LHC Physics and EIC

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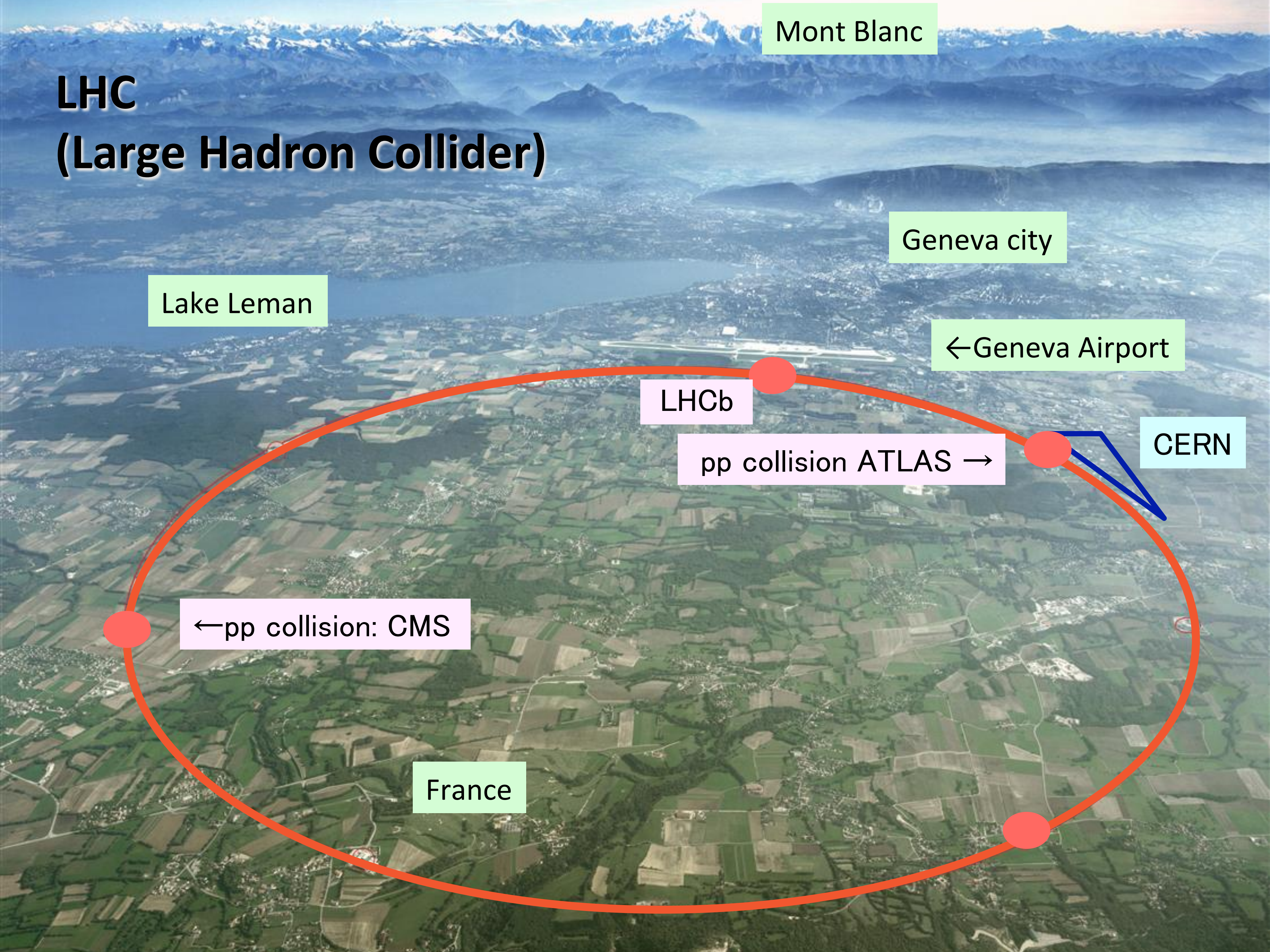
Many thanks to Julia Furletova and Rik Yoshida, for their help!

Disclaimer:
I am **not** in the EIC community.
Your inputs for a discussion are very welcome!


LHC
(Large Hadron Collider)
Mont Blanc
Geneva city
Lake Leman
←Geneva Airport
LHCb
CERN
pp collision ATLAS →
←pp collision: CMS
France

LHC
(Large Hadron Collider)

Mont Blanc

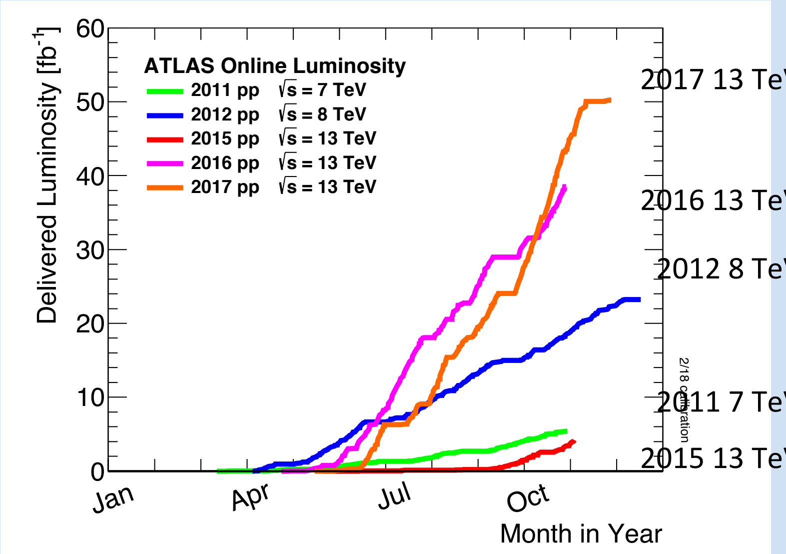
Geneva city

←Geneva Airport

CERN

collision ATLAS →

Since 2009, LHC provided high energy proton-proton collisions at
$\sqrt{s}$=0.9 TeV, 2.76 TeV, 7 TeV, 8 TeV, and 13 TeV.

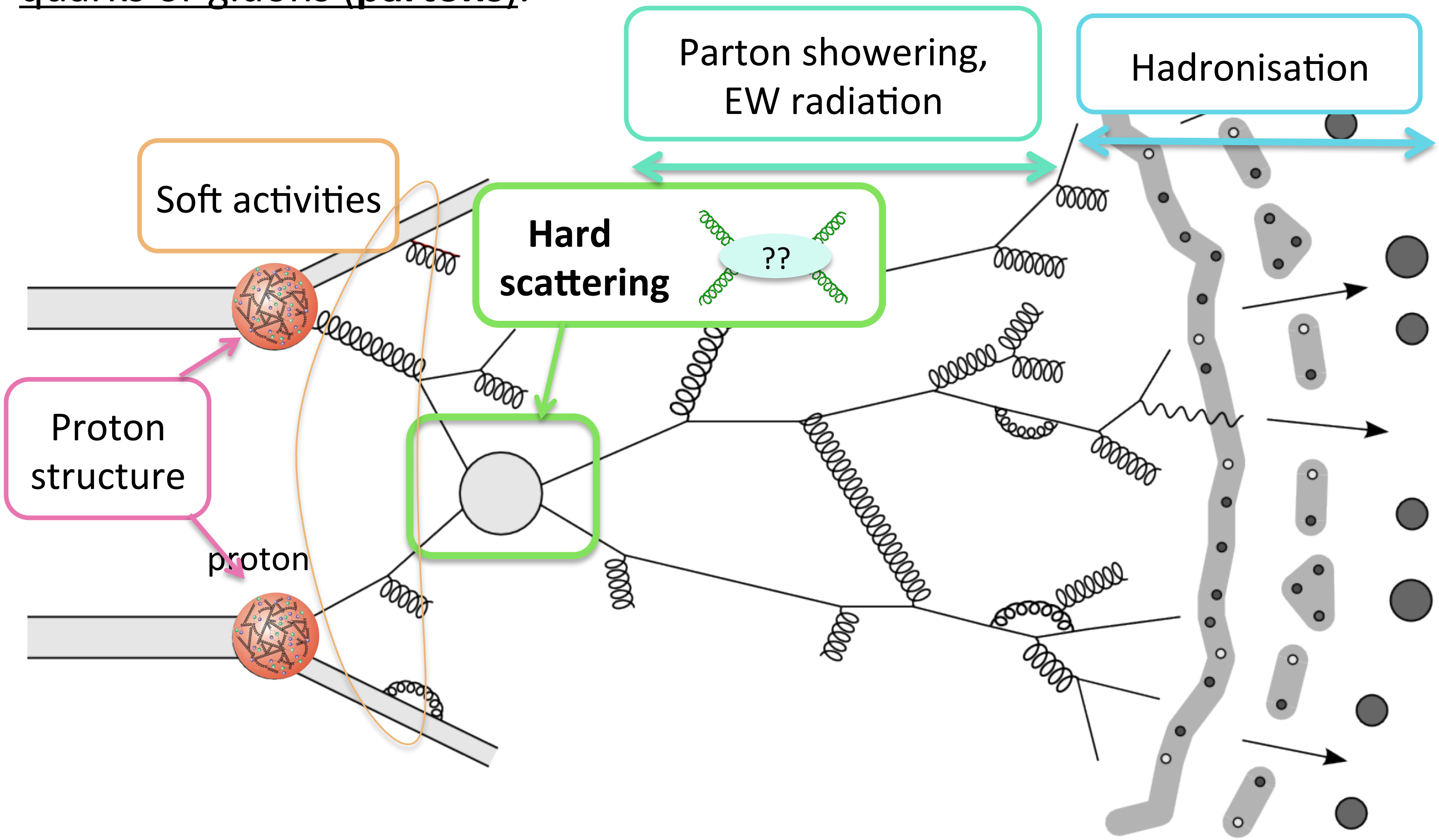


- **Search of new physics beyond the Standard Model.**
- **Precise measurement of the Standard Model physics.**

  e.g. Higgs, top…

Proton-proton collision

ATLAS and CMS look for new physics from hard scattering of quarks or gluons (**partons**).



… and there are a lot of QCD to be understood.

Examples

- **Dilepton search**
  - Increasing uncertainties on background (SM predictions) at high mass region. ← From proton <u>parton distribution functions</u> (PDFs).

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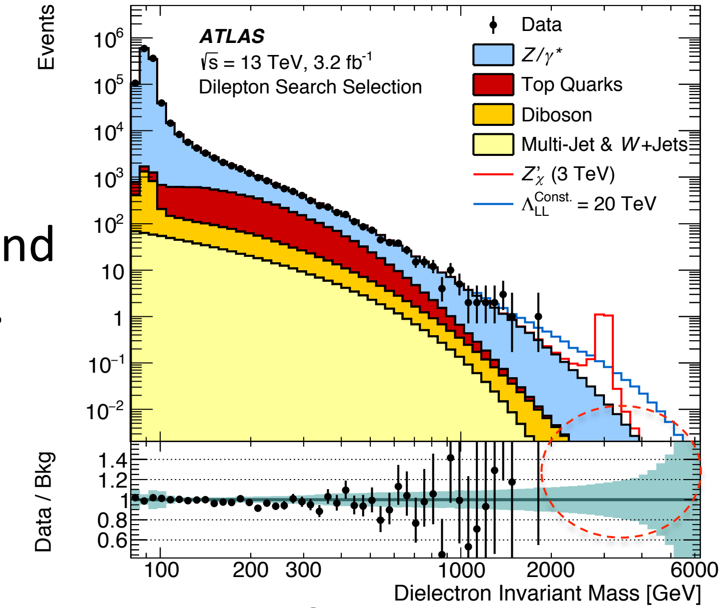
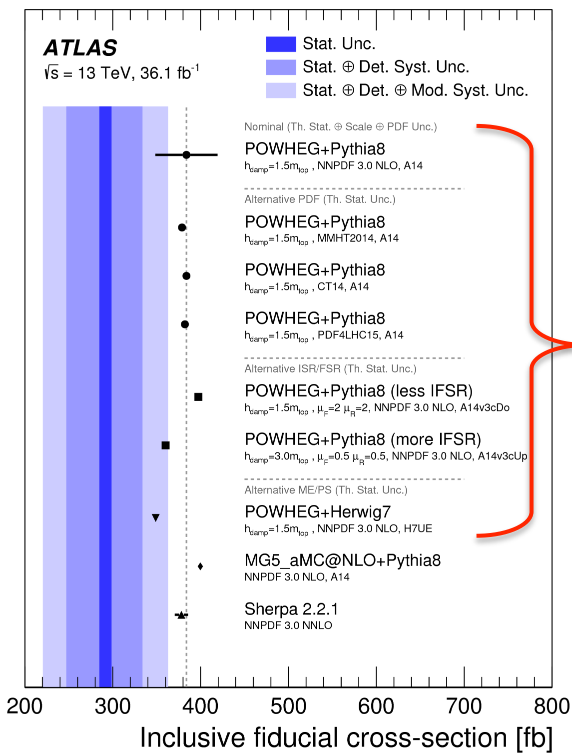


