# Hadron polarization phenomena at the LHC and their implications


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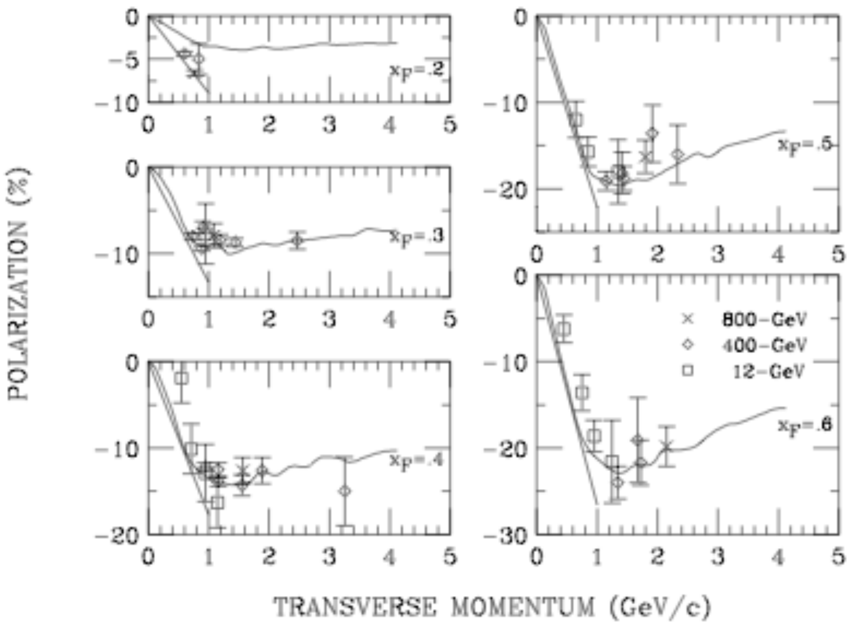
# Large polarization in hadron+hadron



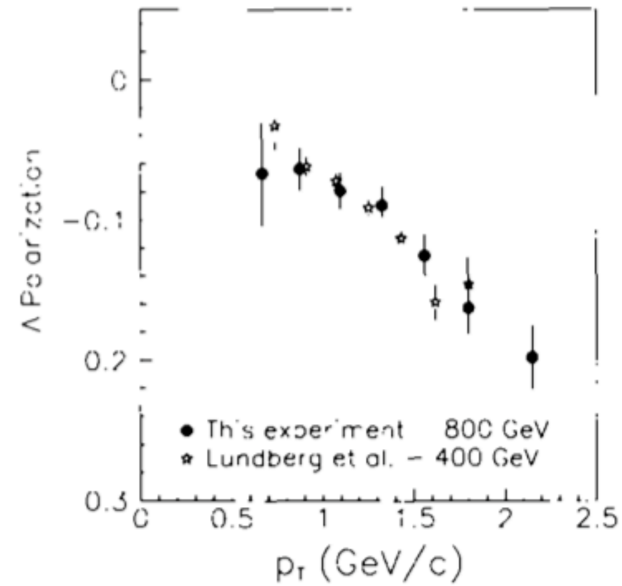



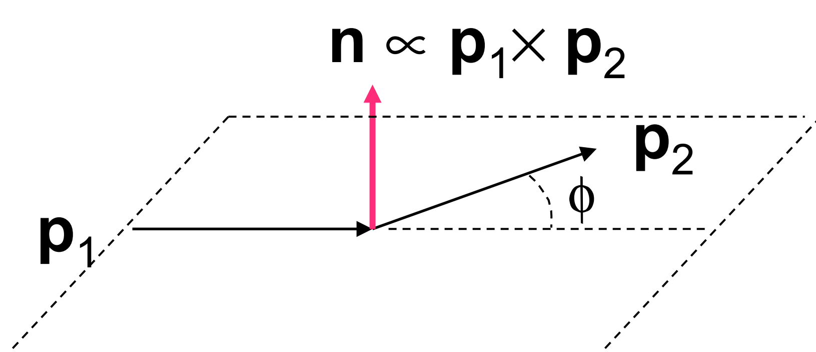

**Fig. 4. Lambda polarization versus production transverse momentum ($p_T$). For comparison, data for 400 GeV production (Ref. 10) are also shown.**

$p+p \rightarrow \Lambda + X$ Polzn($x_F$, $p_T$)
compiled by K.Heller (1997)

Ramberg, et al.,(FNAL) PLB338, 403 (1994)

# Phases & SSA

- Single Spin Asymmetries (SSA) in 2-body
- Parity allows only <**S·n**> non-zero for any single spinning particle. Requires some helicity flip or chirality flip for m=0 quarks & phase.




Cross section for spin S·**n**= +1/2 minus that for S·**n**= -1/2

$<\mathbf{S}\cdot\mathbf{n}> \propto \Sigma f^*_{ab,cd}[\sigma\cdot\mathbf{n}]_{dd'} f_{ab,cd'} \propto \Sigma\, \mathrm{Im}[f^*_{ab,c+}\, f_{ab,c-}]$ for D's SSA

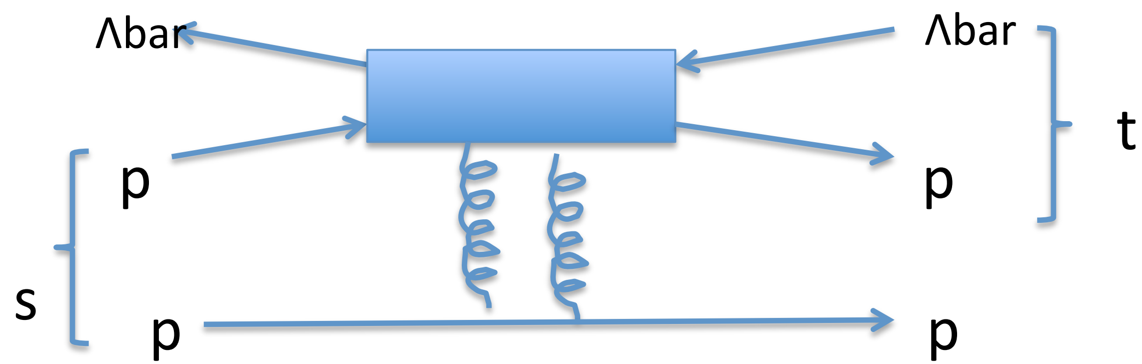
**n** requires some **p**$_2$ transverse to **p**$_1$

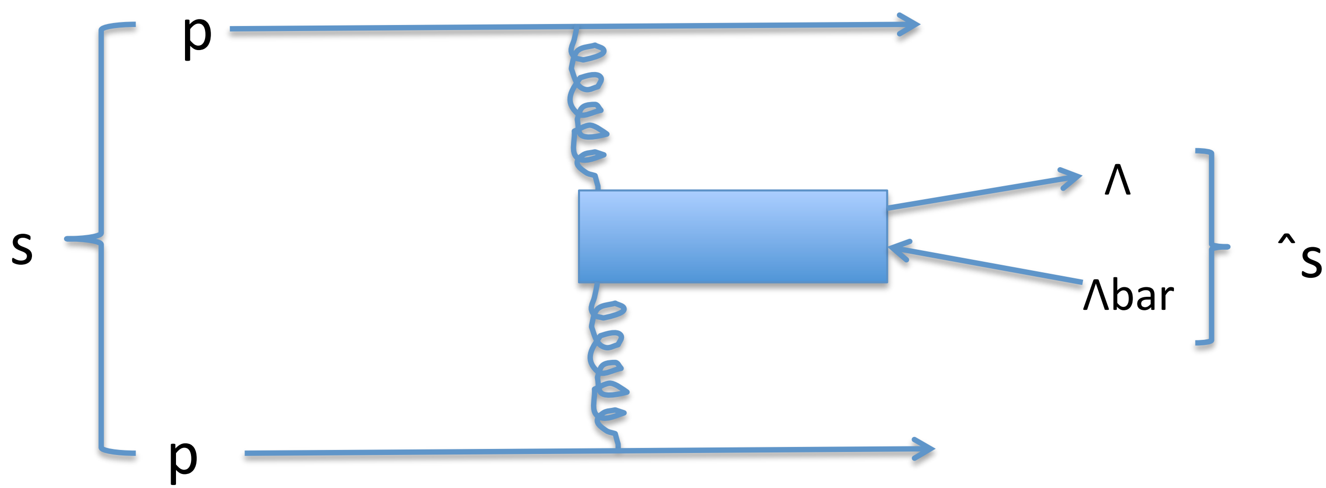
(at quark level? m=0 & PQCD - no SSA) Kane, Pumplin, Repko →$P_L \sim \alpha(\hat{s}) m_q / \sqrt{\hat{s}}$

