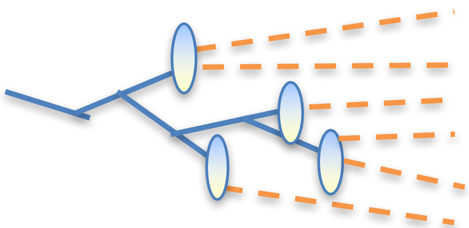
Jets at medium energies

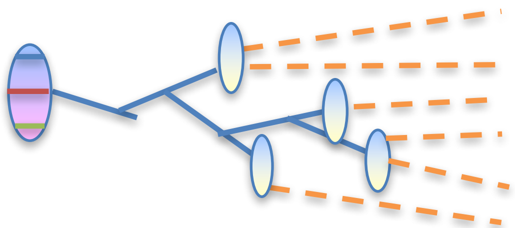
Accardi, Brooks, Diefenthaler, Yulia Furletova, Vitev, Weiss

U.S. DEPARTMENT OF ENERGY · JSA · Jefferson Lab

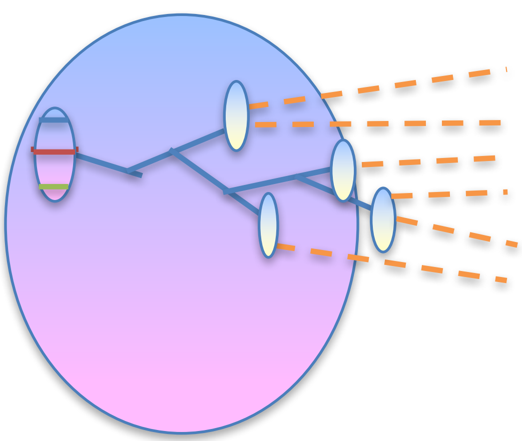
Physics with Jets at EIC



1) **Jets evolution and dynamics**
   - ✓ radiation/hadronization mechanism.
   - ✓ formation of a jet
   - ✓ reconstruction algorithms

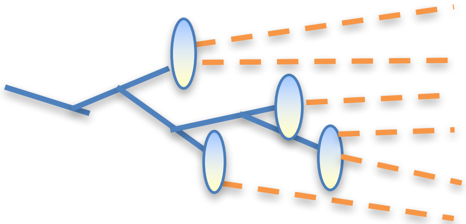


2) **Jets as a probe of partonic initial state**
   - ✓ gluons (at high x) , quarks/ani-quarks

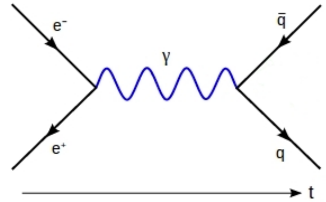


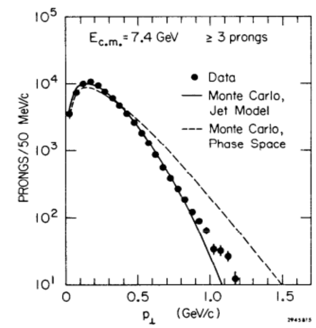
3) **Jets in medium**
   - ✓ energy loss, quenching
   - ✓ broadening
   - ✓ multiple-scattering.

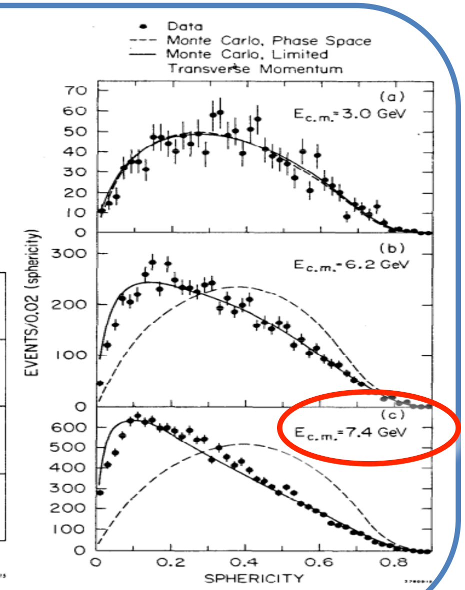
1) JETS EVOLUTION AND DYNAMICS



HISTORY, JETS



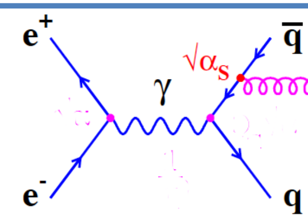


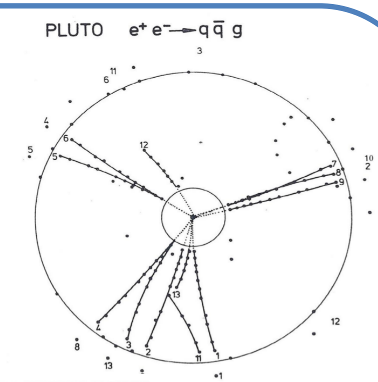


- Evidence for jets arising from quarks was first obtained using the Mark I detector at the SPEAR e+e- at SLAC in 1975
- For very low-energy collisions: no preferred directions for hadrons. At slightly higher energies hadrons fly out in narrow streams that are referred to as jets: sphericity

$$S = \frac{3\sum_i \mathbf{p}_{\perp i}^2}{2\sum_i \mathbf{p}_i^2}$$

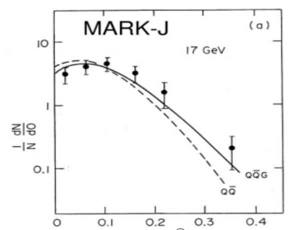
- Gluon jets. PLUTO Collaboration at DORIS (3-10 GeV e+e- at DESY) in 1979 . The 3-jet events were interpreted as quark pairs with an additional hard gluon.
- The ratio of 3-jets events to 2-jets events ~ 0.15 (at $\sqrt{s}$ ~20 GeV). First measurements of α_s.
- The JADE collaboration measured as as a function of Q2 in a limited range of $\sqrt{s}$ (20 < $\sqrt{s}$ < 44 GeV) using the three-jet rate and established the running of α_s (Q2).

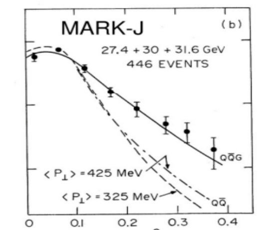




Oblateness:

$O = \Sigma_i \mathbf{p}_i \cdot \mathbf{e2} / \Sigma_i |\mathbf{p}_i| - \Sigma_i \mathbf{p}_i \cdot \mathbf{e3} / \Sigma_i |\mathbf{p}_i|$.

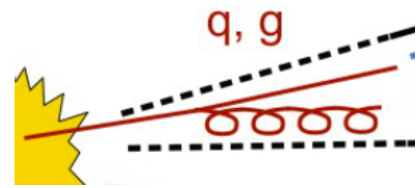




WHAT IS A JET?

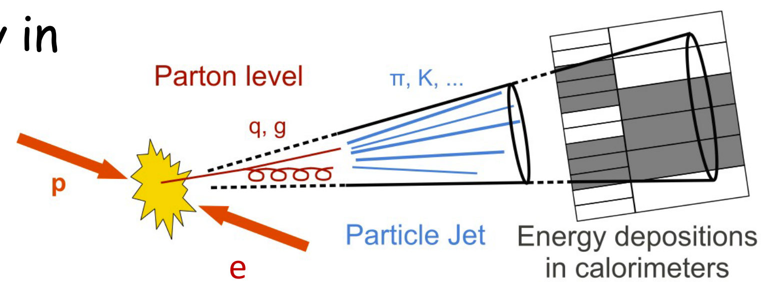
ask Google:

Jets for theorists: number of partons: gluons, quarks

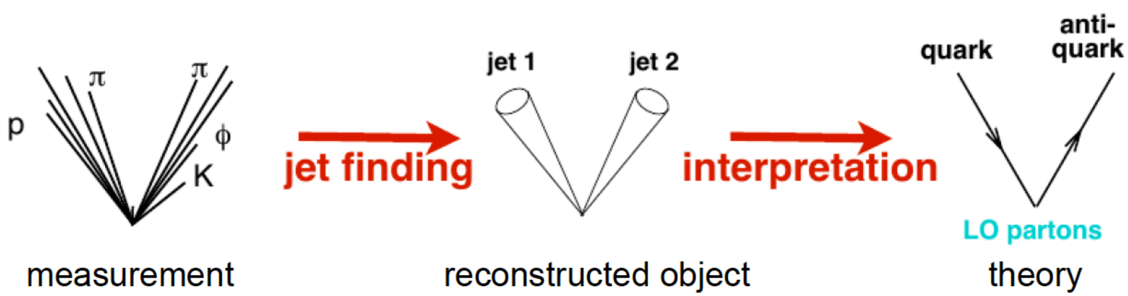


Jets for experimentalists:
number of collimated tracks which leaves energy in a calorimeter

K.Muller



Jet is a bunch of collimated particles (mostly hadrons), moving into direction of initial parton (quark, gluon)

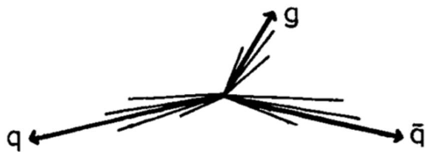


How well do we understand this transition?

JET HADRONIZATION

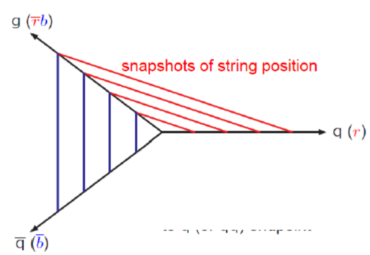
Main models :

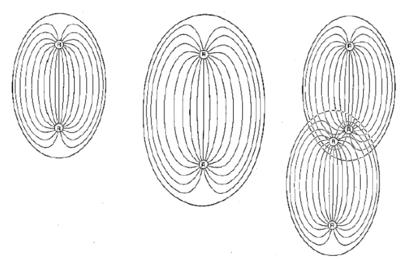
- Independent model (Field-Feynman model) quarks and gluons fragment independently

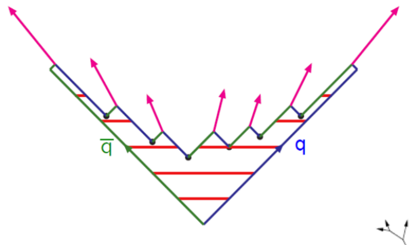


- String Model (Lund) : JETSET PYTHIA

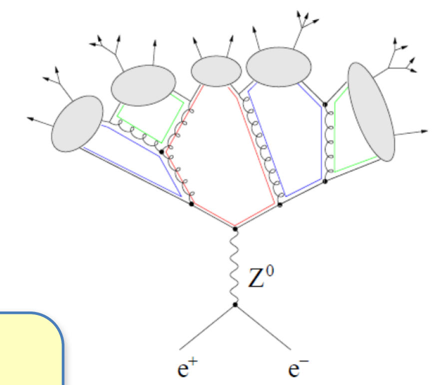
(the most used hadronization model, very successfully tested in e+e-)







Rainer Fries



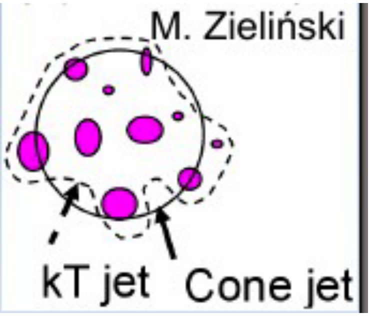
- Cluster Fragmentation Model: HERWIG

force gluon decays into quarks and antiquarks, q-qbar form colorneutral clusters , clusters decay isotropically into 2 hadrons , which can decay further into stable hadrons.

