Hyperon($\Lambda, \overline{\Lambda}, \Sigma^+$) polarization and spin alignment of vector meson in polarized pp collisions at RHIC

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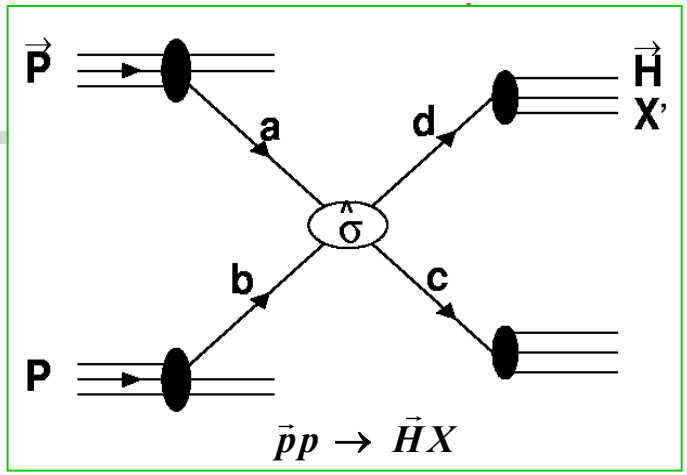
RHIC II spin workshop, BNL, October 8, 2005

- Introduction
- Measurement of Lambda polarization in pp collisions at STAR
- Discussion on future measurements (Σ^+, Vector meson)
- Summary

Introduction



- Λ production in longi. polarized pp collisions:

$$d\Delta\sigma \equiv \sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}$$

$$\frac{d^2\Delta\sigma}{dp_T d\eta} = \sum_{abcd}\int dx_a dx_b dz_c \Delta f_a(x_a,\mu^2) f_b(x_b,\mu^2) \frac{d\Delta\hat{\sigma}^{(ab\to cd)}}{dp_T d\eta} \Delta D_c^H(z_c,\mu^2)$$

helicity distribution function: $\Delta f(x) = f_+(x) - f_-(x)$

longitudinally polarized frag. function:

$$\Delta D = D_{c+}^{H+}(z,\mu^2) - D_{c+}^{H-}(z,\mu^2)$$

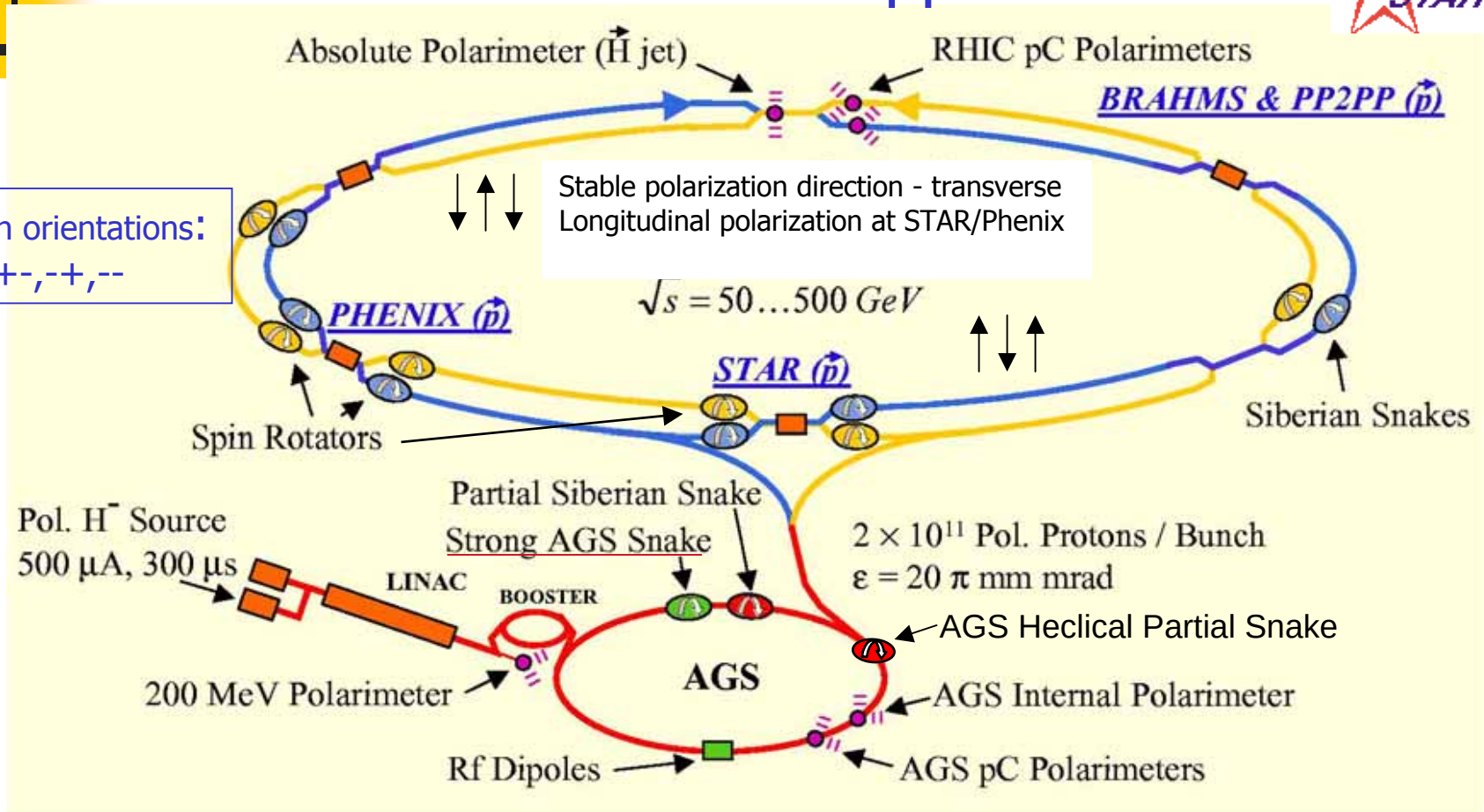
- Measurement of Λ polarization → give new insights into polarized frag. and parton distribution functions.

- Theoretical predictions available:

D.de Florian,M.Stratmann, W.Vogelsang, PRL81(1998)530;
C. Boros, J.T.Londergan, A.W.Thomas, PRD62(2000)014021;
B.Q. Ma, I.Schmidt, J.Soffer, J.J.Yang, NPA703(2002)346;
Xu Q.H., Liu C.X, Liang Z.T., PRD65(2002)114008.

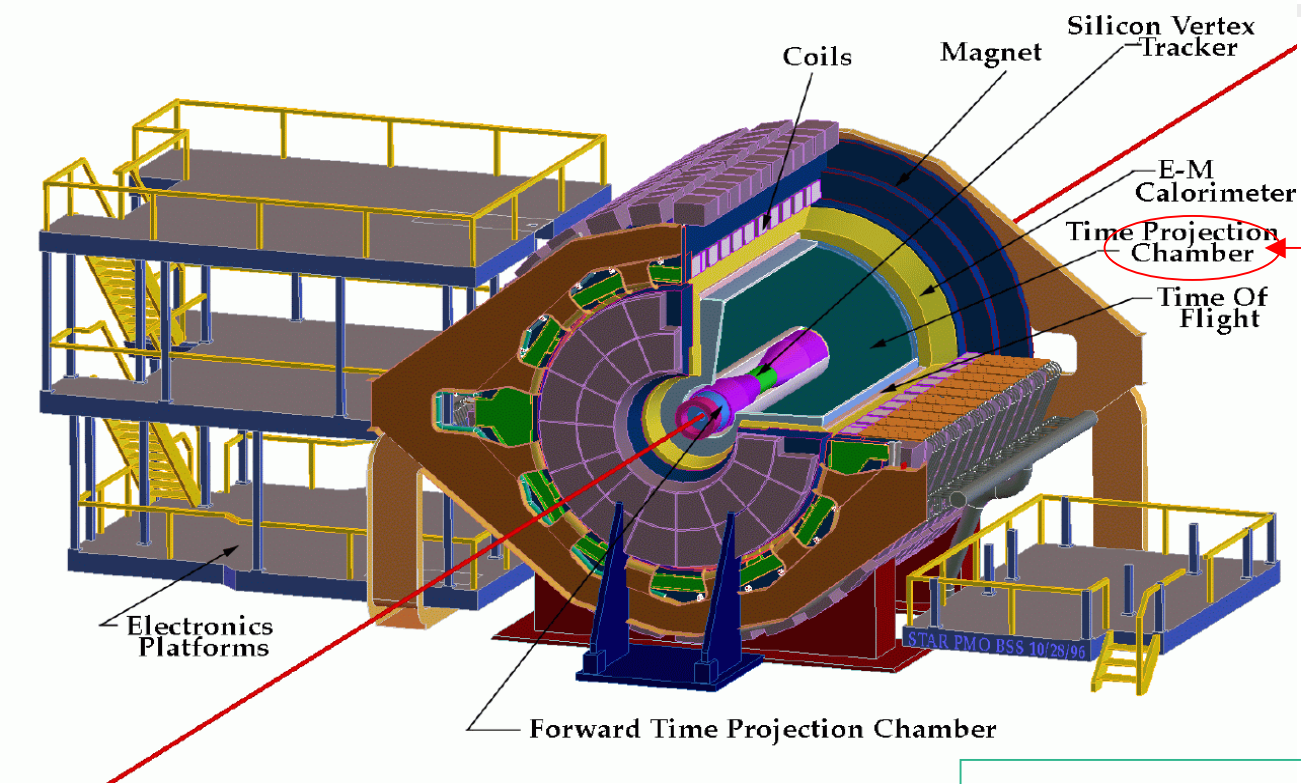
RHIC - First Polarized pp Collider

4 spin orientations:
++,+-,-+,--



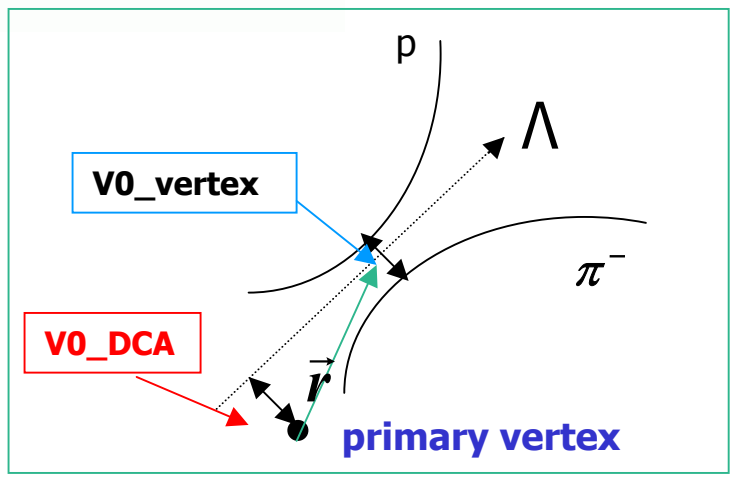
pp Run	2002	2003	2004	2005	> 2006 LongTermGoals	
CM Energy	200 GeV				200 GeV	500 GeV
$\langle P_b \rangle$ and direction at STAR	0.15 T	0.30 T/L	0.40 L	0.45 L	0.7 L/T	0.7 L/T
L_{max} [10^{30} $s^{-1}cm^{-2}$]	2	6	6	16	80	200
L_{int} [pb^{-1}] at STAR	0.3	0.5 / 0.4	0.4	9	320	800

