Balaton workshop, Hungary 2015

The parton and hardon cascade model, PACIAE

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Outline

INTRODUCTION

Primary goal of high energy heavy ion collisions：

- *Study properties of extremely high energy and high density matter*
- *Explore phase transition from HM to QGM, QGP phase transition*

The ways studying high energy heavy ion collisions :

(1)Phenomenologic model (eg. NJL)

(2)Hydrodynamic

(3)Perturbative QCD (pQCD)

- Factorization formalism
- Dynamical simulation
  - Hadron cascade model:

two components dual parton model

PYTHIA(FRITIOF), HERWIG, PHOJET, RQMD, HIJING, VENUS, QGSM, LUCIAE(JPCIAE), HSD, AMPT, uRQMD, MCG, etc.

- *Parton and hadron cascade model:*

  PCM (VNI)

  AMPT (string melting)

  PACIAE

  BAMPS (parton only)

  PHSD

  MARTINI

-In PACIAE model

- A+B collission is decomposed into nn collissions (according to geometry & nn collission cross section)
- nn collission is described by PYTHIA, where nn colli. is decomposed into parton-parton collissions

-The PACIAE constructs a huge building using block of PYTHIA & plays a role like convolution in above convolution formalism

– *The PACIAE model is composed of*

(A) *Parton initialization*

(B) *Parton evolution*

(C) *Hadronization*

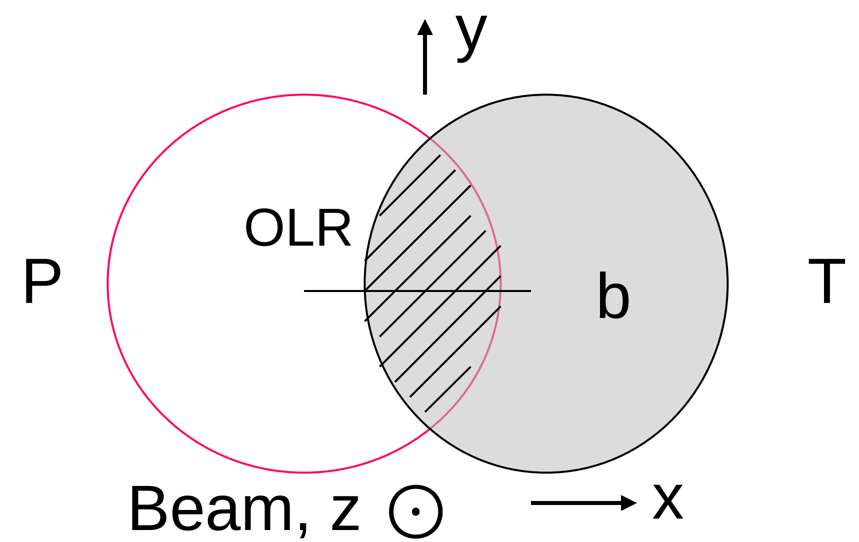
(D) *Hadron evolution*

four parts

(A) Parton Initialization

Distributing participant nucleons inside OLR calculated with GM, spectator nucleon outside OLR but within nucleus

overlap region



PACIAE2.0

$$p_x = p_y = 0, \quad p_z = p_{beam}$$ (for the projectile nucleons)

$$p_x = p_y = p_z = 0$$

(for the target nucleons in the laboratory framework)

$$p_x = p_y = 0, \quad p_z = -p_{beam}$$

(for the target nucleons in the collider framework)

Construct nucleon collision time list with NN total cross section & straight trajectory

Each NN collision performed by PYTHIA with switching-off SF & breaking diquark (anti-diquark)

Resulted initial state ,consist of partons

PACIAE2.0

(B) Parton evolution

(1) Construct parton collision time list with parton-parton total cross section

(2) Perform each parton-parton collision by 2→2 pQCD differential cross section

(C) Parton hadronization with SF or CM

(D) Hadron evolution

(1) Construct hadron collision time list with hh total cross section

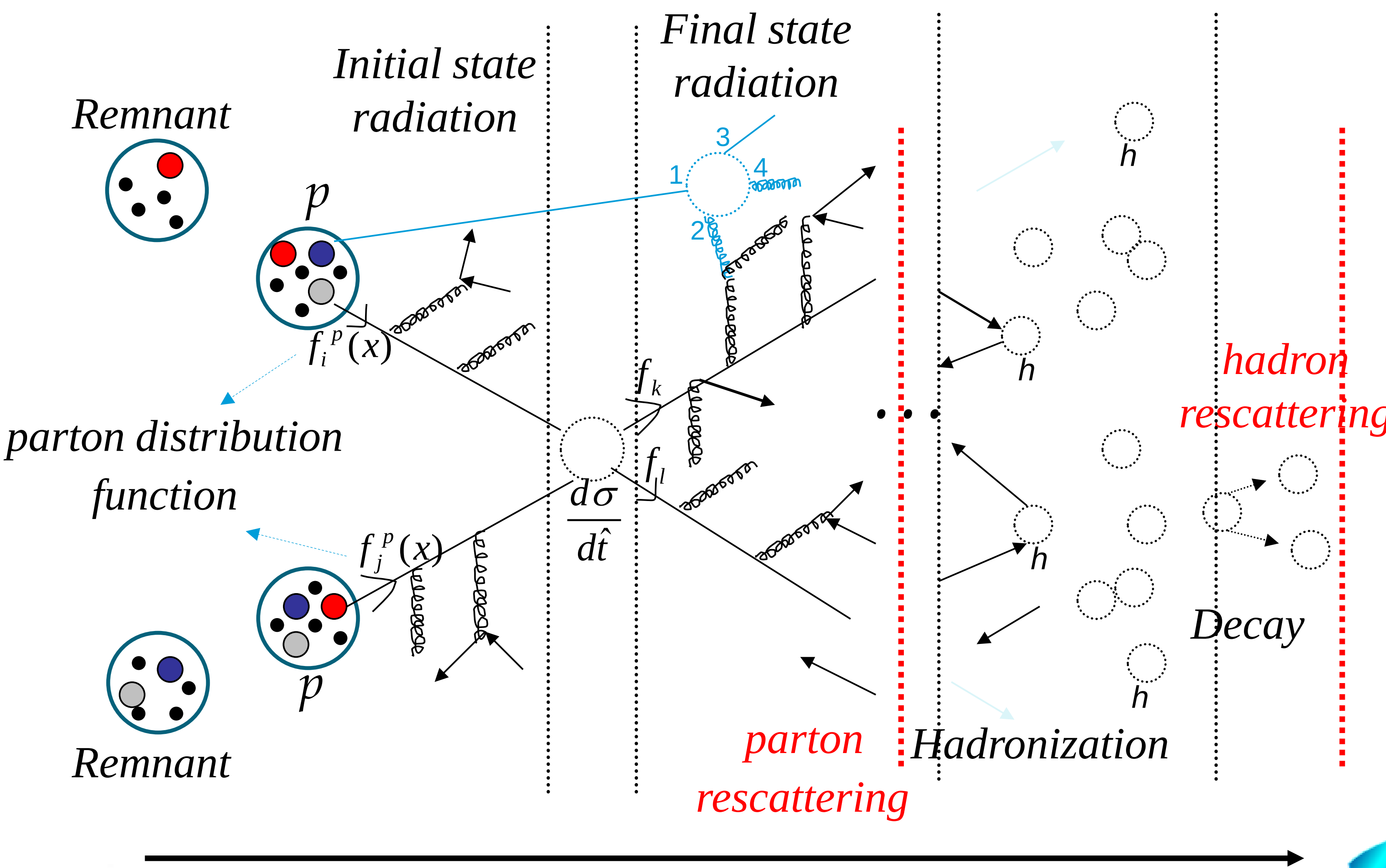
(2) Perform each hh collision by differential hh cross section