Note, those models lead to different distributions for low momentum particles . For high momentum (β-> 1) particles the differences vanish.

Study hadronization on existing colliders (e+e-), so that it could be used by other communities(ep,pp)

JET RECONSTRUCTION



Jet is an object defined by an algorithm:

Two "categories" of jet algorithms:

1) Cone jets (Cone, SisCone, MidCone) traditionally for hadron colliders

-draw cone radius R around starting point (calorimeter towers with energy above threshold, "seeds").

-iterate position of cone until "stable" position is found

2) Clustering: sequential recombination (Jade, k_T, anti-k_T) traditionally e+e-,ep

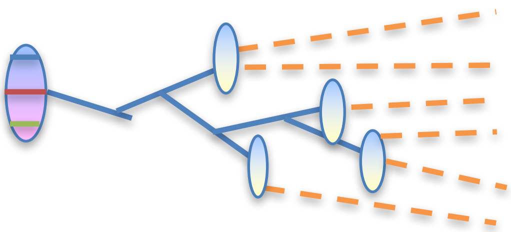
- uses the knowledge that final state particles in a jet are largely collinear ie. have small transverse momentum between their constituent particles.

- algorithm begins to create a list of the momentum-space distance....

k_T algorithms (compared to cone algorithms) have the tendency to combine more energy into jets.

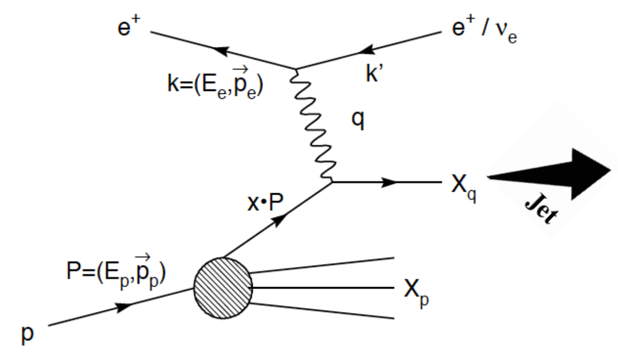
Jet is an object defined by an algorithm. If parameters are right it may approximate a parton. Physics results (particle discovery, masses, PDFs, coupling) should be independent of a choice of jet definition.

2) Jets as a probe of partonic initial state

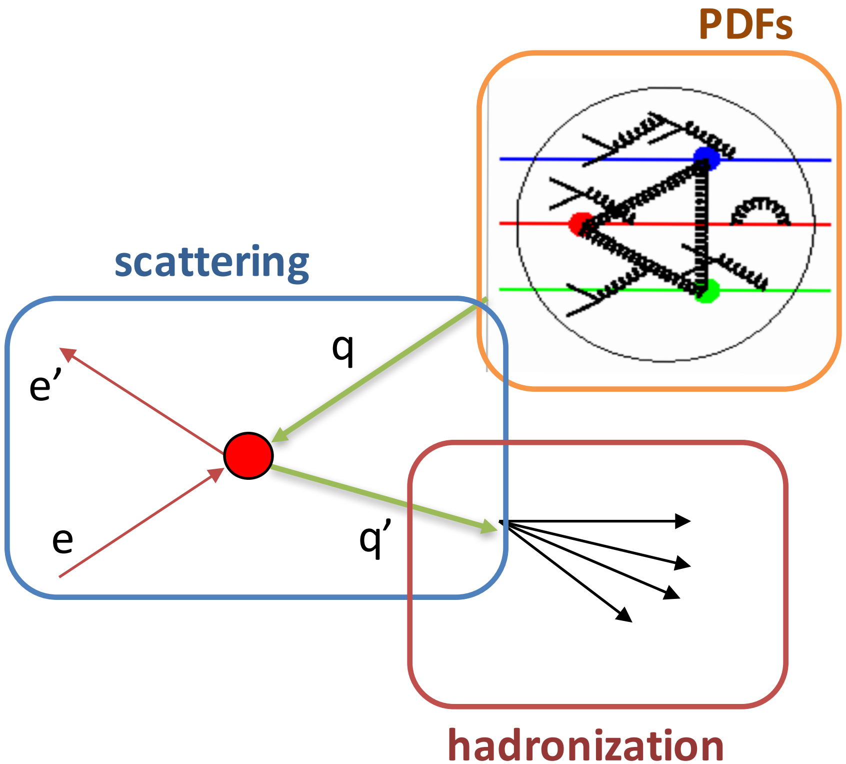


JETs AT EIC

- LO jet production at ep. (DIS)
- Provide a connection between pQCD and non-pQCD



- Initial parton distributions: PDFs
  - Long range = non-perturbative
- Hard scattering of two partons
  - Short range = perturbative
- Hadronization of scattered partons
  - Long range = non-perturbative



Ali Hanks

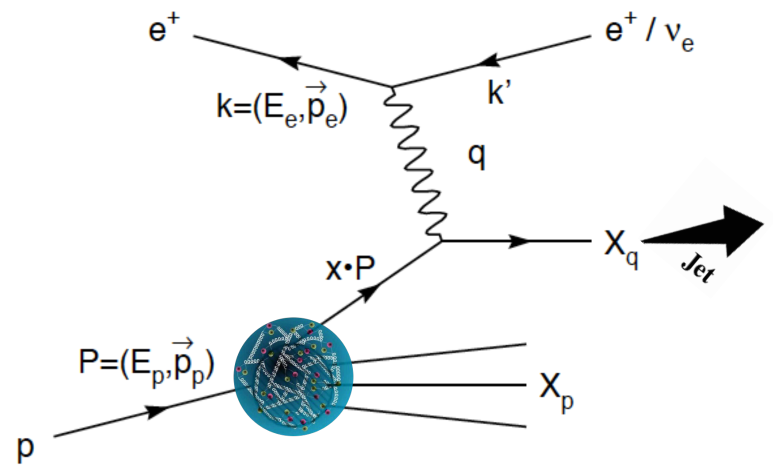
- The emergence of hadrons – mass from massless gluons and nearly-massless quarks
- Emergence of colorless hadrons from the elementary color charge.

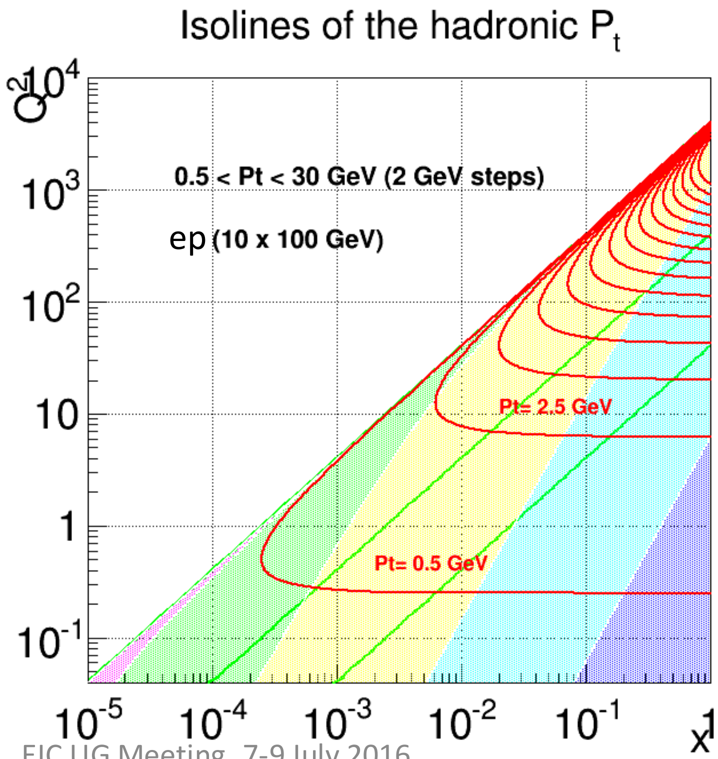
Jets provide a connection between pQCD and non-pQCD

