Particle and nuclear theory at IFJ PAN

Sebastian Sapeta

IFJ PAN

11 September 2024

Divisions and departments

NO2

Division of Nuclear Physics and Strong Interactions

- Department of the Theory of Strong Interactions and Many Body Systems (NZ21)

NO4

Division of Theoretical Physics

- Department of Theory of Structure of Matter (NZ41)
- Department of Particle Theory (NZ42)

NZ21

Staff:

- prof. dr. hab. Antoni Szczurek (Head)
- dr. hab. Rafał Maciuła
- dr. hab. Wolfgang Schäfer
- dr. hab. Mariola Kłusek-Gawenda
- dr. Izabela Babiarz
- dr. Piotr Lebiedowicz

NZ41

Staff:

- prof. dr. hab. Krzysztof Golec-Biernat (Head)
- prof. dr. hab. Wojciech Broniowski
- prof. dr. hab. Robert Kamiński
- dr. hab. Radosław Ryblewski

Students:

- M.Sc. Asaad Daher

NZ42

Staff:

- prof. dr. hab. Krzysztof Kutak (Head)
- prof. dr. hab. Zbigniew Wąs
- prof. dr. hab. Maciej Skrzypek
- dr. hab. Aleksander Kusina
- dr. hab. Andreas van Hameren
- dr. hab. Richard Ruiz
- dr. hab. Sebastian Sapeta
- dr. Rene Poncelet
- prof. dr. hab. Marek Jeżabek (emeritus)

NZ42

Postdocs:

- dr. Stéphane Delorme

Students:

- M. Sc. Peter Baron
- M. Sc. Nasim Derakhshanian
- M. Sc. Grzegorz Ziarko

NZ21

Department of the Theory of Strong Interactions
and Many Body Systems

NZ21

- Light-by-light scattering in ultraperipheral heavy ion collisions.
  Different mechanisms and predictions for different experiments.
- High-energy Coulomb excitation of nuclei in high-energy UPC.
  Emission of neutrons, photons, protons, alpha particles from excited nuclei.
  Multiple photon exchanges and excitations.
- Production of quarkonia in UPC.
- Diffractive dijet and $c\bar{c}$ production in ep and pA collisions.
  Predictions for EIC.
- Exclusive bremmstrahlung production in $\pi\pi$, πp and pp scattering
  Emission of one and two photons. Limits for soft photons.
- Diffractive processes in proton-proton scattering.

NZ21

- Production of heavy quarks in proton-proton collisions, production of heavy mesons, semileptonic decays of the heavy mesons, intrinsic charm, recombination.

- Production of high-energy neutrinos (IceCube, LHC).

- Production of exotic mesons, e.g. tetraquarks, in pp and e^+e^- collisions.

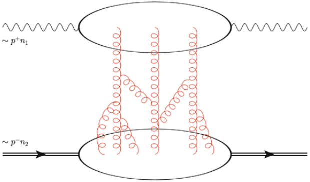
- Two-photon couplings to mesons of different spin and corresponding form factors.
  Production of mesons in $e^+e^- \to e^+e^-M$ reactions.

NZ41

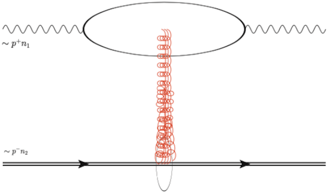
Department of Theory of Structure of Matter

Krzysztof Golec-Biernat - Gluon saturation in DIS at small x

- $q\bar{q}$ color dipole interacts with the proton p through gluon exchanges:



- After Lorentz boost of p - interaction with a classical shock wave:



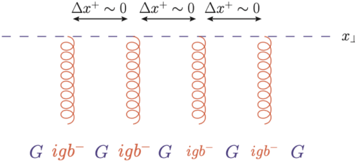
- Dipole interacts with classical color fields $(b^+, b^-, \vec{b}_\perp)$.

Krzysztof Golec-Biernat - Shock wave approach in eikonal limit

- Only $b^-(x^+, \vec{x}_\perp)$ component matters with no x^- dependence:

$$\begin{array}{ccc} b^+(x^+,x^-,\vec{x}) & & \frac{1}{\Lambda} b^+(\Lambda x^+, \frac{x^-}{\Lambda}, \vec{x}) \\ b^-(x^+,x^-,\vec{x}) & \longrightarrow & \Lambda b^-(\Lambda x^+, \frac{x^-}{\Lambda}, \vec{x}) \\ b^k(x^+,x^-,\vec{x}) & \Lambda \sim \sqrt{\frac{s}{m_t^2}} & b^k(\Lambda x^+, \frac{x^-}{\Lambda}, \vec{x}) \end{array}$$

