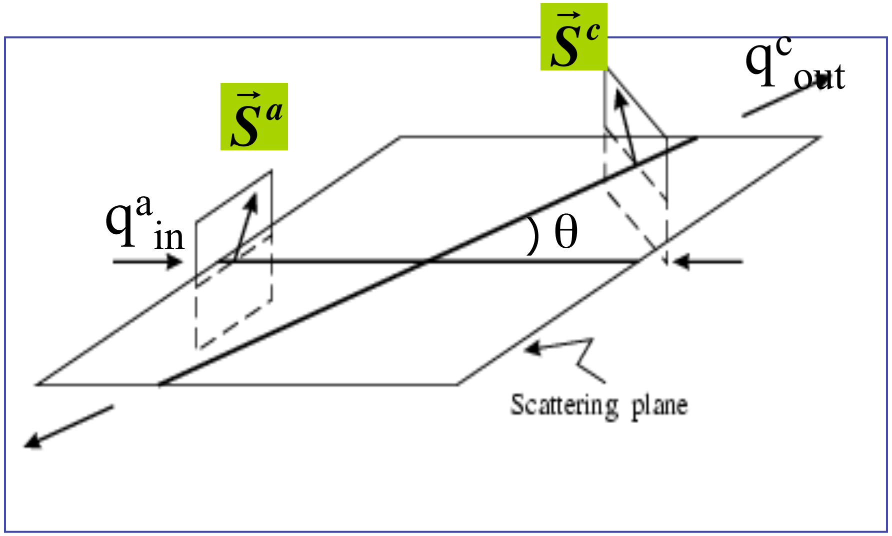
  Helicity density matrix of spin ½ particle (transversely polarized) :

$$\rho^a_{in} = \frac{1}{2}\begin{pmatrix} 1 & P_{aT}e^{-i\phi} \\ P_{aT}e^{i\phi} & 1 \end{pmatrix}$$

P_{aT} : transverse polarization

ϕ: azimuthal angle of pol. vector

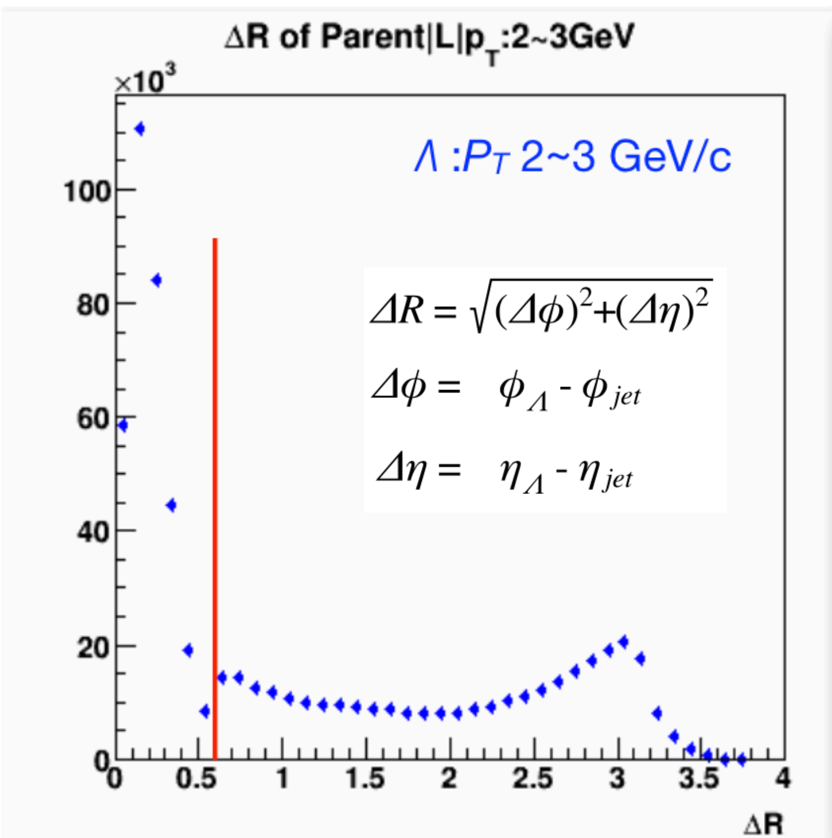
- The direction of transverse polarization is rotated along the normal of scattering plane in partonic scattering:



J.Collins, S.Heppelmann, G.Ladinsky, NPB420 (1994)565

Jet Correlation with hyperons

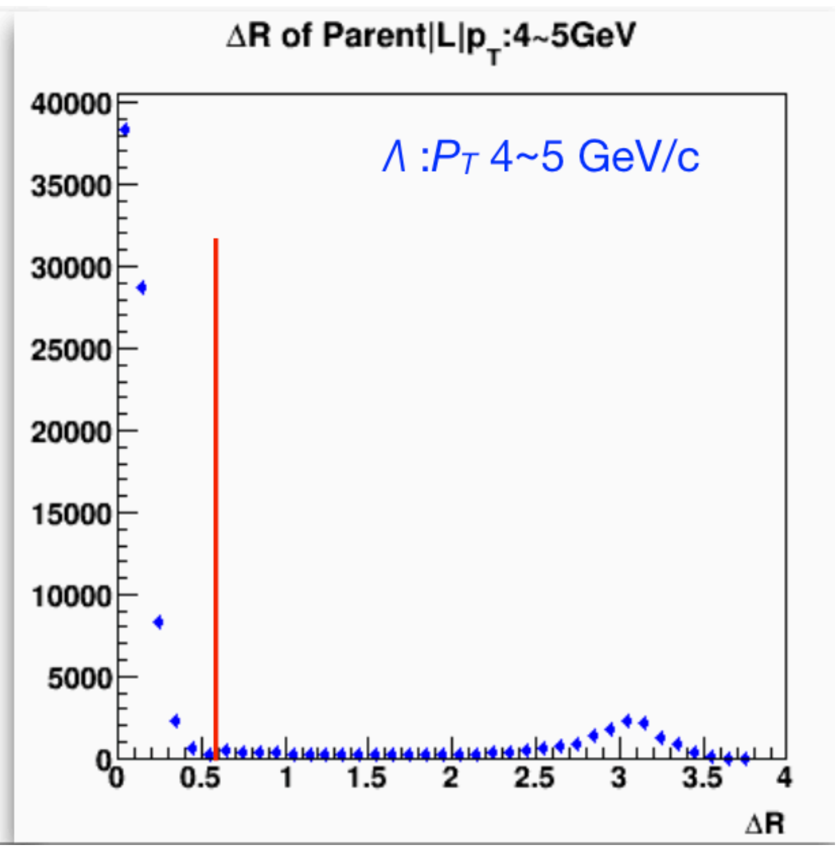
- Anti-Kt algorithm used in jet reconstruction; ΔR is calculated to make correlation between (anti-)Lambda candidate and jet.
- Require η_{jet} ~ (-0.7, 0.9), p_T > 5.0 GeV/c. If $\Delta R < 0.6$ for a hyperon, corresponding jet axis is used as outgoing quark direction to get the quark's transverse polarization direction.



$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

$$\Delta\phi = \phi_\Lambda - \phi_{jet}$$

$$\Delta\eta = \eta_\Lambda - \eta_{jet}$$



Extraction of transverse spin transfer D_{TT}

- D_{TT} is extracted from a cross-ratio asymmetry using Λ counts with opposite beam polarization within a small interval of cosθ* :

-STAR, arXiv: 1808.0800

$$D_{\mathrm{TT}} = \frac{1}{\alpha P_{\mathrm{beam}} \langle \cos\theta^* \rangle} \frac{\sqrt{N^{\uparrow}(\cos\theta^*)N^{\downarrow}(-\cos\theta^*)} - \sqrt{N^{\downarrow}(\cos\theta^*)N^{\uparrow}(-\cos\theta^*)}}{\sqrt{N^{\uparrow}(\cos\theta^*)N^{\downarrow}(-\cos\theta^*)} + \sqrt{N^{\downarrow}(\cos\theta^*)N^{\uparrow}(-\cos\theta^*)}}$$

