Top quark polarization and gluon spin and transversity in the nucleon

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SPIN 2023
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Abstract

Top pair production at LHC is a prime example of production that proceeds primarily via gluon fusion. Decays of polarized top pairs through various channels produce a variety of correlations among the decay products - particles and jets. Combinations of the gluon distributions, either polarized or unpolarized, can be accessed experimentally through angular dependences of decay products, as will be shown, along with predictions from a spectator model of gluon distributions.

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3) Old Dominion/Jlab/Torino

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- GRG, Liuti, DPF 2017, 1710.01683

OUTLINE

- **Gluon pdf's, TMD's, GPD's, in Model– Reggeized spectator "flexible parameterization"**
- **Gluon distributions Polarized Gluons? Transversity & GPDs**
- **t+t-bar production & decay can measure Gluon polarization in p+p @ LHC**
- **Some Observable quantities**

GPD definitions – 8 quark + 8 gluon (twist 2)

Momentum space nucleon matrix elements of quark field correlators

Chiral even GPDs
-> Ji sum rule

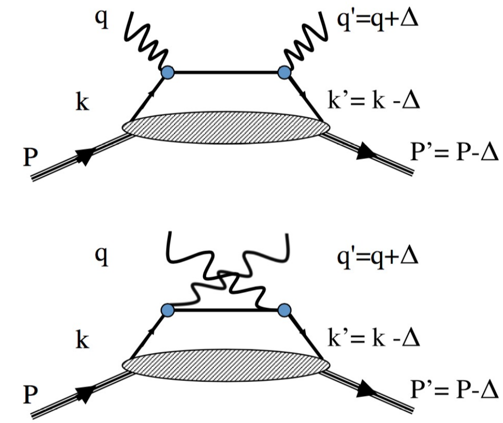
see, e.g. M. Diehl, Eur. Phys. J. C 19, 485 (2001).

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\, \bar{\psi}(-\tfrac{1}{2}z)\,\gamma^+\psi(\tfrac{1}{2}z)\;|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$

$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[H^q\gamma^+ + E^q\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}\right]u(p,\lambda),$$

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\, \bar{\psi}(-\tfrac{1}{2}z)\,\gamma^+\gamma_5\,\psi(\tfrac{1}{2}z)\;|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$

$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[\tilde{H}^q\gamma^+\gamma_5 + \tilde{E}^q\frac{\gamma_5\Delta^+}{2m}\right]u(p,\lambda),$$



$$\left\langle J_q^x \right\rangle = \tfrac{1}{2}\int dx\left[H(x,0,0)+E(x,0,0)\right]x$$

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\, \bar{\psi}(-\tfrac{1}{2}z)\, i\sigma^{+i}\,\psi(\tfrac{1}{2}z)\;|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$

$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\Bigg[H_T^q\, i\sigma^{+i} + \tilde{H}_T^q\,\frac{P^+\Delta^i - \Delta^+P^i}{m^2}$$

$$+ E_T^q\,\frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde{E}_T^q\,\frac{\gamma^+P^i - P^+\gamma^i}{m}\Bigg]u(p,\lambda$$

Chiral odd GPDs
-> transversity
How to measure and/or parameterize them?

Gluon GPDs

$$\frac{1}{\bar{P}^+}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle P',\Lambda'|G^{+i}(-\frac{1}{2}z)G^{+i}(\frac{1}{2}z)|P,\Lambda\rangle\Big|_{z^+=0,\vec{z}_T=0} =$$

$$\frac{1}{2\bar{P}^+}\bar{U}(P',\Lambda')[H^g(x,\xi,t)\gamma^+ + E^g(x,\xi,t)\frac{i\sigma^{+\alpha}(-\Delta_\alpha)}{2M}]U(P,\Lambda)$$

Even t-channel parity & Gluon helicity conserving

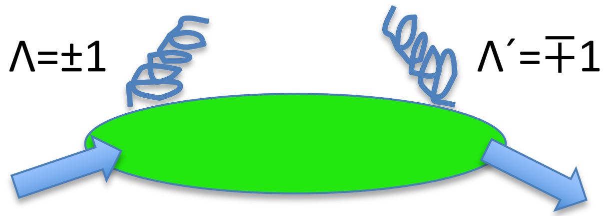
$$\frac{-i}{\bar{P}^+}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle P',\Lambda'|G^{+i}(-\frac{1}{2}z)\tilde{G}^{+i}(\frac{1}{2}z)|P,\Lambda\rangle\Big|_{z^+=0,\vec{z}_T=0} =$$

$$\frac{1}{2\bar{P}^+}\bar{U}(P',\Lambda')[\tilde{H}^g(x,\xi,t)\gamma^+\gamma_5 + \tilde{E}^g(x,\xi,t)\frac{\gamma_5(-\Delta^+)}{2M}]U(P,\Lambda)$$

Odd t-channel parity & Gluon helicity conserving

Gluon GPDs

Extension to Gluon "Transversity"



$$
-\frac{1}{P^+}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\, \mathbf{S} F^{+i}(-\tfrac{1}{2}z)\, F^{+j}(\tfrac{1}{2}z)\, |p,\lambda\rangle \Big|_{z^+=0,\, \mathbf{z}_T=0}
$$

$$
= \mathbf{S}\, \frac{1}{2P^+}\, \frac{P^+\Delta^j - \Delta^+ P^j}{2mP^+}
$$

$$
\times\ \bar{u}(p',\lambda') \Bigg[H_T^g\, i\sigma^{+i} + \tilde{H}_T^g\, \frac{P^+\Delta^i - \Delta^+P^i}{m^2}
$$

$$
+ E_T^g\, \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde{E}_T^g\, \frac{\gamma^+P^i - P^+\gamma^i}{m} \Bigg] u(p,\lambda).
$$