- Multiple interactions collaps at the light-cone time $x^+ \approx 0$



- Wilson line operators appear in the shock wave description:

$$U(\vec{x}_\perp) = P_+ \exp\left\{ \int_{-\infty}^{\infty} dx^+ \, b^-(x^+, \vec{x}_\perp) \right\}$$

Krzysztof Golec-Biernat - Going beyond the eikonal limit

- Examination of beyond the eikonal limit corrections:
  - full dependence on color fields: $b^{\mu}(x^{+}, x^{-}, \vec{x}_{\perp})$
  - finite width $\Delta x^{+} \neq 0$ in multiple interactions
- Impact on the Balitsky-JIMWLK evolution equations
- Impact on processes measured at the planned Electron Ion Collider:
  - exclusive diffractive dijet production
  - photon plus jet production
  - also forward Drell-Yan pair production at LHC

Wojciech Broniowski - Non-perturbative structure of hadrons

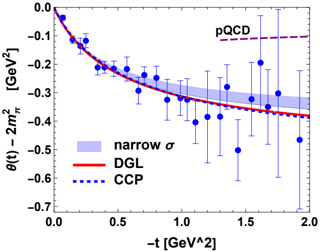
Example: gravitational (energy-momentum) form factors of the pion (see talk on Thursday)

Probing distribution of energy, pressure, and shear, $\exists$ lattice data, $e^+e^- \to \pi^0\pi^0$ experimental data

$$\langle \pi^a(p')|\, T^{\mu\nu}(0) |\pi^b(p)\rangle = \delta_{ab}\left[2P^\mu P^\nu A(t) + \tfrac{1}{2}\left(q^\mu q^\nu - g^{\mu\nu} q^2\right) D(t)\right]$$

T - energy-momentum tensor, a, b - isospin, $P = \frac{1}{2}(p' + p)$, $q = p' - p$, $t = q^2 = -Q^2$

spin-0: $\langle \pi(p')|\, T^\mu_\mu(0) |\pi(p)\rangle \equiv \Theta(t) = 2\left(m_\pi^2 - \frac{t}{4}\right) A(t) - \frac{3t}{2} D(t)$, spin-2: $A(t)$



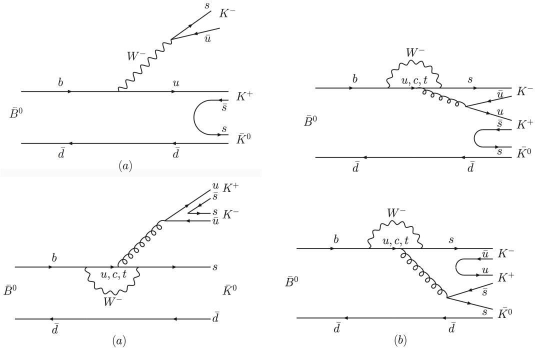
points - MIT lattice data (2023)
lines - variants of meson dominance (nonperturbative) models
dashed - pQCD (Tong et al. 2021)

Description of the data within a very natural, parameter-free approach, role of the σ meson in the scalar channel

Details: WB, E. Ruiz Arriola, 2405.07815

Robert Kamiński

Quark Feynman tree and penguin diagrams

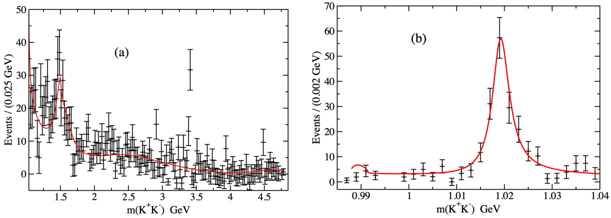


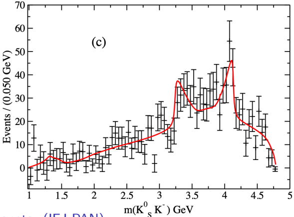
The $B^0 \to K_S^0 K^+ K^-$ decay amplitude in a quasi-two-body QCDF framework has been derived using tree and penguin diagrams. The dominant parts of the decay amplitude are calculated in terms of kaon form factors or B^0 to two kaons transition functions which describe the final state two-body resonances and their interferences. Unitarity constraints are satisfied when two of the three kaons are in a scalar state. The kaon-kaon interactions in the S, P, and D waves are taken into account.