$N^{\uparrow}$: $\Lambda\,(\bar{\Lambda})$ counts with positive beam polarization
$N^{\downarrow}$: $\Lambda\,(\bar{\Lambda})$ counts with negative beam polarization

P_{beam} : polarization of beam
<cosθ*> : mean in each cosθ* bin

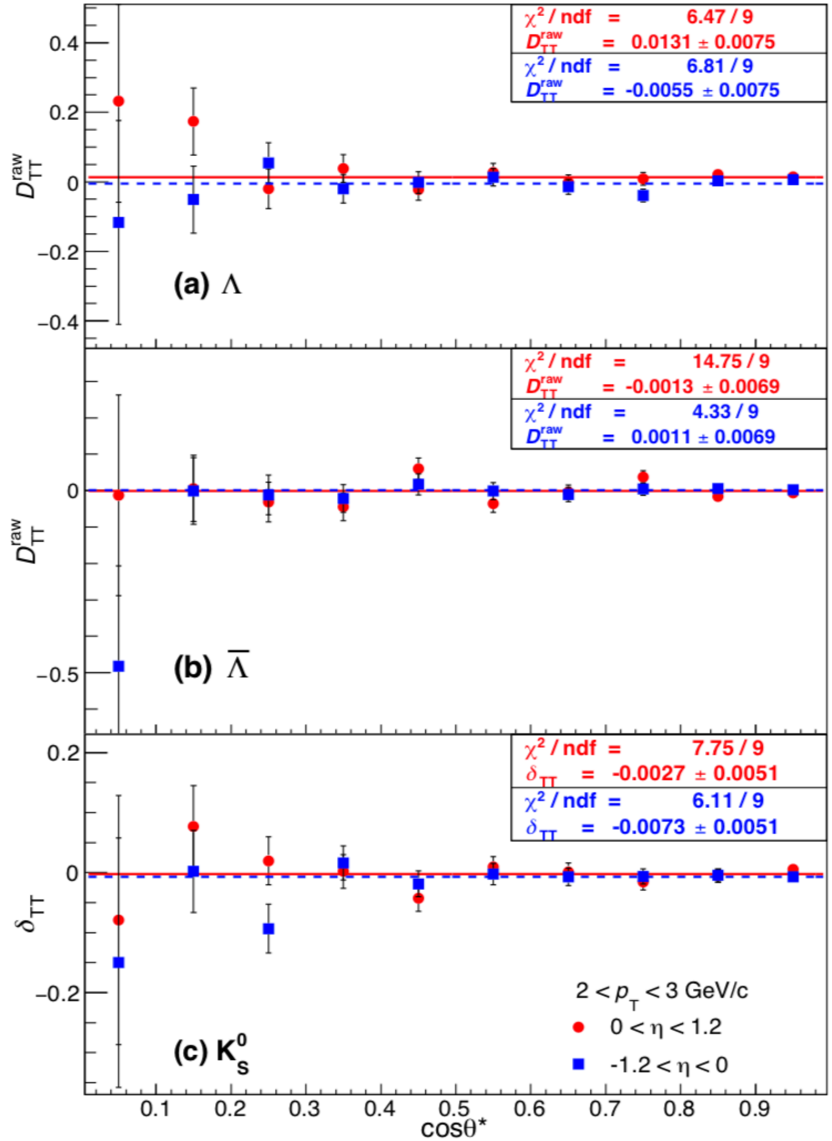
- Acceptance of reverse beam polarization is expected to be the same in each cosθ* bin, thus cancelled
- Luminosity is also cancelled in the cross-ratio asymmetry

Extraction of transverse spin transfer D_{TT}

- Lambda counts versus cosθ*- $N^{\uparrow/\downarrow}(\cos\theta^*)$
- Extract D_{TT} in each cosθ* bin, then average over whole cosθ* range -> $D_{\mathrm{TT}}^{\mathrm{raw}}$
- Background subtraction:

$$D_{\mathrm{TT}} = \frac{D_{\mathrm{TT}}^{\mathrm{raw}} - rD_{\mathrm{TT}}^{\mathrm{bkg}}}{1-r}$$