Inclusive A+B->C+X: sum over all X particles

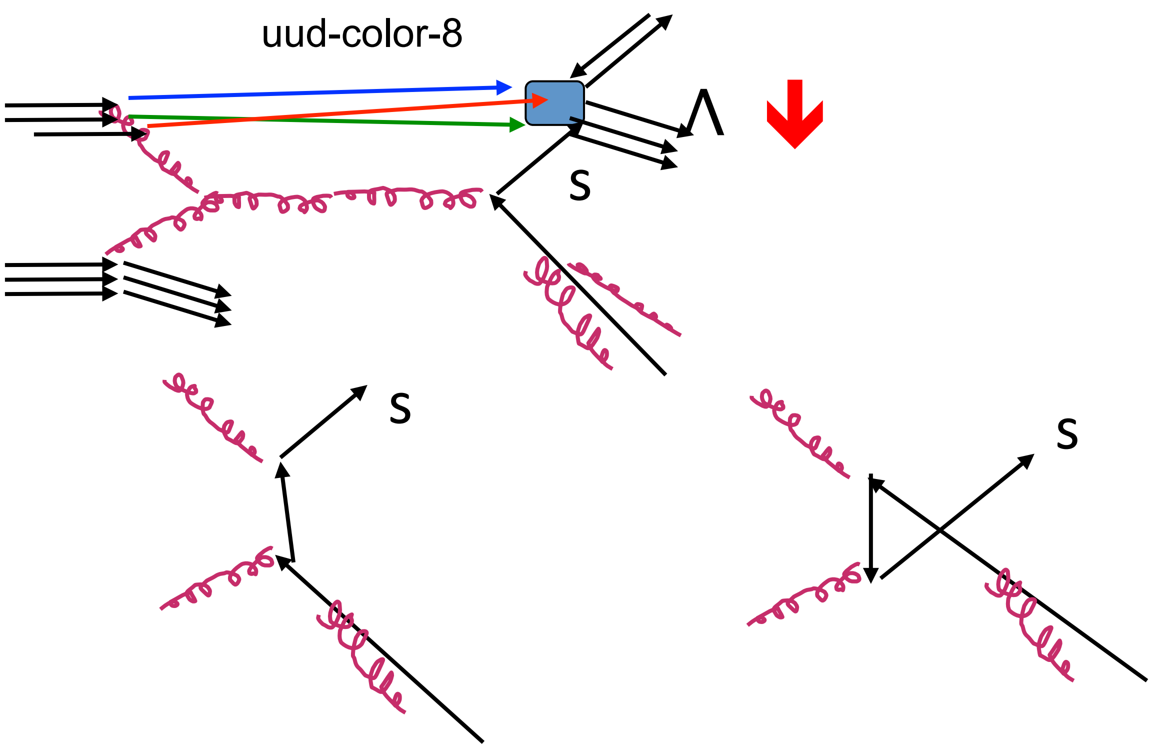
Possibly relate to A+B+anti-C forward elastic. GRG & J.F.Owens (76)