Robert Kamiński

Fit to the Belle and *BABAR* data

Our model reproduces well the Belle and *BABAR* Collaborations data. With 13 strong interaction free parameters modifying the five terms of our amplitude, we fit the 422 observables consisting of the total branching fraction together with the Dalitz-plot projections of Belle and *BABAR* with a χ^2 of 583.6 which leads to a χ^2/ndf of 1.43.





PHYSICAL REVIEW D 110, 013002 (2024)

Amplitude analysis of $B^0 \to K^0_S K^+ K^-$ *decays in a quasi-two-body QCD factorization approach*

J.-P. Dedonder, R. Kamiński, L. Leśniak, B. Loiseau, and P. Żenczykowski

Rdosław Ryblewski

Relativistic spin hydrodynamics — ***NZ41 (R. Ryblewski, A. Daher)***

Nowadays, **relativistic hydrodynamics** is a core component of theoretical models used to **describe the collective dynamics of matter created in high-energy nuclear collisions**.

Ryblewski, In: Understanding the Origin of Matter. Lecture Notes in Physics, vol 999

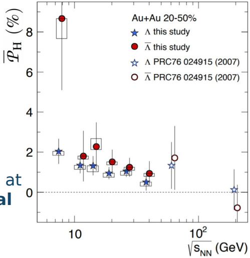
The **observation of global spin polarization** of emitted particles sourced by the orbital angul momentum of incident nuclei has **demonstrate the need to extend this framework** to includ **spin density as a new hydrodynamic variab**

Florkowski, Kumar, Ryblewski, Prog.Part.Nucl.Phys. 108 (2019) 103

Formulation of **spin hydrodynamics** is currently at the frontier of heavy-ion research and is **essential for understanding observed signals**

Singh, Sophys, Ryblewski, Phys.Rev.D 103 (2021) 7, 074024
Florkowski, Ryblewski, Singh, Sophys, Phys.Rev.D 105 (2022) 5, 054007

Florkowski, Kumar, Ryblewski, Mazeliauskas, Phys.Rev.C 100 (2019) 5, 054907; Phys.Rev.C 105 (2022) 6, 064901



Adamczyk et al. (STAR) (2017), Nature 548 (2017) 62-65

Rdosław Ryblewski

Relativistic spin hydrodynamics — *NZ41 (R. Ryblewski, A. Daher)*

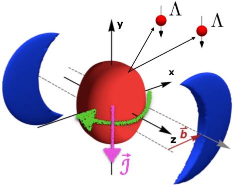
The development of spin hydrodynamics requires deep understanding of various aspects:

- *role of so-called **pseudogauge transformations** and **relocalization of quantum energy, momentum and spin***

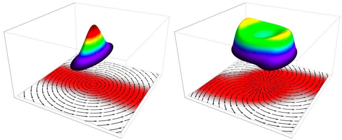
  Daher, Das, Florkowski, Ryblewski, Phys.Rev.C 108 (2023) 2, 024902
  Dey, Florkowski, Jaiswal, Ryblewski, Phys.Lett.B 843 (2023) 137994

- *the determination of the **energy-momentum and spin currents' mean values** and **their spacetime evolution***

  Biswas, Daher, Das, Florkowski, Ryblewski, Phys.Rev.D 108 (2023) 1, 014024



Florkowski, Kumar, Ryblewski, Prog.Part.Nucl.Phys. 108 (2019) 103709



Florkowski, EurekAlert, NEWS RELEASE 21-JUN-2018
Florkowski, Friman, Jaiswal, Speranza, Phys.Rev.C 97 (2018) 4, 041901

- ***stability and causality of equations of motion***

  Biswas, Daher, Das, Florkowski, Ryblewski, Phys.Rev.D 107 (2023) 9, 094022
  Daher, Florkowski, Ryblewski, Taghinavas, Phys.Rev.D 109 (2024) 11, 114001

- ***inclusion of equations of state** for spin-polarized systems*

  Daher, Florkowski, Ryblewski, Phys.Rev.D 110 (2024) 3, 034029
  Becattini, Daher, Sheng, Phys.Lett.B 850 (2024) 138533

- ***role of electromagnetic fields in mean polarization dynamics***

  Bhadury, Florkowski, Jaiswal, Kumar, Ryblewski, Phys.Rev.Lett. 129 (2022) 19, 192301

NZ42

Department of Particle Theory

Andreas van Hameren

Hybrid kT-factorization at NLO

supported by grant No. 2019/35/B/ST 2/03531 of the Polish National Science Centre

Andreas van Hameren with Grzegorz Ziarko (PhD student) and Alessandro Giachino (former postdoc)
and also in collaboration with Leszek Motyka (UJ), Piotr Kotko (AGH), Etienne Blanco (former PhD student IFJ)