4 GPDs: see M.Diehl, EPJC19, 485 (2001)

Gluon & Sea quark distributions
Spectator Model

– generalize Regge-diquark spectator model

- N→ ***g*** + "color octet N" spectator ($8\otimes8\supset1$)

  (could be spin ½ or 3/2)
- (N→ ***anti-u*** + color 3 "tetraquark"uuud)

- How to normalize?

$$H_g(x,\xi,t)_{Q^2} \rightarrow H_g(x,0,0)_{Q^2} = xG(x)_{Q^2}$$

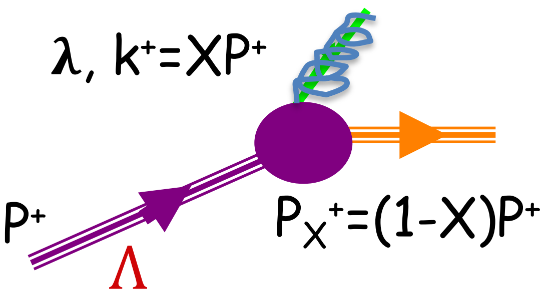
Evolution & small x phenomenology

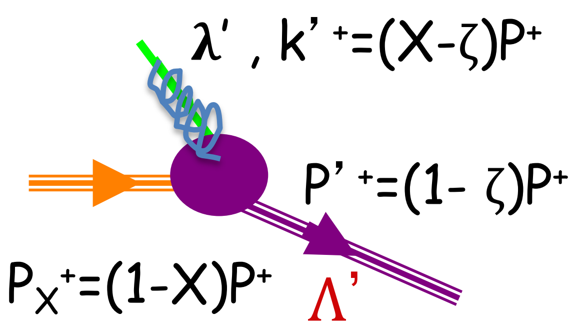
- Sea quark distributions $H_{anti\text{-}u}(x,0,0)$ . . .

- Use pdf's to fix x dependence

- Small x ~ Pomeron

Gluon 'vertex functions' $\mathcal{G}_{\Lambda x\,;\,\Lambda g,\,\Lambda}$





$\mathcal{G}_{+++}(x,\vec{k}_T^2)$	$-\frac{2}{\sqrt{2(1-X)}}\frac{(k_x-ik_y)}{X}$
$\mathcal{G}_{-++}(x,\vec{k}_T^2)$	$-\frac{2}{\sqrt{2(1-X)}}(M(1-X)-M_x)$
$\mathcal{G}_{++-}(x,\vec{k}_T^2)$	0
$\mathcal{G}_{-+-}(x,\vec{k}_T^2)$	$-\frac{2}{\sqrt{2(1-X)}}(1-X)\frac{(k_x-ik_y)}{X}$
$\mathcal{G}^*_{+++}(x,\vec{k}_T'^2)$	$-\frac{2}{\sqrt{2(1-X')}}\frac{(\tilde{k}_x+i\tilde{k}_y)}{X'}$
$\mathcal{G}^*_{-++}(x,\vec{k}_T'^2)$	$-\frac{2}{\sqrt{2(1-X')}}(M(1-X')-M_x)$
$\mathcal{G}^*_{++-}(x,\vec{k}_T'^2)$	0
$\mathcal{G}^*_{-+-}(x,\vec{k}_T'^2))$	$-\frac{2}{\sqrt{2(1-X')}}(1-X')\frac{(\tilde{k}_x+i\tilde{k}_y))}{X'}$

$$X' = \frac{X-\zeta}{1-\zeta},\ \tilde{k}_{i=1,2} = k_i - \frac{1-X}{1-\zeta}\Delta_i$$

GG & S. Liuti, QCD Evolution 2014, IJMP: Conf. 37, 1560038 (2015);
GG, Gonzalez Hernandez, Liuti, Poage, in progress

Gluon "transversity"? Double helicity flip *does not mix* with quark distributions

Transversity for on-shell gluons or photons : no |0> helicity

$$|+1)_{trans} = \{|+1> + |-1>\}/2 = |-1)_{trans}$$

$$|\hat{0})_{trans} = \{|+1> - |-1>\}/\sqrt{2}$$

$$\text{helicity } |\pm 1> = \{-/+\hat{x} - i\hat{y}\}/\sqrt{2}$$

$$\hat{x} = -|0)_{trans} = P_{parallel}$$ **Linear polarization in the plane**

$$\hat{y} = i\sqrt{2}\,|+1)_{trans} = P_{normal}$$ **Linear polarization normal to the plane**

GG&M.J.Moravcsik, Ann.Phys.195,213(1989).