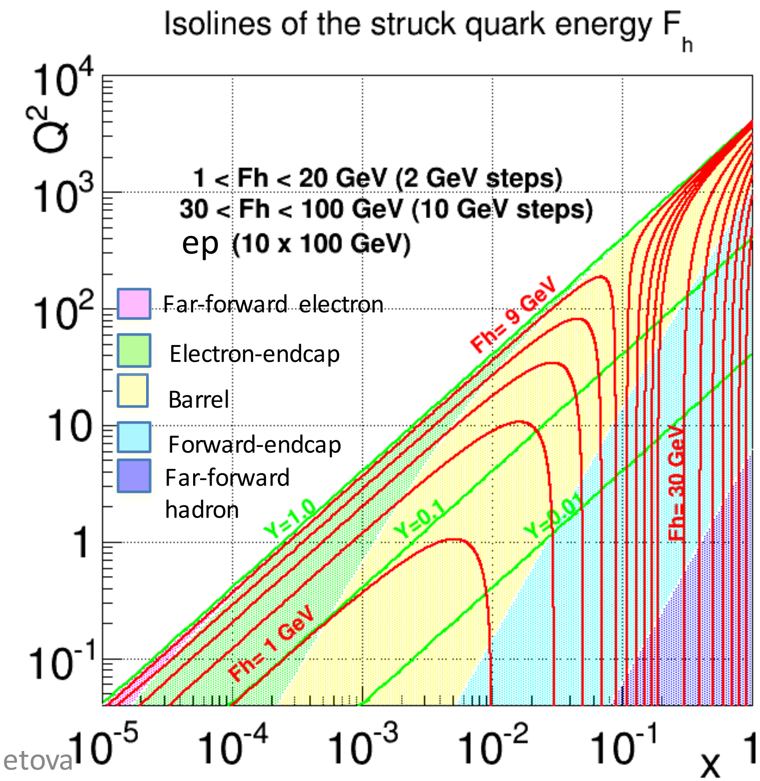
JETS AT EIC

Jet approximates a parton

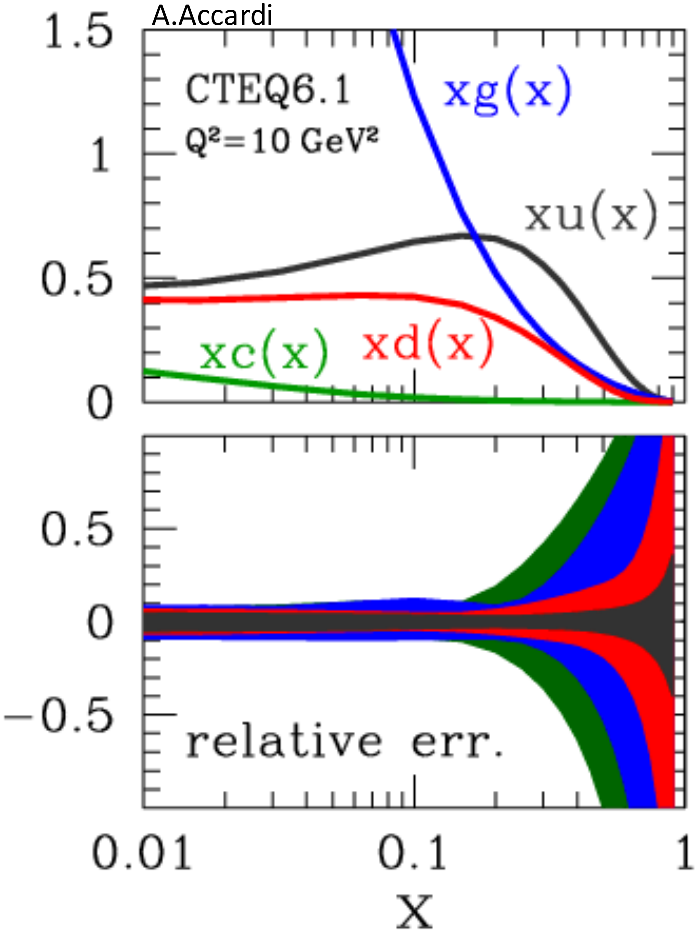
- Struck quark energy Fh ~1-100 GeV



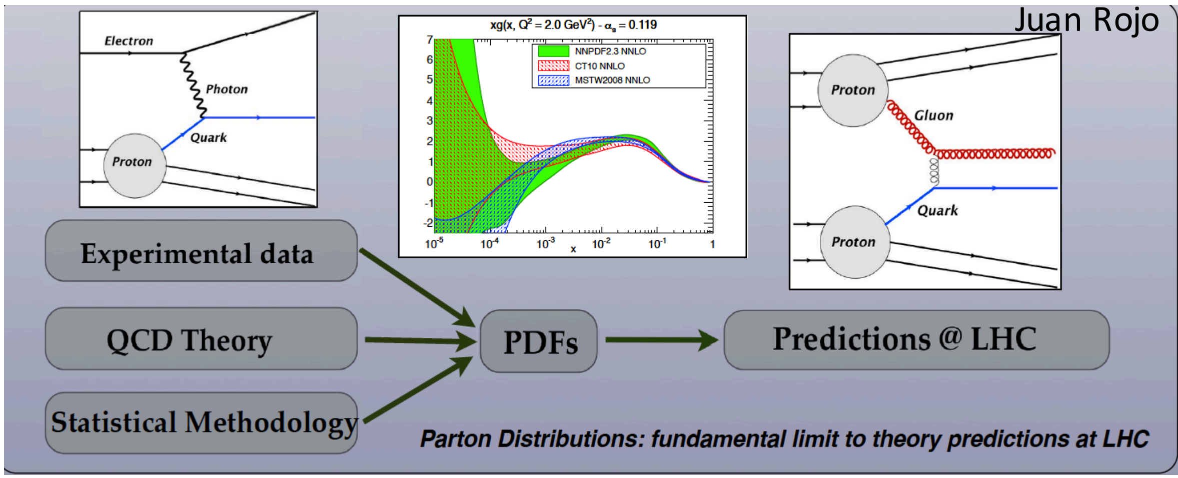




VALENCE AND SEA QUARK PDFs

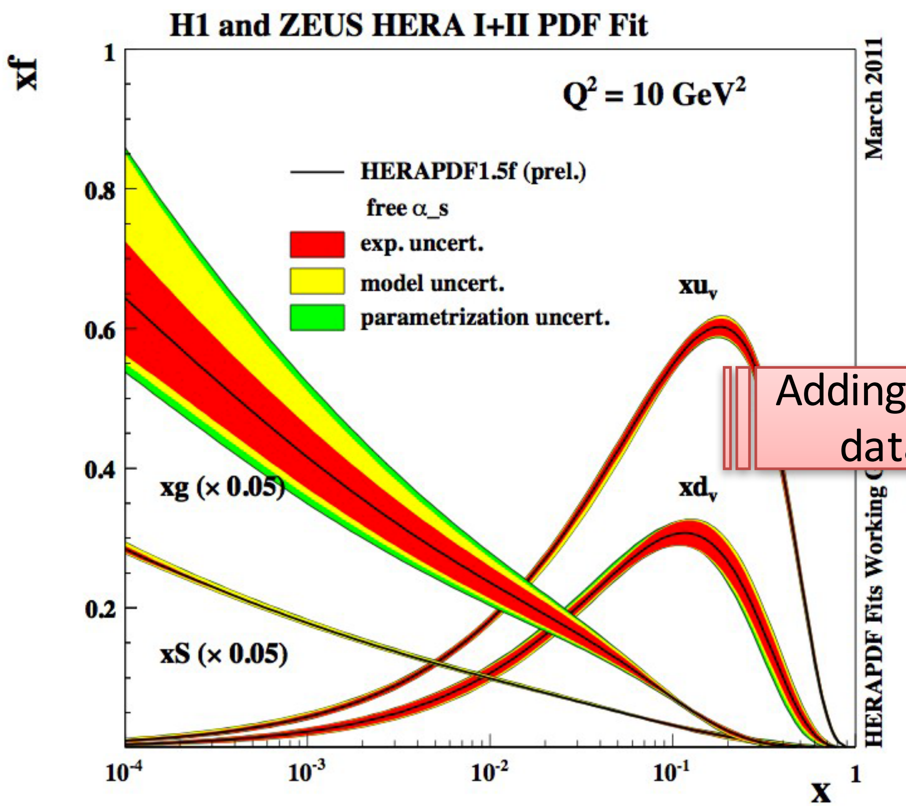


- Large (experimental) uncertainties in Parton Distribution Functions (PDFs)
- Precise PDFs at large x are needed
  - reduce QCD background
  - optimize searches involving large masses
  - precisely characterize new particles

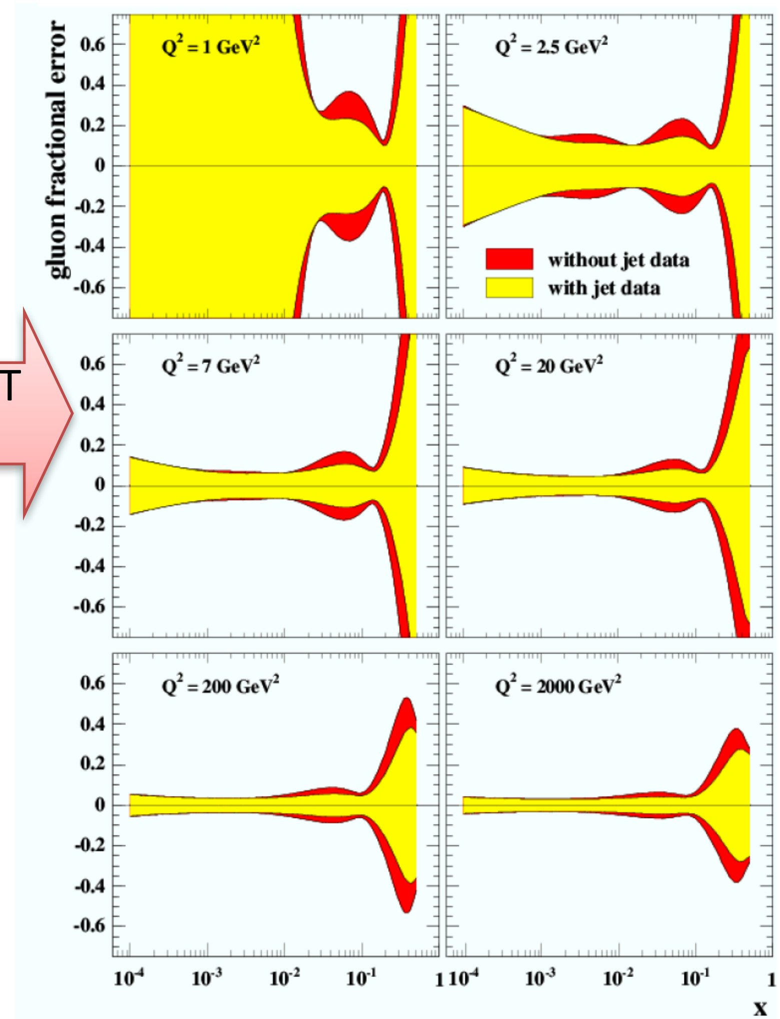


Parton distribution is a fundamental limit to predictions at LHC

GLUON PDF WITH JETS (HERA)



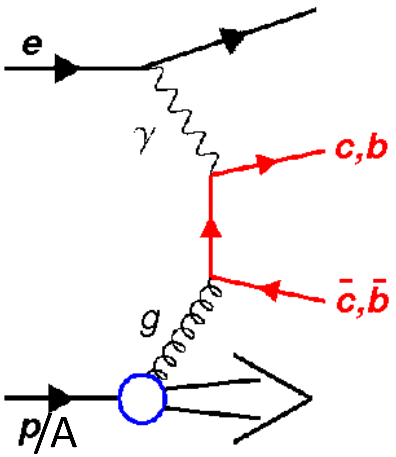
Adding JET data



There is a significant improvement to the PDF uncertainties (particularly at large values of x >0.01)

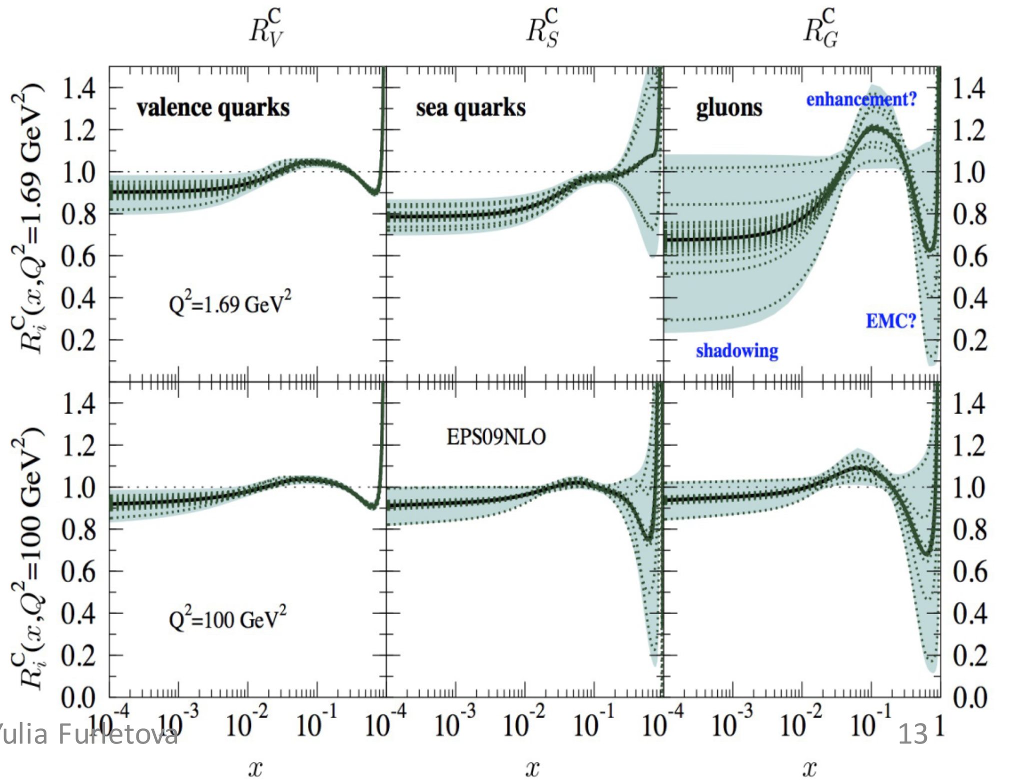
CHARM AND BEAUTY JETS

JLAB LDRD, C. Weiss

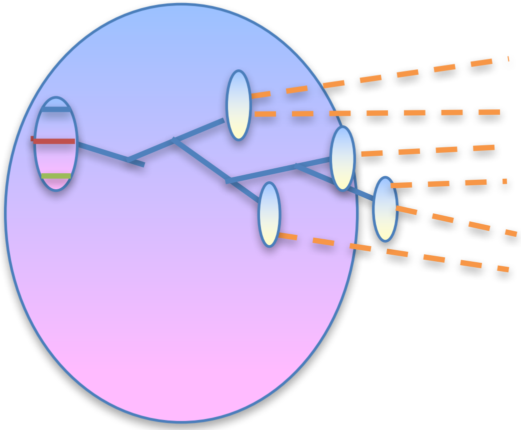


- LO Charm/Beauty production in DIS via Boson-gluon fusion (BGF)