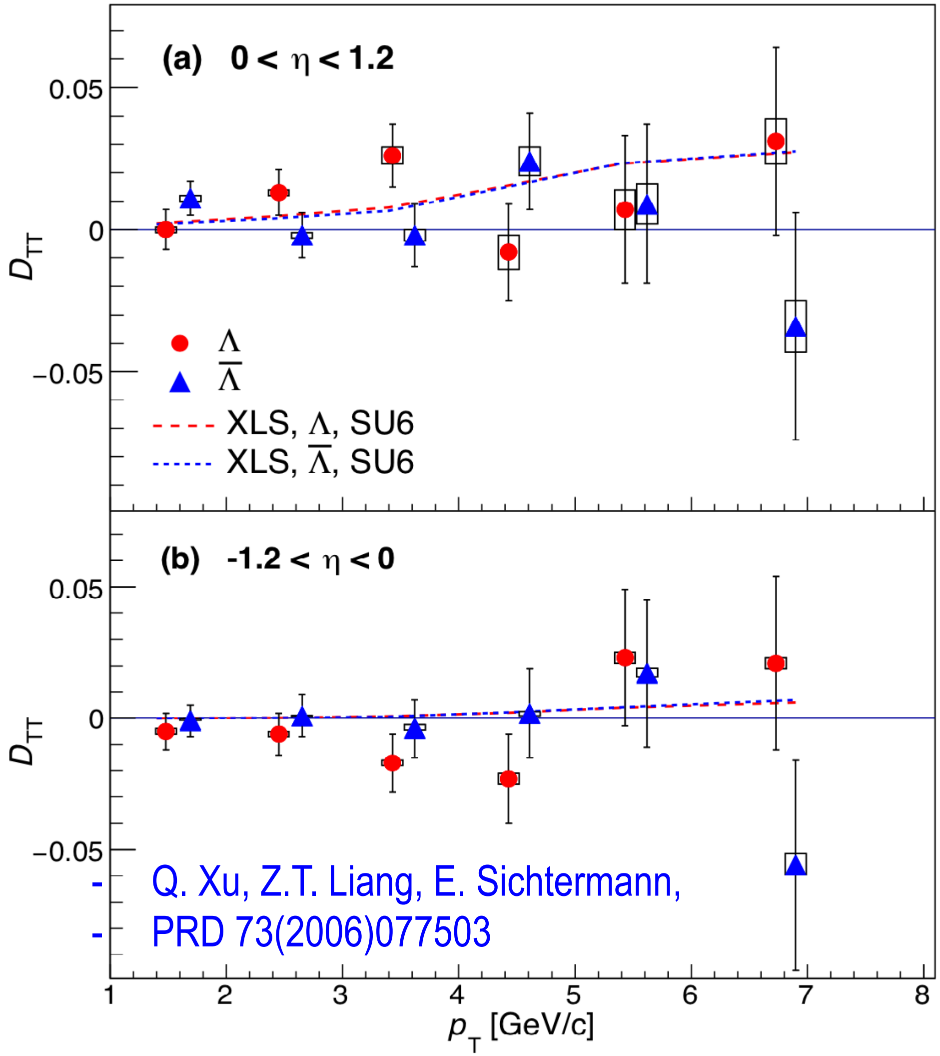
- The method passed the null check with $K_s^0 \to \pi^+ \pi^-$



-STAR, arXiv: 1808.0800

Transverse spin transfer D_{TT} results at STAR

- First D_{TT} measurements in p+p collision at 200 GeV at RHIC:



-STAR, arXiv: 1808.0800

✓ 1st transverse spin transfer measurement in p+p collisions at RHIC.

✓ Most precise measurement on hyperon polarization in p+p collision at RHIC, which reach p_T ~6.7 GeV/c with statistical uncertainty of 0.04.

