$SCET_Q$

An effective theory for Quarkonium in soft background

Yiannis Makris (PV)

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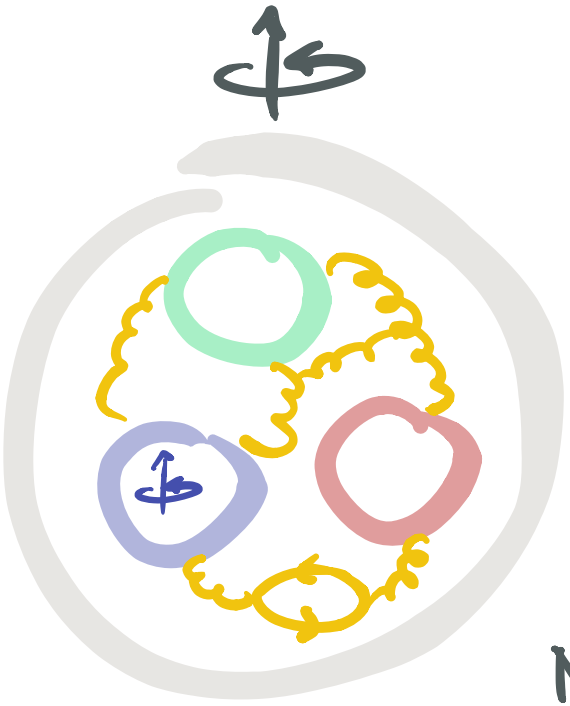
INFN

Fellini
Fellowship for Innovation at INFN

Hadronic Structure

A study of the nucleon in terms of the QCD degrees of freedom



- Momentum distributions
- Density distributions
- Spin correlations

Nucleon Partons

The Electron - Ion - Collider (EIC)

"Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility."

NSAC Nuclear Physics Long Range plan for DOE and NSF

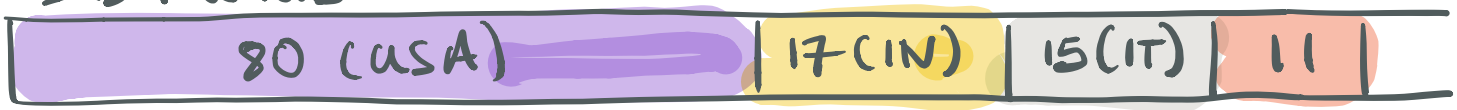
The Electron-Ion-Collider (EIC)

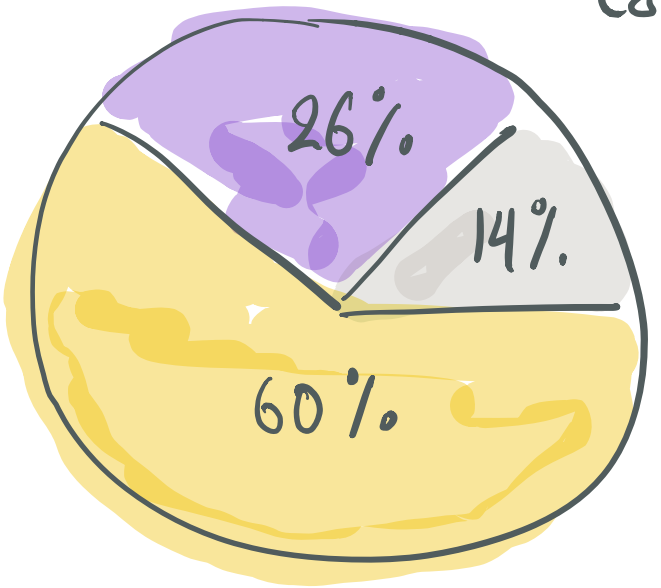
A machine focused on hadronic structure. To be ready in $\mathcal{O}(10^1)$ years