Construct helicity flip amps Spectator Model, then GPDs

$$A_{++,+-} = \sqrt{1-\xi^2}\,\frac{t_0-t}{4M^2}\Big(\tilde{H}_T^g + (1-\xi)\frac{E_T^g+\tilde{E}_T^g}{2}\Big)$$

$$A_{-+,--} = \sqrt{1-\xi^2}\,\frac{t_0-t}{4M^2}\Big(\tilde{H}_T^g + (1+\xi)\frac{E_T^g-\tilde{E}_T^g}{2}\Big)$$

$$A_{++,--} = +e^{-i\phi}(1-\xi^2)\frac{\sqrt{t_0-t}}{2M}\Big(H_T^g + \frac{t_0-t}{M^2}\tilde{H}_T^g - \frac{\xi^2}{1-\xi^2}E_T^g + \frac{\xi}{1-\xi^2}\tilde{E}_T^g\Big)$$

$$A_{-+,+-} = -e^{i\phi}(1-\xi^2)\frac{\sqrt{t_0-t}^3}{8M^3}\tilde{H}_T^g,$$

Compare to spectator model results

$$\tilde{H}_T^g = 0$$

$$(1-X)A^0_{-+.--} = (1-X')A^0_{++,+-}$$

$$\tilde{E}_T^g = 0.$$

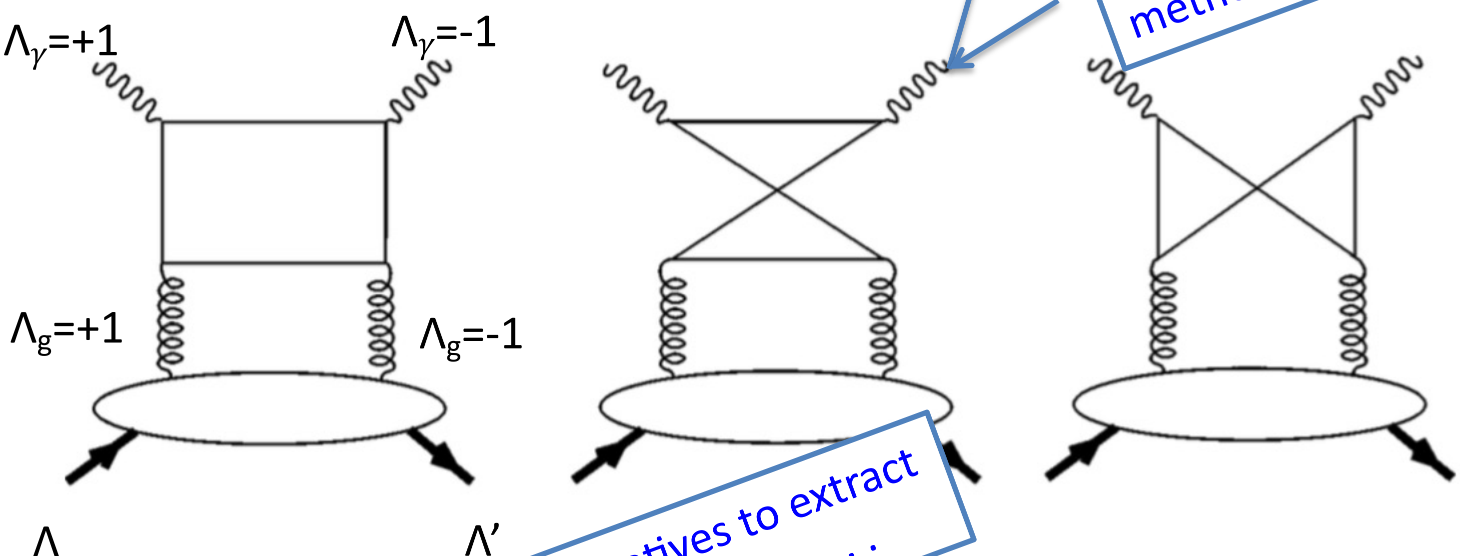
As in Hoodbhoy & Ji, PRD58, 054006 (1998)

$A_{\Lambda',-1;\Lambda,+1}$ contributes to DVCS ~ α_s

$$M_{\Lambda',\Lambda'\gamma=-1;\Lambda,\Lambda\gamma=+1} = -\frac{\alpha s}{2\pi}\sum_q e_q^2 \int_{-1}^{+1} dx \frac{A_{\Lambda',\Lambda' g=-1;\Lambda,\Lambda g=+1}(x,\xi,t)}{(\xi - x - i\varepsilon)(\xi + x - i\varepsilon)} \; C'(x,\xi,Q^2)$$

Interference with Bethe-Heitler contains *cos*3φ modulation to distinguish from (leading twist) quark contribution

$\mu^- \mu^+$ alternative method to extract



other alternatives to extract J/ψ production; jets . . . .

See Hoodbhoy & Ji, PRD58, 054006 (1998)

Measuring Gluons in Nucleons

DVCS

$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}|T|^2$$

$$T(k,p,k',q',p') = T_{DVCS}(k,p,k',q',p') + T_{BH}(k,p,k',q',p').$$

$$|T|^2 = |T_{\rm BH} + T_{\rm DVCS}|^2 = |T_{\rm BH}|^2 + |T_{\rm DVCS}|^2 + \mathcal{I}\ .$$

$$\mathcal{I} = T^*_{BH}T_{DVCS} + T^*_{DVCS}T_{BH}.$$

For unpolarized e+p→e'+γ+p' cross section depends on azimuthal angle ϕ.
cos3ϕ modulation in interference dσ measures gluon transversity GPDs (CFF's)

$$\frac{\sqrt{t_0-t}^3}{8M^3}\left[H^g_TF_2 - E^g_TF_1 - 2\tilde{H}^g_T\left(F_1+\frac{t}{4M^2}F_2\right)\right]\cos 3\phi$$

$\mathcal{H}_T{}^g \sim \int dx\, H^g_T/(x-\xi)(x+\xi)$ CFF's

But $\mathcal{H}_T{}^g \sim$ may need EIC

See Diehl, *et al*. PLB411, 193 (1997);
Diehl, EPJC25, 223 (2002);
Belitsky, Mueller, PLB486, 369 (2000).