$<p_T>$=6.7 GeV and $<\eta>$= 0.5:

$$D_{TT}(\Lambda) = 0.031 \pm 0.033(stat) \pm 0.008(sys)$$

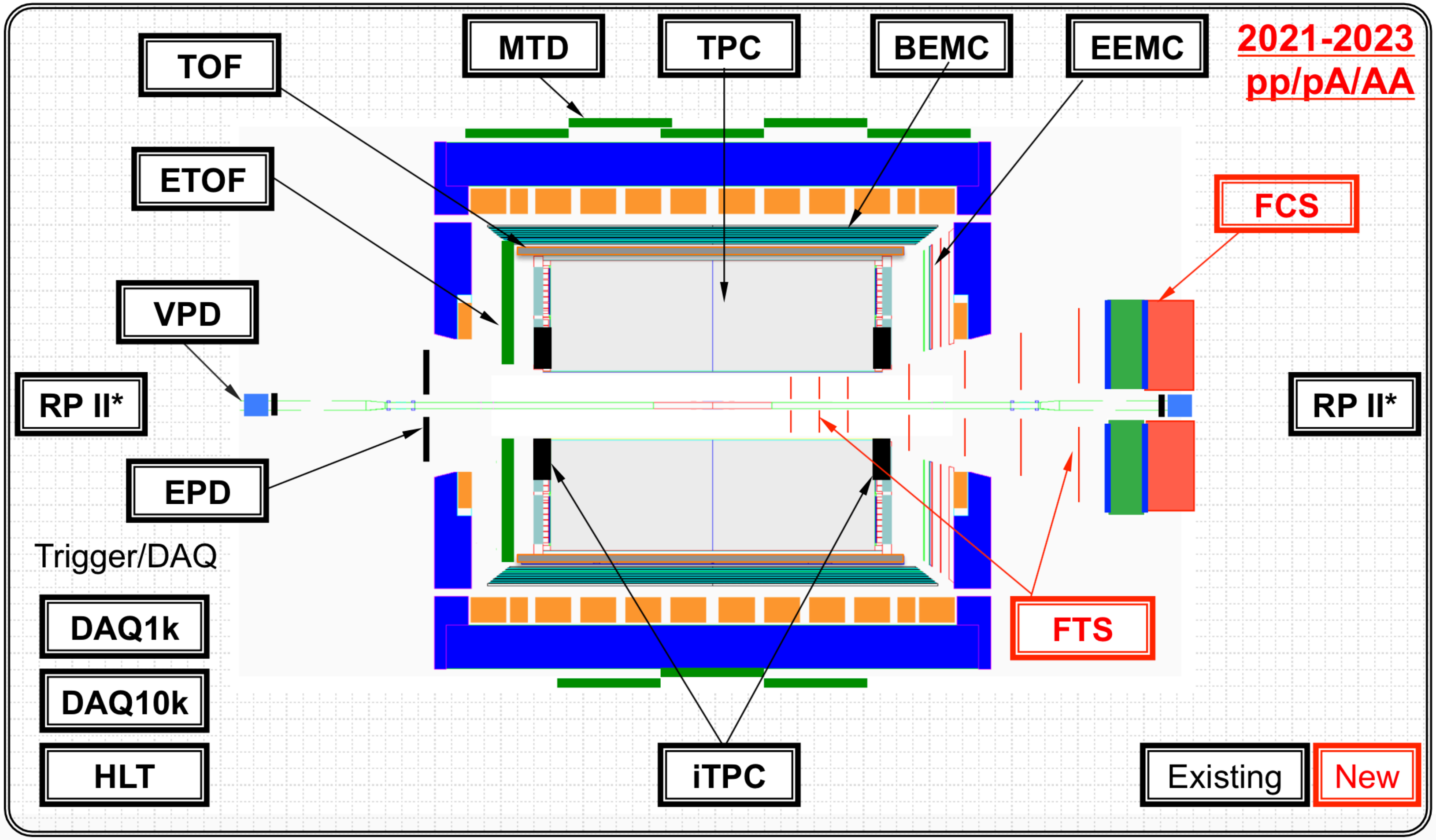
$$D_{TT}(\bar{\Lambda}) = -0.034 \pm 0.040(stat) \pm 0.009(sys)$$