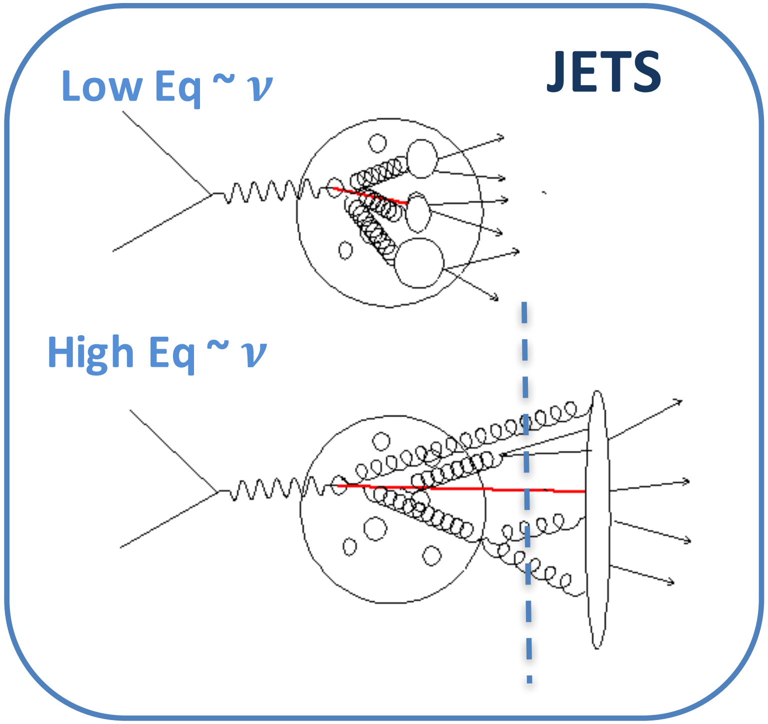
- Charm and beauty jets provide:
  - Direct access to the nuclear gluon
  - Especially at high-x:
    - EMC(x>0.3)
    - Enhancement(x>0.1)
  - Significant constrain on heavy quark mass

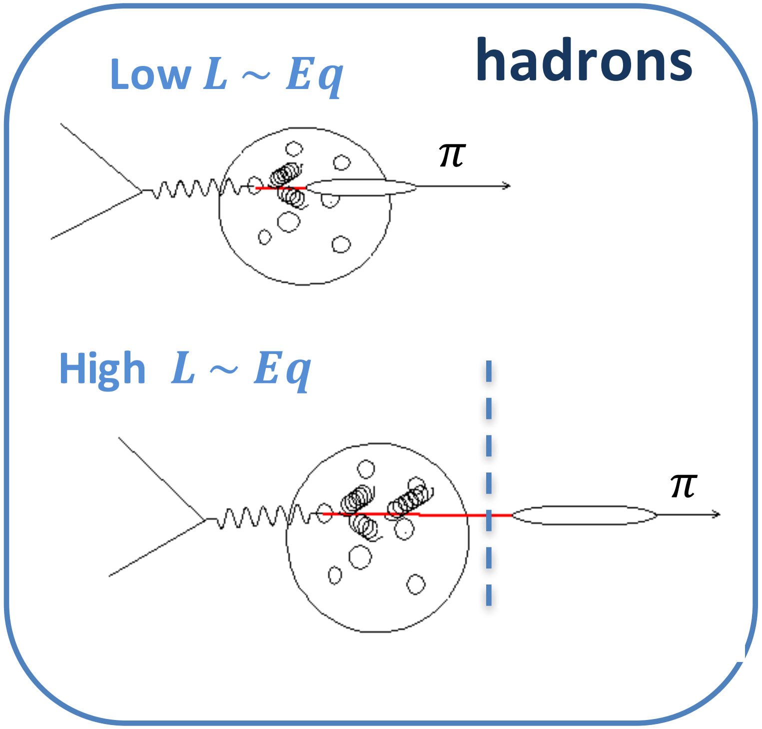


3) JETS IN MEDIUM



JETS VS HADRONS AT EIC

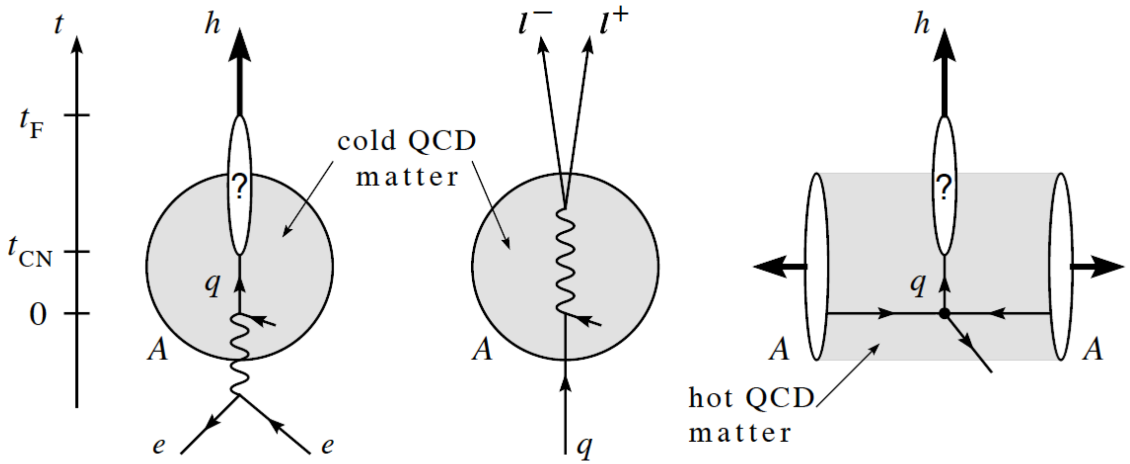




A wide range of EIC kinematic (Eq ~ 1-100 GeV), plus a good control of kinematic variables, would allow to study all of these regions and mechanisms

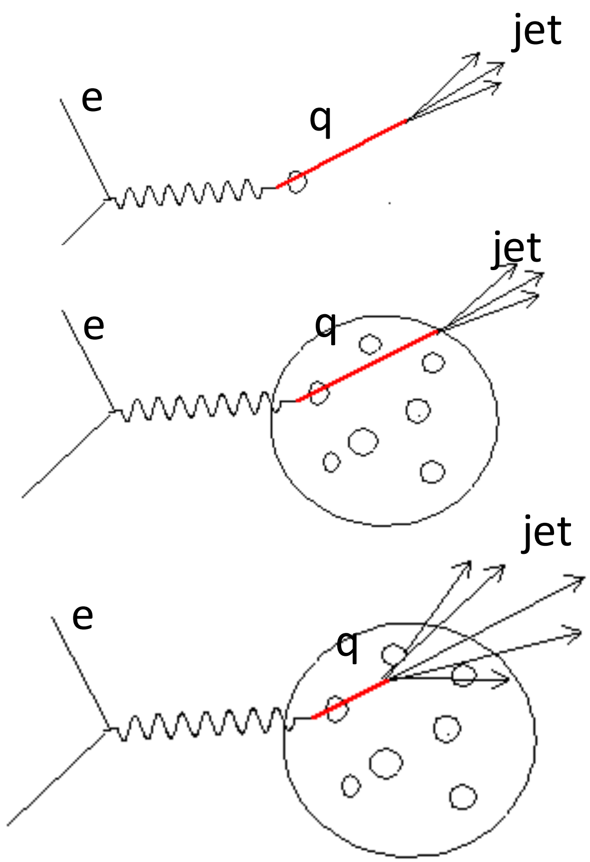
IN-MEDIUM HADRONIZATION AT EIC

Emergence of colorless hadrons from the elementary color charge.



- Nuclear deep-inelastic scattering "Cold QCD matter" provides good experimental control of the kinematics and permits to use nuclei as femtometer-detectors of hadronization process.
- Time scale for neutralization of color charge (pre-hadron formation) and formation of "physical" hadrons = > First step towards understanding of color-charge dynamics.

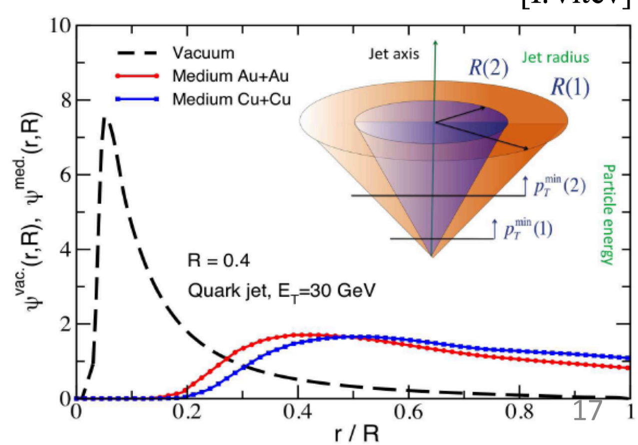
IN-MEDIUM HADRONIZATION AT EIC (EP VS EA)



- In high energy colliders: in-vacuum hadronization.
- For eA where hadronization take place in vacuum or in-medium?
- Low-energy jets for in-medium hadronization studies.
- In-medium hadronization:
  - Broadening of jets ?
  - Number of hadrons in jets? Hadrons recombination? Or enhancement?
  - How would it influence the hadronic structure of jets? (more neutral or more charged hadrons?)