Alternative measurements of H_T^g

p+p → heavy hadron processes at LHC

favor gluon production mechanism

Particularly p+p→ t+tbar +X

via g + g→t+tbar

$xg(x) = H_g(x,0,0)$ for unpolarized gluons

$x\Delta g(x) = \tilde{H}_g(x,0,0)$ "helicity polarized" gluons

in longitudinally polarized target

$x\,\delta g(x) = H_T^g\,(x,0,0)$ "transversity polarized" gluons

in transversely polarized target

Requires gluon **helicity double flip** amps

What is known production of polarized tops?

Top Single Spin Asymmetry and Double Spin Correlations – Measurements

ATLAS PRD93, 012002 (2016) & ref. PRL114, 142001 (2015)

** SSA: B_1 or A_P =-0.035 +\- 0.040. (syst & stat)

*** Double: $C_{helicity}$ =0.315 +\- 0.07 vs. NLO QCD =0.31

(Bernreuther, et al., PRL 87,242002 (2001) QCD corrections but unpolarized gluons)

CMS PRL112, 182001 (2014): Different kinematics & selection criteria

** SSA: A_P=0.005+\- 0.01.

*** Double: $A_{\Delta\phi}=0.113$ +\- 0.01. vs. 0.110 +\- 0.001 (MC & QCD)

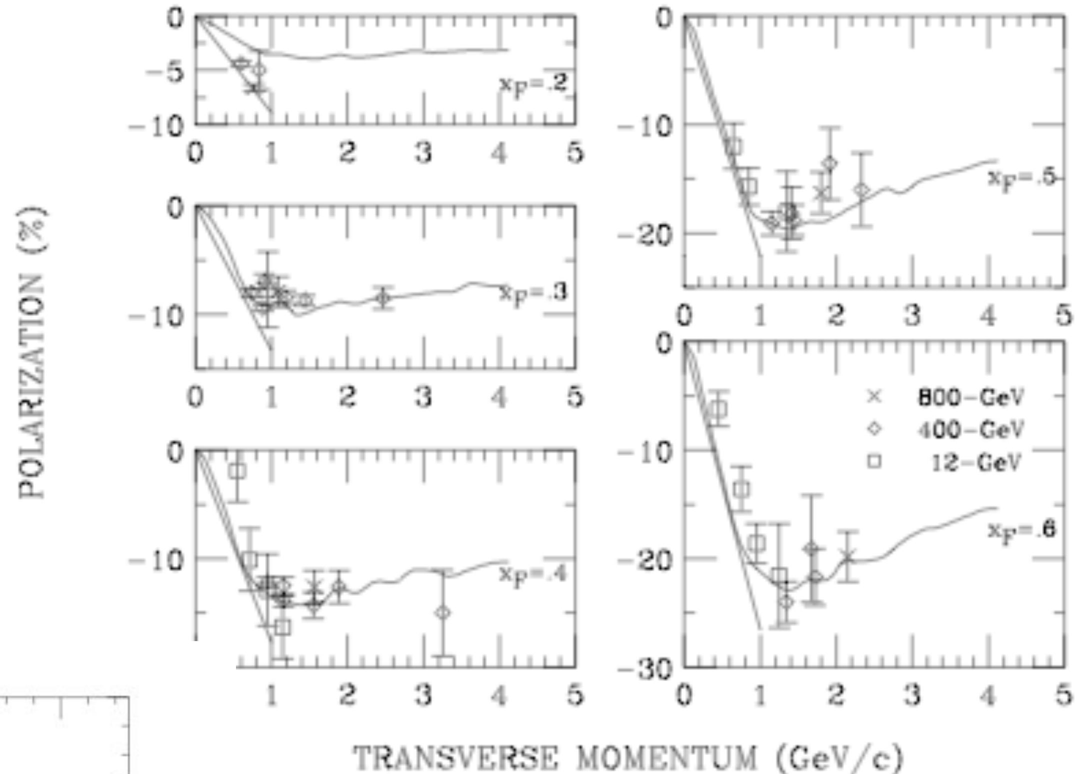
A_{c1c2} = -0.021 +\- 0.03 vs -0.078 +\- 0.001

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + B_1\cos\theta_1 + B_2\cos\theta_2 - C_{\text{helicity}}\cos\theta_1\cdot\cos\theta_2)$$

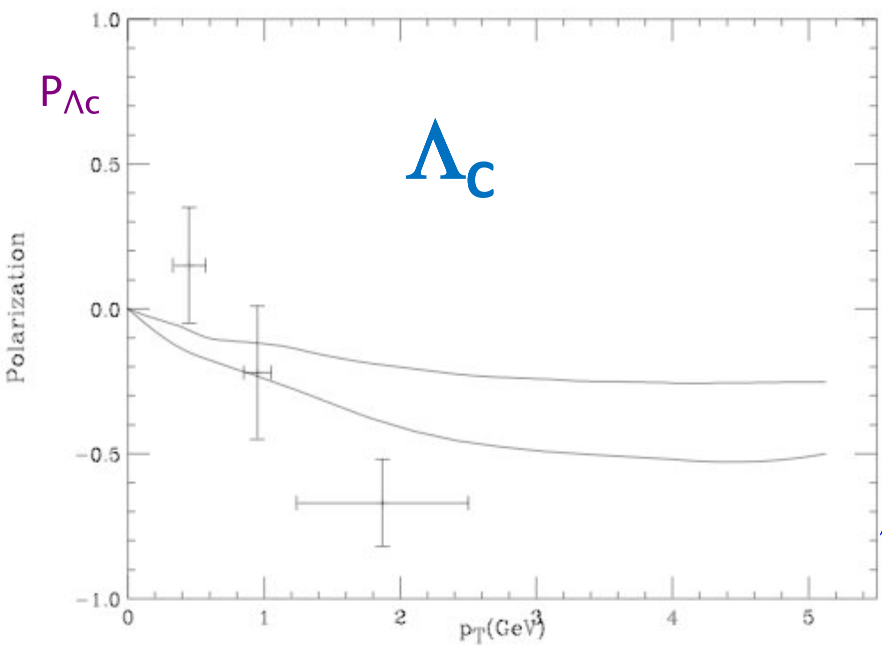
θ_1 θ_2 decay product angles w.r.t. t+tbar CM

