Single-Inclusive Leptoproduction of Hadrons and Jets at NLO

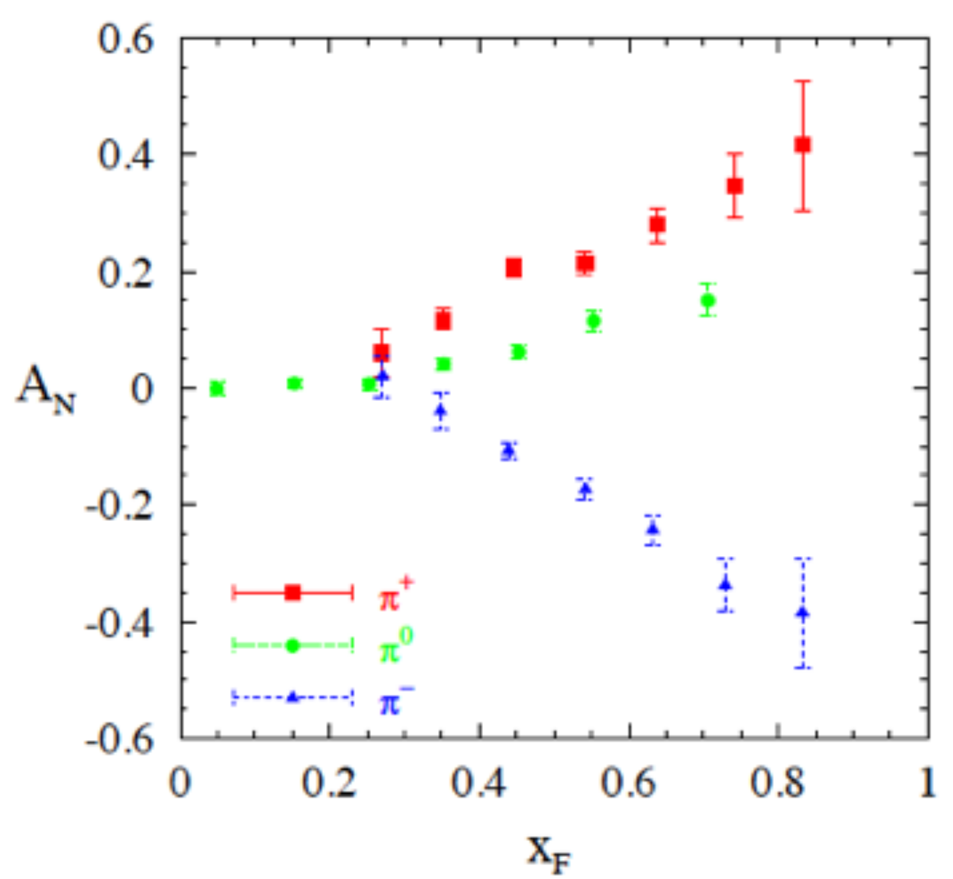
Marc Schlegel
Institute for Theoretical Physics
University of Tübingen

in collaboration with W. Vogelsang and P. Hinderer
based on arXiv:1505.06415

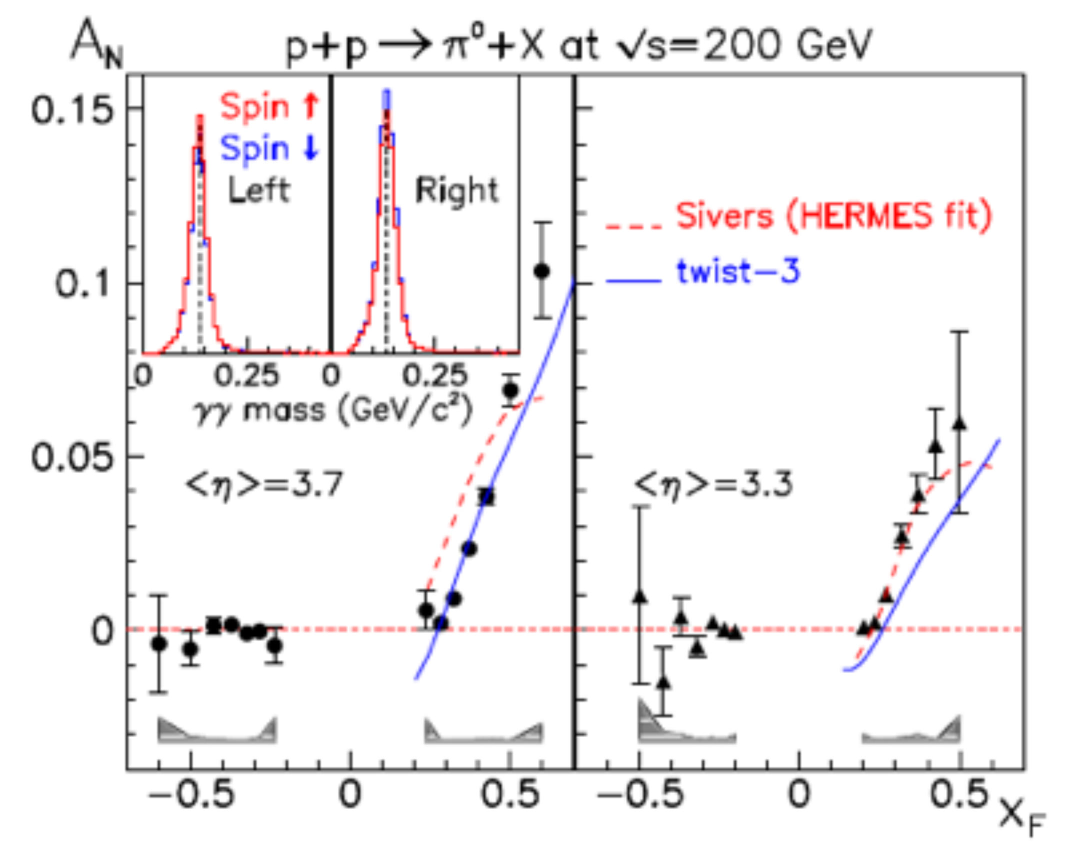
QCD Evolution 2015, JLab, May 27, 2015

Transverse Spin Effects in 1-hadron-inclusive processes

“Show-off” Transverse SSA $p + p^{\uparrow} \rightarrow \pi + X$



$\sqrt{s} = 20$ GeV [*E704 coll. (1991)*]



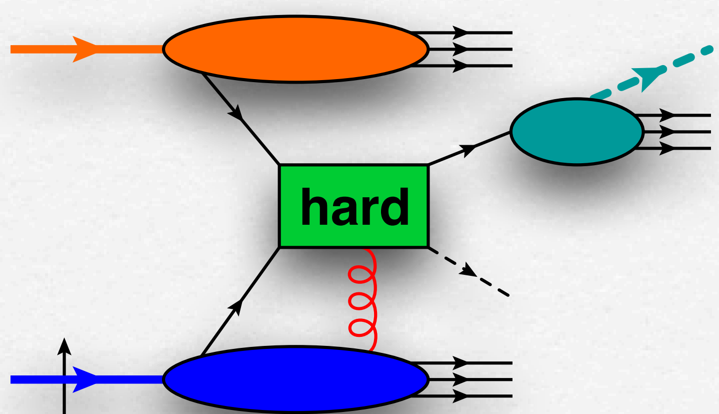
$\sqrt{s} = 200$ GeV [*STAR coll. (2008)*]

- large effects ➙ learned a lot, still not completely understood
- cannot be explained in the naive parton model
  ➙ Twist-3 Formalism

A lot of contributions at LO:

Twist-3 from transversely polarized proton:

[Qiu, Sterman, Kouvaris, Vogelsang, Yuan, Koike, Kang,…]



Quark-Gluon-Quark Correlations

$$\tilde{G}_F^q(x, x') \sim \langle P, S_T | \bar{q}(0)\gamma^+ \gamma_5 g F^{+\alpha}(\eta n) q(\lambda n) | P, S_T \rangle$$

Sivers - type (Soft Gluon Pole):

$$f_{1T}^{\perp(1)}(x) = \frac{\pi}{2} G_F(x, x)$$

Soft Fermion Pole:

$$G_F(x, 0)$$

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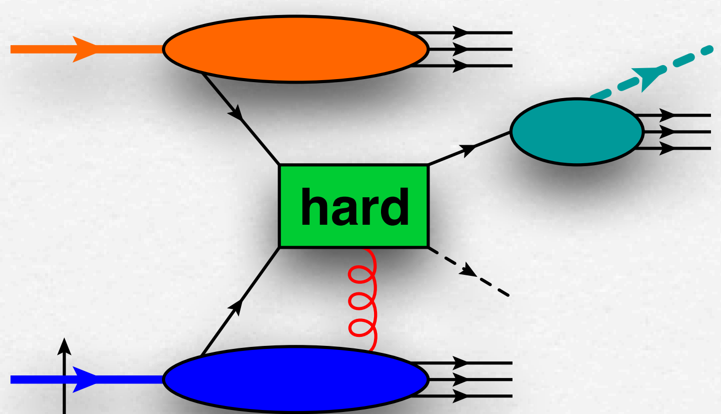

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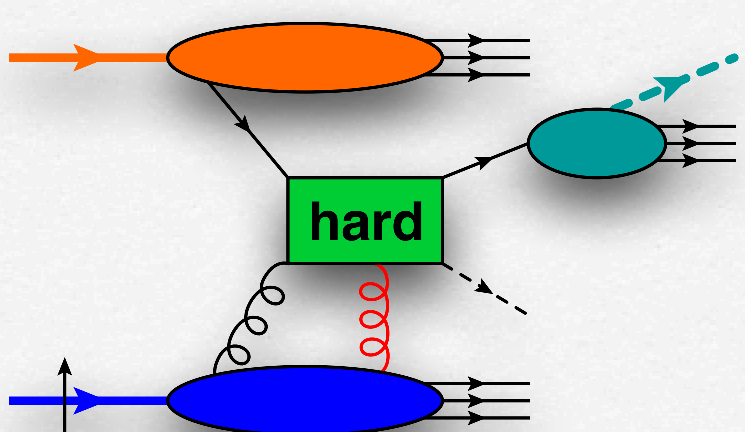


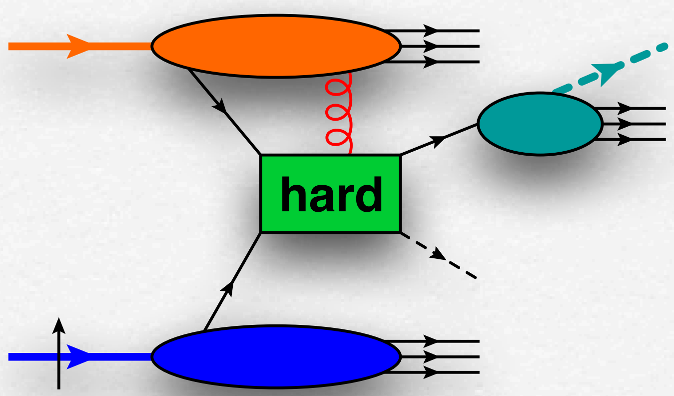
Trigluon Correlations

$$\langle P, S_T | \, F^{+\alpha}(0) \, gF^{+\beta}(\eta n) \, F^{+\gamma}(\lambda n) \, | P, S_T \rangle$$

$O(x,x')\,,\; N(x,x')$ likely small (?)

