High-Energy QCD and Diffraction
Part I

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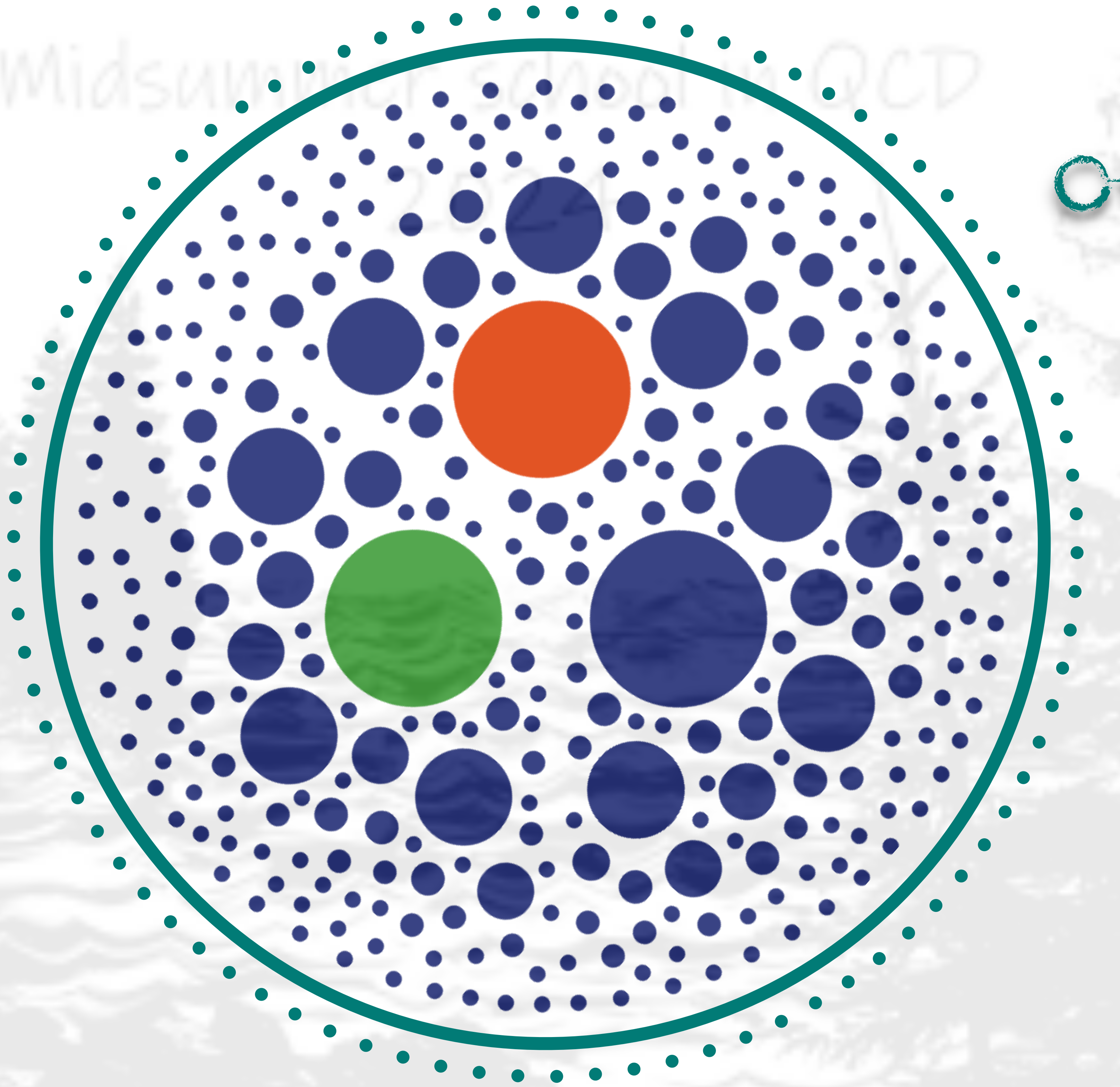
Hors d'œuvre

High-energy QCD in the precision era



LHC & new-gen. colliders:

A new era

for particle physics

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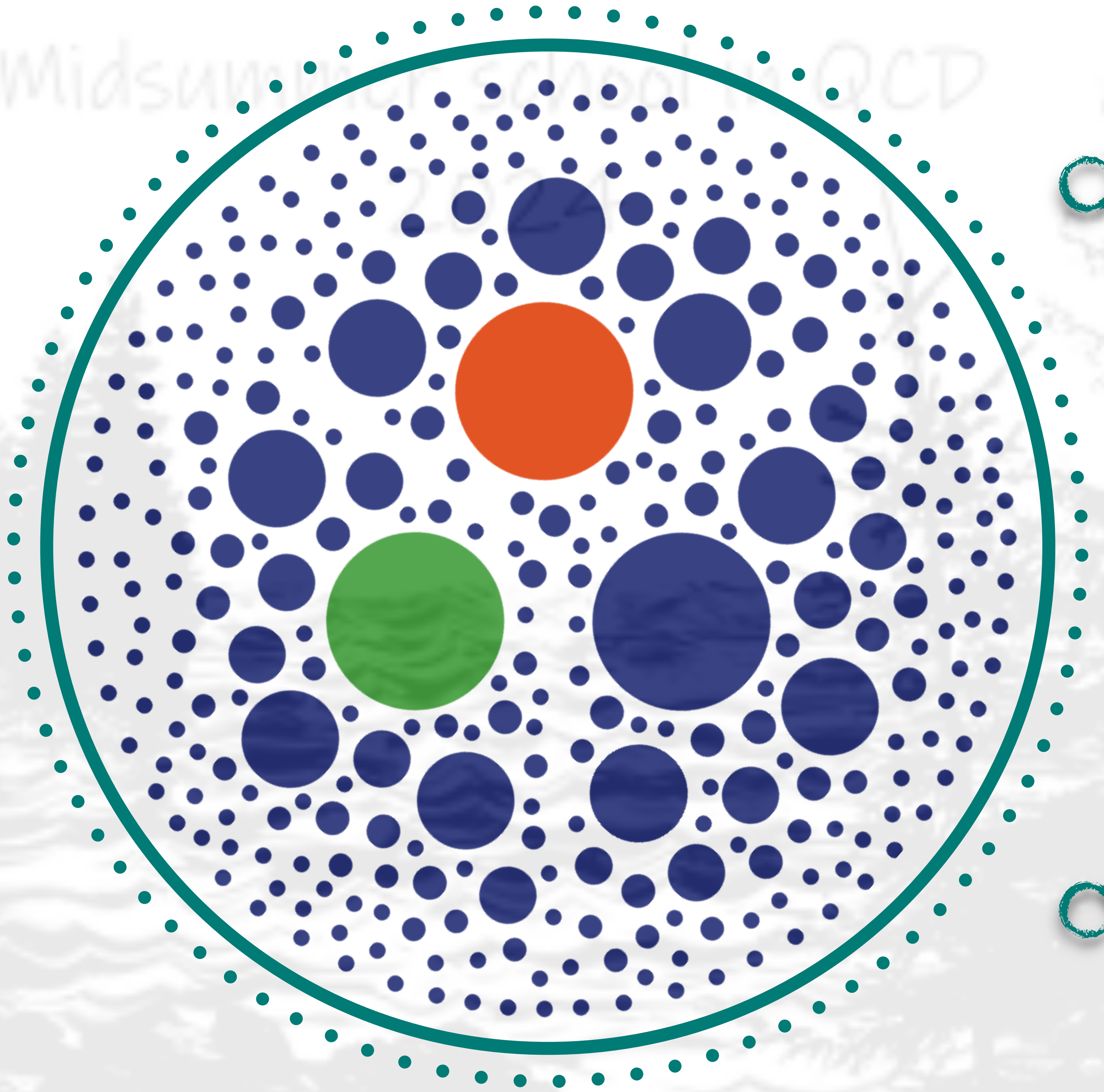

LHC & new-gen. colliders:

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Fixed-order pQCD:

Accurate

calculations

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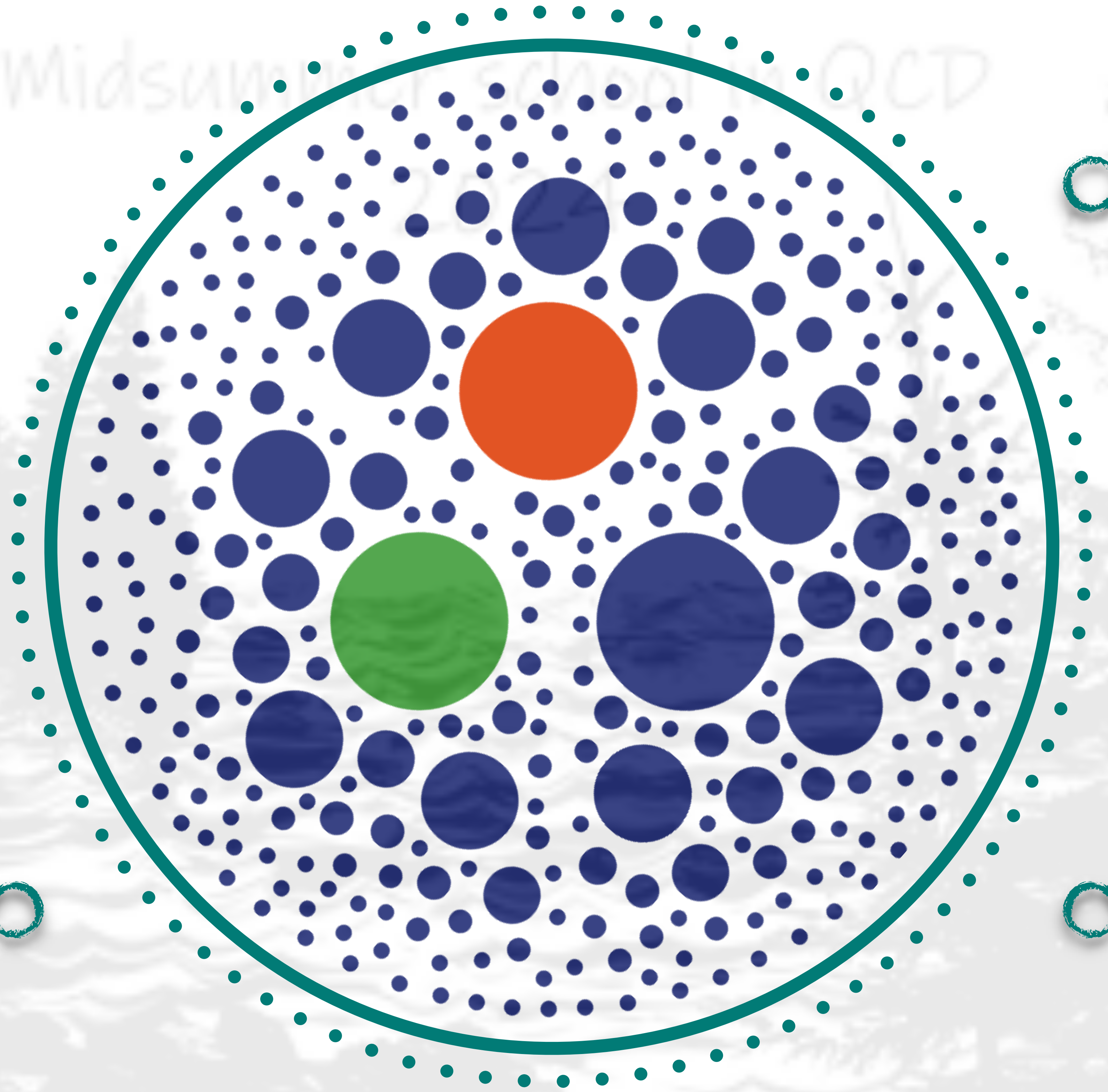

Fixed-order pQCD:
Misses
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Hors d'œuvre

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Restoring convergence:
All-order studies
High-energy resummation

LHC & new-gen. colliders:
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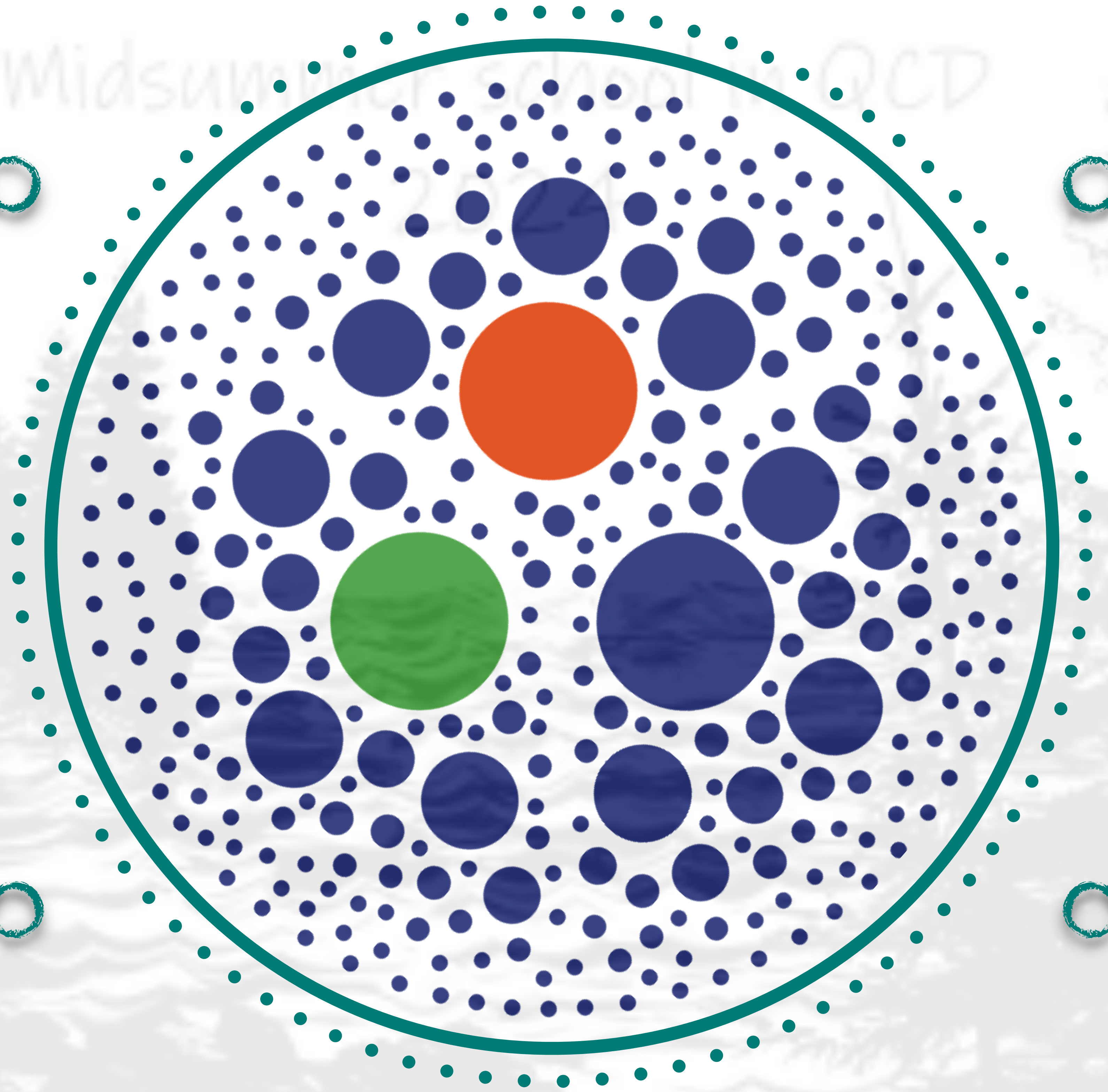

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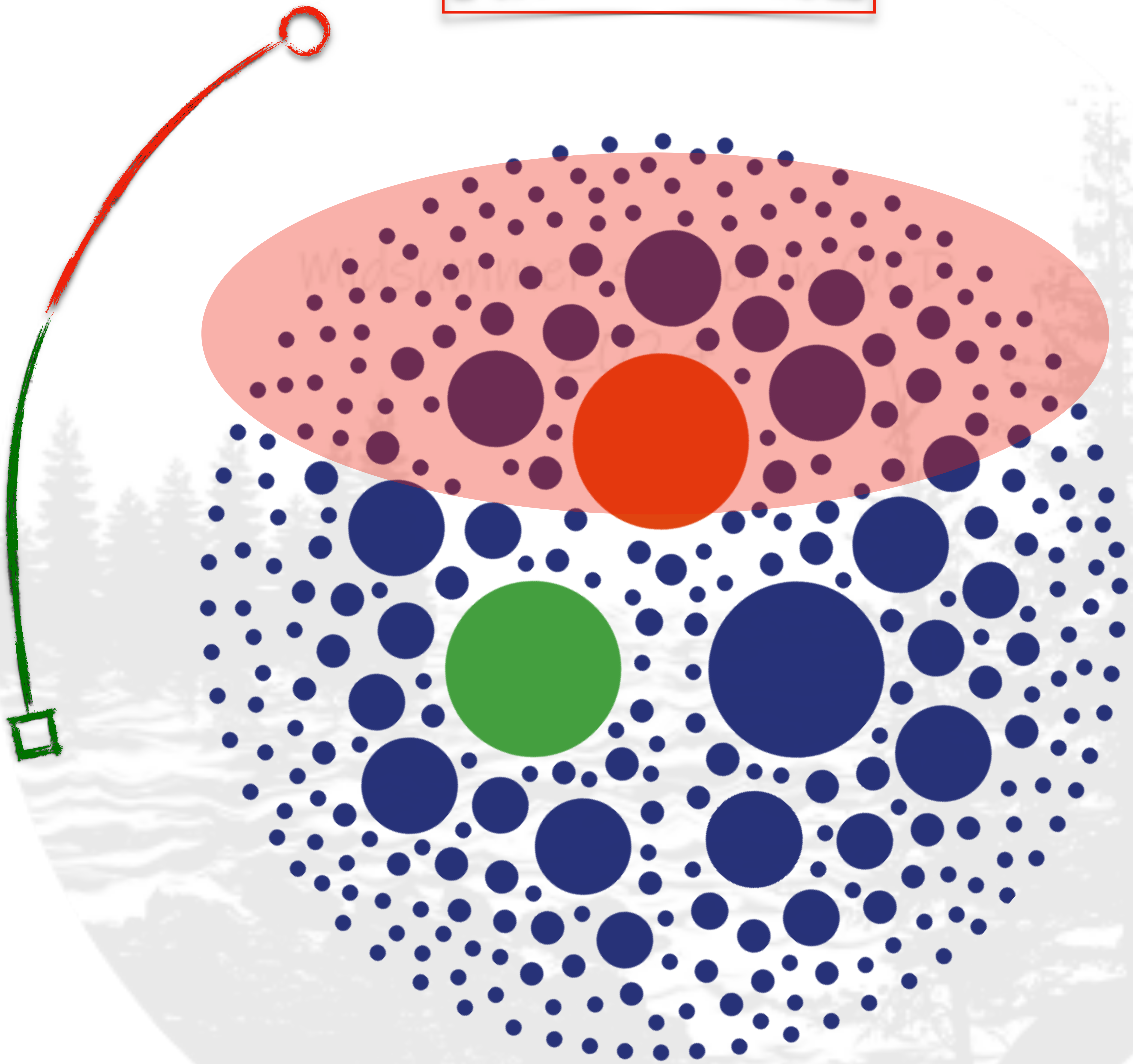
Hors d'œuvre

Factorization



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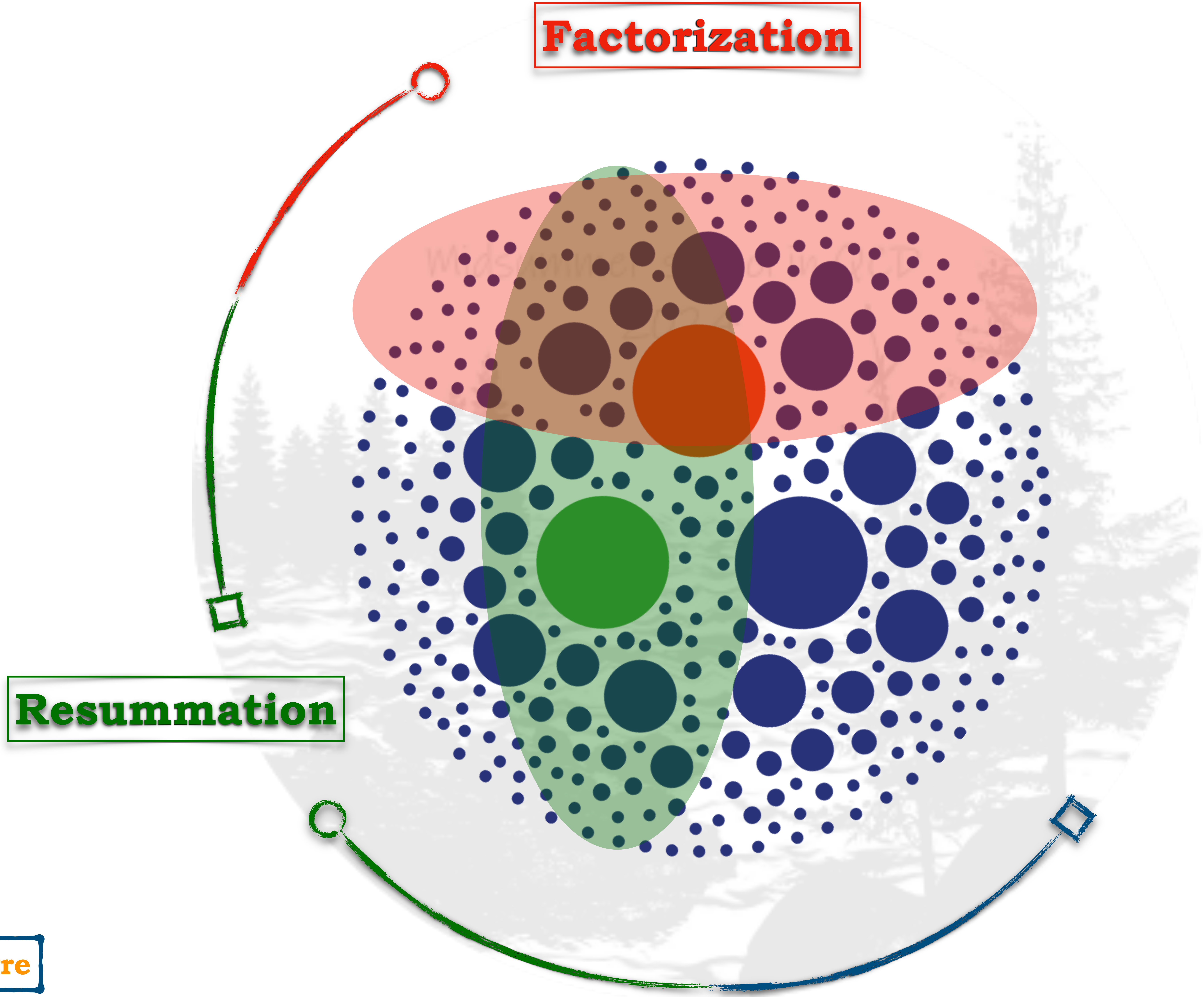

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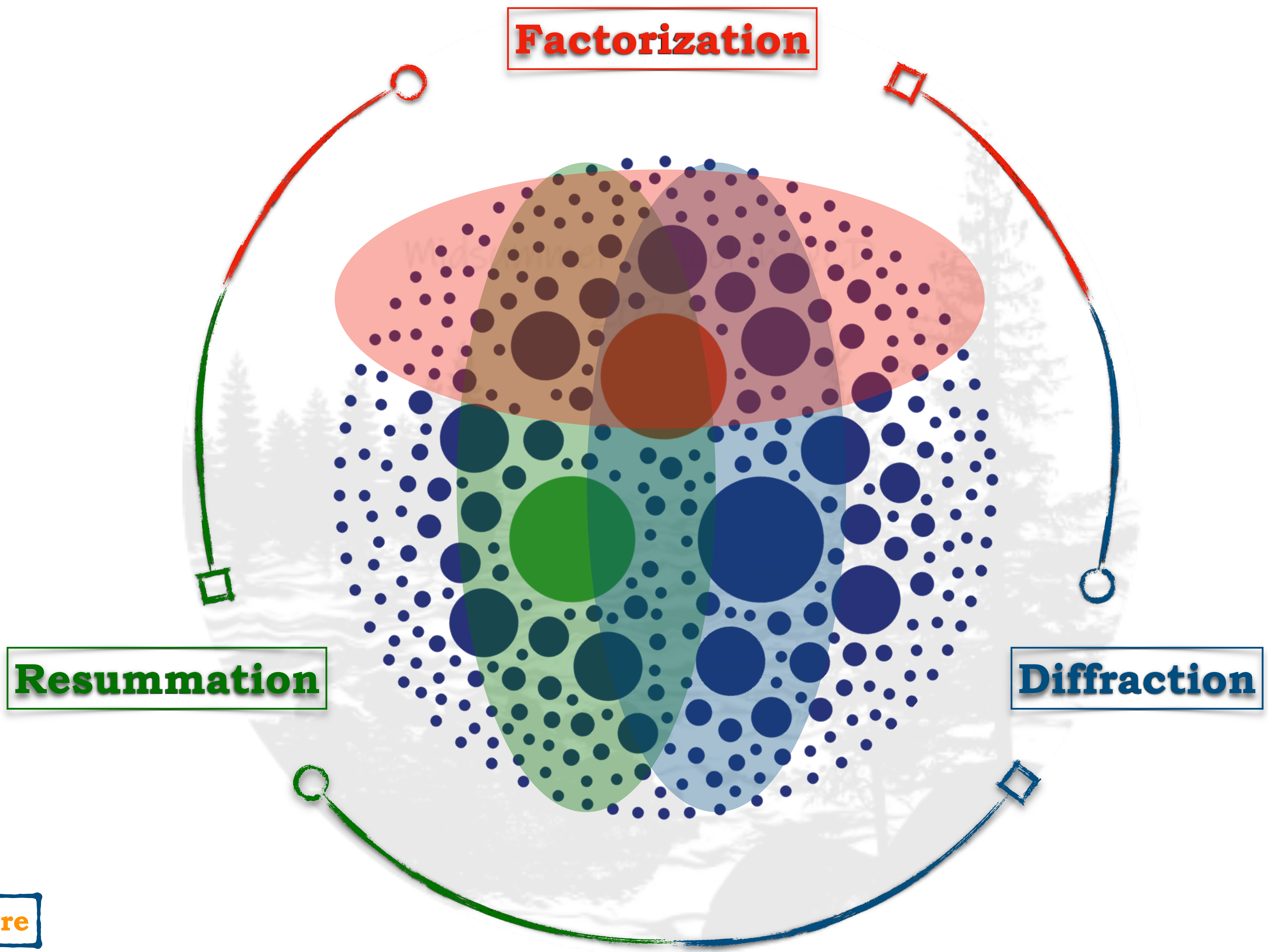

Hors d’œuvre

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A basic overview

QCD & resummations - LL & NLL accuracy - Diffractive processes

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Jet-jet and hadron-jet correlations

Mueller-Navelet jets - Light-flavored hadrons - NLL instabilities

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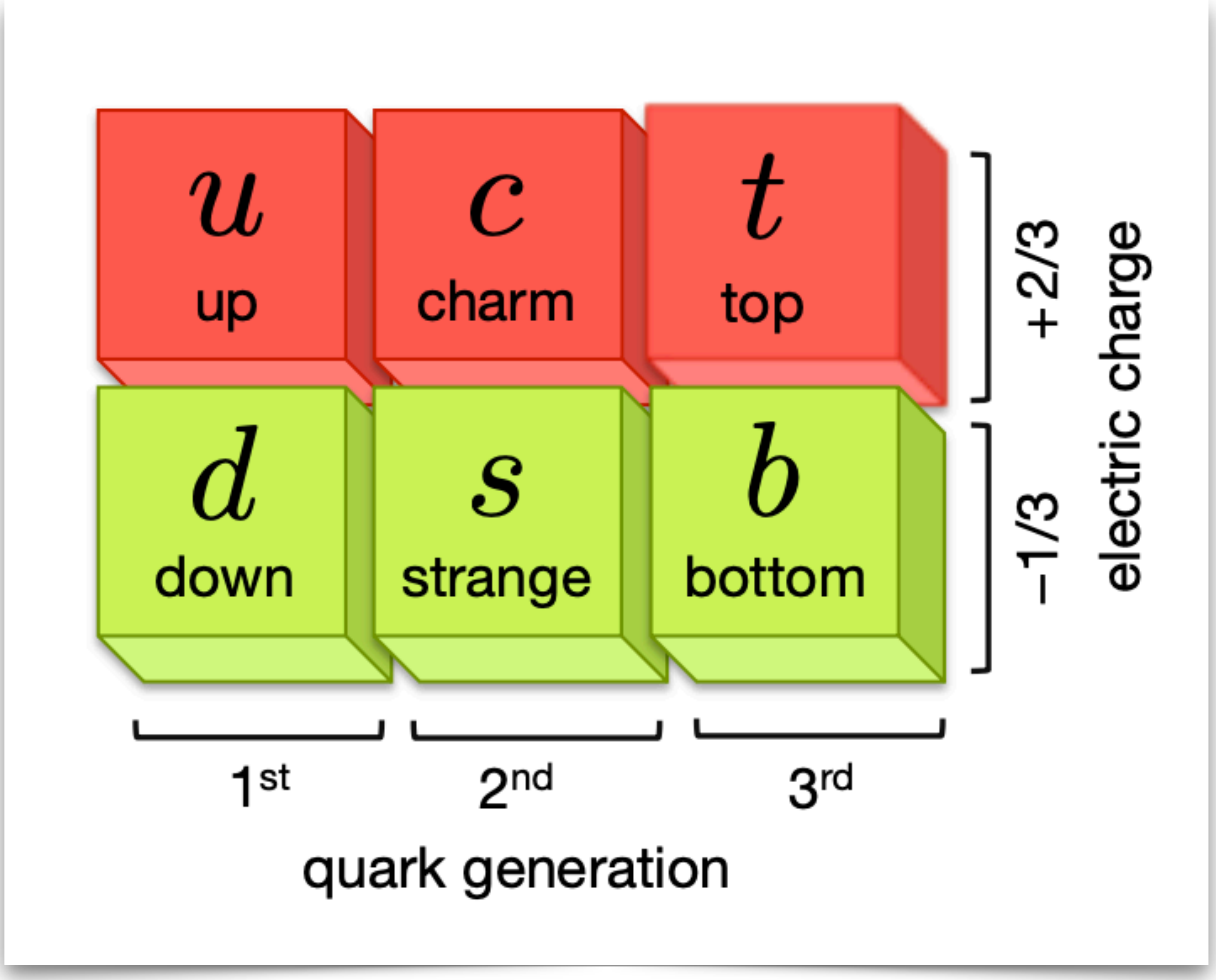
QCD
& resummations

The QCD sector: Quarks & Gluons

Quarks



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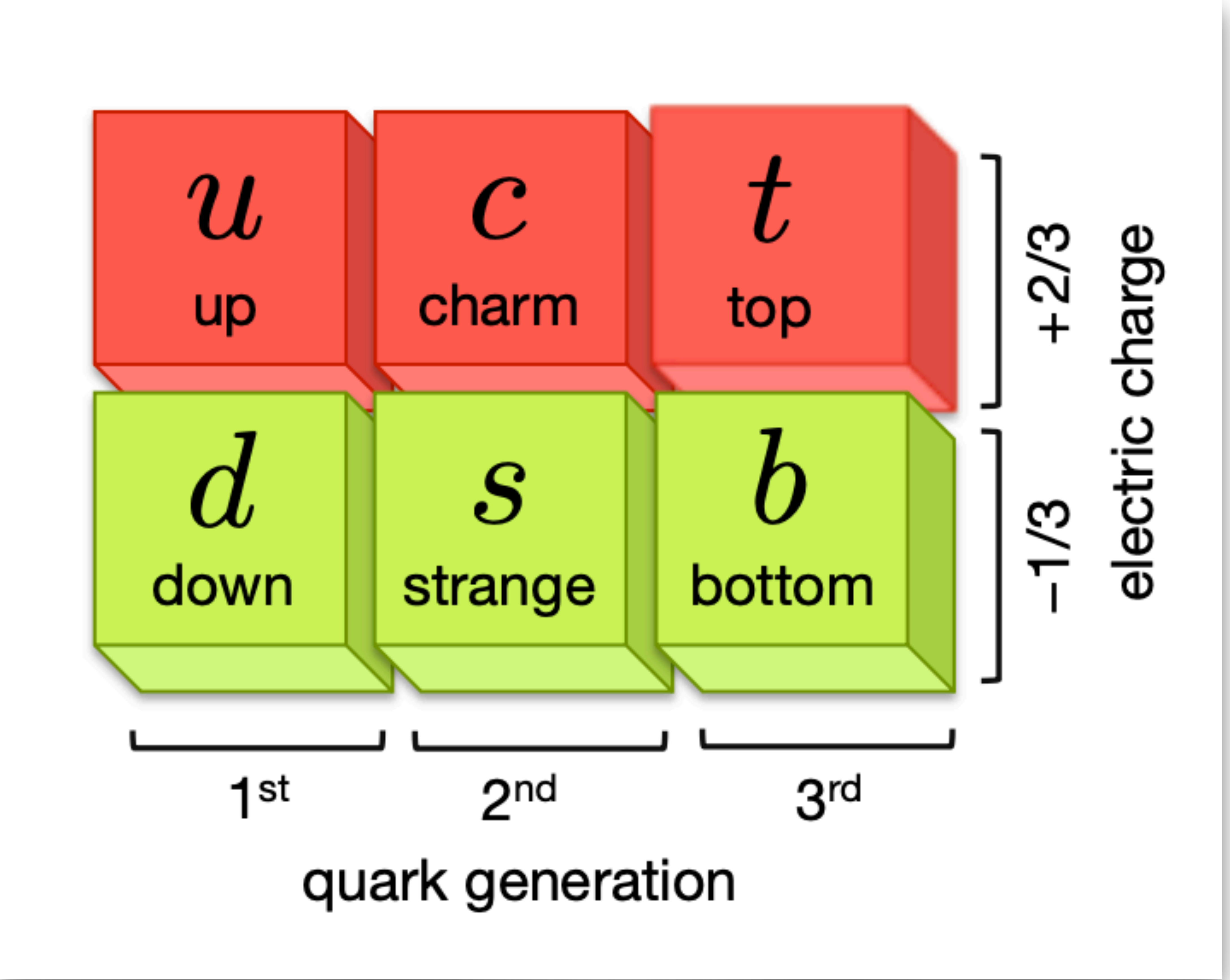
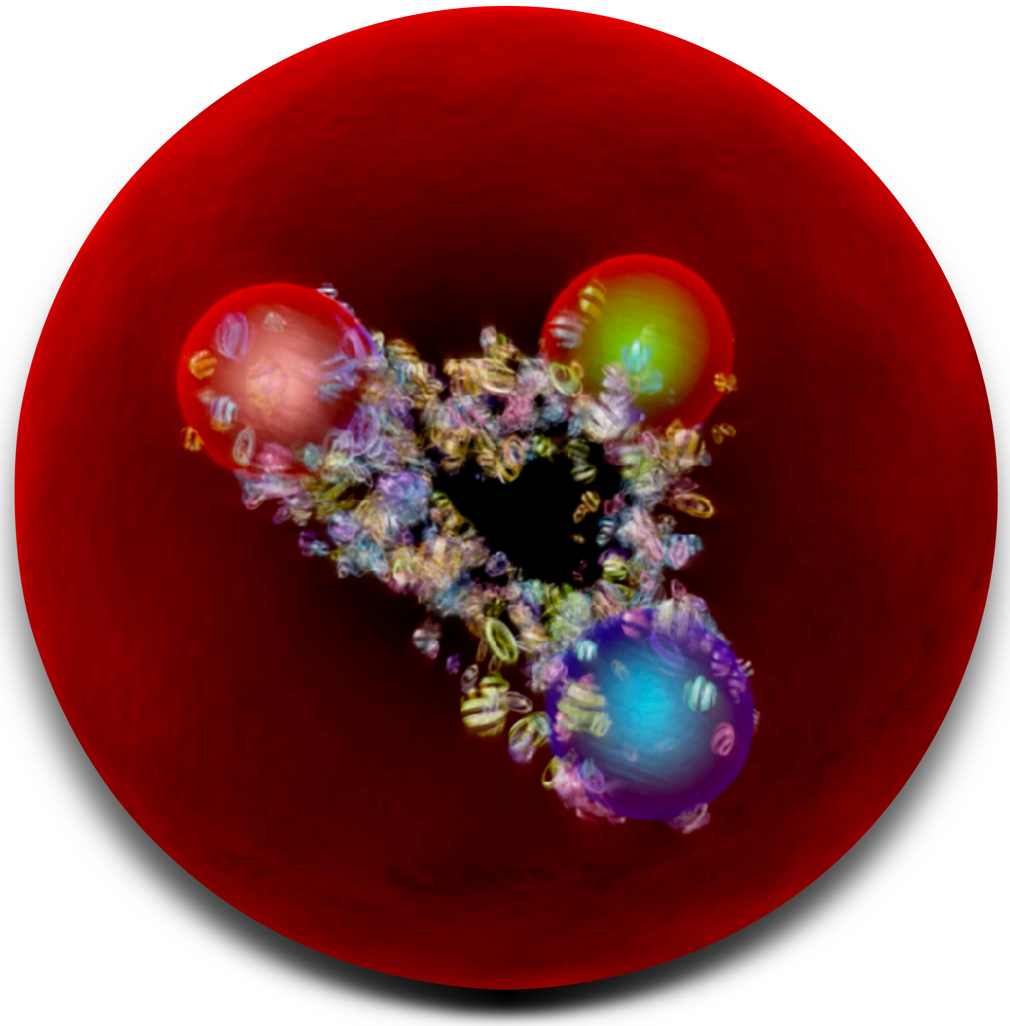


