Group Meeting
October 18, 2019

100 talks in 4½ days

https://indico.cern.ch/event/734913/timetable/#all.detailed

Facilities	Topics	Theoretical Base
JLAB-EIC	**Spectroscopy,** **GPDs,TMDs,** **Factorization,** **& related topics**	**Rel. Bound States** **LFD Pedagogy & Issues** **IFD vs. LFD** **Euclidean vs. Minkowski** **General Tensor Structure** **AdS Holography** **BLFQ** **LFQM**
RHIC-LHC	**Heavy Ion Collisions,** **Jets,** **Hadronization,** **& related topics**	
FRIB	**medium modification,** **&related topics**	

The present and future science program at Jefferson Lab

LIGHT CONE 2019

Ecole Polytechnique, Palaiseau, France
16-20 SEPTEMBER 2019

QCD on the light-cone:

From hadrons to heavy ions

- CEBAF 12 GeV upgrade
- Science & Capabilities
- Recent highlights
- Light-cone physics
- Future projects
- JLab12 to EIC
- Summary

Jianwei Qiu
Theory Center

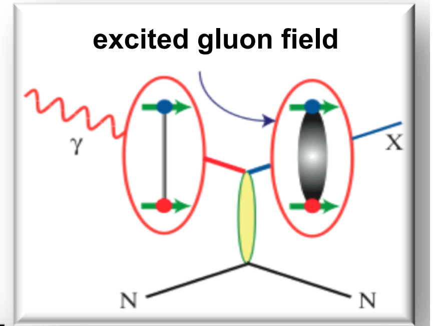
Jefferson Lab

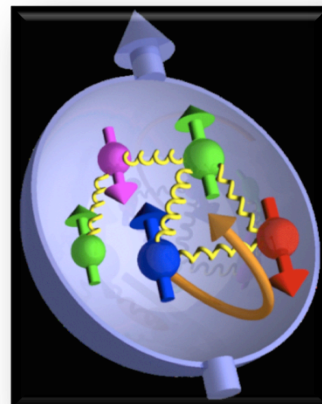
U.S. DEPARTMENT OF ENERGY | Office of Science

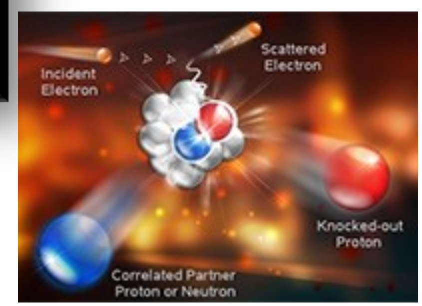
JSA

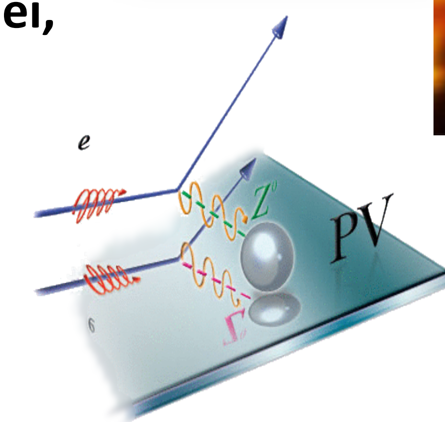
JLab12 Scientific Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?









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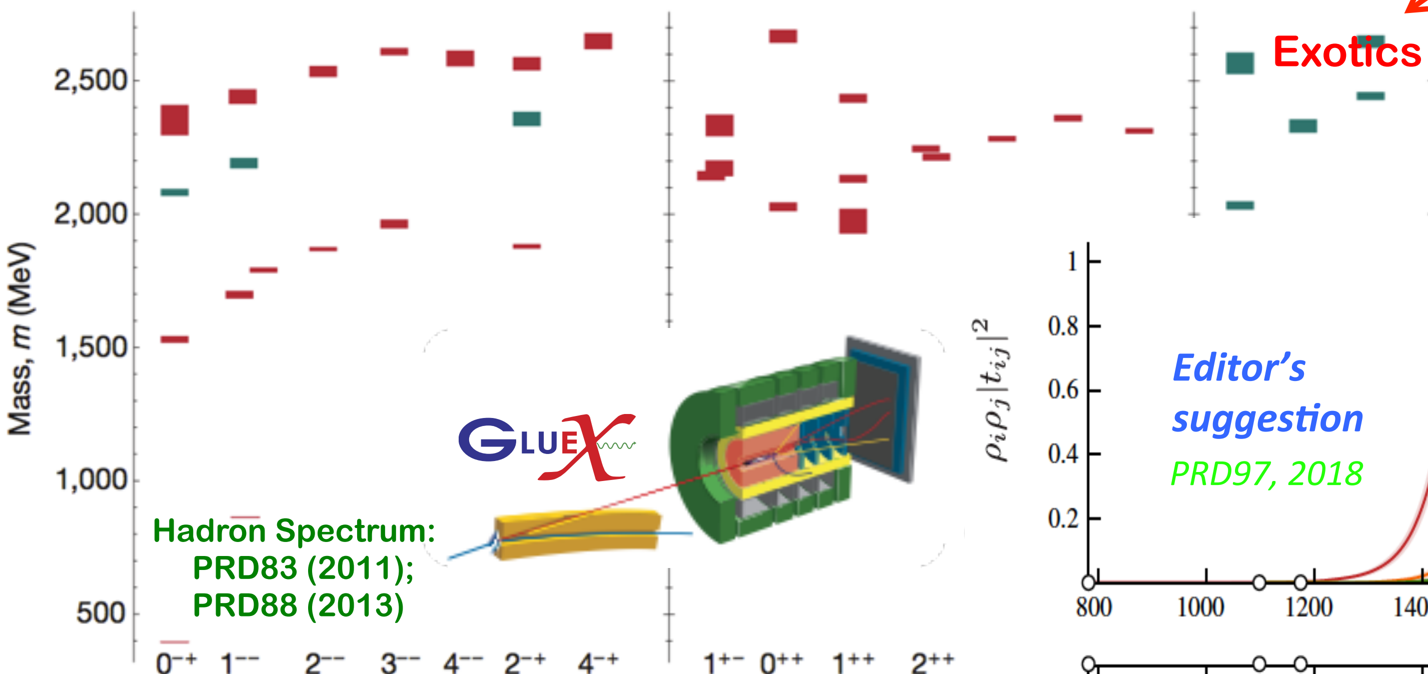
LQCD – beyond the mass spectrum

- ✧ GlueX looking for exotic hybrid mesons in photoproduction
- ✧ Might appear as enhancement in πππ ~ πρ, πσ, πf0(980)…

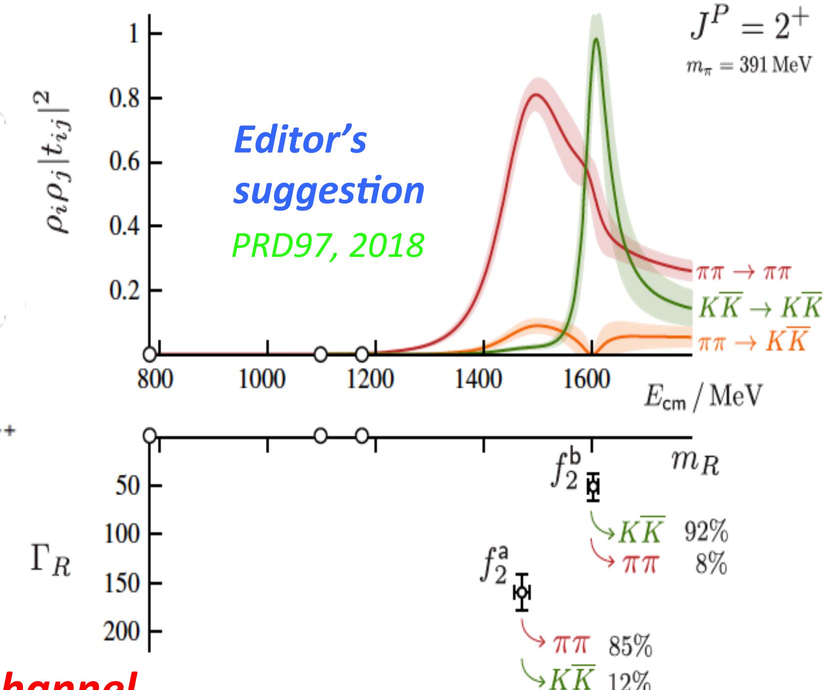
Light quark meson + "exotics" & "hybrids" spectrum



Hadron Spectrum:
PRD83 (2011);
PRD88 (2013)

Predicted

Decay rate



Editor's suggestion
PRD97, 2018

Motivation in GlueX PID upgrade proposal
GlueX actively calibrating in this channel

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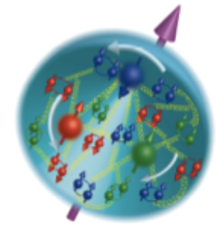
LQCD/PQCD – hadron/nuclear structure

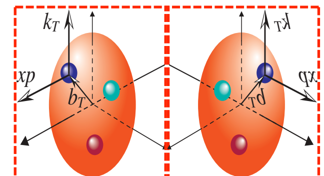
- **No "still picture" for hadron's partonic structure:**

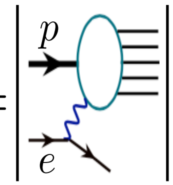
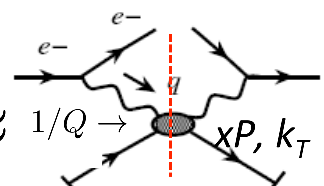
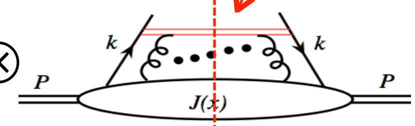


Quarks and gluons are moving relativistically, color is fully entangled!

Partonic structure = "Quantum Probabilities": $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^\mu)|P,S\rangle$

- **High energy probes see partons on the light-cone:**



$\sigma_{\rm DIS}(x,Q^2) = \Big|$  $\Big|^2 \approx$  $\otimes$  $+\, O\left(\frac{1}{QR}\right)$

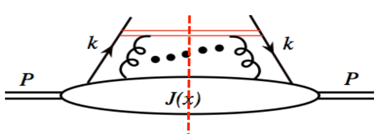
Factorization

Hard-part Probe

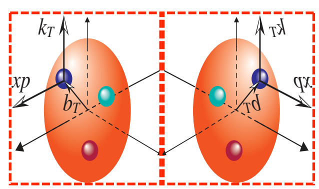
Parton-distribution Structure

Power corrections Approximation

Partnic structure:



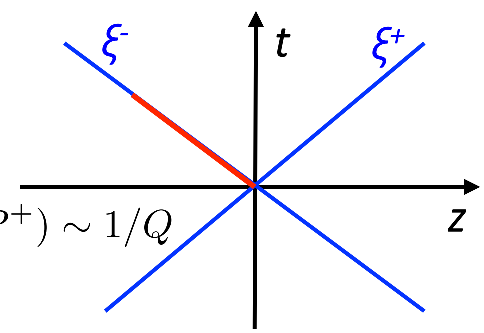
$\Longleftrightarrow$



$$\Longleftrightarrow\quad f_q(x,\mu^2) \equiv \int \frac{dP^+\xi^-}{2\pi}\, e^{-ixP^+\xi^-}$$

$$\times \langle P|\overline{\psi}(\xi^-)\frac{\gamma^+}{2P^+}\exp\left\{-ig\int_0^{\xi^-} d\eta^- A^+(\eta^-)\right\}\psi(0)|P\rangle$$

LQCD – "Wrong" time!



$\xi^- \lesssim 1/(xP^+) \sim 1/Q$

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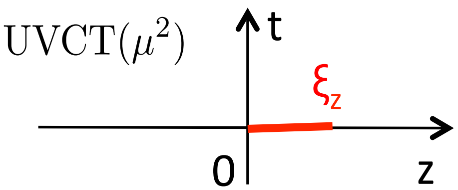
LQCD/PQCD – hadron/nuclear structure

Ji, arXiv:1305.1539

❑ New idea – quasi-PDFs:

$$\tilde{q}(x,\mu^2,P_z) \equiv \int \frac{d\xi_z}{4\pi} e^{-ixP_z\xi_z} \langle P|\overline{\psi}(\xi_z)\gamma_z \exp\left\{-ig\int_0^{\xi_z} d\eta_z A_z(\eta_z)\right\}\psi(0)|P\rangle + \text{UVCT}(\mu^2)$$

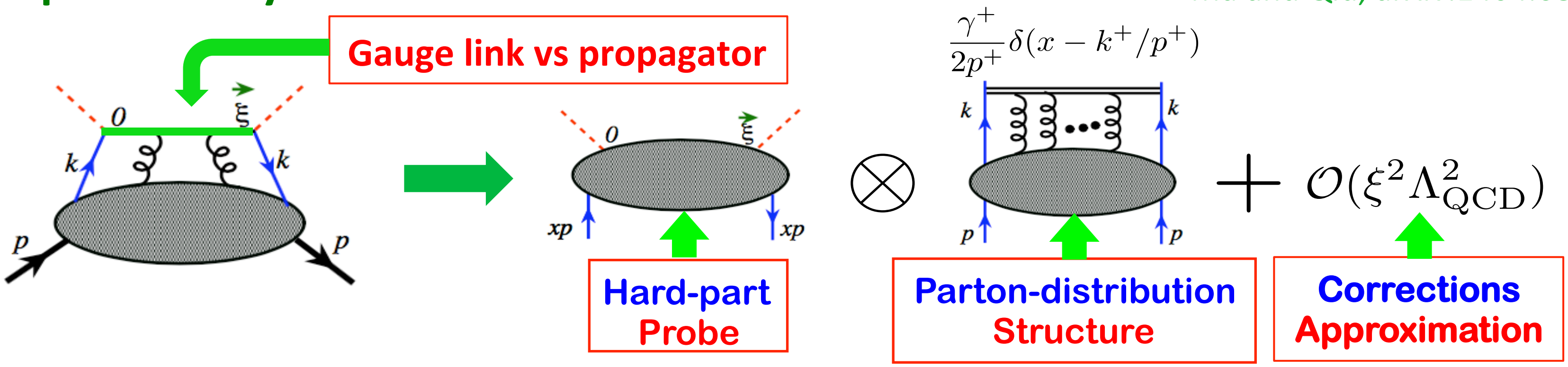


No longer boost invariant + power divergent, …

Key observation: $(0,z) \longrightarrow (0^+,\xi^-)$ when $P_z \to \infty$

❑ Complementary idea – "lattice cross section":

Ma and Qiu, arXiv:1404.6860



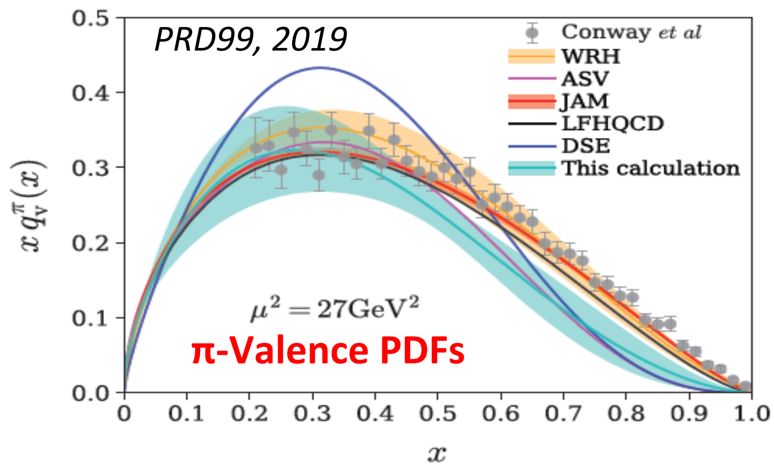
❑ Tremendous potentials:

Access to large-x region, …

Neutron PDFs, … (no free neutron target!)

Meson PDFs, such as pion, kaon, …

More direct access to parton flavor, …



➡ *1st LQCD calculation of pion valence PDFs!*

LQCD/PQCD/EXP – hadron/nuclear structure

- **Predictive power of QCD – Universality & Global analyses::**

arXiv:1905.03788
Submitted to PRL

No modern detector can see quarks and gluons in isolation!