Single Spin Asymmetry

$$pp \to \Lambda^{\uparrow}(\Lambda_c^{\uparrow})X$$



K. Heller, PRD1997
curves from model of
Dharmaratna & GG PRD '90 & '97



E791, PLB 471, 449 (2000)

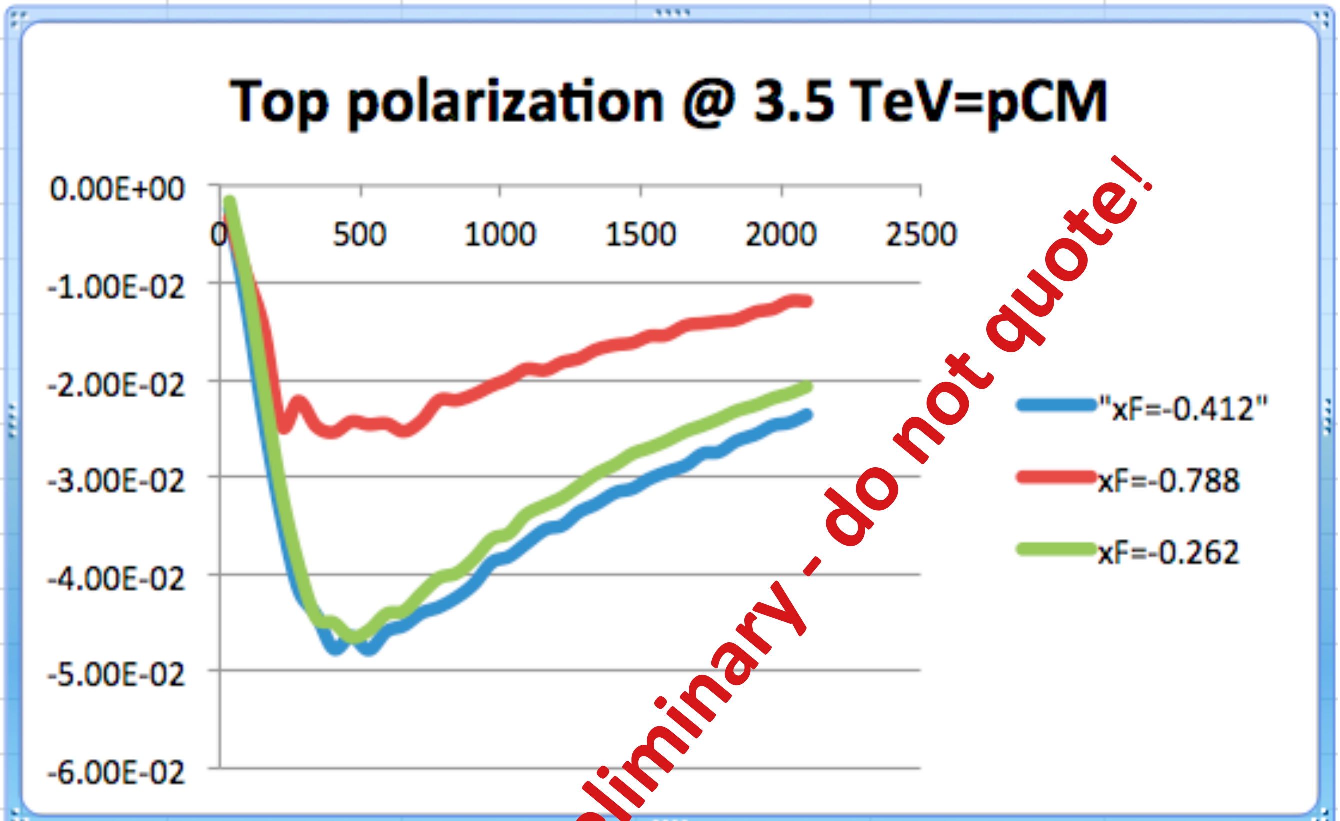
$\pi^- + p \rightarrow \Lambda_C + X$

curves from GG hep-ph/9907573

Direct measure of hard process - top polarization SSA

Top decays weakly before hadronizing

$\Rightarrow$ decay "self-analyzing"

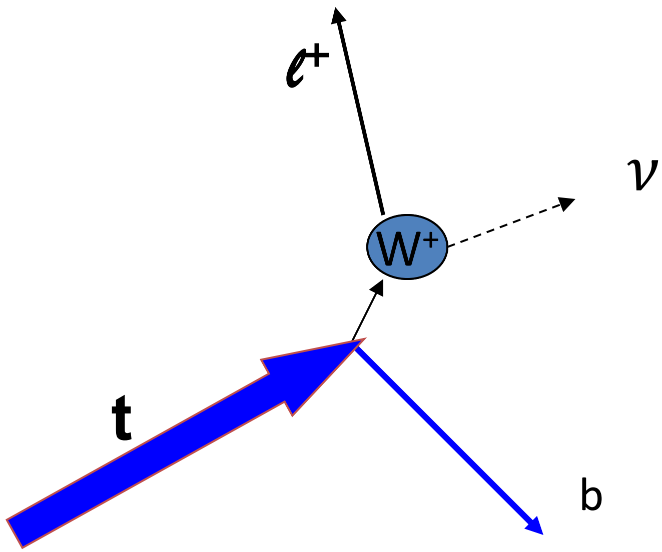


Analyze t--> W^+ b

Contributions to order α_S Imaginary Part

(Dharmaratna & GG 1990,1996)

How is actual top polarization determined?
Its decay is good analyzer.