# Inclusives – peripheral vs. central



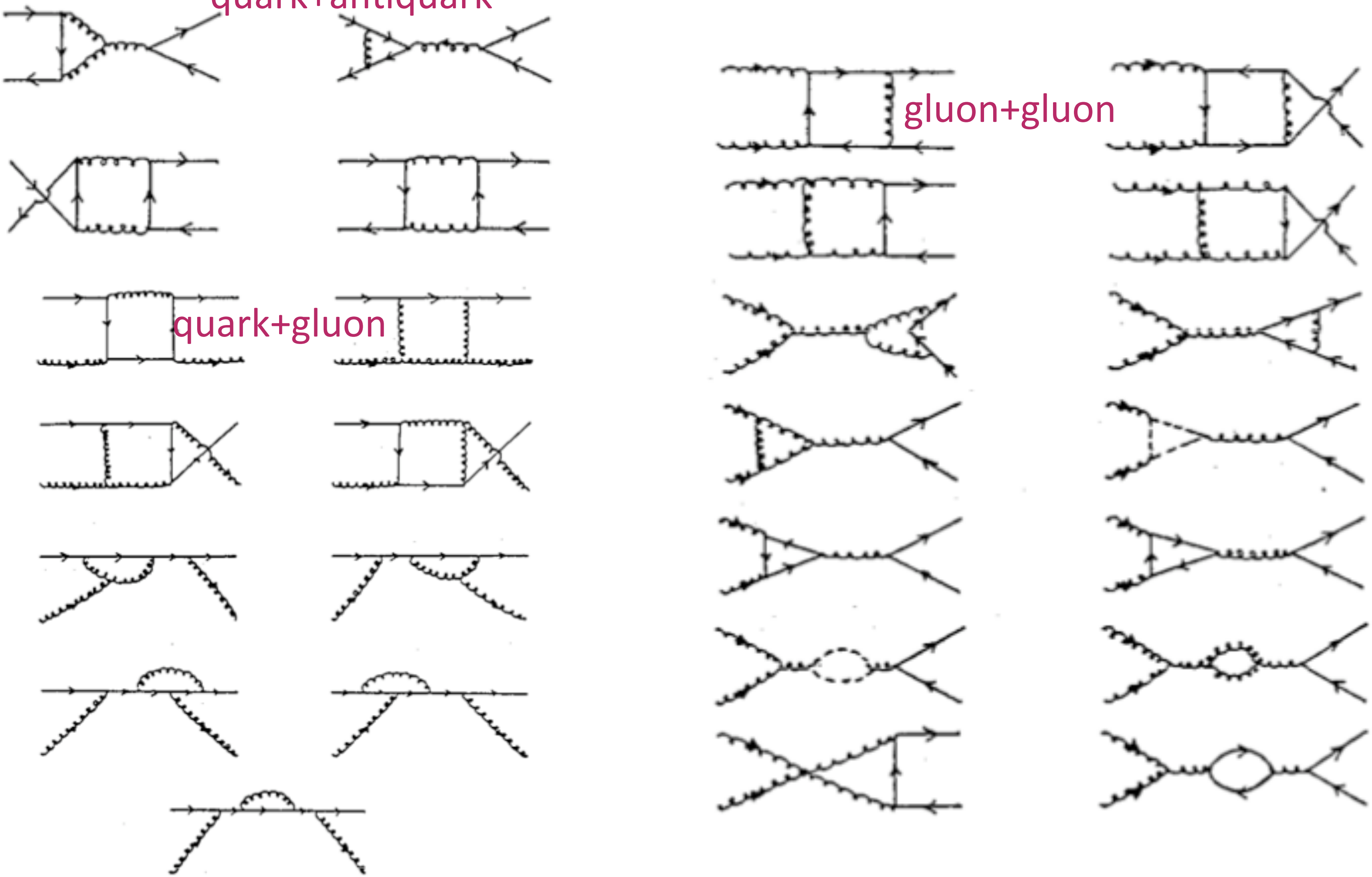



# PQCD lowest order
# g + g → s + s-bar



# Contributions to order $\alpha_S$ Imaginary Part

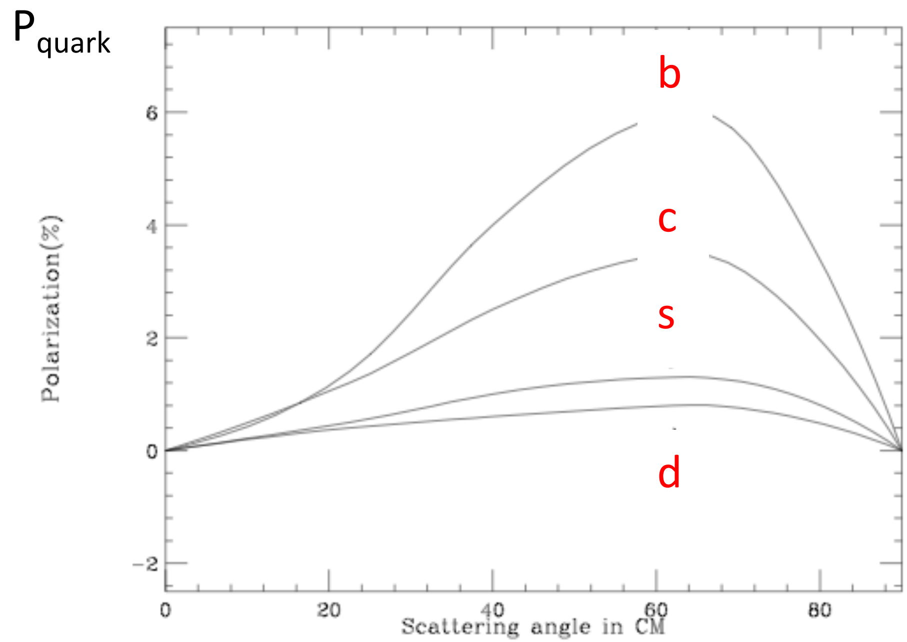
(Dharmaratna & GG 1990,1996)



$P_{quark}$ vs. flavor
from gluon fusion
grows with flavor

Does this give larger $P_{hadron}$ for heavier flavor?

What sets scales? quark “mass” or hyperon mass




g+g→Q+ X

Polzn(Q)~ $m_Q/\sqrt{s}$

Dharmaratna & GRG (1990,96,99)

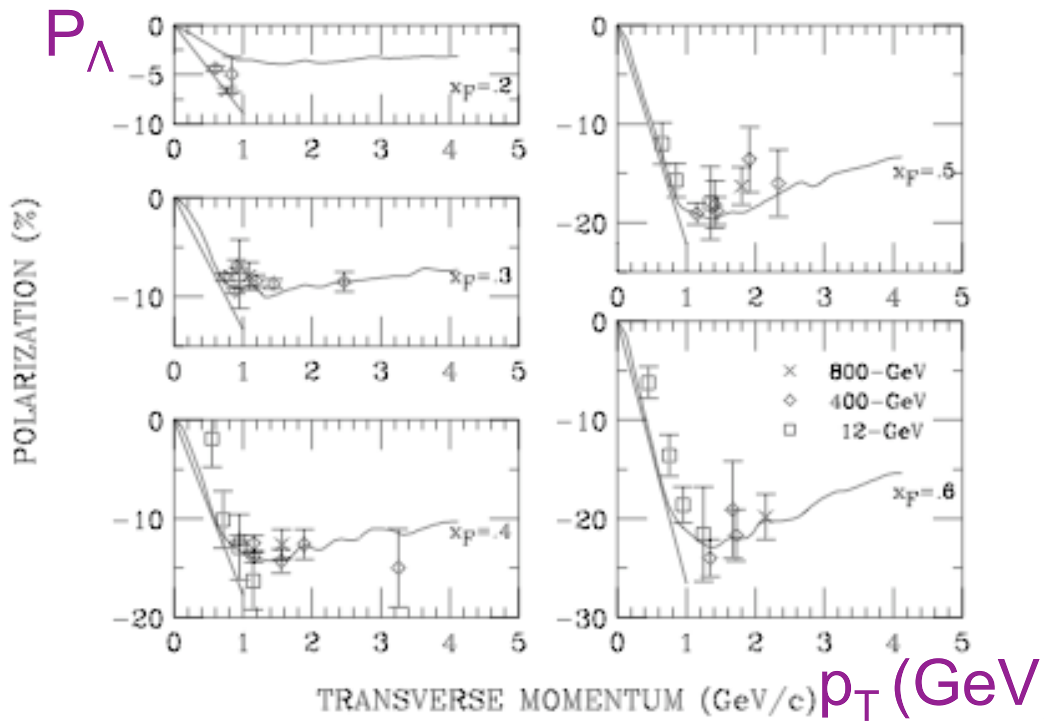
1. p+p $\rightarrow \Lambda\uparrow$ +X has large negative $P_\Lambda$ with flat s dependence & growth with $p_T$ (see Heller . . .)

2. Clues: $K^-$ p $\rightarrow \Lambda\uparrow$ +X at 176 GeV/c or $\sqrt{s}$=18GeV
Polzn even larger - need *s*-quark?

3. Simple factorization expectation
Kane, Pumplin, Repko
$P_\Lambda \sim \alpha(\hat{s}) m_q / \sqrt{\hat{s}}$

helicity flip ~ $m_q$/hard energy scale
Soft phenomenon?

Dharmaratna & GRG: 1. Gluon fusion dominant mechanism for producing polarized
massive quark pair
2. Low $p_T$ phenomenon
3. Recombination rules



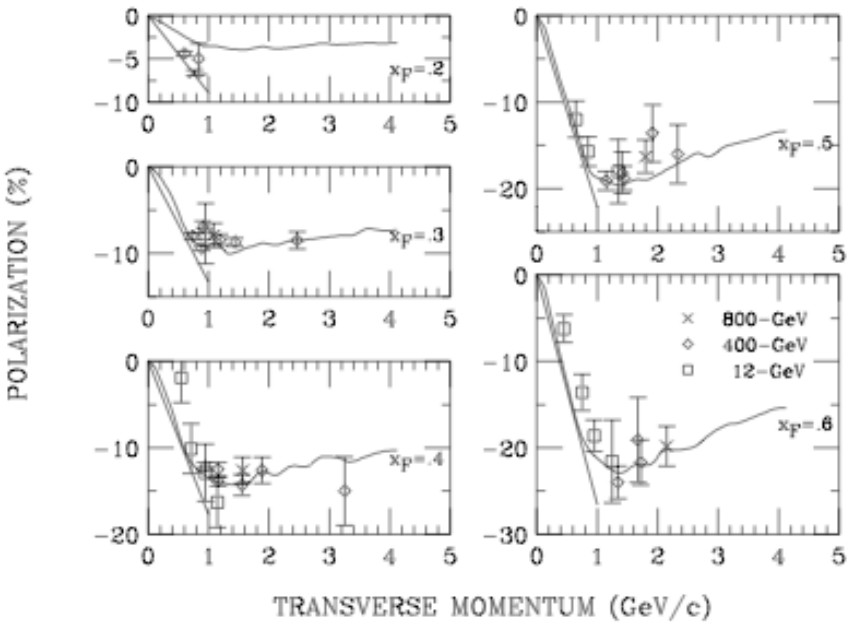

p+p$\rightarrow\Lambda$+ X Polzn($\Lambda$)
compiled by K.Heller (1997)

