“Two Days with Particle Physics” Workshop
Shahid Beheshti University, November 2021

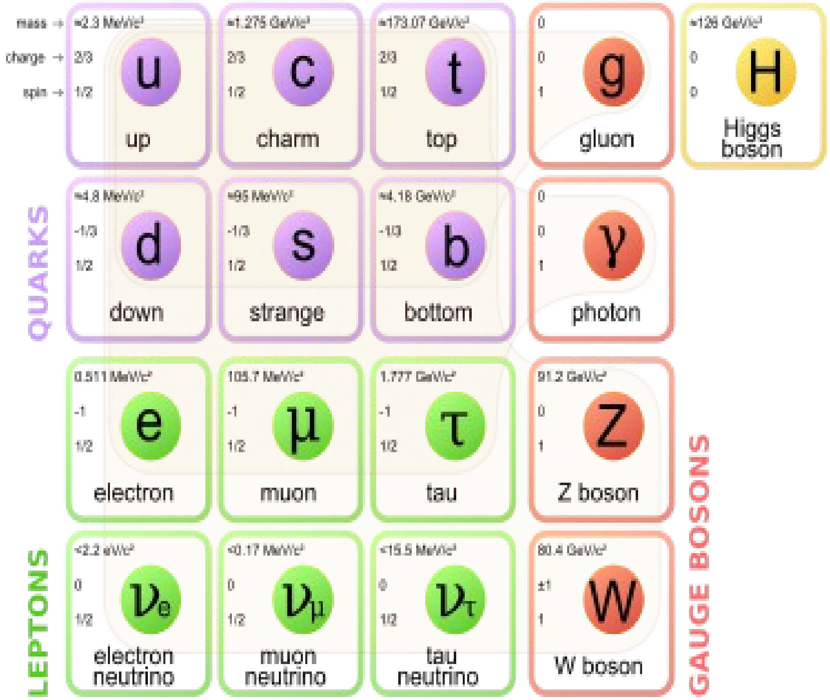
F Hautmann

Quantum Chromodynamics (QCD) and its uses at hadron colliders

- QCD as a gauge field theory of the strong interaction
- High-energy hadron collisions and QCD factorization methods
- Applications to Large Hadron Collider (LHC) physics

QCD as a part of the Standard Model (SM) of Fundamental Interactions

- Quantum Chromodynamics (QCD), the gauge theory of the strong interaction, is the sector of the SM which is expected to exist as a fundamental theory down to arbitrarily short distances



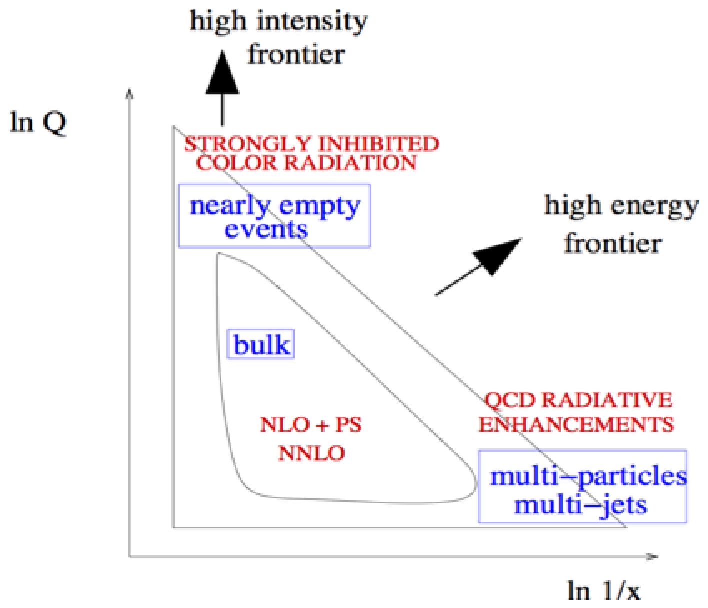
- On one hand, one relies on QCD to search for new physics in the electroweak sector with high-energy experiments
- On the other hand, one investigates in QCD profound questions probing field theory in “extreme” regions

A cartoon picture of collider's phase space

- New physics probed at distances r ~ 1 / Q

  (Q = hard momentum scale)

- Collision energy $s^{1/2} \sim x^{-1} Q$



Phase space in high-energy hadron collisions

- *Bulk of phase space*

  treatable by methods employed routinely in collider physics: LO, NLO, or NNLO perturbation expansions, matched with “parton-shower” Monte Carlo algorithms

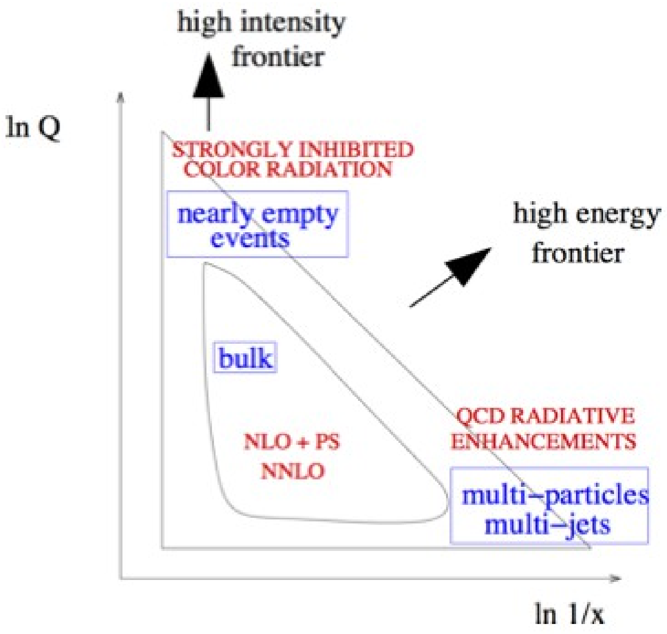
- *Extreme regions near phase space boundary*

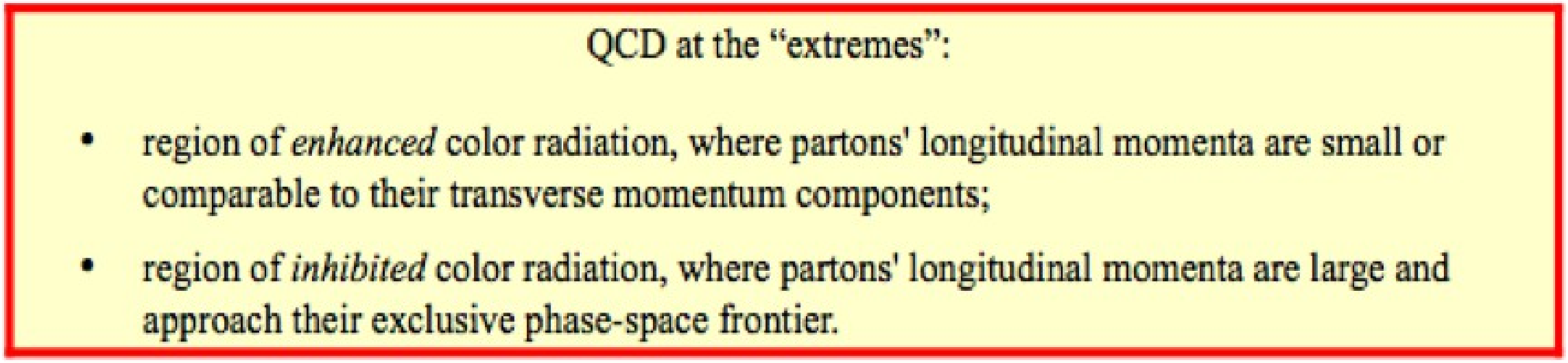
  call for cutting-edge factorization and resummation methods which go beyond finite-order perturbation theory

