Jets in Deep Inelastic Scattering

The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Krzysztof Kutak

Resources

- *Previous lectures by: K. Cichy, K. Golec-Biernat, A. Kusina*
- *„Basics of QCD", „"Jet Physics" Gavin Salam*
- *Talks by F. Ringer, M. Arratia, B. Page, A. Quintero. DIS 2021, BNL workshop on Jets 2020, QCD Evolution 2021, weekly YR working group meetings*
- *„Lectures on Sudakov form factors", B. Xiao, QCD master class*
- *„Quarks and leptons: An Introductory Course in Modern Particle Physics", Halzen, Martin*
- *„Jets at hadron colliders", Prog.Part.Nucl.Phys. 89 (2016) S. Sapeta*

Plan of the lecture

- *Facts about QCD.*
- *Formation of jets.*
- *Jet definition.*
- *Jet algorithm.*
- *Deep Inelastic Scattering.*
- *Collinear factorization.*
- *DESY and selection of recent HERA results.*
- *Non-collinear factorizations*
- *EIC and jet observables.*
- *Low x – dipole and WW gluon density.*
- *Summary.*

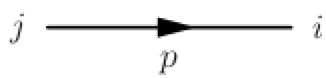
Comment:
I am not going to be very careful about historical aspects of DIS and chronology

Facts about QCD – QCD Lagrangian

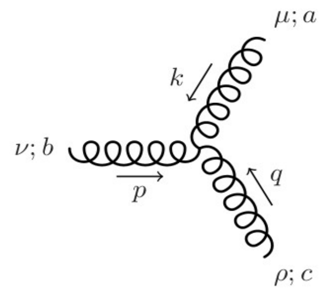
The QCD Lagrangian reads

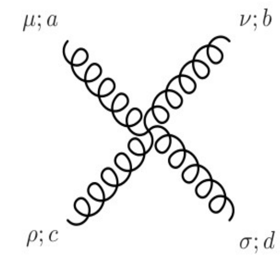
$$\mathcal{L}_{\mathrm{QCD}} \;=\; \overline{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - \tfrac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} - g_s\,\overline{\psi}_i\lambda^a_{ij}\psi_j\,\gamma^\mu A^a_\mu$$

Describes propagation of quarks

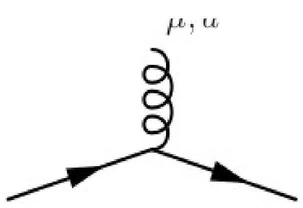


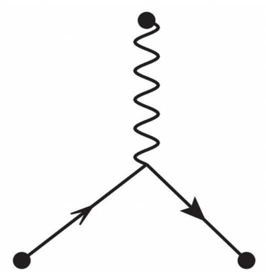
Describes propagation and self interactions of gluons





Describes interaction of quarks and gluons





Quarks have electric charge so they couple to photon. This is important for electron hadron interactions.

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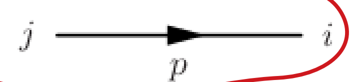

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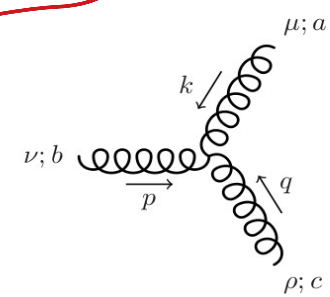

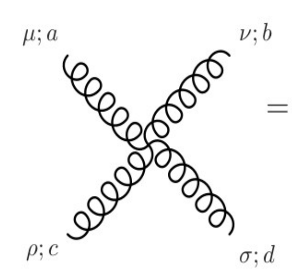

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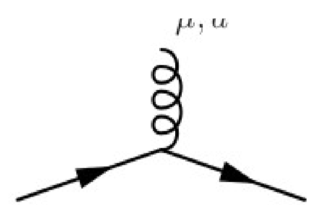

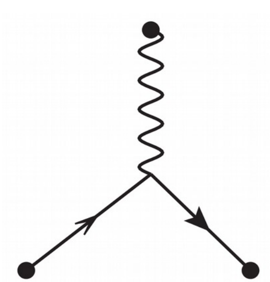

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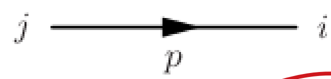

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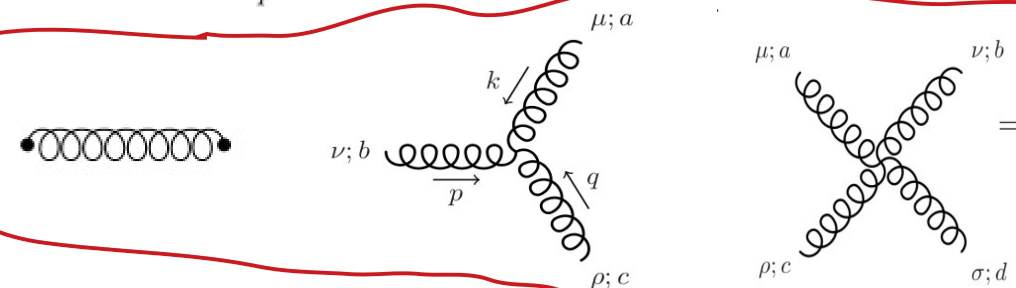

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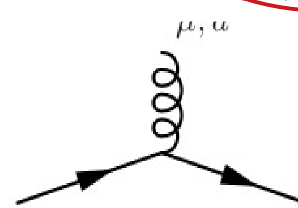

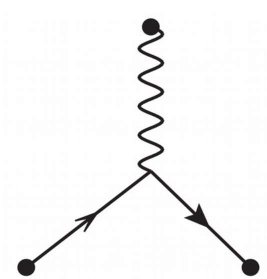

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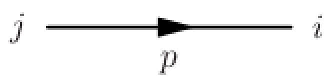

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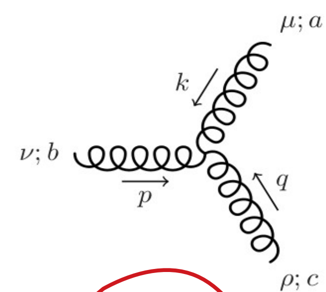

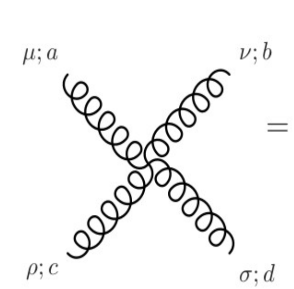

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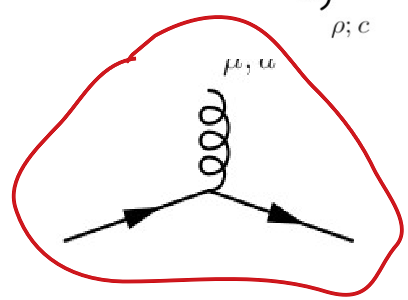

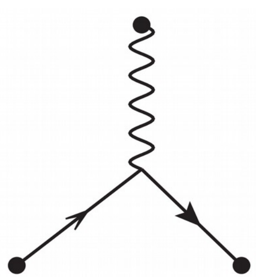

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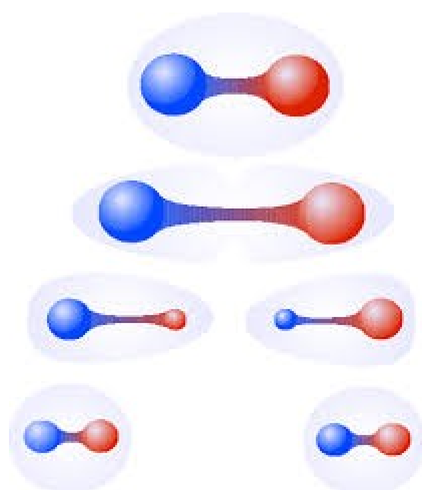
Facts about QCD – asymptotic freedom and confinement

At short distances: partons are weekly coupled: asymptotic freedom

At long distances: confinement i.e. energy is minimized when new hadrons are produced



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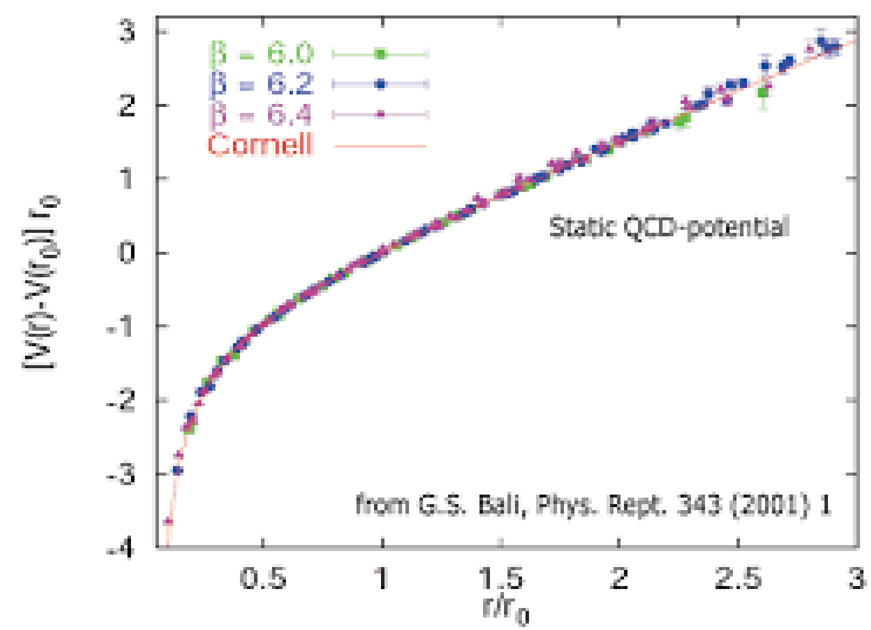
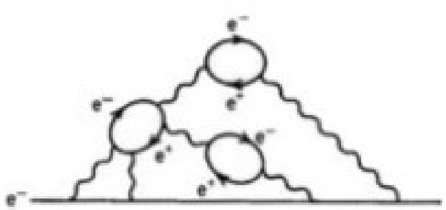


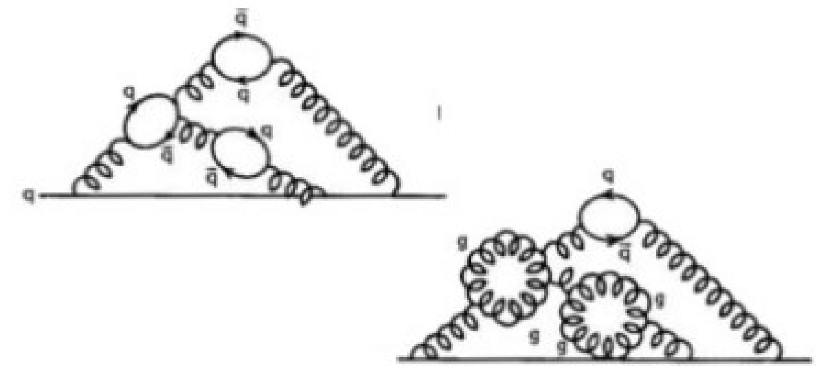
$$V_{QCD} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