STAR Detector



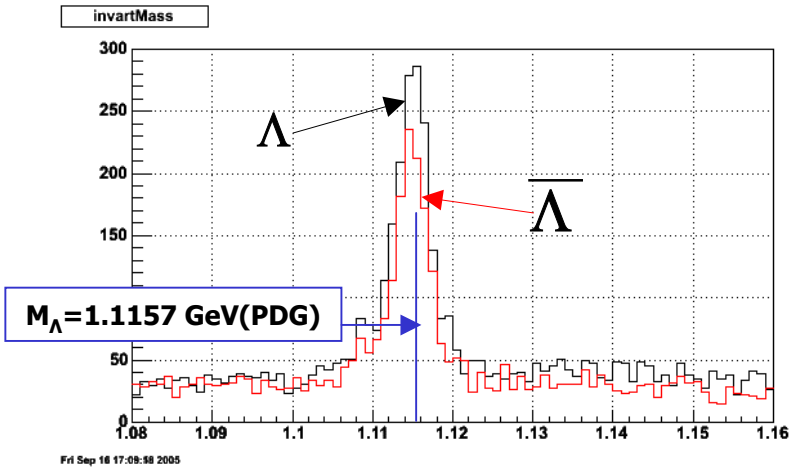
TPC $(|\eta|<1)$

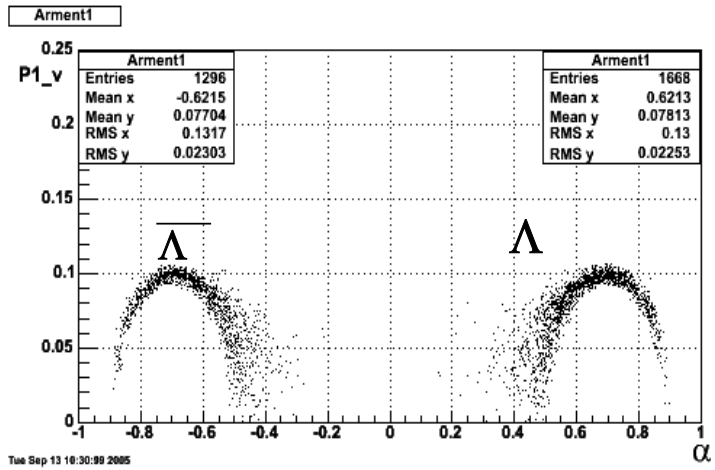
- Λ is reconstructed by combining TPC tracks with opposite charges and applying topological cuts:



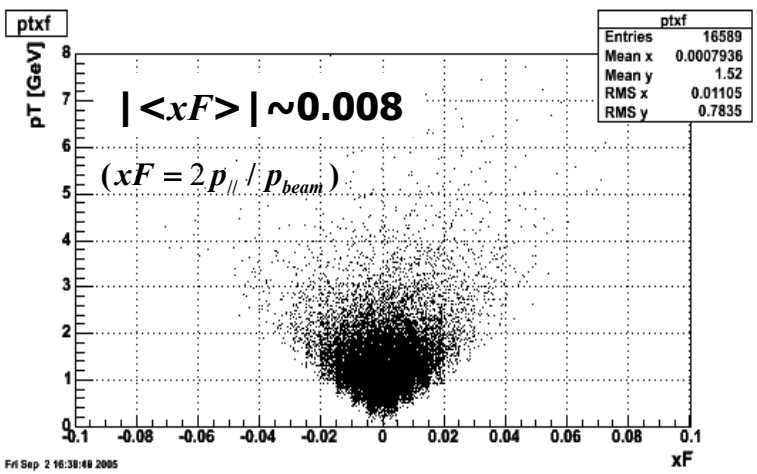
data of 2003 and 2004

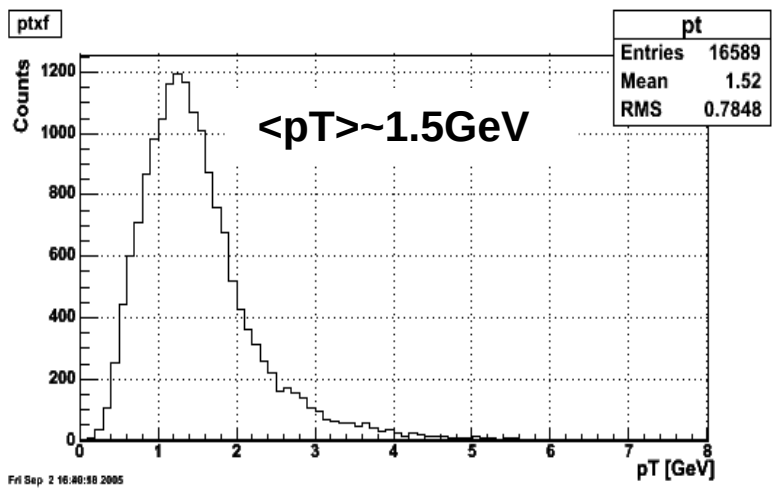
- Invariant mass distribution and Armenteros plot (minbias trigger only) :





- Kinematics of Λ candidates (Minbias+Barrel high tower trigger):





Note: only a part of whole sample

- Standard method to extract Lambda polarization:
  momentum distribution of decay proton in Λ's rest frame(Λ->pπ$^-$)

$P_\Lambda \cos\theta$

$$dN = N_0 A(\cos\theta)(1 + \alpha\, \vec{P}_\Lambda \cdot \hat{p}_p^*)$$

unit vector along proton momentum in Λ rest frame

A(cosθ): detector acceptance from MC simulation

decay parameter 0.642(PDG)

Λ polarization vector, is its moving direction in longi. polarized case

- Consider a narrow bin in θ: [θ_1,θ_2], and define:

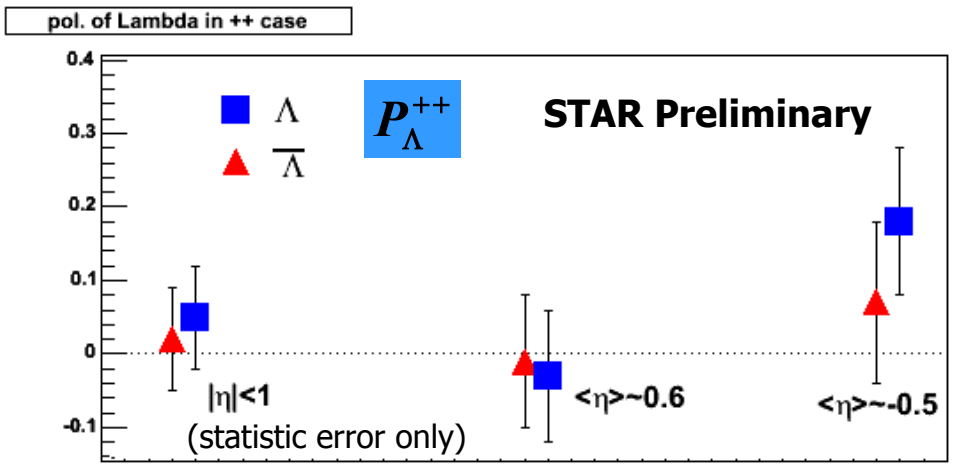
$$A_S = \frac{N(P_\Lambda) - N(-P_\Lambda)}{N(P_\Lambda) + N(-P_\Lambda)} \approx \alpha P_\Lambda \cdot \frac{\cos\theta_1 + \cos\theta_2}{2}$$

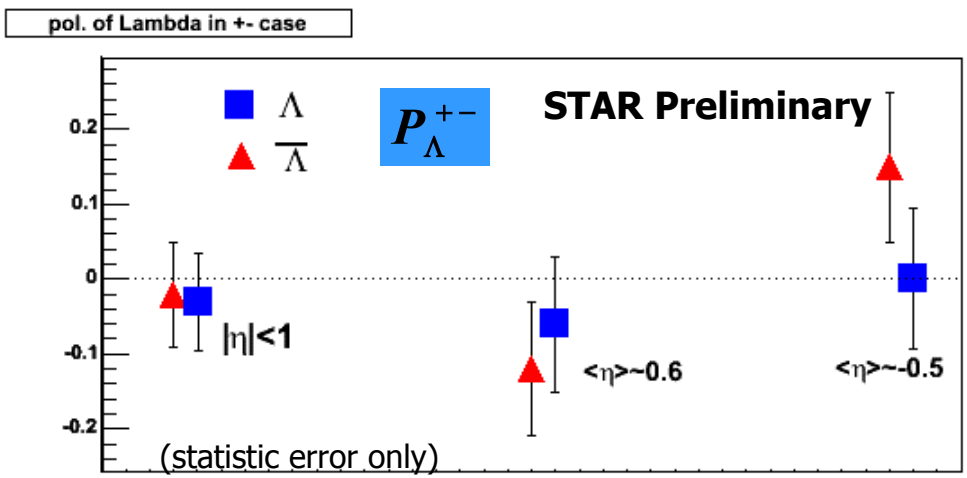
(acceptance is cancelled!)

$$P_\Lambda \approx \frac{2A_S}{\alpha(\cos\theta_2 + \cos\theta_1)}$$

- Symmetry relations: $P_\Lambda^{++}(\eta) = -P_\Lambda^{--}(\eta)$, $P_\Lambda^{+-}(\eta) = -P_\Lambda^{-+}(\eta)$

Preliminary results of Λ and $\bar{\Lambda}$ polarization from 03+04





(limited by statistics)