15

# Polarization in electroproduction?

- Consider electroproduction of $\Lambda$'s. Prelude to hadron production. QCD more under control.
  - Soft matrix elements from TMDs & SIDIS or GPDs &/or Fracture Functions
  - Measurements of $\Lambda$ polarization in e+p→e+K+$\Lambda$ are indeterminant, but small
  - Target polarization effects are legion: Sivers effect

# Large polarization in hadron+hadron




p+p→ Λ+ X Polzn($x_F$, $p_T$)
compiled by K.Heller (1997)

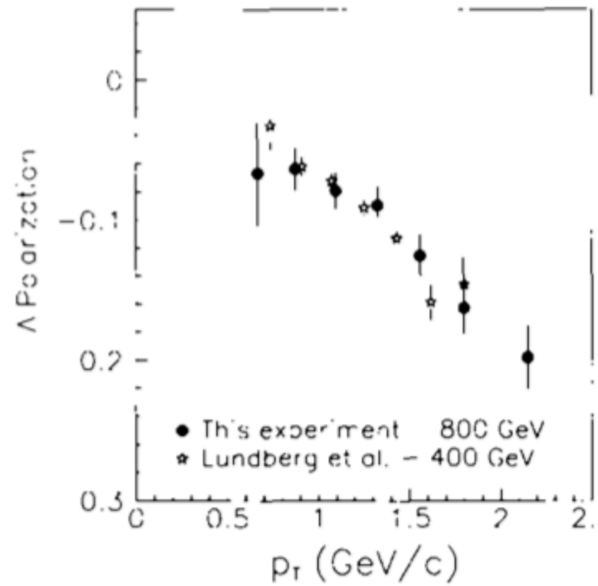



**Fig. 4. Lambda polarization versus production transverse momentum ($p_T$). For comparison, data for 400 GeV production (Ref. 10) are also shown.**

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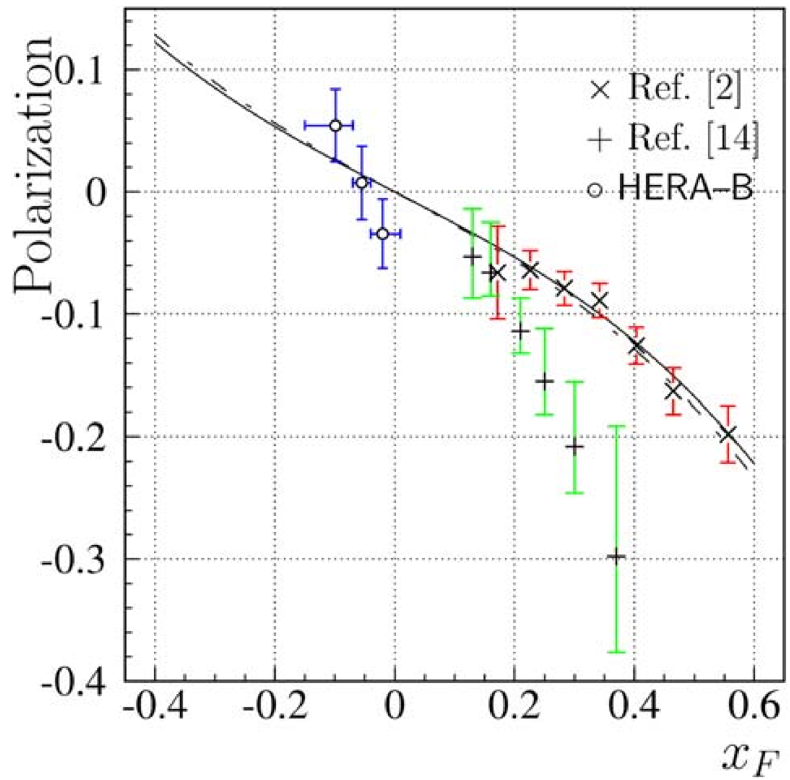
# Recent collection of data




P+fixed target HERA-B

Fig. 4. $\Lambda$ polarization dependence on $x_F$. The curves correspond to Eq. (2) [13] for infinite $p_\perp$ (dashed curve) and for the measured $\langle p_\perp \rangle$ (solid curve).

*HERA-B Collaboration / Physics Letters B 638 (2006) 415–421*

# Evolving Ideas about Source of L Polarization in Hadrons

- Semi-classical: Lund; Thomas precession; SU(6)
- Q Field Th: Single polarization requires interference =>Real x Im part & helicity flip
- Kane, Pumplin, Repko: PQCD (PRL41,1689(1978)→$P_L$~ $\alpha(\hat{s})m_q / \sqrt{\hat{s}}$
- Complete order $a_s$ calculation of quark, antiquark, gluon 2-body scattering →*s*⇑+*s*bar imbedded in hadron+hadron pdf's (but small $m_S$) (Dharmaratna & GG 1990,1996)
- How does s⇑ get translated to Λ⇑ & enhanced?
- Soft "Recombination" with (ud) remnant of N.
- Final State Interactions
- **NPQCD must play a significant role in our understanding of orbital angular momentum & hadron formation.**

$$P_{\text{ext}}(x_F, p_\perp) = \left(C_1 x_F + C_2 x_F^3\right)\left(1 - e^{C_3 p_\perp^2}\right). \qquad (2)$$

The fitted coefficients are: $C_1 = -0.268 \pm 0.003$, $C_2 = -0.338 \pm 0.015$ and $C_3 = -4.5 \pm 0.6\ (\text{GeV}/c)^{-2}$.

Curve from Lundberg, *et al*.
Ref.2 Ramberg E799 PLB 338, 403 (1994)
Ref.14 NA48 (SPS) EPJ C6, 265 (1999)