Born level (accessible for any process with the automated program KaTie [van Hameren 2016])

$$d\sigma^{\mathrm{HF,B}}\big(\overbrace{\{p\}_n}^{\text{final-state momenta of particles and jets}}\big) = \sum_{\bar{\chi}} \int_0^1 dx \int \frac{d^2k_\perp}{\pi} \overbrace{F(x,k_\perp)}^{\text{kT-dependent PDF}} \int_0^1 d\bar{x}\, \overbrace{f_{\bar{\chi}}(\bar{x})}^{\text{collinear PDF}}\, \overbrace{d\Phi\big(x,k_\perp,\bar{x};\{p\}_n\big)}^{\text{differential final-state parton-level phase space}}\, \underbrace{\frac{\big|\overline{M}_{\star\bar{\chi}}\big|^2\big(x,k_\perp,\bar{x};\{p\}_n\big)}{2x\bar{x}S}}_{\text{Tree-level Matrix element}} \overbrace{J_B\big(\{p\}_n\big)}^{\text{\#jets equal to \#final-state partons}}$$

Tree-level Matrix element with one initial-state space-like gluon, or "reggeon".
Uniquely defined for any number of final-state partons.
Calculable with Lipatov's effective action or the auxiliary parton method.

The tasks at hand are to generalize the Born formula to NLO, identify the real and virtual contributions, confirm their computability, establish a renormalization procedure to absorb non-cancelling divergences, and eventually to write an automated program.

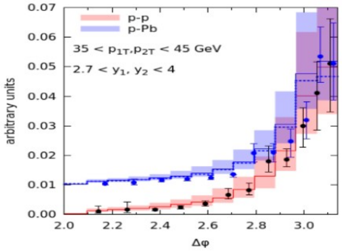
Papers:

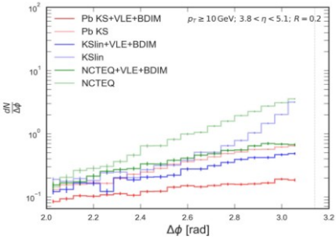
JHEP 11 (2022) 103, arxiv:2205.09585 "Hybrid k_T-factorization and impact factors at NLO"
Nucl.Phys.B 995 (2023) 116322, arxiv:2212.03572 "One-loop gauge invariant amplitudes with a space-like gluon"
JHEP 06 (2024) 167, arxiv:2312.02808 "A new subtraction scheme at NLO exploiting the privilege of k_T-factorization"

Krzysztof Kutak

Saturation, jets, quenching

Systems: p+p, p+Pb, Pb+Pb





projects
supported by
NCN OPUS grant

$p+p \rightarrow 2j + X$,
$p+Pb \rightarrow 2j + X$

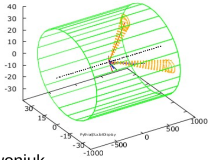
saturation accounted for

van Hameren, Kotko, Kutak, Sapeta ; ...

$Pb+Pb \rightarrow j + \gamma + X$

saturation and quenching
accounted for

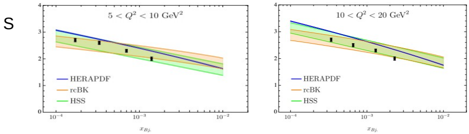
Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk
to appear soon



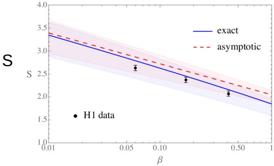
From P. Kotko 1

Krzysztof Kutak

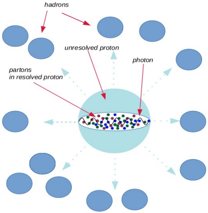
Entanglement entropy of proton



Inclusive DIS



Diffractve DIS



projects
supported by
STRONG 2020 EU grant

Hentschinski, Kutak’21
Hentschinski, Kutak, Straka’22
Hentschinski, Kharzeev,Kutak, Tu ’23
Hentschinski, Kharzeev,Kutak, Tu ’24

Rene Poncelet

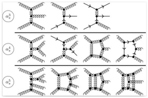
Rene Poncelet – Precision QCD calculations for LHC phenomenology

NNLO
QCD for
LHC

STRIPPER

NNLO QCD
subtraction schemes

Tools
&
methods



Gearing up for the
precision LHC era

high tea

Open-access
“Theory event”
database

$pp \to \gamma jj$

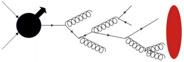
Amplitudes & cross-sections
for multi-scale processes

