Gluon TMD PDF studies at the LHC

QCD@LHC2022 - IJCLab Orsay, 30th November 2022

Francesco Giovanni Celiberto

ECT*/FBK Trento & INFN-TIFPA

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

TIFPA
Trento Institute for Fundamental Physics and Applications

HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

1. Introductory remarks

High-energy QCD and the proton structure

High-energy physics

Proton structure

High-energy QCD and the proton structure

High-energy physics

- Precision studies ⇐ SM and beyond
- Fixed-order perturbative calculations…
- …enhanced by resummations
- SM measurements: H, W, Z mass

Proton structure

High-energy QCD and the proton structure

High-energy physics

- Precision studies ⇐ SM and beyond
- Fixed-order perturbative calculations…
- …enhanced by resummations
- SM measurements: H, W, Z mass

Proton structure

- Inner structure ⇐ intrinsic parton motion
- Parton densities ⇒ nonperturbative nature
- Extracted from experiments via global fits
- Several types: 1D collinear, 3D TMD, and so on

High-energy QCD and the proton structure

High-energy physics

- Precision studies ⇐ SM and beyond
- Fixed-order perturbative calculations…
- …enhanced by resummations
- SM measurements: H, W, Z mass

Proton structure

- Inner structure ⇐ intrinsic parton motion
- Parton densities ⇒ nonperturbative nature
- Extracted from experiments via global fits
- Several types: 1D collinear, 3D TMD, and so on

High-energy physics
assumes knowledge
of proton structure

Reduction of uncertainties
on parton densities
from high-energy studies

High-energy QCD and the proton structure

High-energy physics

- Precision studies ⇐ SM and beyond
- Fixed-order perturbative calculations…
- …enhanced by resummations
- SM measurements: H, W, Z mass

Proton structure

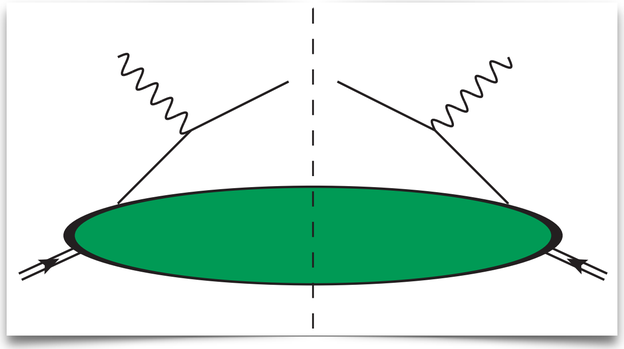
- Inner structure ⇐ intrinsic parton motion
- Parton densities ⇒ nonperturbative nature
- Extracted from experiments via global fits
- Several types: 1D collinear, 3D TMD, and so on

High-energy physics
assumes knowledge
of proton structure

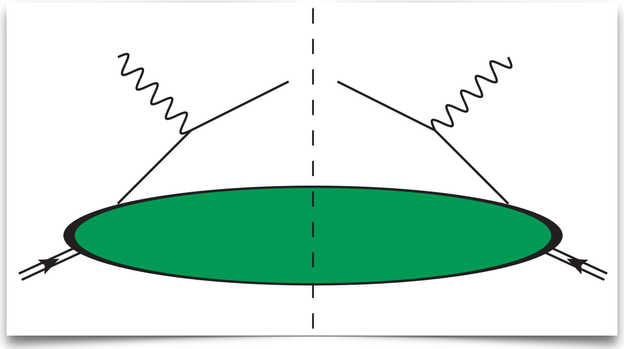
Reduction of uncertainties
on parton densities
from high-energy studies

Perturbative and nonperturbative aspects ⇔ key ingredients to a joint search for New Physics

Gauge links and processes dependence



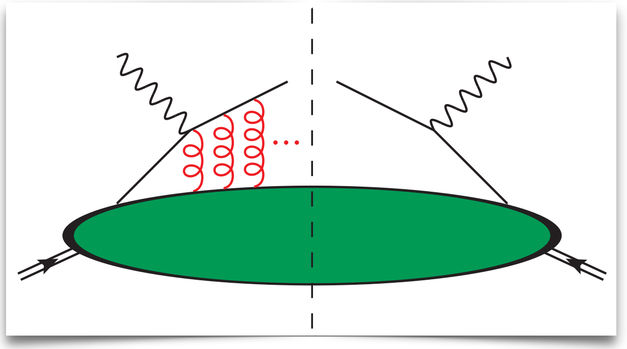
Gauge links and processes dependence



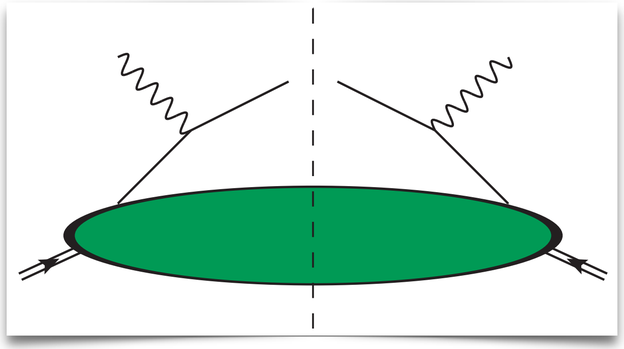
$$\bar{\psi}_j(0)\ U(0,\xi)\ \psi_i(\xi)$$

Gauge link (Wilson line)

Resummation of (calculable)
infinite gluon emissions



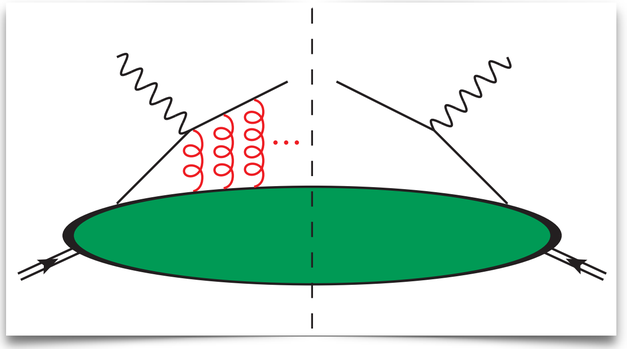
Gauge links and processes dependence



$$\bar{\psi}_j(0)\ U(0,\xi)\ \psi_i(\xi)$$

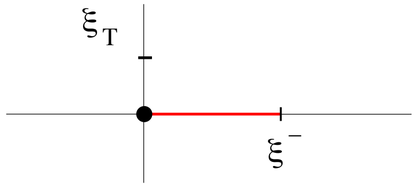
Gauge link (Wilson line)

Resummation of (calculable)
infinite gluon emissions



Collinear PDFs

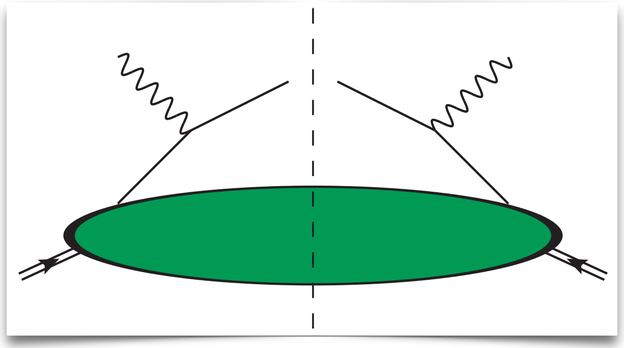
$$\Phi_{ij}(x) \doteq \int d^2\boldsymbol{p}_T \Phi_{ij}(x,\boldsymbol{p}_T) = \int \frac{d\xi^-}{2\pi} e^{ip\cdot\xi} \langle P|\bar{\psi}_j(0)\psi_i(\xi)|P\rangle_{|\xi^+=0,\xi_T=0}$$



- Light-cone: $\xi^+ = 0$, $\boldsymbol{\xi} = 0$
- **Straight** gauge link (unique!)
- $(A^+ = 0)$ light-cone: WL $= \hat{1}$

☑ **Universality warranted**

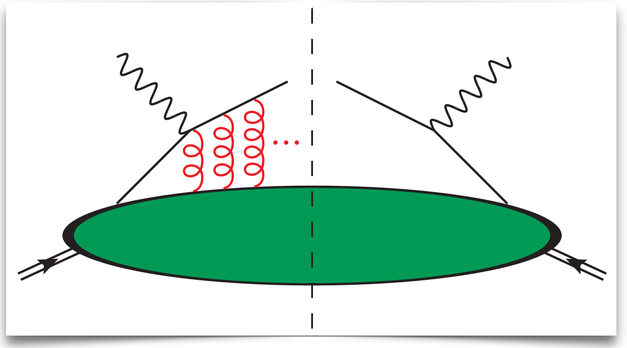
Gauge links and processes dependence



$$\bar{\psi}_j(0)\ U(0,\xi)\ \psi_i(\xi)$$

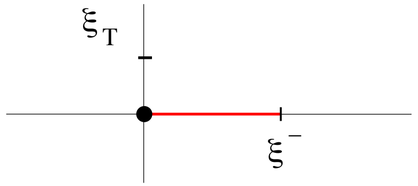
Gauge link (Wilson line)

Resummation of (calculable)
infinite gluon emissions



Collinear PDFs

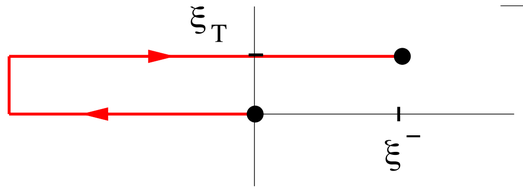
$$\Phi_{ij}(x) \doteq \int d^2\boldsymbol{p}_T \Phi_{ij}(x,\boldsymbol{p}_T) = \int \frac{d\xi^-}{2\pi} e^{ip\cdot\xi} \langle P|\bar{\psi}_j(0)\psi_i(\xi)|P\rangle_{|\xi^+=0,\xi_T=0}$$



- Light-cone: $\xi^+ = 0, \boldsymbol{\xi} = 0$
- **Straight** gauge link (unique!)
- $(A^+ = 0)$ light-cone: WL $= \hat{1}$
- ☑ **Universality warranted**

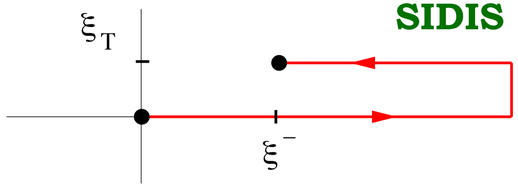
TMD PDFs

- *Transverse* gauge link not eliminated by gauge choice
- **Staple-like** gauge link (not unique!)
- ¡! **Process dependence**



Drell-Yan

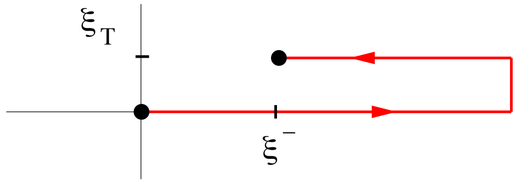
SIDIS

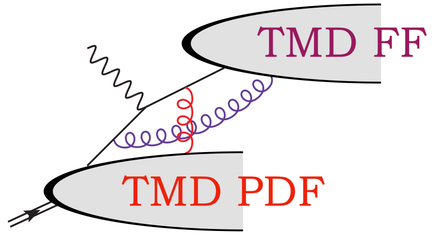


Process dependence of quark TMD PDFs & FFs

SIDIS

[+] staple link





* PDF → color flow annihilated within final state
* FF → color flow from final to initial state

Process dependence of quark TMD PDFs & FFs

SIDIS

[+] staple link

* PDF → color flow annihilated within final state
* FF → color flow from final to initial state

Drell-Yan

[–] staple link

* PDF → color flow from final to initial state

Process dependence of quark TMD PDFs & FFs

SIDIS

[+] staple link

* PDF → color flow annihilated within final state
* FF → color flow from final to initial state

Drell-Yan

[−] staple link

* PDF → color flow from final to initial state

$e^+ + e^- \rightarrow$ hadrons

[+] staple link

* FF → color flow annihilated within final state

🔗 [J. C. Collins, A. Metz (2004)]

Process dependence of quark TMD PDFs & FFs

SIDIS

[+] staple link

* PDF → color flow annihilated within final state
* FF → color flow from final to initial state

Drell-Yan

[−] staple link

* PDF → color flow from final to initial state

Modified universality

* PDFs → change of sign in T-odd densities

$$f_{1T}^{\perp\,[\mathrm{SIDIS}]} \equiv f_{1T}^{\perp\,[+]} = -f_{1T}^{\perp\,[-]} \equiv -f_{1T}^{\perp\,[\mathrm{DY}]}$$

* FFs → standard universality preserved

$e^+ + e^- \rightarrow$ hadrons

[+] staple link

* FF → color flow annihilated within final state

[J. C. Collins, A. Metz (2004)]

Gluon TMD PDFs: gauge links & modified universality

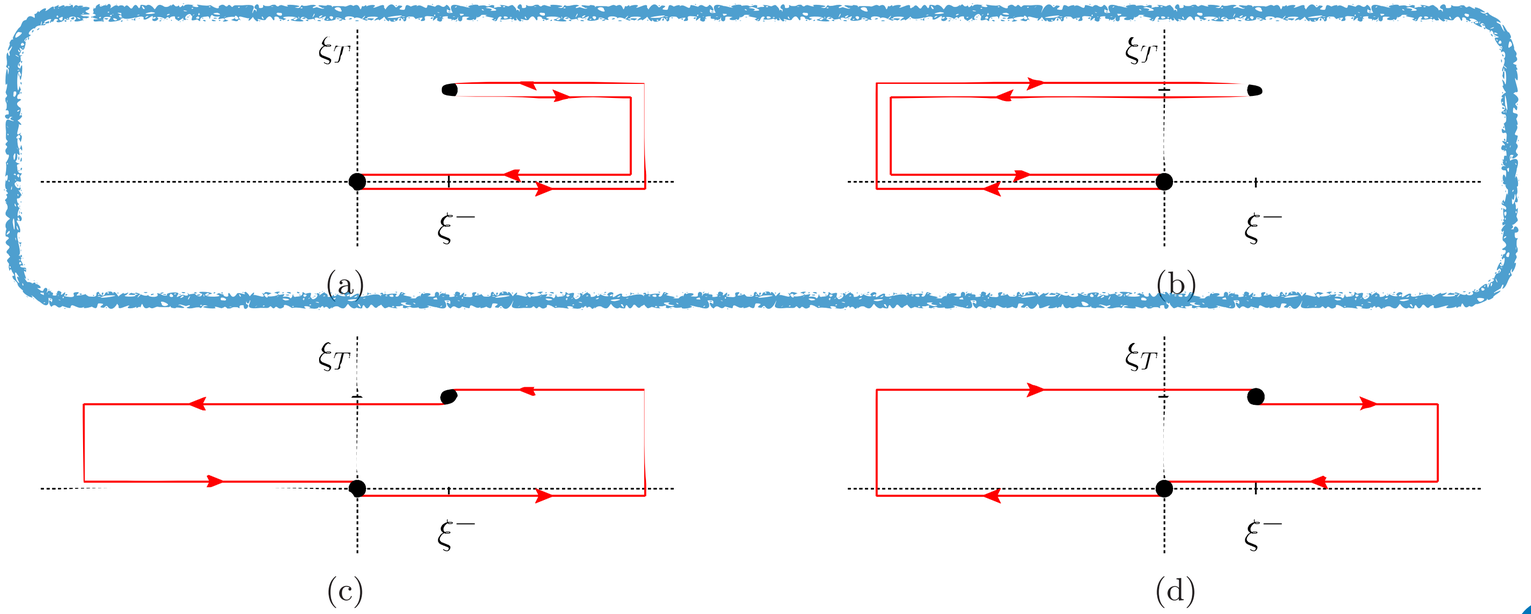
* Gluon TMDs → more complicated structure with respect to quark staple links
* Factorization-preserving processes → two main kinds of modified universality
* Different classes of processes → distinct gluon TMDs, not related to each other

Gluon TMD PDFs: gauge links & modified universality

* Gluon TMDs → more complicated structure with respect to quark staple links
* Factorization-preserving processes → two main kinds of modified universality
* Different classes of processes → distinct gluon TMDs, not related to each other

f-type (WW)

(a) $[+,+]$ or (b) $[-,-]$



Gluon TMD PDFs: gauge links & modified universality

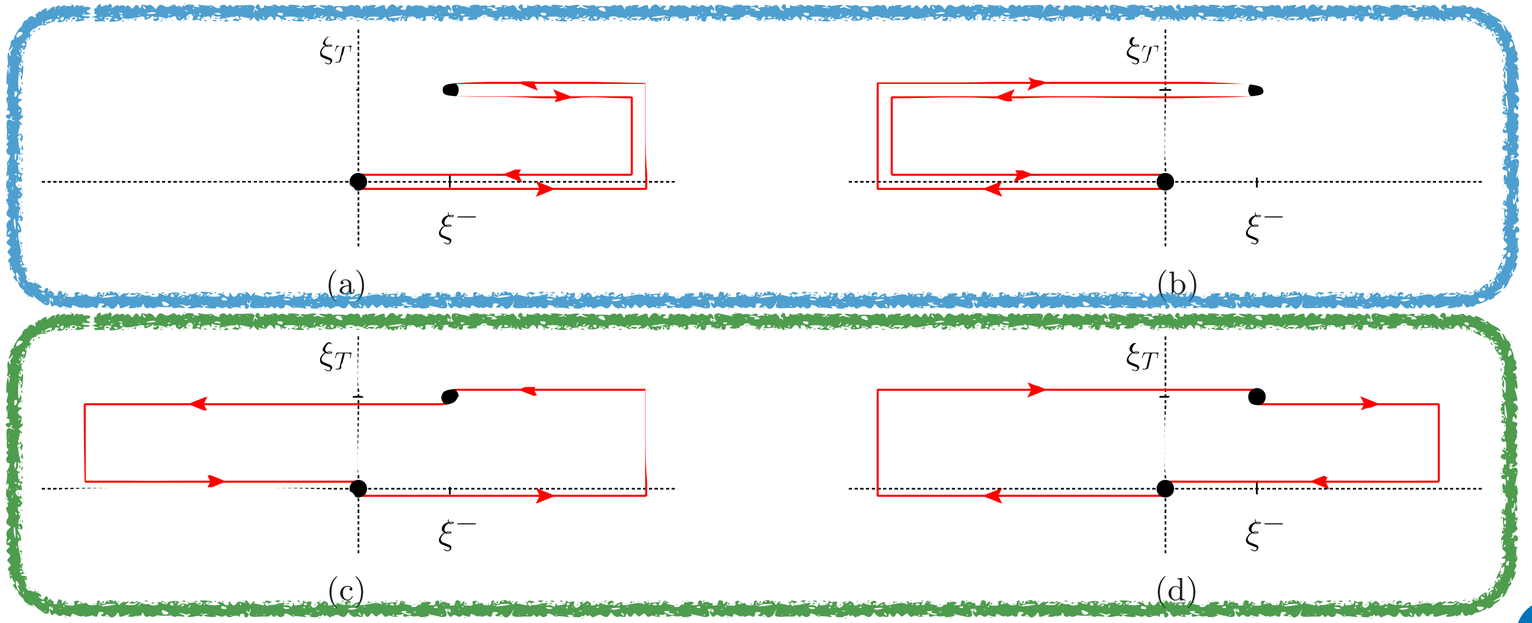
* Gluon TMDs → more complicated structure with respect to quark staple links
* Factorization-preserving processes → two main kinds of modified universality
* Different classes of processes → distinct gluon TMDs, not related to each other

f-type (WW)

(a) $[+,+]$ or (b) $[-,-]$

d-type (dipole)

(c) $[+,-]$ or (d) $[-,+]$

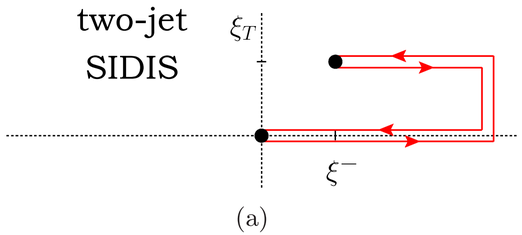


Accessing f-type and d-type gluon TMD PDFs

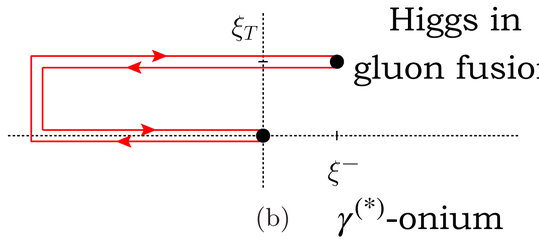
f-type (WW)

(a) $[+,+]$ or (b) $[-,-]$

two-jet
SIDIS



(a)



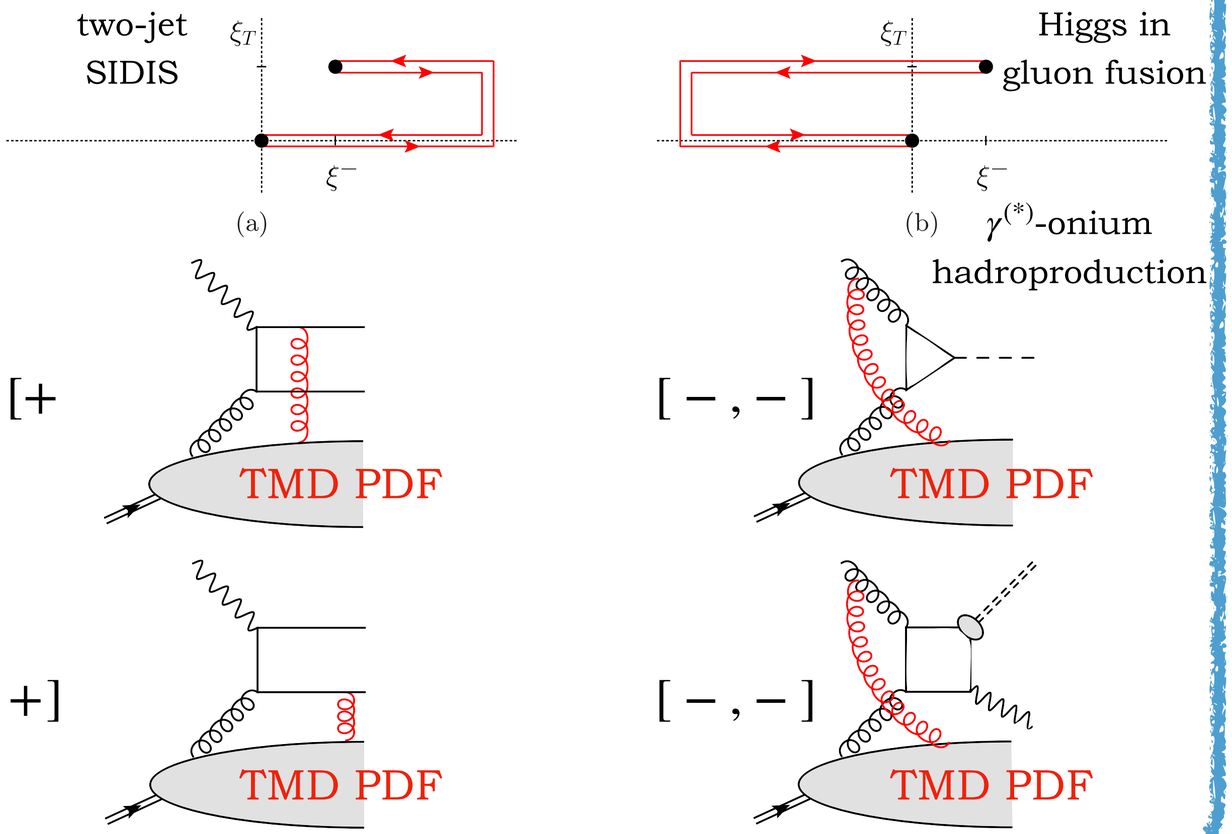
Higgs in
gluon fusion

(b) $\gamma^{(*)}$-onium
hadroproduction

Accessing f-type and d-type gluon TMD PDFs

f-type (WW)

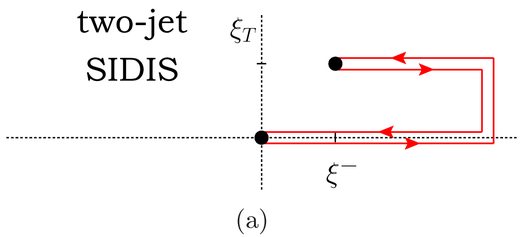
(a) [+ , +] or (b) [− , −]

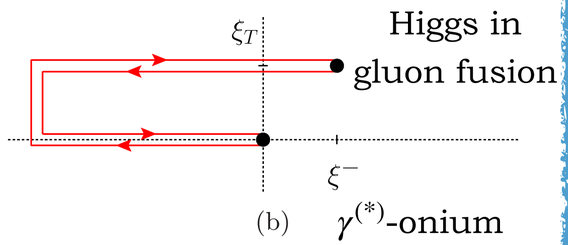


Accessing f-type and d-type gluon TMD PDFs

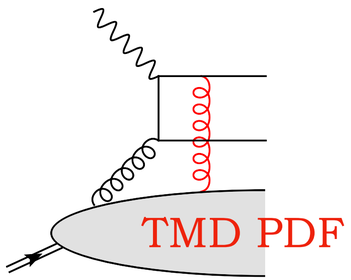
f-type (WW)

(a) [+,+] or (b) [−,−]

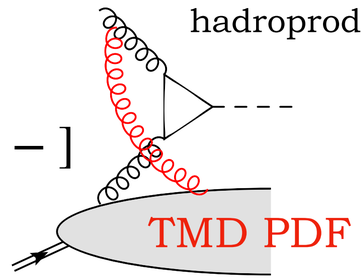




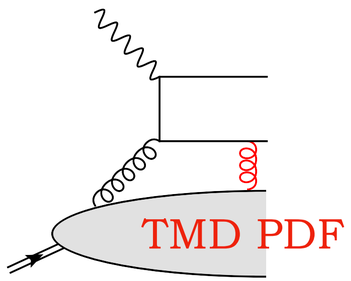
[+



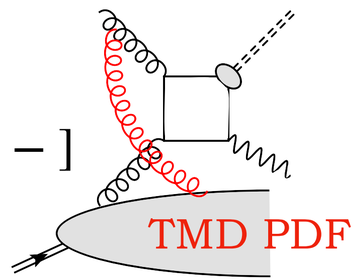
[−,−]



+]

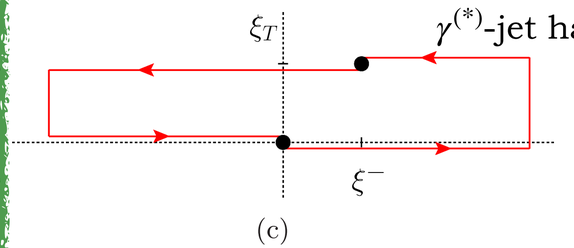


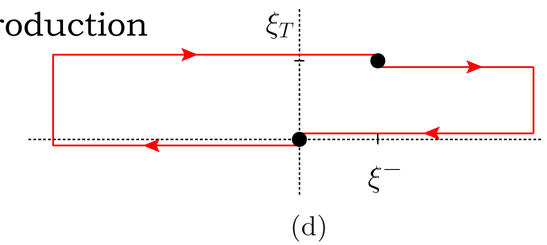
[−,−]



d-type (DP)

(c) [+,−] or (d) [−,+]

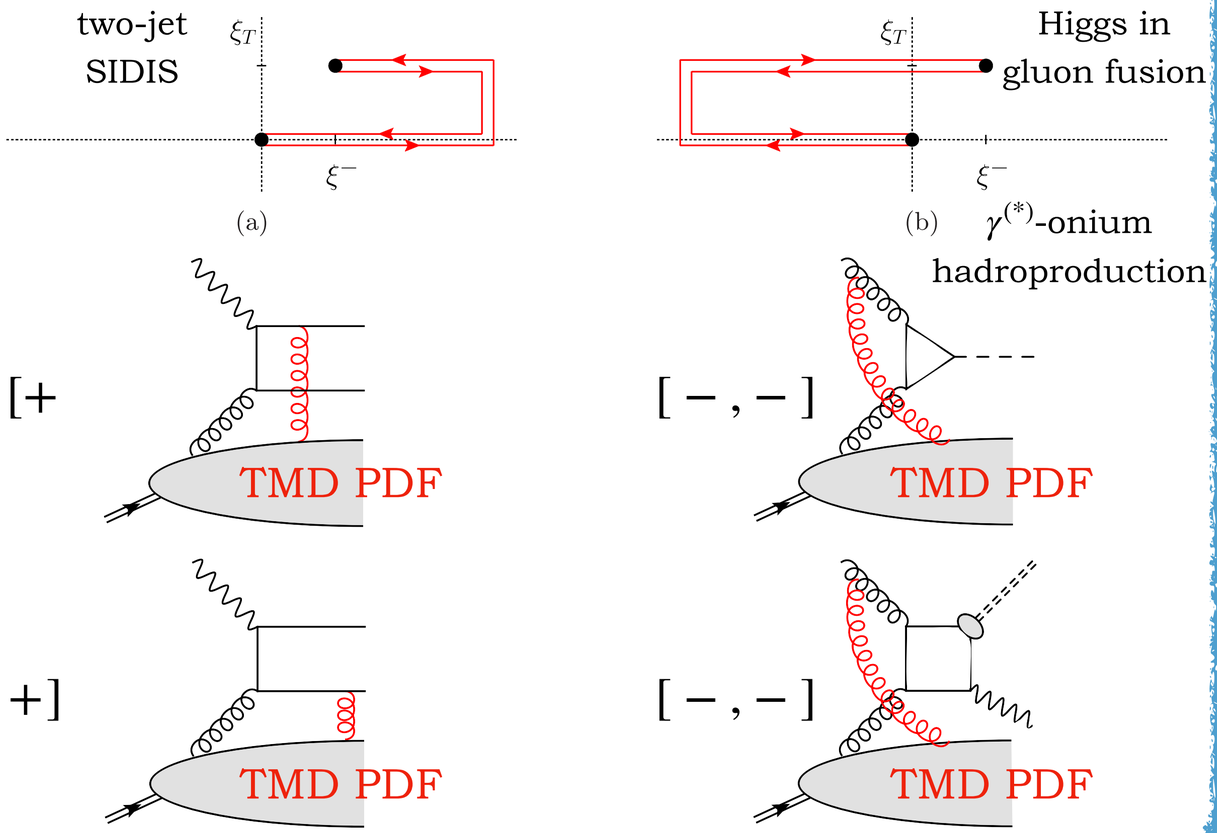




Accessing f-type and d-type gluon TMD PDFs

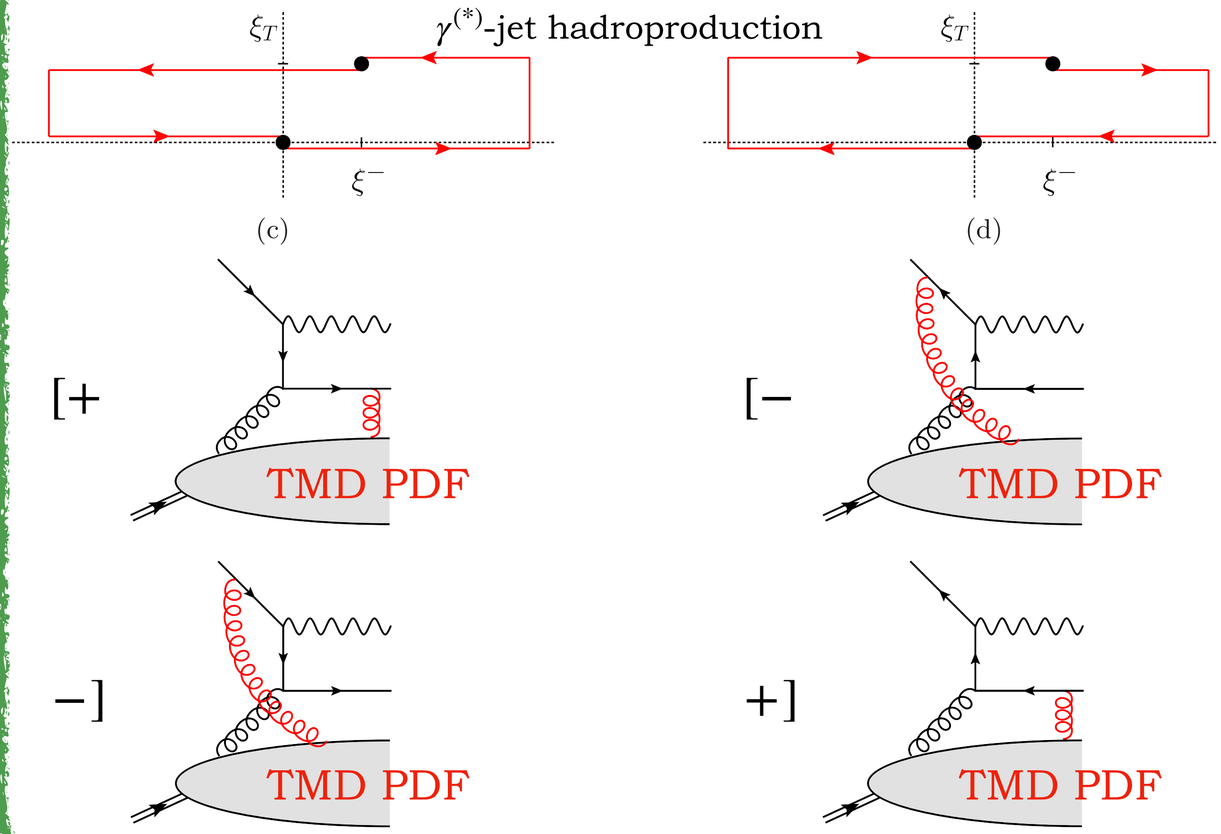
f-type (WW)

(a) [+ , +] or (b) [− , −]



d-type (DP)

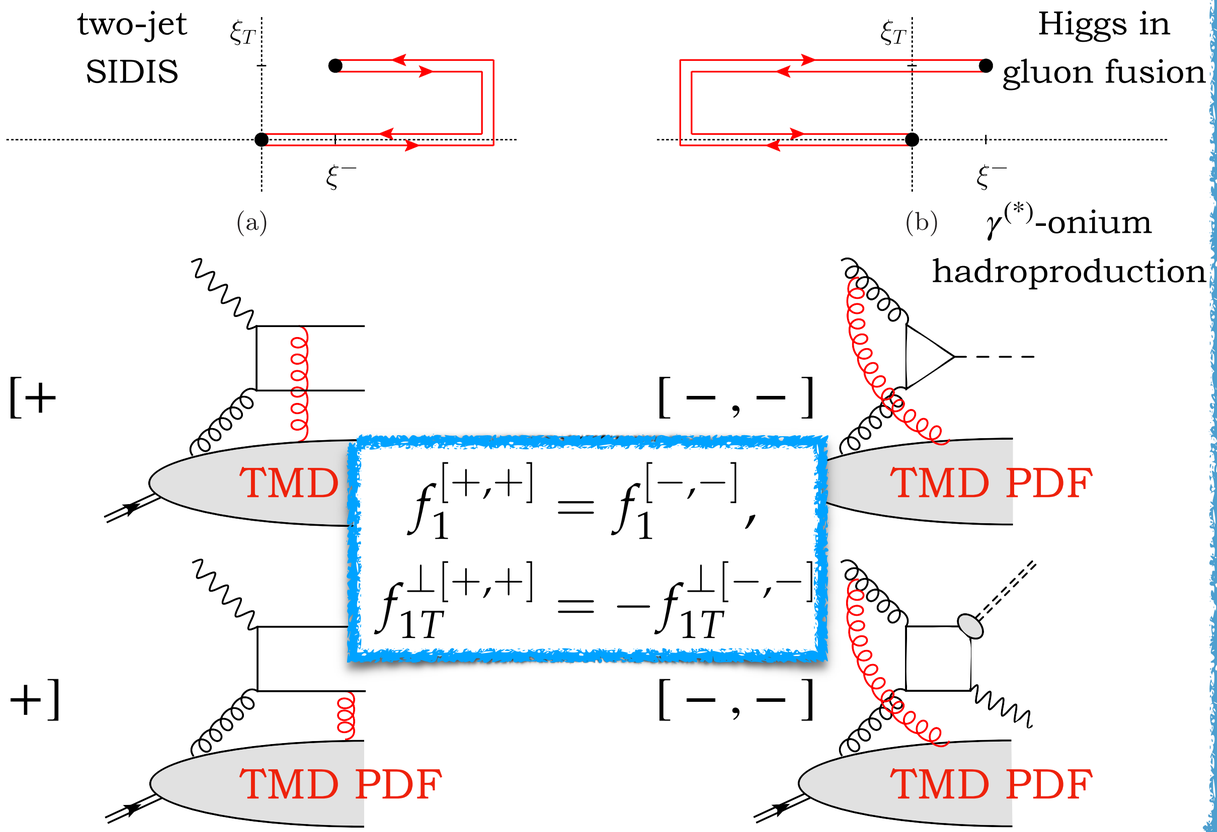
(c) [+ , −] or (d) [− , +]