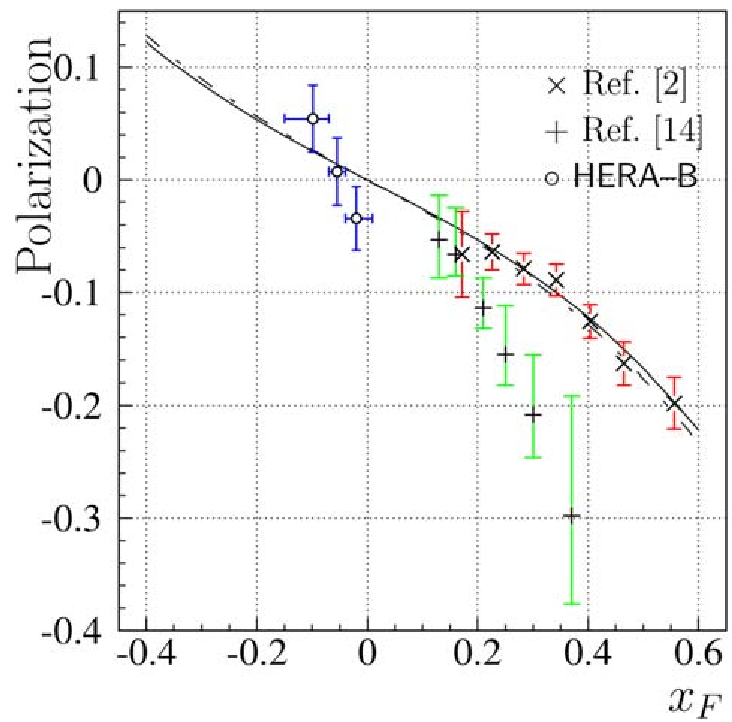
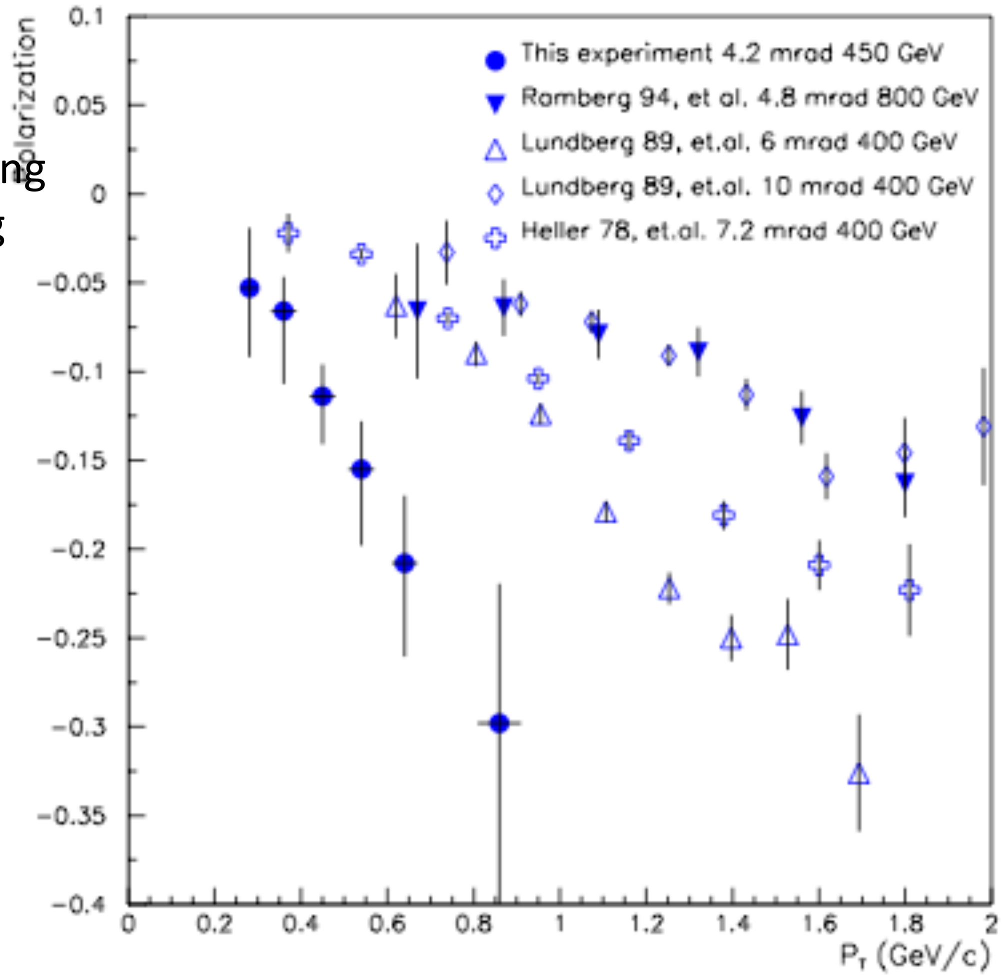



Fig. 4. $\Lambda$ polarization dependence on $x_F$. The curves correspond to Eq. (2) [13] for infinite $p_\perp$ (dashed curve) and for the measured $\langle p_\perp \rangle$ (solid curve).

# Polarization experiments up to 1999

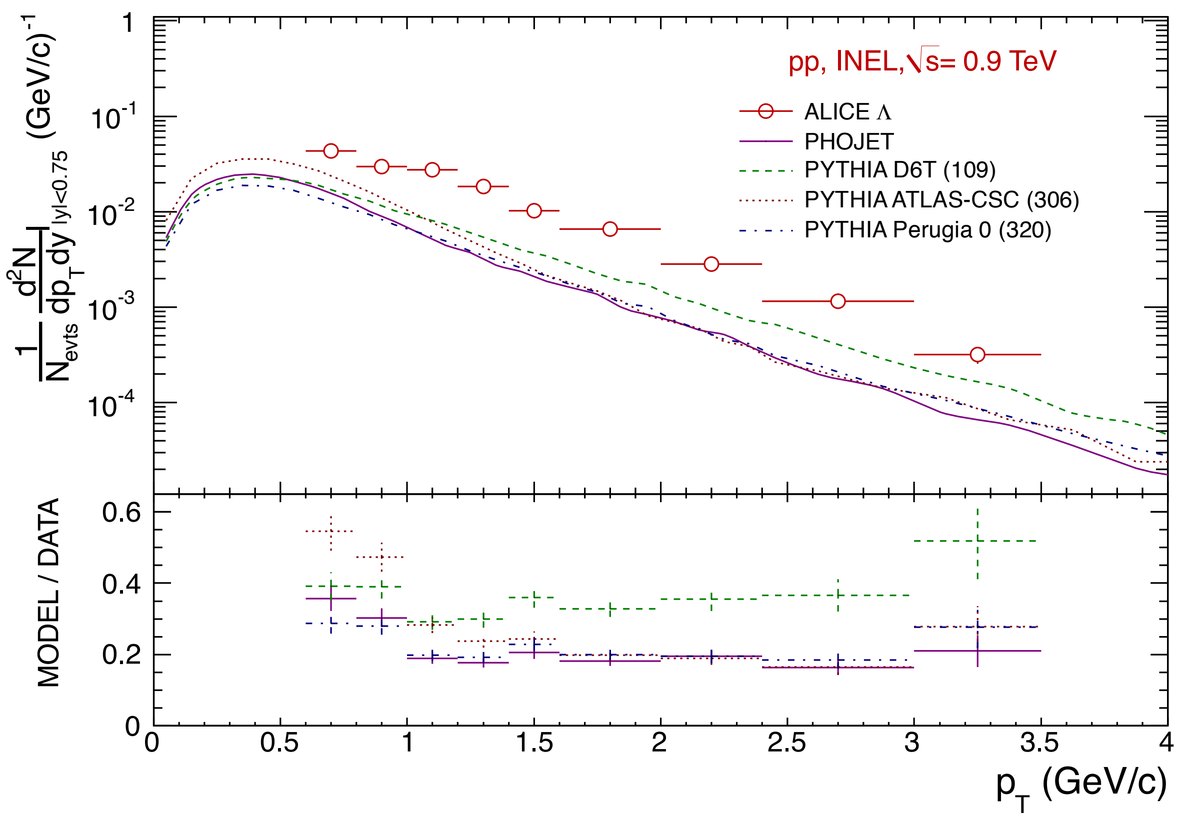
NA48 V.Fanti, *et al.* E.P.J. C6, 265 (1999)

