Are parton distribution functions universal?

Alessandro Bacchetta

DESY

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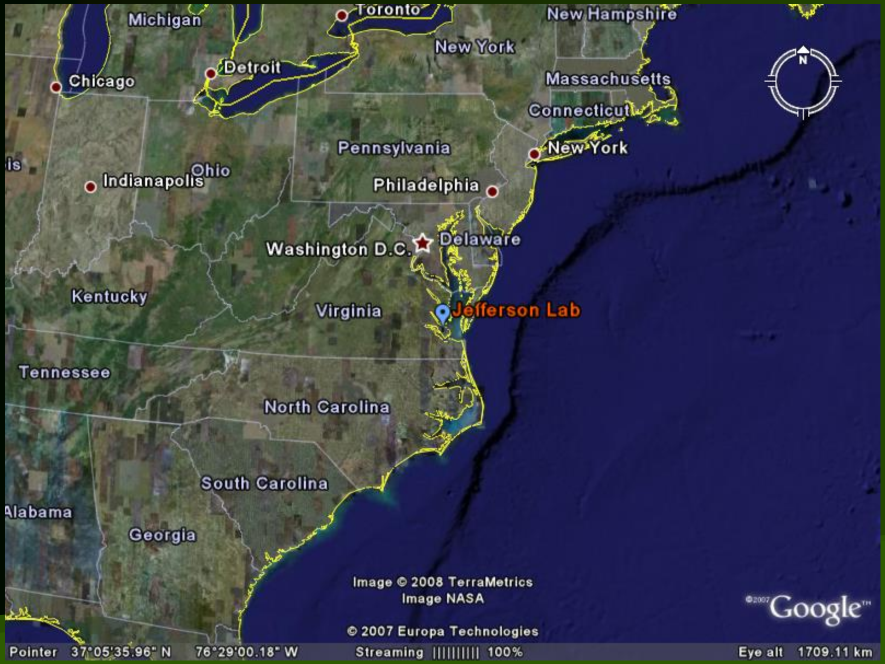
From March 2008

Nathan Isgur Fellow at

Jefferson Lab



ADVERTISMENT

From March 2008

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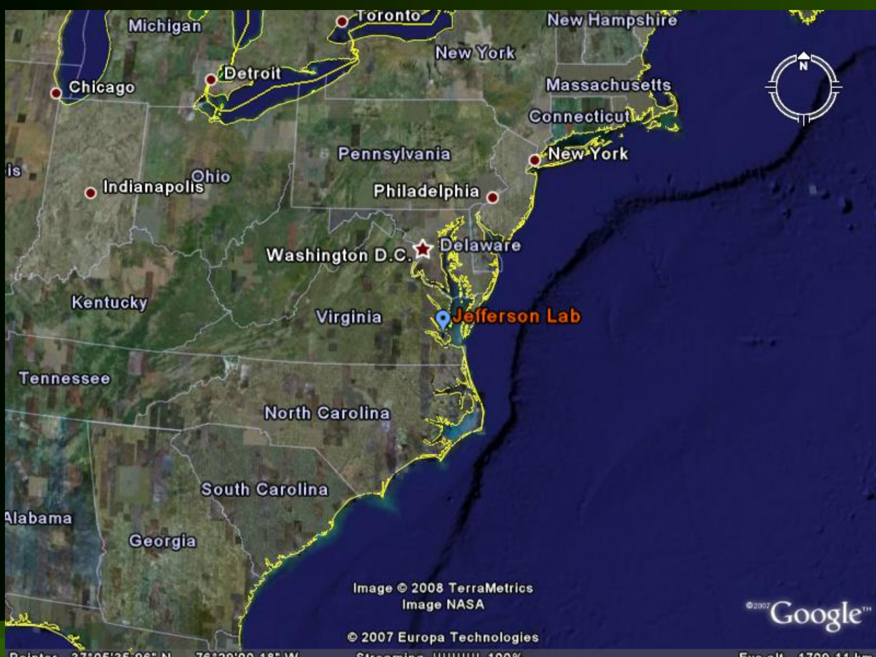

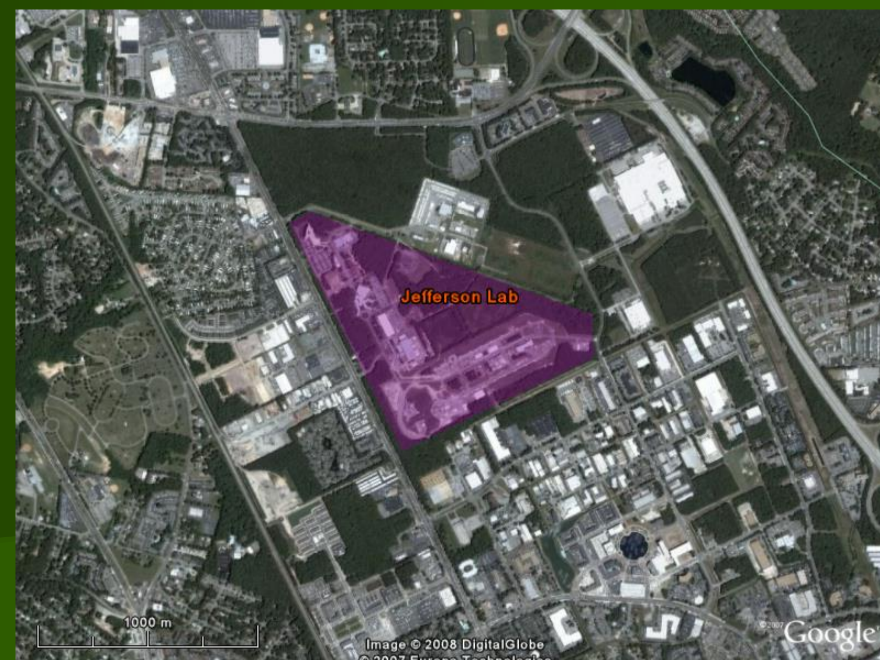

Outline

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- Factorization and universality

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- k_T factorization and unintegrated parton distribution functions

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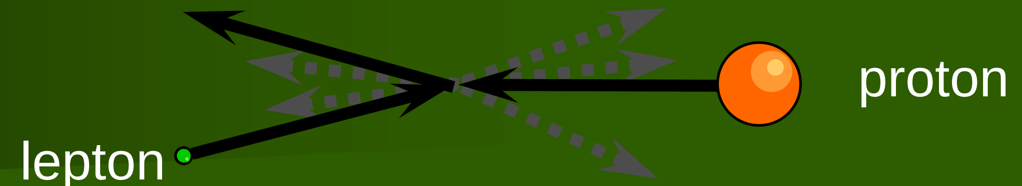
- Gauge links in PDFs
- Gauge links in different processes
- Problems with universality
- Conclusions

DIS

$$\ell + p \rightarrow \ell + X$$



DIS

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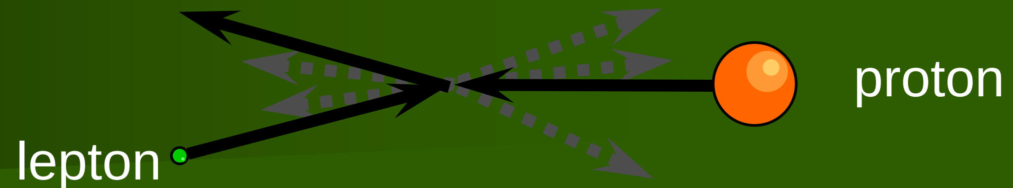
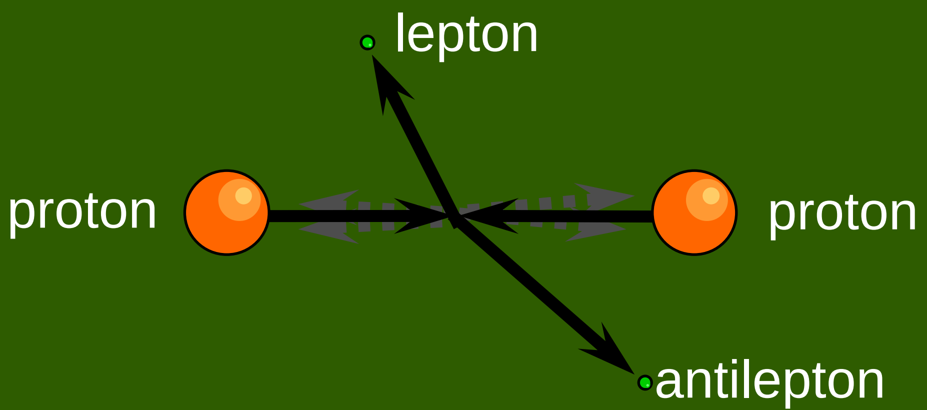


Drell-Yan

$$p + p \to \ell + \overline{\ell} + X$$



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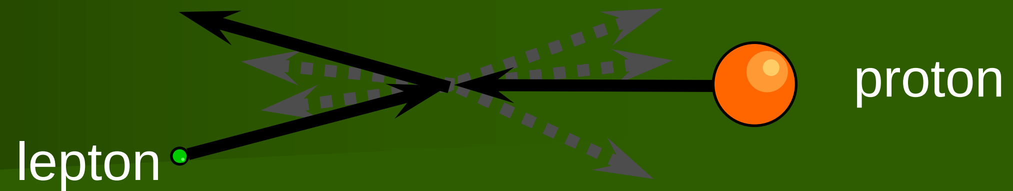

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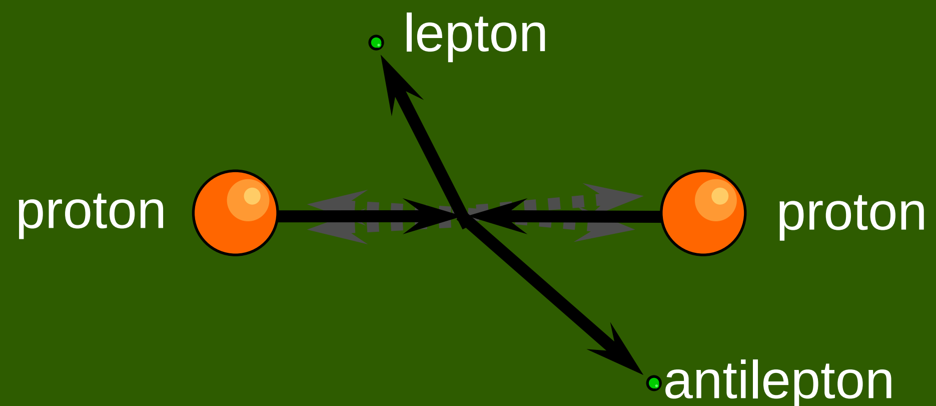
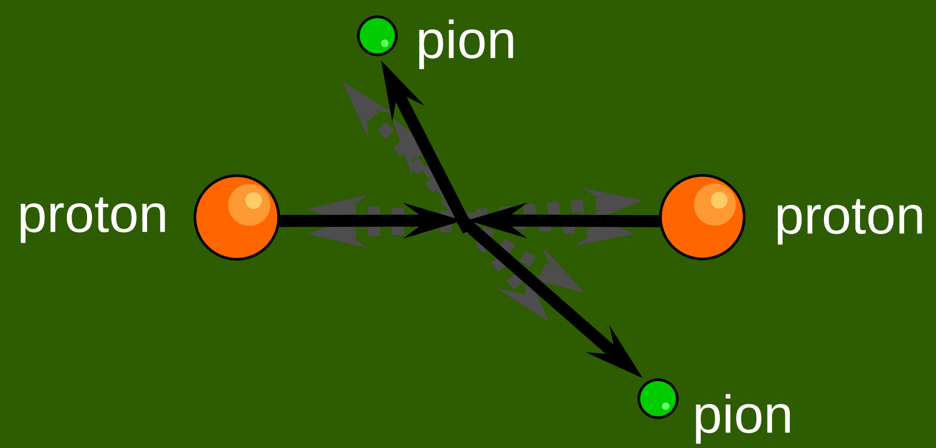


pp to hadrons

$$p + p \to h_1 + h_2 + X$$



DIS

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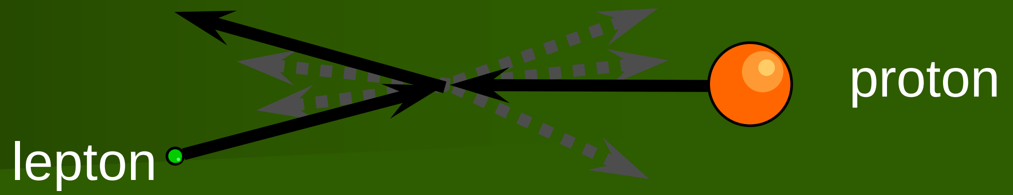
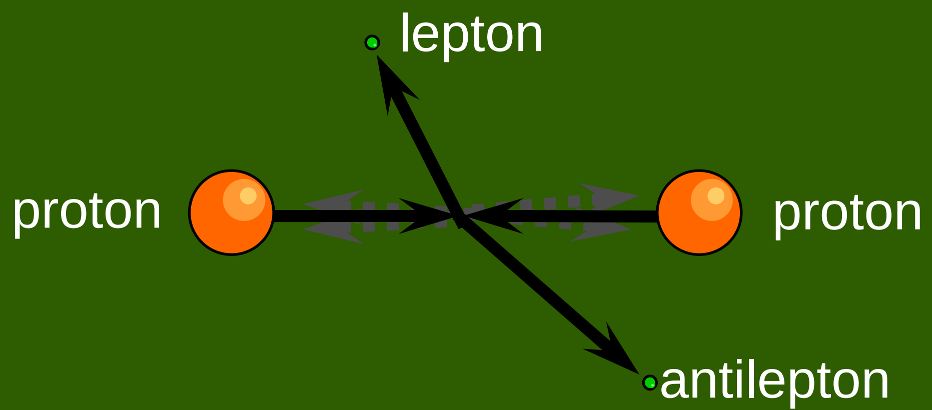


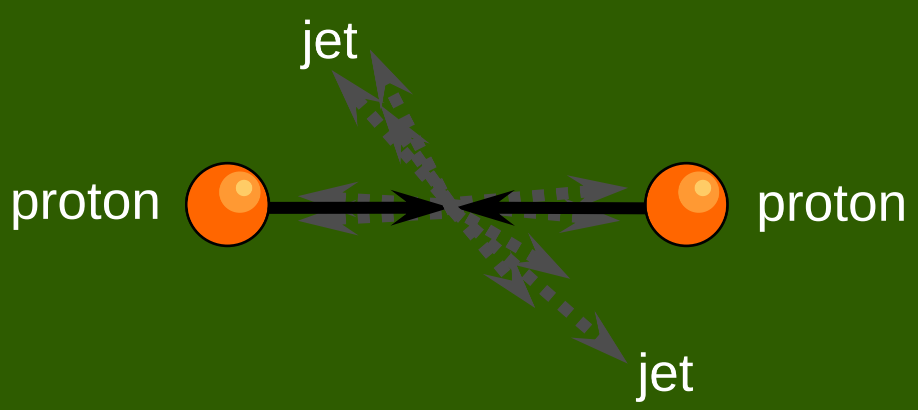
Drell-Yan

$$p + p \to \ell + \overline{\ell} + X$$



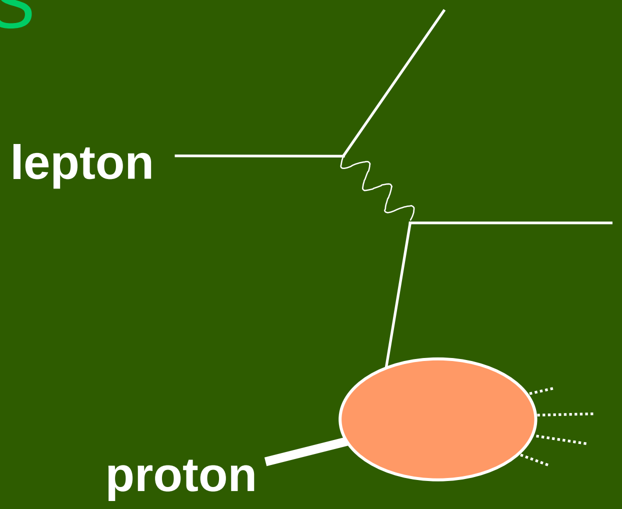
pp to jets

$$p + p \to j_1 + j_2 + X$$



Factorization

DIS



Factorization

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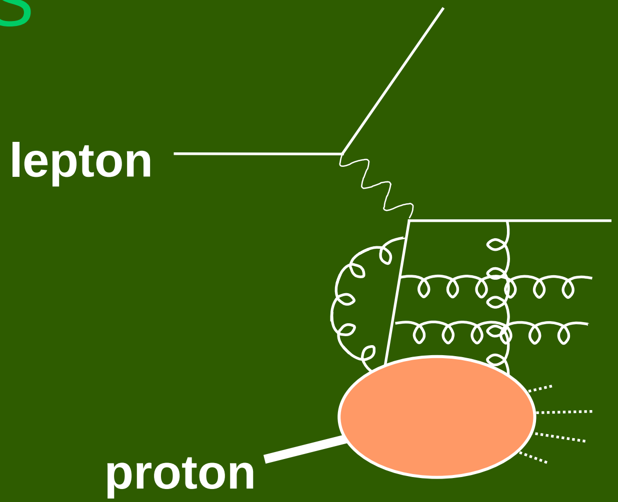

Factorization

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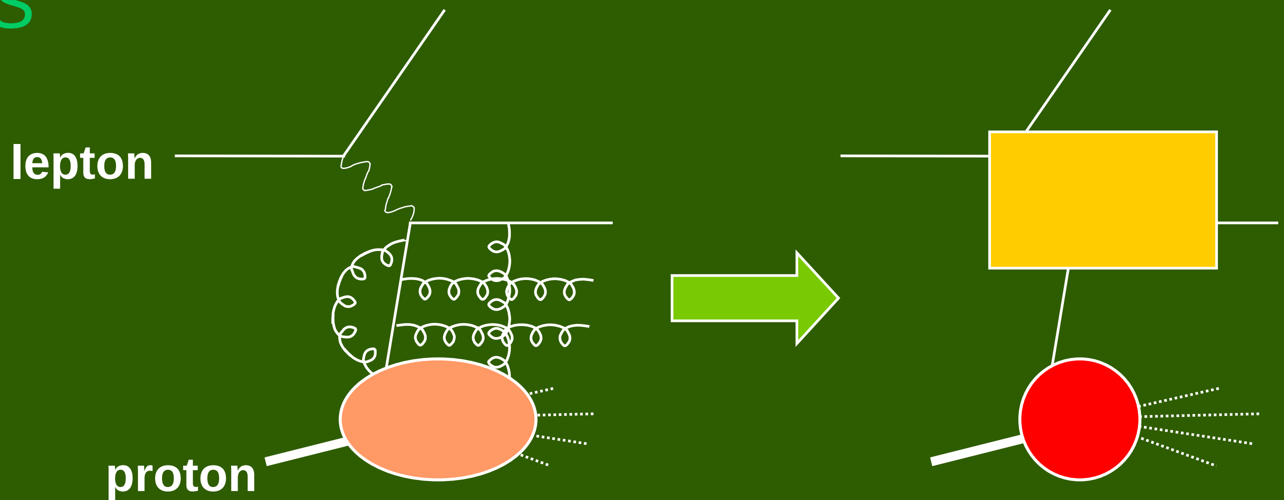