Accessing f-type and d-type gluon TMD PDFs

f-type (WW)

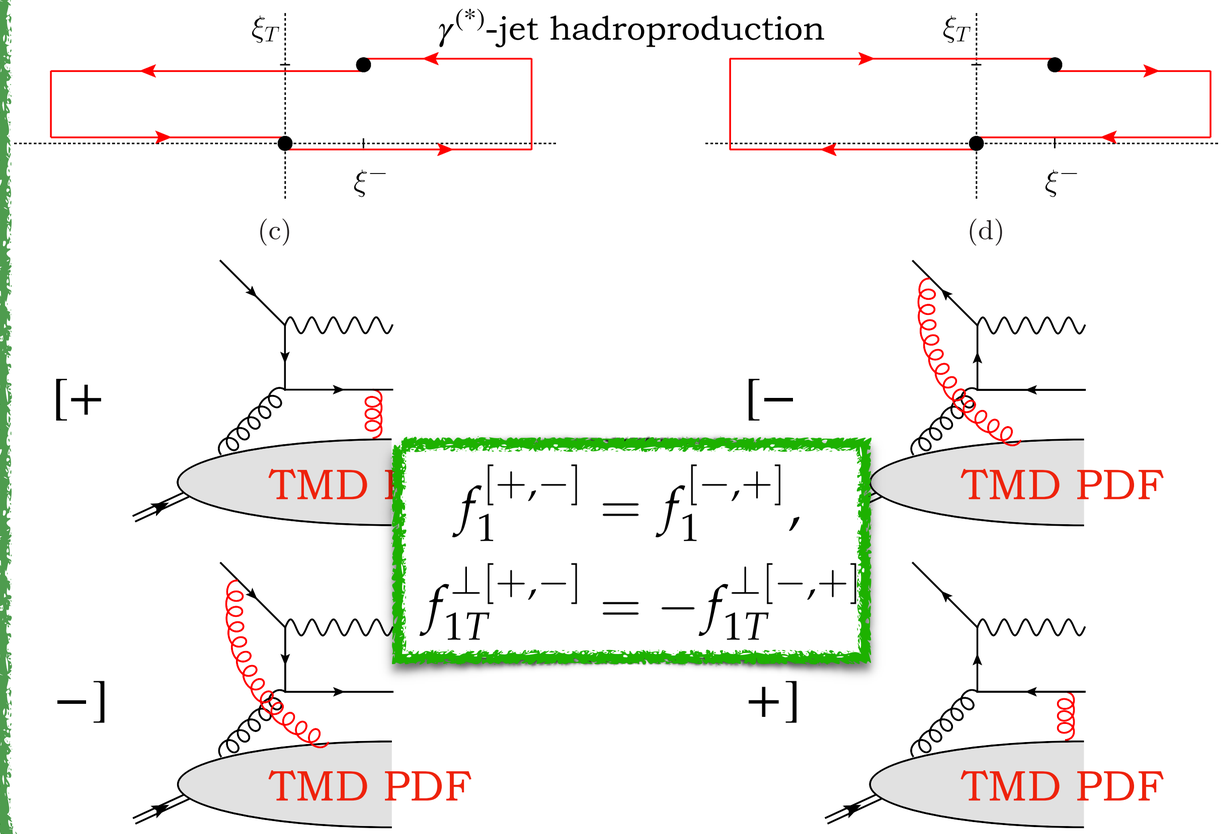
(a) $[+,+]$ or (b) $[-,-]$



$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$

d-type (DP)

(c) $[+,-]$ or (d) $[-,+]$

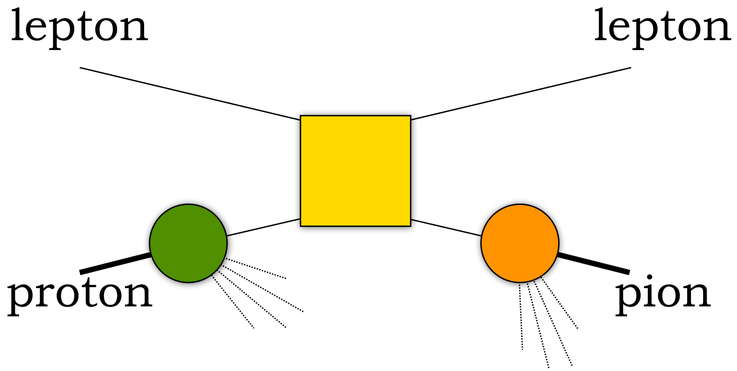


$$f_1^{[+,-]} = f_1^{[-,+]},$$
$$f_{1T}^{\perp[+,-]} = -f_{1T}^{\perp[-,+]}$$

¡ Gauge link → two main independent sets of TMDs, **not related** to each other !