- **No. of events:**

~30 K for Lambda

~27 K for anti-lambda

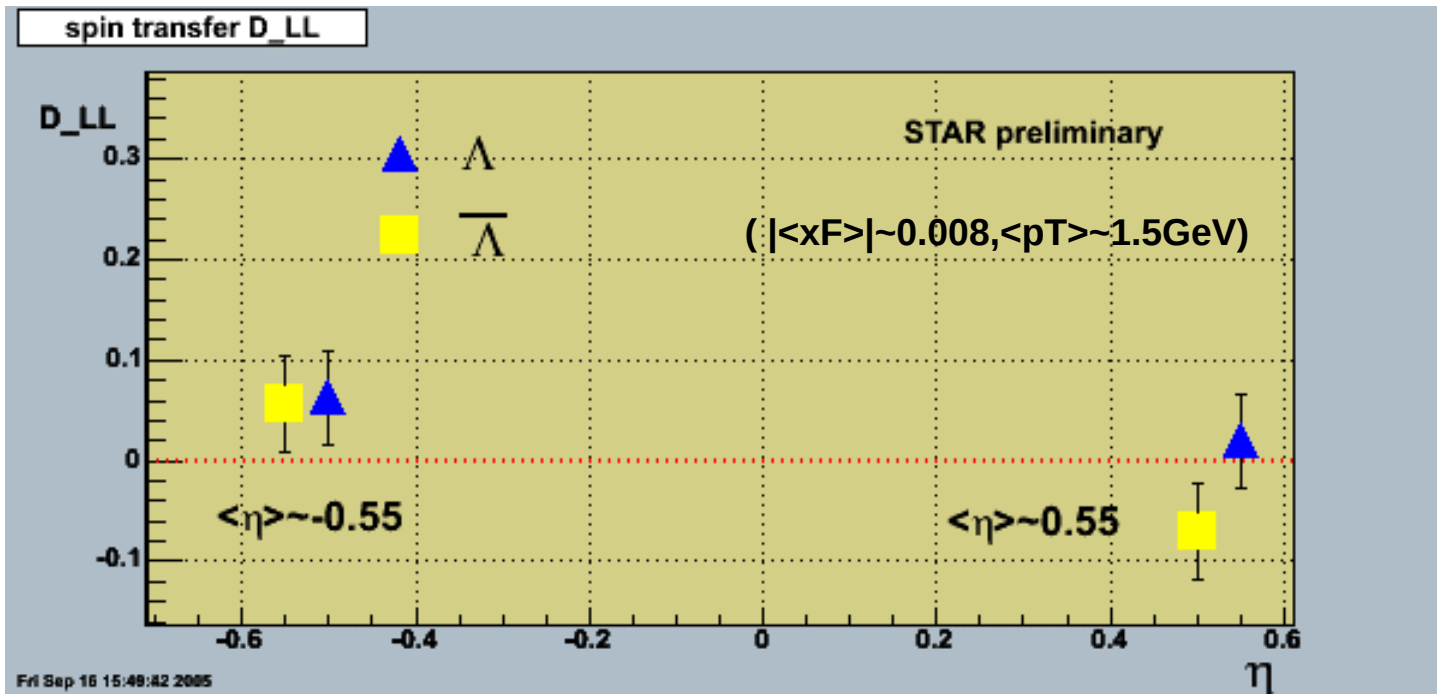
- **Kinematics :**

✓ **|<xF>|~0.008**

✓ **<pT>~1.5GeV**

Spin transfer D_LL $[P_{\Lambda}^{+0}(\eta)]$

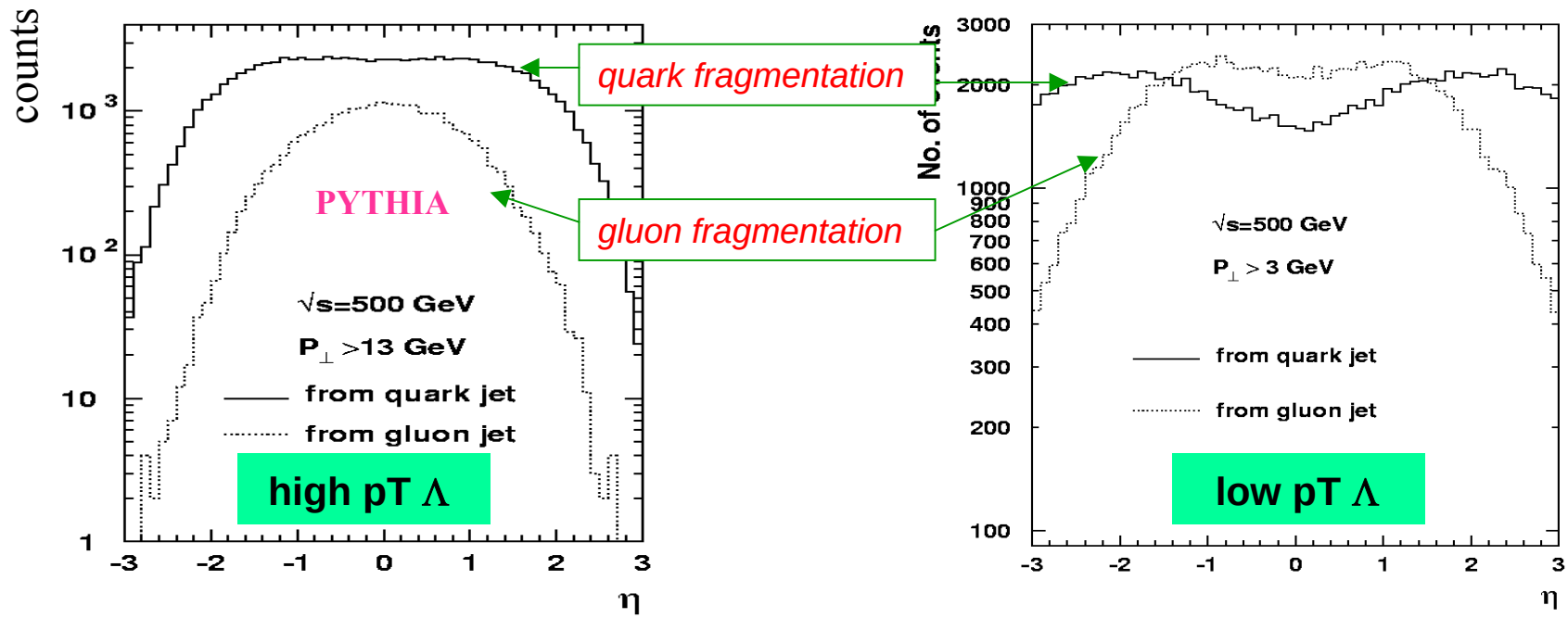
- D_LL: spin transfer from beam to Λ in $\vec{p}p \rightarrow \vec{\Lambda}X$



(limited by statistics)

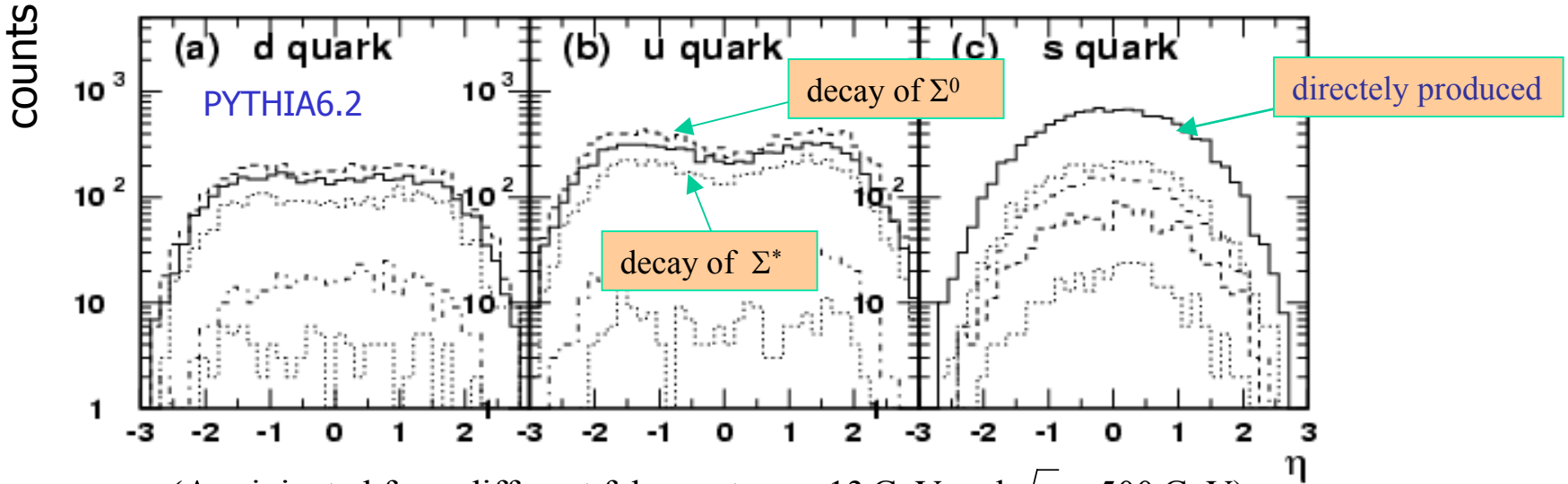
Discussion & outlook:

- Can we understand such small polarization observed so far?
  - It is not surprising, since $|x_F|$~0.01, p_T~1.5GeV.
  - No theoretical predictions, factorization and pQCD fail in this range?!
  - Gluon fragmentation at low p_T becomes important!



➡ Quark jets dominate at high P_T, while gluon frag. becomes important at low p_T!

Do we expect a large polarization for Λ at high p_T?



(Λ originated from different falvors at $p_T > 13$ GeV and $\sqrt{s} = 500$ GeV)

- u quark fragmentation dominates Lambda production.
- Spin content of Λ :
  - u don't carry spin of Λ in QM [SU(6)]
  - only a small fraction in DIS (~-0.17)

  Small P_Λ !
- Uncertainty due to large contribution from heavior hyperon decay! (~50% MC)

Theoretical predictions for Λ polarization:

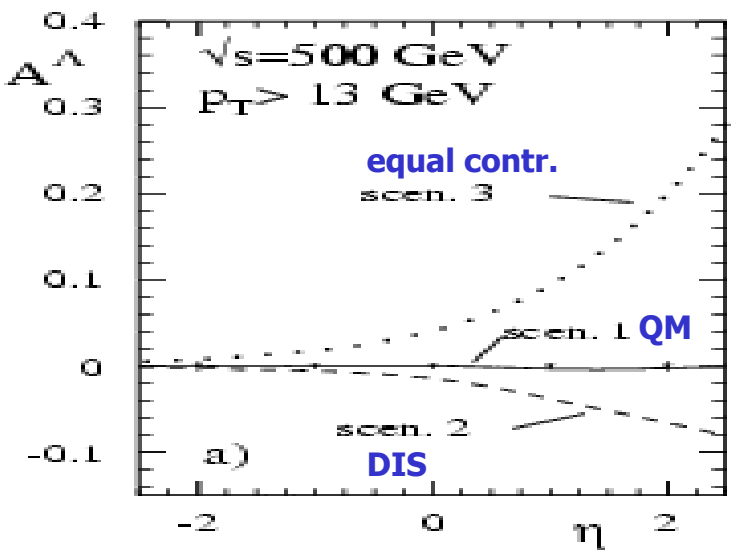
- Main difference comes from ΔD: $(d\Delta\sigma \propto \Delta f \otimes d\Delta\hat{\sigma} \otimes \Delta D)$

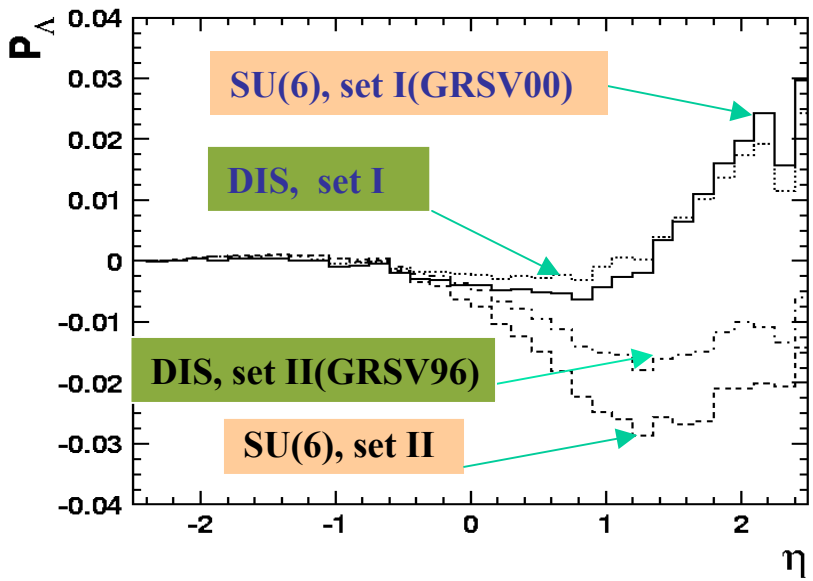
(a) polarized frag. function from available data

(b) model for pol. frag. function according to the origin

(D.de Florian, M.Stratmann, W.Vogelsang, PRL'98)

(Xu Q.H., Liu C.X, Liang Z.T., PRD'02)



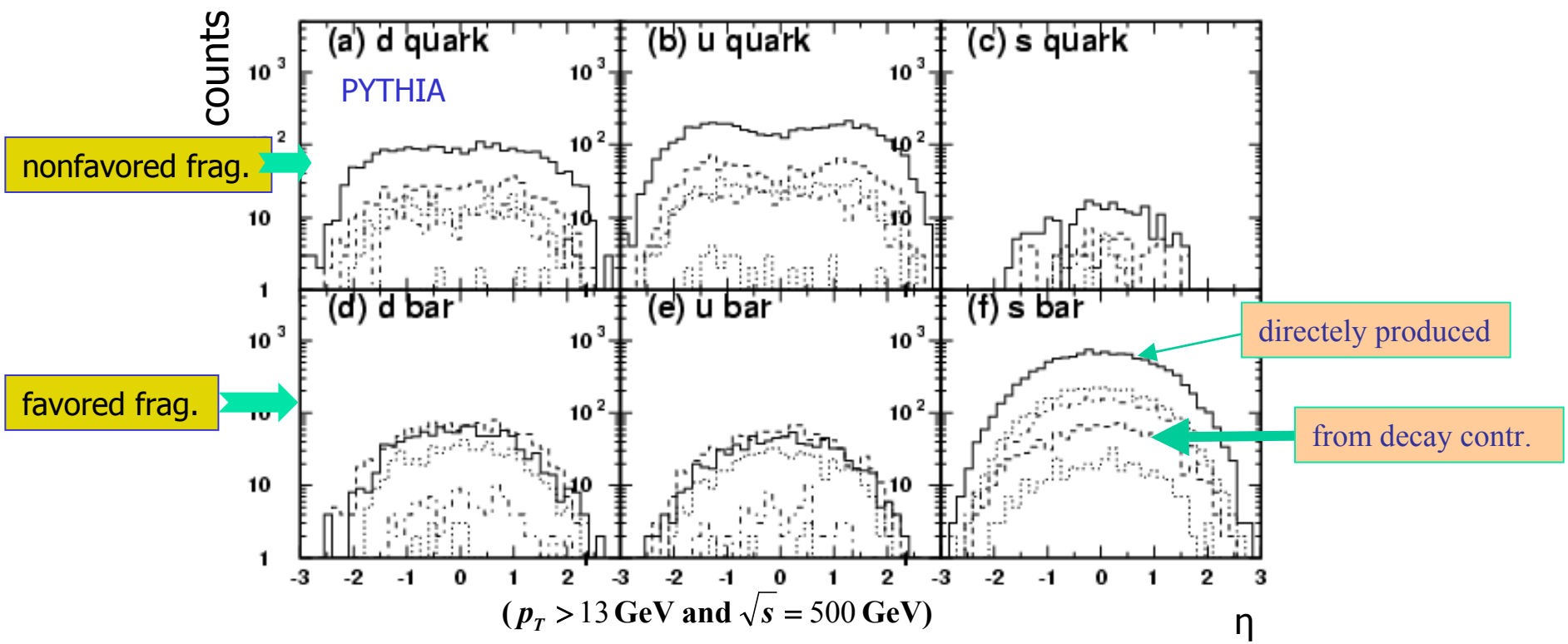


The typical cross section for Λ $(p_T > 13\,\mathrm{GeV}$ and $\sqrt{s} = 500\,\mathrm{GeV})$ ~3nb for |η|<0.5 ,as estimated by D.de Florian, M.Stratmann, W.Vogelsang.