Factorization

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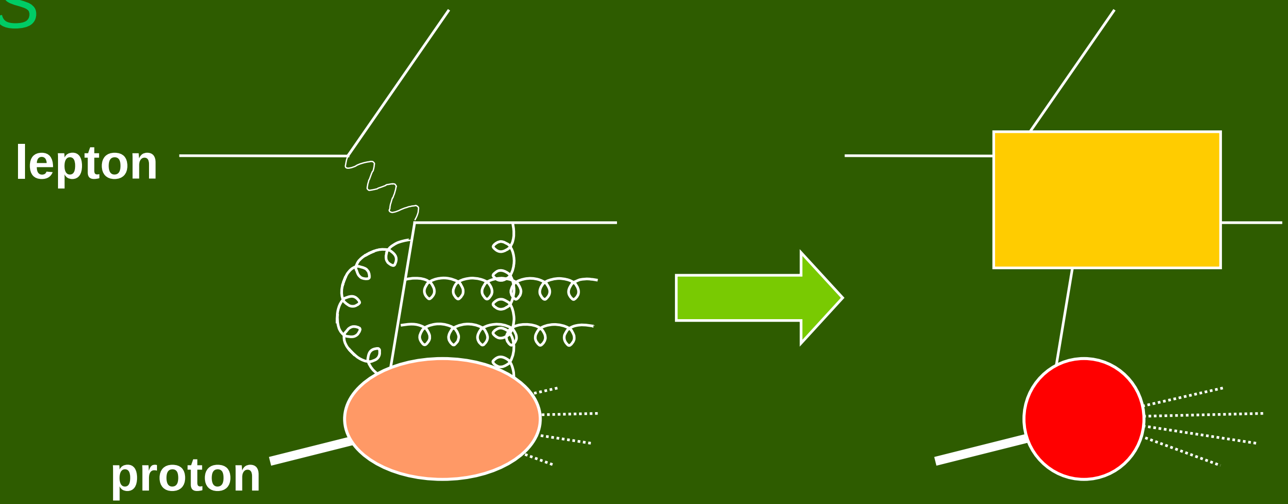
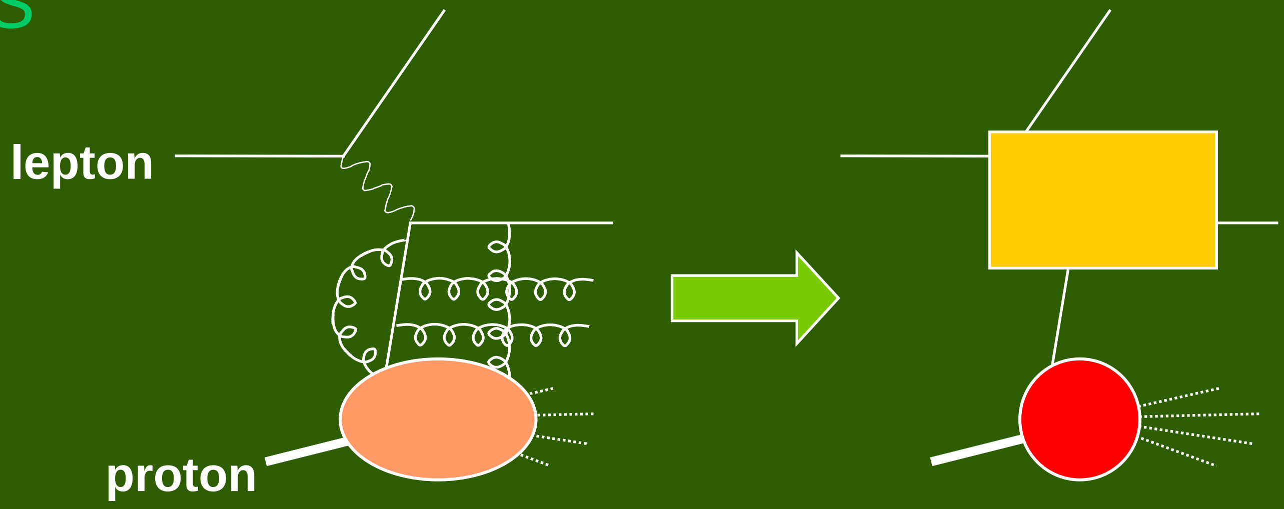


Partonic scattering amplitude

Distribution amplitude

Factorization

DIS



Partonic scattering amplitude

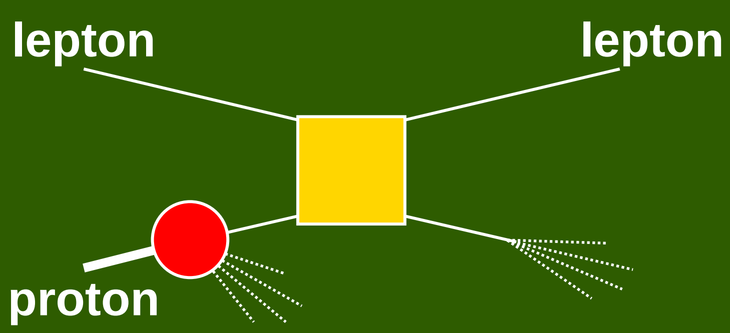
Distribution amplitude

$$d\sigma = H \otimes f$$

Universality

DIS

$$\ell + p \to \ell + X$$



Universality

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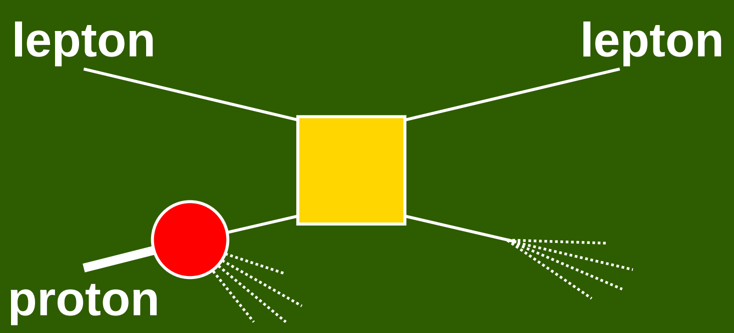
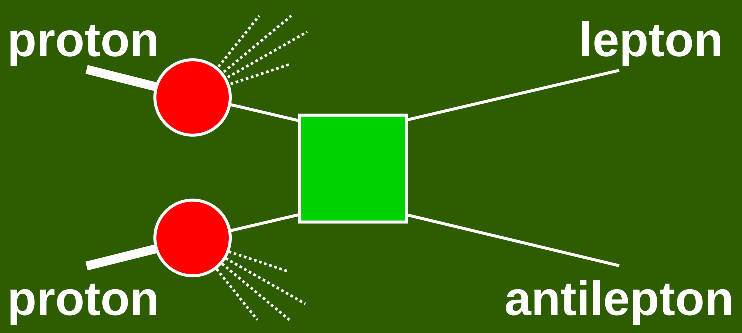


Drell-Yan

$$p + p \to \ell + \overline{\ell} + X$$



Universality

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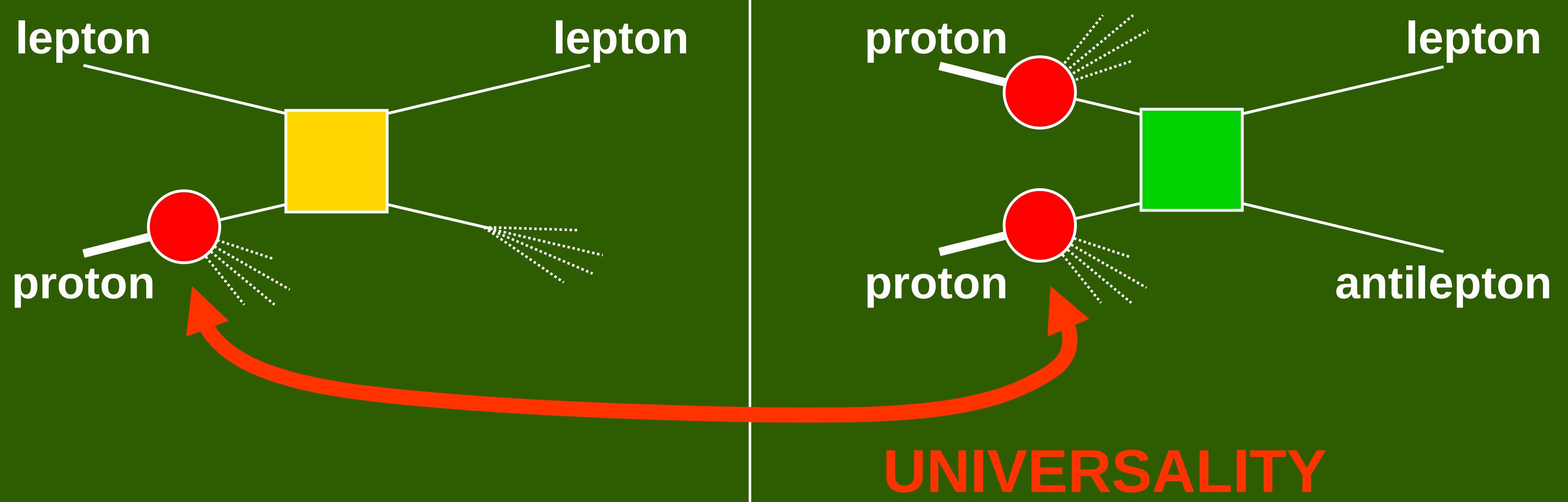
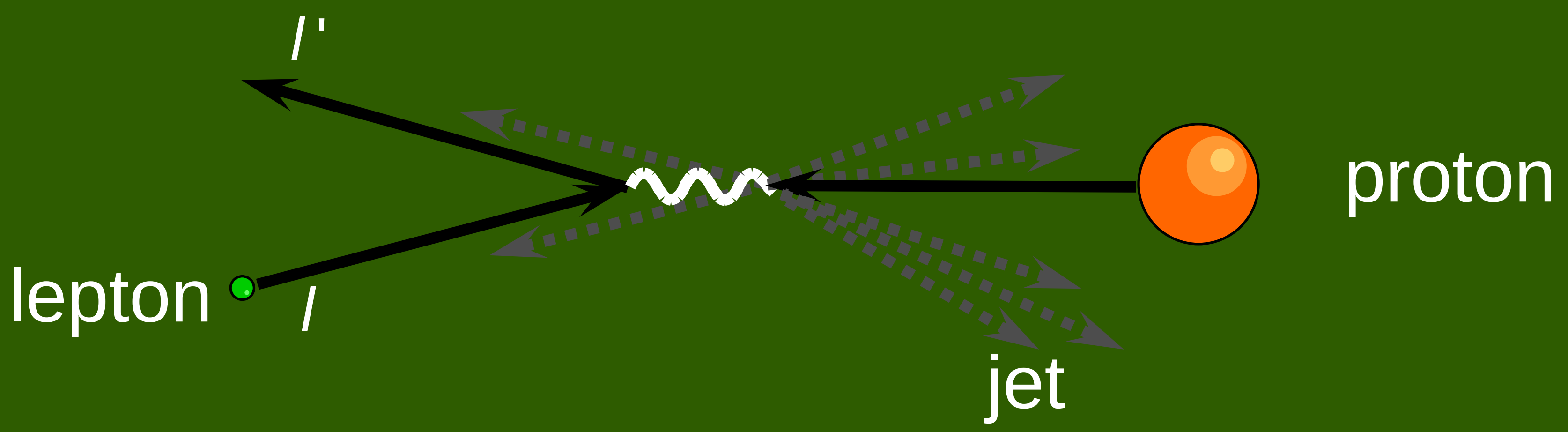


Key concepts in QCD!

Factorization and universality are at the base of much of the predictive power of QCD. For instance, they give the possibility to extract PDFs from HERA data and use them to look for new physics at LHC.

Jet semi-inclusive DIS

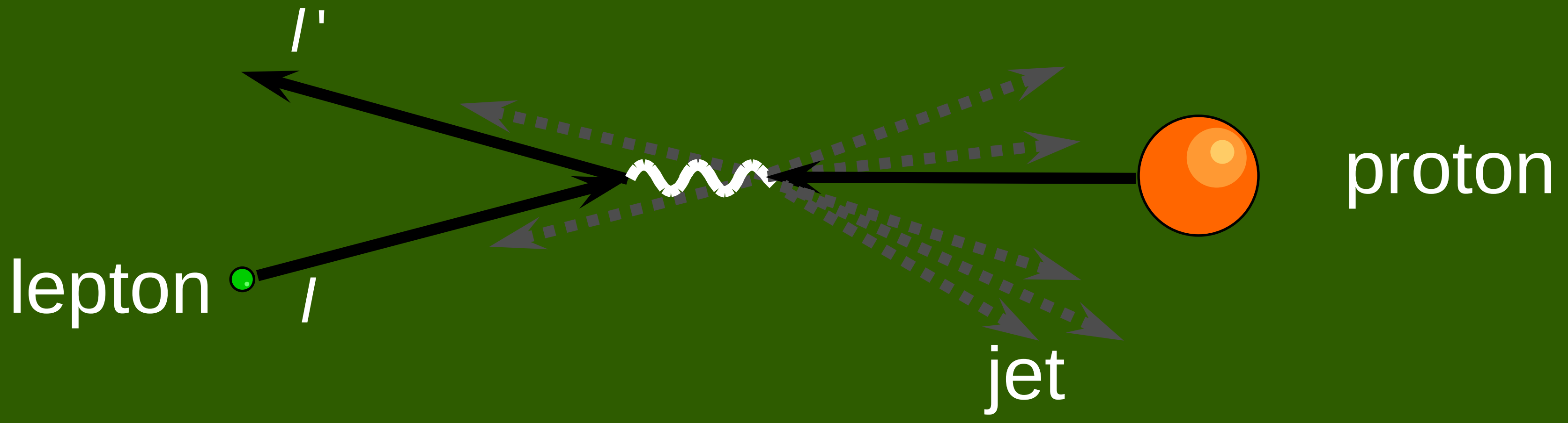
$$\ell(l) + p(P) \to \ell(l') + j(k_j) + X$$



Jet semi-inclusive DIS

$$\ell(l) + p(P) \to \ell(l') + j(k_j) + X$$

$-(l - l')^2 = Q^2 =$ virtuality of photon

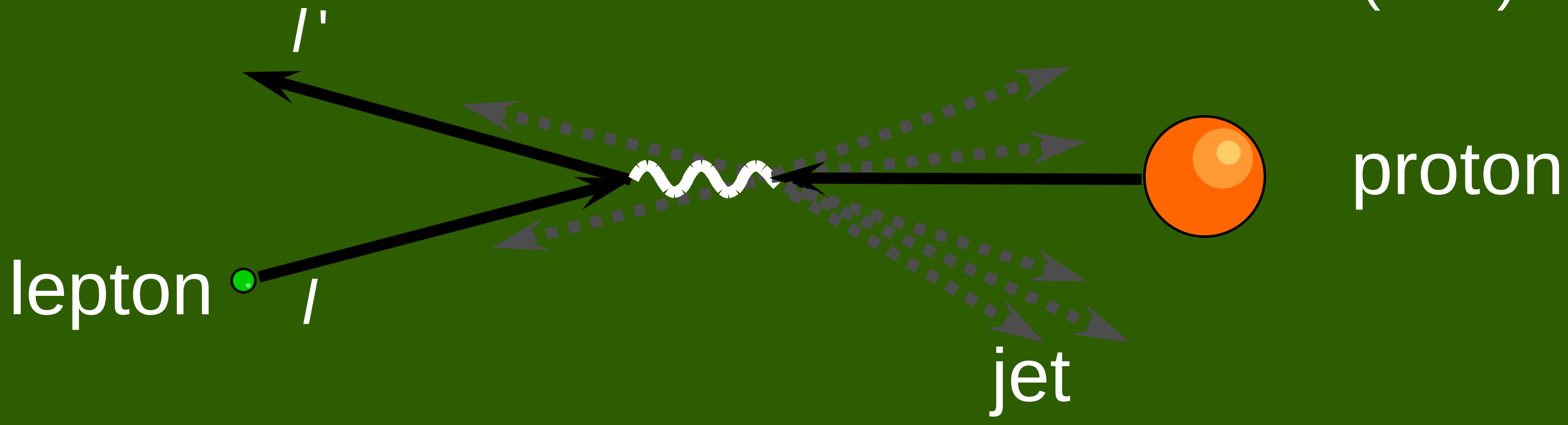


Jet semi-inclusive DIS

$$\ell(l)+p(P)\to\ell(l')+j(k_j)+X$$

$-(l-l')^2 = Q^2 =$ virtuality of photon

$$x=\frac{Q^2}{2P\cdot(l-l')}$$



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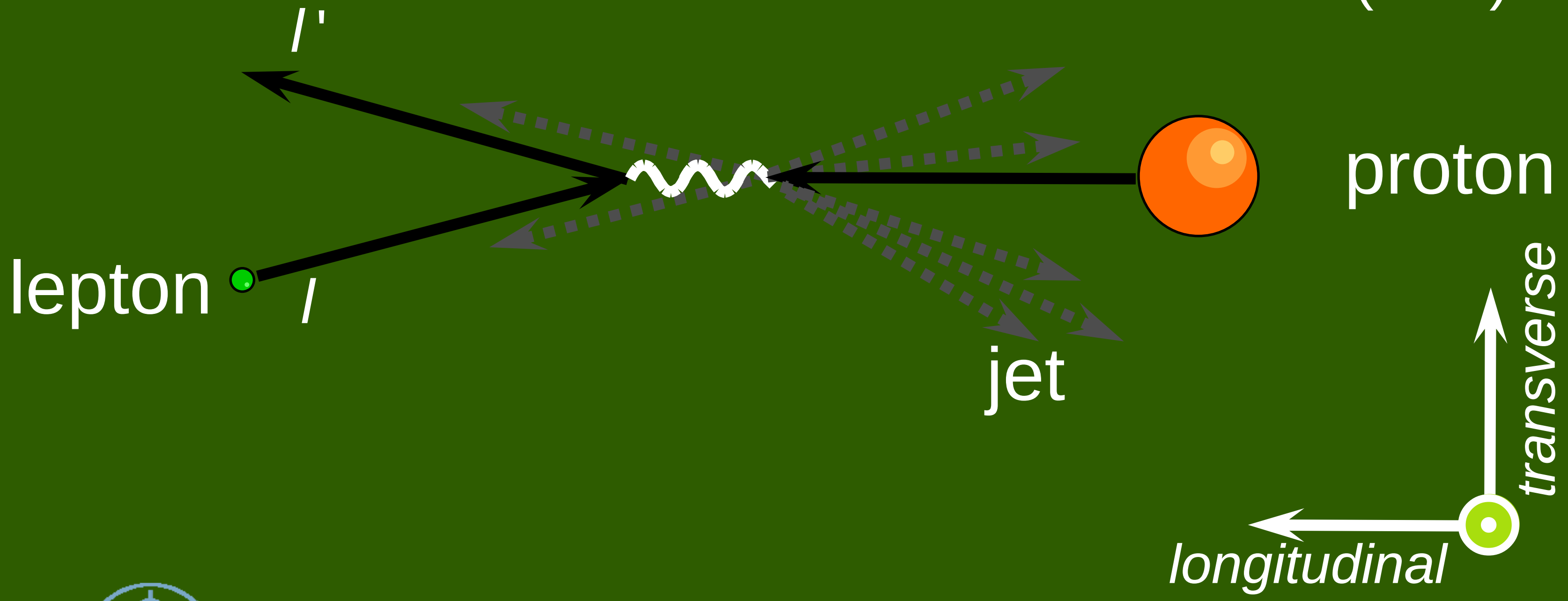

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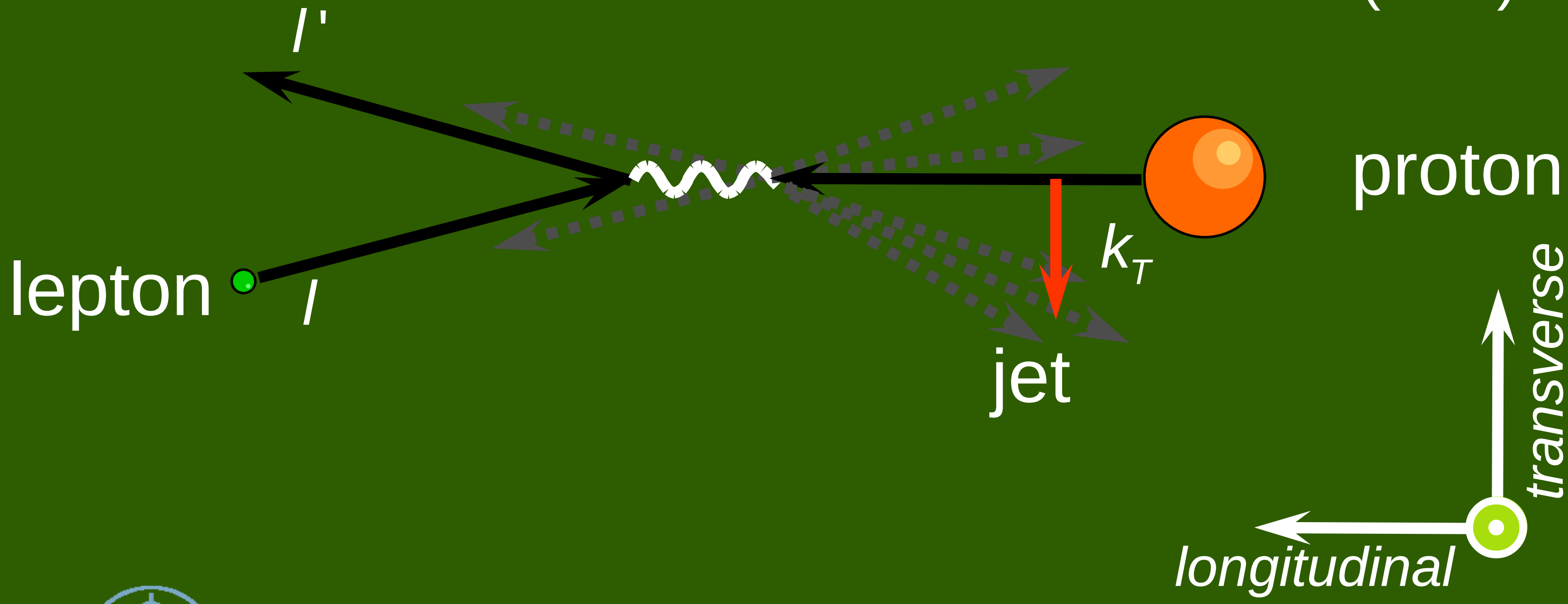
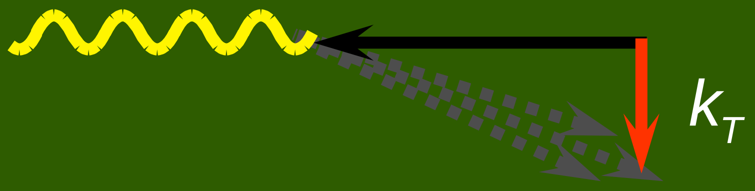