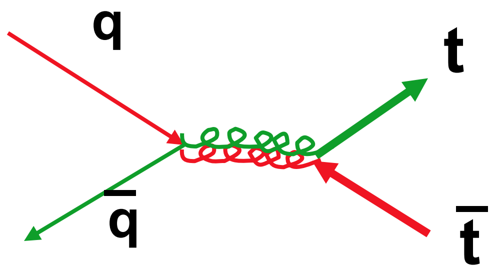


$$U_{t,\bar{t}} = \sum_{\lambda_b} B^*_{\lambda_b,\bar{t}} B_{\lambda_b,t} \propto (I + \vec{p}_{\bar{l}} \cdot \vec{\sigma}_t / p_{\bar{l}})_{t,\bar{t}} (p_b \cdot p_\nu),$$

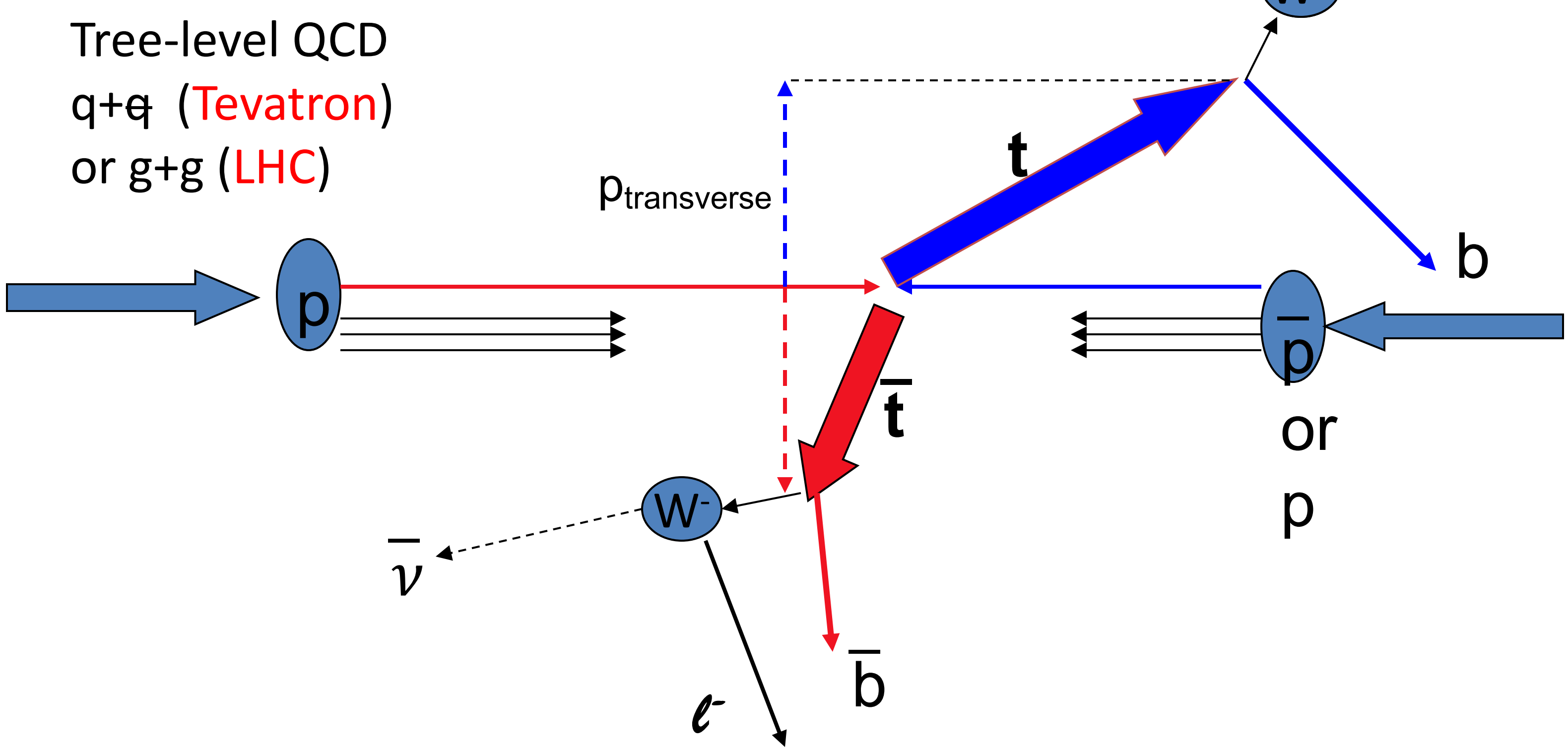
Calculated in top rest frame

Dalitz & GRG, PLB287,225(1992); PRD45, 1531(1992)

Dilepton events



Tree-level QCD
q+q̄ (Tevatron)
or g+g (LHC)