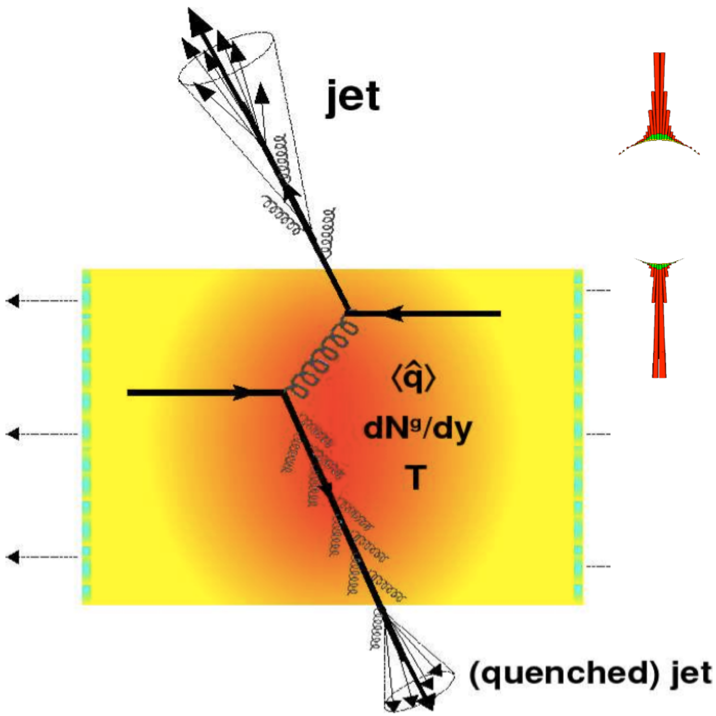
With low energy jets study of a IN-MEDIUM hadronization

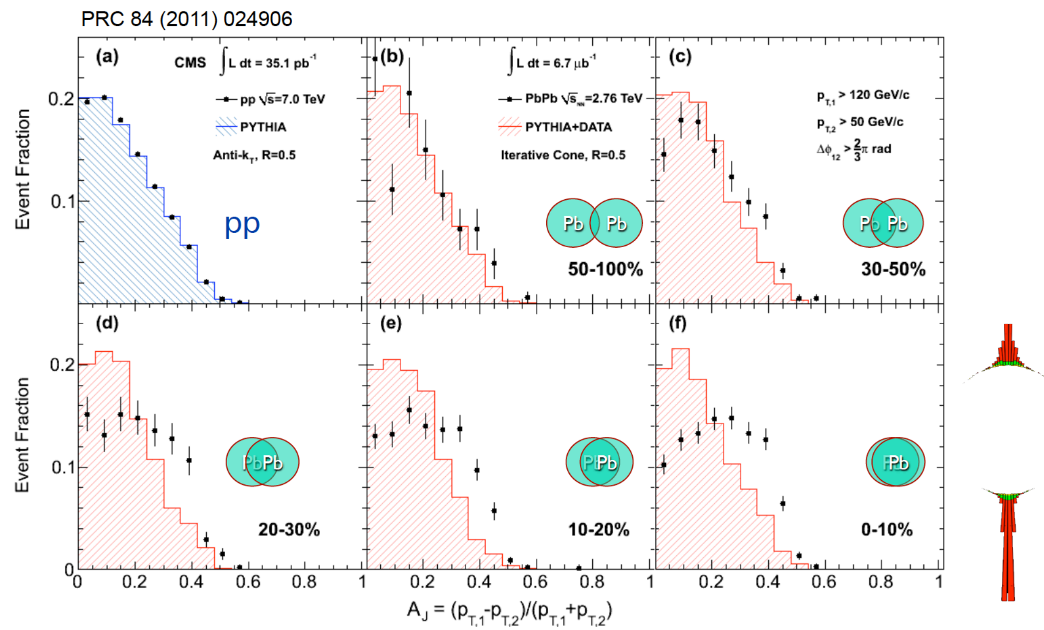
[I.Vitev]



JET QUENCHING

- A hard parton traversing dense strongly-interacting matter looses part of its energy. This effect is called jet quenching and it results in a decreased yield of high-*pt* particles, as observed at RHIC.





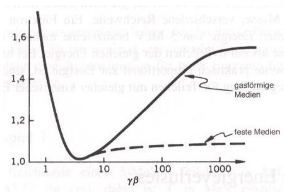
ENERGY LOSS OF QUARKS (JETS)

Interaction of Charged Particles with Matter:

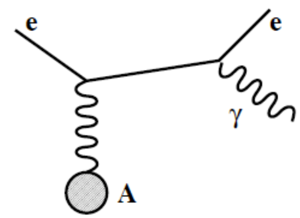
- Interaction with atomic electrons:
  Ionization and excitation

Energy loss is independent of the mass
a charge and velocity of the incoming particle.
Relatively independent of the absorber (Z/A).
At βγ≈3.5 energy loss in the mimimum :
(MIP)

$$\left.\frac{dE}{dx}\right|_{min} \approx 1.5\frac{MeV \cdot cm^2}{g}$$

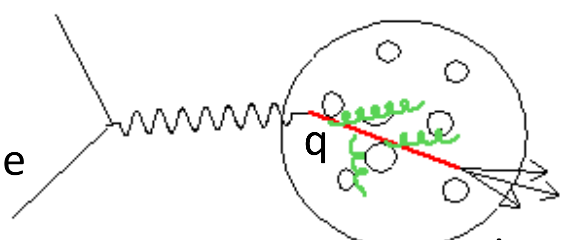


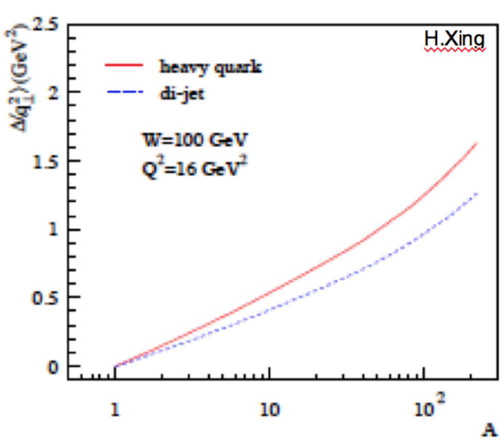
- Interaction with atomic nucleus:
  Bremsstrahlung (for high energy charged particles) , i. e. radiation of photons, in the Coulomb field of the atomic nuclei



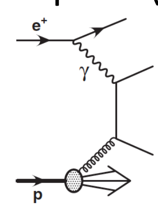
ELECTROMAGNETIC

- At EIC - energy loss of quarks.
- Gluon bremsstrahlung





- Z/A dependence (ep vs eA)
- Energy loss measurements as a function of initial quark energy and type of quark (c,b)

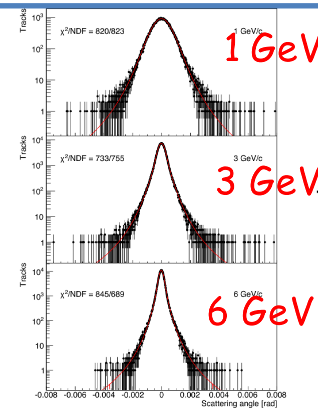


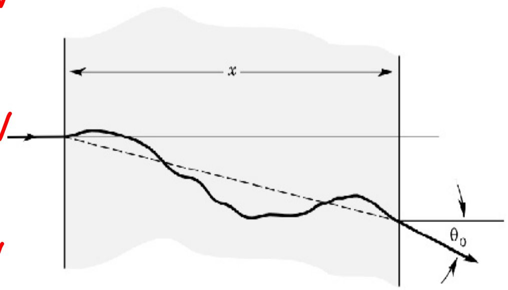
Di-jets

STRONG

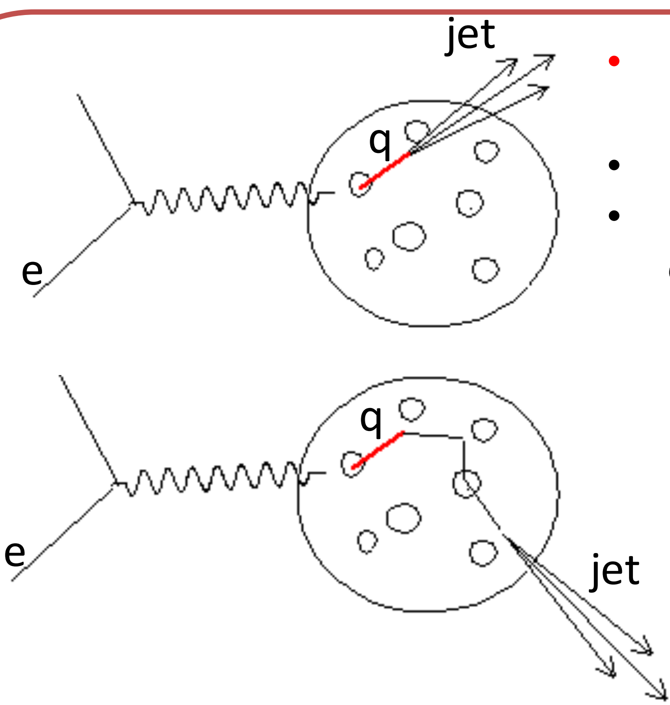
MULTIPLE SCATTERING OF QUARKS (JETS)

A charged particle traversing a medium is deflected by many small-angle scatters. Most of this deflection is due to Coulomb scattering from nuclei, and hence the effect is called multiple Coulomb scattering.

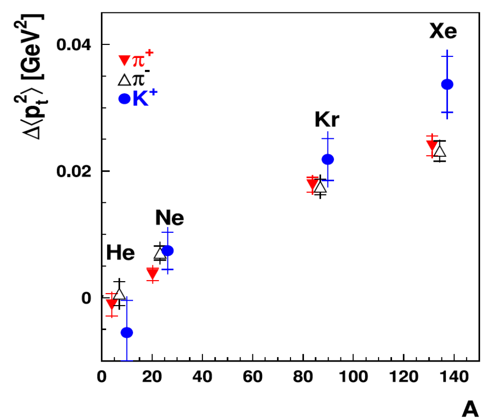




ELECTROMAGNETIC



- Multiple scattering of quarks in strong interacting matter.
- At low/medium energy this effect is more visible?
- Angular distribution, Z/A dependence (ep vs eA), quark energy (mass) dependence



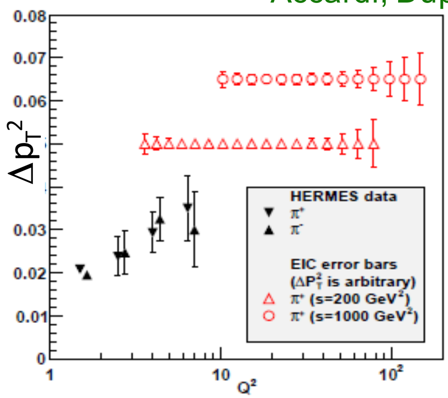
HERMES,
A.Accardi,etc.

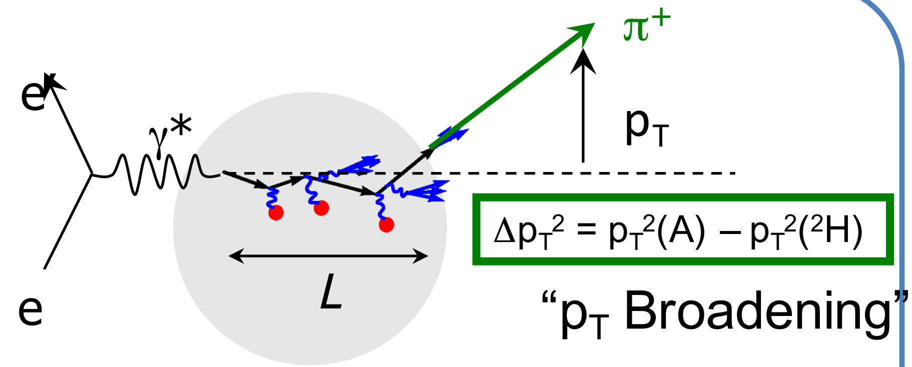
STRONG

PARTON PROPAGATION IN MATTER

Hadrons P_T broadening

Accardi, Dupre



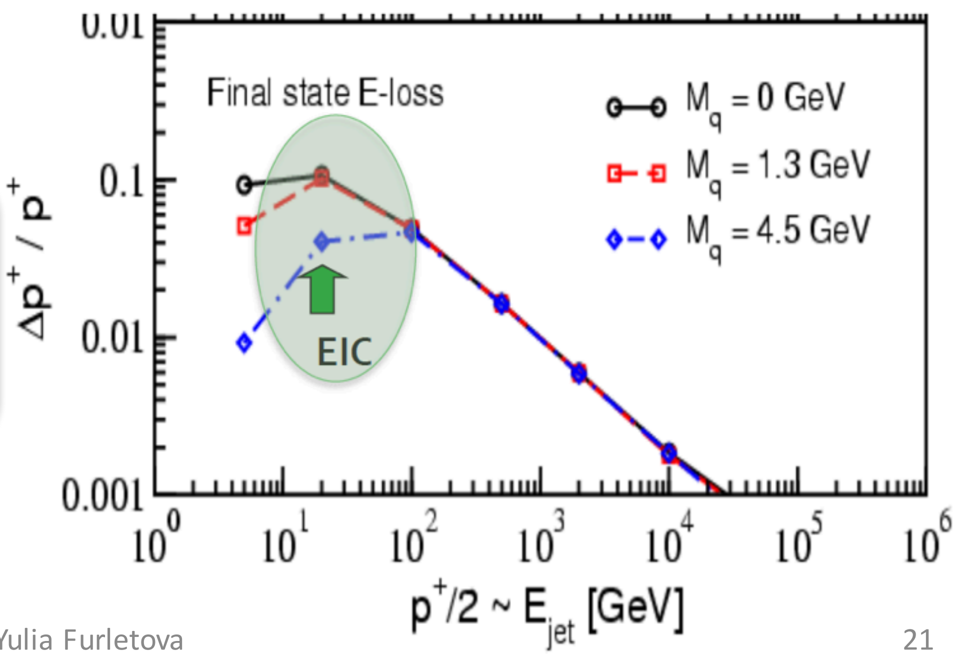


- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution

Heavy-quarks energy-loss

At EIC for the first time - will be able to study in-medium propagation and hadronization of heavy quarks (charm and beauty)