Order of increasing $p_T$ corresponding $x_F$
0.13
0.16
0.21
0.25
0.30
0.37

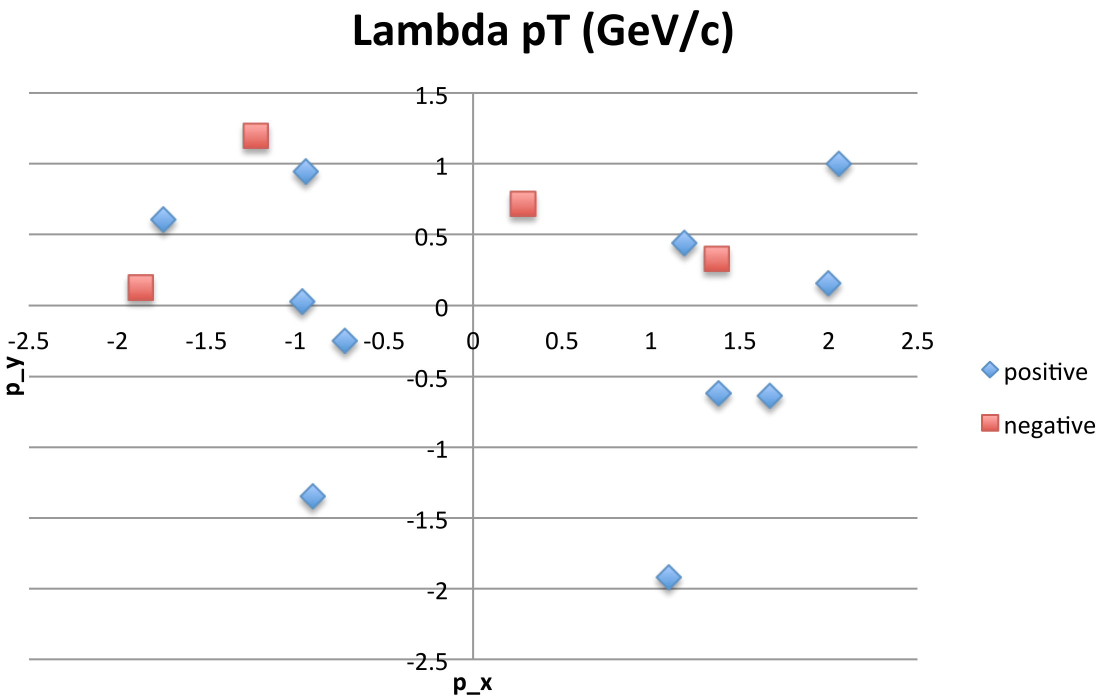


# Λ from ALICE at 0.9 TeV (|y|<0.75) Unpolarized cross section

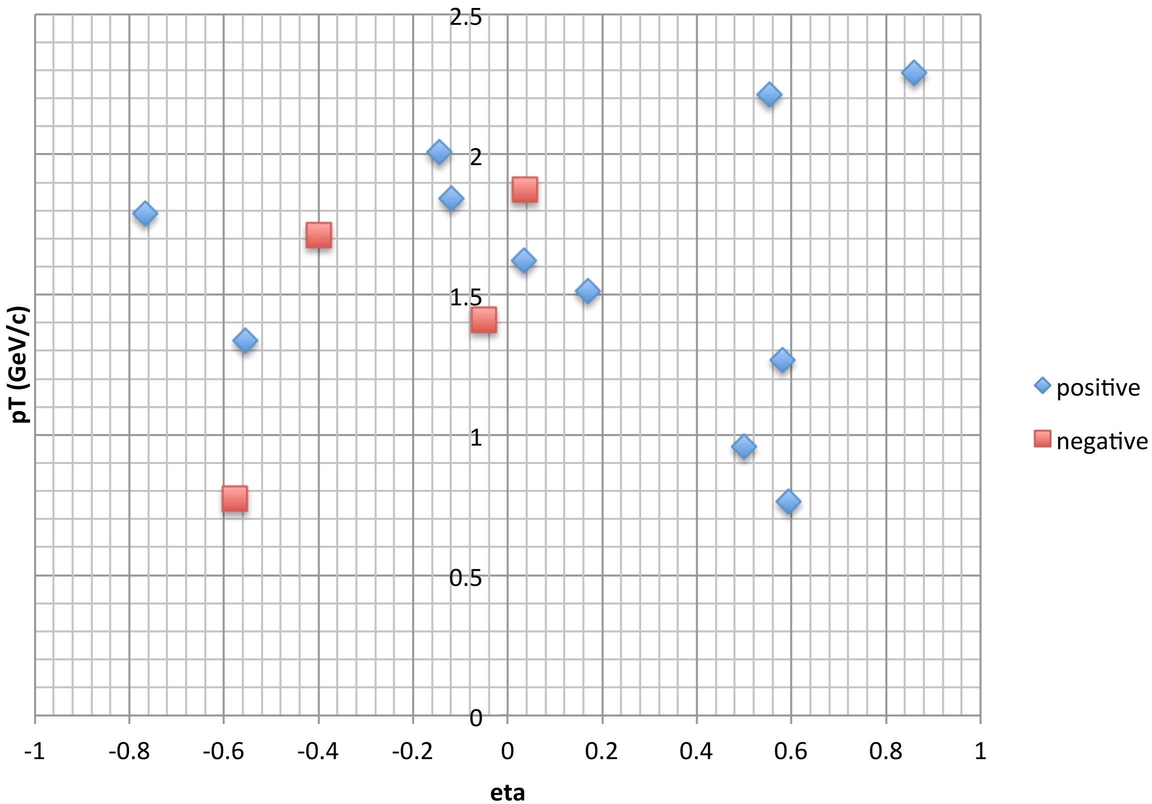
## hep-ex:1012.3257 Fig.16



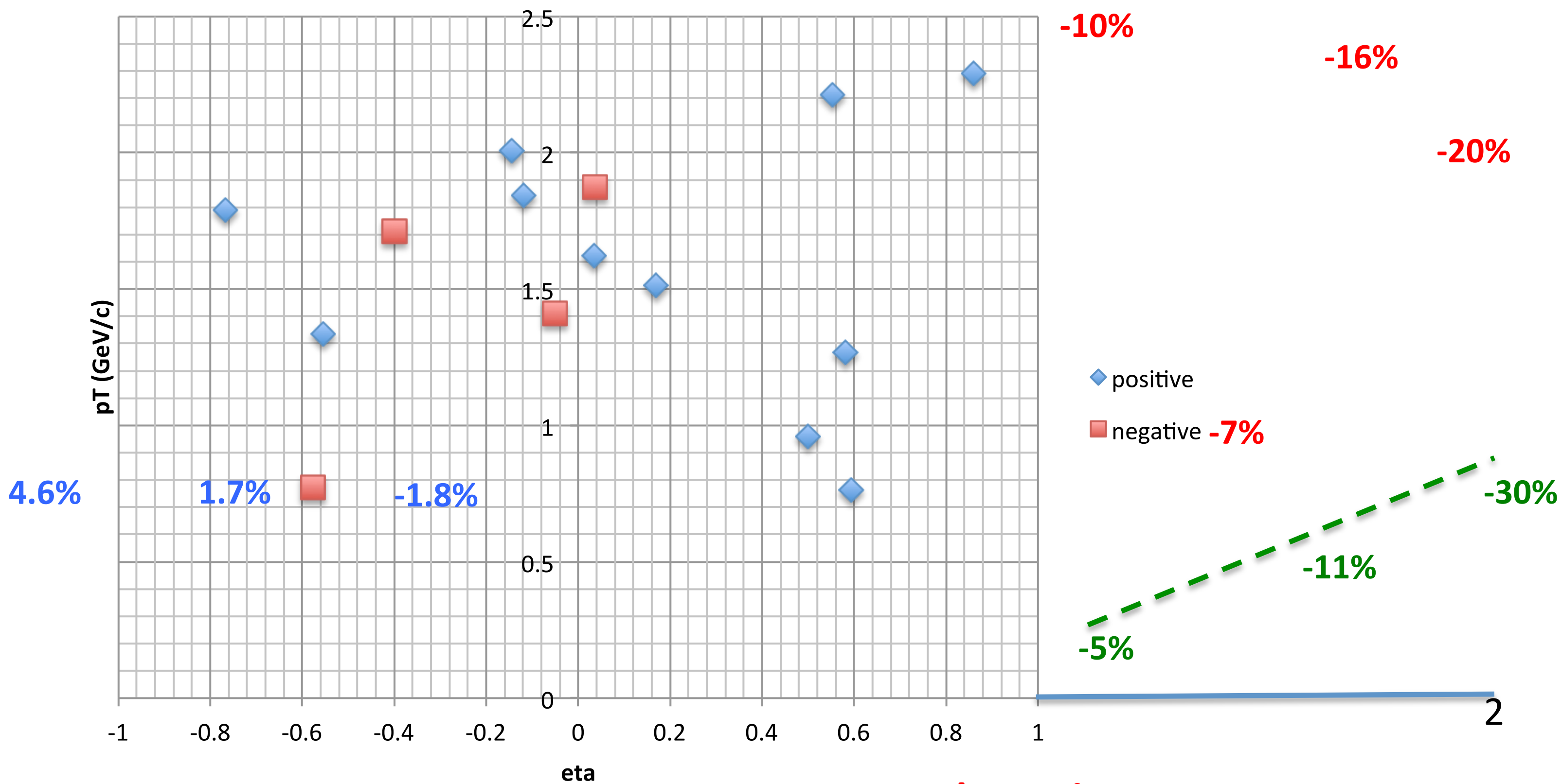
# $p_T$ event distribution
# Λ polarization “Vector’s” Slide 15