$pp \to \gamma\gamma\gamma$

$pp \to \gamma\gamma j$

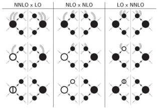
$pp \to Wb\bar{b}$ $pp \to jjj$

Flavoured jet observables
& jet clustering algorithms



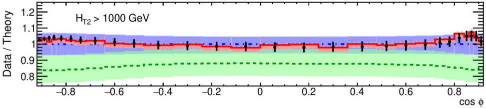
LHC
Pheno

Top-quark pair
production + decay



Rene Poncelet

Example: Strong coupling constant measurement at high energies from multi-jet events through event shapes



[ATLAS 2301.09351]

Next-to-Next-to-Leading Order Study of Three-Jet Production at the LHC
Czakon, Mitov, **Poncelet** [2106.05331]

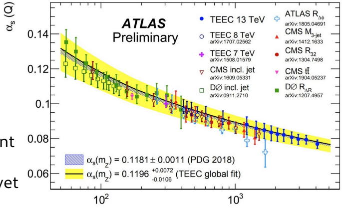
NNLO QCD corrections to event shapes at the LHC
Alvarez, Cantero, Czakon, Llorente, Mitov, **Poncelet** [2301.01086]

NNLO QCD theory reduces uncertainties!

→ most precise measurement at high energy

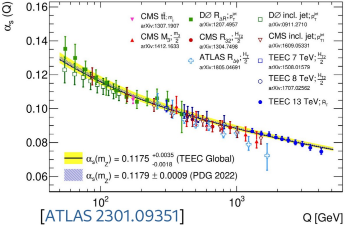
→ highest energies probed yet

NLO QCD



[ATLAS-CONF-2020-025]

NNLO QCD



[ATLAS 2301.09351]

A. Kusina, S. Delorme, N. Derakhshanian

Aleksander Kusina

- Determination of proton and nuclear Parton Distributions Functions (PDFs).
- Connections between nuclear structure on nucleon and parton level.
- Member of the nCTEQ collaboration.
- Exploration of factorization schemes.

Stephane Delorme

- Quarkonium dynamics using Quantum Master Equations.
- Exploration of factorization schemes.

Nasim Derakhshanian

- Determination of PDFs using Markov Chain Monte Carlo methods.

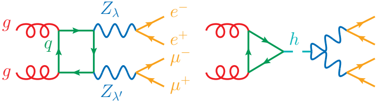
Richard Ruiz

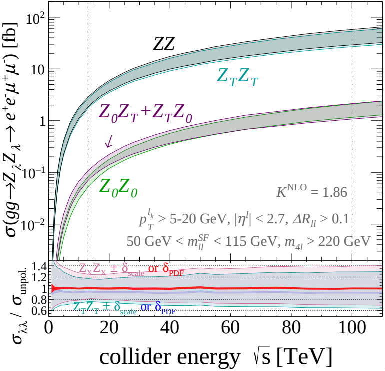
Helicity-polarized parton scattering

Treating helicity polarization as a Feynman rule provides a new method for computing polarized xsec

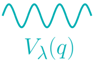
Javurkova, Ruiz, et al (PLB'24) [2401.17365]

- loop-induced processes ✓
- interference between different polarizations configurations ✓
- non-resonant diagrams ✓
- off-shell/finite-width effects ✓

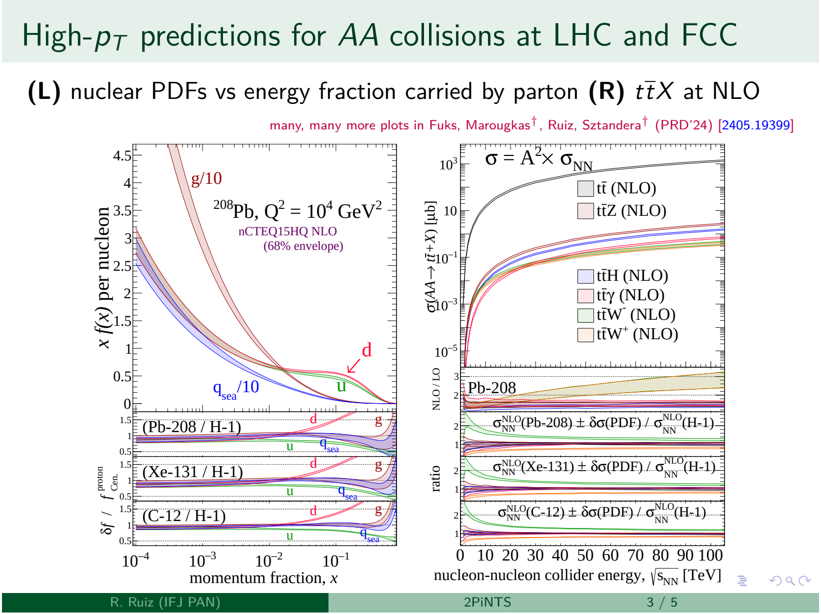




$$\frac{-i\ \varepsilon_\mu(q,\lambda)\ \varepsilon^*_\nu(q,\lambda)}{q^2 - M_V^2} =$$