Quarks + Gluons = Partons



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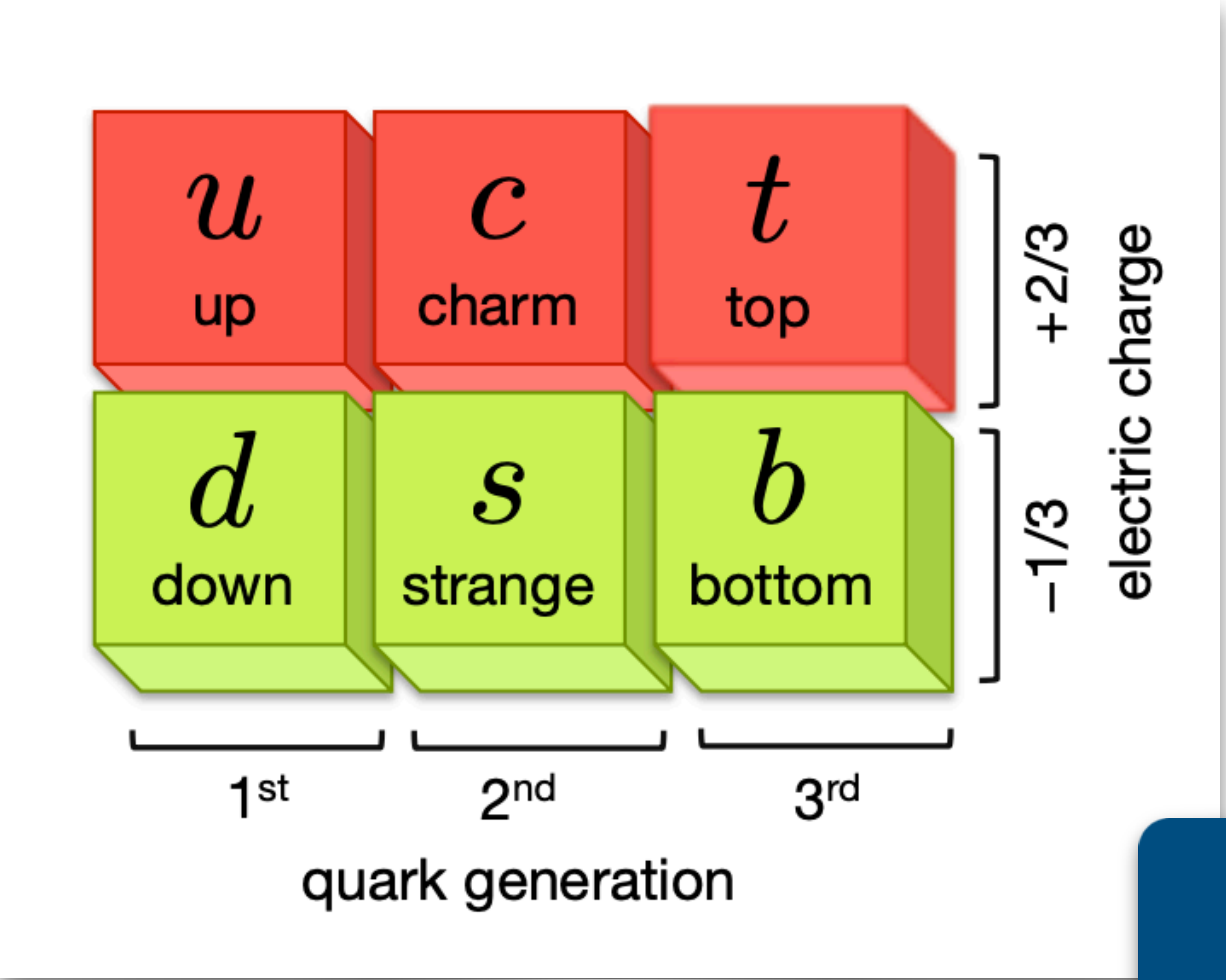

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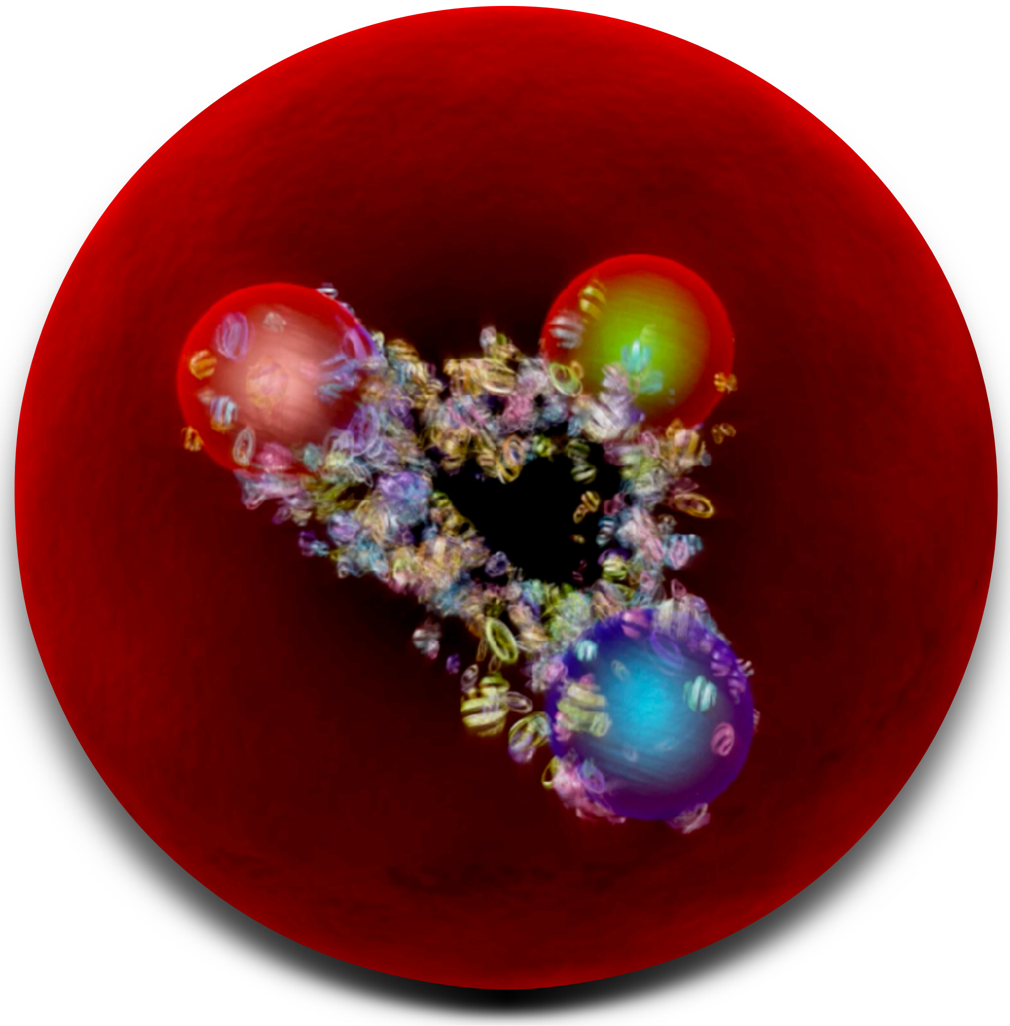
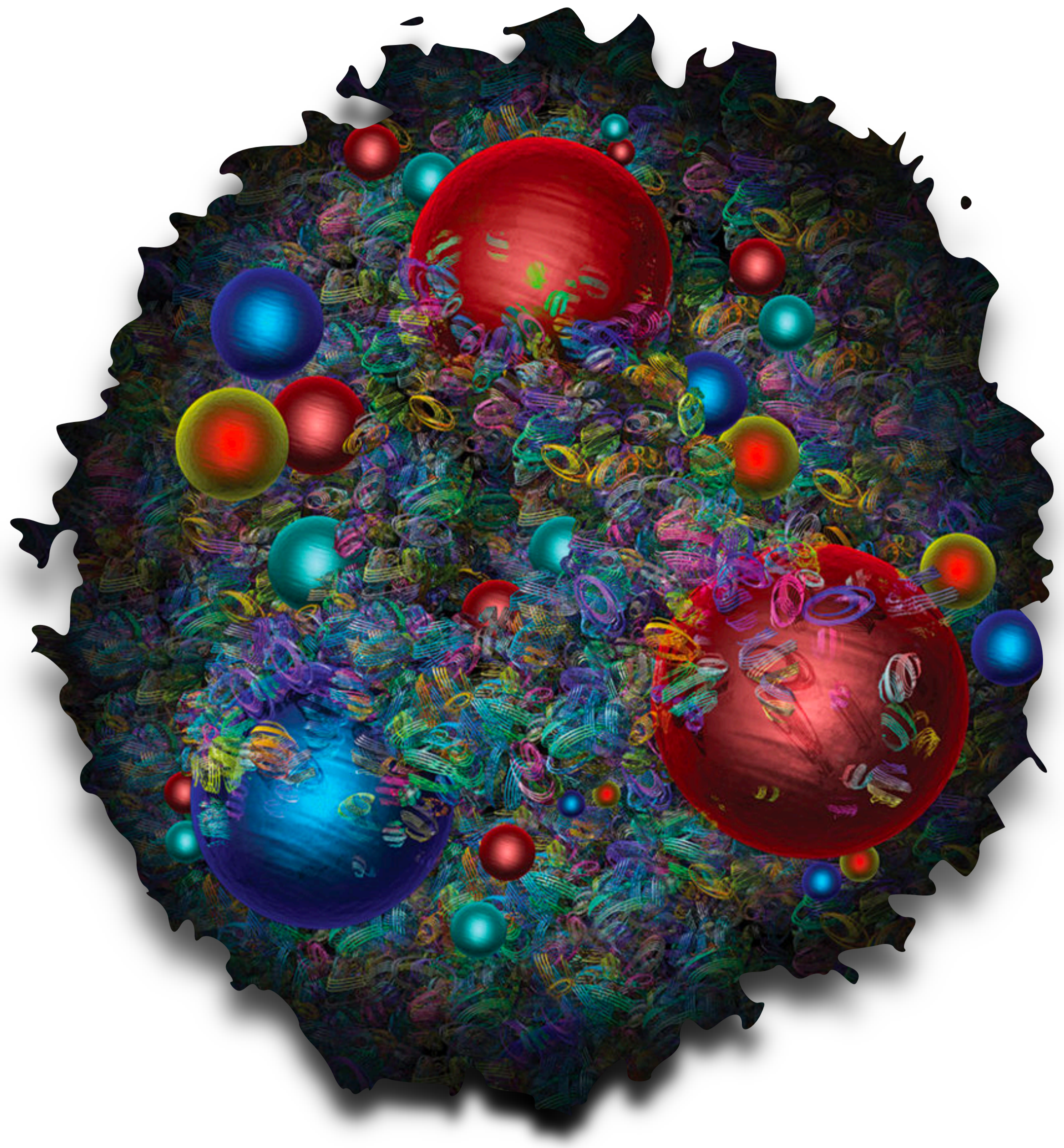


Current quarks
vs
Constituent quarks



Asymptotic freedom & confinement

Observed hadrons are not elementary particles. They are colorless

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Asymptotic freedom

- Strong force decreases with $(\text{distance})^{-1}$
- Partons almost free in the nucleon
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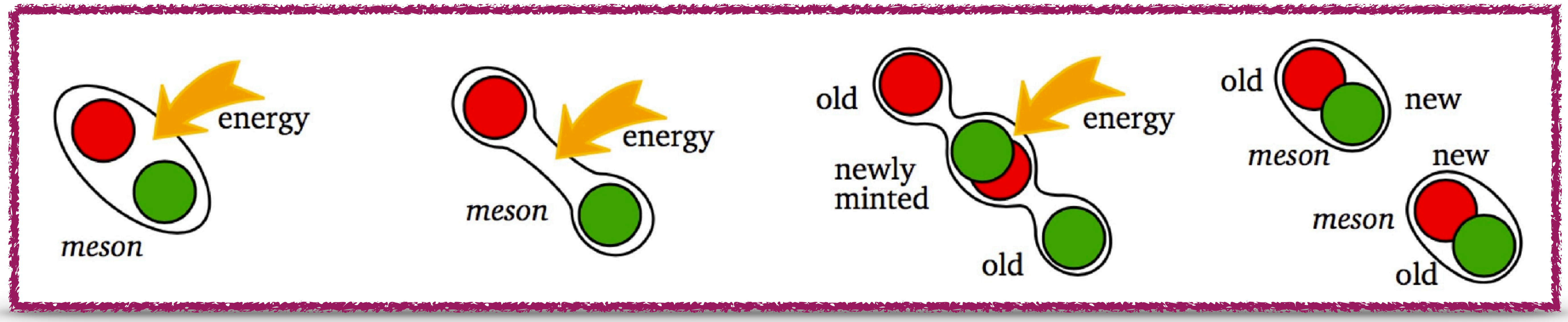

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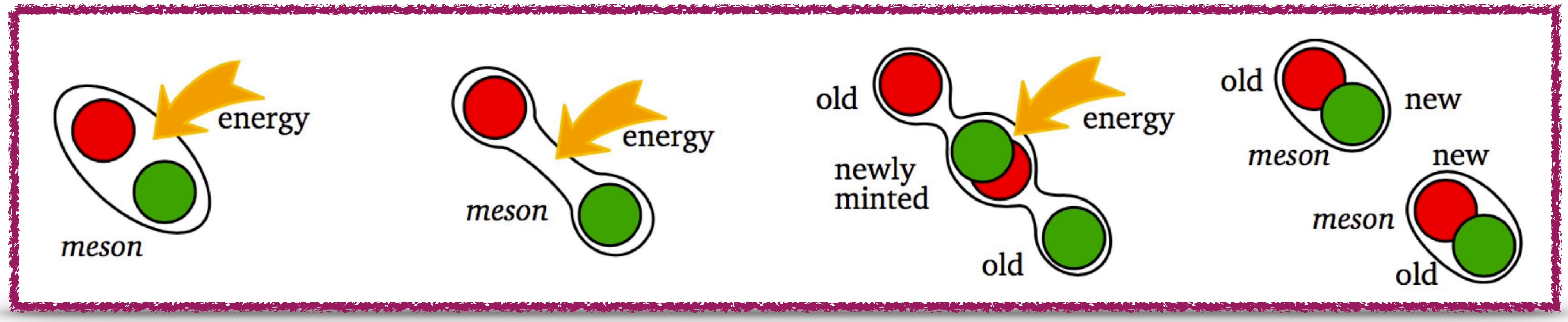
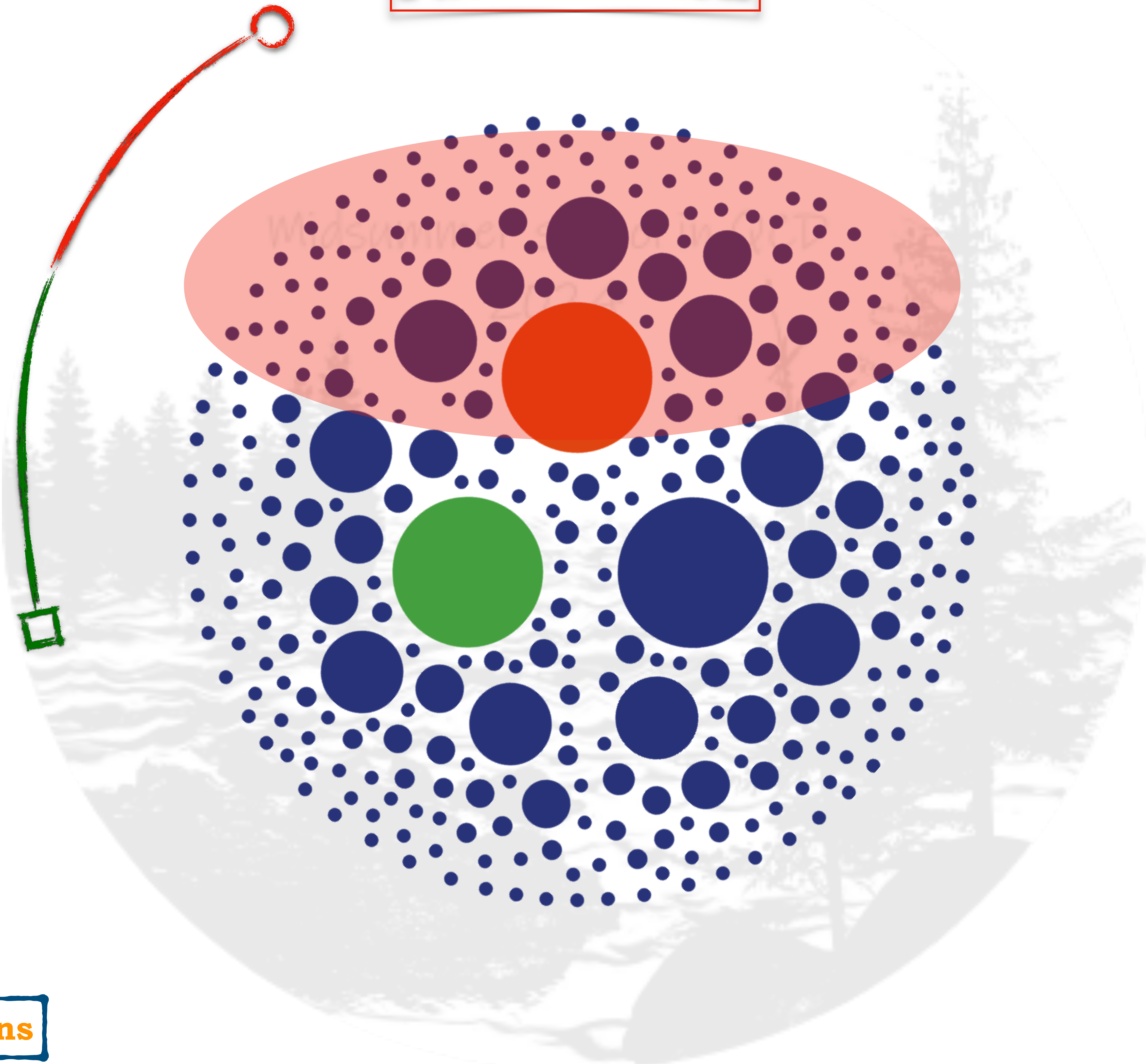


QCD factorization theorems

Factorization



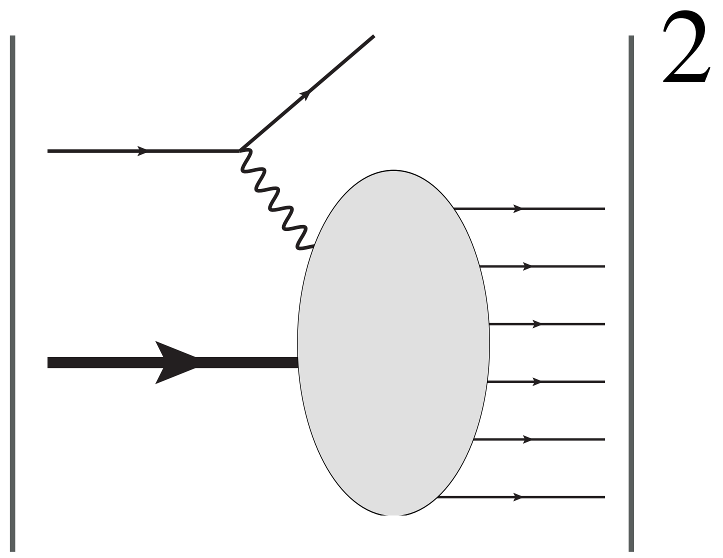
¿ What is factorization ?

Factorization in QCD

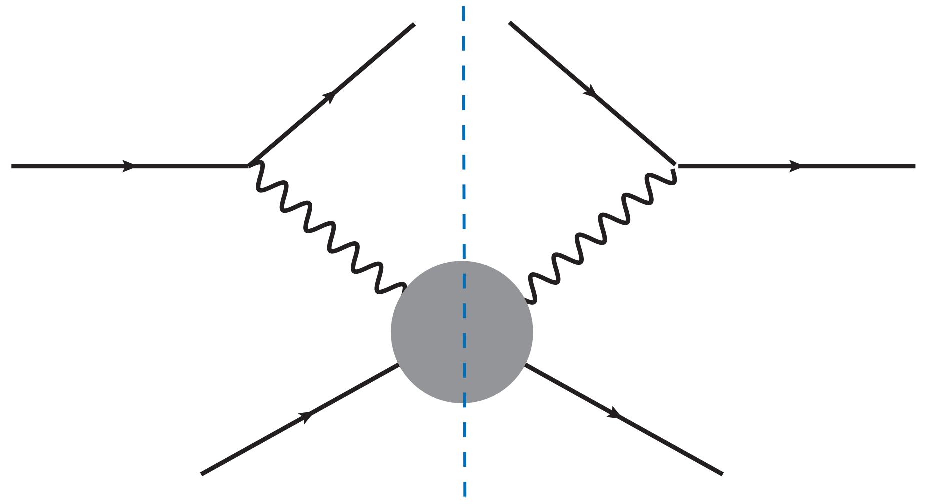
- Vital component of QCD $\rightarrow$ no predictive power in hadronic reactions otherwise
- Consequence of decoupling of long-distance dynamics from short-distance one
- Proof of factorization highly non trivial $\rightarrow$ "as complex as proof of renormalization"
- Exception rather than rule: valid for a few processes, assumed in pheno studies
- Different kinds of factorization $\rightarrow$ PDF universality, evolution equations

Factorization & QCD observables

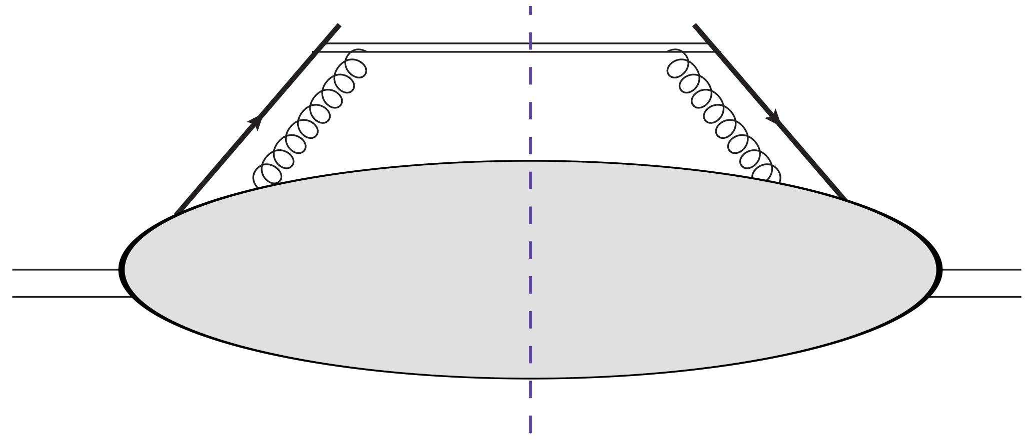
$d\sigma \propto L_{\mu\nu} W^{\mu\nu} \Rightarrow$



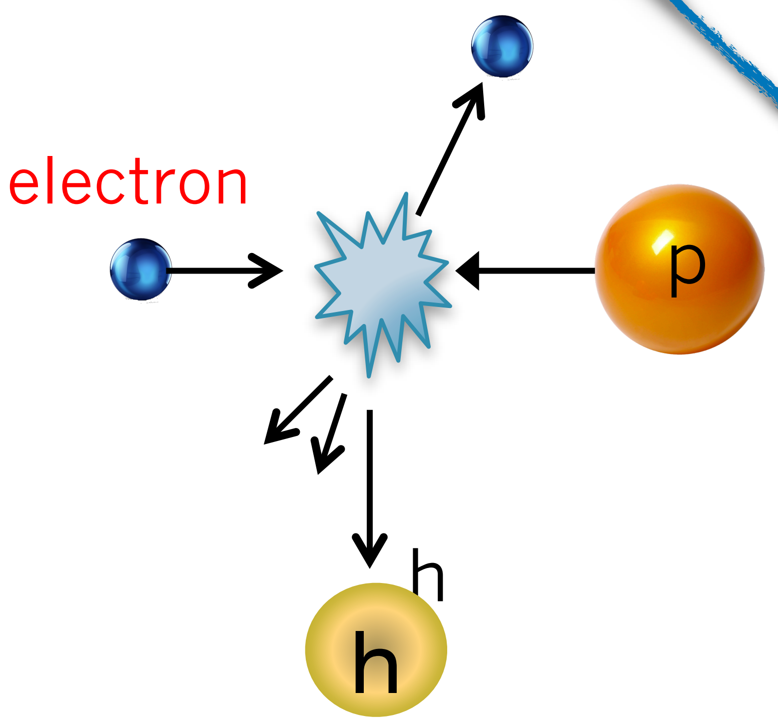
$\approx$



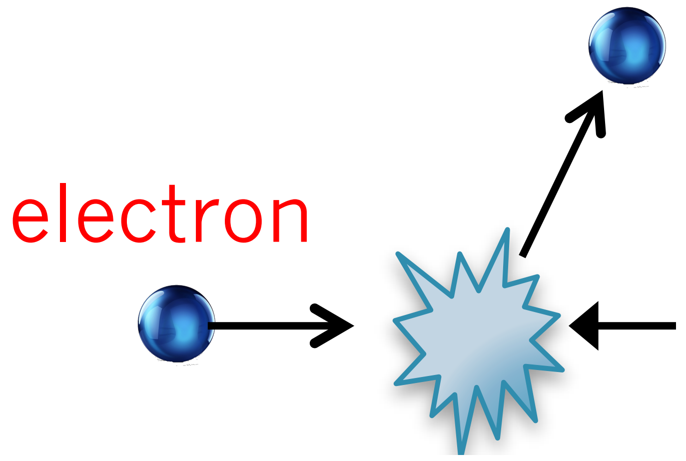
$\otimes$

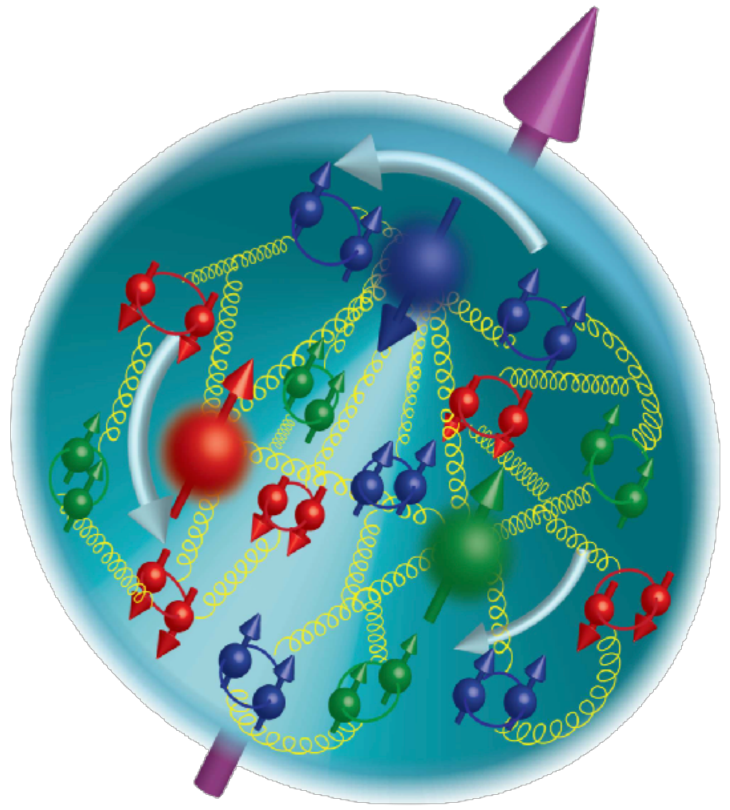


$+\ \mathcal{O}\left(\frac{M}{Q}\right)$



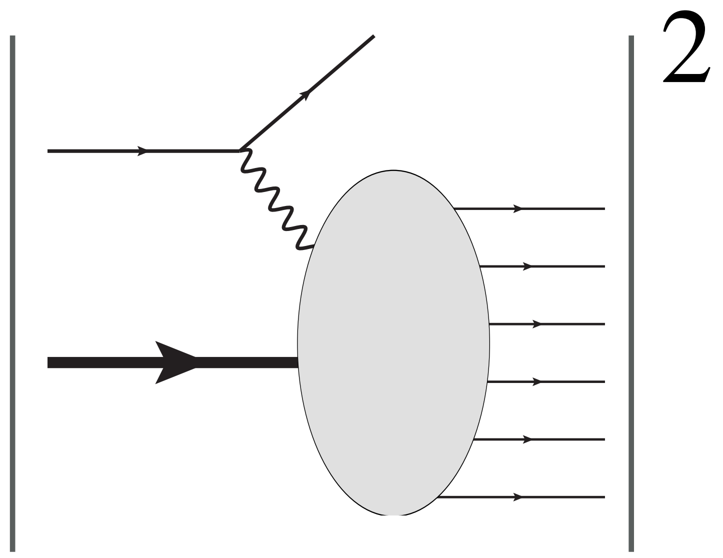
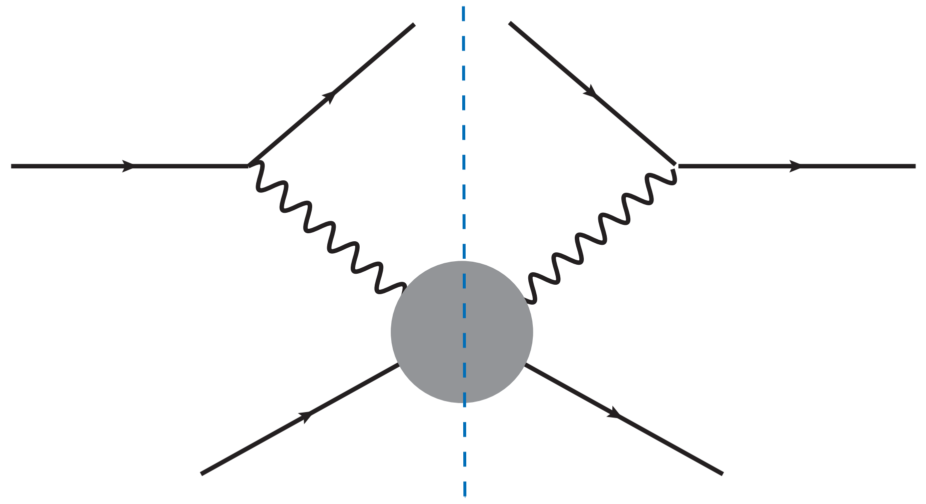
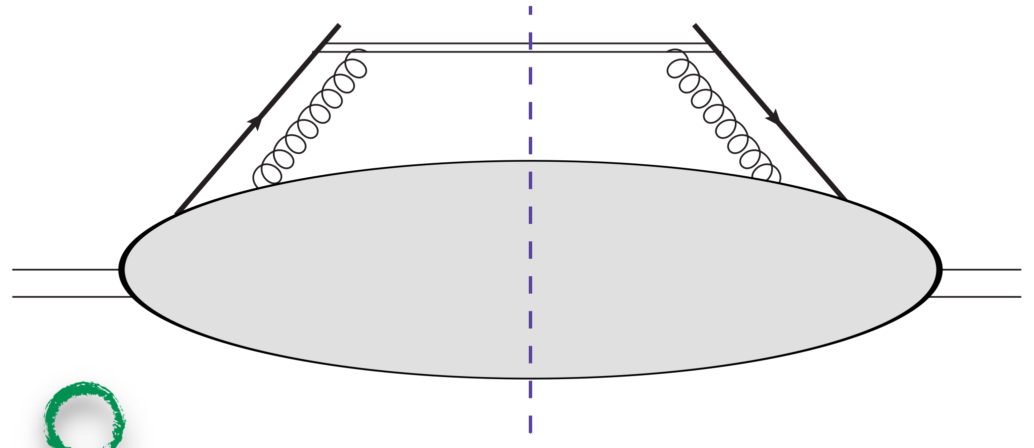
factorization

