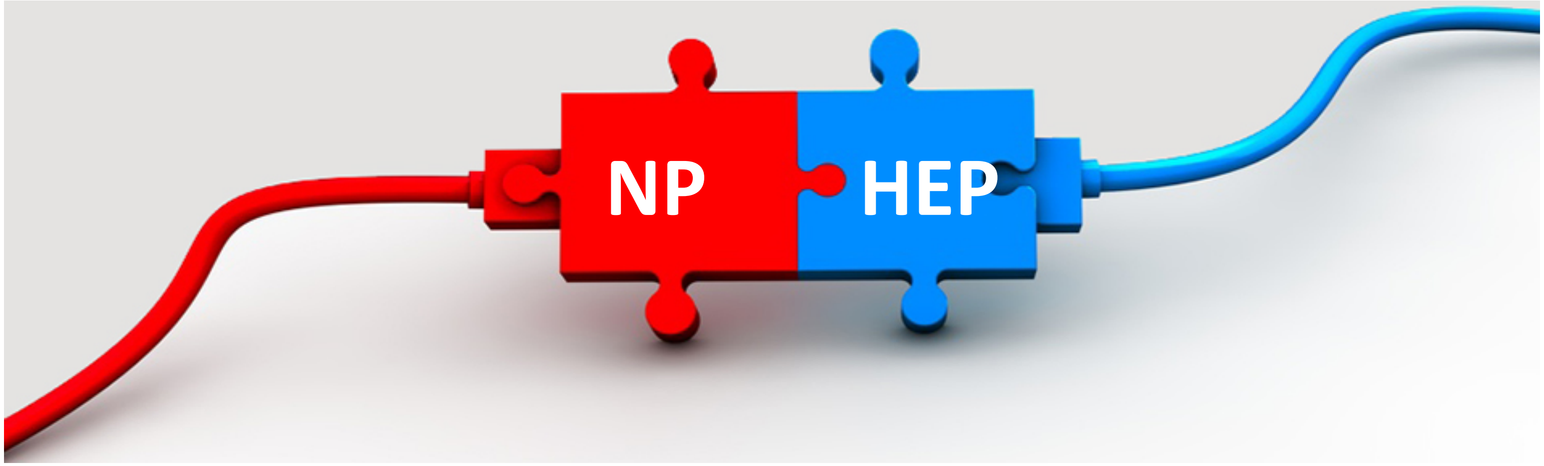
Mapping the hadronization description in the Pythia MCEG to the correlation functions of TMD factorization



Markus Diefenthaler (mdiefent@jlab.org)

INT workshop on "Spatial and Momentum Tomography of Hadrons and Nuclei", September 21st 2017

Introduction

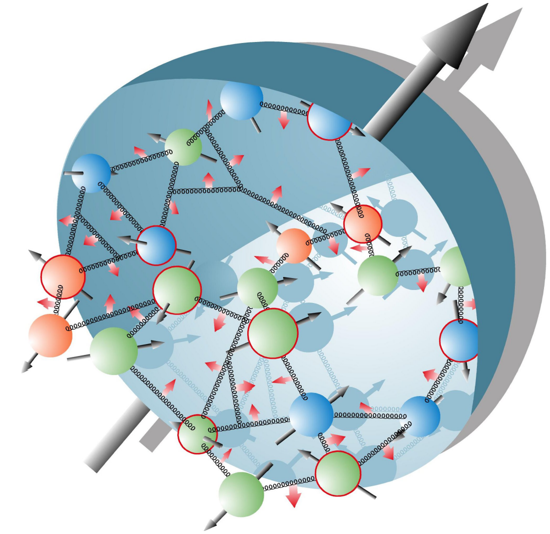
Ultimate measurement of TMDs

EIC: Ideal facility for studying QCD

Polarization

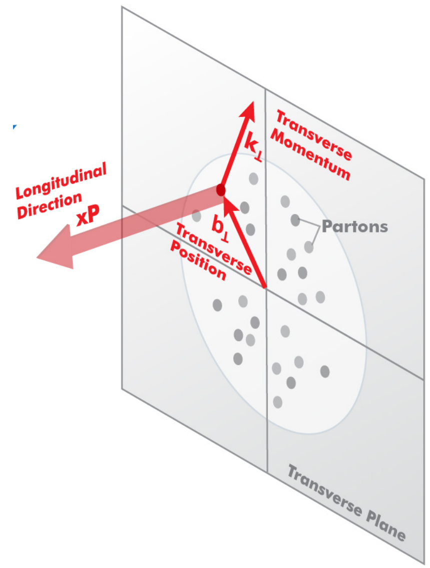
Understanding hadron structure cannot be done without understanding spin:

- polarized **electrons** and
- polarized **protons/light ions**



Transverse and longitudinal polarization of light ions (p, d, ^3He):

- 3D imaging in space and momentum
- spin-orbit correlations



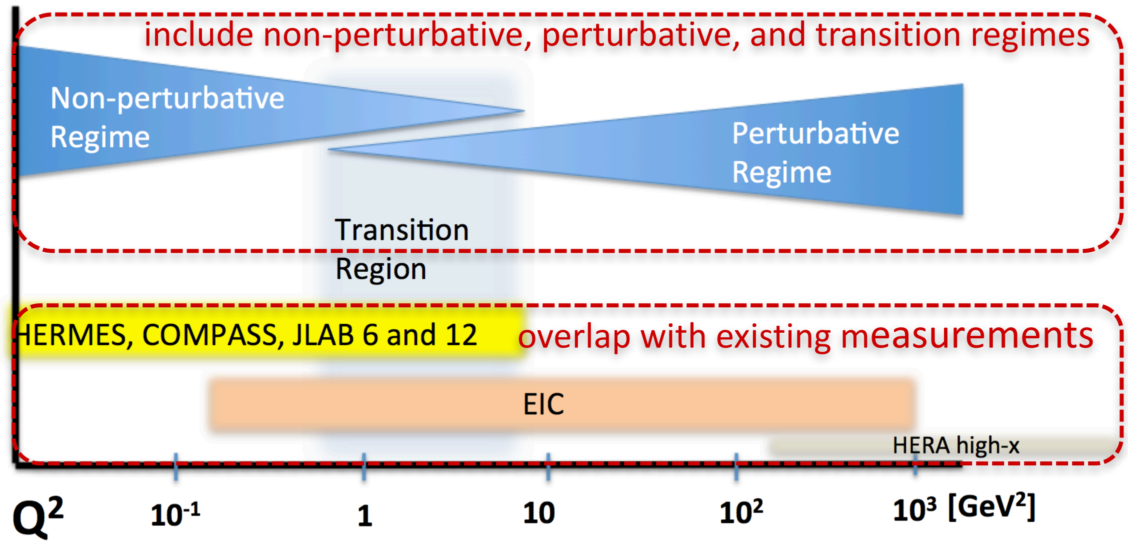
Broad range in A from hydrogen to uranium isotopes:

- 3D imaging in space and momentum
- hadronization in the nuclear medium
- EMC effect for gluons
- gluon saturation

EIC: Ideal facility for studying QCD

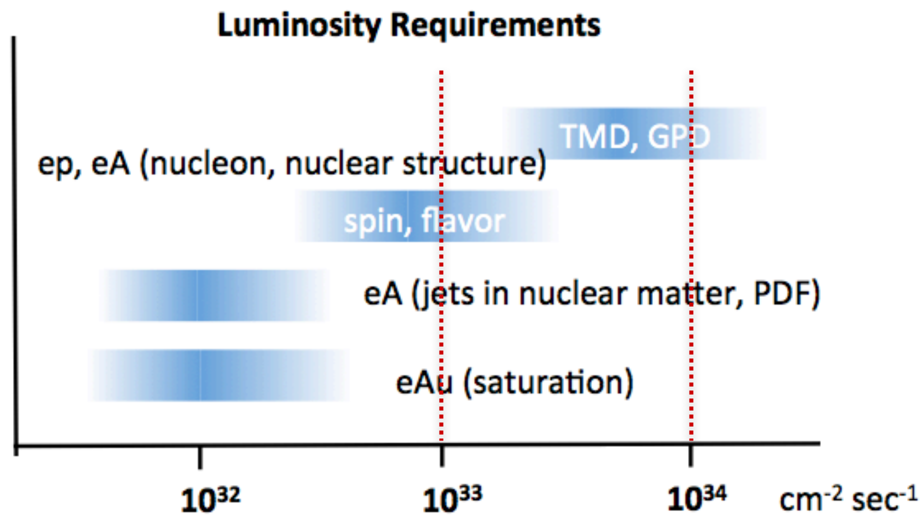
Various beam energy:

broad Q^2 range for
- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments



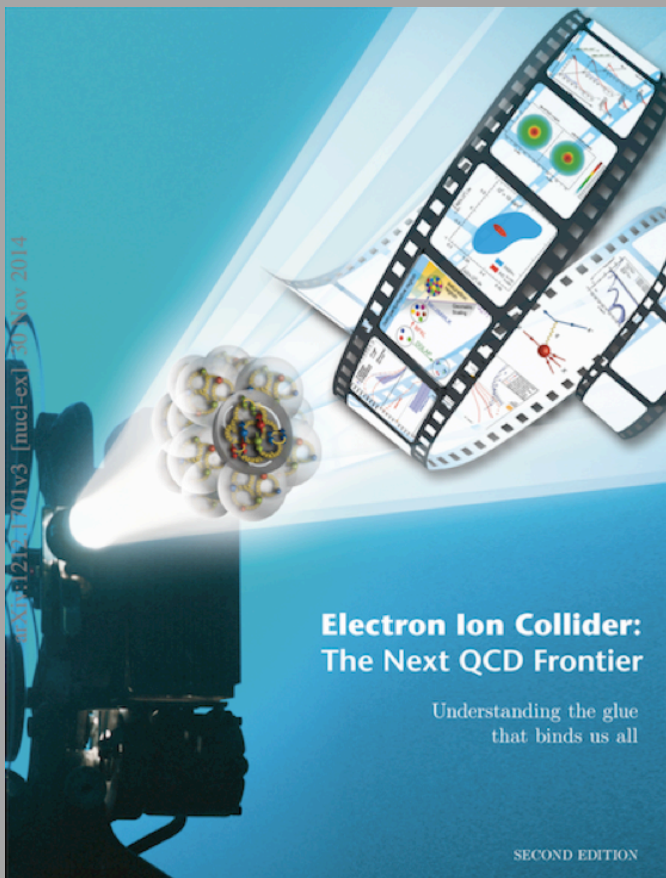
High luminosity:

high precision
- for various measurements
- in various configurations



TMD program in EIC White Paper

EIC: The Next QCD Frontier



Eur.Phys.J. A52 (2016) no.9, 268

Ultimate measurement of TMDs for quarks

- **high luminosity**
  - high-precision measurement
  - multi-dimensional analysis (x, Q^2, ϕ_S, z, P_t, ϕ_h)
- **broad x coverage** $0.01 < x < 0.9$
- **broad Q^2 range** disentangling non-perturbative / perturbative regimes

First (?) measurement of TMDs for sea quarks

First (?) measurement of TMDs for gluons

Systematic factorization studies

Selected analysis requirements

Understanding of hadronization

High-precision analysis tools:
- high-precision MCEG
- radiative correction library
- multi-dimensional analysis

$\mathbf{R_{SIDIS}}$ from JLab 12GeV

Long-lived data repositories
- COMPASS, HERMES, JLab, RHIC
- document analysis publicly for analysis and theory development (RIVET)
- combined *global* analysis (e.g., HERA fit), possibly on event level

Laboratory Directed Research and Development (LDRD): **Study of Hadronization in NP and HEP**