QCD at the "extremes"

Factorization theorems

- implement renormalization group (RG) evolution
- allow one to systematically take into account perturbative and nonperturbative contributions to high-energy cross sections
- Generalizations of RG factorization to multiple-scale problems are required to treat

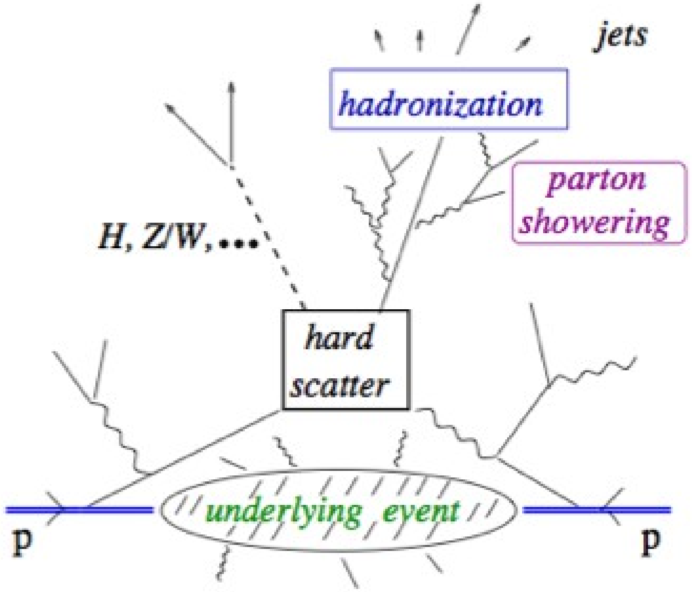




QCD at the "extremes":

- region of *enhanced* color radiation, where partons' longitudinal momenta are small or comparable to their transverse momentum components;
- region of *inhibited* color radiation, where partons' longitudinal momenta are large and approach their exclusive phase-space frontier.

LHC pp collision event



QCD uses an array of techniques to treat high-energy multi-particle production:

- factorization of long-distance dynamics
- perturbative calculat.'s of short-distance processes at fixed order in α_s
- resummation of enhanced radiative corrections to all orders of PT

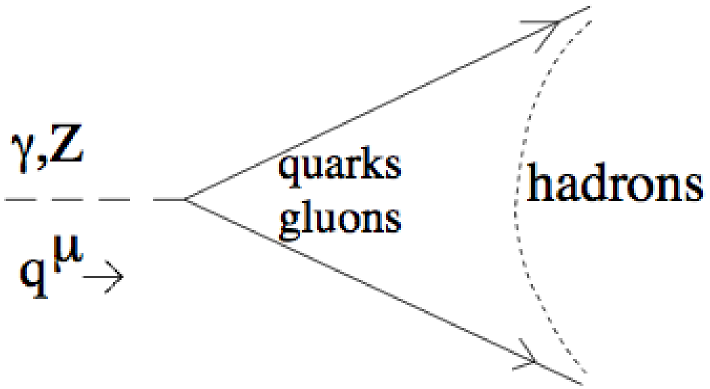
OUTLINE

- Principles of QCD factorization

- Applications to collider processes

PRINCIPLES OF FACTORIZATION

A) $V\!\rightarrow$ hadrons



$\sqrt{Q^2} = \sqrt{q^\mu q_\mu} \gg$ "hadronic scale" $\approx \Lambda_{\rm QCD} \approx 1$ fermi $^{-1}$

- Separate short-time and long-time dynamics: $(\Delta t)_{partonic} \approx Q^{-1} \ll (\Delta t)_{hadroniz.} \approx \Lambda^{-1}_{\rm QCD}$

$$\Rightarrow \quad P(e^+e^-\!\to h) = P(e^+e^-\!\to q\bar{q})P(q\bar{q}\!\to h)$$

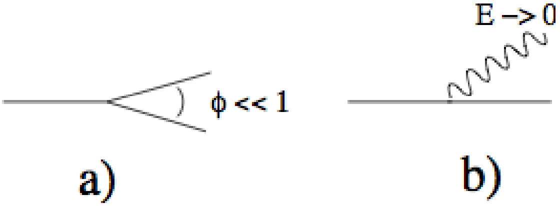
- Next use completeness : $\sum_h P(i\!\to h) = 1 \;\Rightarrow$

$$\begin{aligned}\Rightarrow \quad \sigma_{\rm tot}(e^+e^-\!\to h) \;&\equiv\; \sum_h P(e^+e^-\!\to h) \\ &=\; P(e^+e^-\!\to q\bar{q}) \sum_h P(q\bar{q}\!\to h) = P(e^+e^-\!\to q\bar{q})\end{aligned}$$

▷ almost right — but not quite: rhs is IR-divergent in PT… $\hookrightarrow$

$\hookrightarrow$ particle number nonconservation $\Rightarrow$ add in multi-particle states ($q\bar{q}g$ to 1st order)

$\Rightarrow \sigma(e^+e^- \to q\bar{q}) + \sigma(e^+e^- \to q\bar{q}g)$ insensitive to long-time interactions:



i.e., insensitive to collinear and soft parton emission

- perturbative calculability (= "IR-safety")

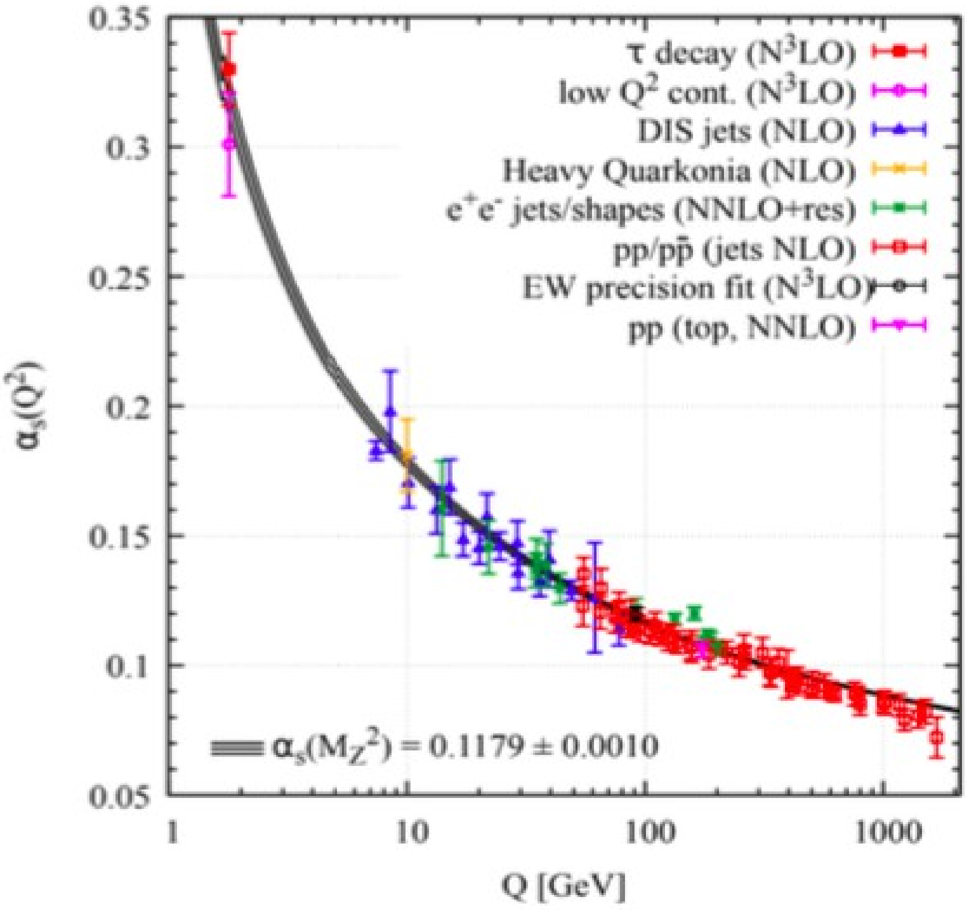
♠ valid to *any* order in α_s:

$$\sigma_{\text{tot}}(e^+e^- \to h) = \sigma_0 \left[1 + \frac{\alpha_s}{\pi} + 1.4092 \left(\frac{\alpha_s}{\pi}\right)^2 - 12.805 \left(\frac{\alpha_s}{\pi}\right)^3 + \ldots \right]$$