Richard Ruiz



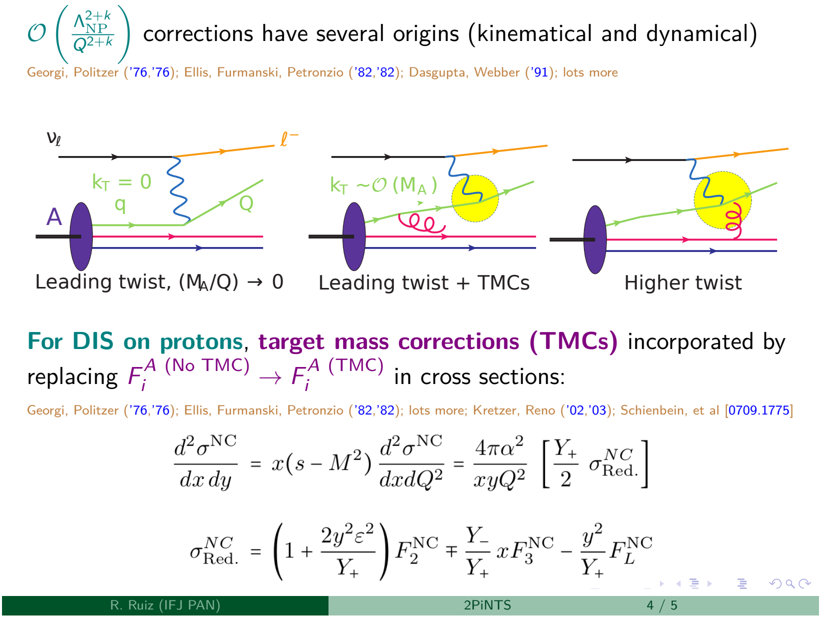
High-p_T predictions for AA collisions at LHC and FCC

(L) nuclear PDFs vs energy fraction carried by parton **(R)** $t\bar{t}X$ at NLO

many, many more plots in Fuks, Marougkas†, Ruiz, Sztandera† (PRD'24) [2405.19399]

R. Ruiz (IFJ PAN) 2PiNTS 3 / 5

Richard Ruiz



$\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{2+k}}{Q^{2+k}}\right)$ corrections have several origins (kinematical and dynamical)

Georgi, Politzer ('76,'76); Ellis, Furmanski, Petronzio ('82,'82); Dasgupta, Webber ('91); lots more

Leading twist, $(M_A/Q) \to 0$ — Leading twist + TMCs — Higher twist

For DIS on protons, **target mass corrections (TMCs)** incorporated by replacing $F_i^{A\ \text{(No TMC)}} \to F_i^{A\ \text{(TMC)}}$ in cross sections:

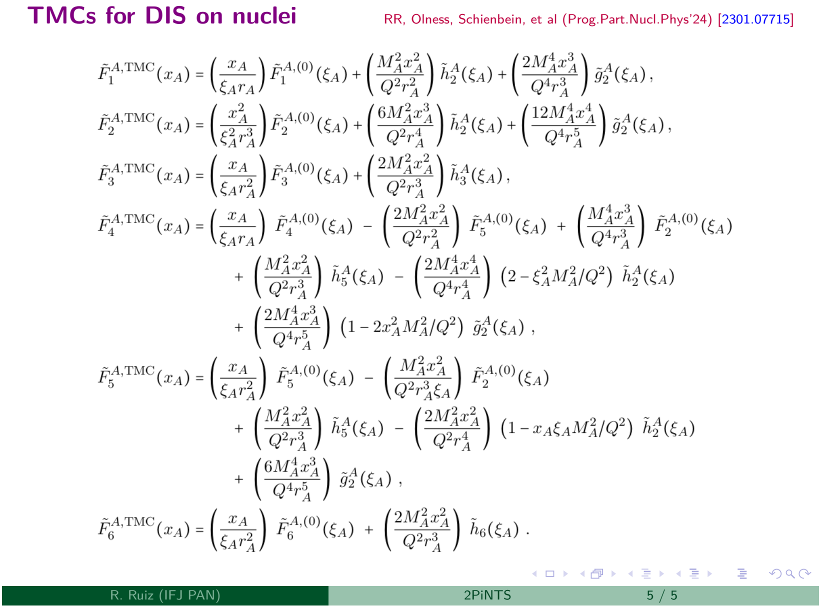
Georgi, Politzer ('76,'76); Ellis, Furmanski, Petronzio ('82,'82); lots more; Kretzer, Reno ('02,'03); Schienbein, et al [0709.1775]