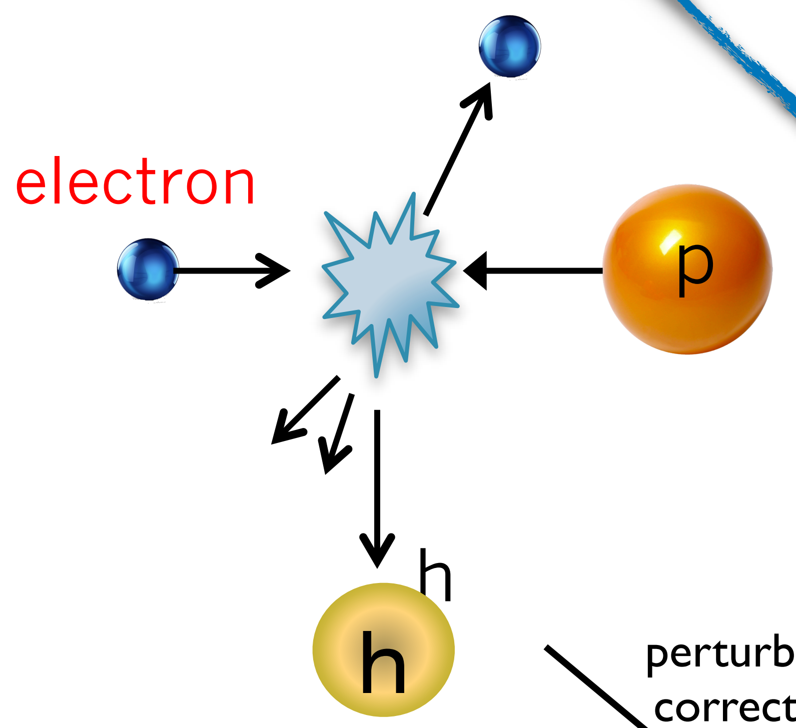


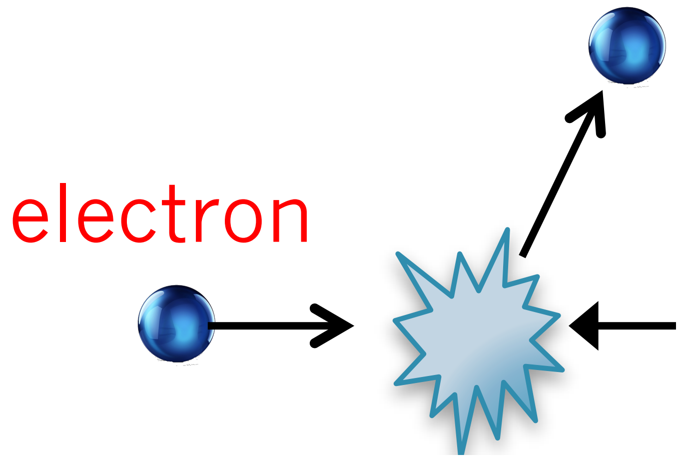


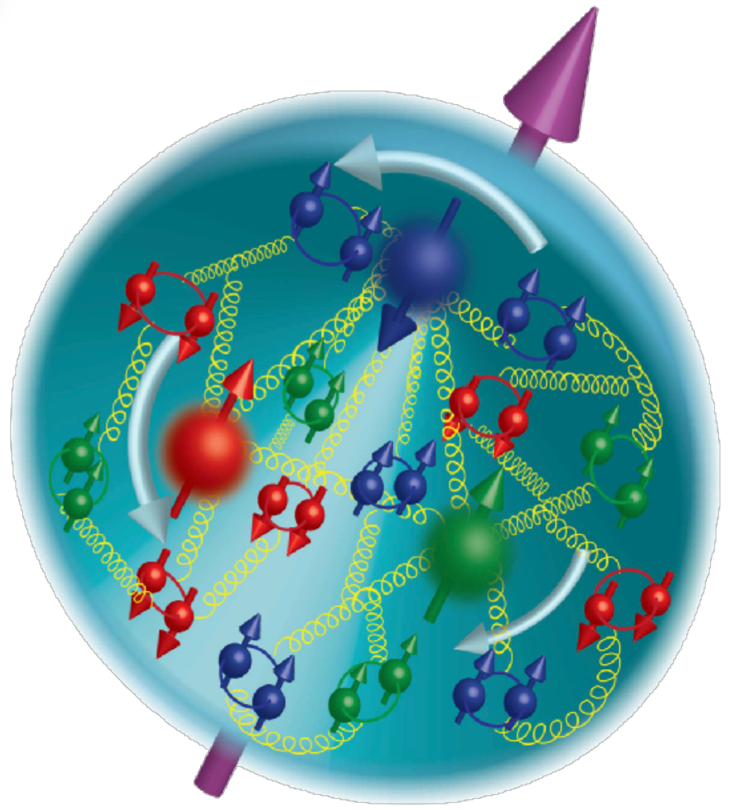
power corrections

Factorization & QCD observables

$d\sigma \propto L_{\mu\nu} W^{\mu\nu} \Rightarrow$  $\approx$  $\otimes$  $+ \mathcal{O}\left(\frac{M}{Q}\right)$

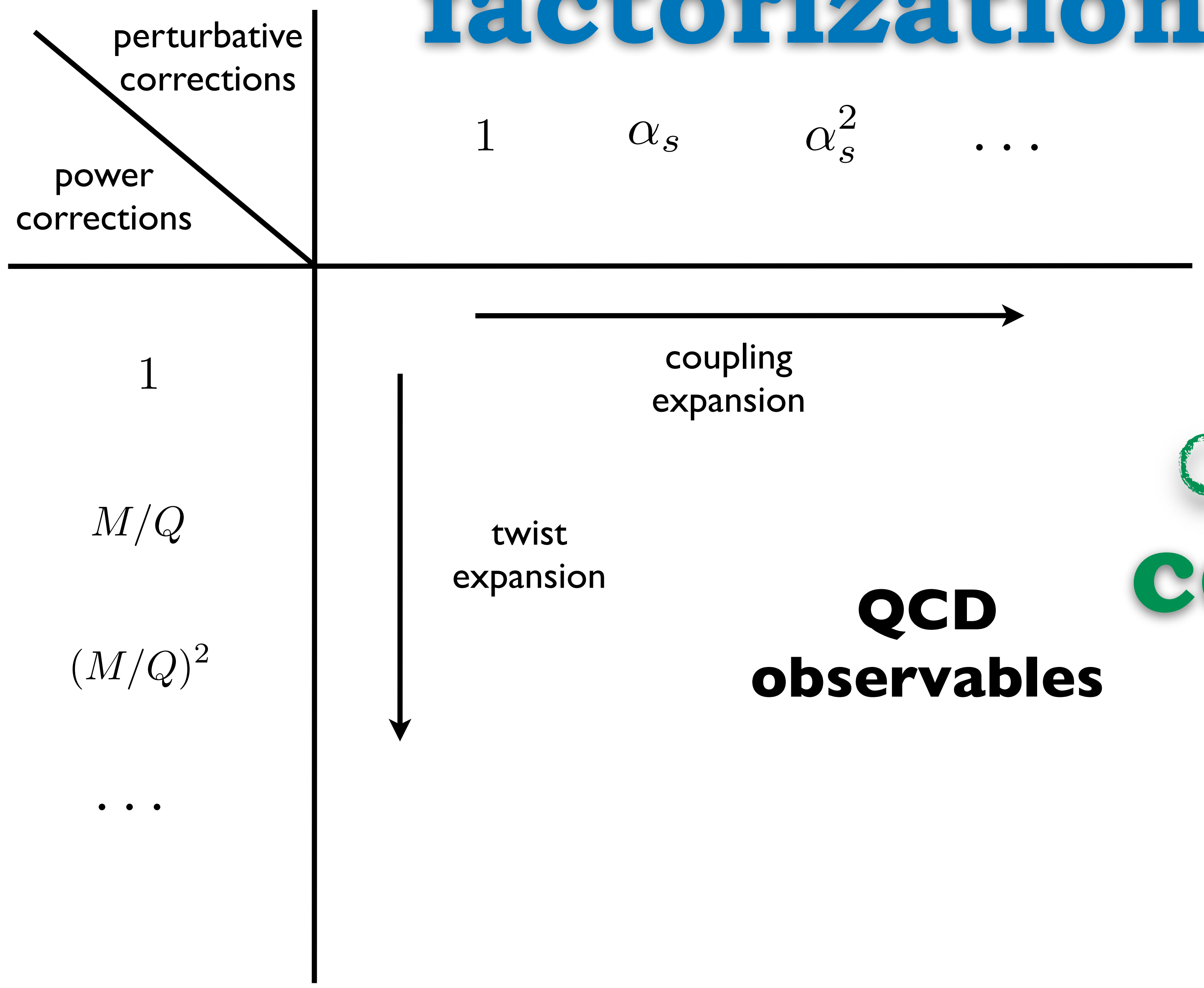






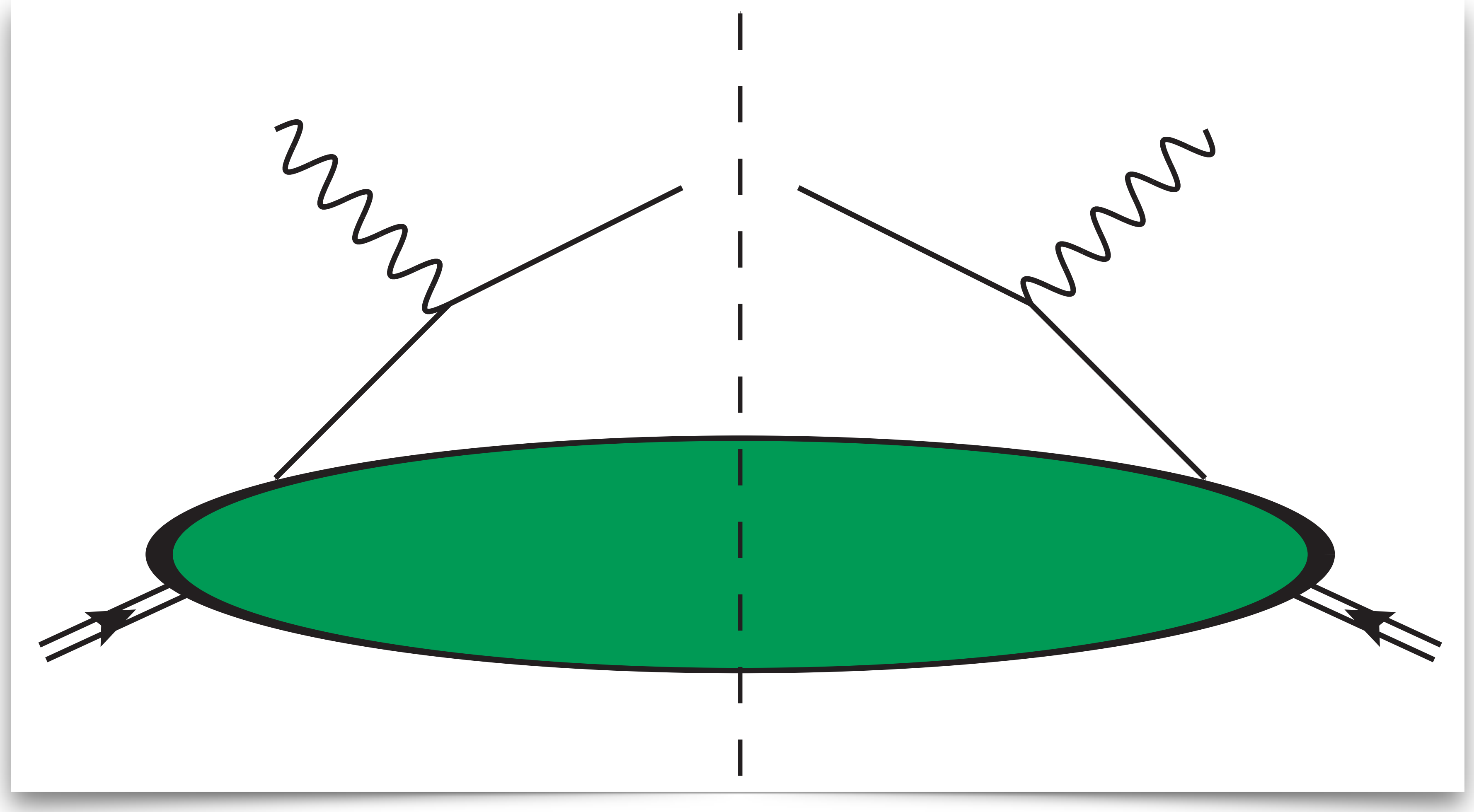
factorization

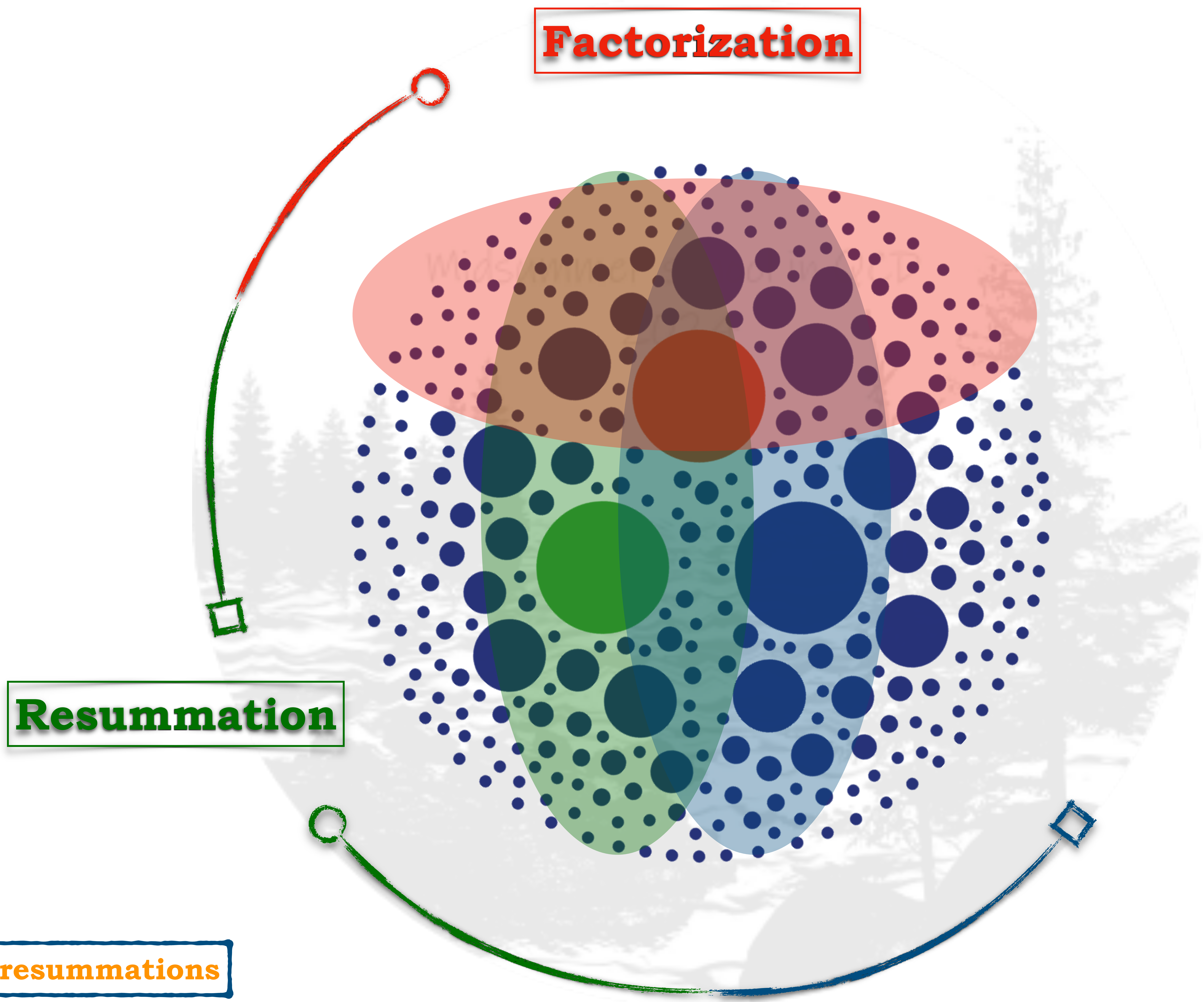
power corrections



QCD observables

parton correlator




Factorization
Resummation

¿ What is a resummation ?

🤔

Resummations in QCD

Resummations in QCD

- Precision QCD $\leftarrow$ fixed-order calculations

Resummations in QCD

$$\alpha_s^m \ln^n(Q_i/Q_j)$$

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- Large logs (p_T/parton shower, x, energy, jet radius, etc.) → spoil pQCD convergence

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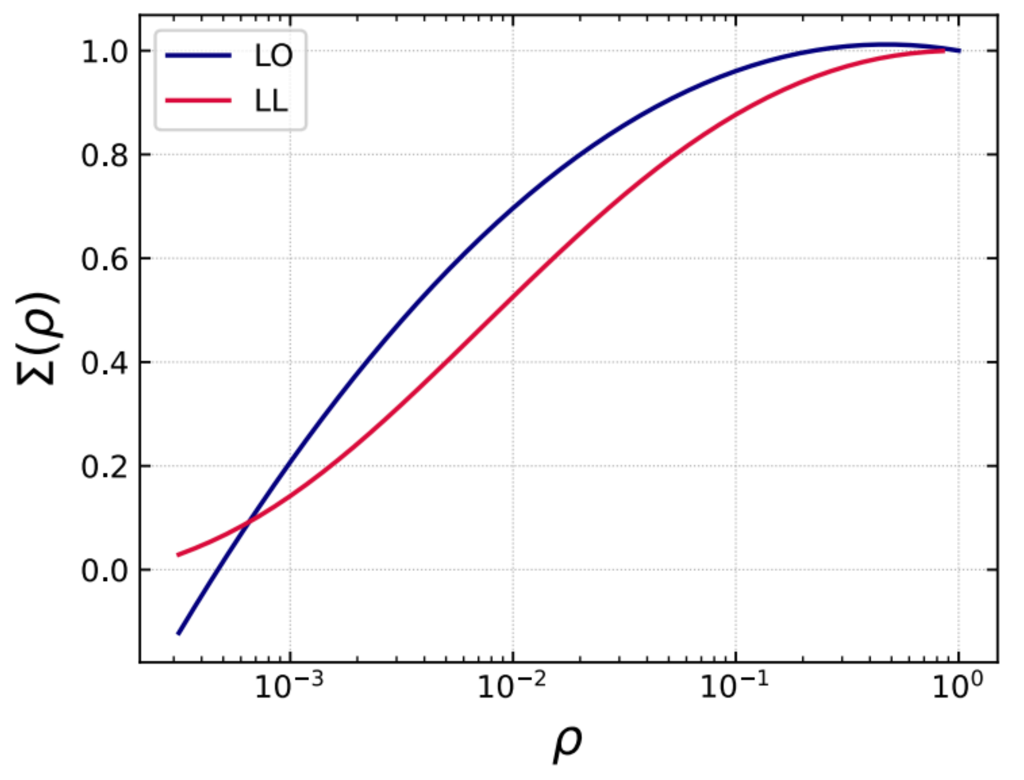
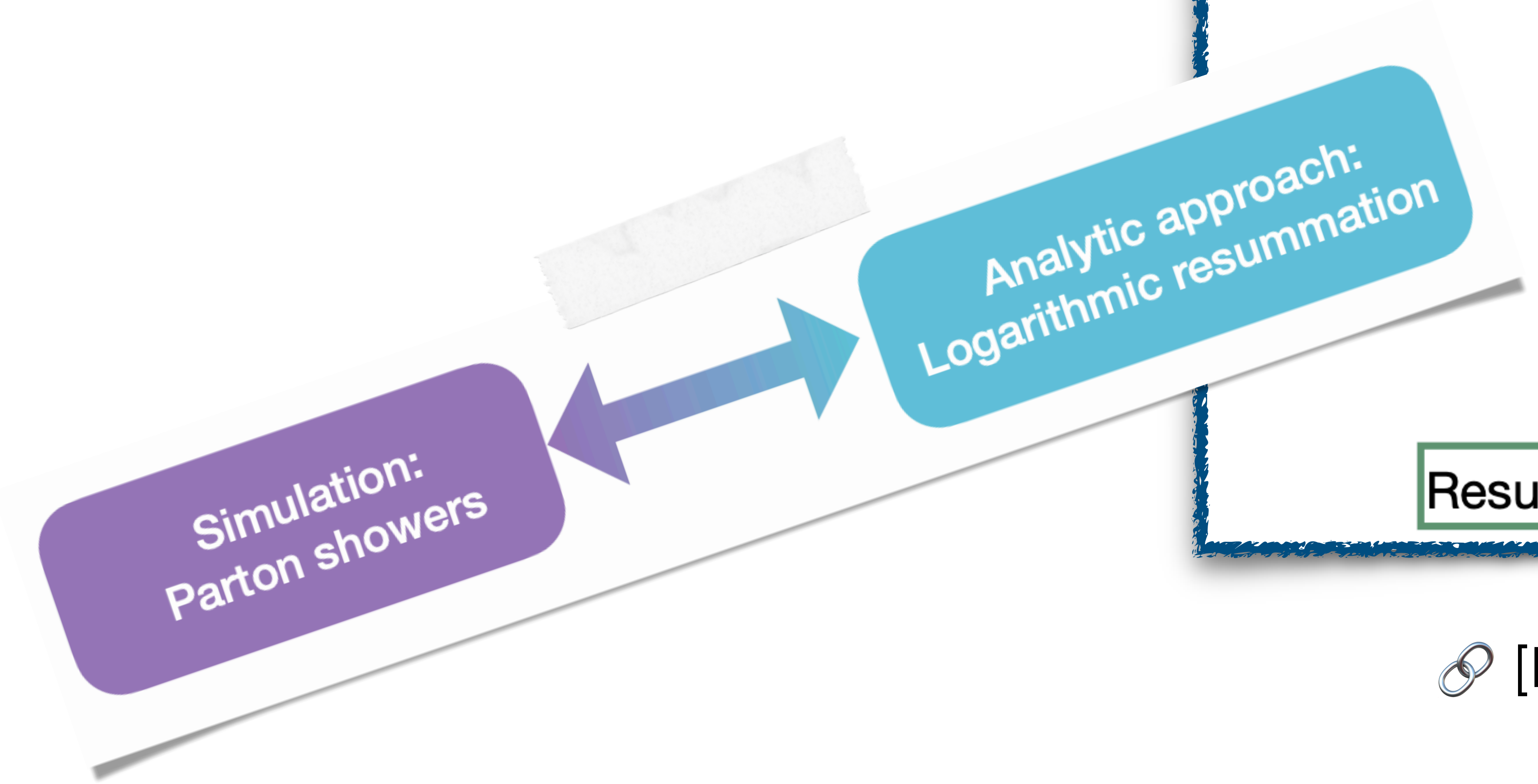
- Restoring convergence → "all-order" resummations

Fixed-order vs resummation at lowest order



Resummation cures the divergence when $\rho \ll 1$



[Lectures by Alba Soto Ontoso]

Resummations in QCD

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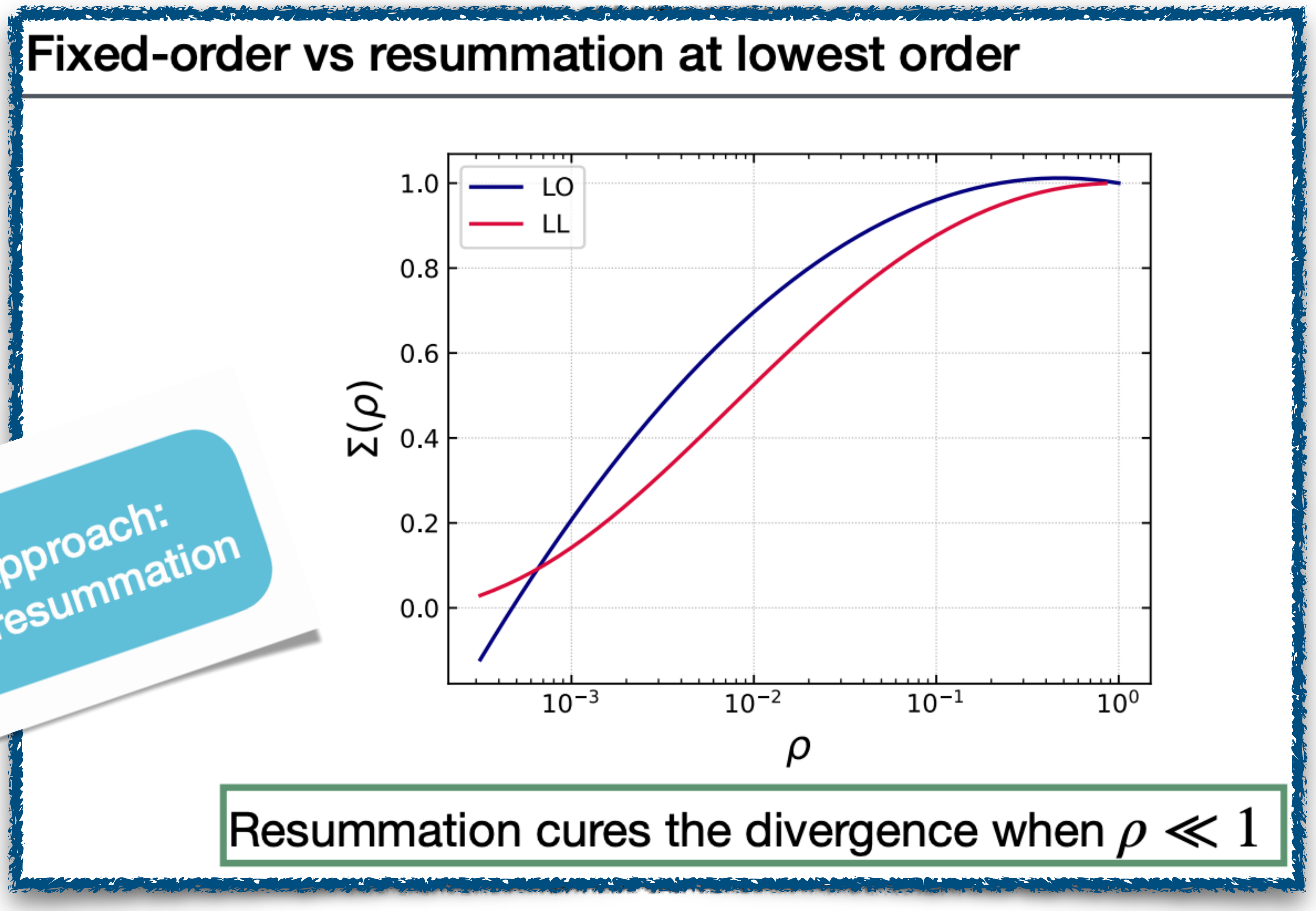
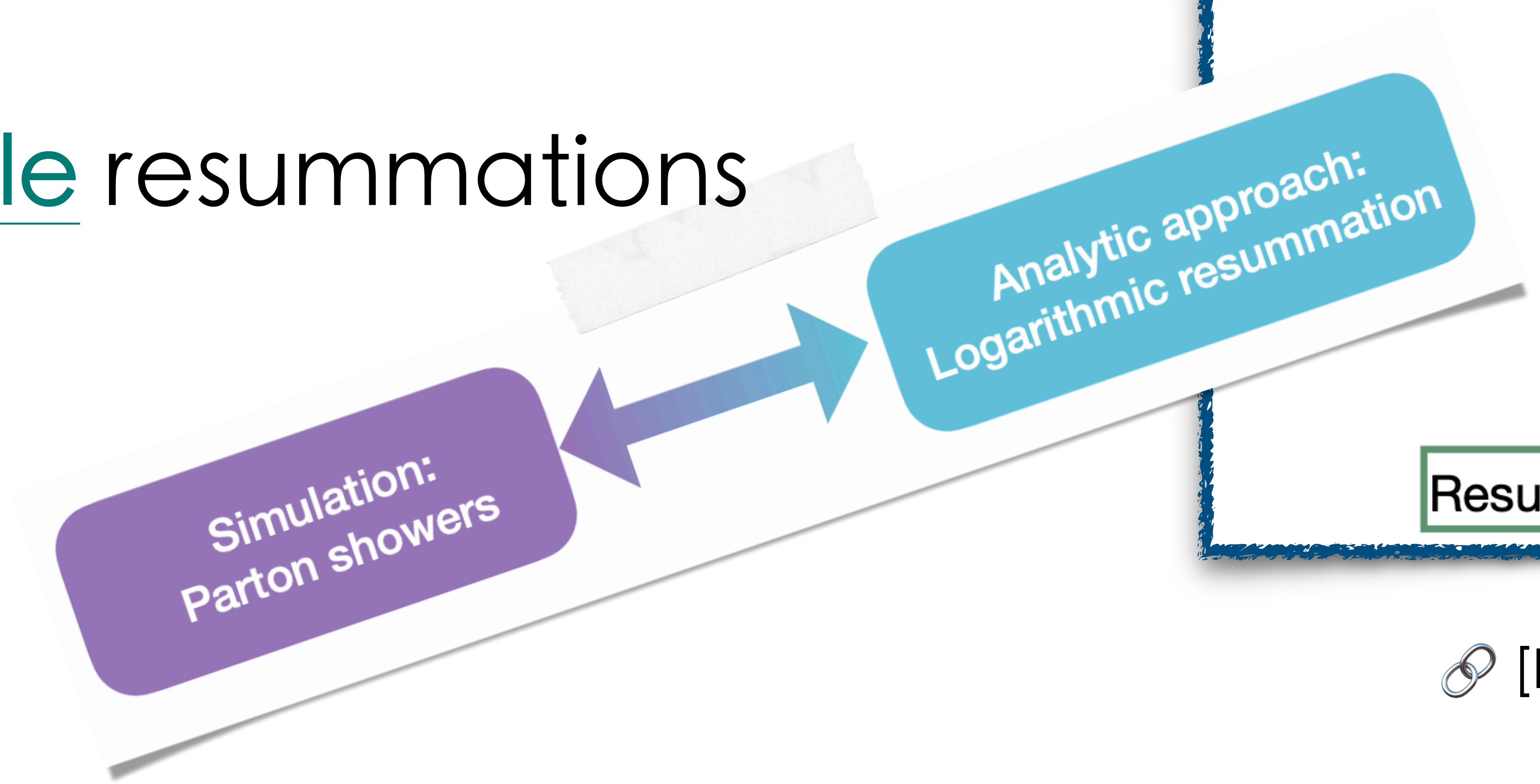
- More kinds of logs → multiple resummations





🔗 [Lectures by Alba Soto Ontoso]

2

LL & NLL accuracy

The semi-hard sector of QCD

High energies reachable at the LHC and at future colliders:

- great opportunity in the search for long-waited signals of New Physics...
- ...faultless chance to test Standard Model in unprecedent kinematic ranges
- only 5% of Universe visible, but most of this described by **strong interactions**

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Diffractive semi-hard processes

Diffractive processes with a stringent **scale hierarchy**: $s \gg \{Q^2\} \gg \Lambda^2_{\rm QCD}$

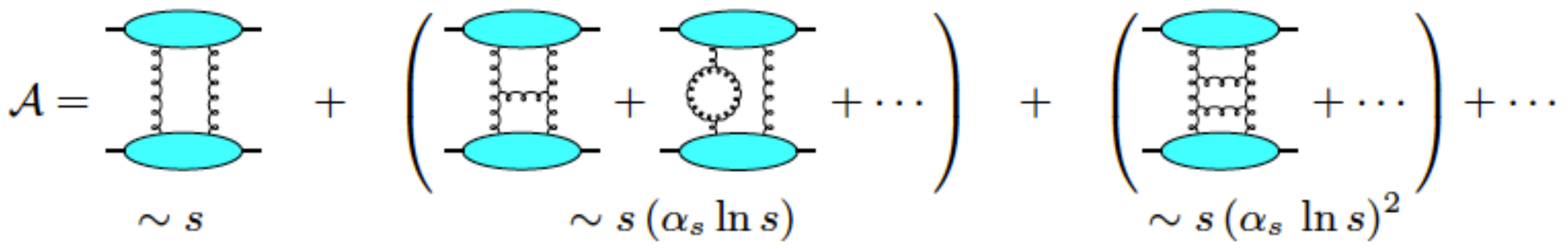
- ◇ $\{Q\}$ is (a set of) process-specific **hard scale**(s) (*e.g.* photon virtuality, heavy quark mass, jet/hadron transverse momentum, t, *etc.*)
- ◇ large $Q \;\Rightarrow\; \alpha_s(Q) \ll 1 \;\Rightarrow\;$ perturbative QCD
- ◇ large $s \;\Rightarrow\;$ large energy single logs
- ¡! Convergence of perturbative series is spoiled when $\alpha_s(Q) \log s \sim 1 \;\Rightarrow\;$ *all-order* **resummation** needed

The high-energy resummation

BFKL resummation: [V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975, 1976, 1977); Y.Y. Balitskii, L.N. Lipatov (1978)]

$\xrightarrow{\text{based on}}$ **gluon Reggeization**

leading logarithmic approximation (LL): $\alpha_s^n (\ln s)^n$



next-to-leading logarithmic approximation (NLL): $\alpha_s^{n+1} (\ln s)^n$

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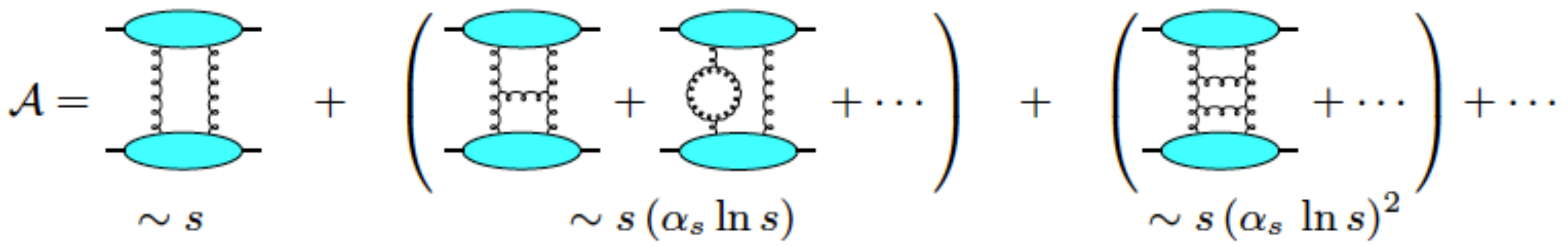

next-to-leading logarithmic approximation (NLL): $\alpha_s^{n+1} (\ln s)^n$

BFKL how to, … pause...

$$A_8(s,t) = A^{(0)}(s,t)\left(1 + \ln\left(\frac{s}{|t|}\right)\epsilon(t) + \frac{1}{2}\ln^2\left(\frac{s}{|t|}\right)\epsilon^2(t) + \ldots\right)$$

An ansatz seems natural: $A_8(s,t) = A^{(0)}(s,t)\left(\frac{s}{|t|}\right)^{\epsilon(t)}$

$$D_{\mu\nu}(s,q^2) = -i\frac{g_{\mu\nu}}{q^2}\left(\frac{s}{\mathbf{k}^2}\right)^{\epsilon(q^2)}$$

The reggeization of the gluon; Bootstrap equation

🔗 [Lectures by Greg Chachamis]

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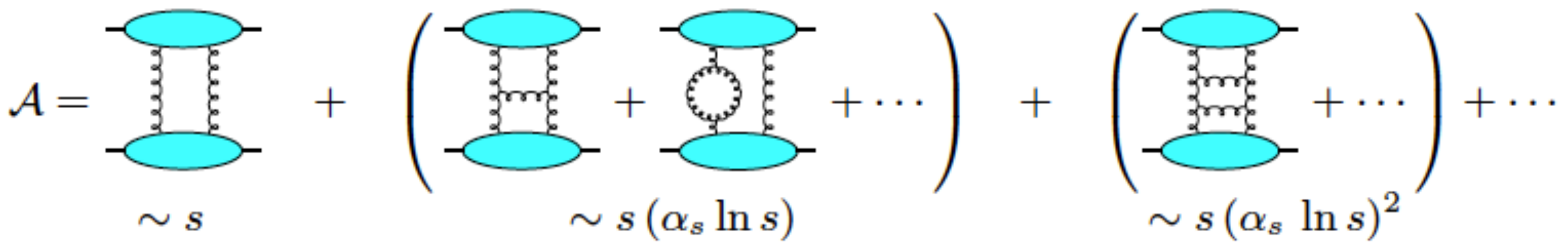