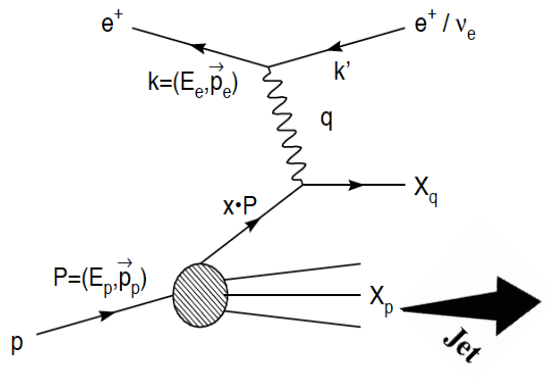
Ivan Vitev



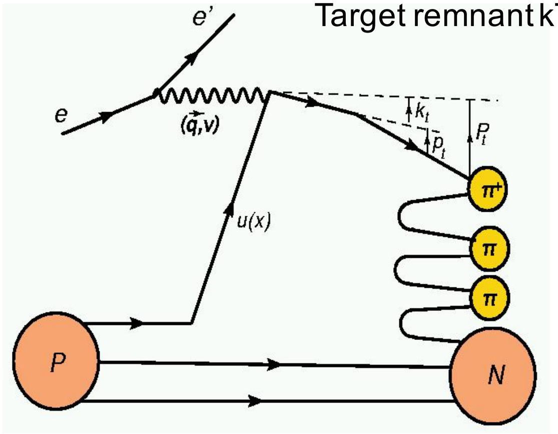
REMNANT JET

REMNANT JETs

DIS

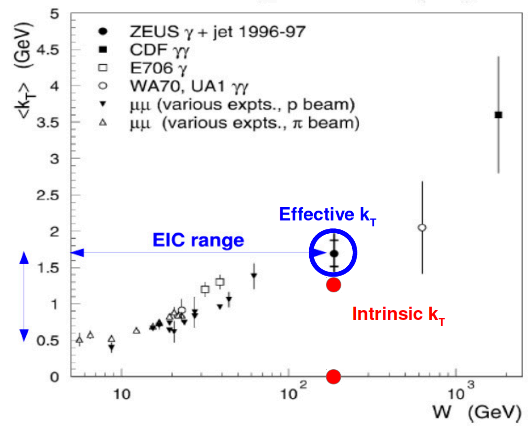


Target remnant kT = - struck parton kT

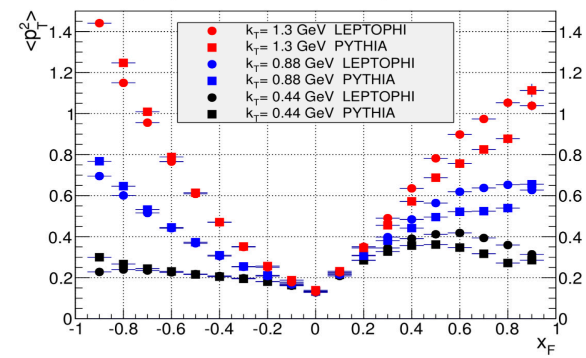


Final transverse momentum $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ *with the transverse momentum generated during the fragmentation* $\mathbf{p}_t$.

ZEUS Collaboration / Physics Letters B 511 (2001) 19–32



M. Backer, E. Aschenauer

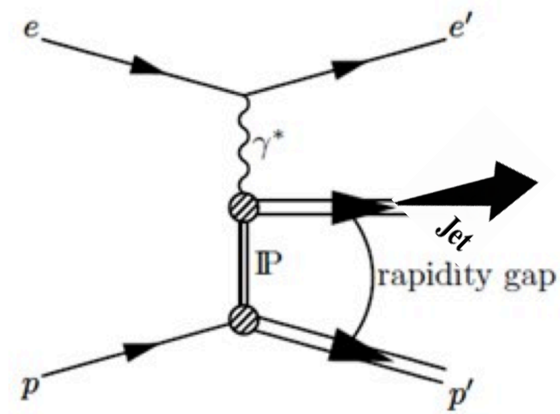


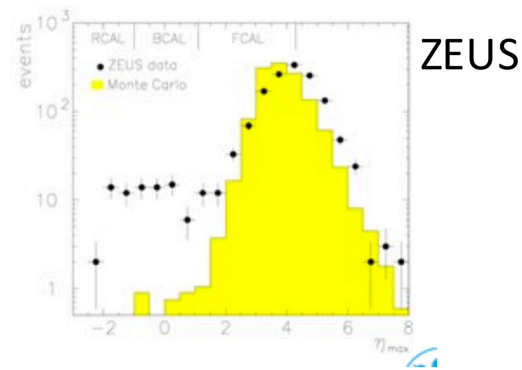
-Evolution of the system from which a color charge has been removed (remnant jet):
-correlations between the current and target fragmentation regions
("color flow", s, s-bar …)

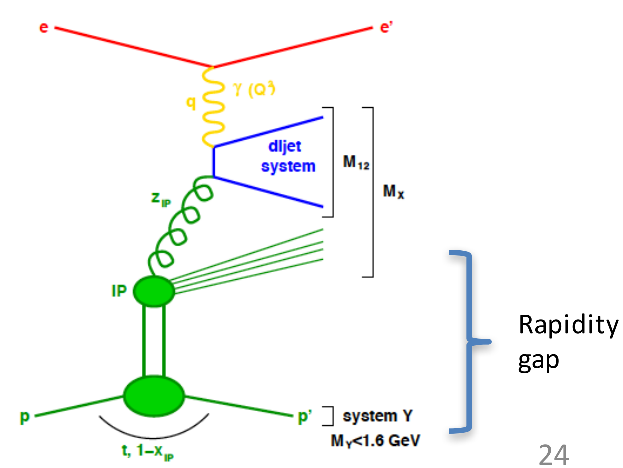
DIFFRACTIVE DPDFS

- Diffractive jets production provide a hard scale for perturbative calculations.
- Pomeron exchange between γ^* and p.
- Identified as absence of hadronic activity in the direction of proton **(large rapidity gap)** or by a direct tagging of scattered proton.
- Diffractive dijet production - probe of the gluon content of the diffractive exchange

(in contrast to inclusive measurements -sensitive to the quarks): diffractive gluon density (DPDF).





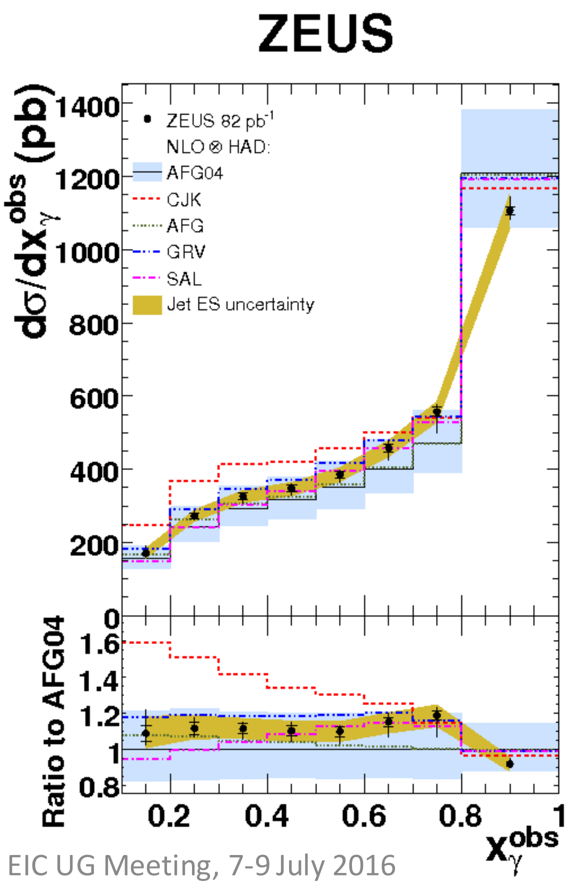


DIJETS IN PHOTOPRODUCTION: SENSITIVITY TO PHOTON PDF

Photon remnant

quasy real photon:

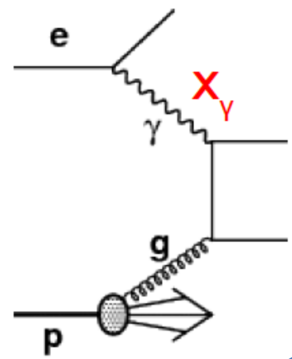
Q2 ≃ 0



photon interacts directly

$x_\gamma = 1$

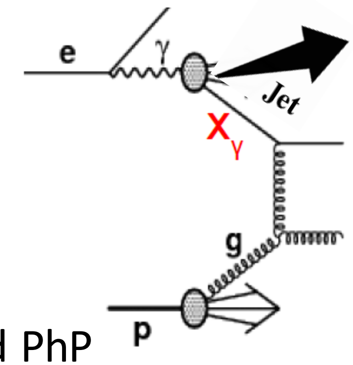
Direct PhP



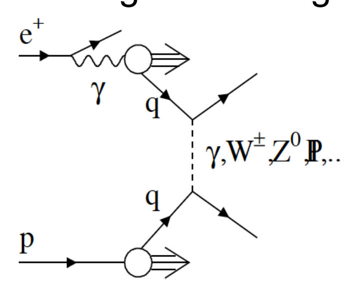
partons from the photon interacts

$x_\gamma < 1$

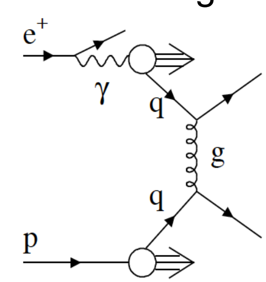
Resolved PhP

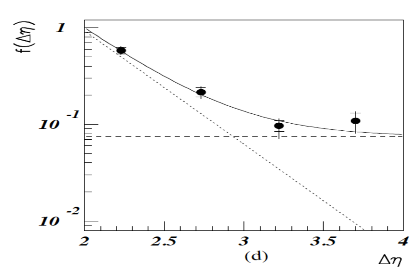


colour singlet exchange

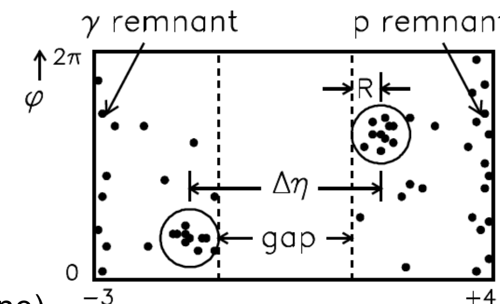


colour non-singlet exchange





colour singlet contribution (dashed line).
non-singlet contribution (dotted line)