Twist-3 from unpolarized proton:

[Kanazawa, Koike]



"chiral-odd" Quark-Gluon-Quark Correlations

$$E_F{}^q(x,x') \sim \langle P|\bar{q}(0) i\sigma^{+\beta}\gamma_5 g F^{+\alpha}(\eta n) q(\lambda n)|P\rangle$$

Boer-Mulders - type (Soft Gluon Pole):

$$h_1^{\perp(1)}(x) = \frac{\pi}{2} E_F(x,x)$$

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➞ small partonic factors

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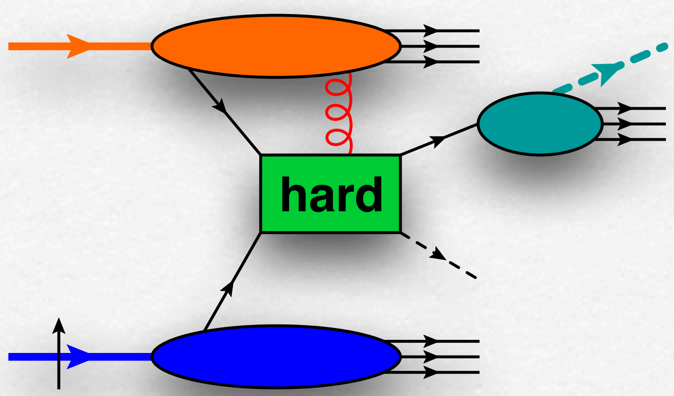

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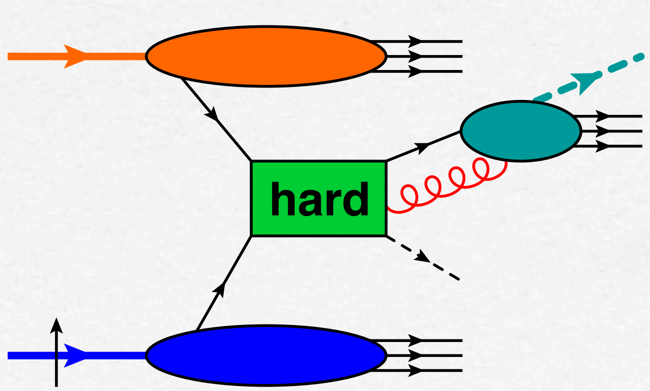
Twist-3 from fragmentation:

[Kanazawa, Koike, Metz, Pitonyak] ; see talk by Pitonyak



"chiral-odd" Quark-Gluon-Quark Fragmentation

$$\hat{H}_{FU}(z,z') \propto \langle 0|q(0)|P_h,X\rangle\langle P_h,X|gF^{+\alpha}(\eta n)\bar{q}(\lambda n)i\sigma^{\beta+}\gamma_5|0\rangle$$

➞ may be dominant

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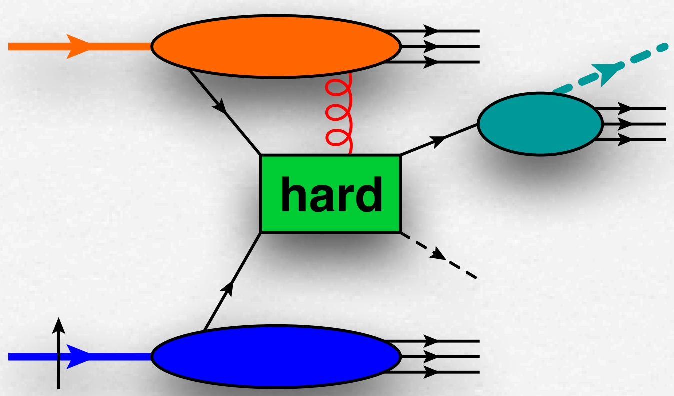

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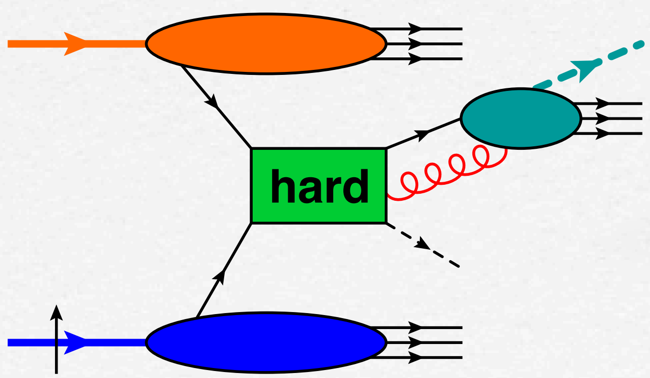

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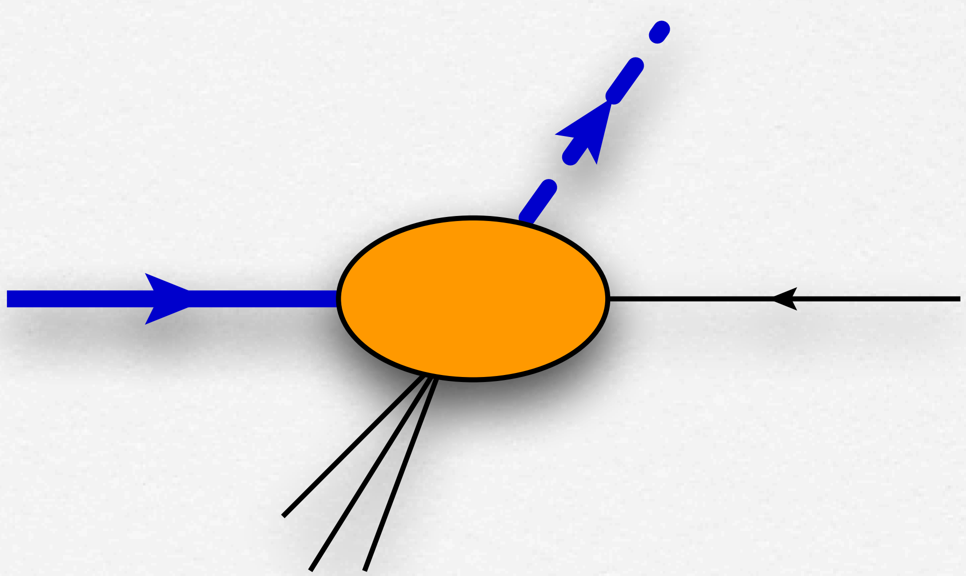
➙ may be dominant

many contributions ➙ simpler processes?

Hadron production in lepton - nucleon collisions

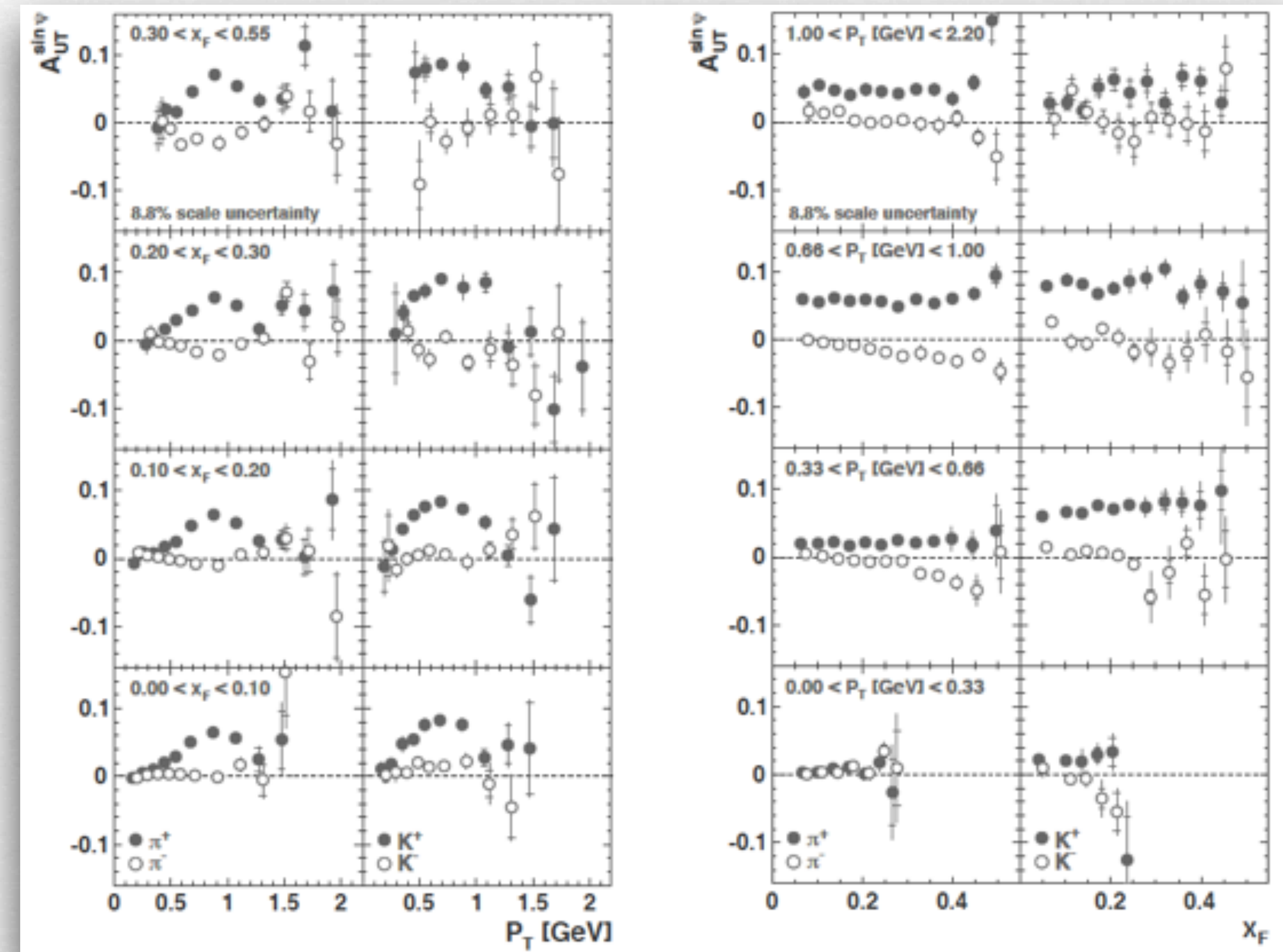
$(e + p^{\uparrow} \longrightarrow h + X)$

$P_T \gg \Lambda_{QCD}$

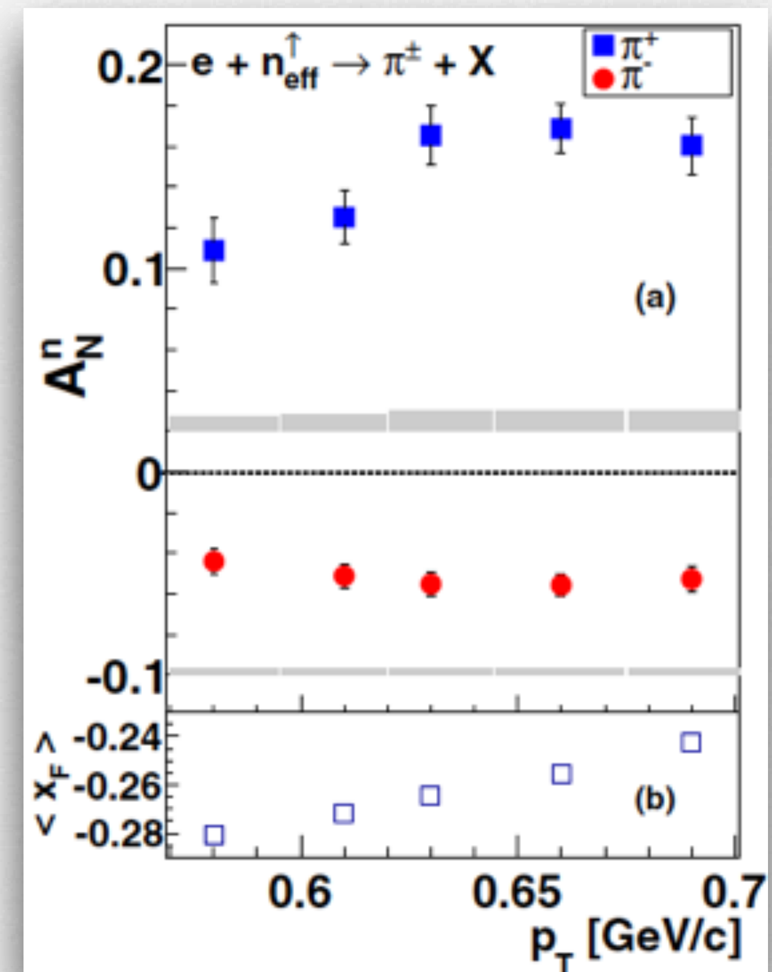


amazingly accurate data from HERMES, JLab…

HERMES [PLB728, 183]



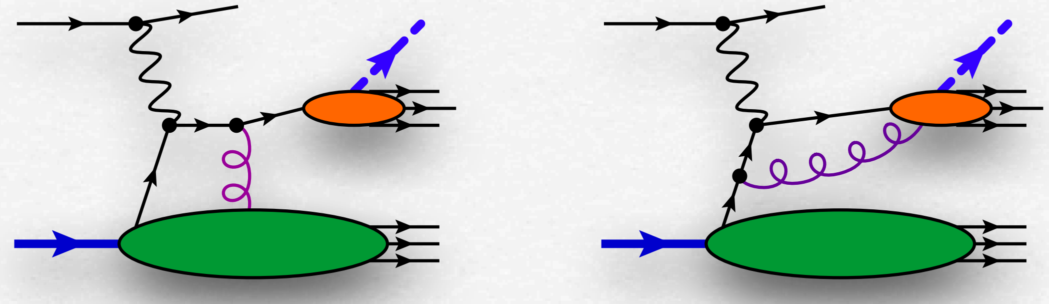
JLab [PRC89, 042201(R)]



$p_T < 1$ GeV ⇒ pQCD?