Facts about QCD – coupling constant

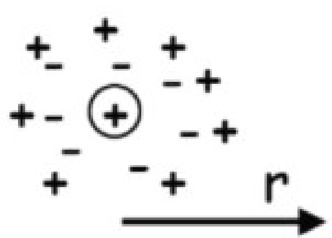
QED

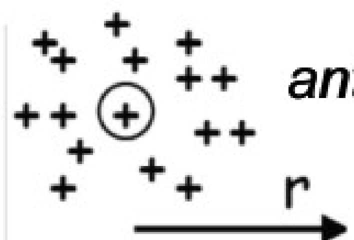
QCD



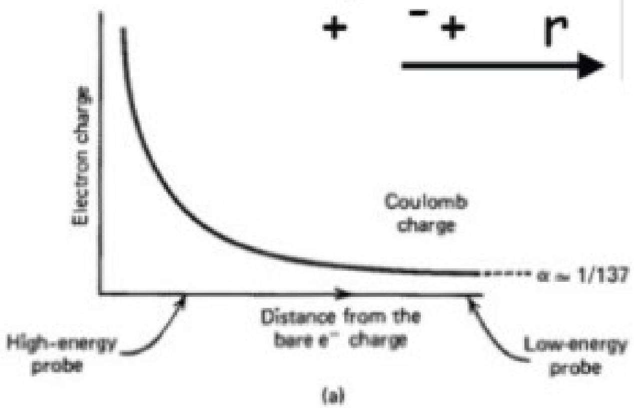


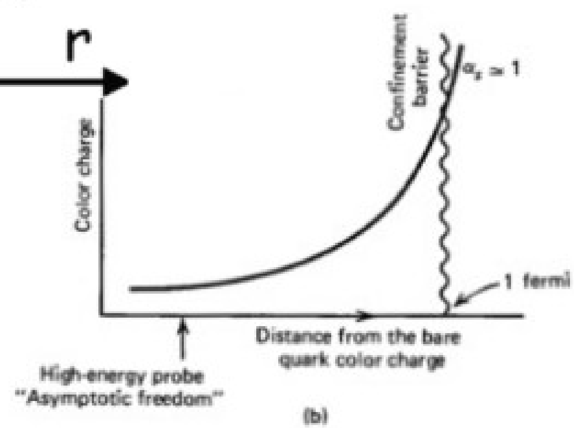
screening





anti-screening





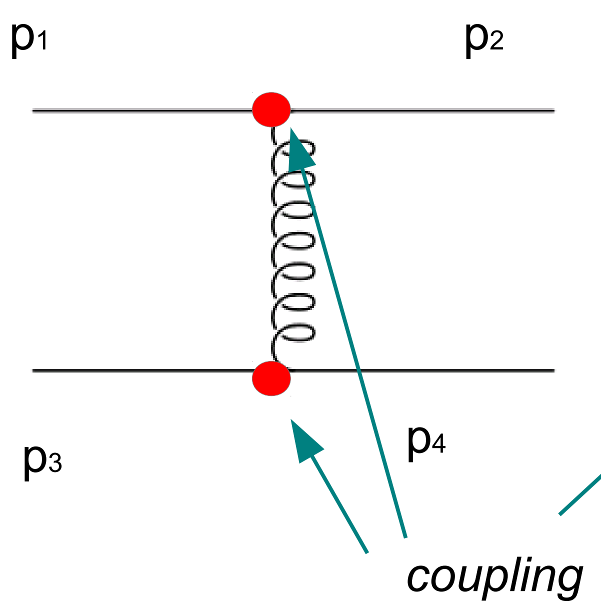
r~1/Q

momentum scale

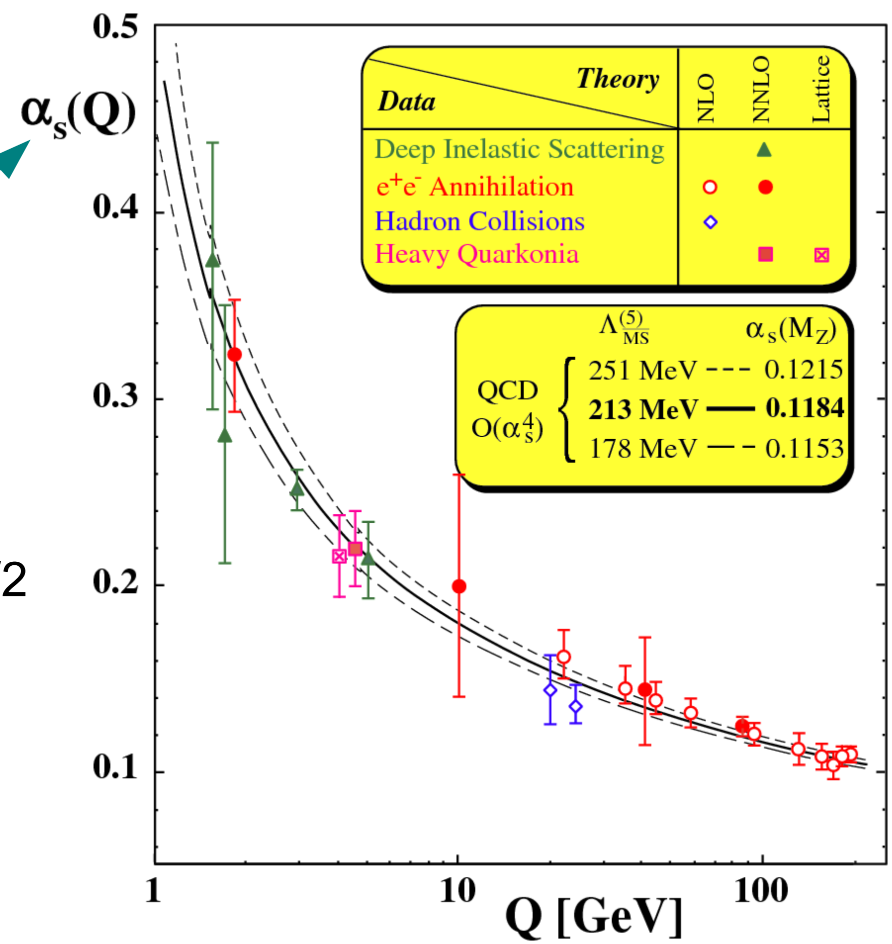
https://particlesandfriends.wordpress.com/2016/10/13/couplings-and-asymptotic-freedom/

Facts about QCD – QCD coupling constant

S. Bethke, J Phys G 26, R27



$Q^2=(p_2+p_4)^2/2$



$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\log Q^2/\Lambda^2_{QCD}}$$

- *Perturbative partons at large scales*
- *Confining dynamics at small scales*

Facts about QCD – QCD coupling constant

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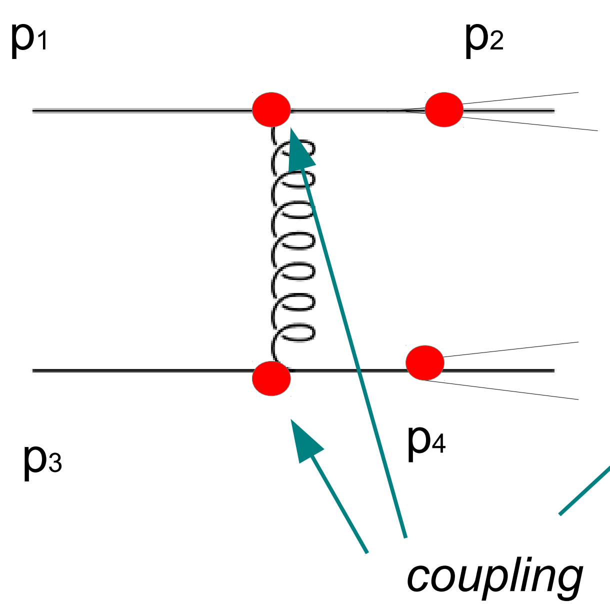

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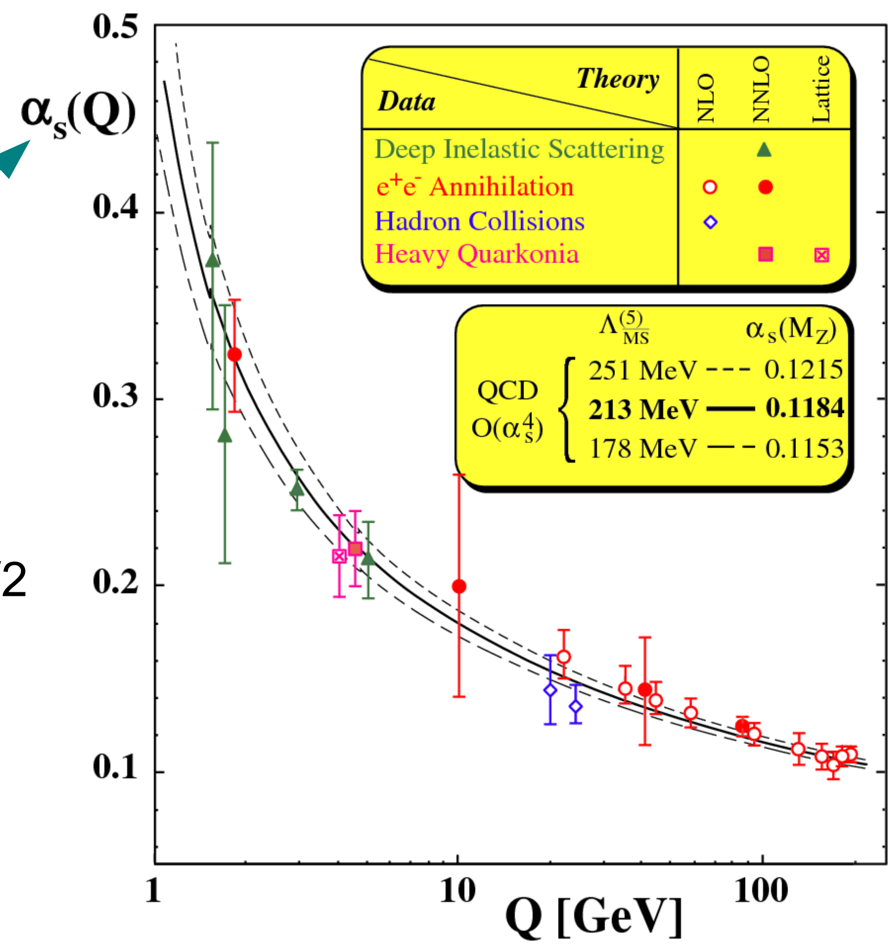
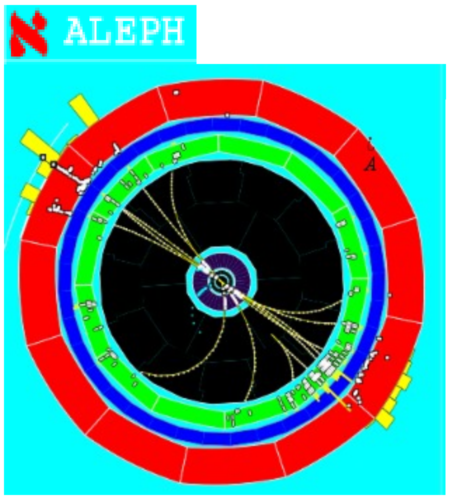


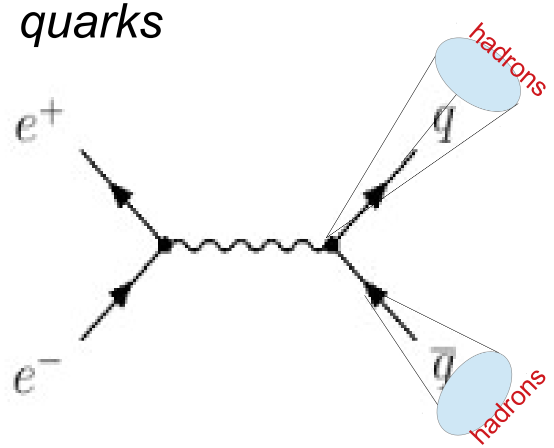
- *Perturbative partons at large scales*
- *Confining dynamics at small scales*
- *This gives rise to sprays of hadrons at final states jets produced in high energy collision*

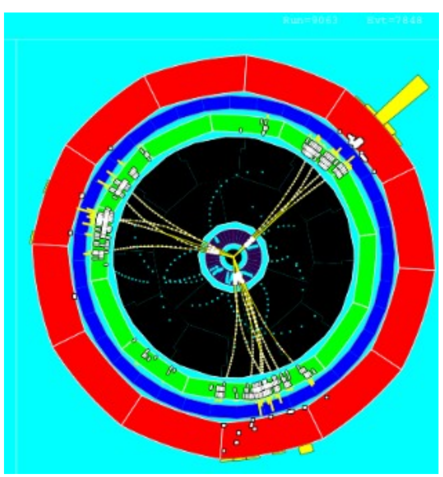
$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log Q^2/\Lambda^2_{QCD}}$$

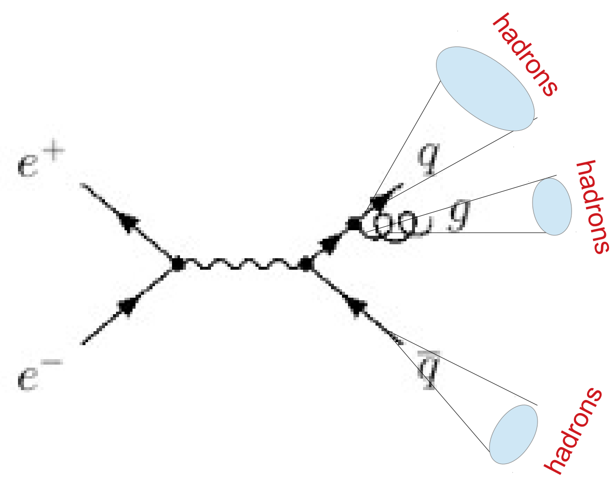
Formation of jets – e+e- annihilation



di-jet event – evidence for quarks







tri-jet event – evidence for gluon

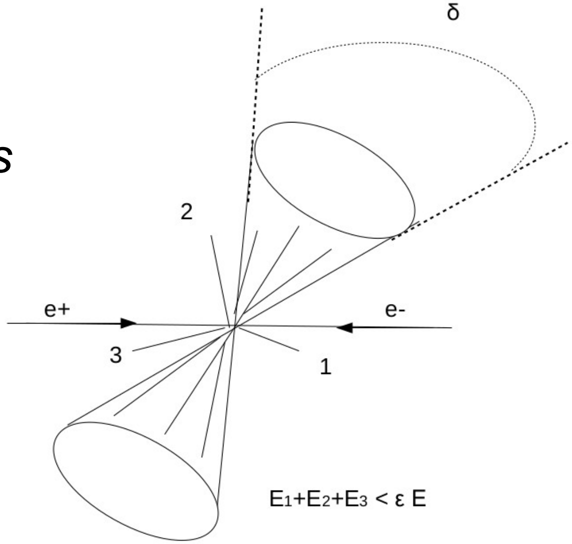
- *We have proliferation of partons that go to the final state.*
- *The partons tend to be collimated.*
- *The collection of color carrying partons turns into color neutral hadrons seen by the detectors*
- *Short distance physics is connected to long distance physics.*
- *Jets are proxy to what is happening in the hard collision. You try to estimate what has happened at the short distance scale.*
- *You cluster together perturbative partons to form hadrons.*
  Jets are fundamentally ambiguous
  There is a tension: partons carry color, hadrons are color neutral.

Initial state as well as final state is color neutral.

Jet definition – jets in e+ e-

Theory definition by Sterman and Weinberg. We define event as jet event if we can find two cones of opening angle δ that contain all of the energy of the event, excluding at most a fraction of the total energy.

Pair of Sterman-Weinberg jets



Jets in experiments are defined as a collimated distribution of hadrons with total energy E within the jet cone size

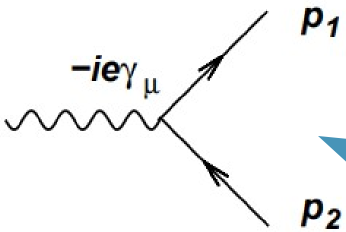
$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

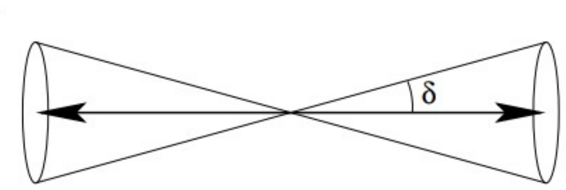
Jet in theory - collimated distribution of partons. Need to assume the parton-hadron duality. More sophisticated jet finding algorithm: k_T, sis-cone and anti-k_T.

Formation of jets – why do jets form?

It is not obvious from Lagrangian that jets are dominant final state products of the collision.