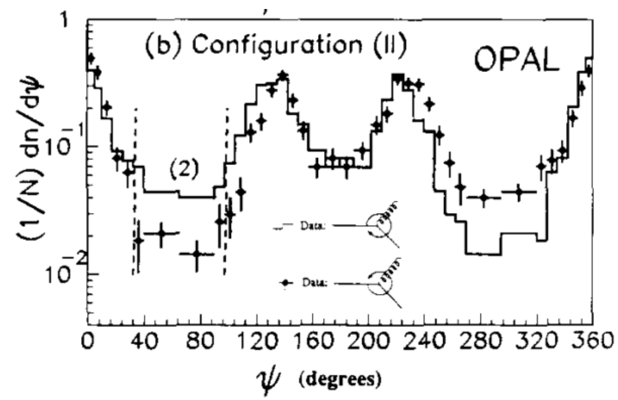
Section

Study of Hadronization in NP and HEP

Describing the hadronization process

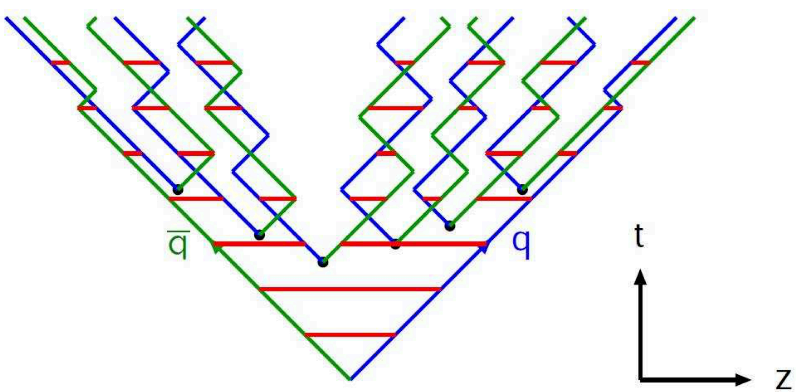
LUND String Model for hadronization (1977 – *now*)

- simple but powerful phenomenological model
- no (promising) new hadronization models in last 40 years
- **ToDo**
  - review
  - connect with modern QCD, including TMD and spin effects

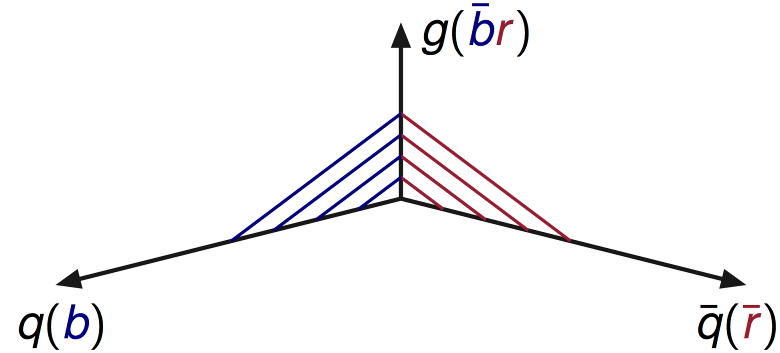


evidence of string effects
particle flow asymmetry at OPAL

String breakup



String drawing



LDRD project at Jefferson Lab

NP – QCD factorization theorem

- interpret collision experiments using QCD factorization theorem
- development driven by **John Collins** (2009 J. J. Sakurai Prize)
- Novel way to study confinement: QCD factorization theorem for TMDs

HEP – Monte Carlo Event Generator

- describe collision processes by a combination of theory and phenomenological models
- **Pythia**, development led by LUND group (**Leif Lönnblad**), recognized by 2012 J. J. Sakurai Prize (for T. Sjöstrand)

Correlation functions of TMD factorization ↔ Pythia MCEG

LDRD goal

LDRD personnel (FY17)

JLab

Pythia

Other

Experimentalists

Theorists

Section

Monte Carlo Event Generator

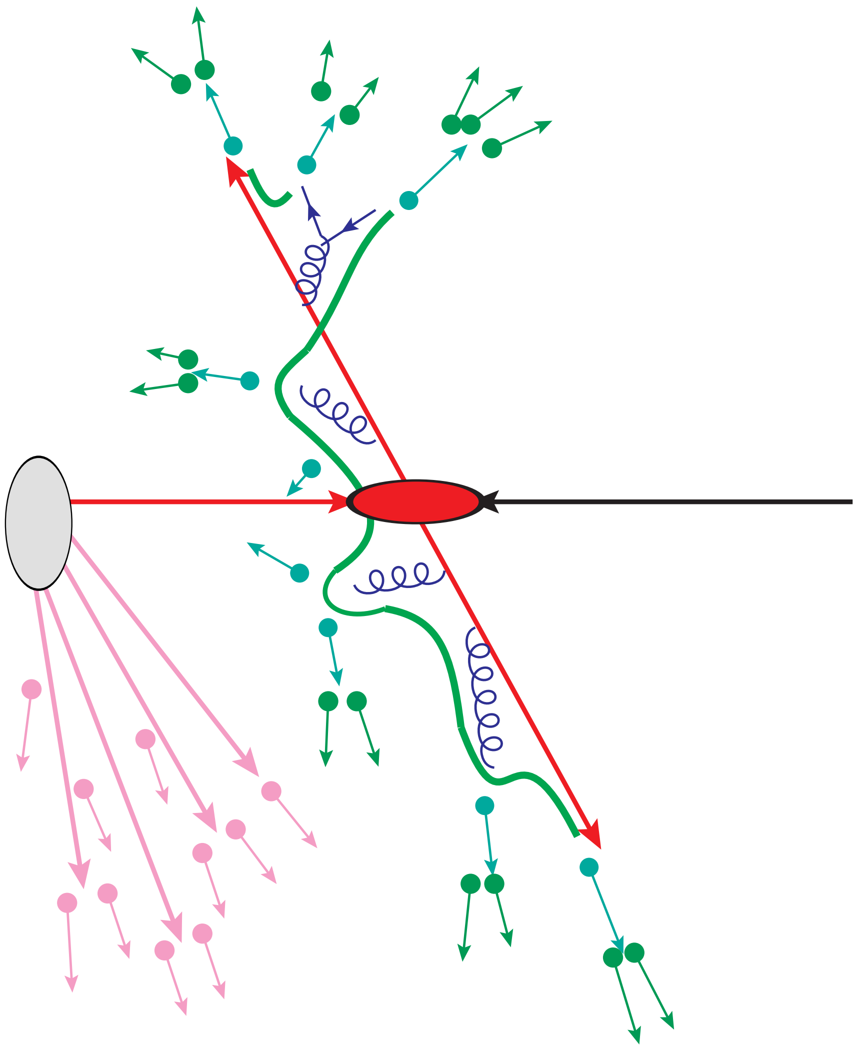
Monte Carlo Event Generator (MCEG)

MCEG:

- faithful representation of QCD dynamics
- based on QCD factorization and evolution equations

Algorithm of general-purpose MCEG:

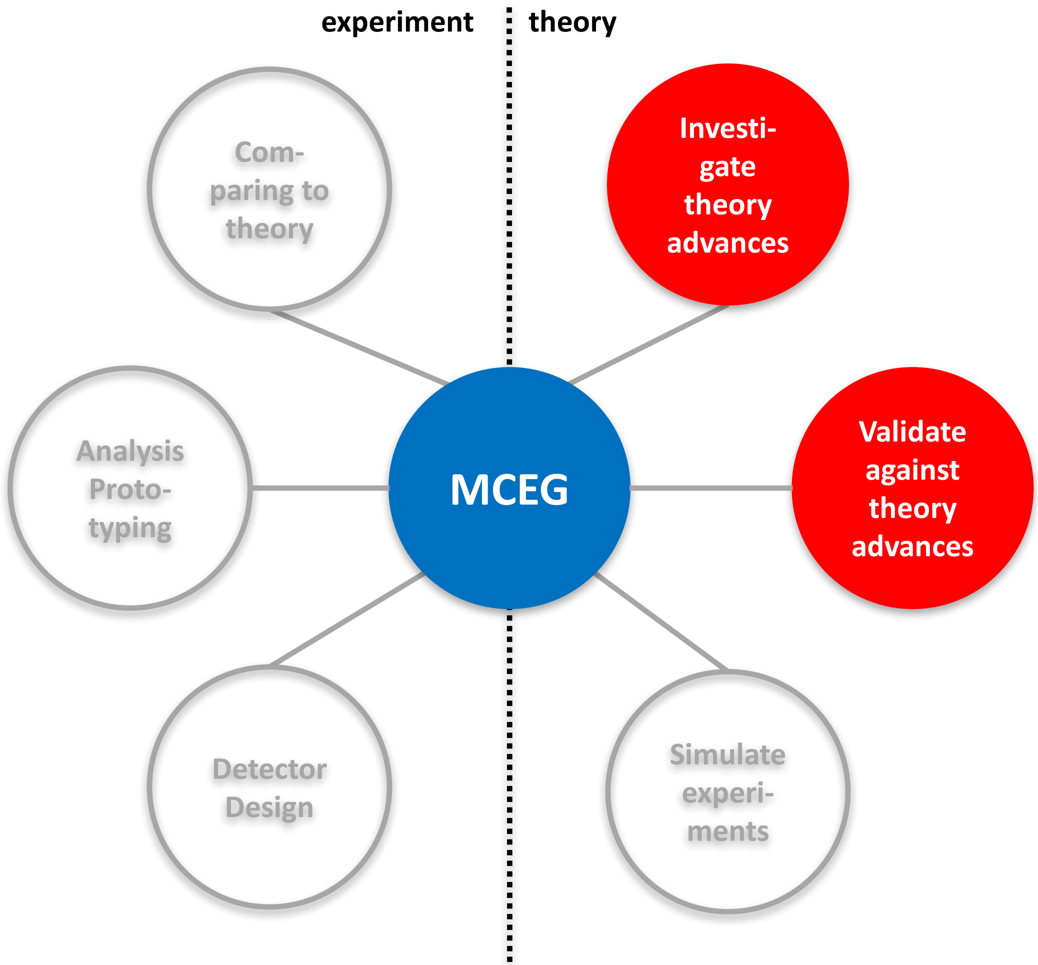
- generate kinematics according to fixed-order matrix elements and a PDF
- parton shower model for resummation of soft gluons and parton-parton scatterings
- hadronize all outgoing partons including the remnants according to a model
- decay unstable hadrons



Events are key

MCEG := Monte Carlo Event Generator

MCEG in HEP and NP

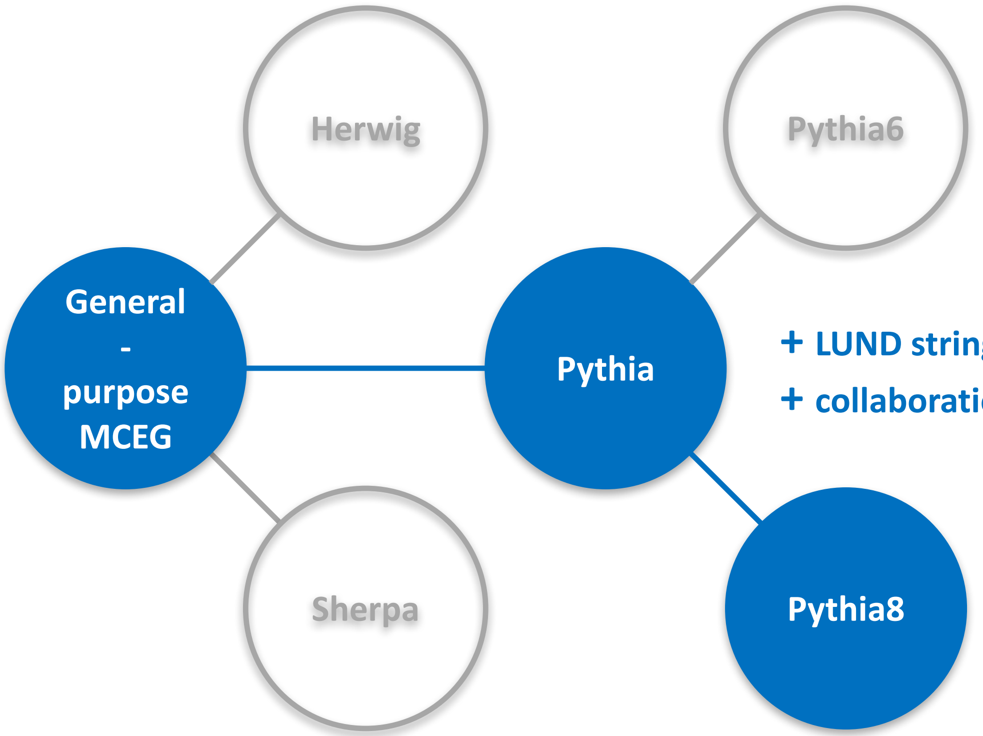


Lesson from HEP: high-precision QCD measurements require high-precision MCEGs

S. Hoeche, Accuracy meets precision: MC event simulation in a decade https://www.jlab.org/indico/event/213/

General-purpose MCEG: HERWIG, Pythia, SHERPA

MCEG for our project



+ LUND string model
+ collaboration with Pythia collaboration

+ active support

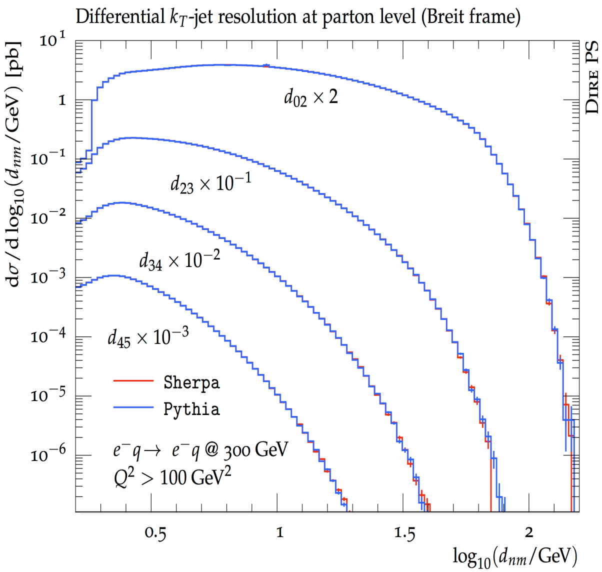
- no ep description

possible with modern DIRE parton shower

DIRE parton shower

Parton shower:
numerical, fully differential solution of evolution equation by iterating parton decay