arXiv: 1801.02052



- **tt cross section measurement**

  Predictions are given by

  <u>Matrix Element MC + Parton Shower MC</u>

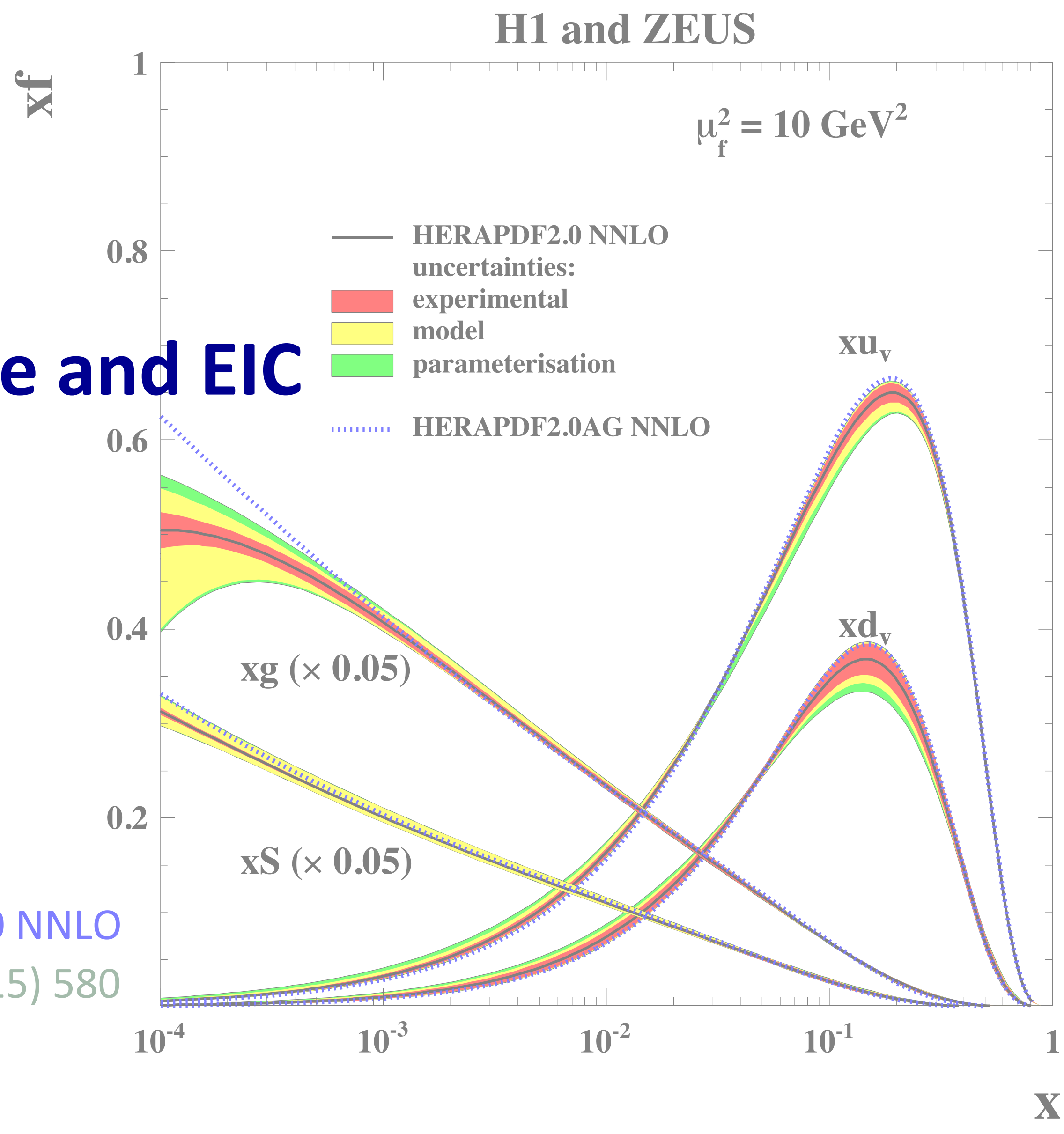
  (Matrix Element → Calculation of the hard scattering.)

All using the same Matrix Element in POWHEG

- Differences come from
  - More/Less radiations
  - Different parton shower MCs

Can EIC give better understanding of them?

Proton structure and EIC

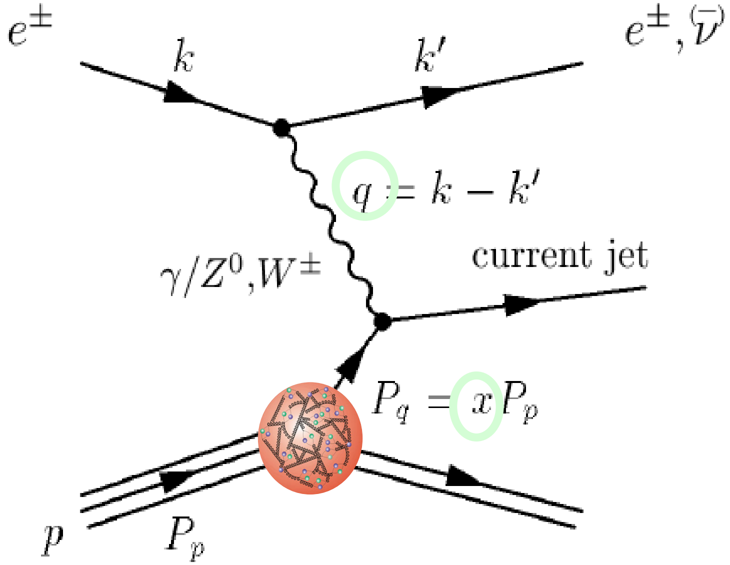


HERAPDF2.0 NNLO

EPJC 75 (2015) 580

Deep Inelastic Scattering (DIS)

***ep* DIS at HERA played a crucial role in understanding of the proton structure.**



- Kinematic variables to describe DIS

  Q^2: Virtuality
  → probing power

  x : Bjorken scaling variable
  → momentum fraction of the struck quark

  y : Inelasticity

  $\sqrt{s}$: center of mass energy

$$Q^2 = sxy \qquad Q^2 = -q^2 = -(k-k')^2 \qquad x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

- Inclusive DIS cross sections can be written with structure functions.

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ \left[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} xF_3(x,Q^2) \right] \qquad Y_\pm = 1 \pm (1-y)^2$$

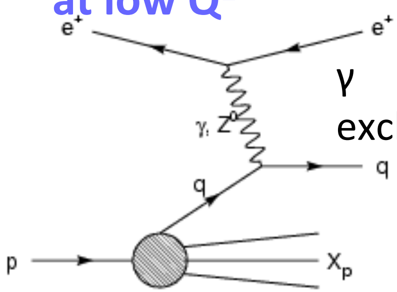
cross section of point-like particles

Structure functions reflect momentum distribution of partons in the proton.

DIS and PDFs

The proton structure is parameterised by <u>Parton Distribution Functions</u> (**PDFs**), ***q*(*x*,*Q*²)** and ***g*(*x*,*Q*²)**.
They are determined from a fit on DIS cross sections.

Neutral current DIS (NC) at low Q^2



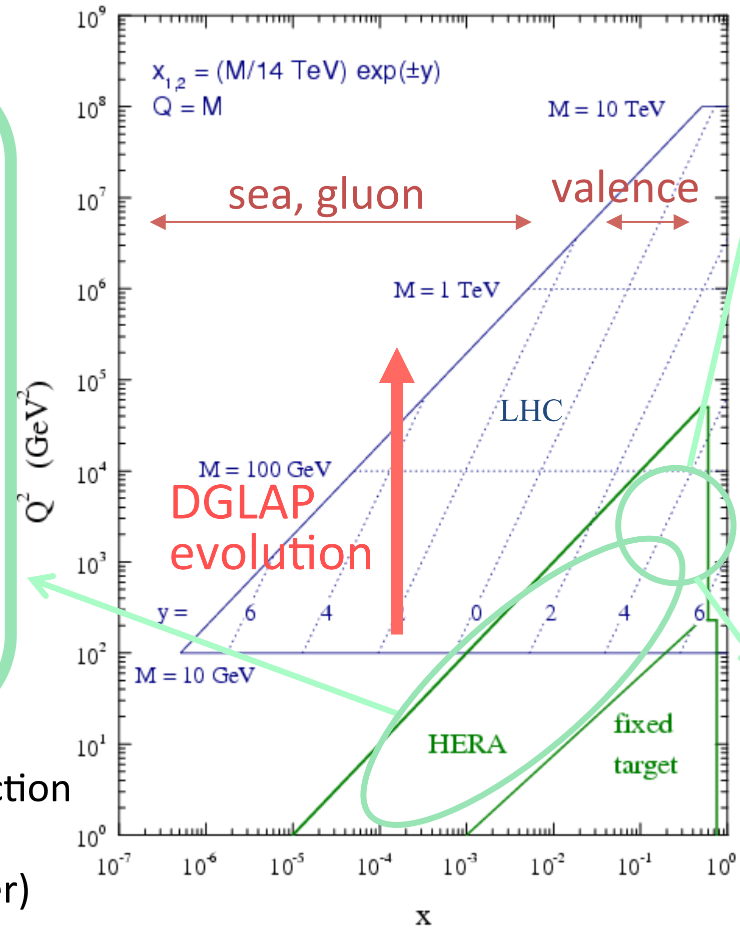
γ exchange

$\gamma \rightarrow F_2 = \sum A_q x(q + \bar{q})$

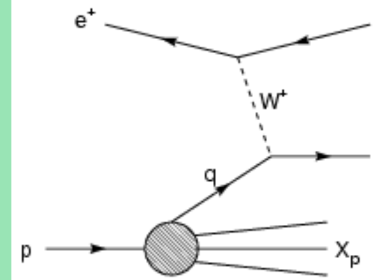
Sea + valence quark

$\frac{\partial F_2}{\partial \ln Q^2} \propto xg$ gluon

F_L: longitudinal structure function
→ gluon
sizable only at high-y (see later)



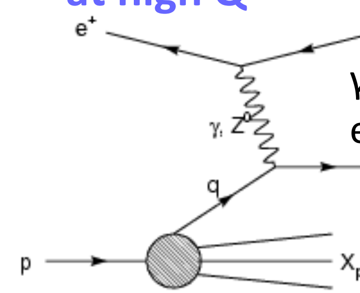
Charged current DIS (CC)



$W^\pm$ exchange

Charge selective interaction
e^- : u quark e^+: d quark

Neutral current DIS (NC) at high Q^2

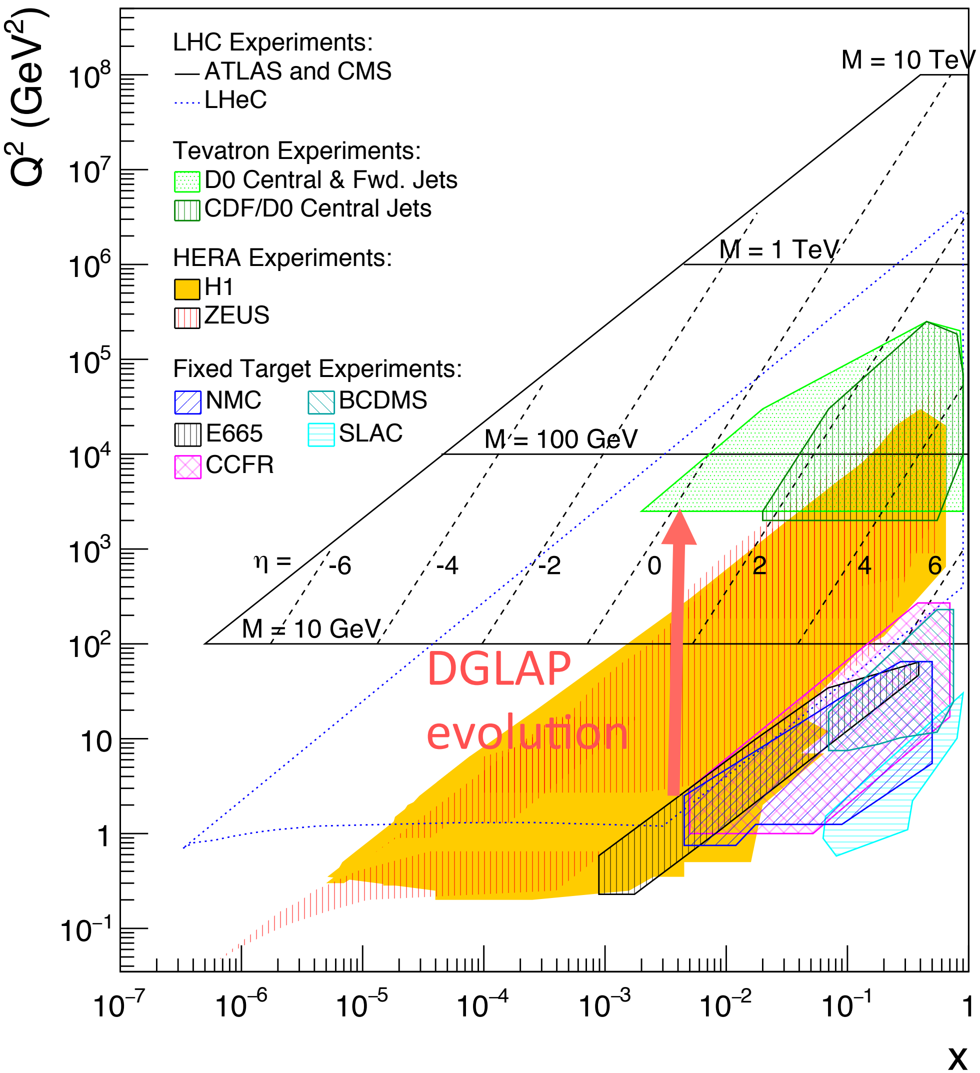


γ, Z^0 exchange

F_2: Sea + valence quark
Z^0 introduces parity violation.
→ $xF_3 = \sum B_q x(q - \bar{q})$
valence quark

The Q^2 evolution can be described by perturbative QCD, using DGLAP equation.