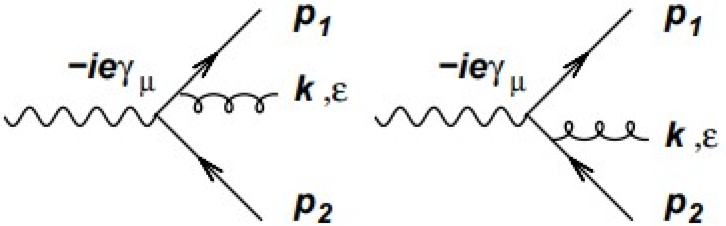
$$\mathcal{M}_{q\bar{q}} = -\bar{u}(p_1) i e_q \gamma_\nu v(p_2)$$





Lowest order contribution

$$\mathcal{M}_{q\bar{q}g} = \bar{u}(p_1) i g_s \not\epsilon t^A \frac{i}{\not p_1 + \not k} i e_q \gamma_\mu \nu(p_2) - \bar{u}(p_1) i e_q \gamma_\mu \frac{i}{\not p_2 + \not k} i g_s \not\epsilon t^A \nu(p_2)$$



Collinear emissions modeled by FS Parton Showers

$$|M^2_{q\bar{q}g}| \simeq |M^2_{q\bar{q}}| C_F g_s^2 \frac{2p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)} \rightarrow \frac{1}{E^2(1-\cos^2\theta)}$$

It diverges for E → 0 – infrared (soft) divergeence

It diverges for θ → 0 and θ → π – collinear divergence - relevant for jets

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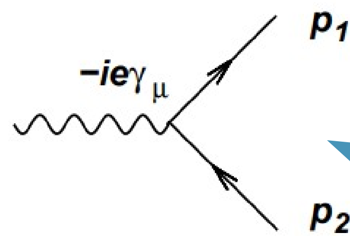

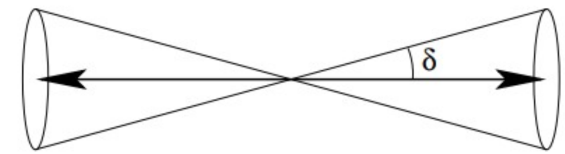

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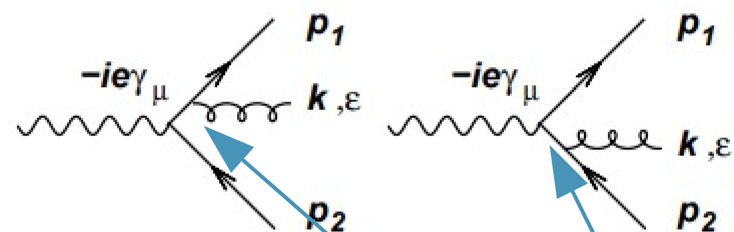

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$$\frac{1}{E^2(1 - \cos^2\theta)}$$

invariant mass approaches 0

It diverges for $E \to 0$ – infrared (soft) divergeence

It diverges for $\theta \to 0$ and $\theta \to \pi$ – collinear divergence - relevant for jets

Jet algorithm

Which particles do you put together into a same jet?

How do you recombine their momenta
(4-momentum sum is the obvious choice, right?)

You cluster together perturbative partons to form hadrons

One needs to use jet definition technically expressed as jet algorithm

$$\text{partons} \quad \{p_i\} \longrightarrow \{k_i\} \quad \text{jets}$$

Clusters of partons are the same as clusters of hadrons up to corrections.

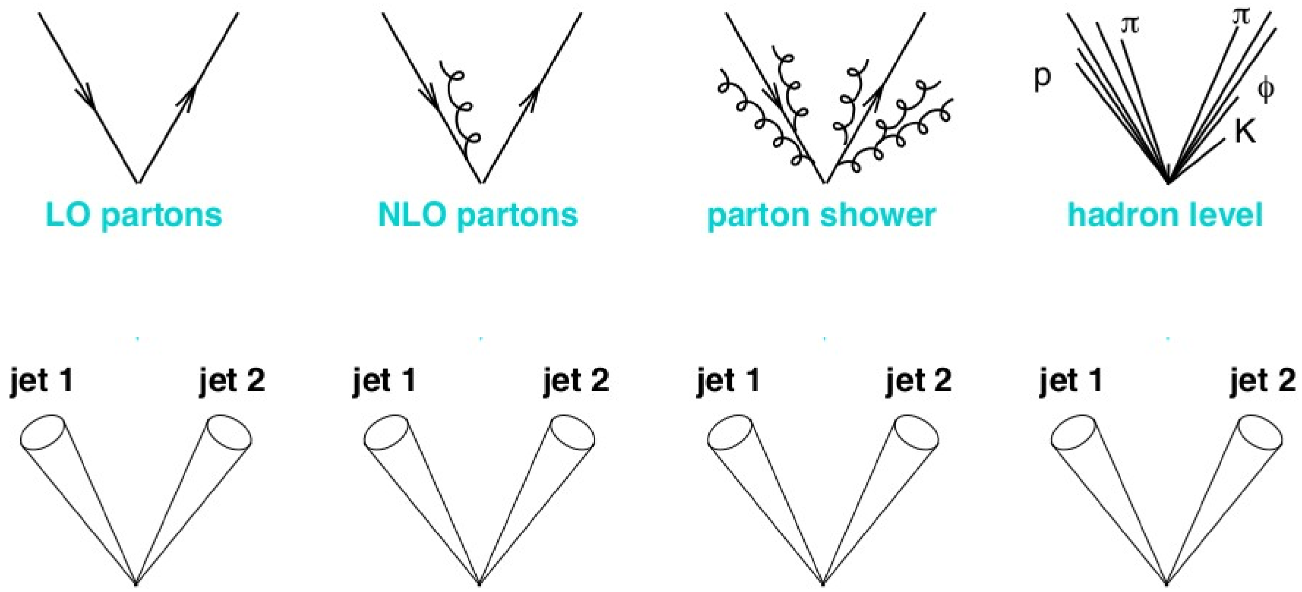
Used jet algorithms: Cone, SISCone, kT,anti-kT, and new developments for jets in DIS

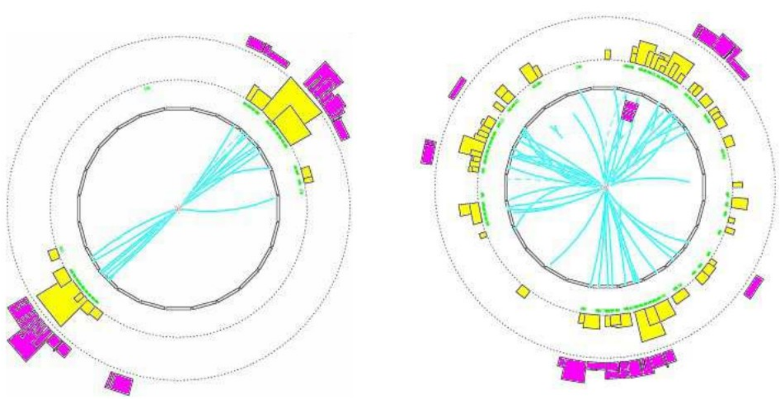
Good algorithm should give unambiguous answer.

Adding soft or collinear emission should not modify the clustering of partons into jet.

Jet algorithm should be infrared safe. Let us ilustrate the problem...

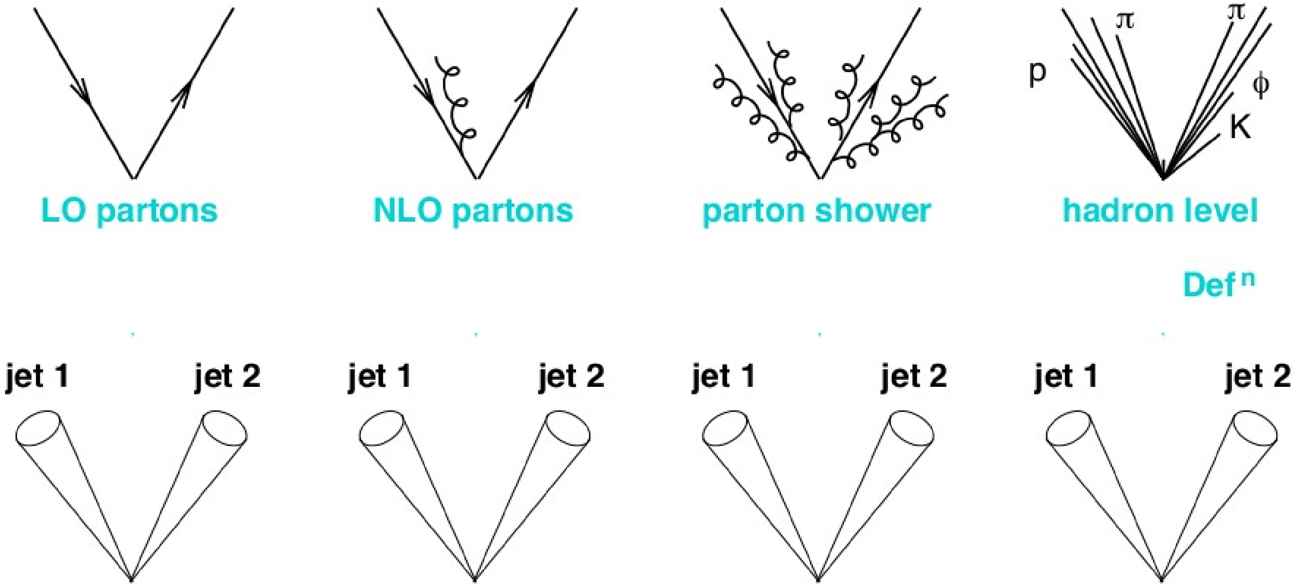
Jet algorithm

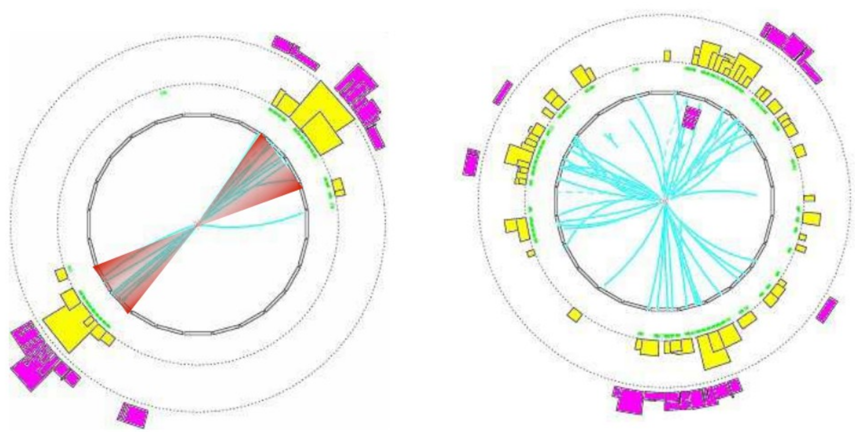




From Gavin Salam

Jet algorithm

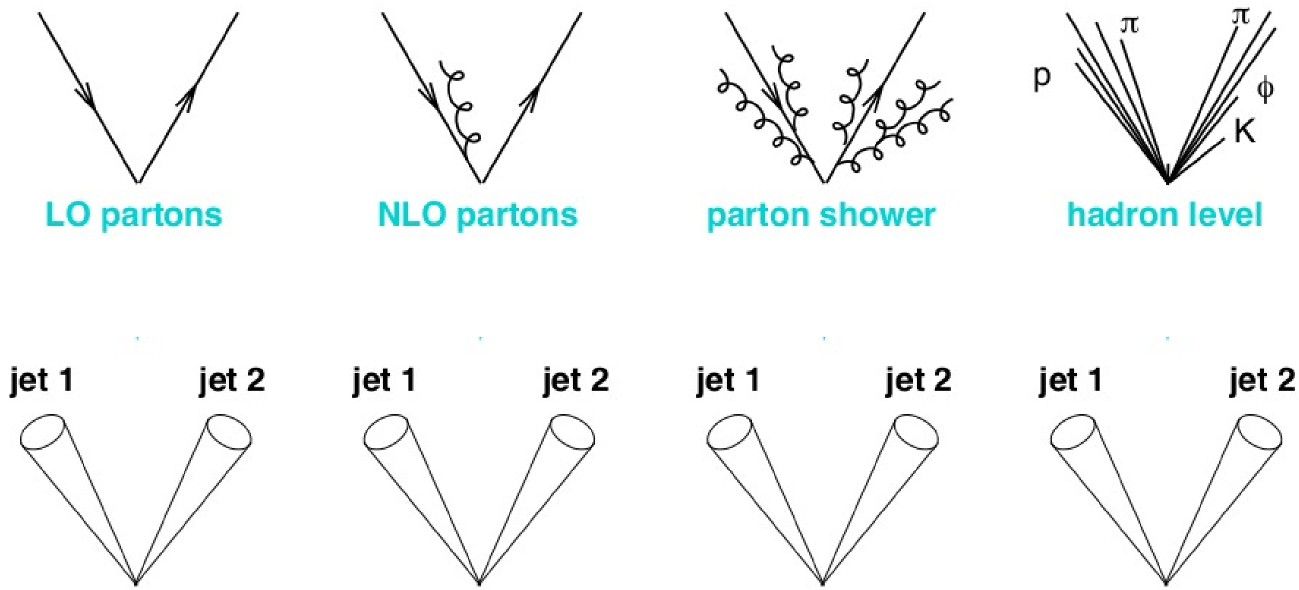




2 clear jets

From Gavin Salam

Jet algorithm



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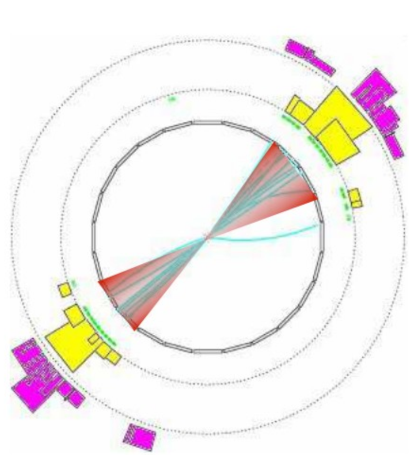

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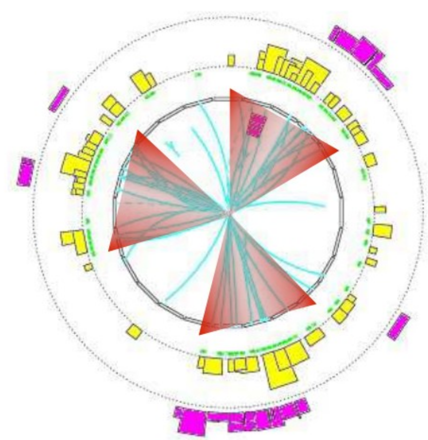
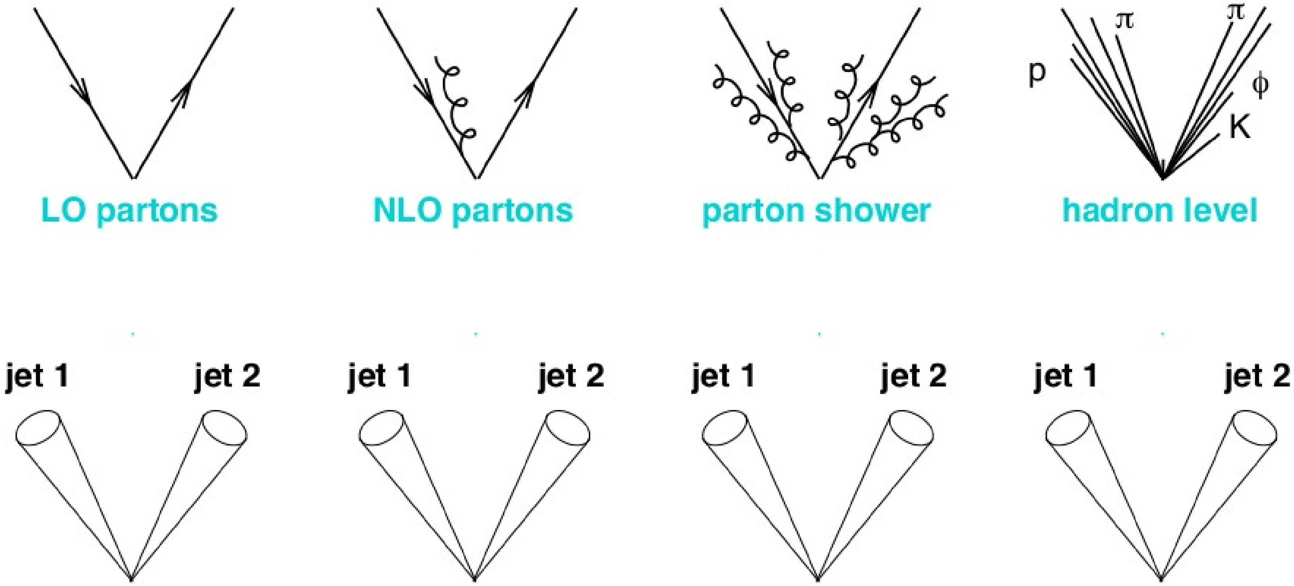


3 jets?