The EIC user group composition as of 20/02/2020

Members

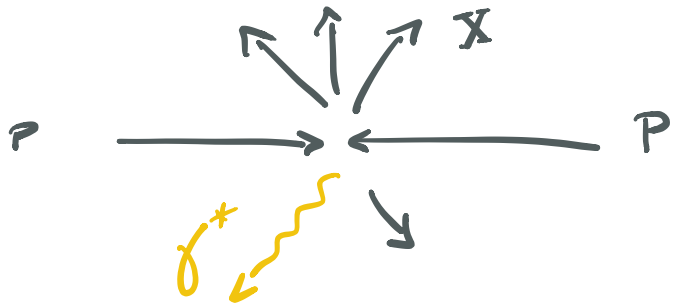
Institutions



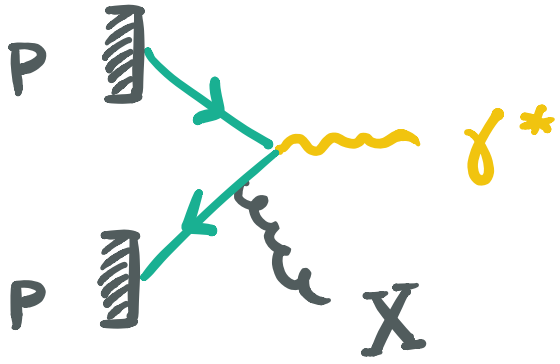


Experiment
Theory
Accelerator

Collider experiments - Factorization



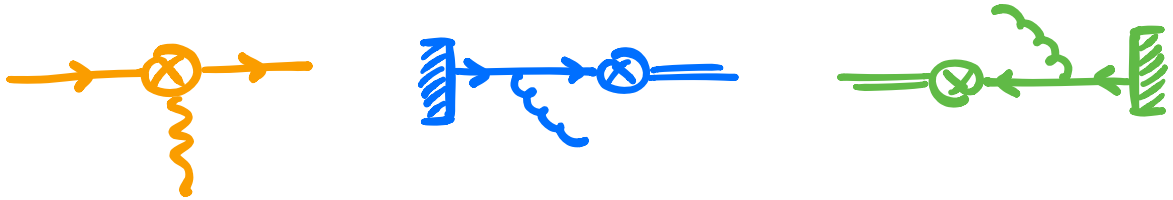
$pp \to \gamma^* + X$



Parton distribution functions

$$\sigma(\text{cuts}) = \int_{\text{cuts}} d\Phi \; \frac{d\sigma}{d\Phi}(ij \to \gamma^* + X) \, f(i \leftarrow P) \, f(j \leftarrow P)$$

PDFs

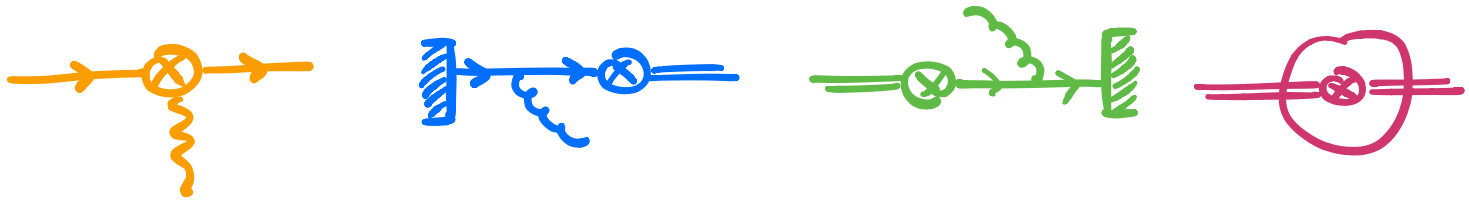


Hard n-Collinear $\bar{n}$-Collinear

More differential → More details

PDFs can only tell us about the longitudinal component of the momentum of the parton inside the proton.

$$\frac{d\sigma}{dq_T} = \int_{cut} d\Phi \; \frac{d\sigma}{d\Phi}(ij \to \gamma^* X) \; f^{\perp}(i \leftarrow P) \otimes f^{\perp}(j \leftarrow P) \otimes S(global)$$