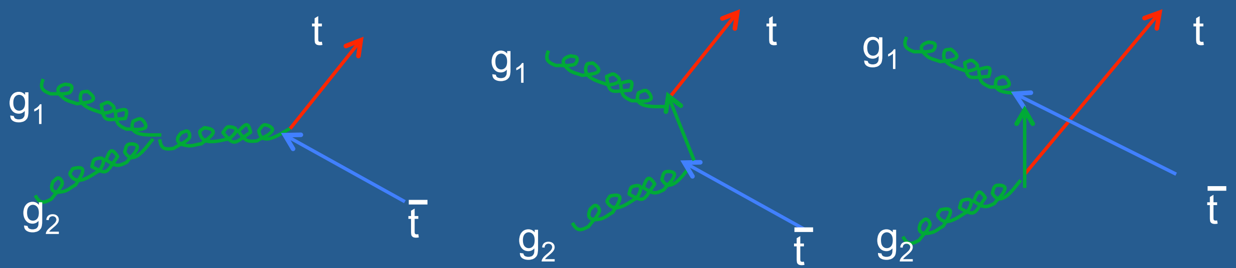
$$\rho_{t',\bar{t}';t,\bar{t}} \propto \sum_{all-helicities-not-tops} \bar{G}_{\bar{\Lambda}_N \bar{\Lambda}_g \bar{\Lambda}'_g} A^{*}_{\Lambda'_g \bar{\Lambda}'_g; t', \bar{t}'} A_{\Lambda_g \bar{\Lambda}_g; t, \bar{t}} G_{\Lambda_N \Lambda_g \Lambda'_g}$$

- The gluon spin correlations are transmitted to (determine the spin of) the decay products.
- The correlations between the lepton directions and the parent top spin (in the top rest frame) produce correlations between the lepton directions.
- The gluon fusion mechanism gives rise to a higher order (wrt quark antiquark) angular distribution due to the combination of two spin 1 gluons.

G.R.Goldstein,``Spin Correlations in Top Quark Production and the Top Quark Mass” in Proc. 12th Intl Symp. High Energy Spin Physics, Amsterdam, ed.C.W. deJager, et al., World Sci., Singapore (1997) p. 328

At LHC:

Gluon fusion tree level mechanism
(Color gauge invariance)



g_1, g_2 carry helicity Λ_1 Λ_2 $= \pm 1$ **OR transversity 1 or 0**

t, *t*-bar carry helicity λ_t $\lambda_{tbar} = \pm$ ½ OR transversity $\pm 1/2$

Introduced in:
G.R.Goldstein,``Spin Correlations in Top Quark Production and the Top Quark Mass'' in Proc. 12th Intl Symp. High Energy Spin Physics, Amsterdam, ed.C.W. deJager, et al., World Sci., Singapore (1997) p. 328.
R.H. Dalitz, G.R. Goldstein and R. Marshall, "Heavy Quark Spin Correlations in e+e- annihilations", Phys. Lett. B215, 783 (1988);
R.H. Dalitz, G.R. Goldstein and R. Marshall, "On the Helicity of Charm Jets", Zeits.f. Phys. C42, 441 (1989).

Gluon linear polarization with like and unlike t-tbar helicities

(work in progress S.Liuti, GG, Gonzalez-Hernandez,Poage)

$F \sim G_{XX}+G_{YY}$, $H \sim G_{XX}-G_{YY}$ or linear polarization

$\rho_{t',\bar{t}';t,\bar{t}}$	$\bar{F}F$	$\bar{H}H$	$\bar{F}H$	$\bar{H}F$
++;++	$\gamma^{-2}(1+\beta^2(1+\sin^4\theta))$	$\gamma^{-2}(-1+\beta^2(1+\sin^4\theta))$	$-2\dfrac{\beta^2}{\gamma^2}\sin^2\theta$	$-2\dfrac{\beta^2}{\gamma^2}\sin^2\theta$
+-;+-	$\beta^2\sin^2\theta(2-\sin^2\theta))$	$-\beta^2\sin^4\theta$	0	0

$g_1+g_2 \rightarrow t + t\text{-bar}$
Spin correlations

Correlations expressed as a weighting factor first ***for unpolarized gluons***.

- The gluon fusion mechanism gives rise to a higher order angular distribution ($\sin^4\theta$) due to the combination of two spin 1 gluons.

$$
\begin{aligned}
W(\theta, p, p_{\bar{l}}, p_l) = \frac{1}{4} - \frac{1}{4}\{&[p^4\sin^4\theta + m^4](\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} + [p^2(p^2-2m^2)\sin^4\theta - m^4](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} \\
&+ [p^4\sin^4\theta - 2p^2(p^2-m^2)\sin^2\theta + m^2(2p^2-m^2)](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} \\
&+ 2mp^2\sqrt{p^2-m^2}\cos\theta\sin^3\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}]\} \\
&/ \left[p^2(2m^2-p^2)\sin^4\theta + 2p^2(p^2-m^2)\sin^2\theta + m^2(2p^2-m^2)\right] \qquad (20)
\end{aligned}
$$

$$
\begin{aligned}
= \frac{1}{4} - \frac{1}{4}\{&[(1-\beta^2)^2 + \sin^4\theta)](\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} \\
&+[-(1-\beta^2)^2 - (1-2\beta^2)\sin^4\theta](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} \\
&+[(1-\beta^4) - 2\beta^2\sin^2\theta + \sin^4\theta](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} \\
&+2\frac{\beta}{\gamma}\sin^3\theta\cos\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}]\Big\} \\
&/ \left[(1-\beta^4) + 2\beta^2\sin^2\theta + (1-2\beta^2)\sin^4\theta\right] \qquad (21)
\end{aligned}
$$

Use these to test SM vs. BSM – Integrated version agrees – with big errors
GG – see also Mahlon & Parke

$g_1 + g_2 \rightarrow t + t\text{-}bar$
Spin correlations

Correlations expressed as a weighting factor first ***for polarized gluons***.