♠ valid for large classes of *infrared-safe* observables:

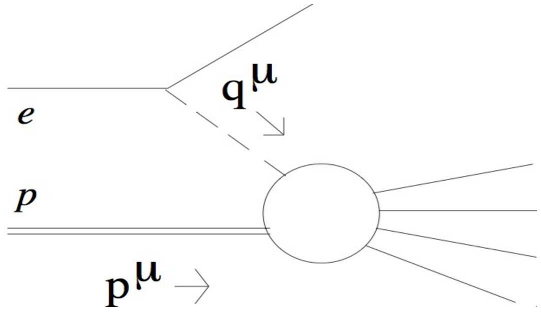
▷ accurate determinations of QCD running coupling $\alpha_s(Q^2)$ from LEP e^+e^- experiments on jet physics (1990's)

THE QCD RUNNING COUPLING



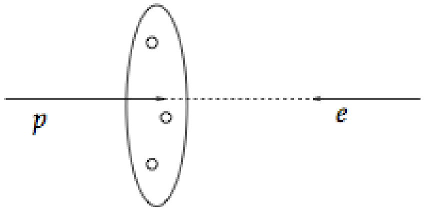
α_s extracted from measurements by using QCD perturbation theory. (Ref: Particle Data Group, Prog. Theor. Exp. Phys. 2020, 083C01 (2020))

B) Hadron scattering. E.g., DIS



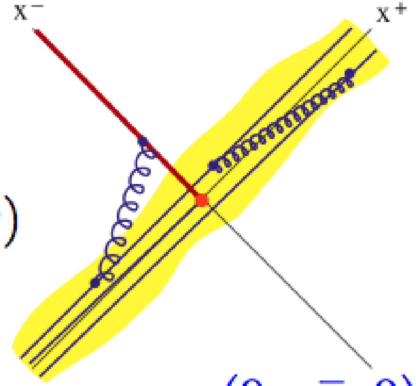
- necessarily sensitive to long timescales, BUT

$$\sigma(Q,m) = C(Q, \text{parton momenta } > \mu) \otimes f(\text{parton momenta } < \mu, m)$$



$\delta t_{\text{scatter}} \ll \tau_{\text{parton}}$ in "infinite-momentum" frame

The collinear parton density functions:



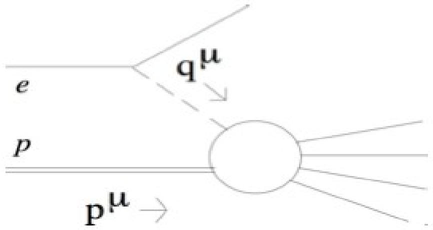
$$\text{Pdf's}: \quad f(x,\mu) = \int \frac{dy^-}{2\pi} \, e^{-ixp^+y^-} \, \widetilde{f}(y)$$

$$\widetilde{f}(y) = \langle \, P \, | \, \overline{\psi}(y) \, V_y^\dagger(n) \, \gamma^+ \, V_0(n) \, \psi(0) \, | \, P \, \rangle \quad , \qquad y = (0, y^-, 0)$$

$$V_y(n) = \mathcal{P} \exp\left(ig_s \int_0^\infty d\tau \; n \cdot A(y + \tau \, n)\right)$$

↖ correlation of parton fields at lightcone distances

Hadron scattering. E.g.: DIS



◇ Renormalization group invariance ⇒

$$\frac{d}{d\ln\mu}\,\sigma = 0 \quad \Rightarrow \quad \frac{d}{d\ln\mu}\,\ln f = \gamma = -\frac{d}{d\ln\mu}\,\ln C$$

↪ DGLAP evolution equations [Altarelli-Parisi
Dokshitzer
Gribov-Lipatov]

$$f = f_0 \times \exp \int \frac{d\mu}{\mu}\,\gamma(\alpha_s(\mu))$$

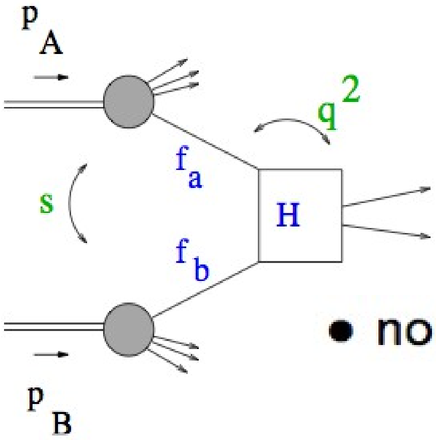
↗ resummation of $(\alpha_s \ln Q/\Lambda_{\rm QCD})^n$ to all orders in PT

Note: expansions $\gamma \simeq \gamma^{(LO)}\,(1 + b_1\alpha_s + b_2\alpha_s^2 + \ldots)$

$$C \simeq C^{(LO)}\left(1 + c_1\alpha_s + c_2\alpha_s^2 + \ldots\right)$$

give LO, NLO, NNLO, ... logarithmic corrections

C) Multiple-scale hard scattering at high energies



$$s \gg q_1^2 \gg \cdots q_n^2 \gg \Lambda_{QCD}^2$$

- nonperturbative components probed near kinematic boundaries $(x \to 0,\ 1 - x \to 0)$

- more complex, potentially large corrections to all orders in α_s, $\sim \ln^k(q_i^2/q_j^2)$

$$e.g.\ \ C \simeq C^{(LO)} \left(1 + c_1\alpha_s + \ldots + c_{n+m}\alpha_s^m(\alpha_s\ L)^n + \ldots\right)\ ,\ L = \text{“large log”}$$

↪ yet summable by QCD techniques that

▷ generalize RG factorization

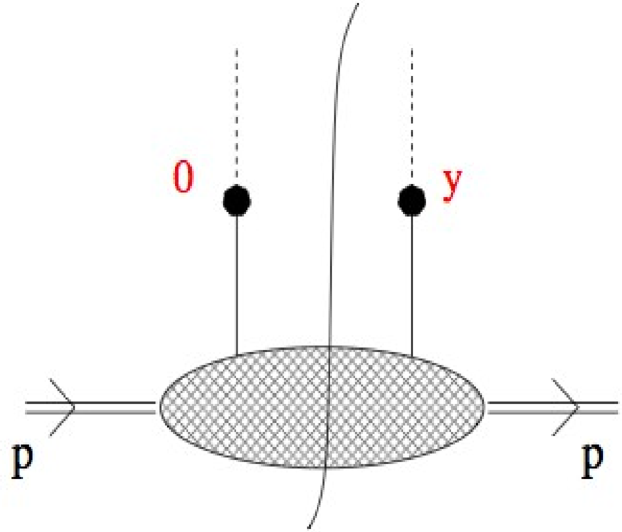
▷ extend parton correlation functions off the lightcone