LO calculation of the transverse SSA:

[Gamberg, Kang, Metz, Pitonyak, Prokudin]



outgoing lepton momentum integrated out:

$$\Delta\sigma_{UT} \quad \sim \quad \left[\left(1 - x\frac{\mathrm{d}}{\mathrm{d}x}\right)G_F(x,x) \otimes D_1(z) \otimes \hat{\sigma}_1\right]$$
$$+h_1(x) \otimes \left[\left(1 - z\frac{\mathrm{d}}{\mathrm{d}z}\right)H_1^{\perp(1)}(z) \otimes \hat{\sigma}_2 + H(z) \otimes \hat{\sigma}_3 + \int \mathrm{d}z' \, \Im[\hat{H}](z,z') \otimes \hat{\sigma}_4\right]$$

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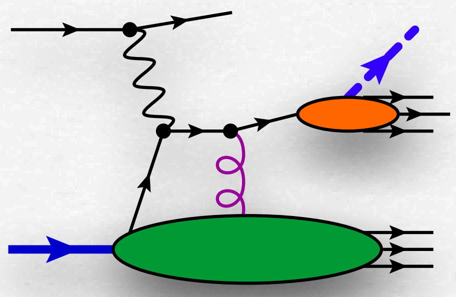

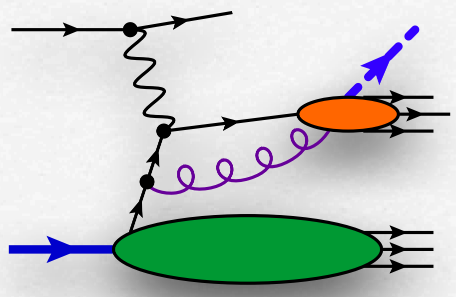

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Longitudinal - Transverse DSA:

[Kanazawa, Metz, Pitonyak, M.S.]

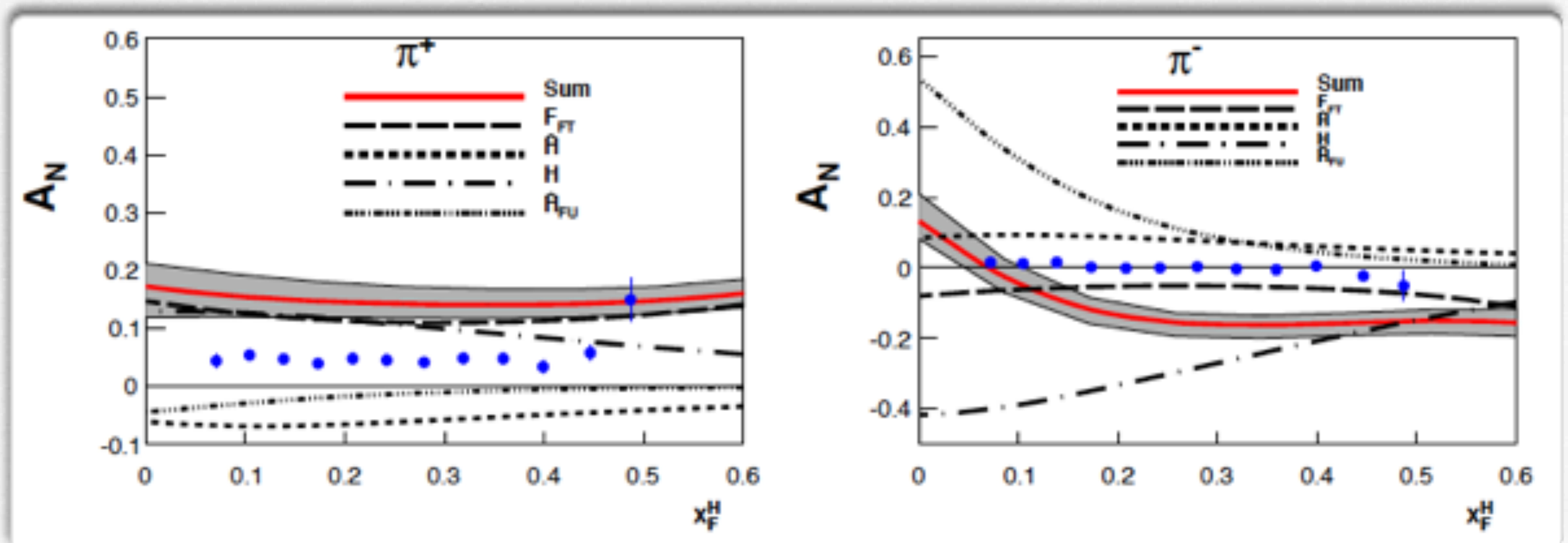
SSA: Imaginary part of hard scattering
DSA: Real part of hard scattering → complementary information

$$\Delta\sigma_{LT} \sim \left[\left(1 - x\frac{\mathrm{d}}{\mathrm{d}x}\right)g_{1T}^{(1)}(x) \otimes \hat{\sigma}_1 + g_T \otimes \hat{\sigma}_2 + \Delta q(x) \otimes \hat{\sigma}_4\right] \otimes D_1(z)$$
$$+h_1(x) \otimes E(z) \otimes \hat{\sigma}_4$$

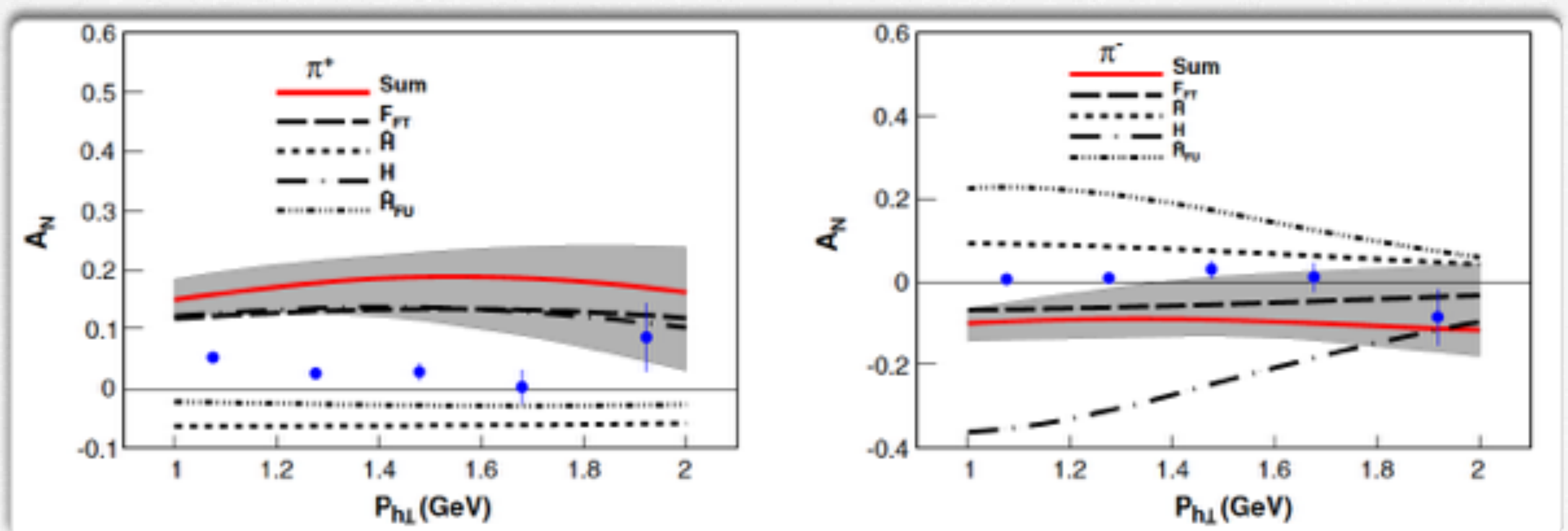
Numerical estimate of the transverse SSA at LO:

[Gamberg, Kang, Metz, Pitonyak, Prokudin]

x_F - dependence:



P_{hT}- dependence:



Input:

- Sivers funct. from SIDIS
- Transversity from SIDIS
- Collins funct. from e^+e^- & SIDIS
- Im[H](z,z') from pp - data

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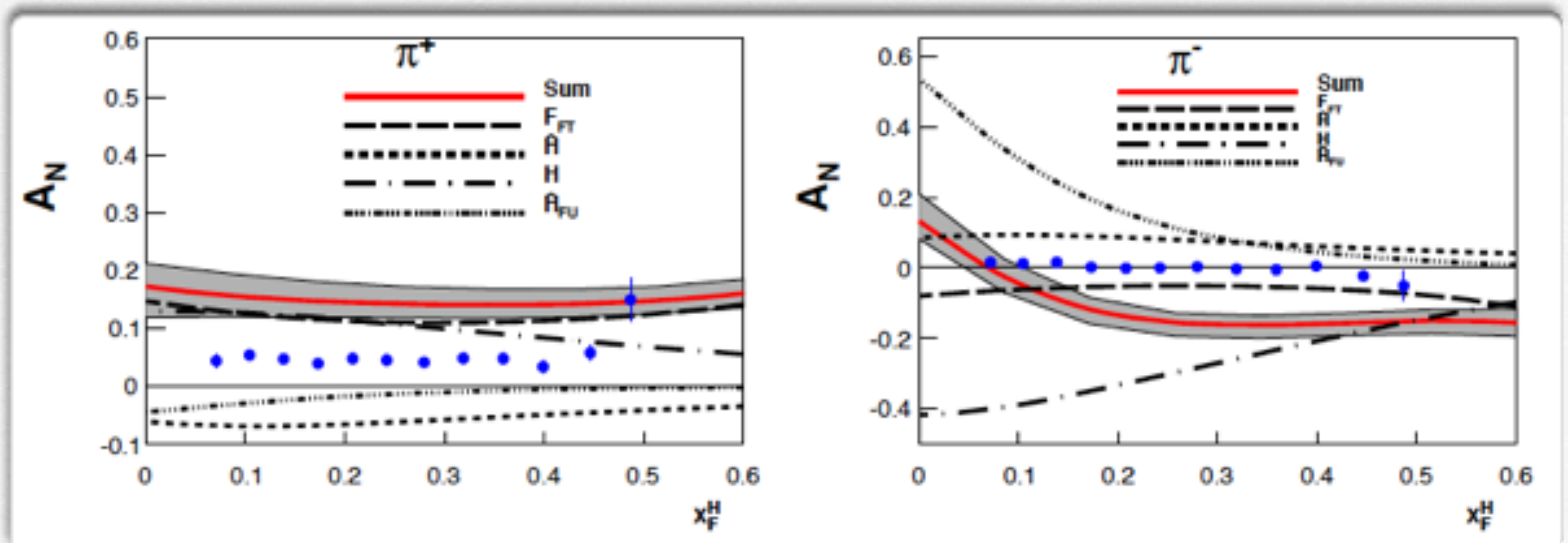

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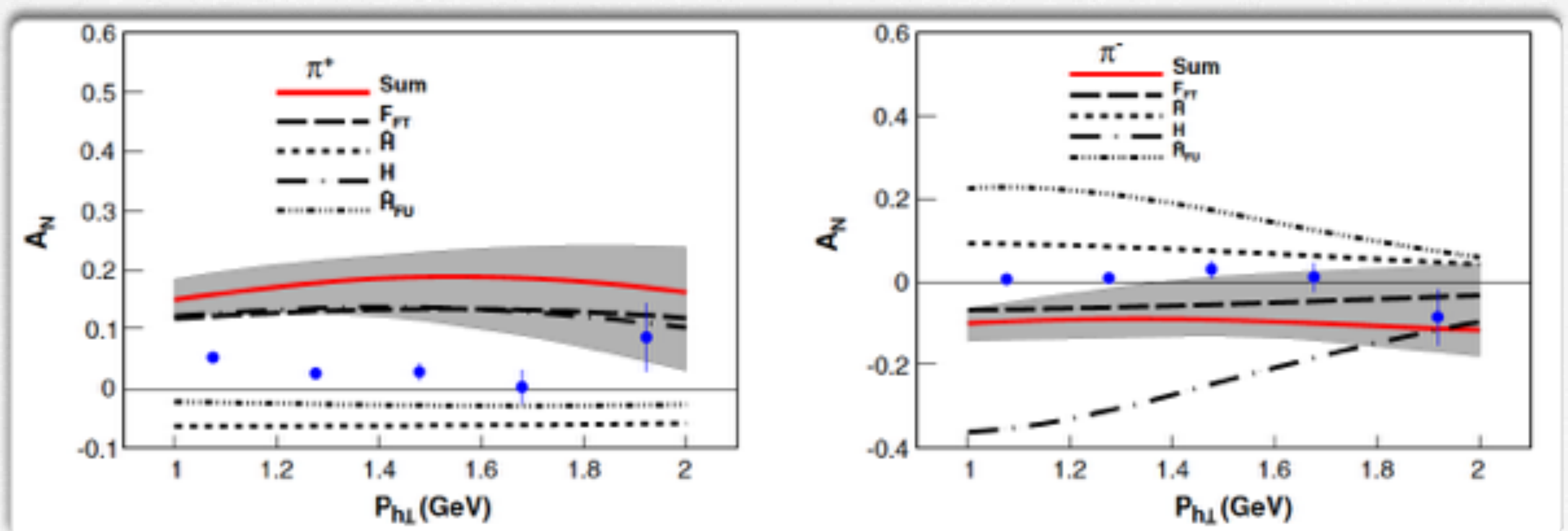

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LO input typically overshoots the data → NLO?