DIRE:
- **Fundamental goal**: compare directly to analytical approaches, e.g., the one by Collins-Soper-Sterman
- **Unique verification**: implemented in both Pythia and Sherpa
- Allows for **DIS simulations** in Pythia8



Section

NP and HP

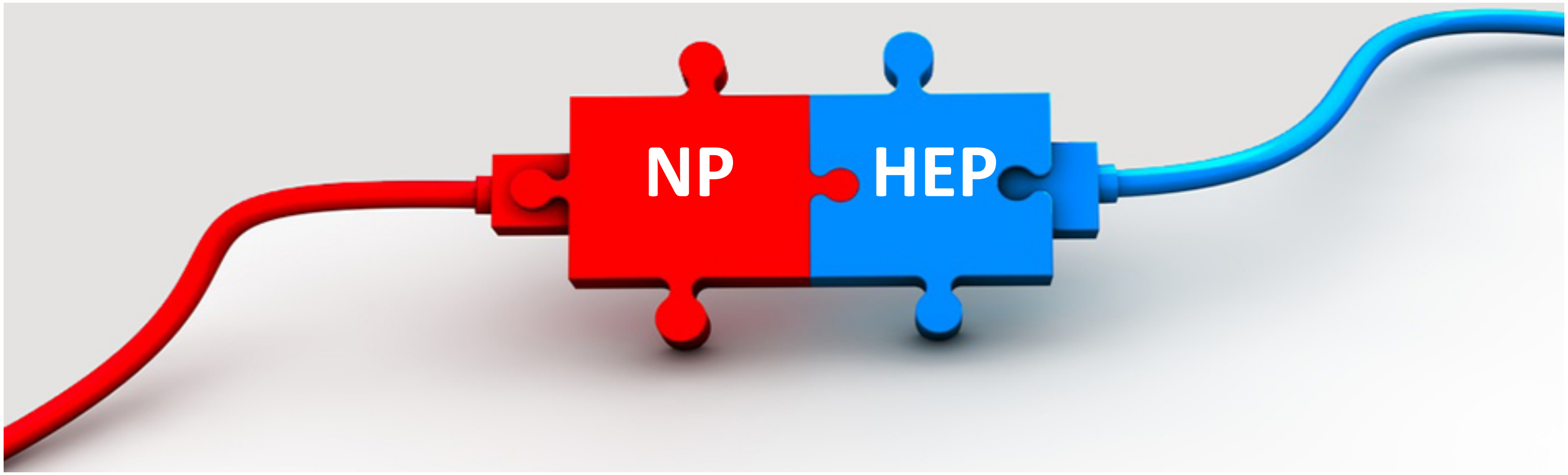
Measurements in NP and HEP

Nuclear physics (NP)

- investigation of nucleon and nuclear structure and associated dynamics
- observables of non-perturbative QCD
- non-perturbative quark-gluon dynamics parameterized in PDFs and FFs

High energy physics (HEP)

- investigation of the elemental constituents of matter and energy and their interactions
- observables of perturbative QCD
- perturbative QCD calculations up to $N^{N}LO$
- assuming the knowledge of the hadron structure / PDFs at low energies



Connection between NP and HEP

NP in HEP: **non-perturbative QCD**, in particular **hadronization**

- **background suppression**, relevant for any analysis and also for the *new physics* searches
- **reducing systematic uncertainties**, e.g., of non-perturbative QCD models
- **high-precision measurements,** e.g., improving the knowledge on the coupling constants by studying the p_T spectra

HEP in NP:

- combine MCEG approaches with first principle QCD calculations to proceed with QCD studies of non-perturbative structure

Section
Status of our project

Work plan

FY17

FY18

FY19

Publication: DIS in Pythia8

Publication: LUND validation

+ TMD observables

Publication: Hadronization in NP and HEP

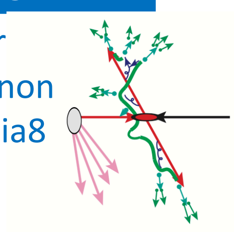
- comparison Pythia8-TMD factorization
- language dictionary
- Pythia8 with spin-independent TMDs

Spin-dependent hadronization

- Incorporate model of trans-verse spin effects (see **Xavier Artru's** talk) into Pythia8
- Anna Martin and Albi Kerbizi will join project in FY18

Hadronization plugin

- user model for one phenomenon
- rest from Pythia8



Section

Describing DIS in Pythia8

Why has DIS been first missing in Pythia8

- Man power is limited and Pythia8 for LHC has been utmost priority. DIS simulation has been neither fully implemented nor validated.
- Problems with default parton shower for DIS:
  - The parton shower has been developed for positron-election annihilation and Drell-Yan.
  - The parton shower is using a s-hat approach where *s-hat* = $x_1 * x_2 * s$ at all scales. This works well for hadron-hadron collisions, e.g., for preserving the W/Z mass in the parton shower.
  - When expanding the parton shower for electron-hadron scattering, one has to replace one incoming parton with an electron at $x=1$. The Bjorken-x value of the event will be not preserved during the reconstruction of the initial state shower, as the introduction of the a transverse momentum will change the value of $P * q$. This also implies that the cross-section is changed.
  - This was solved (for a single splitting) by a very specific handling of the initial and final state cascades and limiting the maximum allowed virtuality to W^2 with additional rejection techniques.
- DIRE doesn't have the problem as the dipole character of the shower allows to project onto the respective collinear directions and thus preserve x.

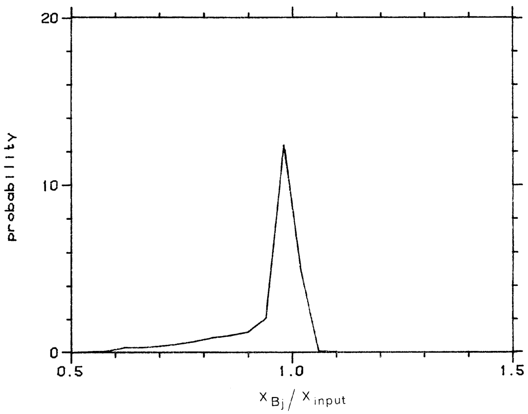


Fig 4

Theoretical pieces

- **Hard core scattering** (DIS, SIDIS…)
  - eq → eq scattering with full Z/γ interference
  - new hard processes, e.g., photon-gluon fusion or QCD Compton, can be interfaced via Les Houches event files, or included as semi-internal hard-cross section plugin codes
  - soft core scattering, e.g., diffractive DIS and photo-production, missing
  - **Observables**: Jet production, hard particle correlations

- **Evolution**
  - not strictly separate from core scattering by virtue of factorization theorem:
    - Hard scattering at high scale = perturbative part of cross section at high scale
    - Hard scatterings at high scale ⊗ shower from high to low scale = perturbative part of cross section at low scale
  - Dire makes evolution of DIS in Pythia8 possible
  - **Observables:** Extends the phase space regions in which perturbative calculations give a reasonable description of data, e.g., generation of pT broadening, smearing allows to describe e.g. small pT imbalances w.r.t. the hard scattering/hard scale. The ”hard” tail of TMDs is governed by this process. Jet energy profiles, jet shapes, thrust are now well-defined.

Theoretical pieces

- **Remnants and hadronization**
  - hadronization and remnants are necessary to neutralize color introduced by hard scattering calculations and evolution.
  - Pythia uses the string model:
    - Color-neutral strings split into lower-energy color-neutral sub-strings. Low-energy color-neutral sub-strings are identified with hadrons.
    - The string model is designed to be predictive at high energies and to describe many-hadron states. For few-hadron states, the string model is less predictive / not good (to be quantified).
    - The string breaks by insertion of a pair of partons with pT w.r.t the original string axis. This means that string break-ups produce hadrons with a certain PT-distribution. After the string break-up, the left-right symmetry and causality of the model means that the pT of the next break-up is again distributed relative to the original string axis. This means that the average pT/PT distribution is flat.
  - Mismatch between NP theory and Pythia: The string model is not based on the parton model; it is a dynamical model of confinement.
  - **Observables**: Identified particle spectra, multiplicities, non-perturbative PT distributions.

Section

Comparisons to the DIS legacy set

Note on predictions and tune

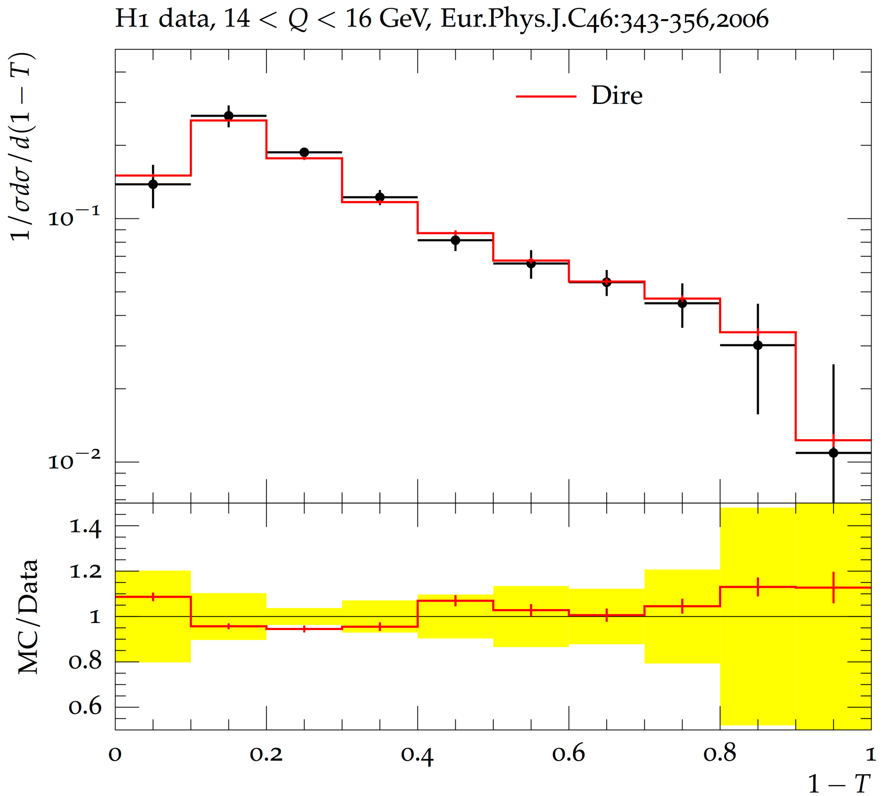
- **Pythia Parameters, e.g.:**
  - `parm StringZ:aLund (default = 0.3; minimum = 0.0; maximum = 2.0) The a parameter of the Lund symmetric fragmentation function.`
  - `parm StringZ:bLund (default = 0.58; minimum = 0.2; maximum = 2.0), The b parameter of the Lund symmetric fragmentation function.`
  - `parm StringFlav:probStoUD (default = 0.217; minimum = 0.0; maximum = 1.0), the suppression of s quark production relative to ordinary u or d one.`