- lepton-hadron reactions (COMPASS, JLab, **EIC**)

$$\sigma^{\rm EXP}_{l+P\to l+H+X} = C_{l+k\to l+k+X} \otimes {\rm PDF}_P \otimes {\rm FF}_H$$

- hadron-hadron reactions (LHC)

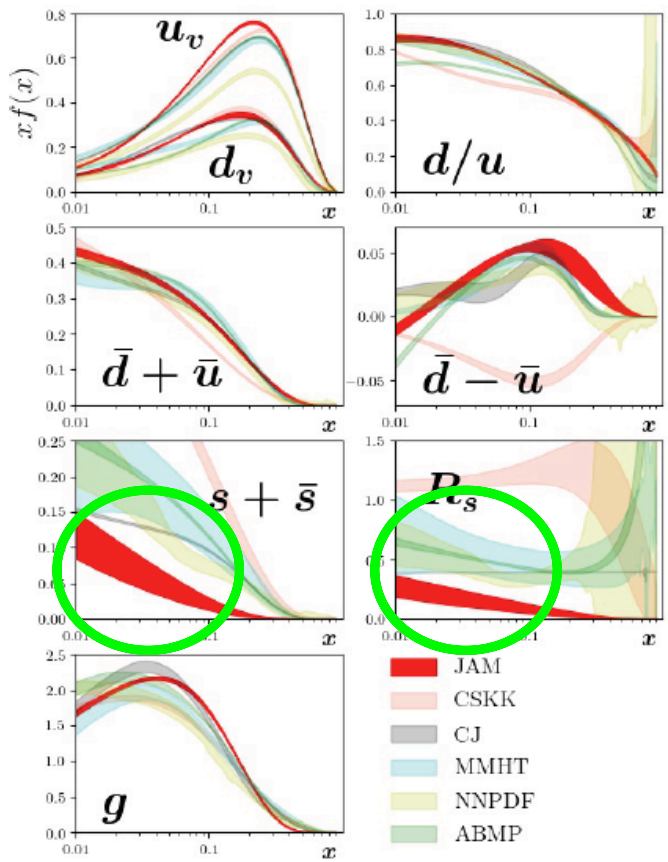
$$\sigma^{\rm EXP}_{P+P\to l+\bar{l}+X} = C_{k+k\to l+\bar{l}+X} \otimes {\rm PDF}_P \otimes {\rm PDF}_P$$

- lepton-lepton reactions (Belle)

$$\sigma^{\rm EXP}_{l+\bar{l}\to H+X} = C_{l+\bar{l}\to k+X} \otimes {\rm FF}_H$$

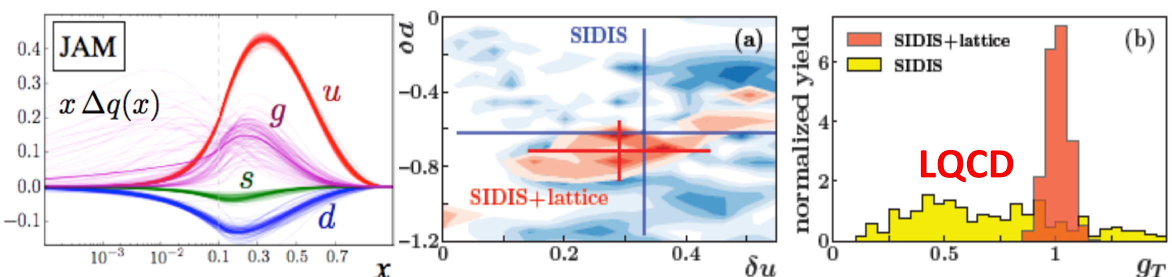
✓ DIS (p, d)
✓ DY (pp, pd)
✓ SIA $(\pi^{\pm}, K^{\pm})$
✓ SIDIS $(\pi^{\pm}, K^{\pm})$

Simultaneous fit



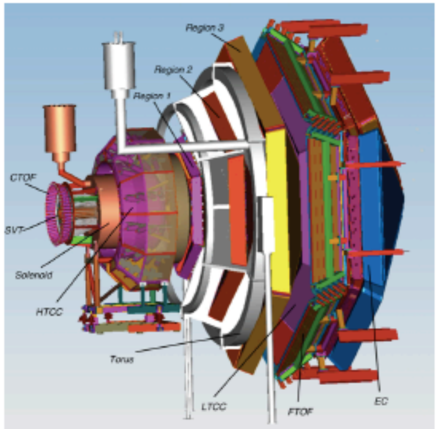
Strange quark suppression!

- **Role of precise lattice data:**



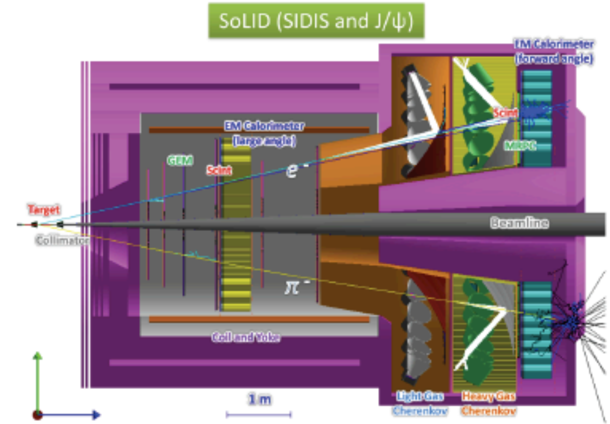
Lin, WM, Prokudin, Sato, Shows, PRL 120, 152502 (2018)

Center for Nuclear Femtography:



DVCS

Lattice QCD

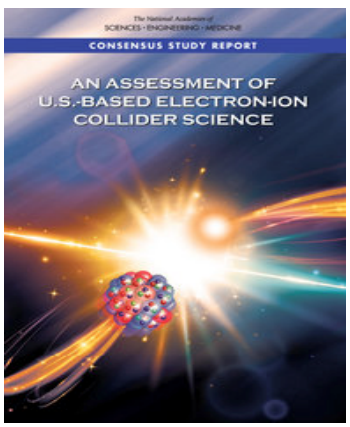


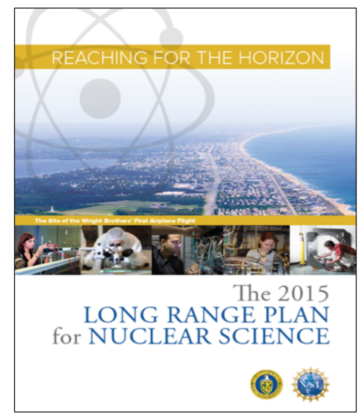
SIDIS

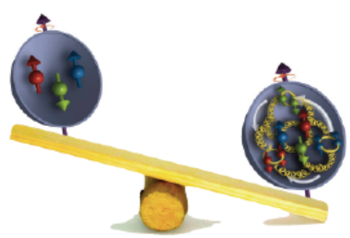
Imaging the Quarks

Electron-Ion Collider

Imaging the Gluons







CENTER for NUCLEAR FEMTOGRAPHY

Understand the glue that binds us all:
The Next QCD Frontier in Nuclear Physics

Jefferson Lab

What EIC can do, but, HERA & other colliders cannot do?

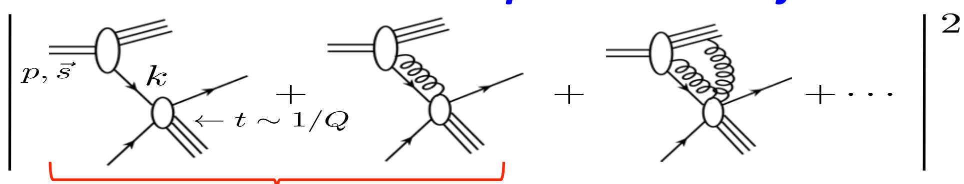
- **What is so special about the Lepton-Hadron Collider?**

  Hit the proton with a well-controlled hard probe without breaking it!

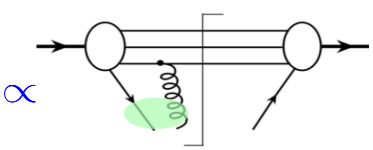
- **Quantum imaging:**
  - **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

- **Quantum interference & entanglement – dual role of hadron spin:**
  - **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!

$\sigma(Q, \vec{s}) \propto$



$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x, x) \propto$

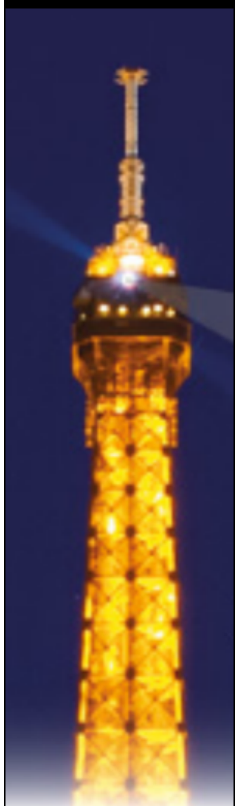


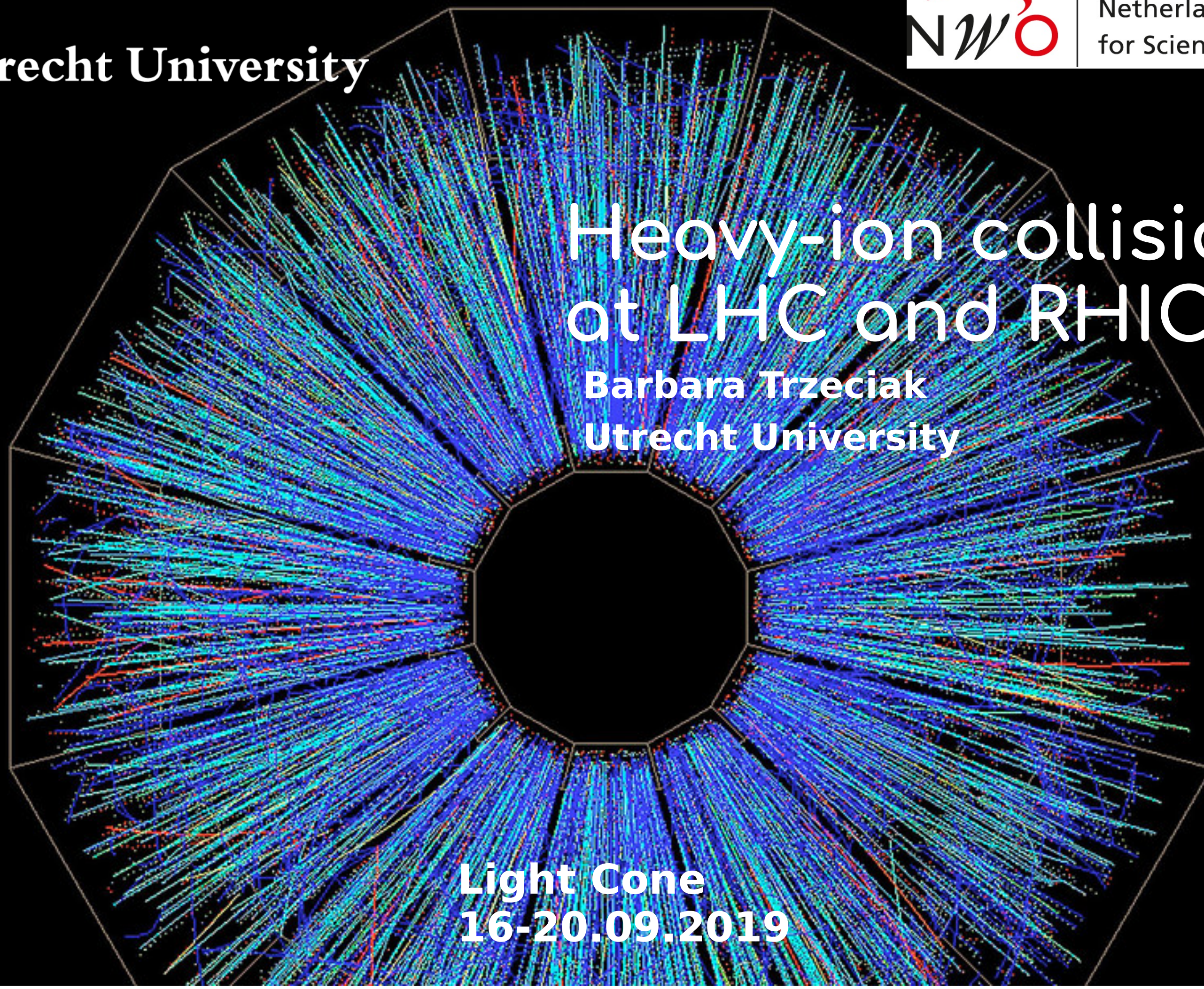
- **Nonlinear quantum dynamics – dual role of nuclei:**
  - **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***
    Catch the transition from chromo-quantum fluctuation
    to chromo-condensate of gluons, …
    Emergence of hadrons (femtometer size detector!),
    – "a new controllable knob" – Atomic weight of nuclei

Jefferson Lab

Utrecht University

Netherlands Organisation for Scientific Research

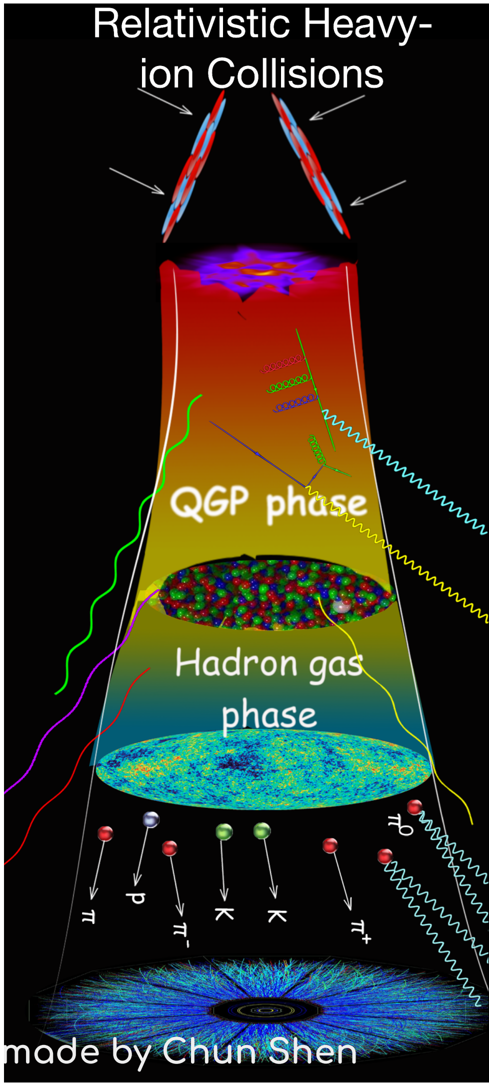


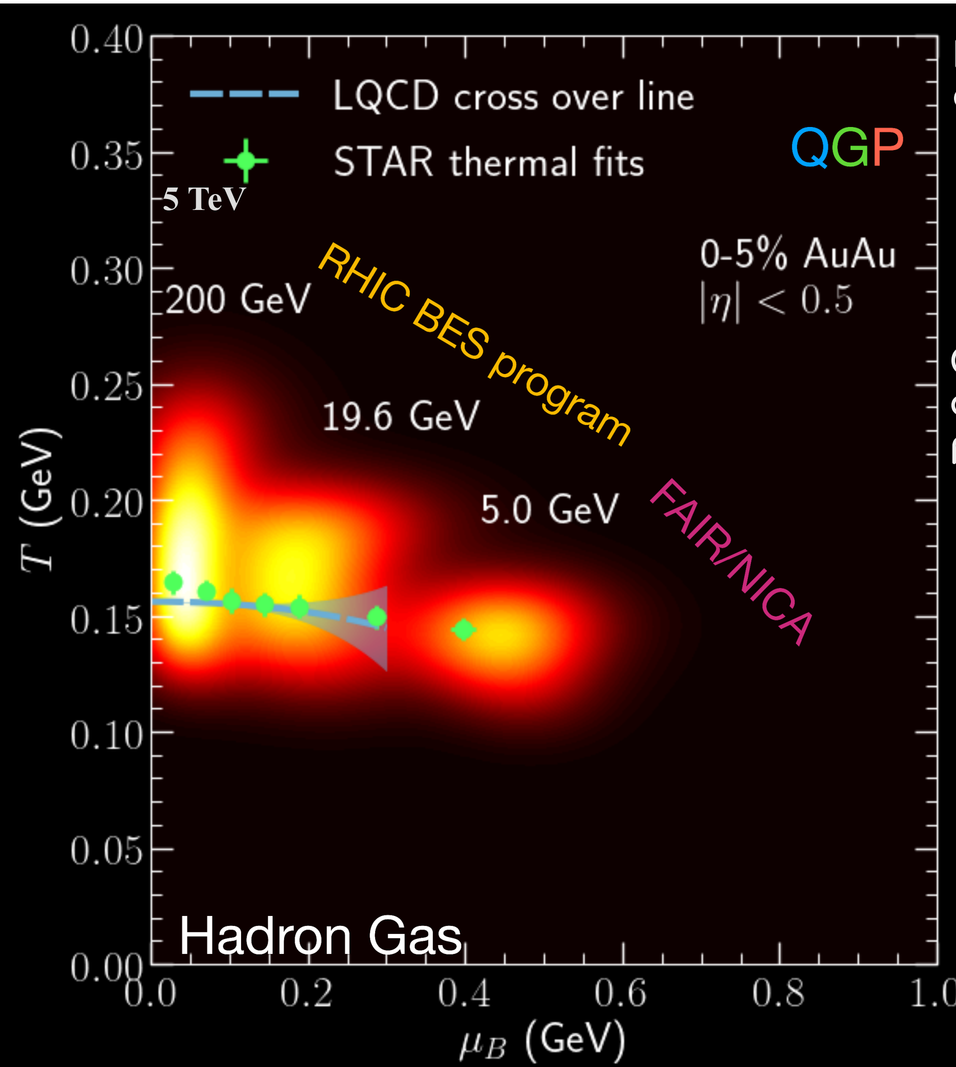


Heavy-ion collisions at LHC and RHIC

Barbara Trzeciak
Utrecht University

Light Cone
16-20.09.2019





Relativistic Heavy-ion collisions:

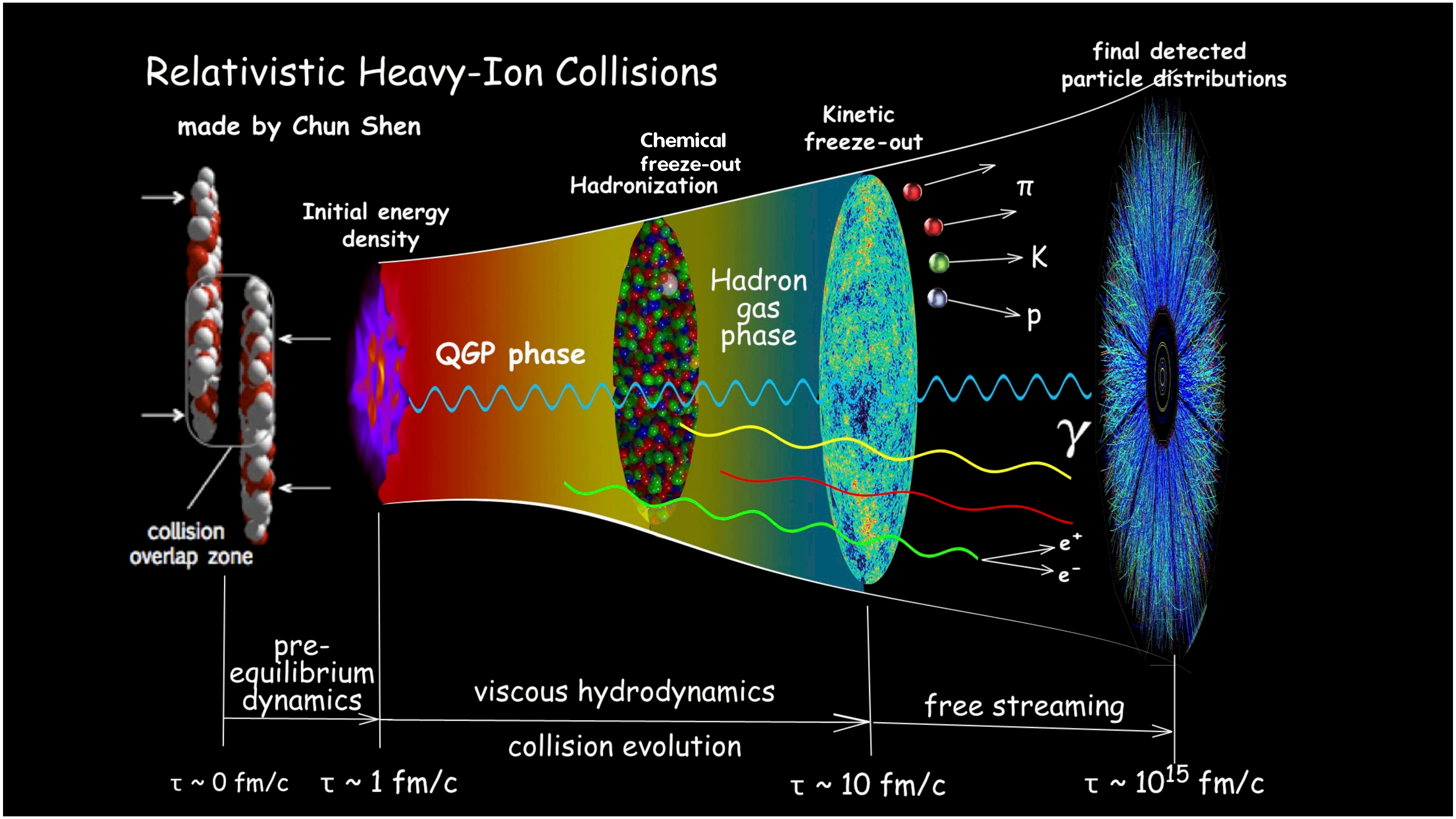
- unique tool to create and study hot QCD matter and its phase transition under controlled conditions

One of the fundamental questions in QCD phenomenology:

- *what are properties of strongly-interacting matter at extreme conditions of temperature and energy density*

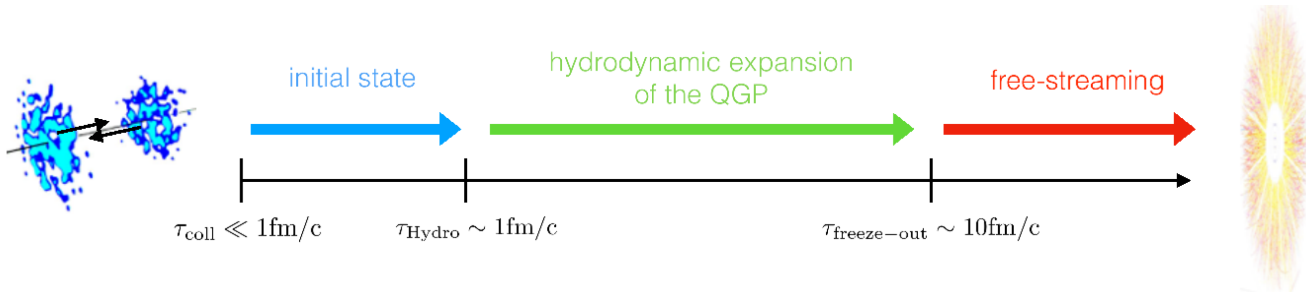
Nearly perfect fluid discovery at RHIC
Nucl. Phys. A 757 (2005)

RHIC: 130-200 GeV
LHC: Pb-Pb: 2.76-5.02,
Xe-Xe: 5.44 TeV


Relativistic Heavy-Ion Collisions
made by Chun Shen
Initial energy density
Chemical freeze-out
Hadronization
Kinetic freeze-out
final detected particle distributions
QGP phase
Hadron gas phase
π
K
p
γ
e+
e−
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Evolution of heavy-ion collisions

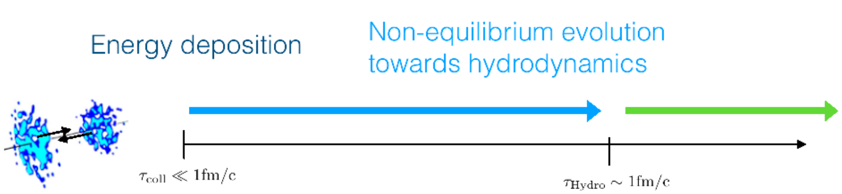
- Description of the heavy-ion collision dynamics from the underlying QCD still challenging

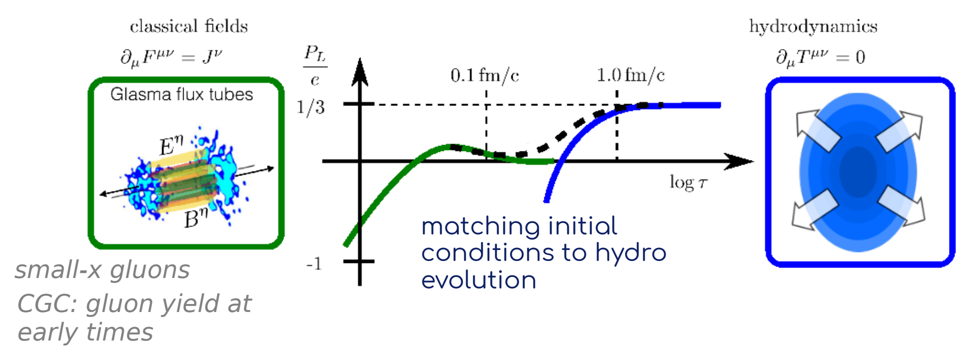


- Bulk dominated by the hydrodynamic expansion
  - Knowledge of the initial state required

Small systems → increased sensitivity to initial state

Early times, Pre-equilibrium





- Early times → classical field evolution
- Energy deposition models, based on:

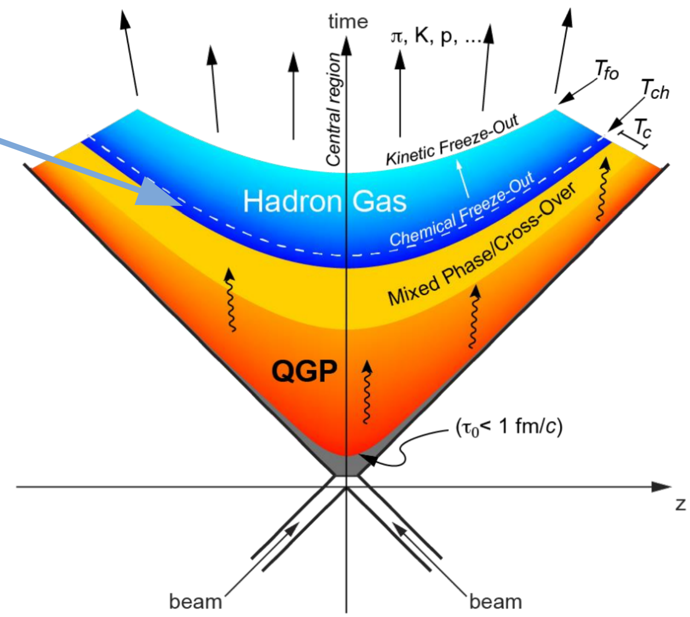
CGC,

Non-equilibrium models:

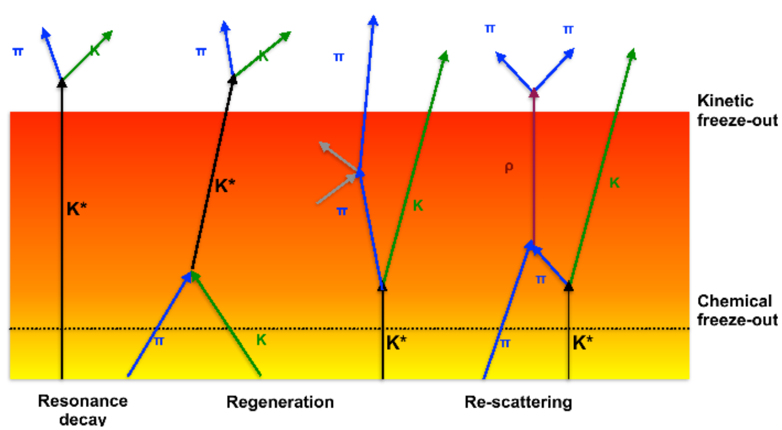
QCD kinetic theory,

Chemical composition

→ Production at **chemical freeze-out**
- Inelastic collisions cease
- Abundances of different hadron species fixed
- Integrated particle yields → conditions at chemical freeze-out



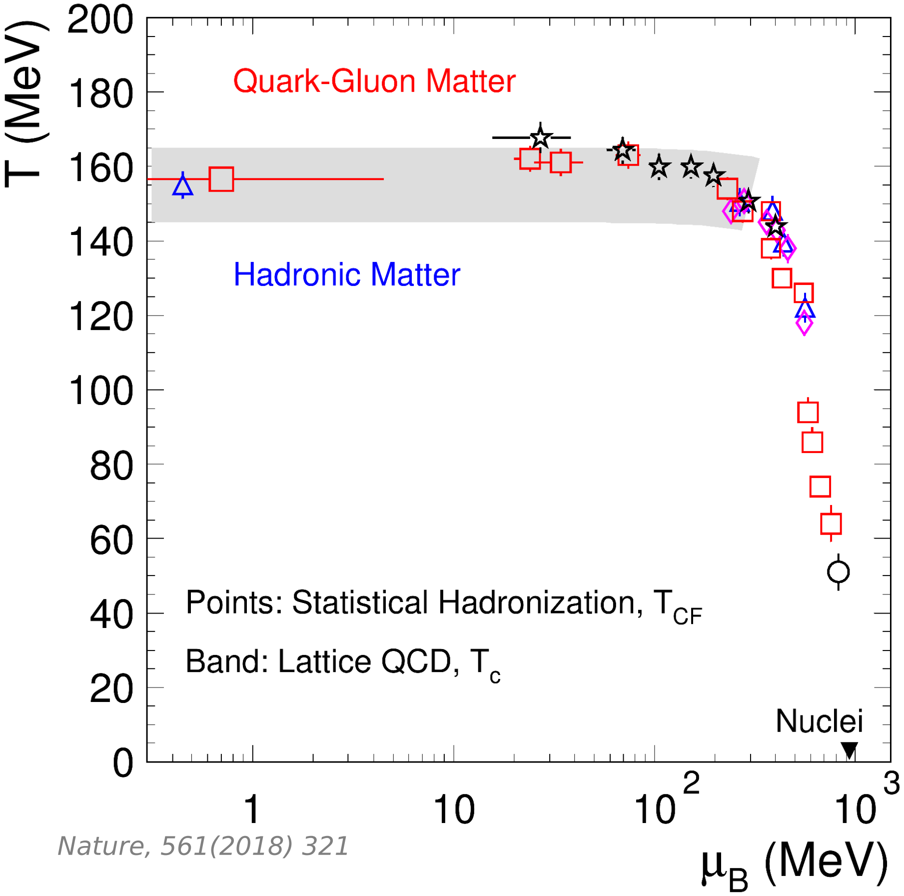
→ Particle yields measured at kinetic freeze-out. Depend on:
- Initial yields after chemical freeze-out
- Lifetime of hadronic phase
- Resonance decays
- Scattering cross-section of decay products
- Baryon final state annihilation ?



Thermodynamic properties

➔ Described by statistical/thermal models with grand canonical ensemble.
- Three parameters: T_{ch}, μ_B, V

➔ With increasing $\sqrt{s_{NN}}$:
- μ_B decreases, vanishes at LHC
- T_{ch} increases up to SPS energies then saturated at ~160 MeV, close to the QGP phase boundary temperature from lattice QCD

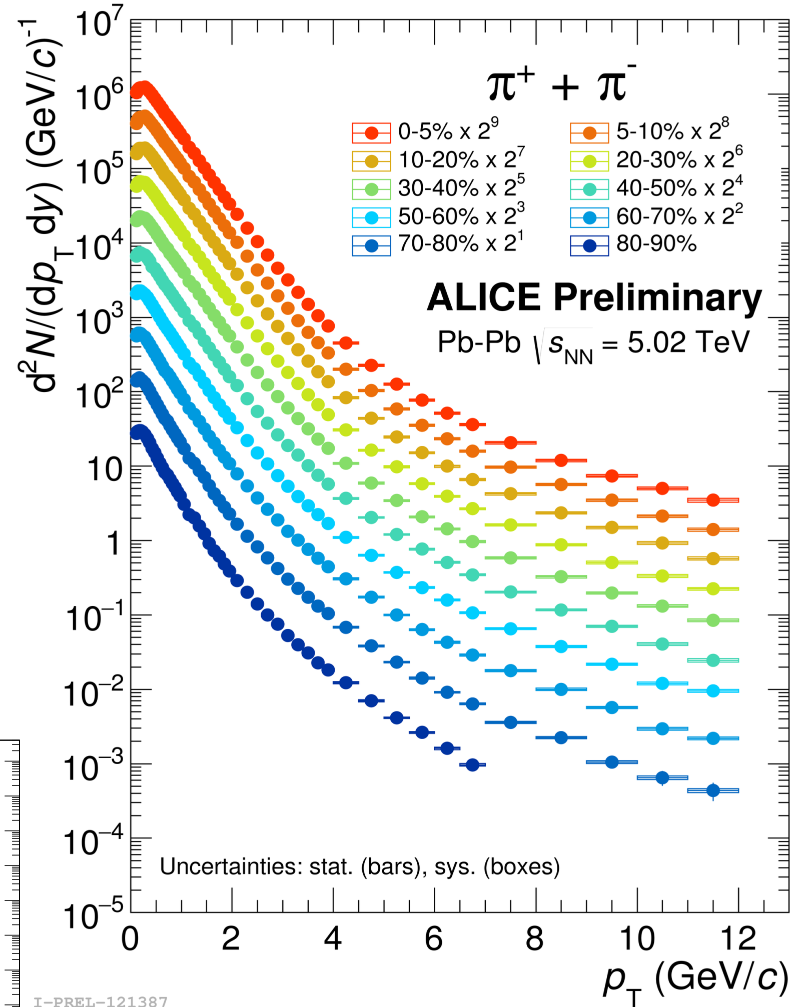


Nature, 561(2018) 321

p_T distributions

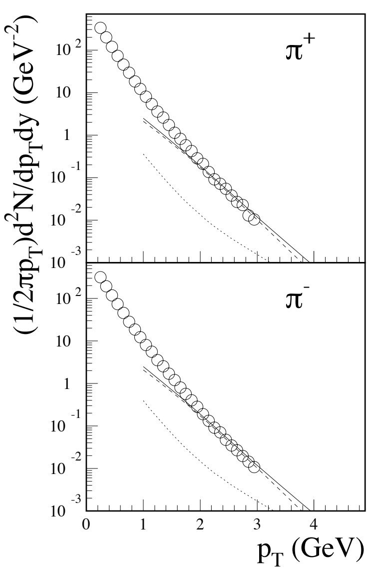
- **Low p_T** (< 2,3 GeV):
  - Bulk-matter (collective phenomena)
    LHC > 95% of the produced particles,
    non-perturbative QCD regime
- **Intermediate p_T:**
  - Fragmentation vs recombination
- **High p_T** (> 8-10 GeV):
  - Hard processes, energy loss