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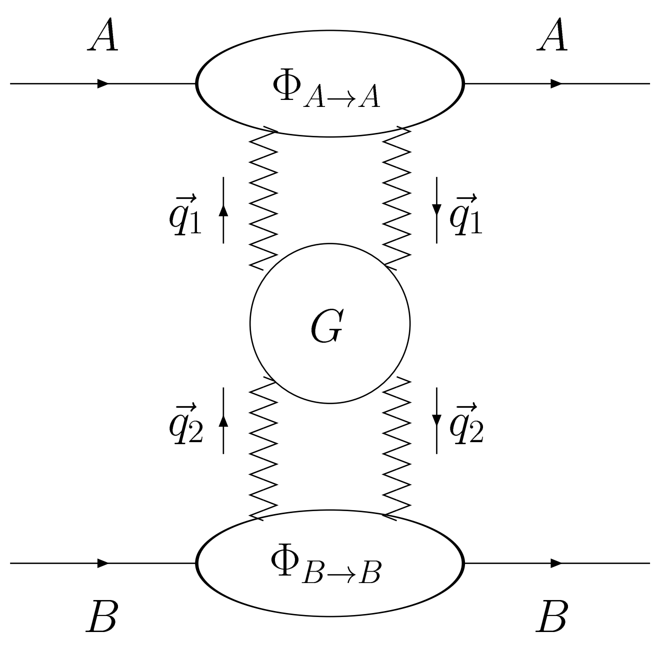
The reggeization of the gluon; Bootstrap equation

[Lectures by Greg Chachamis]

Total cross section for $A + B \to X$: $\sigma_{AB}(s) = \frac{\mathcal{Im}_s\{\mathcal{A}_{AB}^{AB}\}}{s} \Leftarrow$ ***optical theorem***



- $\mathcal{Im}_s\{\mathcal{A}_{AB}^{AB}\}$ factorization:

  convolution of the **Green's function** of two interacting Reggeized gluons with the **impact factors** of the colliding particles

Green's function is **process-independent**, describes energy dependence and obeys BFKL equation; impact factors are known in the **NLL just for few processes**

I.2 LL & NLL accuracy

Gluon Reggeization in pQCD

- Gluon quantum numbers in the t-channel: 8^- representation
- Regge limit: $s \simeq -u \to \infty$, t not growing with s

$\to$ amplitudes governed by **gluon Reggeization** $\to D_{\mu\nu} = -i\frac{g_{\mu\nu}}{q^2}\left(\frac{s}{s_0}\right)^{\alpha_g(q^2)-1}$

$\xrightarrow{\text{feature}}$ all-order resummation: **LLA** $[\alpha_s^n(\ln s)^n]$ + **NLA** $[\alpha_s^{n+1}(\ln s)^n]$

$\xrightarrow{\text{consequence}}$ factorization of elastic and real part of inelastic amplitudes

$\xrightarrow{\text{example}}$ Elastic scattering process: $A + B \longrightarrow A' + B'$

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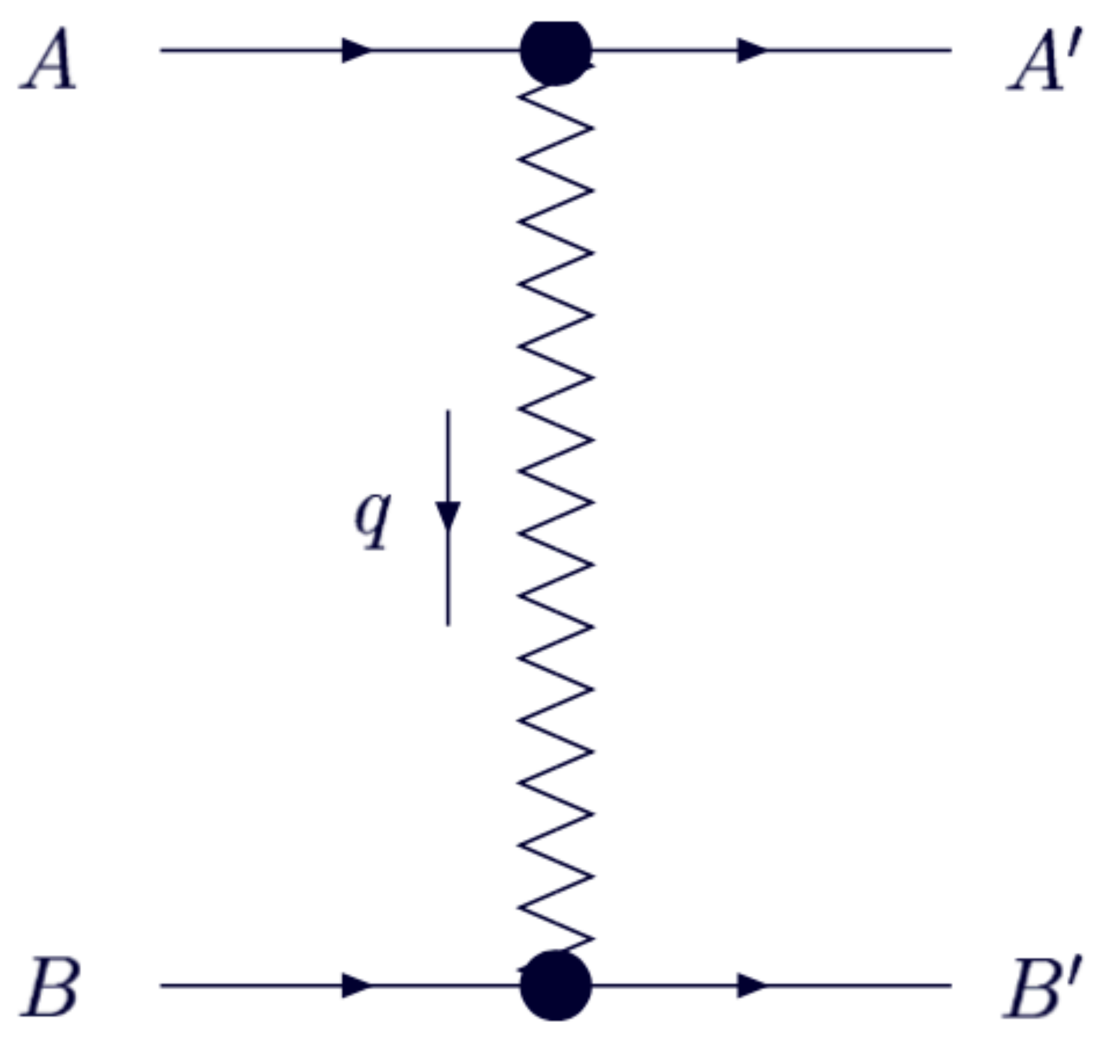


$$(\mathcal{A}_8^-)_{AB}^{A'B'} = \Gamma^c_{A'A}\left[\left(\frac{-s}{-t}\right)^{j(t)} - \left(\frac{s}{-t}\right)^{j(t)}\right]\Gamma^c_{B'B}$$

$$j(t) = 1 + \omega(t)\,, \quad j(0) = 1$$

$\omega(t) \to$ Reggeized gluon trajectory

$\Gamma^c_{A'A} = g\langle A'|T^c|A\rangle\Gamma_{A'A} \to$ PPR vertex

$T^c \to$ fundamental (q) or adjoint (g)

- QCD is the unique SM theory where all elementary particles reggeize
- Possible extensions: N=4 SYM, AdS/CFT,...

The BFKL Green's function

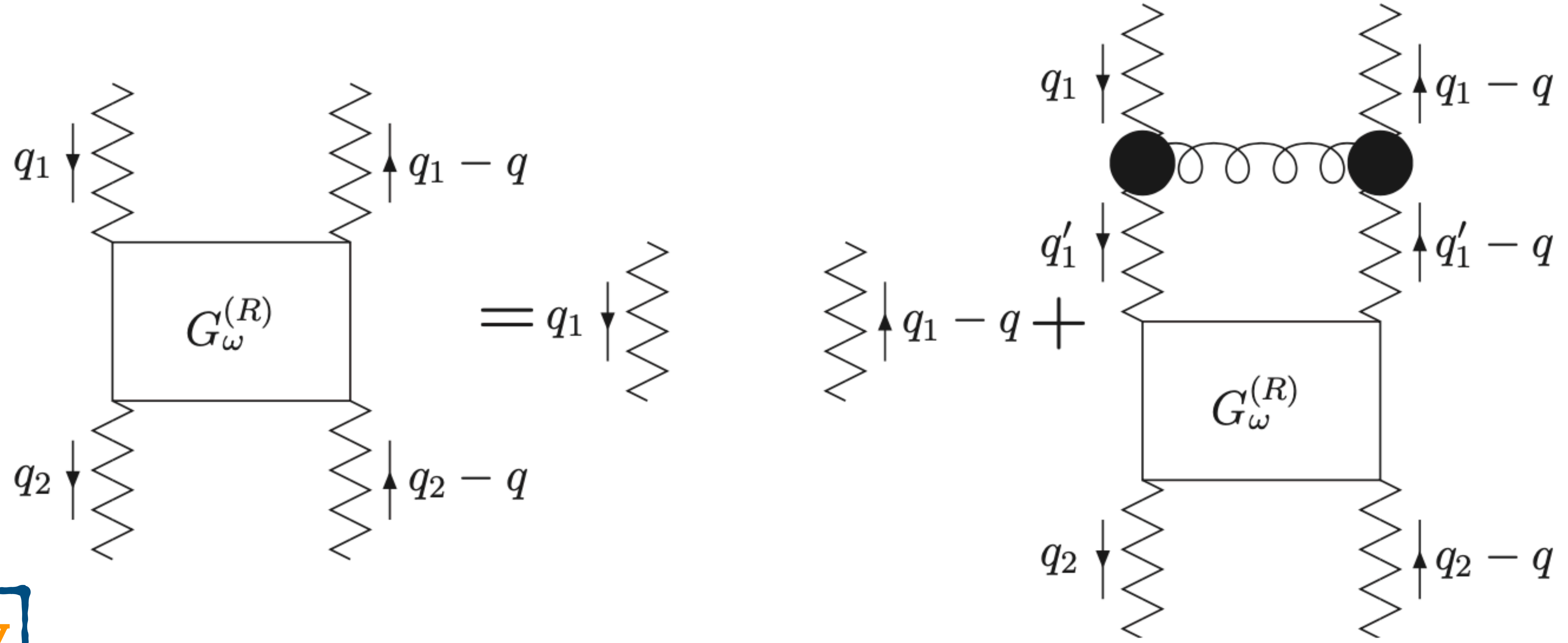
$$\mathrm{Im}_s\left(\mathcal{A}\right) = \frac{s}{(2\pi)^{D-2}}\int\frac{d^{D-2}q_1}{\vec{q}_1^{\,2}}\Phi_A(\vec{q}_1,s_0)\int\frac{d^{D-2}q_2}{\vec{q}_2^{\,2}}\Phi_B(-\vec{q}_2,s_0)\int_{\delta-i\infty}^{\delta+i\infty}\frac{d\omega}{2\pi i}\left(\frac{s}{s_0}\right)^{\omega}G_\omega(\vec{q}_1,\vec{q}_2)$$

- **Green's function** is **process-independent** and takes care of the **energy dependence**

$\longrightarrow$ determined through the **BFKL equation**

[Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

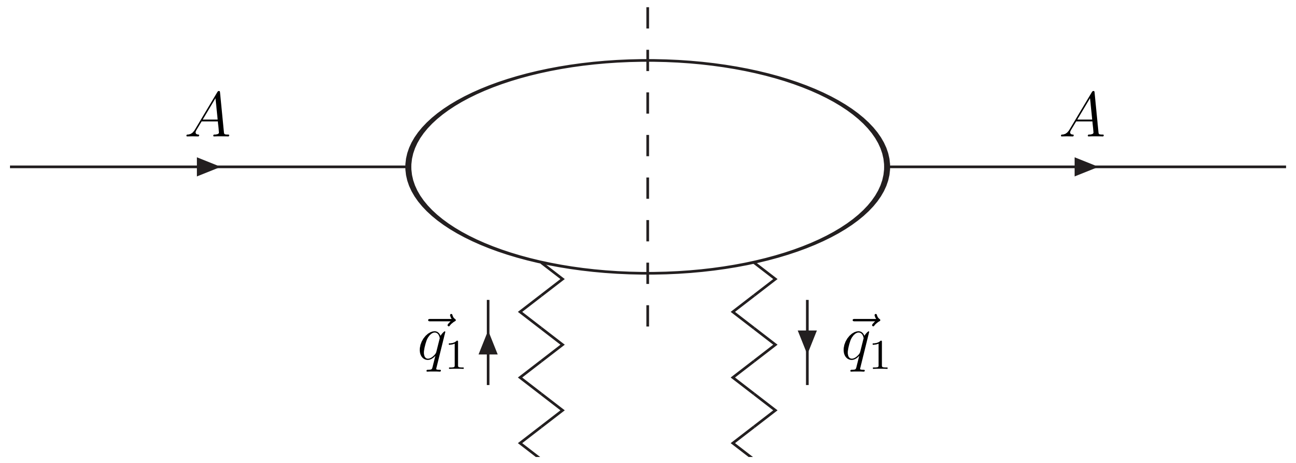
$$\omega\, G_\omega(\vec{q}_1,\vec{q}_2) = \delta^{D-2}(\vec{q}_1-\vec{q}_2) + \int d^{D-2}q\, K(\vec{q}_1,\vec{q})\, G_\omega(\vec{q},\vec{q}_1)\;.$$



The BFKL impact factors

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy

$\longrightarrow$ known in the NLA just for few processes



The BFKL impact factors

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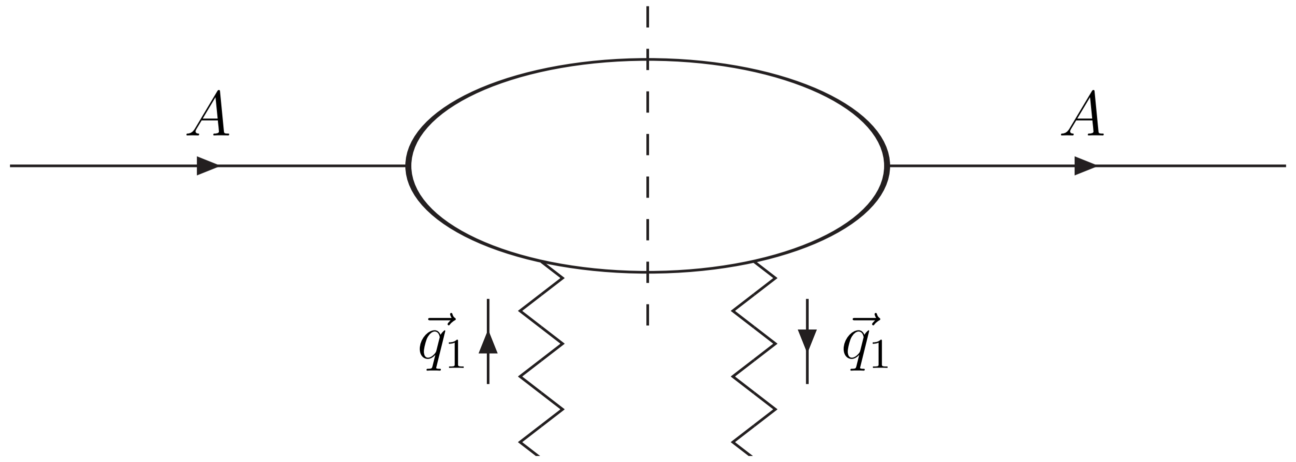
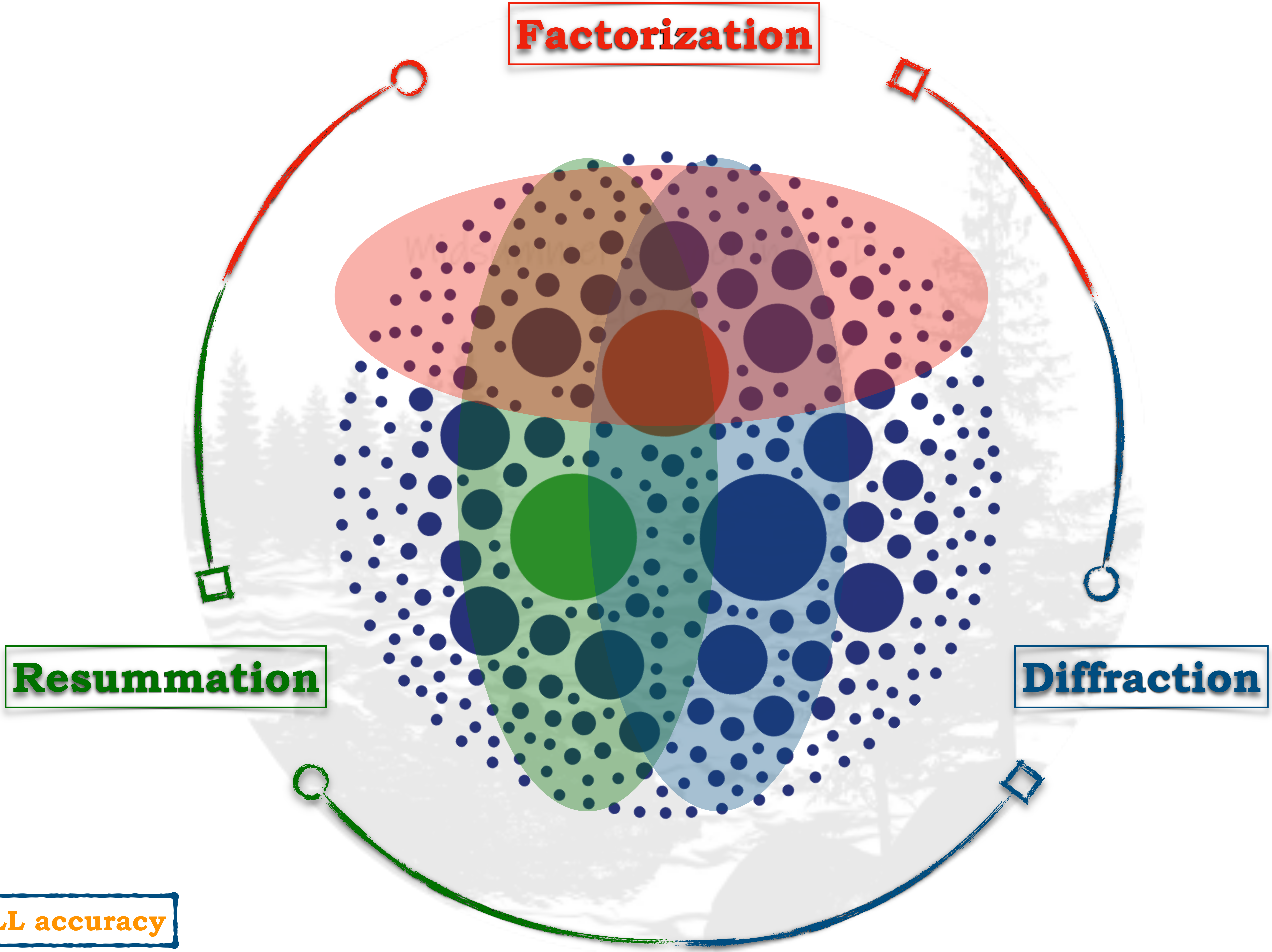


- Successful tests of NLA BFKL in the **Mueller–Navelet** channel with the advent of the LHC; nevertheless, *new BFKL-sensitive observables* as well as *more exclusive final-state reactions* are needed (**di-hadron**, **hadron-jet**, **heavy-quark pair**, **multi-jet**, production processes,...)

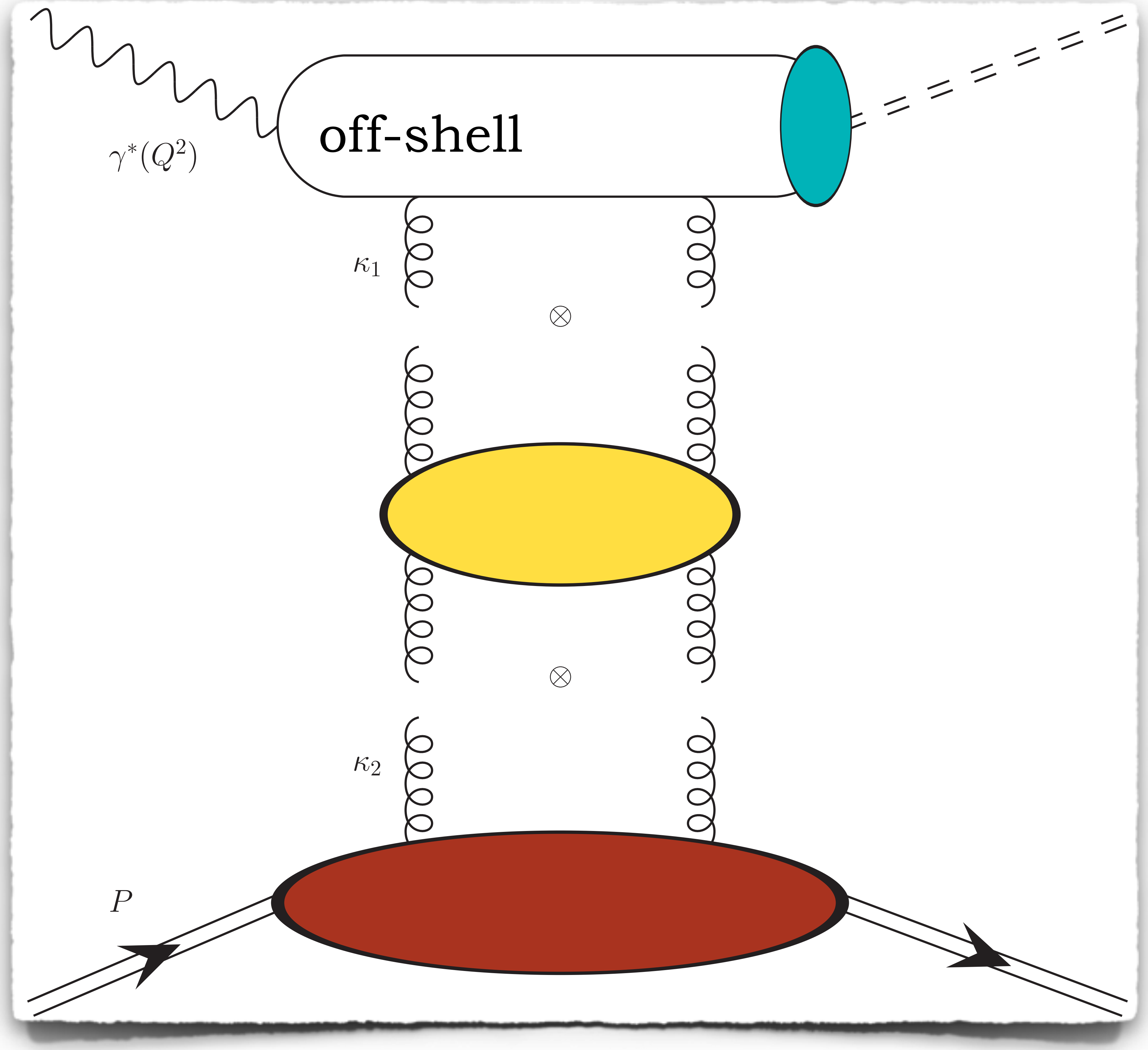
(**MN jets**) [B. Ducloué, L. Szymanowski, S. Wallon (2014); F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2015, 2016)]
(**di-hadron**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]
(**four-jet**) [F. Caporale, F.G.C., G. Chachamis, A. Sabio Vera (2016)]
(**multi-jet**) F. Caporale, F.G.C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016, 2017, 2017)]
(**heavy-quark pair**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M. Fucilla, A. Papa (2018)]
(**hadron-jet**) [M.M.A. Mohammed, MD thesis (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]

(κ_T space) [M. Hentschinski, K. Kutak, A. Van Hameren (2021)]
(κ_T & Mellin) [F.G.C., M. Fucilla, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2022)]

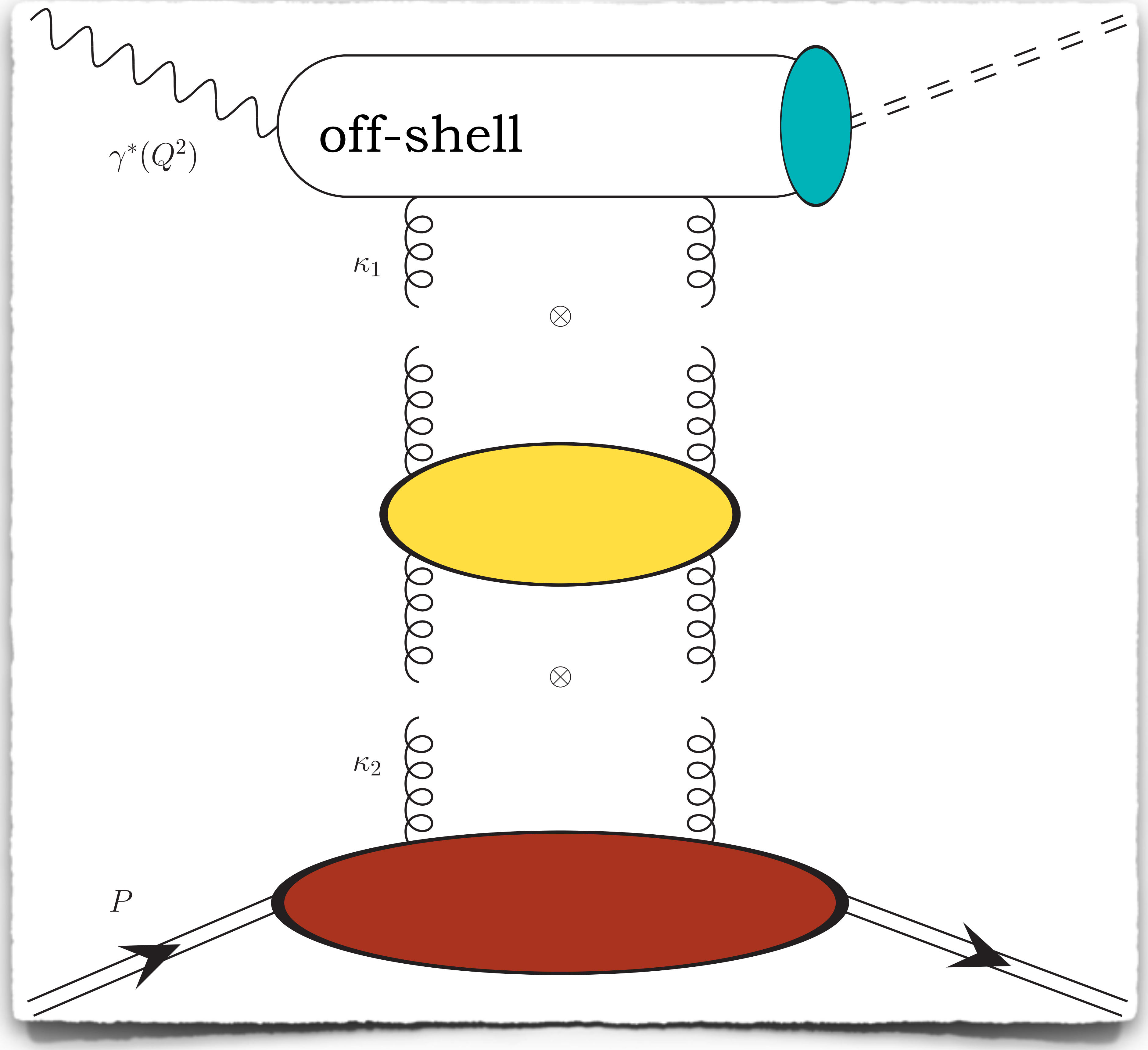

Factorization
Resummation
Diffraction

¿ What about diffractive processes ?

Meson leptoproduction



Meson leptoproduction



$$\Phi^{\gamma^* \to \ldots}$$

$$\otimes$$

$$\mathcal{G}_{\text{BFKL}}$$

$$\otimes$$

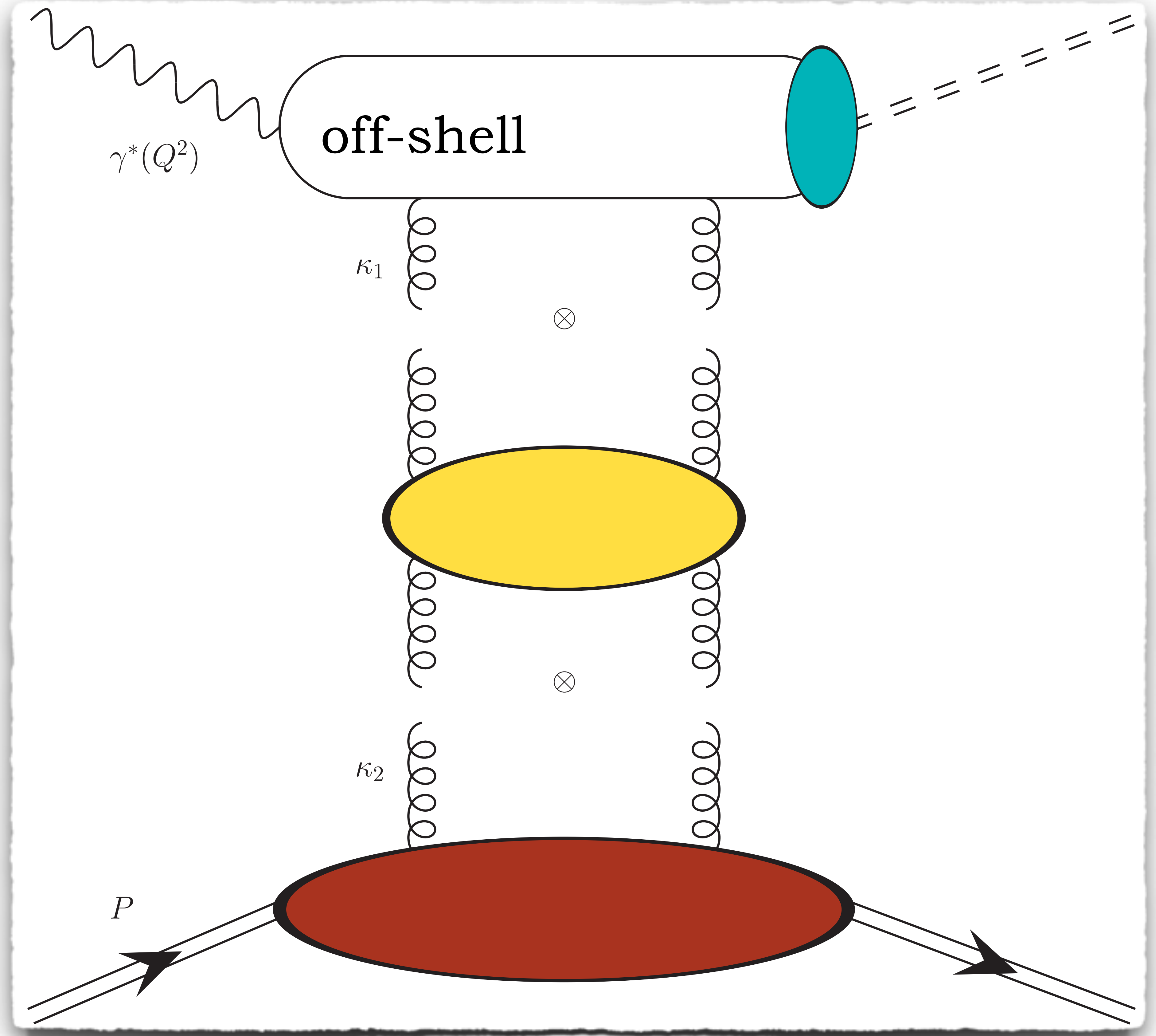
$$\Phi^{P}_{[\text{NP}]}$$

I.2 LL & NLL accuracy

Hard Diffraction: Exclusive vs Inclusive

Meson leptoproduction

Forward DIS



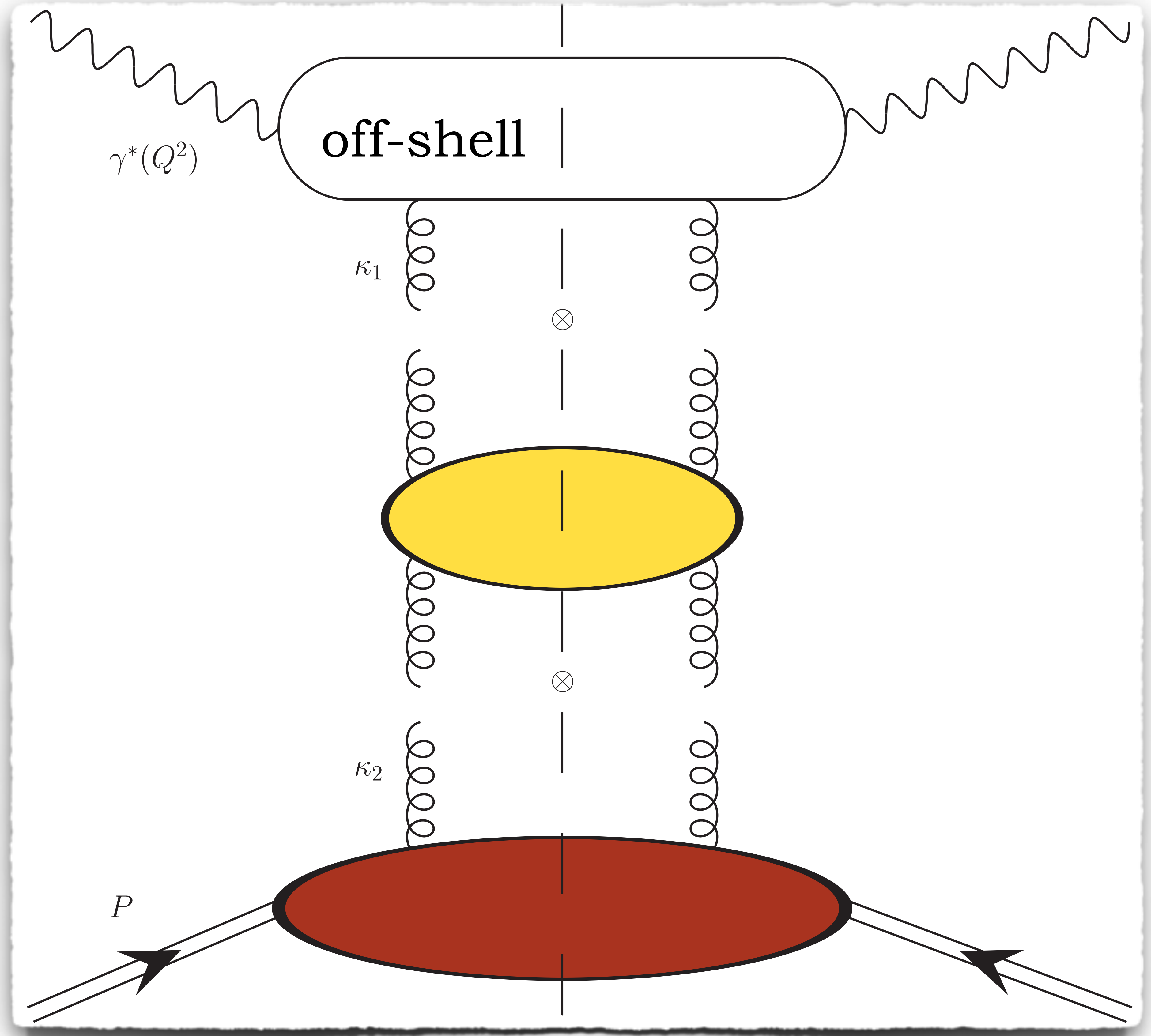
$\Phi^{\gamma^* \to \dots}$

$\otimes$

$\mathcal{G}_{\text{BFKL}}$

$\otimes$

$\Phi^{P}_{[\text{NP}]}$



I.2 LL & NLL accuracy

Hard Diffraction: Exclusive vs Inclusive

Meson leptoproduction

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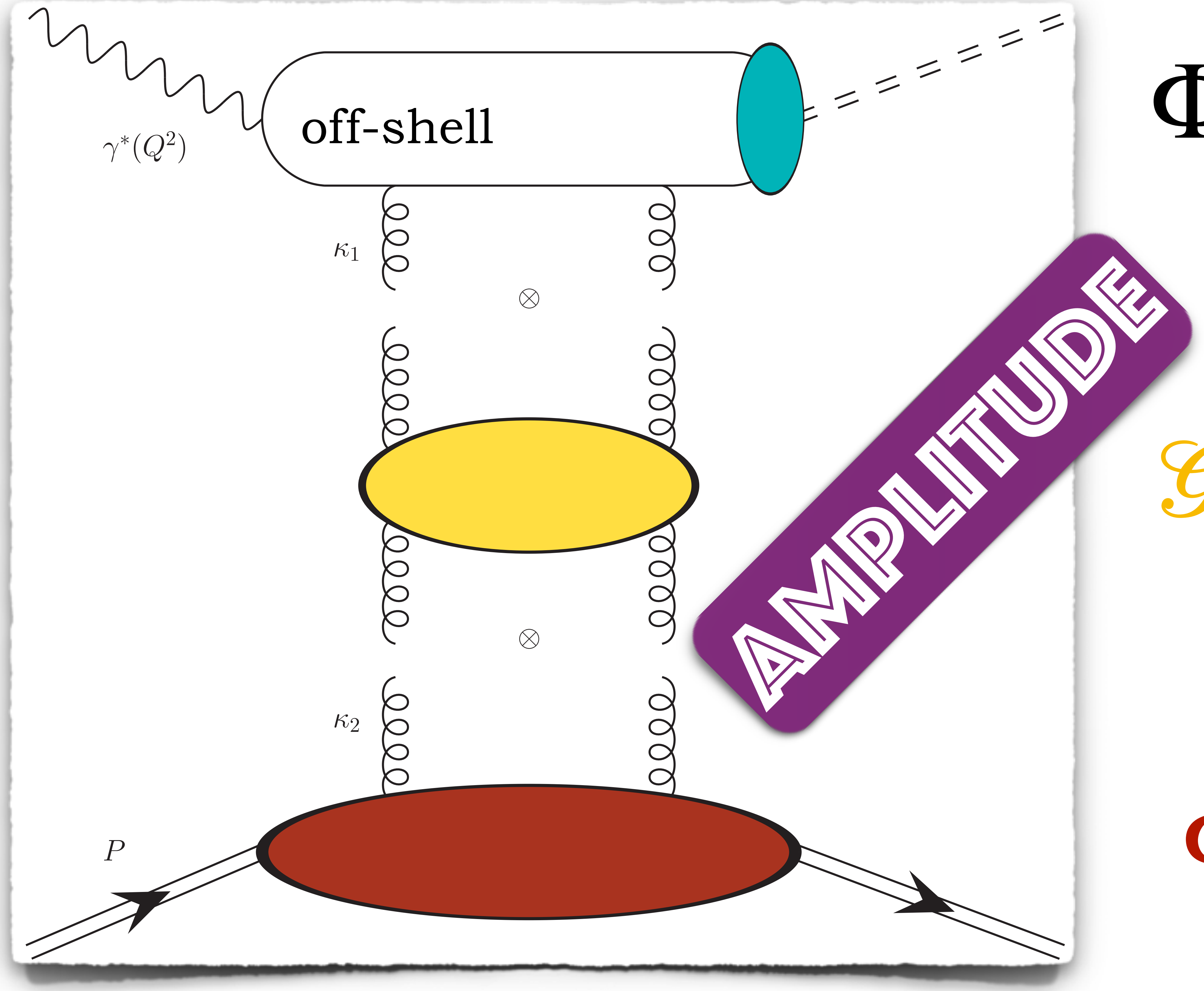