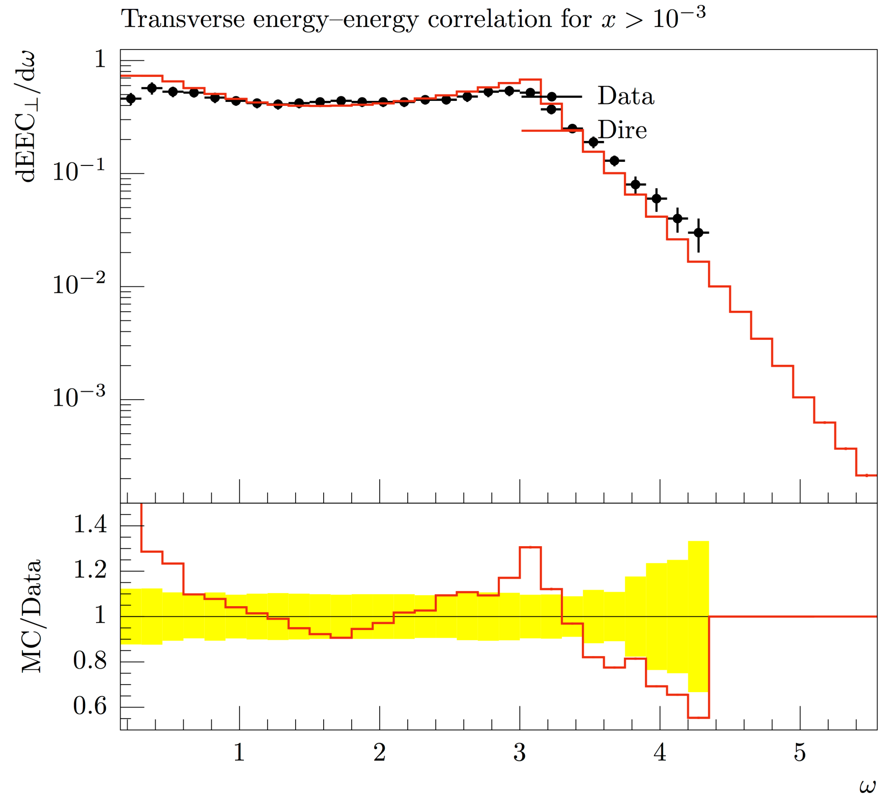
- **Prediction** Run a simulation with the default parameters or a given tune (that does not include the measurements comparing to) and compare to measurements.
- **Tuning** Optimize the Pythia8 Parameters for a best description of the measurements. Tunes can be very specific (e.g., tune to HERMES kinematics only) or include thousands of bins (e.g., 5632 in S. Prestel's latest tune).

- **Improvements beyond tuning** Add subprocesses, radiative corrections, update theory, change models