Hard n-Collinear $\bar{n}$-Collinear Soft

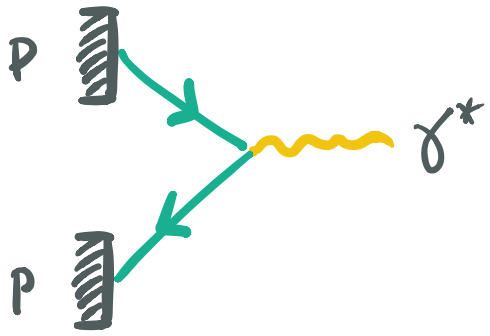
$$\Lambda_{QCD} \lesssim \underbrace{q_T \ll M_{\gamma^*}}_{\text{factorization to hold}}$$

$$\boxed{f^{\perp}(i \leftarrow P)\sqrt{S(global)} = \text{TMDPDF}}$$

Universality - TMD extraction program

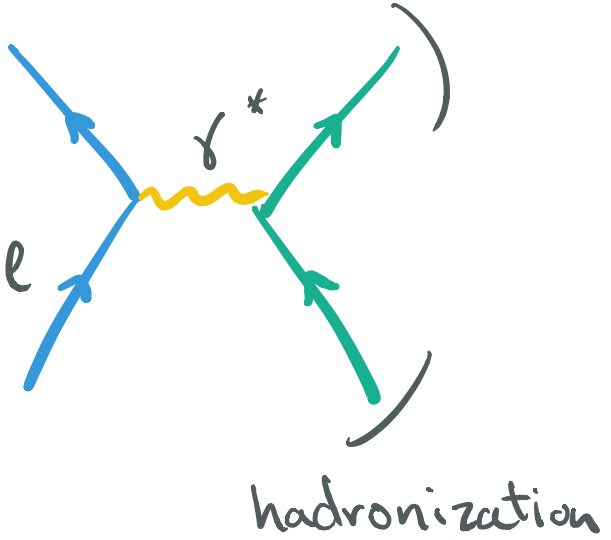
for $\Lambda_{QCD} \lesssim q_\perp$ the transverse momentum comes (part of it) from intrinsic momentum of partons in the proton.

$pp \to (\gamma^* \to l\bar{l}) + X$



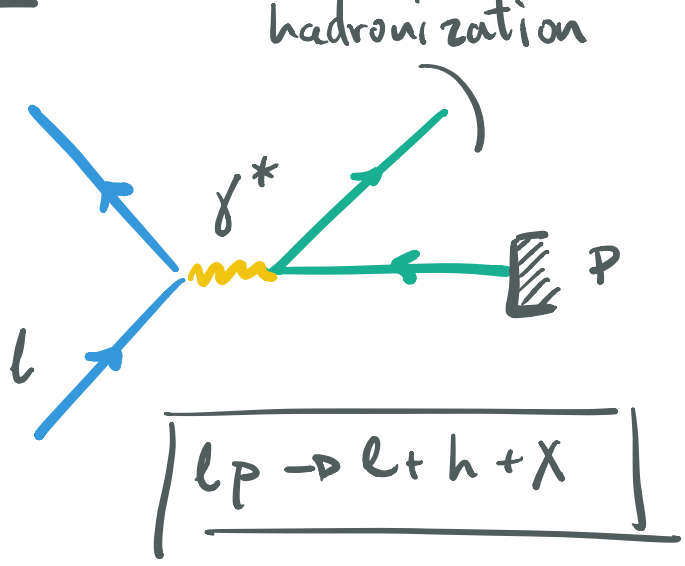
$H_1 \left(f^\perp \otimes f^\perp \otimes S \right)$

$l\bar{l} \to h_1 + h_2 + X$



$H_3 \left(D^\perp \otimes D^\perp \otimes S \right)$

$lp \to l + h + X$



$H_2 \left(f^\perp \otimes D^\perp \otimes S \right)$

Quarkonium (Why)

Gluon-TMDs are hard to isolate and hard to measure. Often lead to factorization breaking effects.

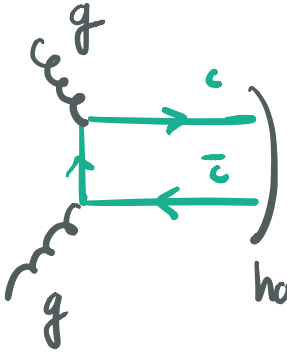
Examples are: $gg \to$ 2 jets/hadrons (factorization breaking)

$e^+e^- \to$ 3 jets (TMDs?)