DGLAP works well…



pre-LHC PDFs succeed to describe LHC data in general.

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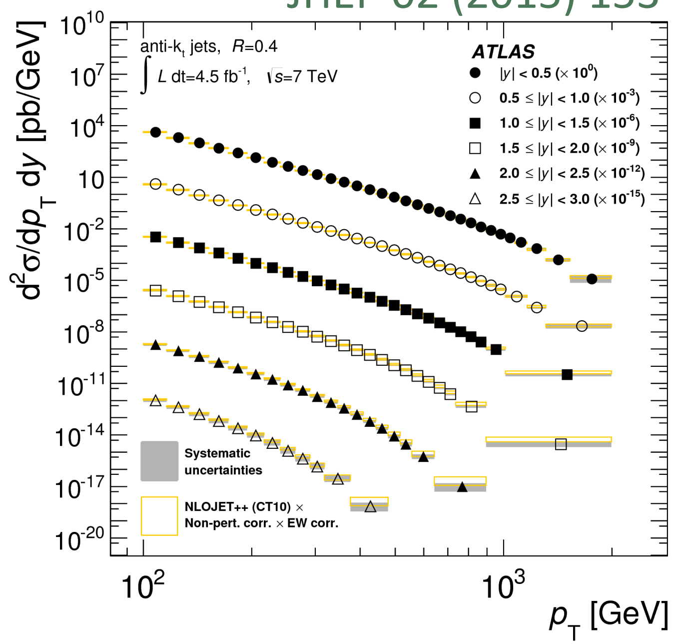


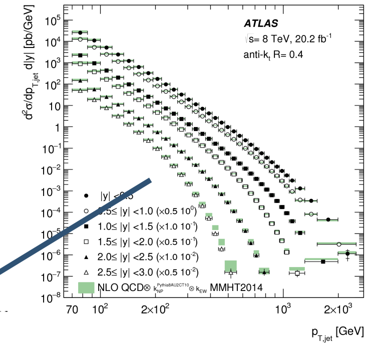
Inclusive jet cross section vs. prediction using CT10 PDFs

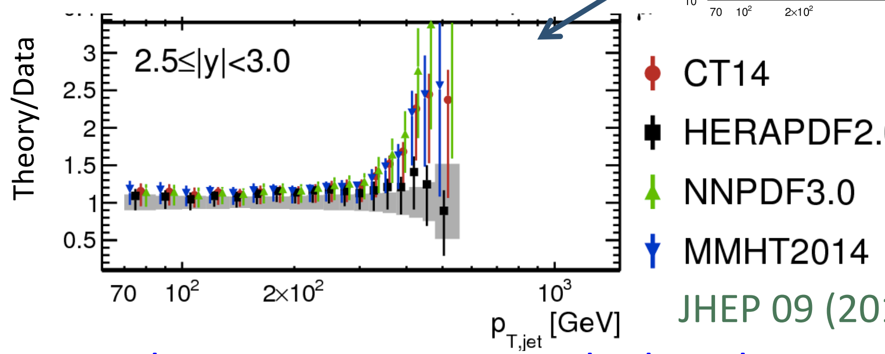
CT10 PDF: HERA DIS, Fixed target, Tevatron W/Z, jets

LHC provides more input

LHC measurements show their own preferences of PDF sets.

→ Good inputs for further constraints on PDFs.





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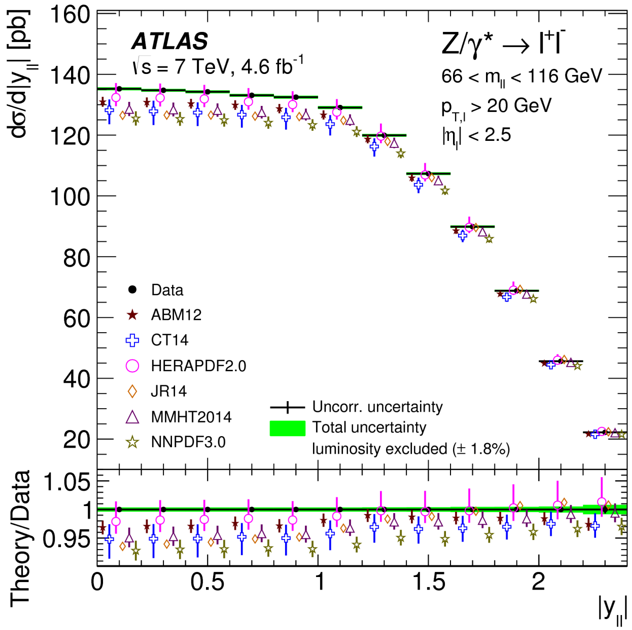
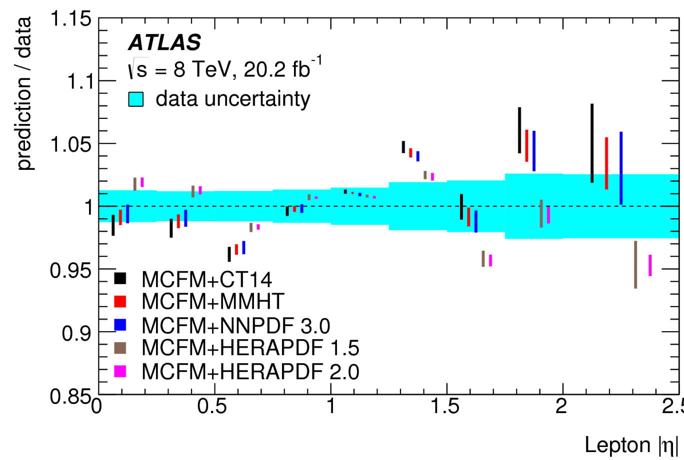
Inclusive jet @ 8 TeV → high-x gluon, quarks

EPJC 77 (2017) 367



Z/γ production @ 7 TeV
→ quark distributions



EPJC 77 (2017) 804

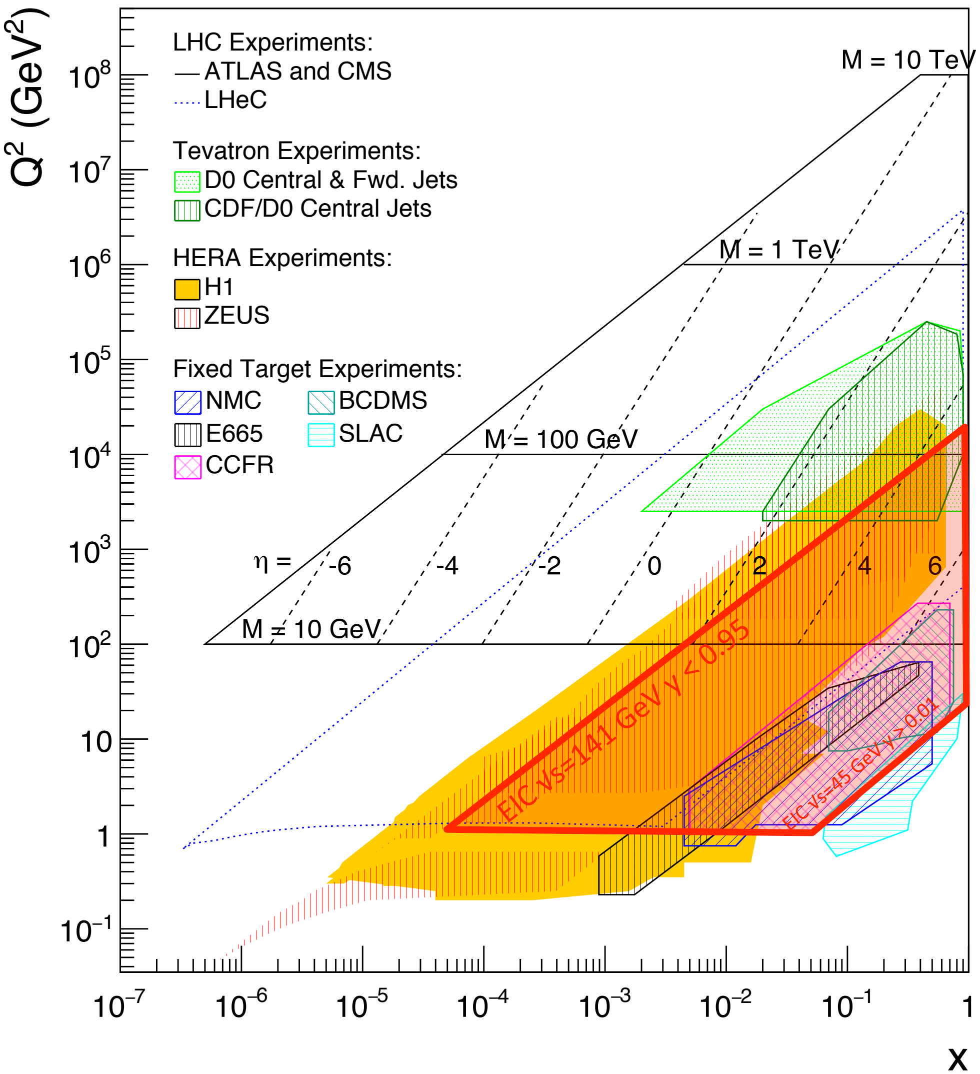
tt cross section from leptonic decay @ 8TeV
→ high-x gluon

However, it is not ideal situation for LHC searches.

- Looking for deviations from the SM, but SM uses PDFs with LHC feedbacks.

➔ Great to have other cross checks and/or more inputs from other experiments.

EIC provides opportunity for improvement



With √s up to 141 GeV, EIC ep has a decent coverage of kinematic region.

- Free from target correction and nuclear effect.
- Free from unknown physics at TeV scale.
- In a region where DGLAP is (probably) applicable.

EIC aims 10-100 fb^{-1}/year of data.

c.f. HERA: <~0.5 fb^{-1} in total, for each experiment.

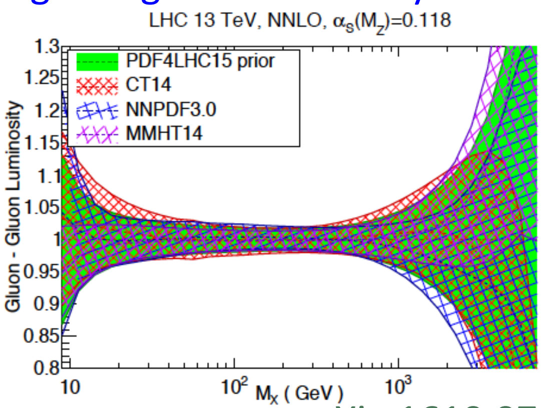
➔ **Can provide useful and powerful inputs for PDF determination.**

- **High-x measurements**
  - **Charged Current DIS**
- **F_L measurement**

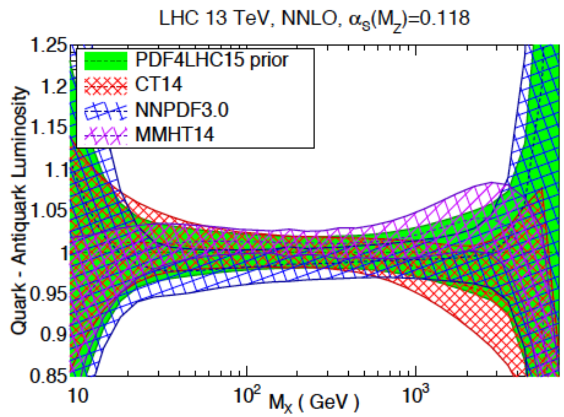
Why is high-x important?

- As a search goes higher mass, more precision at **high-x** is needed.
  - Uncertainties are large.