Pythia8: Simulating HERA collider results

preliminary

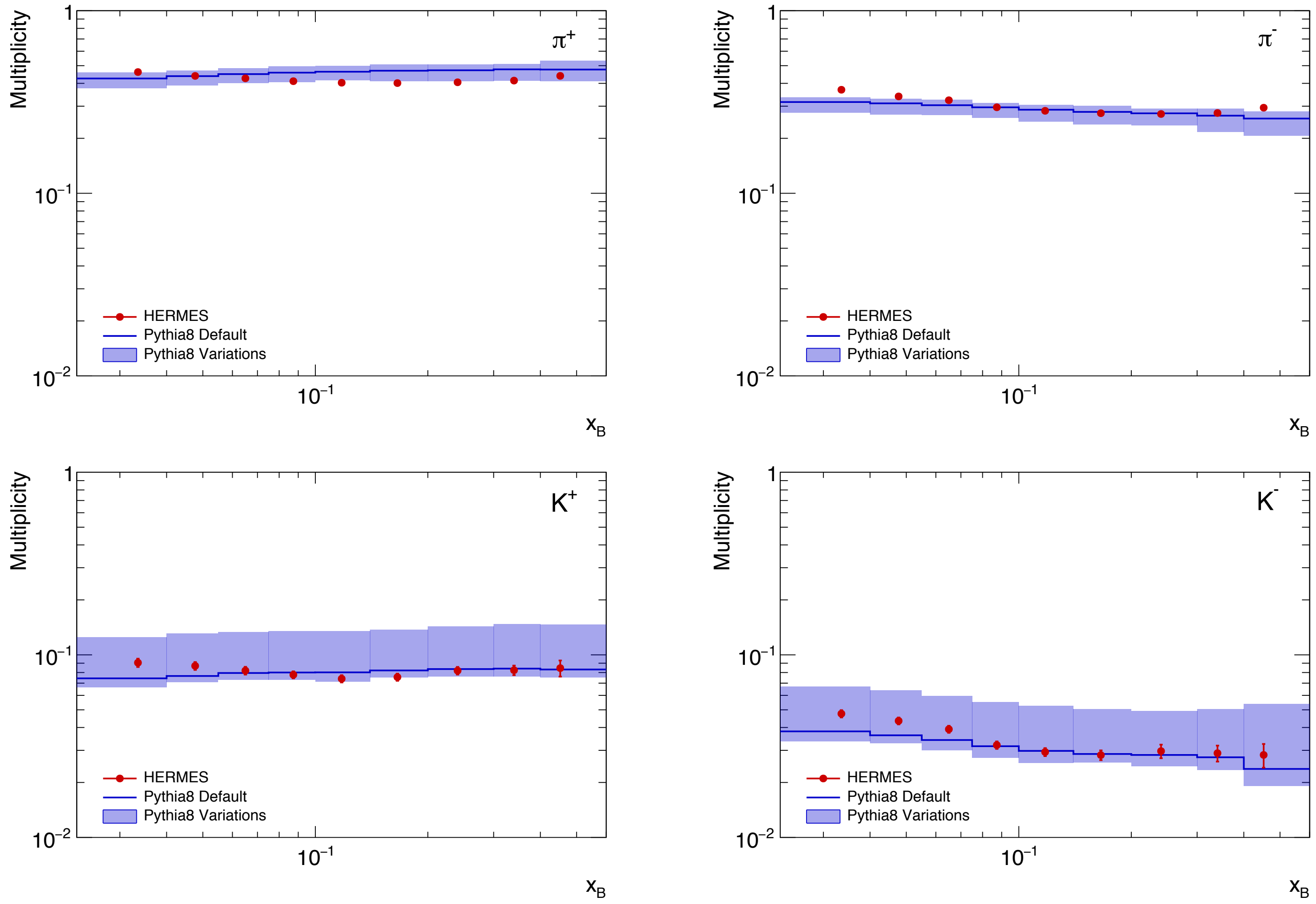




Pythia8: Simulating HERA fixed-target results

preliminary

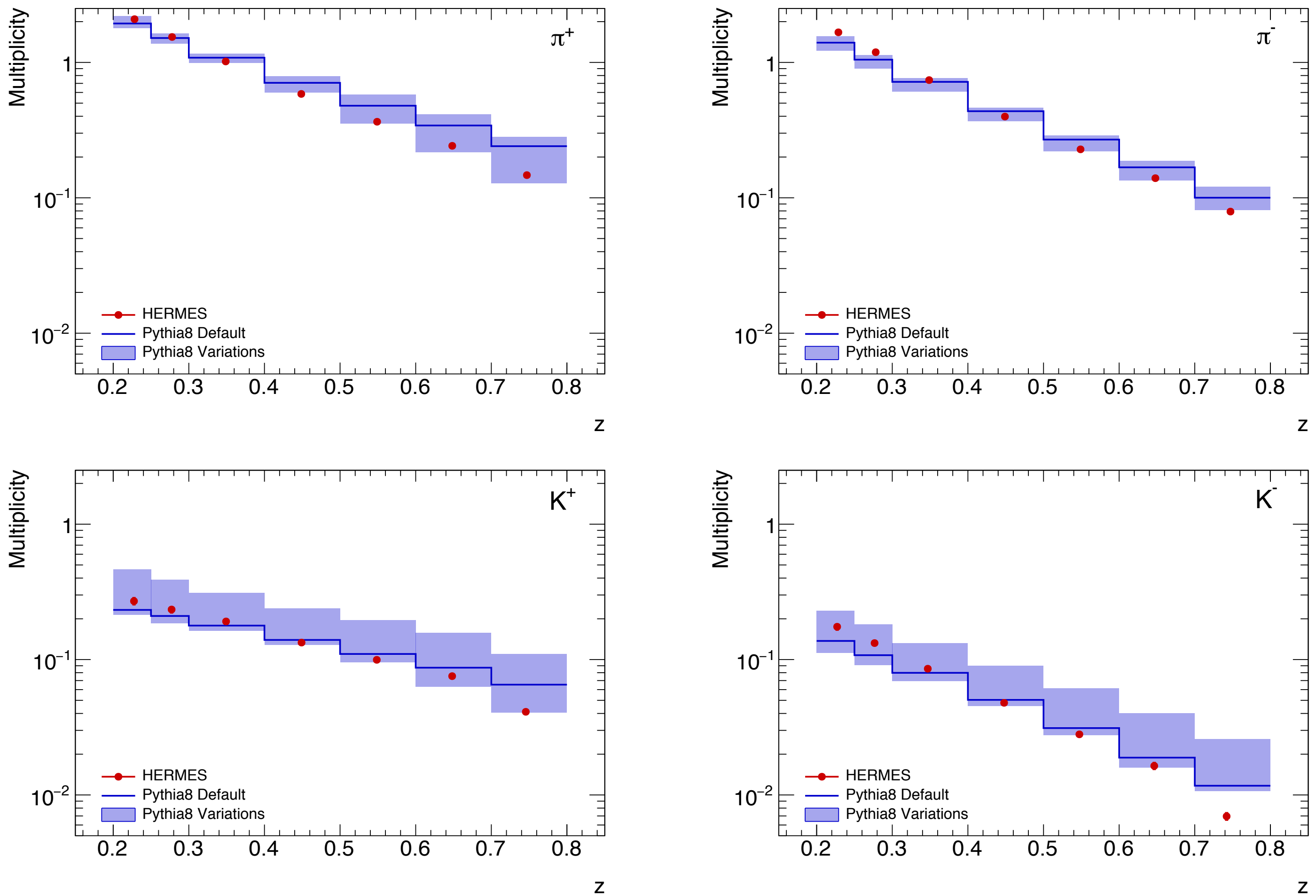
Multiplicities versus x_B



Pythia8: Simulating HERA fixed-target results

Multiplicities versus *z*

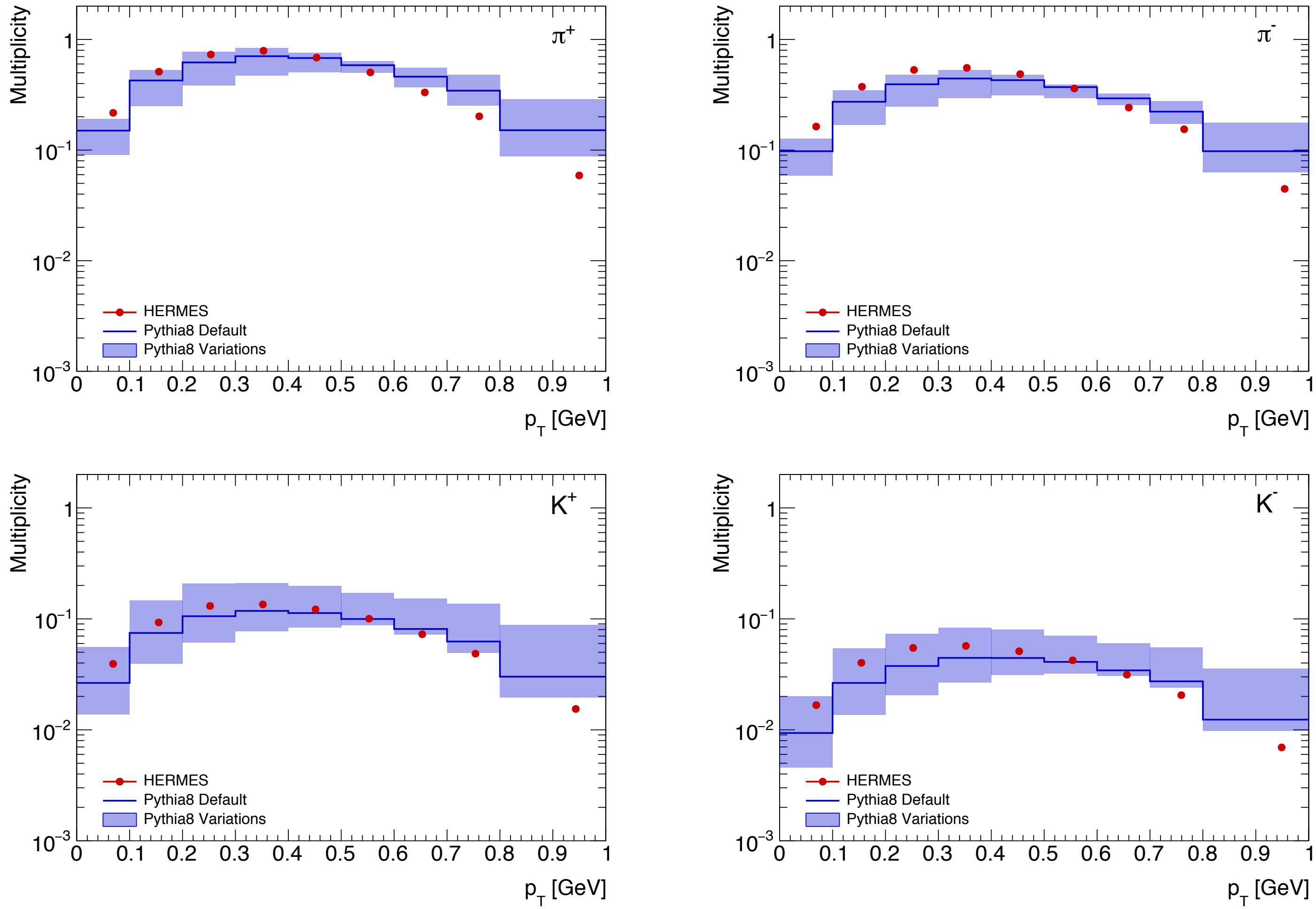
preliminary



Pythia8: Simulating HERA fixed-target results

Multiplicities versus p_T

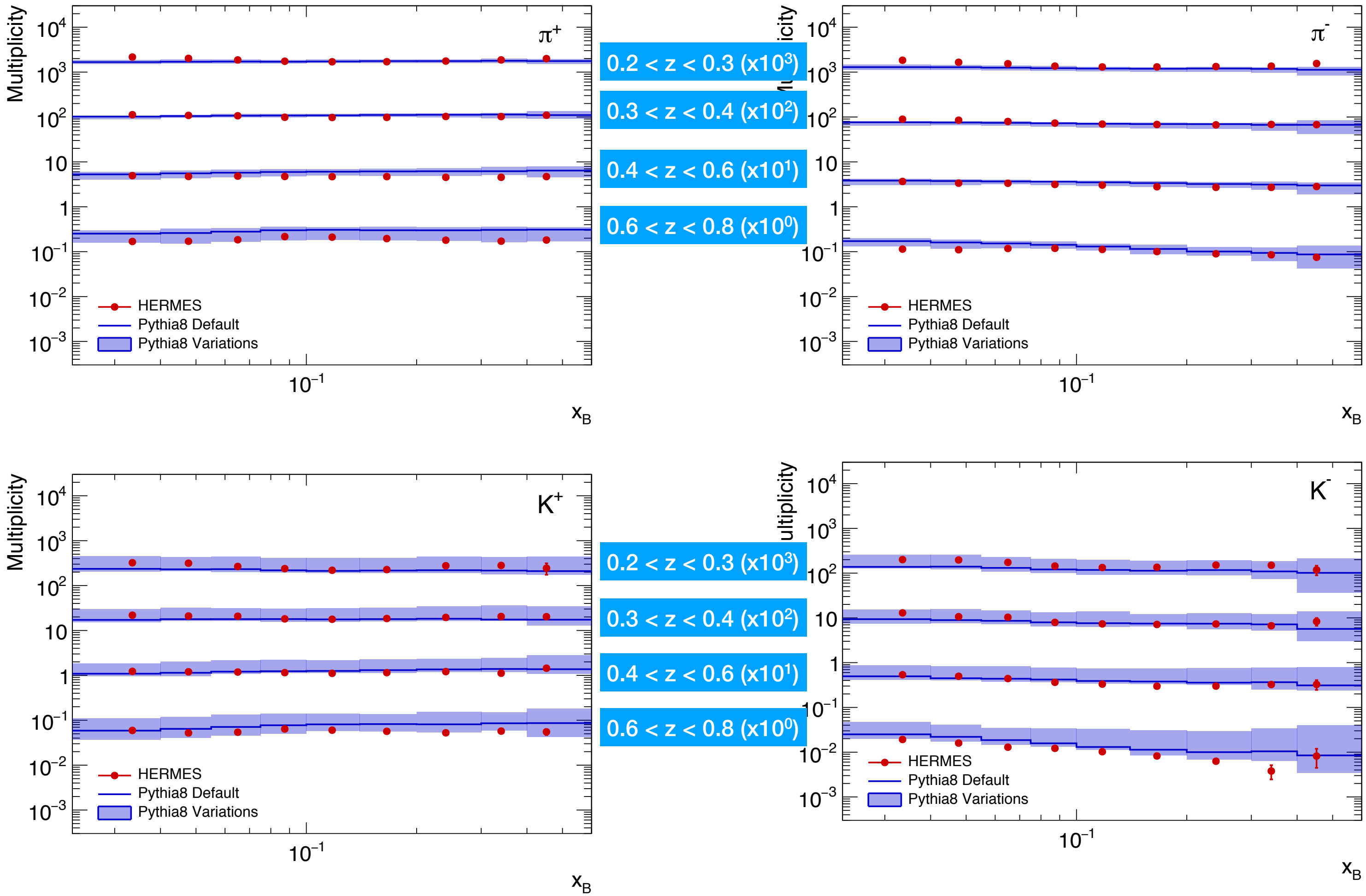
preliminary



Pythia8: Simulating HERA fixed-target results