# $p_T$ vs. η event distribution Λ polarization "Vector's" Slide 15



# $p_T$ vs. η & y *comparing* -15%




**Polzn points**: FNAL 400GeV on Be

Plot of y & $p_T$

**Polzn points**: NA48 450 GeV on N

**Polzn points**: HERA-B sqrt(s) 41.6GeV on C & W

# Polarization measurements (y,$p_T$)

| y & xF for FNAL @ 400GeV on Be | | | | |
|---|---|---|---|---|
| xF | pT | mT | y | Polzn percent |
| 0.2 | 0 | 1.116 | 1.650553888 | |
| 0.2 | 1 | 1.498484568 | 1.383257094 | -7 |
| 0.3 | 0 | 1.116 | 2.035682047 | |
| 0.3 | 2.5 | 2.737783045 | 1.213524278 | -10 |
| 0.4 | 0 | 1.116 | 2.315946925 | |
| 0.4 | 3.2 | 3.389019917 | 1.276429821 | -15 |
| 0.5 | 0 | 1.116 | 2.535601107 | |
| 0.5 | 2.4 | 2.646782197 | 1.699677814 | -16 |
| 0.6 | 0 | 1.116 | 2.716011852 | |
| 0.6 | 2.2 | 2.466871703 | 1.939323634 | -20 |

y & xF for HERA-B @ sqrt(s) 41.6 GeV on C & W

| | | | | |
|---|---|---|---|---|
| -0.099 | 0.82 | 1.384866781 | -1.187491366 | 0.046 |
| -0.054 | 0.81 | 1.37896918 | -0.743967498 | 0.017 |
| -0.02 | 0.84 | 1.396802062 | -0.293587387 | -0.018 |

**Table 1.** The mean values of $p_t$, $x_F$ and $P_x$ measured in corresponding $p_t$ intervals (systematic errors are presented following the statistical errors)

| $p_t$ interval [GeV/c] | $p_t$ [GeV/c] | $x_F$ | $P_x$ |
|---|---|---|---|
| 0.2 - 0.3 | $0.28 \pm 0.02$ | $0.13 \pm 0.01$ | $-0.053 \pm 0.034^{+0.001}_{-0.019}$ |
| 0.3 - 0.4 | $0.36 \pm 0.03$ | $0.16 \pm 0.01$ | $-0.066 \pm 0.018^{+0.007}_{-0.037}$ |
| 0.4 - 0.5 | $0.45 \pm 0.03$ | $0.21 \pm 0.01$ | $-0.114 \pm 0.017^{+0.006}_{-0.021}$ |
| 0.5 - 0.6 | $0.54 \pm 0.03$ | $0.25 \pm 0.01$ | $-0.155 \pm 0.025^{+0.010}_{-0.035}$ |
| 0.6 - 0.7 | $0.64 \pm 0.03$ | $0.30 \pm 0.01$ | $-0.208 \pm 0.035^{+0.015}_{-0.039}$ |
| 0.7 - 1.0 | $0.86 \pm 0.05$ | $0.37 \pm 0.02$ | $-0.298 \pm 0.074^{+0.026}_{-0.077}$ |

# Gluon fusion – tree level

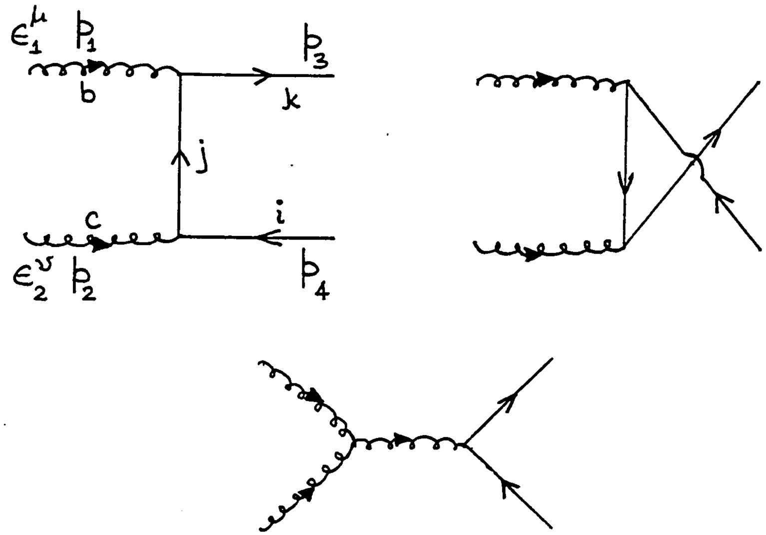



Figure 3.4: Lowest order Feynman diagrams for Gluon Fusion.

6 independent helicity amps

$\Phi_1$ $(++ \to ++)$

$\Phi_2$ $(++ \to --)$

$\Phi_3$ $(+- \to +-)$

$\Phi_4$ $(+- \to -+)$

$\Phi_5$ $(++ \to -+)$

$\Phi_6$ $(+- \to ++)$

$$\mathcal{M} = -g^2(\lambda^c\lambda^b)_{ik}\Big[\frac{\bar{u}(p_3)[2p_3.\epsilon_1 - \not{\epsilon}_1\not{p}_1]\not{\epsilon}_2 v(p_4)}{2p_1.p_3} + \big(\bar{u}(p_3)\frac{\gamma^\kappa}{\hat{s}}v(p_4)\big)C_{\mu\nu\kappa}\epsilon_1^\mu\epsilon_2^\nu\Big]$$
$$-g^2(\lambda^b\lambda^c)_{ik}\Big[\frac{\bar{u}(p_3)\not{\epsilon}_2[\not{p}_1\not{\epsilon}_1 - 2p_4.\epsilon_1]v(p_4)}{-2p_1.p_4} - \big(\bar{u}(p_3)\frac{\gamma^\kappa}{\hat{s}}v(p_4)\big)C_{\mu\nu\kappa}\epsilon_1^\mu\epsilon_2^\nu\Big],$$

where

$$C_{\mu\nu\kappa} = g_{\mu\nu}(p_1 - p_2)_\kappa + g_{\nu\kappa}(2p_2 + p_1)_\mu + g_{\kappa\mu}(-2p_1 - p_2)_\nu.$$

# Gluon fusion -- cont'd

$$\phi_\alpha = -g^2[(\lambda^c\lambda^b)_{ik} f_\alpha + (\lambda^b\lambda^c)_{ik} h_\alpha]$$