(For L=300 pb^{-1}, δP_{Λ} ~ 0.01, for P_B=70%)

How about anti_lambda?

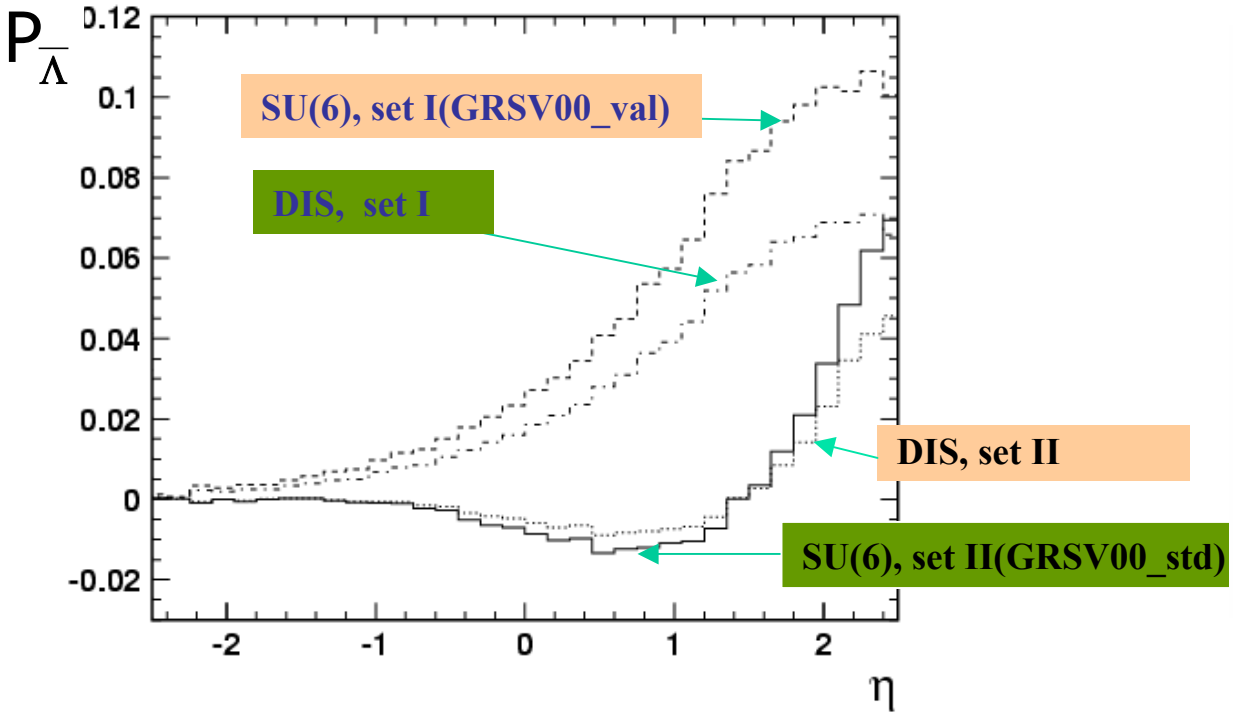
- Yield at high p_T: ~70% of Λ
- Decay contribution: ~40% (compare ~50% for Λ)
- s-bar frag. dominates its production by favored fragmentation!

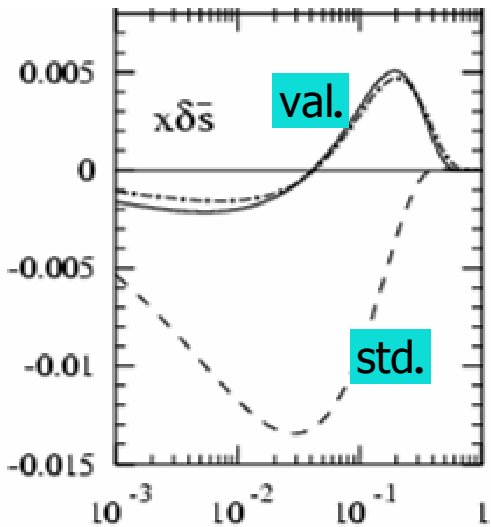


Anti-lambda polarization is sensitive to strange polarization !

- A prediction for anti-lambda polarization at RHIC using method (b):

$(p_T > 13\ \mathbf{GeV}\ \mathbf{and}\ \sqrt{s} = 500\ \mathbf{GeV})$



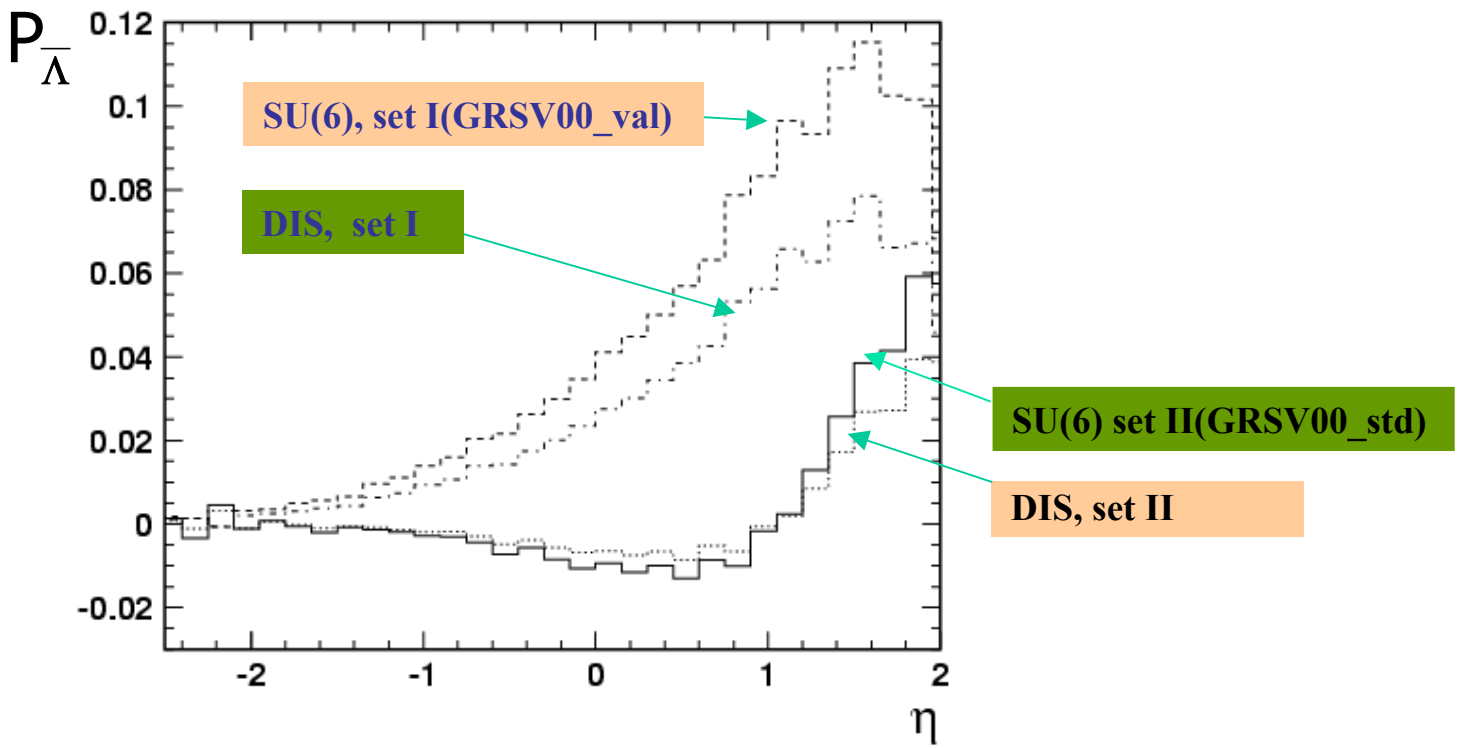


GRSV2000(PRD63,2001)

- For L=300 pb^{-1}, $\delta P_{\bar{\Lambda}}$ ~ 0.012, for P_B=70%, $\sigma_{\bar{\Lambda}} \sim \mathbf{0.6}\ \sigma_{\Lambda}$

- A prediction for anti-lambda polarization at RHIC using method (b):

($p_T > 8$ GeV and $\sqrt{s} = 200$ GeV)



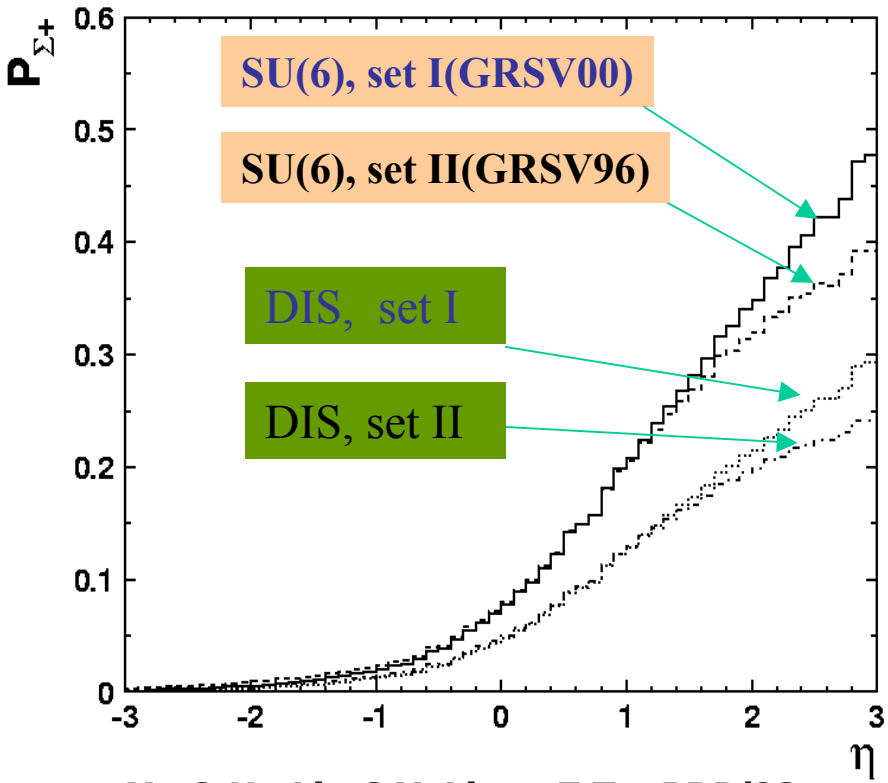
Σ^+ polarization at RHIC:

- Σ^+ polarization can be measured at RHIC $(\Sigma^+ \to p\,\pi^0\ ,\ \mathrm{Br} = 51\%,\ \alpha = -0.98)$
- The yield is ~50% of Λ's!
- The decay contribution of Σ^+ is very small (<10%).
- How about Σ^+ polarization?