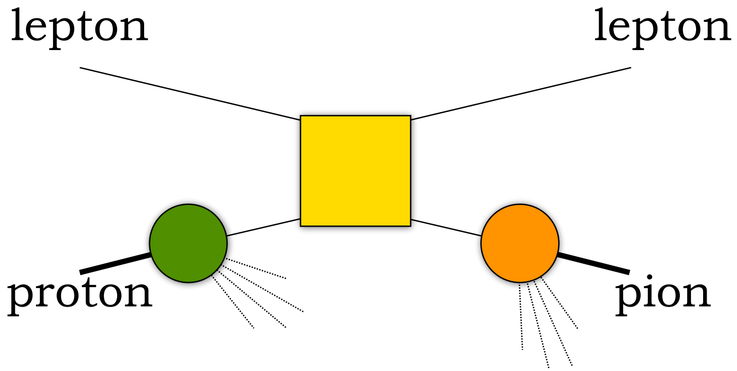
Factorization and universality

SIDIS

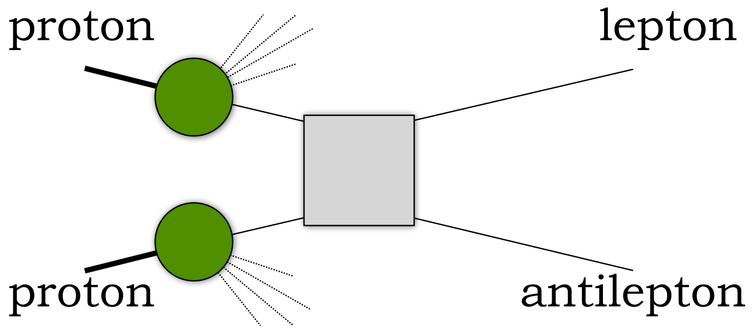


Factorization and universality

SIDIS

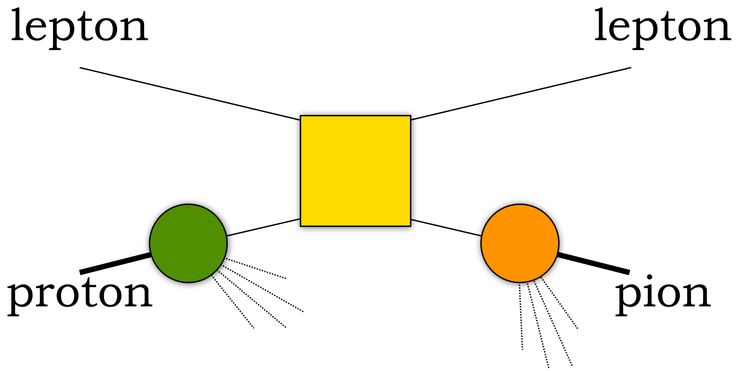


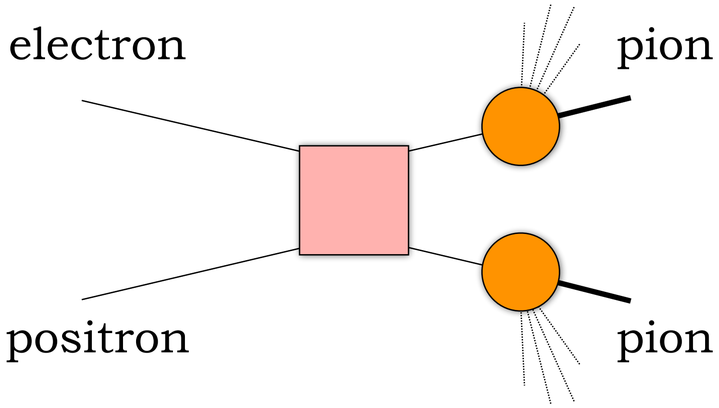
Drell-Yan



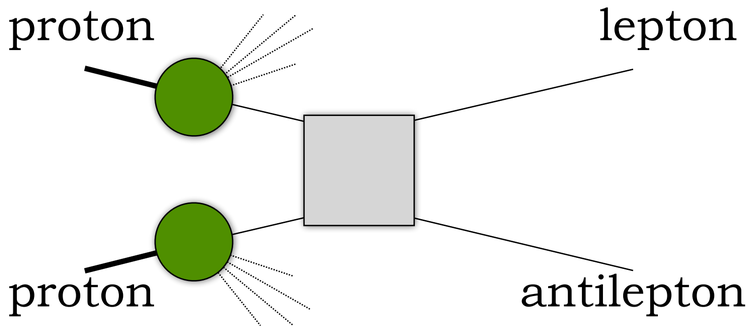
Factorization and universality

SIDIS





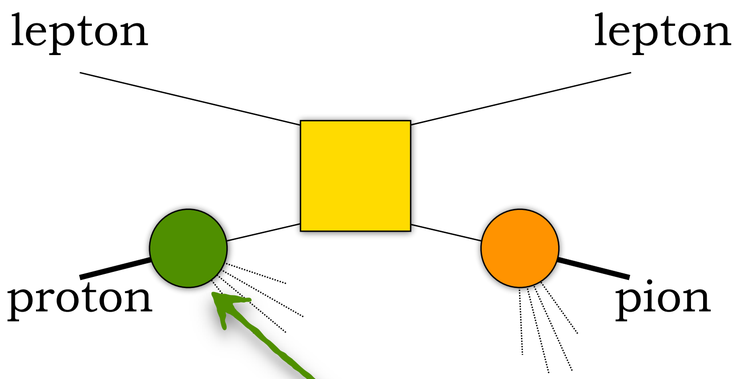
Drell-Yan

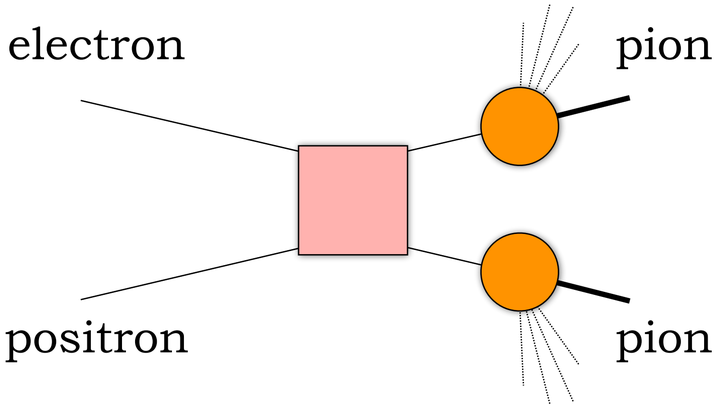


$e^+ + e^- \rightarrow$ **hadrons**

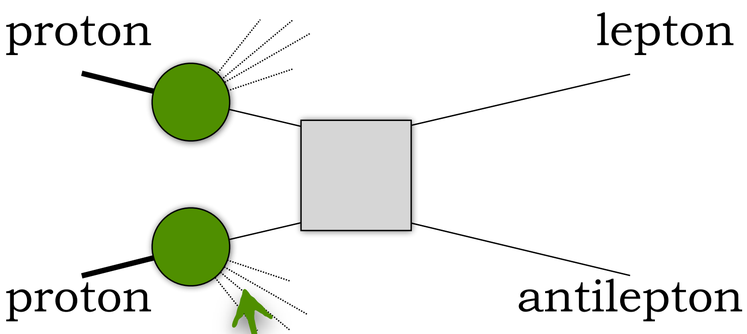
Factorization and universality

SIDIS





Drell-Yan

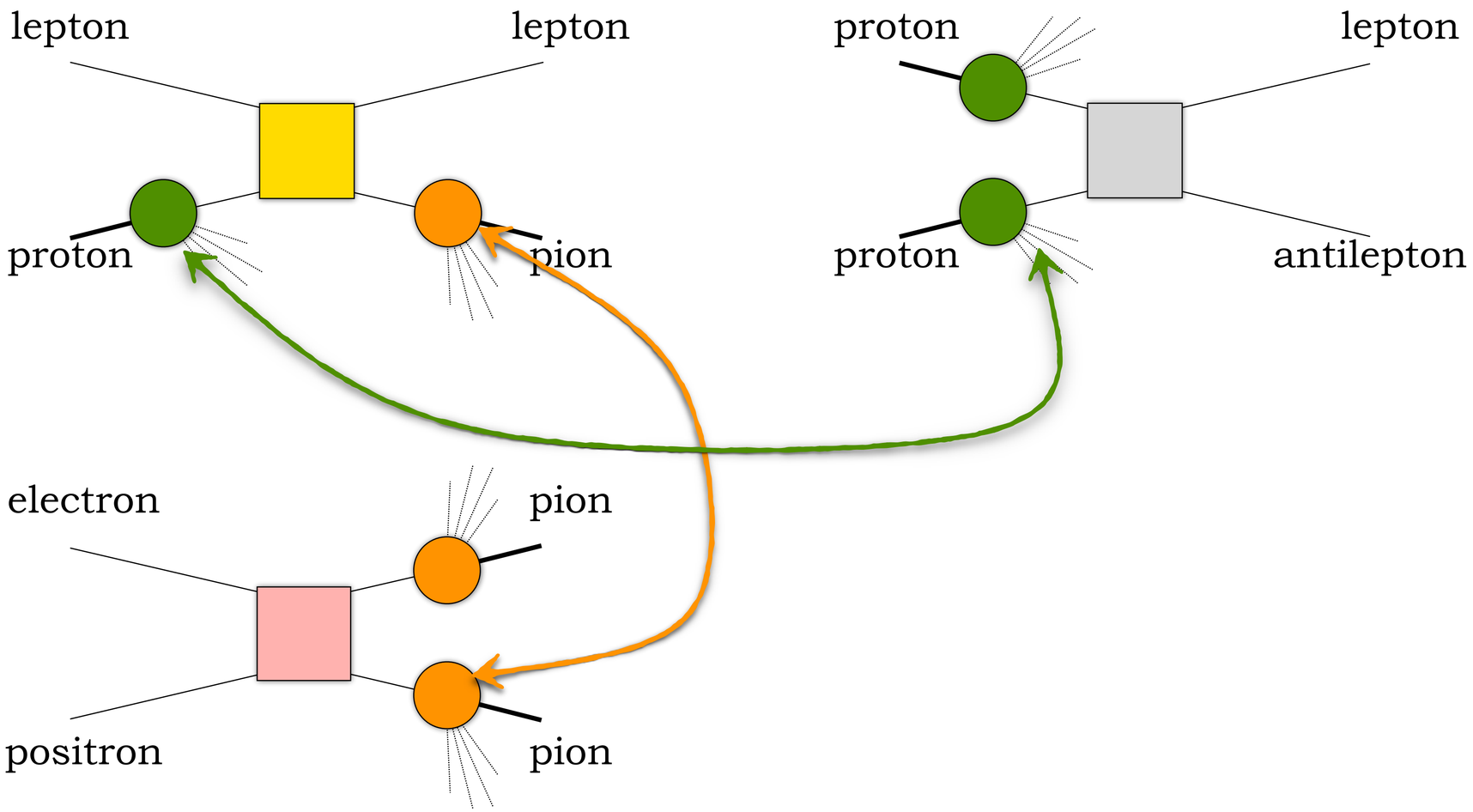


$e^+ + e^- \rightarrow$ **hadrons**

Factorization and universality

SIDIS

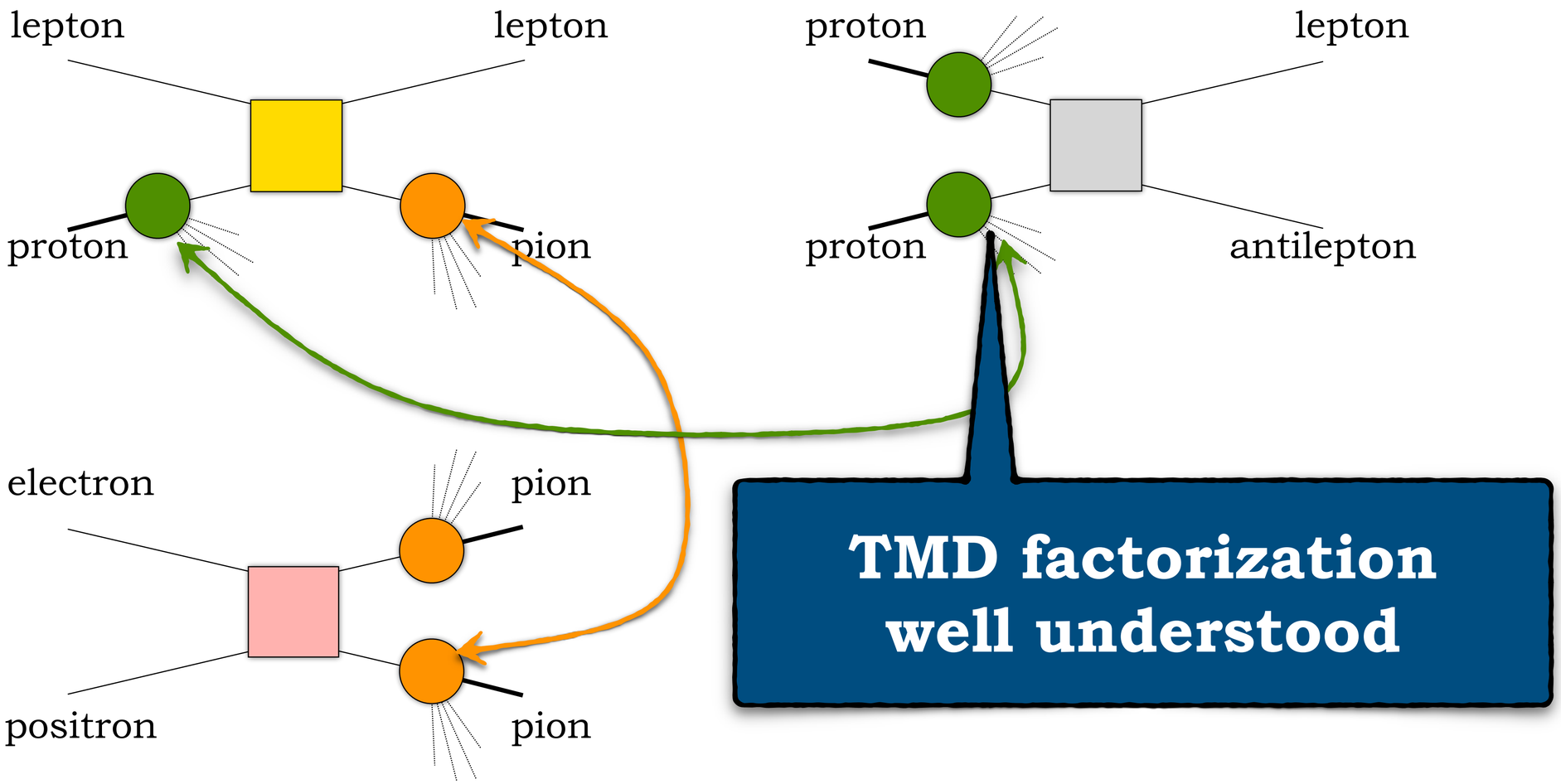
Drell-Yan



$e^+ + e^- \rightarrow$ **hadrons**

Factorization and universality

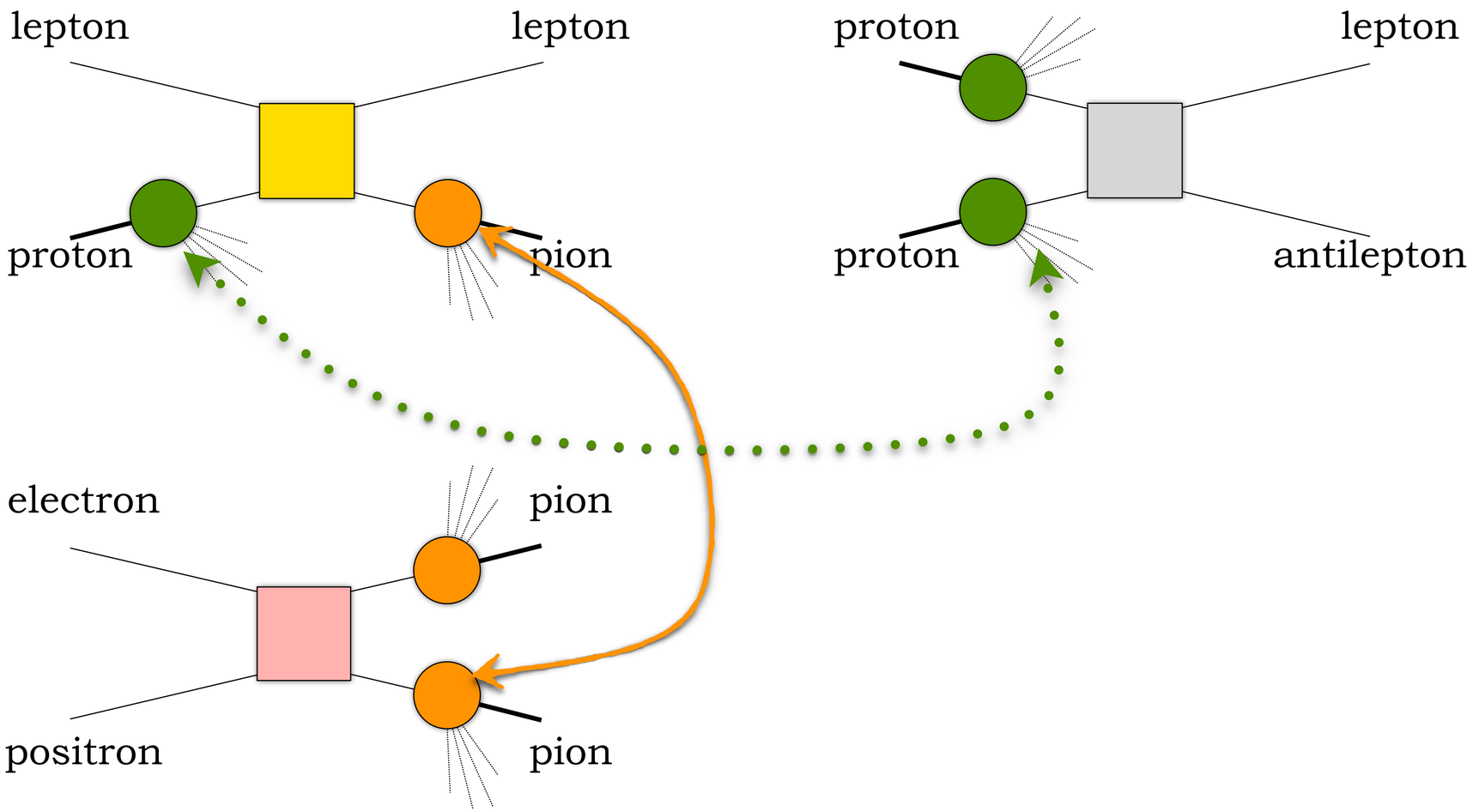
SIDIS **Drell-Yan**



$e^+ + e^- \rightarrow$ **hadrons**

Factorization and universality

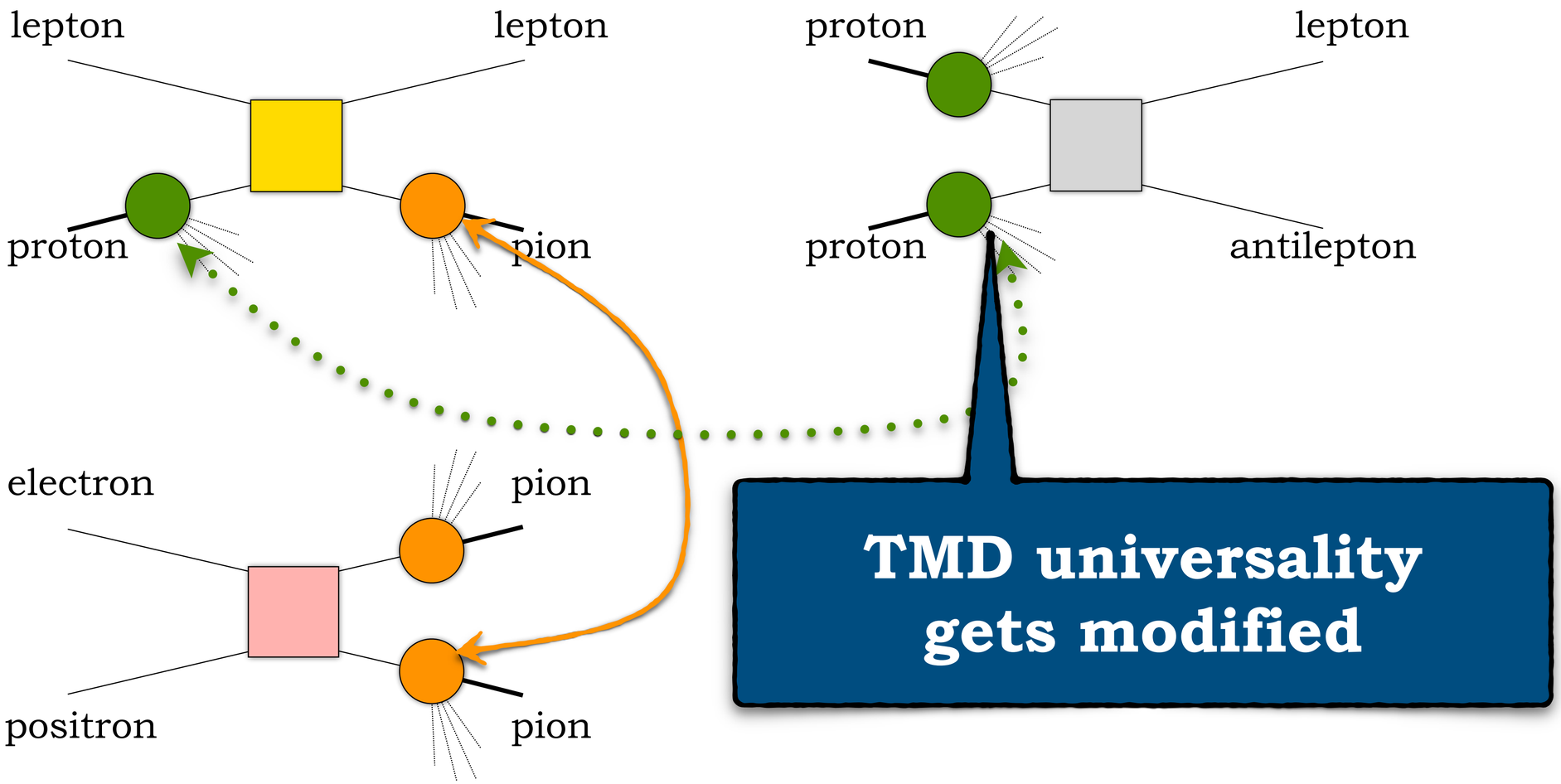
SIDIS **Drell-Yan**



$e^+ + e^- \rightarrow$ **hadrons**

Factorization and universality

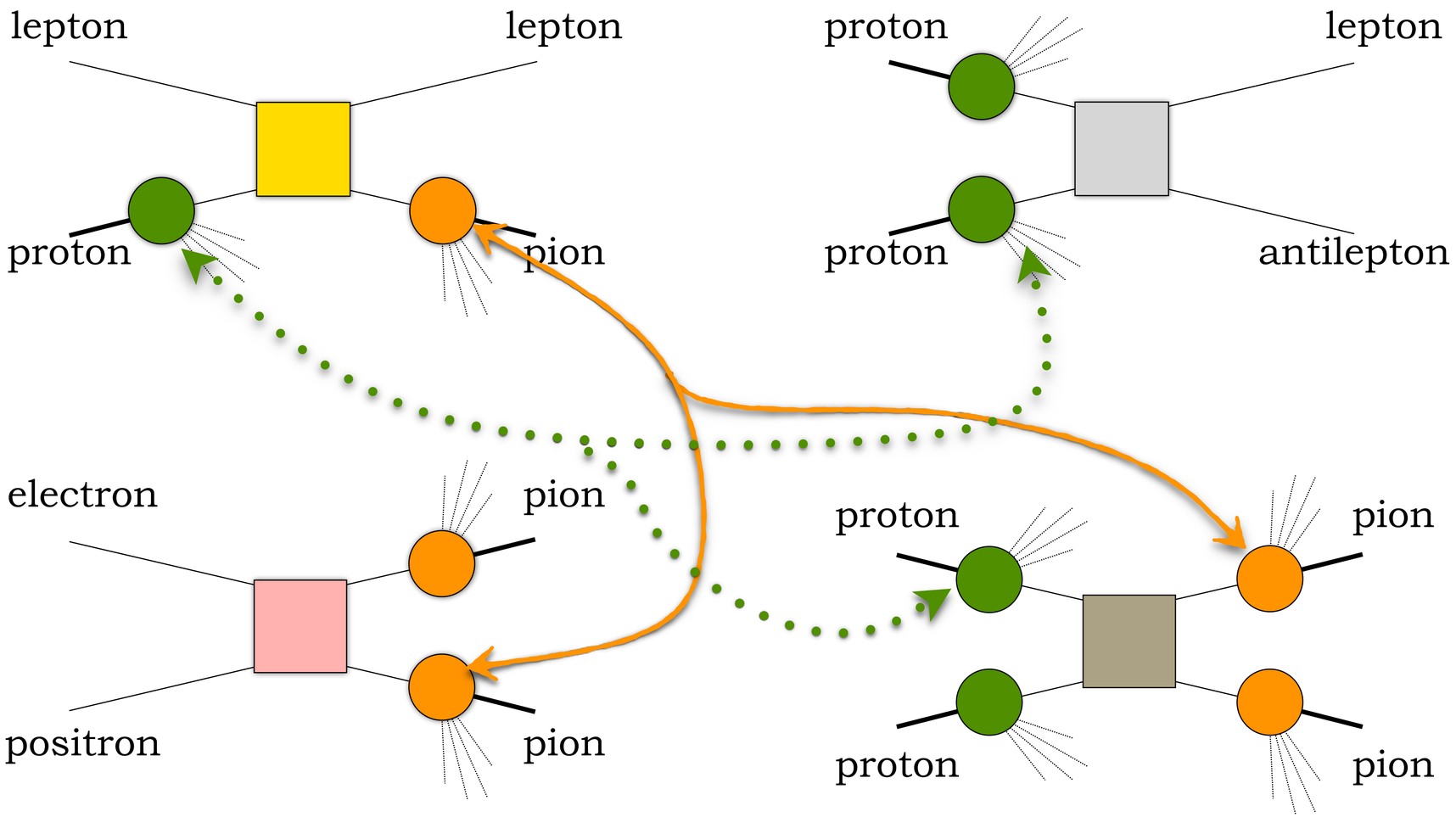
SIDIS **Drell-Yan**



$e^+ + e^- \rightarrow$ **hadrons**

Factorization and universality

SIDIS **Drell-Yan**



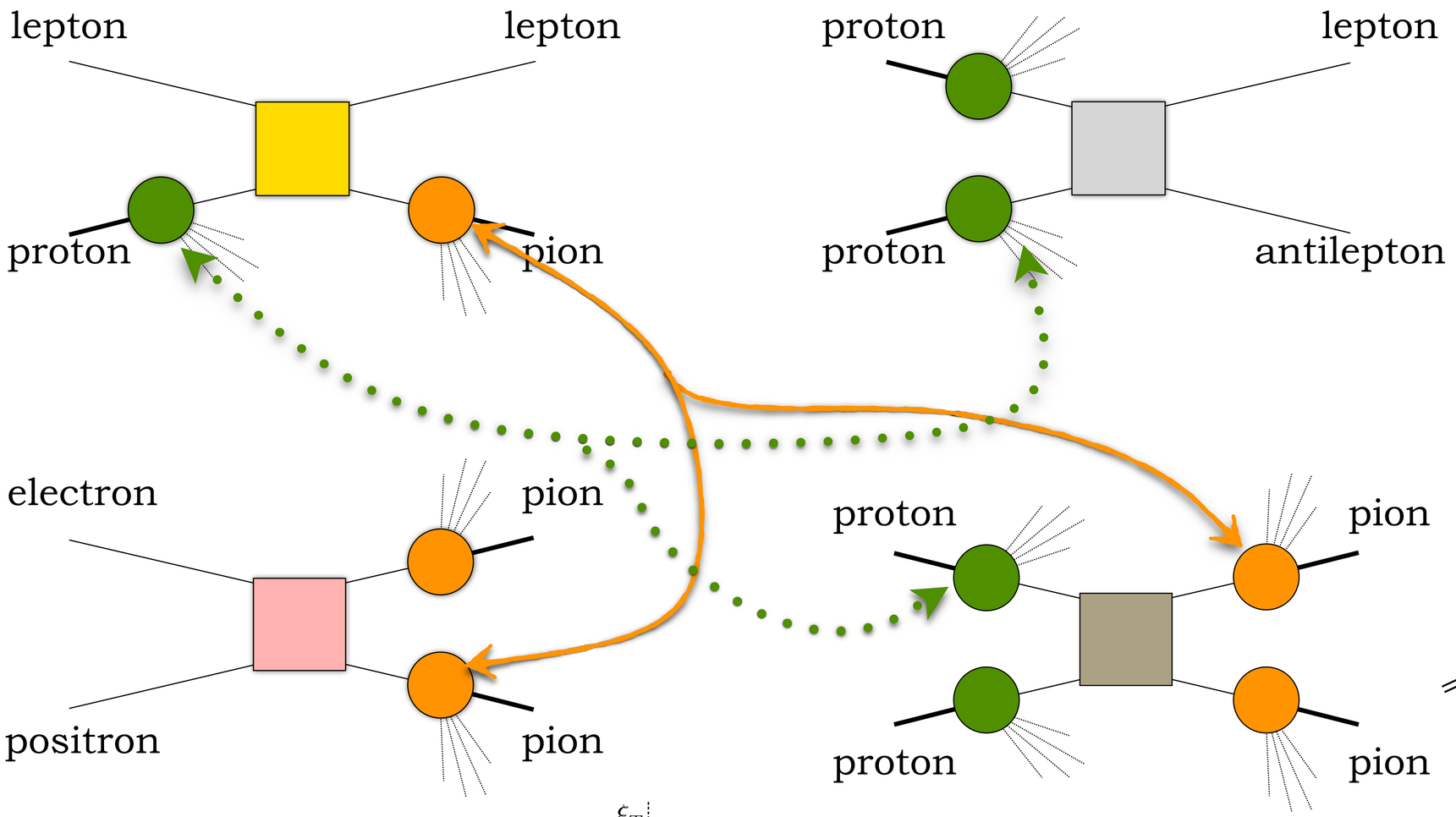
$e^+ + e^- \rightarrow$ **hadrons**

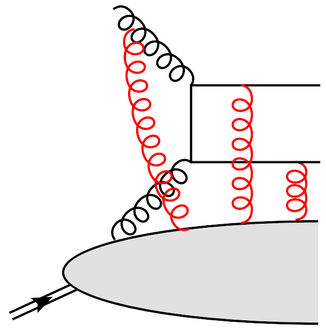
$p + p \rightarrow$ **hadrons**

Factorization and universality

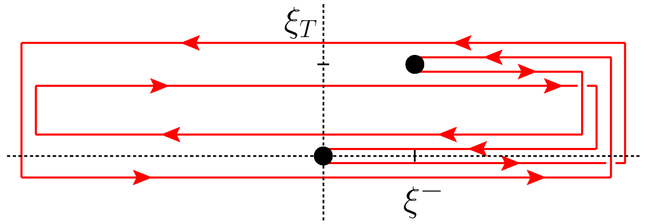
SIDIS

Drell-Yan





$e^+ + e^- \rightarrow$ **hadrons**

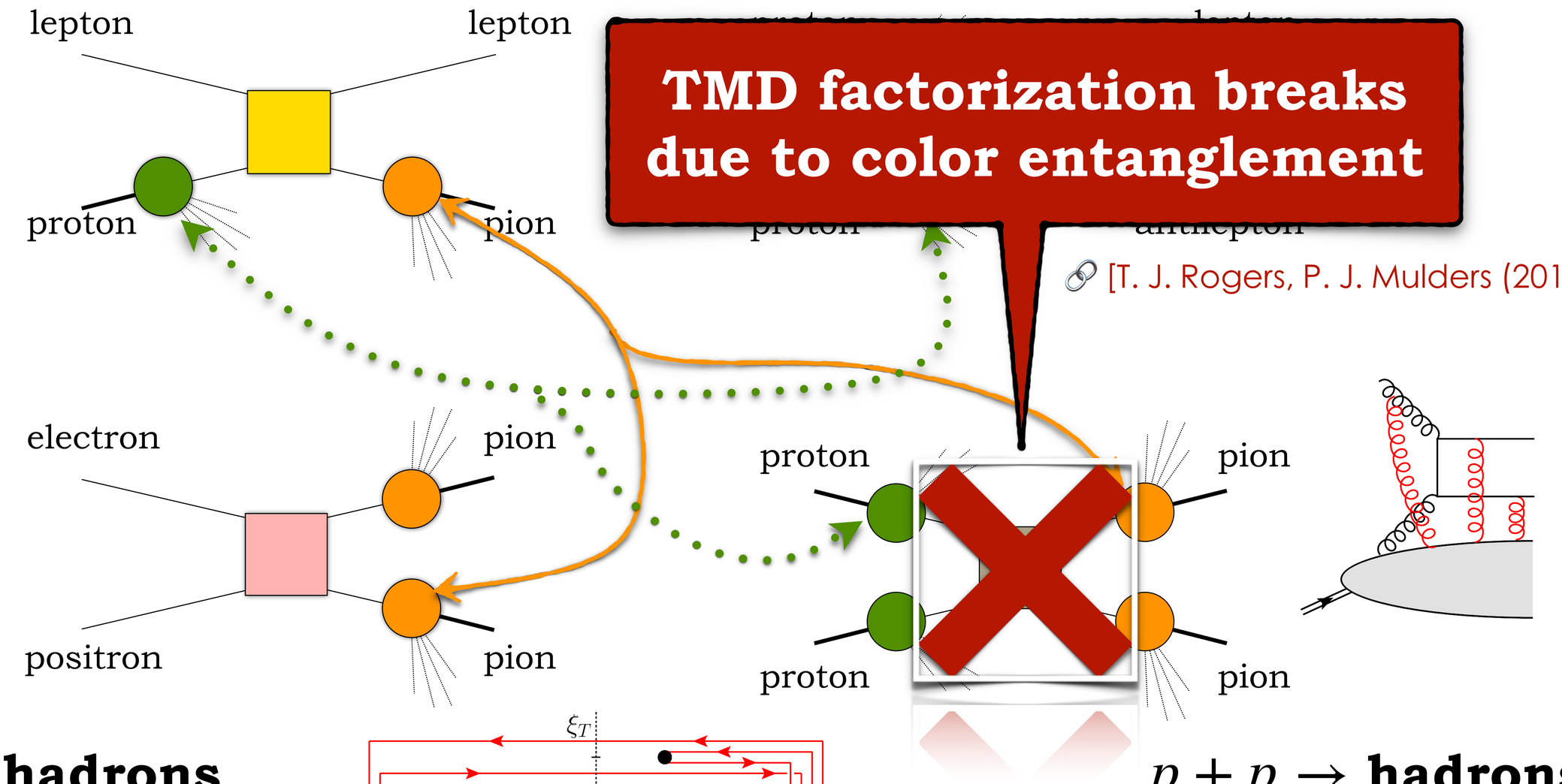


$p + p \rightarrow$ **hadrons**

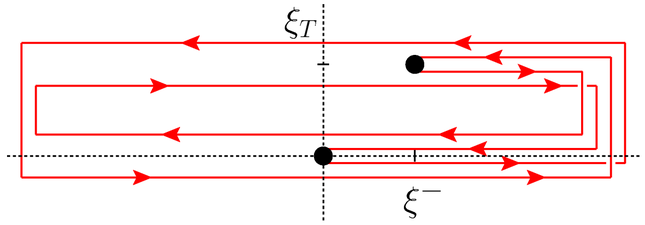
(also) gluon-induced channel

Factorization and universality

SIDIS **Drell-Yan**



$e^+ + e^- \to$ **hadrons**

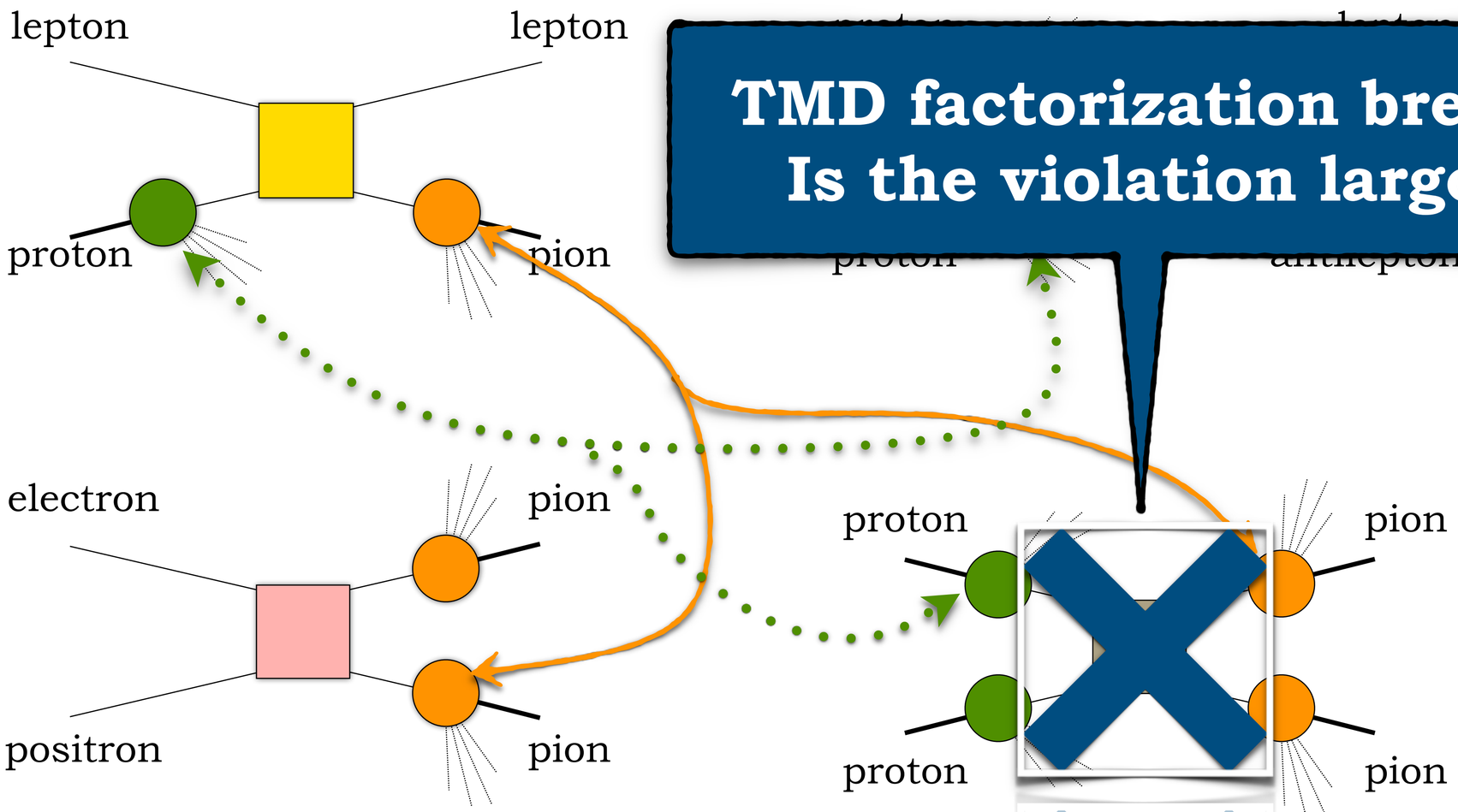


$p + p \to$ **hadrons**

(also) gluon-induced channel

Factorization and universality

SIDIS **Drell-Yan**



$e^+ + e^- \rightarrow$ **hadrons**

$p + p \rightarrow$ **hadrons**

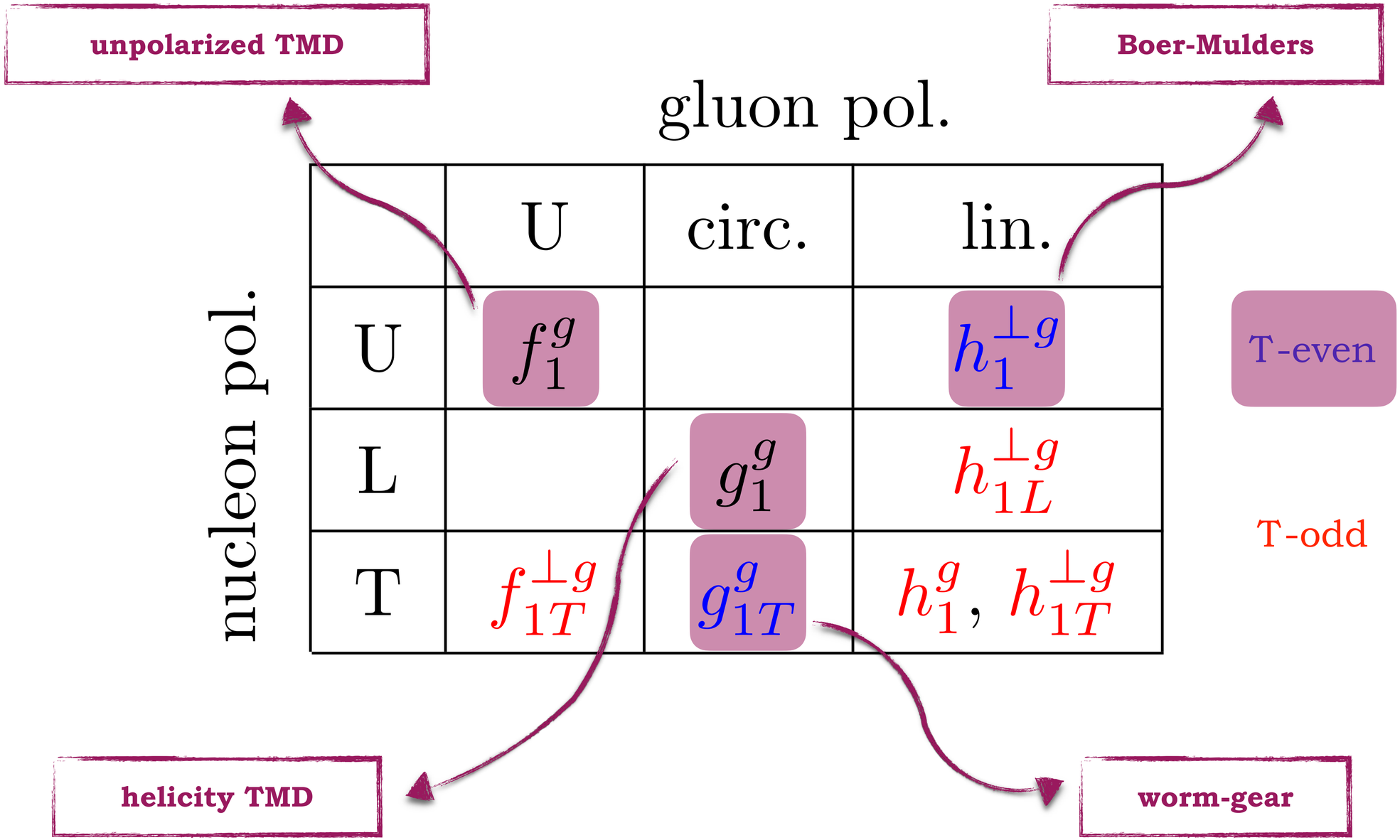
Gluon TMD PDFs at leading twist

nucleon pol. \ gluon pol.	U	circ.	lin.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

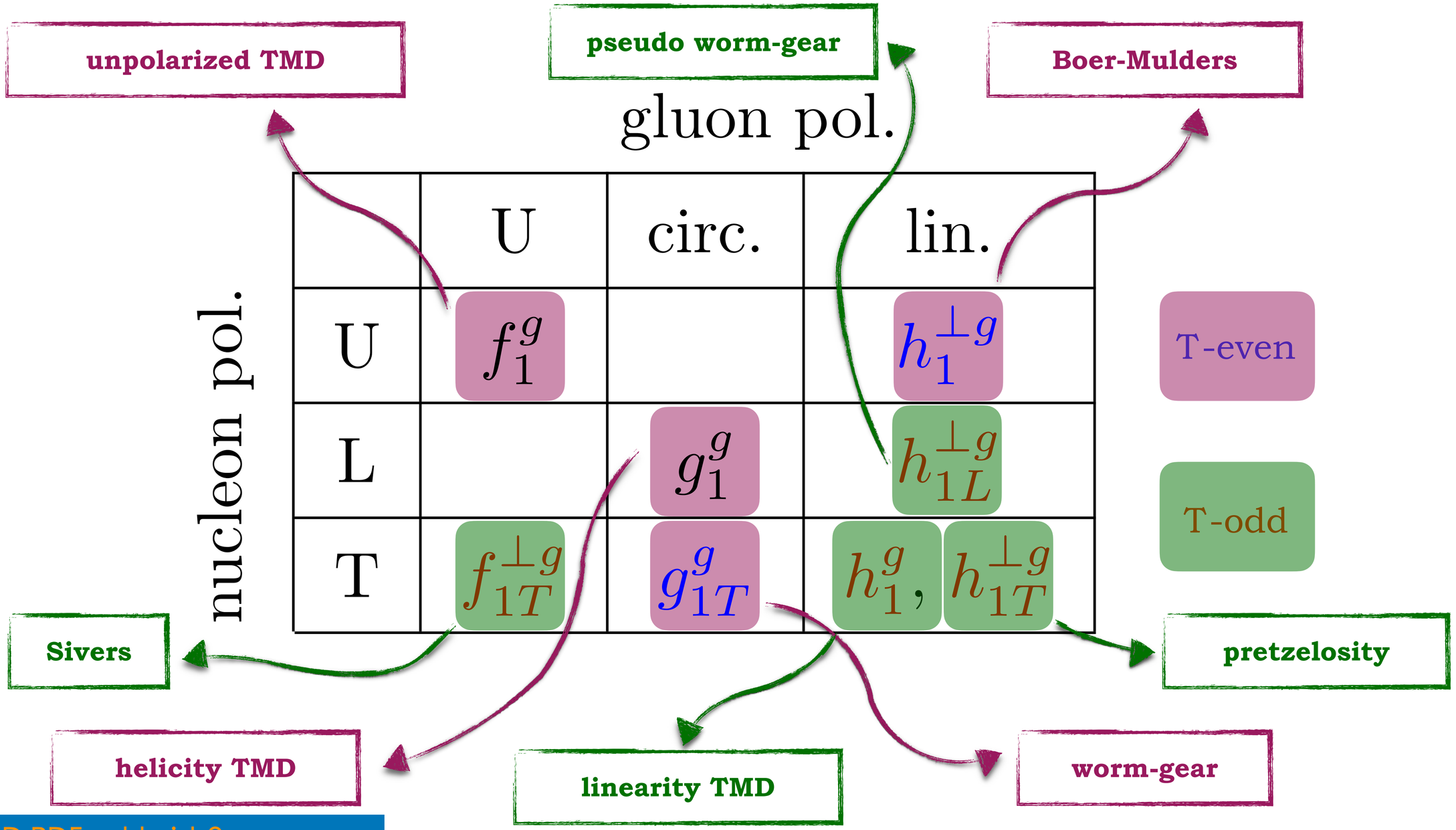
T-even

T-odd

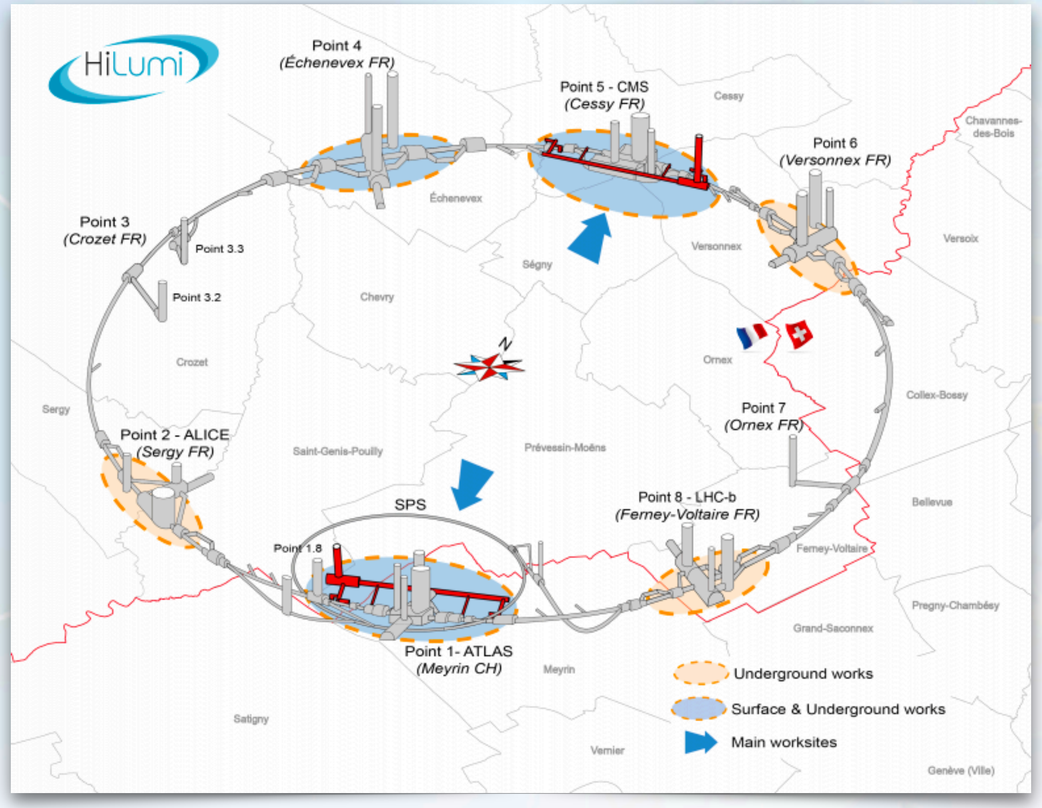
Gluon TMD PDFs at leading twist



Gluon TMD PDFs at leading twist



Gluon TMD PDFs at Hi-Lumi & Fixed Target LHC

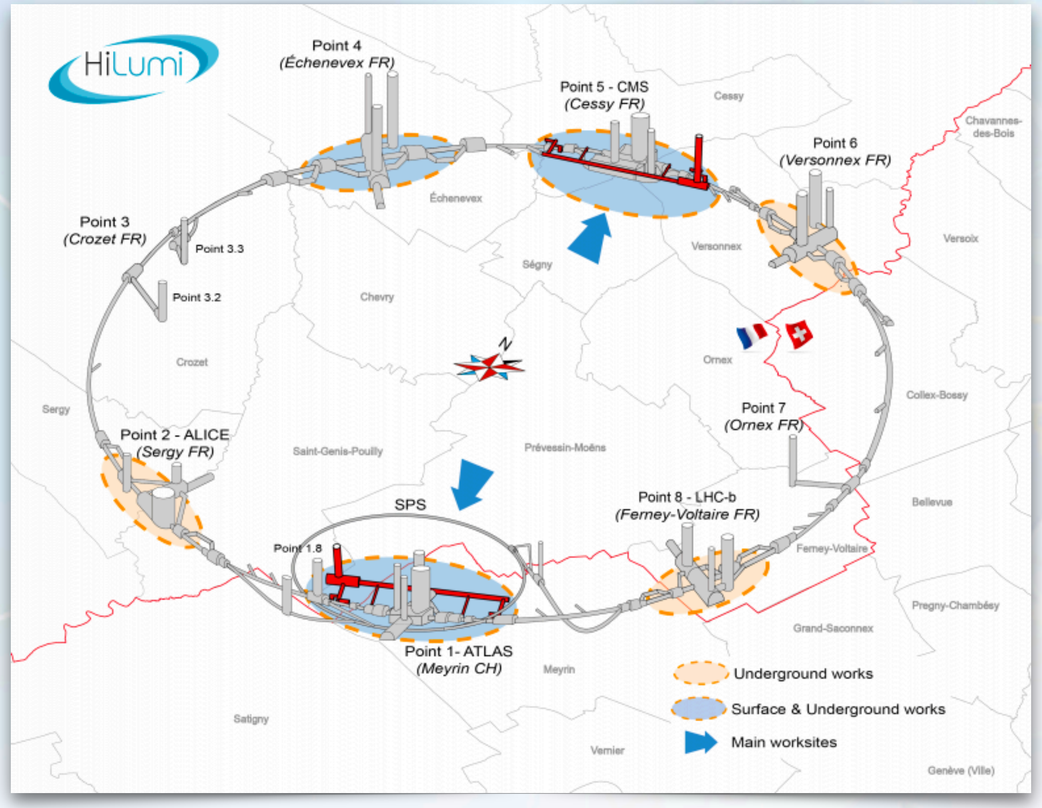


Hi-Lumi & Fixed Target

Quarkonium @ HL-LHC 🔗 [Prog. Part. Nucl. Phys. 122 (2022) 103906]

Proton structure at the LHC & future upgrades

Gluon TMD PDFs at Hi-Lumi & Fixed Target LHC



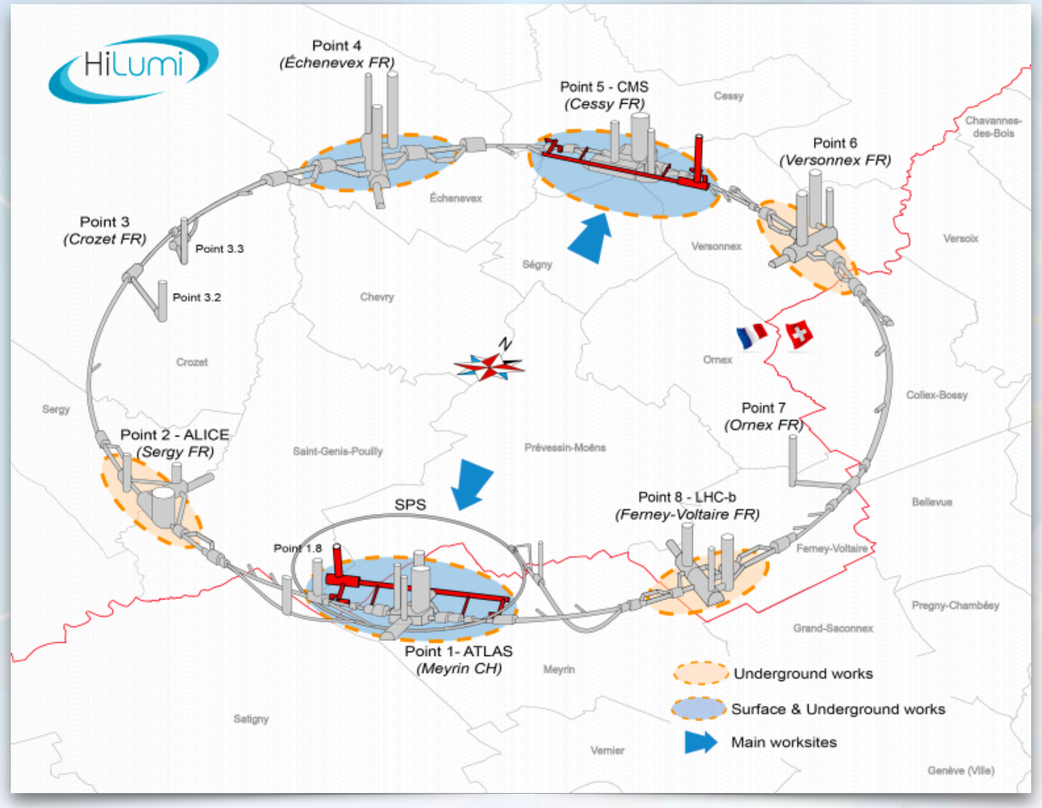
Hi-Lumi & Fixed Target

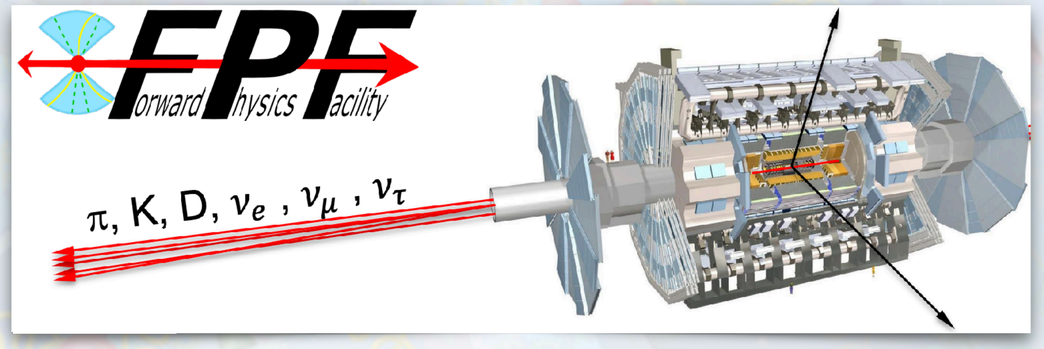
Quarkonium @ HL-LHC 🔗 [Prog. Part. Nucl. Phys. 122 (2022) 103906]

Proton structure at the LHC & future upgrades

Intrinsic effect of gluon polarization in unpolarized pp & single-spin asymmetries (SSAs)

Gluon TMD PDFs at Hi-Lumi & Fixed Target LHC





Hi-Lumi & Fixed Target

Forward Physics Facility

Quarkonium @ HL-LHC 🔗 [Prog. Part. Nucl. Phys. 122 (2022) 103906]

The Forward Physics Facility (FPF) 🔗 [Phys. Rept. 968 (2022) 1-50]

Proton structure at the LHC & future upgrades

- Intrinsic effect of gluon polarization in unpolarized pp & single-spin asymmetries (SSAs)
- Precision studies of proton structure via natural stability of high-energy resummation

  Light mesons + heavy flavor 🔗 [F.G.C., Phys. Rev. D 105 (2022) 11, 114008]

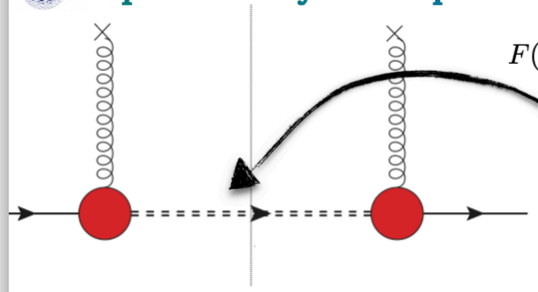
2. Modeling gluon TMD PDFs

Spectator-model gluon TMDs

Our model at a glance

Spectator-system spectral-mass function

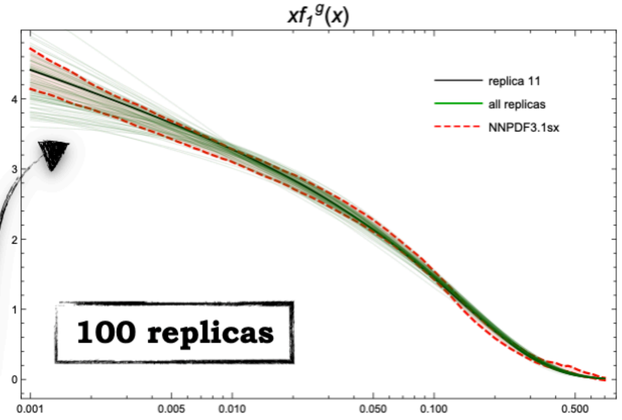
$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$



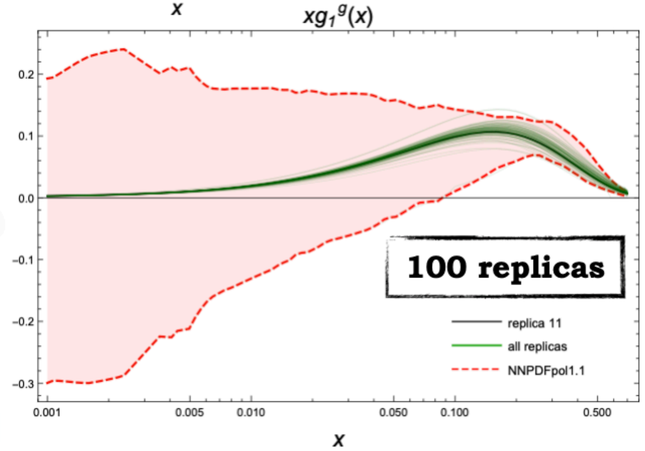
Instead of a single on-shell spectator, a continuum of spectators

Link with collinear factorization

p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution



Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)



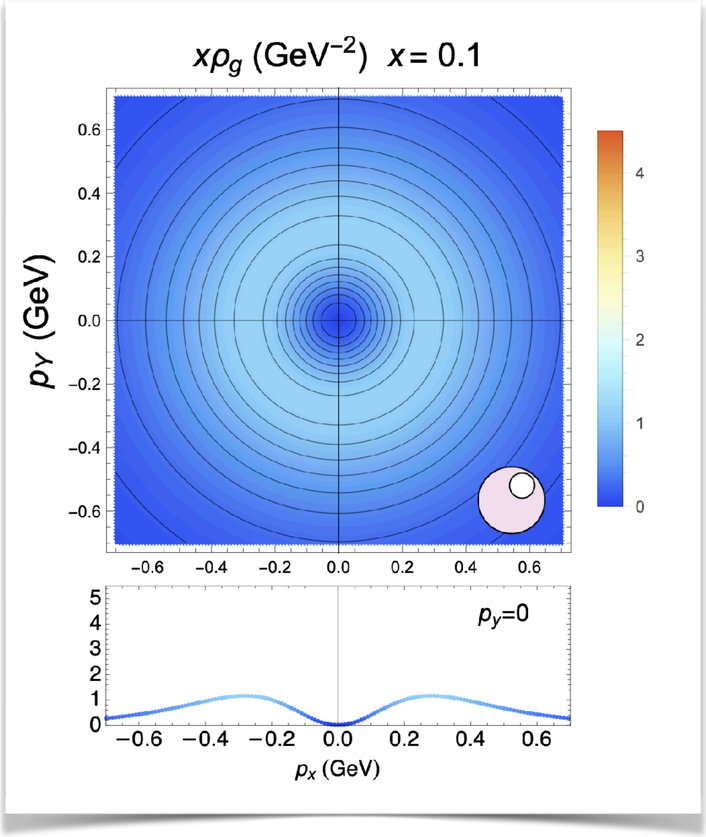
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs
- ☑ Inclusion of small-x resummation effects (**BFKL**)
- ☑ Calculation of all leading-twist T-even gluon TMDs

2.3 Modeling gluon TMDs 🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

14

3D proton tomography: T-even gluon TMD PDFs

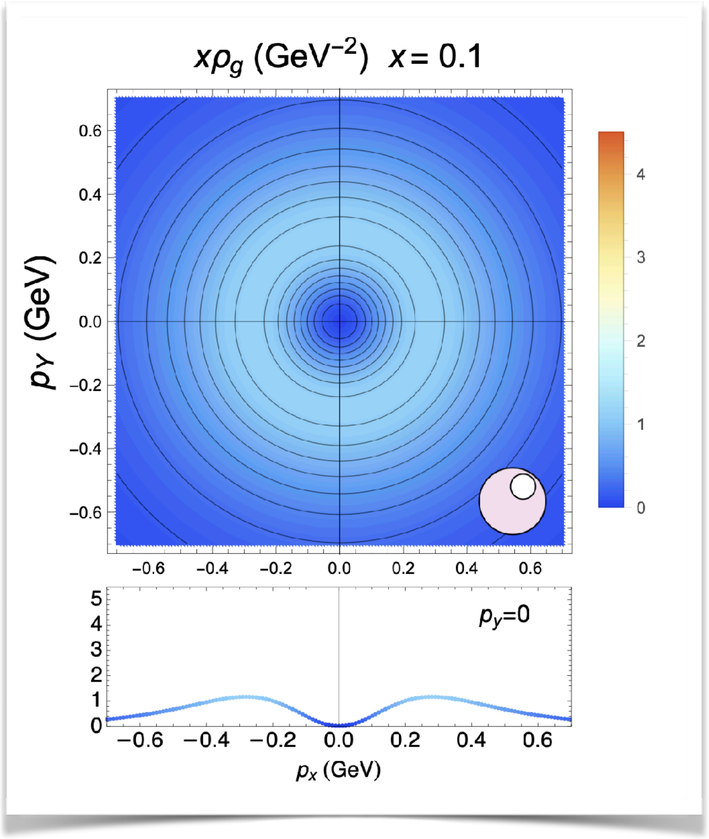
unpolarized TMD



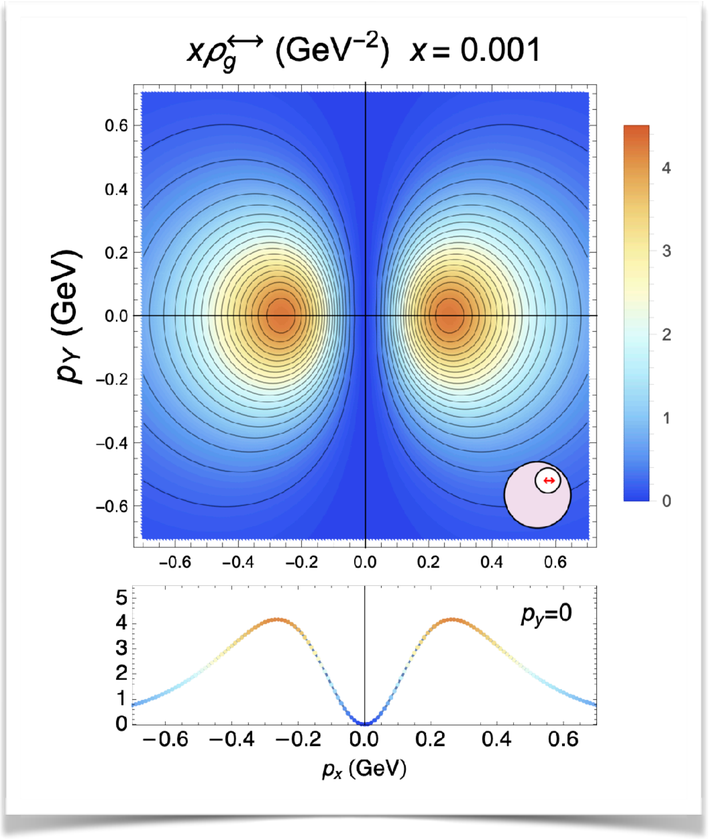
🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels, Eur. Phys. J. C 80 (2020) no.8 [arXiv:2005.02288]]