Transverse momentum effects

SIDIS



Transverse momentum effects

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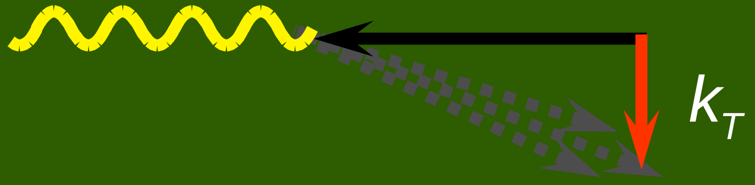
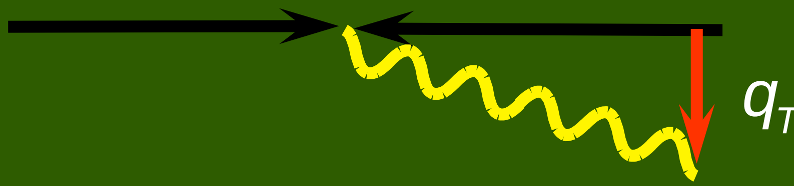
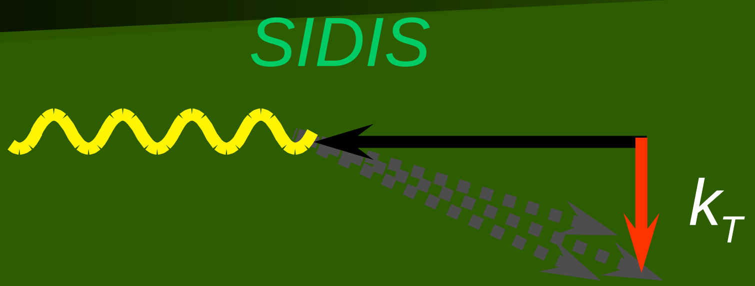
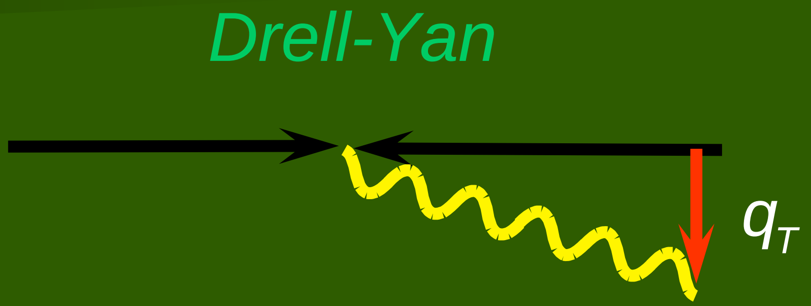


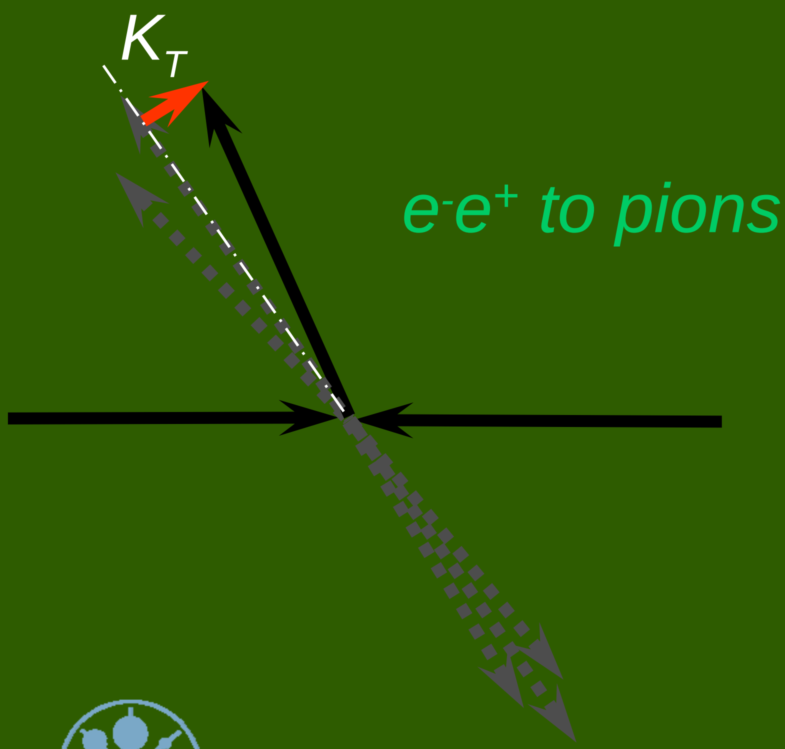
Drell-Yan



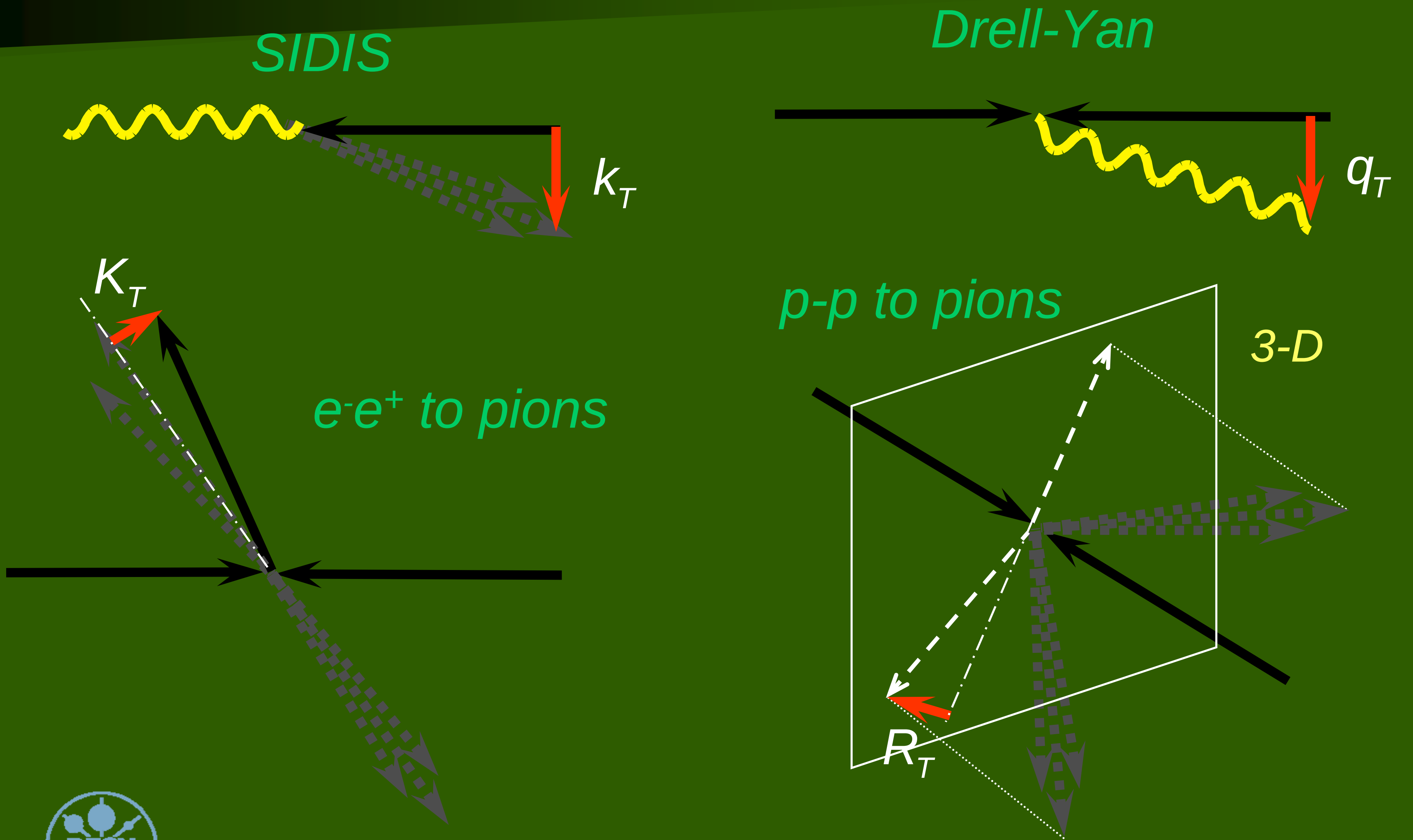
Transverse momentum effects



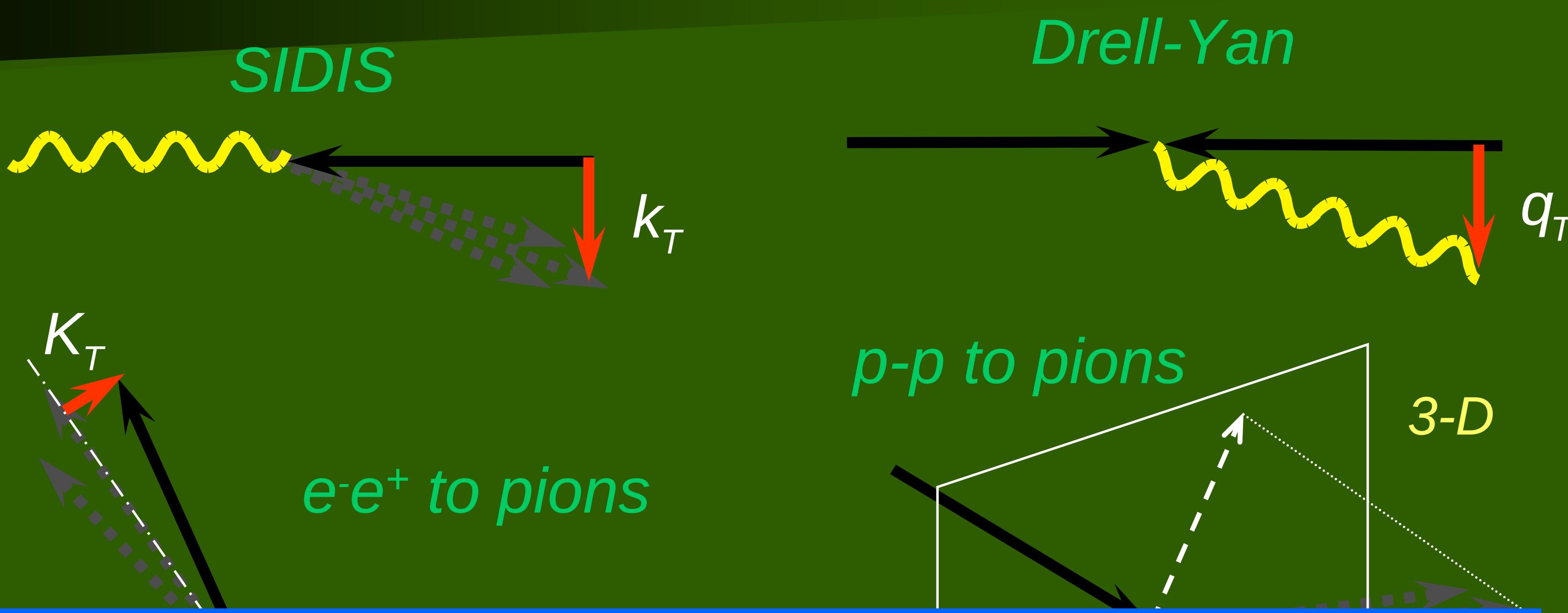




Transverse momentum effects



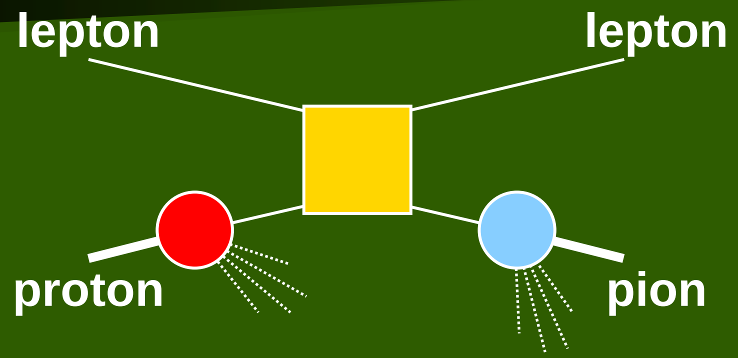
Transverse momentum effects



Whenever we measure transverse-momentum effects, we need k_T-factorization and we need transverse momentum dependent (or unintegrated) parton distributions

Collins, Soper, NPB 193 (81)

k_T factorization and universality



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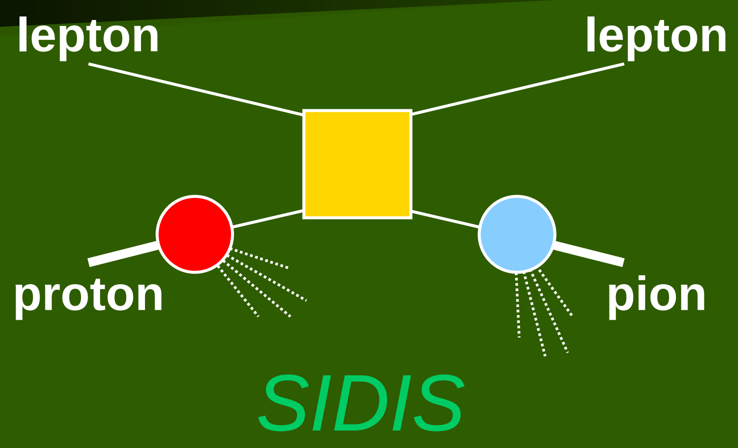
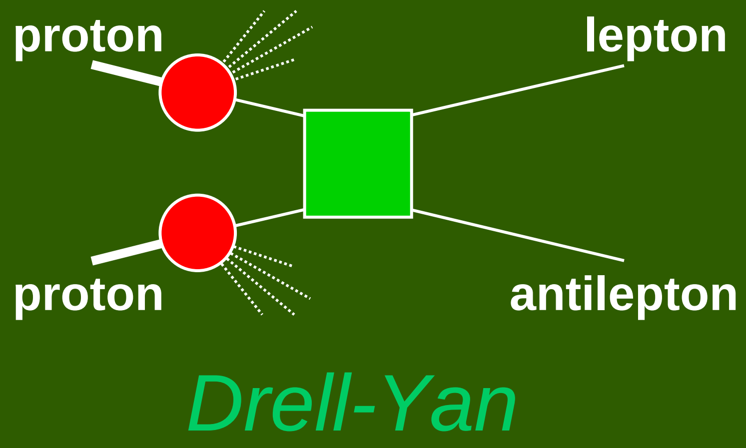
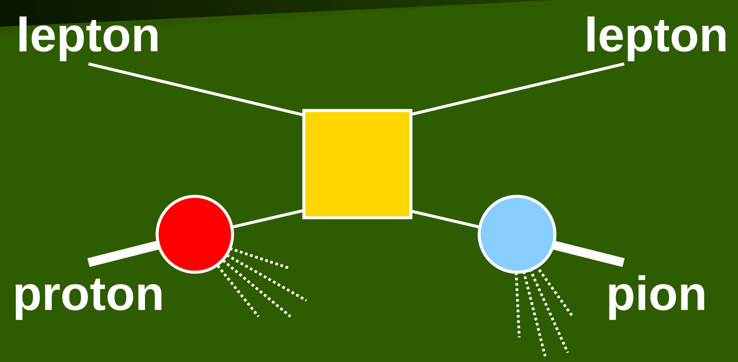
k_T factorization and universality





k_T factorization and universality



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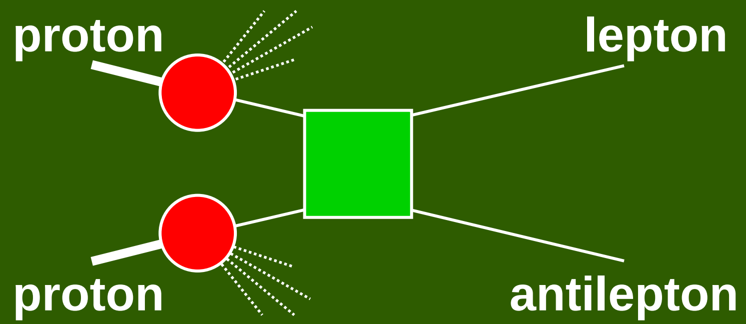
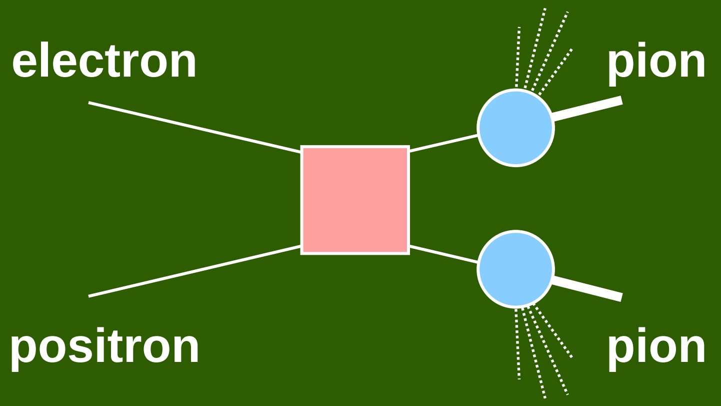
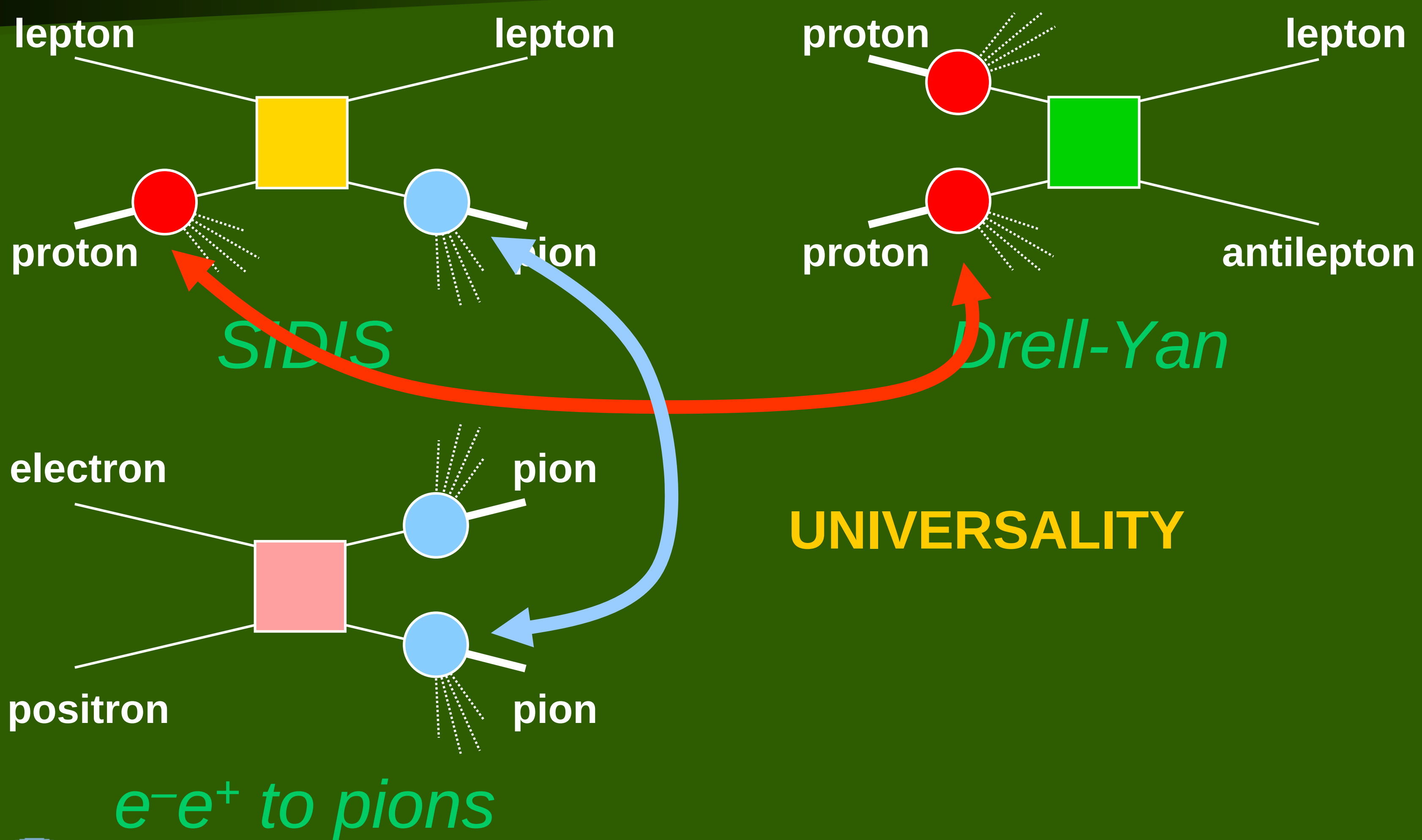