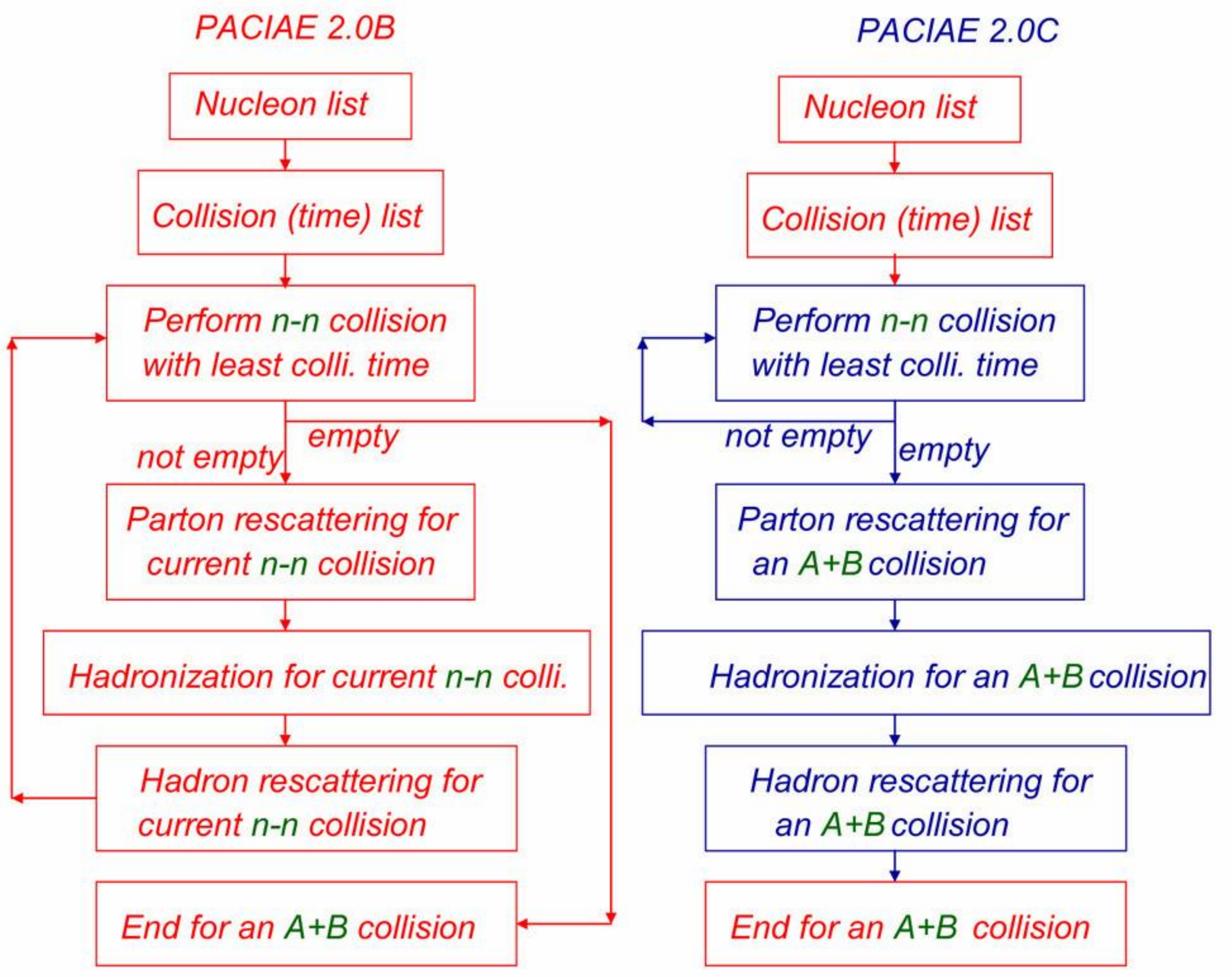
Comput. Phys. Commun., 183(2012)333; 184(2013)1476.

PACIAE*A:
elementary collisions of pp, $p\bar{p}, e^{+}e^{-}$ and lepton-nucleon DIS

PACIAE*B and PACIAE*C:
relativistic nuclear-nucleus collision of p+A and A+B as well as lepton-nucleus DIS

Sketch for pp simulation (PYTHIA & PACIAE2.0A)





Four parts are performed for each nn collision pairs independently until all the nn collision pairs are collided

The partonic initialization is first performed for all the nn collision pairs, then subsequent parts

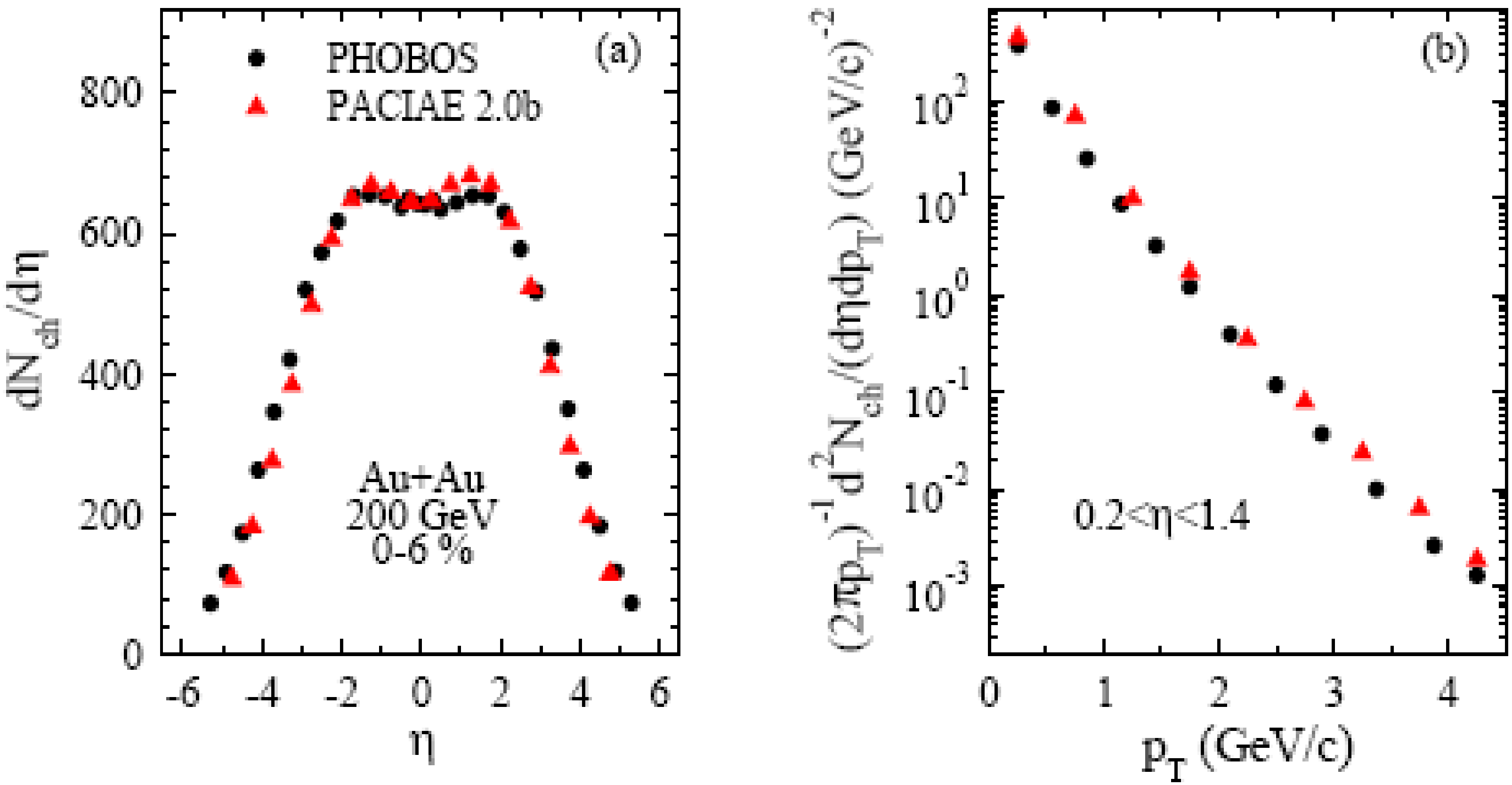
Charged multiplicity and pseudo-rapidity density

Reaction	$\sqrt{s_{NN}}$ TeV	Exp.	PACIAE 2.0b	PACIAE 2.0c	PACIAE 2.0c_c
Au+Au	0.2	$5060 \pm 250^{\dagger}$	4940	4961	4746
Pb+Pb	2.76	$1601 \pm 60^{\ddagger}$	1554	1542	1540

Au+Au: 0-6%, total charged multiplicity, $\sqrt{s_{NN}} = 0.2\,TeV$

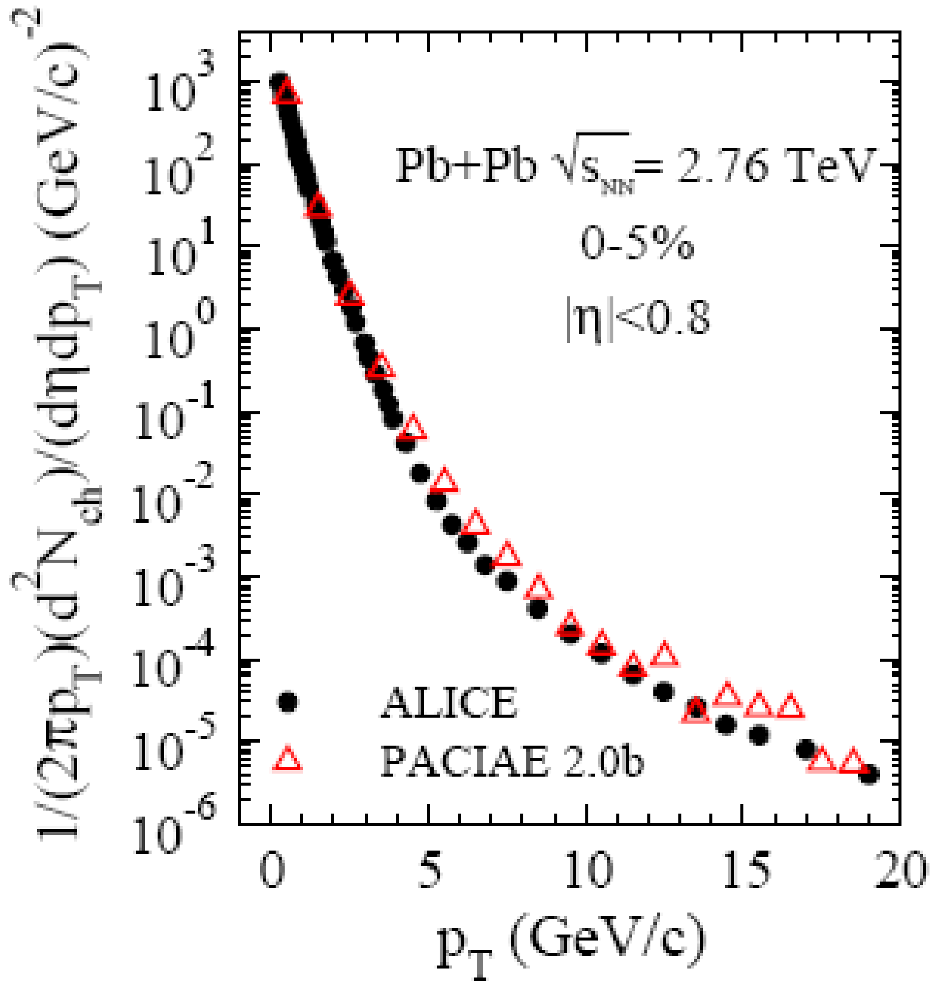
Pb+Pb: 0-5%, charged particle pseudorapidity density

$$(|\eta| < 0.5),\quad \sqrt{s_{NN}} = 2.76\,TeV$$



(a) Charged particle pseudorapidity distribution

(b) Transverse momentum distribution



Transverse momentum distribution

Upgrade to PACIAE2.1

t

Initial spatial space asymmetry:

(ellipse)

$$a = R_A(1-\delta_r) \longrightarrow$$ ***Half minor axis of the ellipse***

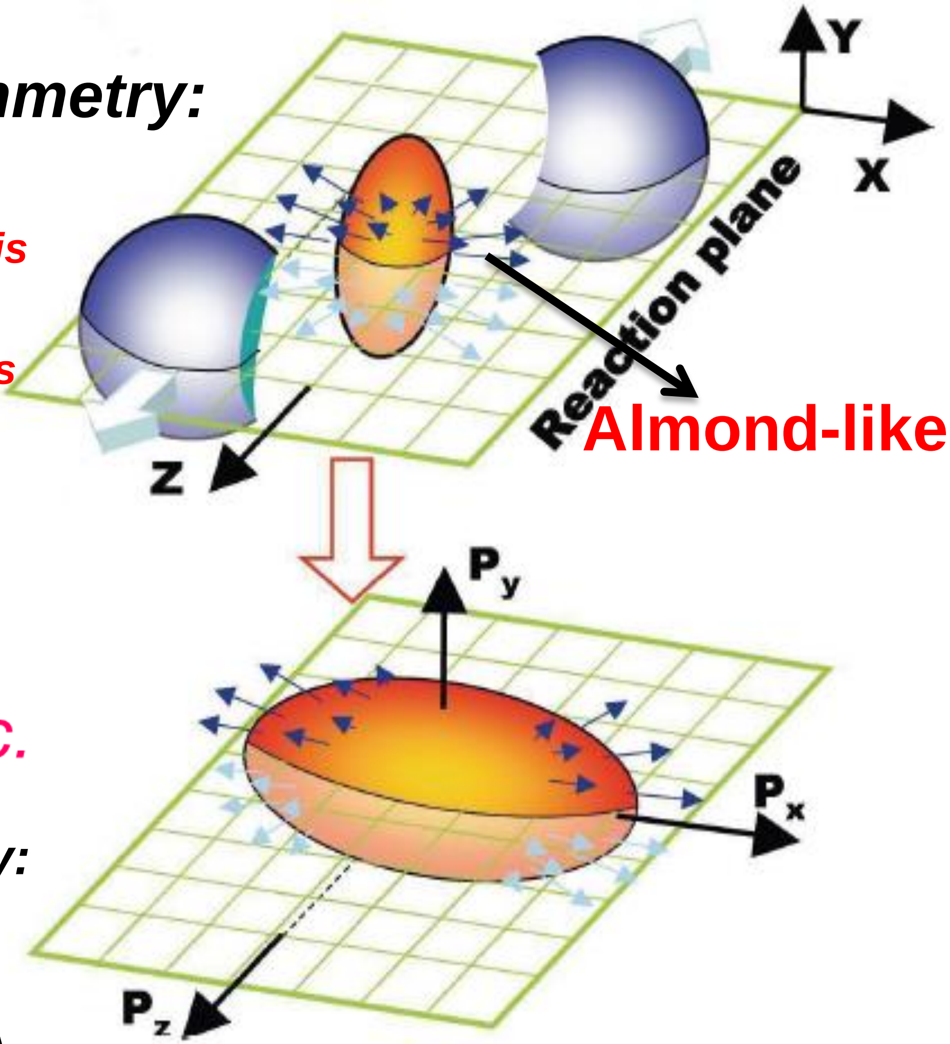
$$b = R_A(1+\delta_r) \longrightarrow$$ ***Half major axis of the ellipse***

R_A the radius of nucleus

parton rescattering, etc.

final momentum space asymmetry:

$$\text{large} \quad \langle v_2 \rangle_p = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle_p$$



However, in PYTHIA (PACIAE2.0) particle momentum from SF (string fragmentation)

azimuthal angle of particle transverse momentum

arranged on the circle with radius of p'_T

$$p'_x = p'_T \cos(\phi'), \quad p'_y = p'_T \sin(\phi')$$

sampled according to exponential/Gaussian distribution

This symmetry arrange strongly cancels the final hadronic state transverse momentum asymmetry

Upgrade to PACIAE2.1

We modify it by

$$p'_x = p'_T(1+\delta_p)\cos(\phi'),\quad p'_y = p'_T(1-\delta_p)\sin(\phi')$$

half major axis

half minor axis

On the circumference of an ellipse

With extra deformation parameter δ_p, experimental V_2 data are then able to be better described.

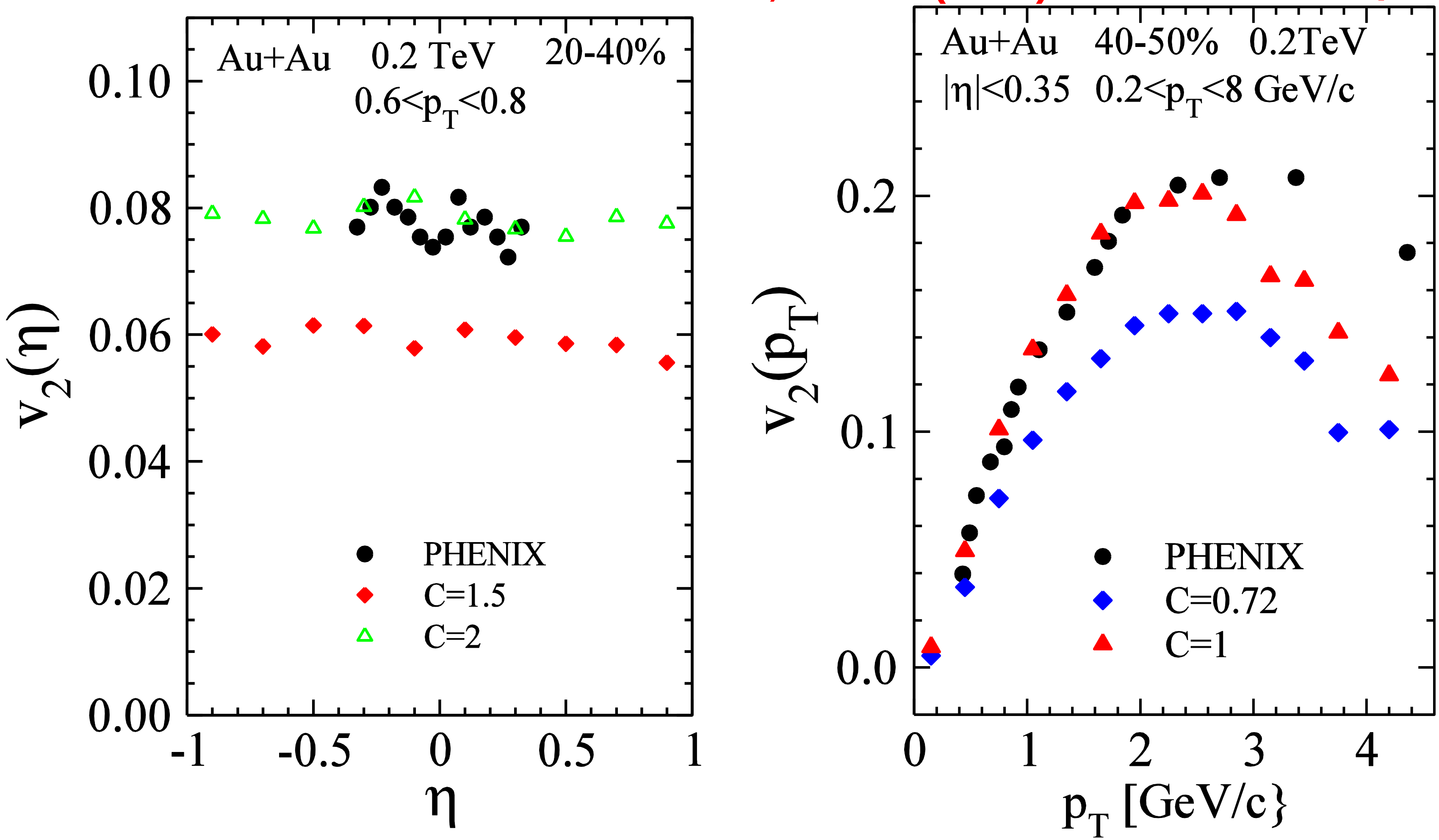
Ben- Hao Sa, Dai-Mei Zhou, et al., CPC184(2013)1476