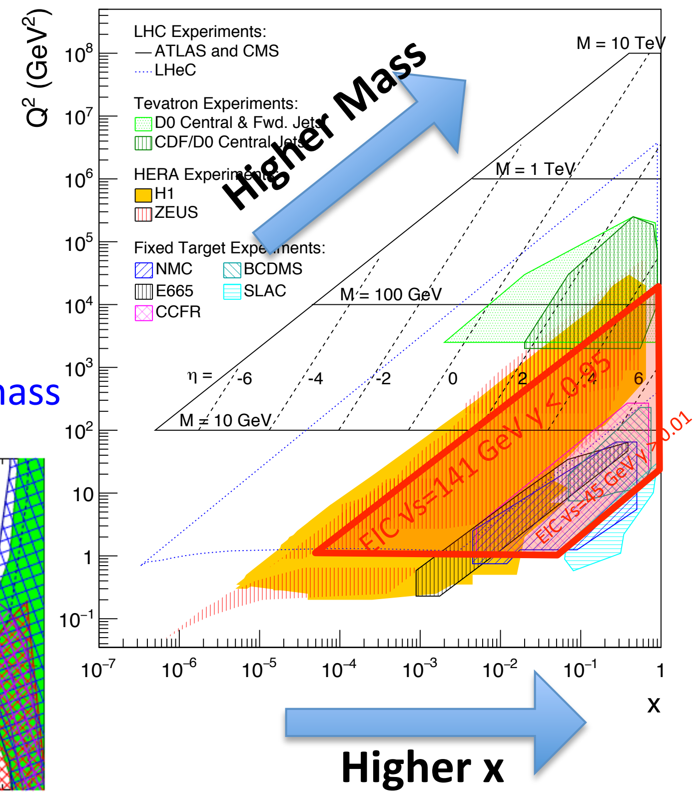
Comparison of gluon-gluon luminosity vs mass



Comparison of quark-antiquark lumi. vs mass

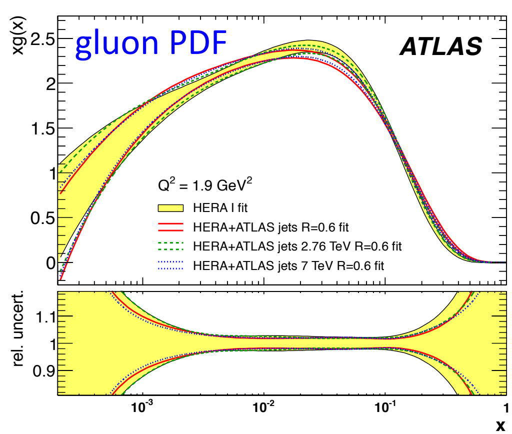


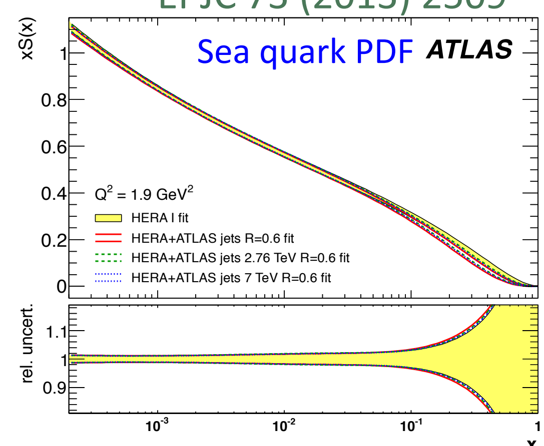
arXiv:1610.07922



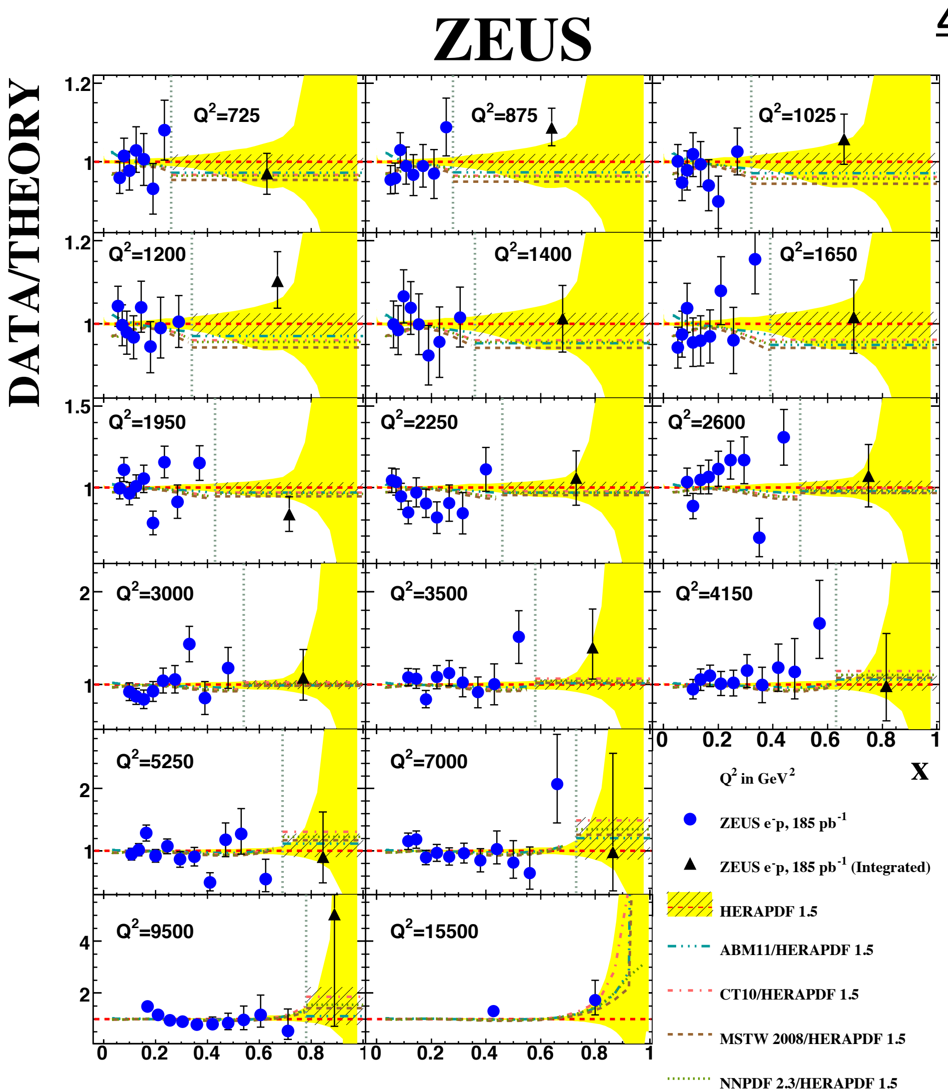
EPJC 73 (2013) 2509

- High-x determination from HERA still has a room for improvement.
  - Shape of gluon and sea-quark PDFs can move with ATLAS jet data.





High-x measurement from HERA



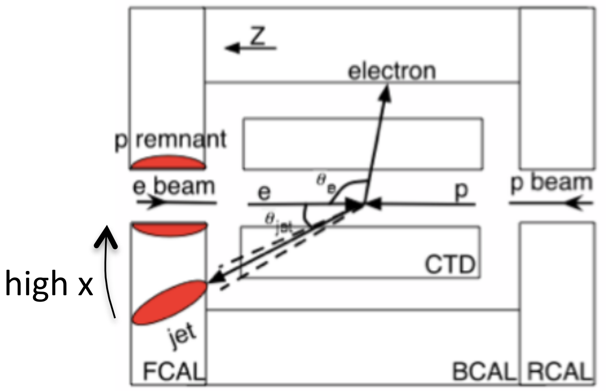
PRD 89 (2014) 072007

<u>ZEUS high-x measurement</u>

(Not in the PDF fit)

- Measured at relatively high Q^2
- At very high x, struck quark escapes from the beam pipe

→ Highest-x bin ($x>x_{edge}$) shows the integrated cross section.



Stat. error dominant

→Does EIC allow a better measurement?

HERA vs EIC for high-x measurement

In the ZEUS measurement:

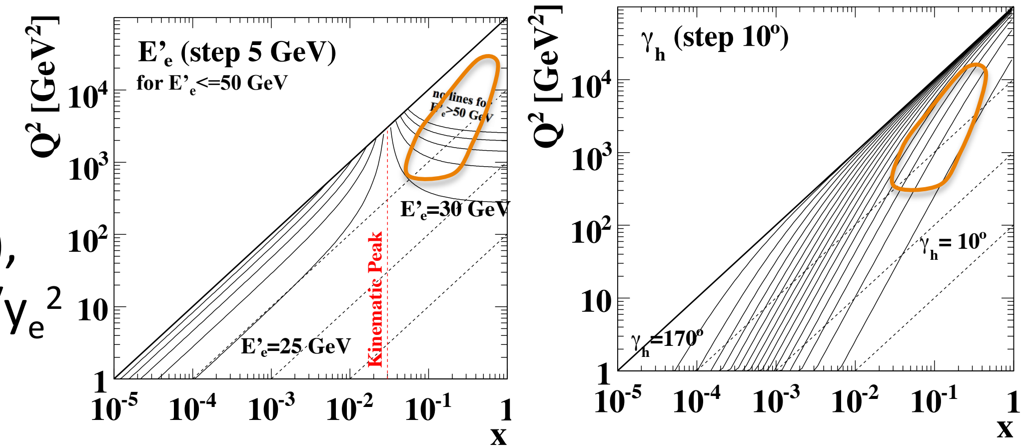
Kinematic reconstruction

- Q^2 from the scattered electron

$$Q^2 = 2E_e E_e'(1+\cos\theta_e)$$

- x from jet* energies and angles (γ_h), to avoid large uncert. from $\Delta x/x \sim 1/y_e^2$
  - if e and jet balance, E'_{eT} and jet angle are used.

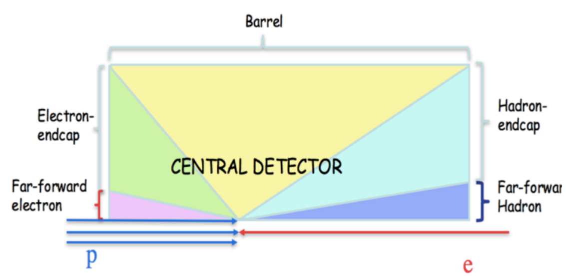
~Measured region
(N.B. my hand-drawing)

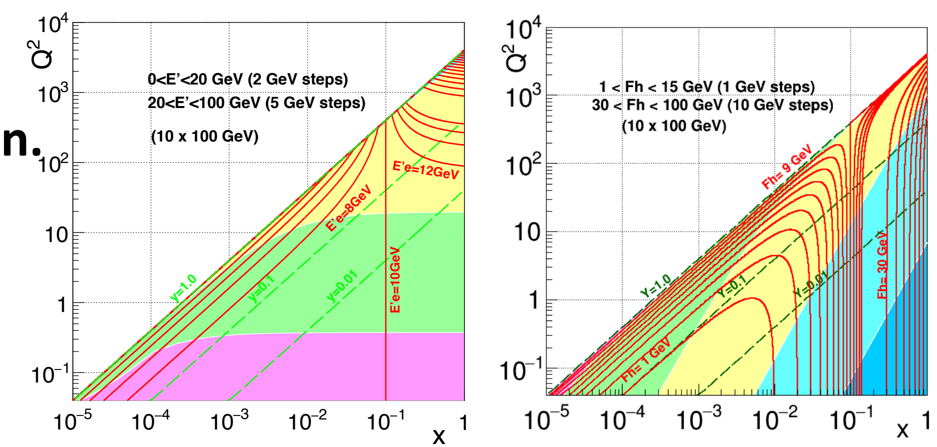


*jet ~ hadrons from scattered quark

At EIC:

- Scattered electron will be well in the central region.
- How about the scattered quark??
  - **Need good energy/angle measurement in the forward region.**





HERA vs EIC for high-x measurement

~Measured region
(N.B. my hand-drawing)

In the ZEUS measurement:

Kinematic reconstructi

- Q^2 from the scatte

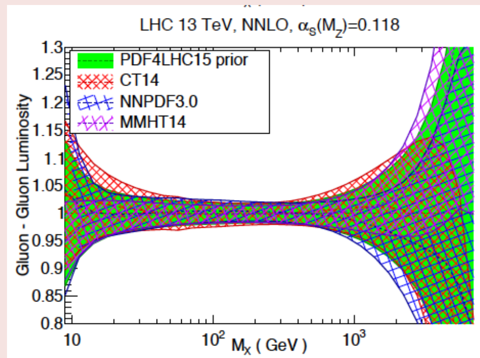
$$Q^2 = 2E_eE_e'(1 +$$

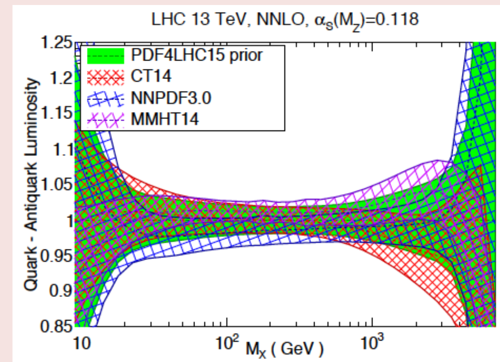
- x from jet* energie
  to avoid large unce
  - if e and jet bala
    E'_{eT} and jet angl

At EIC:

- Scattered electron
- How abou the scattered quark??
  - **Need good energy/angle measurement in the forward region**

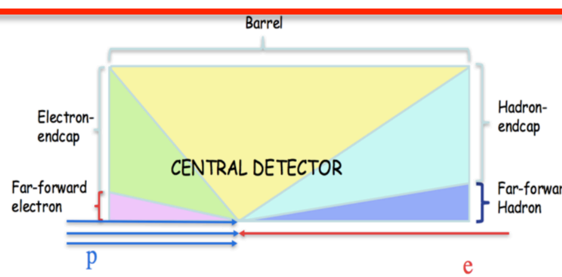
If it is achieved, EIC *might* improve these uncertainties

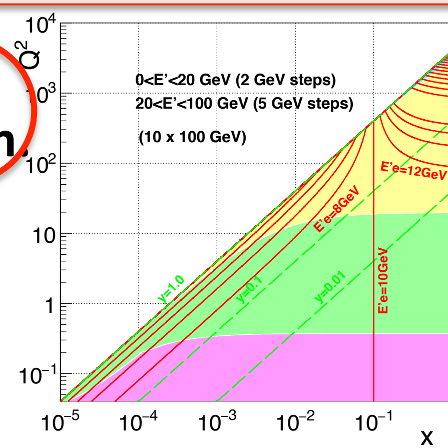


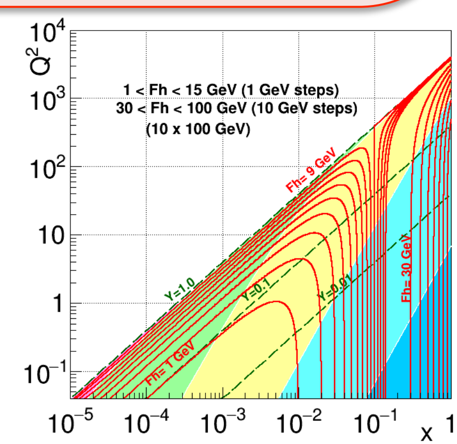


from its advantage of large statistics.