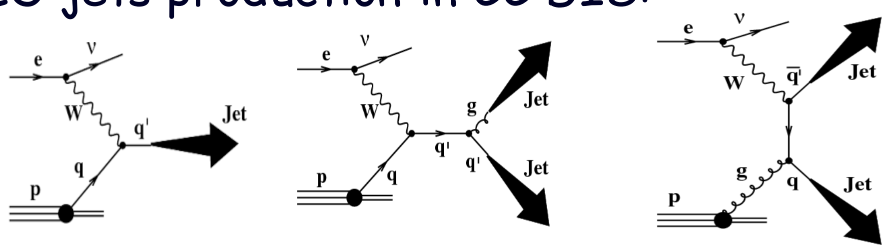


M.Derrick

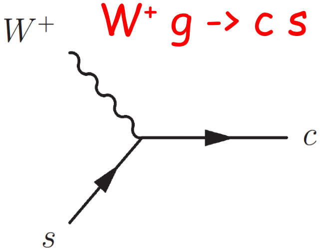
An other processes

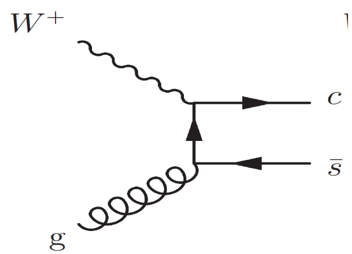
DIRECT MEASUREMENTS OF STRANGE QUARK PDFS WITH CHARM JETS IN CHARGED CURRENT DIS

LO jets production in CC DIS:

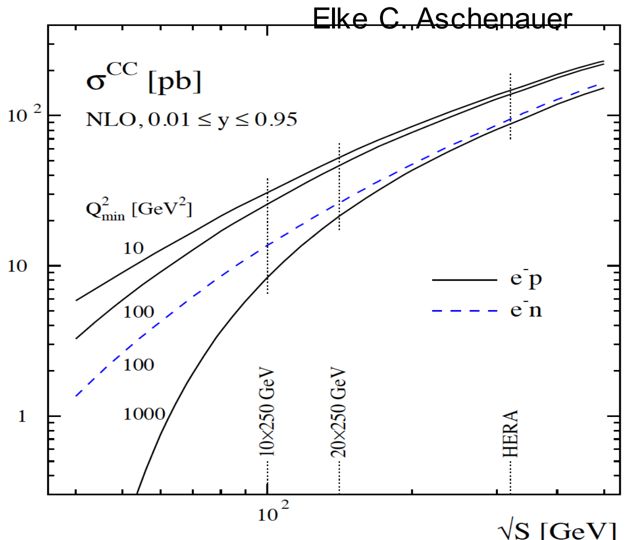


- Direct measurements of
  strange quark distribution.
  $W^+ s \to c$ | Vsc| =0.97
- Flavor mixing
  $W^+ d \to c$ |Vcd| =0.224
- BGF
  $W^+ g \to c\, s$





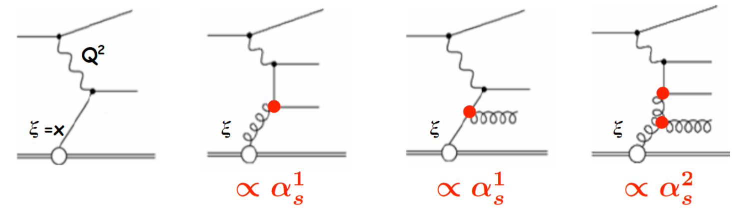
For CC DIS: No electron => reconstruction of kinematic variables (x,Q2) only from hadronic (jets) final states!!!



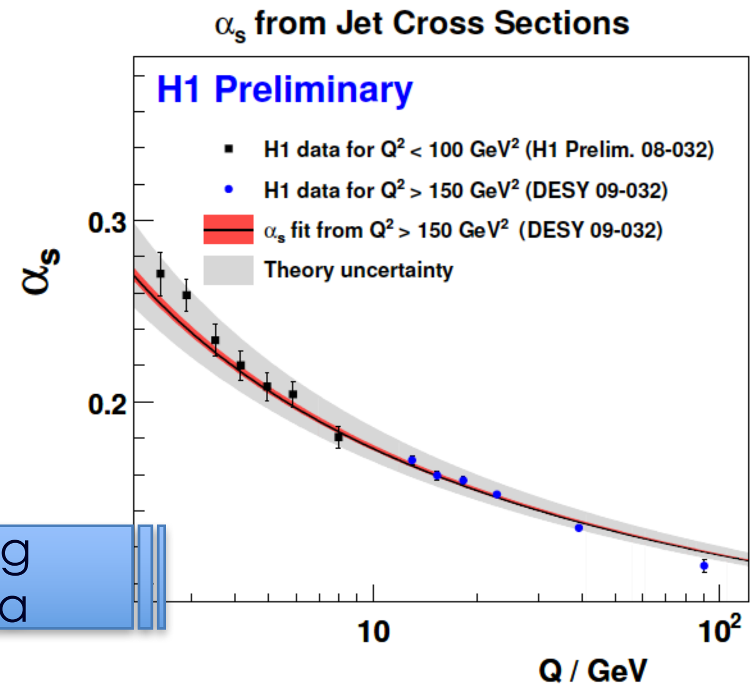
Charm production in Charged Current e+ p DIS is charge asymmetric, only the charm and no anti-charm quark is produced in the hard process.

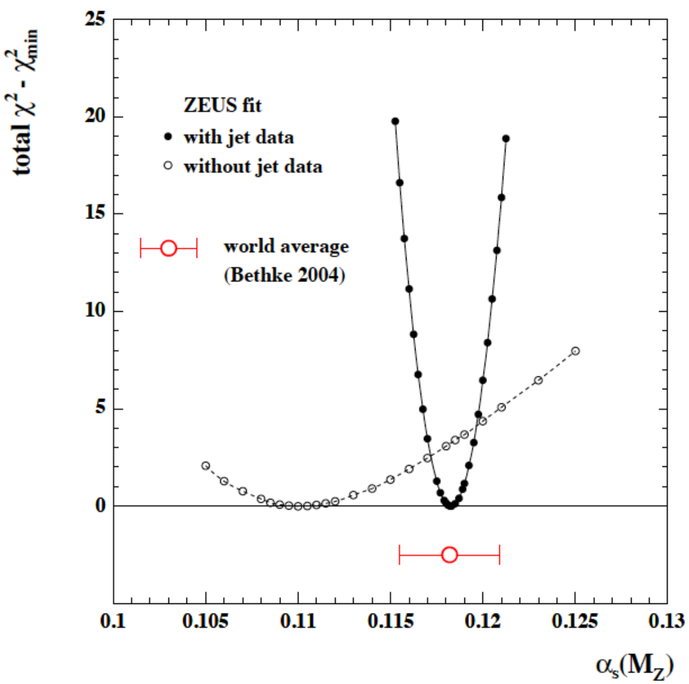
<u>At HERA:</u>
σ(CC DIS) ~ 50pb (HERA Q^2>200GeV^2)
σ(CC DIS + charm) ~ 5pb (HERA Q^2>200GeV^2)
<u>At EIC :</u>
σ(CC DIS) ~ 10 pb (Q^2>10GeV^2)
σ(CC DIS + charm) ~ 1 pb (Q^2>10GeV^2)
~ 1 event/ minute (with L~10^{34})

STRONG COUPLING CONSTANT



- Determination of α_s from the inclusive jet cross section in DIS
- The α_s is extracted individually from the inclusive jets at low Q2 and from the inclusive, 2-jet and 3-jet at high Q2.



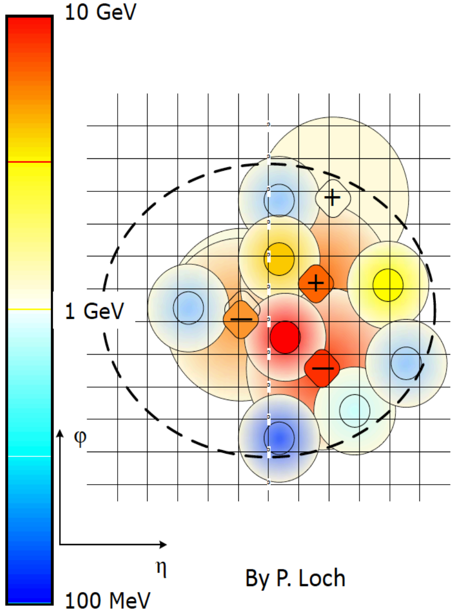


Including JETs data

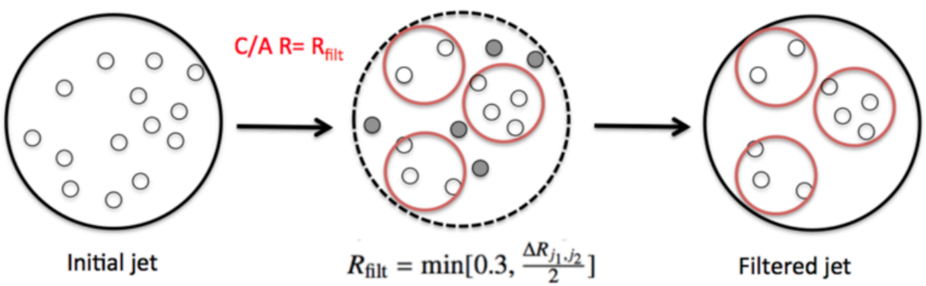
Could EIC data improve α_s measurements?
At HERA – main uncertainty due to JETs energy measurements (ZEUS HCAL $\sigma_E/E \sim 35\%/\sqrt{E}$!!!)
=> New method for jet energy measurements!
=> Particle Flow Calorimeter (see a talk by Jose Repond)

JET-SUBSTRUCTURE, JETS-TAGGING, TAU-JETS

JET SUBSTRUCTURE, Micro-jets

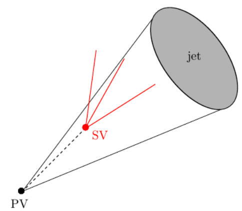


By P. Loch

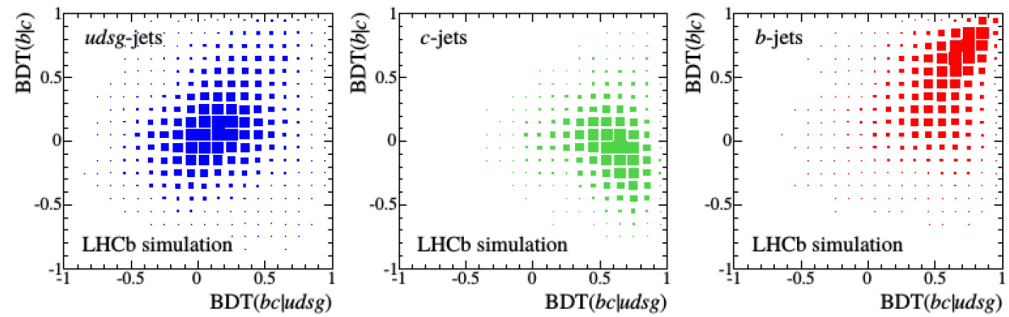


$R_{\mathrm{filt}} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}]$

C,B JET-TAGGING

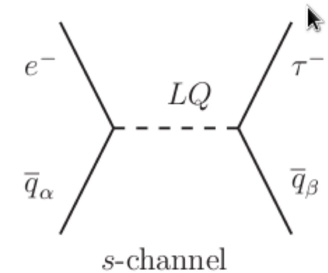


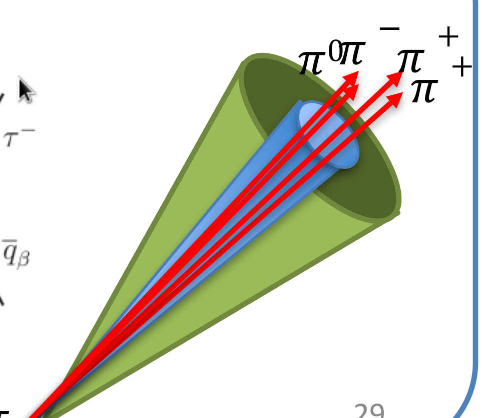
Multivariate analysis (MVA),eg boosted decision tree (BDT), artificial neural net (ANN) to distinguish light quark, gluon and heavy-quark jets.