3D proton tomography: T-even gluon TMD PDFs

unpolarized TMD



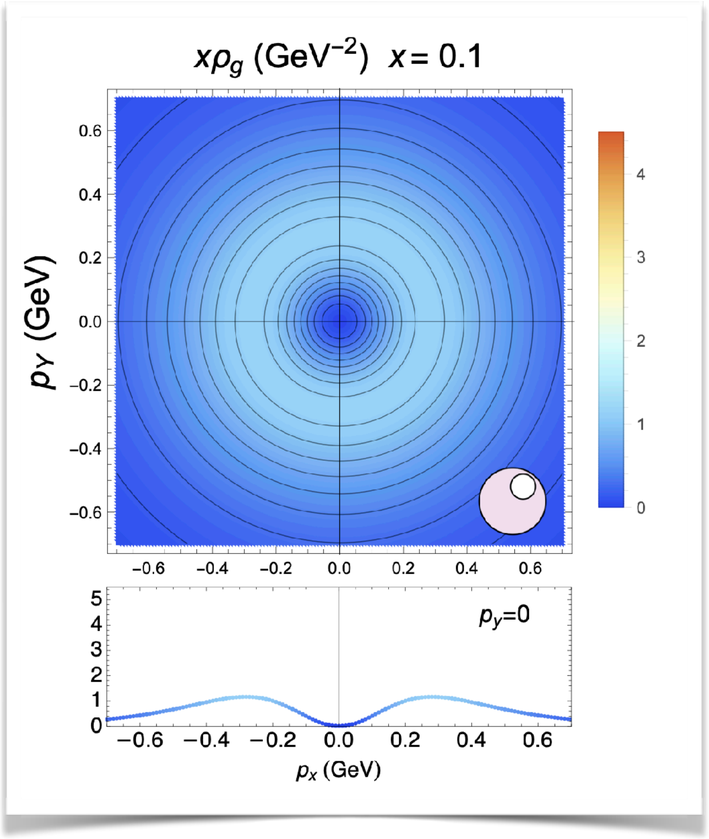
Boer-Mulders



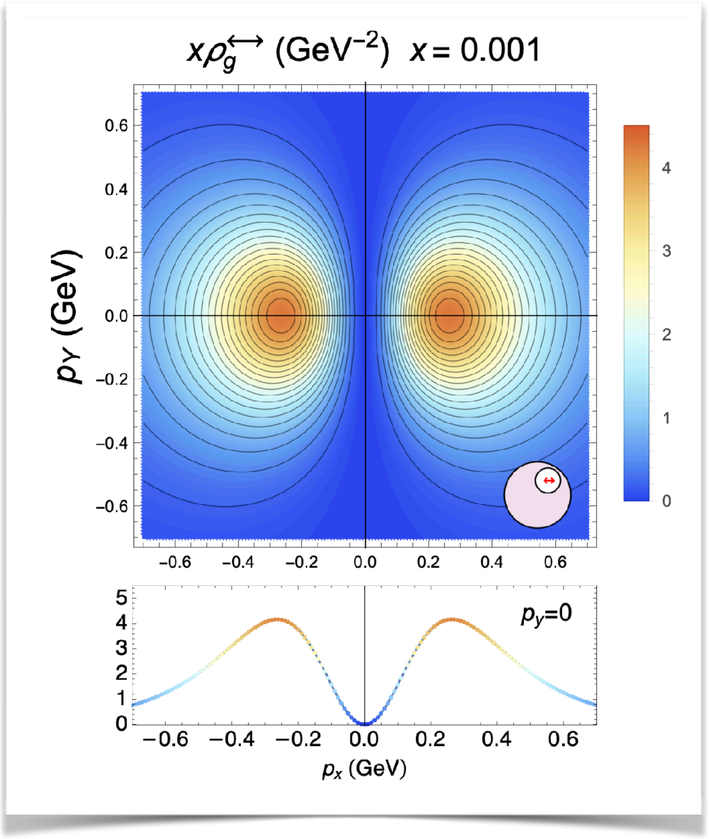
🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels, Eur. Phys. J. C 80 (2020) no.8 [arXiv:2005.02288]]

3D proton tomography: T-even gluon TMD PDFs

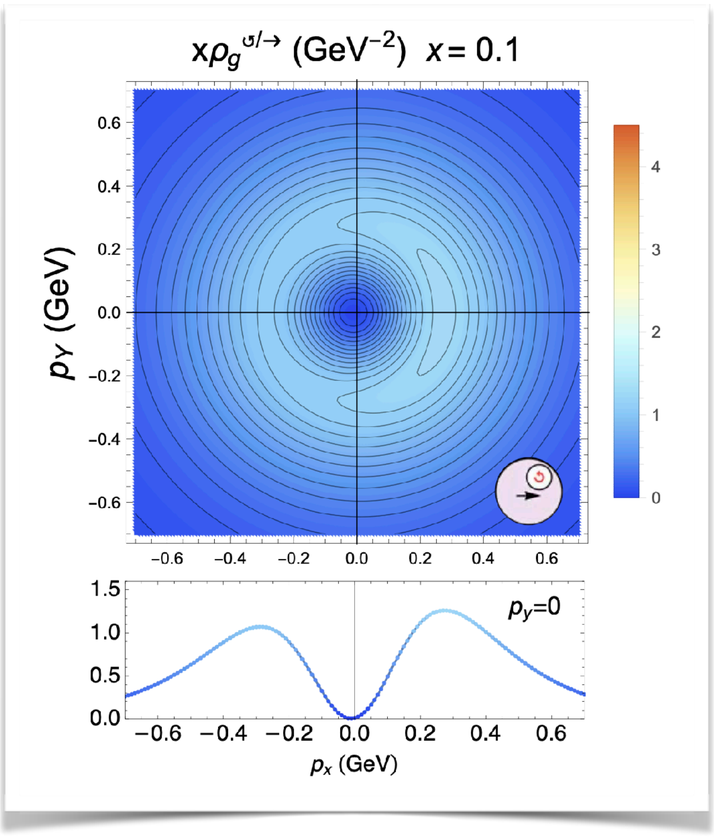
unpolarized TMD



Boer-Mulders

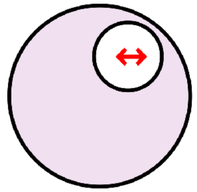


worm-gear



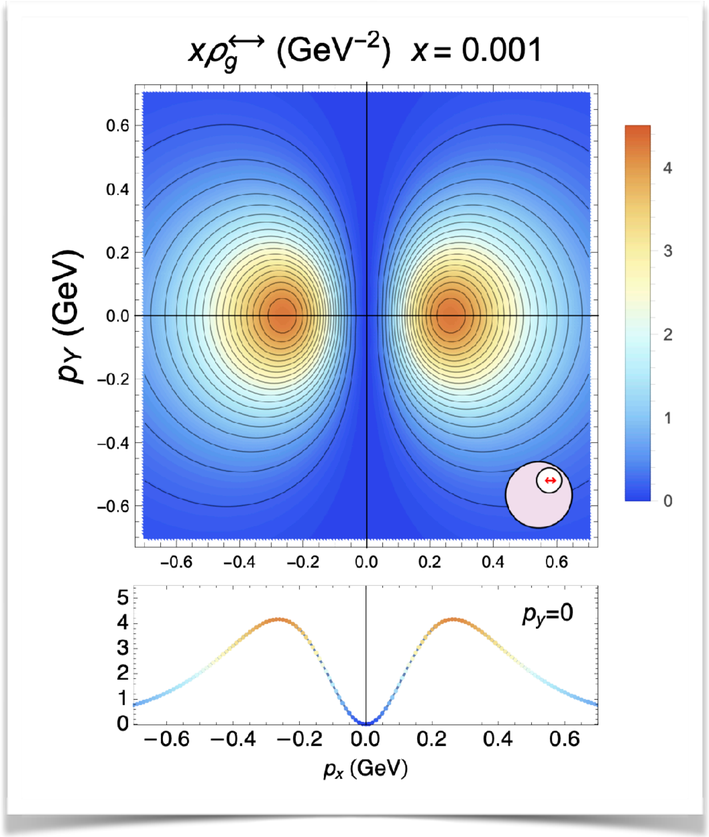
🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels, Eur. Phys. J. C 80 (2020) no.8 [arXiv:2005.02288]]

Boer-Mulders effect in unpolarized pp collisions



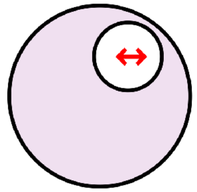
$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^\perp(x,p_x,p_y)$$

unpol. Boer-Mulders



[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Boer-Mulders effect in unpolarized pp collisions



$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. Boer-Mulders

(Pseudo)scalar p_T-distributions: Higgs, $\eta_{c,b}$

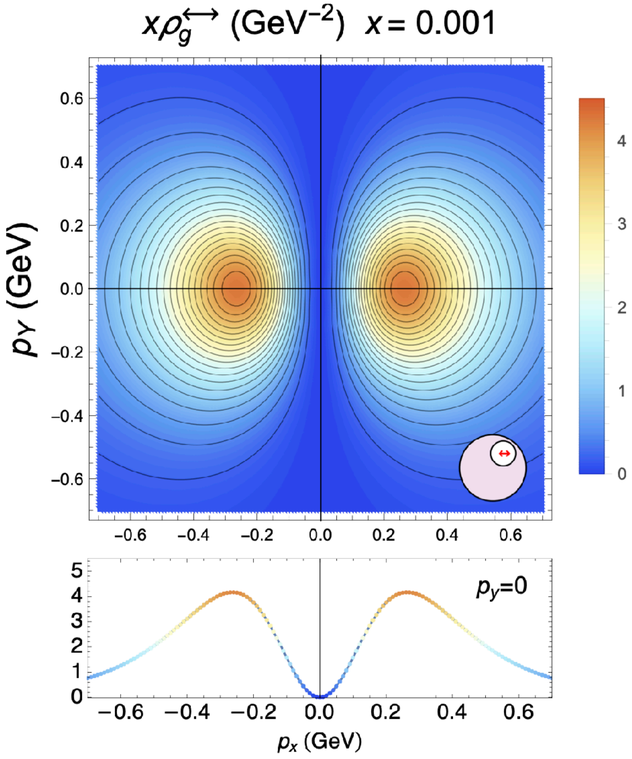
$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2 \quad \text{at low transverse momentum for (pseudo)scalar state}$$

$$\sim \mathcal{C}[\, f_1^{g/A} \; f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \; h_1^{\perp g/B} \,]$$

unpolarized gluons — **lin. polarized** gluons

NRQCD

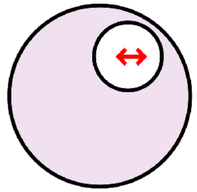
$$\frac{\text{CS}}{\text{CO}} \sim \frac{1}{v^4}$$



[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Boer-Mulders effect in unpolarized pp collisions



$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. Boer-Mulders

(Pseudo)scalar p_T-distributions: Higgs, $\eta_{c,b}$

$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2 \qquad \text{at low transverse momentum for (pseudo)scalar state}$$

$$\sim \mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$$

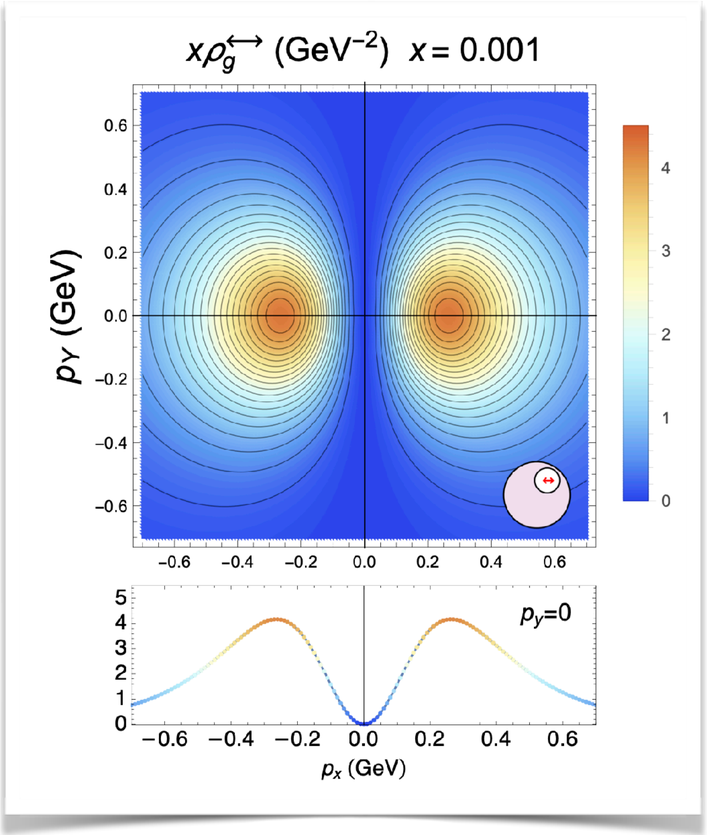
$\mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,]$: **unpolarized** gluons

$\mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$: **lin. polarized** gluons

NRQCD

$$\frac{\text{CS}}{\text{CO}} \sim \frac{1}{v^4}$$

[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

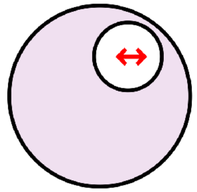


[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Model prediction at low x

$$\frac{f_1^g(x,p_T^2)}{h_1^{\perp g}(x,p_T^2)} \underset{x\to 0^+}{\sim} \text{constant}$$

Boer-Mulders effect in unpolarized pp collisions



$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. Boer-Mulders

(Pseudo)scalar p_T-distributions: Higgs, $\eta_{c,b}$

$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2 \qquad \text{at low transverse momentum for (pseudo)scalar state}$$

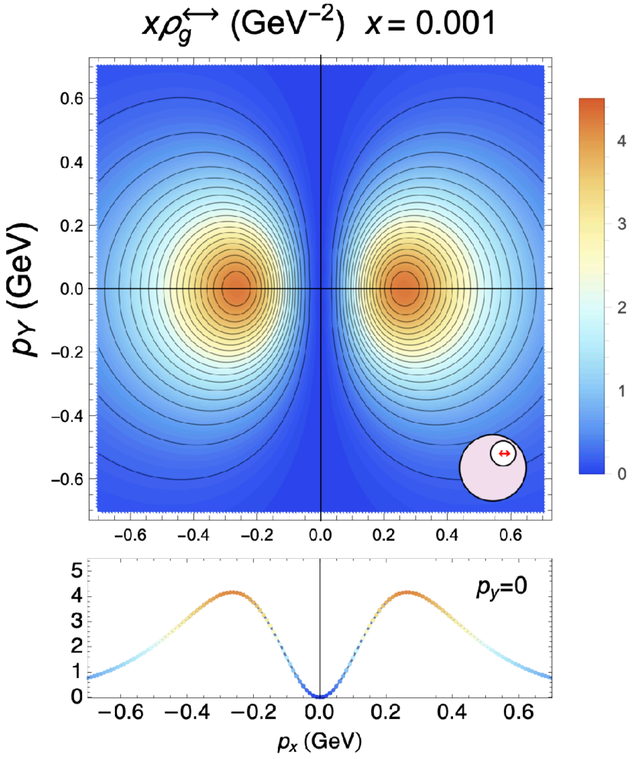
$$\sim \mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$$

$\mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,]$: **unpolarized** gluons

$\mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$: **lin. polarized** gluons

NRQCD

$$\frac{\text{CS}}{\text{CO}} \sim \frac{1}{v^4}$$



[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Model prediction at low x

$$\frac{f_1^g(x,p_T^2)}{h_1^{\perp g}(x,p_T^2)} \underset{x\to 0^+}{\sim} \text{constant}$$

BFKL regime (linear low-x evolution)

$$f_1^g(x,p_T^2) = h_1^{\perp g}(x,p_T^2) + \text{higher twist}$$

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

$$F(x,\mathbf{b};\mu,\zeta) = \sum_j \left(C_j^{(F)} \otimes F^j \right)(x,b_*;\mu_b) e^{S(b_*;\mu_b,\mu,\zeta)} e^{S_{\rm NP}(b)} F_{\rm NP}(x,b)$$

perturbative Sudakov

perturbative expansion in $\alpha_s(\mu)$

resummation of

$$L = \ln \frac{Q^2}{\mu_b^2}$$

define logarithmic ordering

slide adapted from C. Bissolotti

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

$$F(x,\mathbf{b};\mu,\zeta) = \sum_j \left(C_j^{(F)} \otimes F^j \right)(x,b_*;\mu_b) e^{S(b_*;\mu_b,\mu,\zeta)} e^{S_{\rm NP}(b)} F_{\rm NP}(x,b)$$

perturbative expansion in $\alpha_s(\mu)$

perturbative Sudakov

resummation of $L = \ln \dfrac{Q^2}{\mu_b^2}$

Model input

define logarithmic ordering

slide adapted from C. Bissolotti

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

$$F(x,\mathbf{b};\mu,\zeta) = \sum_j \left(C_j^{(F)} \otimes F^j \right)(x,b_*;\mu_b)\, e^{S(b_*;\mu_b,\mu,\zeta)}\, e^{S_{\rm NP}(b)}\, F_{\rm NP}(x,b)$$

perturbative expansion in $\alpha_s(\mu)$

perturbative Sudakov

resummation of $L = \ln \dfrac{Q^2}{\mu_b^2}$

Model input

define logarithmic ordering

slide adapted from C. Bissolotti

$$f_1(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(f_1)} \otimes f_1^j = \left[1 + \mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

$$F(x,\mathbf{b};\mu,\zeta) = \sum_j \left(C_j^{(F)} \otimes F^j \right)(x,b_*;\mu_b)\, e^{S(b_*;\mu_b,\mu,\zeta)}\, e^{S_{\rm NP}(b)}\, F_{\rm NP}(x,b)$$

perturbative expansion in $\alpha_s(\mu)$

perturbative Sudakov

resummation of $L = \ln \dfrac{Q^2}{\mu_b^2}$

Model input

define logarithmic ordering

slide adapted from C. Bissolotti

$$f_1(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(f_1)} \otimes f_1^j = \left[1+\mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

$$h_1^\perp(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(h_1^\perp)} \otimes f_1^j = \left[\mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

¿ Suppression of genuine NP effects ?

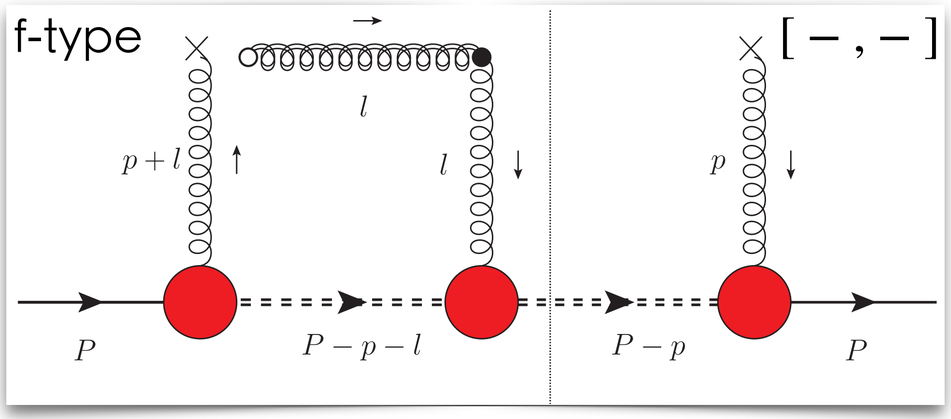
T-odd gluon TMDs in a spectator model

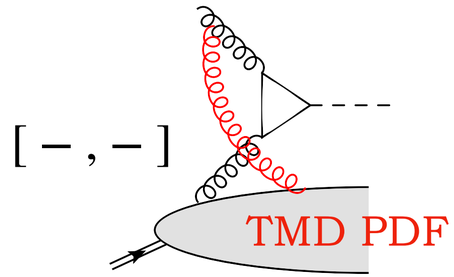
- No residual gluon-spectator interaction at tree level
- Interference with one-gluon exchange (eikonal)

T-odd gluon TMDs in a spectator model

- No residual gluon-spectator interaction at tree level
- Interference with one-gluon exchange (eikonal)

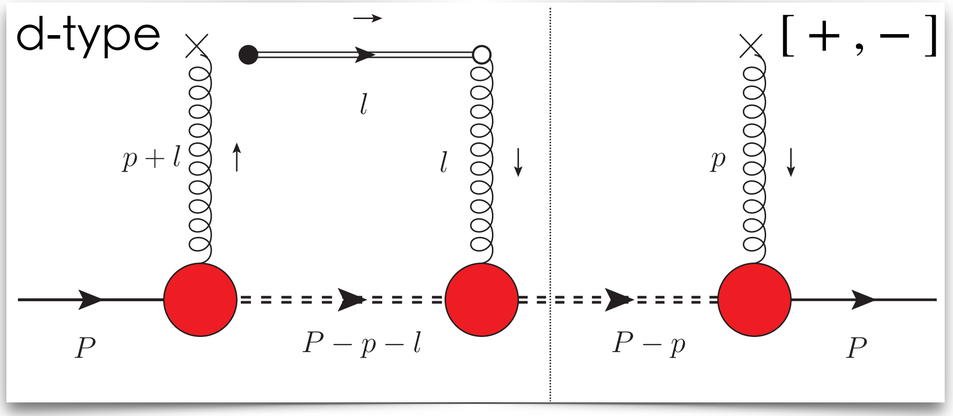
$gg \to H$





f-type (WW) structure

$qg \to \gamma^{(*)}$-jet

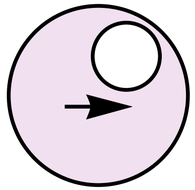


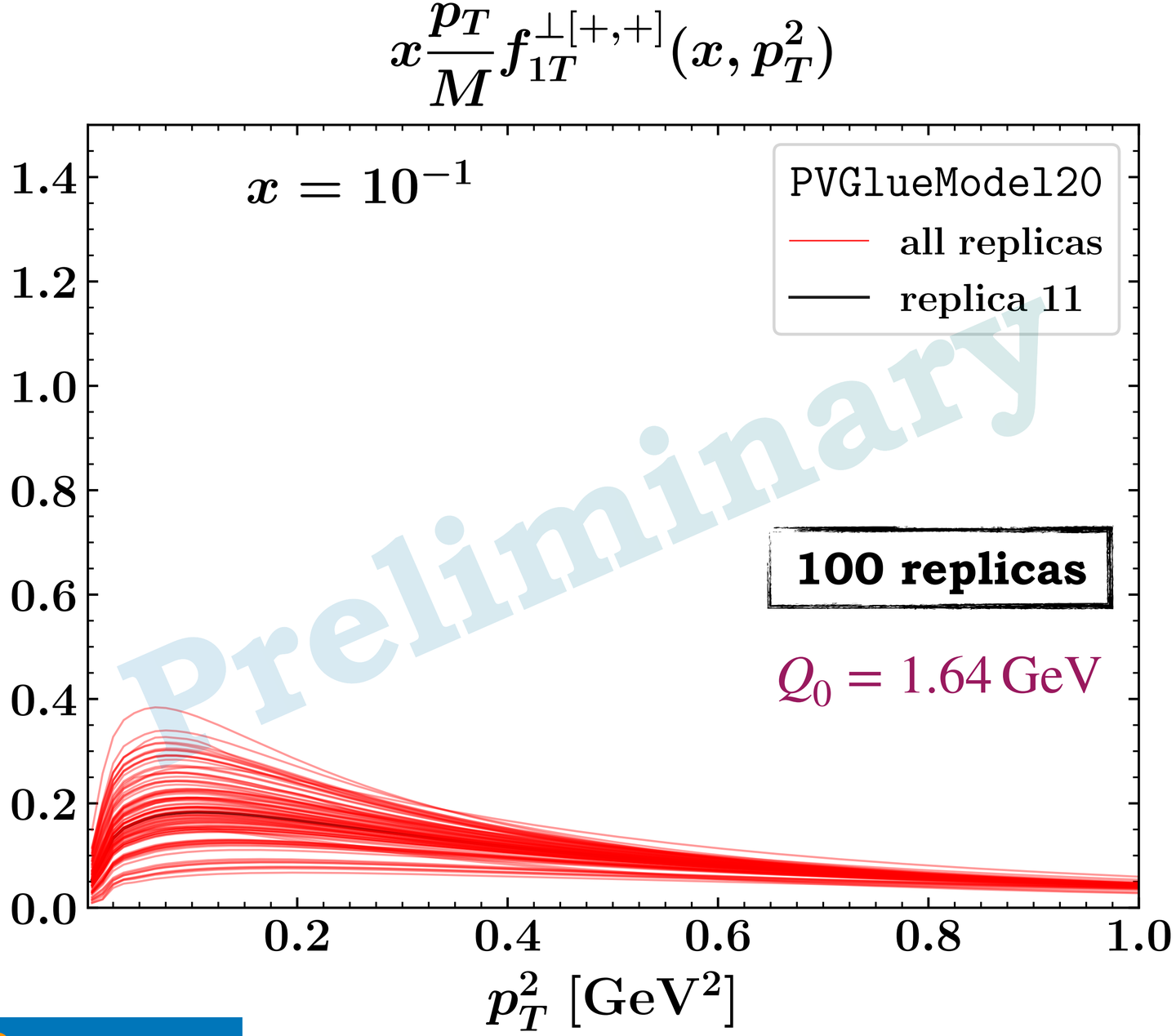
d-type (dipole) structure

(Sivers & linearity) 🔗🔗 [A. Bacchetta, F.G.C., M. Radici, EPS-HEP, PANIC (2021)]

Preliminary results for Sivers

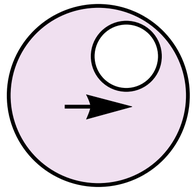
[A. Bacchetta, F.G.C., M. Radici (in preparation)]

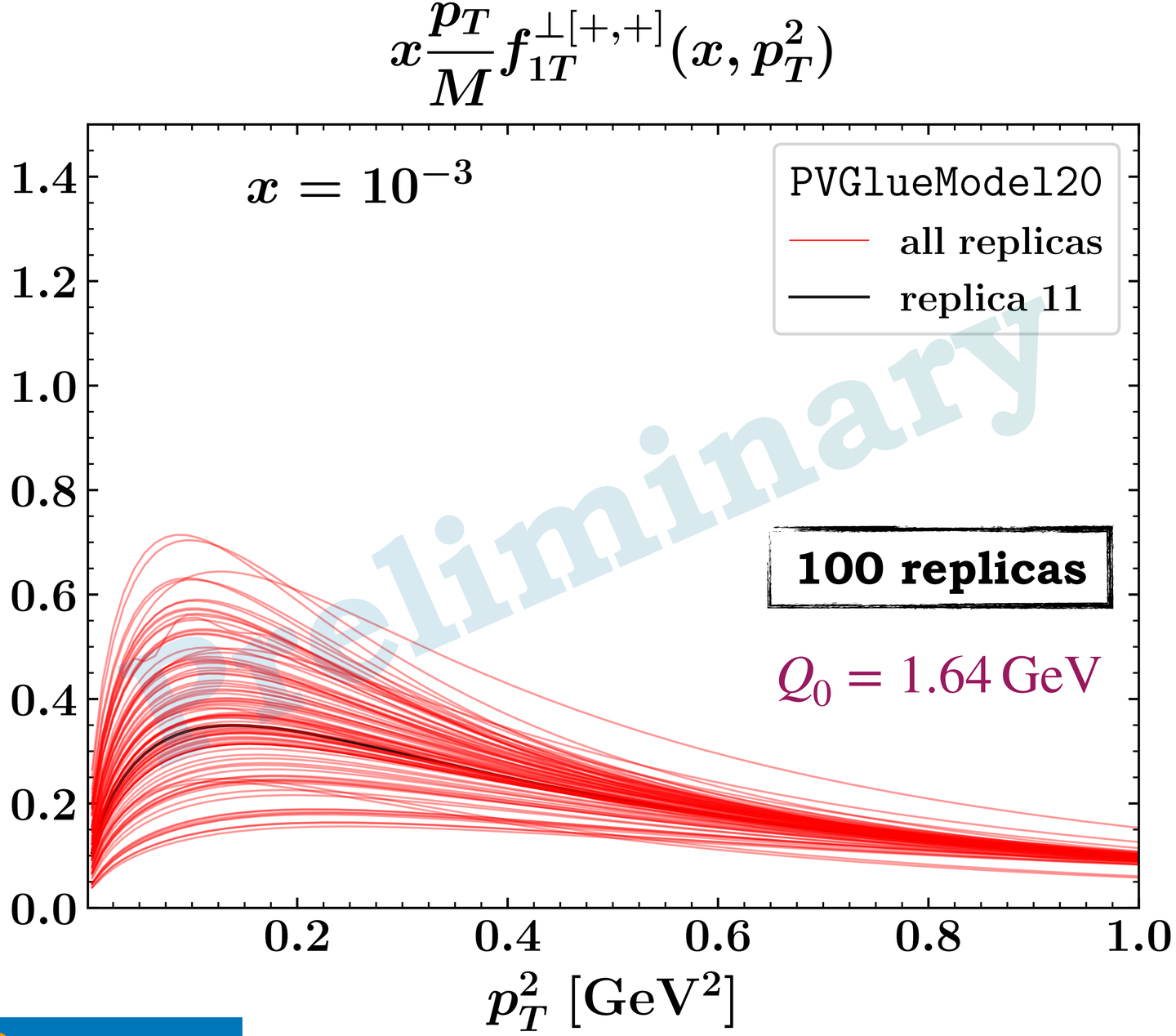




Preliminary results for Sivers

[A. Bacchetta, F.G.C., M. Radici (in preparation)]

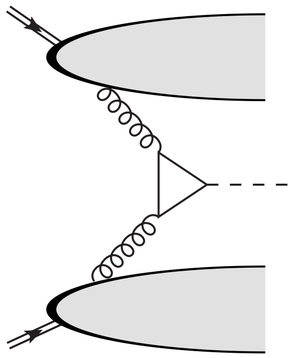




3. Accessing gluon TMDs @LHC

Golden channels for gluon TMD PDFs @LHC

Higgs in gluon fusion

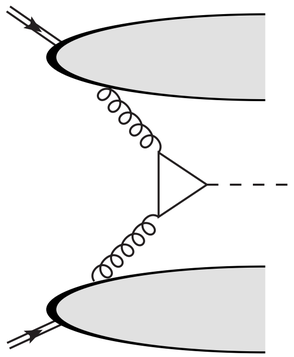


✓ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

Golden channels for gluon TMD PDFs @LHC

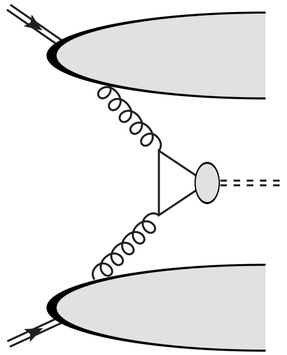
Higgs in gluon fusion



✓ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

Single quarkonium



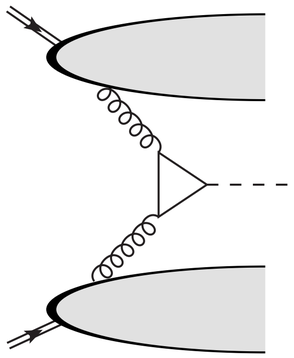
✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$

TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @FT-LHC

Golden channels for gluon TMD PDFs @LHC

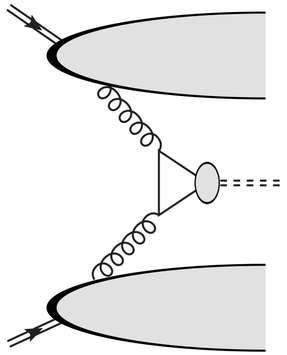
Higgs in gluon fusion



✓ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

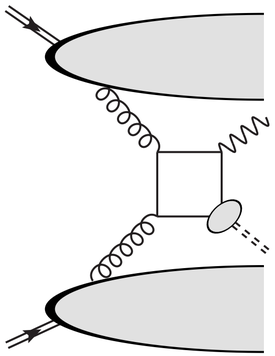
Single quarkonium



✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @FT-LHC

$J/\psi + \gamma^{(*)}$

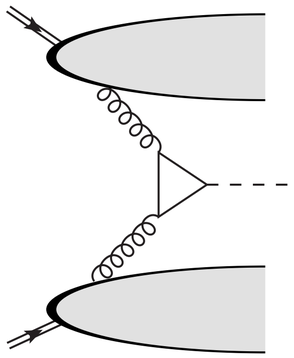


¡! Color entanglement
Potential TMD violation (CO)
Back-to-back suppresses CO

¡! Currently no low-p_T data
Possible studies @HL-LHC

Golden channels for gluon TMD PDFs @LHC

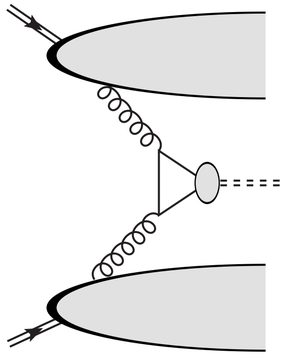
Higgs in gluon fusion



✓ No color entanglement
TMD factorization

¡! Large low-p_T bin @CMS
More data @HL-LHC

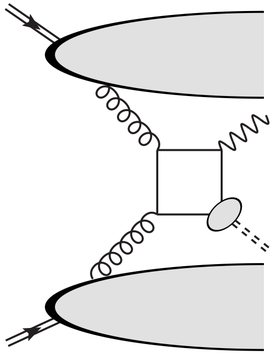
Single quarkonium



✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$
TMD factorization
C-parity selection rules

¡! Large-p_T data @LHCb
More data @FT-LHC

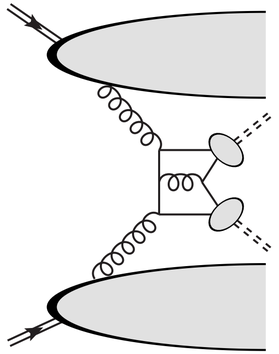
$J/\psi + \gamma^{(*)}$



¡! Color entanglement
Potential TMD violation (CO)
Back-to-back suppresses CO

¡! Currently no low-p_T data
Possible studies @HL-LHC

$J/\psi + J/\psi$



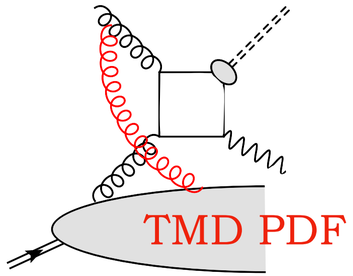
✓ No color entanglement
TMD factorization (CSM)

✓ Low-p_T data @LHCb
Opportunities @HL- & @FT-LHC

Quarkonia: assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

Sivers	$e\,p^{\uparrow} \to e'\,Q\,\overline{Q}\,X$ $e\,p^{\uparrow} \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[-,-]}$	√
$f_{1T}^{\perp\,g\,[+,-]}$	×

(overview) [D. Boer (2017)]

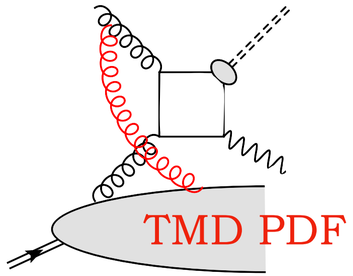
Boer-Mulders	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$
$h_1^{\perp\,g\,[-,-]}$(WW)	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×