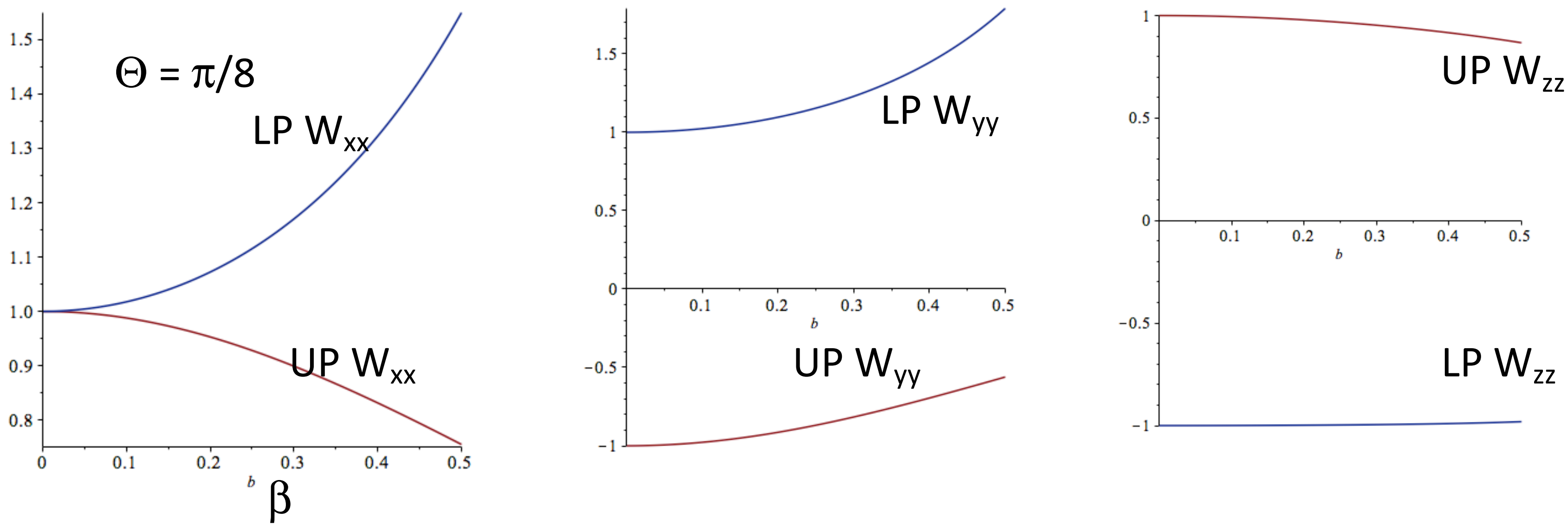
- The gluon fusion mechanism gives rise to a higher order angular distribution ($\sin^4\theta$) due to the combination of two spin 1 gluons.

$$
\begin{aligned}
W^{(LP,LP)}(\theta, p, p_{\bar{l}}, p_l) = -\frac{1}{4} + \frac{1}{4}\Big\{ & [(1-\beta^4) + \beta^2 \sin^2\theta(-2 + (2-\beta^2)\sin^2\theta)](\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} \\
& + [(1-\beta^4) + \beta^2 \sin^2\theta(2 - \beta^2 \sin^2\theta)](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} \\
& + [-(1-\beta^2)^2 + \beta^2(2-\beta^2)\sin^4\theta](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} \\
& \quad -4\frac{\beta^2}{\gamma}\sin^3\theta\cos\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}] \Big\} \\
& \quad / \left[(1-\beta^2)^2 + \beta^4 \sin^4\theta\right]
\end{aligned}
$$

Use these to compare with unpolarized to extract the Gluon transversity or linear polarizations G_{xx}-G_{yy}

Comparing lepton directional correlations

Weighting factors for lepton$^+$ lepton$^-$ when $\theta=\pi/8$



Each event has μ^- μ^+ momenta → $p^{\pm}$ (x, y, z) as well as θ & β
Probability for given event configuration is given by
$G(UP)\,W(\theta,p,p^{-}l,pl)$ $+G(LP)\,W^{LP}(\theta,p,p^{-}l,pl)$
Quite distinct! x & y components are aligned for LP, anti-aligned for UP

Separating polarized gluons

* Each event has μ^- μ^+ momenta → $p^\pm$ (x, y, z)
in t & tbar rest frame

* t+tbar CM determines θ direction as well as β for t & tbar

* Probability for given event configuration is given by

G(UP) $W(\theta,p,\bar{p}l,pl)$ +G(LP) $W^{LP}(\theta,p,\bar{p}l,pl)$ (ignoring light quarks)

- Quite distinct! x & y components are
- aligned for LP, anti-aligned for UP

Summary

- Flexible parameterization for chiral even valence quarks from form factors, pdfs & DVCS **R**×Dq
- Extended **R**×Dq to **R**×Spectator
- **New Extension to gluons & the sea**
- Considered Gluon sector
  - *Helicity* conserving & Helicity →gluon ***Transversity***
- Measurements? Top polarization
- **via lepton decays**
- **More phenomenology to come**