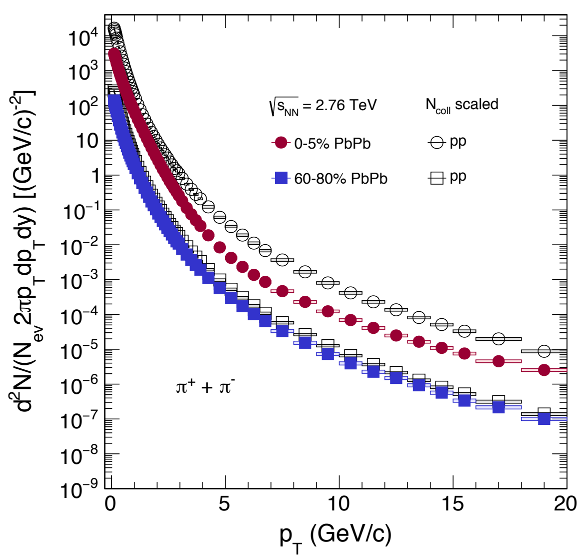
- Hardening of the spectra with centrality



ALI-PREL-121387

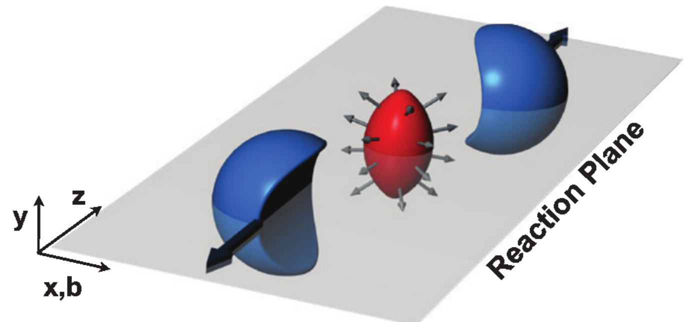
B.Hong,C.Ji,D. Min, PRC73,054901(2006)





QGP: Collectivity in the system

non-central HI collision

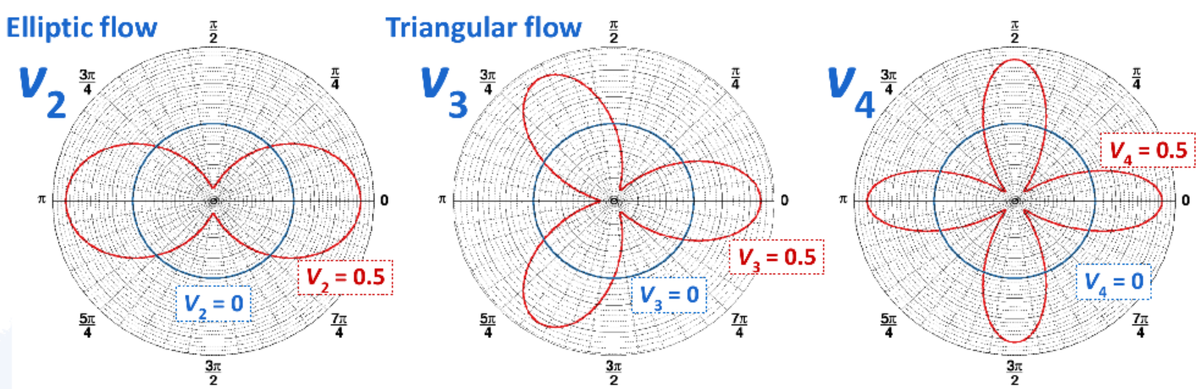


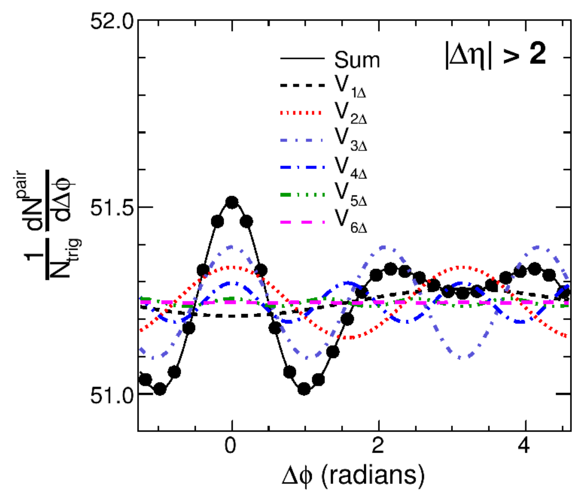
- ➔ initial spacial anisotropy → **azimuthal anisotropies** in particle momentum distributions
- ➔ Fourier expansion:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[(\varphi - \Psi_n)]\right)$$

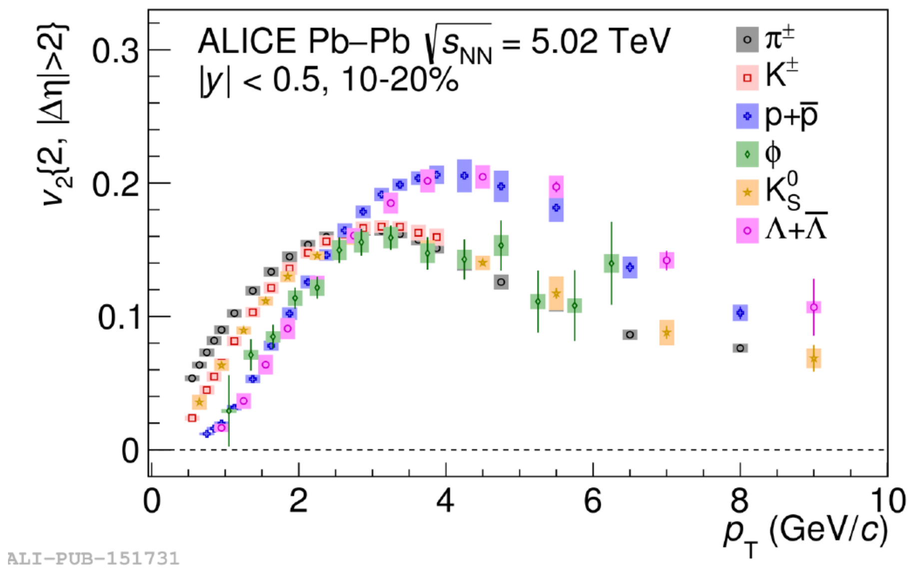
$$v_n(p_T, y) = \langle\cos[n(\varphi - \Psi_n)]\rangle$$

v_1: directed flow v_2: elliptic flow v_3: triangular flow





Azimuthal anisotropy – elliptic flow

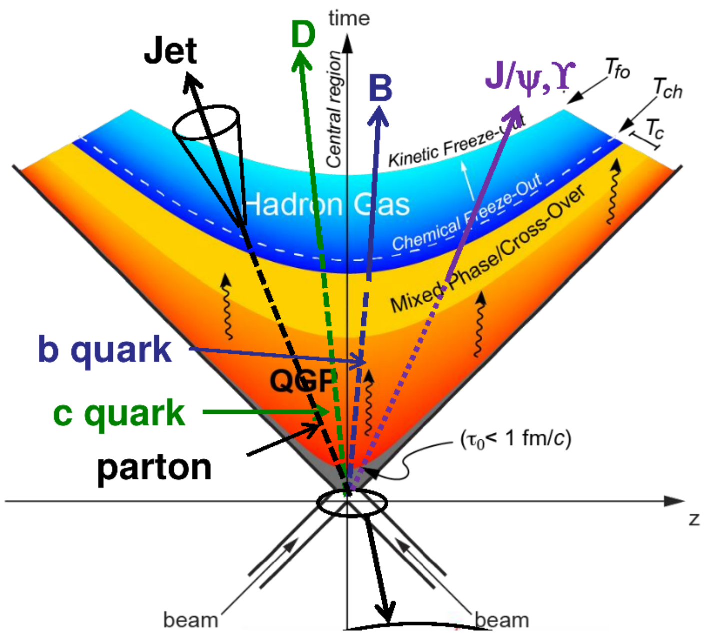


- **Low p_T (<2 GeV/c): mass ordering**

  collective radial flow velocity,
  isotropic expansion
- **p_T ~2.5 GeV/c**: crossing between v_2 of mesons and baryons
- **p_T > 2.5~8 GeV/c: baryon-meson grouping**

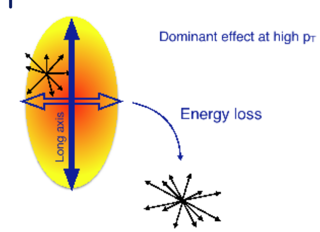
  baryon v_2 > meson v_2,
  flow driven by quark content
- **Φ meson** follows mass ordering at low p_T and quark contents at intermediate p_T

Hard probes

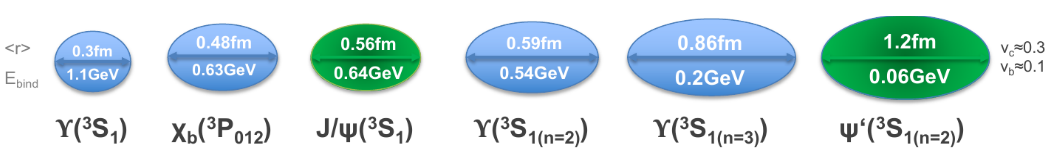


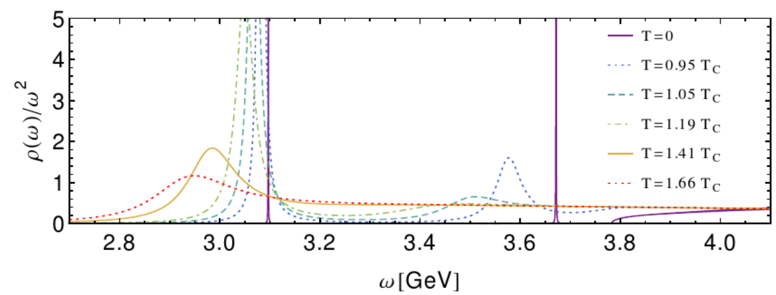
- Medium properties studied via parton modification in the medium

➔ High-p_T partons and heavy quarks
  - Collisional and radiative parton energy loss, flavour and mass dependence
  - Dependence on medium properties and traversed path lengths



➔ Quarkonia: suppression of different states due to colour screening
  - "QGP thermometer"



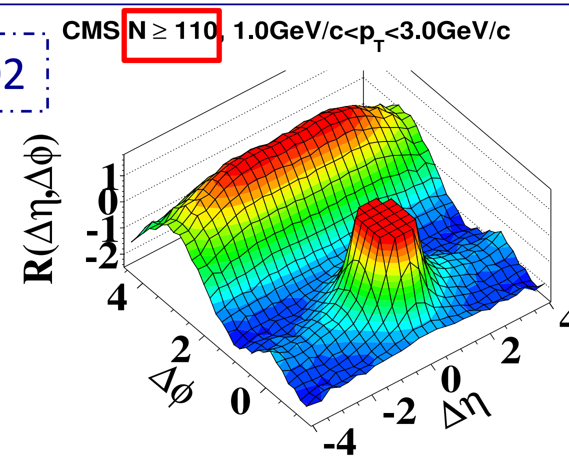


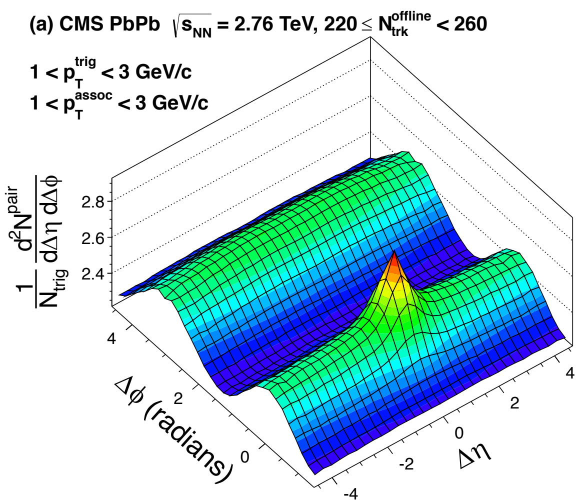
➢ Discovery of the ridge

- Long range correlation
- Signature of collective flow!

PRL (2016)116, 172302

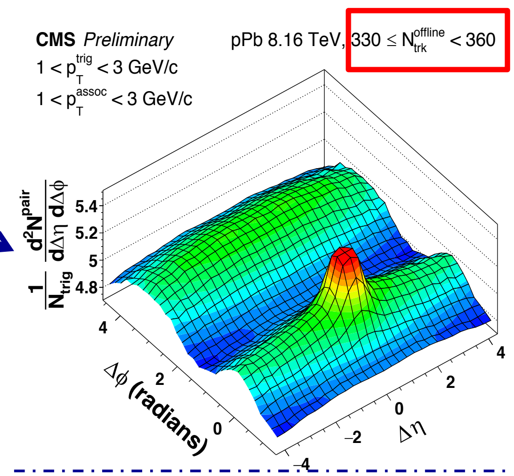
PLB (2016) 12, 009





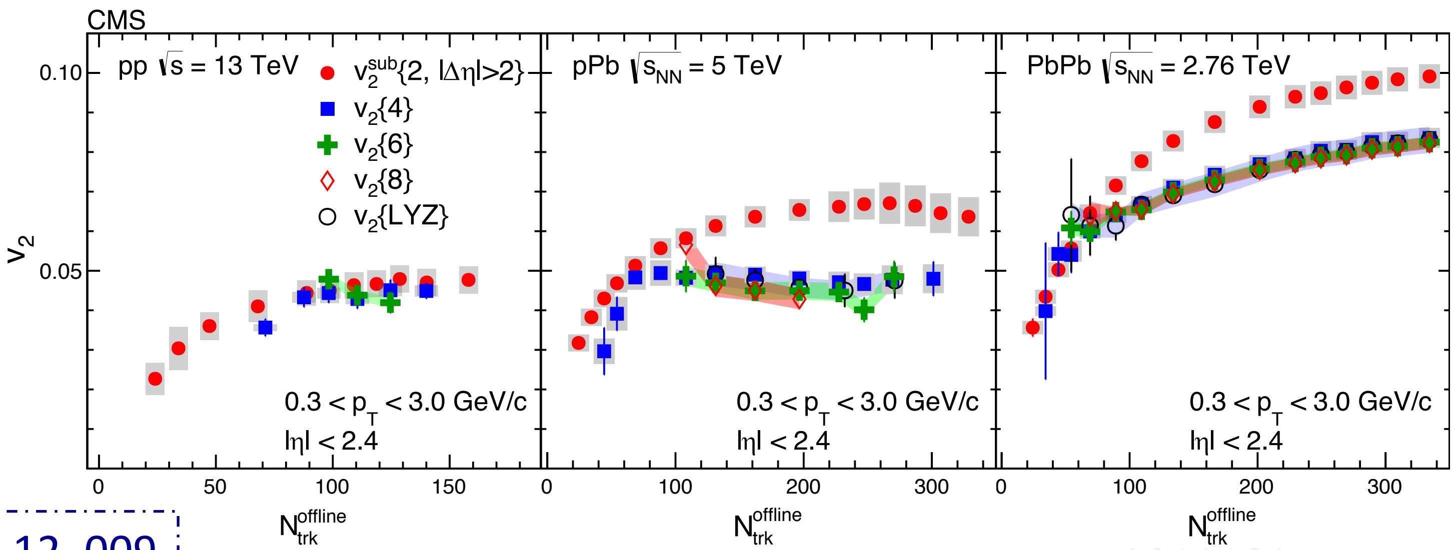
PLB (2013) 06, 028

Ridge observed in high multiplicity events for small colliding systems



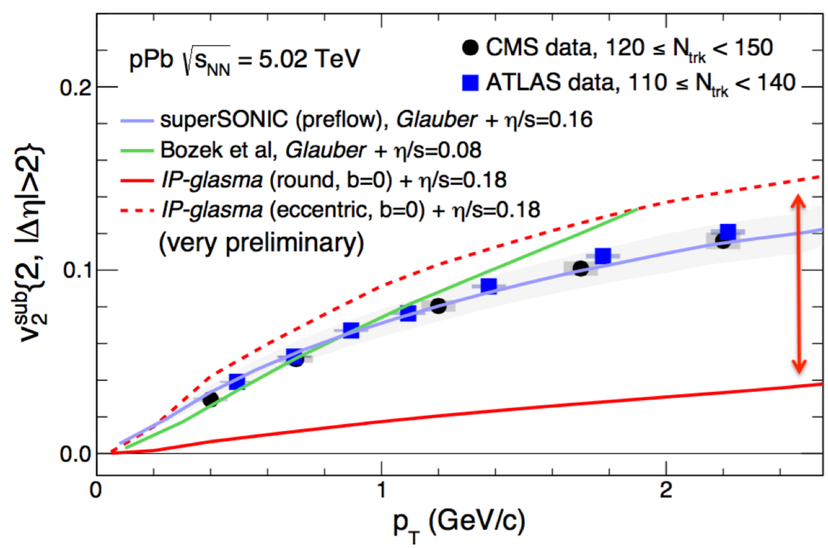
PRL (2018)120, 092301

Nature of the “Ridge”