Challenges

Quarkonia: assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

Sivers	$e\,p^{\uparrow} \to e'\,Q\,\overline{Q}\,X$ $e\,p^{\uparrow} \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[-,-]}$	√
$f_{1T}^{\perp\,g\,[+,-]}$	×

(overview) [D. Boer (2017)]

Boer-Mulders	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$
$h_1^{\perp\,g\,[-,-]}$(WW)	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×

$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \sim \mathcal{C}[\, f_1^{g/A}\ f_1^{g/B}\,] \pm \mathcal{C}[\, h_1^{\perp g/A}\ h_1^{\perp g/B}\,]$$

at low transverse momentum for (pseudo)scalar state

unpolarized gluons

lin. polarized gluons

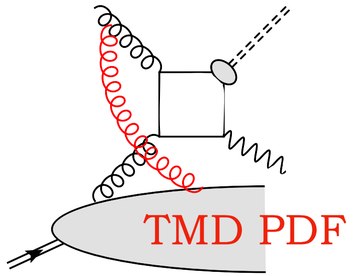
(factorization) [M. García Echevarría (2019)]
(pheno) [A. Bacchetta, F.G.C., J.-P. Lansberg, M. Radici, et al. (in progress)]

Challenges

Quarkonia: assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

(overview) [D. Boer (2017)]

Sivers	$e\,p^{\uparrow} \to e'\,Q\,\overline{Q}\,X$ $e\,p^{\uparrow} \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[-,-]}$	√
$f_{1T}^{\perp\,g\,[+,-]}$	×

Boer-Mulders	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$
$h_1^{\perp\,g\,[-,-]}$(WW)	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×

$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \sim \mathcal{C}[\, f_1^{g/A}\ f_1^{g/B}\,] \pm \mathcal{C}[\, h_1^{\perp g/A}\ h_1^{\perp g/B}\,]$$

at low transverse momentum for (pseudo)scalar state

unpolarized gluons

lin. polarized gluons

(factorization) [M. García Echevarría (2019)]

(pheno) [A. Bacchetta, F.G.C., J.-P. Lansberg, M. Radici, et al. (in progress)]

Challenges

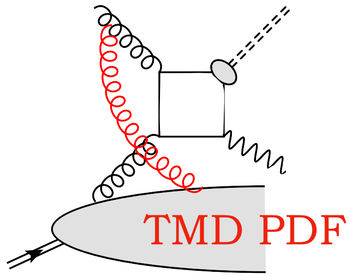
Precision TMD ⇔ production mechanism(s)

(production mechanisms, LHC) [J.-P. Lansberg (2020)]

Quarkonia: assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

(overview) [D. Boer (2017)]

Sivers	$e p^{\uparrow} \to e' Q \overline{Q} X$ $e p^{\uparrow} \to e' j_1 j_2 X$
$f_{1T}^{\perp g\,[-,-]}$	√
$f_{1T}^{\perp g\,[+,-]}$	×

Boer-Mulders	$e p \to e' Q \overline{Q} X$ $e p \to e' j_1 j_2 X$
$h_1^{\perp g\,[-,-]}$(WW)	√
$h_1^{\perp g\,[+,-]}$ (DP)	×

$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \quad \text{(at low transverse momentum for (pseudo)scalar state)}$$

$$\sim \mathcal{C}[\, f_1^{g/A}\ f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A}\ h_1^{\perp g/B} \,]$$

unpolarized gluons — **lin. polarized** gluons

(factorization) [M. García Echevarría (2019)]

(pheno) [A. Bacchetta, F.G.C., J.-P. Lansberg, M. Radici, et al. (in progress)]

Challenges

Precision TMD ⇔ production mechanism(s)

(production mechanisms, LHC) [J.-P. Lansberg (2020)]

Color Evaporation Model

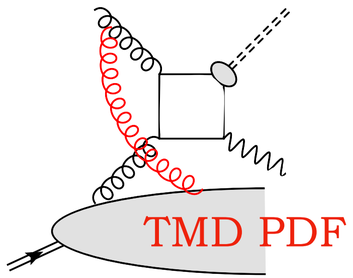
$(Q\bar{Q})$ decorrelated from onium, semi-soft gluon emissions

Overshoots data at large p_T

Quarkonia: assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

(overview) [D. Boer (2017)]

Sivers	$e p^{\uparrow} \to e' Q \overline{Q} X$ $e p^{\uparrow} \to e' j_1 j_2 X$
$f_{1T}^{\perp g\,[-,-]}$	√
$f_{1T}^{\perp g\,[+,-]}$	×

Boer-Mulders	$e p \to e' Q \overline{Q} X$ $e p \to e' j_1 j_2 X$
$h_1^{\perp g\,[-,-]}$(WW)	√
$h_1^{\perp g\,[+,-]}$ (DP)	×

$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \quad \text{(at low transverse momentum for (pseudo)scalar state)}$$

$$\sim \mathcal{C}[\, f_1^{g/A}\ f_1^{g/B}\,] \pm \mathcal{C}[\, h_1^{\perp g/A}\ h_1^{\perp g/B}\,]$$

unpolarized gluons — **lin. polarized** gluons

(factorization) [M. García Echevarría (2019)]

(pheno) [A. Bacchetta, F.G.C., J.-P. Lansberg, M. Radici, et al. (in progress)]

Challenges

Precision TMD ⇔ production mechanism(s)

(production mechanisms, LHC) [J.-P. Lansberg (2020)]

Color Evaporation Model

$(Q\bar{Q})$ decorrelated from onium, semi-soft gluon emissions

Overshoots data at large p_T

Color Singlet Model

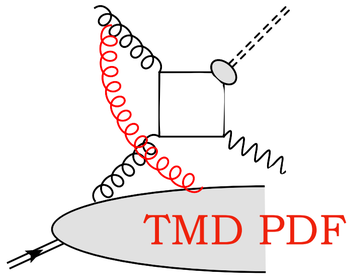
$(Q\bar{Q})$ to onium, no gluon emissions

Fails at large p_T, improves at NLO

Quarkonia: assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

(overview) [D. Boer (2017)]

Sivers	$e p^{\uparrow} \to e' Q \overline{Q} X$ $e p^{\uparrow} \to e' j_1 j_2 X$
$f_{1T}^{\perp g\,[-,-]}$	√
$f_{1T}^{\perp g\,[+,-]}$	×

Boer-Mulders	$e p \to e' Q \overline{Q} X$ $e p \to e' j_1 j_2 X$
$h_1^{\perp g\,[-,-]}$(WW)	√
$h_1^{\perp g\,[+,-]}$ (DP)	×

$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \sim \mathcal{C}[\, f_1^{g/A}\ f_1^{g/B}\,] \pm \mathcal{C}[\, h_1^{\perp g/A}\ h_1^{\perp g/B}\,]$$

at low transverse momentum for (pseudo)scalar state

unpolarized gluons

lin. polarized gluons

(factorization) [M. García Echevarría (2019)]

(pheno) [A. Bacchetta, F.G.C., J.-P. Lansberg, M. Radici, et al. (in progress)]

Challenges

Precision TMD ⇔ production mechanism(s)

(production mechanisms, LHC) [J.-P. Lansberg (2020)]

Color Evaporation Model

$(Q\bar{Q})$ decorrelated from onium, semi-soft gluon emissions

Overshoots data at large p_T

Color Singlet Model

$(Q\bar{Q})$ to onium, no gluon emissions

Fails at large p_T, improves at NLO

NRQCD and Color Octet

Higher Fock states, soft gluon emissions

Problems at low p_T, fails on polarization

Quarkonia: a path toward precision

TMD & shape functions

NRQCD ⇒ double expansion: $\alpha_s \oplus v$

NRQCD ⇒ $\mathrm{d}\sigma(|\mathcal{Q}\rangle) \propto \mathscr{H} \otimes \mathrm{LDME}$

$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^1S_0^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3D_J^{(1,8)}gg]\rangle + \ldots.$$

S-wave quarkonium wave function

Quarkonia: a path toward precision

TMD & shape functions

- NRQCD ⇒ double expansion: $\alpha_s \oplus v$
- NRQCD ⇒ $\mathrm{d}\sigma(|\mathcal{Q}\rangle) \propto \mathscr{H} \otimes \mathrm{LDME}$

$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^1S_0^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3D_J^{(1,8)}gg]\rangle + \dots .$$

S-wave quarkonium wave function

- TMD ⇒ from LDMEs to shape functions (ShFs)
- 2 mechanisms: bound state + soft-gluon

(factorization) 🔗 [M. Garcia Echevarria (2019)]
(SCET) 🔗 [S. Fleming, Y. Makris, T. Mehen (2020)]
(unpol. J/ψ) 🔗 [D. Boer, U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2020)]
(pol. J/ψ) 🔗 [D. Boer, U. D'Alesio, L. Maxia, F. Murgia, C. Pisano, R. Sangem (2022)]

Quarkonia: a path toward precision

TMD & shape functions

NRQCD ⇒ double expansion: $\alpha_s \oplus v$

NRQCD ⇒ $\mathrm{d}\sigma(|\mathcal{Q}\rangle) \propto \mathscr{H} \otimes \mathrm{LDME}$

$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^1S_0^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3D_J^{(1,8)}gg]\rangle + \dots .$$

S-wave quarkonium wave function

TMD ⇒ from LDMEs to shape functions (ShFs)

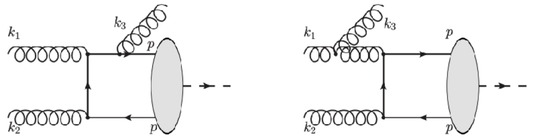
2 mechanisms: bound state + soft-gluon

(factorization) [M. Garcia Echevarria (2019)]
(SCET) [S. Fleming, Y. Makris, T. Mehen (2020)]
(unpol. J/ψ) [D. Boer, U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2020)]
(pol. J/ψ) [D. Boer, U. D'Alesio, L. Maxia, F. Murgia, C. Pisano, R. Sangem (2022)]

NLO collinear negative distributions

Recap of NLO calculation & origin of negative numbers

$\hat{s}$-dependence only present in real corrections $(g(k_1) + g(k_2) \to \eta_Q(P) + g(k_3))$



- Real-emission corrections are perfect square ($|\mathcal{M}^{(\mathrm{Real})}|^2$) and thus positive
- IR singularities in the real emissions only reveal themselves after taking the phase-space integration: $\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1}(z) = \int d\hat{t}\, \frac{\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1}}{d\hat{t}}$

$$\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1}(z) = -\frac{1}{\epsilon_{\mathrm{IR}}}\frac{\alpha_s}{\pi}\left(\frac{4\pi\mu_R^2}{M_Q^2}\right)^{\epsilon}\Gamma(1+\epsilon)\hat{\sigma}_0^{\mathrm{LO}} z P_{gg}(z) + 2C_A\frac{\alpha_s}{\pi}\hat{\sigma}_0^{\mathrm{LO}}\overline{A}_{gg}(z)$$

- For $\epsilon_{\mathrm{IR}} \to 0^-$, $\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1} \geq 0$ for all $0 \leq z < 1$ as expected
- Initial-state collinear divergences are absorbed/subtracted into PDF via *process-independent* Altarelli-Parisi counterterm in $\overline{\mathrm{MS}}$-scheme

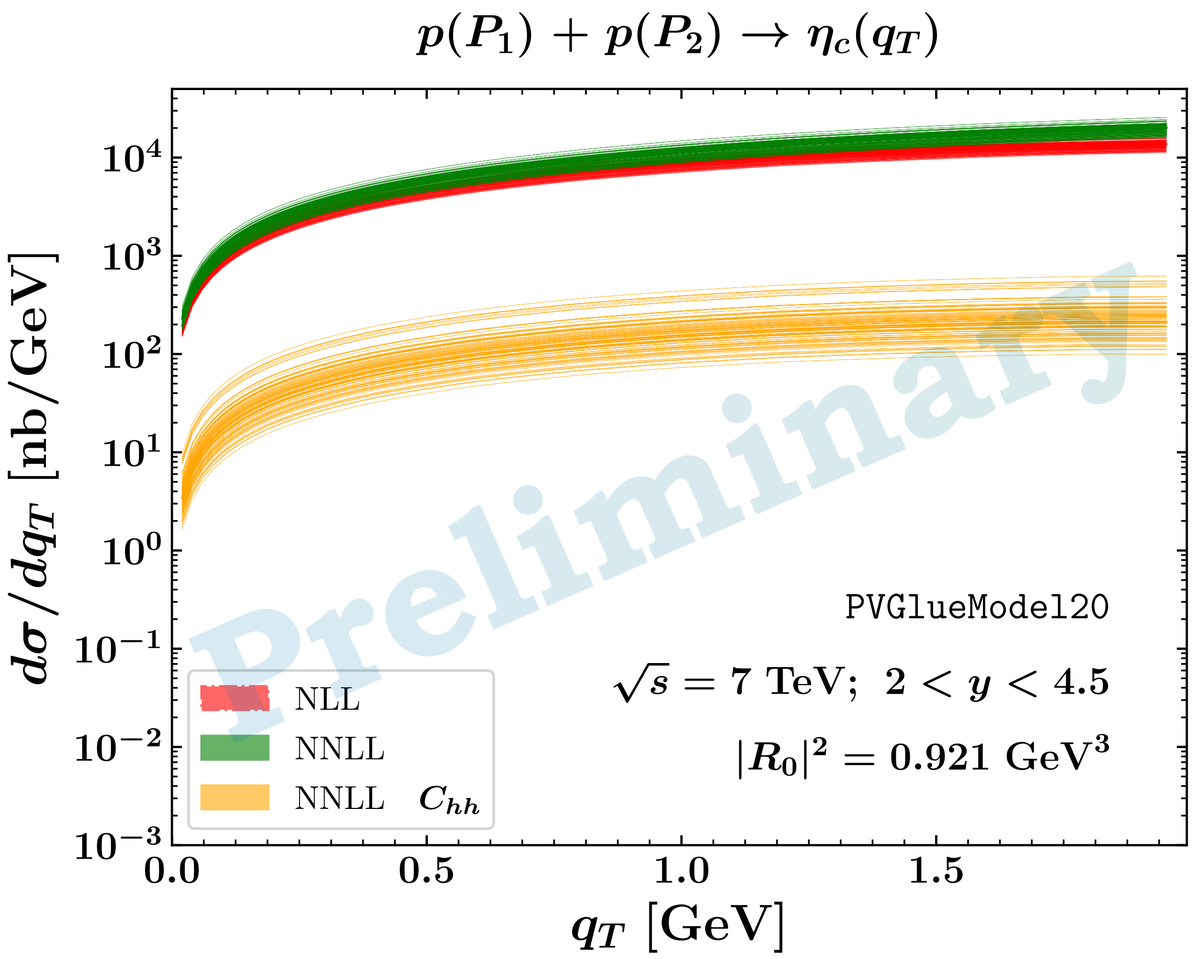
$$\overline{\sigma}_{gg}^{\mathrm{AP\text{-}CT}}(z) = \frac{1}{\epsilon_{\mathrm{IR}}}\frac{\alpha_s}{\pi}\left(\frac{4\pi\mu_R^2}{\mu_F^2}\right)^{\epsilon}\Gamma(1+\epsilon)\hat{\sigma}_0^{\mathrm{LO}} z P_{gg}(z)$$

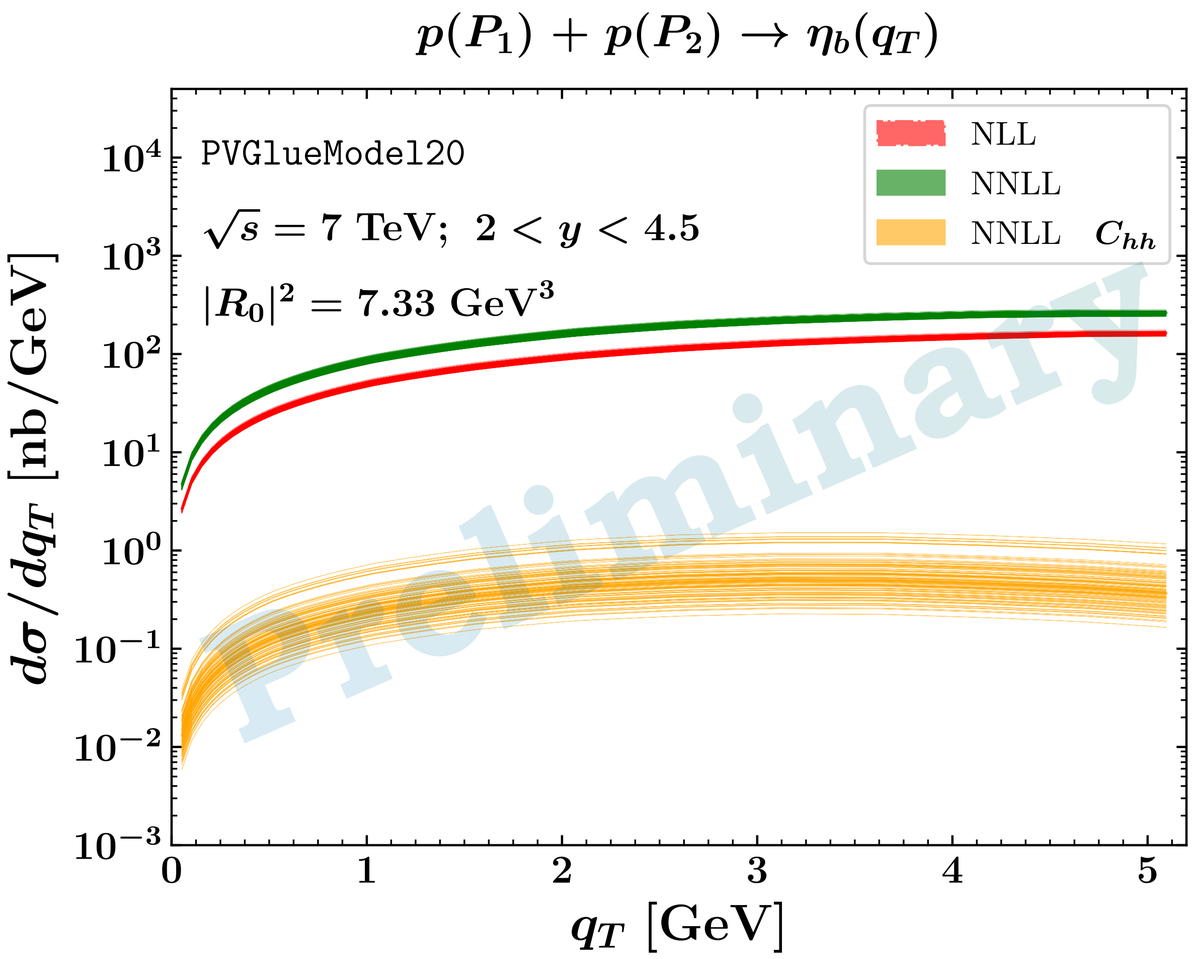
J.P. Lansberg (IJCLab) | Quarkonium production | September 28, 2022 | 5 / 20

(this slide) [Diffraction 2022's talk by Jean-Philippe Lansberg]
(this session) [Today's talk by Maxim Nefedov]
(collinear/HEF matching) [J.-P. Lansberg, M. Nefedov, M.A. Ozcelik (2022)]
(scale fixing) [J.-P. Lansberg and M. Ozcelik (2021)]
(scale fixing) [A. Colpani Serri et al. (2021)]

$\eta_{c,b}$ production @ 7TeV LHCb

Perturbative scales fixed, NP-evolution parameters fixed, TMD 100-replica analysis, NRQCD w/o ShFs



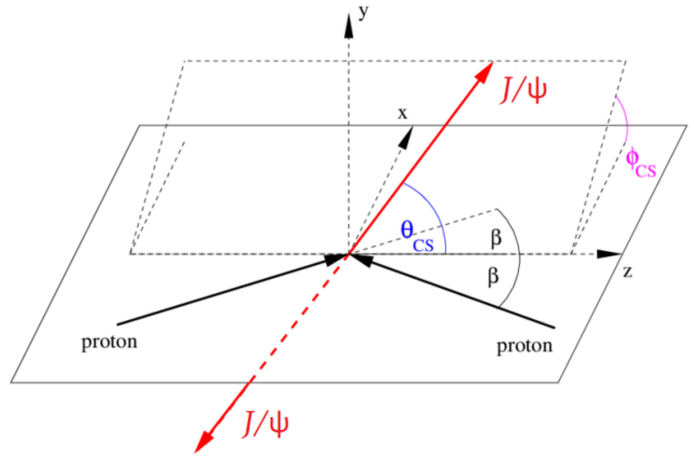


[A. Bacchetta, F.G.C., M.G. Echevarria, J.-P. Lansberg, M. Ozcelik, M. Radici, A. Signori (in preparation)]

Double J/ψ production @(HL-)LHC

- More spin asymmetries, measurable @HL-LHC

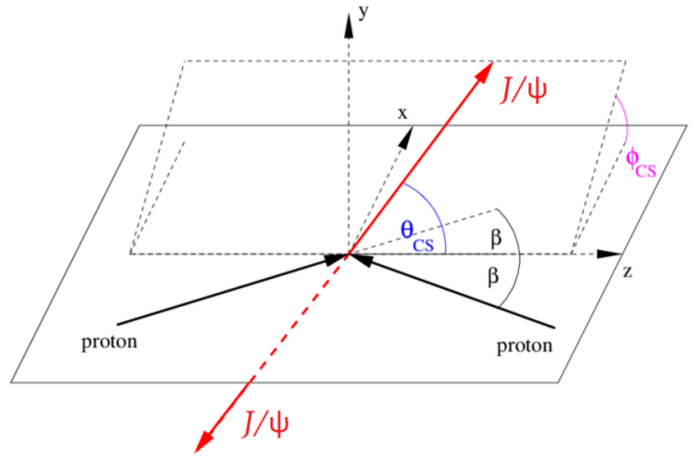
$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{QQ}\mathrm{d}Y_{QQ}\mathrm{d}^2\boldsymbol{P}_{QQ_T}\mathrm{d}\Omega} = \frac{\sqrt{Q^2-4M_Q^2}}{(2\pi)^2 8s\,Q^2}\Big\{F_1\,C\Big[f_1^g f_1^g\Big] + F_2\,C\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big] + \cos 2\phi_{\mathrm{CS}}\Big(F_3 C\Big[w_3 f_1^g h_1^{\perp g}\Big] + F_3' C\Big[w_3' h_1^{\perp g} f_1^g\Big]\Big) + \cos 4\phi_{\mathrm{CS}} F_4 C\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big]\Big\},$$



Double J/ψ production @(HL-)LHC

More spin asymmetries, measurable @HL-LHC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{QQ}\mathrm{d}Y_{QQ}\mathrm{d}^2\boldsymbol{P}_{QQ_T}\mathrm{d}\Omega} = \frac{\sqrt{Q^2-4M_Q^2}}{(2\pi)^2 8s\,Q^2}\Big\{F_1\,C\Big[f_1^g f_1^g\Big] + F_2\,C\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big] + \cos 2\phi_{\mathrm{CS}}\Big(F_3 C\Big[w_3 f_1^g h_1^{\perp g}\Big] + F_3' C\Big[w_3' h_1^{\perp g} f_1^g\Big]\Big) + \cos 4\phi_{\mathrm{CS}} F_4 C\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big]\Big\},$$



TMD Models

[J.-P. Lansberg et al. (2018)]

$$f_1^g(x,\boldsymbol{k}_T^2,\mu) = \frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2\rangle}\Big)$$

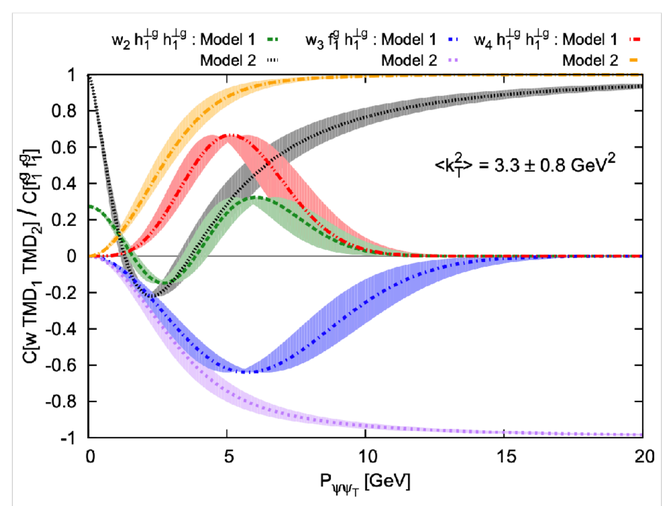
¿ $f_1^g / h_1^{\perp g}\,(p_T \to 0)$? $\quad\Rightarrow\quad |h_1^{\perp g}| \le f_1^g$

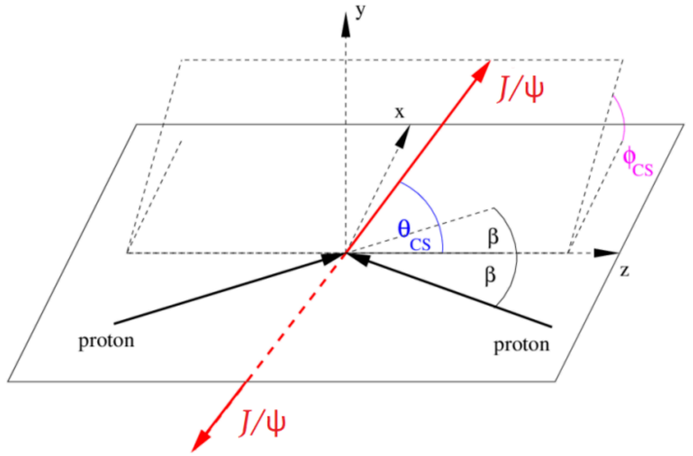
$$h_1^{\perp g}(x,\boldsymbol{k}_T^2,\mu) = \frac{2M_p^2}{\langle k_T^2\rangle}\frac{(1-r)}{r}\frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(1-\frac{\boldsymbol{k}_T^2}{r\langle k_T^2\rangle}\Big)$$

Double J/ψ production @(HL-)LHC

More spin asymmetries, measurable @HL-LHC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{QQ}\mathrm{d}Y_{QQ}\mathrm{d}^2\boldsymbol{P}_{QQ_T}\mathrm{d}\Omega} = \frac{\sqrt{Q^2-4M_Q^2}}{(2\pi)^2 8s\,Q^2}\Big\{F_1\,C\Big[f_1^g f_1^g\Big] + F_2\,C\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big] + \cos 2\phi_{\mathrm{CS}}\Big(F_3 C\Big[w_3 f_1^g h_1^{\perp g}\Big] + F_3' C\Big[w_3' h_1^{\perp g} f_1^g\Big]\Big) + \cos 4\phi_{\mathrm{CS}} F_4 C\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big]\Big\},$$





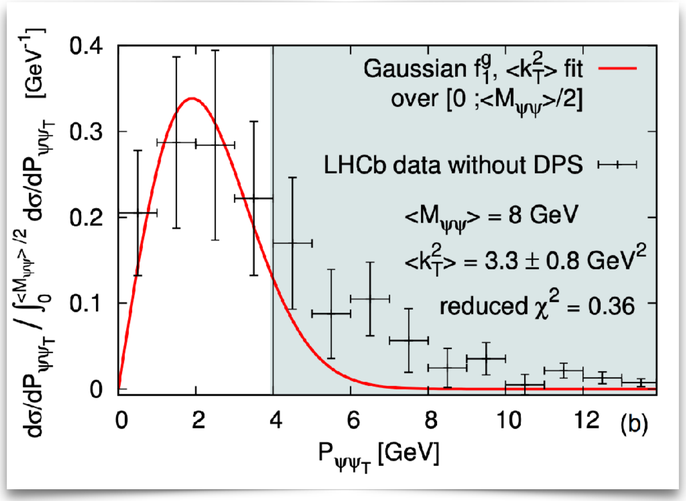
TMD Models

[J.-P. Lansberg et al. (2018)]

$$f_1^g(x,\boldsymbol{k}_T^2,\mu) = \frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2\rangle}\Big)$$

¿ $f_1^g / h_1^{\perp g}(p_T \to 0)$? $\Rightarrow$ $|h_1^{\perp g}| \le f_1^g$

$$h_1^{\perp g}(x,\boldsymbol{k}_T^2,\mu) = \frac{2M_p^2}{\langle k_T^2\rangle}\frac{(1-r)}{r}\frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(1-\frac{\boldsymbol{k}_T^2}{r\langle k_T^2\rangle}\Big)$$

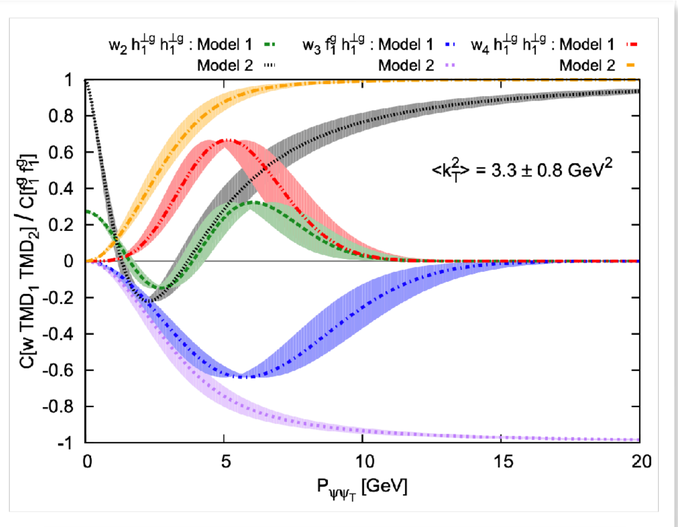


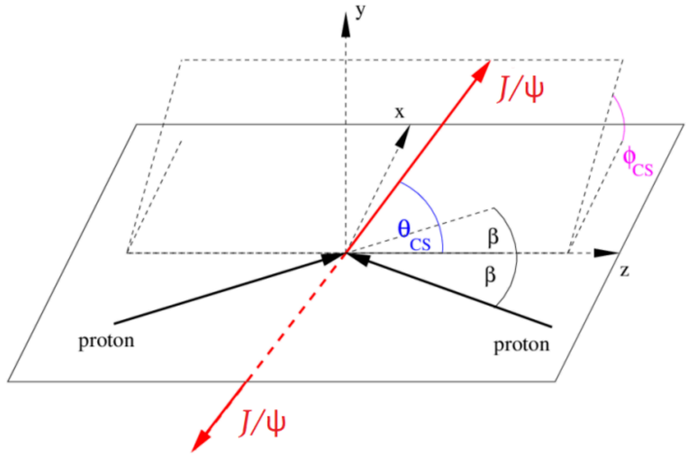
[Model-dependent fit on 13 TeV LHCb data]

Double J/ψ production @(HL-)LHC

More spin asymmetries, measurable @HL-LHC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{QQ}\mathrm{d}Y_{QQ}\mathrm{d}^2\boldsymbol{P}_{QQ_T}\mathrm{d}\Omega} = \frac{\sqrt{Q^2-4M_Q^2}}{(2\pi)^2 8s\,Q^2}\Big\{F_1\,C\Big[f_1^g f_1^g\Big] + F_2\,C\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big] + \cos 2\phi_{\mathrm{CS}}\Big(F_3 C\Big[w_3 f_1^g h_1^{\perp g}\Big] + F_3' C\Big[w_3' h_1^{\perp g} f_1^g\Big]\Big) + \cos 4\phi_{\mathrm{CS}} F_4 C\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big]\Big\},$$





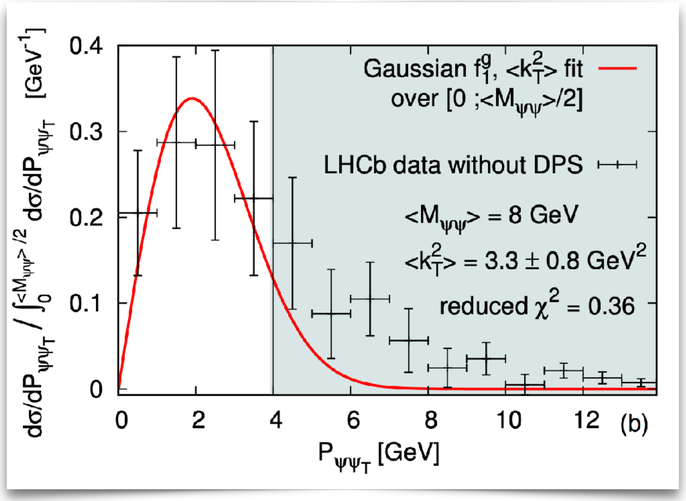
TMD Models

[J.-P. Lansberg et al. (2018)]

$$f_1^g(x,\boldsymbol{k}_T^2,\mu) = \frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2\rangle}\Big)$$

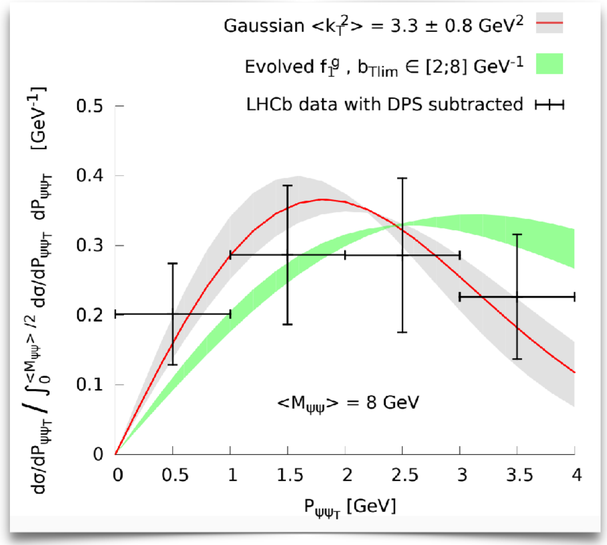
¿ $f_1^g / h_1^{\perp g}(p_T \to 0)$? $\Rightarrow$ $|h_1^{\perp g}| \le f_1^g$

$$h_1^{\perp g}(x,\boldsymbol{k}_T^2,\mu) = \frac{2M_p^2}{\langle k_T^2\rangle}\frac{(1-r)}{r}\frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(1-\frac{\boldsymbol{k}_T^2}{r\langle k_T^2\rangle}\Big)$$



[Model-dependent fit on 13 TeV LHCb data]