Parameter of δ_p can be related to the deformation parameter of δ_r in the initial spatial phase space as

$$\delta_p = C\delta_r$$

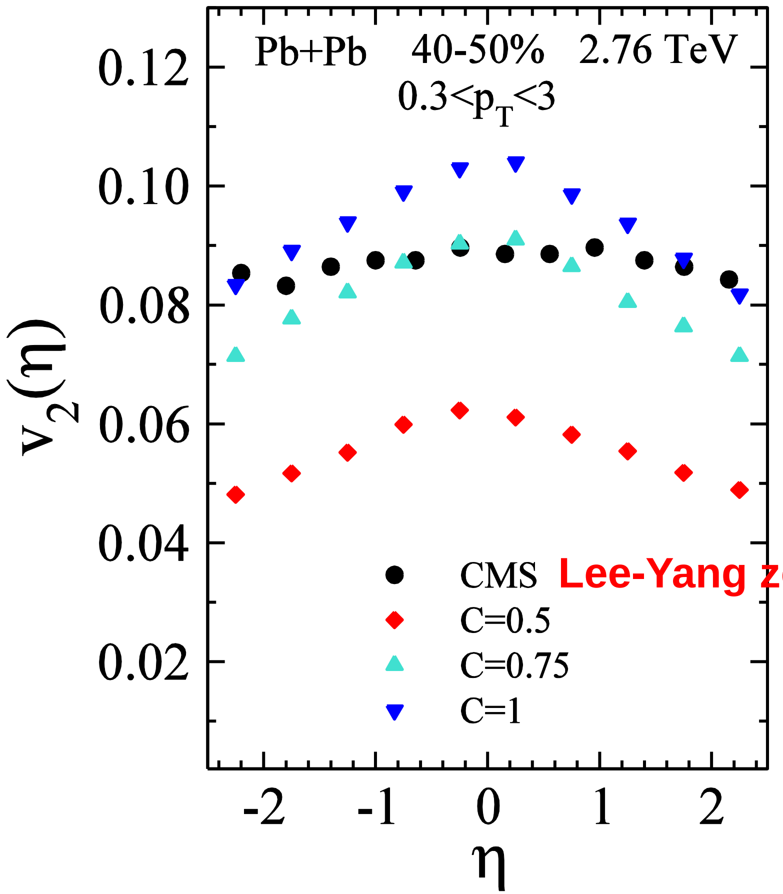
an extra model parameter instead of δ_p

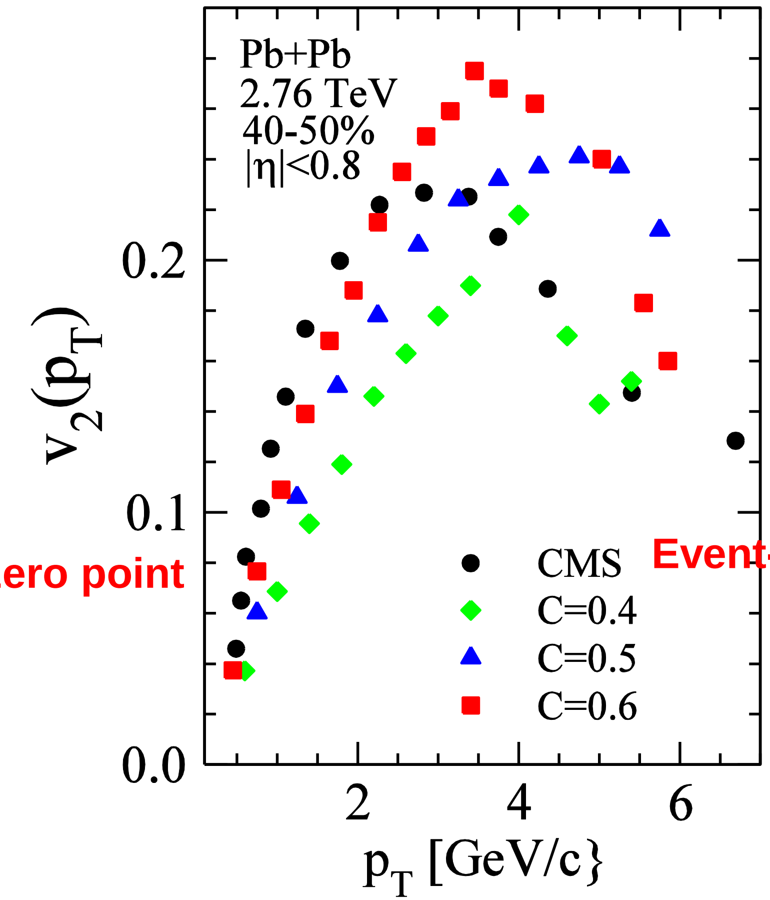
PHENIX, PRC80 (2003) 024909 event-plane



As for the best model parameter C~2 in the left panal but 1 in the right panel, which should be attributed to the particle transverse asymmetry may be difference among the different centrality and η and/or p_T

CMS, PRC87(2013)014902





Charged particle $v_2(\eta)$ *and* $v_2(p_T)$ in the Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76\ TeV$

Upgrade to PACIAE2.2

(Inclusive) Deep inelastic scattering (IDIS), an impotent & hot frontier in between nuclear & particle physics, since eighties of last century.

It plays a crucial role in the field of :

(1) Confinement of quark and gluon in hadron: such as extraction of PDF, FF, & α_s, etc.

(2) Hadronization processes: such as space and time evolutions of hadronization, energy loss, ...

(3) Electron ion collider (EIC) programs:

eRHIC (ELIC)(e-p CM energy, ~20 – 150 GeV),

LHeC (e-p CM energy, more than 1 TeV),

and EIC China → DIS era (yield great insight into the nucleon structure)

We, extend PACIAE for l-p and l-A, to confront with DIS era

Upgrade to PACIAE2.2

Some additions

(1)For p+p & p+A (A+p), OZ is not introduced

(2)l+p & l+A are dealt like p+p & p+A, respectively

(3)For p+Au at RHIC energies, incident proton collides with a few (~3-5) nucleons in target nucleus when it passes through the target

(4)As l+p x-section is a few order of magnitude smaller than p+p, one expects incident lepton collides with nucleon once only when it passes through nuclear target

(5)Struck nucleon is the one with lowest approaching distance from incident lepton

l-p differential cross section can be formally factorized as

$$\frac{d^2\sigma}{dxdQ^2} = \frac{d^2\sigma^{Born}}{dxdQ^2}(1+\delta^{QED})(1+\delta^{weak})(1+\delta^{QCD})$$

$$\frac{d^2\sigma^{Born}}{dxdQ^2} = \frac{4\pi\alpha^2}{xyQ^2}\eta^I$$

$$\left(\left(1-y-\frac{x^2y^2M^2}{Q^2}\right)F_2^I + y^2xF_1^I \mp (y-\frac{y^2}{2})xF_3^I\right)$$

δ^{QED} : QED radiative correction

δ^{weak} : Weak radiative correction

δ^{QCD} : Corrections for QCD processes

QCD radiation:

$V^{*}q \rightarrow q$ *leading order*

$V^{*}q \rightarrow gq$

$V^{*}g \rightarrow q\bar{q}$

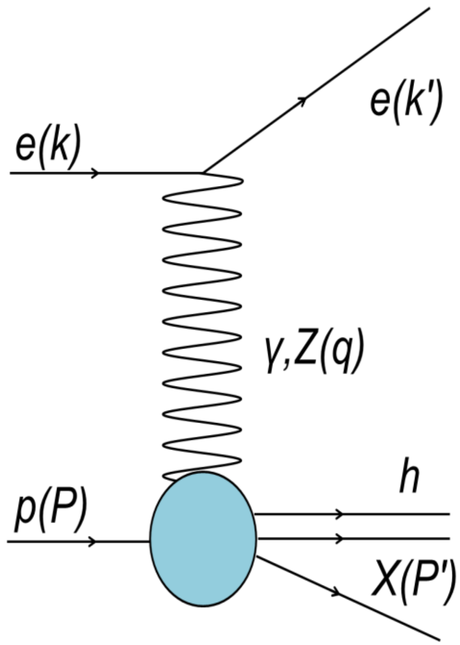
} *first order*

V^{*} : *exchanged virtual boson*

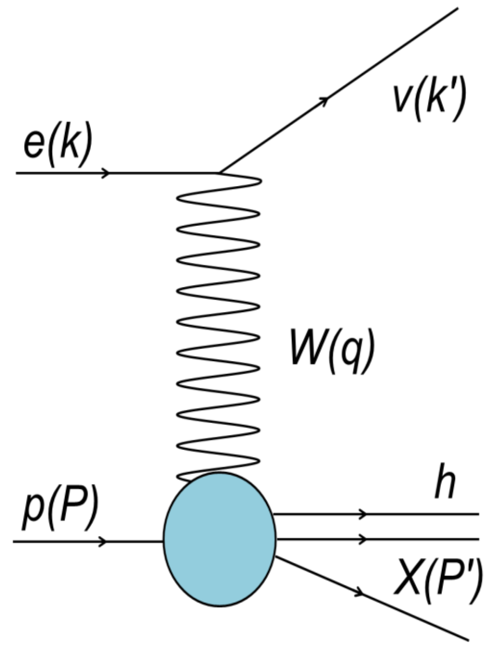
α : *fine structure constant*

$$I = NC : ep \rightarrow eX \text{, by exchange of } \gamma^{*} \,\&\, Z^{0}$$

$$CC : ep \rightarrow vX \text{, by exchange of } W^{\pm}$$



Neutral Current (NC)