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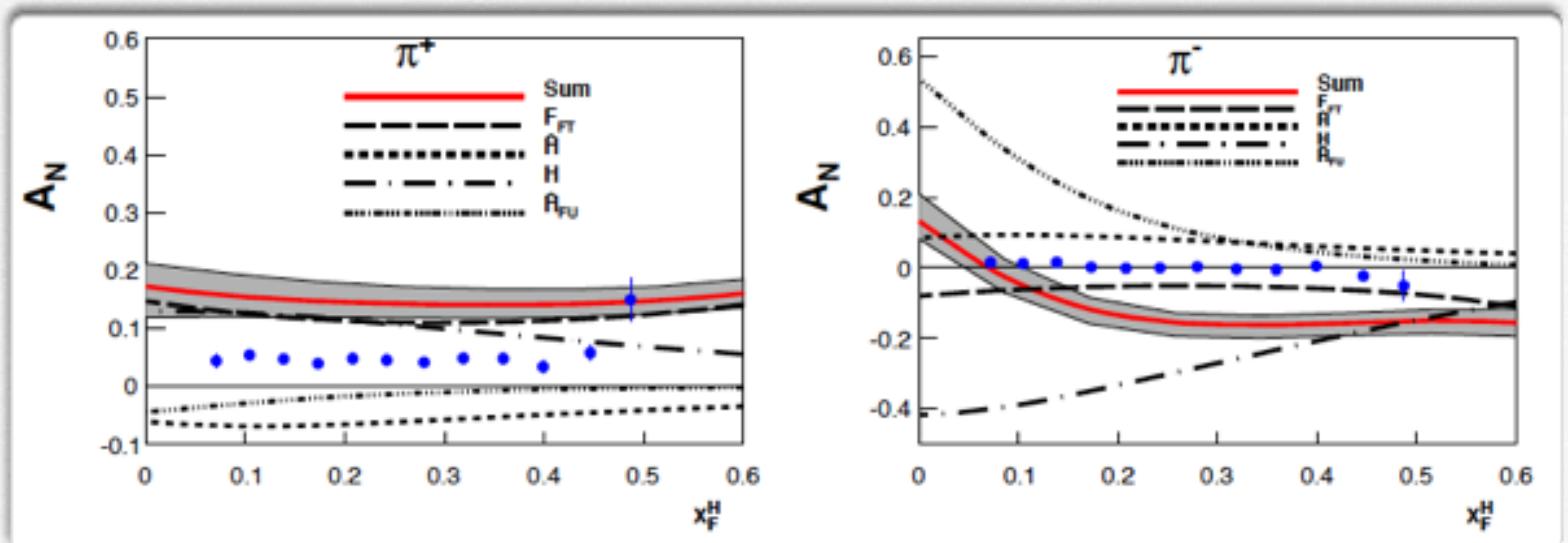

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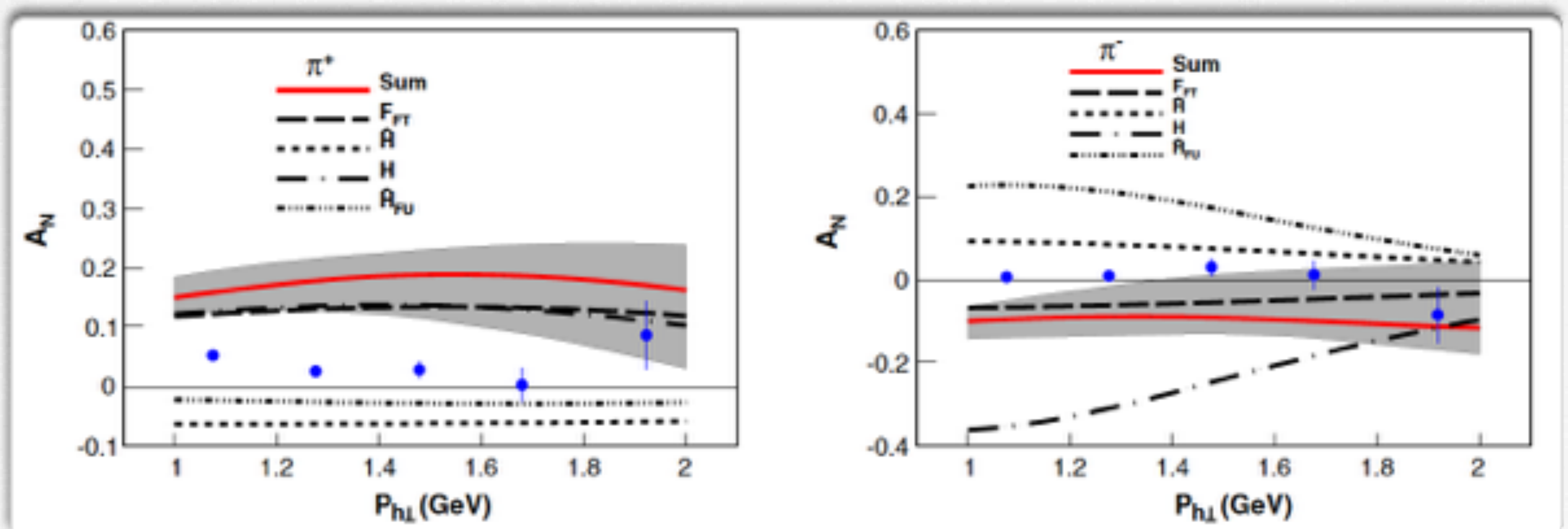

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LO input typically overshoots the data
→ NLO?

$$\boxed{A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}}$$

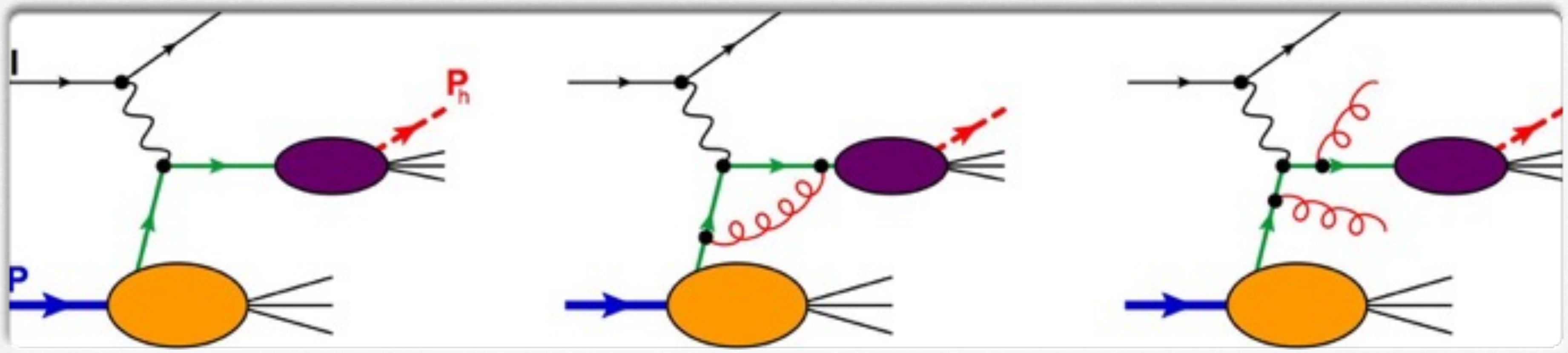
unpolarized cross section

Unpolarized Cross Section at NLO

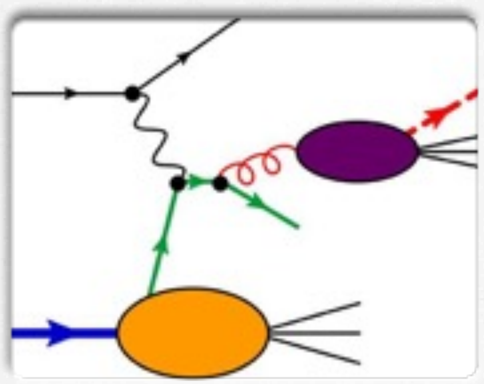
[Hinderer, M.S., Vogelsang, arXiv:1505.06415]

3 partonic channels: (outgoing lepton momentum integrated out!)

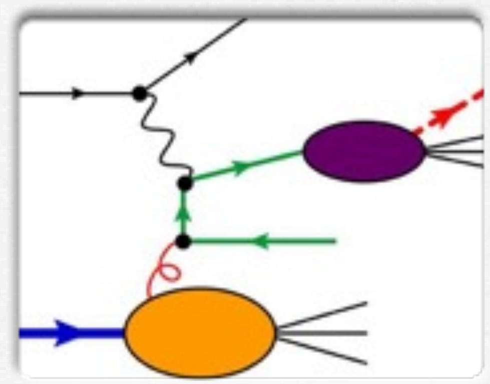
quark ⟶ quark



quark ⟶ gluon



gluon ⟶ quark



Initial / Final State collinear singularities cancel after MSbar - renormalization of PDFs and FFs!

Peculiarity: Collinear singularities of final state

Final state lepton singularities artefact of massless lepton

1) massive lepton (complicated!) → expansion in m_l

$$\boxed{\hat{\sigma}_{\rm NLO}(s,t,u,m_l^2) = \ln\left(\frac{m_l^2}{\Lambda^2}\right)\hat{\sigma}_1(s,t,u) + \hat{\sigma}_2(s,t,u,\Lambda^2) + \mathcal{O}(m_l^2/\Lambda^2)}$$

‘Weizsäcker - Williams’ term: quasi-real, collinear photons

How to choose scale Λ? → ‘scheme’ - dependence

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How to choose scale Λ? → 'scheme' - dependence

<u>HERA physics:</u>

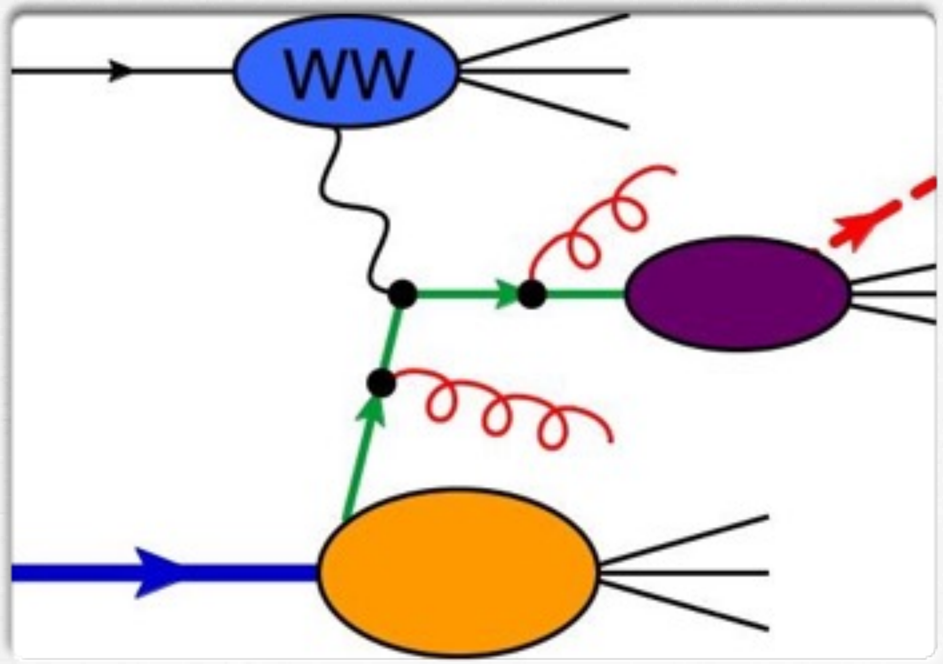
SIDIS at low Q and large P_{hT} → experimental cut Q < 1 GeV

$$\boxed{\Lambda \propto Q_{\mathrm{max}}}$$

Weizsäcker - Williams approximation: $\boxed{\sigma_{WW} \sim \sigma_{\mathrm{NLO}}}$