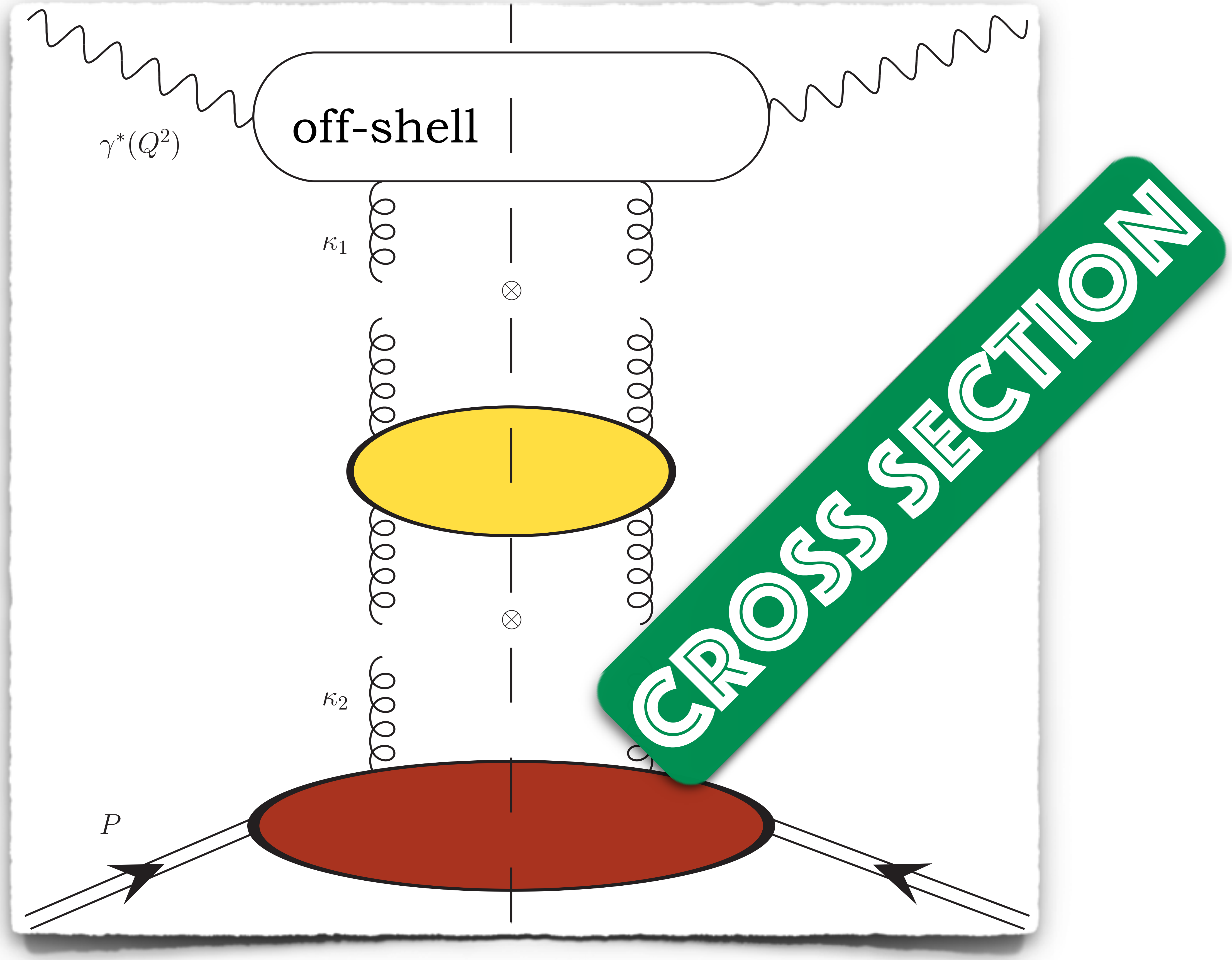
$\Phi^{\gamma^* \to \ldots}$

$\otimes$

$\mathcal{G}_{\rm BFKL}$

$\otimes$

$\Phi^{P}_{[\rm NP]}$



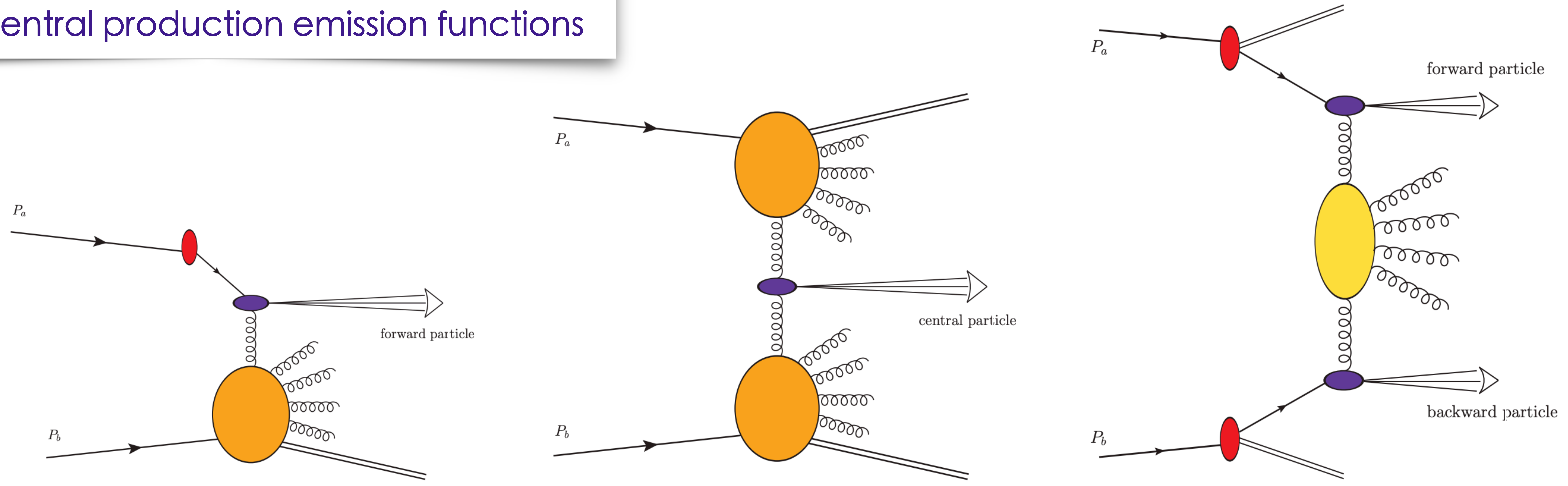
I.2 LL & NLL accuracy

3

Diffractive processes

High-energy factorization at a glance

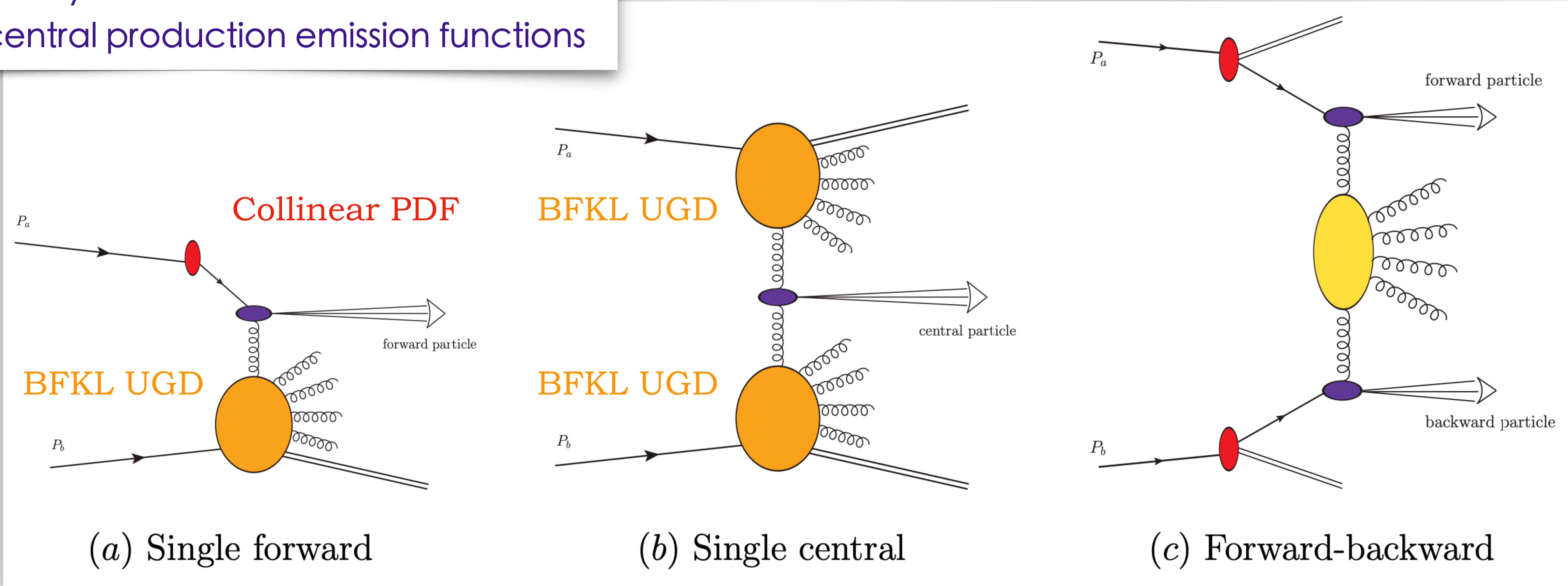
Singly/doubly off-shell coefficient functions
Forward/central production emission functions



(a) Single forward (b) Single central (c) Forward-backward

High-energy factorization at a glance

Singly/doubly off-shell coefficient functions
Forward/central production emission functions

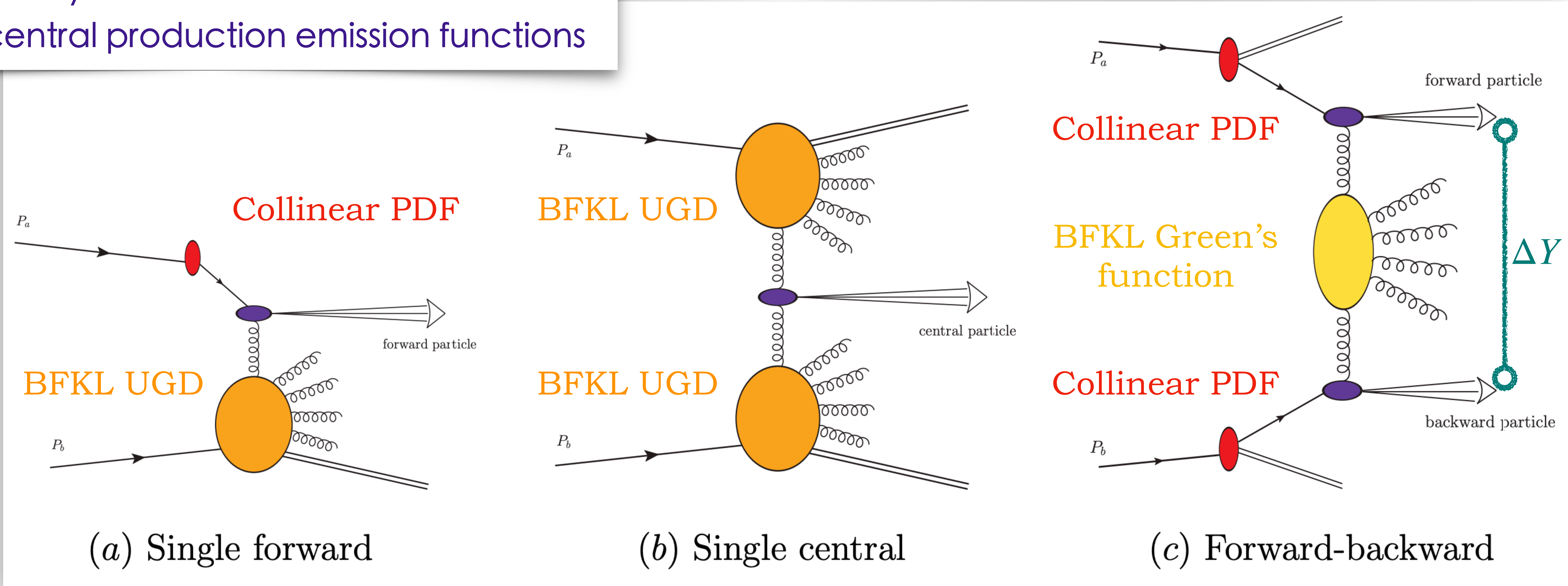


Fast q/g + small-x g	gg induced
Hybrid factorization	High-energy factorization
BFKL + Threshold	BFKL or small-x improved PDFs

🔗 [M. Bonvini, S. Marzani (2018)]

High-energy factorization at a glance

Singly/doubly off-shell coefficient functions
Forward/central production emission functions

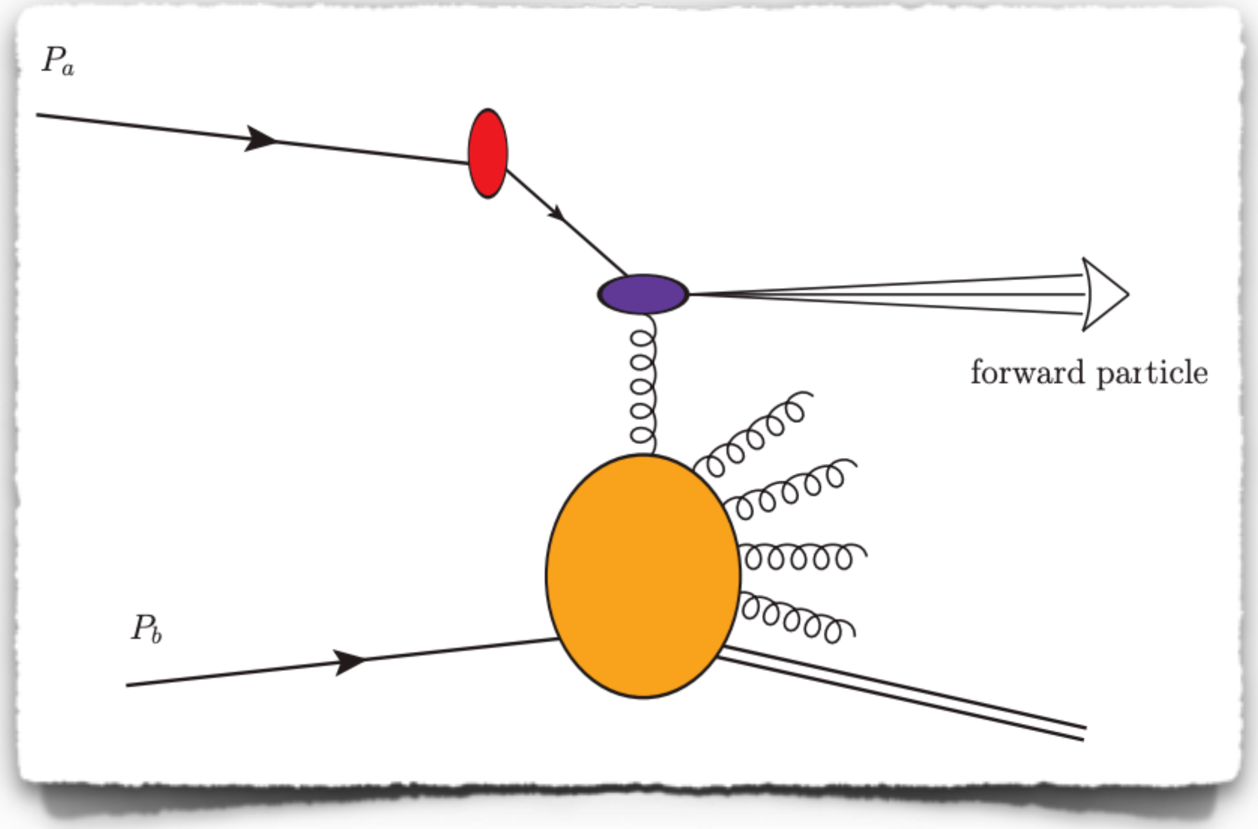


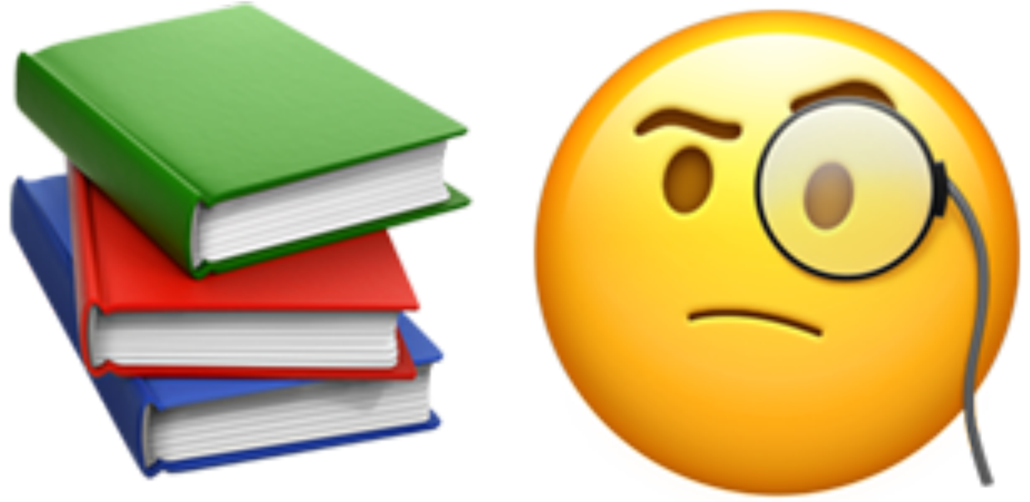
Single forward	Single central	Forward-backward
Fast q/g + small-x g	gg induced	Large rapidity distances, $\Delta Y \gg 1$
Hybrid factorization	High-energy factorization	High energies, moderate x
BFKL + Threshold	BFKL or small-x improved PDFs	PDFs + t-channel BFKL (NLL/NLO HyF)
	🔗 [M. Bonvini, S. Marzani (2018)]	Imbalance logs ← back-to-back

I.3 Diffractive processes

(a)

Single-forward emissions



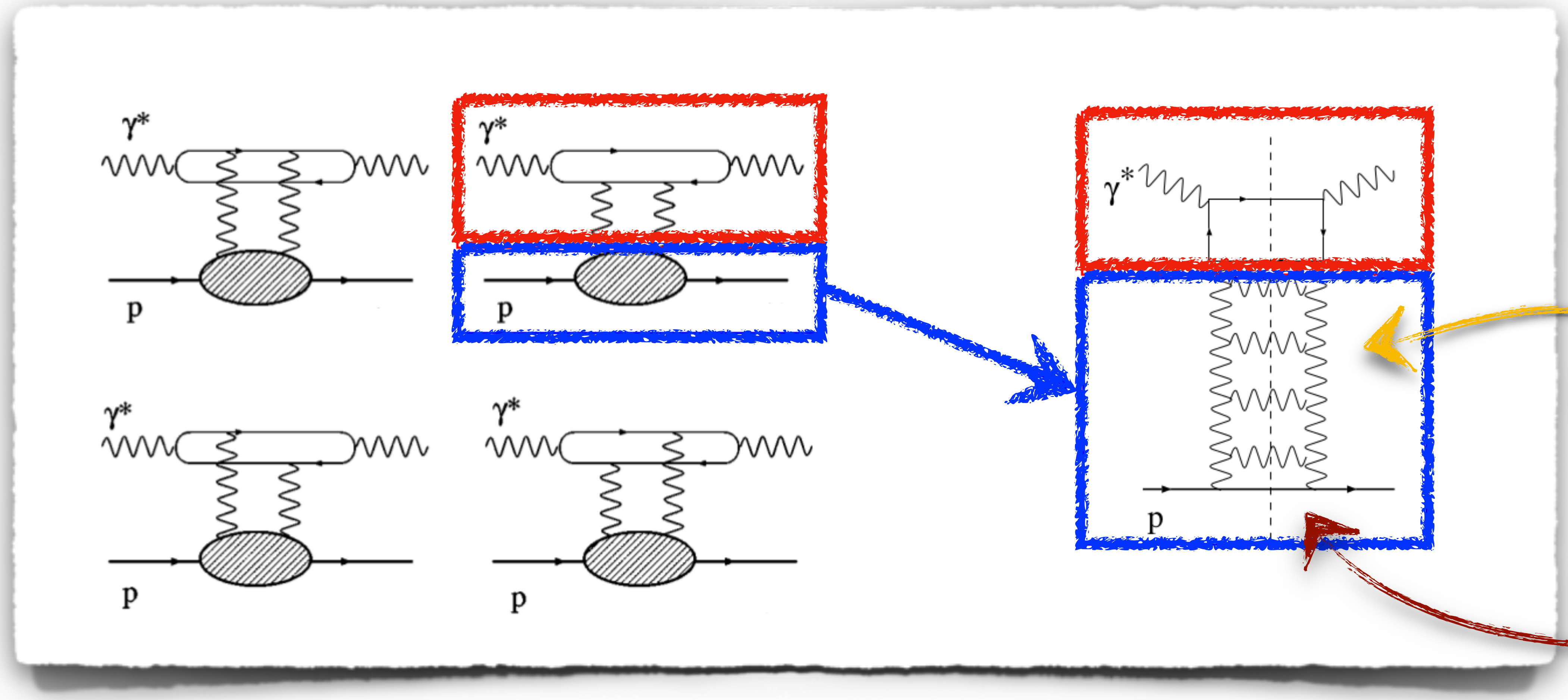


High-energy factorization and the UGD

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

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

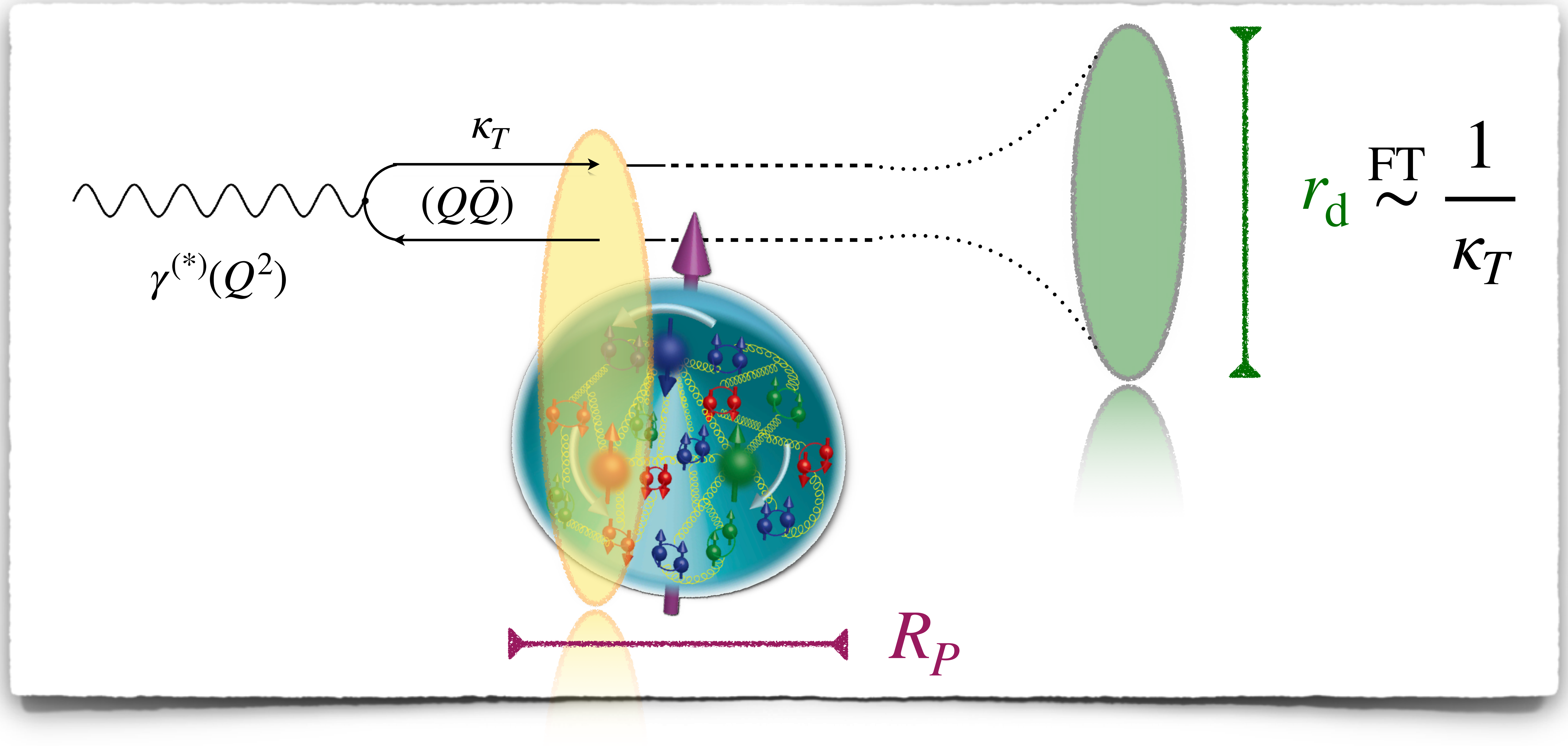
◇ $\mathcal{F}(x, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton



▶ Small-x limit: **UGD** = [**BFKL gluon ladder**] ⊛ [**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 ⟹ UGD needs to be modeled!

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

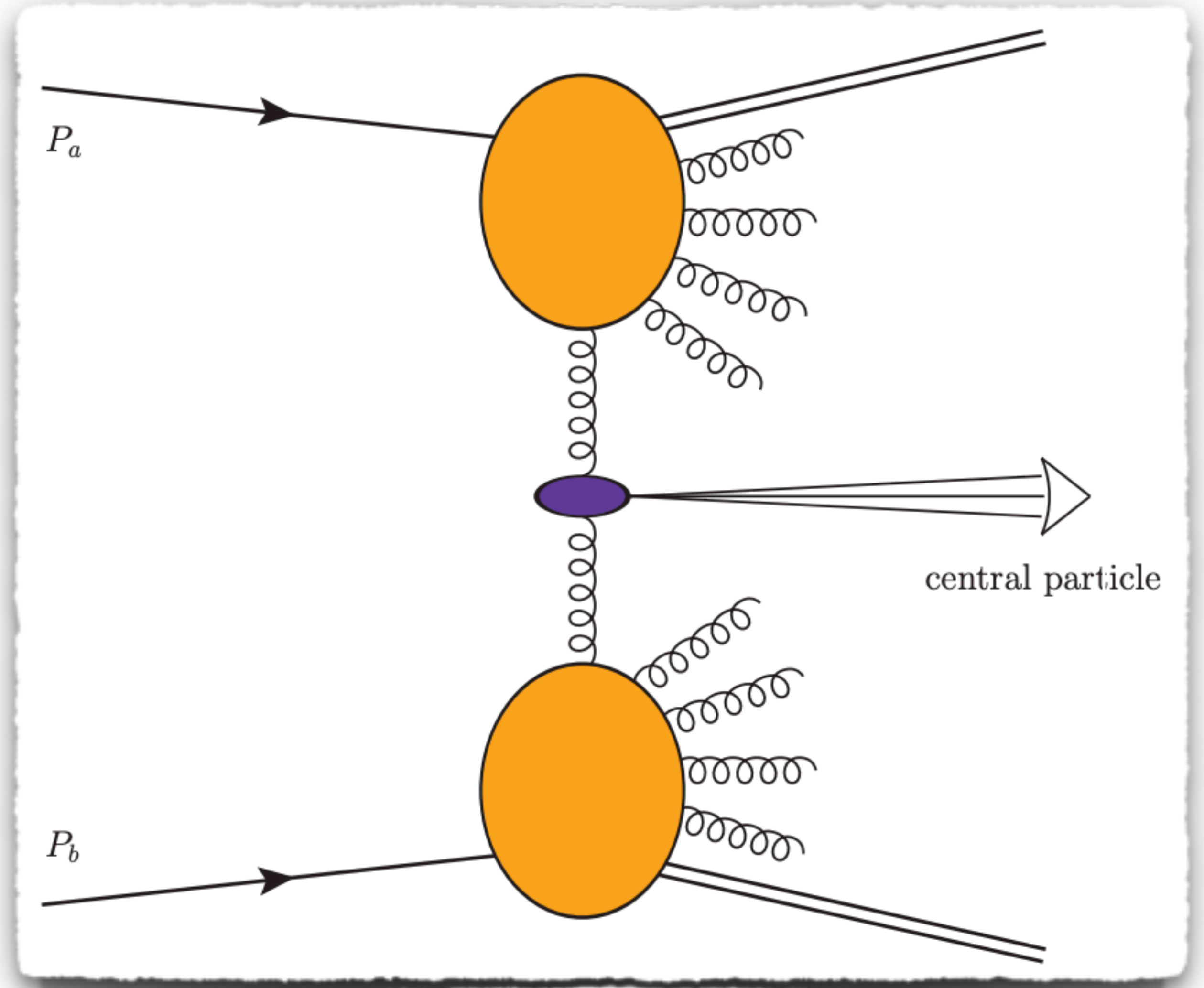


$$W_{\mu\nu} \propto \mathrm{Im}\left\{ i \int d^4x \, e^{i\,q\cdot x} \langle P \,|\, \mathrm{T}\,[J_\mu(x)\, J_\nu(0)] \,|\, P \rangle \right\}$$

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

(b)

Single-central emissions



Marco Bonvini

INFN, Rome 1 unit

REF2019, Pavia — Friday 29 November 2019

Ingredients for resummation

Small-x resummation is based on the interplay of

Collinear factorization: $$\sigma(x,Q^2) = \int_x^1 \frac{dz}{z}\, C_i(z,\alpha_s(Q^2))\, f_i\left(\frac{x}{z},Q^2\right)$$

DGLAP evolution: $$\mu^2 \frac{d}{d\mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dz}{z}\, P_{ij}(z,\alpha_s(\mu^2))\, f_j\left(\frac{x}{z},\mu^2\right)$$

with

k_t factorization: $$\sigma(x,Q^2) = \int_x^1 \frac{dz}{z} \int_0^\infty dk_t^2\, \mathcal{C}_g(z,k_t^2,\alpha_s)\, \mathcal{F}_g\left(\frac{x}{z},k_t^2\right)$$

BFKL evolution: $$-x\frac{d}{dx}\mathcal{F}_g(x,k_t^2) = \int_0^\infty \frac{dq_t^2}{k_t^2}\, \mathcal{K}\left(\frac{k_t^2}{q_t^2},\alpha_s(\cdot)\right) \mathcal{F}_g(x,q_t^2)$$

- $\mathcal{F}_g(x,k_t^2)$: unintegrated (k_t-dependent) PDF
- $\mathcal{C}_g(z,k_t^2,\alpha_s)$: off-shell coefficient function

Consistency between equations allows to resum small-x logs:

- DGLAP + BFKL eqns $\to$ resum $P(x,\alpha_s)$
- collinear + k_t factorizations $\to$ resum $C(x,\alpha_s)$ and heavy quark matching $A(x,\alpha_s)$

Small-x resummation: Altarelli-Ball-Forte & HELL

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with

k_t factorization: $\sigma(x,Q^2) = \int_x^1 \frac{dz}{z} \int_0^\infty dk_t^2\, \mathcal{C}_g($

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- collinear + k_t factorizations → resum $C(x,\alpha_s)$ and heavy

Federico Silvetti

Institute for Particle Physics Phenomenology, Durham University

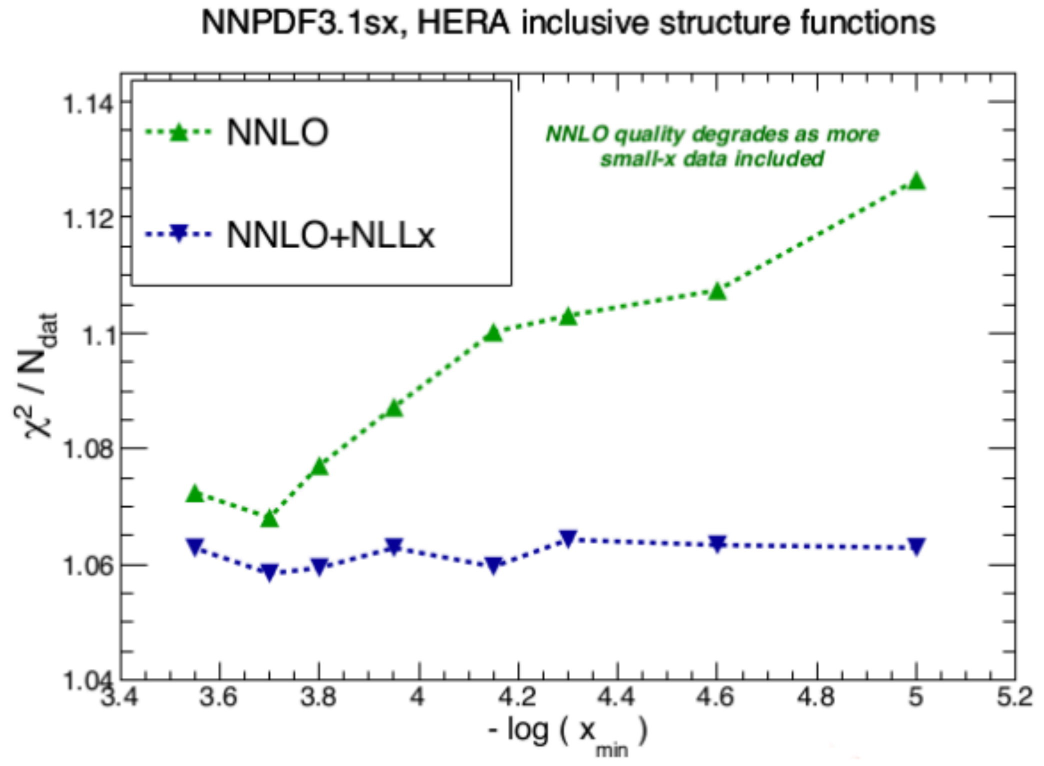
MPI@LHC 2023: Manchester, 23 November 2023

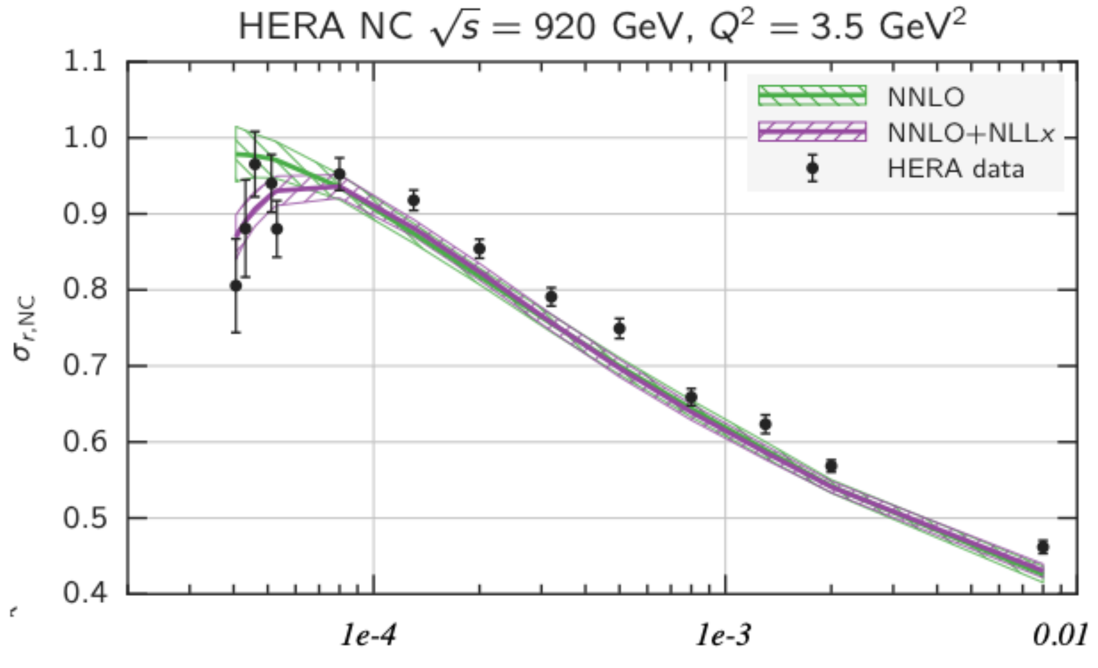
Fits with small-x resummed theory

Successful description of this region when including

- NNPDF3.1 framework [Ball,Bertone,Bonvini,Marzani,Rojo,Rottoli 1710.05935]
- xFitter framework [xFitterCollaboration,Bonvini 1802.00064]

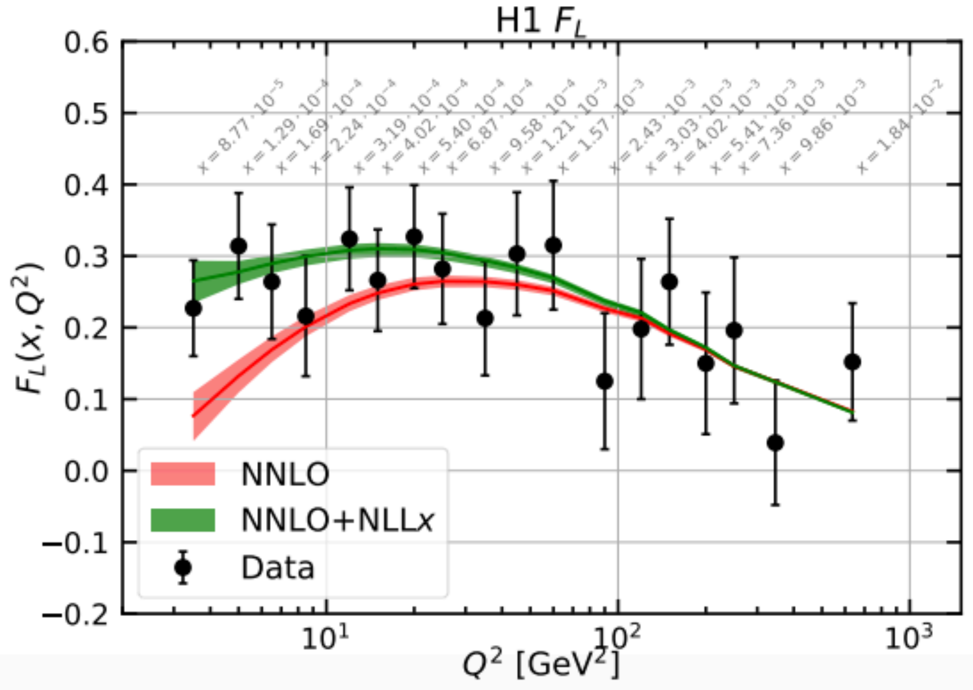
Turnover reproduced →





χ^2/N_{dat}	NNLO	NNLO+NLLx
xFitter	**1.23**	**1.17**
NNPDF3.1sx	**1.130**	**1.100**

reduction!

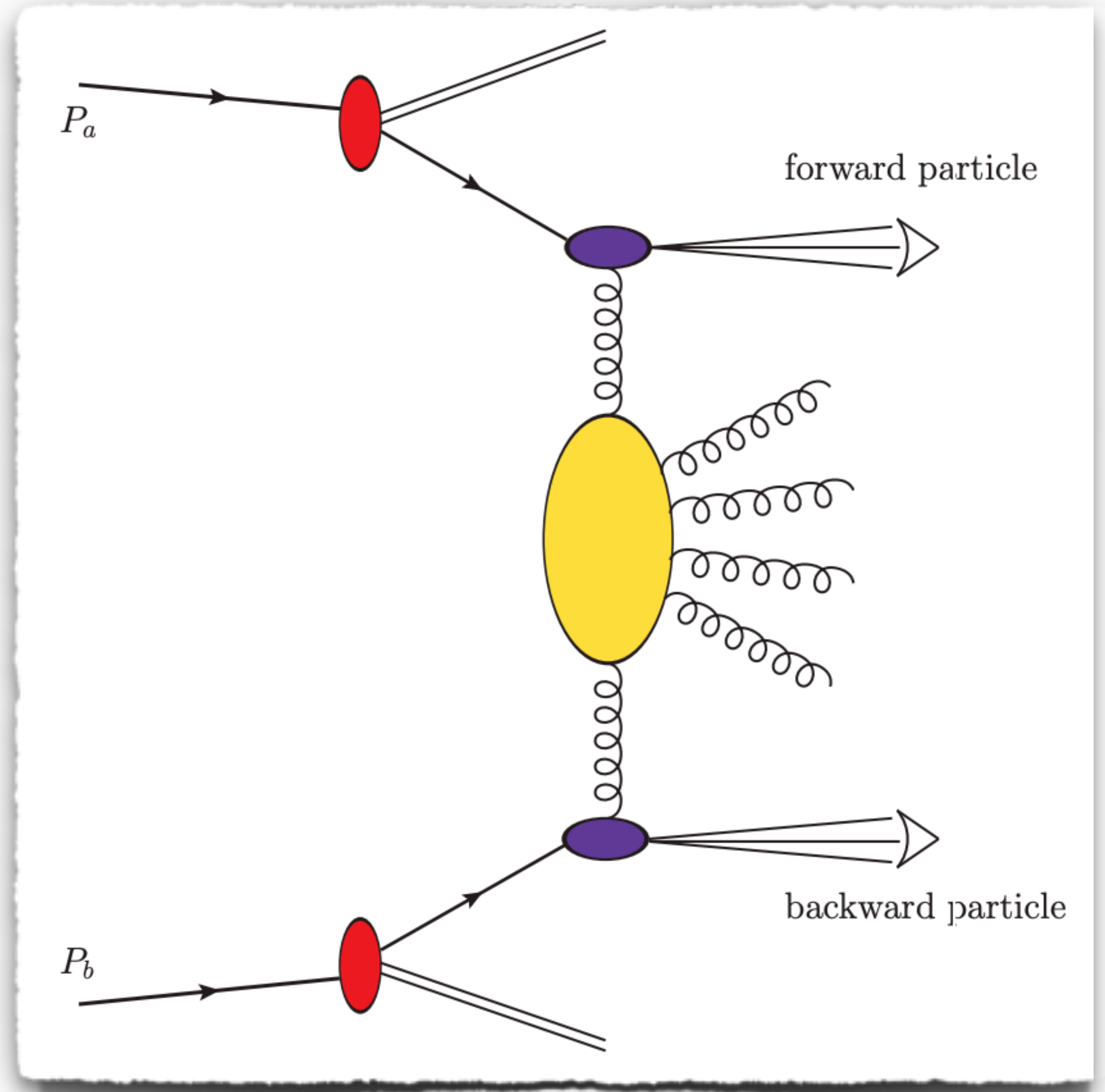


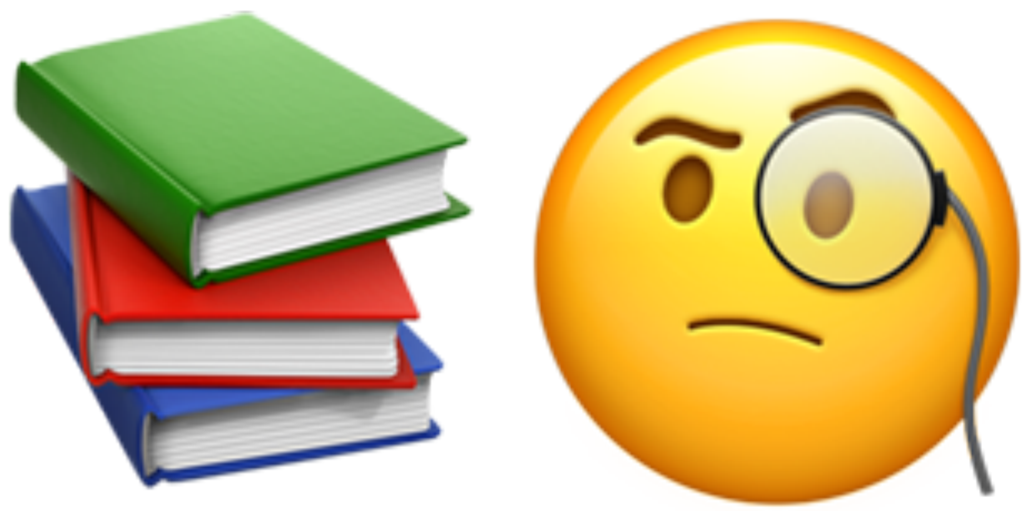
No extra parameters →**refined theory only**

I.3 Diffractive processes

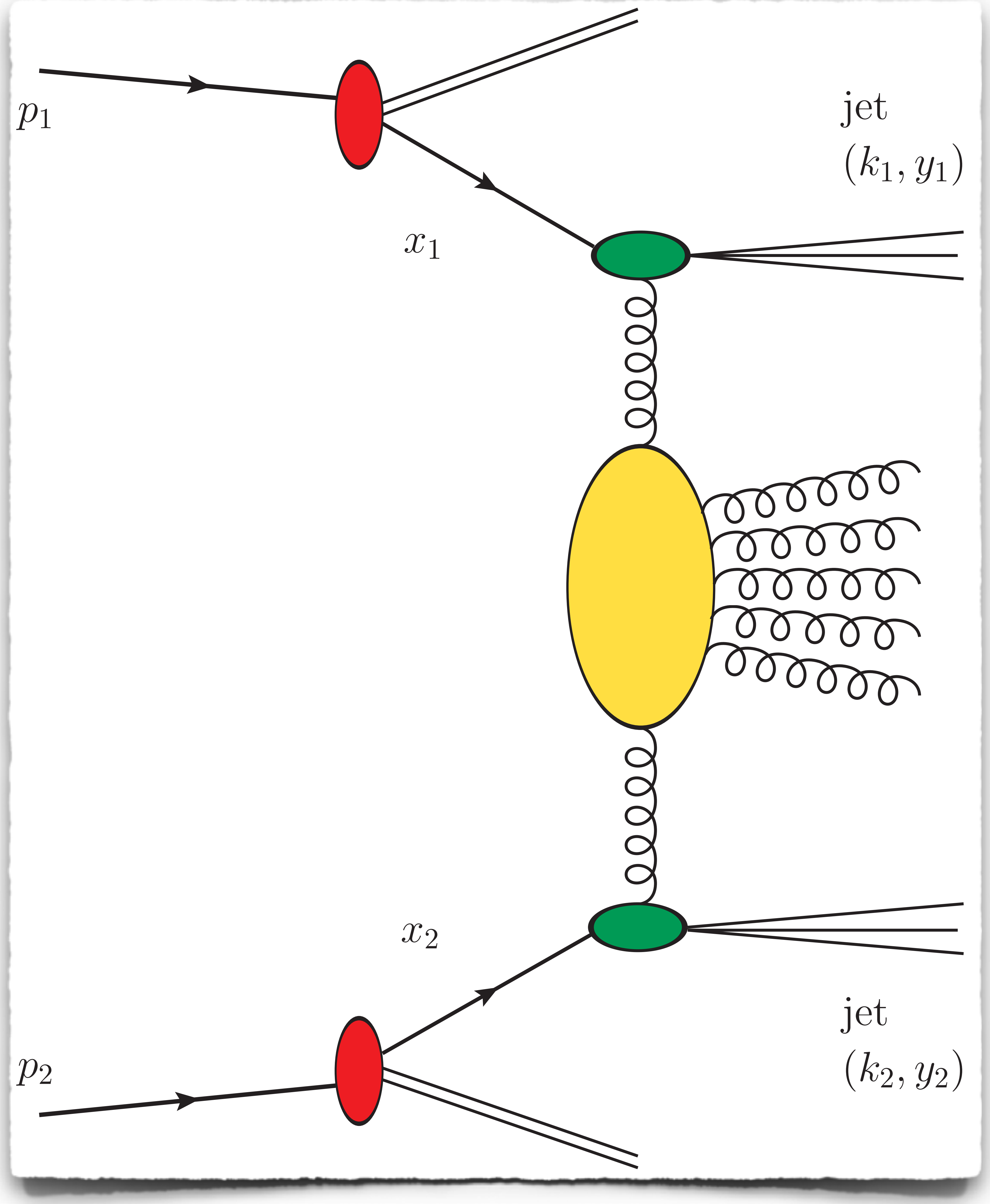
(c)

Forward-backward emissions





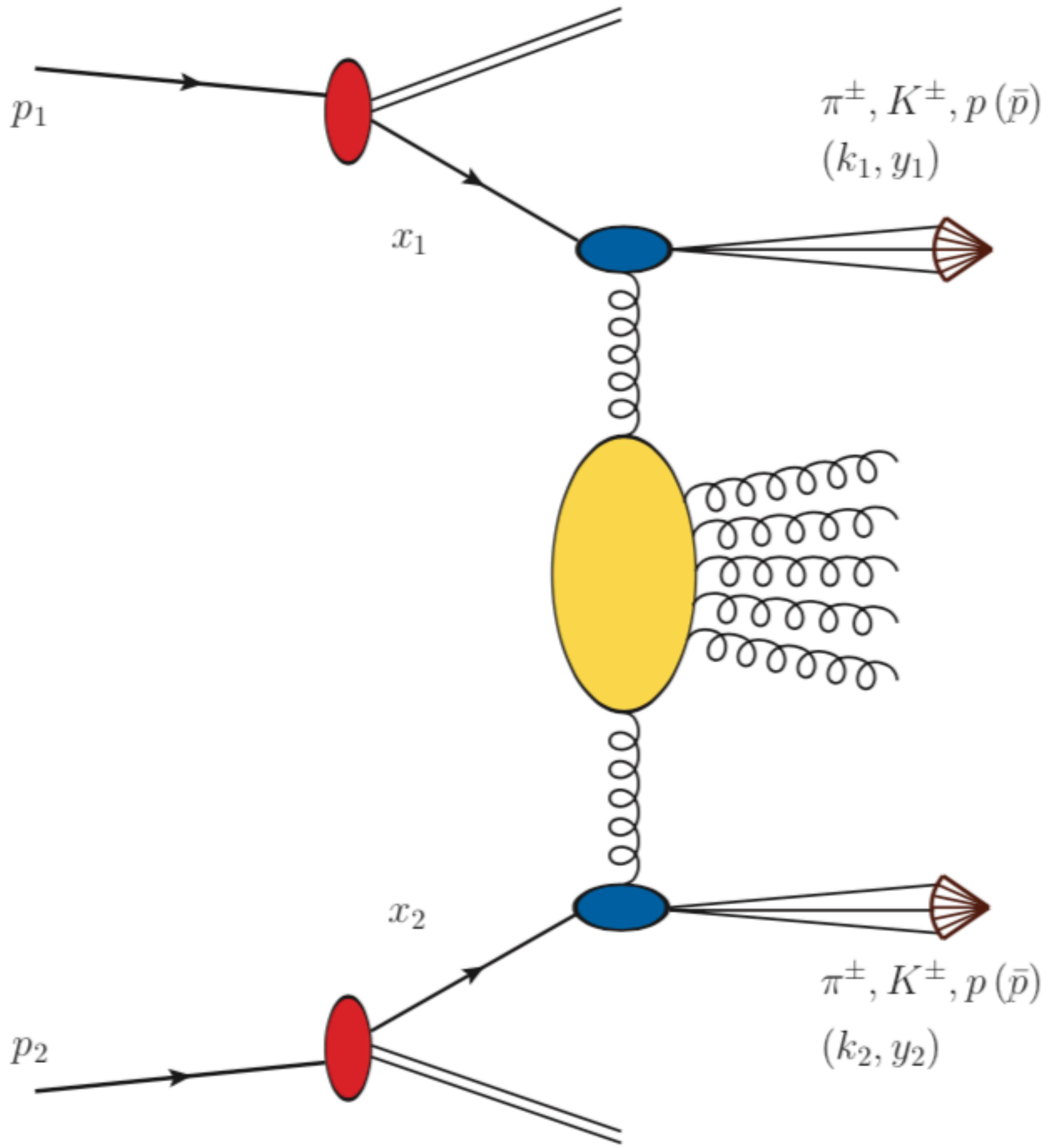
Mueller-Navelet jets: The "Mother" reaction



🔗 [A. H. Mueller, H. Navelet, Nucl. Phys. B 282 (1987) 727-744]

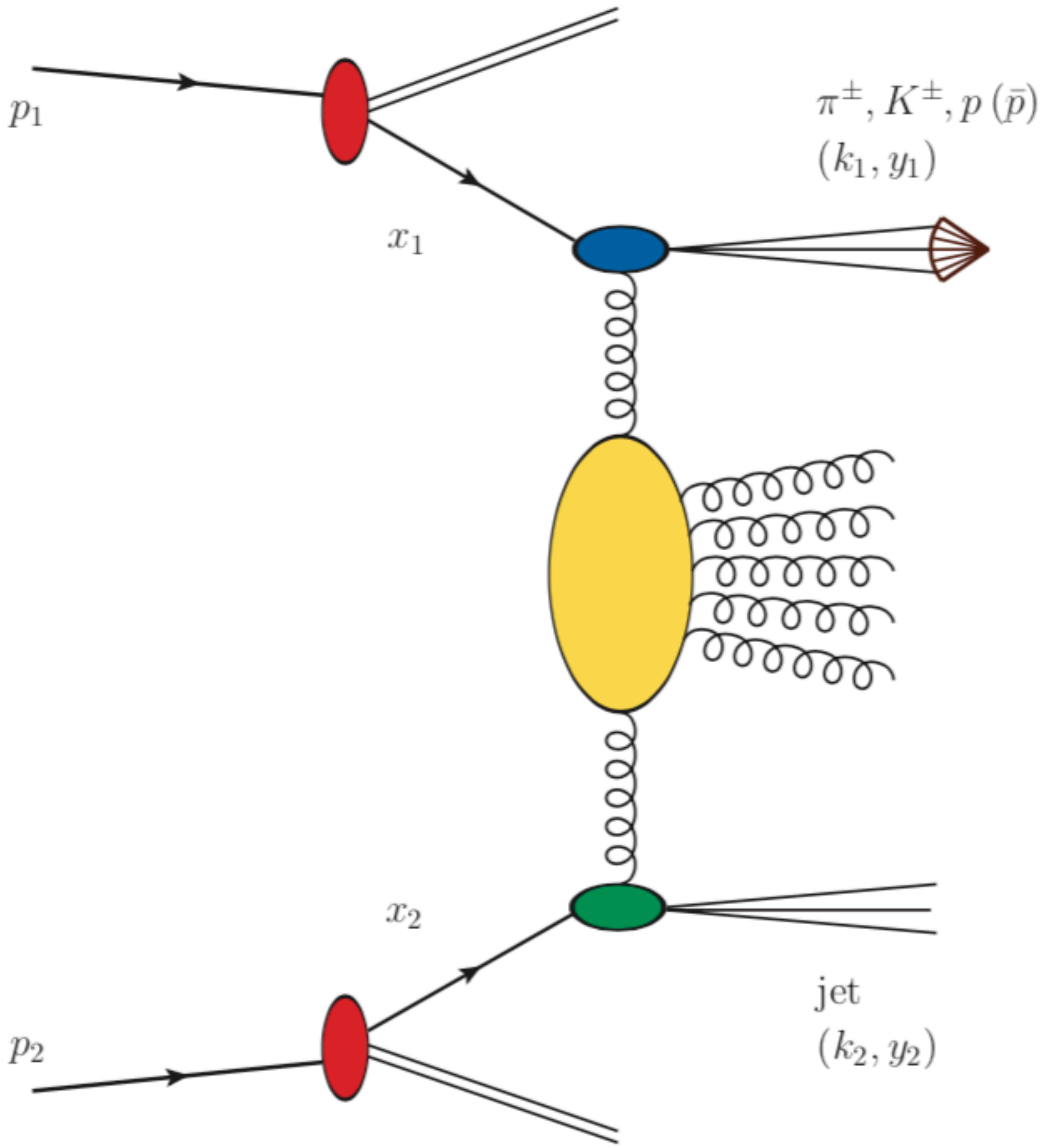
Inclusive di-hadron production

[D.Yu. Ivanov, A. Papa (2012)] (NLO forward-hadron impact factor)
[F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]



Inclusive hadron-jet production

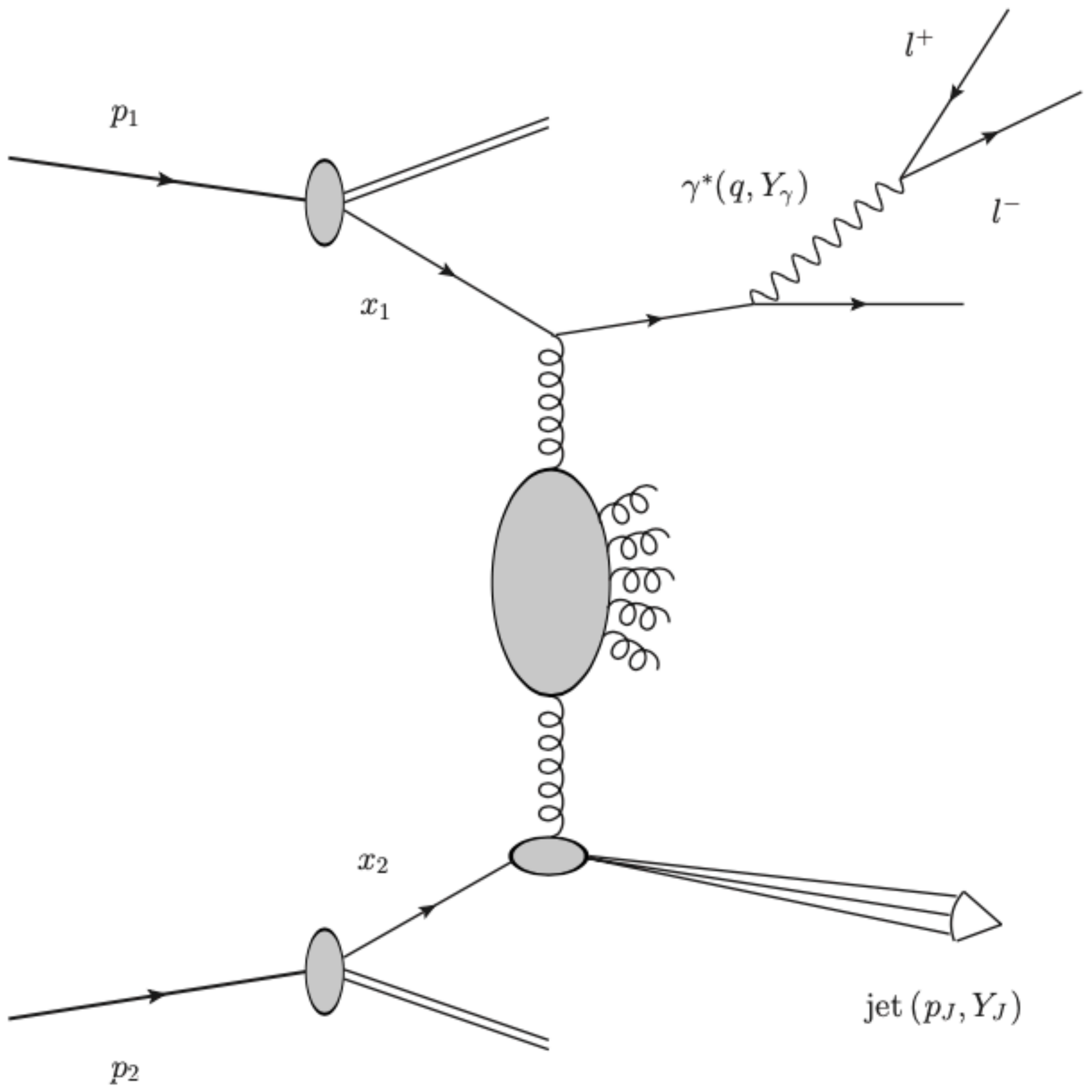
[A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]



Electroweak & Higgs physics

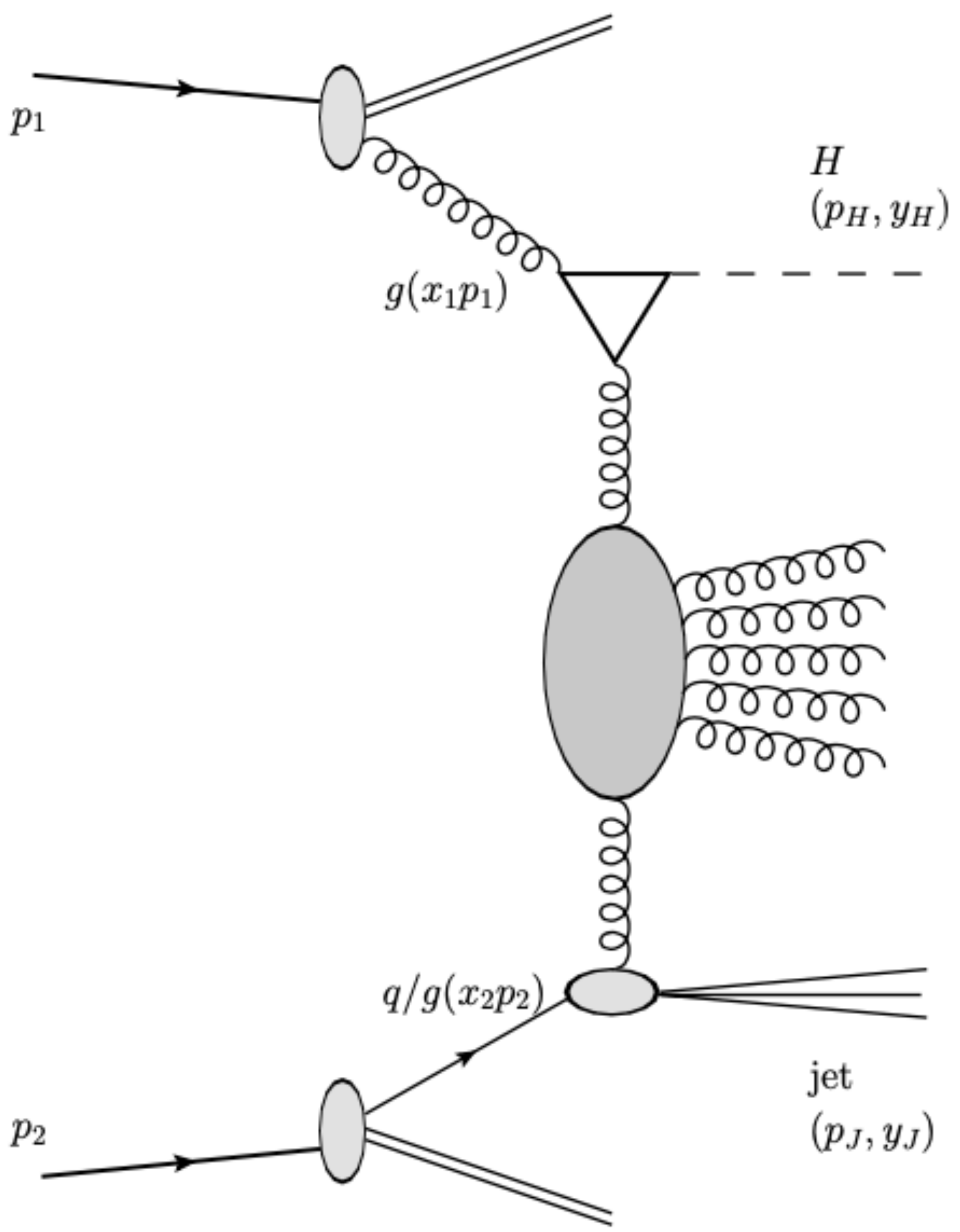
Drell–Yan-plus-jet production

[K.J. Golec-Biernat, L. Motyka, T. Stebel (2018)]
[F.G. C., D. Gordo Gómez, M. Hentschinski, A. Sabio Vera (in progress)]



Higgs-plus-jet production

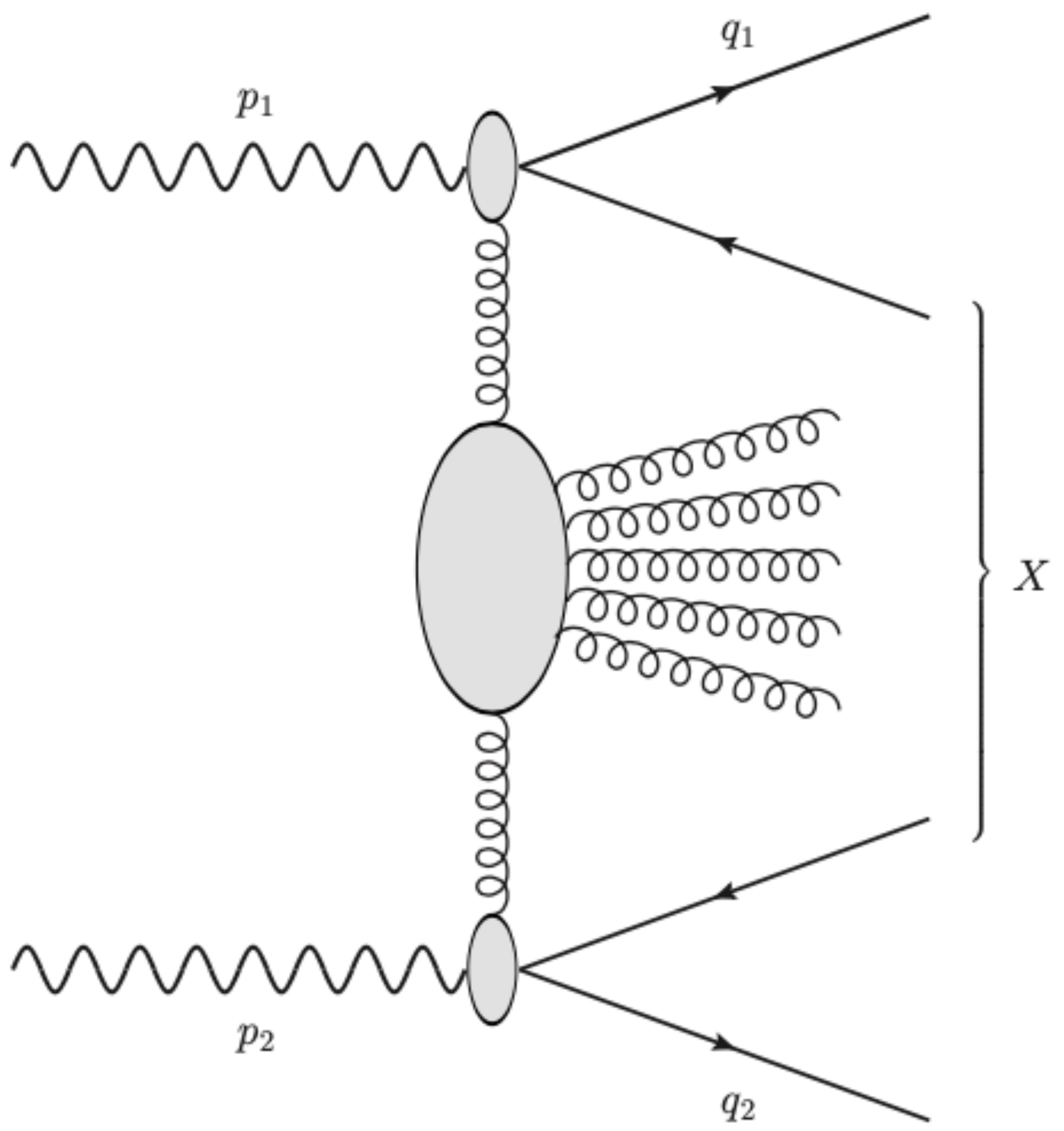
[B. Xiao, F. Yuan (2018)]
[F.G. C., M.M.A. Mohammed, A. Papa (in preparation)]