⇒ unintegrated (or TMD) pdf's

♠ new nonperturbative information; generalized evolution equations

Transverse momentum dependent (TMD) parton density functions

Generalize matrix element to non-lightlike distances:



$$p = (p^+ , m^2 / 2 p^+ , 0_\perp)$$

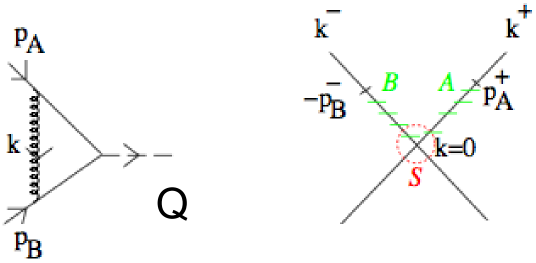
$$\tilde{f}(y) = \langle \, P \mid \overline{\psi}(y) \; V_y^\dagger(n) \; \gamma^+ \; V_0(n) \; \psi(0) \mid P \, \rangle \quad , \qquad y = (0, y^- , y_\perp)$$

TMD pdf's:

$$f(x, k_\perp) = \int \frac{dy^-}{2\pi} \frac{d^{d-2} y_\perp}{(2\pi)^{d-2}} e^{-ixp^+ y^- + ik_\perp \cdot y_\perp} \tilde{f}(y)$$

Examples: generalized evolution equations

- Sudakov form factor S:



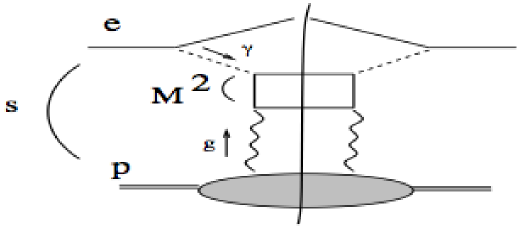
(a) (b)

▷ entering Drell-Yan production, W/Z boson $q_\perp$ distribution, . . .

$\Rightarrow \partial S / \partial \eta = K \otimes S$ $\boxed{\text{CSS evolution equations}}$ [Collins-Soper-Sterman]

↖ resums $\alpha_s^n \ln^m Q/q_T$

- High-energy resummation: $s \gg M^2 \gg \Lambda_{\rm QCD}^2$



◊ energy evolution: $\boxed{\text{BFKL equation}}$ [Balitsky-Fadin-Kuraev-Lipatov]

↖ resums $(\alpha_s \ln \sqrt{s}/M)^n$

↪ corrections down by $1/\ln s$ rather than $1/M$

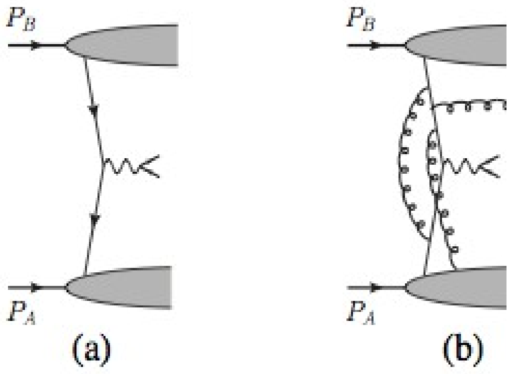
Example I:
Drell Yan production at low pT

- CSS formalism

$$\frac{d\sigma}{d^4q} = \sum_{ij} H_{ij}(Q^2/\mu^2, \alpha_s(\mu)) \int d^2b_\perp \, e^{iq_\perp \cdot b_\perp} \; f_i(x_1, b_\perp; \zeta_1, \mu) \; f_j(x_2, b_\perp; \zeta_2, \mu)$$

$$+ \, Y\text{–term} \, + \, \mathcal{O}\left(\Lambda^2_{\rm QCD}/Q^2\right)$$

TMD factorization



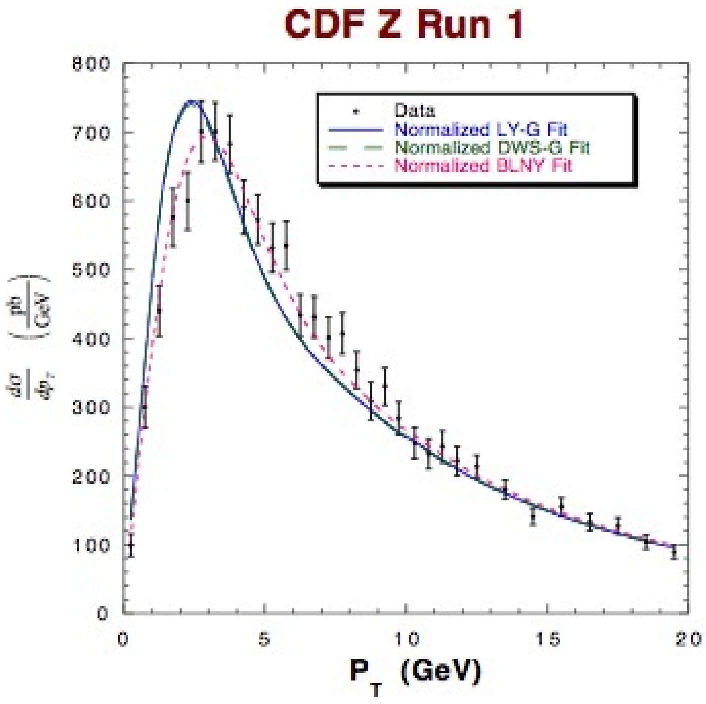
(a) (b)

where $$\frac{\partial \ln f}{\partial \ln \sqrt{\zeta}} = K(b_\perp, \mu) \quad \text{and} \quad \frac{d \ln f}{d \ln \mu} = \gamma_f(\alpha_s(\mu), \zeta/\mu^2)$$

$$\frac{dK}{d \ln \mu} = -\gamma_K(\alpha_s(\mu))$$ cusp anomalous dimension

- Soft Collinear Effective Theory (SCET) provides alternative approach to comparable results

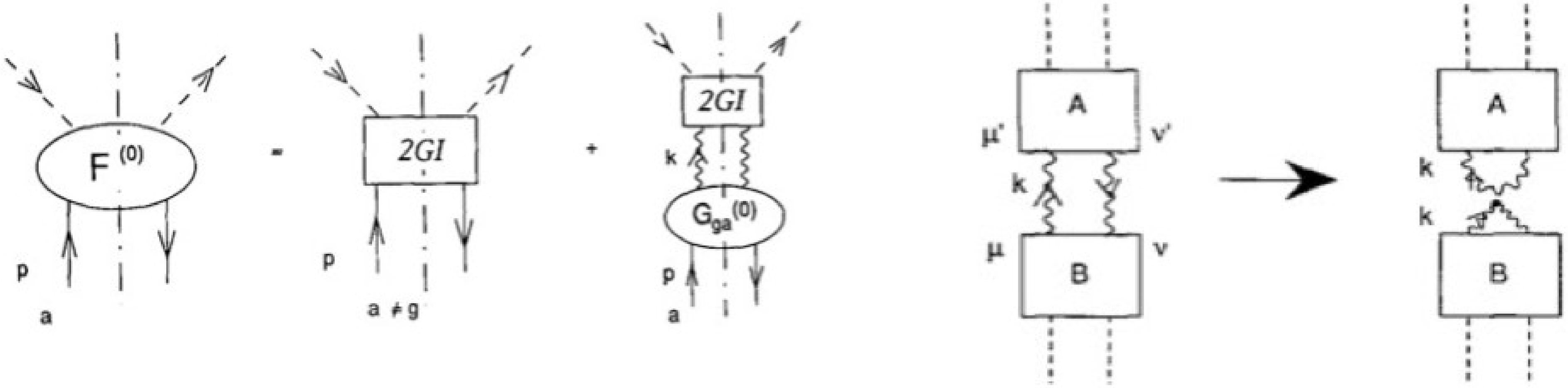
[Echevarria, Idilbi, Scimemi 2012; Chiu, Jain, Neill, Rothstein 2012; Becher, Neubert 2011; Mantry, Petriello 2011]



Landry et al.