Charge Current (CC)

$$\eta^{NC} = 1, \eta^{CC} = (1 \pm \lambda)^2 \eta_W$$

$$\eta_W = \frac{1}{2}\left(\frac{G_F M_W^2}{4\pi\alpha}\frac{Q^2}{Q^2 + M_W^2}\right)$$

$$G_F = \frac{e^2}{4\sqrt{2}\sin^2\theta_W M_W^2}$$

λ : *lepton helicity*

M_W : *mass of W boson*

θ_W : *Weinberg angle*

Corrections are small. Extraction of PDF and FF based on Born approximation is reliable

In quark parton model, structure function of F^{I} can be expressed by PDF:

For NC process:

$$\left[F_2^{\gamma}, F_2^{\gamma Z}, F_2^{Z}\right] = x\sum_q \left[e_q^2, 2e_q g_V^q, g_V^{q2} + g_A^{q2}\right](q+\bar{q})$$

$$\left[xF_3^{\gamma}, xF_3^{\gamma Z}, xF_3^{Z}\right] = x\sum_q \left[0, 2e_q g_A^q, 2g_V^{q2} g_A^{q2}\right](q-\bar{q})$$

$$q = u, c, t: \;\; g_A^q = \frac{1}{2}, \; g_V^q = g_A^q - \frac{4}{3}\sin^2\theta_W$$

$$q = d, s, b: \;\; g_A^q = -\frac{1}{2}, \; g_V^q = g_A^q + \frac{2}{3}\sin^2\theta_W$$

e_q: charge of quark q,

$2xF_1 = F_2$: Callan-Gross relation

For $e^-, \mu^-, \tau^-, \bar{\upsilon}_e, \bar{\upsilon}_\mu, \bar{\upsilon}_\tau$ CC process

$$F_2^W = 2x(u + \bar{d} + c + \bar{s} + t + \bar{b})$$

$$3F_3^W = 2x(u - \bar{d} + c - \bar{s} + t - \bar{b})$$

For $e^+, \mu^+, \tau^+, \upsilon_e, \upsilon_\mu, \upsilon_\tau$ CC process

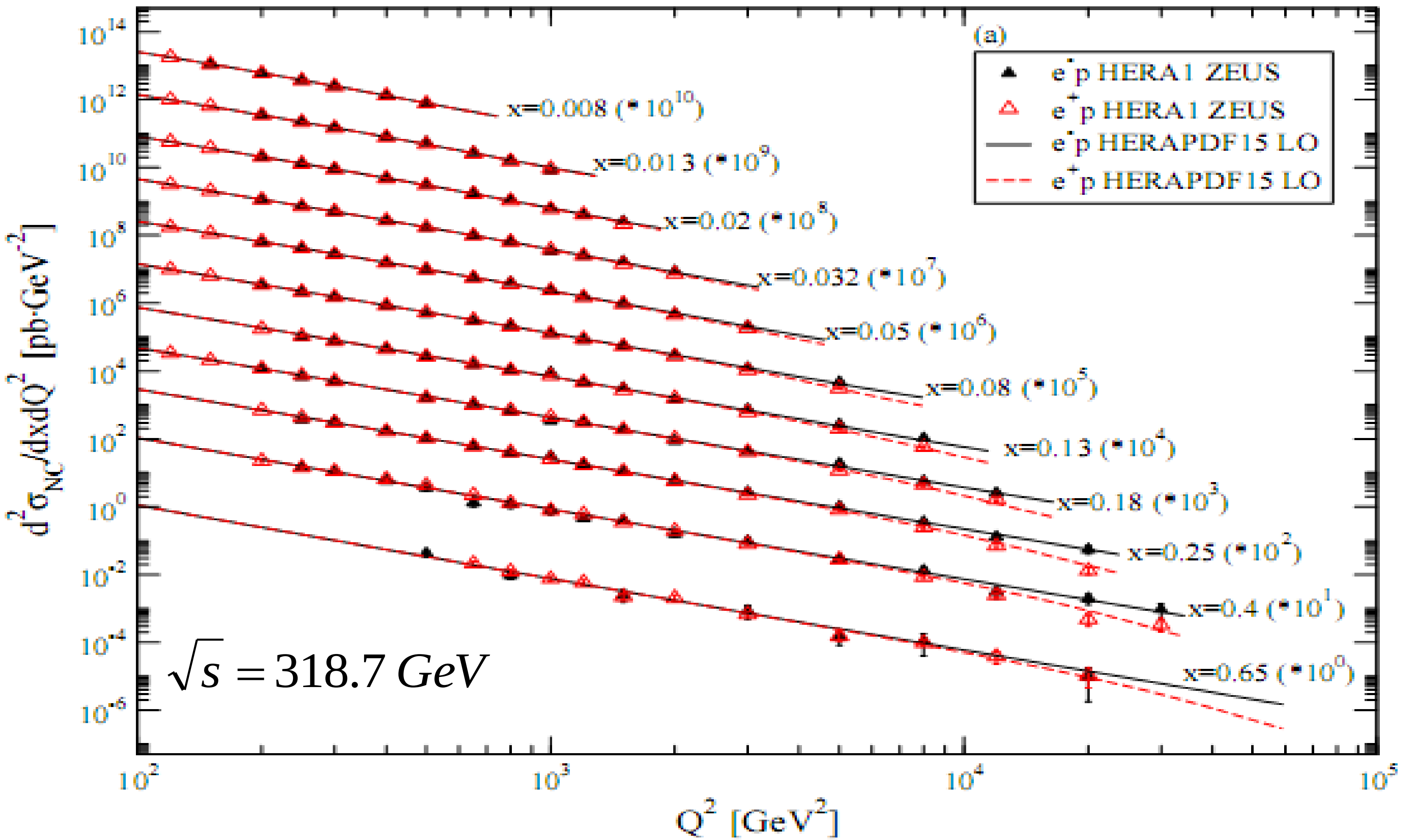
$$F_2^W = 2x(\bar{u} + d + \bar{c} + s + \bar{t} + b)$$

$$3F_3^W = 2x(-\bar{u} + d - \bar{c} + s - \bar{t} + b)$$

PDF can not calculate in first principle

Extracted from QCD fits by a measure of agreement between experimental data of lepton-nucleon DIS x-section and the theoretical calculations