➢ u quark frag. dominates high p_T Σ^+(uus) production;

➢ spin content of Σ^+: 4/3 in SU(6); ~0.82 in DIS

Larger polarization than Λ!



Xu Q.H., Liu C.X, Liang Z.T., PRD'02

Polarization of vector meson

- Spin density matrix of a vector meson:

$$\rho = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

$$(\rho = \sum_i P_i \,|\, i \rangle\langle i \,|)$$

- ρ_{mm}: the diagonal element of spin density matrix of V .
- ρ_{11}: the probability to be in $h=1$ state, similar for ρ_{-1-1} and ρ_{00} .
- For $V \to M_1 + M_2$, M_1 and M_2 are two pseudo-scalar mesons,

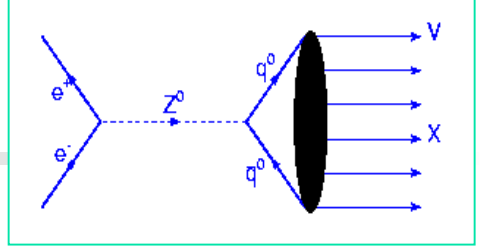
$(K^{*0} \to K^+\pi^-, K^{*\pm} \to K_s^0\pi^\pm)$

$$\mathbf{W(\cos\theta)} = \frac{3}{4}[(1-\rho_{00}) + \boxed{(3\rho_{00}-1)}\cos^2\theta]$$

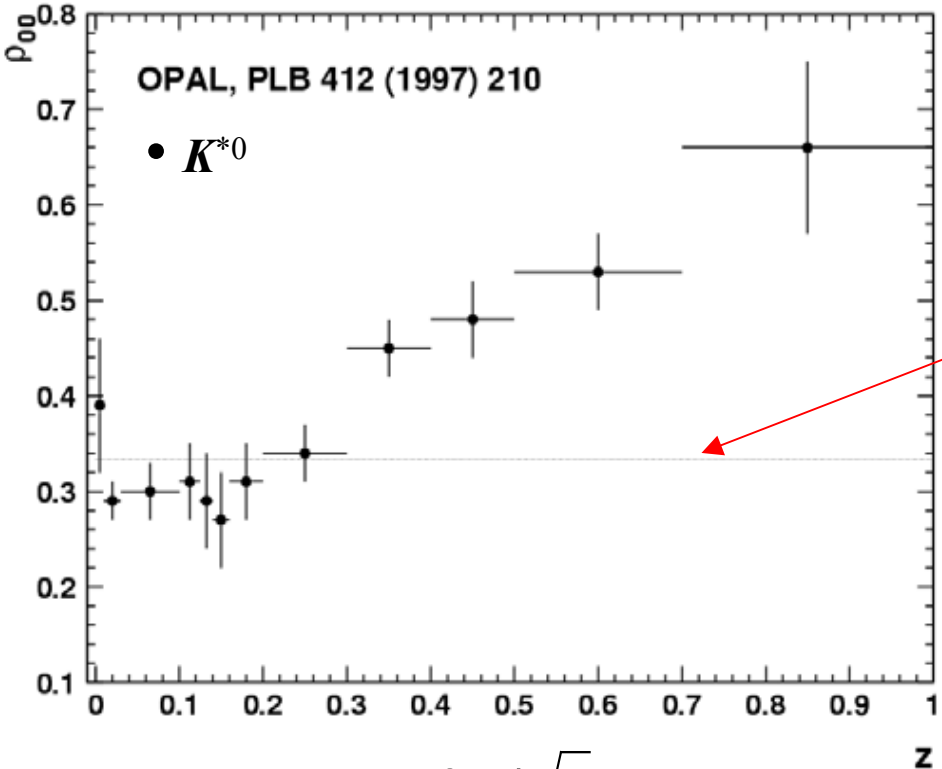
θ: Polar angle of M_1 to the quantization axis in V's rest frame

"Spin alignment" , J.F.Donoghue, PRD19, 1979.

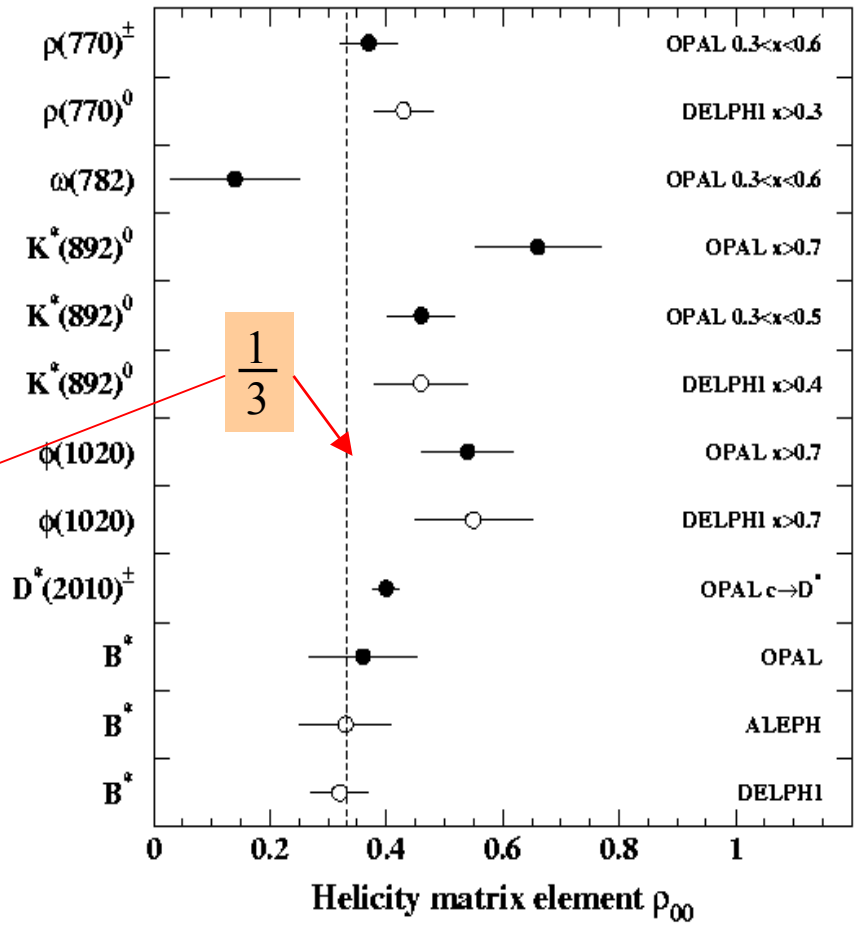
Spin alignment of V in $e^+e^- \to Z^0 \to VX$



- **The data at LEP:**



$z \equiv 2p/\sqrt{s}$



Eur.Phys.J. C16, 61 (2000)

ρ_{00} >1/3 for most of the mesons in large *z* region !

What can we learn from the data at LEP?

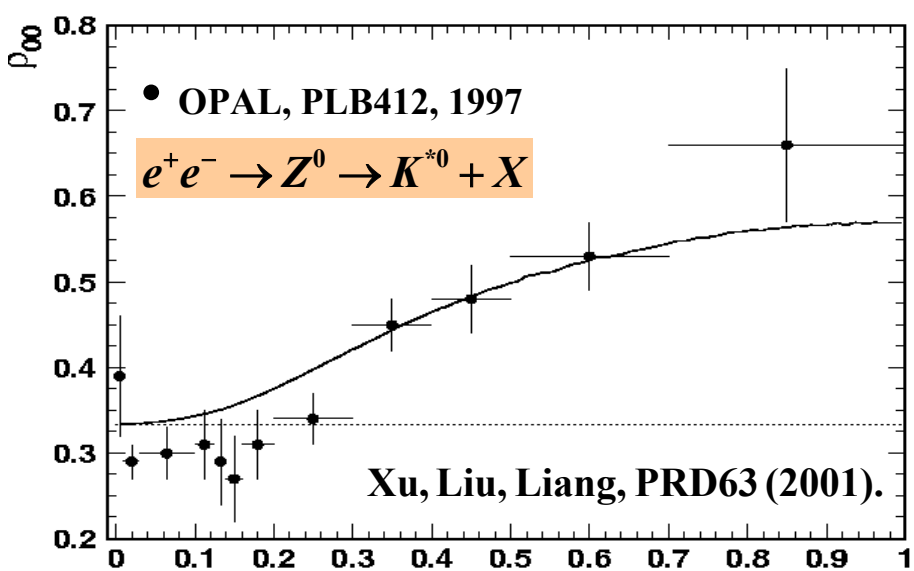
- The primary quark(anti-quark) at Z_0 pole are longitudinally polarized. ($\langle P_f \rangle = -0.94$ for $f=s,d,b$; $\langle P_f \rangle = -0.67$ for $f=u,c$.)
- ρ_{00} can be calculated simply from the spin density matrices of its constituent quarks in naive Quark Model. $(\vec{S}_{V(q\bar{q})} = \vec{s}_q + \vec{s}_{\bar{q}})$
- By fitting the LEP data(K^{*0}), we obtained that:

$$P_z = -\alpha P_f, \quad \alpha \approx 0.5$$

P_z : polarization of antiquark

P_f : polarization of primary quark

The results of other vector mesons also agree with the data!

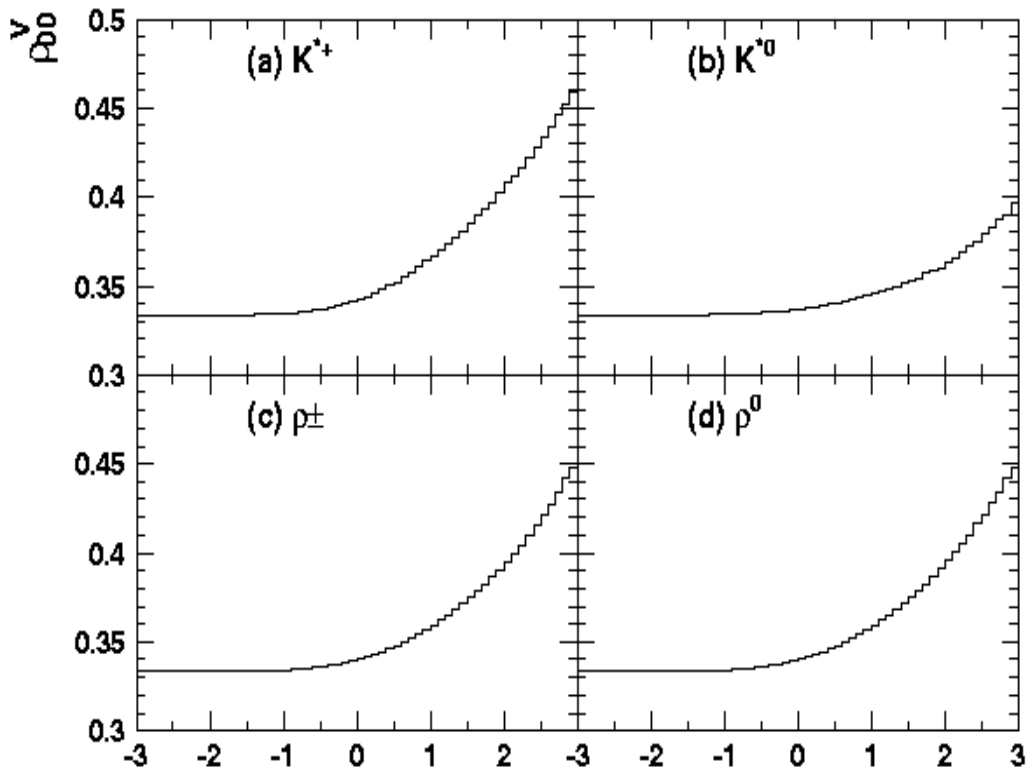


Spin alignment of V in pp-->VX

- Is this relation universal for the fragmentation of a longitudinally polarized quark ?

$$P_z = -\alpha P_f$$

- There are also polarized quarks' fragmentation in pp collisions after a hard scattering !