Multiplicities versus x_B in z-slices

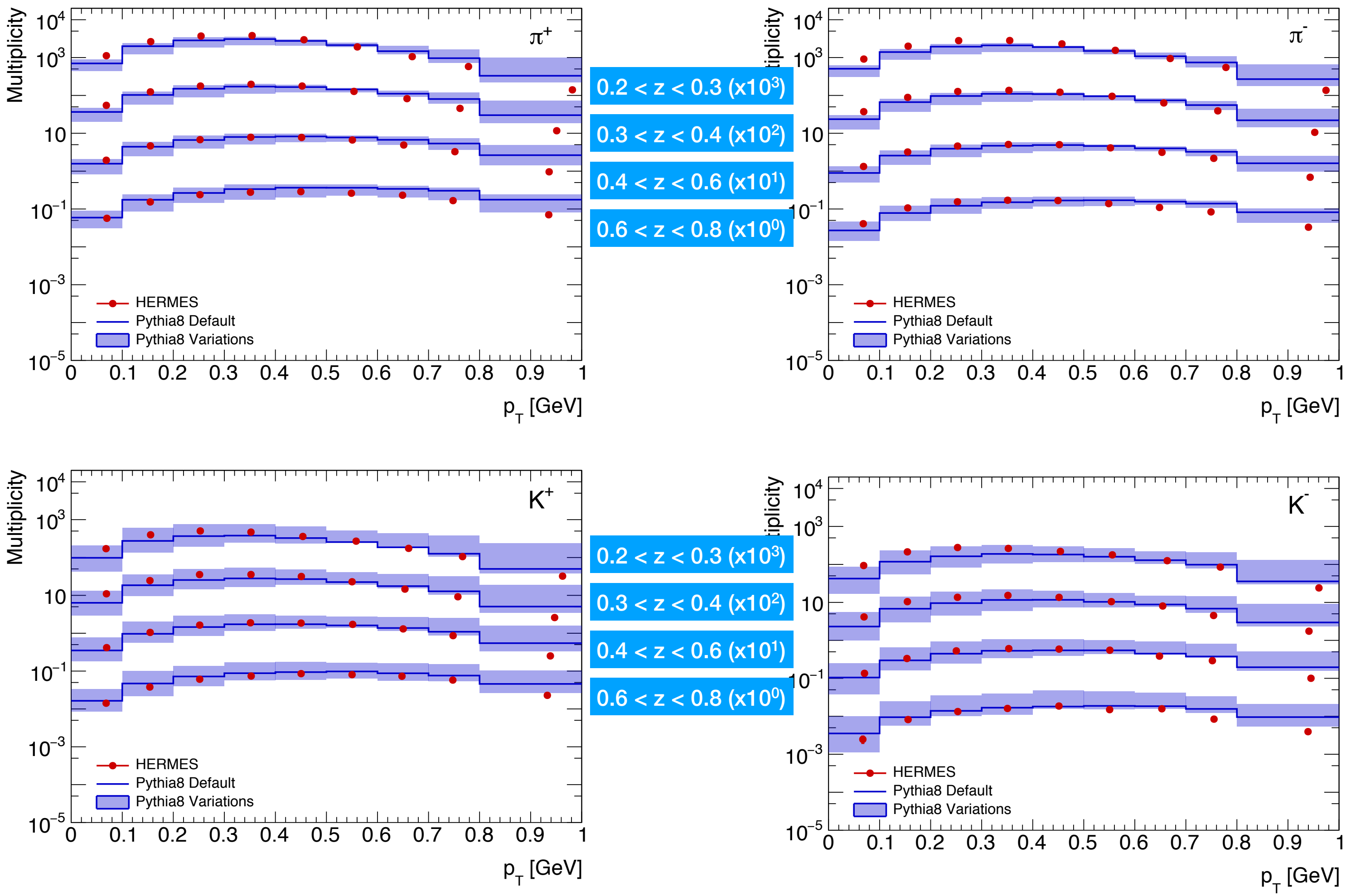
preliminary



Pythia8: Simulating HERA fixed-target results

Multiplicities versus p_T in z-slices

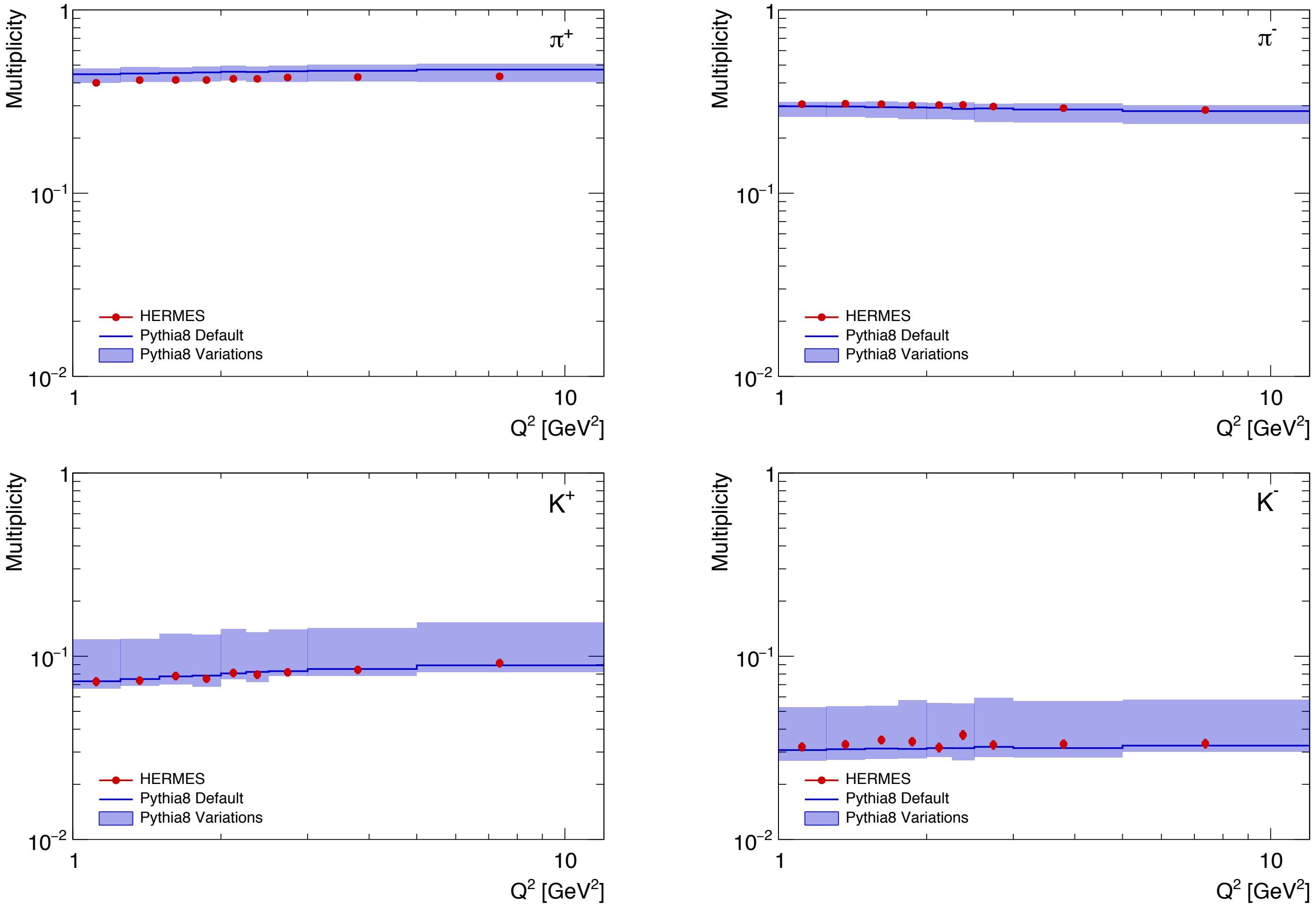
preliminary



Pythia8: Simulating HERA fixed-target results

Multiplicities versus *Q2*

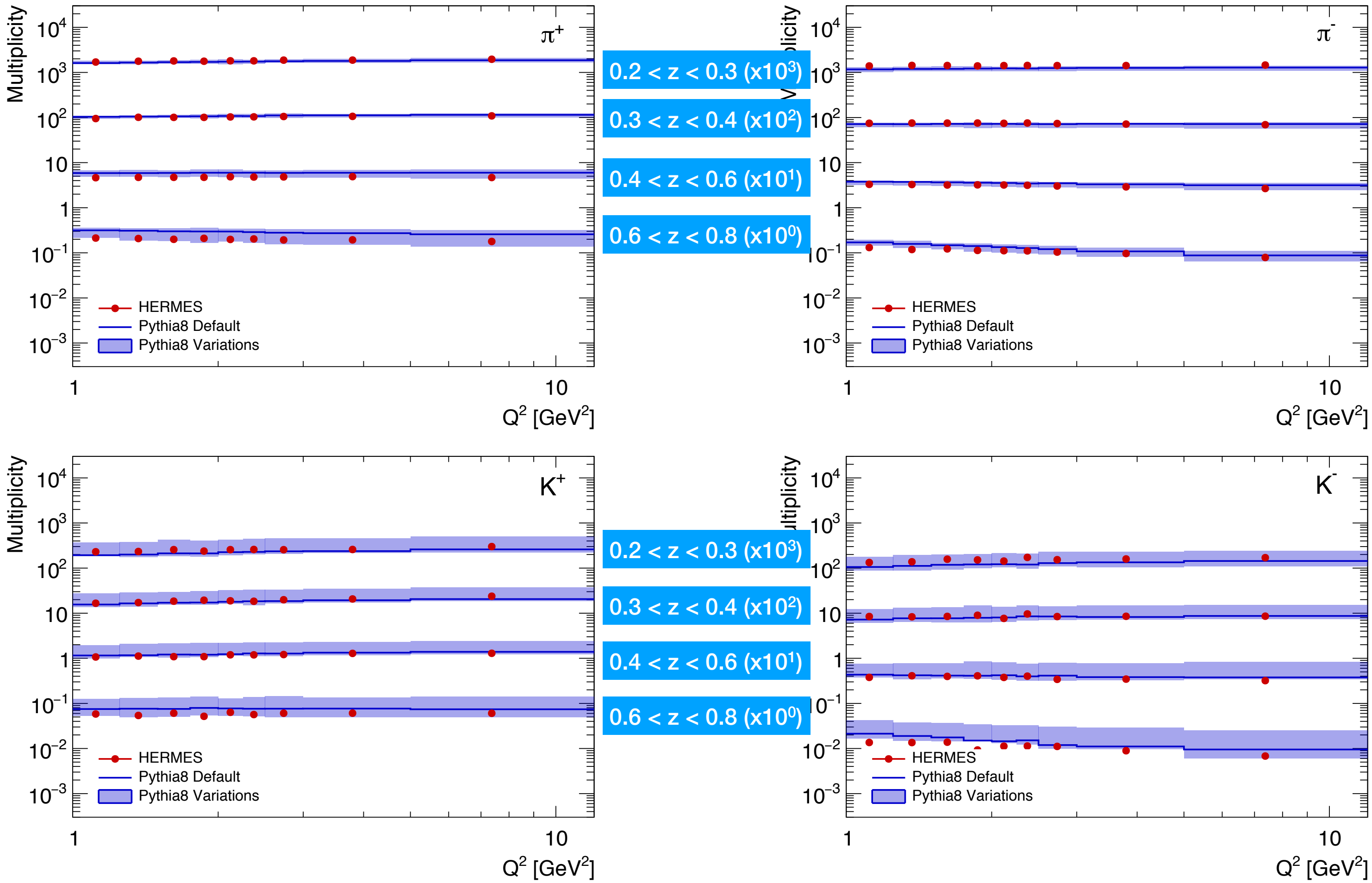
preliminary



Pythia8: Simulating HERA fixed-target results

Multiplicities versus *Q2* in *z*-slices

preliminary



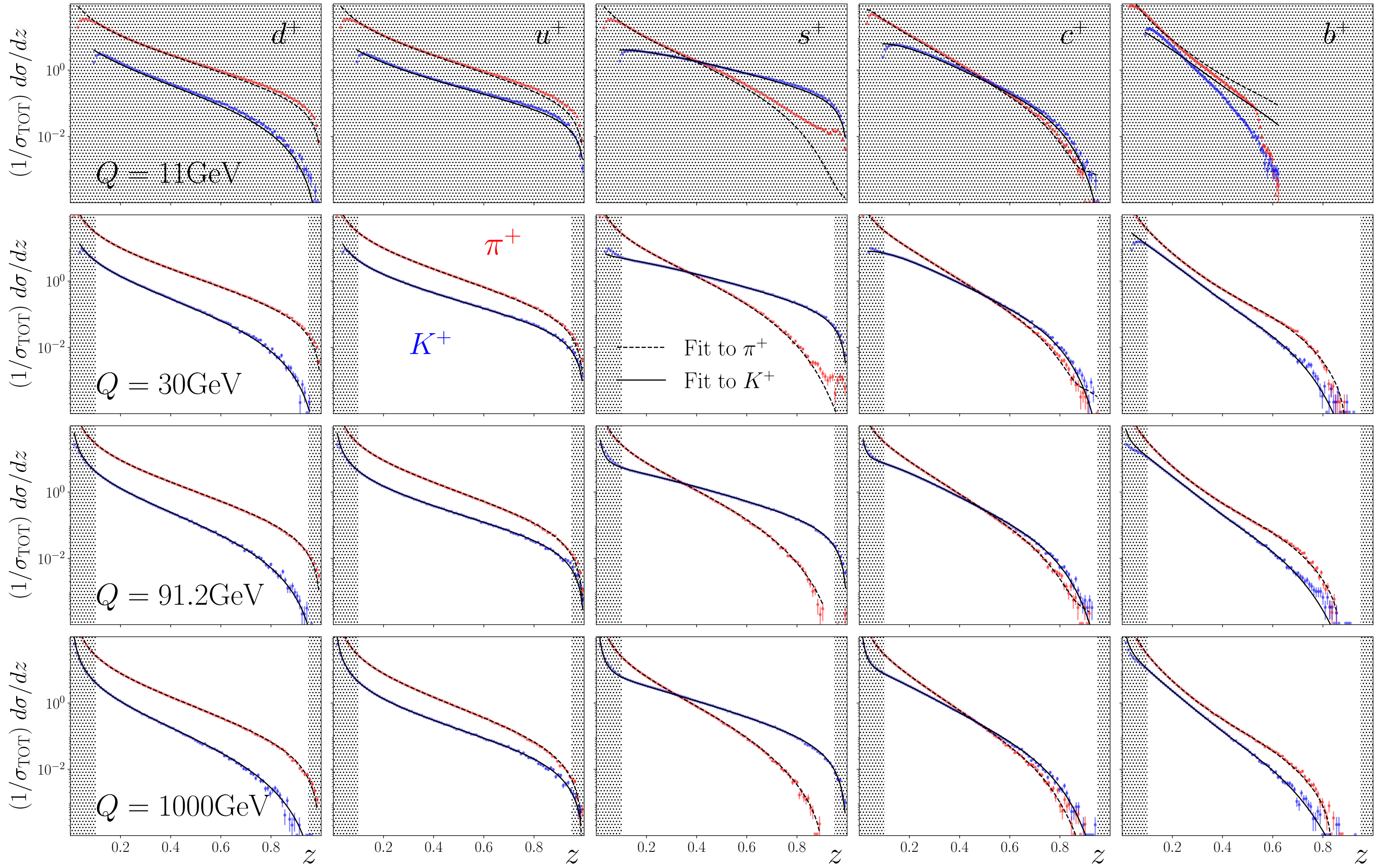