With PDF set at hand, one can calculate DIS differential & total x-sections

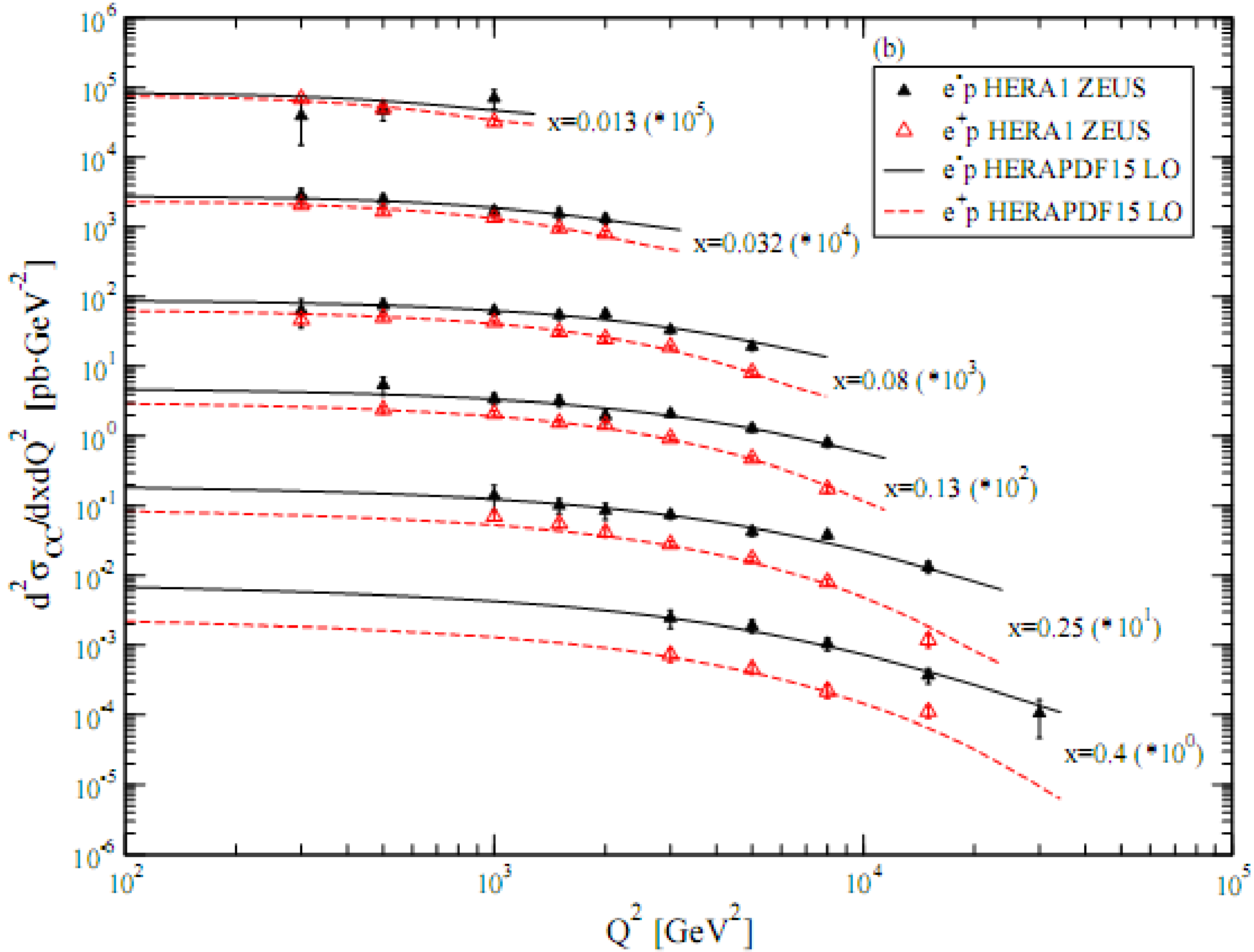


*Triangles are data <- F.D.Aaron, etal., JHEP, **01**,01 (2010)*

Lines are calculated with PDF set of HERAPDF1.5 LO <-

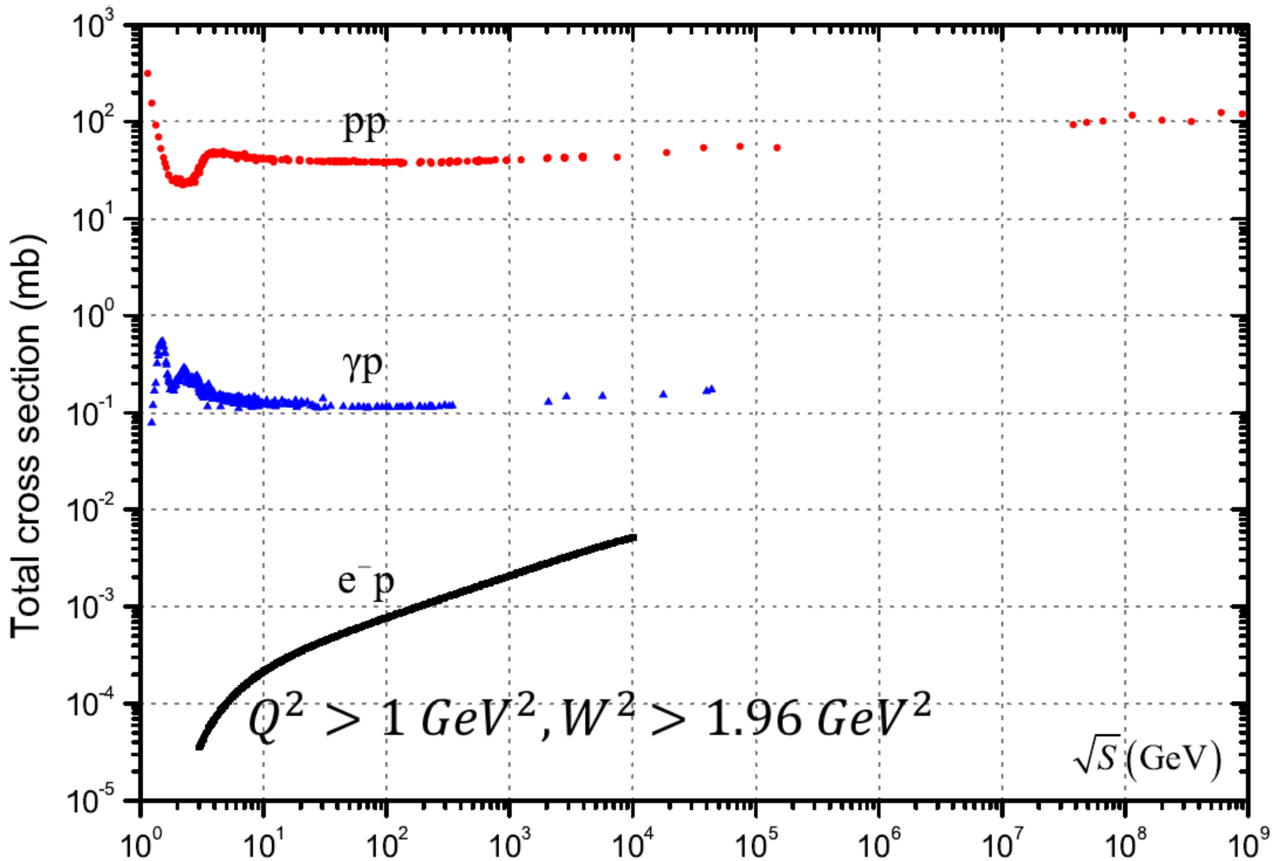
H1 and ZEUS Collab., H1 prelim 13-141 and ZEUS-prel-13-003

agreement between theory & experiment is good


(b)
e⁻p HERA1 ZEUS
e⁺p HERA1 ZEUS
e⁻p HERAPDF15 LO
e⁺p HERAPDF15 LO
x=0.013 (*10^5)
x=0.032 (*10^4)
x=0.08 (*10^3)
x=0.13 (*10^2)
x=0.25 (*10^1)
x=0.4 (*10^0)
d²σ_CC/dxdQ² [pb·GeV⁻²]
Q² [GeV²]

One sees here: the agreement between theory & experiment is good

Properly integrating differential x-section, total x-section is obtained, shown in following figure



pp & γ p <- Review of Particle Physics

e⁻p total x-section, ~four order of magnitude smaller than pp

HERMES Collaboration identifies that, specific charged hadron yield of π^+, π^-, K^+,& K^- in DIS is crucial for reliable extraction of FF, with quark FF of $D_q^h(z, Q^2)$ distinguished from antiquark FF of $D_{\bar{q}}^h(z, Q^2)$

HERMES measured $\pi^+, \pi^-, K^+, \& K^-$ yields in e^--p & e^--D DIS at 27.6 GeV beam energy, and corrected the measured yield of type h hadrons for:

- limitation in geometric acceptance
- radiative effect
- detector resolution

Born-level yield is then obtained which is of benefit to the extraction of PDF

On the other hand, they normalize the measured yield by DIS yield (yield of scattered e⁻) & obtain the normalized hadron yield as a function of z, for instance

$$\frac{1}{N_{DIS}}\frac{dN^h}{dz}=\frac{1}{N_{DIS}}\int d^5N^h(x_B,Q^2,z,P_{h\perp},\phi_h)dx_B dQ^2 dP_{h\perp}d\phi_h$$

integrate it over all the dimensions, except z
z refers to fraction energy of generated hadron

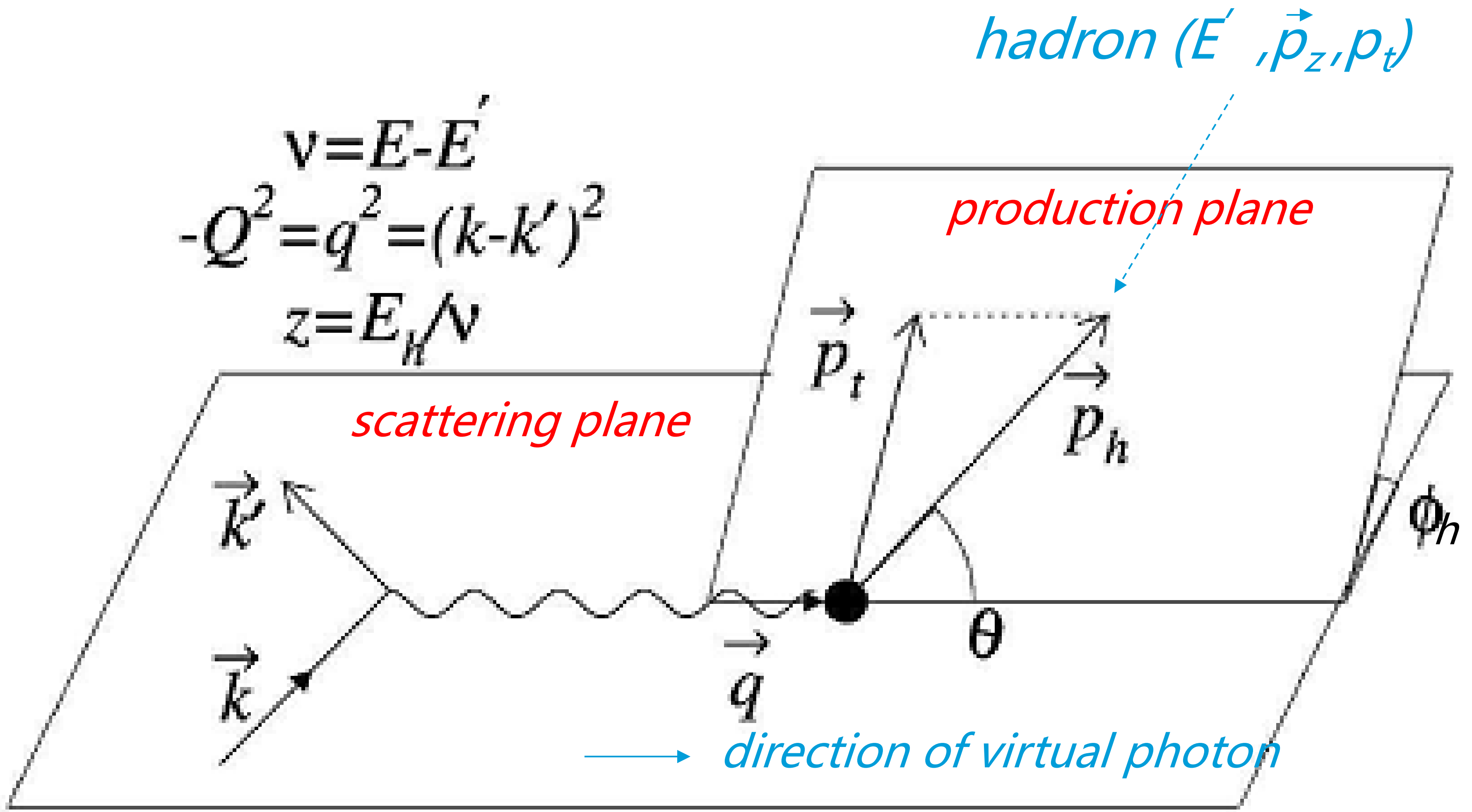
TABLE I: Kinematic variables in the lepton-nucleon DIS.