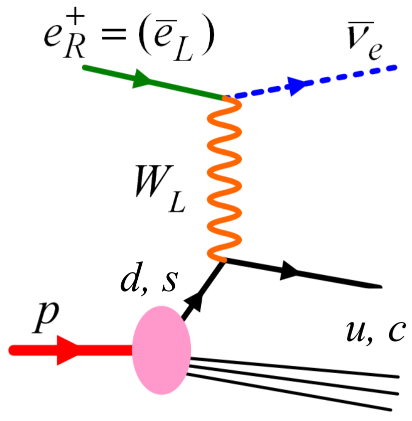
might: need to know kinematic coverage and precision.







Charged Current DIS



Charge selective interaction via W exchange

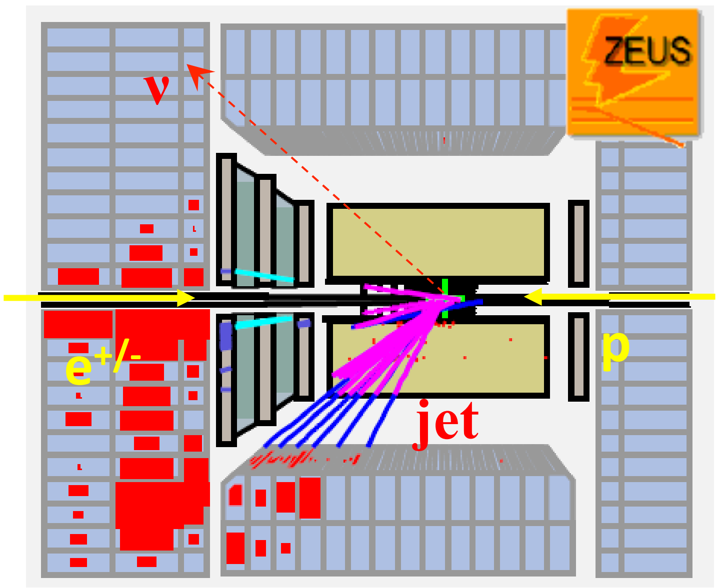
$$e^- q^{(+)} \rightarrow \nu q^{(-)}$$
$$e^+ q^{(-)} \rightarrow \bar{\nu} q^{(+)}$$

Neutrinos at the final state
= **no scattered electron**

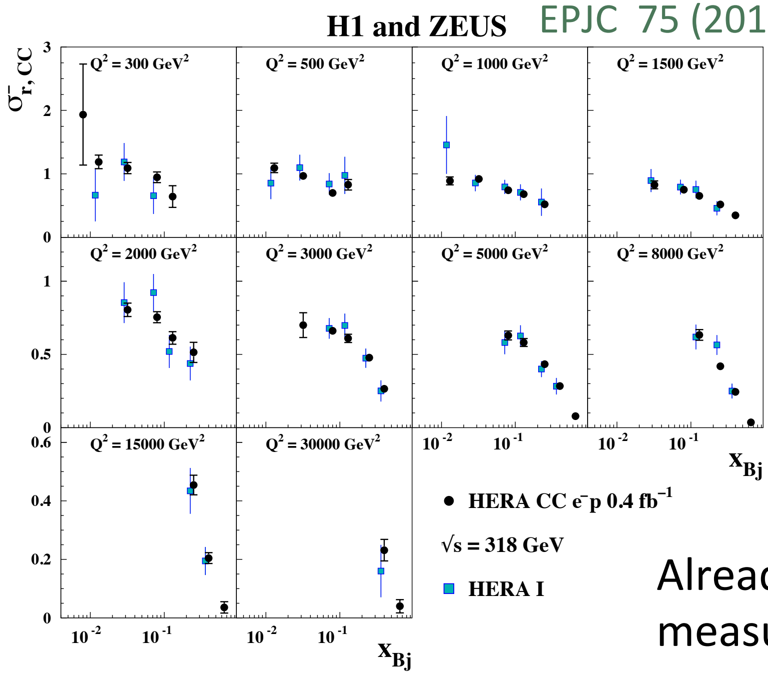
Electron/Positron beams give flavour separation of PDFs

$$\tilde{\sigma}(e^+ p) \propto [(\bar{u} + \bar{c}) + (1-y)^2 (d + s)]$$

$$\tilde{\sigma}(e^- p) \propto [(u + c) + (1-y)^2 (\bar{d} + \bar{s})]$$

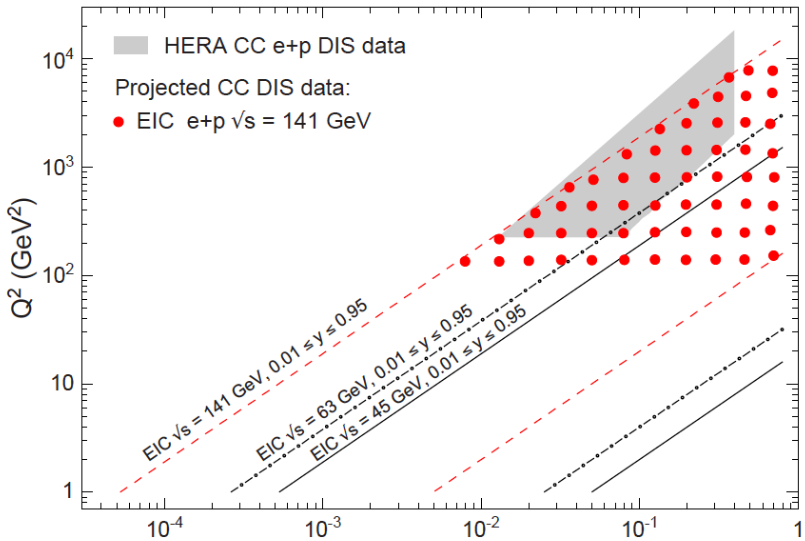


EPJC 75 (2015) 580



Already quite well measured at HERA

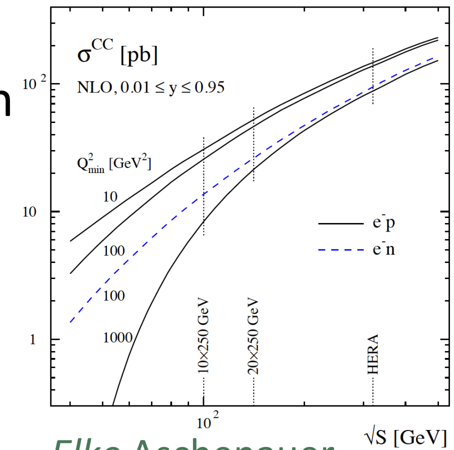
Charged Current DIS at EIC?



EIC may extend the measurement to higher x.

- Small cross section but large statistics would help.

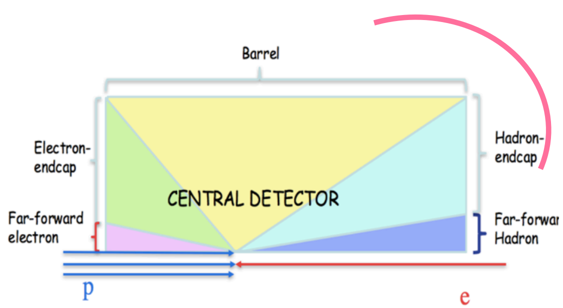
arXiv:1708.01527



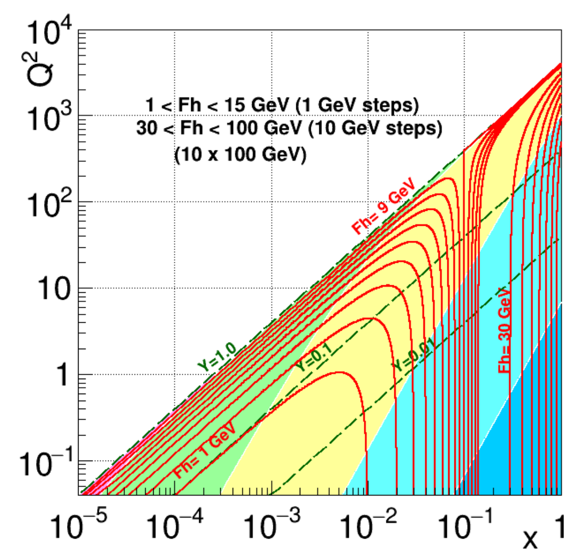
Elke Aschenauer

A neutrino at the final state: Large p_T^{Miss}, No scattered electron.

→ Kinematic variables should be reconstructed from **hadron activities** (γ_h, E_h).

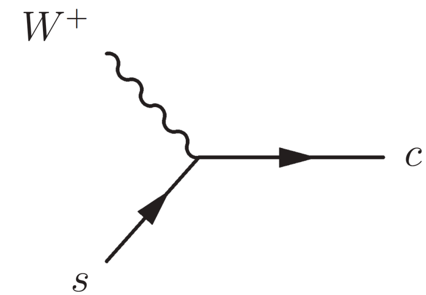


Good measurement of hadronic energy in this region.

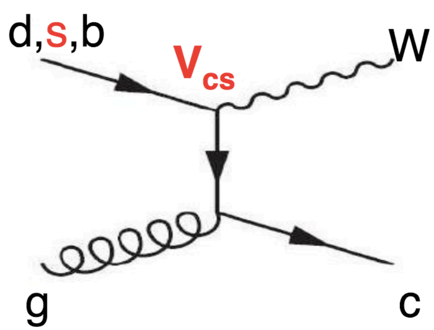


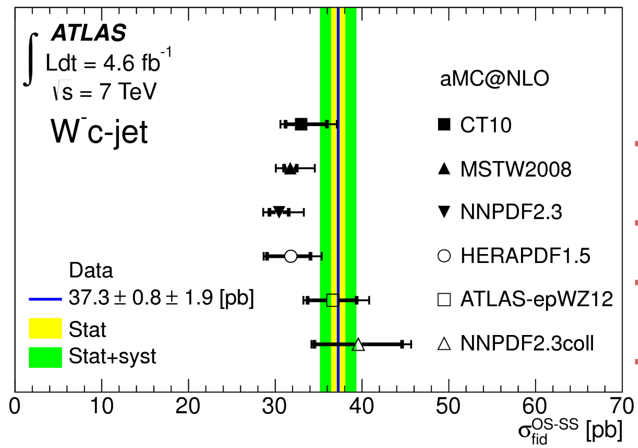
A study requires decent description by Monte Carlo.

Charm-tagged Charged Current DIS



- If a charm is tagged in CC DIS, the cross section has a sensitivity to the intrinsic strange.
- Strange quark distribution is not well determined.
  - ATLAS data prefers more strangeness than fixed target data?





JHEP05(2014)068

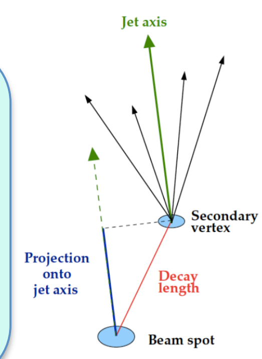
Asymmetric s and sbar, derived from CCFR and NuTeV (neutrino−nucleon DIS)

LHC data included

- Charm-tagged CC DIS at EIC would be interesting.
  - Free from the nuclear/target correction.
  - Requires charm tagging in the Central-Forward region.

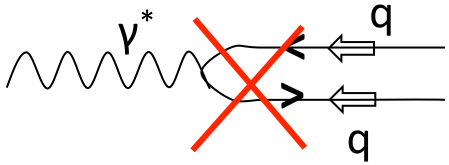
Y. Furletova

At EIC
($\sqrt{s}$~70 GeV, Q^2>100GeV^2):
σ(e^+p -> ν_e +c +X) ~ 0.1 pb
⇒ with 10fb^{-1} /year
⇒ ~ 1000 events/year



Longitudinal structure function F_L

- F_L is proportional to the cross section of longitudinal photon interacting with proton. $F_L \propto \sigma_L$
- In naïve Quark Parton Model, proton has co-linear spin ½ quarks only.



Longitudinal photon cannot interact with a quark → $F_L=0$

- **Gluon emission** in the proton → $\mathbf{F_L \neq 0}$

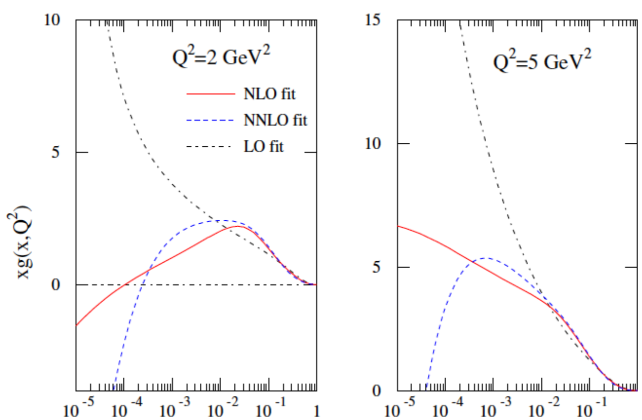
  i.e. F_L directly reflects gluon dynamics in the proton.

In perturbative QCD:

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) zg(z) \right]$$

gluon PDF

F_L provides another validity check of the gluon PDFs and even the DGLAP framework at low Q^2.