Drell-Yan

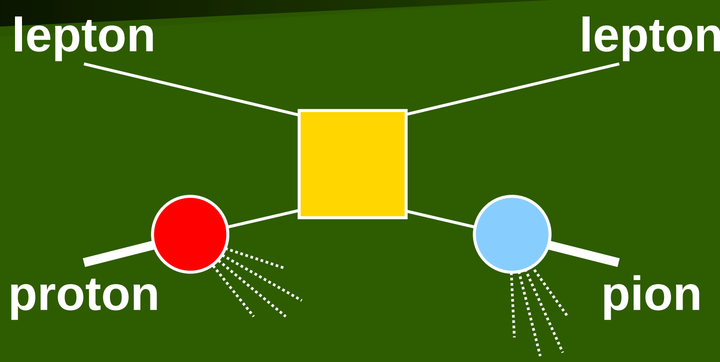


e^-e^+ to pions

k_T factorization and universality



k_T factorization and universality



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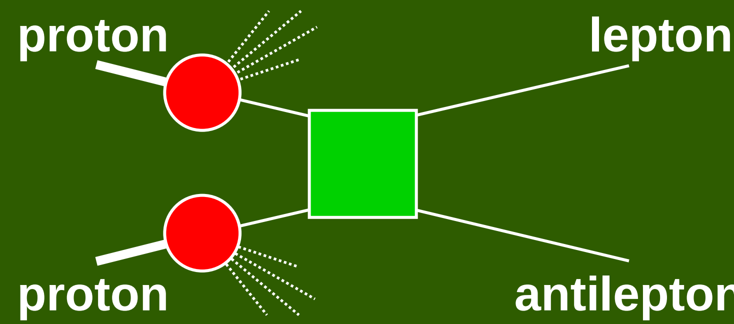

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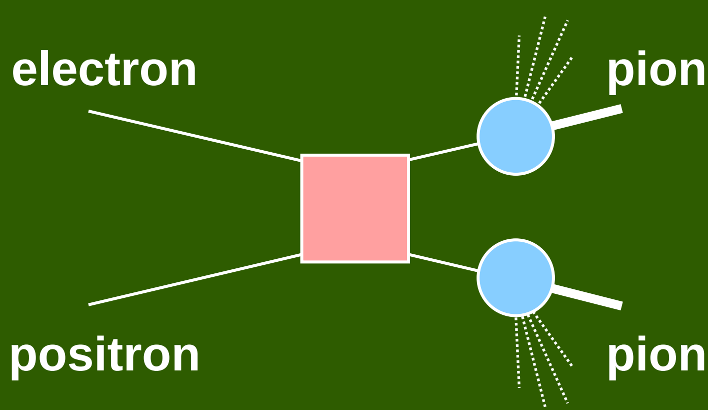
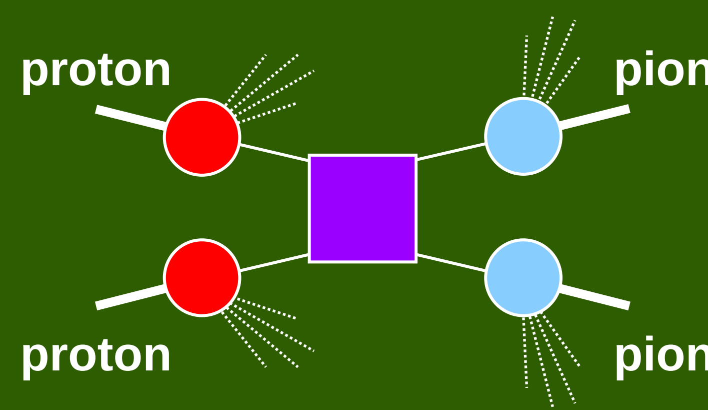
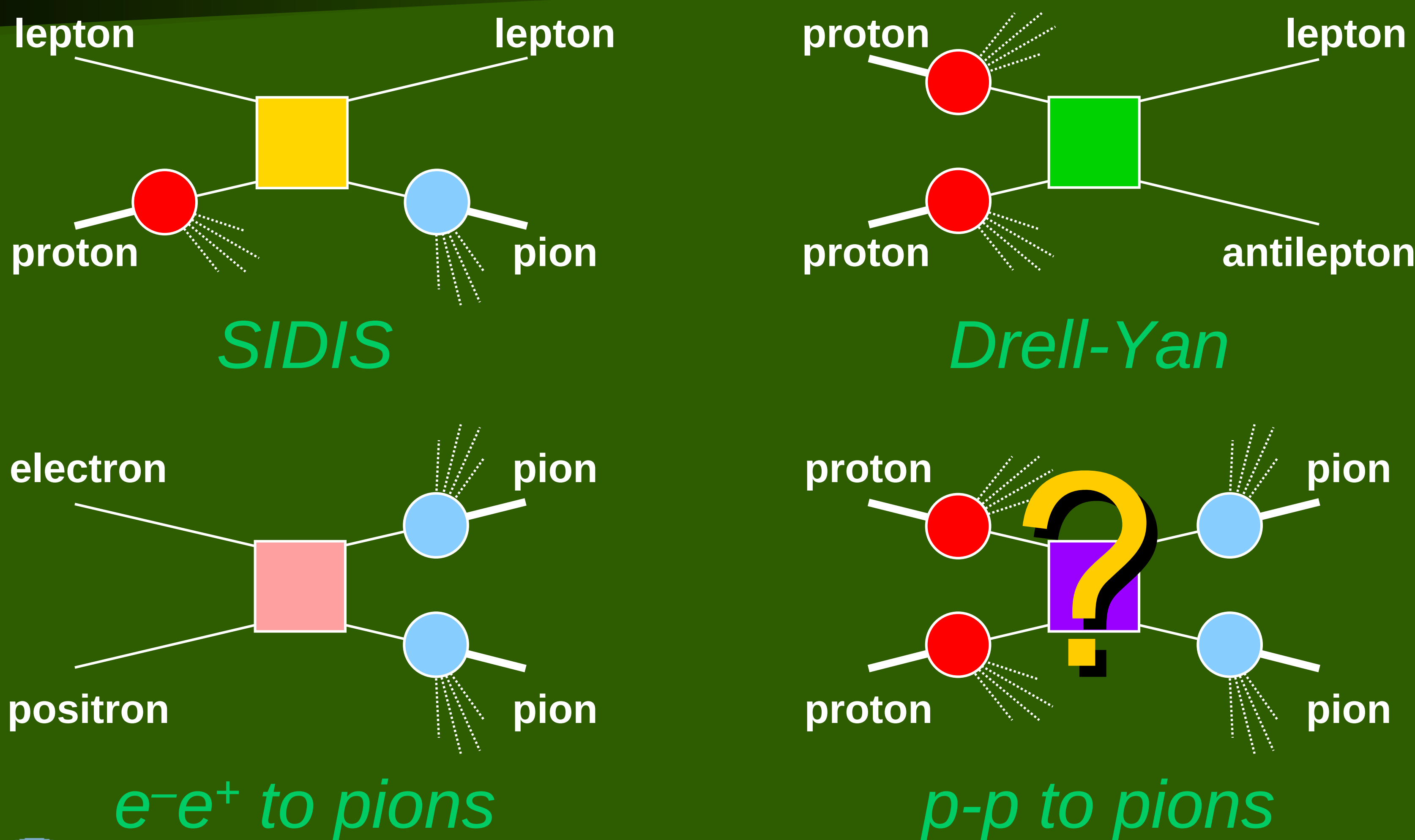


e^-e^+ to pions

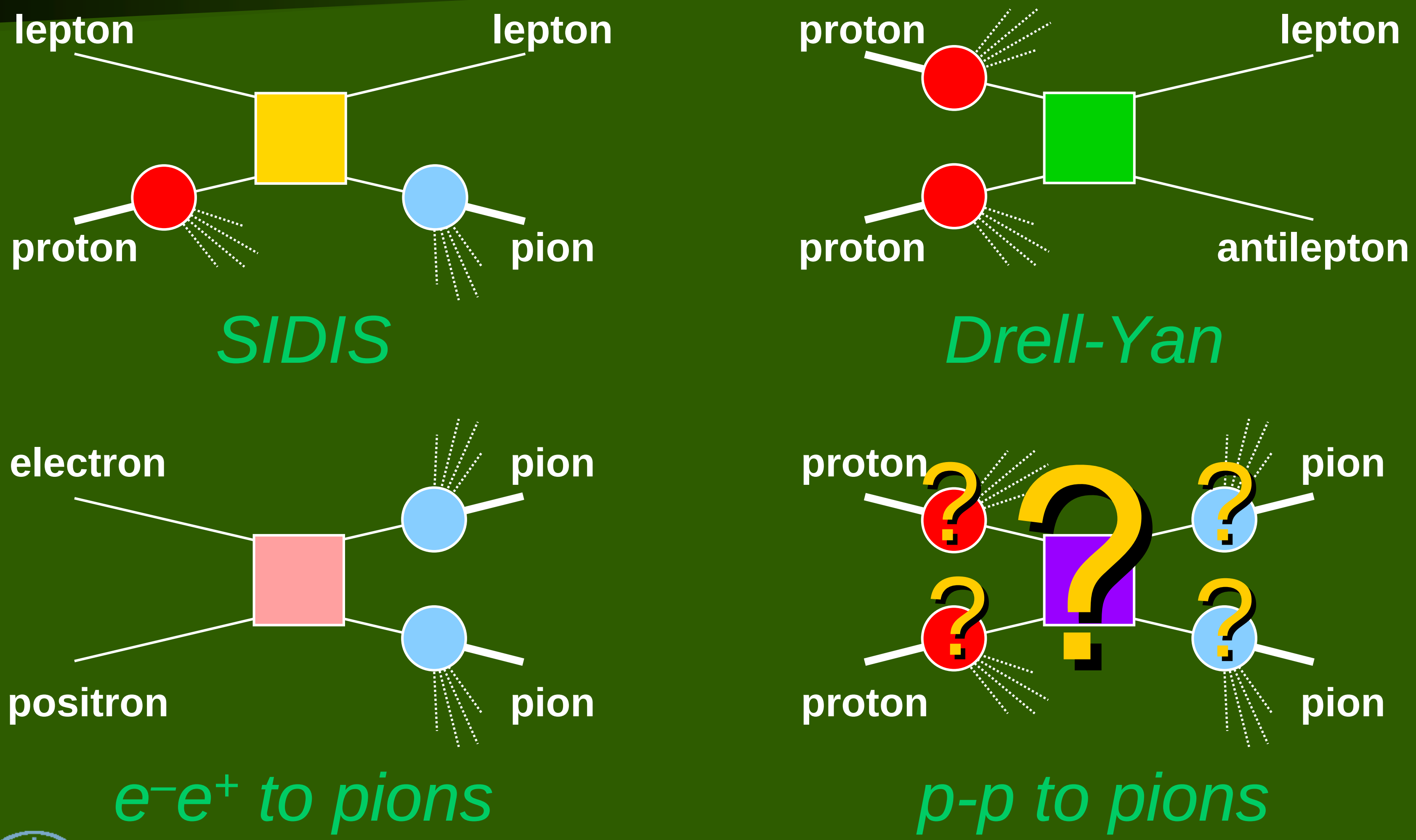


p-p to pions

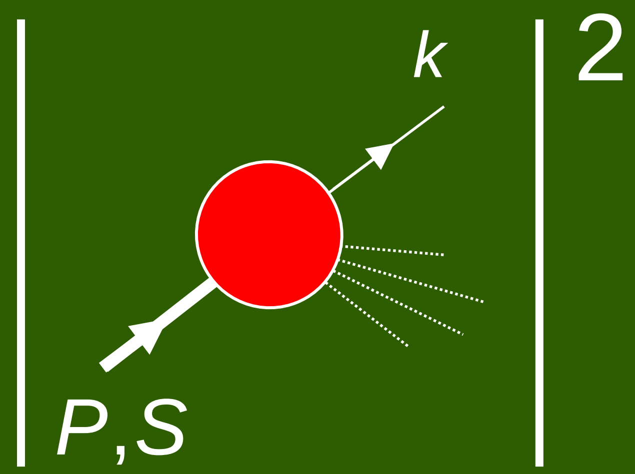
k_T factorization and universality



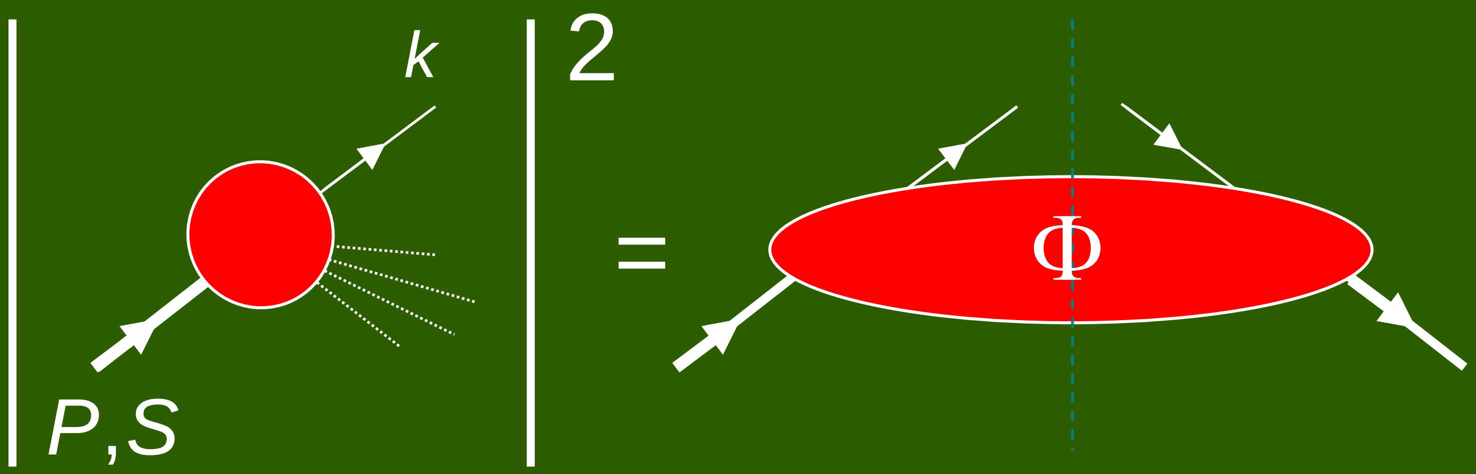
k_T factorization and universality



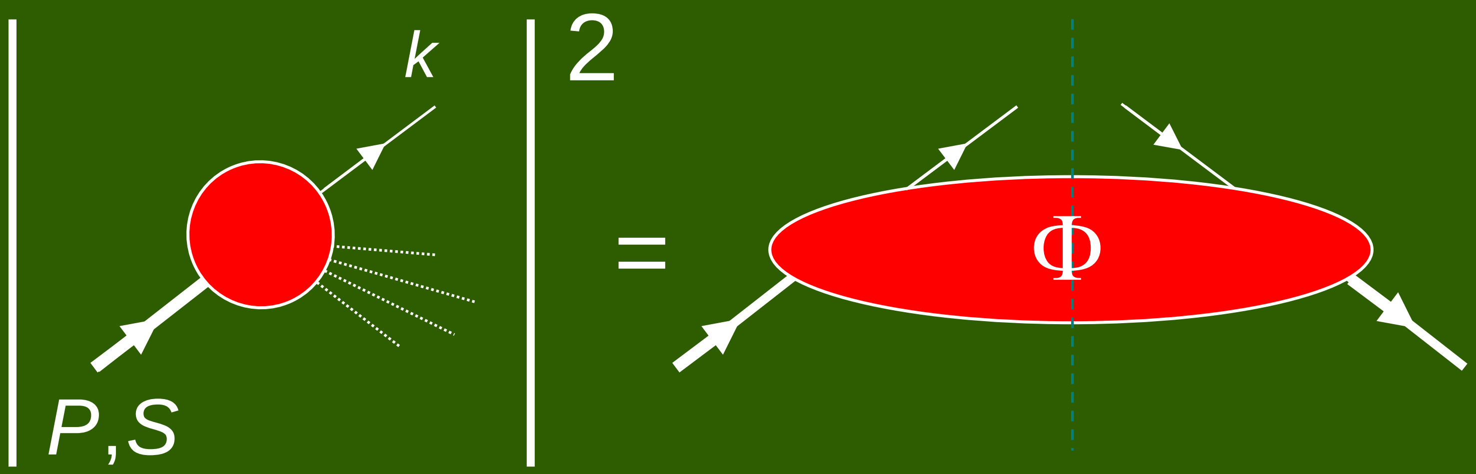
Parton distribution functions



Parton distribution functions

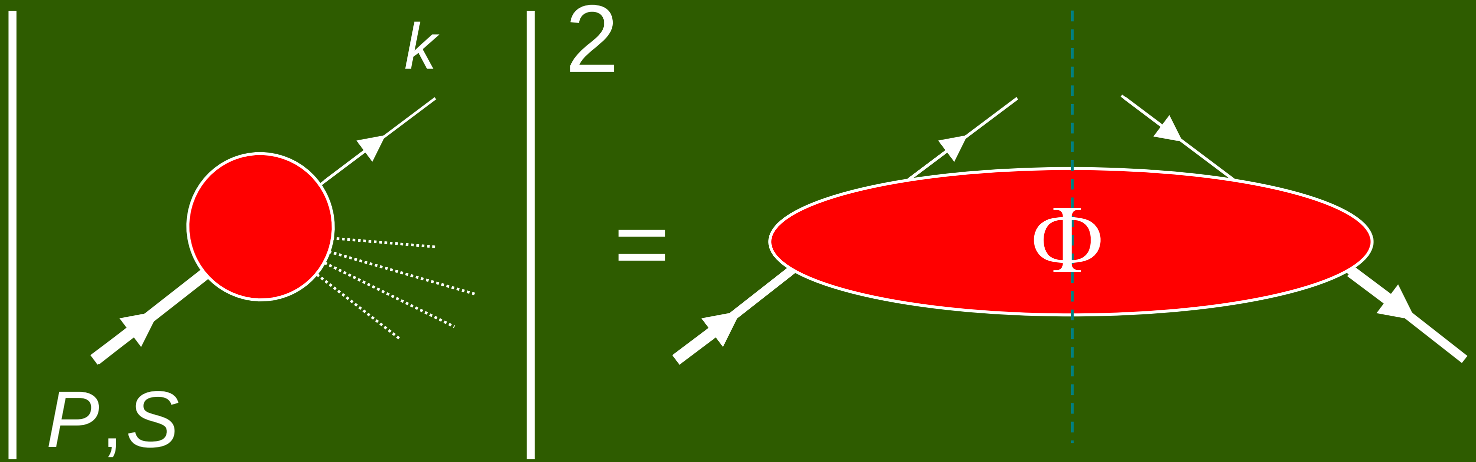


Parton distribution functions



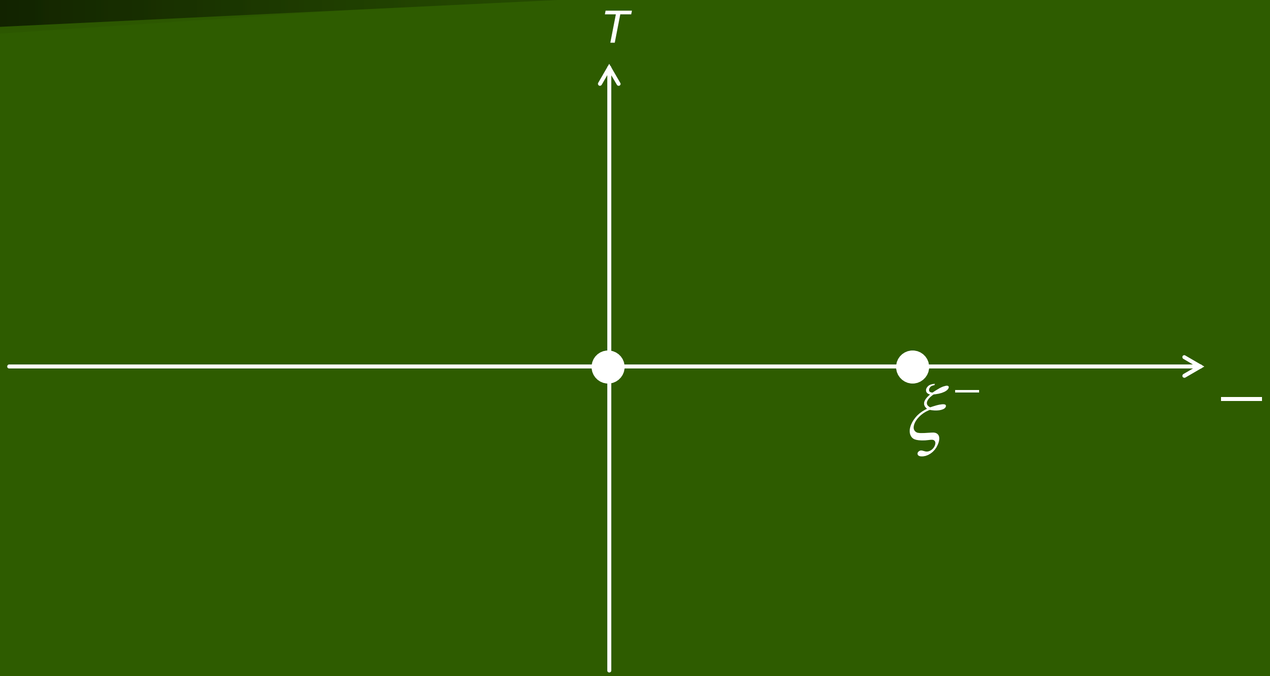
$$\Phi_{ij}(x) = \int \frac{d\xi^-}{2\pi} e^{i\,x P^+ \xi^-} \left\langle P \middle| \overline{\psi}_j(0)\, \psi_i(\xi^-) \middle| P \right\rangle$$