$k = \left(E, \vec{k}\right), k' = \left(E', \vec{k}'\right)$	incident, scattered lepton 4-momentum
$P \overset{\text{lab}}{=} \left(M, \vec{0}\right)$	4-momentum of the target nucleon
$q = k - k'$	squared 4-momentum transfer (4-momentum of the virtual photon)
$Q^2 = -q^2 \overset{\text{lab}}{\approx} 4EE'\sin^2\left(\frac{\theta}{2}\right)$	Negative squared 4-momentum transfer
$\nu = \frac{P\cdot q}{M} \overset{\text{lab}}{=} E - E'$	Energy transfer to the target nucleon
$W^2 = (P+q)^2$	Squared invariant mass of the photon-nucleon system
$y = \frac{P\cdot q}{P\cdot k} \overset{\text{lab}}{=} \frac{\nu}{E}$	Fractional energy of the virtual photon (inelasticity)
$z = \frac{P\cdot P_h}{P\cdot q} \overset{\text{lab}}{=} \frac{E_h}{\nu}$	Fractional energy of hadron h
$x_{\text{B}} = \frac{Q^2}{2P\cdot q} \overset{\text{lab}}{=} \frac{Q^2}{2M\cdot\nu}$	Bjorken scaling variable
ϕ_h	Azimuthal angle between the lepton scattering plane and the hadron production plane
$P_{h\perp} \overset{\text{lab}}{=} \frac{\left\lvert\vec{q}\times\vec{P}_h\right\rvert}{\lvert\vec{q}\rvert}$	Component (transverse to q) of the hadron momentum (P_h)

Two independent variables:

in the past: (E', θ)

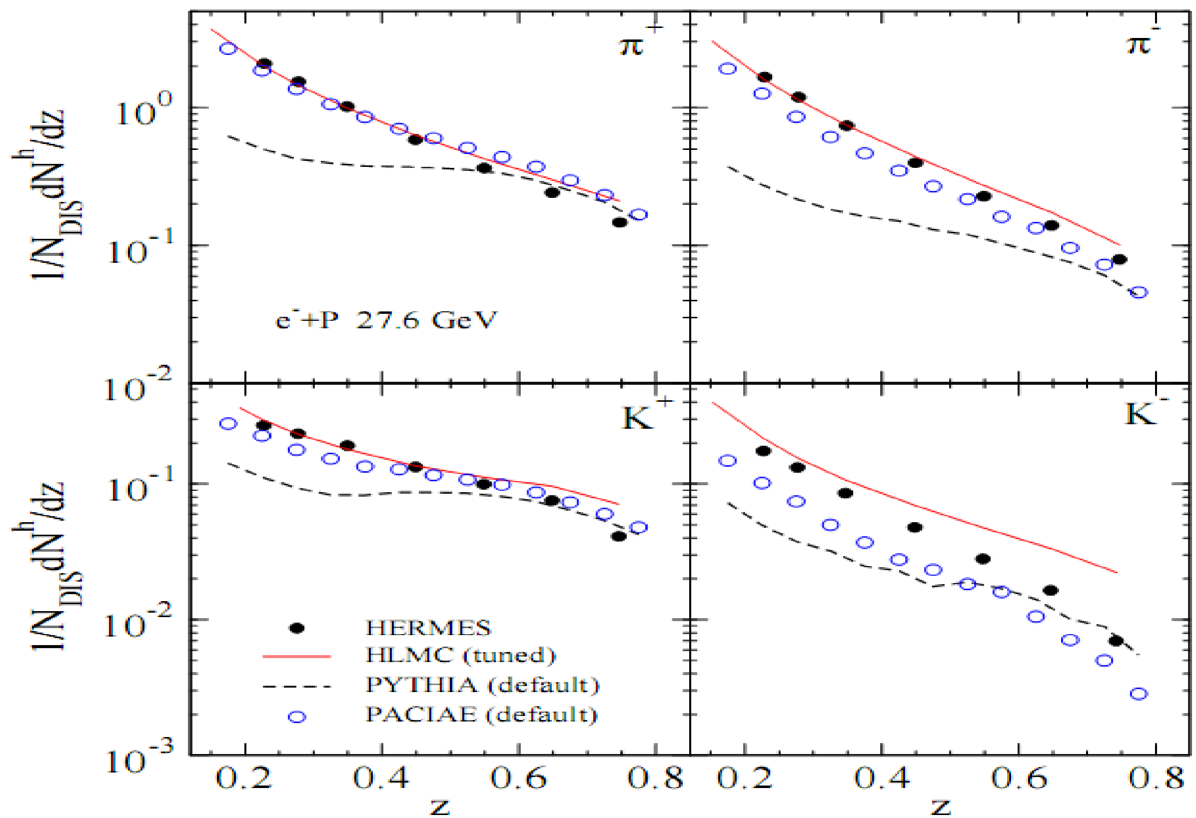
presently: (x_B, Q^2); or (x_B, W^2); or (x_B, y)



hadron (E′ ,$\vec{p}_z$,p_t)
ν=E-E′
$-Q^2=q^2=(k-k')^2$
$z=E_h/\nu$
production plane
scattering plane
$\vec{p}_t$
$\vec{p}_h$
$\vec{k}'$
$\vec{k}$
$\vec{q}$
θ
ϕ_h
direction of virtual photon

DIS normalized hadron yield is not so sensitive to the above corrections, therefore it is of benefit to the comparison among measurements and between experiment and theory

Comparison with HERMES data



- Default PYTHIA disagrees with HERMES data
- Default PACIAE agrees with HERMES data & agreement, ~same as HLMC

HLMC: composed of

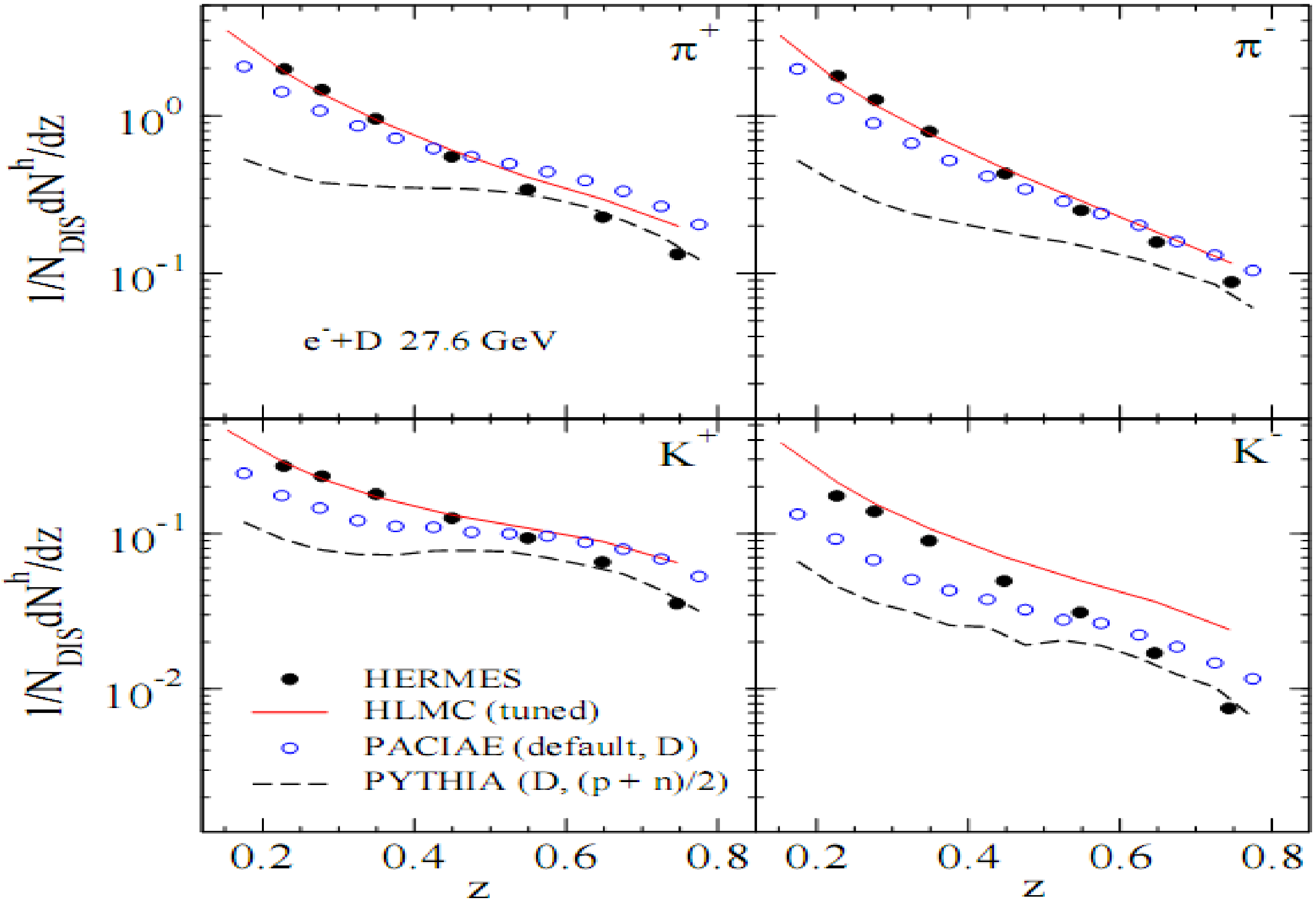
(1)Lepto e-p event generator

<- JETSET 7.4 & PYTHIA 5.7

(2)Program for detector simulation <- GEANT

(3)Event reconstruction

HLMC results, calculated with thirteen parameters tuned to the yield as function of z, pT, & η of pion-, kaon-, & anti-proton