Jet algorithm



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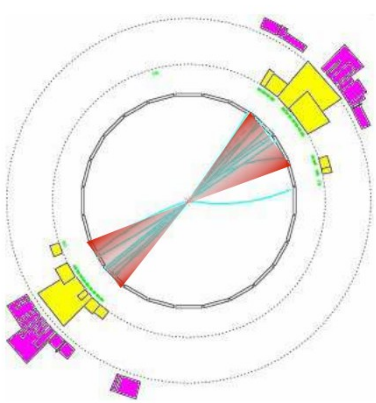
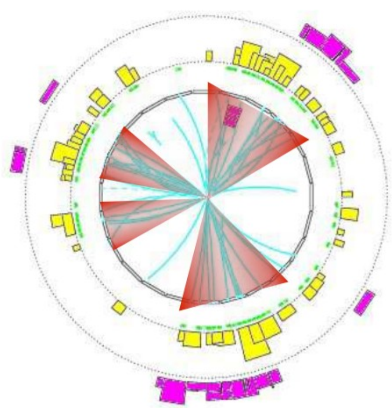


2 clear jets

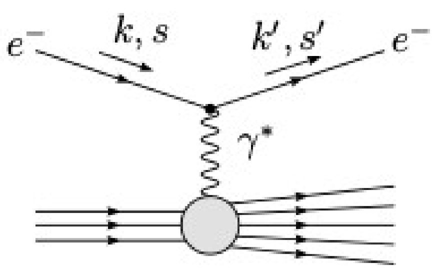


3 jets?
or 4 jets?

Good algorithm should give unambiguous answer.
Should be collinear safe.

Deep inelastic scattering

$p_e = E_e(1,0,0,1)$



$p_p = E_p(1,0,0,-1)$

Parameters from DESY

$E_{e^-} \sim 27\ \mathrm{GeV}$

$E_P \sim 820\ \mathrm{GeV}$

$\sqrt{s} \sim 300\ \mathrm{GeV}$

$E_\gamma \sim \sqrt{Q^2} \sim k$

From the uncertainity principle we get $\Delta x \, \Delta k \sim 1$

$$\Delta x \sim \frac{1}{k} \sim \frac{1}{\sqrt{Q^2}}$$

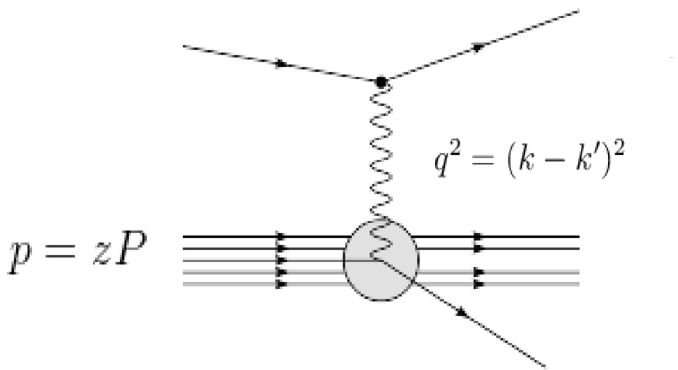
The final state depends on the virtuality of photon $Q^2 = -q^2$

$Q^2 << M_p^2$ *proton behaves like an elementary pointlike particle*

$Q^2 \sim M_p^2$ *proton stays intact but the observables depend on its structure*

$Q^2 >> M_p^2$ *proton gets distructed and new particles are created - DIS*

Collinear factorization



Momentum of proton $P = E_p(1, 0, 0, -1)$

Momentum of parton $p_j = z_j P$

$$\sigma_{\mathcal{O}} = \sum_j \mathcal{O} \otimes f_j(x/x_p, Q^2)$$

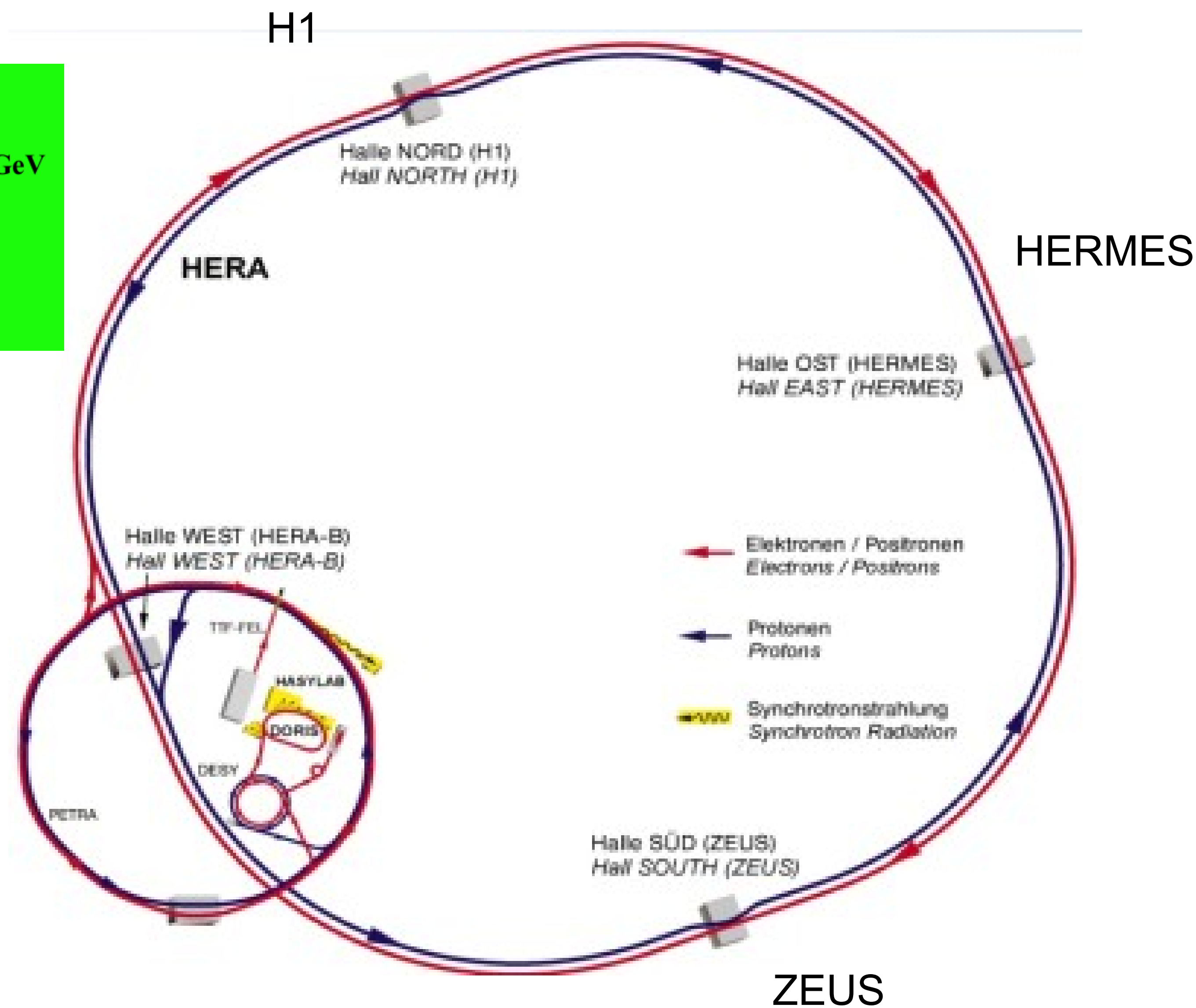
cross section

matrix element
defining opbservable

$f_{j/P}$ *probability of*
finding parton j in the proton

DESY

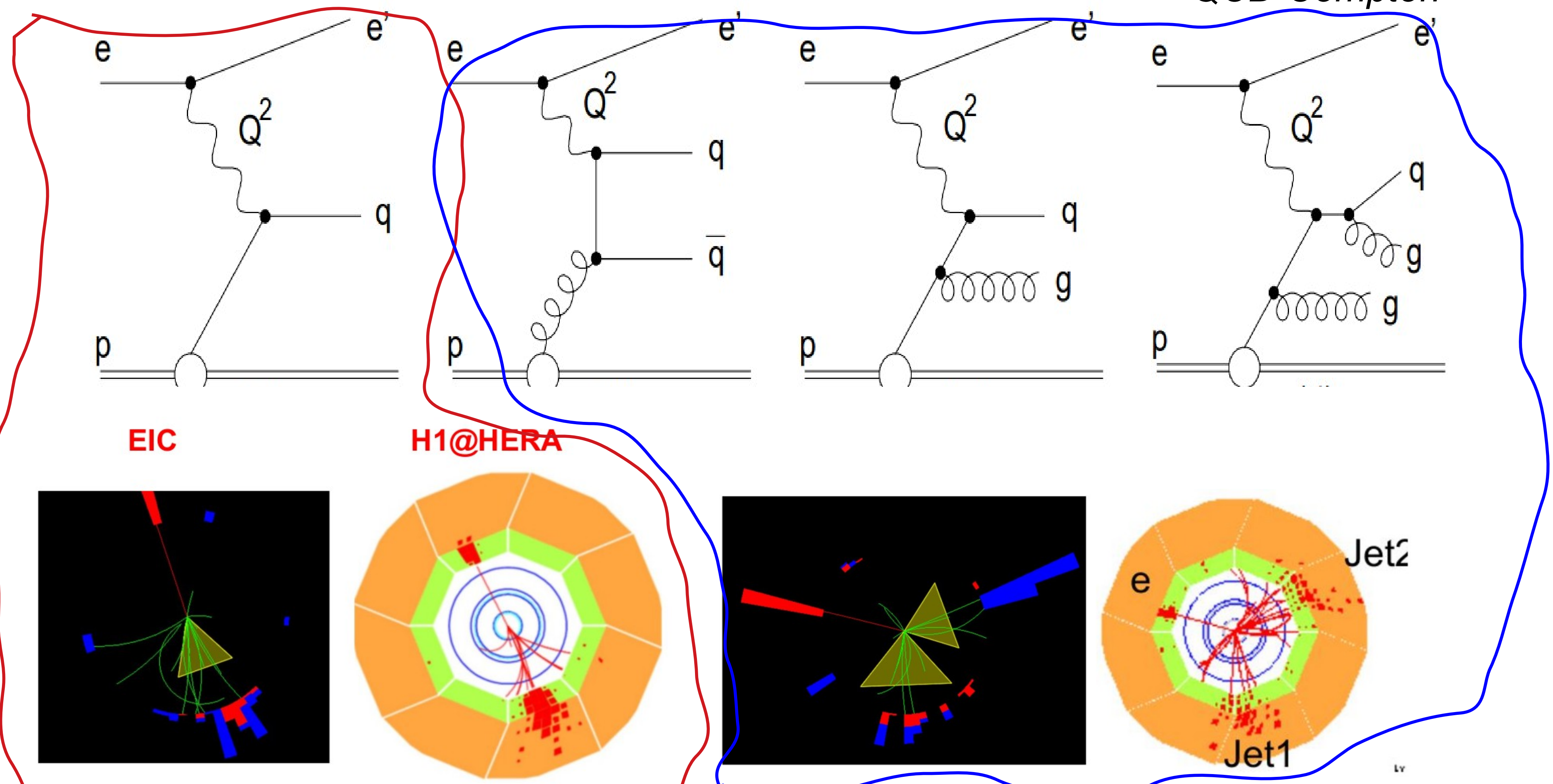
Circumference:	**6.3 km**	
Proton Beam:	**Injection Energy**	**40 GeV**
	Lumi-Energy	**(820) 920 GeV**
Electron Beam:	**Injection Energy**	**12 GeV**
	Lumi Energy	**27.5 GeV**
Magnetic field p-ring:	**5.1 Tesla**	
	at I=5500 A for 920 GeV	