Example II:

DIS at high energies



transverse momentum dependent
high-energy factorization :

[Catani et al.]

$$F_j(x,Q^2) = \int_x^1 \frac{dz}{z} \int d^{2+2\varepsilon}\mathbf{k}\; \underbrace{\hat{\sigma}_j\left(x/z, \mathbf{k}/Q, \alpha_s (Q/\mu)^{\varepsilon}, \varepsilon\right)}_{2GI\ kernel}\; \mathcal{A}(z,\mathbf{k},\mu,\varepsilon) \qquad j = 2, L$$

where $$\mathcal{A}(z,\mathbf{k},\mu,\varepsilon) = \int \frac{dk^2}{2(2\pi)^{4+2\varepsilon}}\; P^{(H)}_{\mu\nu}\; G^{\mu\nu}(k,p)$$

fulfills BFKL evolution equation

high-energy projector
(spin and momentum)

unintegrated (TMD) gluon density

REF RESUMMATION, EVOLUTION, FACTORIZATION WORKSHOP

NOVEMBER 15-19, 2021

https://indico.desy.de/event/28334/

Resummation, Evolution, Factorization 2021

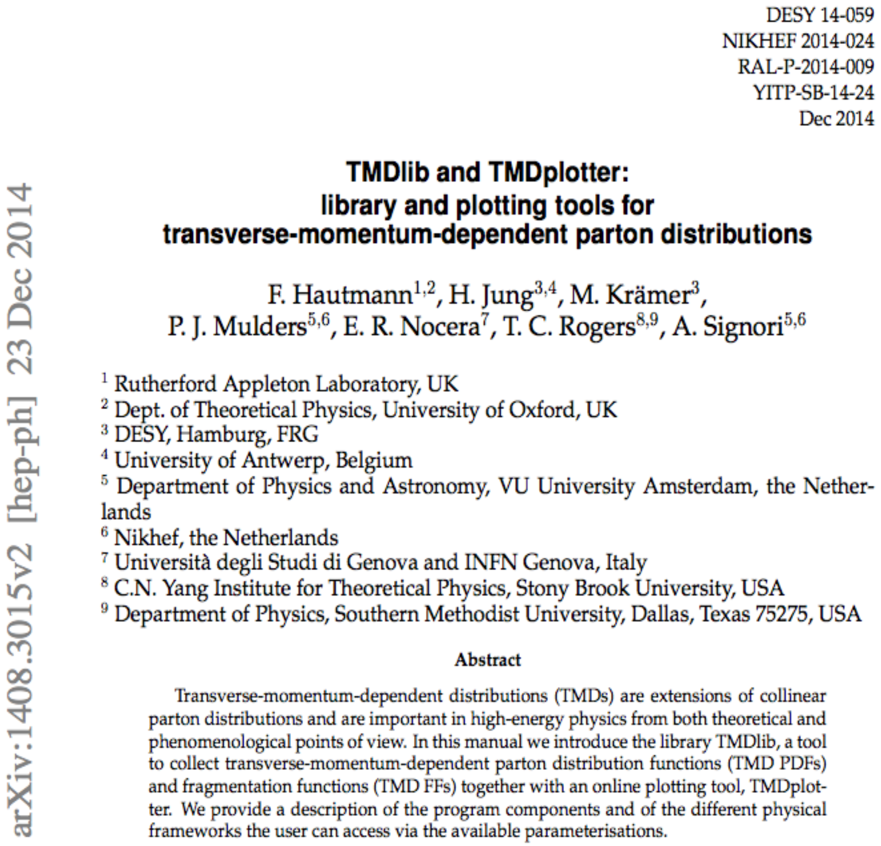
15-19 November 2021
Europe/Berlin timezone

REF 2021 is the 8th edition in the series of workshops on ***Resummation, Evolution, Factorization***. The workshop focuses on transverse momentum dependent (TMD) parton densities and their connection with Monte Carlo event generators, as well as on the experimental measurements aimed at extracting information on TMD densities at the LHC, HERA and future colliders. The interplay between the necessary factorization theorems, resummation of large logarithms and the corresponding evolution equations are crucial towards higher precision calculations, necessary not only for the understanding of the data recorded by facilities like the LHC but especially for future experiments like the EIC. The workshop is sponsored by European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093 (STRONG 2020).

“The TMDlib project” http://tmdlib.hepforge.org/

- a platform for theory and phenomenology of TMD pdfs

- library of fits and parameterizations LHApdf style



DESY 14-059
NIKHEF 2014-024
RAL-P-2014-009
YITP-SB-14-24
Dec 2014

arXiv:1408.3015v2 [hep-ph] 23 Dec 2014

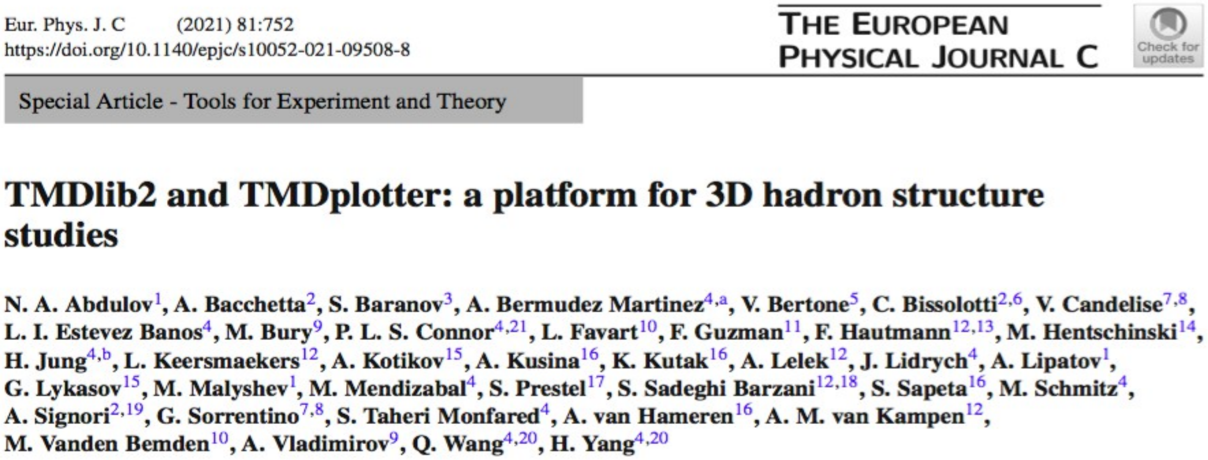
TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions

F. Hautmann[1,2], H. Jung[3,4], M. Krämer[3],
P. J. Mulders[5,6], E. R. Nocera[7], T. C. Rogers[8,9], A. Signori[5,6]

[1] Rutherford Appleton Laboratory, UK
[2] Dept. of Theoretical Physics, University of Oxford, UK
[3] DESY, Hamburg, FRG
[4] University of Antwerp, Belgium
[5] Department of Physics and Astronomy, VU University Amsterdam, the Netherlands
[6] Nikhef, the Netherlands
[7] Università degli Studi di Genova and INFN Genova, Italy
[8] C.N. Yang Institute for Theoretical Physics, Stony Brook University, USA
[9] Department of Physics, Southern Methodist University, Dallas, Texas 75275, USA

Abstract

Transverse-momentum-dependent distributions (TMDs) are extensions of collinear parton distributions and are important in high-energy physics from both theoretical and phenomenological points of view. In this manual we introduce the library TMDlib, a tool to collect transverse-momentum-dependent parton distribution functions (TMD PDFs) and fragmentation functions (TMD FFs) together with an online plotting tool, TMDplotter. We provide a description of the program components and of the different physical frameworks the user can access via the available parameterisations.