NP + TM resummation



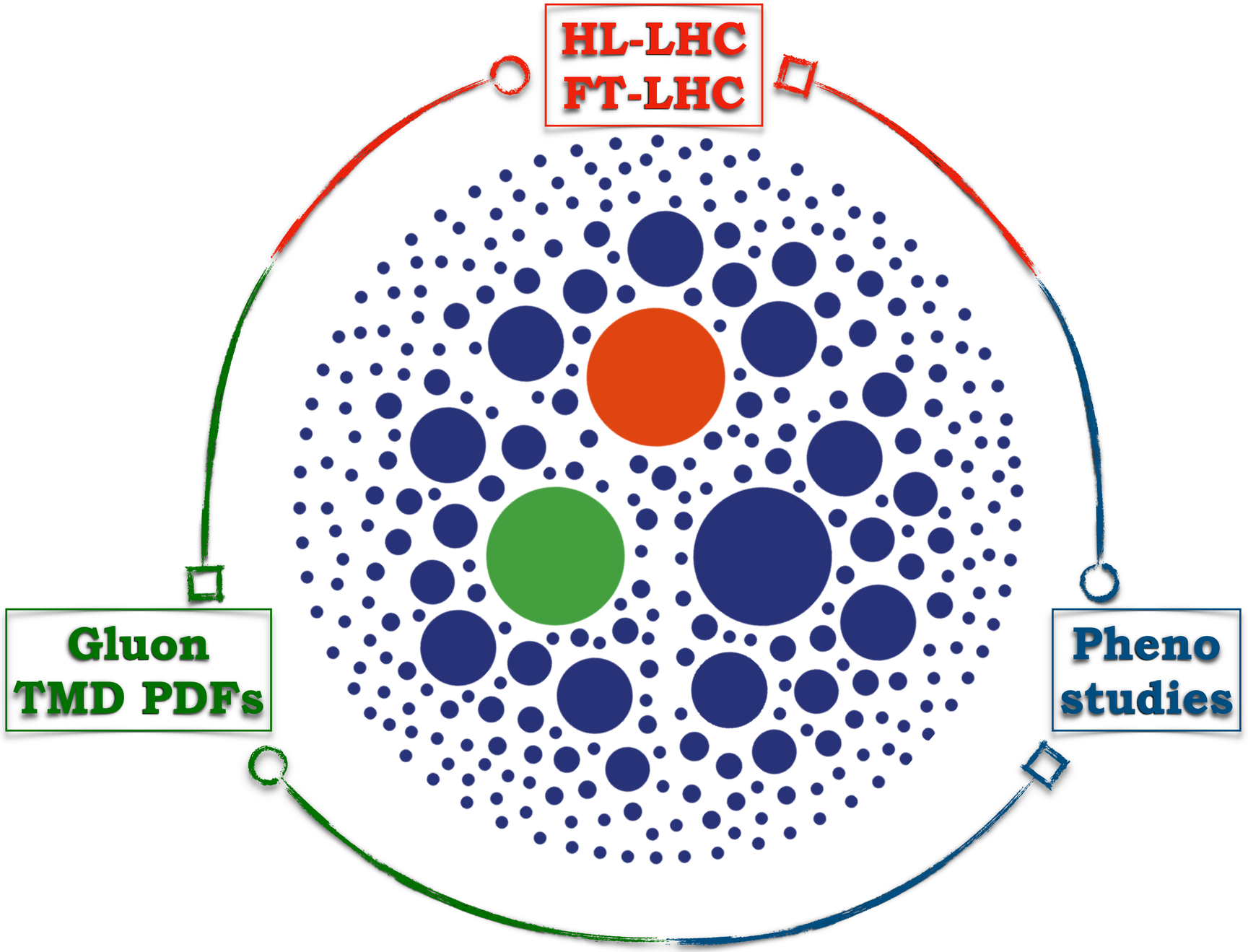
[F. Scarpa et al. (2020)]

(MC) [V. Kartvelishvili, D. Hagan (in progress)]

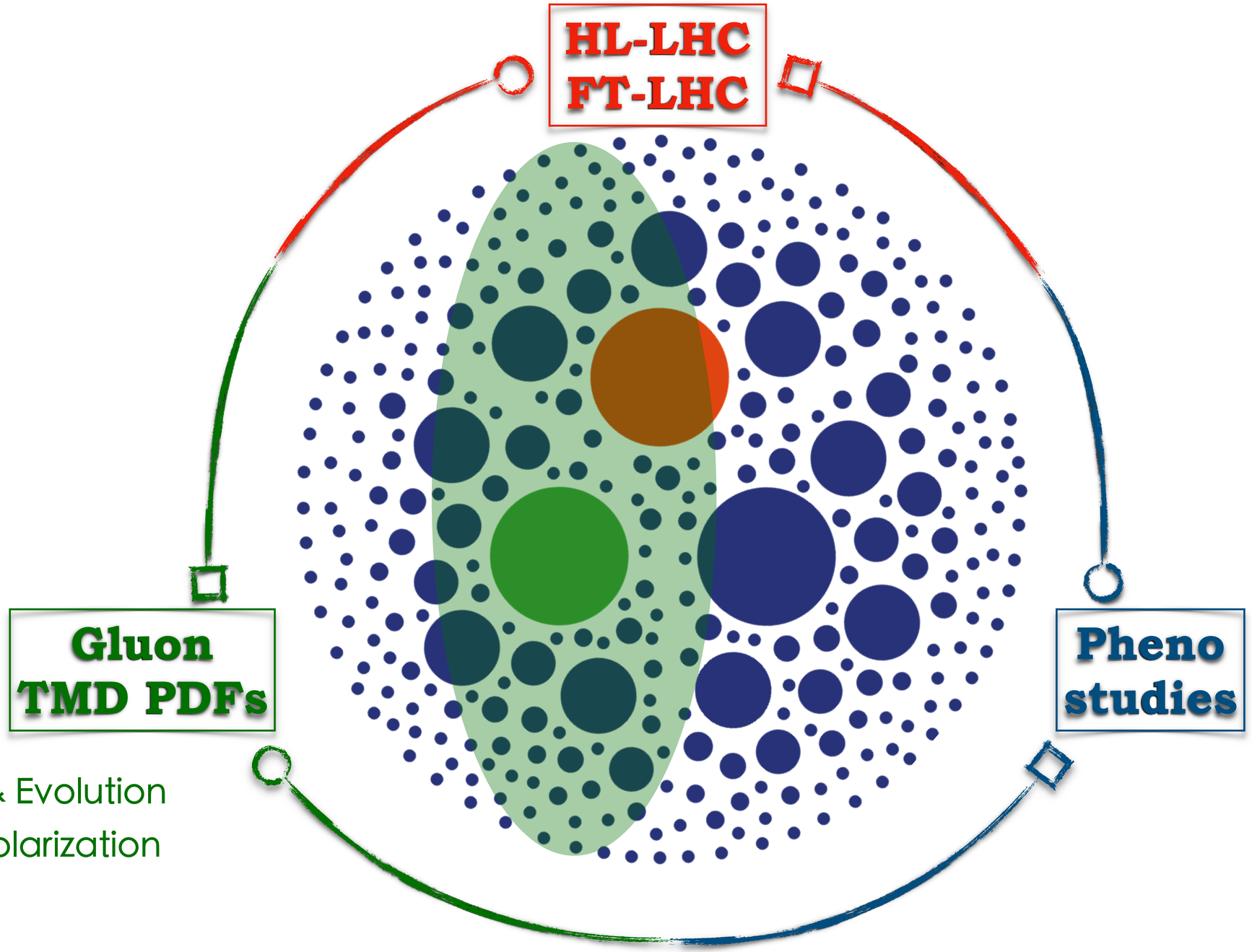
Gluon TMD PDFs @LHC: a win-win strategy

- Onia & Higgs as Tools ⇒ 3D proton imaging via gluon TMD PDFs
- Gluon TMDs as Tools ⇒ unveil onium production mechamisms

Gluon TMD PDFs @LHC: a win-win strategy



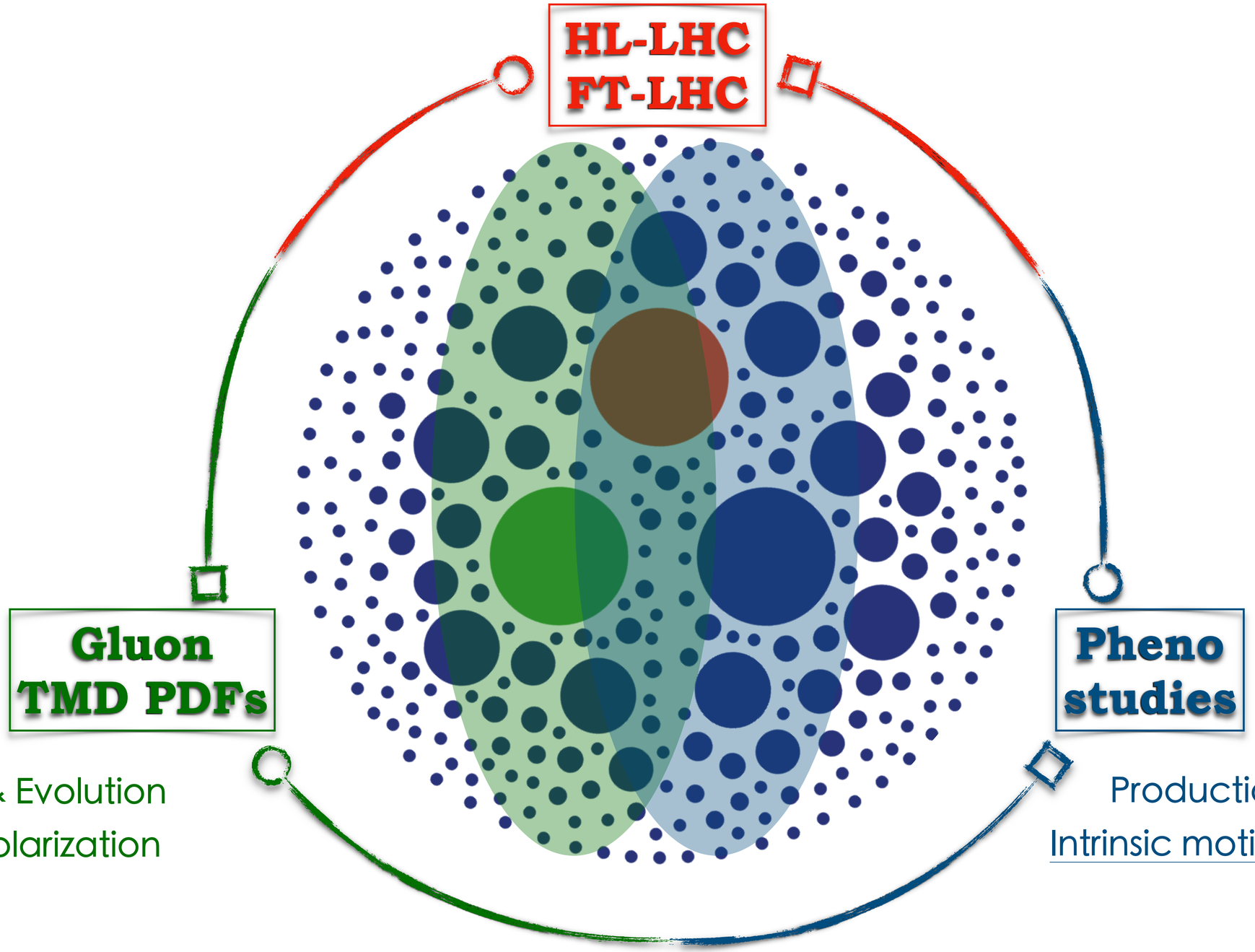
Gluon TMD PDFs @LHC: a win-win strategy



Models & Evolution

Linear polarization

Gluon TMD PDFs @LHC: a win-win strategy



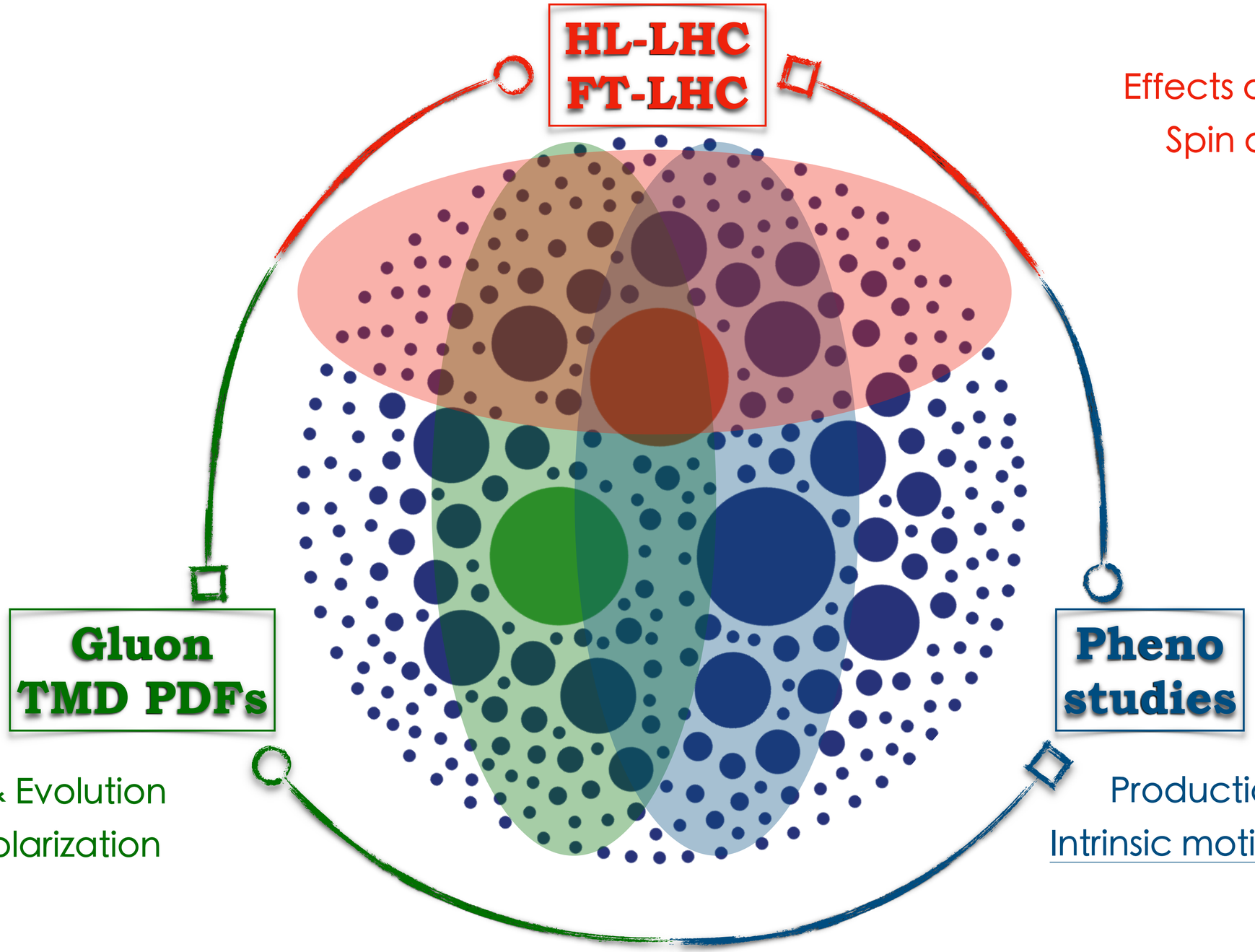
Models & Evolution

Linear polarization

Production mechanisms

Intrinsic motion & Resummation

Gluon TMD PDFs @LHC: a win-win strategy



Effects on p_T spectrum

Spin asymmetries

Models & Evolution

Linear polarization

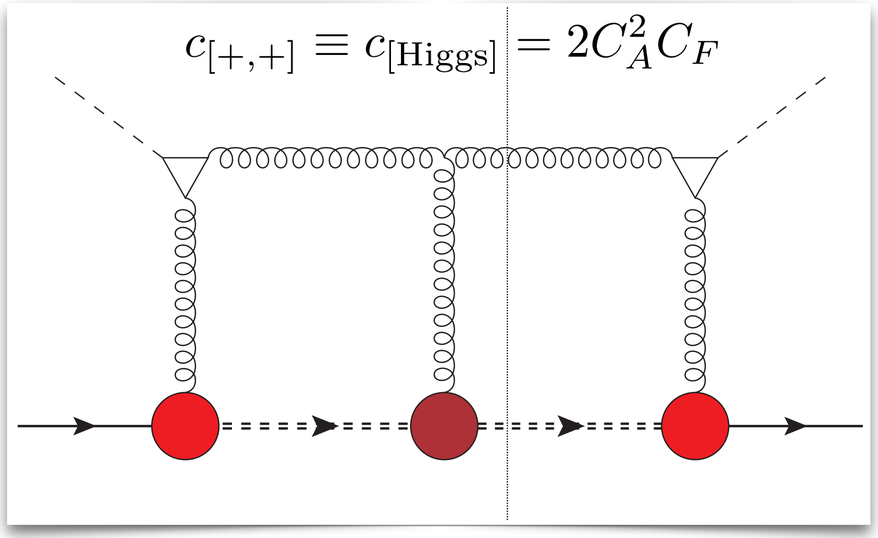
Production mechanisms

Intrinsic motion & Resummation

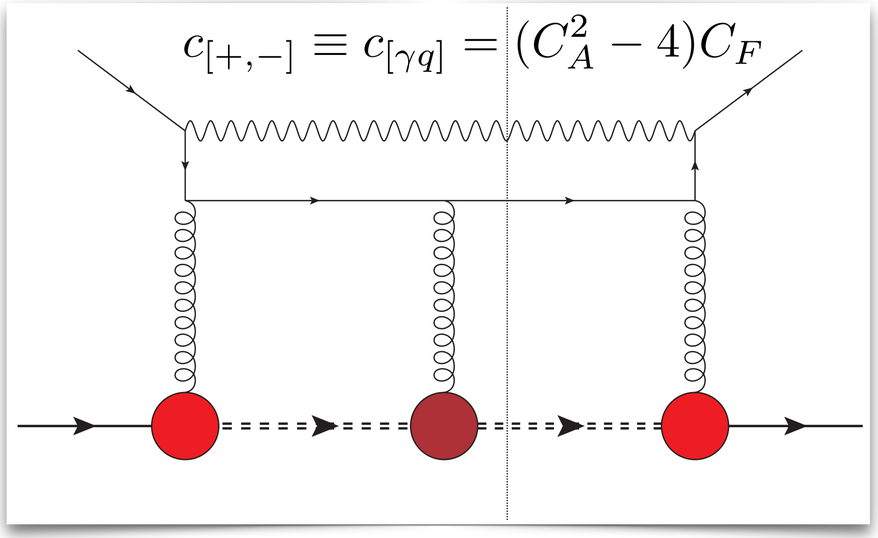
Extras

T-odd gluon TMDs in a spectator model

Higgs-gluon fusion $\Rightarrow$ f-type [+ , +]



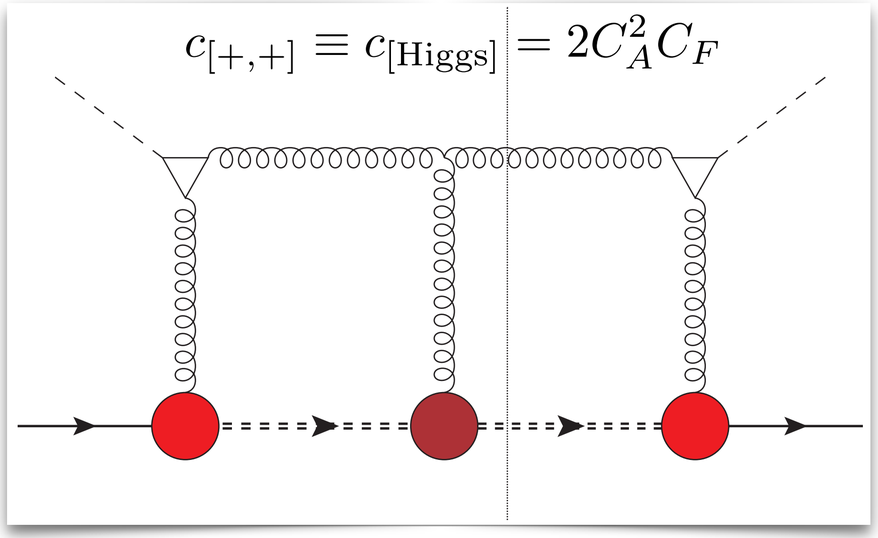
Photon-jet emission $\Rightarrow$ d-type [+ , –]



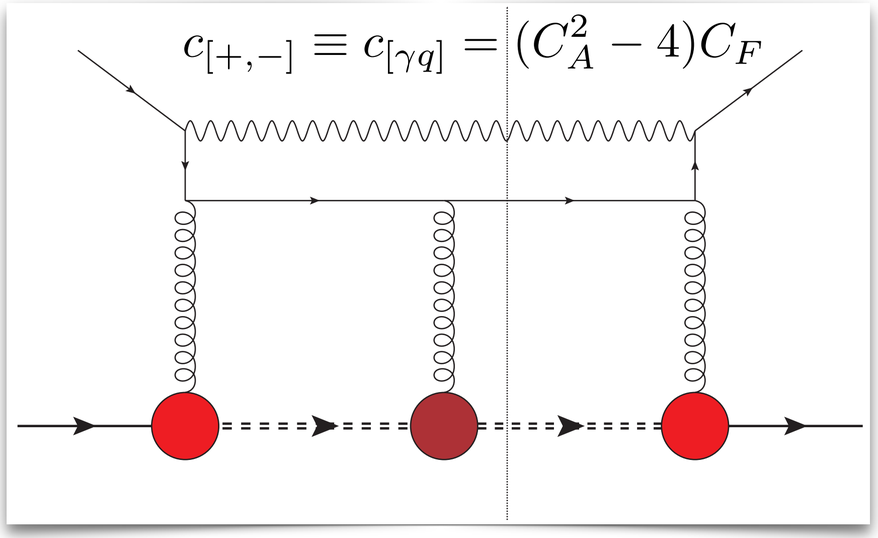
Backup

T-odd gluon TMDs in a spectator model

Higgs-gluon fusion $\Rightarrow$ f-type $[+,+]$



Photon-jet emission $\Rightarrow$ d-type $[+,-]$



nucleon-gluon-spectator

$$\mathcal{Y}^{\mu}_{bc}(p^2) = \delta_{bc}\left[g_1(p^2)\,\gamma_\mu + g_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

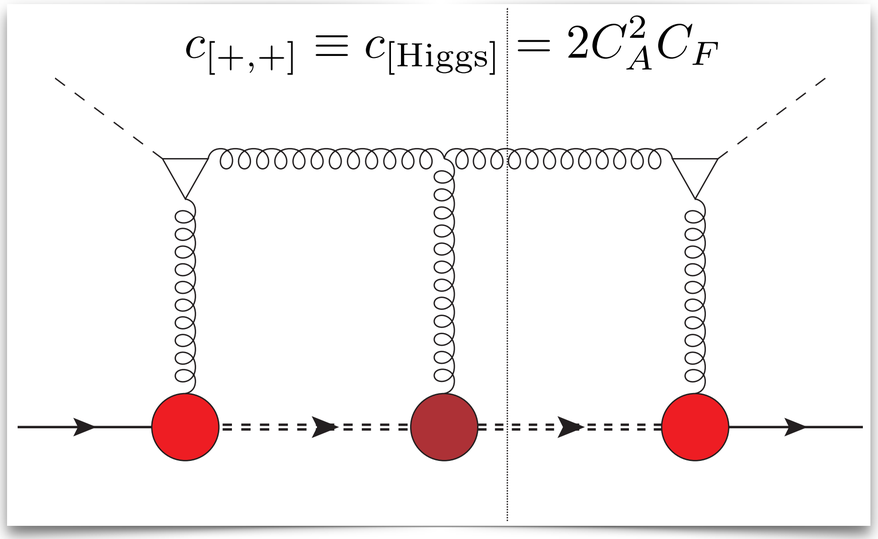
spectator-gluon-spectator

$$\mathcal{X}^{\mu}_{abc}(p^2) = f^{abc}\left[g_1^f(p^2)\,\gamma^\mu + g_2^f(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right] - i\,d^{abc}\left[g_1^d(p^2)\,\gamma^\mu + g_2^d(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

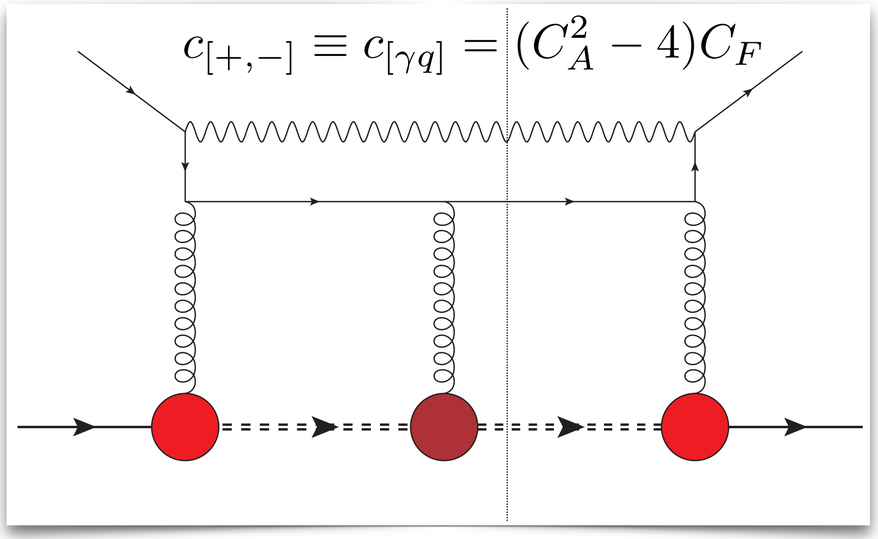
Backup

T-odd gluon TMDs in a spectator model

Higgs-gluon fusion $\Rightarrow$ f-type $[+,+]$



Photon-jet emission $\Rightarrow$ d-type $[+,-]$



nucleon-gluon-spectator

$$\mathcal{Y}^{\mu}_{bc}(p^2) = \delta_{bc}\left[g_1(p^2)\,\gamma_\mu + g_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

spectator-gluon-spectator

$$\mathcal{X}^{\mu}_{abc}(p^2) = f^{abc}\left[g_1^f(p^2)\,\gamma^\mu + g_2^f(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right] - i\,d^{abc}\left[g_1^d(p^2)\,\gamma^\mu + g_2^d(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

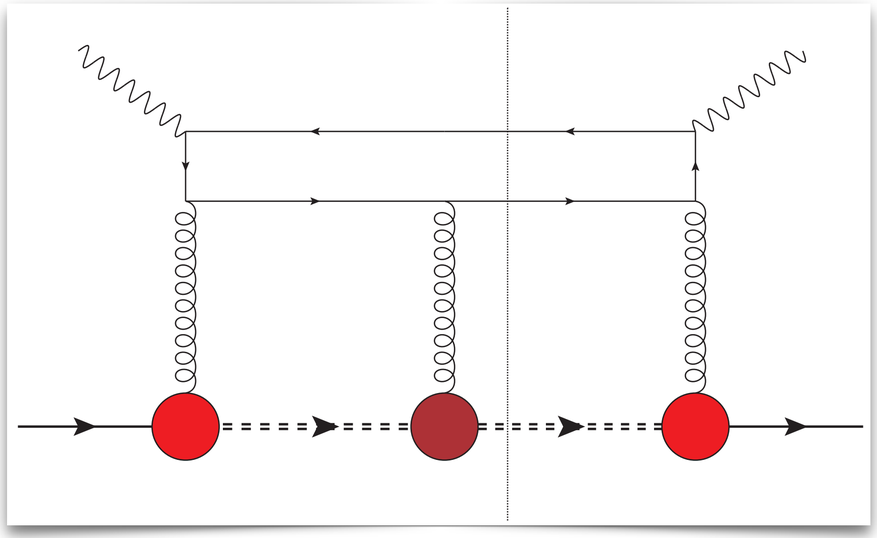
Assumption: $g^d_{1,2}(p^2) = g^f_{1,2}(p^2) \equiv g_{1,2}(p^2)$ $\Leftrightarrow$ $f_{1T}^{\perp[+,-]} = \dfrac{c_{[+,-]}}{c_{[+,+]}} f_{1T}^{\perp[+,+]} \equiv \dfrac{5}{18} f_{1T}^{\perp[+,+]}$

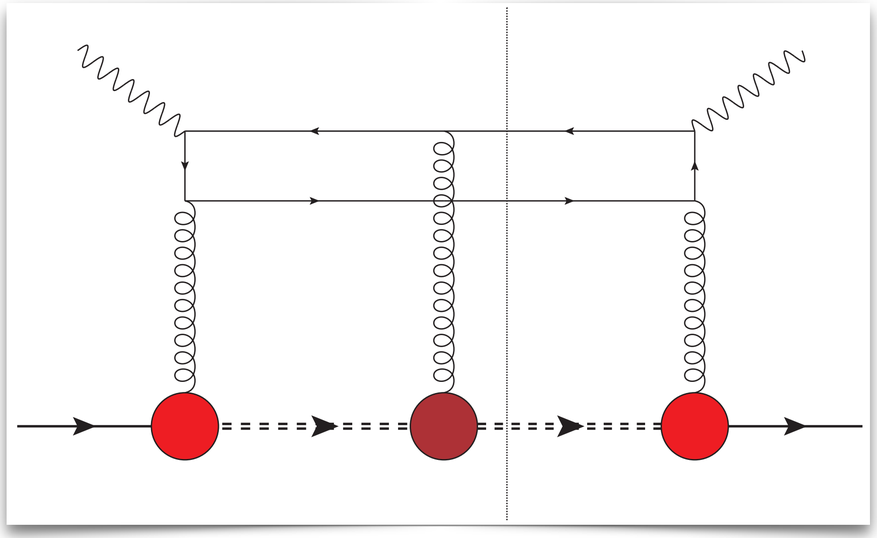
[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Backup

Analytic structure of T-odd gluon TMDs

Two-jet SIDIS $\Rightarrow$ f-type [+ , +]



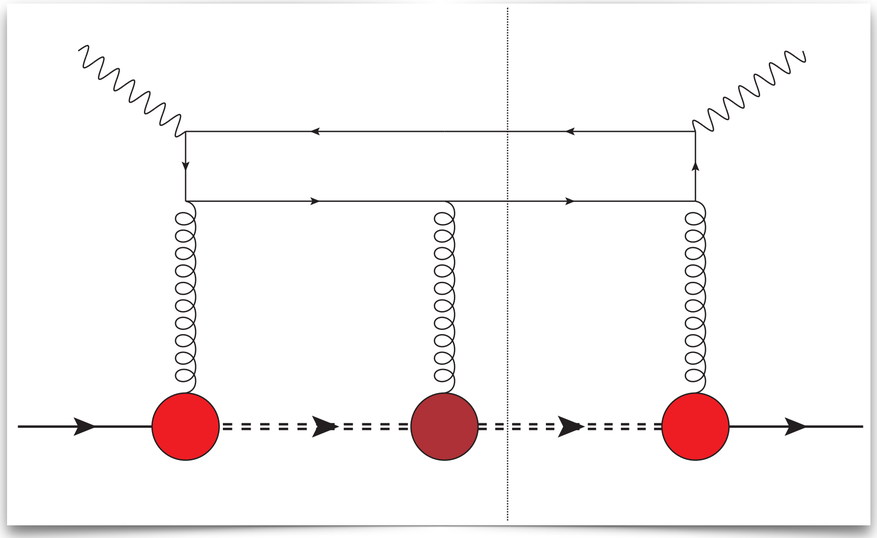


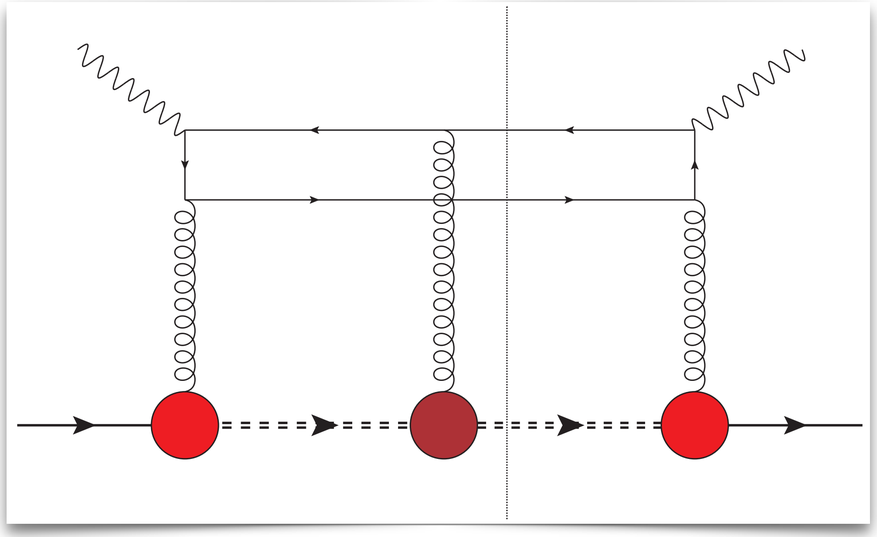
Backup

[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Analytic structure of T-odd gluon TMDs

Two-jet SIDIS $\Rightarrow$ f-type [+ , +]





nucleon-gluon-spectator

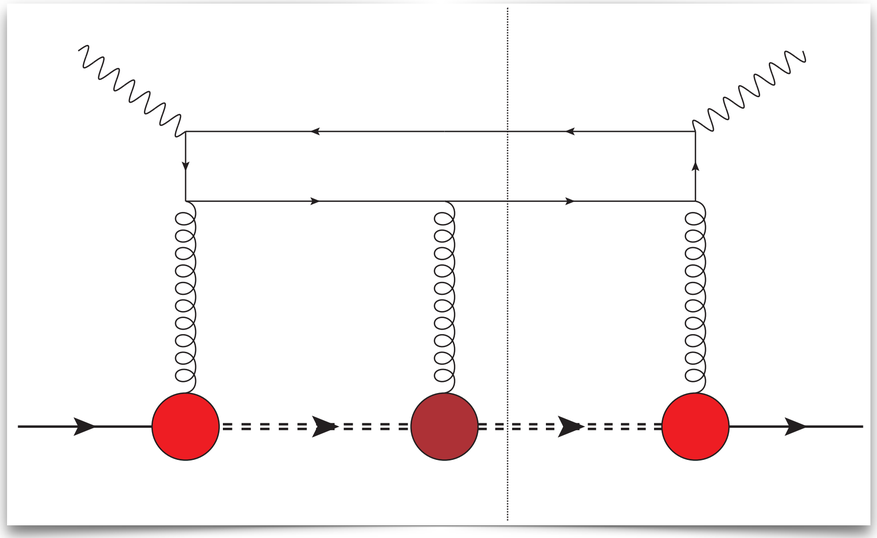
spectator-gluon-spectator

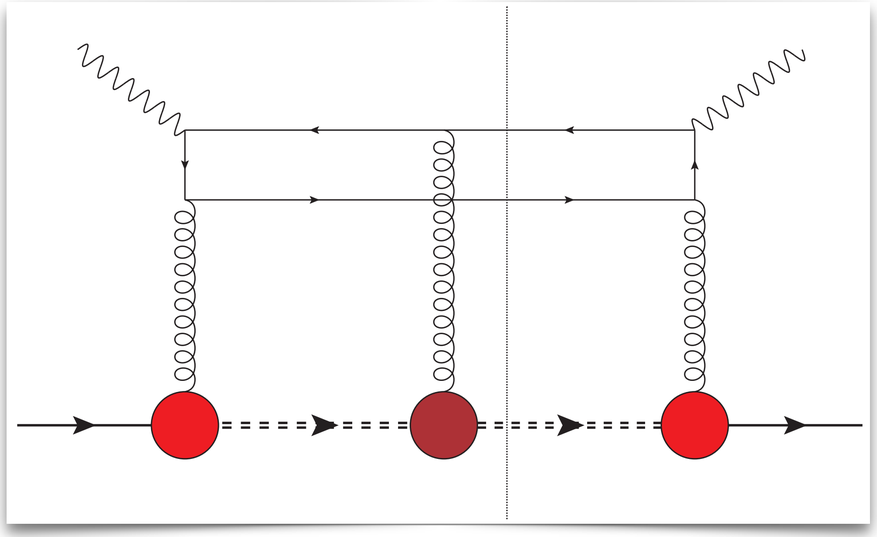
Backup

[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Analytic structure of T-odd gluon TMDs

Two-jet SIDIS $\Rightarrow$ f-type [+ , +]





nucleon-gluon-spectator

spectator-gluon-spectator

$$F(x, \boldsymbol{p}_T^2) = \sum_{i,j,k}^{1,2} C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2)\, g_i(\boldsymbol{p}_T^2)\, g_j(\boldsymbol{p}_T^2)\, g_k(\boldsymbol{p}_T^2)$$