Xu, Liang, PRD67 (2003).

- Make measurements at RHIC!

(The yield of K^{*0} is ~6 times of Λ's)

spin alignment of V in $\vec{p}p \rightarrow VX$ at $\sqrt{s}$=500 GeV and p_T>13 GeV.

Summary & outlook

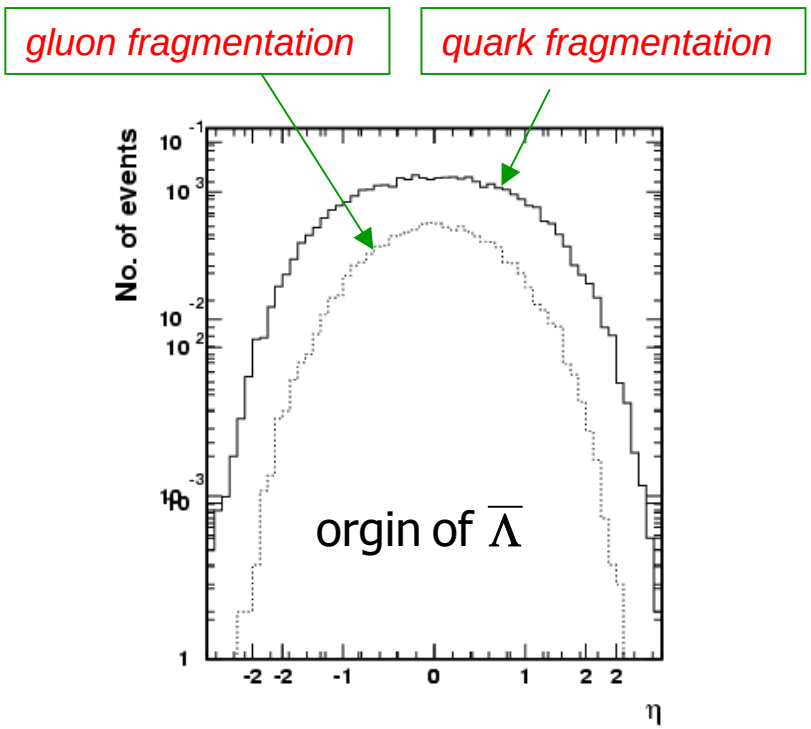
- Lambda (anti-Lambda) polarization at low p_T was measured at $\sqrt{s}$=200 GeV with STAR.
- Discussion on future measurements at RHIC:
  - ✓ anti-lambda polarization at high p_T can give new insights into $\Delta s(x)$!
  - ✓ Σ^+ polarization at high pT can distinguish different pictures of spin transfer in fragmentation process !
  - ✓ Spin alignment of vector meson (K*0…) can also provide useful information for polarized fragmentation function!

Extra Slides

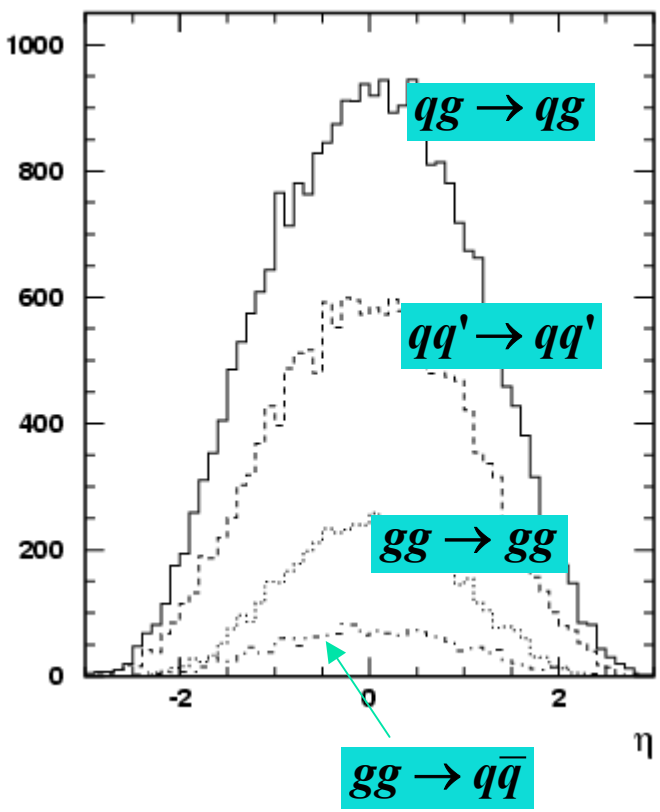
$$P_{\Lambda}^{++} = \frac{\sigma_{p^+p^+\to\Lambda^+X} - \sigma_{p^+p^+\to\Lambda^-X}}{\sigma_{p^+p^+\to\Lambda^+X} + \sigma_{p^+p^+\to\Lambda^-X}}$$

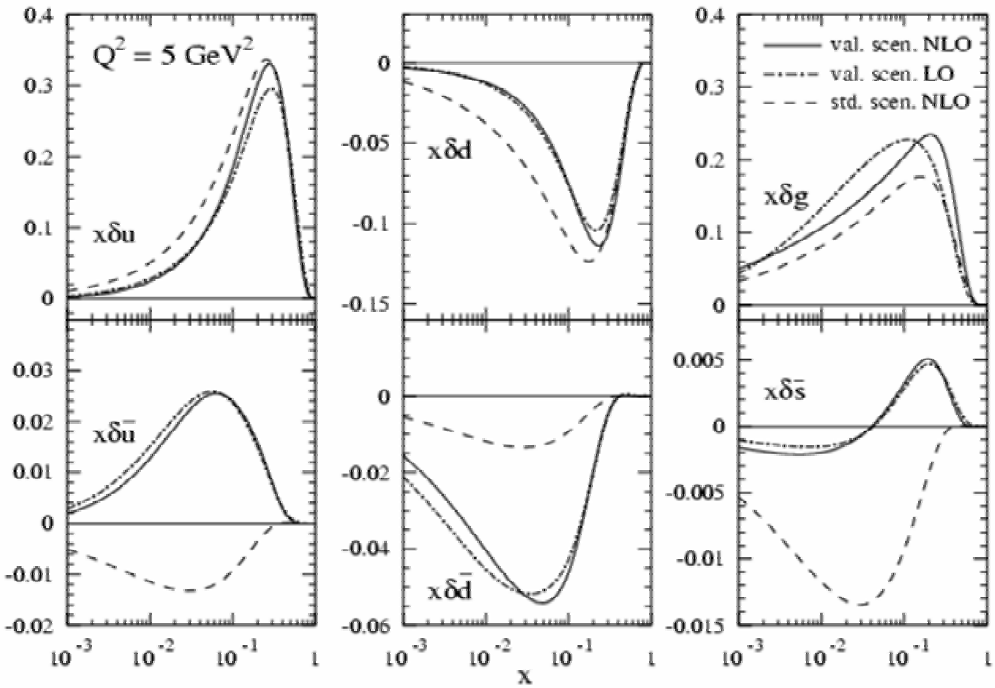
$$= \frac{\Delta f_1 f_2 \Delta\hat{\sigma}\Delta D + f_1 \Delta f_2 \Delta\hat{\sigma}'\Delta D}{f_1 f_2 \hat{\sigma} D + \frac{1}{2}\Delta f_1 \Delta f_2 (\sigma_{++} - \sigma_{--})}$$

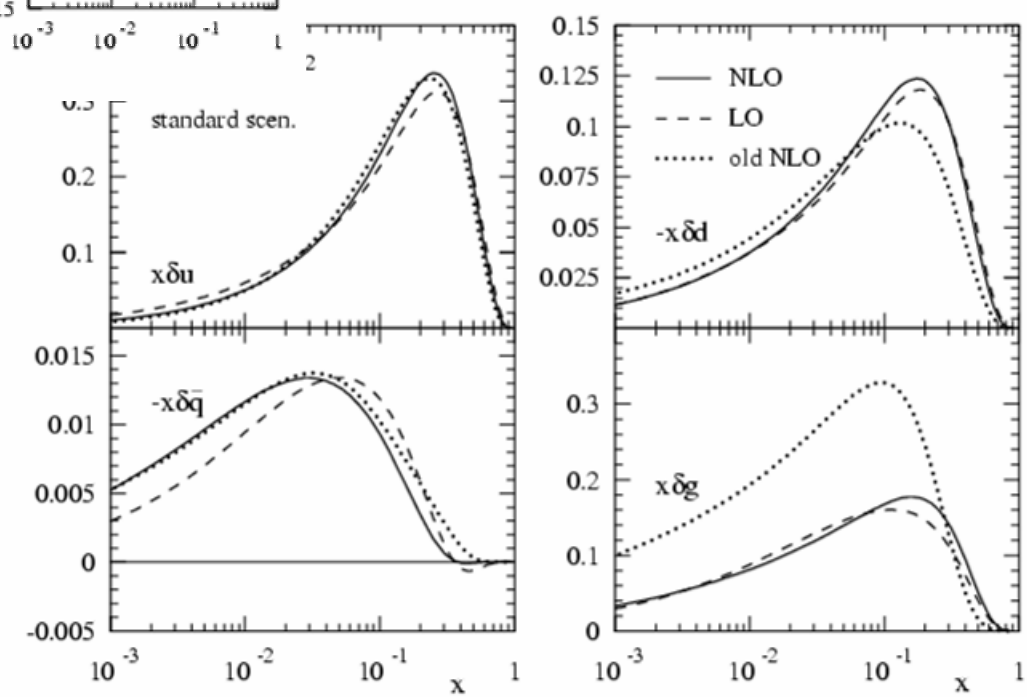
Contr. of different subp. To anti-Lambda production:



($p_T > 13$ GeV and $\sqrt{s} = 500$ GeV)



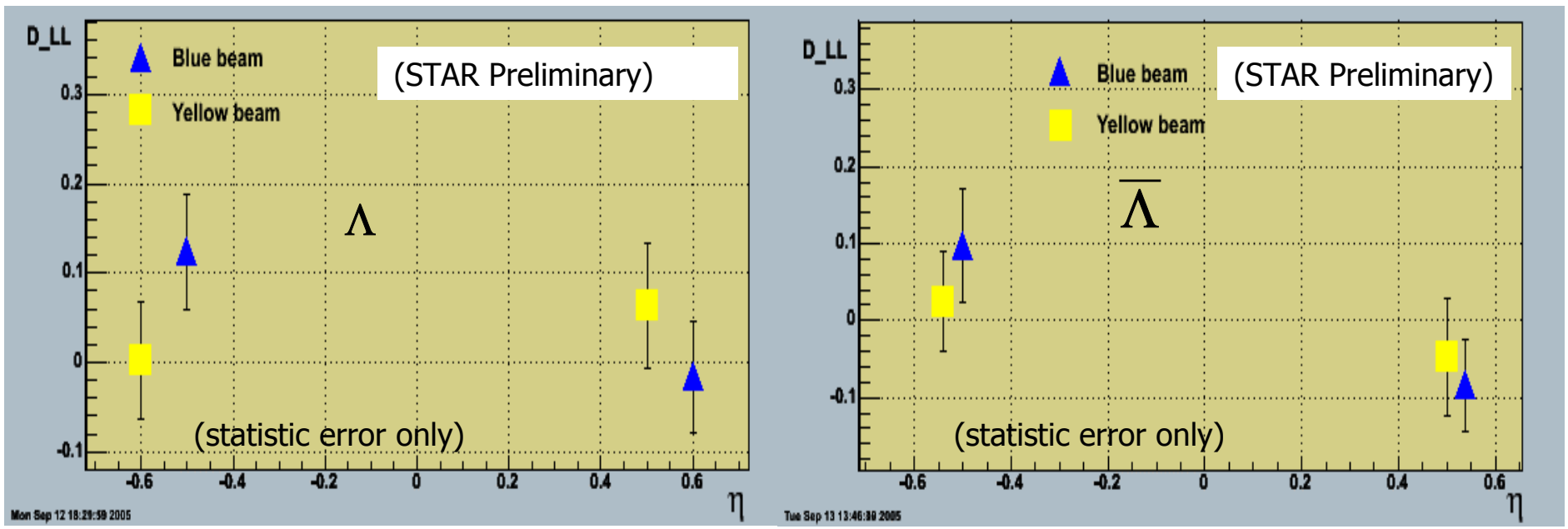




M.Gluck, E.Reya, M. Stratmann, and W.vogelsang, GRSV2000

Natural extension : spin transfer D_LL [$P_{\Lambda}^{+0}(\eta)$]