PLB (2016) 12, 009

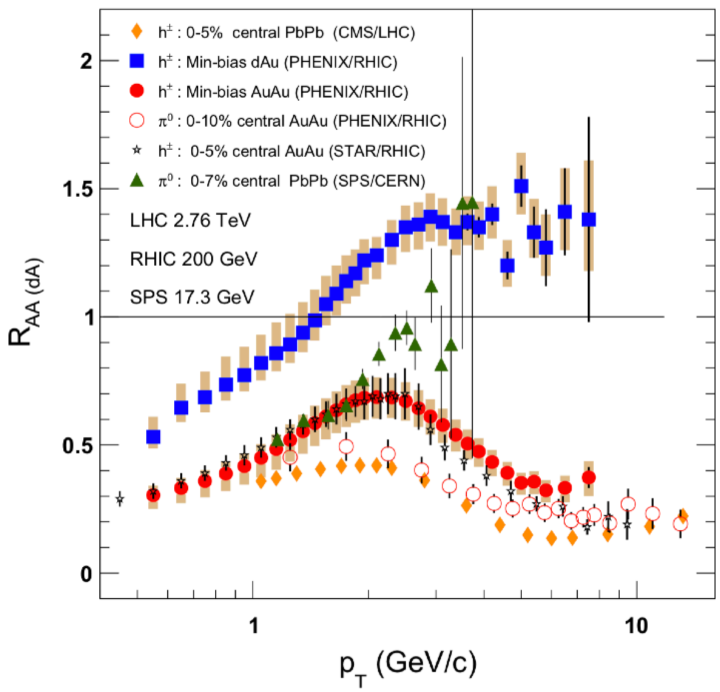
- **Collective nature**
  - Multi-particle correlation
  - Similar patterns
- **Initial State (IS) matters**



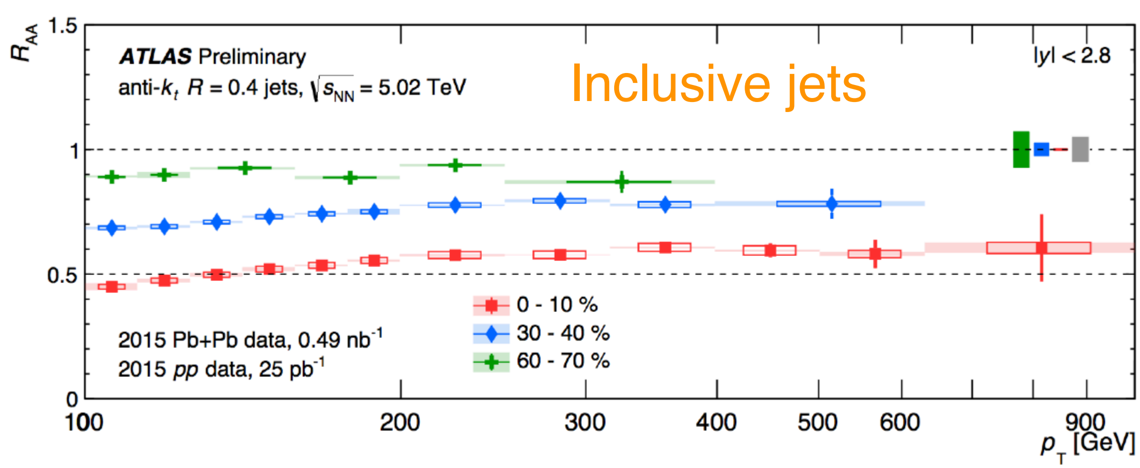
Jet quenching in heavy ion collisions

- Two decades after Bjorken prediction, jet quenching phenomenon was observed at RHIC in the suppression of high-pT hadrons and confirmed at LHC where a strong suppression of 1 TeV jets was observed
- Use jets as test particles to learn about the properties of of the Quark-Gluon-Plasma (QGP)

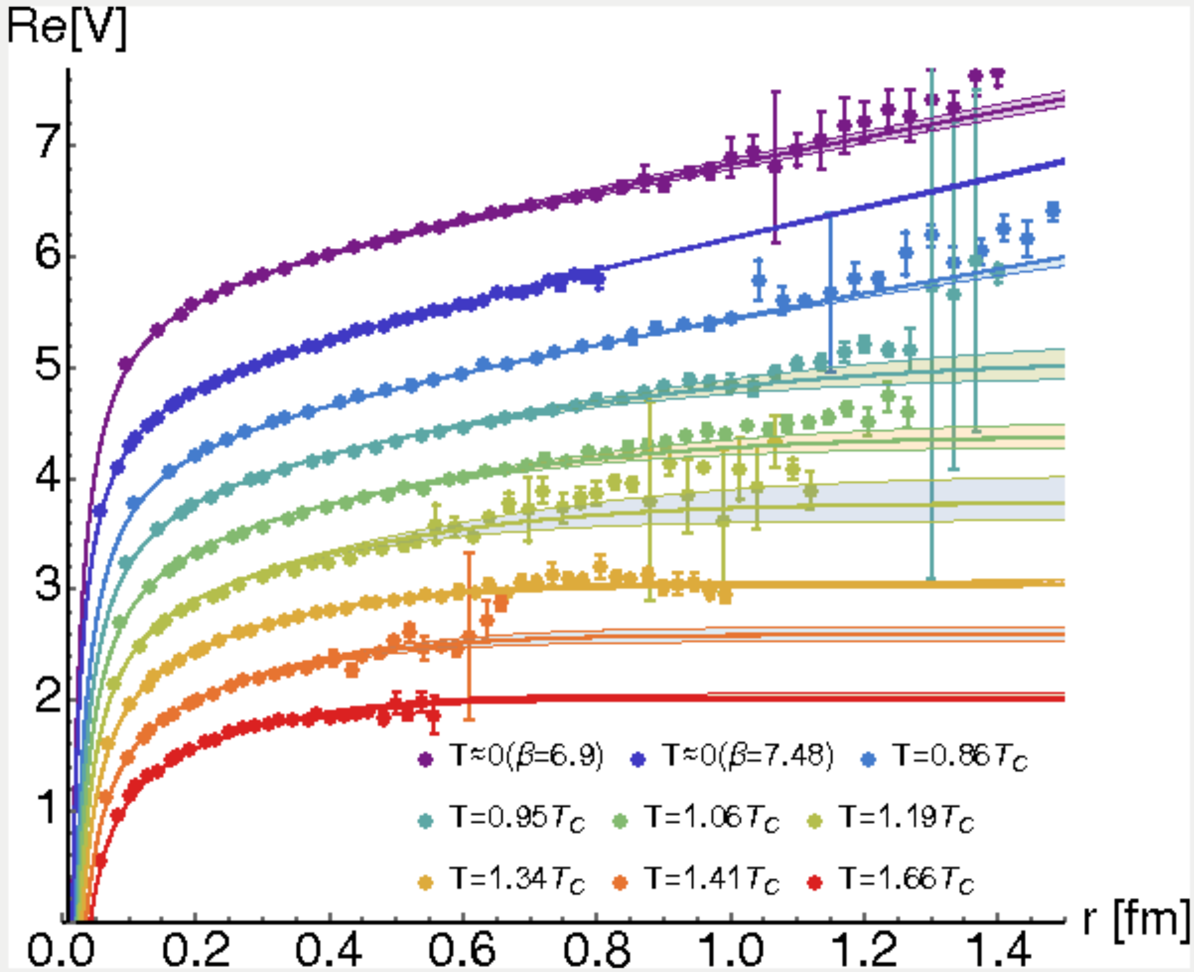
Inclusive hadrons



$$R_{AA} \equiv \frac{1}{N_{coll}} \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\mathrm{d}N_{pp}/\mathrm{d}p_T}$$



Quark-antiquark potential at high temperature



Small collision systems
and
the Electron Ion Collider

Michael Winn

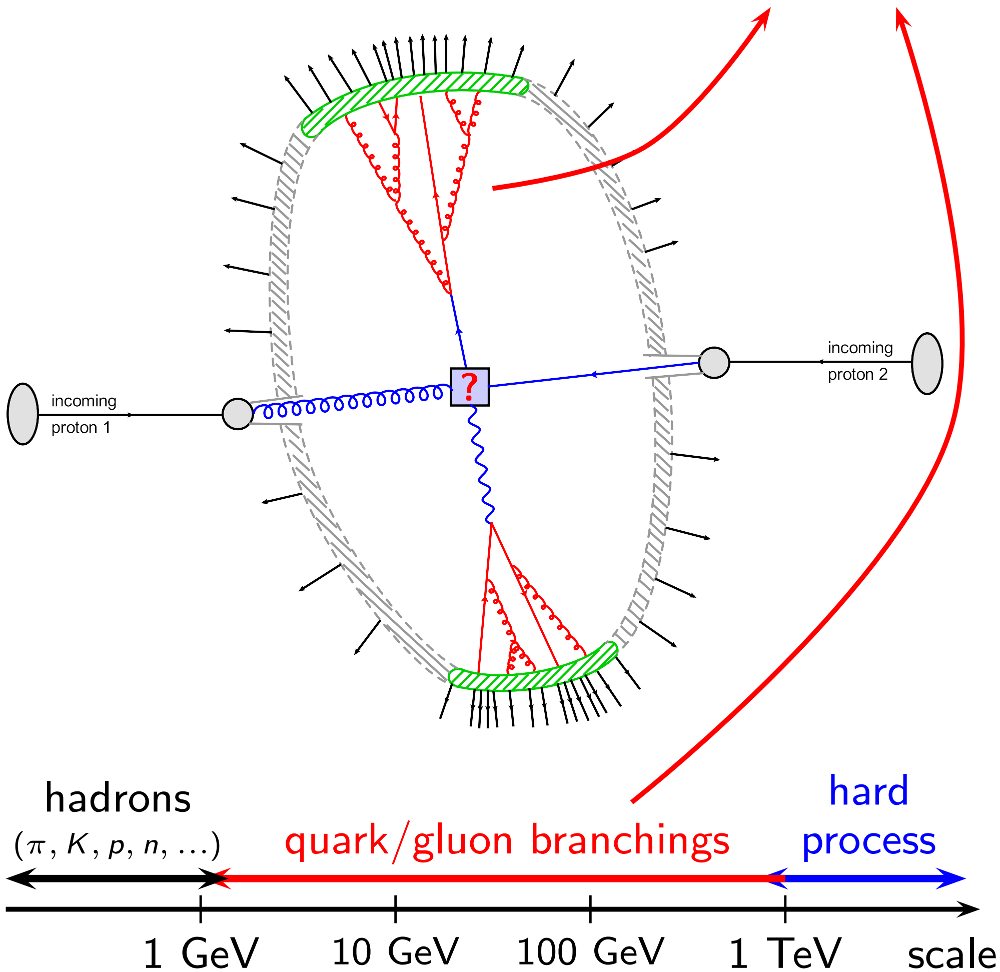
Nuclear physics division, IRFU-CEA

Light-Cone Conference, Palaiseau, 17th of September 2019

- open: which degrees of freedom & scales, "transitions" & thermalisation, role of geometry in coordinate & momentum space, implications for High-Energy-Physics-modelling?
- precision input from the electron ion collider for "initial state" with "point-like" probe:
  important for hadronic collisions as constraint

Colliders study fundamental interactions at high energy

topic #1 for this talk



Hard + branchings

- perturbative QCD
- controlled, solid
- predictive with genuine theory uncertainties

Hadronisation

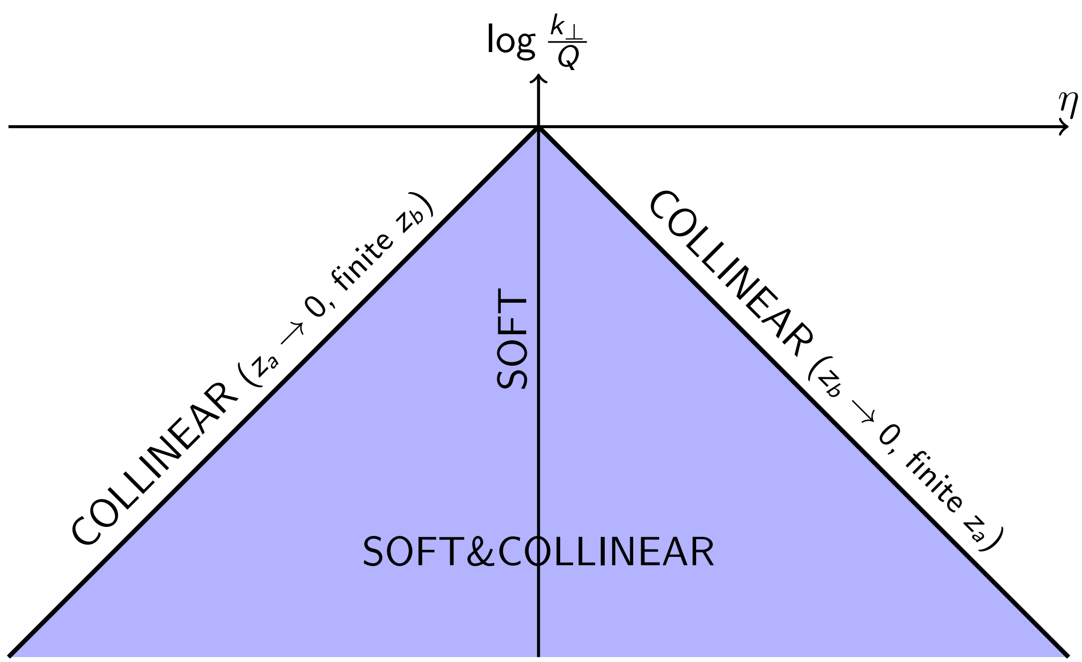
- NON-perturbative
- needs modelling
- model-dependent

Monte Carlo generators

Generic picture:

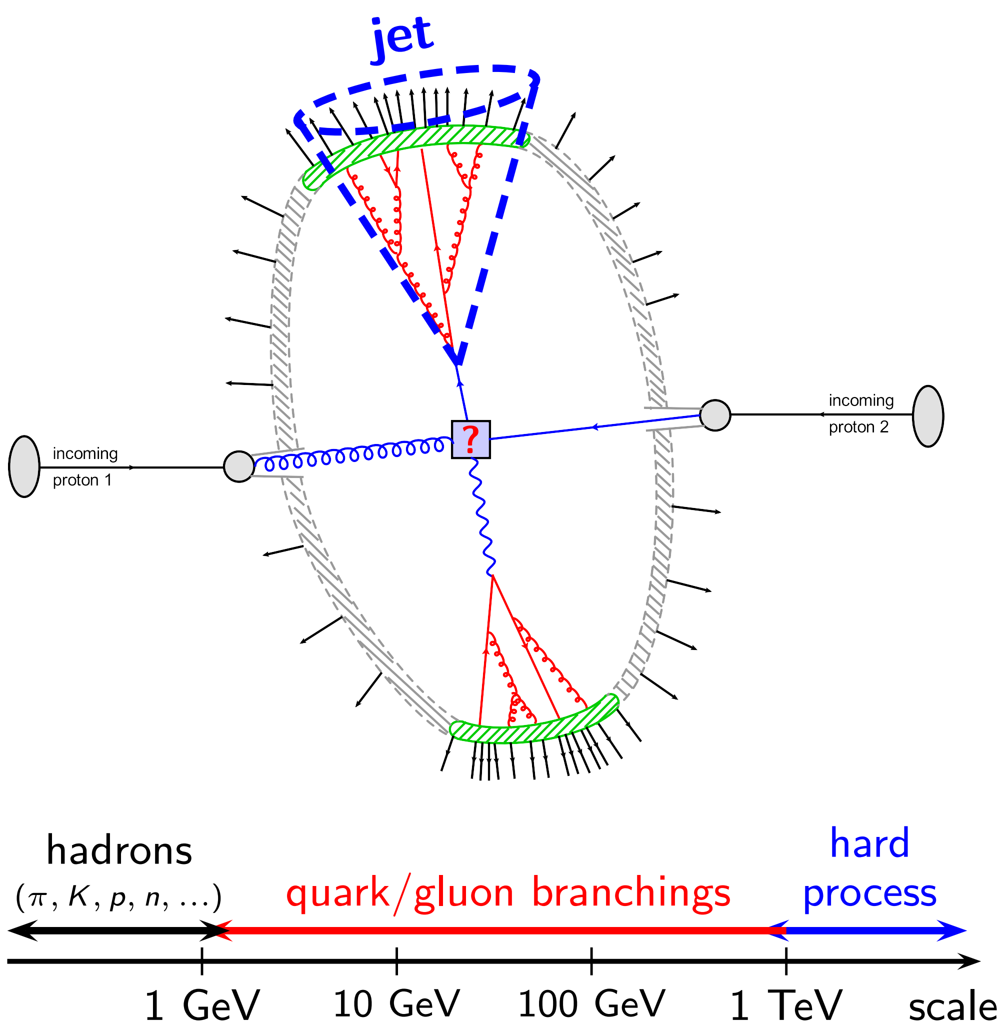
- "all-purpose" (Monte Carlo) Event generators to simulate collisions
- Most used tools in particle physics (Pythia, Herwig, Sherpa, ...)
- Central piece: parton shower (connecting hard to soft perturbative scales)