$8 \times 7 \times 4$

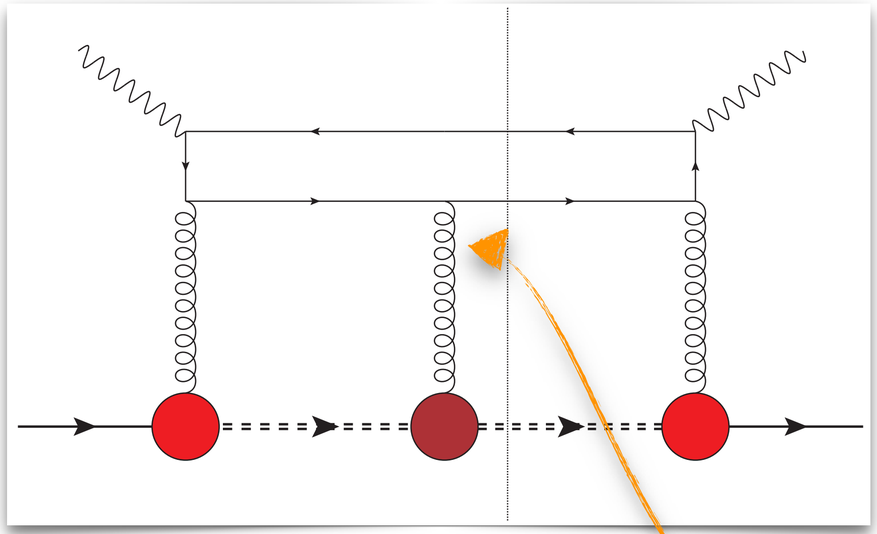
$$C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2) = \sum_{l=1}^{7} \mathcal{C}_{ijk}^{(F),l}(x, \boldsymbol{p}_T^2)\, \mathcal{D}_l(x, \boldsymbol{p}_T^2)$$

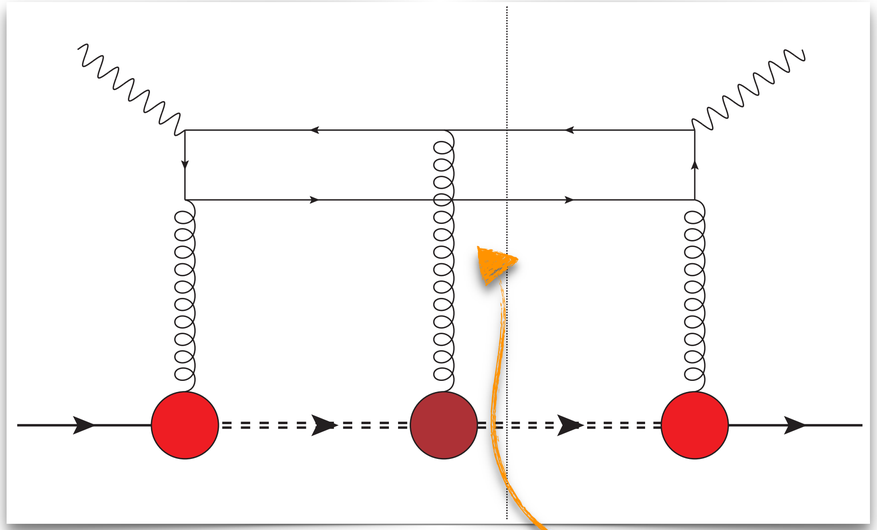
[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Backup

Analytic structure of T-odd gluon TMDs

Two-jet SIDIS $\Rightarrow$ f-type [+ , +]





nucleon-gluon-spectator

spectator-gluon-spectator

$$F(x, \boldsymbol{p}_T^2) = \sum_{i,j,k}^{1,2} C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2)\, g_i(\boldsymbol{p}_T^2)\, g_j(\boldsymbol{p}_T^2)\, g_k(\boldsymbol{p}_T^2)$$

$8 \times 7 \times 4$

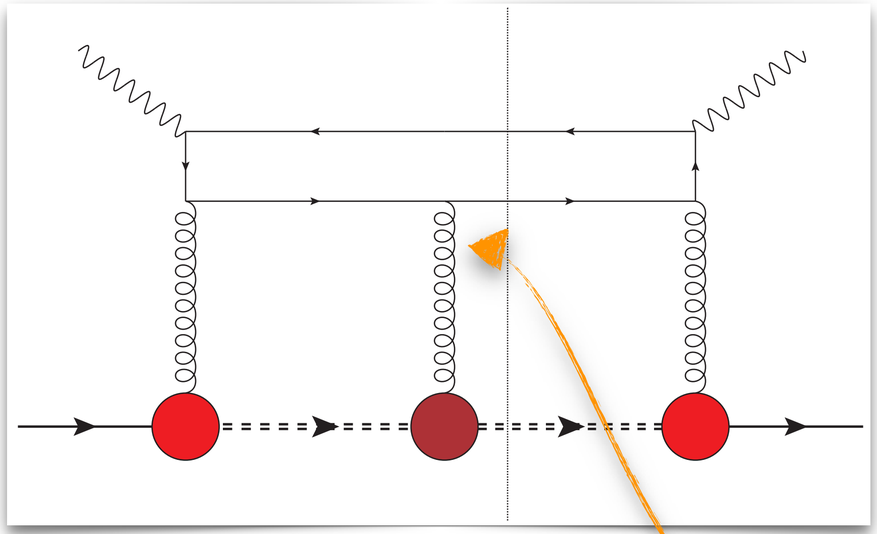
$$C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2) = \sum_{l=1}^{7} \mathcal{C}_{ijk}^{(F),l}(x, \boldsymbol{p}_T^2)\, \mathcal{D}_l(x, \boldsymbol{p}_T^2)$$

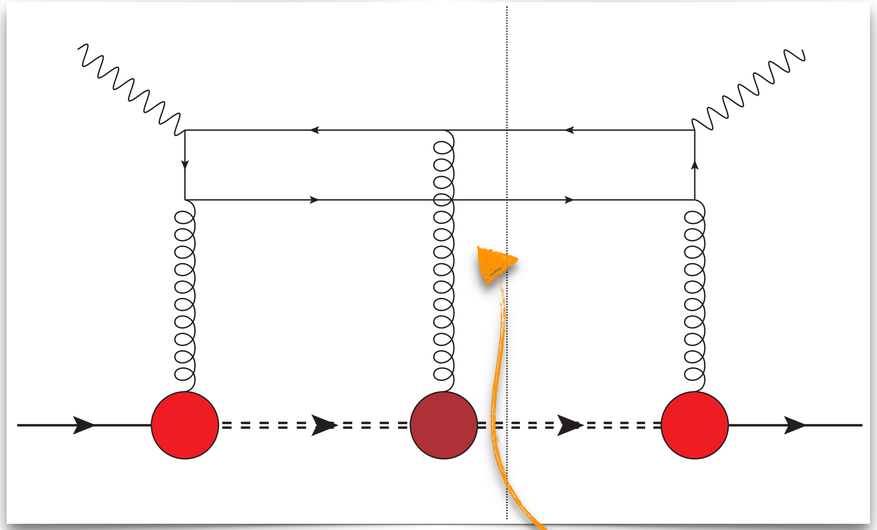
[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Backup

Analytic structure of T-odd gluon TMDs

Two-jet SIDIS $\Rightarrow$ f-type [+ , +]





nucleon-gluon-spectator

spectator-gluon-spectator

$$F(x,\boldsymbol{p}_T^2) = \sum_{i,j,k}^{1,2} C_{ijk}^{(F)}(x,\boldsymbol{p}_T^2)\, g_i(\boldsymbol{p}_T^2)\, g_j(\boldsymbol{p}_T^2)\, g_k(\boldsymbol{p}_T^2)$$

$8 \times 7 \times 4$

$$C_{ijk}^{(F)}(x,\boldsymbol{p}_T^2) = \sum_{l=1}^{7} \mathcal{C}_{ijk}^{(F),l}(x,\boldsymbol{p}_T^2)\, \mathcal{D}_l(x,\boldsymbol{p}_T^2)$$

[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Backup

TMD factorization

Parton densities: an incomplete family tree

Wigner distributions $\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$ **5D**

$\int d^2\mathbf{k}_T$

$\int d^2\mathbf{b}_T$

Generalized Parton Distributions

GPDs

Transverse Momentum Distributions

TMDs **3D**

$\int d^2\mathbf{k}_T$

Parton Distribution Functions

PDFs **1D**

slide adapted from C. Bissolotti

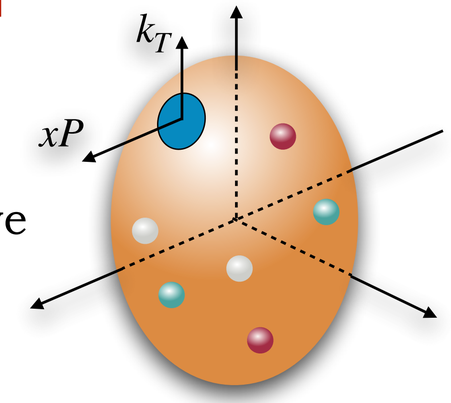
Backup

Parton densities: an incomplete family tree

3D

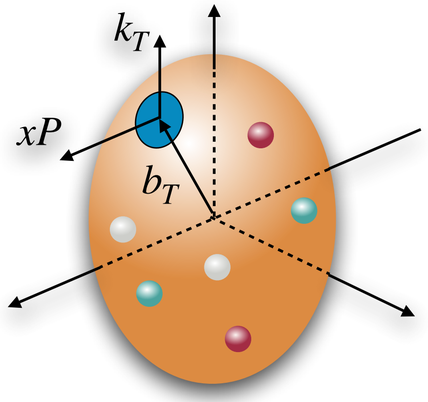
TMDs

(semi-)inclusive



5D

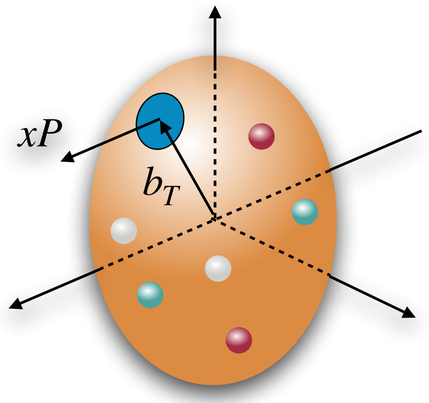
Wigner distributions



3D

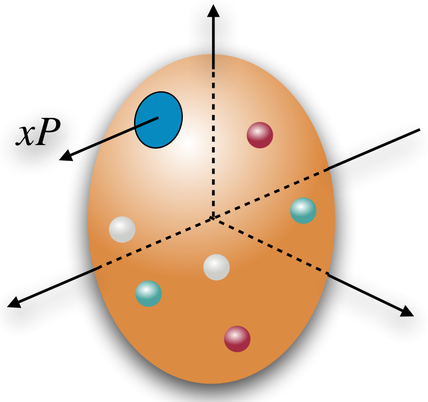
FT of GPDs

exclusive

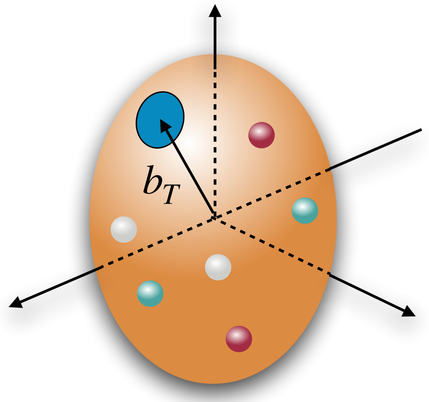


PDFs

(semi-)inclusive



FT of Form Factors



1D

$\vec{b}_\perp$ dependence

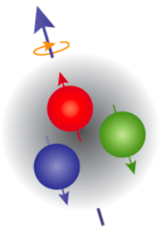
$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

2D

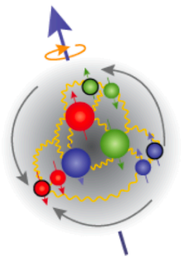
Backup

The proton spin crisis



quarks helicity

~ 30 %



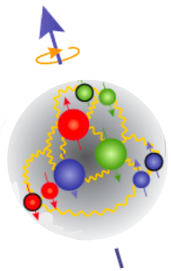
orbital angular momentum

unknown!

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

gluons helicity

~ 20% – 50 % **?**



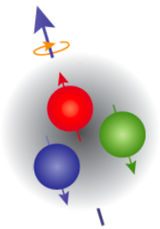
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

🔗 (proton spin crisis) [EMC Collaboration, CERN (1987)]

slide adapted from C. Bissolotti

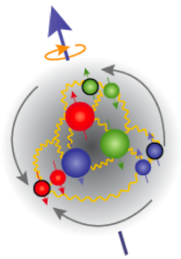
Backup

The proton spin crisis



quarks helicity

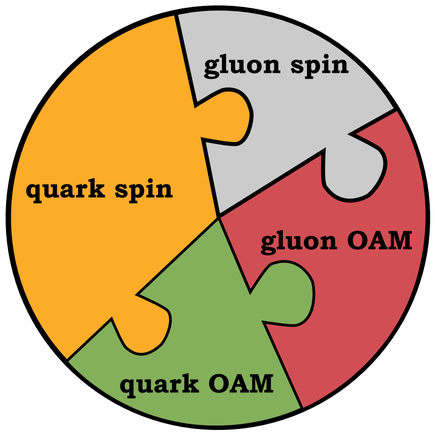
~ 30 %



orbital angular momentum

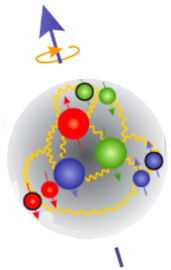
unknown!

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



gluons helicity

~ 20% – 50 % **?**



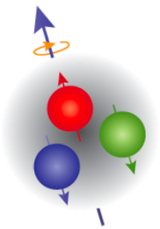
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

🔗 (proton spin crisis) [EMC Collaboration, CERN (1987)]

slide adapted from C. Bissolotti

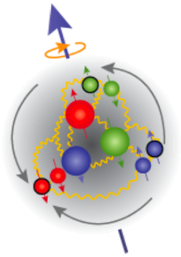
Backup

The proton spin crisis



quarks helicity

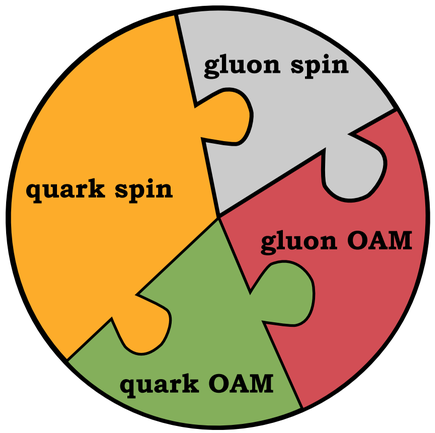
~ 30 %



orbital angular momentum

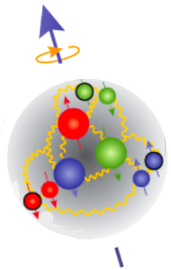
unknown!

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



gluons helicity

~ 20% – 50 % **?**



…many other effects in hadronic interactions cannot be understood in the purely collinear approach

Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

🔗 (proton spin crisis) [EMC Collaboration, CERN (1987)]

slide adapted from C. Bissolotti

Backup

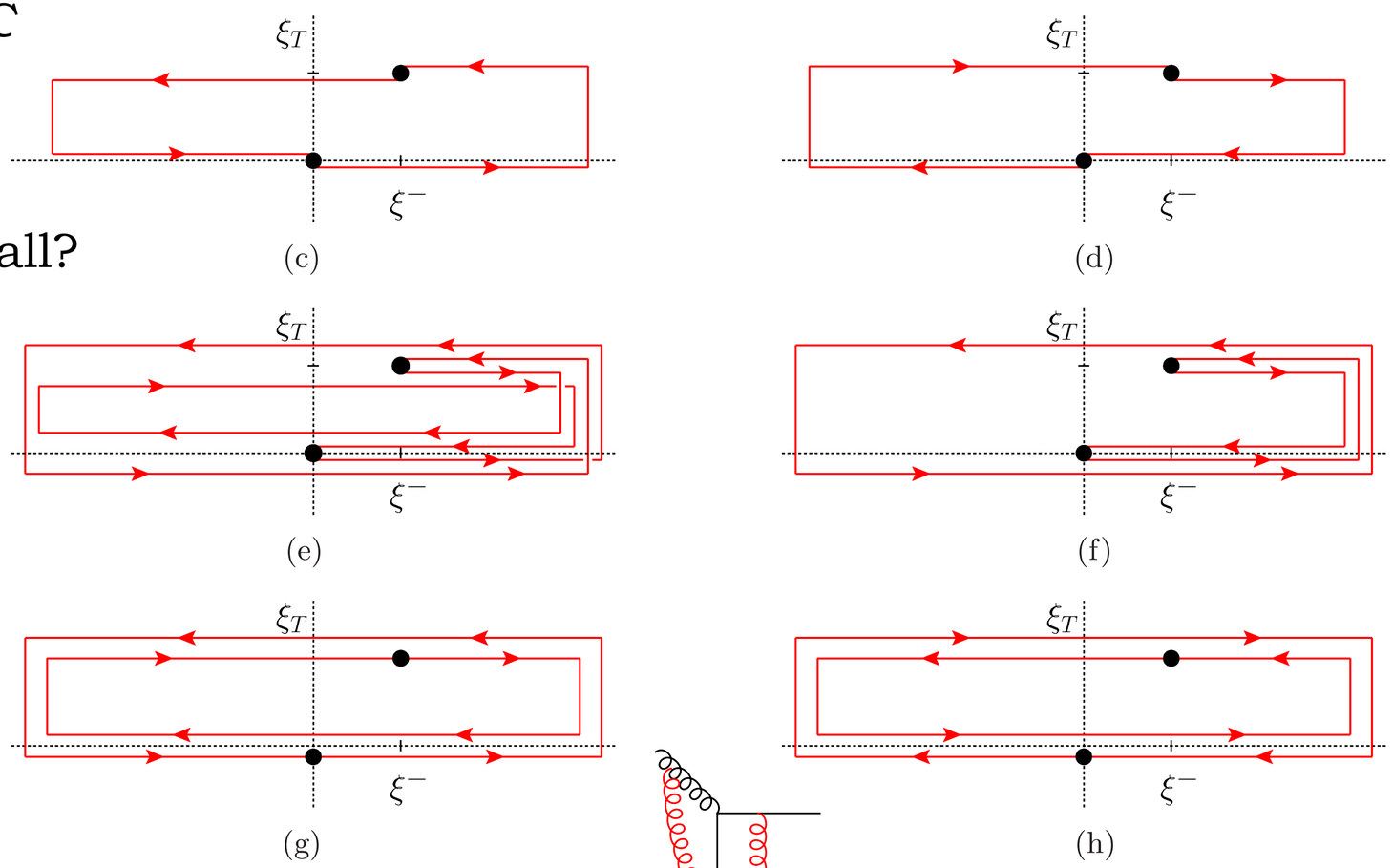
Dihadron hadroproduction and factorization breaking

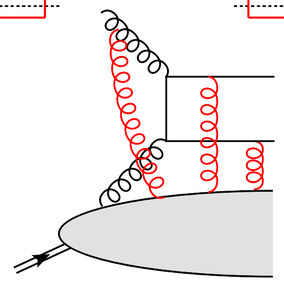
- Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
- Assumed factorization in SCET and CGC
- Significance of low-x studies
- Size of factorization-breaking effects small?
- DP TMDs:

  (c) $[+,-]$ and (d) $[-,+]$
- Appearance of new gauge **loop links**:

  (e) $[+\square,+\square]$, (f) $[+,+\square]$,

  (g) $[\square,\square]$, and (h) $[\square,\square]$





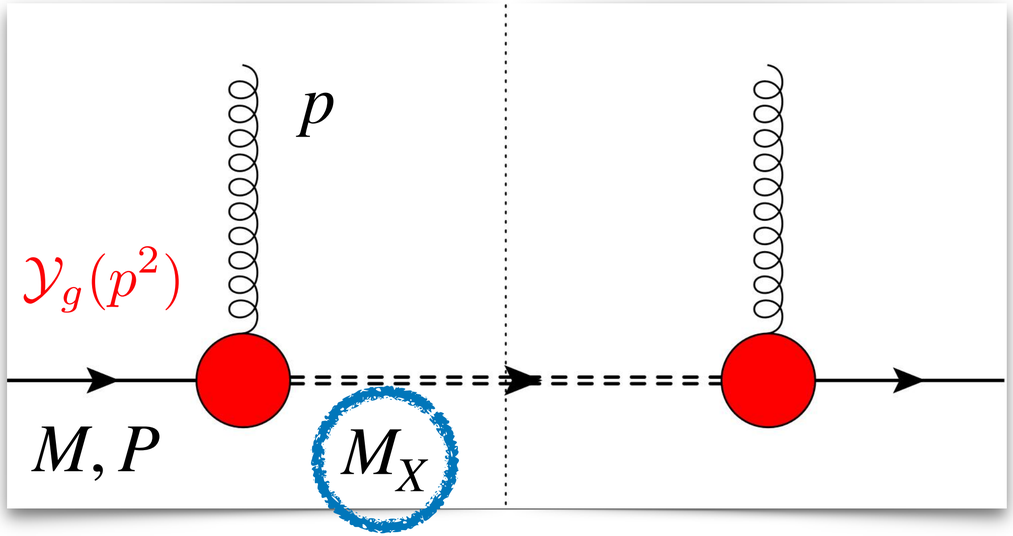
Backup

Small-x improved gluon TMDs

Assumptions of the model

Spin-1/2 spectator

Lowest Fock state:
tri-quark spectator
on-shell and
with mass M_X

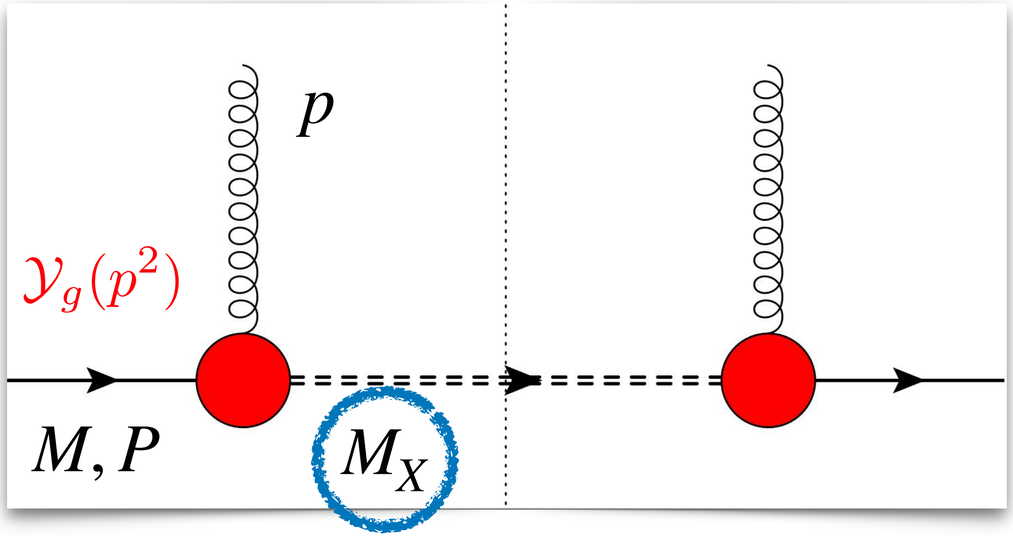


Backup

Assumptions of the model

Spin-1/2 spectator

Lowest Fock state:
tri-quark spectator
on-shell and
with mass M_X



Nucleon-gluon-spectator vertex

$$\Phi_g = \frac{1}{2(2\pi)^3(1-x)P^+} Tr\left[(\not{P}+M)\frac{1+\gamma^5\not{S}}{2}G^*_{\mu\rho}(p)G^{\nu\sigma}(p)\mathcal{Y}_g^{\rho *}\mathcal{Y}_{g\sigma}(\not{P}-\not{p}+M)\right]$$

$$\mathcal{Y}_g^\mu = g_1(p^2)\gamma^\mu + i\frac{g_2(p^2)}{2M}\sigma^{\mu\nu}p_\nu$$

mimics proton form factors
(conserved EM current
of a free nucleon)

Backup

Assumptions of the model

Link with collinear factorization

1. p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution
2. TMDs and PDFs *decouple* due to evolution

Backup

Assumptions of the model

Link with collinear factorization

1. p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution
2. TMDs and PDFs *decouple* due to evolution

Dipolar form factor(s)

$$g_{1,2}(p^2) = \kappa_{1,2} \frac{p^2}{|p^2 - \Lambda_X^2|^2}$$

1. Cancels singularity of gluon propagator
2. Suppresses effects of high p_T
3. Compensates log divergences arising from p_T-integration
4. Adds three more parameters: $\kappa_{1,2}$ and Λ_X

Backup

Assumptions of the model

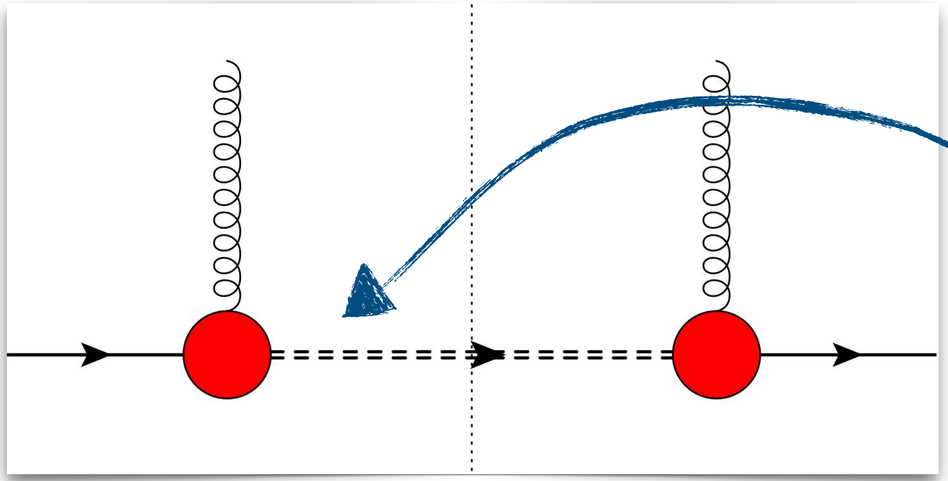
Spectator-system spectral-mass function

$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$

spectral-mass function

spectator-model TMD

[Inspired by G.R. Goldstein, J.O.G. Hernandez, S. Liuti (2011)]



$\mathcal{Y}_g(p^2)$

Instead of a single on-shell spectator, a continuum of spectators

Backup

Assumptions of the model

Spectator-system spectral-mass function

spectral-mass function

$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$

spectator-model TMD

[Inspired by G.R. Goldstein, J.O.G. Hernandez, S. Liuti (2011)]

$$\rho_X\left(M_X; \{X^{(\mathrm{pars})}\} \equiv \{A, B, a, b, C, D, \sigma\}\right) = \mu^{2a}\left[\frac{A}{B + \mu^{2b}} + \frac{C}{\pi\sigma} e^{-\frac{(M_X - D)^2}{\sigma^2}}\right]$$

low-x (high-μ^2) tail $\propto (a - b)$

$q\bar{q}$ contributions energetically available at large M_X

$$\mu^2 = M_X^2 - M^2$$

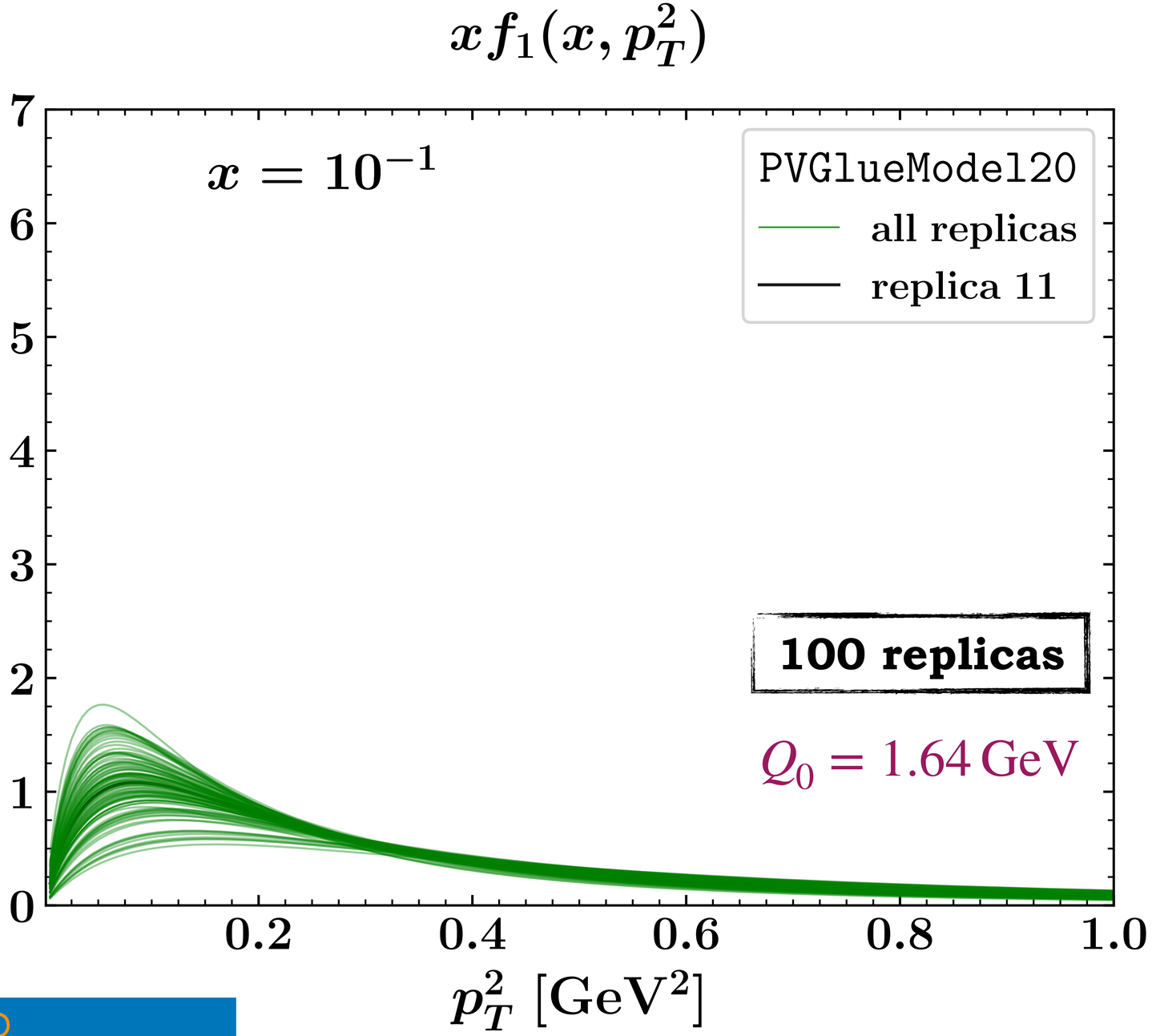
moderate-x trend

pure tri-quark contribution at low M_X

Backup

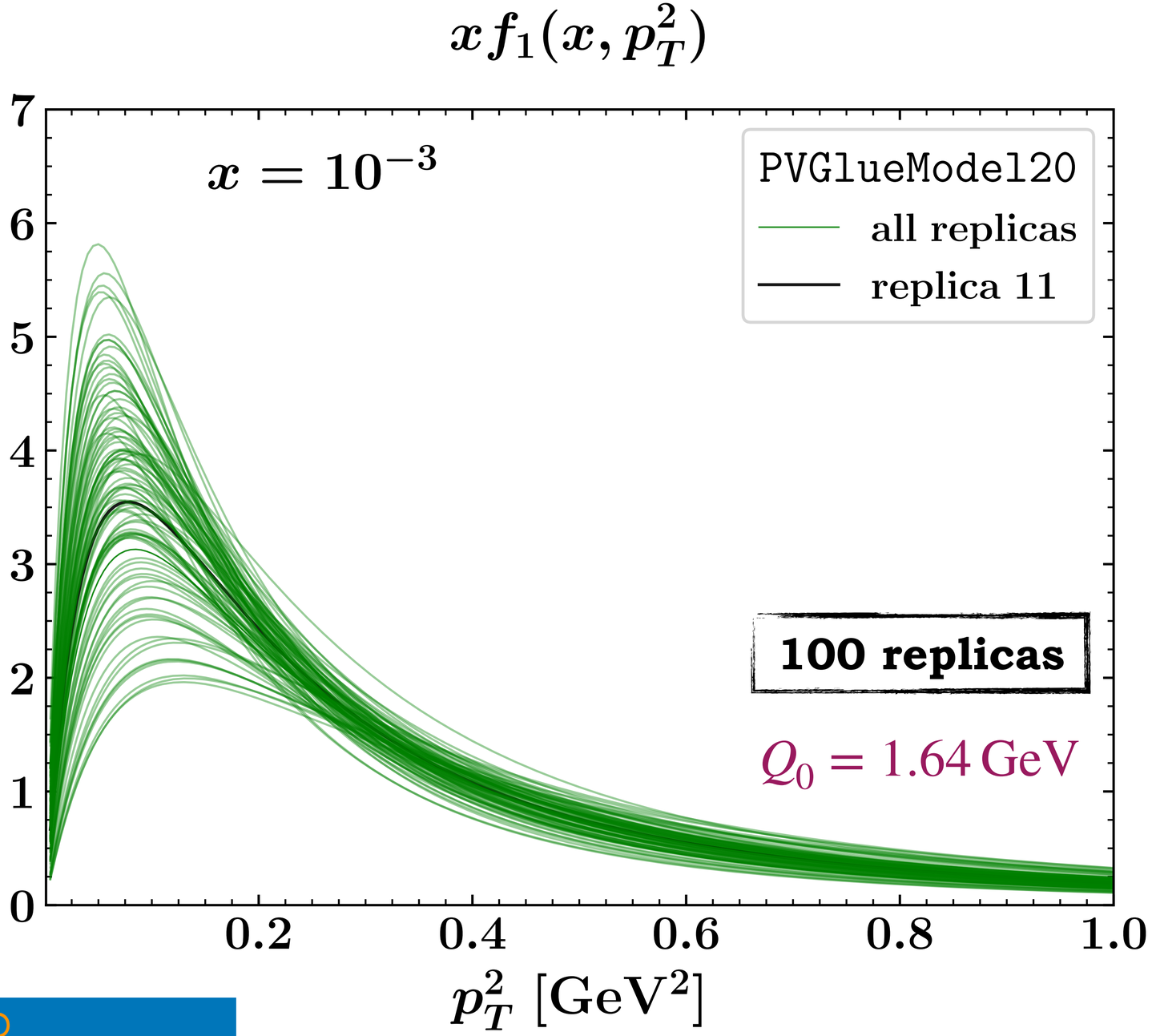
Unpolarized gluon TMD

[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]



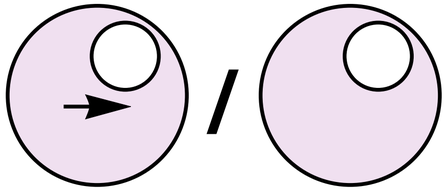
Unpolarized gluon TMD

[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

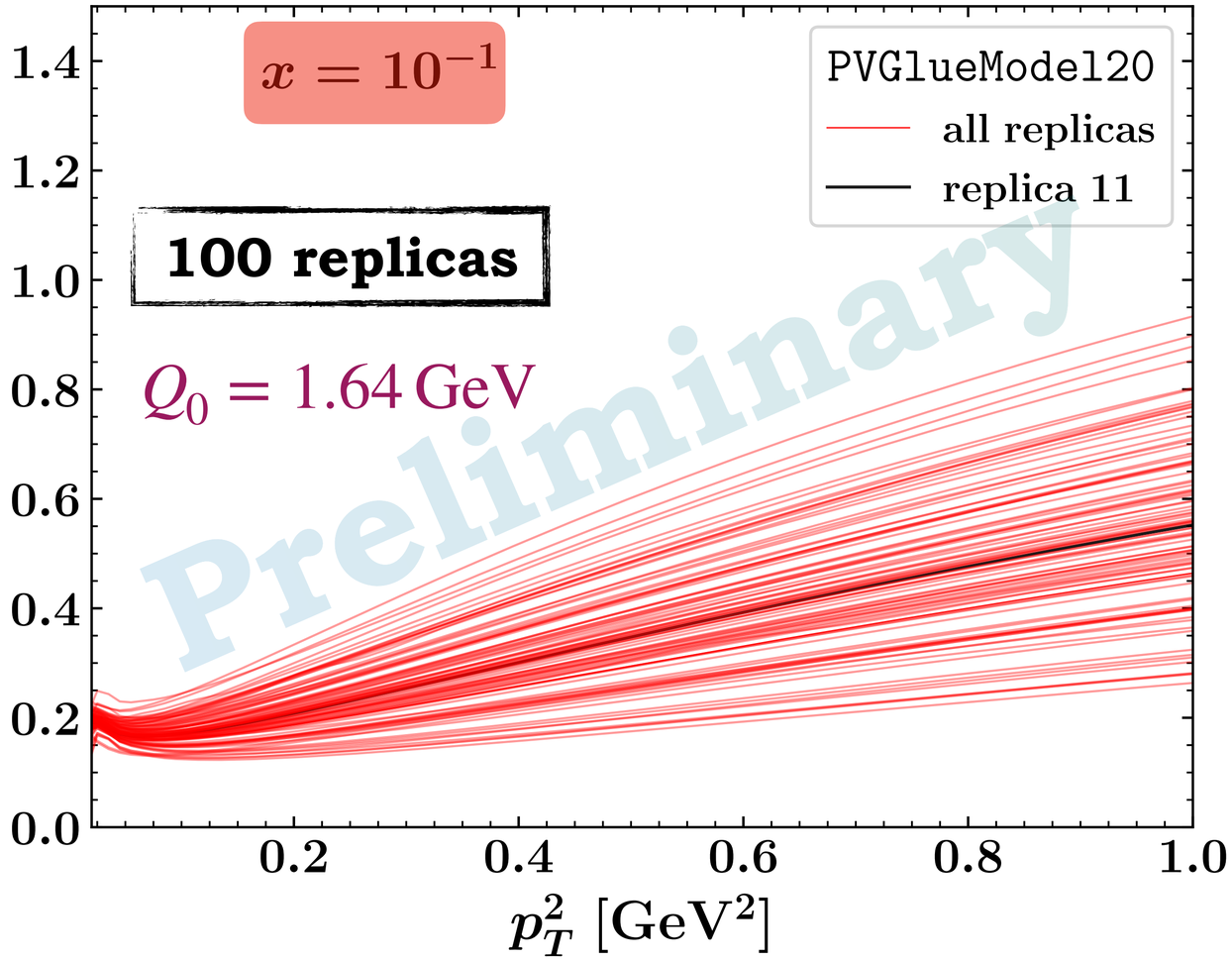


f-type Sivers/unpol.