From: desy.de

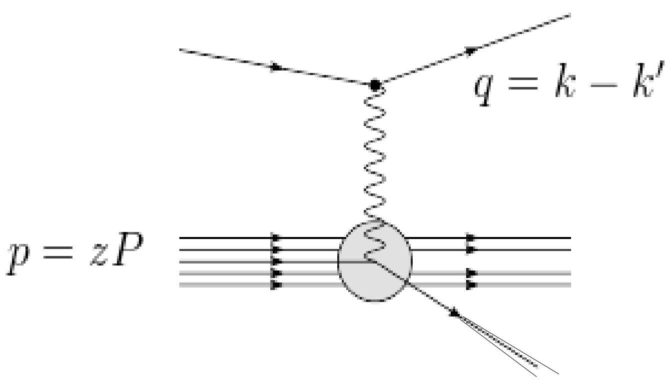
Examples for jet production in DIS

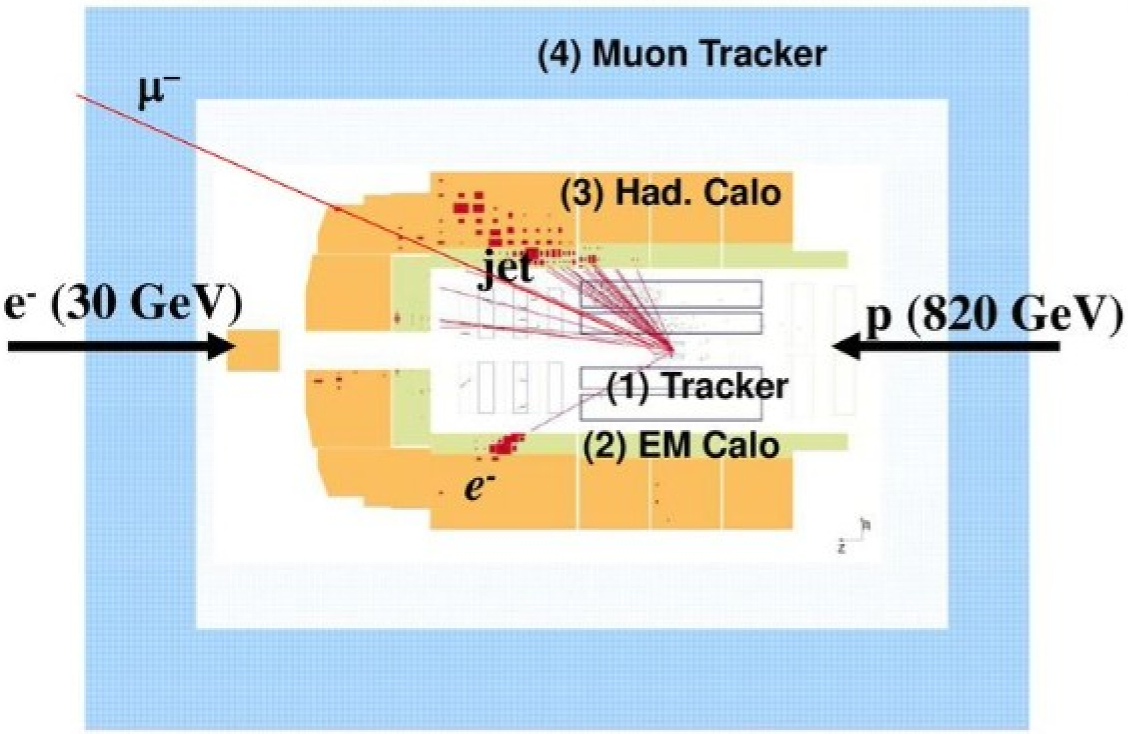
Semi-inclusive DIS | *Boson-gluon fusion* | *QCD Compton* | *QCD Compton*



From Miguel Arratia, QCD Evolution 2021

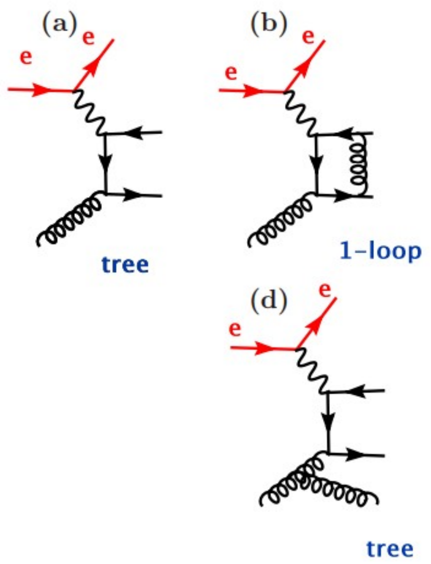
Production of jet in DIS

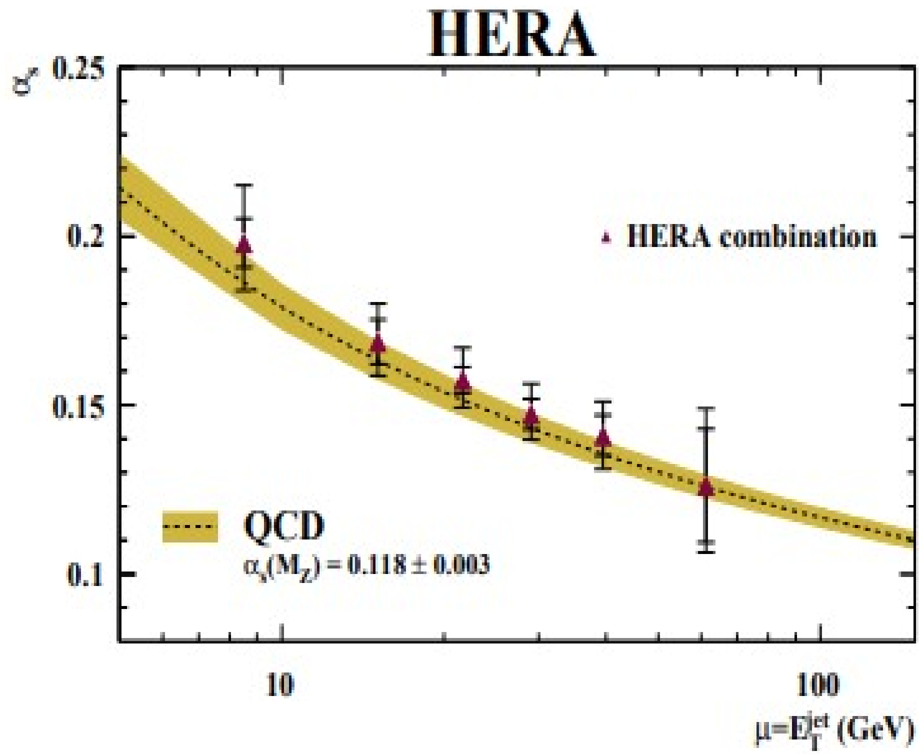




Example from HERA: NLO inclusive jet production in DIS

Phys.Lett.B 691 (2010) 127-137





Measurements motivated to test and further improve QCD calculations.

Notice: three different jet algorithms were used

Other results from HERA: NLO inclusive jet production in DIS

High ET dijet photoproduction at HERA (PRD 76 (2007) 072011, arXiv:0706.3809)
Inclusive jets with anti-kt and SISCONE algorithms (arXiv:1003.2923 , Phys. Lett. B 691 (2010) 127-137).

Inclusive jets in photoproduction (arXiv:1205.6153, Nucl. Phys. B864 (2012), 1-37).

Isolated photons accompanied by jets in DIS (arXiv:1206.2270, Phys Lett B 715 (2012) 88-97).

Isolated photons plus jets in PHP (arXiv:1312.1539 , Phys.Let B (2014) Volume 730, 293-301)

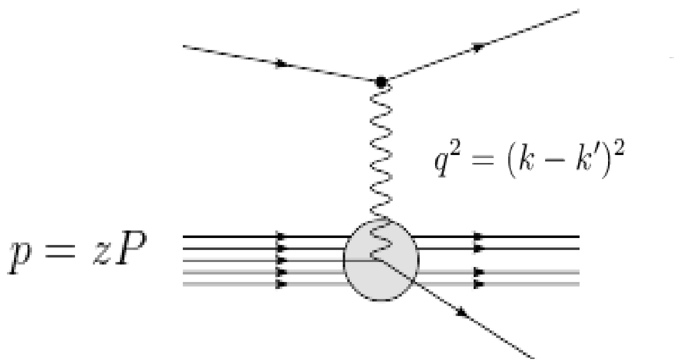
More on isolated photons plus jets in PHP (arXiv:1405.7127 , JHEP 2014 (23)).

Diffractive di-jet production in DIS (Eur. Phys. J. C 76 (2016) 16).

Diffractive photoproduction of isolated photons at HERA (arXiv: 1705.10251 , Phys. Rev. D 96 (2017) 032006)

Non-collinear factorizations

Transverse Momentum Dependent factorization, Color Glass Condensate,
Improved Transverse Momentum Dependent factorization, Soft Collinear Effective Theory



Momentum of proton $P = E_p(1, 0, 0, -1)$

Momentum of parton $p = zP + k_T$

imbalance

$$\sigma_{\mathcal{O}} = \sum_j \mathcal{O}(k_T) \otimes \mathcal{S}(Q^2) \otimes \mathcal{F}_j(x/x_p, Q^2, k_T)$$

cross section

matrix element
defining opbservable

Possible additional
factors – depend on exact
type of factorization

probability of
finding parton j in the proton.
Possible that this TMD obeys
nonlinear evolution equation

Why jets are useful?

For jets we have

$$\sigma_{\mathcal{O}} = \sum_j \mathcal{O}(k_T)\otimes\mathcal{S}(Q^2)\otimes\mathcal{F}_j(x/x_p, Q^2, k_T)$$

For individual particles we have

fragmentation function

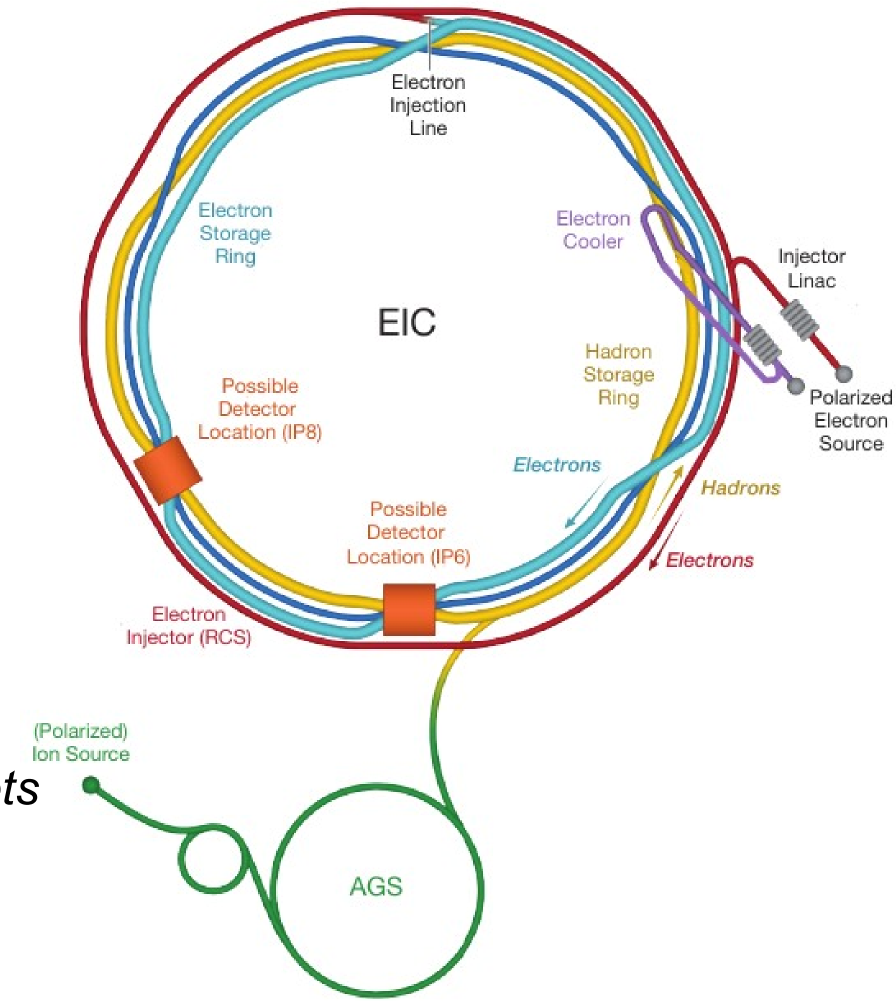
$$\sigma_{\mathcal{O}} = \sum_j \mathcal{O}(k_T)\otimes\mathcal{S}(Q^2)\otimes D\otimes\mathcal{F}_j(x/x_p, Q^2, k_T)$$

- *jets avoid nonperturbative TMD fragmentation functions*
- *modern jet substructure techniques offer new methods for precise QCD calculations and to control nonperturbative effects*
- *one can minimize hadronization effects or study TMD evolution*

Electron Ion Collider (EIC)

Will use the existing RHIC complex at Brookhaven National Laboratory

- *Variable center of mass energies: 20-140 GeV*
- *Ion beams: from d to Au, Pb, U*
- *High luminosity: 10 33 − 10 34 cm −2 s −1*
- *Highly polarized (70%) electron and nucleon beams*



The future Electron-Ion Collider (EIC) [1]

will produce the first jets in polarized and nuclear DIS,

which will enable a rich jet program

Complementary to semi-inclusive DIS observables, jets avoid nonperturbative TMD fragmentation functions.