Convenient representation: the Lund plane



Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy



branchings mostly collinear

$\Downarrow$

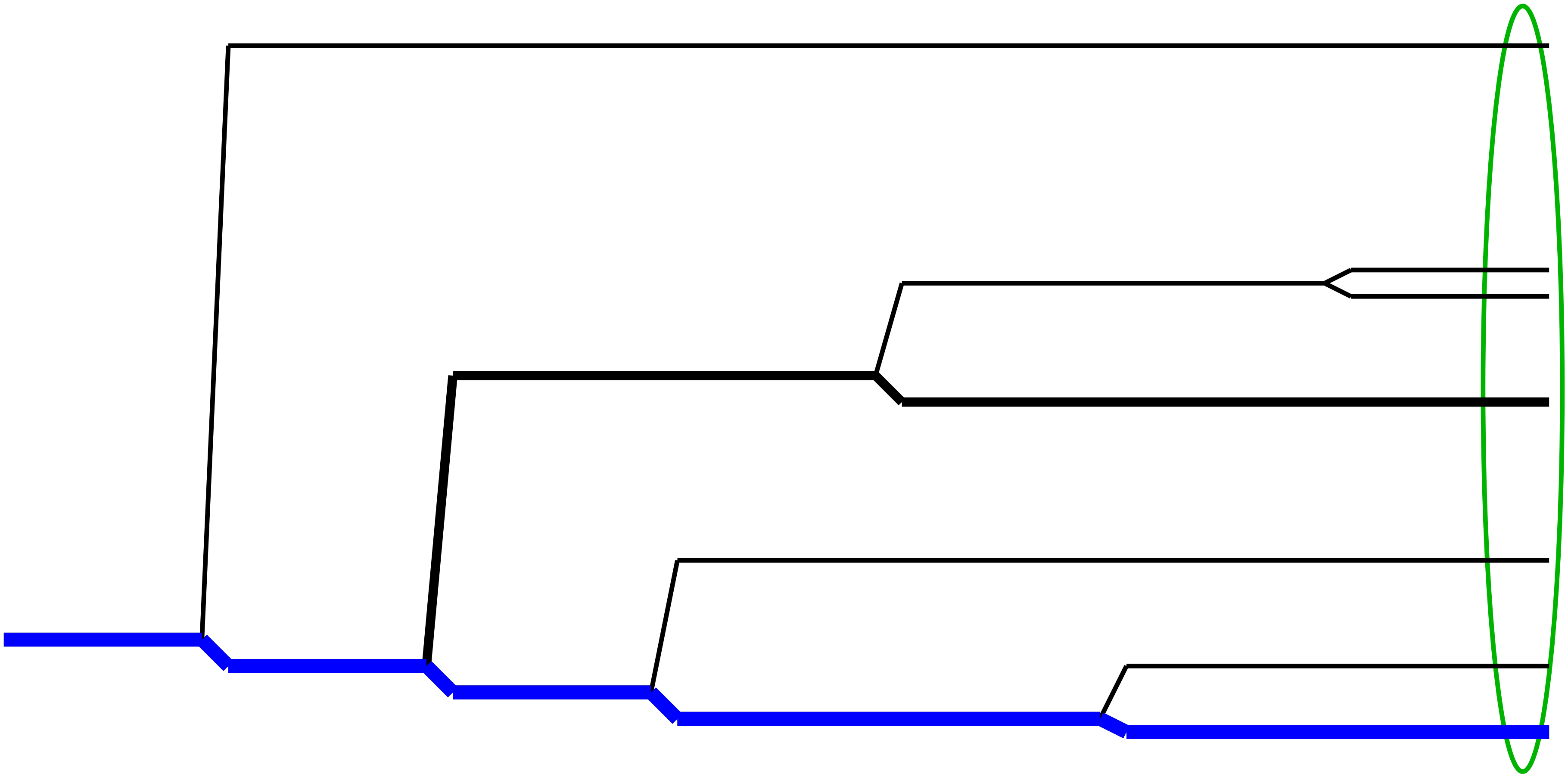
"high-energy parton" $\rightarrow$ collimated shower of particles $\equiv$ JET

Jet $\equiv$ proxy to hard parton

our topic #2

Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair

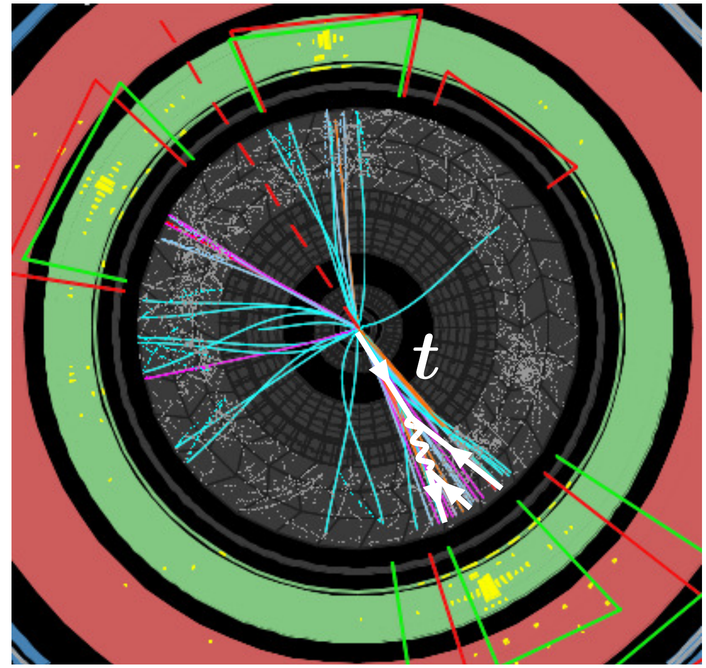


Usage: iteratively undo the clustering to study internal jet dynamics

Typically: follow the hardest branch (largest p_t or z)

What jet do we have here?

- a quark?
- a gluon?
- a W/Z (or a Higgs)?
- a top quark?



Source: ATLAS boosted top candidate

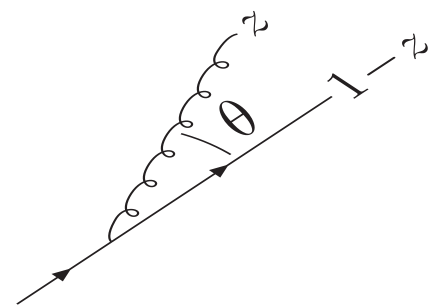
- Main idea:

  Boosted jet $\Rightarrow p_t \gg m$

  $$\Rightarrow \rho \equiv \frac{m^2}{p_t^2 R^2} \ll 1$$

  $\Rightarrow$ expect $\log\rho$ coming with α_s

  $\Rightarrow$ need for all-order resummation



- Example: jet mass with one (soft-and-collinear) gluon emission

$$\text{Prob}_1(>\rho) \simeq \int_0^1 \frac{d\theta^2}{\theta^2}\frac{dz}{z}\frac{\alpha_s C_R}{\pi}\Theta(z\theta^2 > \rho) \simeq \frac{\alpha_s C_R}{2\pi}\log^2(1/\rho)$$

- Use the same Sudakov parametrisation as for "Monte-Carlo generators" seen earlier, but now treat things analytically

High energy scattering in QCD: from low to high Bjorken x

Jamal Jalilian-Marian

Baruch College and CUNY Graduate Center

New York, NY

QCD at high transverse momentum:

collinear factorization (twist expansion)

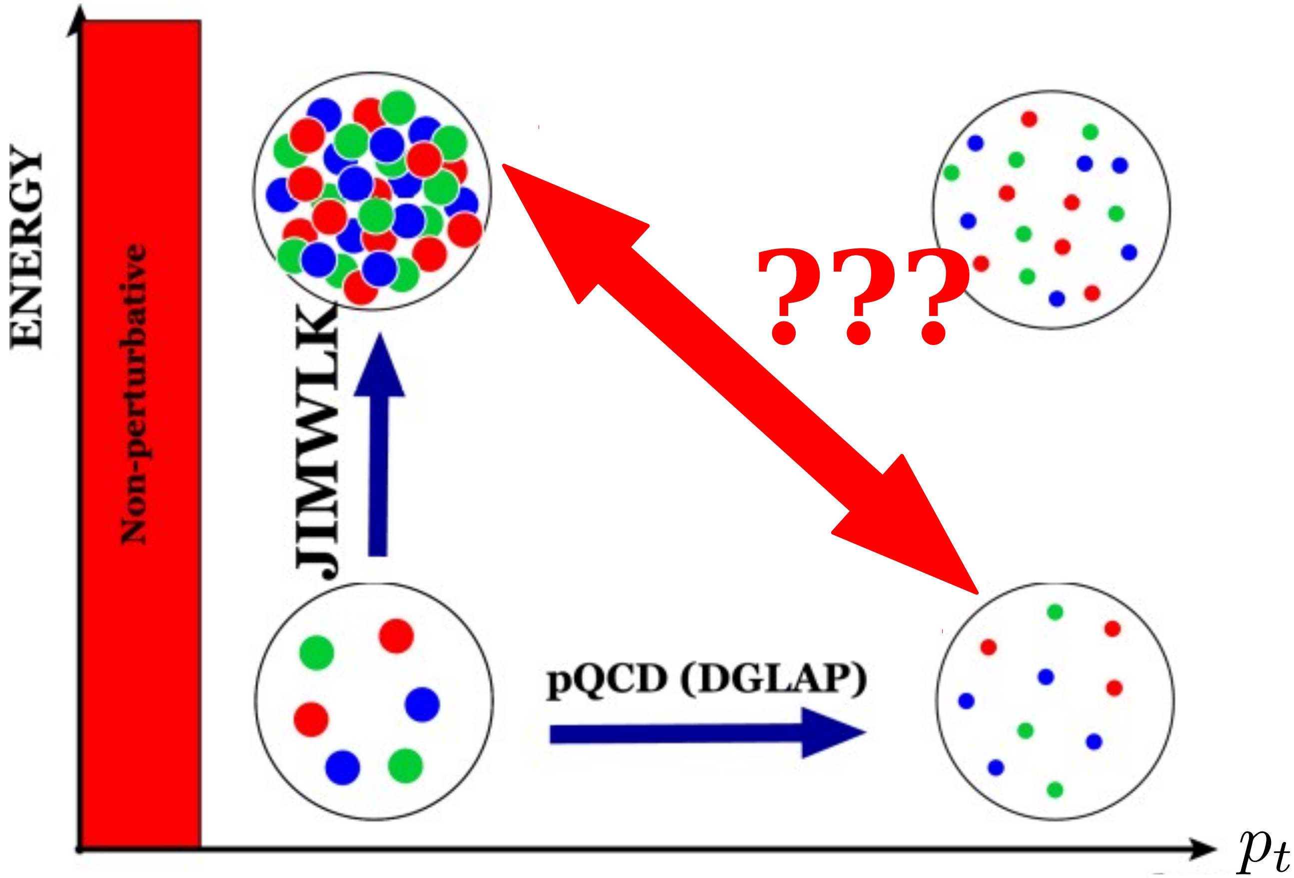
QCD at high energy (CGC):

high gluon density effects

Toward a unified formalism:

beyond eikonal approximation

QCD kinematic phase space



unifying saturation with high p_t (large x) physics?

<u>kinematics of saturation: *where is saturation applicable?*</u>

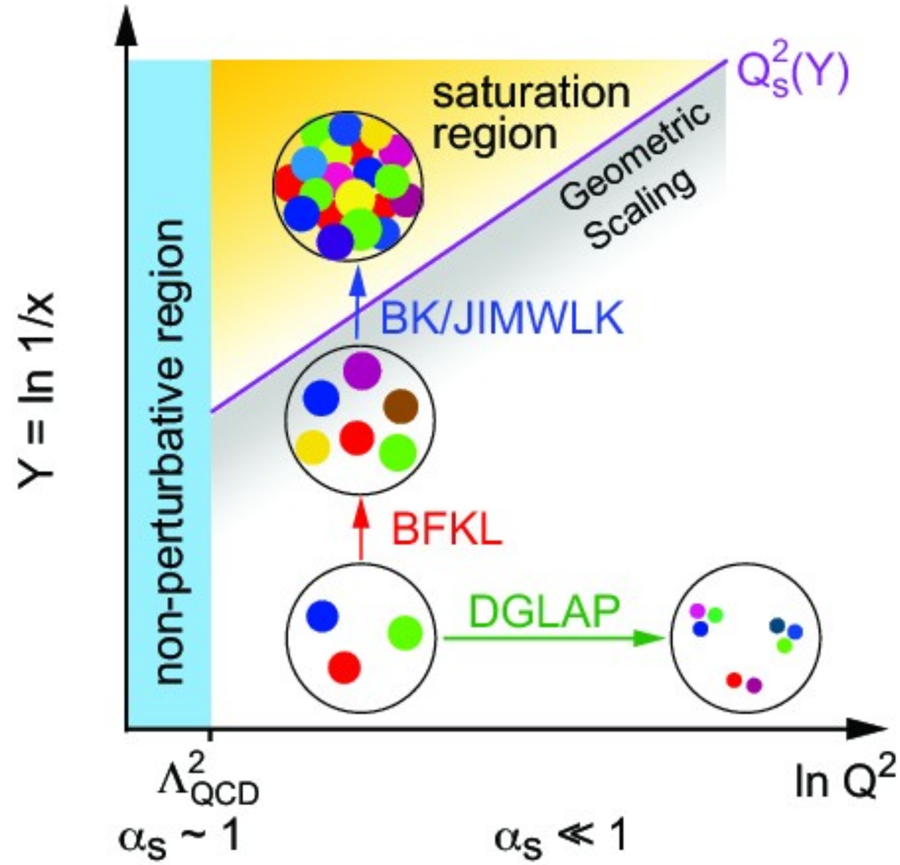
jet physics, high p_t (polar and azimuthal) angular correlations

cold matter energy loss, spin physics, ...

Low-x world

Radek Žlebčík

- The beyond DGLAP dynamics (BFKL, saturation, k_T distribution)
- The gluon density can be enhanced by colliding nucleons



DIS	pp-collisions (forward production)
$x = \dfrac{Q^2}{s_{\gamma p}}$	$x = \dfrac{M^2}{s_{pp}}$