Parton distribution functions

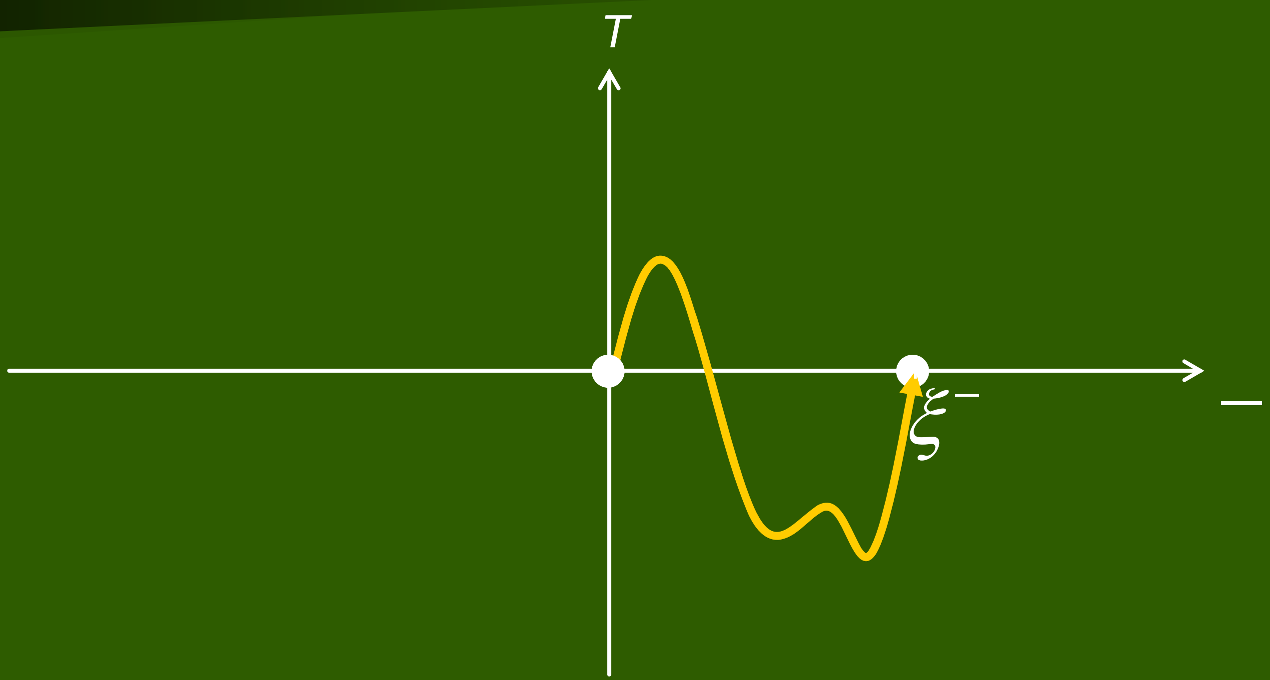


$$\Phi_{ij}(x) = \int \frac{d\xi^-}{2\pi} e^{i\,x P^+ \xi^-} \left\langle P \middle| \bar{\psi}_j(0)\, \mathcal{U}_{[0,\xi^-]}\, \psi_i(\xi^-) \middle| P \right\rangle$$

Gauge link or Wilson line



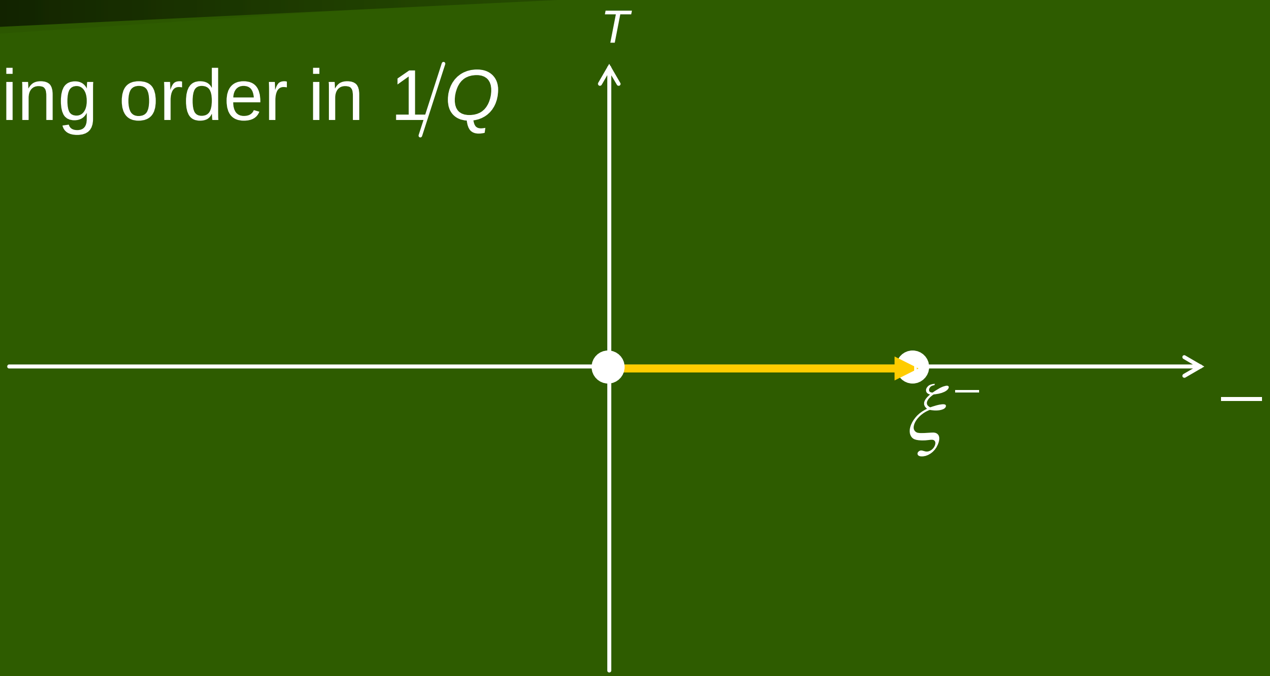
Gauge link or Wilson line



$$\mathcal{U}_{\left[0,\xi^-\right]}$$

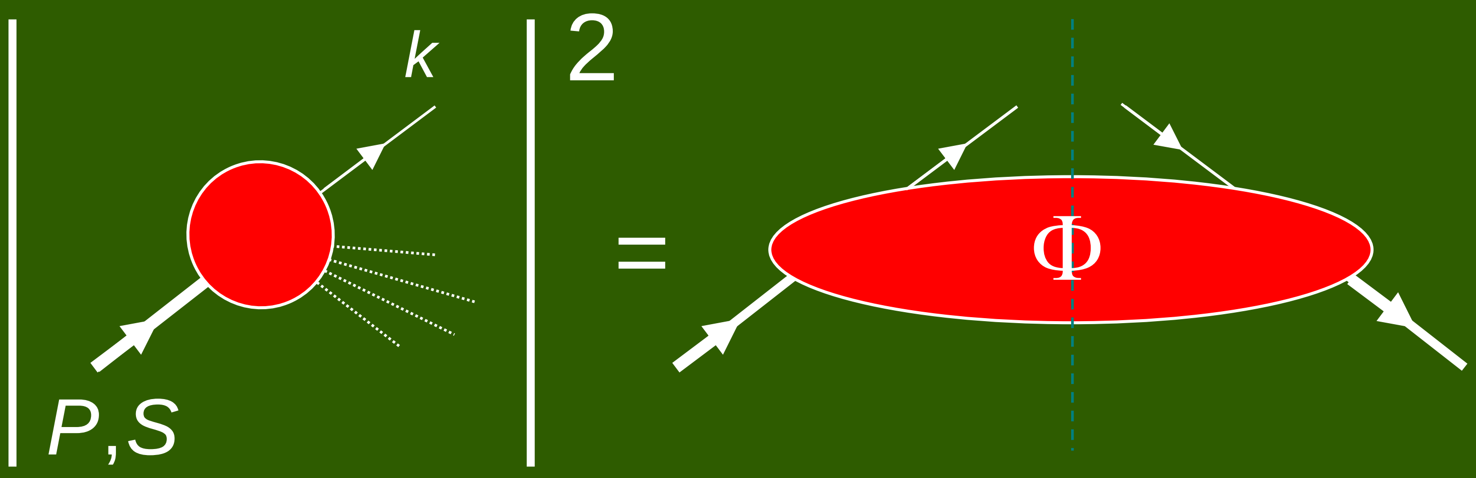
Gauge link or Wilson line

At leading order in $1/Q$

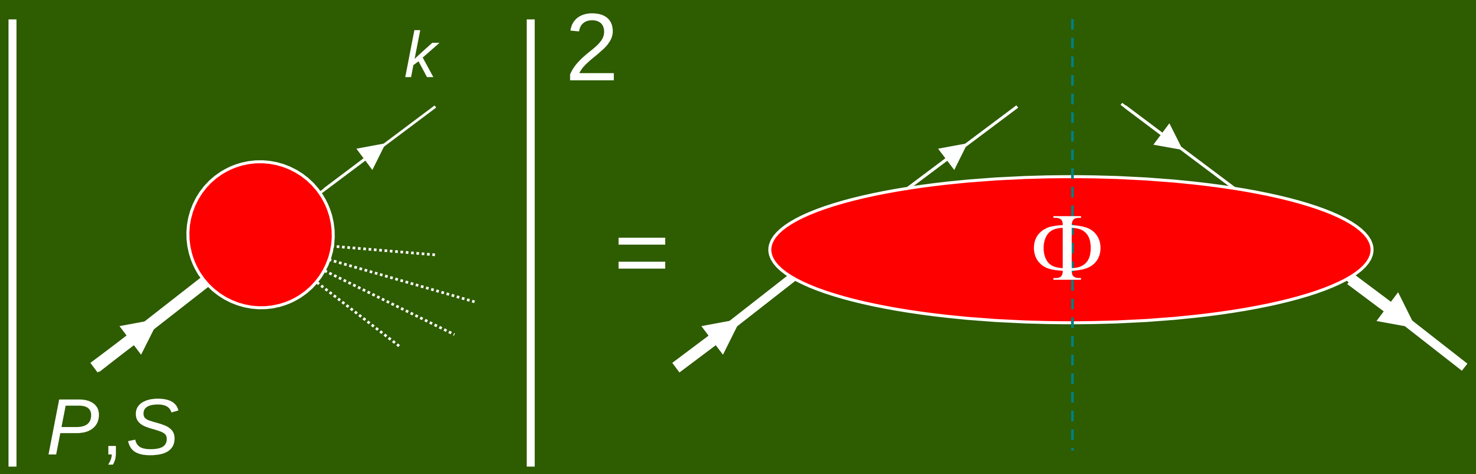


$$\mathcal{U}^{-}_{[0,\xi^-]} \equiv \mathcal{P} \exp\left(-ig \int_0^{\xi^-} d\zeta^- A^+ \right)$$

Unintegrated parton distribution functions

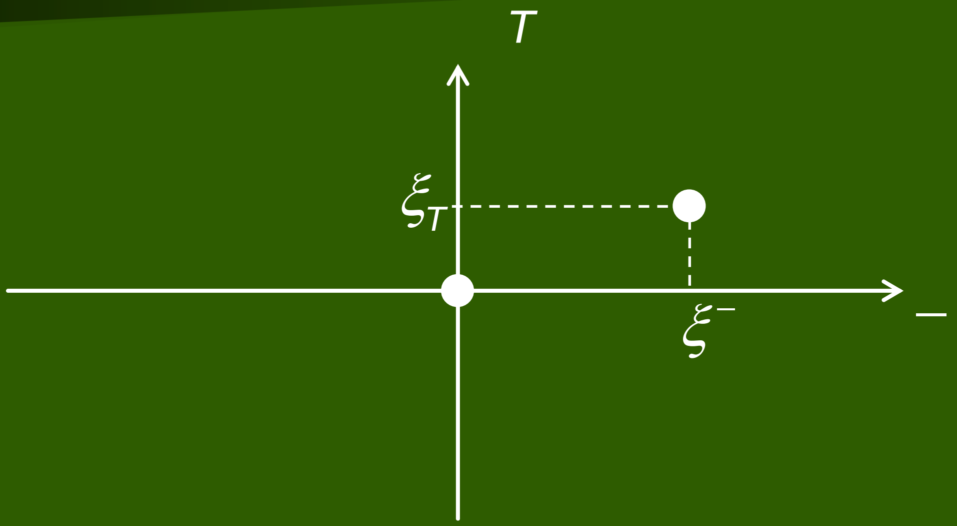


Unintegrated parton distribution functions

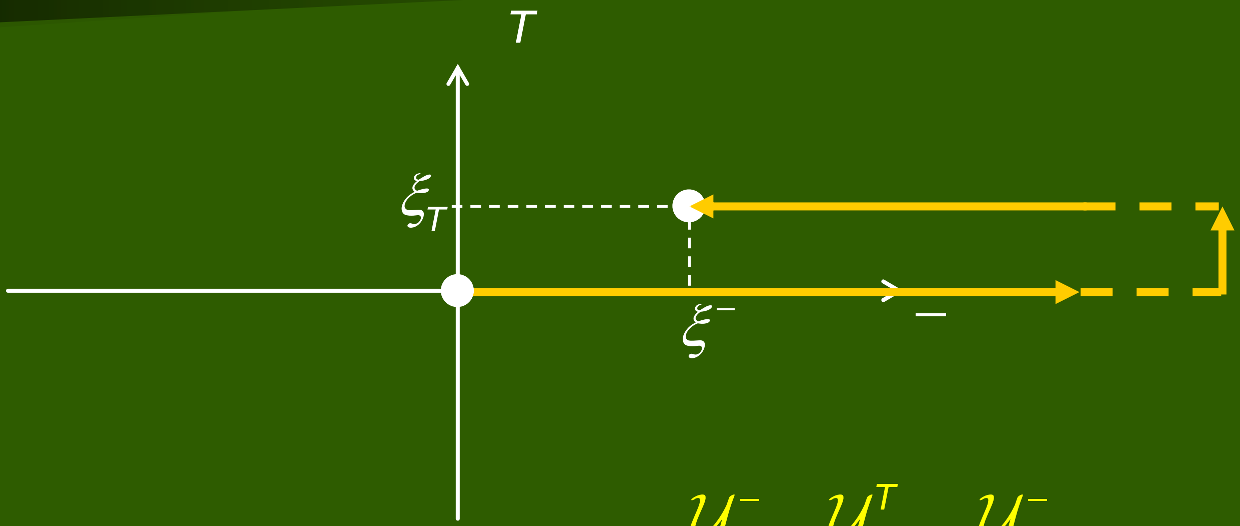


$$\Phi_{ij}(x,{\color{red}k_T}) = \int \frac{d\xi^- d^2\xi_T}{8\pi^3} e^{i\,k\cdot\xi} \left\langle P \left| \bar{\psi}_j(0)\, {\color{yellow}\mathcal{U}_{[0,\xi]}}\, \psi_i(\xi) \right| P \right\rangle \Big|_{\xi^+=0}$$

Gauge link

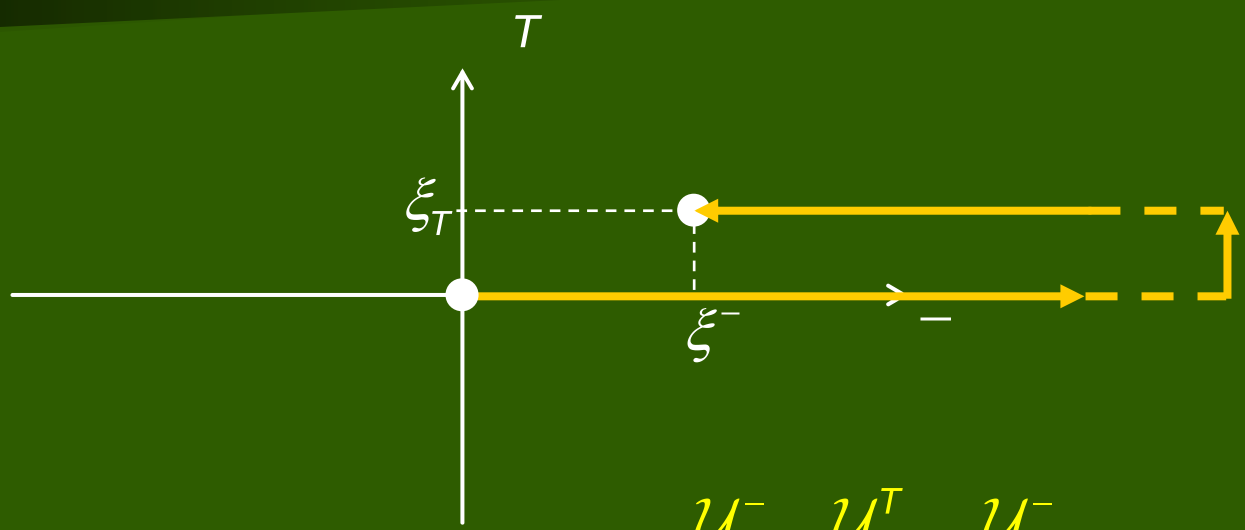


Gauge link



$$\mathcal{U}^{-}_{[0,\infty]}\,\mathcal{U}^{T}_{[0,\xi_T]}\,\mathcal{U}^{-}_{[\infty,\xi^-]}$$

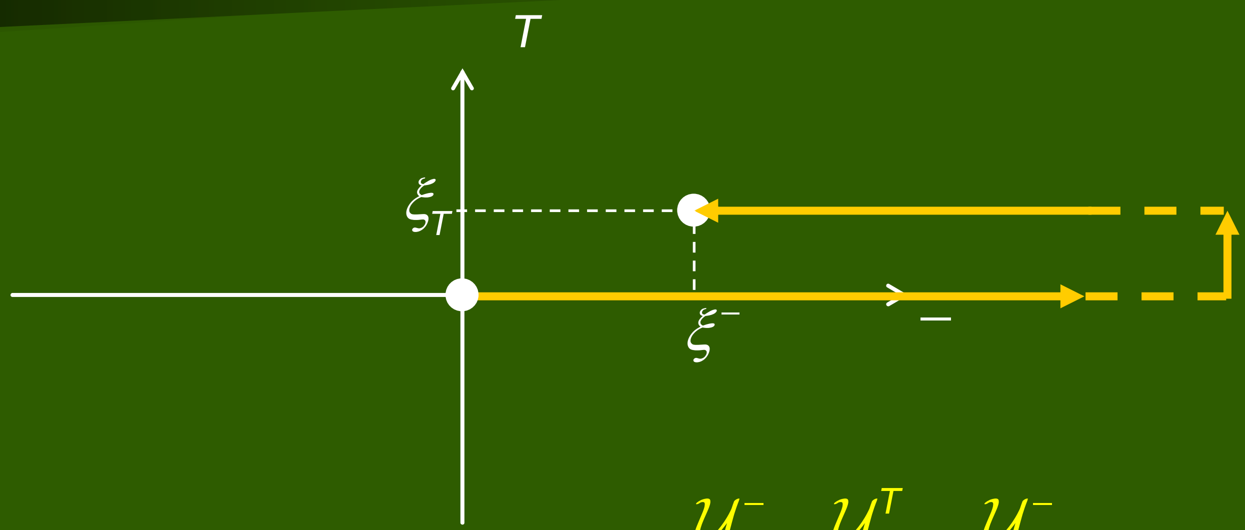
Gauge link



$$\mathcal{U}^-_{[0,\infty]}\,\mathcal{U}^T_{[0,\xi_T]}\,\mathcal{U}^-_{[\infty,\xi^-]}$$

at ∞^-

Gauge link

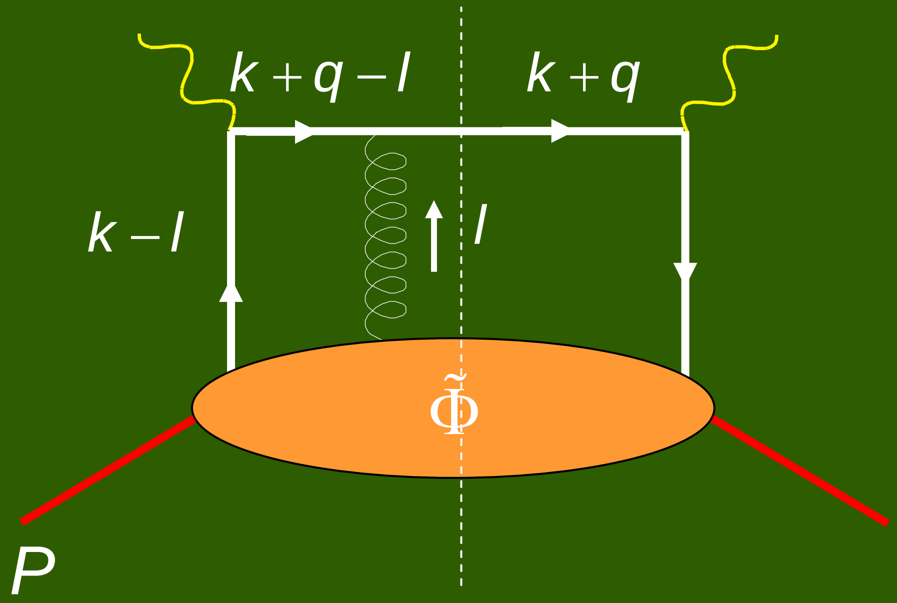


$$\mathcal{U}^-_{[0,\infty]}\,\mathcal{U}^T_{[0,\xi_T]}\,\mathcal{U}^-_{[\infty,\xi^-]}$$

at ∞^-

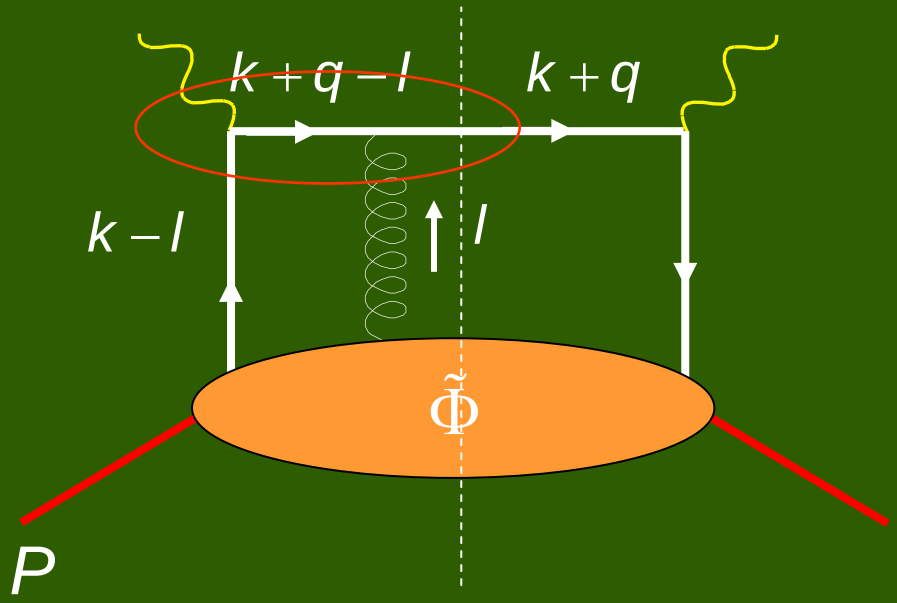
$$\mathcal{U}^-_{[0,\xi^-]} \equiv \mathcal{P}\exp\left(-ig\int_0^{\xi^-} d\zeta^- A^+\right) \qquad \mathcal{U}^T_{[0,\xi_T]} \equiv \mathcal{P}\exp\left(-ig\int_0^{\xi_T} d\zeta_T \cdot A_T\right)$$