True at HERA → cut Q < 1 GeV enforces WW approximation

2) massless lepton → add 'photon-in-lepton' distribution



$$d\sigma_{WW} \sim f_1^{WW}(y) \otimes f_1(x) \otimes D_1(z) \otimes \hat{\sigma}^{\gamma i \to f x}$$

'Weizsäcker-Williams' distribution

$$f_{1,\mathrm{ren}}^{WW}(y,\mu) \sim \langle l | F^{+\alpha}(0)\, F^{+\beta}(\lambda n) | l \rangle$$

Lepton source of quasi-real photons

MSbar renormalization of 'WW' distribution → cancels lepton singularities

QED: $$f_{1,\mathrm{ren}}^{WW}(y,\mu) = \frac{\alpha}{2\pi}\frac{1+(1-y)^2}{y}\left[\ln\left(\frac{\mu^2}{y^2 m_l^2}\right) - 1\right]$$

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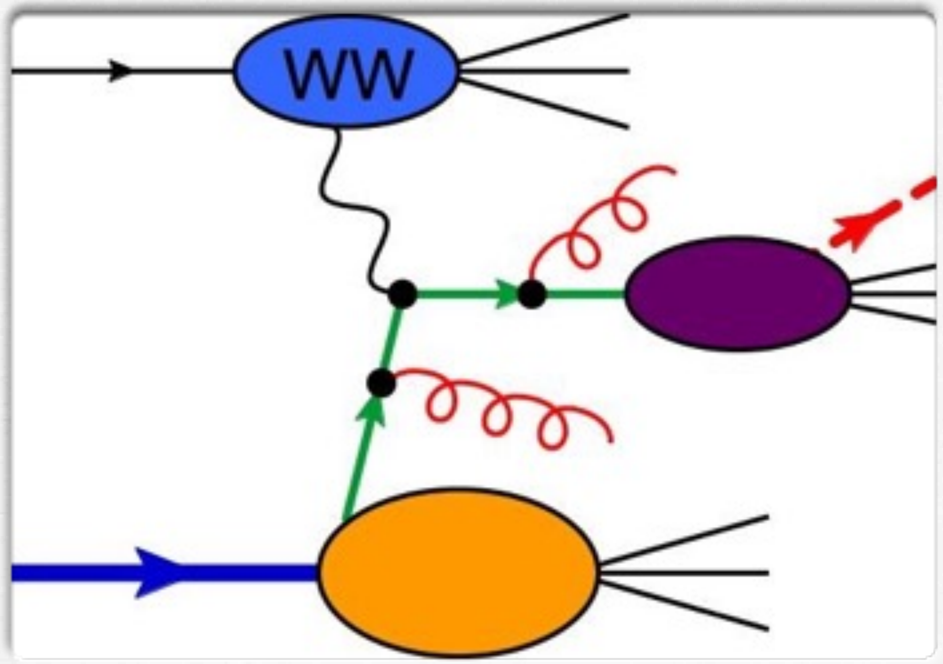

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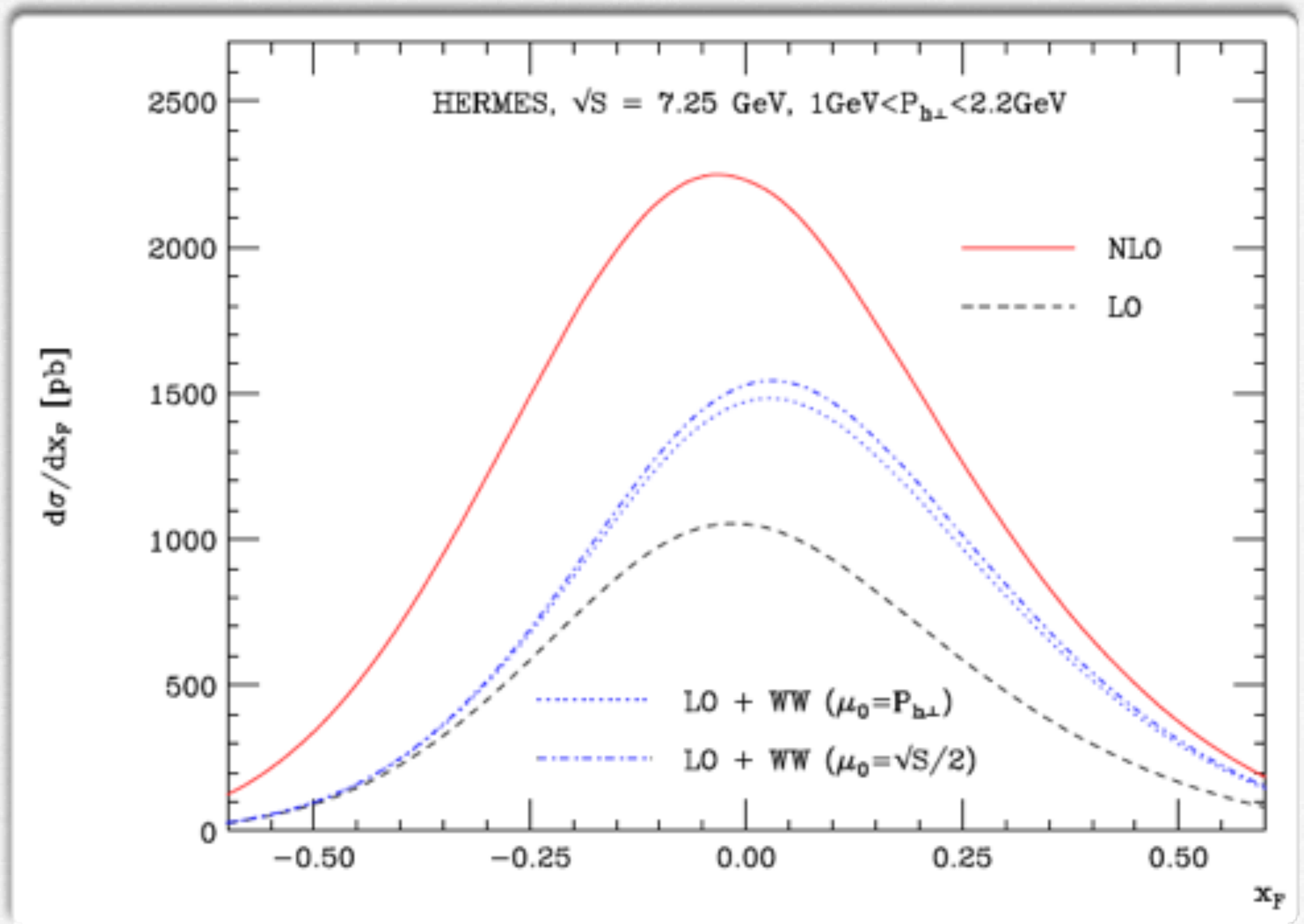
- Equivalent to massive lepton calculation for $\Lambda^2 = \mu^2/y^2 e$!
- WW cross section $\sigma^{\gamma i \to fx}$ simple!
- WW approximation tremendous simplification for spin-dep. cross section!

Is the ‘Weizsäcker-Williams’ approximation valid for eN → hX?

NLO prediction for HERMES (fixed target)

x_F - dependence:



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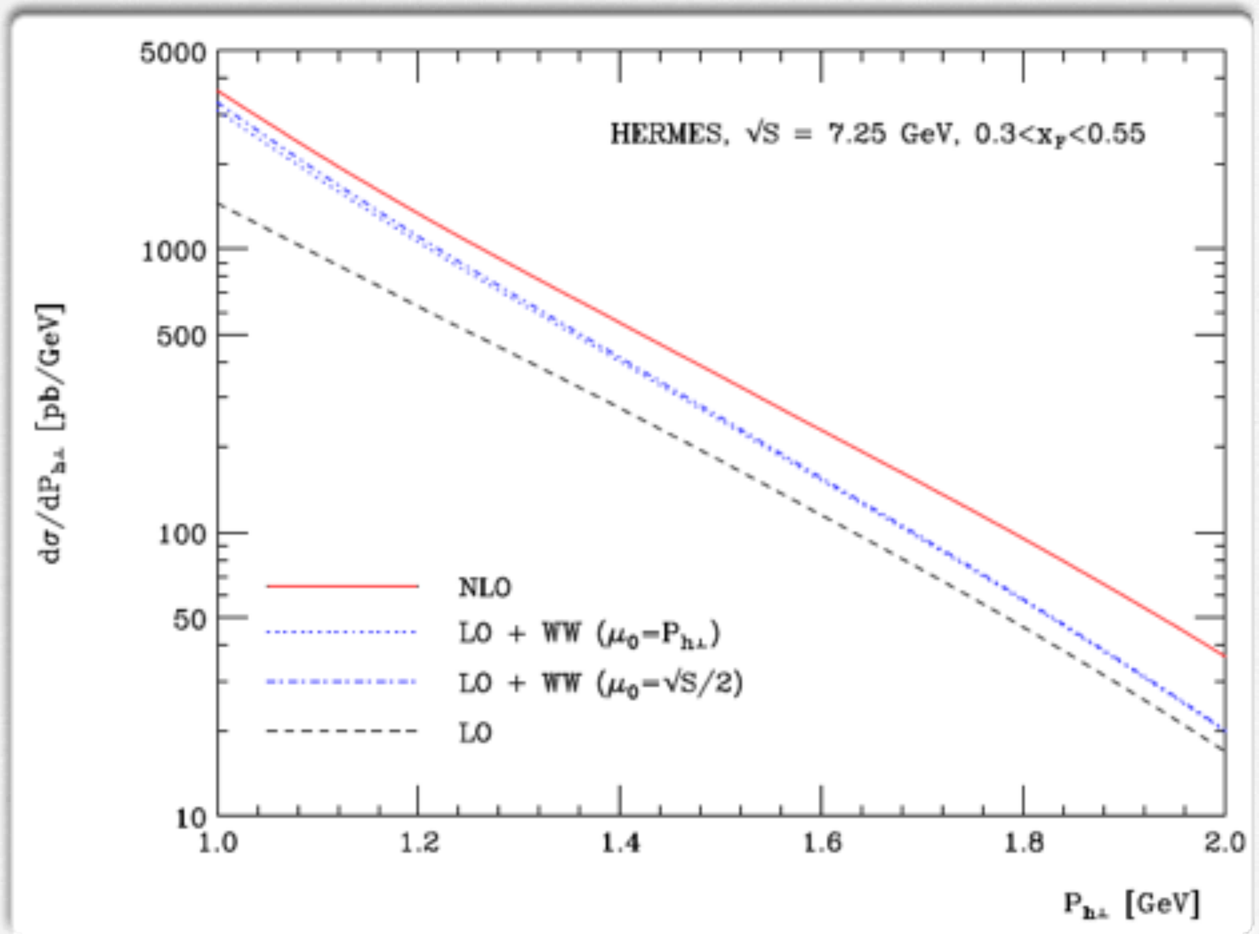


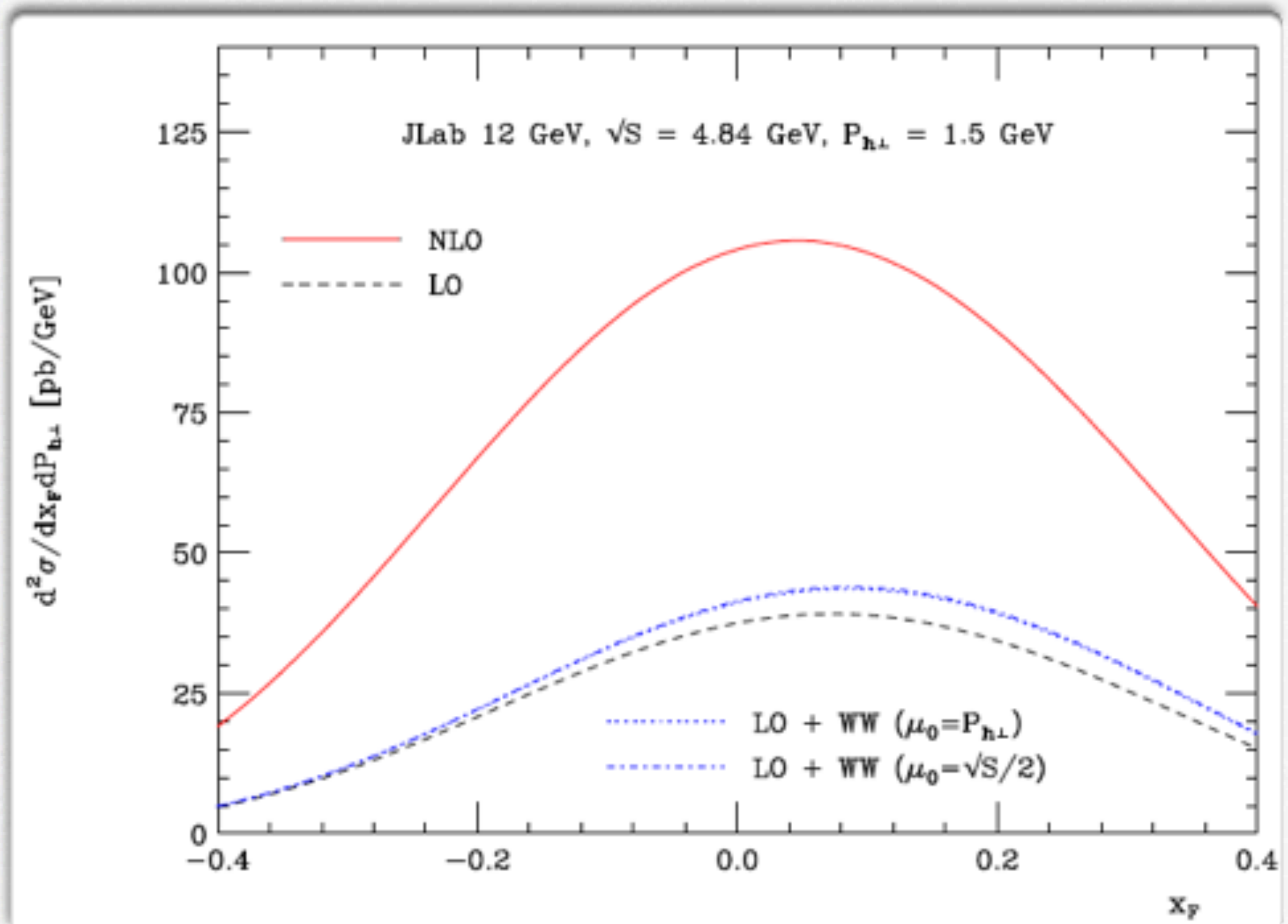
K-factor: ~ 2
NLO seizable!