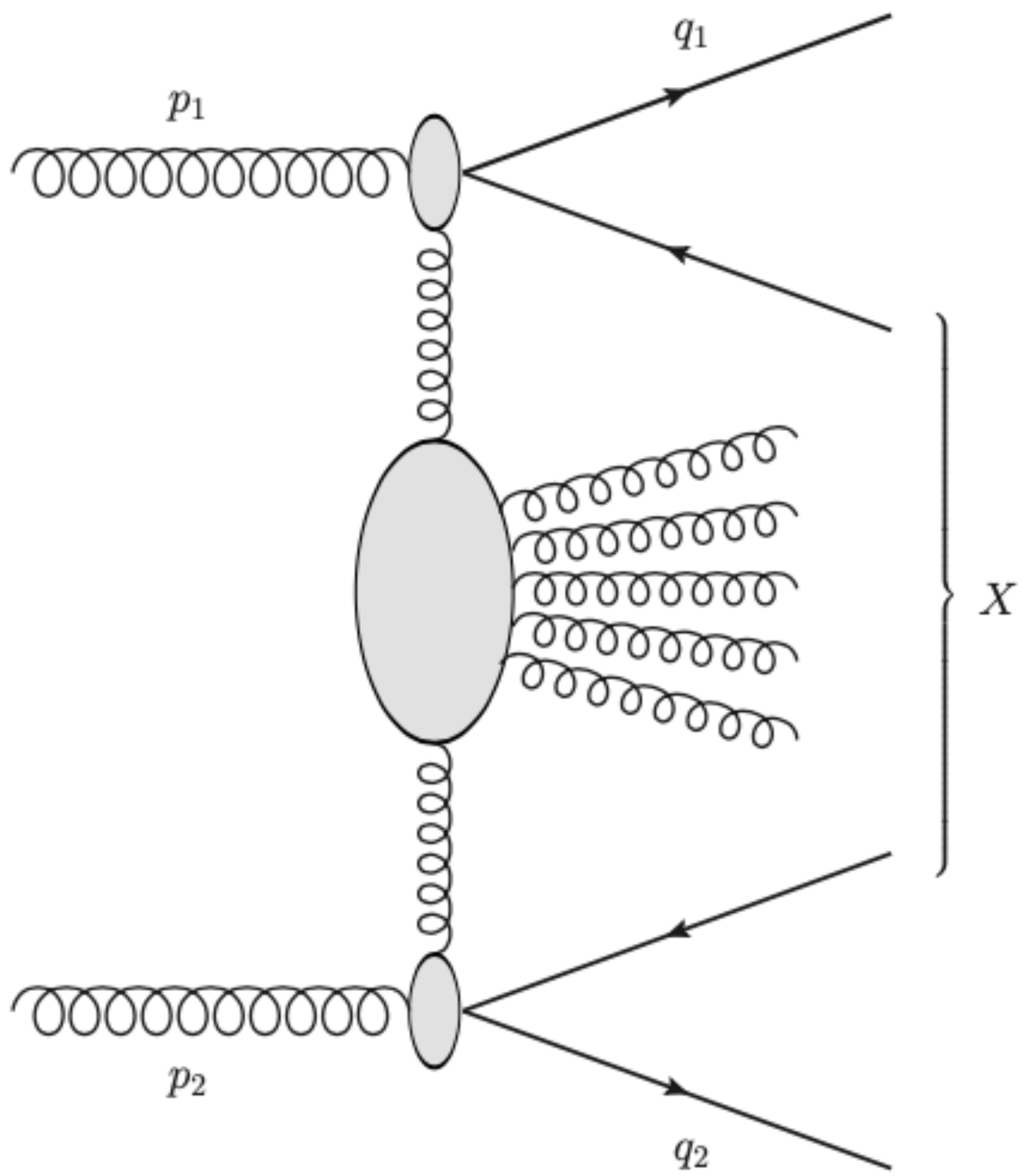
- large invariant masses stabilize the resummation series
- p_T-distributions probe kinematic ranges sensitive also to other resummations

Inclusive heavy-flavored jet photo- and hadroproduction

[F.G. C., D.Yu. Ivanov, B. Murdaca, A. Papa (2018)]



[A.D. Bolognino, F.G. C., M. Fucilla, D.Yu. Ivanov, A. Papa (2019)]



- ...convolution with FFs to describe *heavy-light meson* emissions

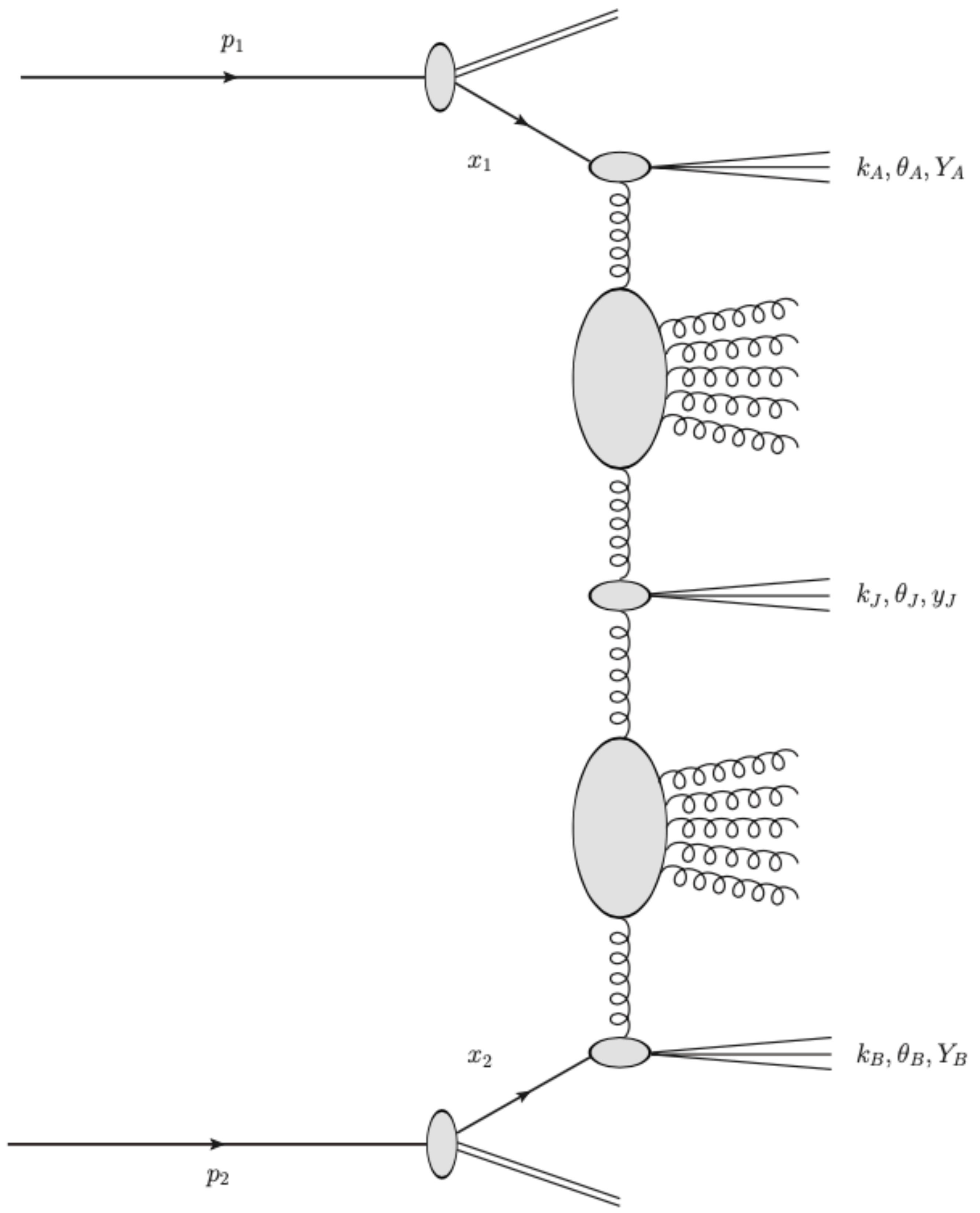
[A.D. Bolognino, F.G. C., M. Fucilla, D.Yu. Ivanov, A. Papa (in progress)]

- ...extension of our formalism $\xrightarrow{\text{to calculate}}$ $(q,\bar{q})$ *bound-state* impact factors

More exclusive final states

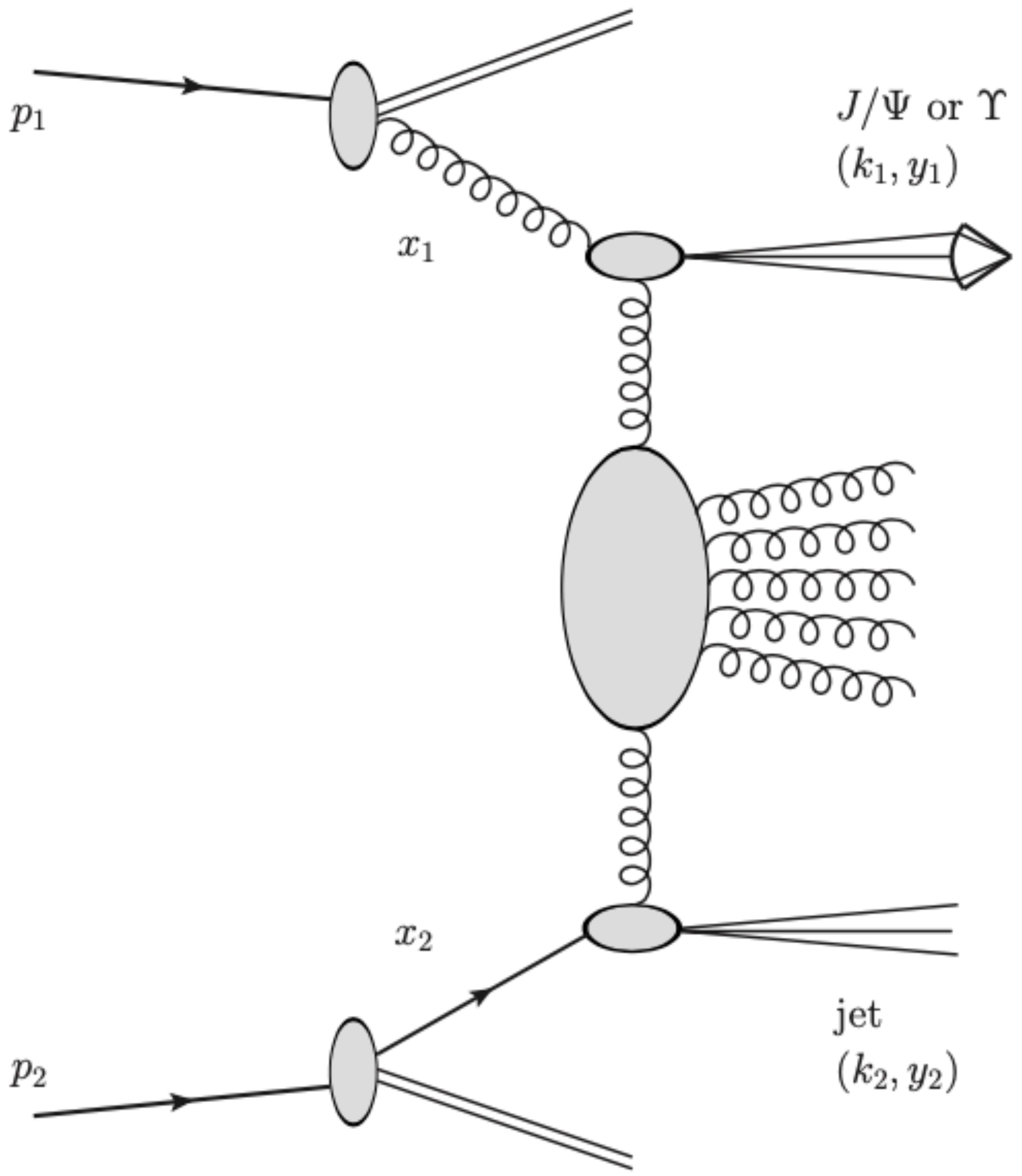
Inclusive multi-jet production

[F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2015)]
[F. Caporale, F.G.C., G. Chachamis, A. Sabio Vera (2016)]
[F. Caporale, F.G.C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016, 2017)]



Inclusive J/Ψ-plus-jet production

[R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon (2018)]



- ◇ new BFKL observables (multi-jet), quarkonium-prod. mechanisms (J/Ψ+jet)
- ◇ collinear contaminations (multi-jet), early-stage phenomenology (J/Ψ+jet)

Lecture I Checkpoint

Lecture I: Summary & Outlook

Checkpoint of Lecture I

Lecture I: Summary & Outlook

BFKL resummation $\Rightarrow$ Needed to access high-energy QCD

Checkpoint of Lecture I

Lecture I: Summary & Outlook

- BFKL resummation ⇒ Needed to access high-energy QCD
- BFKL Green's function ⇒ Small-x evolution of proton UGD

Checkpoint of Lecture I

Lecture I: Summary & Outlook

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- BFKL Green's function ⇒ Small-x evolution of proton UGD
- Forward-backward processes ⇒ Test field for Hard Diffraction

Checkpoint of Lecture I

Lecture I: Summary & Outlook

- BFKL resummation ⇒ Needed to access high-energy QCD

- BFKL Green's function ⇒ Small-x evolution of proton UGD

- Forward-backward processes ⇒ Test field for Hard Diffraction

- Hunting BFKL at the LHC as well as at new-generation colliders

Checkpoint of Lecture I

Extras

QCD & Resummations

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

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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

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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 $\Leftarrow$ SM and beyond
- Fixed-order perturbative calculations…
- …enhanced by resummations
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Proton structure

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High-energy physics
assumes knowledge
of proton structure

Reduction of uncertainties
on parton densities
from high-energy studies

Perturbative and nonperturbative aspects $\Leftrightarrow$ key ingredients to a joint search for New Physics

First experimental evidence of color

Existence of the $\Delta^{++} \equiv |uuu\rangle$ resonance with spin 3/2 $\rightarrow$ $|u^{\uparrow}u^{\uparrow}u^{\uparrow}\rangle$

Spacial wave function is symmetric $\rightarrow$ Pauli's principle would be violated

Color number introduced to restore its validity $\rightarrow$ hadrons are colorless

First experimental evidence of color

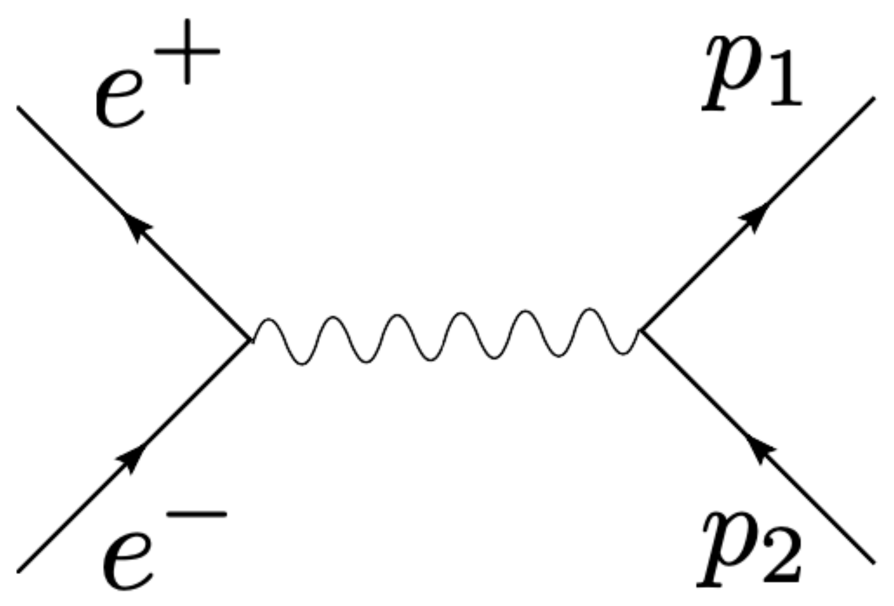
- Existence of the $\Delta^{++} \equiv |uuu\rangle$ resonance with spin 3/2 $\rightarrow$ $|u^\uparrow u^\uparrow u^\uparrow\rangle$

  Spacial wave function is symmetric $\rightarrow$ Pauli's principle would be violated

  Color number introduced to restore its validity $\rightarrow$ hadrons are colorless

- R-ratio $\rightarrow$ ratio of (e^+e^- to hadrons) / (e^+e^- to $\mu^+\mu^-$)

$$R \equiv \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-} \propto N_c \sum_f Q_f^2$$



Data compatible with $N_c = 3$

Quantum ElectroDynamics vs ChromoDynamics

Quantum Electromagnetism (QED) versus Strong Interactions (QCD)

Quantum ElectroDynamics vs ChromoDynamics

Quantum Electromagnetism (QED) versus Strong Interactions (QCD)

- Quarks are like leptons, but there are three of each (color)

Quantum ElectroDynamics vs ChromoDynamics

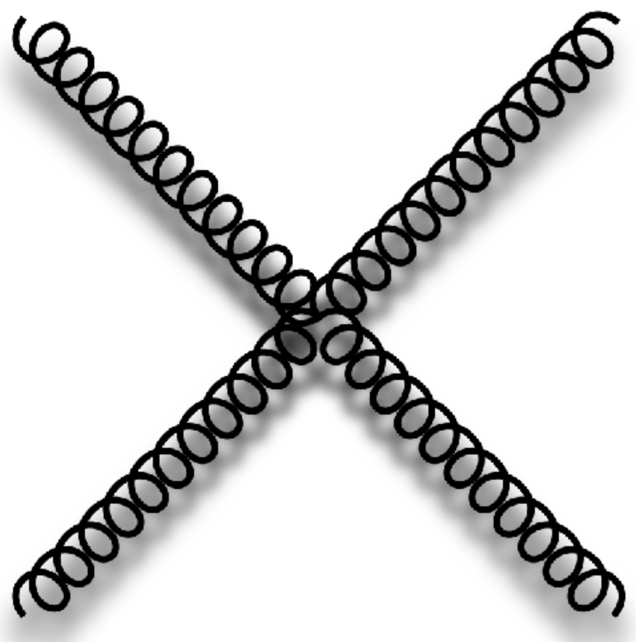
Quantum Electromagnetism (QED) versus Strong Interactions (QCD)

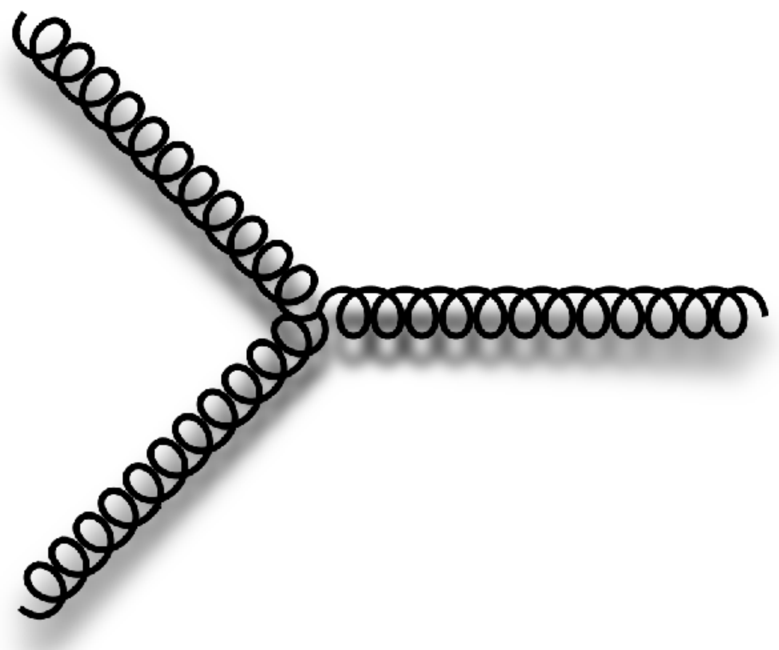
- Quarks are like leptons, but there are three of each (color)
- Gluons are like photons, but there are eight of each

Quantum ElectroDynamics vs ChromoDynamics

Quantum Electromagnetism (QED) versus Strong Interactions (QCD)

- Quarks are like leptons, but there are three of each (color)
- Gluons are like photons, but there are eight of each
- Gluons interact with themselves, photons do not



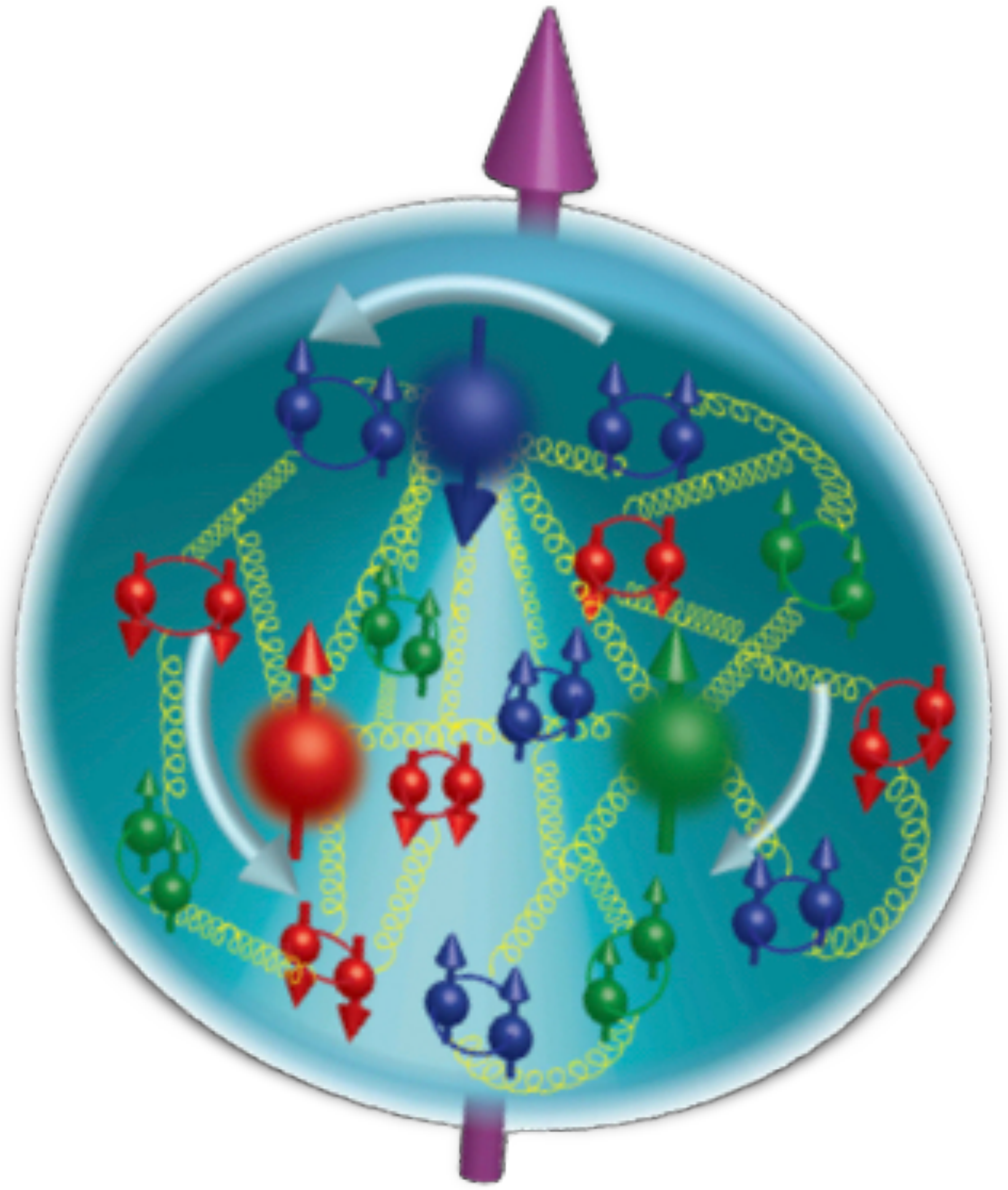


Parton Distribution Functions & Fragmentation Functions

PDFs & FFs → relevant for the search of **New Physics** from a **precision background**

→ ...crucial role in the understanding and **exploration** of **QCD**

- Describe the internal structure of the nucleon (PDFs) and the dynamic formation of hadrons (FFs)
- **Nonperturbative** objects that enter the expression of cross sections
- Can be *extracted* from experiments via *global fits*



Parton Distribution Functions & Fragmentation Functions

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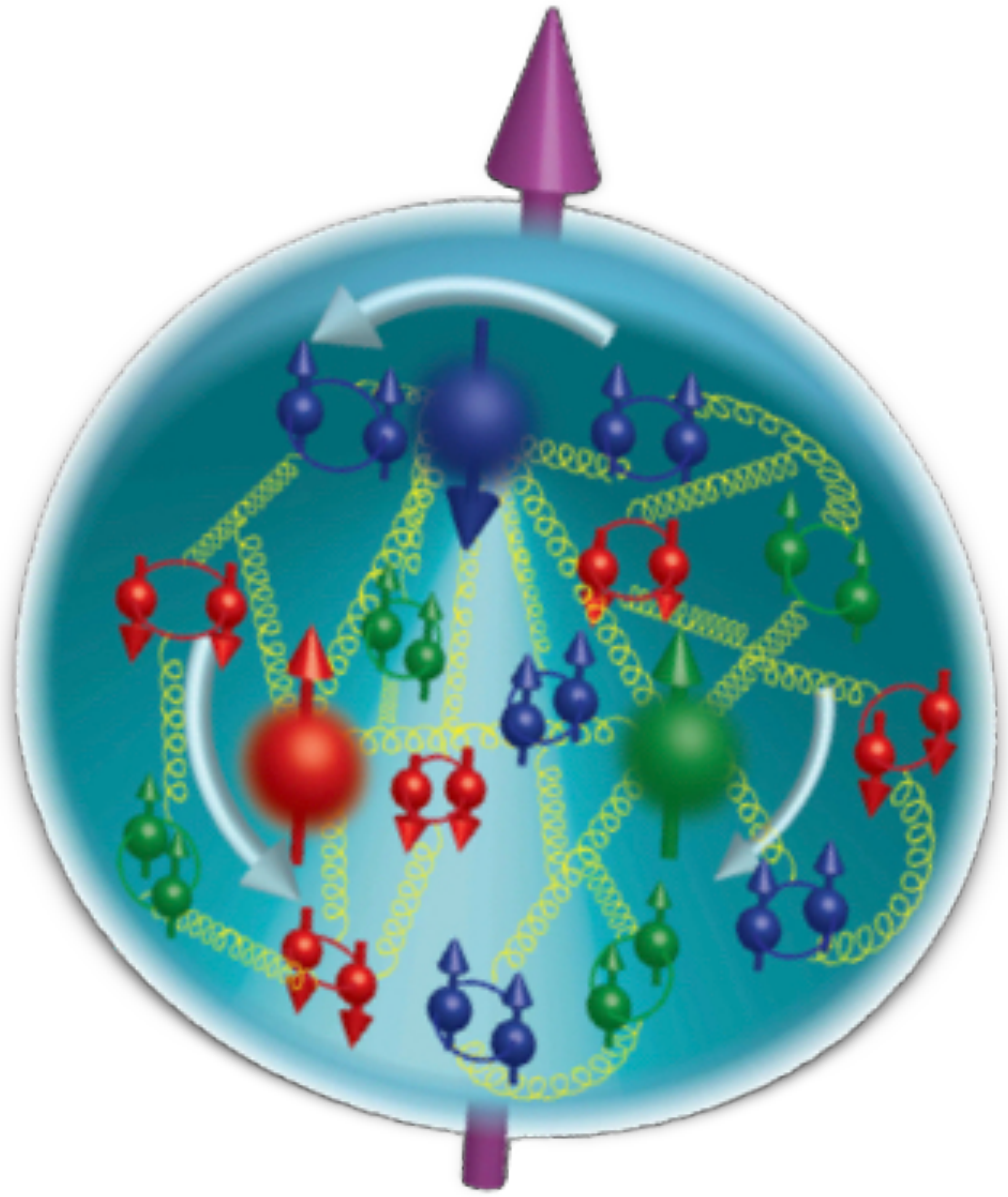
  - Describe the internal structure of the nucleon (PDFs) and the dynamic formation of hadrons (FFs)
  - **Nonperturbative** objects that enter the expression of cross sections
  - Can be *extracted* from experiments via *global fits*

- Several types of functions (**1D collinear**, 3D TMD, 3D GPD, ...)
  - Follow from different **factorization theorems**
  - Exhibit peculiar **universality properties**
  - Obey distinct **evolution equations**

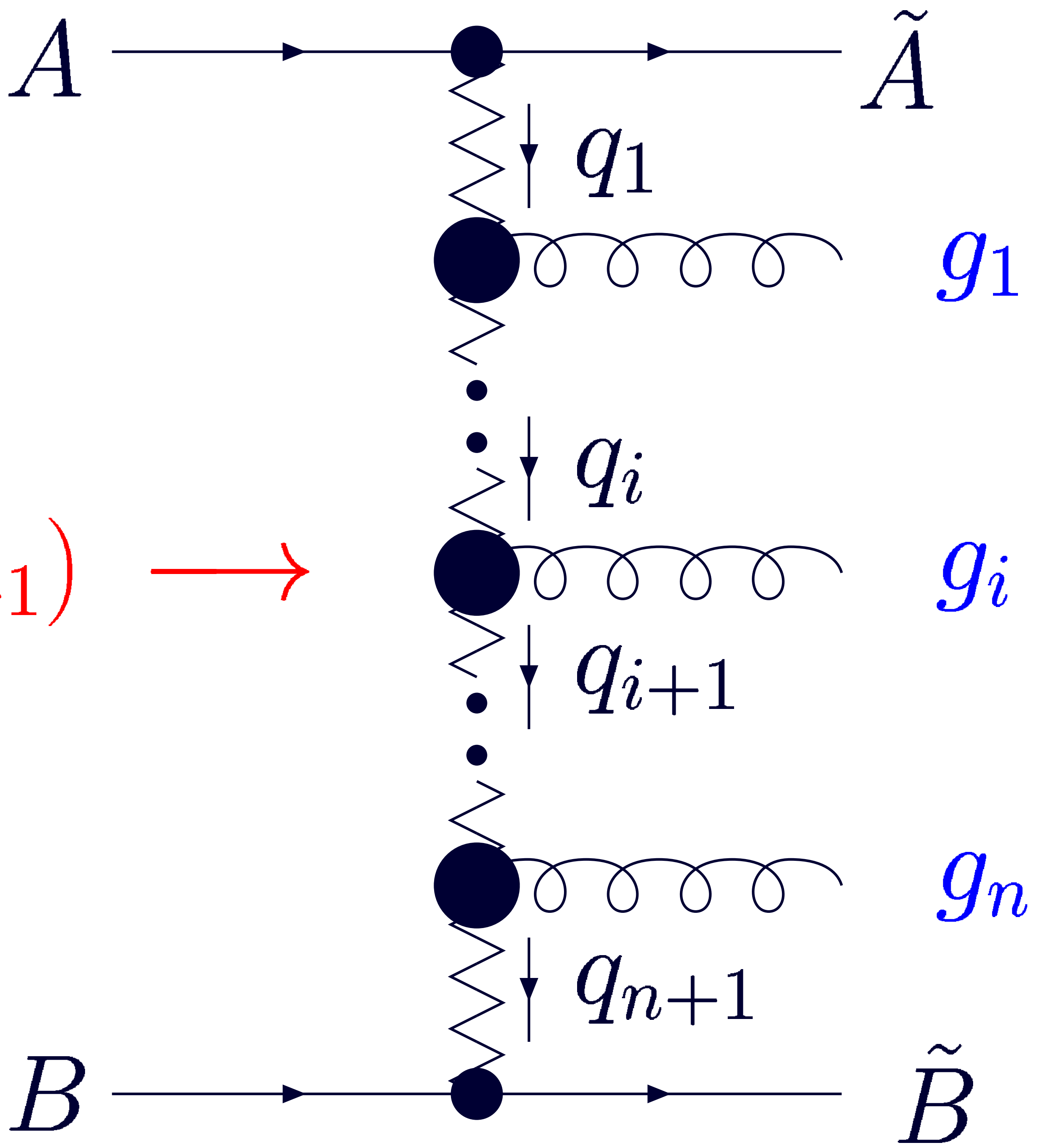


LL & NLL Accuracy

BFKL in the LL approximation

Inelastic scattering process $A + B \;\to\; \tilde{A} + \tilde{B} + n$ in the LLA