Obtaining the gauge link



Ji, Yuan, PLB 543 (02)
Belitsky, Ji, Yuan, NPB656 (03)

Obtaining the gauge link



Ji, Yuan, PLB 543 (02)
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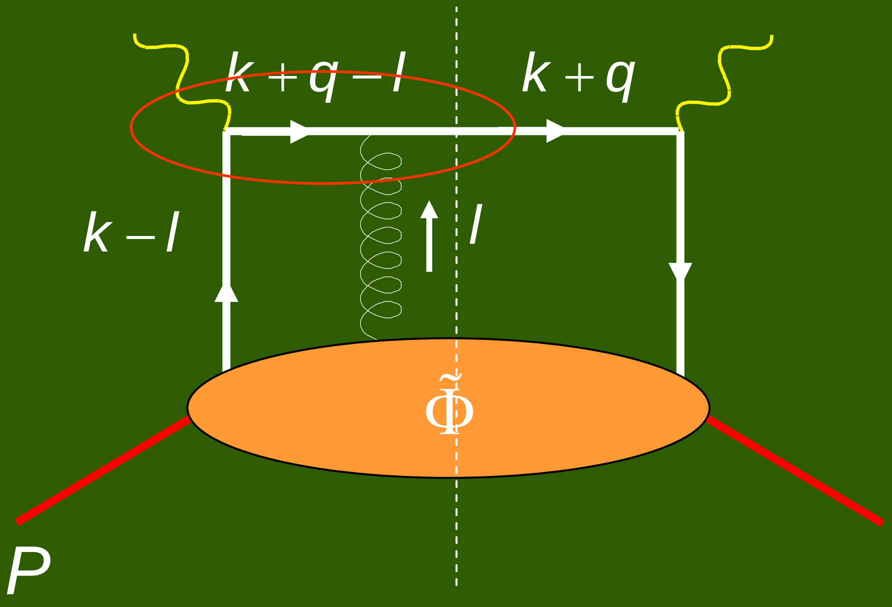
Obtaining the gauge link

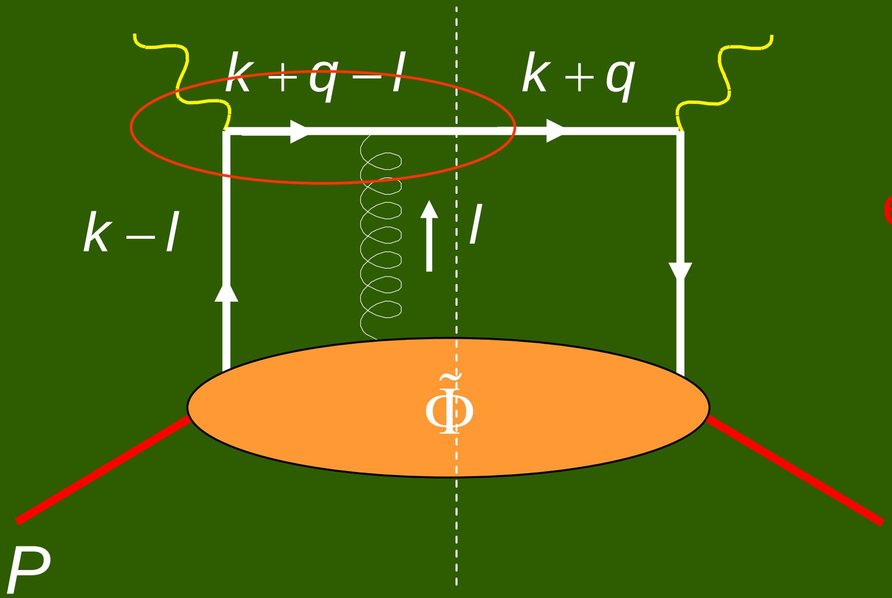


$$(\not{k} + \not{q}) g \not{A} \frac{(\not{k} + \not{q} - \not{l})}{\left[(k+q-l)^2 + i\varepsilon\right]} \gamma^\mu$$

Ji, Yuan, PLB 543 (02)

Belitsky, Ji, Yuan, NPB656 (03)

Obtaining the gauge link



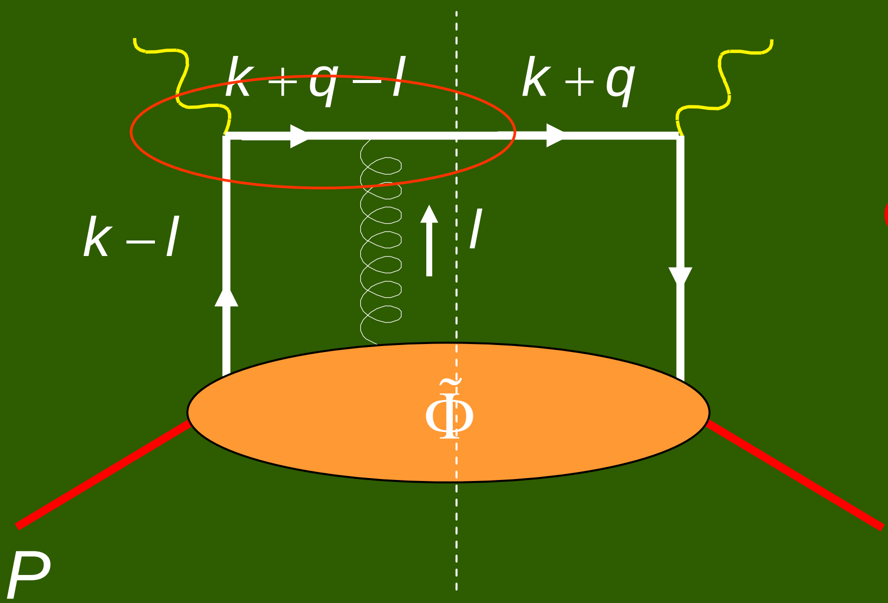
$$(\not{k}+\not{q})\, g\not{A}\, \frac{(\not{k}+\not{q}-\not{l})}{\left[(k+q-l)^2+i\varepsilon\right]}\, \gamma^{\mu}$$

eikonal approximation: $(k+q) \approx q^- n_+$

Ji, Yuan, PLB 543 (02)

Belitsky, Ji, Yuan, NPB656 (03)

Obtaining the gauge link



$$(\not k + \not q)\, g \not A \, \frac{(\not k + \not q - \not l)}{\left[(k+q-l)^2 + i\varepsilon\right]}\, \gamma^\mu$$

eikonal approximation: $(k+q) \approx q^- n_+$

$$\approx q^- \gamma^+ g A^+ \gamma^- \frac{q^- \gamma^+}{\left[-2q^- l^+ + i\varepsilon\right]}\, \gamma^\mu$$

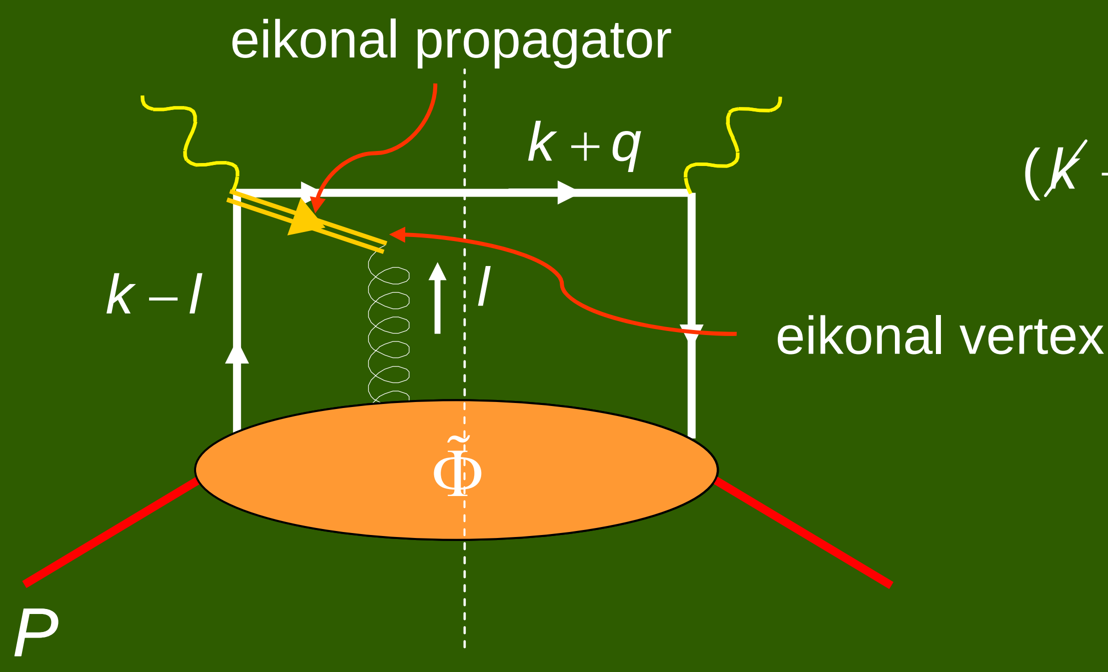
$$= -q^- \gamma^+ \frac{\gamma^- \gamma^+}{2} \gamma^\mu \frac{g A^+}{\left[l^+ - i\varepsilon\right]}$$

$$\approx (\not k + \not q)\, \gamma^\mu \frac{g A^+}{\left[-l^+ + i\varepsilon\right]}$$

Ji, Yuan, PLB 543 (02)

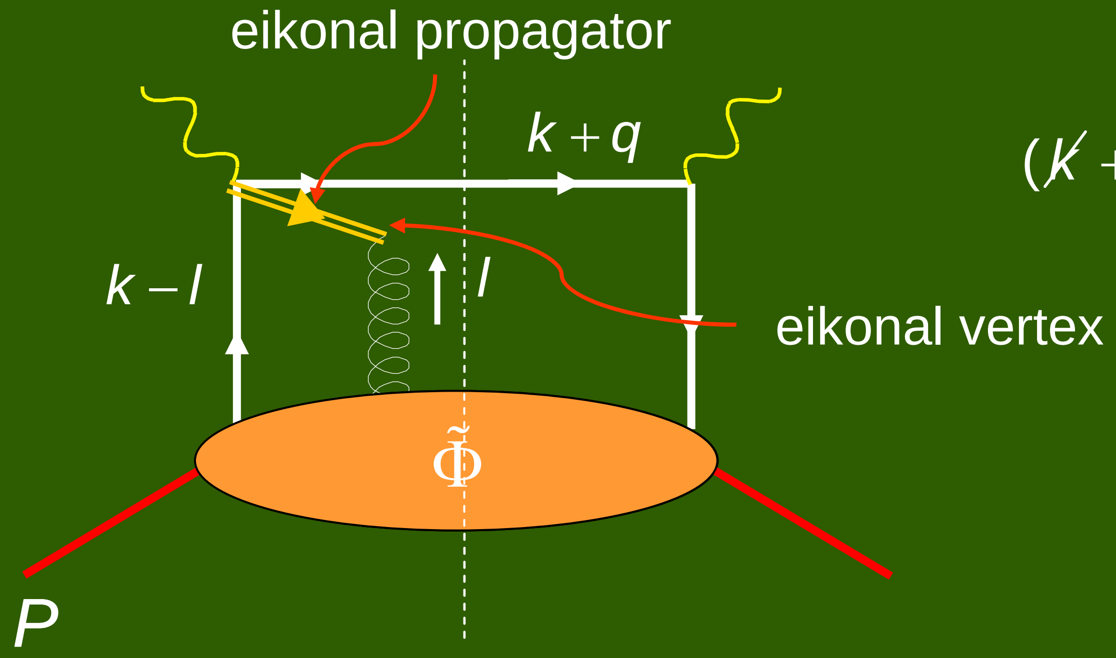
Belitsky, Ji, Yuan, NPB656 (03)

Eikonal propagator



$$(\not{k} + \not{q})\gamma^{\mu} \frac{gA^{+}}{\left[-l^{+} + i\varepsilon\right]}$$

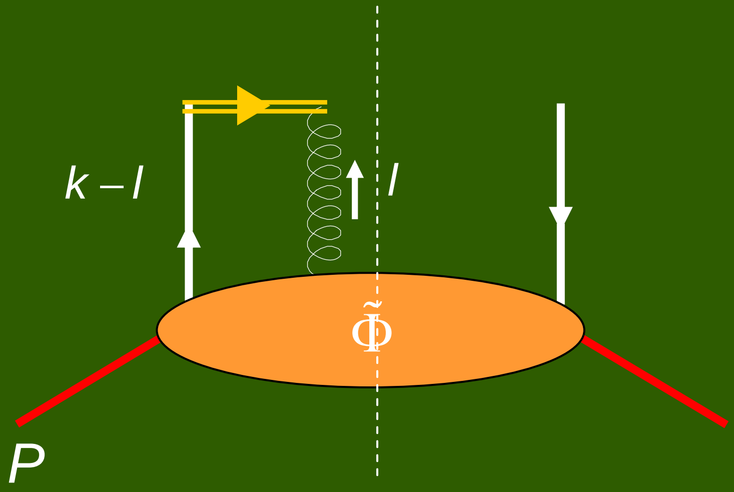
Eikonal propagator



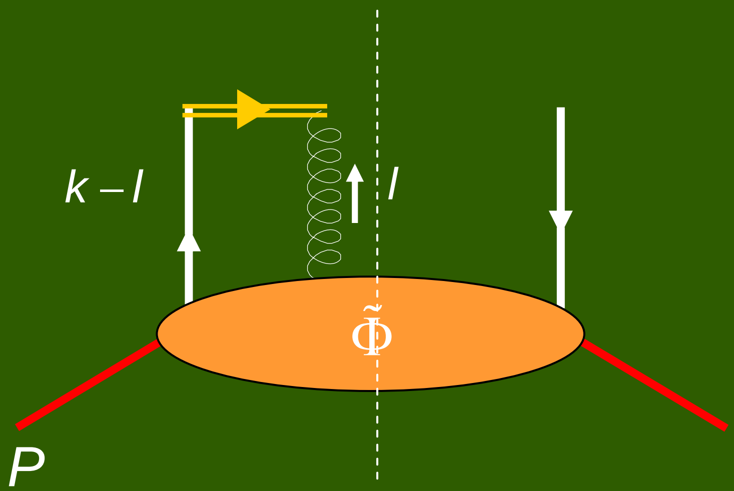
$$(\not{k} + \not{q})\gamma^{\mu} \frac{gA^{+}}{\left[-l^{+} + i\varepsilon\right]}$$

$$\frac{gA^{+}}{\left[-l^{+} + i\varepsilon\right]} = -\mathrm{PV}\frac{gA^{+}}{l^{+}} - i\pi\,\delta(l^{+})\,gA^{+}$$

Gauge link at order g



Gauge link at order g



$$\int \frac{d^4 l}{(2\pi)^4} \frac{g A^+(l)}{\left[-l^+ + i\varepsilon\right]} = -ig \int \frac{d^2 l_\perp \, dl^-}{(2\pi)^3} A^+(l)\Big|_{l^+=0}$$

$$= -ig \int_0^\infty d\zeta^- \, A^+(\zeta)\Big|_{\zeta^+=\zeta_\perp=0}$$

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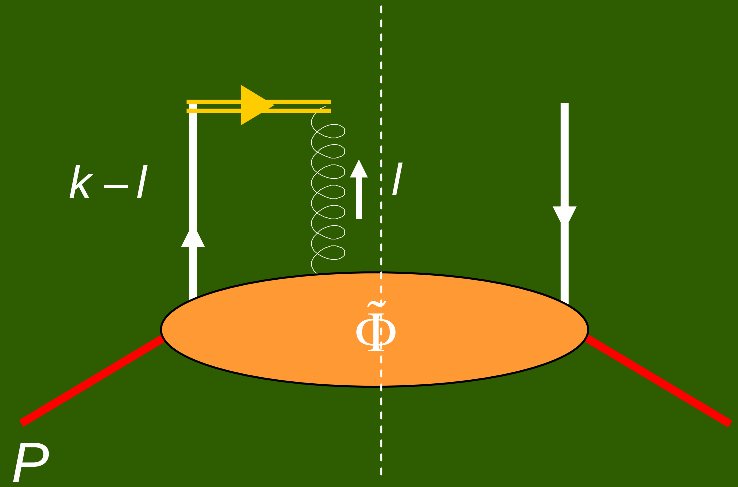

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$$= -ig \int_0^\infty d\zeta^- A^+(\zeta)\Big|_{\zeta^+=\zeta_\perp=0}$$

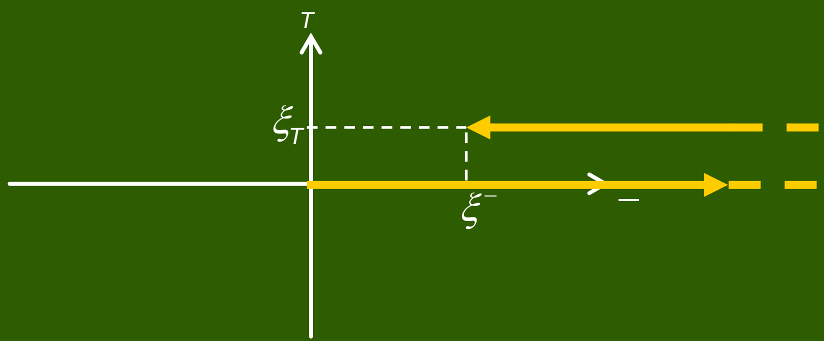
$O(g)$ contribution to gauge link!

$$\mathcal{U}^-_{[0,\infty]} \equiv \mathcal{P} \exp\left(-ig \int_0^\infty d\zeta^- A^+(\zeta^-)\right)$$

Gauge link in different gauges

Feynman gauge

Axial gauge (A^+=0)



Gauge link in different gauges

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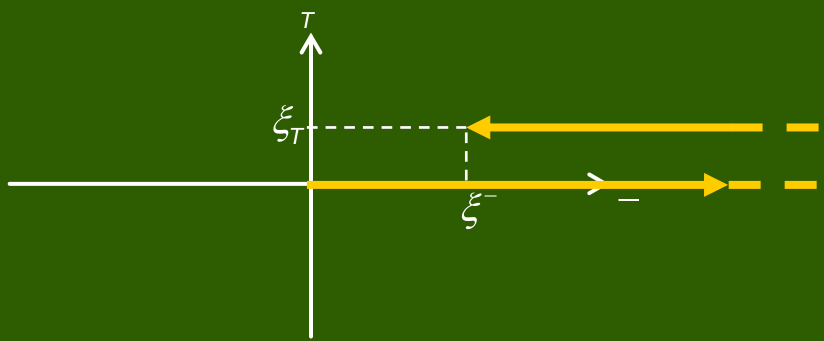

$$\mathcal{U}^-_{[0,\infty]}\;\mathcal{U}^-_{[\infty,\xi^-]}$$

$$\mathcal{U}^-_{[0,\xi^-]} \equiv \mathcal{P}\exp\left(-ig\int_0^{\xi^-} d\zeta^- A^+\right)$$