WW - approximation:
far forward lepton ✔
forward nucleon ✘
middle region ✘

WW works better at small $P_{h\perp}$ ~ 1 GeV

NLO prediction for JLab12 (fixed target)

x_F - dependence:



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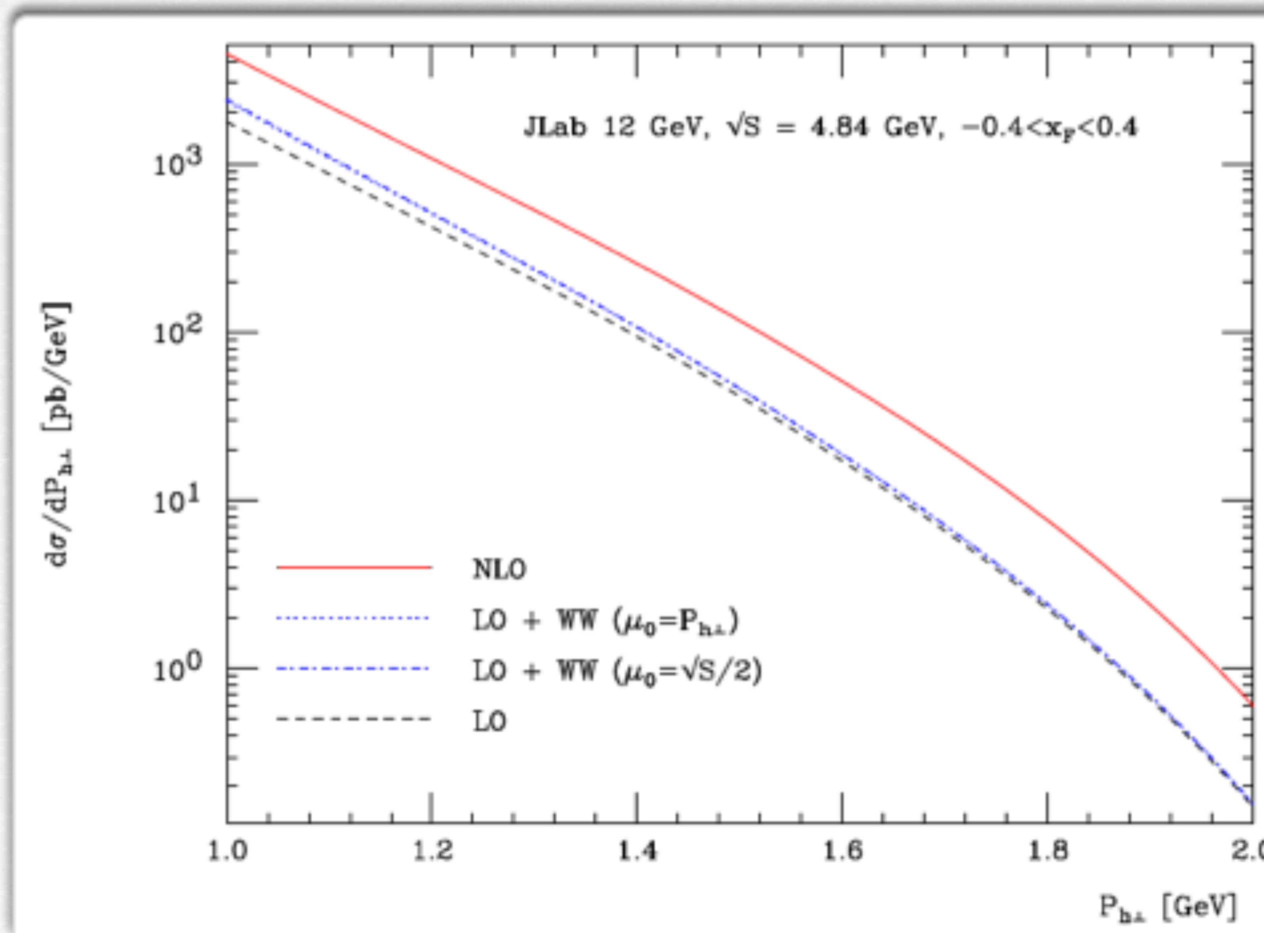


K-factor: ~ 2 - 3

NLO huge!

WW - approximation:

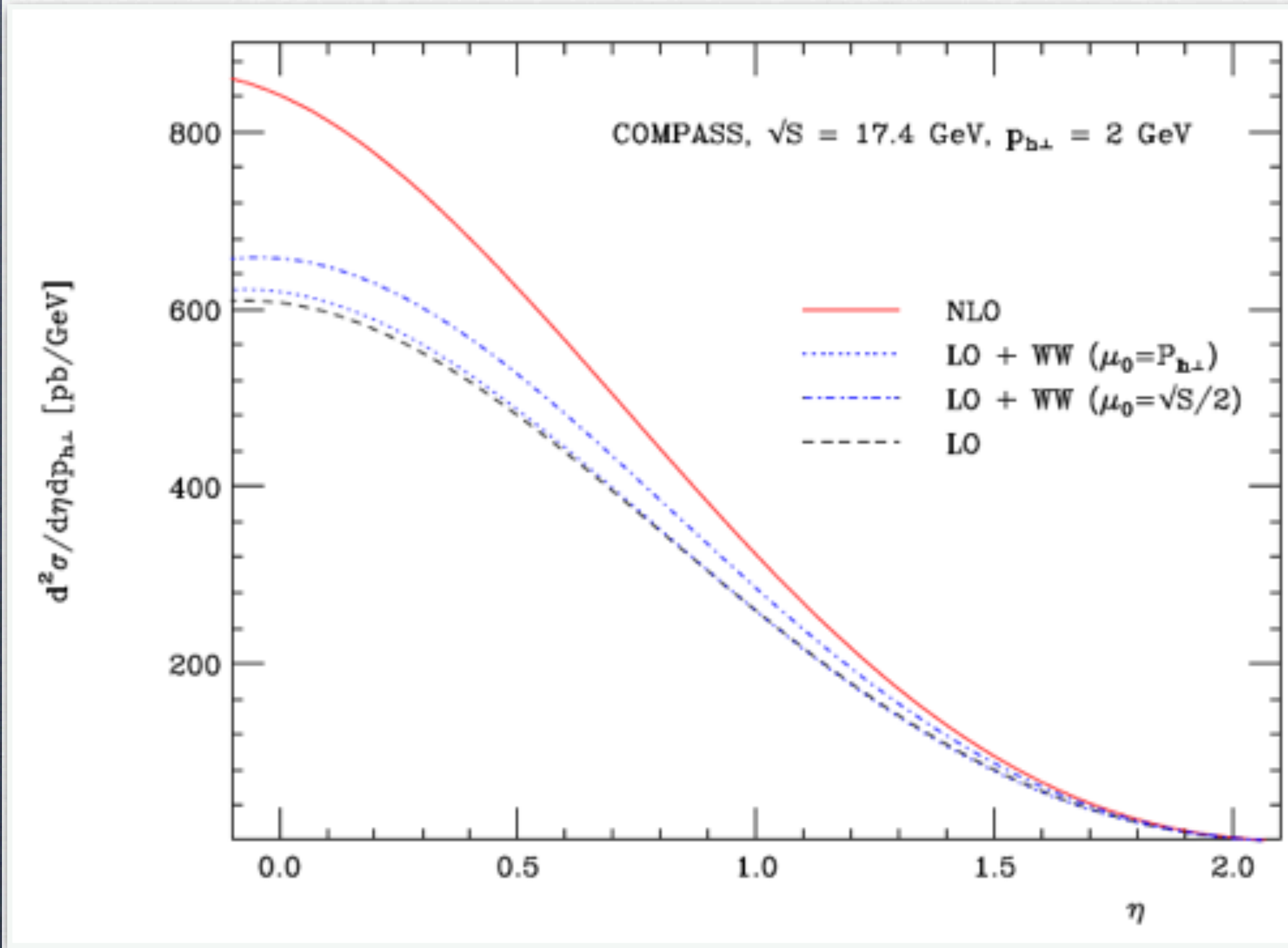
doesn't work at all!

near threshold $\frac{2P_{h\perp}}{\sqrt{S}} \simeq 0.6$

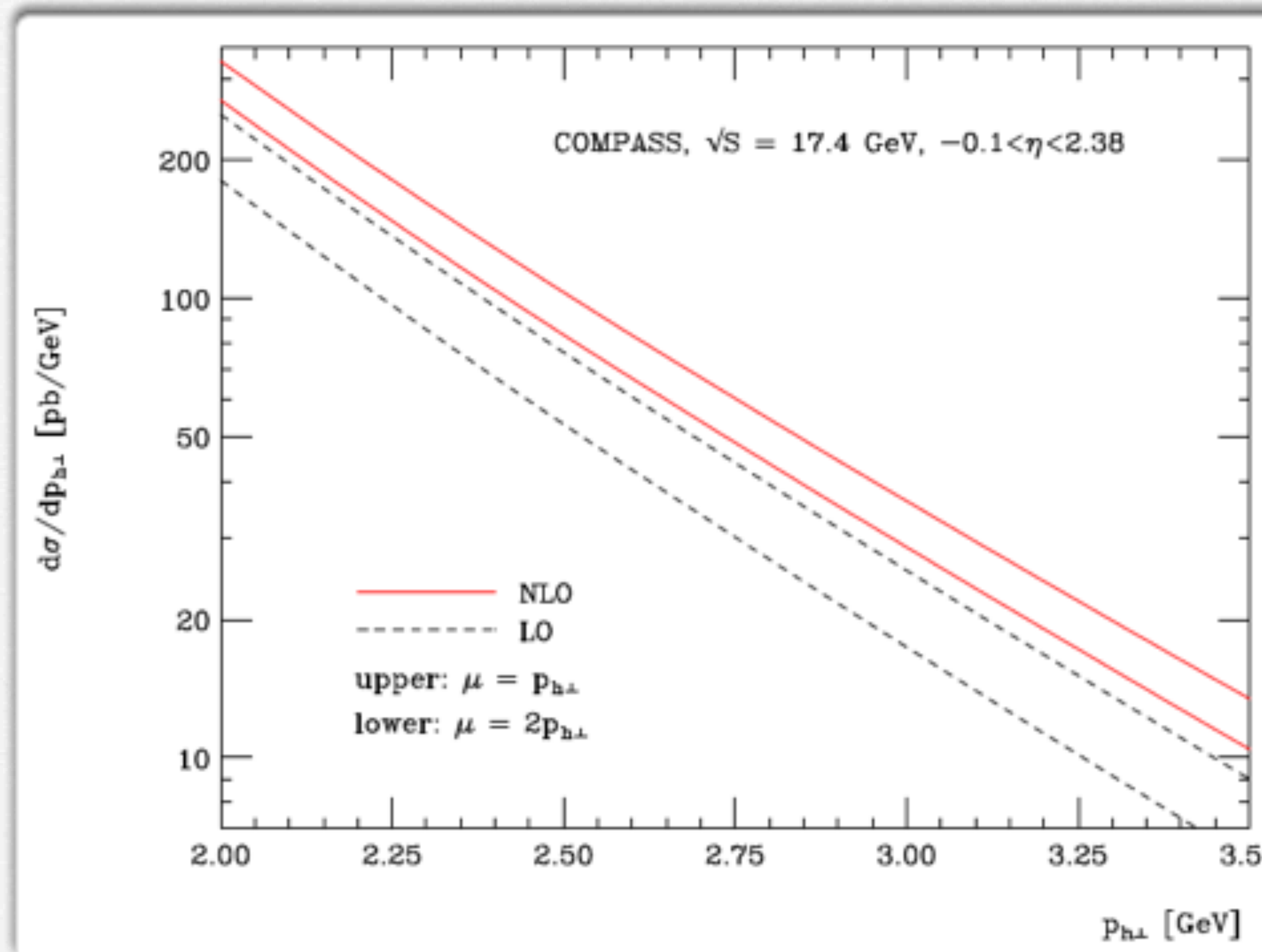
$$\hat{\sigma}_{\rm NLO} \sim \left(\frac{\ln(1-w)}{1-w}\right)_+ + \frac{1}{(1-w)_+} + \ldots$$