This figure tells us same story as previous one, but for $e^{-}D$ SIDIS at same beam energy

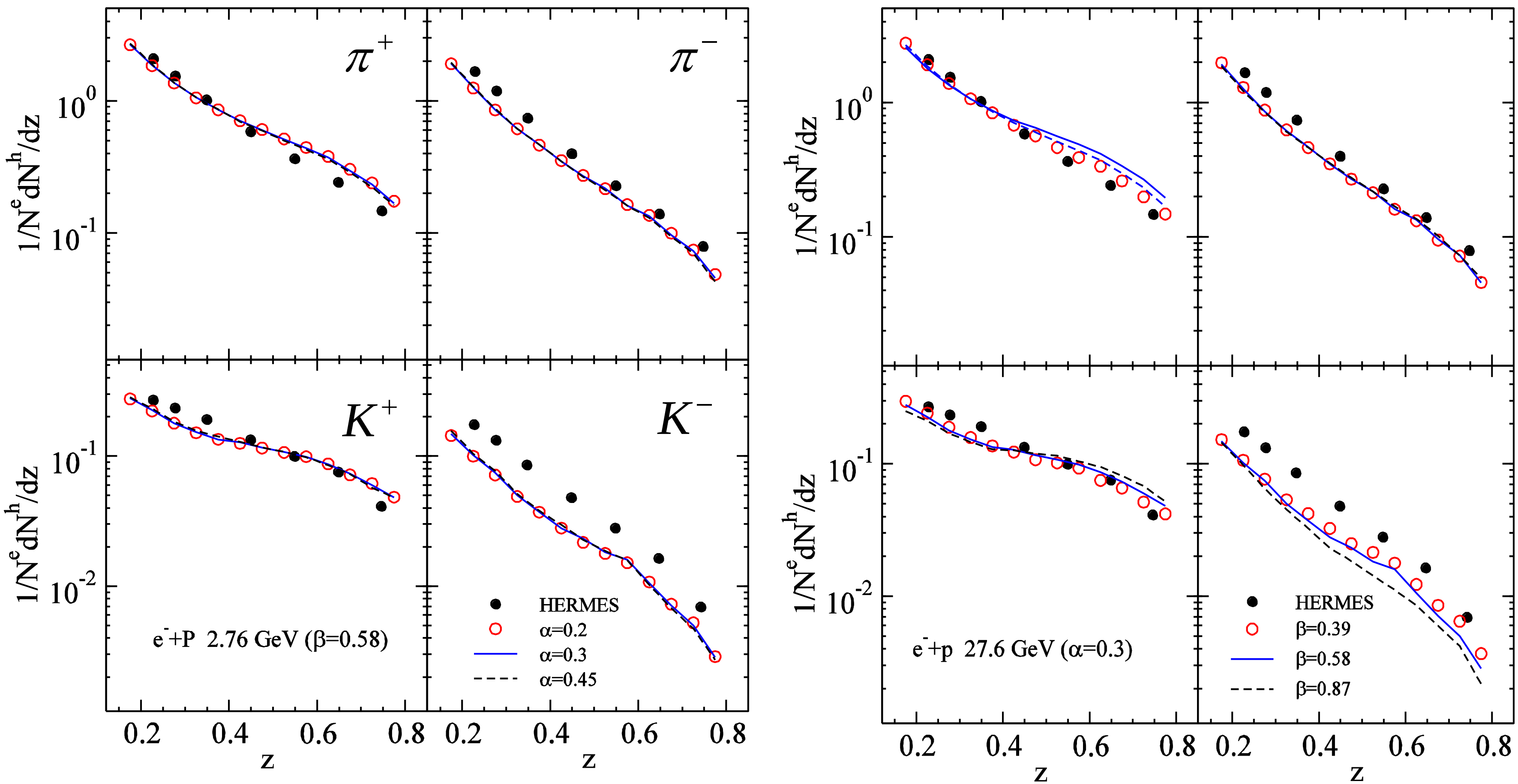
Investigated the effect of α and β parameters

in the Lund string fragmentation function on the

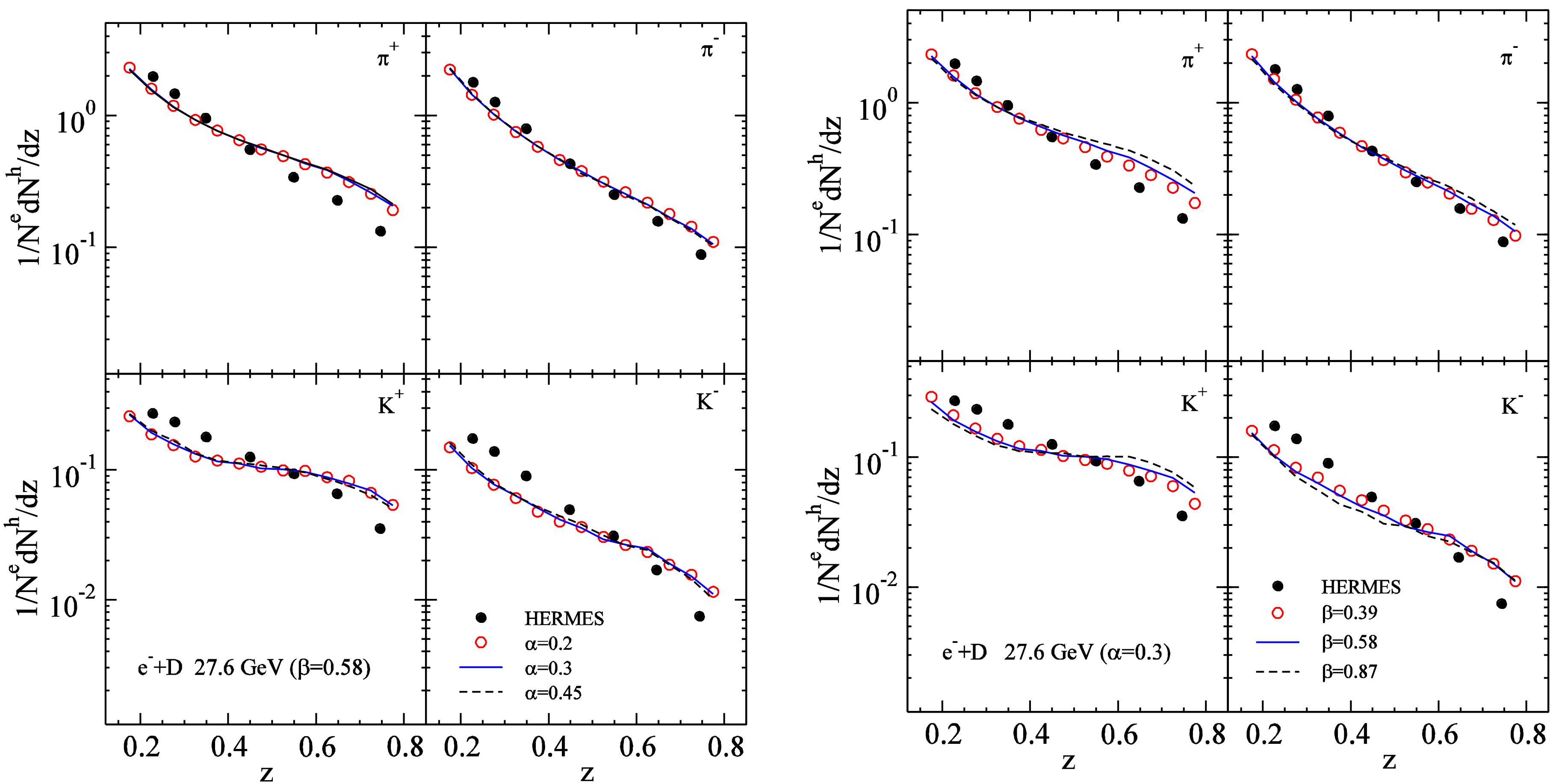
multiplicity

$$f(\bar{z}) \propto \frac{1}{\widehat{z}}(1-\widehat{z})^{\alpha} \exp(-\frac{\beta m_T^2}{\widehat{z}})$$

$\widehat{z}$ The fraction lightcone variable taken by the fragmented hadron out of the fragmenting particle



The multiplicity increases (decreases) with $\alpha(\beta)$ increasing


π+
π-
K+
K-
1/N^e dN^h/dz
z
e-+D 27.6 GeV (β=0.58)
HERMES
α=0.2
α=0.3
α=0.45
e-+D 27.6 GeV (α=0.3)
β=0.39
β=0.58
β=0.87

Conclusions

PACIAE can describe the corresponding experimental data

Big discrepancy between results of PYTHIA and PACIAE has to be attributed to the initial partonic state, introduced in PACIAE, not in PYTHIA

Thanks for your attention!