Electron Ion Collider – science program with jets and results relevant for EIC jet studies

Recent publications

- *The spin of the proton, PDFs*

Hinderer, Schlegel, Vogelsang `15, `17, Abelof, Boughezal, Liu, Petriello `16, Boughezal, Petriello, Xing `18, Aschenauer, Chu, Page `19, Borsa, Florian, Pedron `20, Arratia, Furletova, Hobbs, Olness, Sekula `20

- *3D nucleon/nucleus tomography*

Zheng, Aschenauer, Lee, Xiao, Yin `18, Liu, FR, Vogelsang, Yuan `19,
Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `19,
Hatta, Mueller, Ueda, Yuan `19, Arratia, Kang, Prokudin, FR `20

- *Saturation*

Hatta, Xiao, Yuan `17, Salazar, Schenke `19, Roy, Venugopalan `19, Kang, Liu `19
P. Kotko, K. Kutak, A. Stasto, M. Strikman, S. Sapeta` 17
T. Altinoluk, R. Boussarie, C. Marquet, P. Taels `20
T. Altinoluk, C. Marquet, P. Taels `20

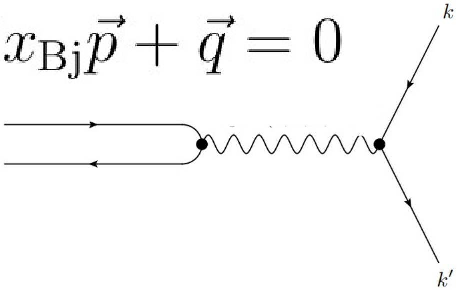
- *Hadronization and quarks and gluons in the nucleus*

Klasen, Kovarik `18, Aschenauer, Lee, Page, FR `19,
Qin, Wang, Zhang `19, Arratia, Song, FR, Jacak `19, Li et al. `20

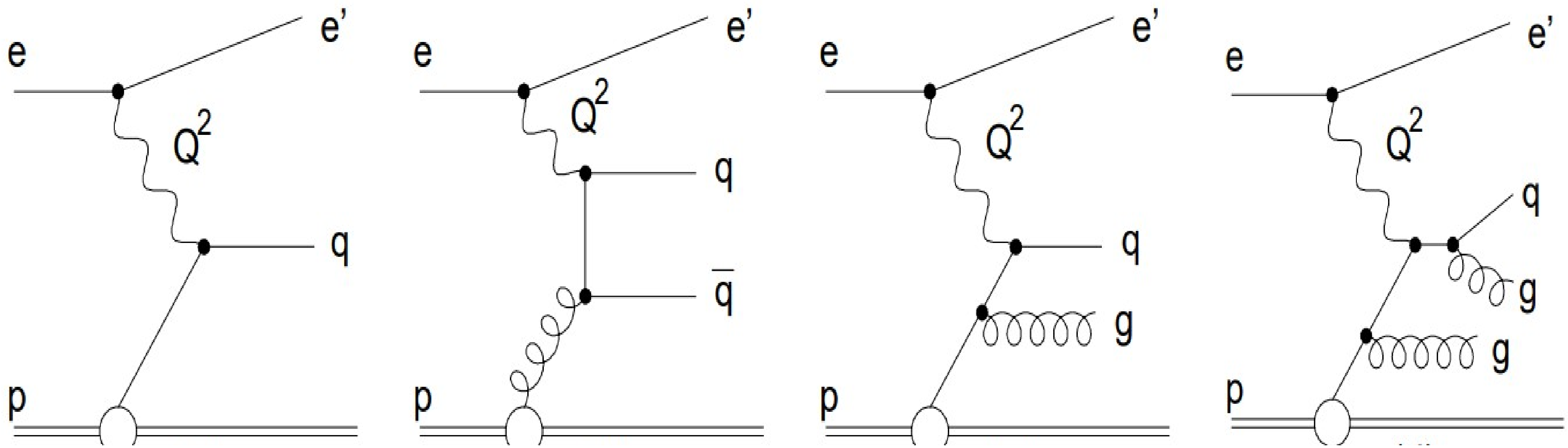
For most HERA studies

Background
~ 0 p_T in Breit frame

$$2x_{\mathrm{Bj}}\vec{p} + \vec{q} = 0$$



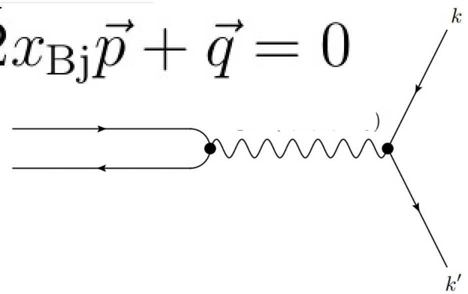
Signal (gluon PDFs, α_s)
High p_T in Breit frame



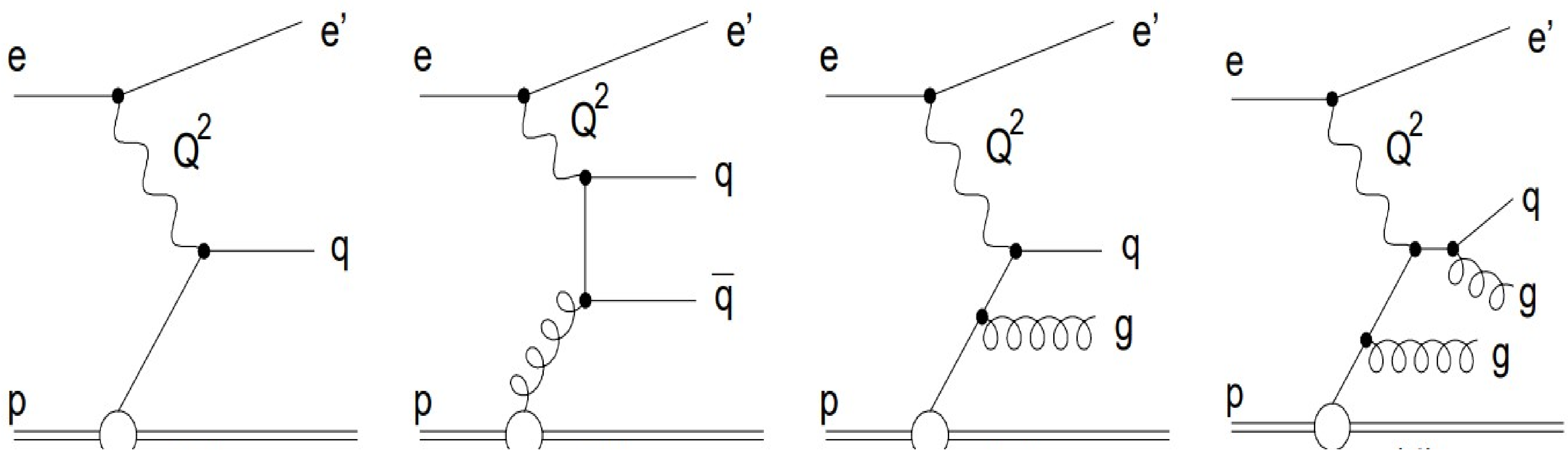
At the EIC we expect

Signal: quark TMDs
~ 0 p_T in Breit frame

$$2x_{\mathrm{Bj}}\vec{p} + \vec{q} = 0$$



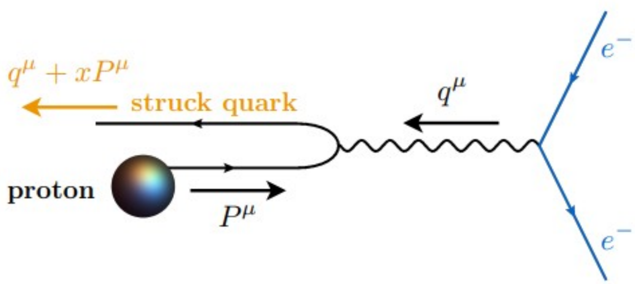
Signal: gluons
High p_T in Breit frame

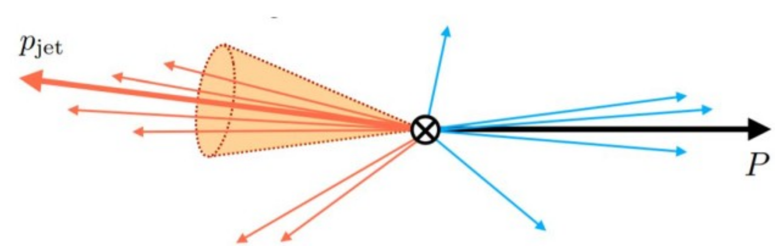


Jets algorithm for EIC

The HERA jet measurements in DIS targeted gluon initiated processes by requiring large transverse momentum in the Breit frame. This suppresses the Born configuration, which has recently been postulated as key to probe transverse-momentum dependent (TMD) PDF.

M. Arratia, Y. Makris, D. Neill, F. Ringer, N. Sato 2006.10751



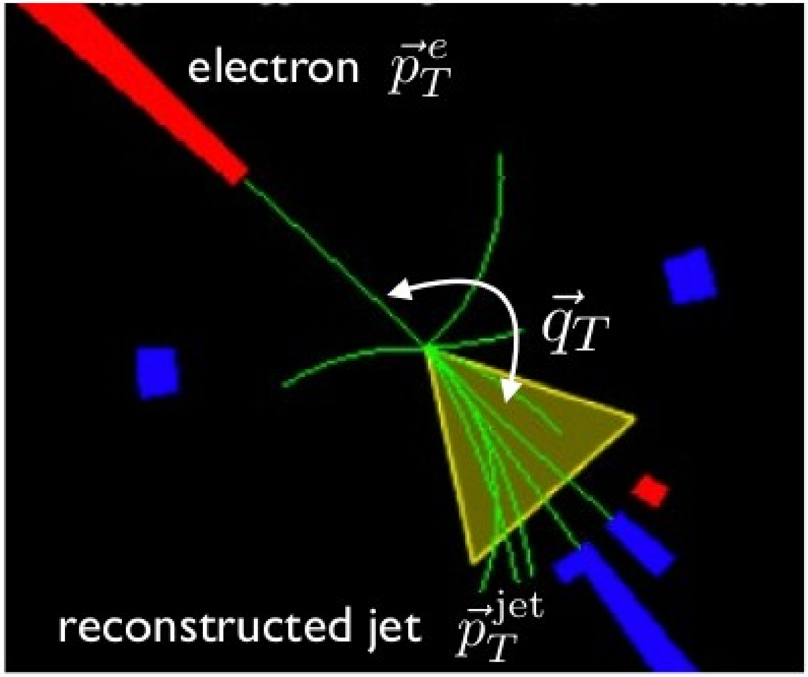


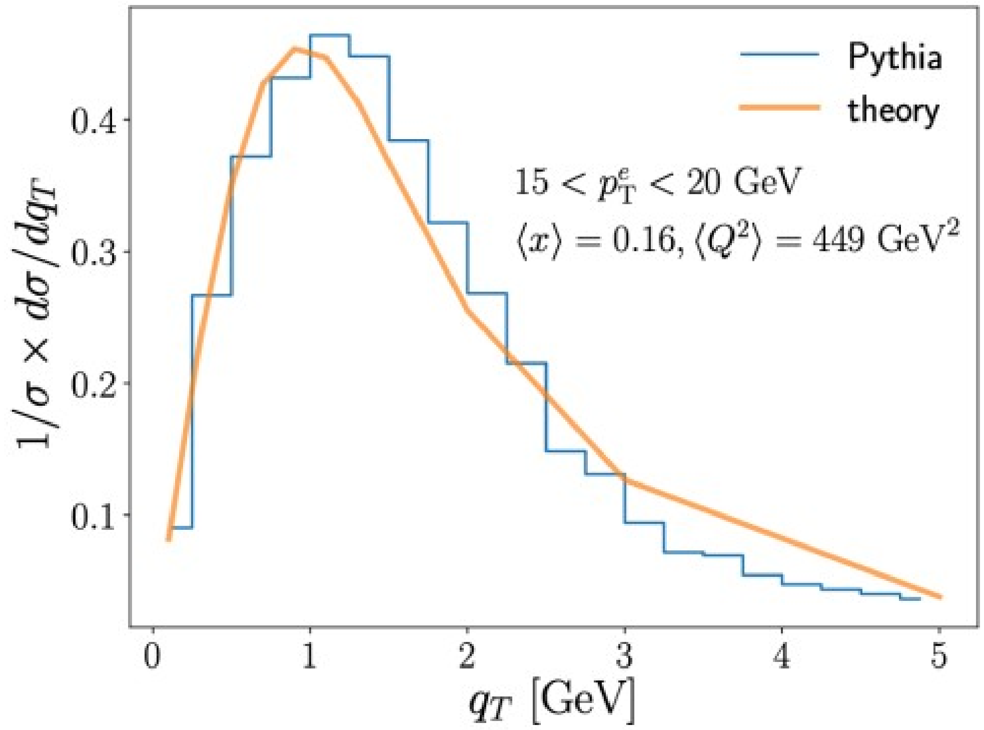
M. Arratia, QCD Evolution 2021

It is important for separation the beam remnant from forward jets. is longitudinally invariant along the Breit frame beam axis but yet captures the struck-quark jet.

New longitudinally-invariant algorithm that is asymmetric in the backward and forward directions, Centauro.

Distribution in imbalance – EIC

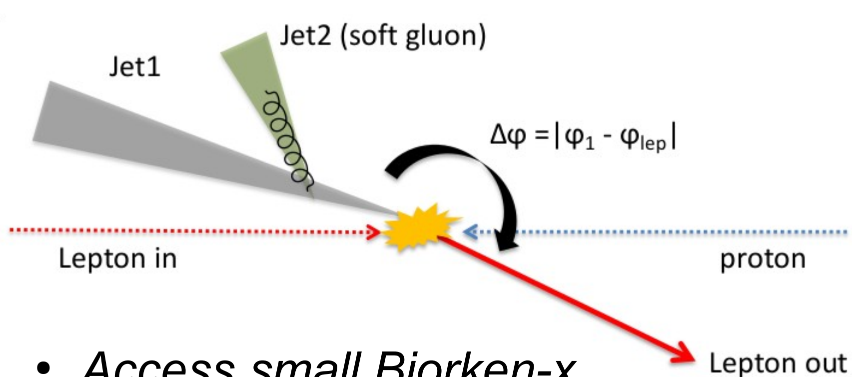


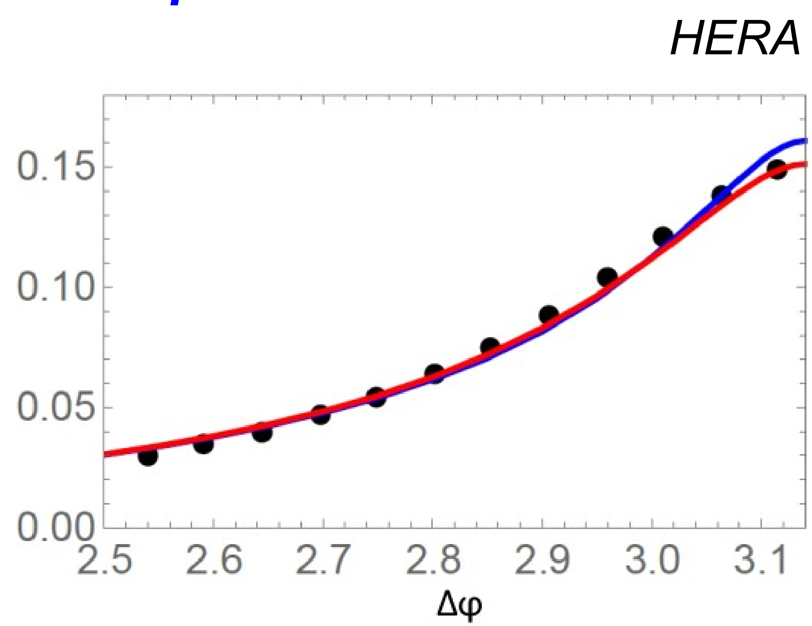


imbalance $$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}|$$

i.e. transverse momentum of quark in hadron

Lepton-Jet Correlations in Deep Inelastic Scattering





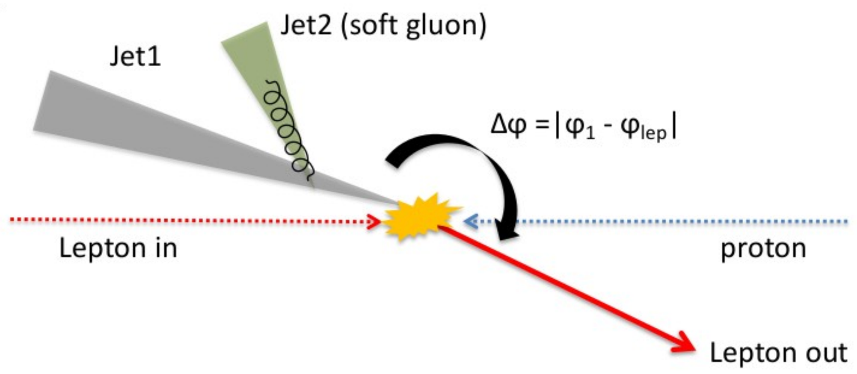
- *Access small Bjorken-x (HERA kinematic region)*
- *Study Q^2 dependence onTMD evolution.*
- *Study parton radiation effects.*
- *Test pQCD and MC generators.*