NLO prediction for COMPASS (fixed target)

η - dependence:



$P_{h\perp}$- dependence:



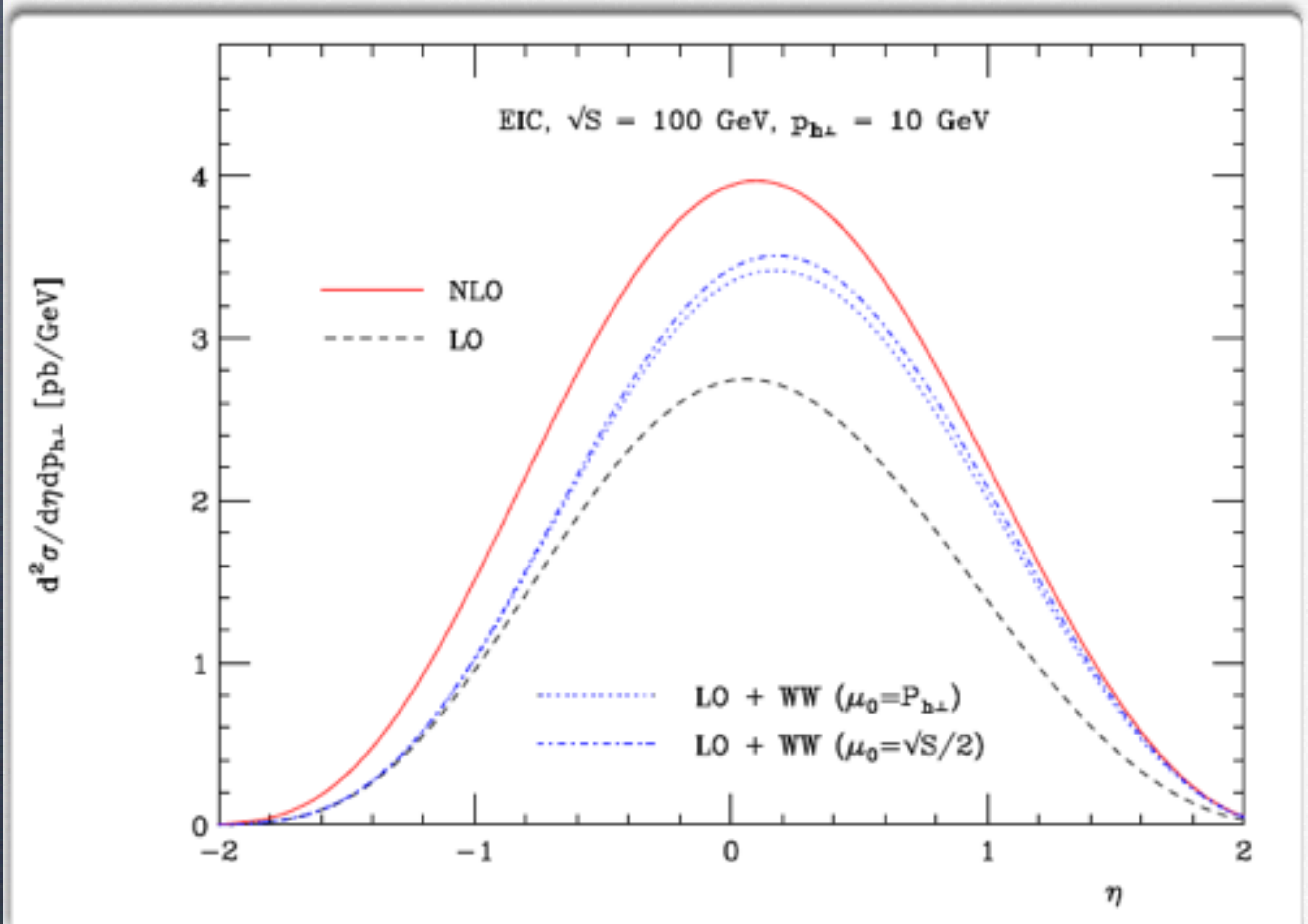
K-factor: ~ 1.3 - 1.4
NLO significant,
but not as large

WW - approximation:
doesn't work at all!
$m_\mu >> m_e$

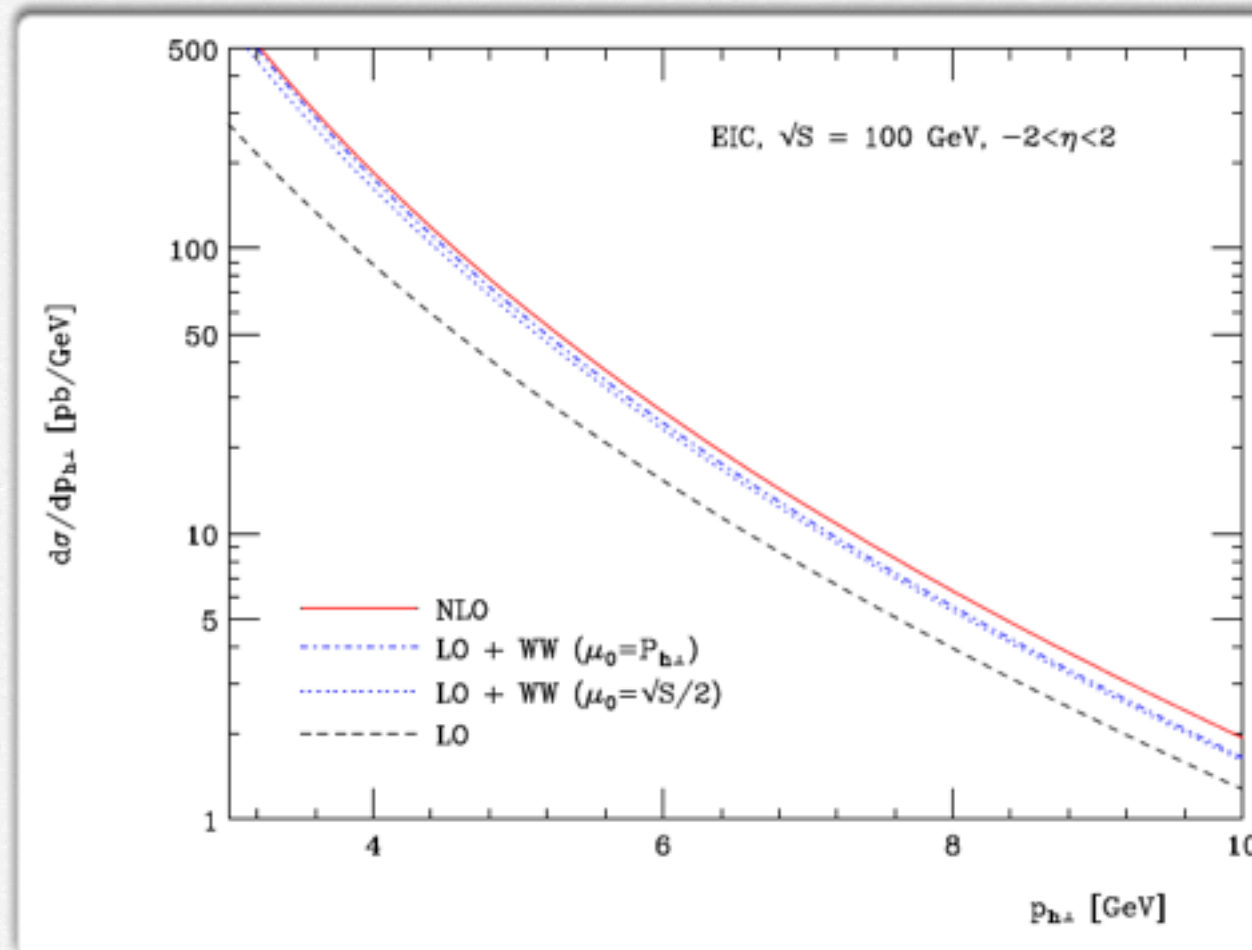
scale dependence:
slightly decreased
at NLO

NLO prediction for EIC (collider mode)

η - dependence:



$P_{h\perp}$- dependence:



K-factor: ~ 1.5
NLO significant

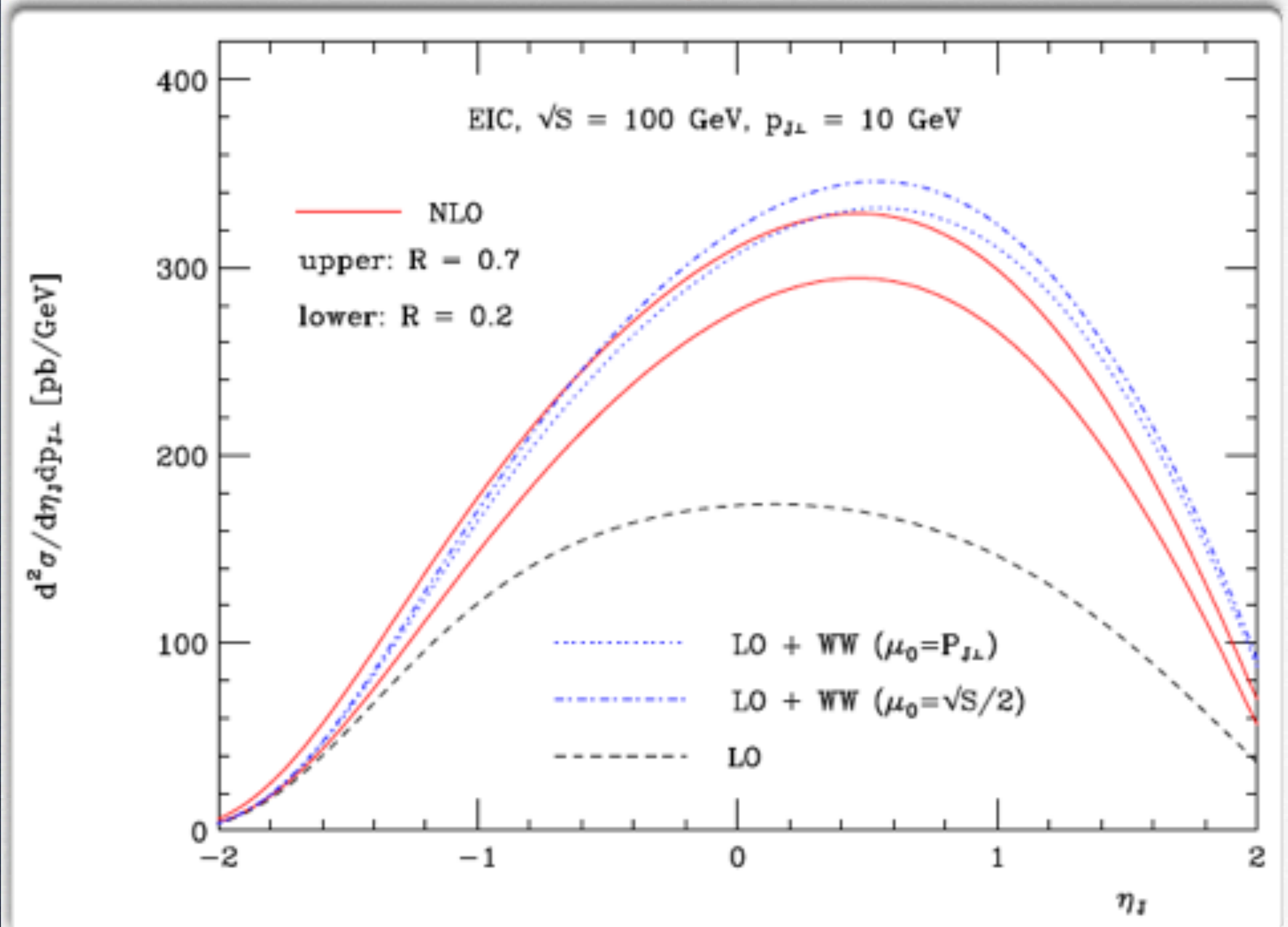
q → q channel
still dominant!