$$\frac{d^2\sigma^{\rm NC}}{dx\,dy} = x(s-M^2)\,\frac{d^2\sigma^{\rm NC}}{dxdQ^2} = \frac{4\pi\alpha^2}{xyQ^2}\left[\frac{Y_+}{2}\,\sigma^{NC}_{\rm Red.}\right]$$

$$\sigma^{NC}_{\rm Red.} = \left(1+\frac{2y^2\varepsilon^2}{Y_+}\right)F_2^{\rm NC} \mp \frac{Y_-}{Y_+}\,xF_3^{\rm NC} - \frac{y^2}{Y_+}F_L^{\rm NC}$$

R. Ruiz (IFJ PAN) 2PiNTS 4 / 5

Richard Ruiz



TMCs for DIS on nuclei

RR, Olness, Schienbein, et al (Prog.Part.Nucl.Phys'24) [2301.07715]

$$\tilde{F}_1^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A}{\xi_A r_A}\right)\tilde{F}_1^{A,(0)}(\xi_A) + \left(\frac{M_A^2 x_A^2}{Q^2 r_A^2}\right)\tilde{h}_2^A(\xi_A) + \left(\frac{2M_A^4 x_A^3}{Q^4 r_A^3}\right)\tilde{g}_2^A(\xi_A),$$

$$\tilde{F}_2^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A^2}{\xi_A^2 r_A^3}\right)\tilde{F}_2^{A,(0)}(\xi_A) + \left(\frac{6M_A^2 x_A^3}{Q^2 r_A^4}\right)\tilde{h}_2^A(\xi_A) + \left(\frac{12M_A^4 x_A^4}{Q^4 r_A^5}\right)\tilde{g}_2^A(\xi_A),$$

$$\tilde{F}_3^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A}{\xi_A r_A^2}\right)\tilde{F}_3^{A,(0)}(\xi_A) + \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_3^A(\xi_A),$$

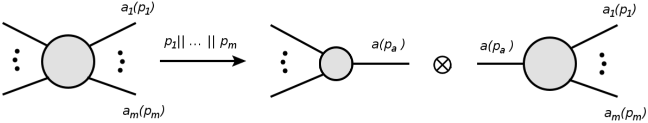
$$\begin{aligned}\tilde{F}_4^{A,\mathrm{TMC}}(x_A) = &\left(\frac{x_A}{\xi_A r_A}\right)\tilde{F}_4^{A,(0)}(\xi_A) - \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^2}\right)\tilde{F}_5^{A,(0)}(\xi_A) + \left(\frac{M_A^4 x_A^3}{Q^4 r_A^3}\right)\tilde{F}_2^{A,(0)}(\xi_A)\\ &+ \left(\frac{M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_5^A(\xi_A) - \left(\frac{2M_A^4 x_A^4}{Q^4 r_A^4}\right)\left(2 - \xi_A^2 M_A^2/Q^2\right)\tilde{h}_2^A(\xi_A)\\ &+ \left(\frac{2M_A^4 x_A^3}{Q^4 r_A^5}\right)\left(1 - 2x_A^2 M_A^2/Q^2\right)\tilde{g}_2^A(\xi_A),\end{aligned}$$

$$\begin{aligned}\tilde{F}_5^{A,\mathrm{TMC}}(x_A) = &\left(\frac{x_A}{\xi_A r_A^2}\right)\tilde{F}_5^{A,(0)}(\xi_A) - \left(\frac{M_A^2 x_A^2}{Q^2 r_A^3 \xi_A}\right)\tilde{F}_2^{A,(0)}(\xi_A)\\ &+ \left(\frac{M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_5^A(\xi_A) - \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^4}\right)\left(1 - x_A\xi_A M_A^2/Q^2\right)\tilde{h}_2^A(\xi_A)\\ &+ \left(\frac{6M_A^4 x_A^3}{Q^4 r_A^5}\right)\tilde{g}_2^A(\xi_A),\end{aligned}$$

$$\tilde{F}_6^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A}{\xi_A r_A^2}\right)\tilde{F}_6^{A,(0)}(\xi_A) + \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_6(\xi_A).$$