$eg \to$ 2 jets (mixing with $eq \to$ 2 jets)

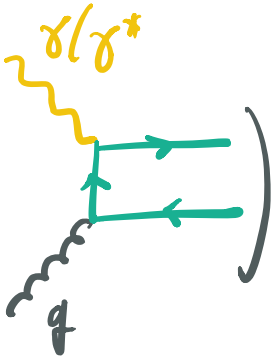
Quarkonium may offer a solution:

$gg \to \eta_{c/b}$:



hadronization

$eg \to \psi / \Upsilon(1S)$:

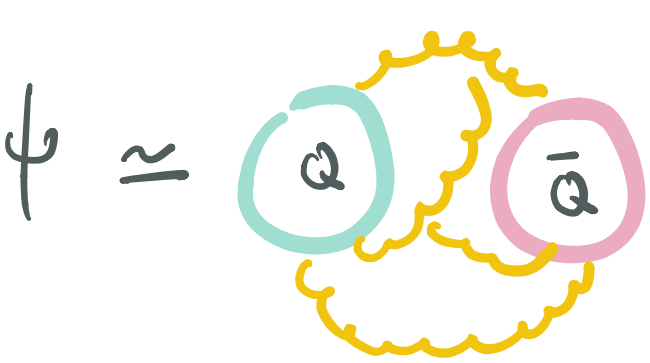


Quarkonium (What)

- QCD bound-state made primarily out of a heavy quark (charm/bottom) and the corresponding anti-quark

$[M_\psi < M_{open}] \xrightarrow{+QED}$ $Br[J/\psi \to \mu^+\mu^-] \sim 6\%$

$Br[\Upsilon(1S) \to \mu^+\mu^-] \sim 2.5\%$



- Quark gluon plasma
- Hadronization
- Hadronic Structure

→ Clean experimental signature with a di-muon decay at $M^2_{\mu\mu} \sim M^2_{J/\psi}$

NR-QCD

- The heavy quark-antiquark are thought to be non-relativistic in the Quarkonium rest frame

$v \ll 1$ is the relative velocity

m : hard

mv : soft

mv^2 : ultra-soft

} hierarchy of scales suggests the use of effective field theory

$\longrightarrow$ NR-QCD

$$\sum_{[n]} c\,\bar{c}\,\Big|_{[n]} \xrightarrow{\langle \mathcal{O}^{\psi}_{[n]} \rangle} \text{Quarkonium}$$

$$d\sigma \sim \sum_n d\sigma(Q\bar{Q}[n])\,\langle \mathcal{O}[n] \rangle \sim v^{M[n]}$$

Quarkonium (How)

$$\Lambda_{QCD} \sim mv \sim q_\perp$$

→ Quarkonium sounds like a good approach to gluon TMDs but introduces new effects, yet completely unexplored!

Hadronization effects from $Q\bar{Q}$ → Quarkonium need to be incorporated.

- Develop an effective field theory approach SCET + NR-QCD (since 2003)
- Standardized notation and simplify methodology
- Develop numerical packages.

Quarkonium (How)

Developed through a series of projects (various processes)

Quarkonium → $h_1 + h_2 + X$ (sets the formalism)

Sean Fleming, Yiannis Makris, Thomas Mehen

$ep \to$ Quarkonium $+ X$ (-"- -"- + phenomenology)

Sean Fleming, Justin Lieffers, Yiannis Makris, Thomas Mehen

$i \to$ Quarkonium $+ X$ (TMD-Fragmentation)

Miguel Echevarria, Yiannis Makris, Ignazio Scimemi

$ep \to$ Quarkonium + Jet (-"- -"-)

The role of jets in TMDs?

SCET q project and Pavia

HasQCD Alessandro Bacchetta (Fellini host) Marco Guagnelli
Barbara Pasquini Marco Radici Giuseppe Bozzi
Miguel Echevaria Valerio Bertone Francesco Celiberto

Actively involved in the EIC-UG and in EIC related research

Projects:

3D-Spin (ERC-funded : 3-dimensional maps of the spinning nucleon)

GlueCore (M. S-Curie ind. fellowship : maping the 3-dimensional structure of the proton)

3D-Glue (FARE program: Extraction of the 3-dimensional distribution of gluons in the proton)

Secondment

Academia: With the EIC spectrum of interest there are many intitutions with good alignment to my research:

- Extension of SCETq to more generic observables

- Jet TMDs w/ or w/o Quarkonium

Industry: Transferable skills through the period of the 24-month SCETq project. 12-month transition period.