- D_LL: spin transfer from beam to Λ in $\vec{p}p \rightarrow \vec{\Lambda}X$

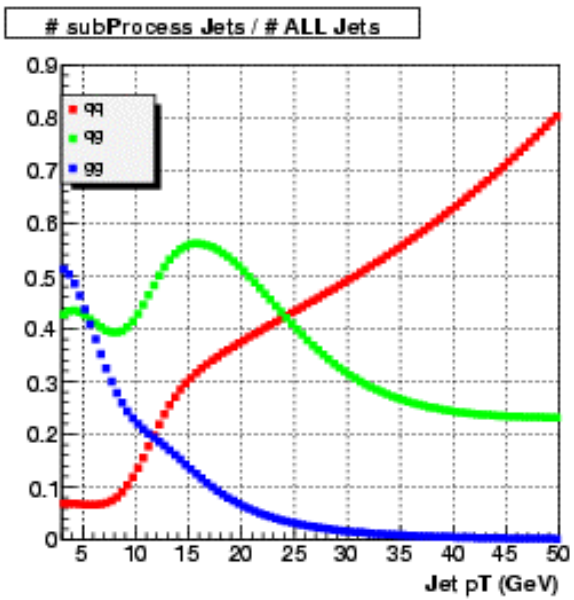


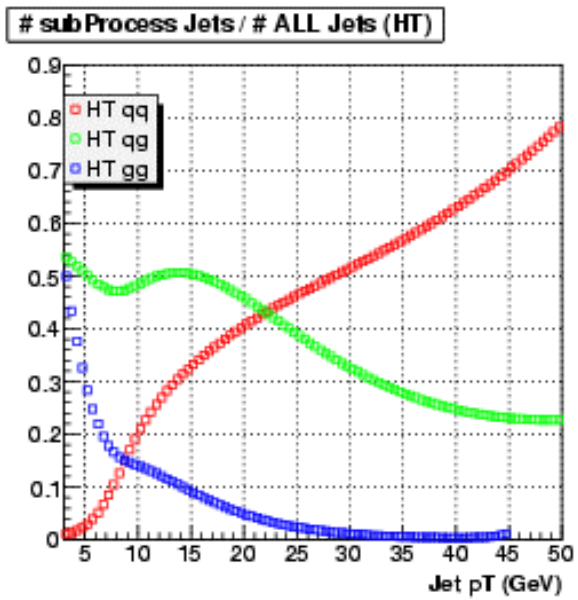
(limited by statistics)

- **Kinematics : |<xF>|~0.008; <pT>~1.5GeV**

Trigger bias by high tower trigger:

- The relative contribution from different subproces (changed by ht trigger):





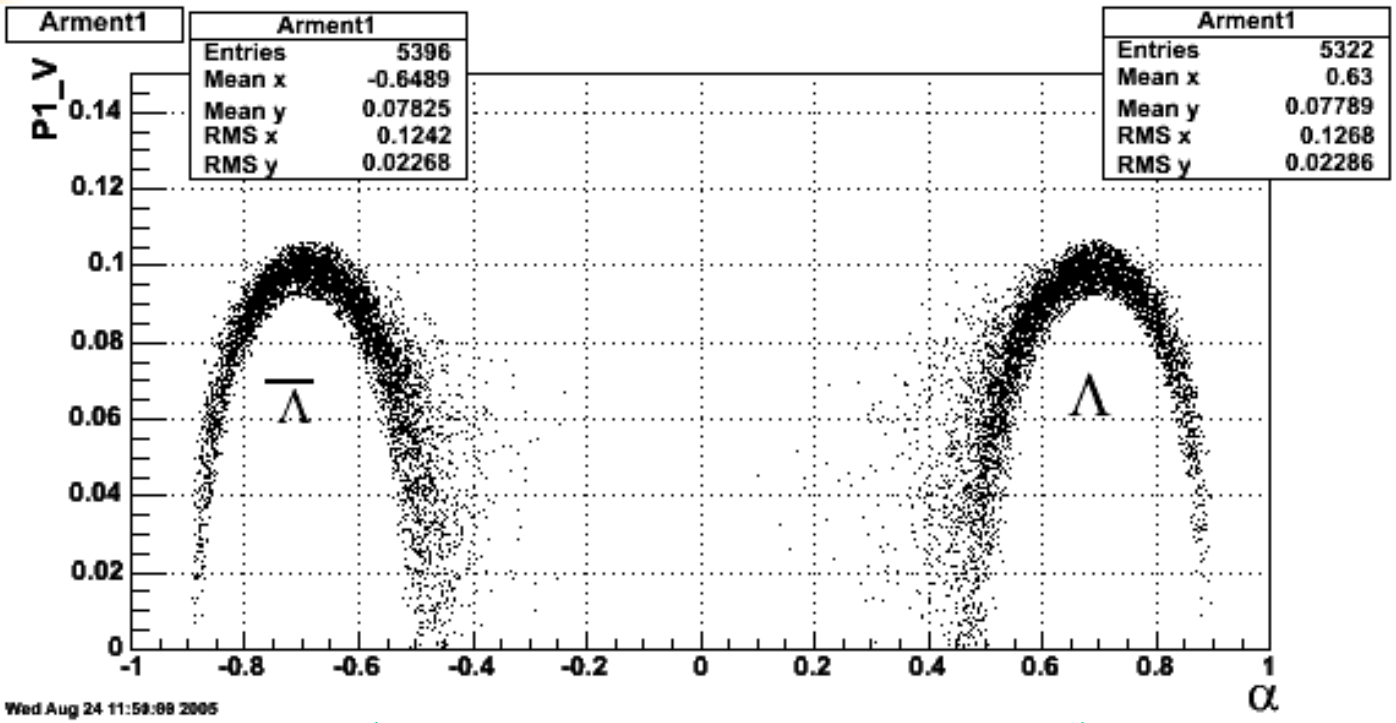
- Λ Production with high tower (E-M calorimeter):

  a) Away-side from the triggered jet

  b) Leading particle in the triggered jet

  ✓ Both will be studied when enough statistics available

- Podalanski-Armenteros plot for lambda and anti-lambda:



$$\alpha = (p_L^+ - p_L^-)/(p_L^+ + p_L^-) \text{ and } p_v$$

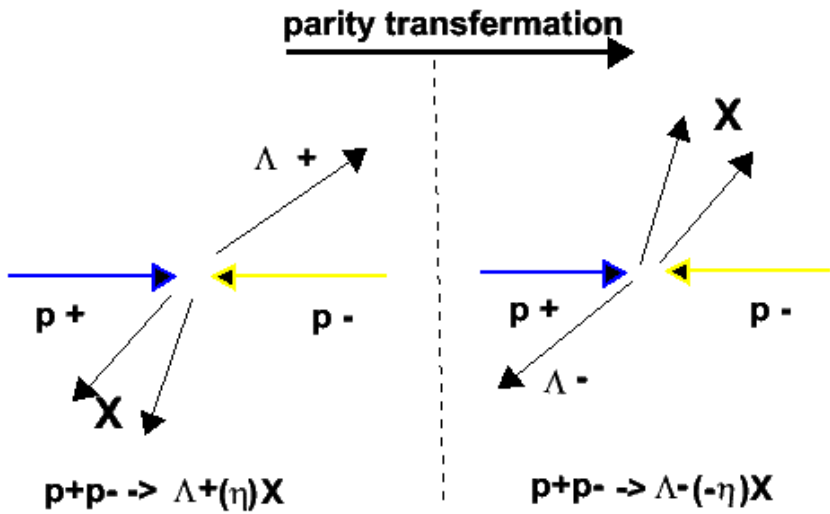
- ✓ P_L^+ (P_L^-): momentum of positive (negative) tracks parallel to the V0 momentum.
- ✓ P_v : momentum of tracks perpendicular to the V0 direction.

- No. of Lambda candidates:
  - ➢ 2003: ~60K, ~15% for Minbias, ~44% for BHT, ~16% for BJP;
  - ➢ 2004: ~64K, ~9% for Minbias, ~41% for BHT,~15% for BJP;

Symmetries in +- & -+ case:

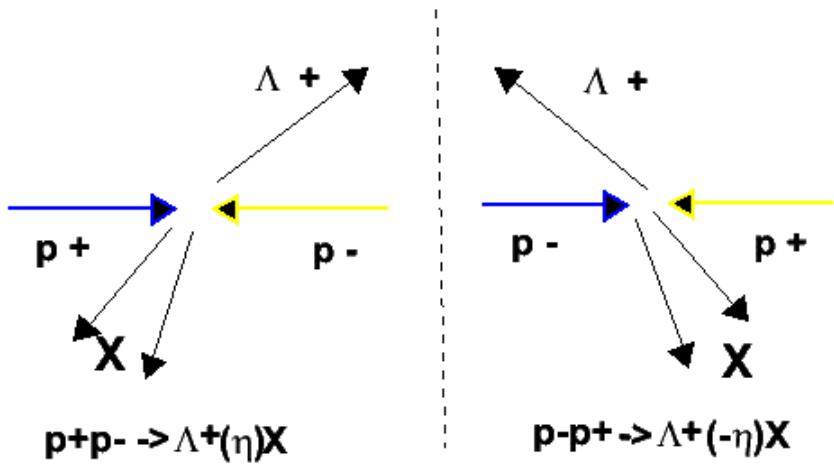
- Parity transformation:

$$\sigma_{p^+p^- \to \Lambda^+(\eta)X} = \sigma_{p^+p^- \to \Lambda^-(-\eta)X}$$
$$\Rightarrow P_\Lambda^{+-}(\eta) = -P_\Lambda^{+-}(-\eta)$$



- Symmetry of space:

$$\sigma_{p^+p^- \to \Lambda^+(\eta)X} = \sigma_{p^-p^+ \to \Lambda^+(-\eta)X}$$
$$\Rightarrow P_\Lambda^{+-}(\eta) = P_\Lambda^{-+}(-\eta)$$



$$P_\Lambda^{+-}(\eta) = -P_\Lambda^{-+}(\eta)$$

- Similar result for +- &-+ case:
  (and singly polarized case)

$$P_\Lambda^{+0}(\eta) = -P_\Lambda^{-0}(\eta)$$

Toward a method without acceptance :
---Symmetries of Λ polarization in pp collisions

- Our notation: $p^+p^+ \to \Lambda^+(\eta)X$, the first is blue beam, second is yellow.
- Λ polarization definition ("*++" case for example*):

$$P_\Lambda^{++}(\eta) = \frac{\sigma_{p^+p^+\to\Lambda^+(\eta)X} - \sigma_{p^+p^+\to\Lambda^-(\eta)X}}{\sigma_{p^+p^+\to\Lambda^+(\eta)X} + \sigma_{p^+p^+\to\Lambda^-(\eta)X}}$$