Section

Pythia as a theory tool

Mismatches Pythia-Factorization theorem

Data Pythia simulation of e+e- at Q = 30, 91.2, 1000 GeV

preliminary

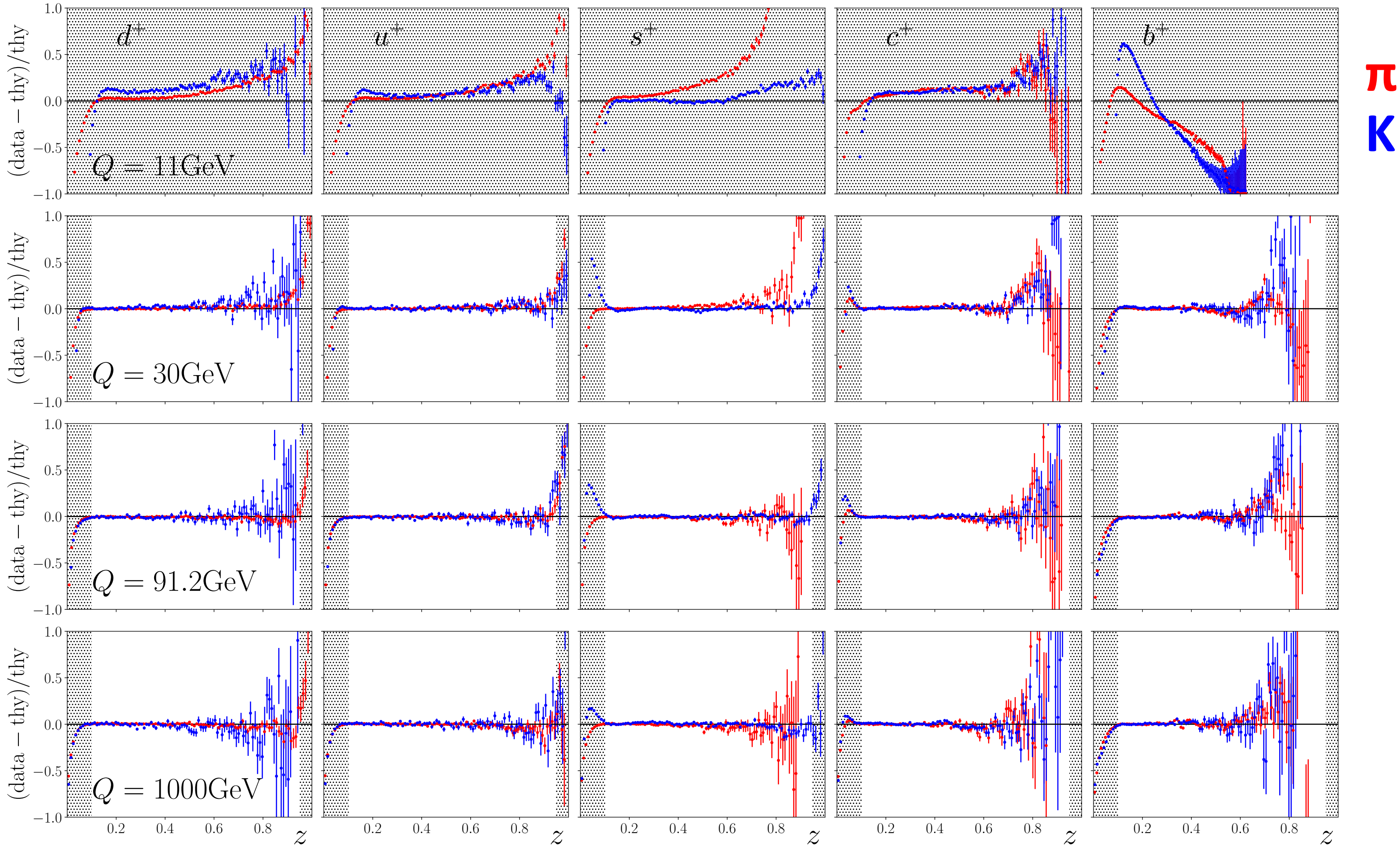


Mismatches Pythia-Factorization theorem

Data Pythia8 simulation of e^+e^-

Theory collinear factorization

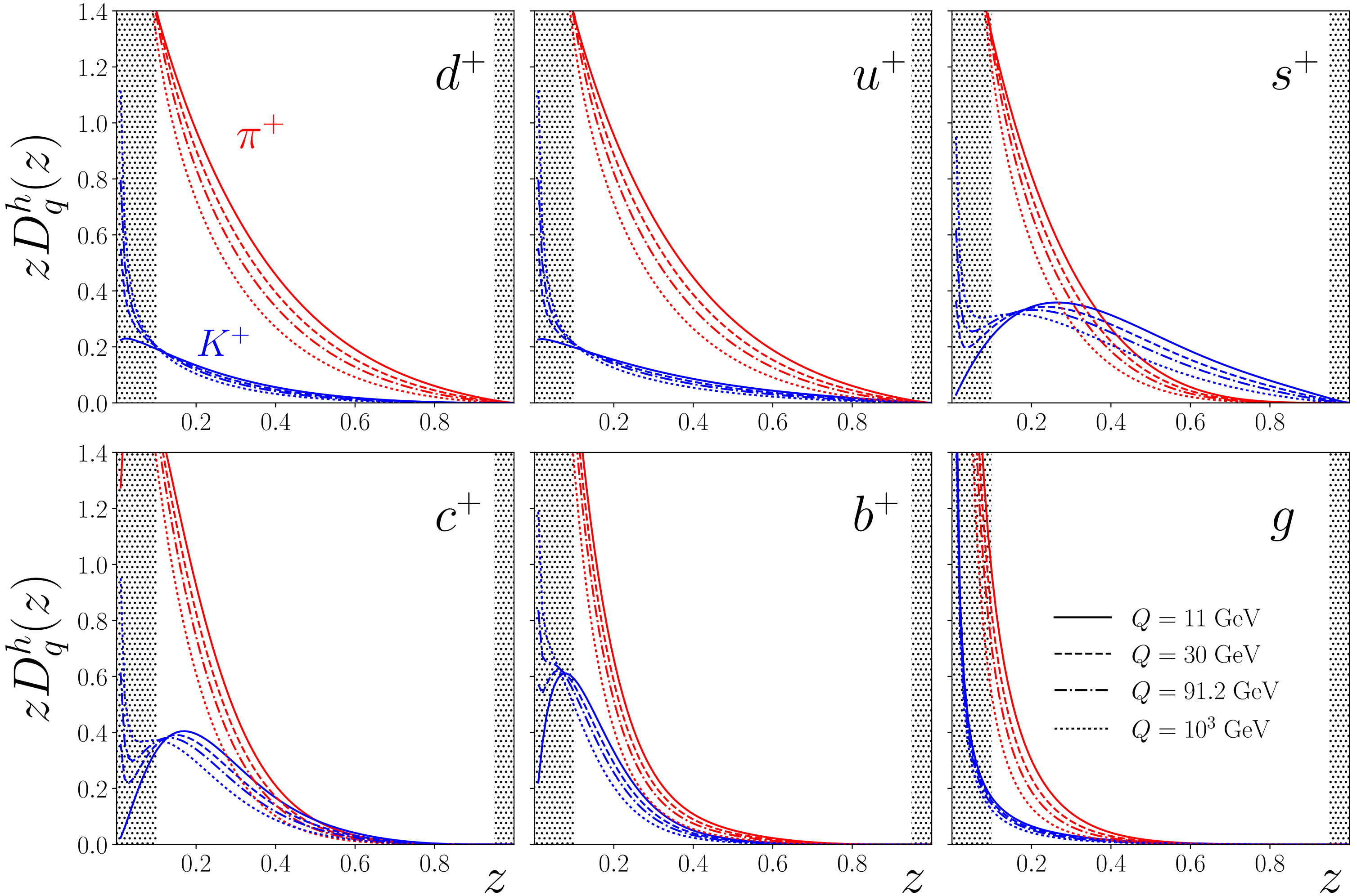
preliminary



Fragmentation functions (FFs) from Pythia8

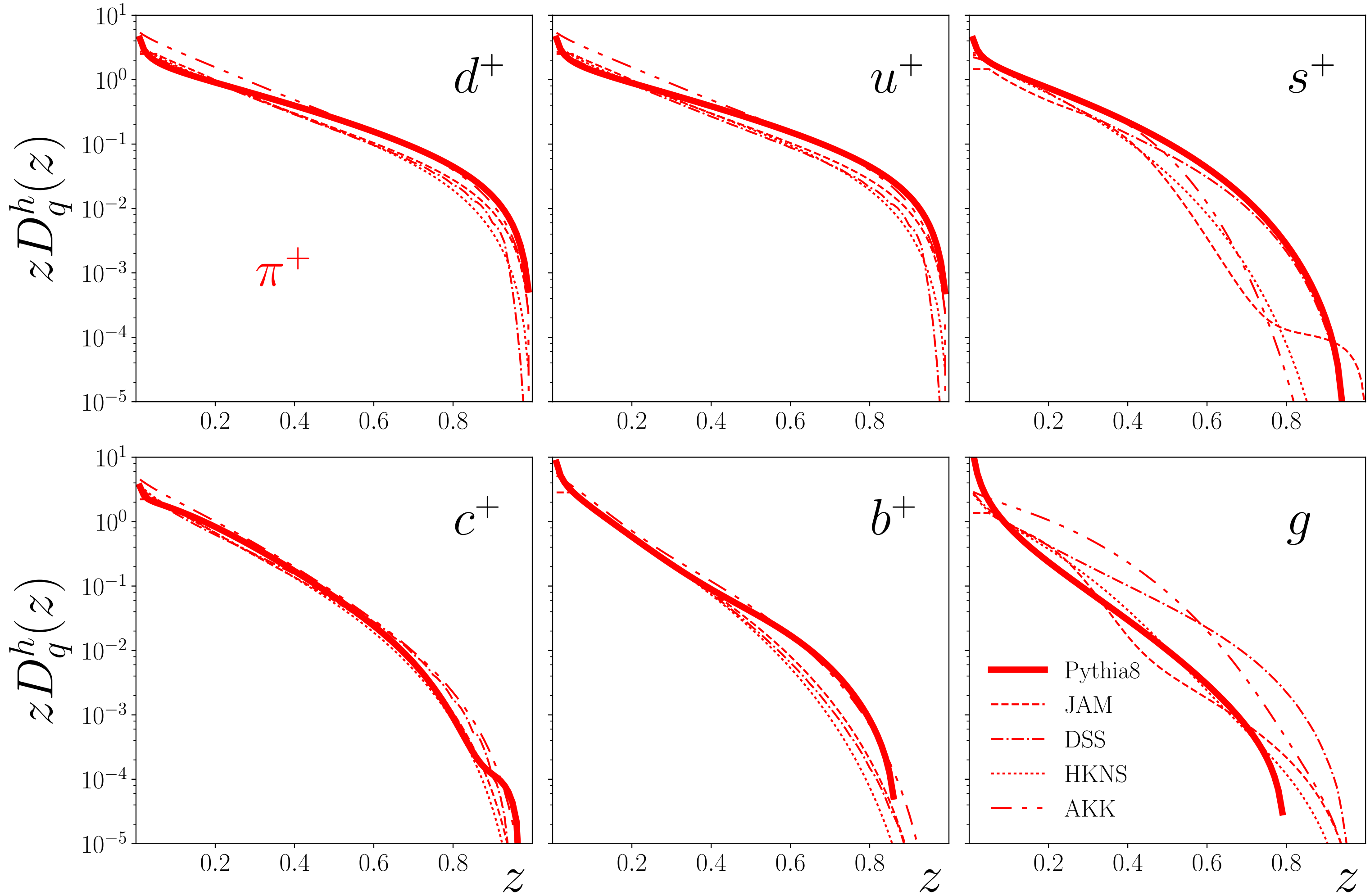
Fit π and K FFs from Pythia8 pseudodata using pQCD @ NLO