The Q^2 or M^2 must be within pQCD regime and experimentally accessible

low x → high energies

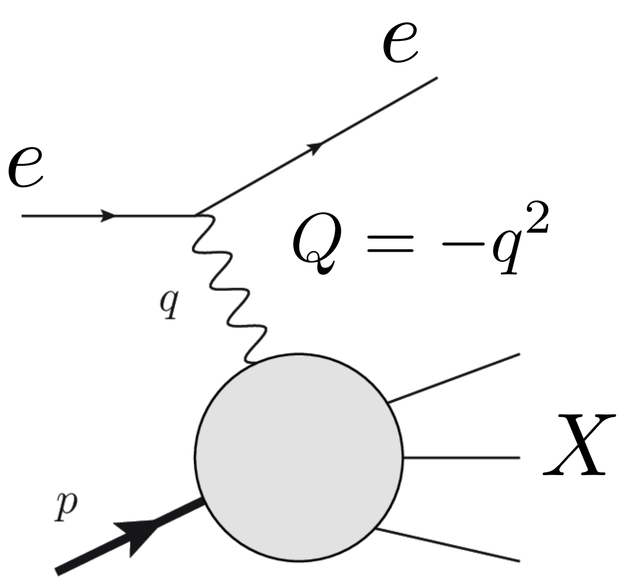
Inclusive DIS at HERA

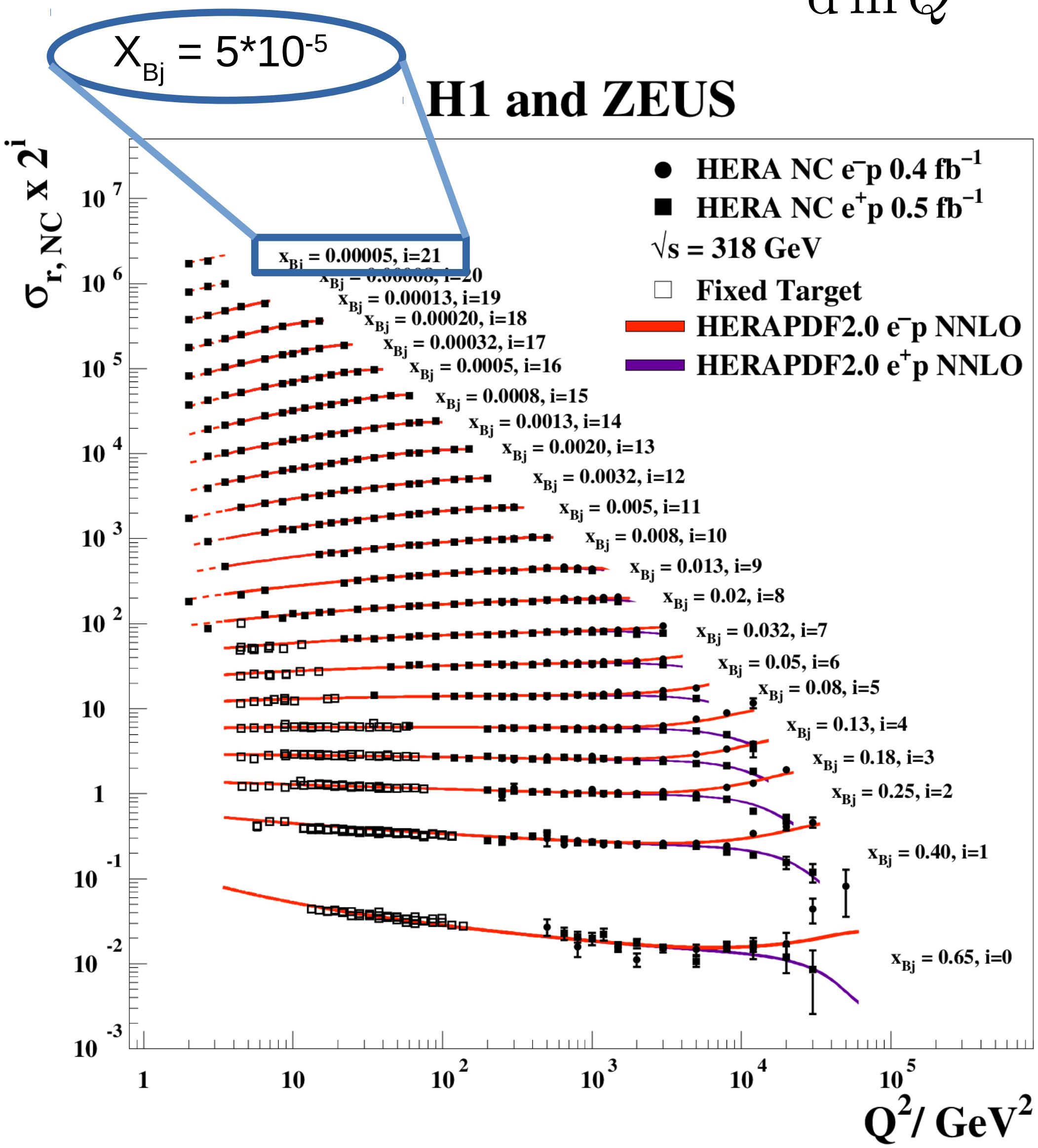
H1 & ZEUS legacy

$$g(x) \sim \frac{\mathrm{d}F_2}{\mathrm{d}\ln Q^2}$$

- ep: 27.6 + 920 GeV
- ~0.5 fb^{-1} per experiment
- Inclusive = any X

$$x_{\mathrm{Bj}} = \frac{Q^2}{2p\cdot q} \simeq \frac{Q^2}{W^2}$$





Eur.Phys.J. C75 (2015) no.12, 580

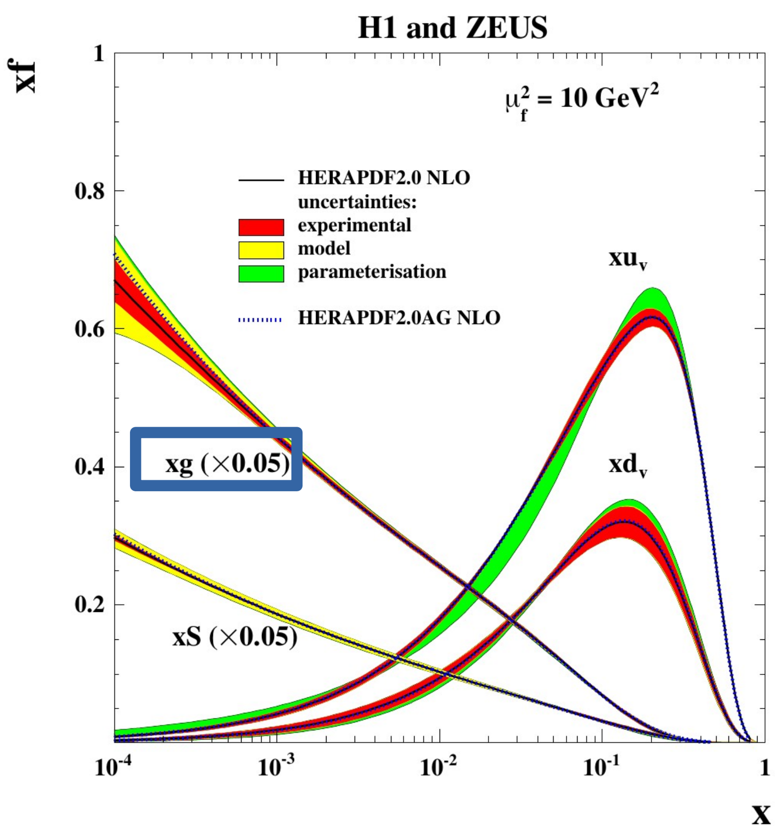
Inclusive DIS at HERA

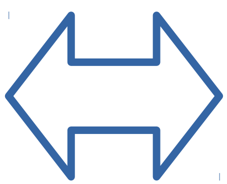
Eur.Phys.J. C75 (2015) no.12, 580

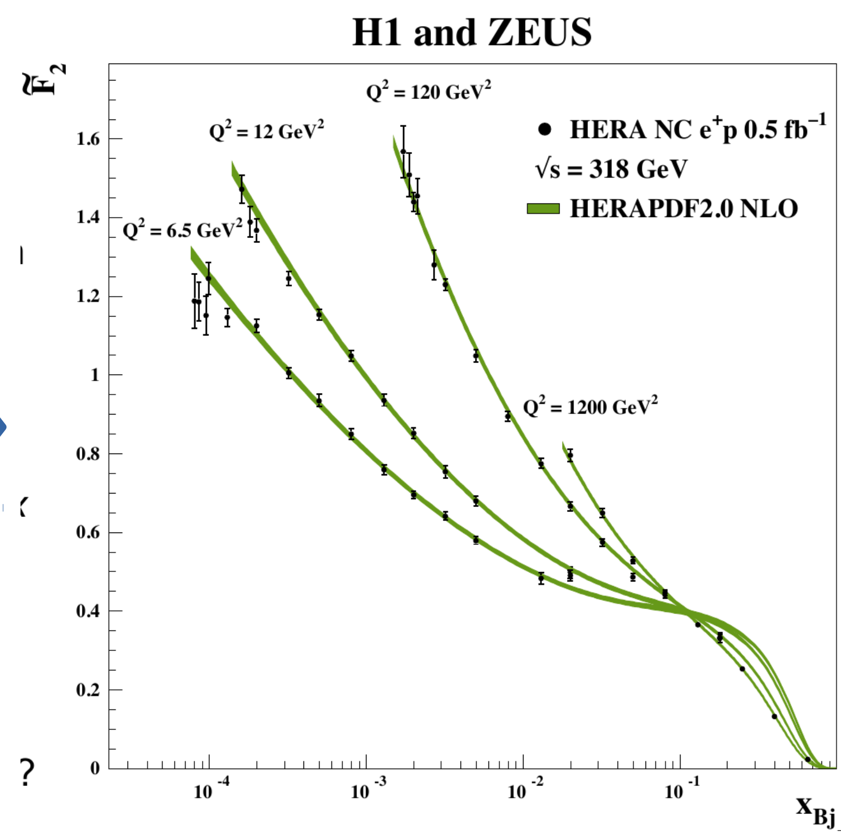
Low-x region

$$g(x) \sim \frac{\mathrm{d}F_2}{\mathrm{d}\ln Q^2}$$

- At small x huge rise of gluon and F_2
- Higher-Q^2 leads even to steeper rise







Discussed measurements

1) Inclusive (D)DIS – HERA
2) Exclusive production of di-jets & di-photons – LHC, Tevatron
3) Exclusive J/psi photoproduction – HERA, LHC
4) Forward jets – LHC
5) Forward-backward jets – LHC

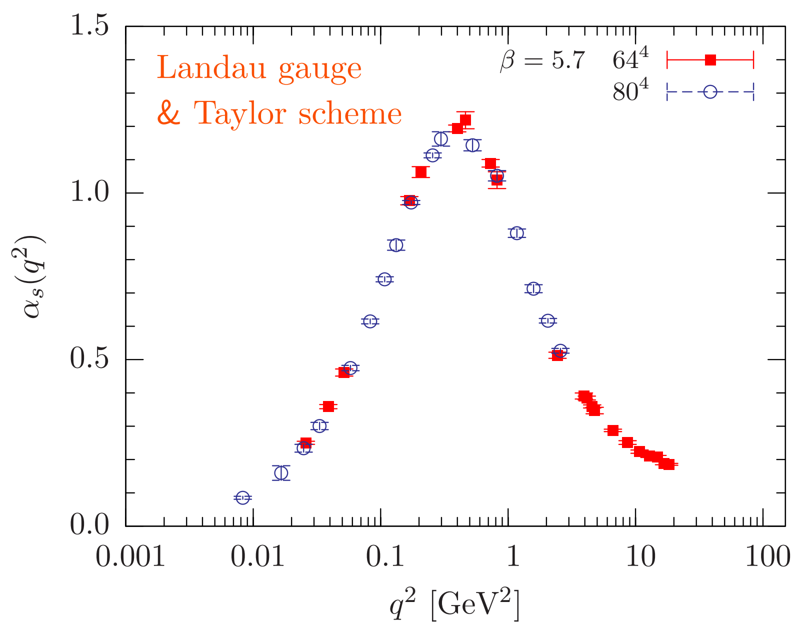
- With current experiment we access up to x ~ 10^{-5}
- Indications for BFKL dynamics for several observables
- Saturation?
- High-luminosity data with protons tagged
  → AFP, CT-PPS
- Future ep experiments
  → LHeC – energy frontier
  → EIC – luminosity frontier
- **Precision era in low-x?**

QCD AT FINITE TEMPERATURE AND DENSITY FROM THE CURCI-FERRARI MODEL

Urko Reinosa*

(based on various collaborations with J. A. Gracey, J. Maelger, M. Peláez, M. Tissier, J. Serreau and N. Wschebor)

RUNNING COUPLING FROM THE LATTICE



[I. L. Bogolubsky, E. M. Ilgenfritz, M. Müller-Preussker, A. Sternbeck, Phys. Lett. B676, 69 (2009).]

IMAGINARY CHEMICAL POTENTIAL

$$\cdots + \sum_{f=1}^{N_f} \int_x \left\{ \bar{\psi}_f (\not{\partial} - ig\not{A}^a t^a + M_f - i\mu_i \gamma_0) \psi_f \right\}, \text{with } M_f \gg T, \mu$$

Not really physical, but much praised by the lattice community since the sign problem is absent. For us, immense source of data to which we can compare to.

For $\mu_i = (\pi/3)T$, the action admits a new symmetry (Roberge-Weiss), combining center transformations, abelian gauge transformations and charge conjugation.

The Roberge-Weiss (RW) symmetry is known to be broken for large enough temperatures.

The massive gluon and the massless pion

Julien Serreau
Université de Paris

& the Montevideo-Paris collaboration

J. Maelger, M. Peláez, U. Reinosa
M. Tissier, N. Wschebor

- The Curci-Ferrari model for infrared QCD
- Chiral symmetry breaking
- Pion decay constant
- Phase diagram at $T, \mu \neq 0$

Overview of GPDs

Paweł Sznajder
National Centre for Nuclear Research, Poland

Getting access to generalized parton distributions in exclusive photoproduction of a large invariant mass γ-meson pair

Samuel Wallon Sorbonne Université

based on works with:
B. Pire (CPhT, Palaiseau), R. Boussarie (BNL, Brookhaven),
L. Szymanowski (NCBJ, Warsaw), G. Duplančić, K. Passek-Kumerički (IRB, Zagreb)

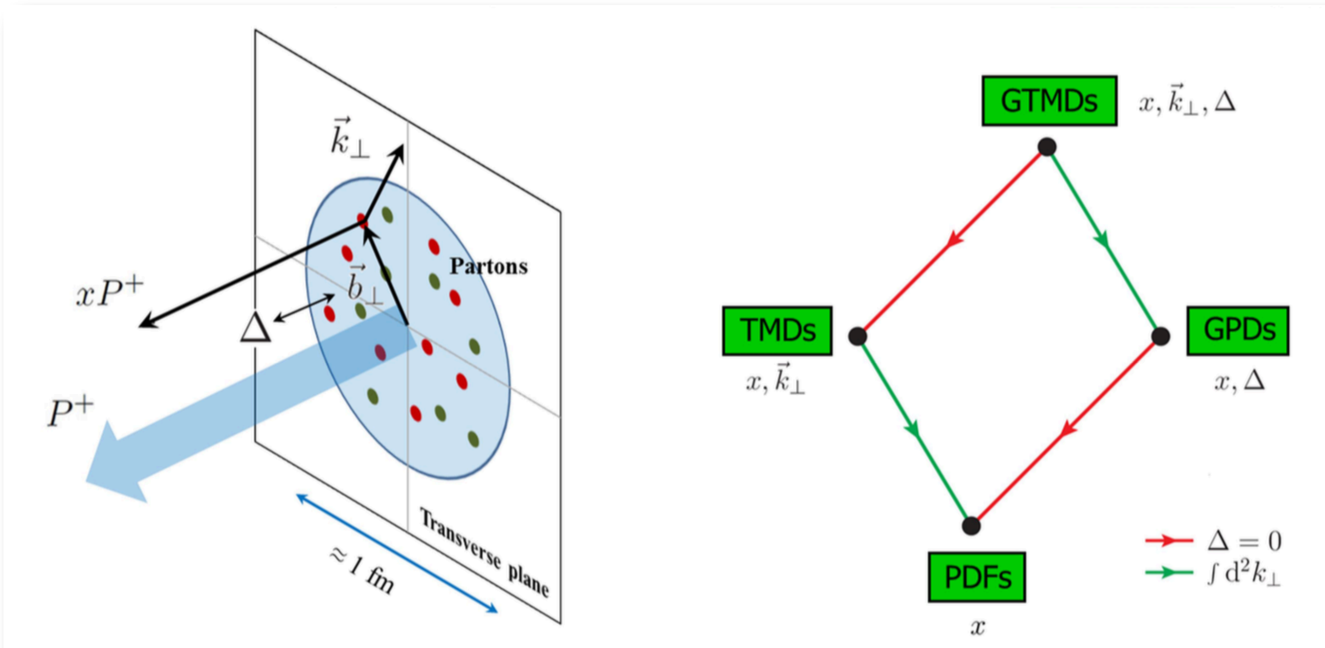
Overview of TMDs

Miguel G. Echevarría
Universidad de Alcalá

Timelike Compton Scattering with CLAS12 at Jefferson Lab

Pierre Chatagnon
Institut de Physique Nucleaire d'Orsay
For the CLAS Collaboration

Goal: understand 3D (momentum space) and spin structure of nucleons



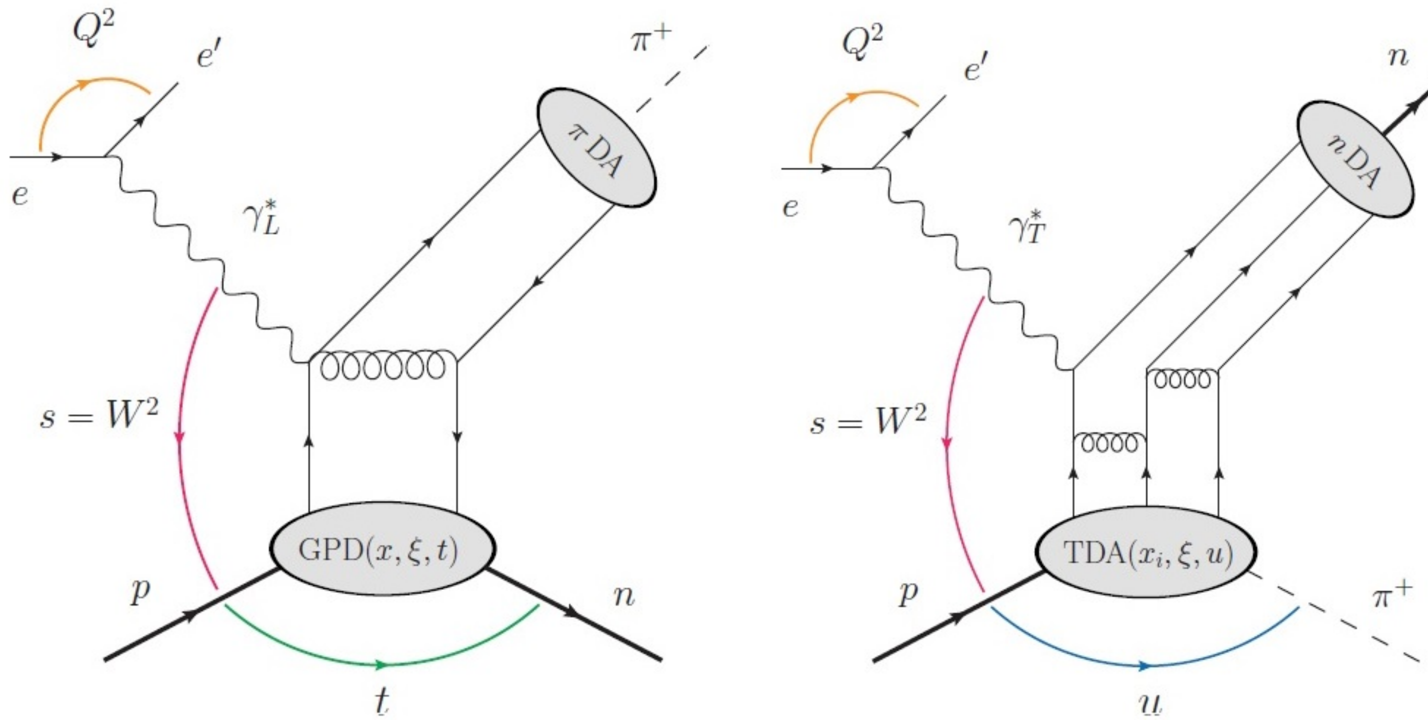
- In theory, all information contained in: $\langle PS|\,\mathcal{O}(\bar{\psi}, \psi, A^\mu)\,|PS\rangle$
- In practice, color confinement prevents us from calculating them. So?
- Lattice or **FACTORIZATION THEOREMS**

$$\sigma = \sigma_{partonic} \otimes [\text{PDFs / FFs / Jets / etc}] + \text{power suppressed}$$