$f_\alpha$ and $h_\alpha$ ($\alpha$ takes 1 to 6) are

$$f_1 = \frac{m(p+k)}{p(p-k\cos\theta)} \qquad h_1 = \frac{m(p+k)}{p(p+k\cos\theta)}$$

$$f_2 = \frac{-m(p-k)}{p(p-k\cos\theta)} \qquad h_2 = \frac{-m(p-k)}{p(p+k\cos\theta)}$$

$$f_3 = \frac{4k\sin\frac{\theta}{2}\cos^3\frac{\theta}{2}}{(p-k\cos\theta)} \qquad h_3 = \frac{4k\sin\frac{\theta}{2}\cos^3\frac{\theta}{2}}{(p+k\cos\theta)}$$

$$f_4 = \frac{4k\sin^3\frac{\theta}{2}\cos\frac{\theta}{2}}{(p-k\cos\theta)} \qquad h_4 = \frac{4k\sin^3\frac{\theta}{2}\cos\frac{\theta}{2}}{(p+k\cos\theta)}$$

$$f_5 = 0 \qquad h_5 = 0$$

$$f_6 = \frac{-4mk\sin^2\frac{\theta}{2}\cos^2\frac{\theta}{2}}{p(p-k\cos\theta)} \qquad h_6 = \frac{-4mk\sin^2\frac{\theta}{2}\cos^2\frac{\theta}{2}}{p(p+k\cos\theta)}$$

p & k are initial & final CM momenta
$\boldsymbol{\theta}$ is $p_3$ polar angle
Relate to $x_1$, $x_2$
$p_L$ , $p_T$

# 2-body interpretation g+g→ s+s-bar →Λ+Λbar

$$\frac{d\sigma}{dt} = \frac{1}{64\pi \hat{s} p^2} \frac{|\mathcal{M}|^2}{4}$$

$$\frac{|\mathcal{M}|^2}{4} = \frac{1}{2}\left[\Phi_1{}^2 + \Phi_2{}^2 + \Phi_3{}^2 + \Phi_4{}^2 + 2\Phi_5{}^2 + 2\Phi_6{}^2\right]$$

$$\mathcal{P} = 2Im \quad \frac{\left[\Phi_5(\Phi_1 + \Phi_2)^* + \Phi_6(\Phi_3 - \Phi_4)^*\right]}{\left[\Phi_1^2 + \Phi_2^2 + \Phi_3^2 + \Phi_4^2 + 2\Phi_5^2 + 2\Phi_6^2\right]}$$

# Inclusive polarization & optical theorem

$$s\,\frac{d^2\sigma}{dt\,dM_X^2} = \frac{1}{(2s_a+1)}\,\frac{1}{(2s_b+1)}\,\frac{1}{32\pi^2 s}\sum_{abc\Delta}\sum_{i=1}^{\infty}\int d\phi_i\,|f^{(i)}_{c\Delta,ab}(s,t,M_X^2)|^2$$

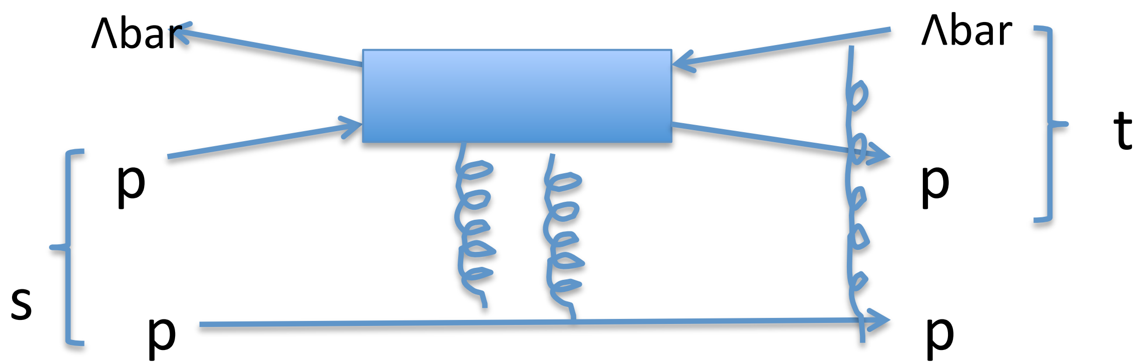
$$Dg_{a'b'\bar{c}',\,ab\bar{c}}(s,t,M_X^2) = \tfrac{1}{2}\sum_{X,\Delta} f_{c\Delta,ab}\,f^{*}_{c'\Delta,a'b'}$$

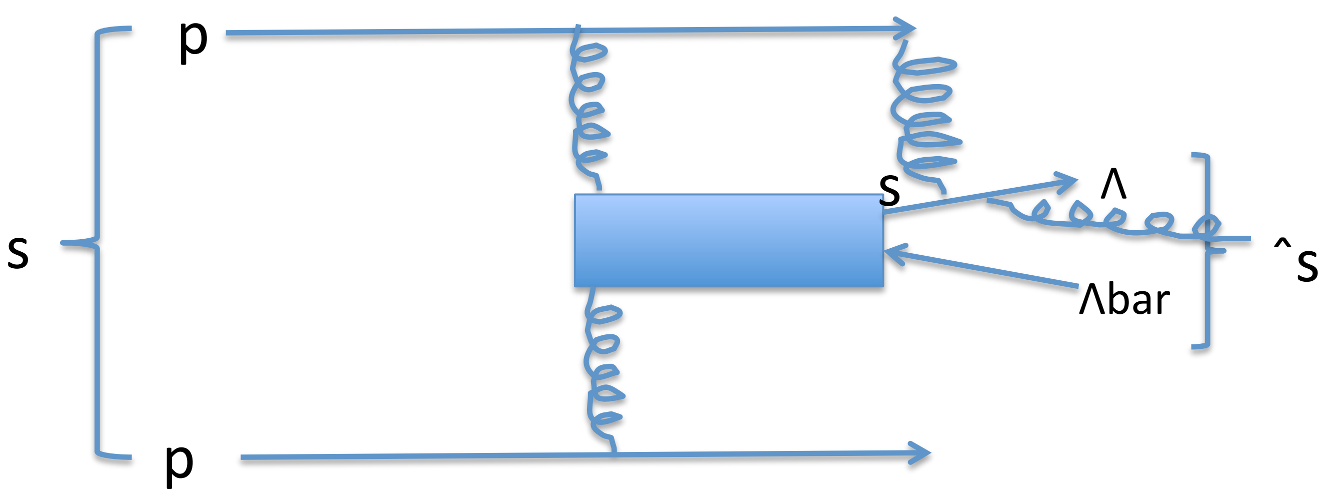
$$\rho^{f}_{cc'}(A,B) = (2s_a+1)(2s_b+1)\,\frac{\sum_X \sum_{aa'bb'\Delta} f_{c\Delta,ab}\,\rho^{(A,B)}_{aa'bb'}\,f^{*}_{c'\Delta,a'b'}}{\sum_X \sum_{abc\Delta} |f_{c\Delta,ab}|^2}$$

p+p→ Λ + X  20 helicity amps – 4 combinations in *Polzn*

$$P = \frac{2\sum_{ab} \mathrm{Im}\,Dg_{ab+,ab-}}{\sum_{ab\bar{c}} Dg_{ab\bar{c},\,ab\bar{c}}} = \sin\theta\,\frac{\sum_{ab} \mathrm{Im}\,D\bar{g}_{ab+,ab-}}{\sum_{ab\bar{c}} Dg_{ab\bar{c},\,ab\bar{c}}}.$$

# Inclusives – peripheral vs. central



# Questions

Is $x_F$ or y the significant scaled momentum variable?

Are there rapidity gaps around central region Λ ‘s or graduated central emissions ?

Does s-quark or Λ rescatter before or after central creation?