Eur. Phys. J. C (2021) 81:752
https://doi.org/10.1140/epjc/s10052-021-09508-8

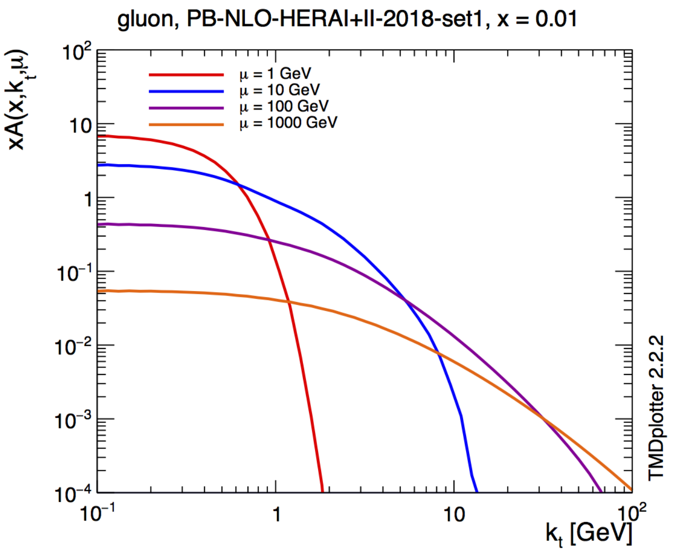
THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

TMDlib2 and TMDplotter: a platform for 3D hadron structure studies

N. A. Abdulov[1], A. Bacchetta[2], S. Baranov[3], A. Bermudez Martinez[4,a], V. Bertone[5], C. Bissolotti[2,6], V. Candelise[7,8], L. I. Estevez Banos[4], M. Bury[9], P. L. S. Connor[4,21], L. Favart[10], F. Guzman[11], F. Hautmann[12,13], M. Hentschinski[14], H. Jung[4,b], L. Keersmaekers[12], A. Kotikov[15], A. Kusina[16], K. Kutak[16], A. Lelek[12], J. Lidrych[4], A. Lipatov[1], G. Lykasov[15], M. Malyshev[1], M. Mendizabal[4], S. Prestel[17], S. Sadeghi Barzani[12,18], S. Sapeta[16], M. Schmitz[4], A. Signori[2,19], G. Sorrentino[7,8], S. Taheri Monfared[4], A. van Hameren[16], A. M. van Kampen[12], M. Vanden Bemden[10], A. Vladimirov[9], Q. Wang[4,20], H. Yang[4,20]

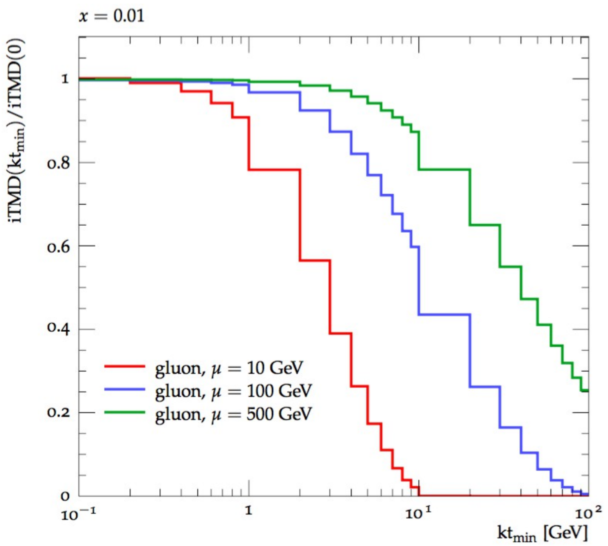
TMD Parton Distributions (from fits to experimental data)

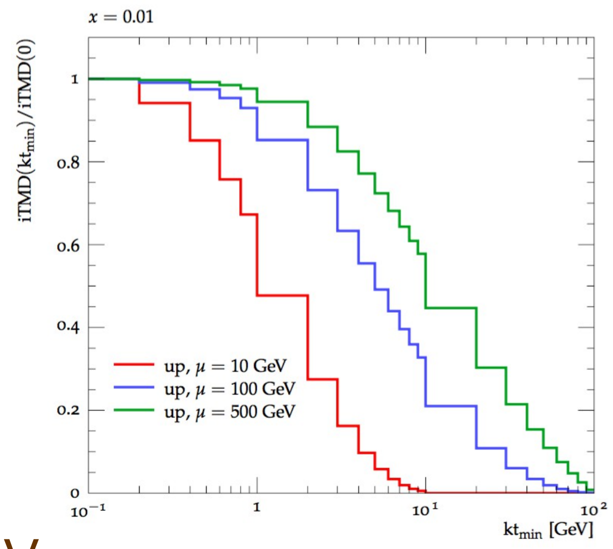


- Large kT broadening due to multiple parton radiation

- To assess the impact on hard production processes, consider the integrated distribution above the scale kT:

$$a_j(x, \boldsymbol{k}, \mu^2) = \int \frac{d^2\boldsymbol{k}'}{\pi} \mathcal{A}_j(x, \boldsymbol{k}', \mu^2)\ \Theta(\boldsymbol{k}'^2 - \boldsymbol{k}^2)$$



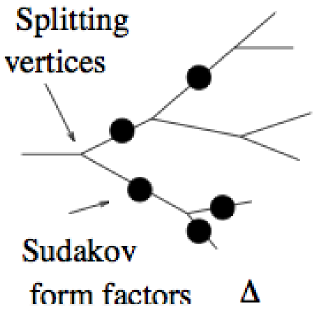


- For instance, for mu = 100 (500) GeV, 30% probability that the gluon has developed kT larger than 20 (80) GeV

FROM QCD TO MONTE CARLO EVENT GENERATORS

- Factorizability of QCD x-sections ⟶ probabilistic branching picture

◇ QCD evolution by "parton showering" methods:

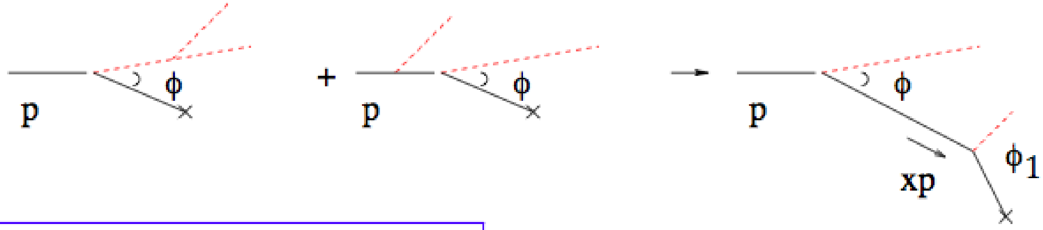


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S(q^2) \; P(z) \; \Delta(q^2, q_0^2)$$

↪ collinear, incoherent emission

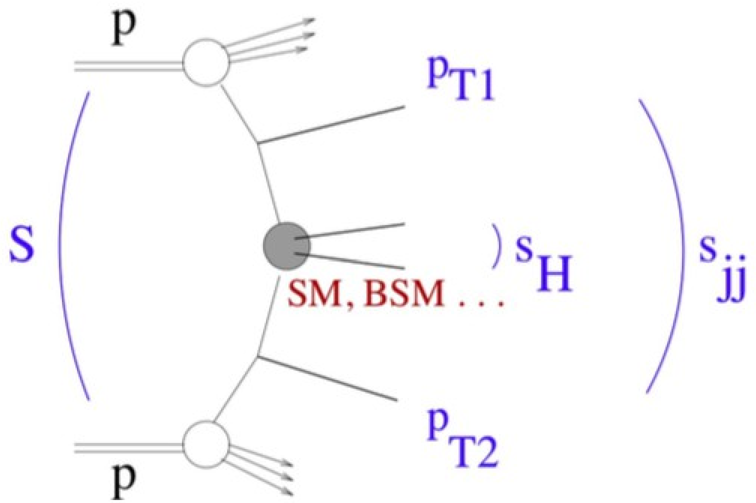
◇ Soft emission ⟶ interferences ⟶ ordering in decay angles:

↪ gluon coherence for $x \sim 1$



◇ Gluon coherence for $x \ll 1$ ⇒ corrections to angular ordering:

↪ $k_\perp$-dependent parton showers



--> multiple-scale processes from large ratios of sub-energies S, s_{jj} and s_H :

probe regions near phase space boundary --> call for factorization/resummation methods beyond finite-order perturbation theory

APPLICATIONS TO VECTOR BOSON AND JET PRODUCTION

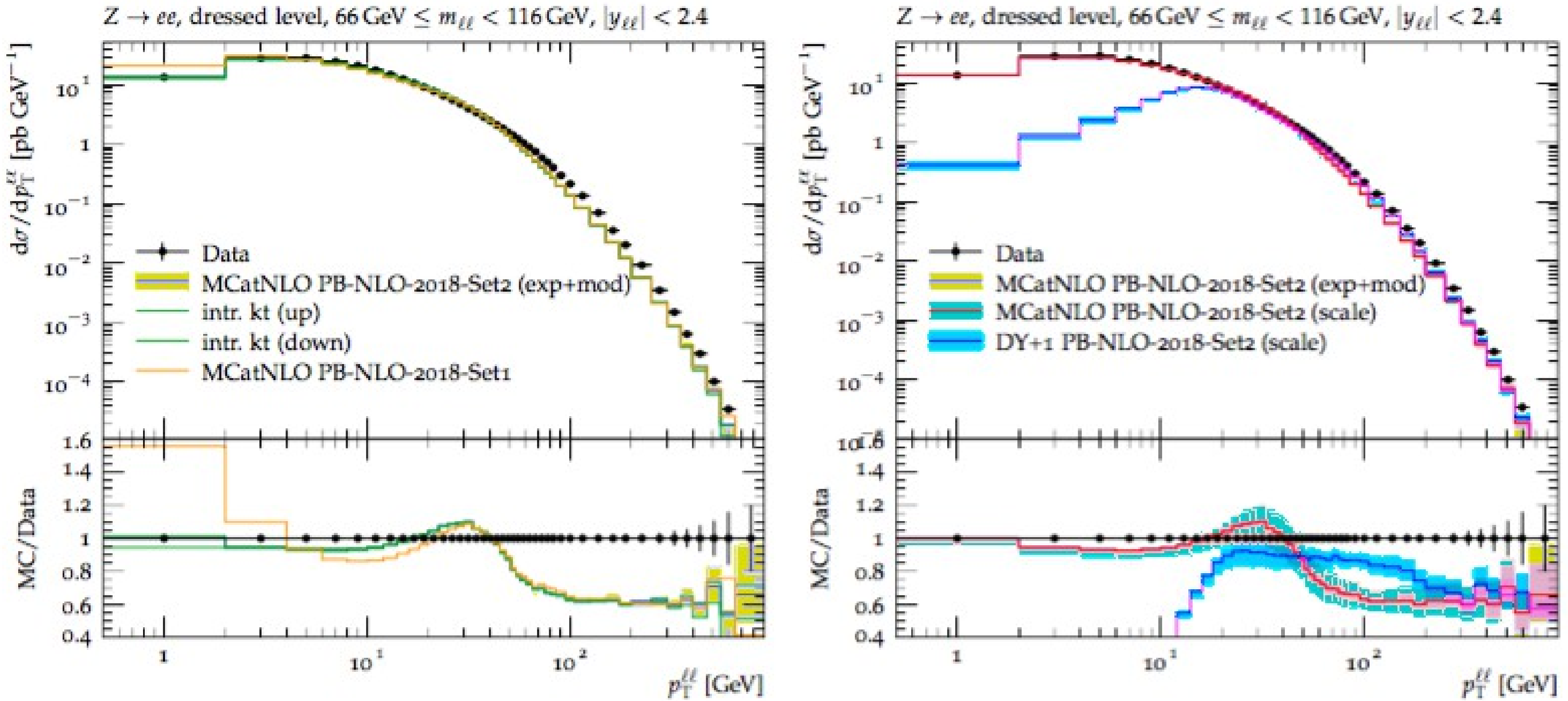
Z-boson Drell-Yan production at the LHC:

(TMDs fitted to inclusive DIS) x (NLO DY calculation)

A Bermudez et al, PRD 100 (2019) 074027
[arXiv:1906.00919]

- Use MadGraph5_aMC-at-NLO
- Apply PB-TMD
- Set matching scale mu_m (kT < mu_m)

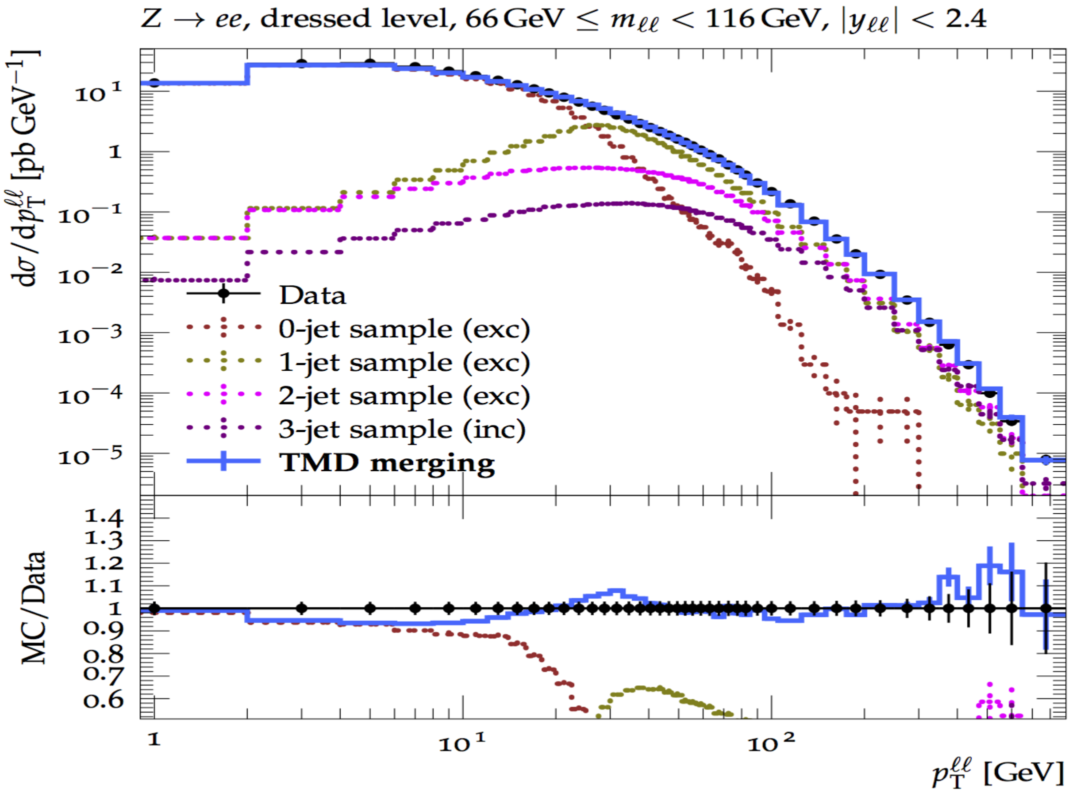
ATLAS 8 TeV data [E. Phys. J. C76 (2016) 291]



- Theoretical uncertainties dominated by scale dependences; TMD uncertainties moderate
- Low-pT spectrum sensitive to angular ordering (PB-TMD Set 2)
- Missing higher orders at high pT: DY + jet contribution (blue curve on right hand side)