✓ D_{TT} of $\Lambda / \bar{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

Forward Λ physics with STAR forward upgrade

- STAR forward detector upgrade enables forward Λ reconstruction:
  - with forward tracking system and forward calorimeter system in 2021*

-STAR upgrade talk by Ken Barish (Sep. 12)



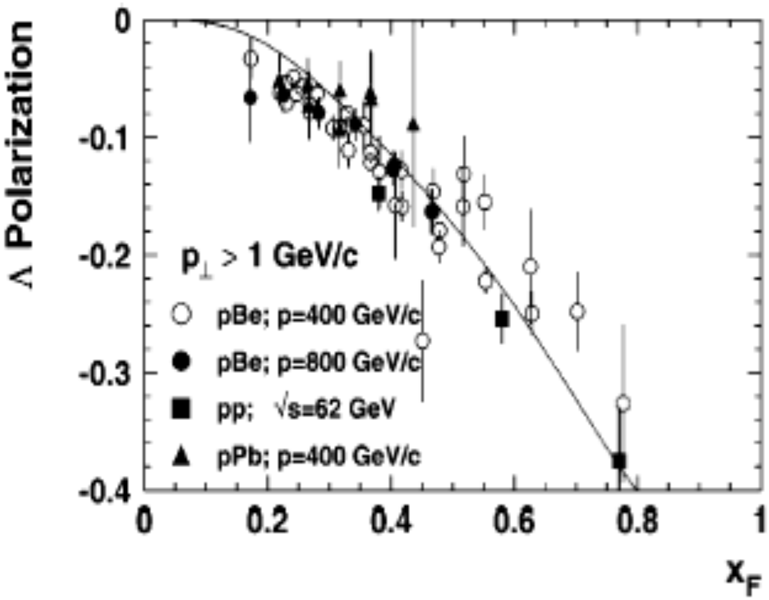
* FTS: Forward Tracking System; FCS: Forward Calorimeter System

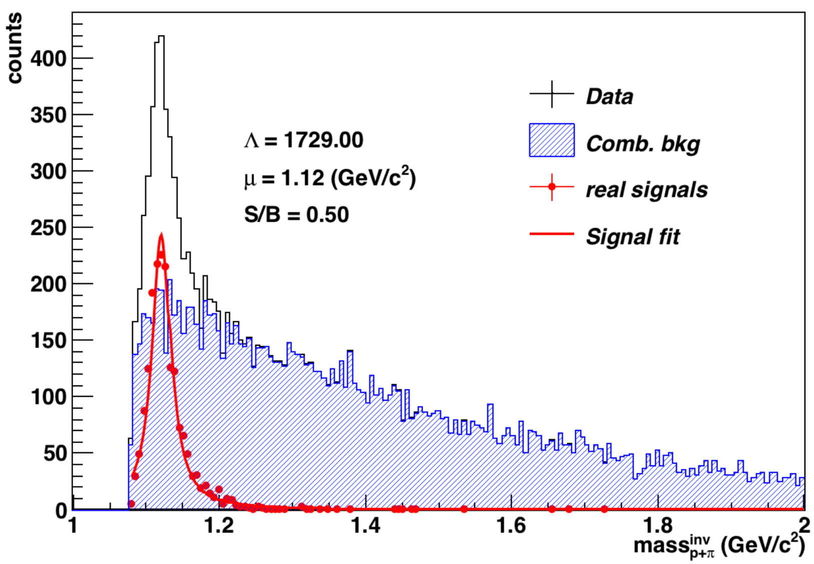
Forward Λ physics with STAR forward upgrade

- STAR forward detector upgrade enables forward Λ reconstruction:
  - with forward tracking system and forward calorimeter system in 2021^+

✓ Induced polarization in unpolarized p+p collision at large x_F

✓ Sizable spin transfer in both longitudinal and transverse polarized p+p in the forward region : D_{LL} & D_{TT}