preliminary



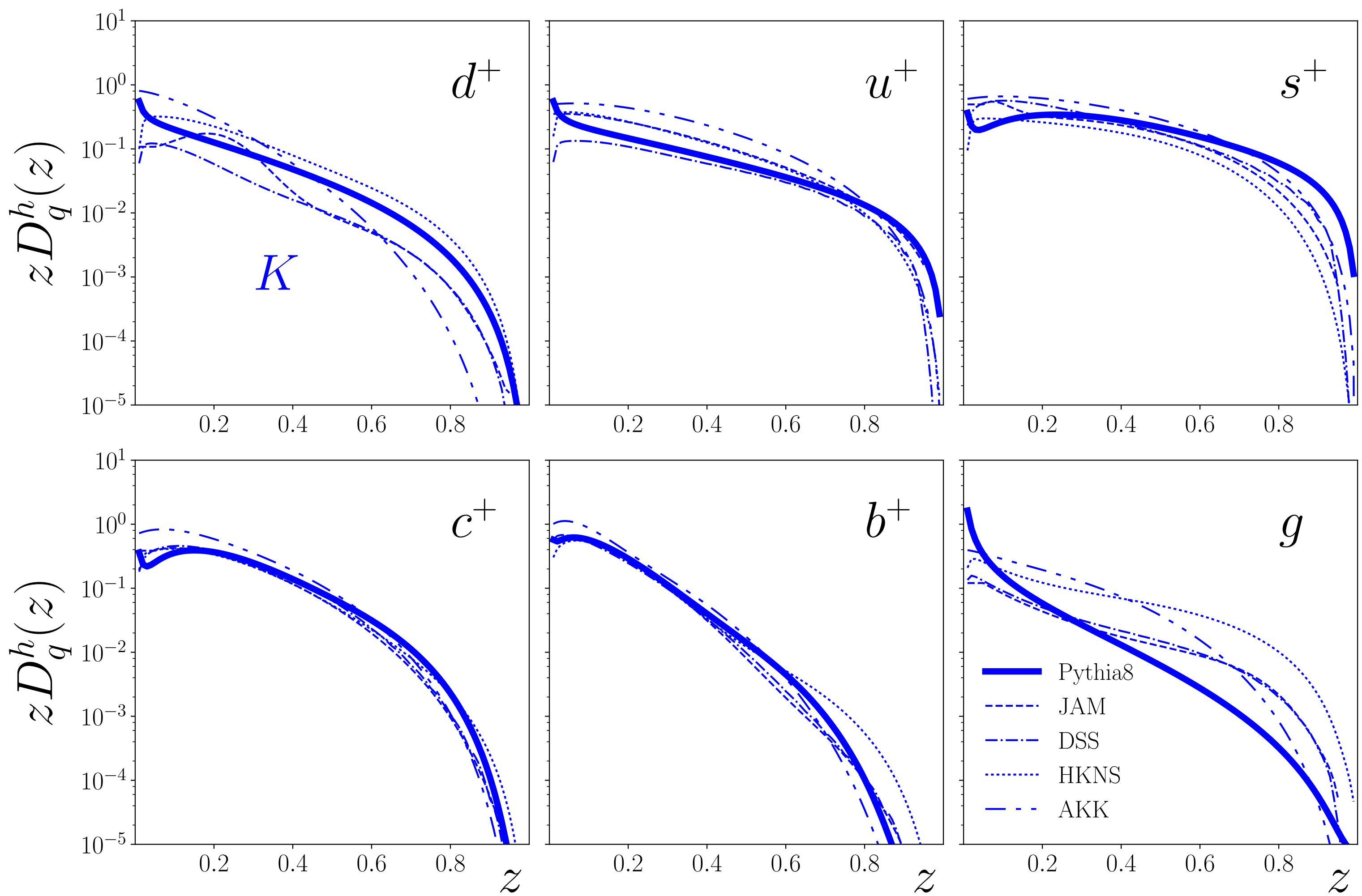
Comparison to global FFs for pions

preliminary



Comparison to global FFs for kaons

preliminary



Study of Hadronization in NP and HEP

LDRD:
started in FY17
at **JLab**

Connection between **NP** and **HEP**

Correlation functions of TMD factorization ⟷ Pythia MCEG LUND string model

Urgent requirement
- MCEG for TMDs
- Understanding of hadronization process

Unique approach Connection between hadronization phenomena in **NP** and **HEP**.

By doing so:
- **NP** Improve theoretical framework for TMDs.
- **HEP** Improve hadronization models.

Work plan

FY17

FY18

FY19

Publication: DIS in Pythia8

Publication: LUND validation

+ TMD observables

Publication: Hadronization in NP and HEP

- comparison Pythia8-TMD factorization
- language dictionary
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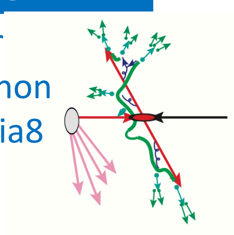
- user model for one phenomenon
- rest from Pythia8



Addendum

And there is more

Selected analysis requirements

Understanding of hadronization

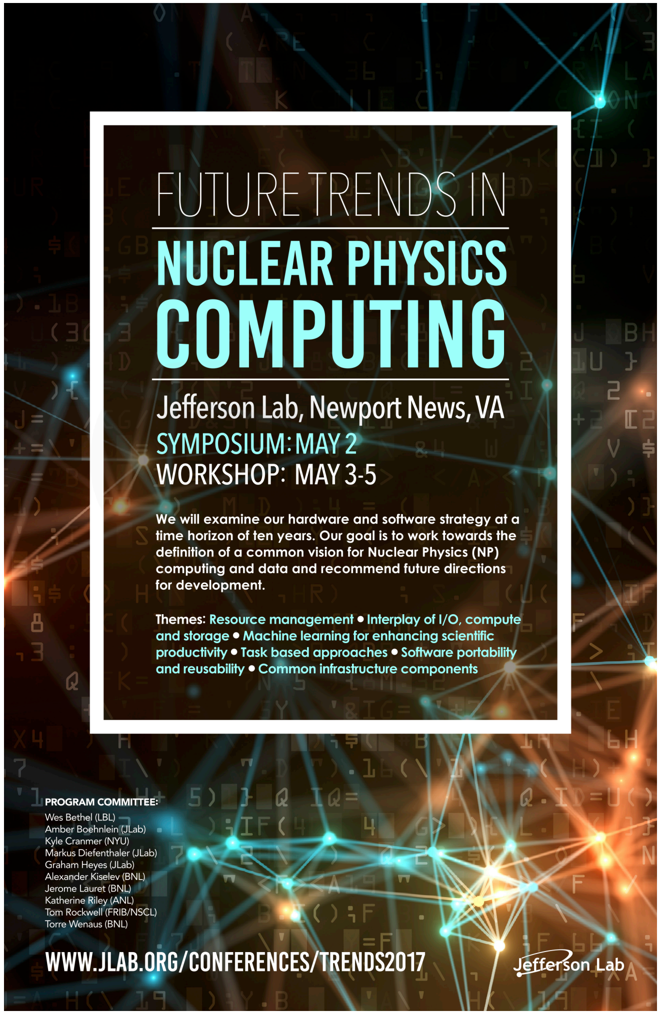
High-precision analysis tools:
- high-precision MCEG
- radiative correction library
- multi-dimensional analysis

R_{SIDIS} from JLab 12GeV

Long-lived data repositories
- COMPASS, HERMES, JLab, RHIC
- document analysis publicly for analysis and theory development (RIVET)
- combined *global* analysis (e.g., HERA fit), possibly on event level

Related to MCEG R&D

EIC Software Consortium (ESC)



Interfaces and integration

- connect existing frameworks / toolkits
- identify the key pieces for a future EIC toolkit
- collaborate with other R&D consortia

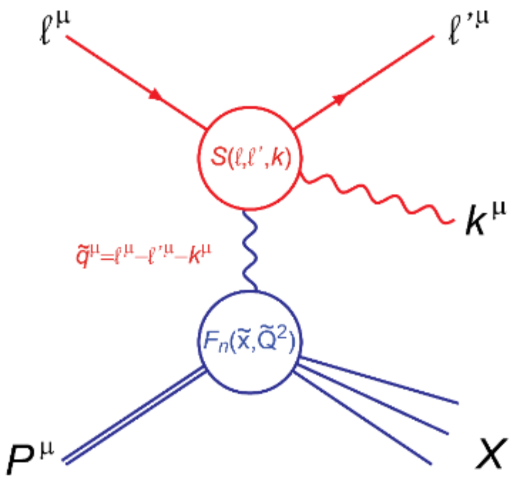
Planning for the future with future compatibility

- workshop to discuss new scientific computing developments and trends
- incorporating new standards
- validating our tools on new computing infrastructure

Organizational efforts with an emphasis on communication

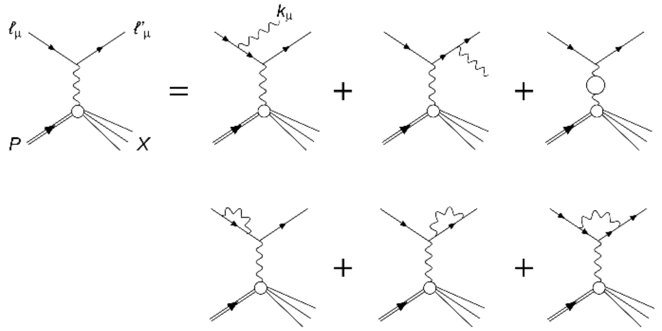
- build an active working group and foster collaboration
- documentation about available software
- maintaining a software repository
- workshop organization

ESC project on radiative corrections



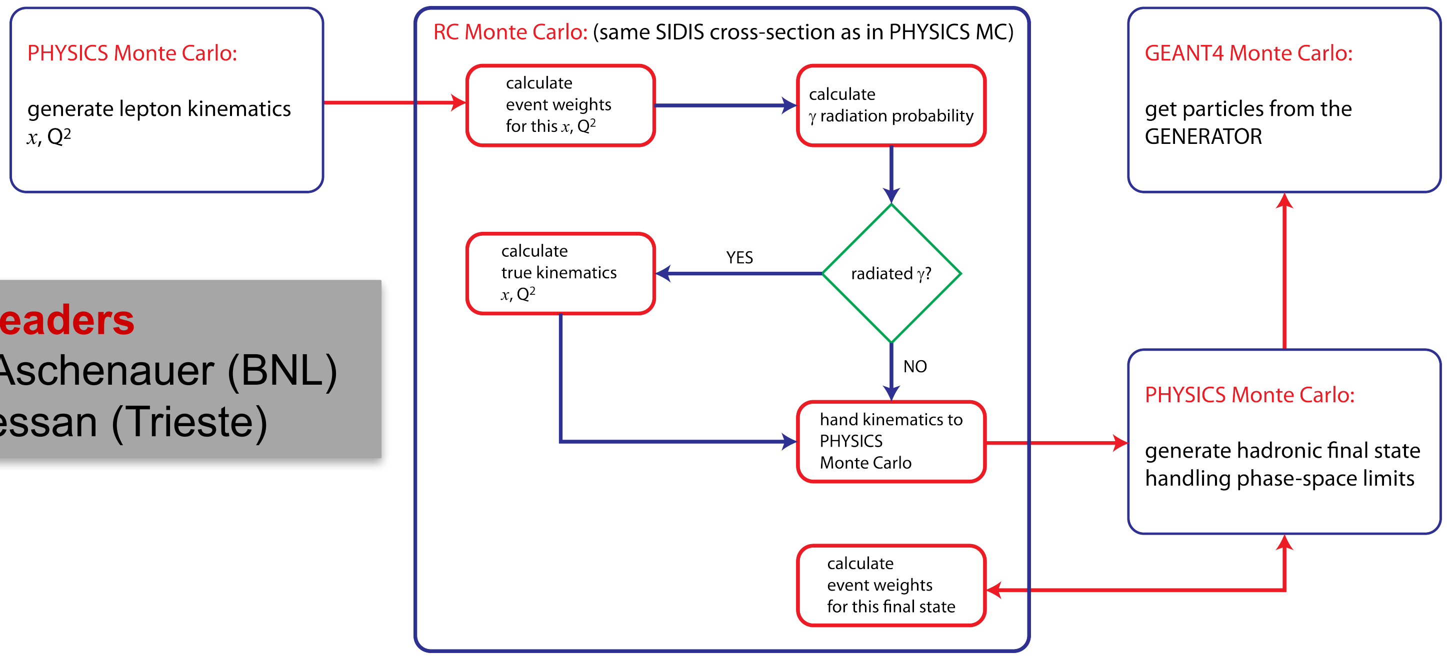
$$\bar{Q}^2 = -(\ell - \ell' - k)^2$$

$$\bar{x} = \frac{\bar{Q}^2}{2P \cdot (\ell - \ell' - k)}$$



- Photon radiation from the leptons modify the one boson cross-section and change the DIS kinematics on the event by event basis
- The direction of the virtual photon is different from the one reconstructed from the leptons, giving rise to:
    - False asymmetries in the azimuthal distribution of hadrons calculated with respect to the virtual photon direction
    - Smearing of the kinematic distributions (e.g. z and P_{hT})
- To take into account correctly this effect in the SIDIS cross-section we need both the correct weights for every event and an unfolding procedure for the smearing. THIS can ONLY be done by using a Monte Carlo code for RC

Status of ESC project on radiative corrections



Project leaders
- E.-C.Aschenauer (BNL)
- A. Bressan (Trieste)

Deliverables achieved at the end of FY17:

- Calculate radiative corrections for transverse polarized observables to measure TMDs and polarized exclusive observables.
- Provide proof that the MC phase space constrains on the hadronic final state is equal to calculating radiative corrections for each polarized and unpolarized semi-inclusive hadronic final state independently.
- Define a software framework and develop a library based on this framework, which integrates the radiative corrections depending on polarization and other determining factors in a wrapper-software.

What is RIVET?

- **Task** validate MCEG against experimental data
- **Challenge**
  - analysis methods and experimental cuts often poorly documented
  - treasure of data values often guarded by experimental groups
  - Sisyphean task to extract information for MCEG-data comparison
- **RIVET solution**
  - common interface between data and MCEG**s**
  - experimentalist encode analysis method and cuts in RIVET and validate results against published results
  - MCEG comparison to published results by calling the validated analysis and data values from RIVET
- **Work on RIVET**
  - everyone is encouraged to provide their results in RIVET
  - but not everyone provides the results in RIVET
  - **first NP contribution to RIVET** Sylvester and Stefan included the HERMES multiplicity analysis in RIVET

Thank you very much for attending my seminar!