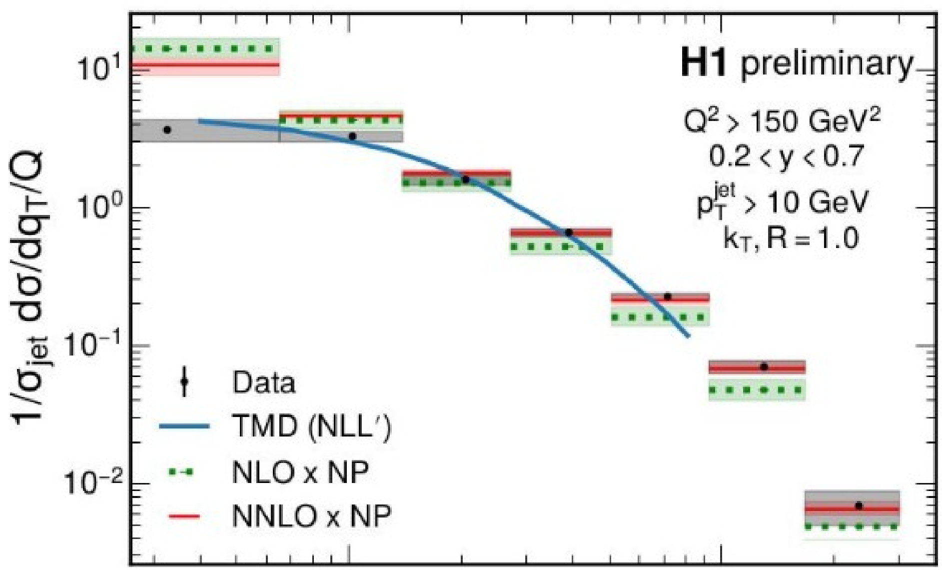
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\rm TMD}(Q, \mu_F) S_J(\lambda_\perp, \mu_F) \times \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp).$$

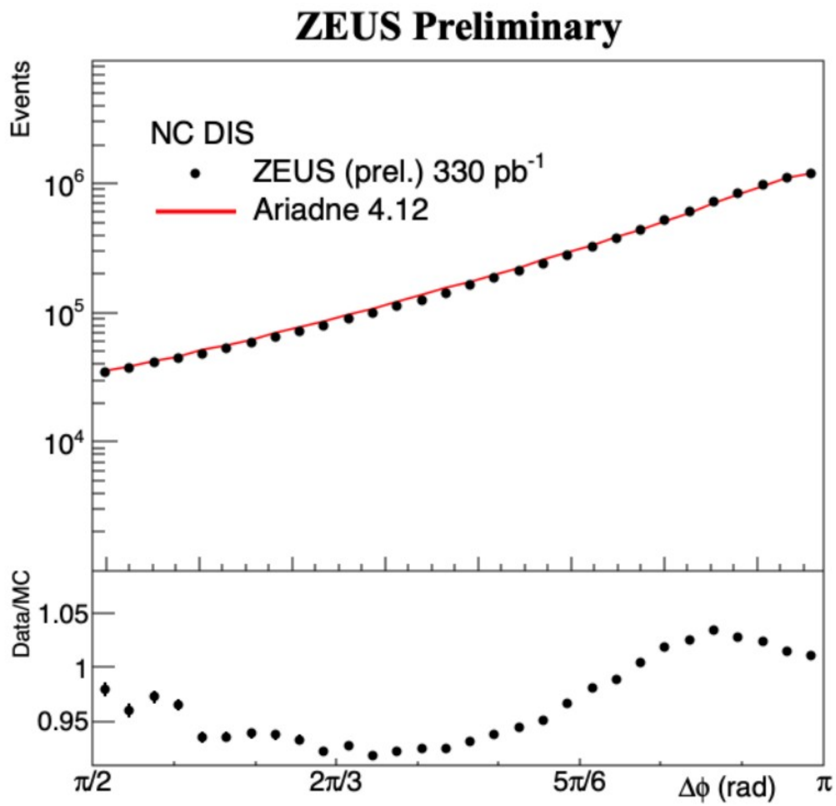
Imbalance $q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\rm jet}|$

from A. Quintero, DIS 2021

Lepton-Jet Correlations in Deep Inelastic Scattering



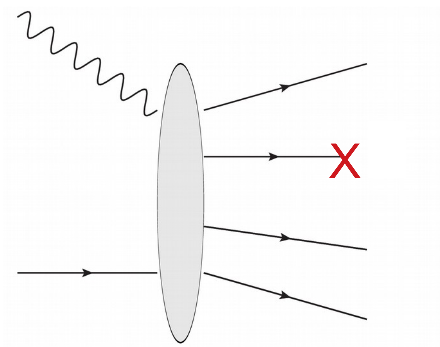


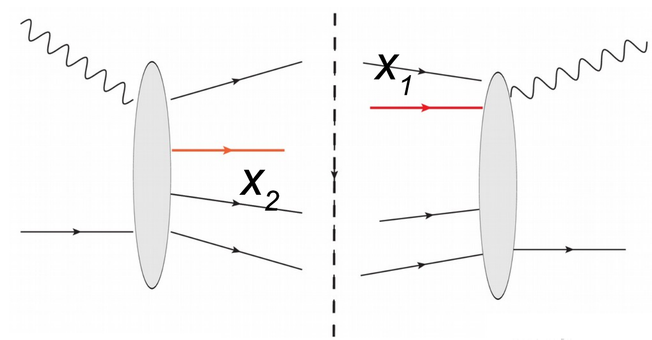


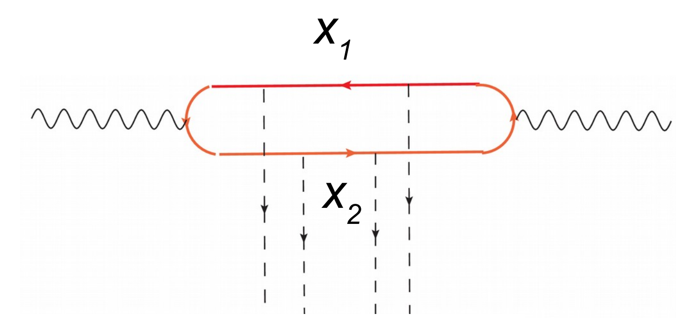
Imbalance $q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\rm jet}|$

Gluon densities in DIS and low x – dipole density

Contributes to semi-inclusive DIS and F_2 at low x





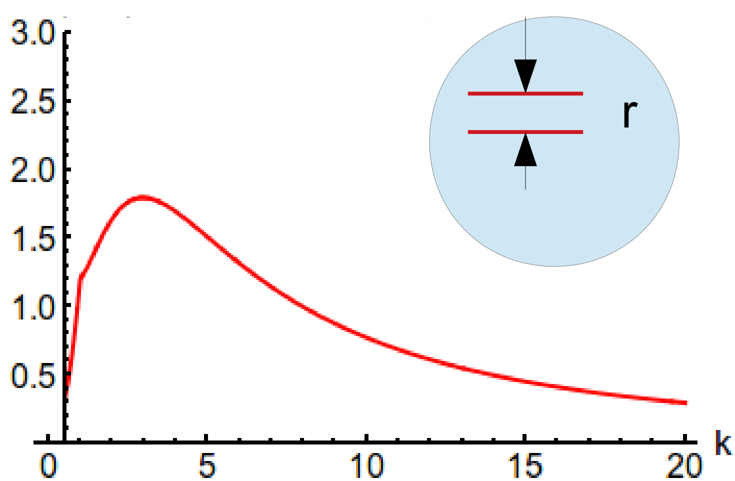


$$S(x_g, r) \propto \langle Tr(U^\dagger(x_1)U(x_2))$$

that target is homogenious and large as compared to dipole size we can express it in terms of dipole size

$$\mathcal{F}_{dip}(k_T) \propto F.T.S(r)$$

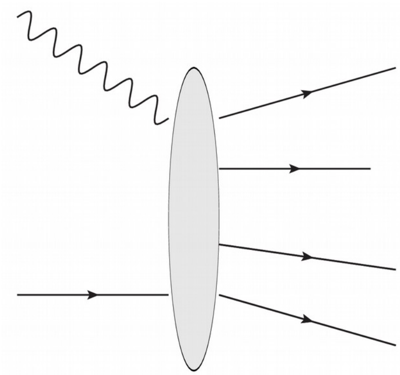
$$r \equiv x_1 - x_2$$

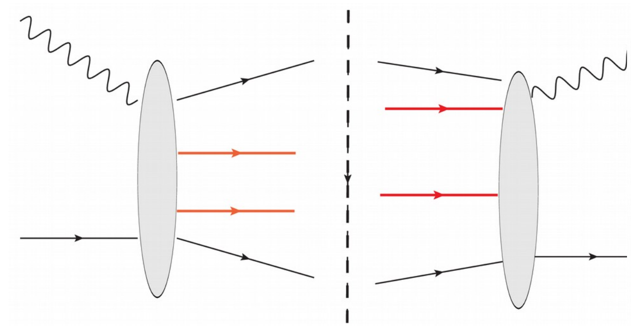


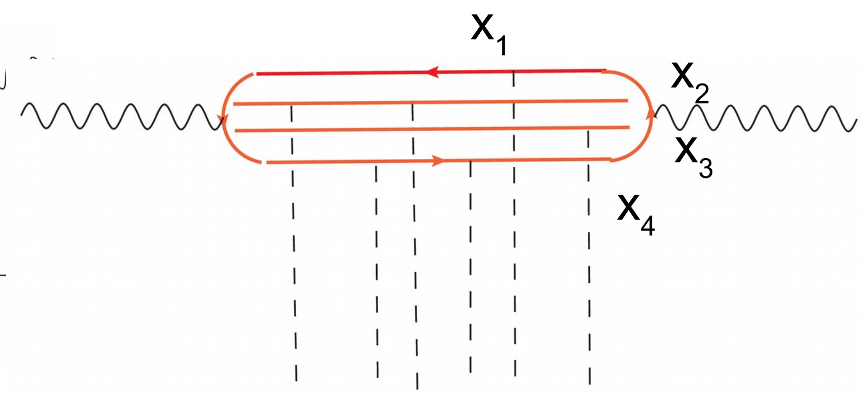
This gluon density can be used to introduce unintegrated quark density at low x.

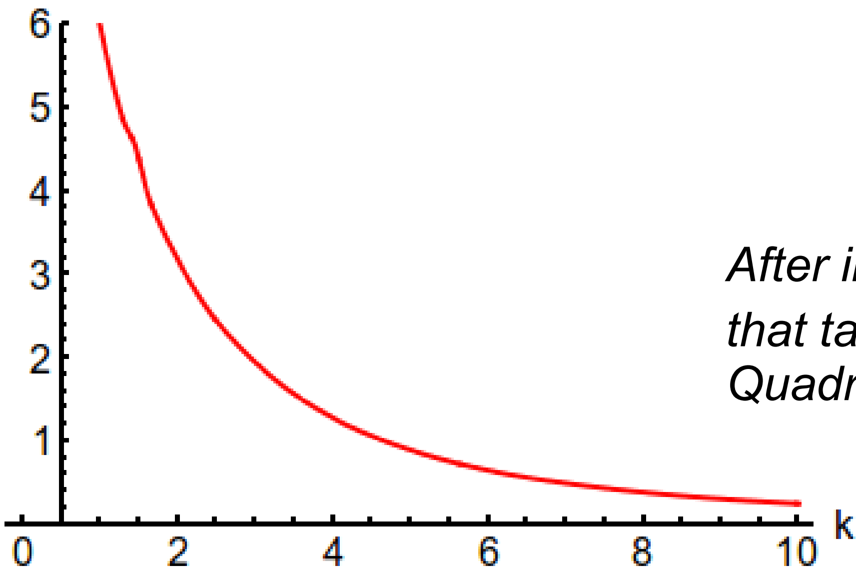
Gluon densities in DIS and low x – Weizsacker-Williams density