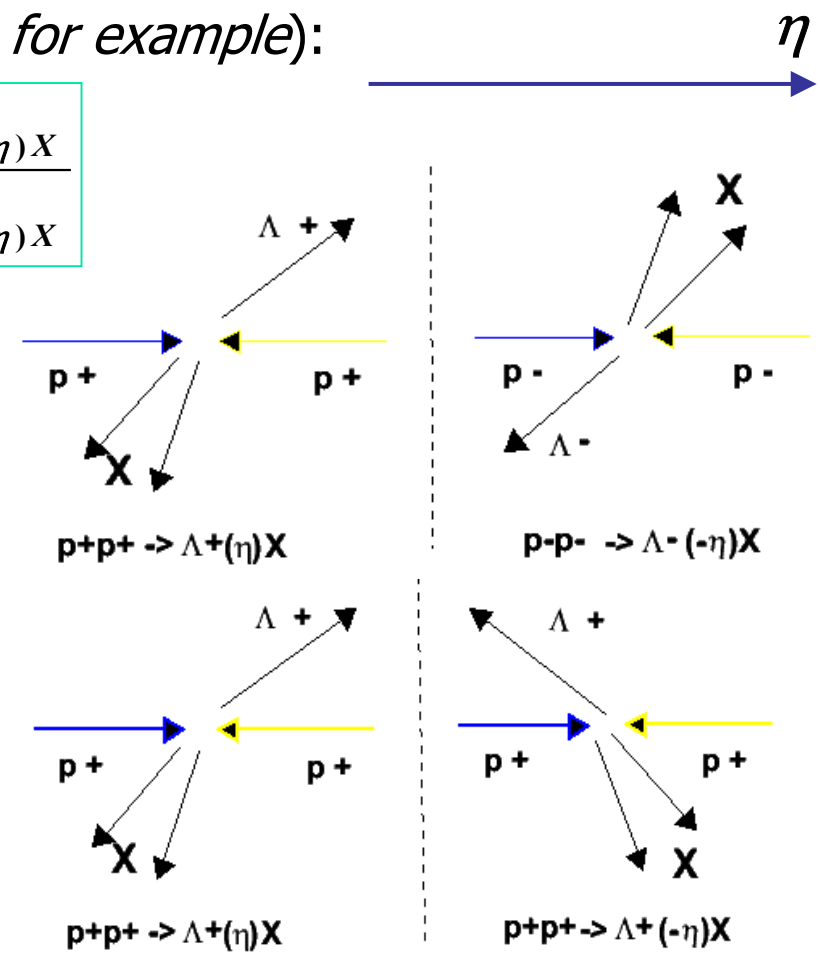
- Parity transformation:

$$\sigma_{p^+p^+\to\Lambda^+(\eta)X} = \sigma_{p^-p^-\to\Lambda^-(-\eta)X}$$
$$\Rightarrow P_\Lambda^{++}(\eta) = -P_\Lambda^{--}(-\eta)$$

- Symmetry of space:

$$\sigma_{p^+p^+\to\Lambda^+(\eta)X} = \sigma_{p^+p^+\to\Lambda^+(-\eta)X}$$
$$\Rightarrow P_\Lambda^{++}(\eta) = P_\Lambda^{++}(-\eta)$$

$$P_\Lambda^{++}(\eta) = -P_\Lambda^{--}(\eta)$$



- Similar result for +- &-+ case: $P_\Lambda^{+-}(\eta) = -P_\Lambda^{-+}(\eta)$

Higher order of asymmetry:

- For a wider bin of θ, we define a mean acceptance :

$$N(P) = \int_{\cos\theta 1}^{\cos\theta 2} A(\cos\theta) N_{th}(P,\cos\theta) d\cos\theta = \bar{A}(P,\theta_2,\theta_1) \int N_{th}(P,\cos\theta) d\cos\theta$$

$$N_{th}(P,\cos\theta) = N_0(1+\alpha P\cos\theta) \qquad \bar{A}(P,\theta_2,\theta_1) = \frac{\int A(\cos\theta) N_{th}(P,\cos\theta) d\cos\theta}{\int N_{th}(P,\cos\theta) d\cos\theta}$$

$$N(P) = \bar{A}(P,\theta_2,\theta_1) N_0 \left\{ \cos\theta_2 - \cos\theta_1 + \frac{\alpha}{2} P(\cos^2\theta_2 - \cos^2\theta_1) \right\}$$

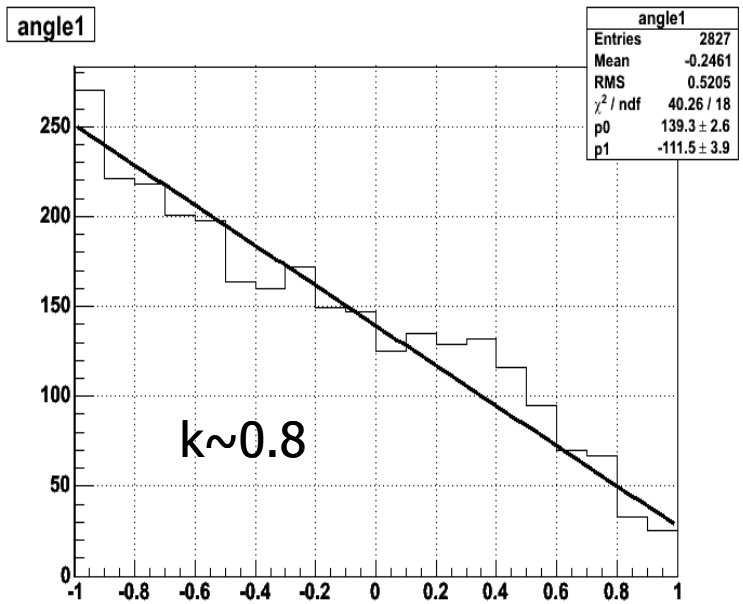
$$A_N = \frac{N(P)-N(-P)}{N(P)+N(-P)} = \frac{\bar{A}(P,\theta_2,\theta_1)\alpha P(\cos^2\theta_2 - \cos^2\theta_1) - \delta A}{2\cdot\bar{A}(P,\theta_2,\theta_1)(\cos\theta_2 - \cos\theta_1) + \delta A}$$

$$\delta A = [\bar{A}(-P,\theta_2,\theta_1) - \bar{A}(P,\theta_2,\theta_1)][\cos\theta_2 - \cos\theta_1 + \frac{\alpha}{2} P(\cos^2\theta_2 - \cos^2\theta_1)]$$

$$\delta A << \bar{A}(P,\theta_2,\theta_1)\alpha P(\cos^2\theta_2 - \cos^2\theta_1),$$

$$A_N \approx \frac{\alpha P(\cos\theta_2 + \cos\theta_1)}{2}$$

- To estimate the magnitude of δA, we need to know about A(cosθ) !
- From the cos(θ) distribution of Λ candidates,

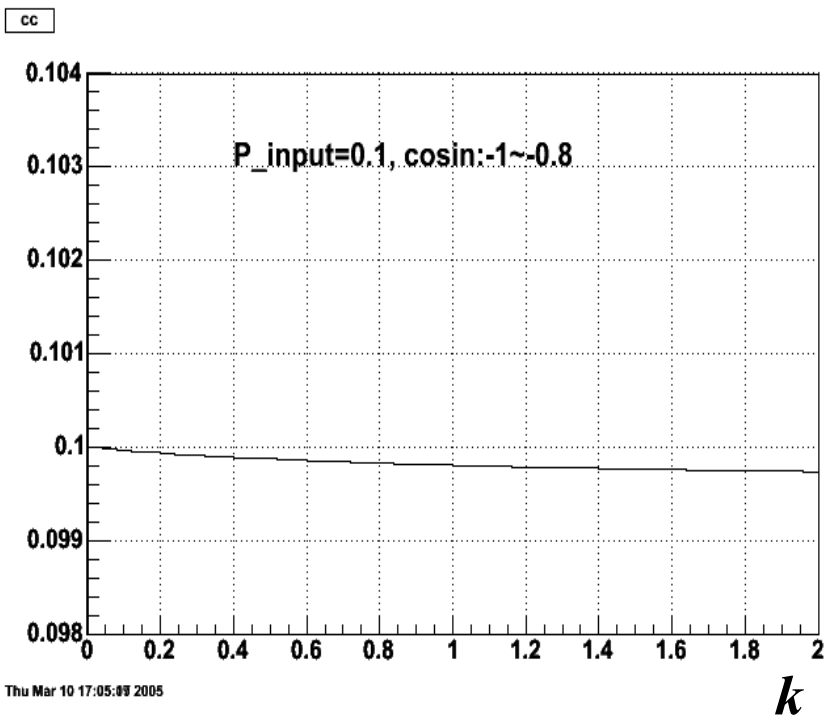


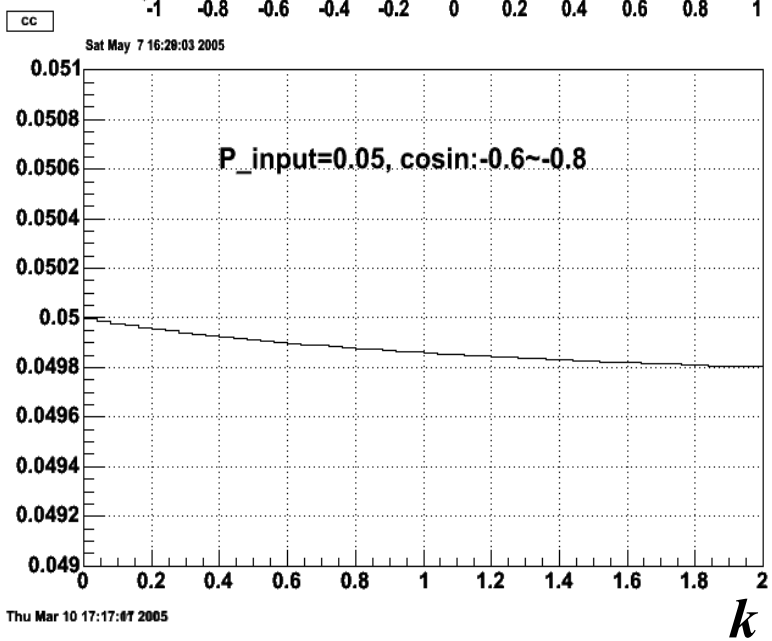
- For a simple example of A(cosθ) like that:

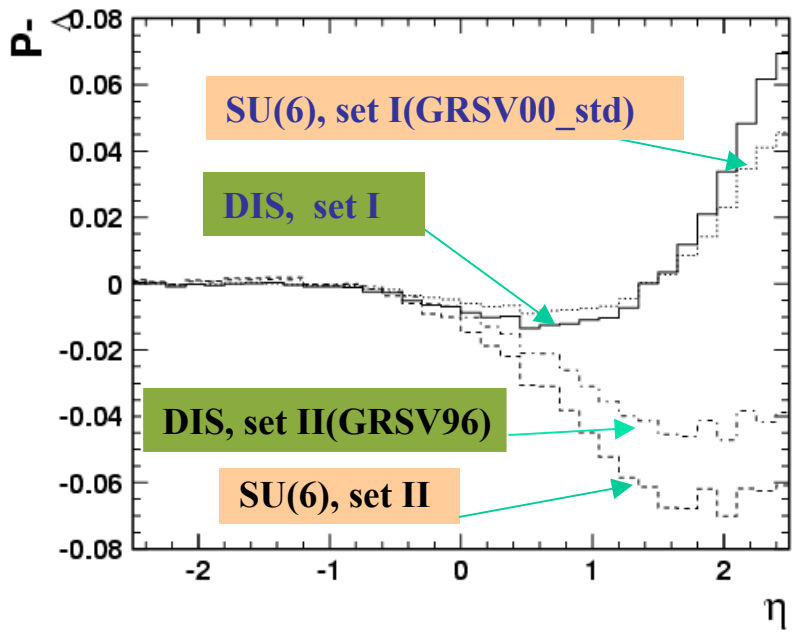
  $A(\cos\theta)=N_1(1-k\cos\theta)$,

  N_1: normalization factor

- The asymmetry trick works well!







($p_T > 13$ GeV and $\sqrt{s} = 500$ GeV)