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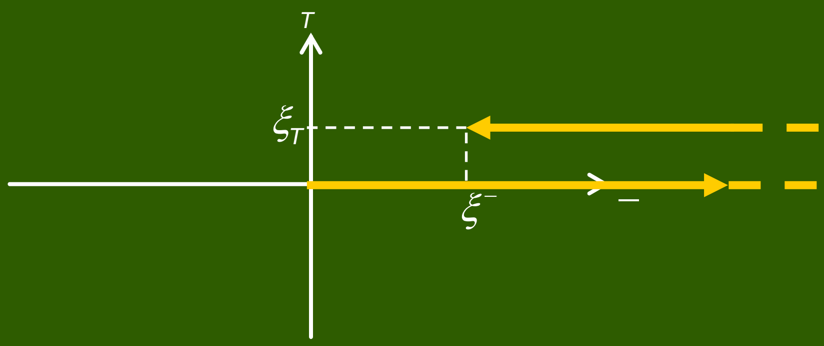

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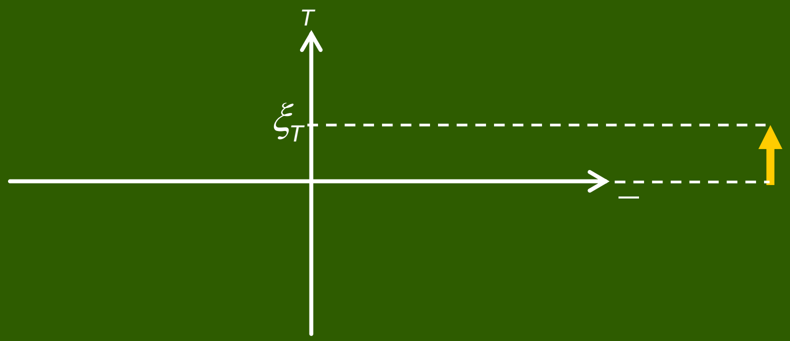
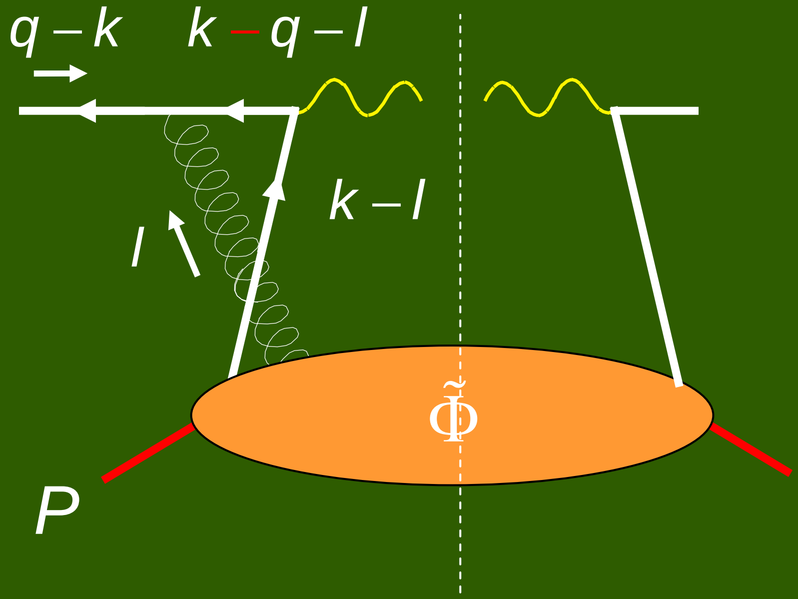


$$\mathcal{U}^{T}_{[0,\xi_T]}$$

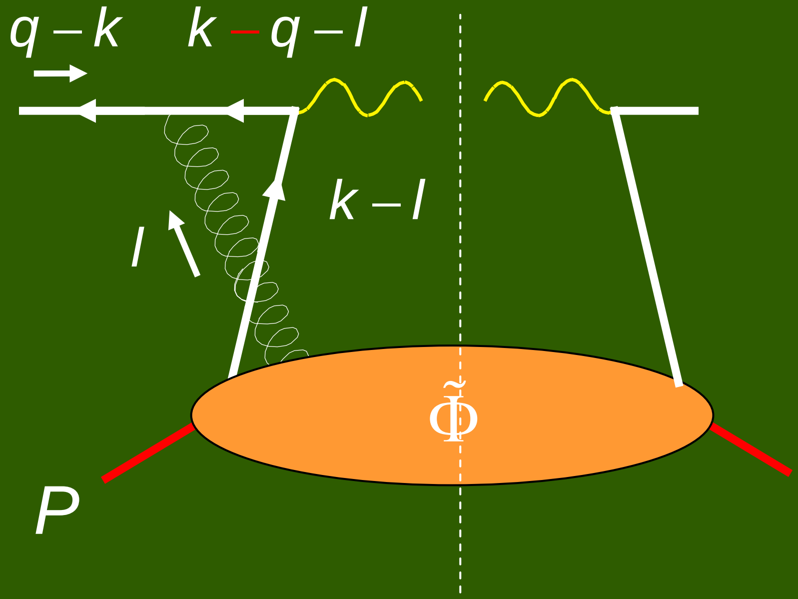
$$\mathcal{U}^{T}_{[0,\xi_T]} \equiv \mathcal{P}\exp\left(-ig\int_0^{\xi_T} d\zeta_T \cdot A_T\right)$$

Drell-Yan processes



Collins, PLB 536 (02)

Drell-Yan processes



$$(\not q - \not k)\, g \not A \frac{(\not k - \not q - \not l)}{\left[(k - q - l)^2 + i\varepsilon\right]} \gamma^\mu$$

$$\approx q^- \gamma^+ g A^+ \gamma^- \frac{-q^- \gamma^+}{\left[2q^- l^+ + i\varepsilon\right]} \gamma^\mu$$

$$= q^- \gamma^+ \frac{\gamma^- \gamma^+}{2} \gamma^\mu \frac{g A^+}{\left[-l^+ - i\varepsilon\right]}$$

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Collins, PLB 536 (02)

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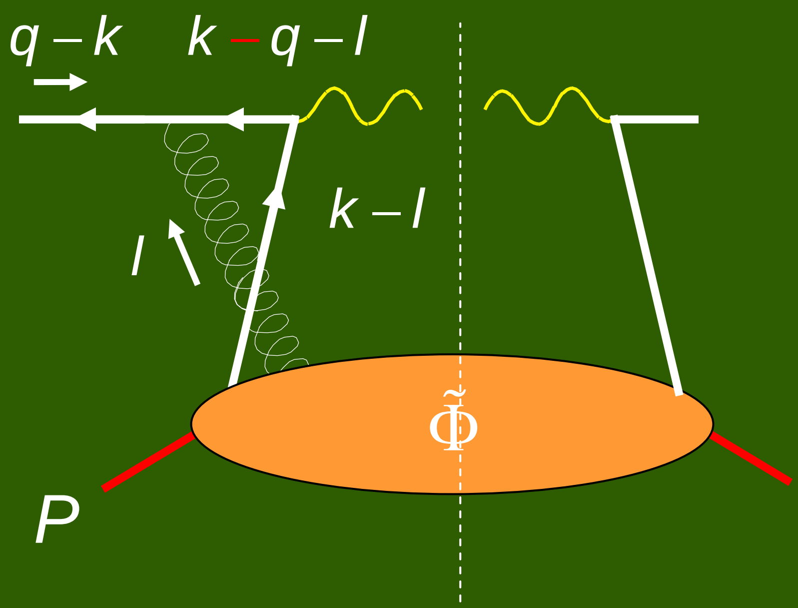

$$(\not q - \not k) g \not A \frac{(\not k - \not q - \not l)}{\left[(k - q - l)^2 + i\varepsilon\right]} \gamma^\mu$$

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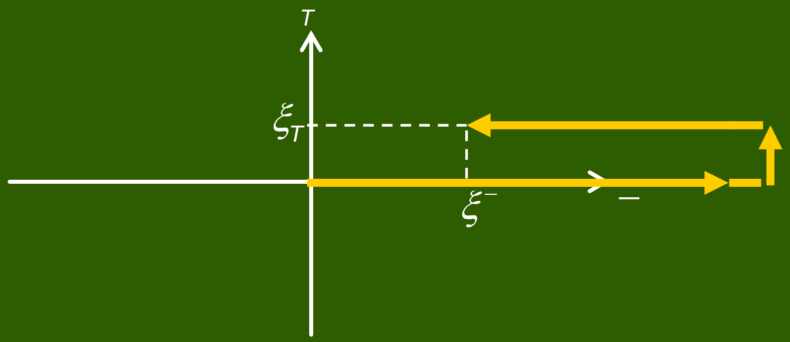
$$\approx (\not q - \not k) \gamma^\mu \frac{g A^+}{\left[-l^+ - i\varepsilon\right]}$$

Collins, PLB 536 (02)

There is a change of sign in the imaginary part of the eikonal propagator

Gauge link or Wilson line

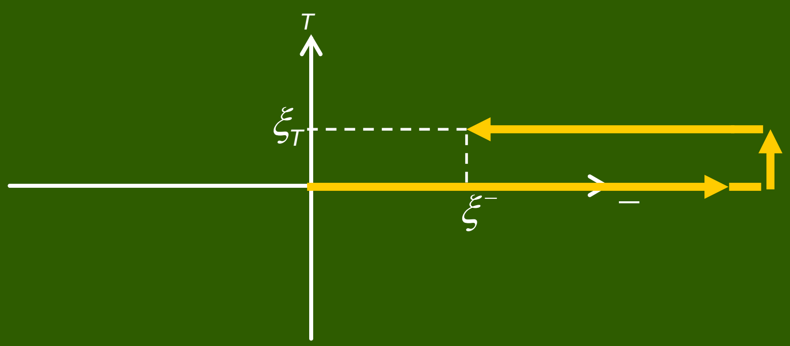
DIS



$$\mathcal{U}^{-}_{[0,\infty]}\,\mathcal{U}^{T}_{[0,\xi_T]}\,\mathcal{U}^{-}_{\left[\infty,\xi^-\right]}$$

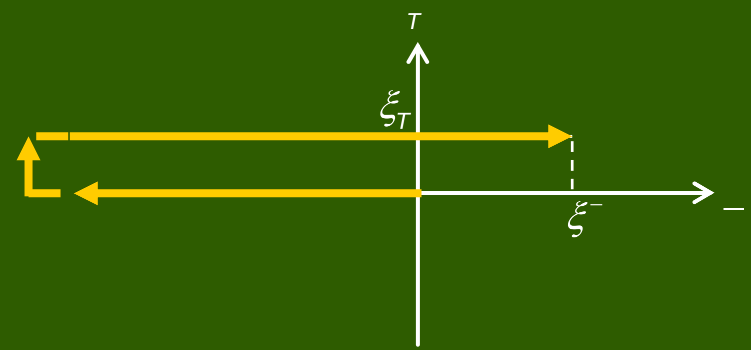
Gauge link or Wilson line

DIS



$$\mathcal{U}^{-}_{[0,\infty]}\,\mathcal{U}^{T}_{[0,\xi_T]}\,\mathcal{U}^{-}_{\left[\infty,\xi^-\right]}$$

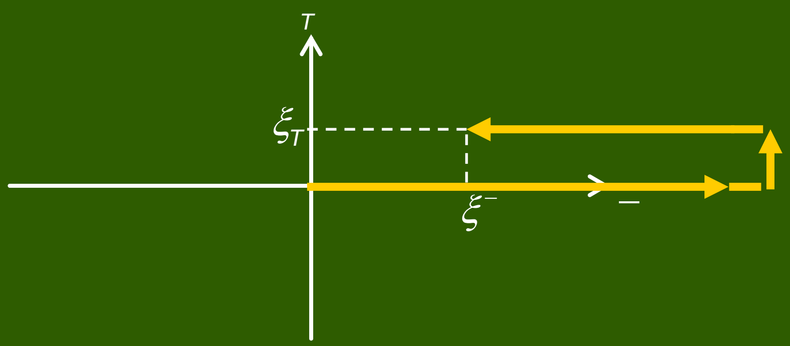
Drell-Yan



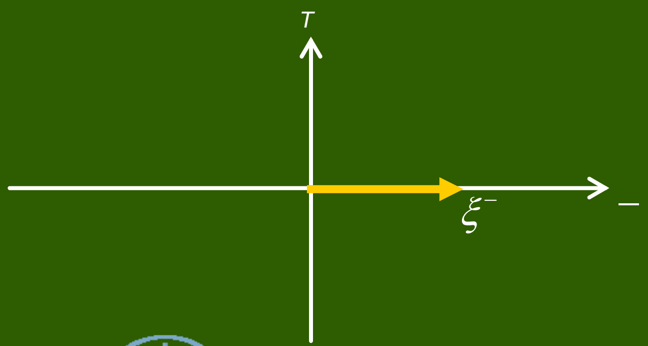
$$\mathcal{U}^{-}_{[0,-\infty]}\,\mathcal{U}^{T}_{[0,\xi_T]}\,\mathcal{U}^{-}_{\left[-\infty,\xi^-\right]}$$

Gauge link or Wilson line

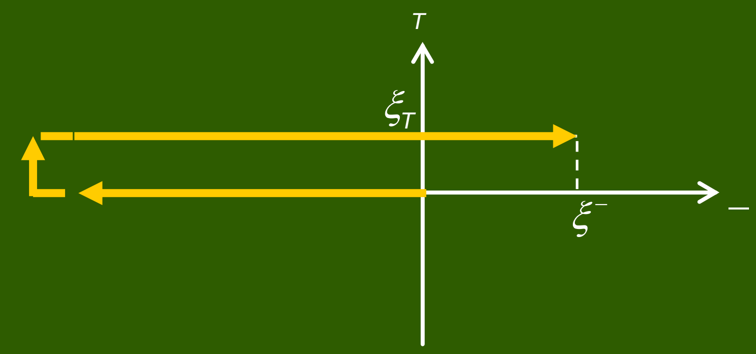
DIS



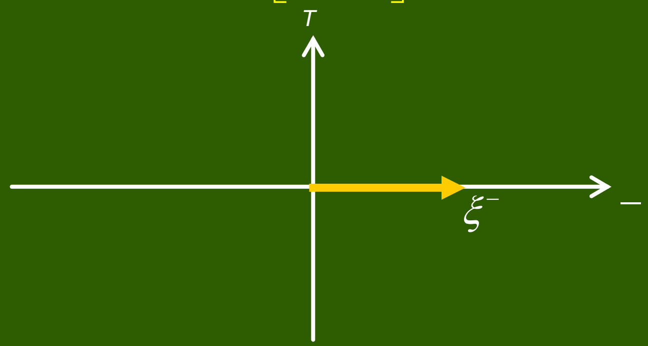
$$\mathcal{U}^{-}_{[0,\infty]}\,\mathcal{U}^{T}_{[0,\xi_T]}\,\mathcal{U}^{-}_{[\infty,\xi^-]}$$



Drell-Yan



$$\mathcal{U}^{-}_{[0,-\infty]}\,\mathcal{U}^{T}_{[0,\xi_T]}\,\mathcal{U}^{-}_{[-\infty,\xi^-]}$$



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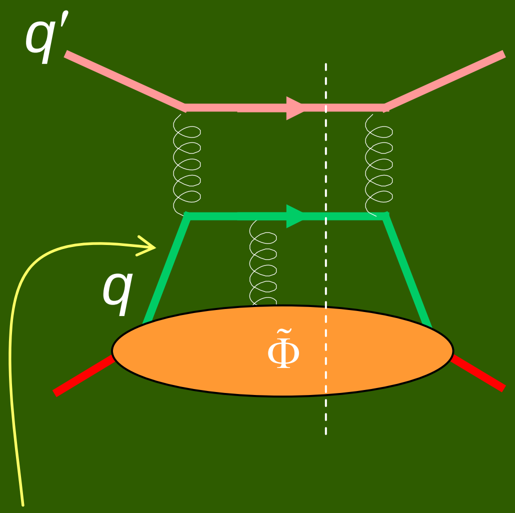
A slightly more complex example

Collins, Qiu, PRD 75 (07)



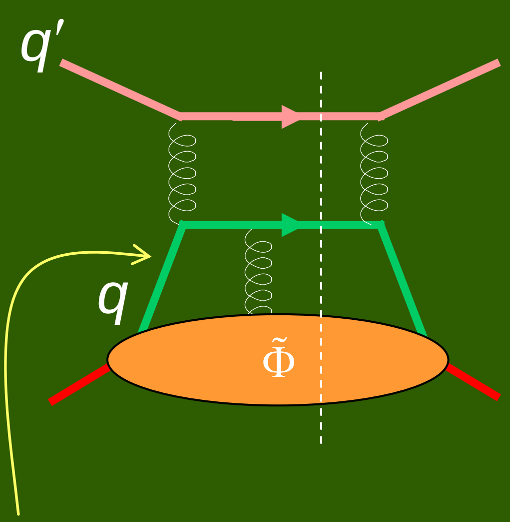
parton with charge g_1

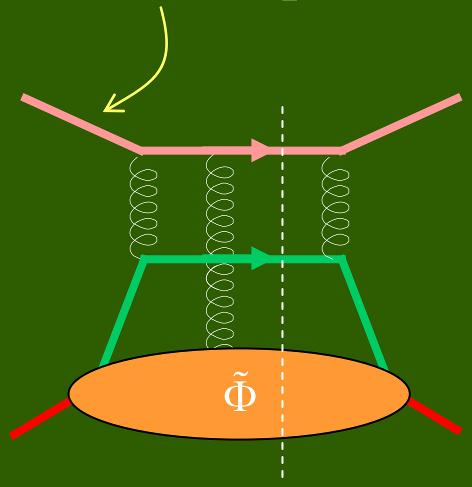
$$\frac{g_1}{\left[-l^+ + i\varepsilon\right]}$$

A slightly more complex example

Collins, Qiu, PRD 75 (07)

parton with charge g_2





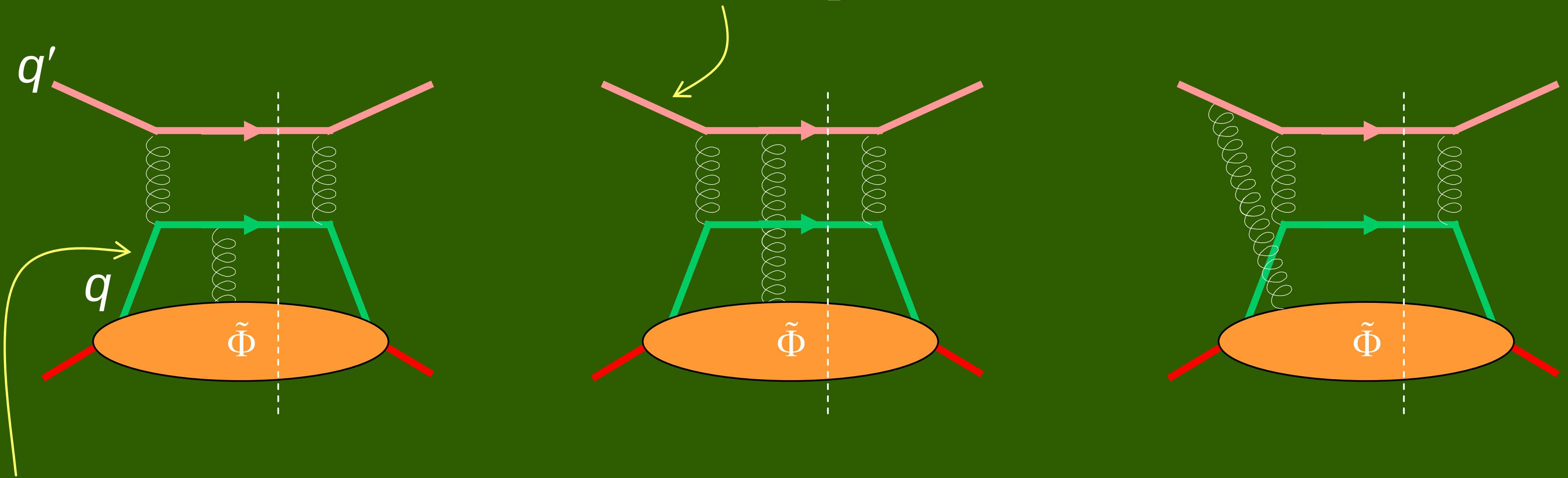
parton with charge g_1

$$\frac{g_1}{\left[-l^+ + i\varepsilon\right]} \qquad \frac{g_2}{\left[-l^+ + i\varepsilon\right]}$$

A slightly more complex example

Collins, Qiu, PRD 75 (07)

parton with charge g_2



parton with charge g_1

$$\frac{g_1}{\left[-l^+ + i\varepsilon\right]} \qquad \frac{g_2}{\left[-l^+ + i\varepsilon\right]} \qquad -\frac{g_2}{\left[-l^+ - i\varepsilon\right]}$$