An overview of baryon-to-meson transition distribution amplitudes: formalism and experimental perspectives

K. Semenov-Tian-Shansky

Petersburg Nuclear Physics Institute, National Research Centre “Kurchatov Institute”, Gatchina, Russia



Spin Physics at Hadron Facilities

Oleg Eyser

BROOKHAVEN NATIONAL LABORATORY

Nucleons & Nuclei

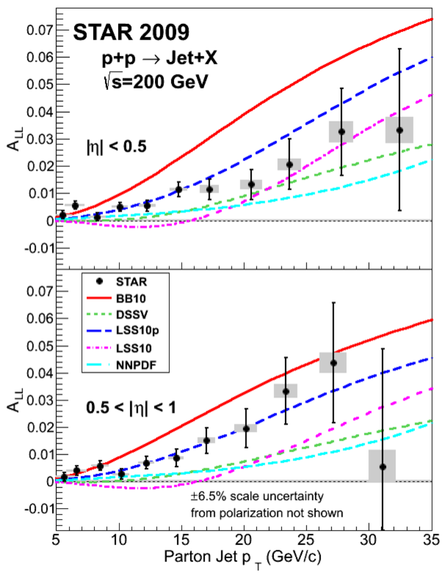
- What is the nature of the spin of the proton?
- How do gluons contribute to the proton spin?
- What is the landscape of the polarized sea in the nucleon?
- What do transverse spin phenomena teach us about the proton structure?
- How can we describe the multi-dimensional landscape of nucleons and nuclei?
- How do quarks and gluons hadronize into final state particles?
- What is the nature of the initial state in nuclear collisions?

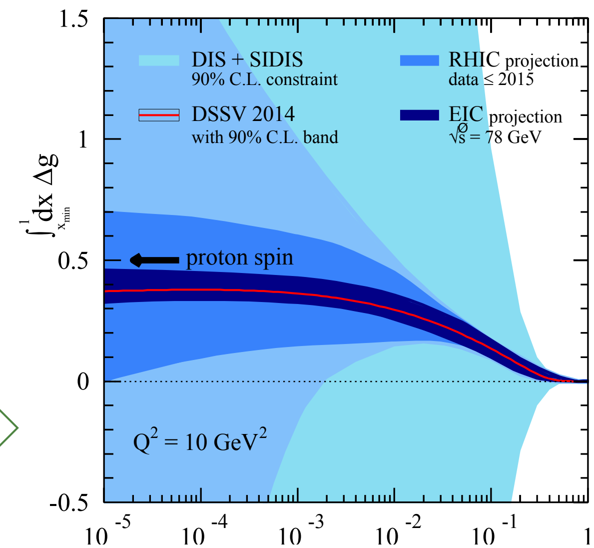
The Proton Spin

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

Gluon Polarization

PRL 115 (2014) 092002

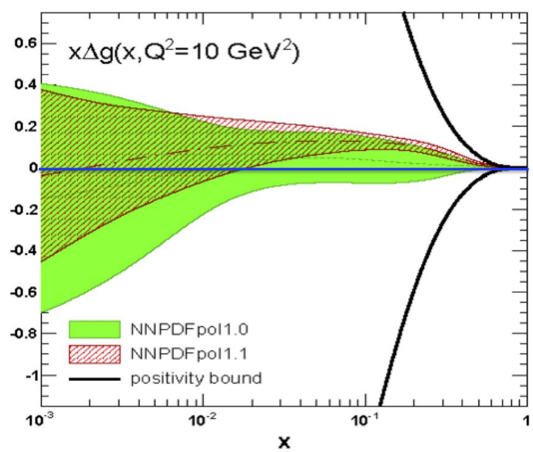




DSSV

PRL 113 (2014) 012001

$$\int_{0.05}^{1} \Delta g(x)dx = 0.2^{+0.06}_{-0.07}$$



NNPDF

NPB 887 (2015) 276

$$\int_{0.05}^{0.5} \Delta g(x)dx = 0.23 \pm 0.07$$

- Inclusive jet asymmetries at $\sqrt{s} = 200$ GeV (midrapidity)
- First evidence of non-zero gluon polarization

Beam Spin Asymmetry in the Electroproduction of 0^{-+} or 0^{++} Meson off the Scalar Target

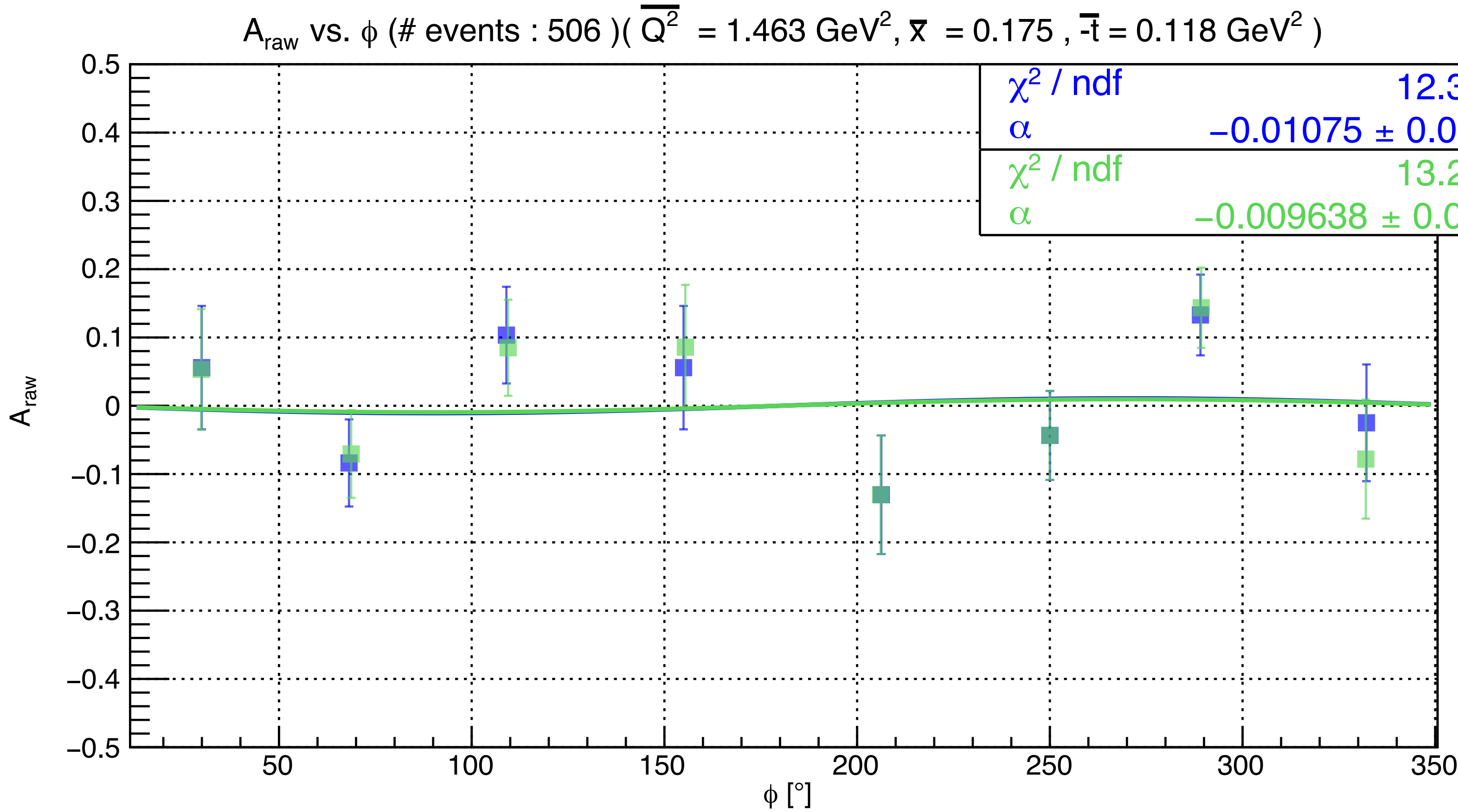
Chueng-Ryong Ji
North Carolina State University

In collaboration with H.-M.Choi,A.Lundeen,B.Bakker & Y.Choi

September 18, 2019

Salient Features

- No interference from Bethe-Heitler process
- BSA of exclusive coherent electroproduction of the π^0 off ^{4}He has been measured.
- Data appear consistent with our benchmark BSA prediction for 0^{-+} meson production off the scalar target.
- General formulation of hadronic amplitudes in Meson Production off the Scalar Target (0^{++} vs. 0^{-+})
- Comparison/Contrast with the leading twist GPD formulation.



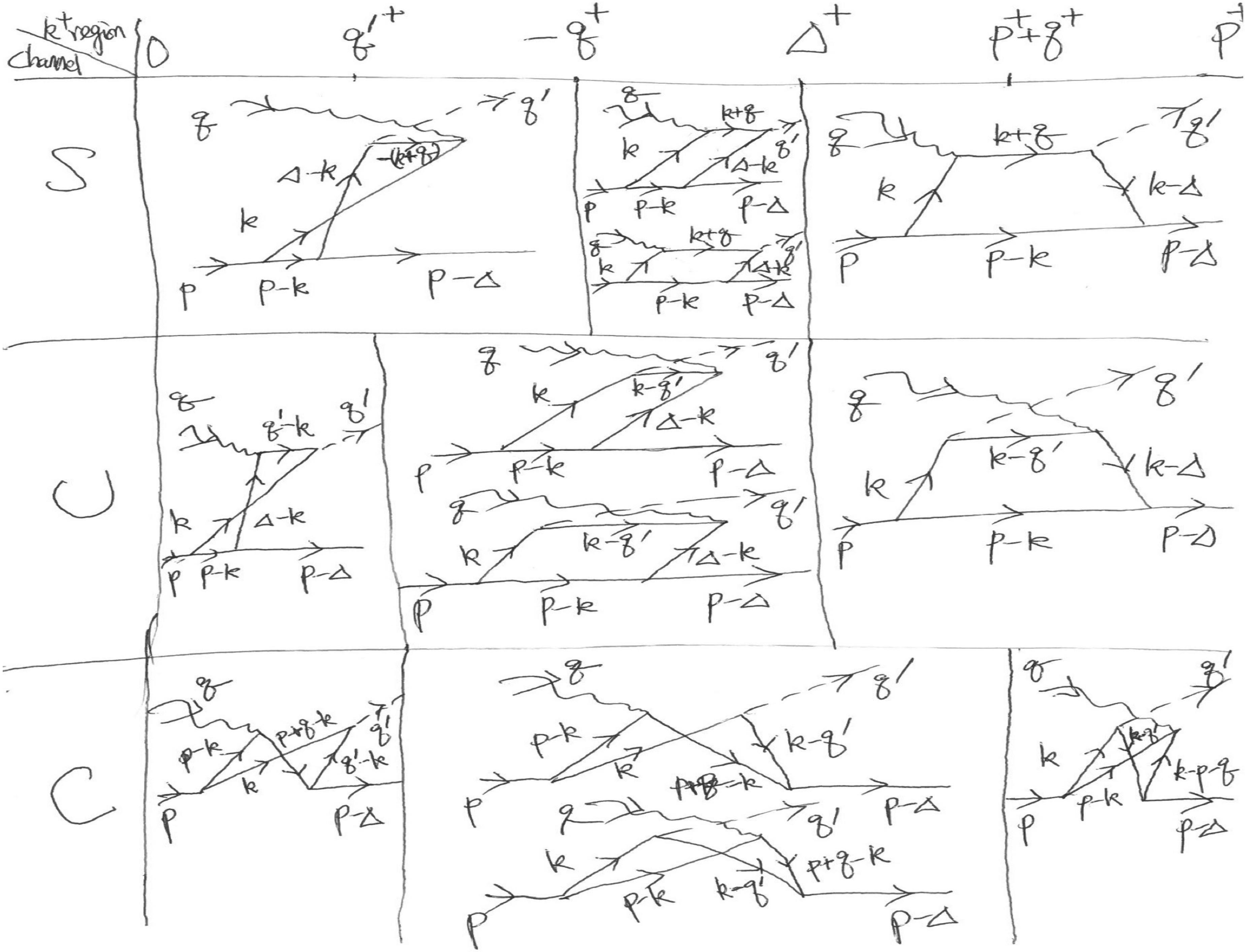
$$A_{LU}\left(\phi\right) = A_{LU}^{90^\circ}\sin\phi$$

$$A_{LU}^{90^\circ} = -1.08 \pm 3.22\,(\text{stat.}) \pm 2.83\,(\text{sys.})\,\%$$

4-26-2019

Beam-Spin Asymmetry of Exclusive Coherent Electroproduction of the π0 Off 4He

Frank Thanh Cao
University of Connecticut - Storrs, franktcao@gmail.com



k+ region
channel
0
q'+
−q+
Δ+
p+ + q+
p+
S
U
C
q
q'
k
p
p−k
p−Δ
Δ−k
k+q
k−Δ
q'−k
k−q'
p+q−k
k−p−q

Most General Hadronic Tensor for Scalar Target

$$T^{\mu\nu} = G^{\mu\nu}_{qq'} S_1 + G^{\mu\lambda}_{q} G_{q'\lambda}{}^{\nu} S_2 + G^{\mu\lambda}_{q\bar{P}} G_{\bar{P}q'\lambda}{}^{\nu} S_3$$

$$+ (G^{\mu\lambda}_{q\bar{P}} G_{q'\lambda}{}^{\nu} + G^{\mu\lambda}_{q} G_{\bar{P}q'\lambda}{}^{\nu}) S_4 + G^{\mu\lambda}_{q} \bar{P}_{\lambda} \bar{P}_{\lambda'} G^{\lambda'\nu}_{q'} S_5$$

$$G^{\mu\nu}_{qq'} = g^{\mu\nu} q \cdot q' - q'^{\mu} q^{\nu}$$

$$G^{\mu\nu}_{q} = g^{\mu\nu} q^2 - q^{\mu} q^{\nu}$$

$$G^{\mu\nu}_{q'} = g^{\mu\nu} q'^2 - q'^{\mu} q'^{\nu}$$

$$G^{\mu\nu}_{q\bar{P}} = g^{\mu\nu} q \cdot \bar{P} - \bar{P}^{\mu} q^{\nu}$$

$$G^{\mu\nu}_{\bar{P}q'} = g^{\mu\nu} q' \cdot \bar{P} - q'^{\mu} \bar{P}^{\nu}$$

For $q'^2 = 0$, only $S_{1,}$ S_2 and S_4 contribute.

Energy-Momentum Tensor and Light Cone

Oleg Teryaev
JINR, Dubna

MAKING SENSE OF THE NAMBU-JONA-LASINIO MODEL VIA SCALE INVARIANCE

Philip D. Mannheim University of Connecticut

Poincaré constraints on the gravitational form factors

Peter Lowdon (Ecole Polytechnique)

The Energy-Momentum Tensor for massive hadrons

Sabrina Cotogno
(Institut Polytechnique de Paris)

Color Confinement and Supersymmetric Features of Hadron Physics from Light-Front Holography and Superconformal Algebra

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY · DIE LUFT DER FREIHEIT WEHT · 1891

with Guy de Tèramond, Hans Günter Dosch, Marina Nielsen,
F. Navarra, Tianbo LIu, Liping Zou, S. Groote, S. Koshkarev, C. Lorcè, R. S. Sufian, A. Deur

Anji Yu

Hadronic Properties
From Basis Light Front Quantization

James P. Vary
Department of Physics and Astronomy
Iowa State University

Chandan Mondal　Xingbo Zhao　Pieter Maris　Meijian Li

Wenyang Qian　Anji Yu　Lekha Adhikari

Light-front quantum mechanics and quantum field theory

W. N. Polyzou

The University of Iowa

Much Ado About Nothing

an introduction to the LF vacuum

Matthias Burkardt

New Mexico State University

Minkowski space approach to self-energies and scale invariance

Tobias Frederico
Instituto Tecnológico de Aeronáutica
São José dos Campos – Brazil