Contributes to 2,3,… jets







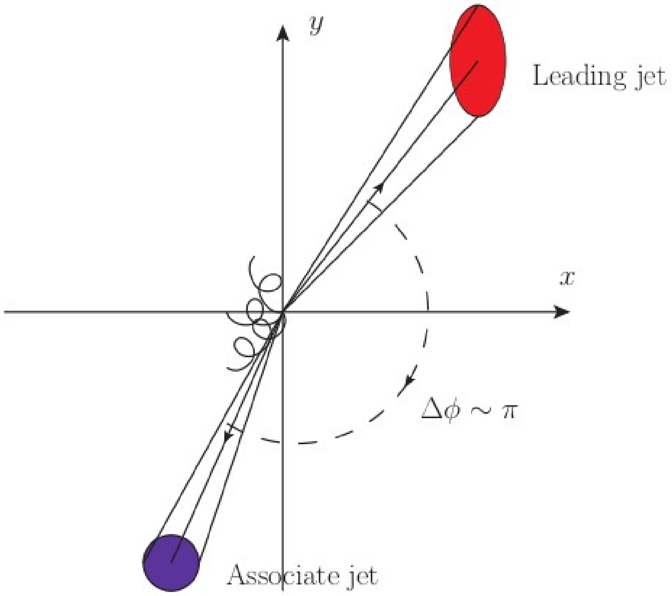


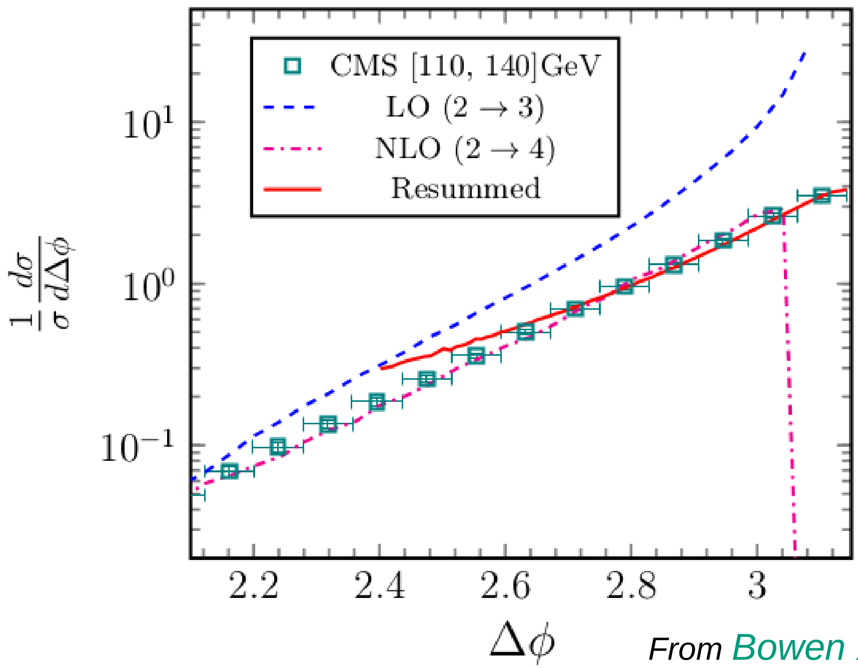
$$Q \propto \langle Tr(U^\dagger(x_1)U(x_2)U^\dagger(x_3)U(x_4))\rangle$$

After introducing large N_c approximation and and assuming that target is homogenious and large we can express Quadrupol in terms of one transverse variable

$$\mathcal{F}_{WW}(x_g, k_T) \propto F.T.\tilde{Q}(x_g, r)$$

Sudakov, back-to-back jets and collinear physics





From Bowen Xiao lecture at QCD 2019 master class

In collinear physics at LO for 2 → 2 we get delta function since the colliding partons do not carry transverse momentum. Adding more jet we get some improvement 2 → 3, 2 → 4. The unobserved partons can be soft and can introduce large logs. Note: k_t factorization also smears the delta function but takes into account also low x effects

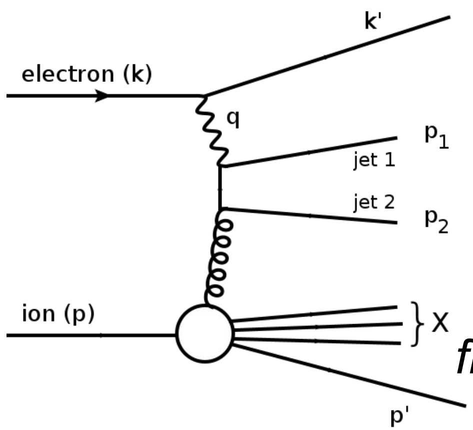
$$p_t >> k_t$$

divergence $L \sim \ln^2 \frac{p_t^2}{k_t^2}$ *needs to be resummed*

leading jet

imbalance between leading jet and associated jet – in forward jet scenario this can be linked to k_t of incoming parton

Decorelations and WW gluon in DIS



from S. Sapeta

This process allows to probe the Weizsacker-Williams TMD

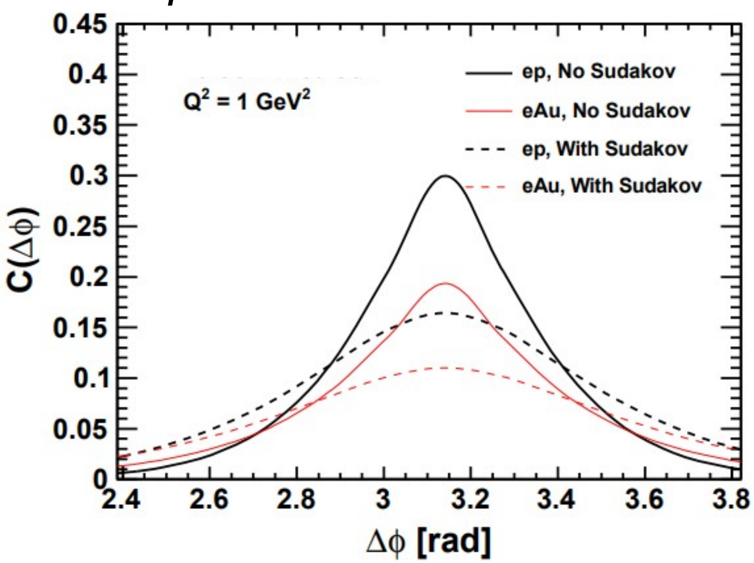
$$d\sigma_{\gamma^* A\to 2j+X} \propto \int \frac{dx}{x} d^2k_T\, \mathcal{F}^{(3)}_{gg}(x,k_T,\mu)\, \mathcal{M}_{\gamma^* g^*\to 2j}$$

A. Mueller, B-W. Xiao, F. Yuan, 2013

$$S^{g\to q\bar{q}}_{\rm Sud}(\mu, b_T) = \frac{\alpha_s N_c}{4\pi} \ln^2 \frac{\mu^2 b_T^2}{4e^{-2\gamma_E}}$$

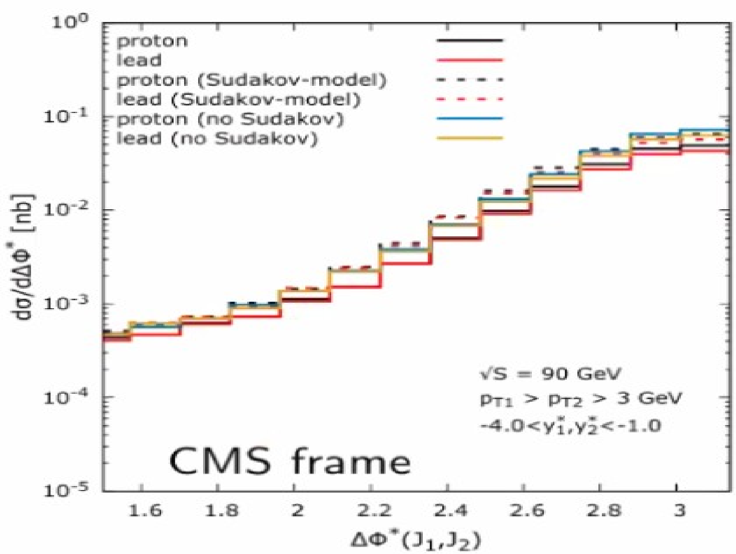
The Weizsacker-Williams TMD with Sudakov resummation to account for soft emissions

particles



L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, 2014

jets



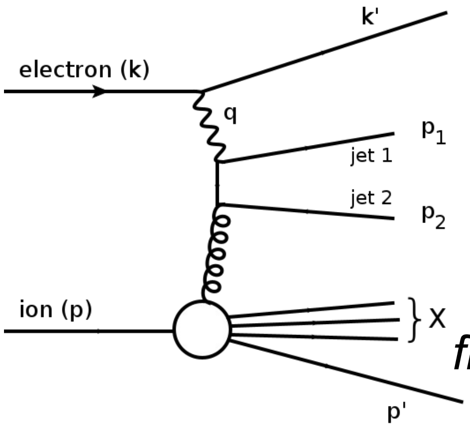
In progress, P. Kotko, K. Kutak, Sapeta, A. van Hameren E. Żarow

Related studies for dijet/dihadron at EIC

A. Dumitru, V. Skokov, 2018

H. Mantysaari, N. Mueller, F. Salazar, B. Schenke, 2019, F. Salazar, B. Schenke, 2020

Decorelations and WW gluon in DIS



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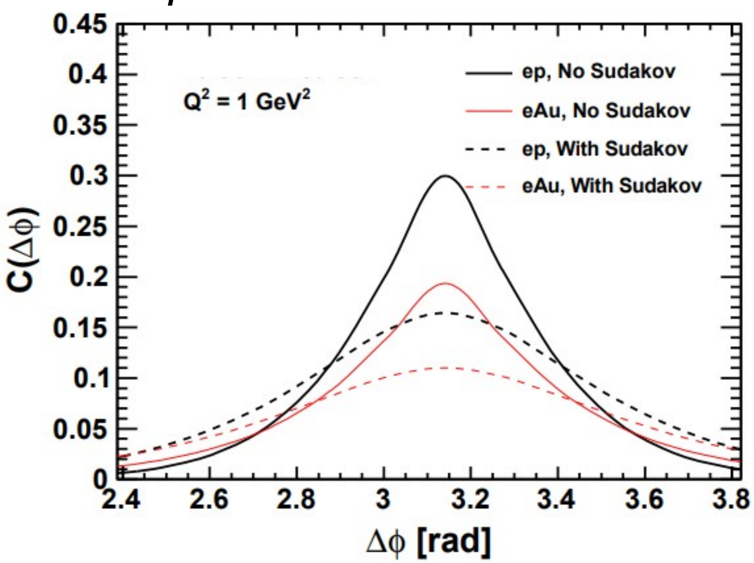
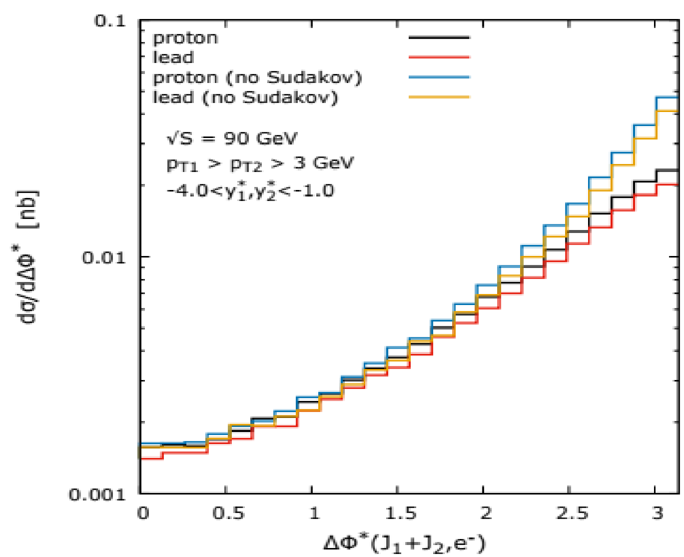


L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, 2014

jets



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Summary and further comments

- *Jets are relevant to understand better QCD*
- *EIC offers new opportunities in studies of QCD using jets*
- *There are many more results that I did not have time to talk about*

Summary and further comments

- Jets are relevant to understand better QCD
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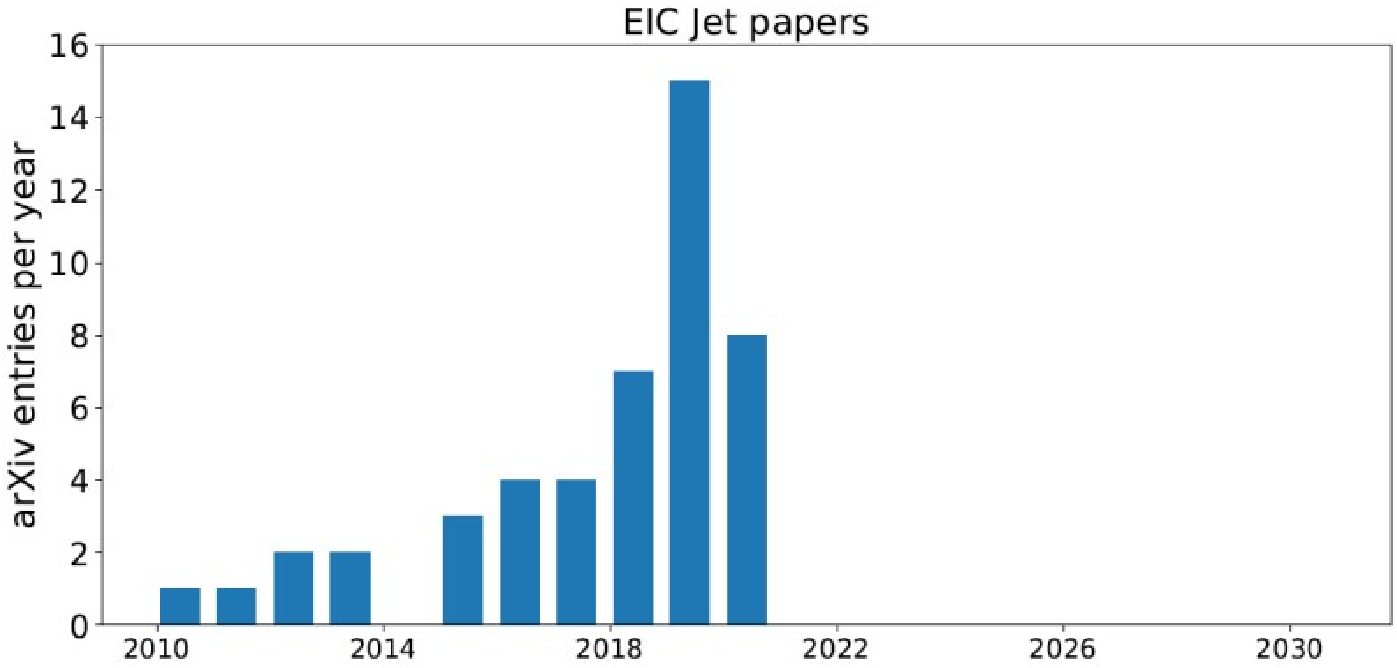

From F. Ringer Jet Observables at the Electron-Ion Collider 2020, BNL