WW - approximation:
forward lepton ✔
forward nucleon ✘
mid-rapidity ✘

WW works better at
small $P_{h\perp}$ ~ few GeV

NLO prediction for Jet Production at EIC

η - dependence:



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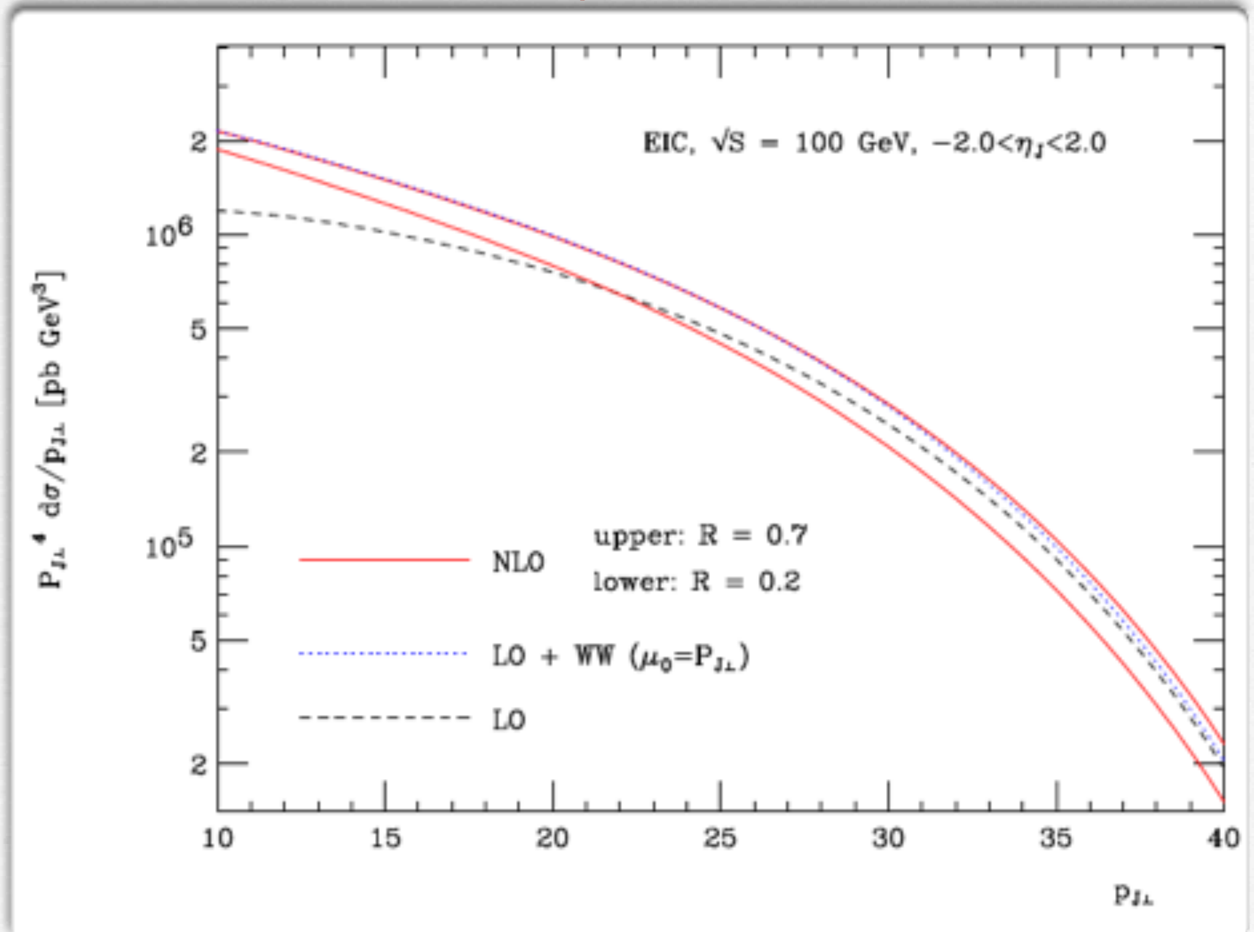


K-factor: ~ 2
NLO seizable

NLO correction depends on jet parameter R

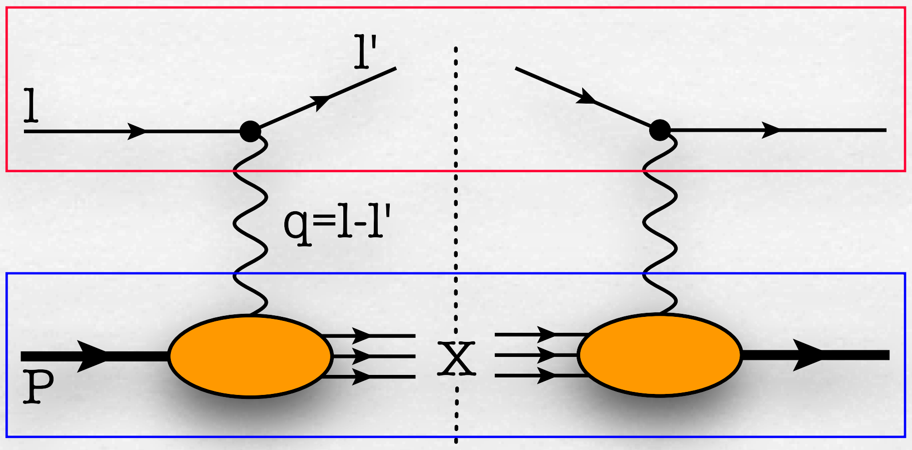
WW - approximation:
does not depend on R
seems to work for R = 0.7 (coincidentally)

Jet Production:
important to disentagle twist-3 contributions (no fragmentation)

Summary

- Leptoproduction of hadrons and jets nice ‘playground’ to study transverse spin effects.
- Precise data can be expected from various experiments.
- Unpolarized Cross Section: NLO corrections important, Weizsäcker-Williams approximation fails.
- Next Step: Polarized Cross Section at NLO

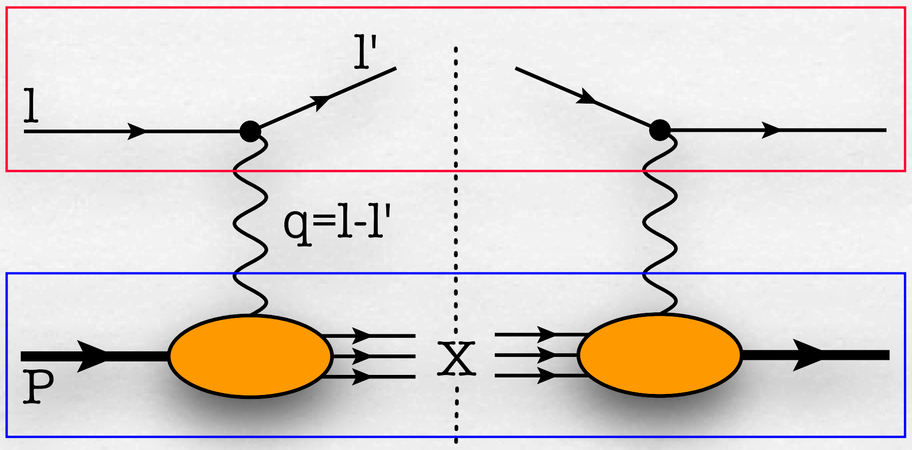
The archetype: g_2 in DIS ($e^{\rightarrow} + p^{\uparrow} \longrightarrow e + X$)



Structure functions

$$\boxed{\frac{d\sigma}{dx_B\ dy} \propto (F_1, F_2) + \lambda_e\ S_L g_1 + \lambda_e\ S_T \cos\phi_s (g_1 + g_2)}$$

The archetype: g_2 in DIS ($e^{\rightarrow} + p^{\uparrow} \longrightarrow e + X$)

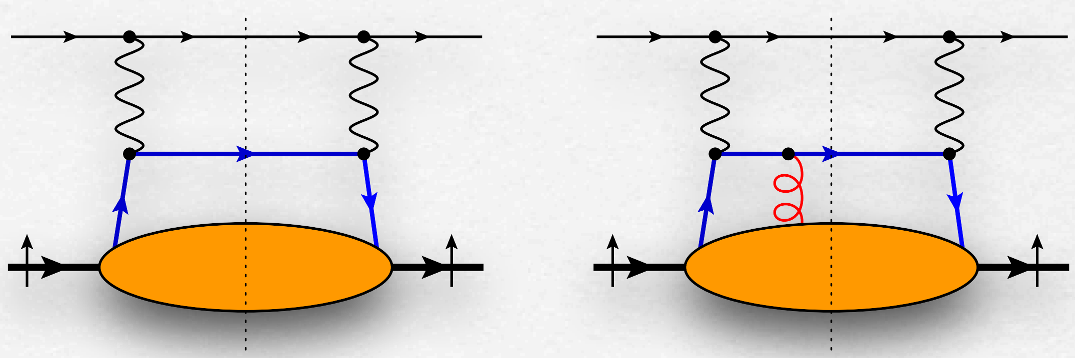


Structure functions

$$\frac{d\sigma}{dx_B\, dy} \propto (F_1, F_2) + \lambda_e\ S_L g_1 + \lambda_e\ S_T \cos\phi_s (g_1 + g_2)$$

Twist - 3 formalism

Hard part to LO:



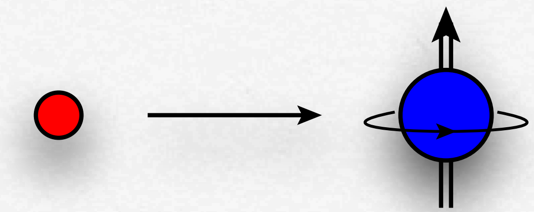
Double-Spin Asymmetry:

$$A_{LT} \propto (g_1 + g_2) \quad \propto \quad x g_T(x) + g_{1T}^{(1)}(x) + \frac{m_q}{M} h_1(x) + \int_0^1 dx' \frac{G_F(x,x') + \tilde{G}_F(x',x)}{2(x'-x)}$$

$$(\mathrm{QCD-EOM}) \ \longrightarrow 2\ x g_T(x)$$

Transverse Single-Spin Asymmetry

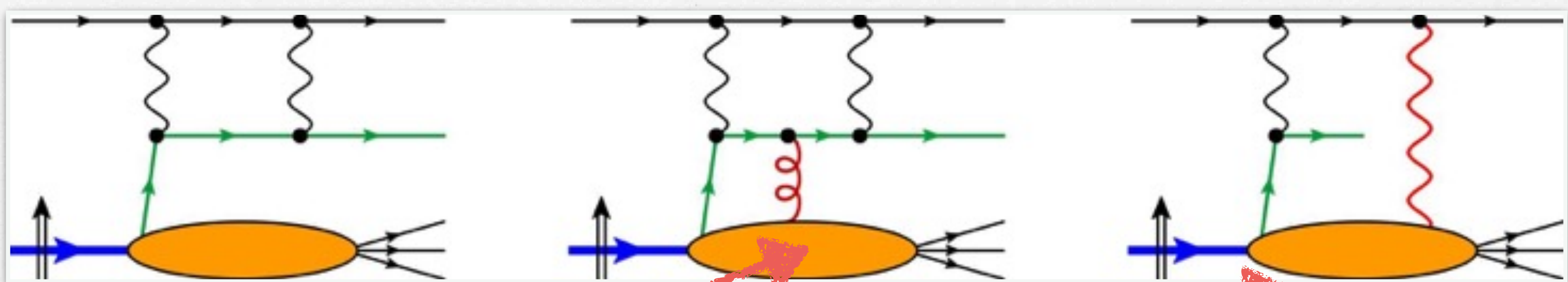
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



[Metz, Pitonyak, Schäfer, M.S., Vogelsang, Zhou; M.S.]

A_N = 0 for One-Photon Exchange [Christ, Lee, 1966]

$\Longrightarrow$ Need for a Two-Photon Exchange!



'q-g-q / q-γ-q correlation functions'

$\boxed{G_F(x, x')}$

$\Longrightarrow$ probe full support of quark-gluon-quark correlations

$\Longrightarrow$ non-zero effect at JLab 6, further measurements at JLab 12!