Instability of gluon PDF at low Q^2

R. Throne DIS2008

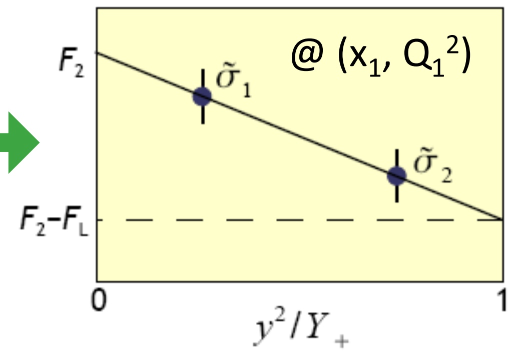
F_L measurement from HERA

$$0 < y < 1, \quad Y_+ = 1 + (1-y)^2 \rightarrow 1 < Y_+ < 2$$

Reduced DIS cross section at low Q^2

(xF_3 is ignored)

$$\tilde{\sigma} = \frac{Q^2 Y_+}{2\pi\alpha^2}\frac{d\sigma^2}{dx dQ^2} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$



slope = F_L

F_L measurement requires

- **large y** to see F_L contribution
- Comparison at the same (x, Q^2) but the different y

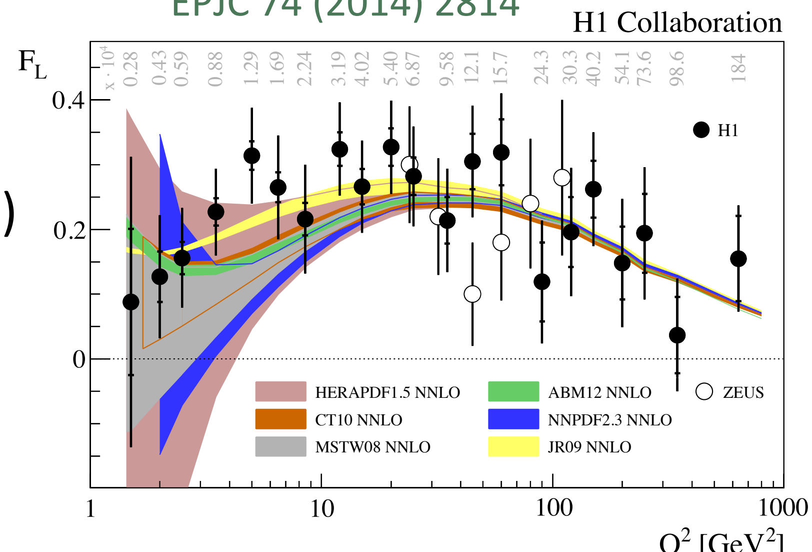
$$y = \frac{Q^2}{sx}$$

→ **multiple beam energies**

Dedicated data taking
with **lowered proton beam energies**
(920 GeV → 460 GeV 14pb^{-1}, 575 GeV 8pb^{-1})
at the last 3 months of HERA

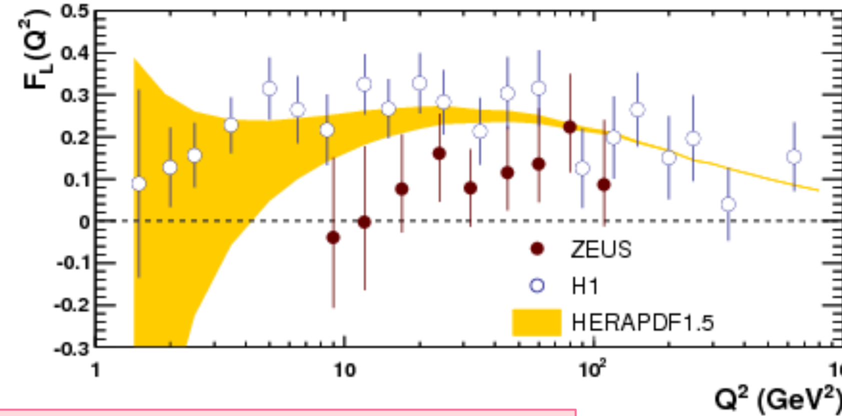
→ First direct F_L measurement at collider experiments

EPJC 74 (2014) 2814



PRD 90 (2014) 072002

What was the difficulty?



Q: H1 did a better job. Why?

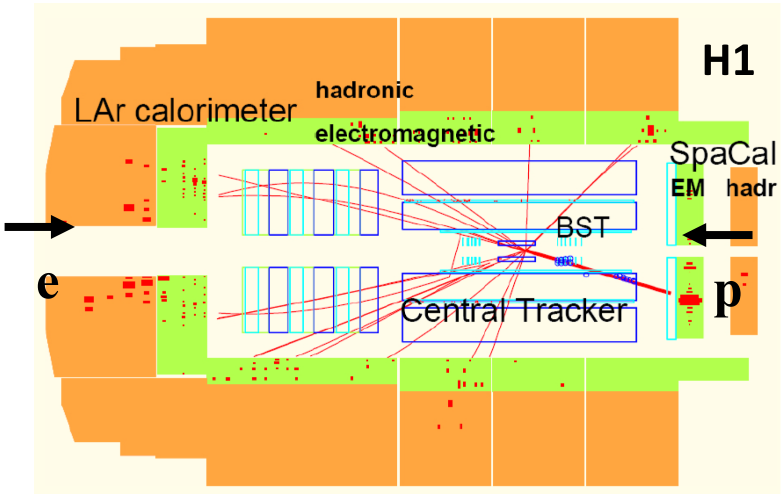
A: Detector!

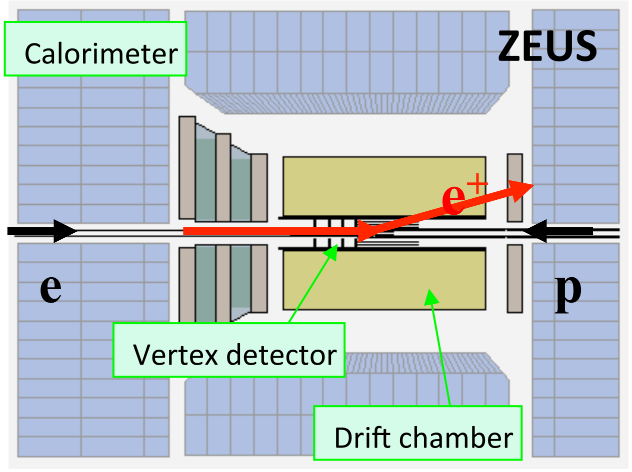
$$y_{el} = 1 - \frac{E'_e}{2E_e}(1 - \cos\theta_e)$$

$$Q^2_{el} = 2E_eE'_e(1 + \cos\theta_e)$$

Low Q^2 : Lower electron angle
High y : Lower electron energy

If electron ID fails, large amount of background (photoproduction) comes in.





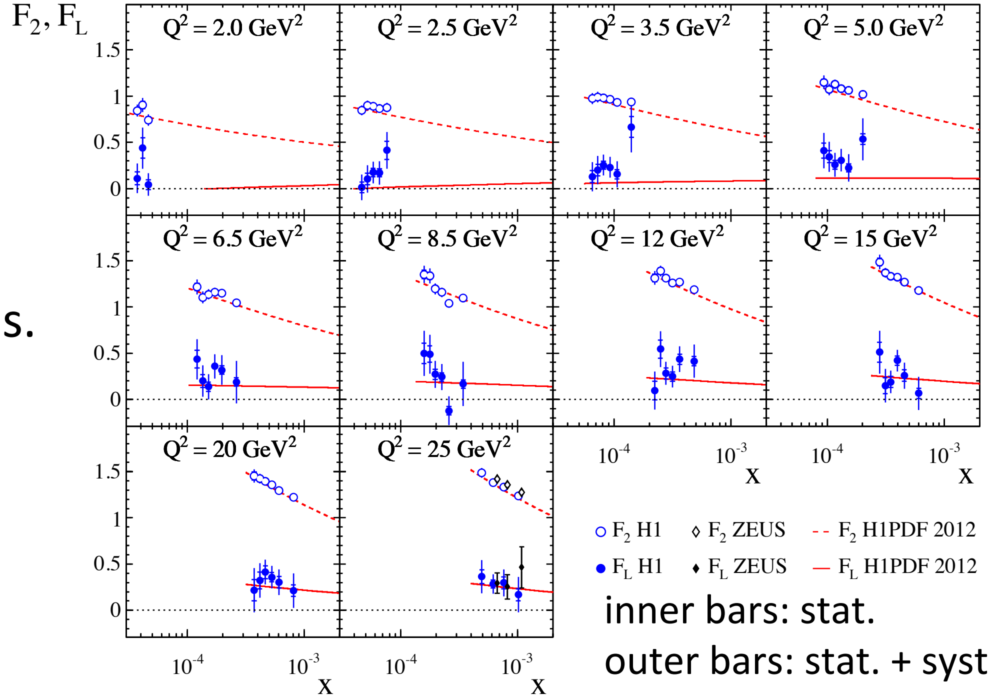
Measured at:
H1 $E'_e > 3.4$ GeV
ZEUS $E'_e > 6$ GeV

H1 was equipped with detectors for good electron identification in rear side.

Can EIC do better job?

EPJC 74 (2014) 2814

H1 Collaboration

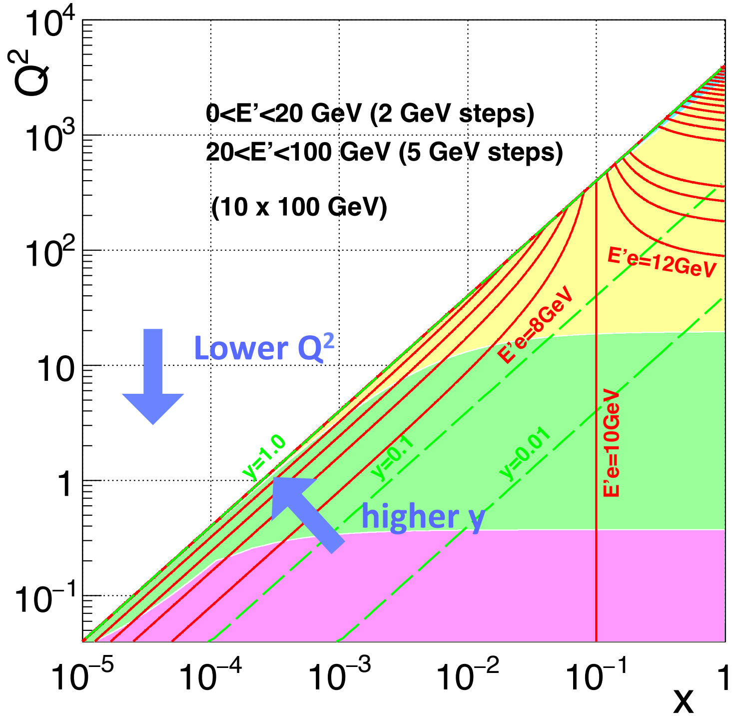


inner bars: stat.

outer bars: stat. + syst.

Advantages of EIC

- Variable centre of mass energies.
- High luminosity
- (Better systematics?)

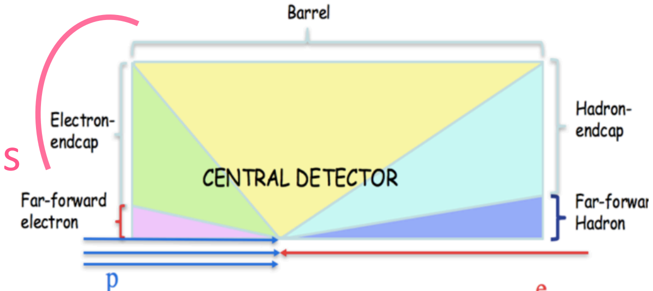


EIC: $Q^2 \sim 5$ GeV gives $x \sim 10^{-3}$-10^{-2}

(depends on how CM energies varies)

→ Would be intersting to see gluons

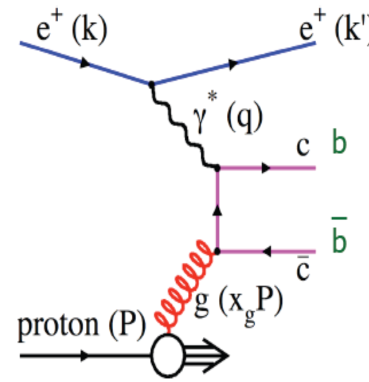
How well can electrons be measured in this region?



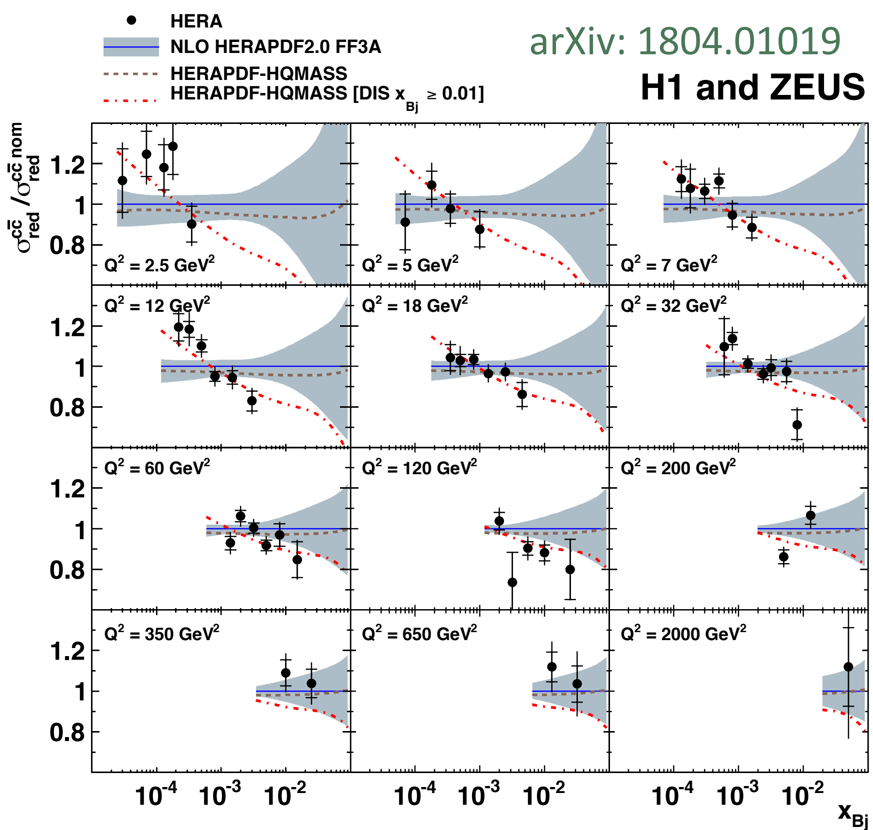
Also, hadrons should be reasonably measured for identification of DIS events.