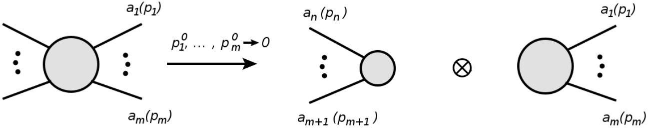
Sebastian Sapeta - QCD scattering amplitudes at higher orders

- Collinear limit



$$\mathcal{A}_{a_1 \dots a_m \dots}(p_1, \dots, p_m, \dots, p_n) \xrightarrow{p_1||p_2||\dots||p_m} \mathcal{A}_{a \dots}(p_a, \dots)\, \textbf{Split}_{a \to a_1 \dots a_m}(p_1, \dots, p_m)$$

- Soft limit

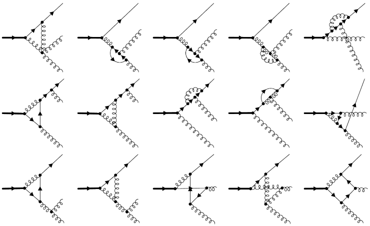


$$\mathcal{A}_{a_1 \dots}(p_1, \dots, p_m, \dots, p_n) \xrightarrow{p_1^0, p_2^0, \dots p_m^0 \to 0} \mathcal{A}_{a_{m+1} \dots}(p_{m+1}, \dots, p_n)\, \mathbf{J}_{a_1, \dots, a_m}(p_1, \dots, p_m)$$

Sebastian Sapeta - QCD scattering amplitudes at higher orders

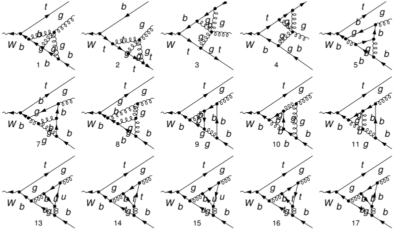
Complete set of one-loop,
triple-collinear splitting functions,
[Czakon, Sapeta, JHEP 07 (2022) 052]

Example set: $q \to qgg$



Two-loop soft current for massive fermions
[Czakon, Sapeta, in progress]

$W \to tbg$



- reduction to master integrals $\{M_i\}$
- systems of differential equations $dM_i = A_{ij} M_j$
- canonical form $d\tilde{M}_i = \epsilon\, S_{ij} \tilde{M}_j$

Zbigniew Wąs - Precision Monte Carlos for accelerator physics

(A) Monte Carlo programs such as `Bhlumi` for luminosity measurements with Bhabha scattering or `KKMC` for lepton pair productions, were demonstrated thanks to associated efforts that the precision for observables with complex cuts of sub permille level (even for 0.043% Opal luminosity measurement) were possible.

(B) Main building aspects enabling such precision:

1. Phase space (issues of iterations), unique solutions, last years extensions include exact parametrizations and generation for configuration with additional lepton pairs.
2. Matrix Elements and spin (issues of iterations). Because of required precision and need for compatibility with exclusive exponentiation. Last year contributions include effects of anomalous electric and magnetic dipole moments and effects of dark photons or light scalars on top of precision Standard Model simulations.
3. Tests and design of new observables. Essential part of the work.

Zbigniew Wąs

(C) `KKMC` is for $e^+e^- \to l^+l^-(n\gamma)$ and `photos` for radiative corrections in decays, `tauola` for τ lepton decays.

(D) Each of these programs main publications have 1000+ citations in INSPIRE as of 09 Sep 2024; these counts continue to grow. Programs versions in F77 and C++ are public.

- S. Jadach, B. F. L. Ward and Z. Was, "The Precision Monte Carlo event generator K K for two fermion final states in e+ e- collisions," Comput. Phys. Commun. **130** (2000), 260-325, 1200 citations
- P. Golonka and Z. Was, "PHOTOS Monte Carlo: A Precision tool for QED corrections in Z and W decays," Eur. Phys. J. C **45** (2006), 97-107 , 1486 citations
- S. Jadach, Z. Was, R. Decker and J. H. Kuhn, "The tau decay library TAUOLA: Version 2.4," Comput. Phys. Commun. **76** (1993), 361-380, 1117 citations
- S. Banerjee, A. Y. Korchin and Z. Was, "Spin correlations in τ-lepton pair production due to anomalous magnetic and electric dipole moments," Phys. Rev. D **106** (2022) no.11, 113010
- S. Antropov, S. Banerjee, Z. Was and J. Zaremba, "TAUOLA update for decay channels with e+e− pairs in the final state," Comput. Phys. Commun. **283** (2023), 108592