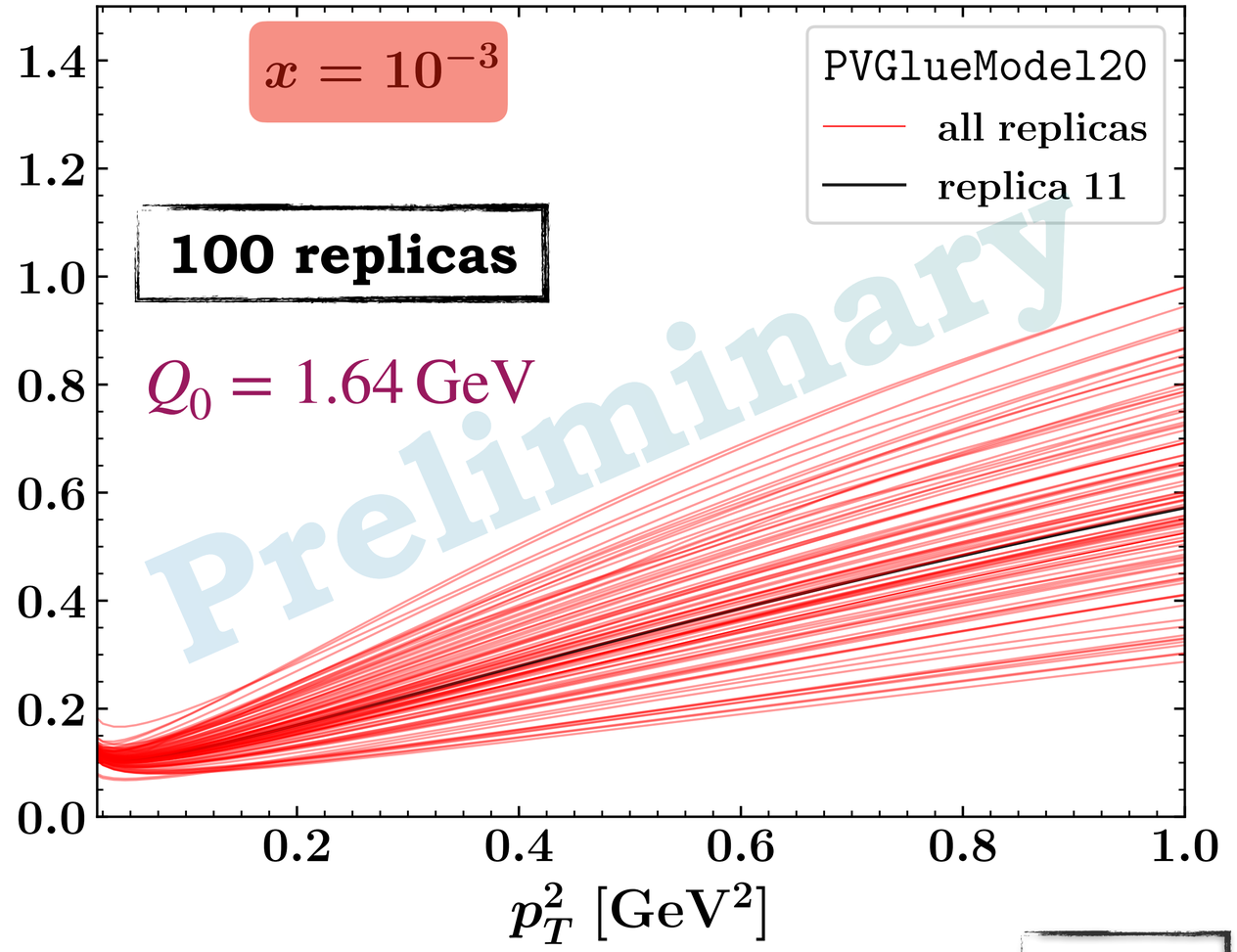
A. Bacchetta, F.G. C., M. Radici (in preparation)]



$\frac{p_T}{M} f_{1T}^{\perp[+,+]} / f_1$



$\frac{p_T}{M} f_{1T}^{\perp[+,+]} / f_1$



Backup

Gluon TMD correlator and T-odd gluon densities

$$\Gamma_U^{ij}(x,\boldsymbol{k}) = x\left[\delta_T^{ij} f_1(x,\boldsymbol{k}^2) + \frac{k_T^{ij}}{M^2} h_1^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha} S_L}{2M^2} h_{1L}^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$

Backup

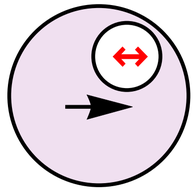
Gluon TMD correlator and T-odd gluon densities

$$\Gamma_U^{ij}(x,\boldsymbol{k}) = x\left[\delta_T^{ij} f_1(x,\boldsymbol{k}^2) + \frac{k_T^{ij}}{M^2} h_1^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha} S_L}{2M^2} h_{1L}^{\perp}(x,\boldsymbol{k}^2)\right]$$

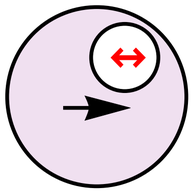
$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$

pseudo worm-gear



linearity TMD

pretzelosity



Backup

Gluon TMD correlator and T-odd gluon densities

$$\Gamma_U^{ij}(x,\boldsymbol{k}) = x\left[\delta_T^{ij} f_1(x,\boldsymbol{k}^2) + \frac{k_T^{ij}}{M^2} h_1^\perp(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_\alpha k_T^{j\}\alpha} S_L}{2M^2} h_{1L}^\perp(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^\perp(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_\alpha k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^\perp(x,\boldsymbol{k}^2)\right]$$

pseudo worm-gear

linearity TMD

pretzelosity

Sivers

$$\frac{\epsilon_T^{S_T k_T}}{M} f_{1T}^\perp(x,\boldsymbol{k}^2) = \frac{1}{2}\delta_{Tij}\Gamma_T^{ij}(x,\boldsymbol{k})$$

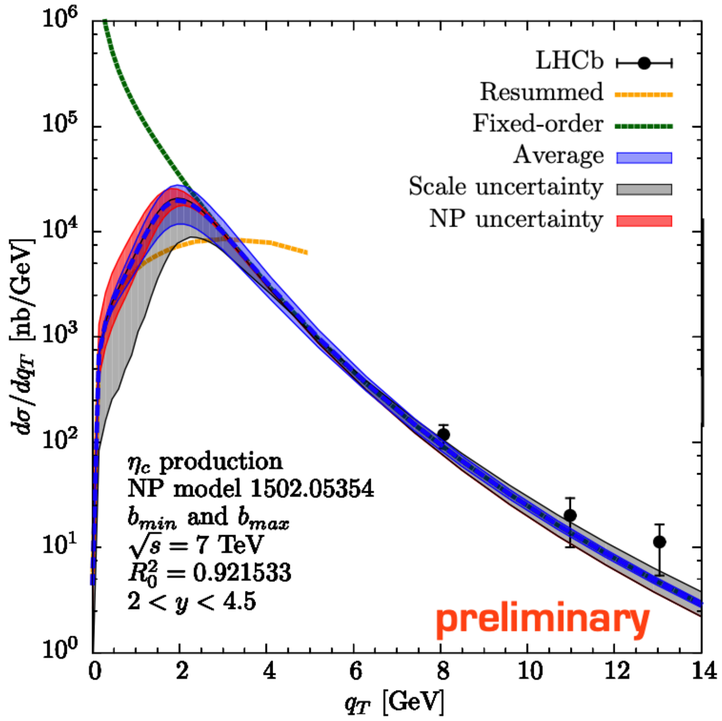
Backup

Gluon TMD phenomenology

$\eta_{c,b}$ production @ 7TeV LHCb

η_c production at LHC

full transverse momentum spectrum:
low qT matched with high qT region



blue band: uncertainty from matching

grey band: scale uncertainty

red band: nonpert. uncertainty

$$S_{NP}(\bar{b}_T) = -\left[\frac{a_1}{2} + \frac{a_2}{2} \ln Q^2\right] \bar{b}_T^2$$

a_i = 0.5 GeV², var. 50%, envelope
both for unpolarized and
linearly polarized distributions

the formalism is in good shape!
we need the data at low qT

Jefferson Lab

25

slide by Andrea Signori (INT 2017)

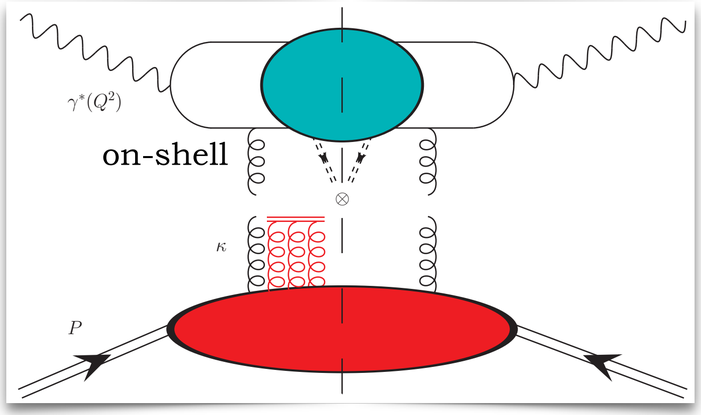
Backup

HEF and the UGD

TMD versus high-energy factorization

TMD

* Semi-inclusive processes
* $\kappa_T \ll$ hardest scale
* Language of parton correlators
* Diagram: SIDIS onium



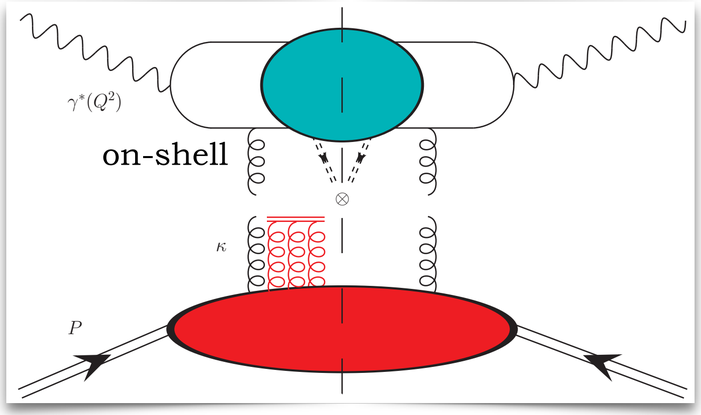
TMD
PDF

Backup

TMD versus high-energy factorization

TMD

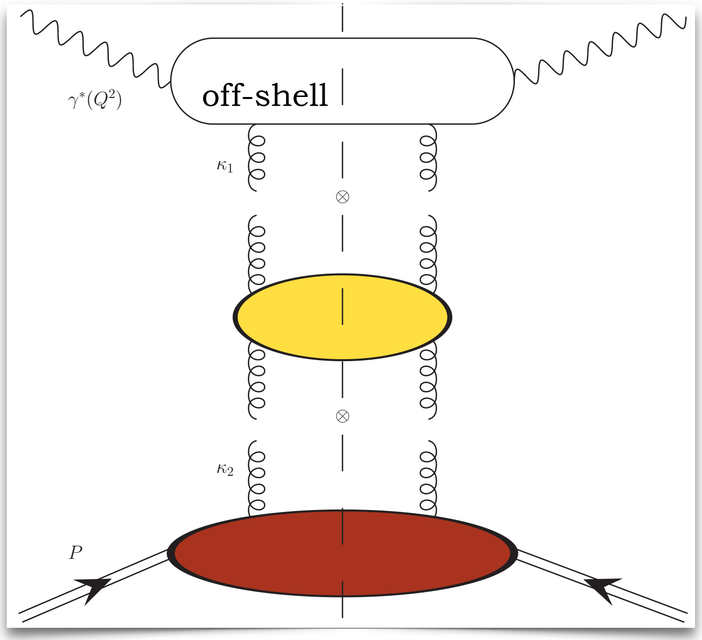
- Semi-inclusive processes
- $\kappa_T \ll$ hardest scale
- Language of parton correlators
- Diagram: SIDIS onium



TMD PDF

HEF

- Inclusive or exclusive processes (!)
- Small x, large κ_T
- Language of Reggeized gluons
- Diagram: DIS



$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\mathrm{BFKL}} \otimes \Phi^{P}_{[\mathrm{NP}]}$$

Backup

TMD versus high-energy factorization

TMD

IR-safe colorless $\{\Phi^{i\to o}\}$

(Fadin-Martin theorem)

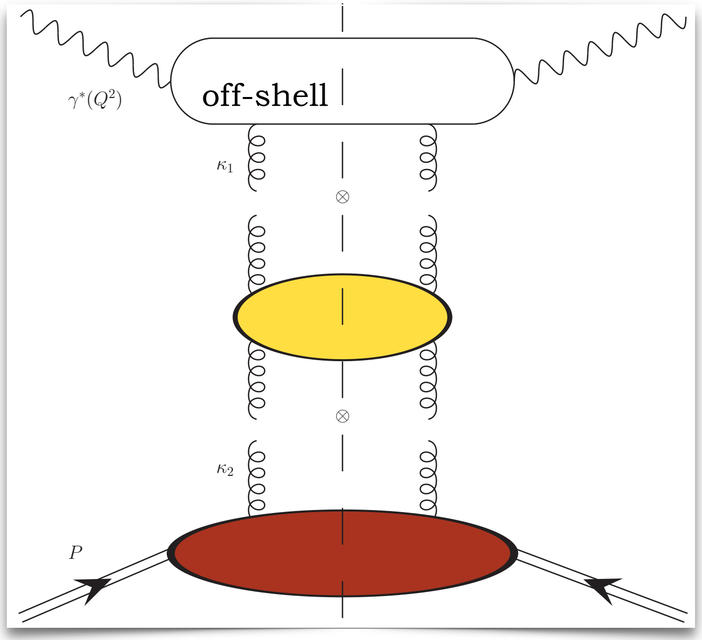
[V.S. Fadin, A.D. Martin (1999)]

* Semi-inclusive processes
* $\kappa_T \ll$ hardest scale
* Language of parton correlators
* Diagram: SIDIS onium

TMD PDF

HEF

* Inclusive or exclusive processes (!)
* Small x, large κ_T
* Language of Reggeized gluons
* Diagram: DIS



$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\text{BFKL}} \otimes \Phi^{P}_{[\text{NP}]}$$

Backup

TMD versus high-energy factorization

TMD

IR-safe colorless $\{\Phi^{i\to o}\}$

(Fadin-Martin theorem)

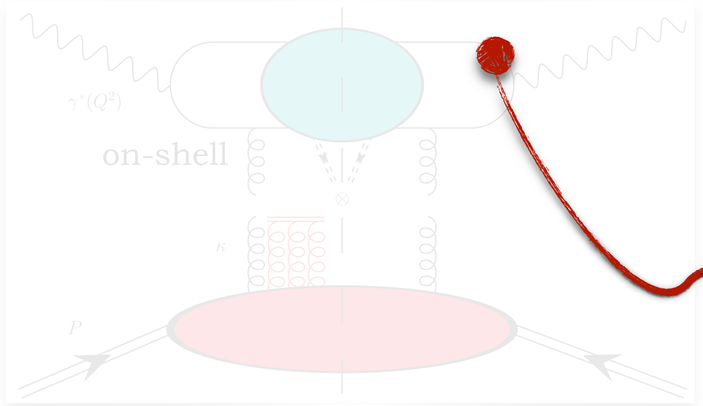
[V.S. Fadin, A.D. Martin (1999)]

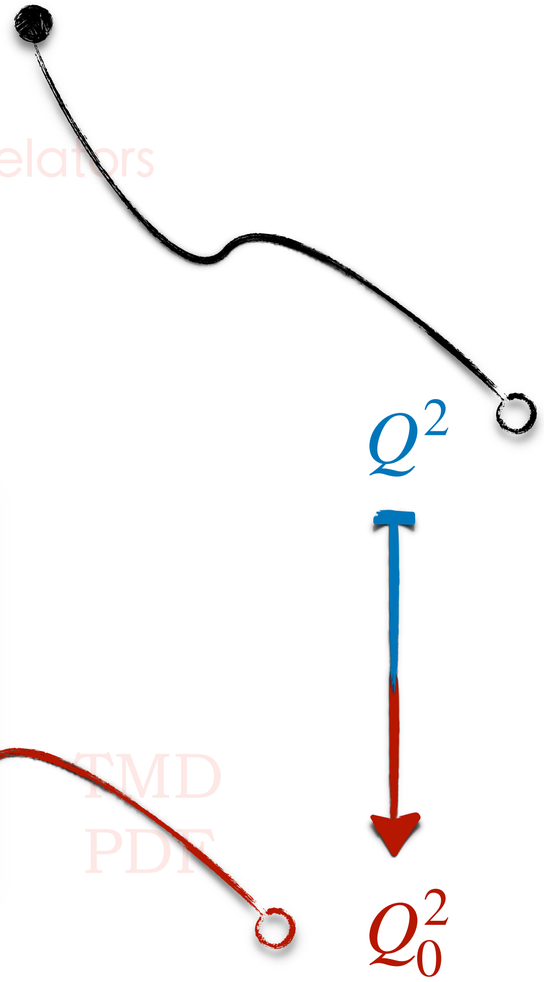
* Semi-inclusive processes
* $\kappa_T \ll$ hardest scale
* Language of parton correlators
* Diagram: SIDIS onium

IR diffusion pattern

(Bartels' cigar)

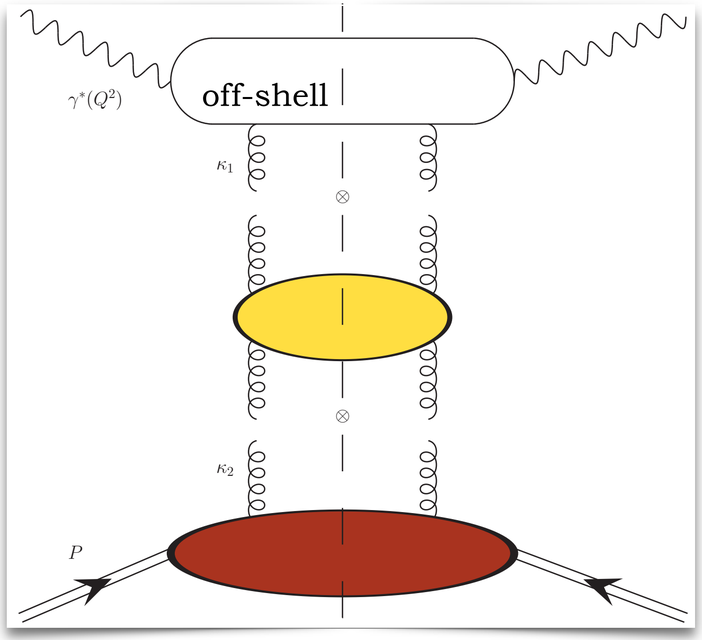
[J. Bartels, H. Lotter (1993)]





HEF

* Inclusive or exclusive processes (!)
* Small x, large κ_T
* Language of Reggeized gluons
* Diagram: DIS



$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\text{BFKL}} \otimes \Phi^{P}_{[\text{NP}]}$$

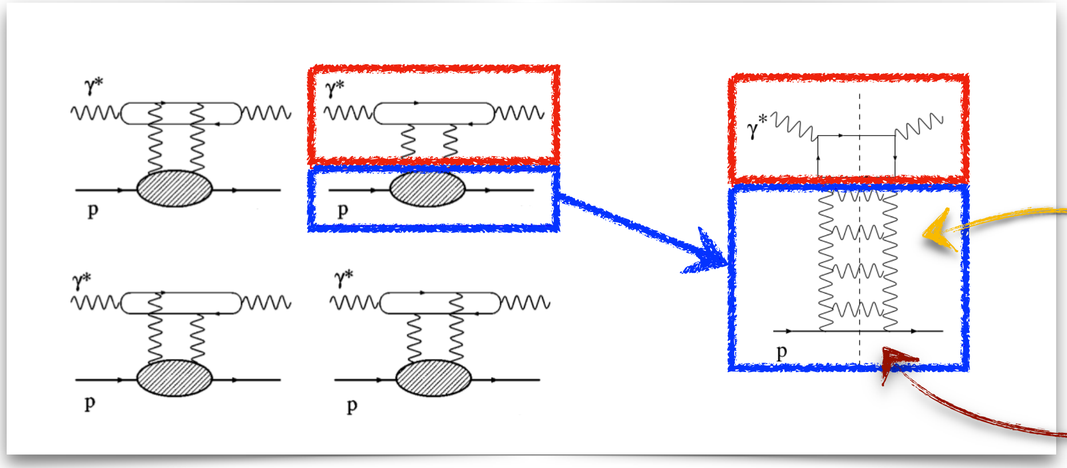
Backup

High-energy factorization and the UGD

- example: **virtual photoabsorption** in **high-energy factorization**

$$\sigma_{\text{tot}}(\gamma^* p \to X) \propto \mathcal{I}m_s\{\mathcal{A}(\gamma^* p \to \gamma^* p)\} \equiv \Phi_{\gamma^* \to \gamma^*} \circledast \mathcal{F}(x, \kappa^2)$$

◇ $\mathcal{F}(x, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton



▶ Small-x limit: **UGD** = [**BFKL gluon ladder**] $\circledast$ [**proton impact factor**]

◇ Takes into account the resummation of high-energy logs

◇ Describes the coupling of the gluon Green's function to the proton

▶ Proton impact factor is non-perturbative $\Longrightarrow$ UGD needs to be modeled!

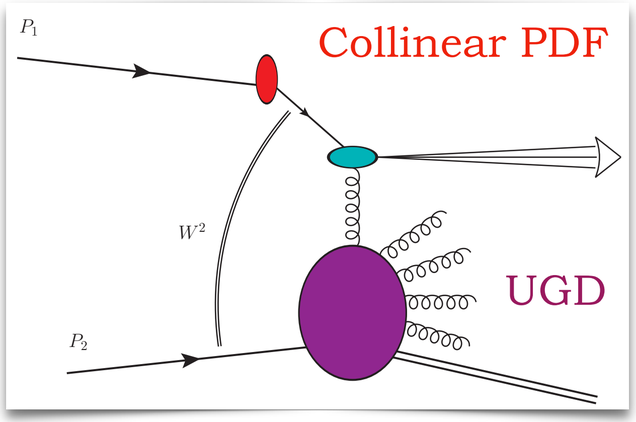
Backup

Hybrid or pure factorization?

Forward emissions

* *Asymmetric* config. ↔ fast parton + small-x gluon

* Hybrid **high-energy**/**collinear** factorization



* *Distinctive signals* of small-x dynamics **expected**

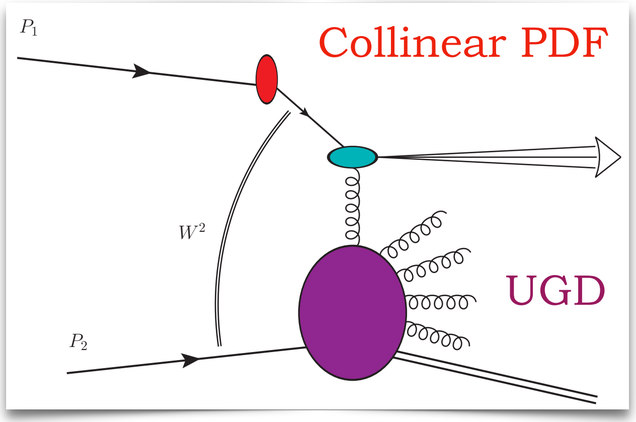
* Phenomenology:
  forward jet, Drell-Yan, Higgs or vector meson

Backup

Hybrid or pure factorization?

Forward emissions

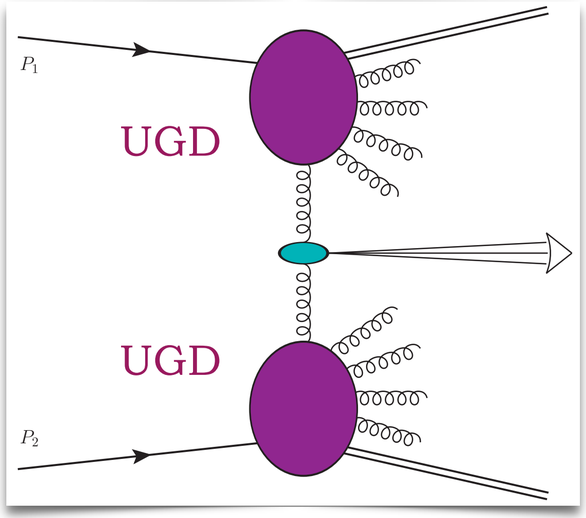
* *Asymmetric* config. ↔ fast parton + small-x gluon
* Hybrid **high-energy**/**collinear** factorization



* *Distinctive signals* of small-x dynamics **expected**
* Phenomenology:
  forward jet, Drell-Yan, Higgs or vector meson

Central emissions

* *Gluon induced* ↔ small-x gluons
* Pure **high-energy** factorization



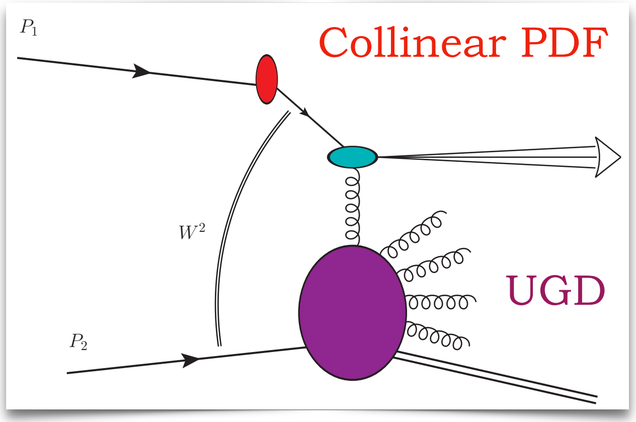
* Small-x dynamics to **enhance** f.o. description
* Phenomenology:
  central jet, Higgs or vector meson

Backup

Hybrid or pure factorization?

Forward emissions

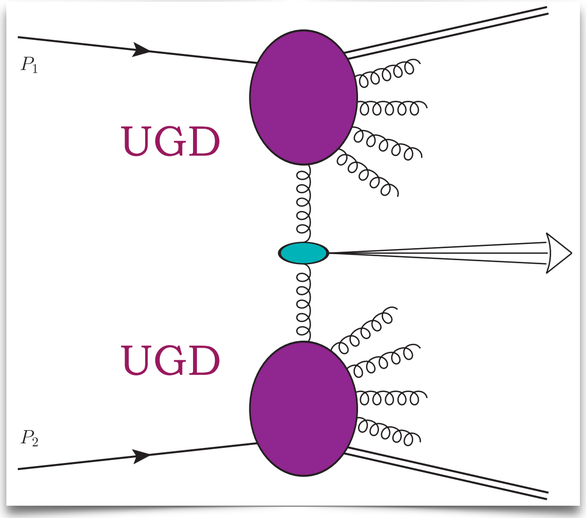
* *Asymmetric* config. ↔ fast parton + small-x gluon
* Hybrid **high-energy**/**collinear** factorization



* *Distinctive signals* of small-x dynamics **expected**
* Phenomenology:
  forward jet, Drell-Yan, Higgs or vector meson

Central emissions

* *Gluon induced* ↔ small-x gluons
* Pure **high-energy** factorization

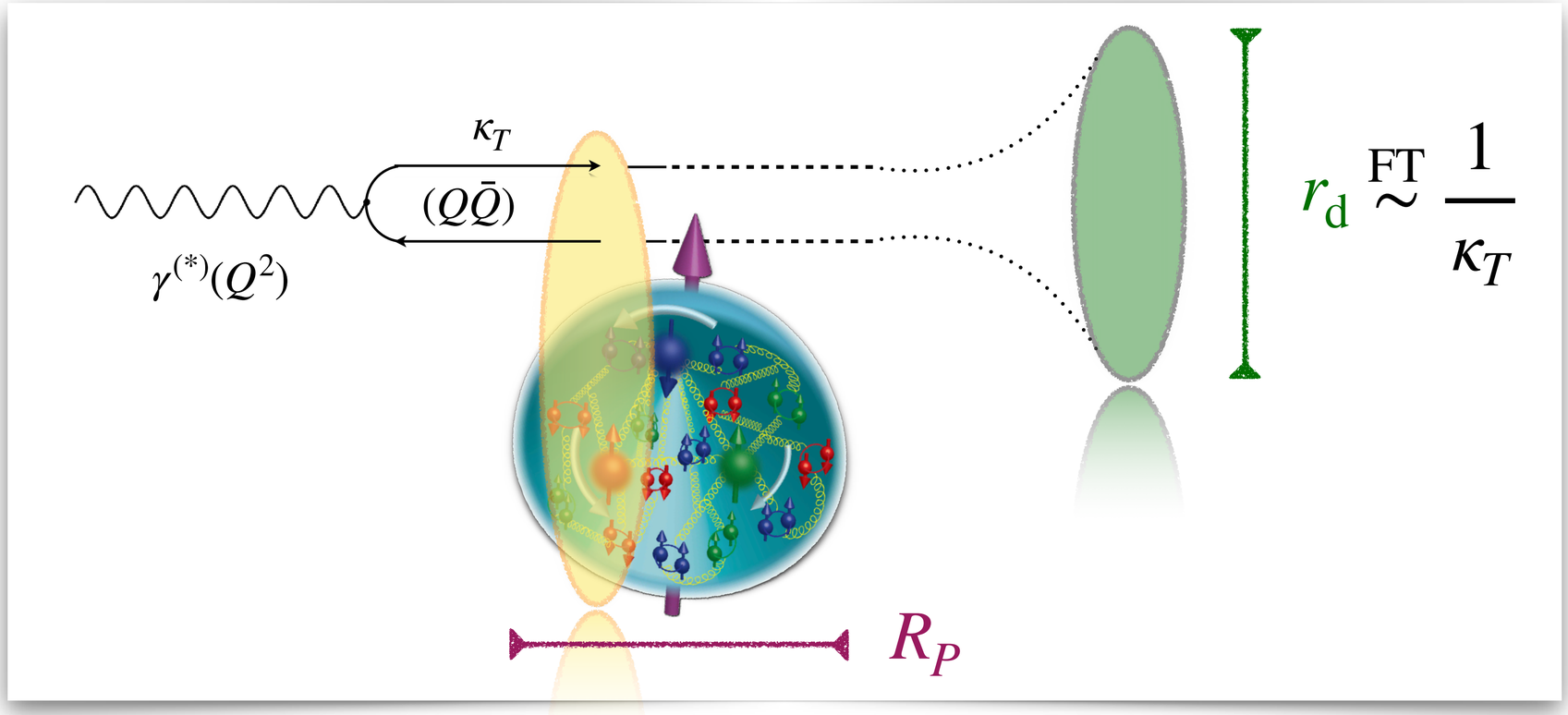


* Small-x dynamics to **enhance** f.o. description
* Phenomenology:
  central jet, Higgs or vector meson

Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

Backup

Diffractive $\gamma^* P$ scatterings and color dipoles



$$W_{\mu\nu} \propto \mathrm{Im}\left\{ i \int \mathrm{d}^4x\, e^{i\,q\cdot x} \langle P | \mathrm{T}\,[J_\mu(x)\, J_\nu(0)] | P \rangle \right\}$$

- Small-x $\Rightarrow$ Ioffe time $\gg R_P$
- At least one J_μ outside proton…
- …color dipole picture!

Backup

Exclusive forward ρ meson leptoproduction

Single forward emissions

Exclusive light VM: ρ^0, ω, ϕ

* *Small-size* dipoles $\Rightarrow$ large κ_T
* Collinear description: twist-2/-3 LVM NP **DAs**

$$\Phi^{\gamma^* \to \rho} \propto \int_0^1 \mathrm{d}z \, T_H^{\gamma^* \to \rho}(z, \kappa_T, Q, \mu_R, \mu_F) \, \phi^{\lambda_\rho}(z, \mu_F)$$

* Significance of small κ_T under investigation…
* HERA indication: no large-r_d dynamics
* LVMs as tools: discrimination among UGD models
* LVMs as tools: UGD extraction $\Leftarrow$ HERA + EIC fits

Backup

Single forward emissions

Exclusive light VM: ρ^0, ω, ϕ

* *Small-size* dipoles ⇒ large κ_T
* Collinear description: twist-2/-3 LVM NP **DAs**

$$\Phi^{\gamma^* \to \rho} \propto \int_0^1 \mathrm{d}z \, T_H^{\gamma^* \to \rho}(z, \kappa_T, Q, \mu_R, \mu_F) \, \phi^{\lambda_\rho}(z, \mu_F)$$

* Significance of small κ_T under investigation…
* HERA indication: no large-r_d dynamics
* LVMs as tools: discrimination among UGD models
* LVMs as tools: UGD extraction ⇐ HERA + EIC fits

Quarkonia

* Size of dipoles ⇒ wide range of κ_T
* Description: **NRQCD** (combined with LFWFs)

$$\left[\mathrm{LFWF} \otimes \mathscr{A}_{\mathrm{dip.}} \right] \overset{\text{dilute}}{\longleftrightarrow} \left[\Phi^{\gamma^* \to J/\Psi} \otimes \mathrm{UGD} \right]$$

* Validity of *small-size* dipoles questionable…
* NRQCD: large-r_d dynamics for $\Psi(2s)$ ($\Upsilon(2s)$?)

🔗 [K. Suzuki *et al.* (2000)]; 🔗 [J. Cepila *et al.* (2019)]; 🔗 [M. Hentschinski *et al.* (2020)]

* Onia as tools: scan of TMD/HEF intersection range

Backup