Z-boson Drell-Yan production at the LHC using "TMD multi-jet merging"

Bermudez et al, PLB 822 (2021) 136700 [arXiv:2107.01224]

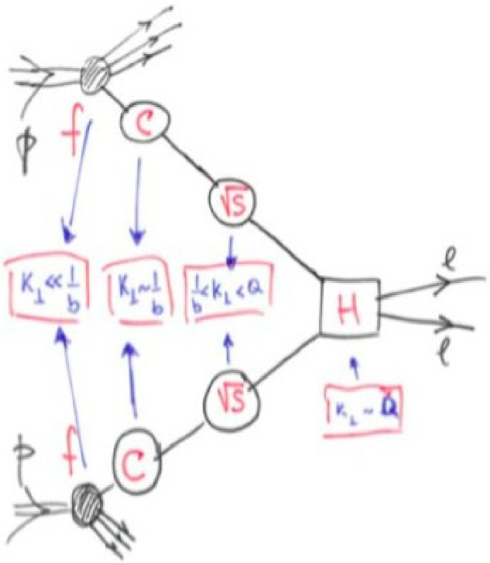


- Z +0 jet gives the main contribution at low pT; the impact of larger jet multiplicities increases with increasing pT.

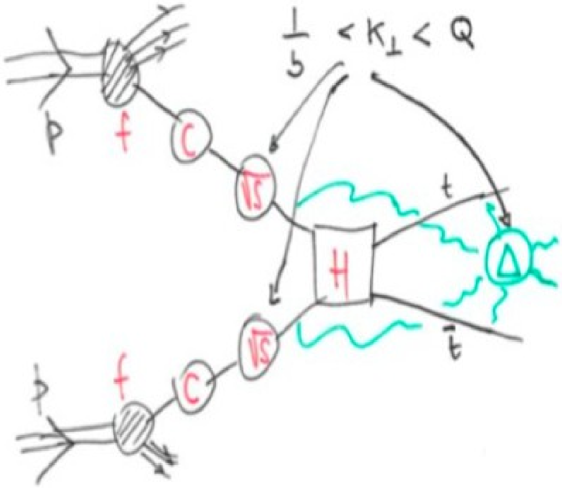
- The "TMD merging" prediction retains the good description at low pT already seen by applying TMD evolution, and improves the behavior at high pT by including higher multiplicities.

From Color Neutral to Color Charged Final States

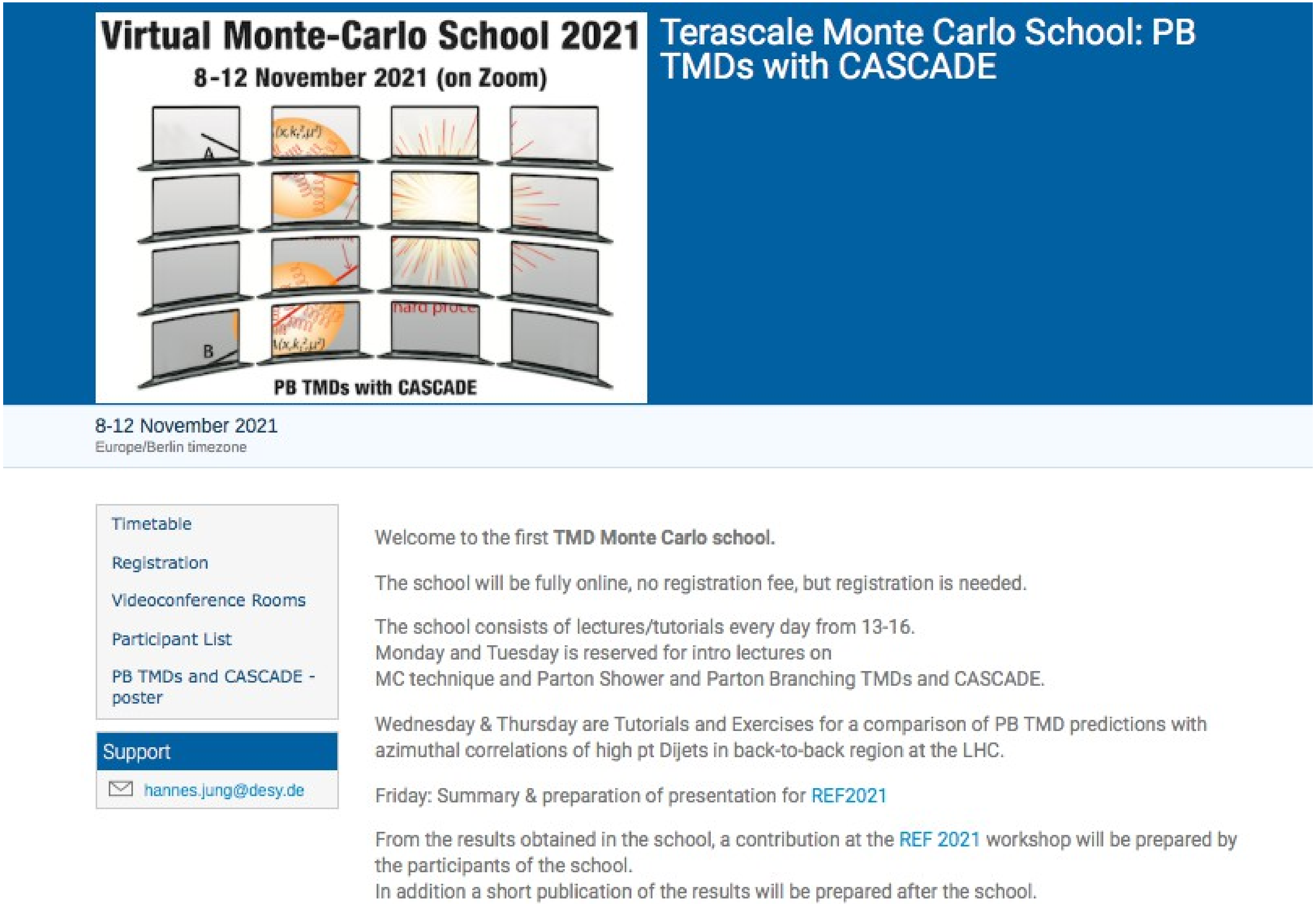
Color neutral:



Color charged:



- What is the role of potentially new soft-gluon correlations between initial states and final states?
- What is the behavior of jet azimuthal asymmetries?
- How does this vary as the transverse momenta of the individual jets increase?



Terascale Monte Carlo School: PB TMDs with CASCADE

8-12 November 2021
Europe/Berlin timezone

- Timetable
- Registration
- Videoconference Rooms
- Participant List
- PB TMDs and CASCADE - poster

Support

hannes.jung@desy.de

Welcome to the first **TMD Monte Carlo school.**

The school will be fully online, no registration fee, but registration is needed.

The school consists of lectures/tutorials every day from 13-16.
Monday and Tuesday is reserved for intro lectures on
MC technique and Parton Shower and Parton Branching TMDs and CASCADE.

Wednesday & Thursday are Tutorials and Exercises for a comparison of PB TMD predictions with azimuthal correlations of high pt Dijets in back-to-back region at the LHC.

Friday: Summary & preparation of presentation for REF2021

From the results obtained in the school, a contribution at the REF 2021 workshop will be prepared by the participants of the school.
In addition a short publication of the results will be prepared after the school.

Conclusion

- new physics searches at highest mass and shortest distances depend on chromodynamic effects which probe the structure of the theory beyond finite-order perturbation expansions.

  - Infrared-sensitive observables
  - Multi-scale processes and RG generalizations
  - Parton matter at high density

- will affect the upgrade phase of the LHC (the “intensity frontier”) and also the “energy frontier” - future colliders as well as high-energy non-accelerator experiments.