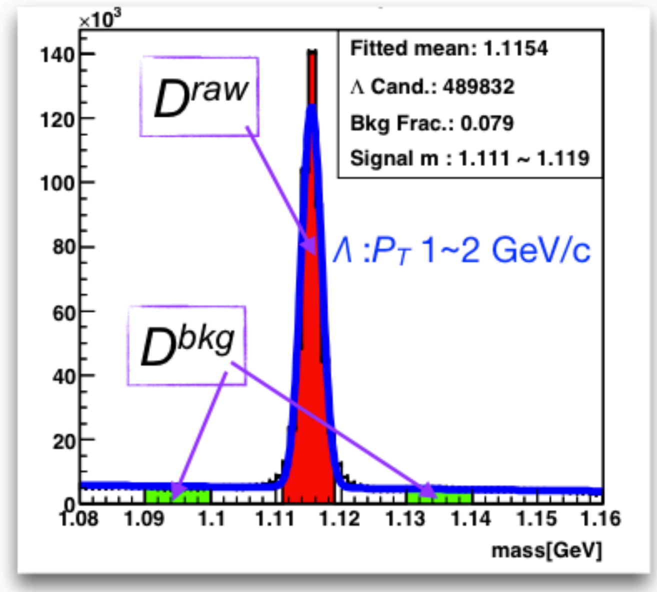
- Simulation of forward Λ reconstruction with FCS+FTS in p+p at STAR

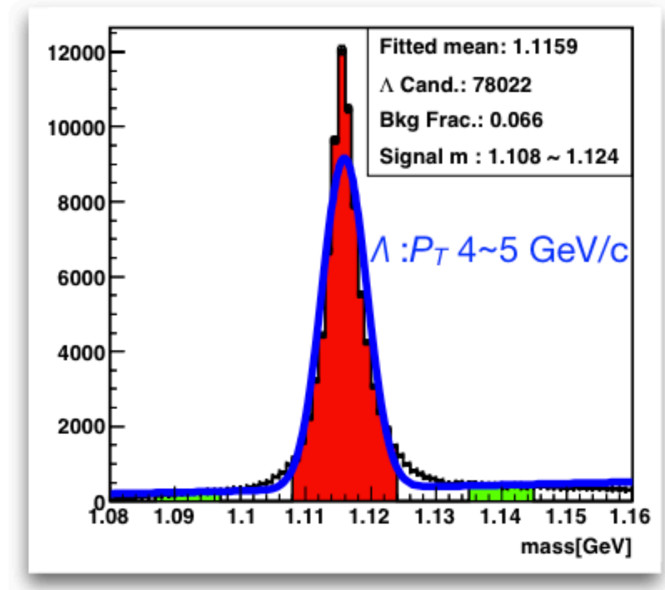
Summary and Outlook

- Improved measurement on longitudinal spin transfer D_{LL} in pp for $\Lambda / \bar{\Lambda}$ at STAR, related to strange quark polarization (Δs) at high p_T .
- First measurement of $\Lambda / \bar{\Lambda}$ transverse spin transfer (D_{TT}) in pp collisions at RHIC, sensitive to transversity and transversely polarized fragmentation function.
- Both D_{LL} and D_{TT} results are comparable to model calculation and also consistent with zero at current precision.
- STAR p+p data taken in 2015 are two times larger, and better D_{TT} and D_{LL} precision is expected.
- STAR forward detector upgrade enables rich forward Λ physics, by reconstructing Λ's with forward tracking system and forward calorimeter system in 2021^+ at STAR.

Backup

- Λ and $\bar{\Lambda}$ are reconstructed via decay channels to (anti-)proton and pion:





- Residual backgrounds are subtracted with D_{TT} extraction:

$$D_{TT} = \frac{D_{TT}^{raw} - rD_{TT}^{bkg}}{1-r}$$

$$\delta D_{TT} = \frac{\sqrt{(\delta D_{TT}^{raw})^2 + \left(r\delta D_{TT}^{bkg}\right)^2}}{1-r}$$

- r: the residual background fraction, estimated with side-band method, <10%