σ^{cc}, σ^{bb}

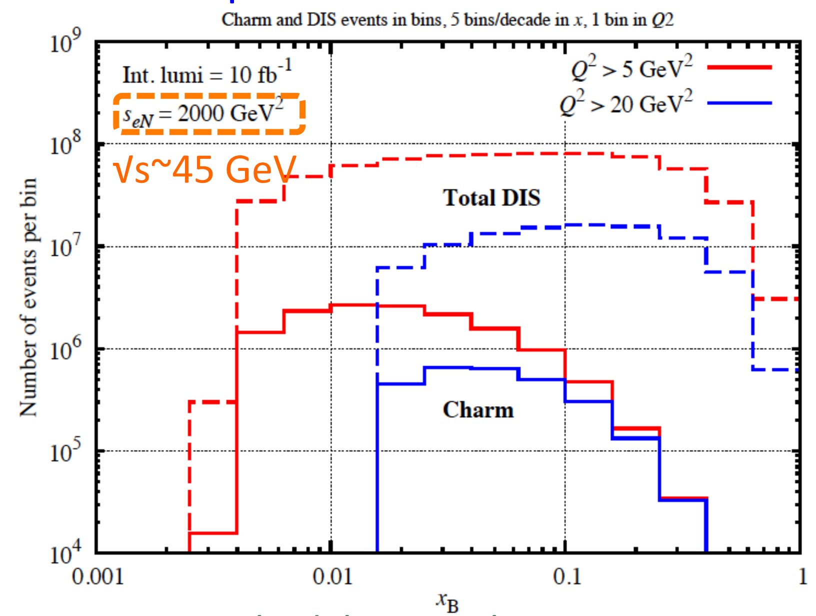
- Cross section with heavy-flavoured quark pair (cc, bb).
- <u>Sensitive to gluons</u>,
  but the description of heavy flavour production is complicated.



Latest HERA results show some difficulty in describing both σ^{cc} and low-x $\sigma^{inc.\ DIS}$.



Charm production rate at low √s eN



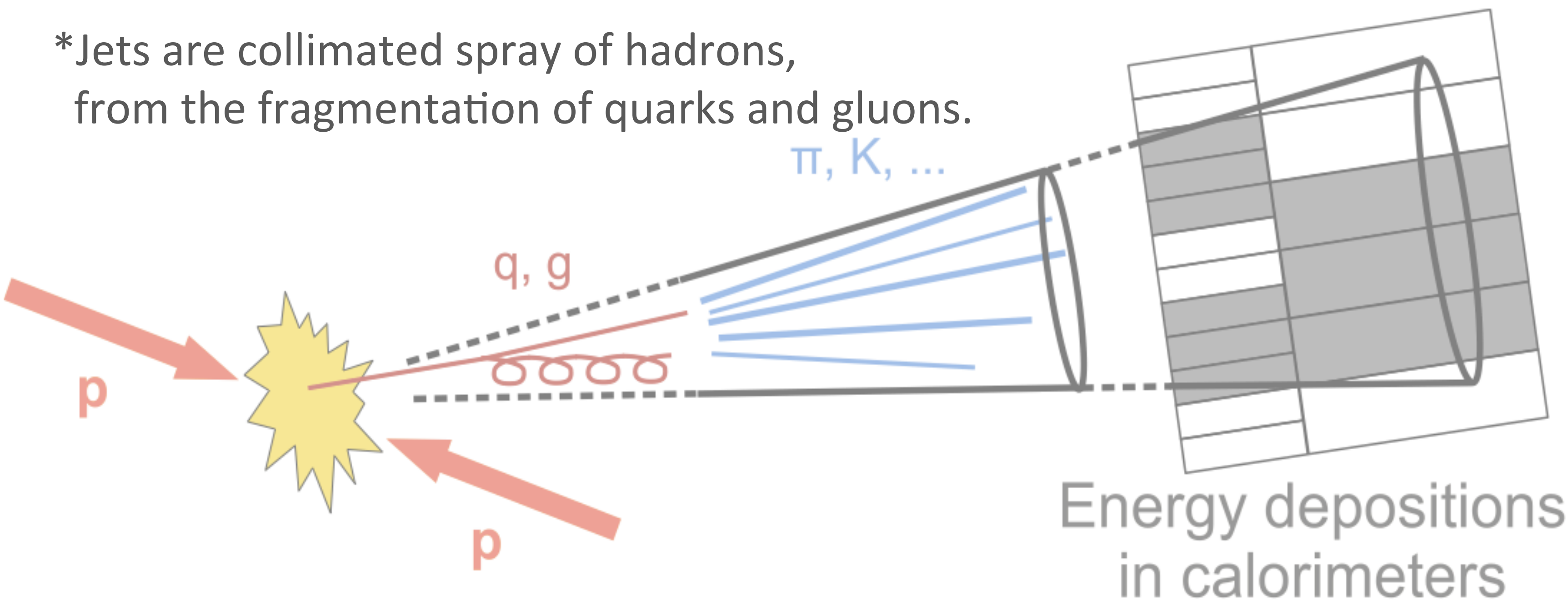
E. Chudakov et. al. arXiv: 1610.08536

With √s>~100 GeV and large stat., perhaps EIC can clarify the situation.

Jet physics at EIC?

Random thoughts…

*Jets are collimated spray of hadrons,
from the fragmentation of quarks and gluons.



Description of jet physics at LHC

Understanding and description of jet production is quite important at LHC.

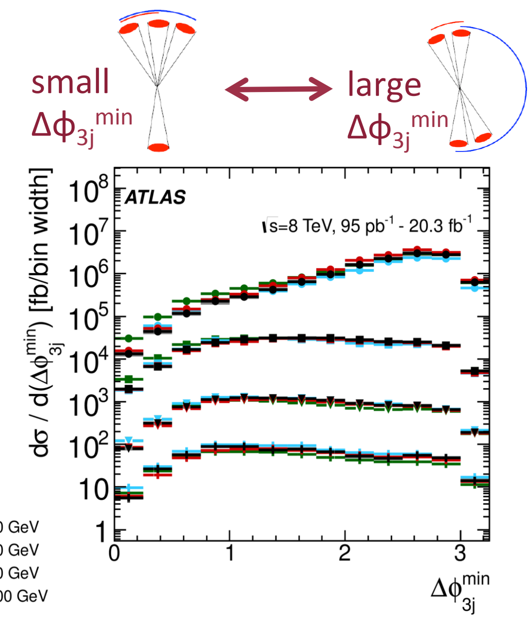
- Multijet is a severe background in searches and measurements.
- Hard radiation gives one of the major uncertainties in a precise measurement of e.g. top quarks.

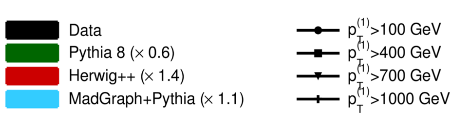
Several MCs are tested in various measurements using various observables.

- LO 2→ 2 MCs with parton shower models.
  - Easy event generation to test analysis methods.
- Multi-leg (2→N) LO MCs
- NLO MCs, matched to parton shower MCs.
- MC with all-order sum of wide angle QCD radiation.

JHEP 12 (2015) 105

ATLAS 4jets, $\Delta\phi_{3j}$

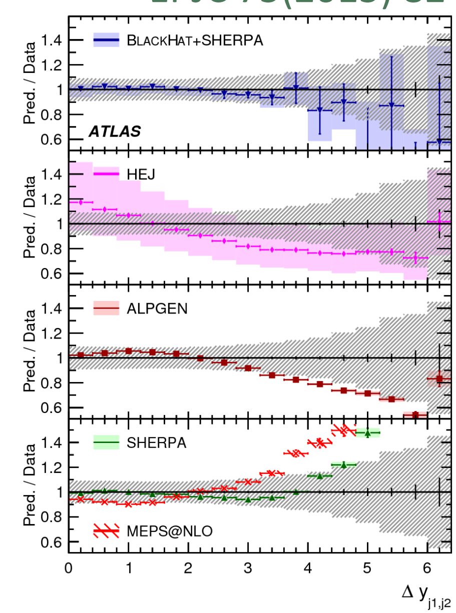




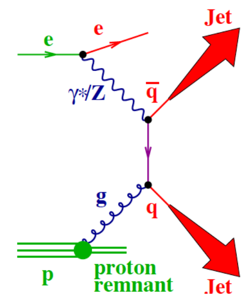
ATLAS W+2jets, $\Delta y_{j1, j2}$

$\sqrt{s}$=7 TeV, 4.6fb^{-1}

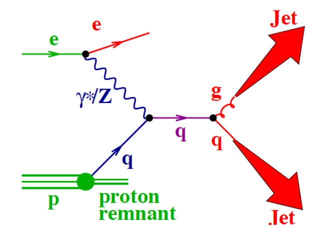
EPJC 75(2015) 82



Jet production at EIC



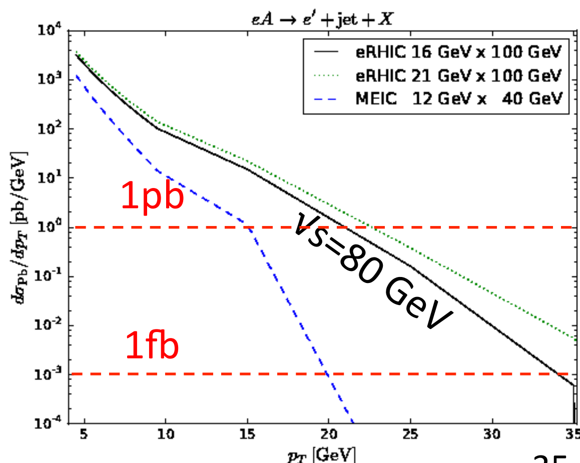
Boson-gluon fusion



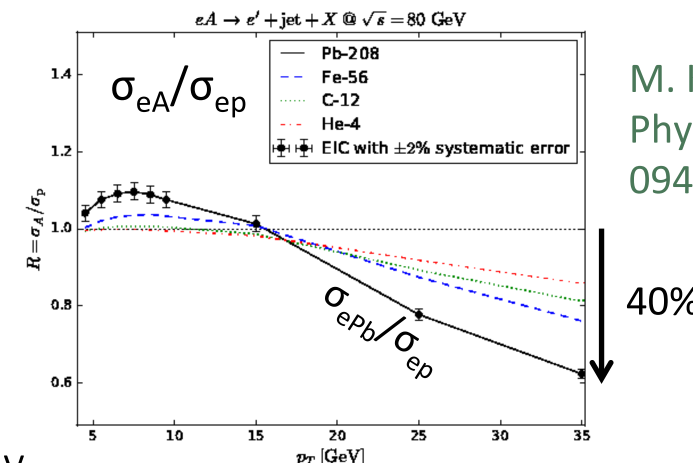
QCD Compton

- ep colliders give a cleaner circumstance than pp.
- How limited is the p_T reach?

inclusive jet $d\sigma/dp_T$ @ePb DIS

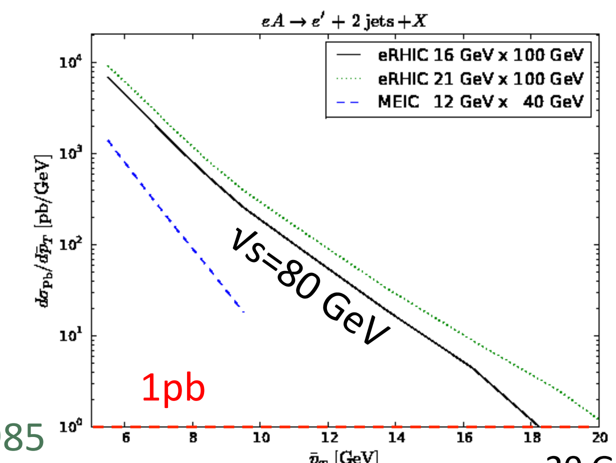


35 GeV



M. Klasen et al., Phys. Rev. D 95, 094013 (2017)

dijet $d\sigma/dp_T$ @ ePb photo-production



20 GeV

M. Klasen, K.Kovarik arXiv 1803.10985

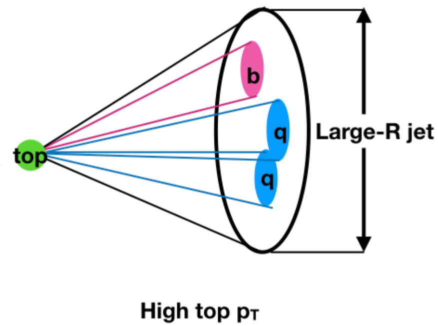
Probably jets with **p_T~ O(10) GeV** (or more?) can be studied at EIC ep collisions.