Charged Lepton Flavor Violation (LFV) :

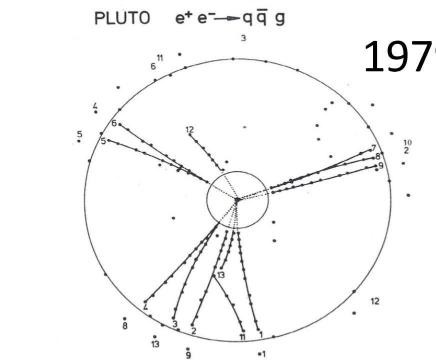
ep → τ X





TAU-JETS

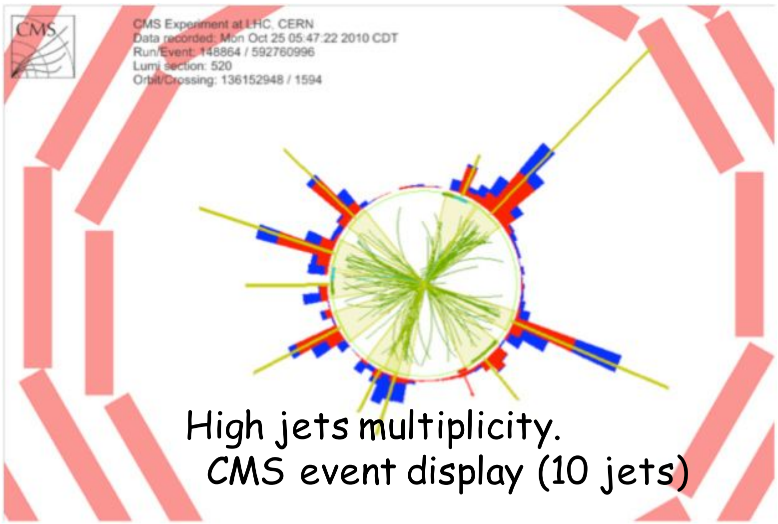
GUESS WHO? TYPES OF JETS



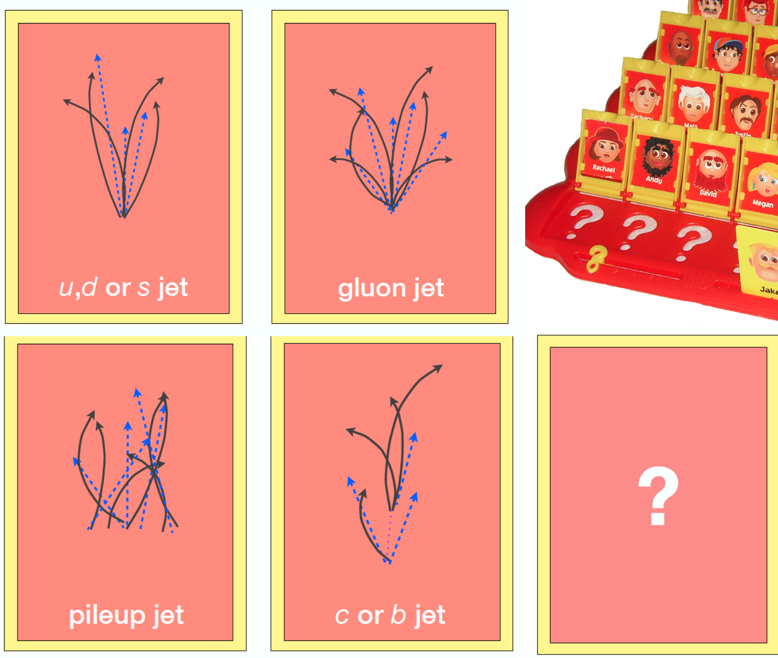
1979

- Quark/ani-quark jets (u,d or s)
- Gluon jets
- Heavy-quark jets
- τ - jets
- ….

now



High jets multiplicity.
CMS event display (10 jets)

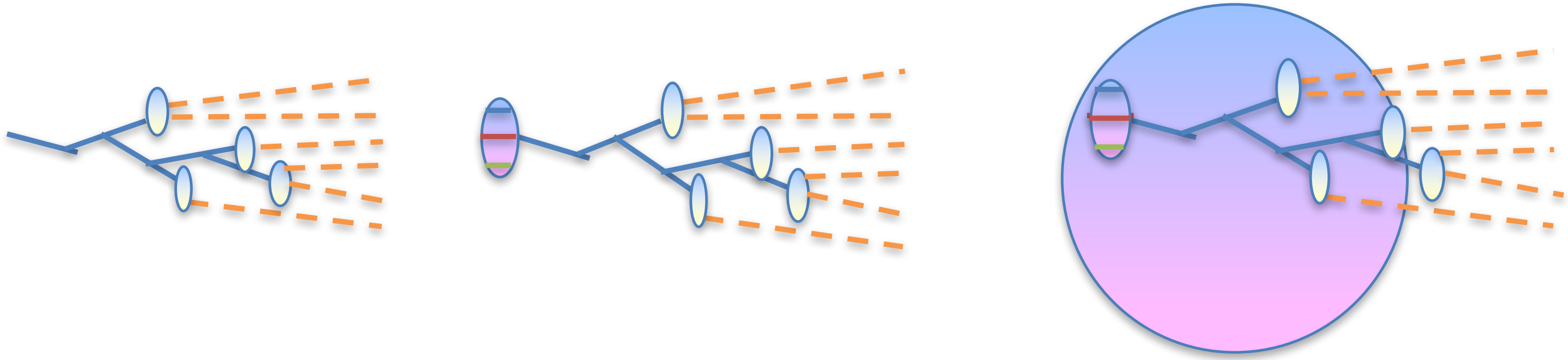


- E_T, θ, φ …
- Calorimeter, tracking, vertex…
- Shapes, subjets, PID, m …

Understanding of jets could be valuable for all physics searches

CONCLUSIONS:
JETS ARE A TOOLS TO STUDY QCD

- Jet physics allows to study the properties of partons.
- Events that contain jets could be used as tools in several different/complementary analysis
- Understanding of jets could be valuable for many physics searches



Many thanks to: Rolf Ent and Rik Yoshida

BACKUP

PARTICLE FLOW CALORIMETER (ILC)

<u>In a typical jet :</u>
60 % of jet energy in charged hadrons
30 % in photons (mainly from $\pi 0 \rightarrow \gamma\gamma$)
10 % in neutral hadrons (mainly n, K_L)

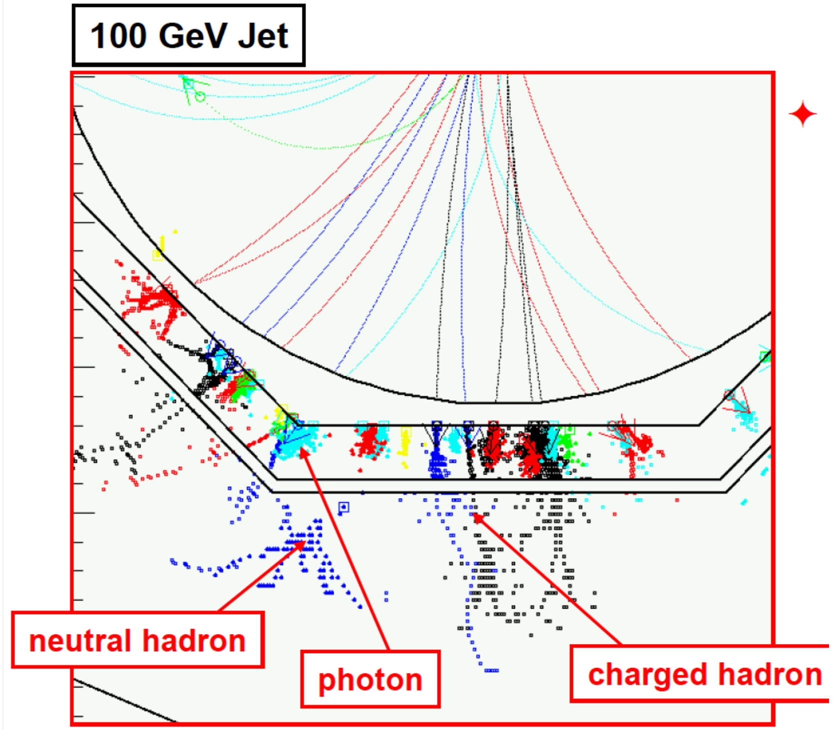
<u>Traditional calorimetric approach:</u>
-Measure all components of jet energy in ECAL/HCAL
-70% of energy measured in HCAL with poor resolution : $\sigma_E/E \sim 60\%/\sqrt{E}$

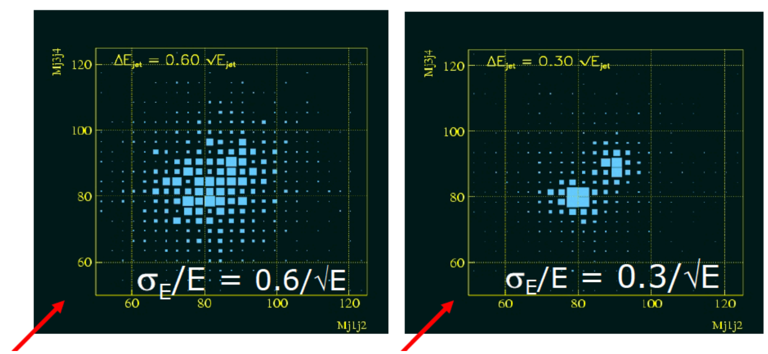
E_{JET}=EMCAL+HCAL

<u>Particle Flow Calorimetry:</u>
-charged particles measured in tracker (essentially perfectly)
-Photons in ECAL: : $\sigma_E/E \sim 2\text{-}10\%/\sqrt{E}$
-Neutral hadrons (ONLY) in HCAL =>
Only 10 % of jet energy from HCAL

$E_{JET} = E_{track} + E\gamma + E_n$

much improved resolution!!!





Mark Thomson

PROOF OF JETS AT EA

- **E665: proof of principle in e+A**
  - Jets can be measured in e+A at √s > 30 GeV

All ratios show the clear signal of shadowing in the region x < 0.01.