Consequences

$$\frac{g_1}{\left[-l^+ + i\varepsilon\right]} + \frac{g_2}{\left[-l^+ + i\varepsilon\right]} - \frac{g_2}{\left[-l^+ - i\varepsilon\right]}$$

$$= -i\pi(2g_2 + g_1)\delta(l^+) - \mathrm{PV}\frac{g_1}{l^+}$$

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Consequences

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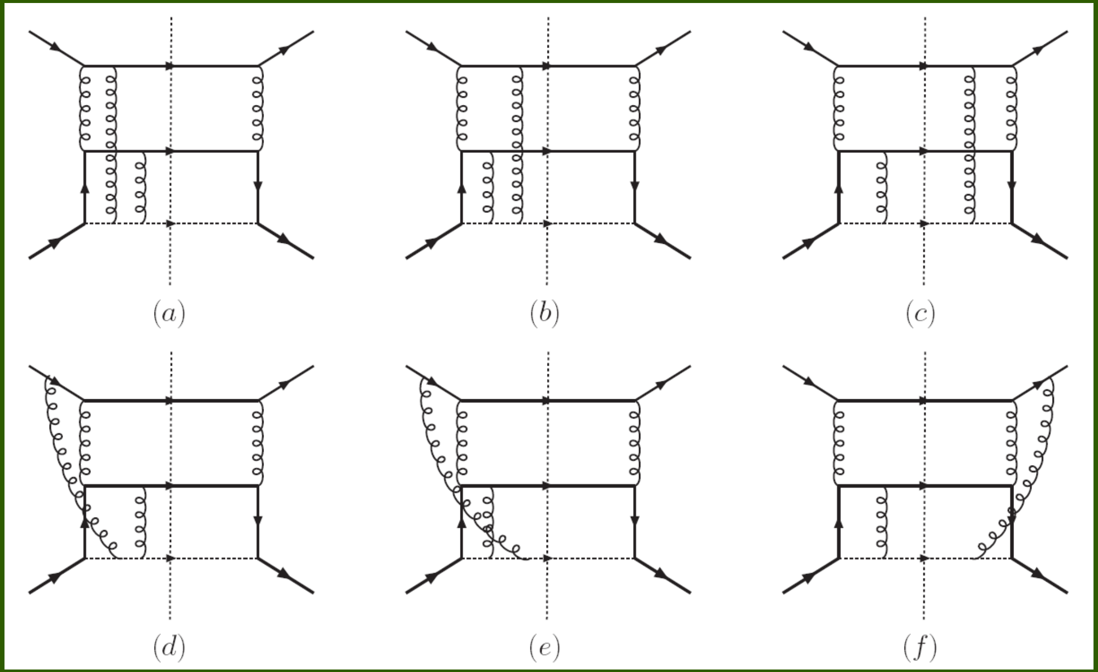
$$= -i\pi(2g_2 + g_1)\delta(l^+) - \mathrm{PV}\frac{g_1}{l^+}$$

- Up to this order, the real part is unchanged, the imaginary part gets more than just a simple sign change and depends on the charge of ANOTHER parton!
- Still possible to get around it: PDFs could still be universal, but the ones sensitive to the imaginary part (those involved in single spin asymmetries) have to be multiplied by $g_1/(2g_2+g_1)$

Two-gluon exchange

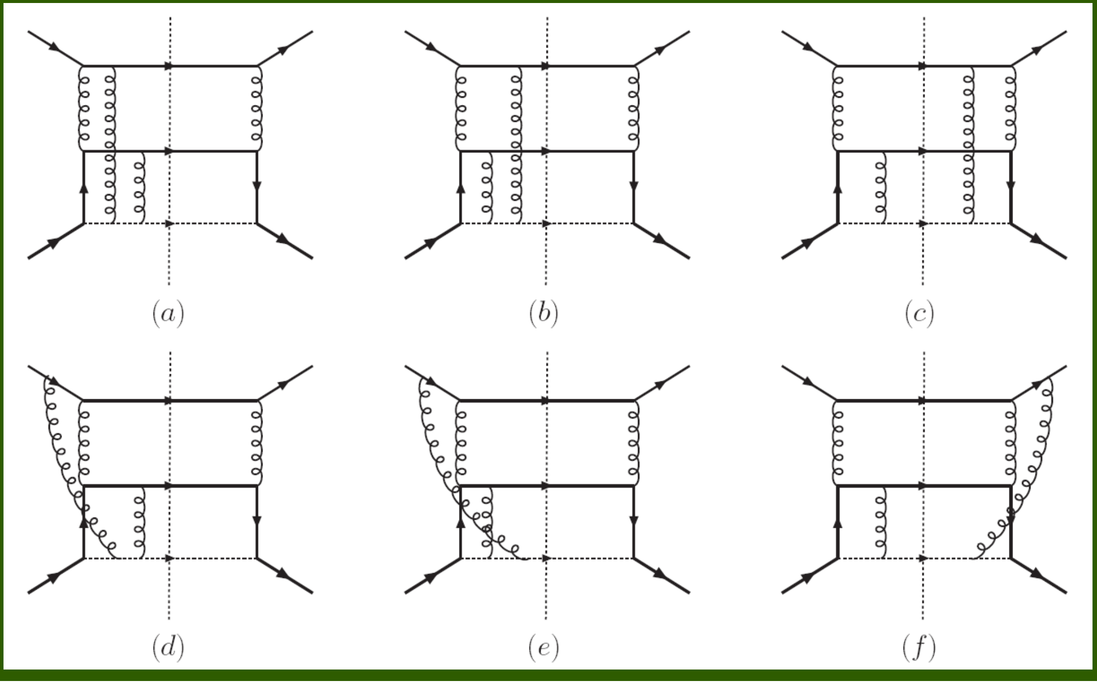
Collins, 0708.4410 [hep-ph]   Vogelsang, Yuan, 0708.4398 [hep-ph]



+ more

Two-gluon exchange

Collins, 0708.4410 [hep-ph] *Vogelsang, Yuan, 0708.4398 [hep-ph]*



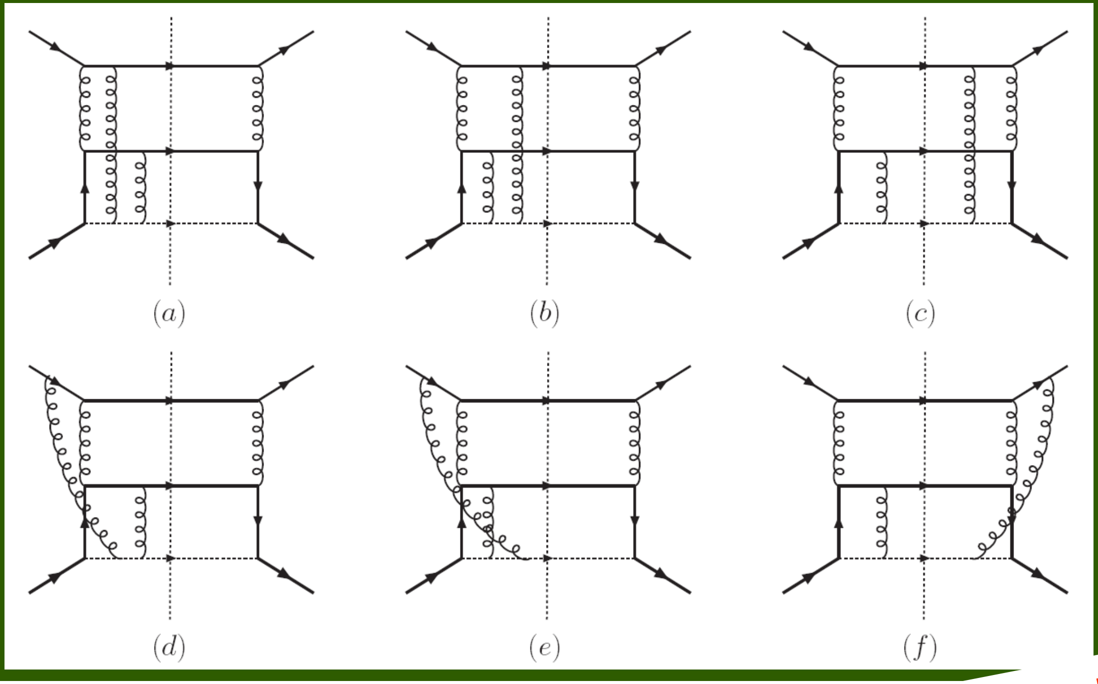
+ more

$$g_1^2 \left[\frac{1}{k_1^+ k_2^+} + (-i\pi)^2 \delta(k_1^+)\delta(k_2^+) \right] + g_1(g_1 + 2g_2)(i\pi) \left[\frac{\delta(k_2^+)}{k_1^+} + \frac{\delta(k_1^+)}{k_2^+} \right]$$

$$+4\left(g_1 g_2 + g_2^2\right)(-i\pi)^2 \delta(k_1^+)\delta(k_2^+) \ .$$

Two-gluon exchange

Collins, 0708.4410 [hep-ph] *Vogelsang, Yuan, 0708.4398 [hep-ph]*



+ more

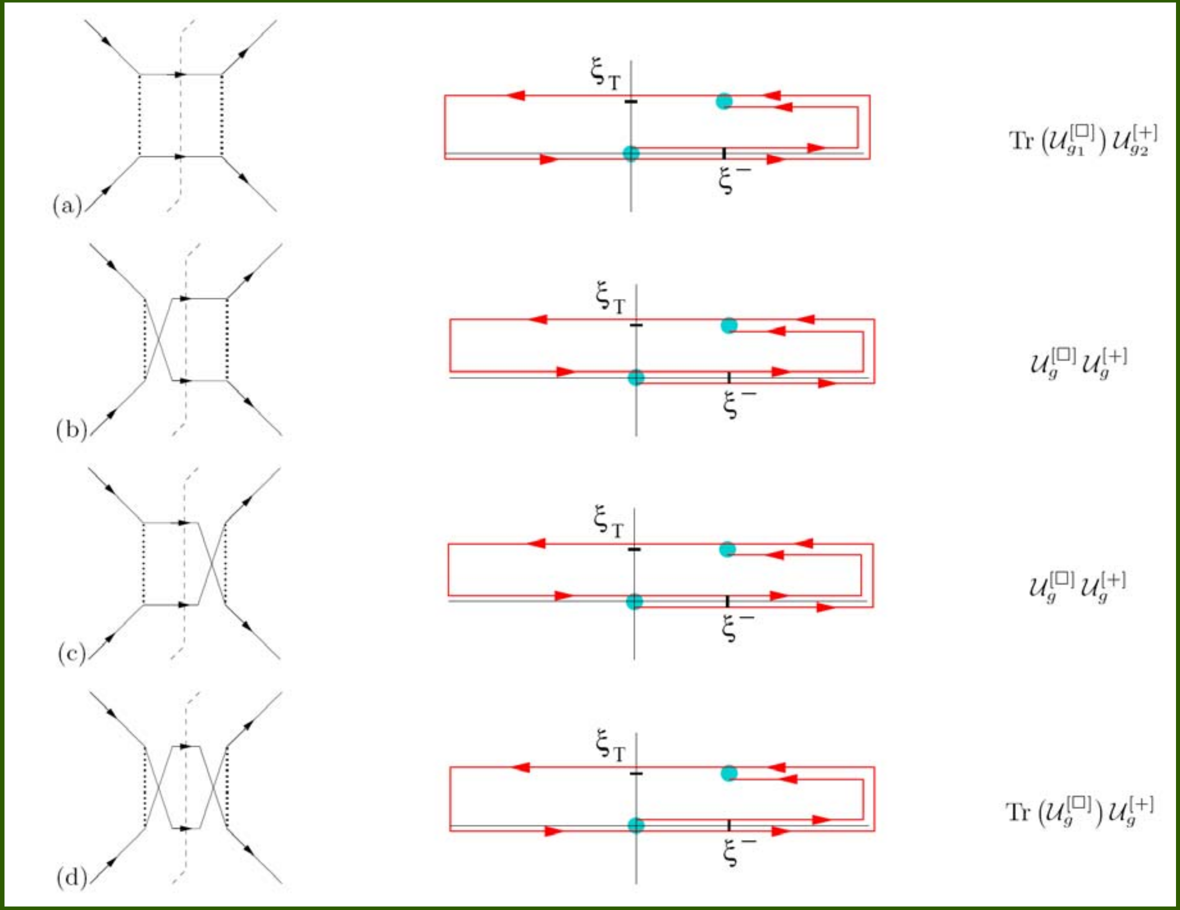
$$g_1^2 \left[\frac{1}{k_1^+ k_2^+} + (-i\pi)^2 \delta(k_1^+)\delta(k_2^+) \right] + \ldots$$ [illegible] $$\ldots k_2^+ \Big]$$

$$+4\left(g_1 g_2 + g_2^2\right)(-i\pi)^2 \delta(k_1^+)\delta(k_2^+) \; .$$

Breaking of universality, and not only in single-spin asymmetries

Infinitely many gluons and different processes

Bomhof, Mulders, Pijlman, PLB 596 (04)



Weighted cross sections

A.B., Bomhof, Mulders, Pijlman, PRD72 (05)

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$$\int (k_T \cdot n) \frac{d\sigma_{DIS}}{dk_T}\, dk_T = K_{DIS} \otimes g$$

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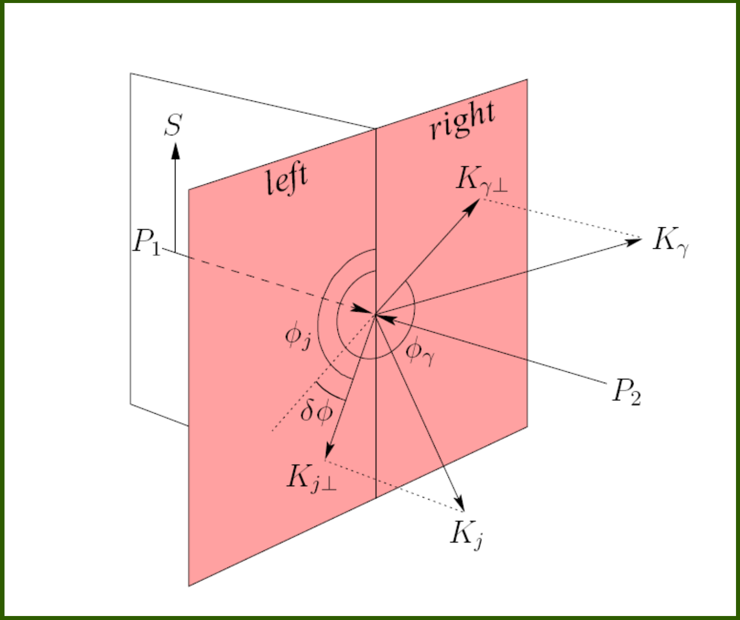
$$\int (k_T \cdot n) \frac{d\sigma_{pp}}{dk_T}\, dk_T = K_{pp} \otimes g' = K_{pp} \otimes C\, g$$

$$= C\, K_{pp} \otimes g = K'_{pp} \otimes g$$

Example of phenomenology

A.B., D'Alesio, Bomhof, Mulders, Murgia,PRL99 (07)



$p^{\uparrow} p \to \gamma$ jet X at RHIC

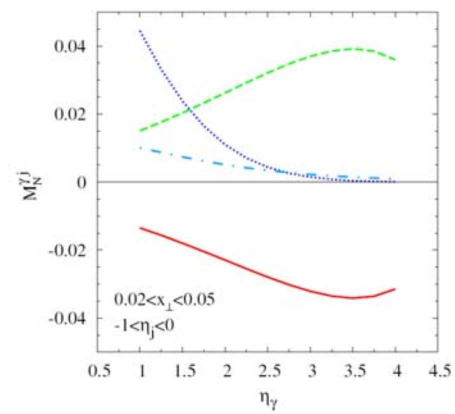
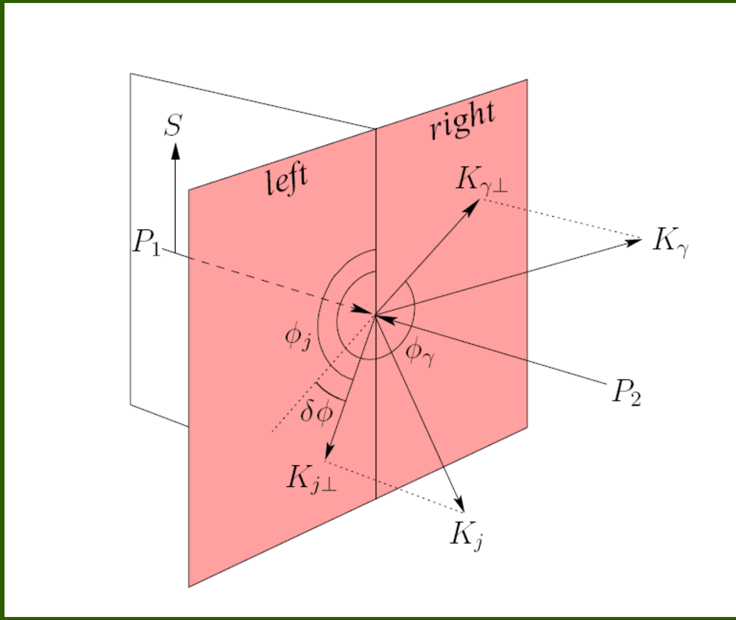


FIG. 5: Prediction for the azimuthal moment $M_N^{\gamma j}$ at $\sqrt{s} =$ 200 GeV, as a function of η_γ, integrated over $-1 \le \eta_j \le 0$ and $0.02 \le x_\perp \le 0.05$. Solid line: using gluonic-pole cross sections. Dashed line: using standard partonic cross sections. Dotted line: maximum contribution from the gluon Sivers function (absolute value). Dot-dashed line: maximum contribution from the Boer-Mulders function (absolute value).

Example of phenomenology

A.B., D'Alesio, Bomhof, Mulders, Murgia,PRL99 (07)

"Standard" universality



$p^{\uparrow} p \to \gamma$ jet X at RHIC

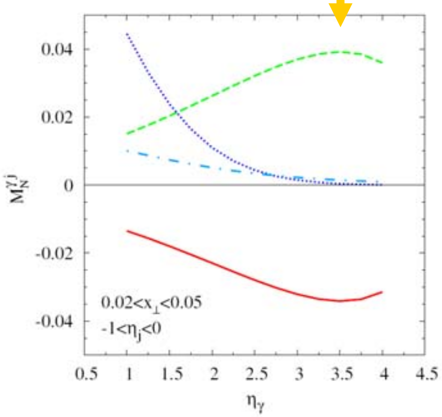
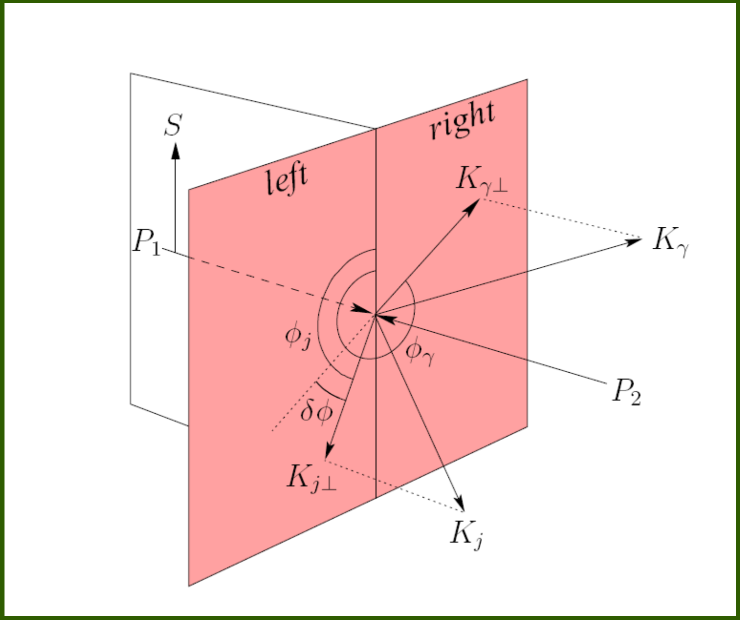


FIG. 5: Prediction for the azimuthal moment $M_N^{\gamma j}$ at $\sqrt{s}$ = 200 GeV, as a function of η_γ, integrated over $-1 \le \eta_j \le 0$ and $0.02 \le x_\perp \le 0.05$. Solid line: using gluonic-pole cross sections. Dashed line: using standard partonic cross sections. Dotted line: maximum contribution from the gluon Sivers function (absolute value). Dot-dashed line: maximum contribution from the Boer-Mulders function (absolute value).

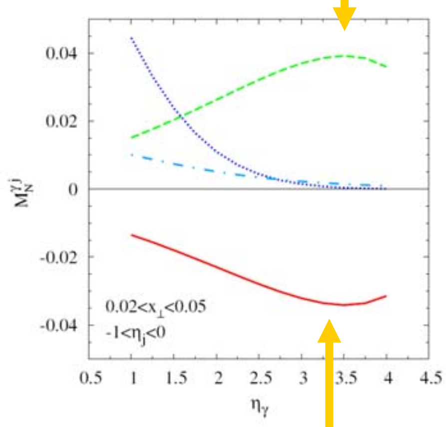
Example of phenomenology

A.B., D'Alesio, Bomhof, Mulders, Murgia, PRL99 (07)

"Standard" universality



$p^\uparrow p \to \gamma$ jet X at RHIC



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"Generalized" universality

Conclusions

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- No problem has been found with integrated parton distribution functions
- k_T factorization can still hold in principle, even if the functions are non-universal
- The non-universality occurring in some weighted asymmetries can be calculated (and checked)

Outlook

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- Pessimistic: in hadrons to hadrons processes many different PDFs are involved and no easy relation between them exists. k_T factorization becomes almost useless in these processes