$\gamma^{G_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \longrightarrow$



multi-Regge kinematics

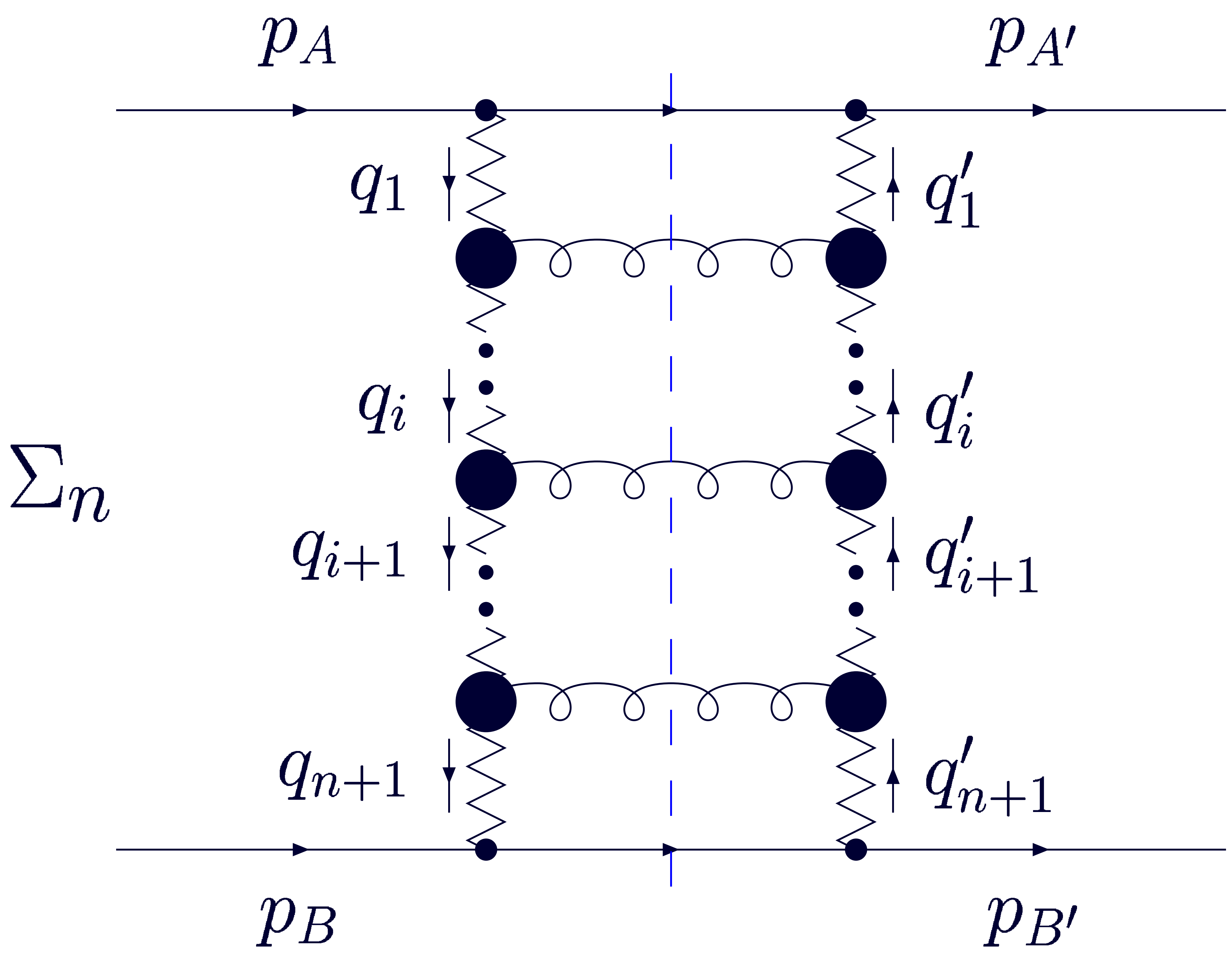
$$\mathrm{Re}\mathcal{A}^{\tilde{A}\tilde{B}+n}_{AB} = 2s\,\Gamma^{c_1}_{\tilde{A}A}\left(\prod_{i=1}^{n}\gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1})\left(\frac{s_i}{s_R}\right)^{\omega(t_i)}\frac{1}{t_i}\right)\frac{1}{t_{n+1}}\left(\frac{s_{n+1}}{s_R}\right)^{\omega(t_{n+1})}\Gamma^{c_{n+1}}_{\tilde{B}B}$$

$\gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \;\to\;$ RRG vertex

$s_R \;\to\;$ energy scale, irrelevant in the LLA

BFKL in the LL approximation

Elastic amplitude $A + B \longrightarrow A' + B'$ in the LLA via s-channel unitarity

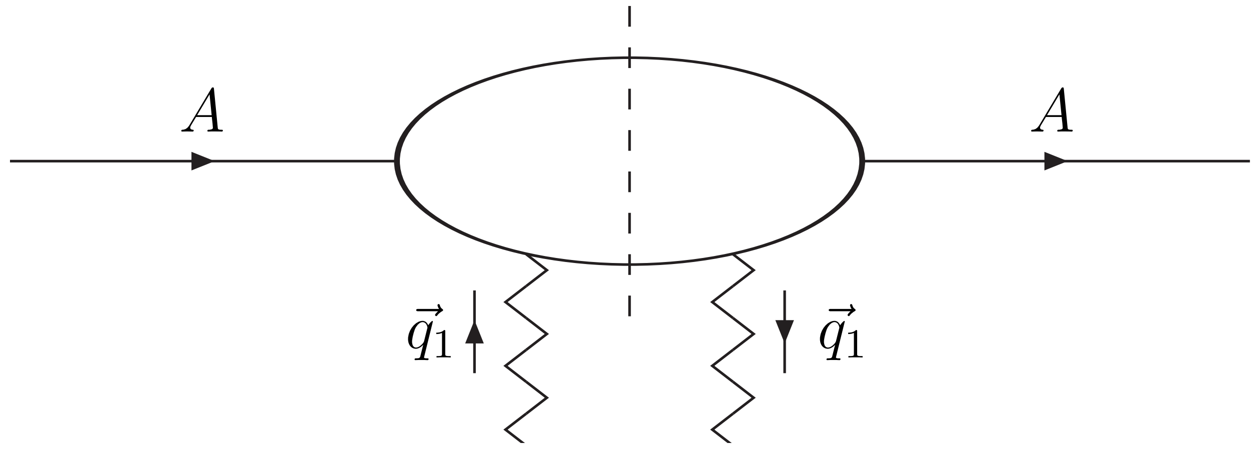


$$\mathcal{A}_{AB}^{A'B'} = \sum_{\mathcal{R}} (\mathcal{A}_{\mathcal{R}})_{AB}^{A'B'} \,, \qquad \mathcal{R} = 1 \text{ (singlet)}, \, 8^- \text{ (octet)}, \ldots$$

The 8^- color representation is important for the bootstrap, i.e. the consistency between the above amplitude and that with one Reggeized gluon exchange

BFKL impact factors known within NLL

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy
  $\longrightarrow$ known in the NLA just for few processes



◇ **colliding partons**

[V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
[M. Ciafaloni, G. Rodrigo (2000)]

◇ $\gamma^* \longrightarrow V$, with $V = \rho^0,\ \omega,\ \phi$, forward case

[D.Yu. Ivanov, M.I. Kotsky, A. Papa (2004)]

◇ forward jet production

[J. Bartels, D. Colferai, G.P. Vacca (2003)]
(exact IF) [F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa, A. Perri (2012)]
(small-cone IF) [D.Yu. Ivanov, A. Papa (2012)]
(several jet algorithms discussed) [D. Colferai, A. Niccoli (2015)]

◇ forward identified hadron production

[D.Yu. Ivanov, A. Papa (2012)]

◇ $\gamma^* \longrightarrow \gamma^*$

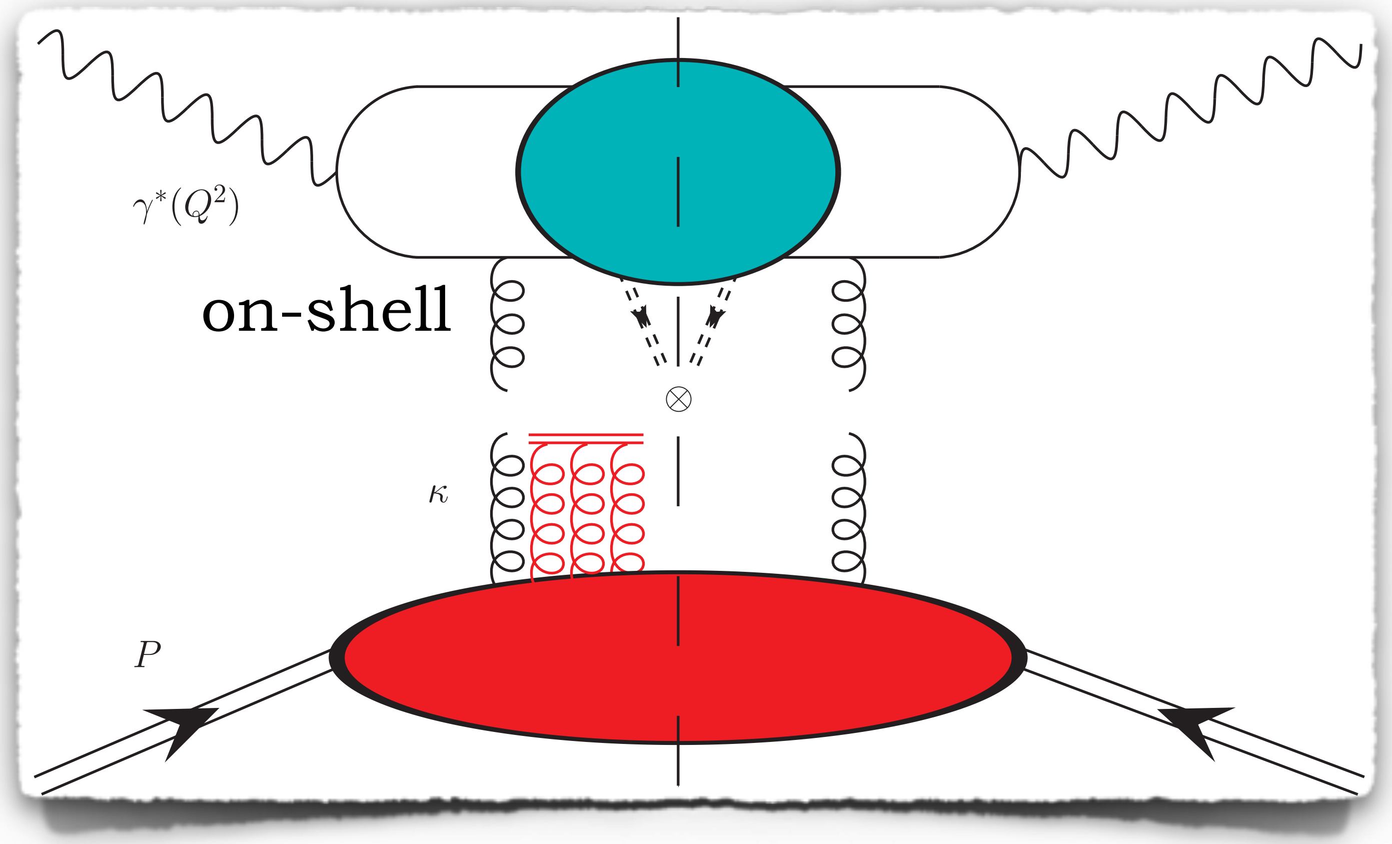
[J. Bartels *et al.* (2001), I. Balitsky, G.A. Chirilli (2011, 2013)]

Diffractive Processes

TMD versus high-energy factorization

TMD

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



TMD
PDF

TMD versus high-energy factorization

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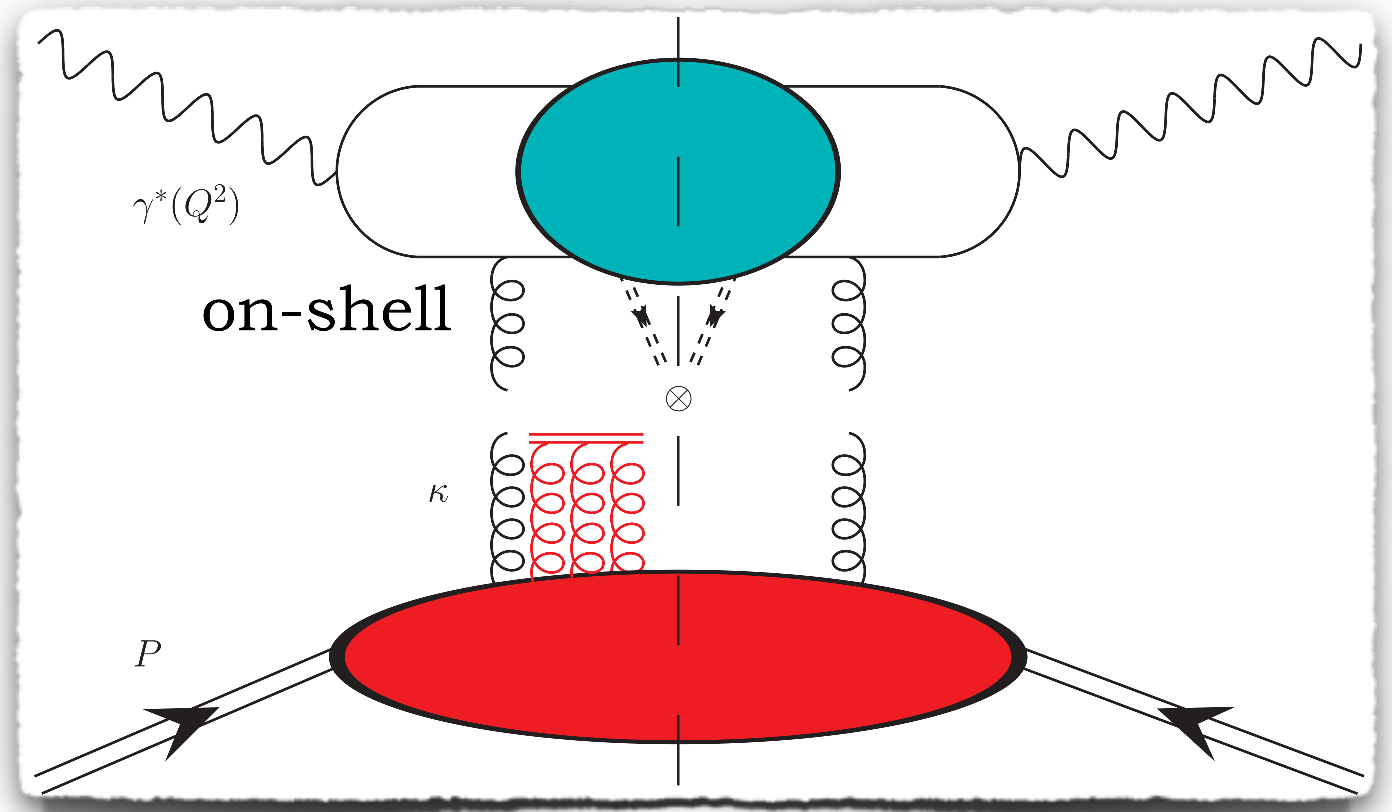
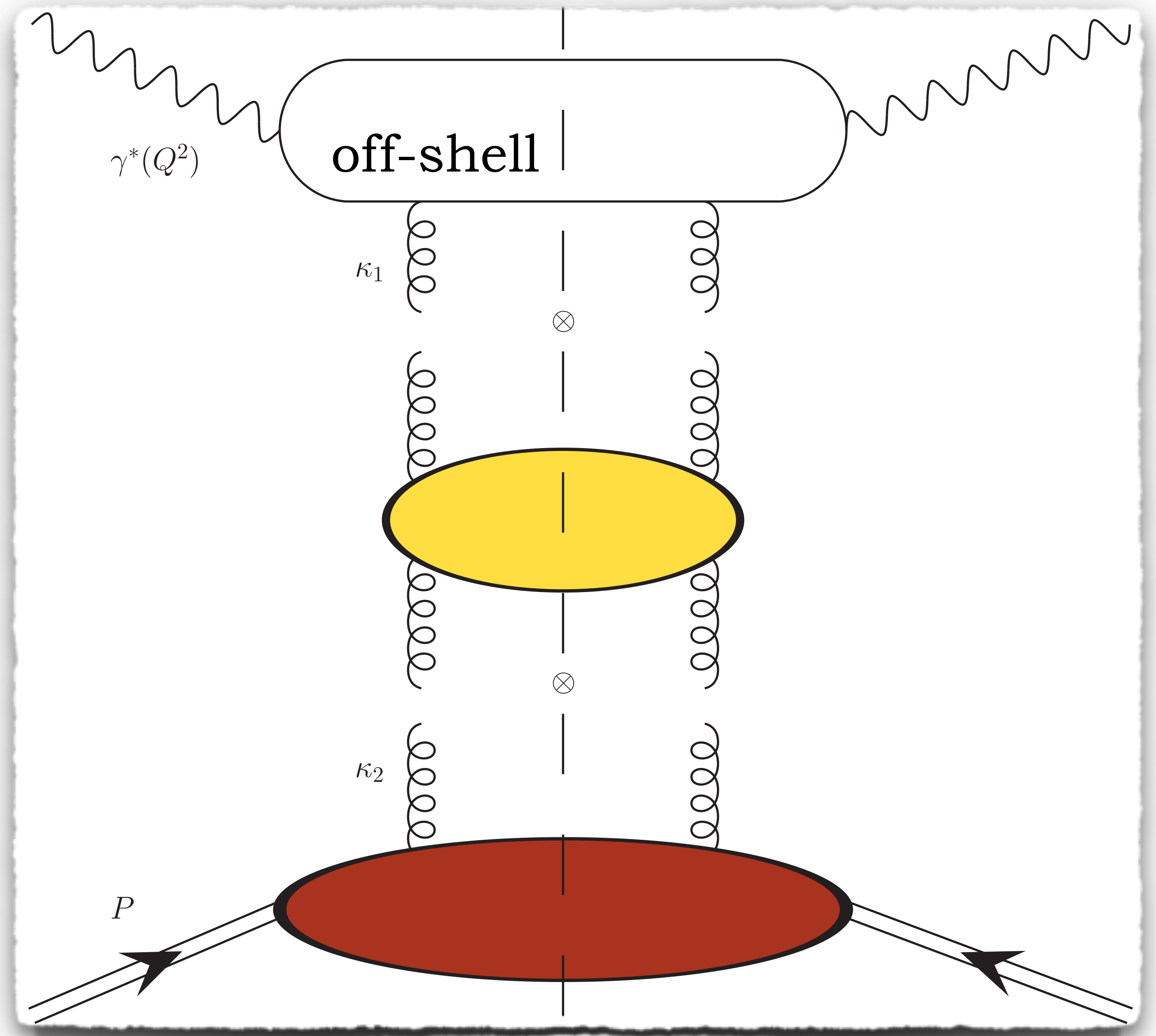


TMD PDF

HEF

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



$\Phi^{\gamma^* \to \gamma^*}$

$\otimes$

$\mathcal{G}_{\rm BFKL}$

$\otimes$

$\Phi^{P}_{[\rm NP]}$

TMD versus high-energy factorization

TMD

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IR-safe colorless $\{\Phi^{\mathrm{i}\to\mathrm{o}}\}$
(Fadin-Martin theorem)
[V.S. Fadin, A.D. Martin (1999)]

TMD PDF

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* Inclusive or exclusive processes (!)
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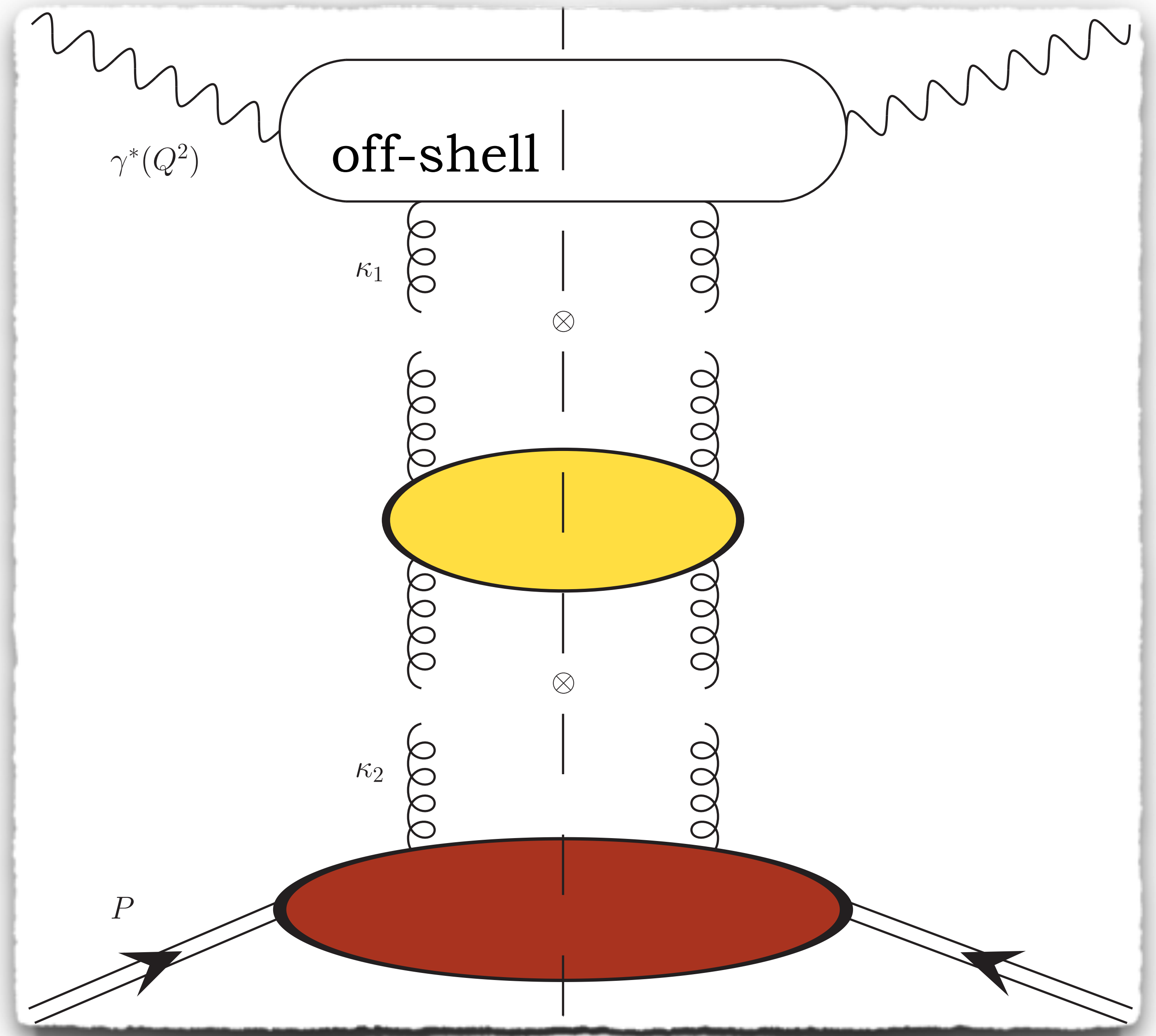

$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\mathrm{BFKL}} \otimes \Phi^{P}_{[\mathrm{NP}]}$$

TMD versus high-energy factorization

TMD

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

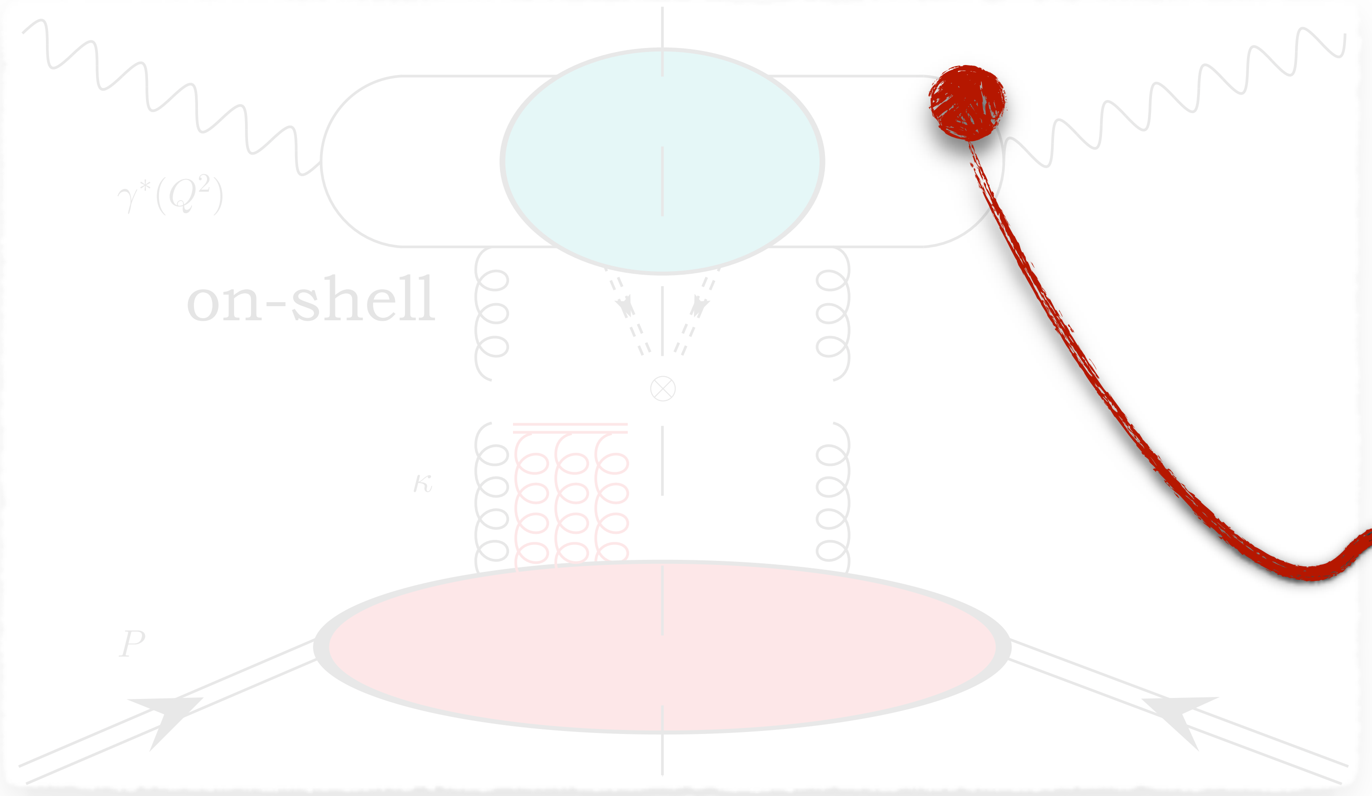
(Fadin-Martin theorem)

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

IR diffusion pattern

(Bartels' cigar)

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



TMD PDF

Q^2

Q_0^2

HEF

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* Small x, large κ_T
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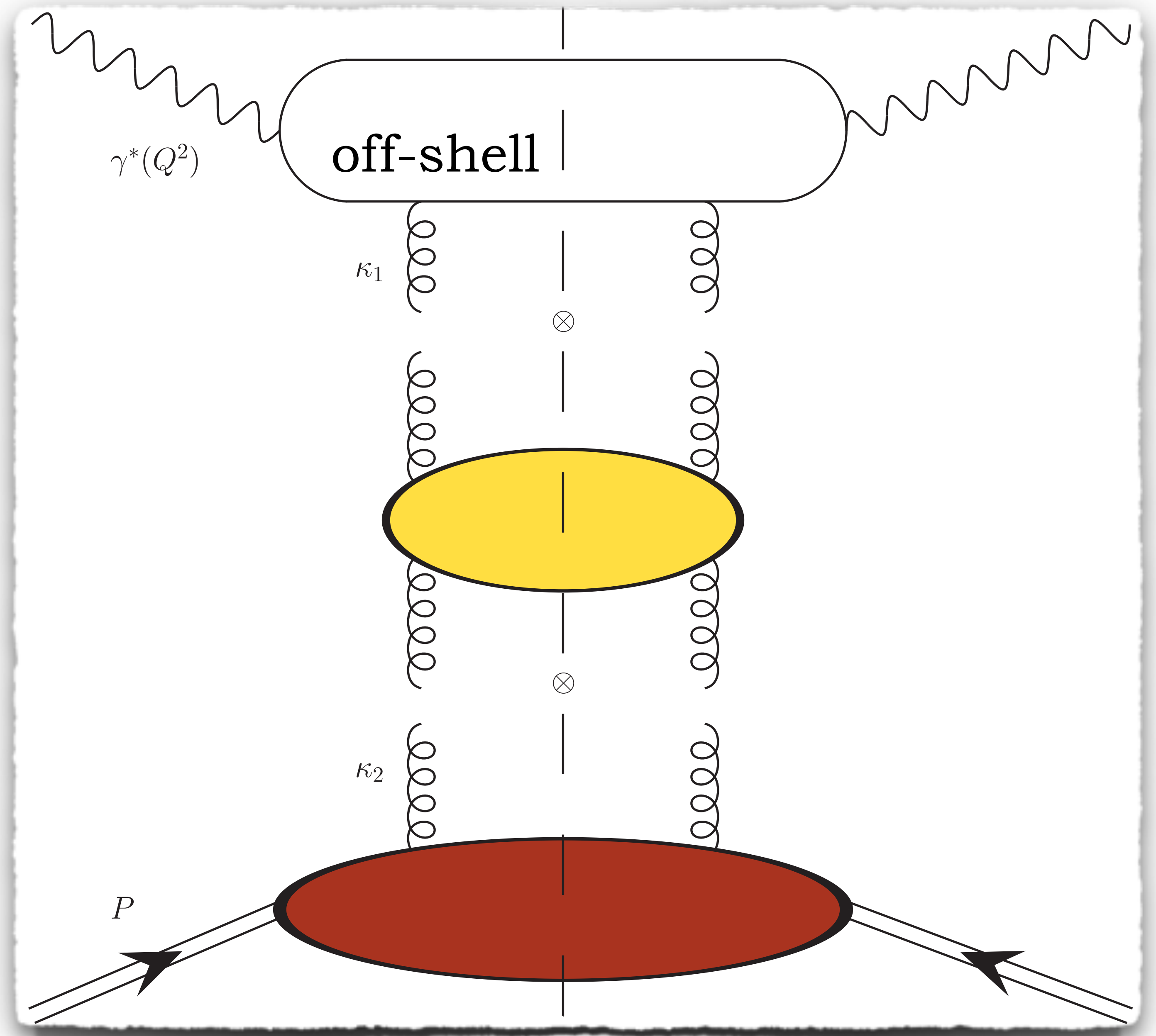
* Diagram: DIS



$\Phi^{\gamma^*\to\gamma^*}$

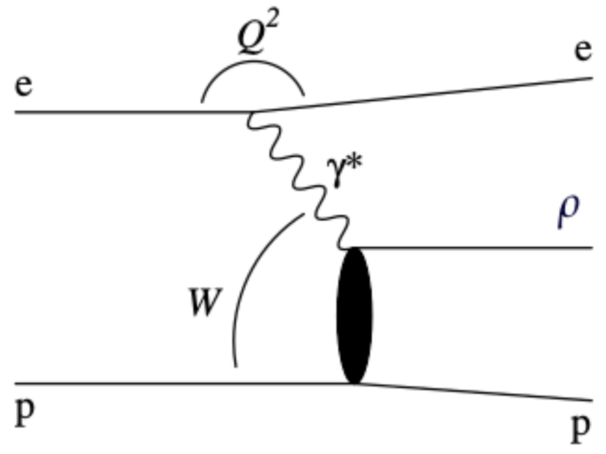
$\otimes$

$\mathcal{G}_{\mathrm{BFKL}}$

$\otimes$

$\Phi^{P}_{[\mathrm{NP}]}$

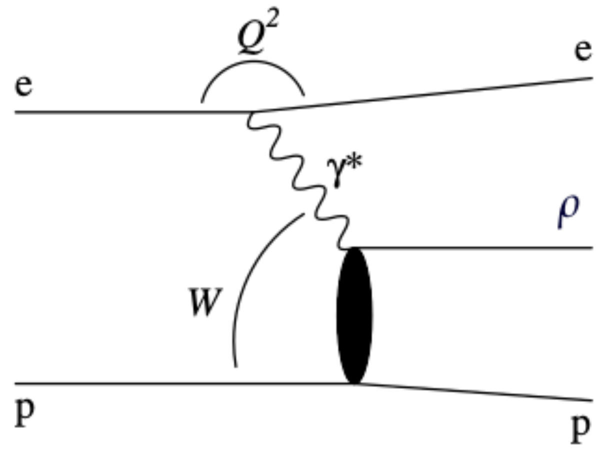
Exclusive forward ρ-meson leptoproduction



- High-energy regime:
  $s \equiv W^2 \gg Q^2 \gg \Lambda^2_{\rm QCD} \implies$ small $x = \frac{Q^2}{W^2}$
- photon virtuality Q is the **hard scale** of the process

▶ **Process solved in helicity** $\implies$ so far **unexplored testfield** for UGD

Exclusive forward ρ-meson leptoproduction



- High-energy regime:
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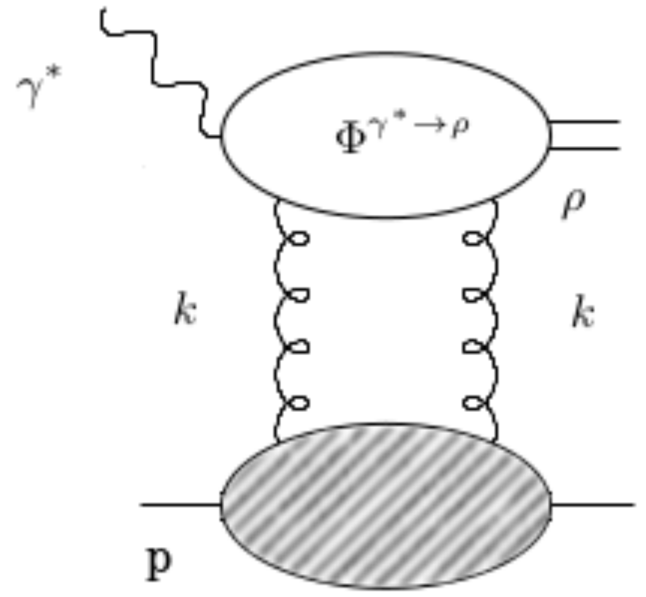
▶ **Process solved in helicity** $\implies$ so far **unexplored testfield** for UGD

Leading **helicity amplitudes** are known

Assumption:

- $\mathcal{I}m_s\{\mathcal{A}(\gamma^* p \to \rho\, p)\}$
- same W- and t-dependence for T_{11} and T_{00} $\implies$ high-energy factorization
  - $\to$ same physical mechanism, scattering of small transverse size of dipole on the proton target, at work $\Rightarrow$ high-energy factorization

$$T_{\lambda_\rho \lambda_\gamma}(s; Q^2) = is \int \frac{d^2\kappa}{(\kappa^2)^2}\, \Phi^{\gamma^*(\lambda_\gamma)\to\rho(\lambda_\rho)}(\kappa^2, Q^2)\, \mathcal{F}(x, \kappa^2)\,, \quad x = \frac{Q^2}{s}$$



Interesting transitions:

- $\gamma^*_L \to \rho_L \xrightarrow{\text{encoded by}} \Phi^{\gamma^*_L \to \rho_L}$
- $\gamma^*_T \to \rho_T \xrightarrow{\text{encoded by}} \Phi^{\gamma^*_T \to \rho_T}$

$\implies$ **DAs** enter in $\Phi^{\gamma^* \to \rho}$

Toward precision studies of high-energy QCD?

Conclusions and Outlook

Direction 1. Semi-hard reactions as probes of BFKL

- Distinctive signals of the **high-energy resummation** emerge at the energies and at the exclusive kinematic congurations of **current** LHC analyses, and can be effectively disengaged from (pure) fixed-order, DGLAP ones
- Successful tests with NLA accuracy in the **Mueller–Navelet** configuration; nevertheless, *new sensitive observables* as well as *more exclusive final states* are needed. Feedback from the experimental Collaboration is **essential**

Direction 2. BFKL as tool

- Analyses of more differential distributions covering broader kinematic ranges require an ineludible effort to develope a *transversal formalism* in which distinct resummations are concurrently encoded (high-energy/small-x, threshold, transverse-momentum, Sudakov)
- **From open to bound heavy-quark states**: an *ongoing program* (theory + pheno) on the description of heavy-flavored jets, heavy-light mesons and quarkonia

(talk by **Michael**) [Cosenza Collaboration (2018, 2019, in progress)]