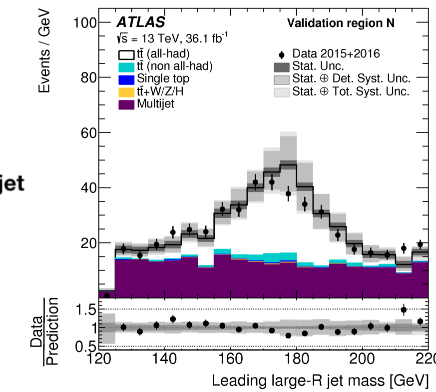
- Higher √s or larger stat. allow higher p_T reach.

Jet substructure measurements?

- Quite a progress in understanding of jet substructure during the LHC era.
- Jet substructure is an important tool to identify boosted objects at LHC.

High p_T top or W/Z bosons decaying hadonically can be observed as large size jets.





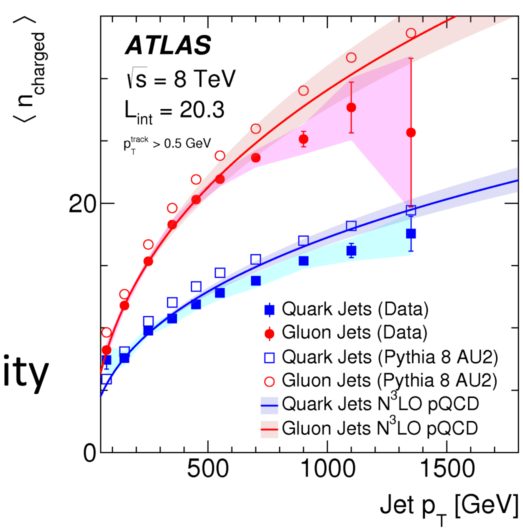
arXiv: 1801.02052

Mass of large-R jets in ttbar cross section measurement

- Several observables are measured at LHC.
  - Jet mass, k_T splitting, jet charge, charged particle multiplicity.

Gluon/quark-initiated jets have different rapidity dependence.

→ Studies of charged particle multiplicity accesses to the origin of jets.



EPJC 76 (2016) 1

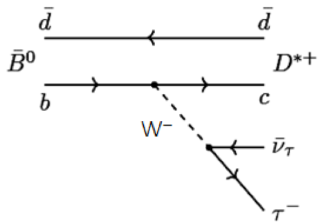
Are they interesting at EIC as well?

Leptoquark search

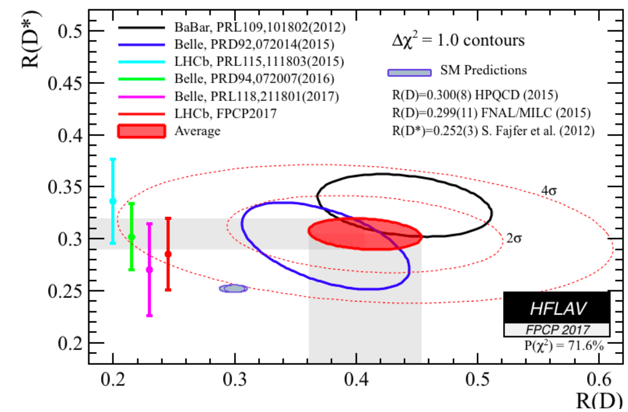
Particular attention on leptoquarks

Anomalies seen in B physics invoke a lot of interest on leptoquarks.

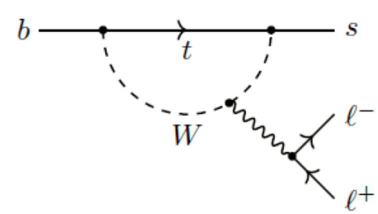
- Larger branching fraction of $B \to D^{(*)}\tau\nu$. (~4σ)
  - Seen by Belle, Babar, LHCb.



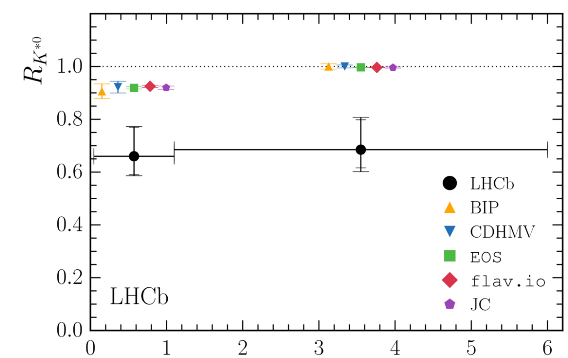
$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu_\tau)}{\mathrm{Br}(B \to D^{(*)}l\nu_l)}$$



- Smaller branching fraction of $b \to s\mu^+\mu^-$ process.
  - LHCb driven.
    - Smaller than $b \to se^+e^-$ (~2.5σ)
    - Analyses of decay angles show tensions. (~3.4σ)

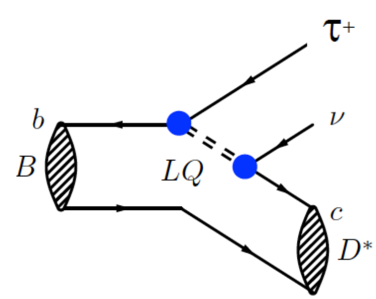


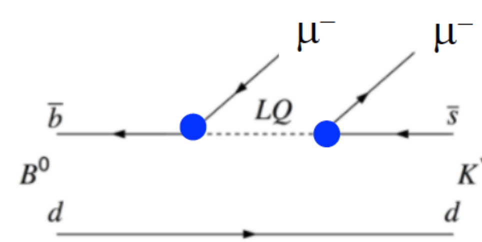
$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$



JHEP 08 (2017) 055

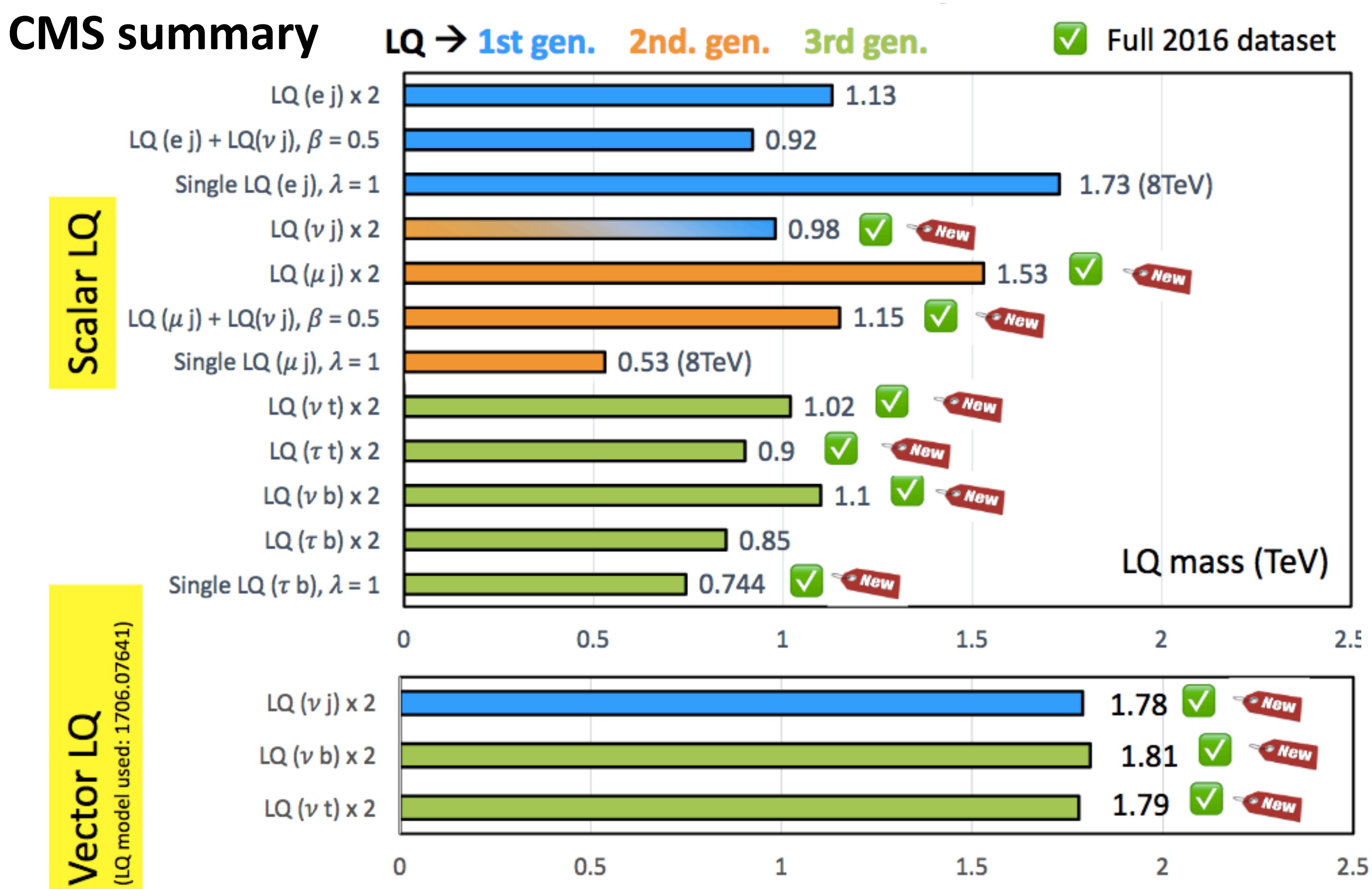
> Leptoquarks can explain the both anomalies.

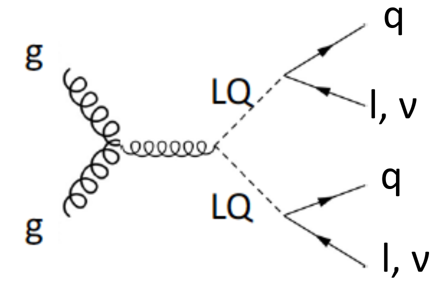


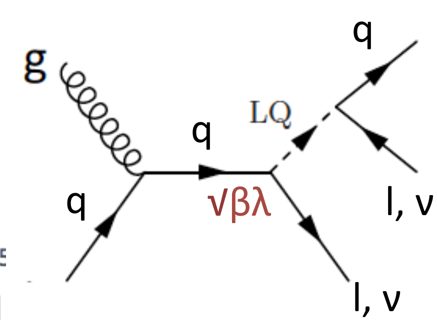


LHC Leptoquark searches

- Searches are done through LQ pair production or single production.
- Limits depend on branching ratio (β or 1-β). (shown for specific β (1, 0, or 0.5))
- Single production has a dependence on the coupling λ.





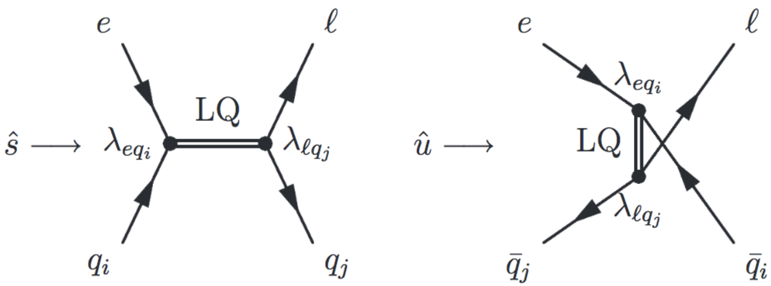


M_{LQ} <~ O(1) TeV are excluded.

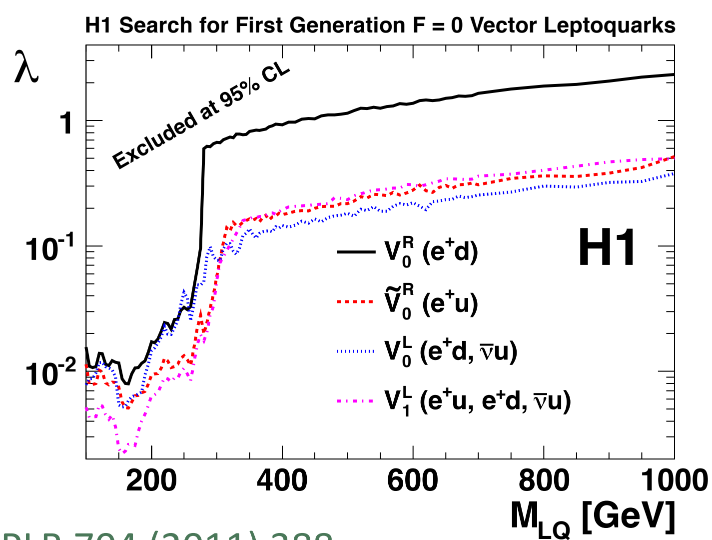
Y. Takahashi, Moriond2018

Leptoquark search at ep collider

14 categories of leptoquarks via s-channel or u-channel are looked for, in $ep \to lX$



Limits are set on $\dfrac{\lambda_{eq_i}\lambda_{lq_j}}{M_{\mathrm{LQ}}^2}$



PLB 704 (2011) 388

LQ type	J	F	Q	Production and decay modes	Coupling	β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	λ_L	1/2
				$e_L^- u_L \to \nu_\ell d$	$-\lambda_L$	1/2
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	$-\lambda_L$	1/2
				$e_L^- u_L \to \nu_\ell d$	$-\lambda_L$	1/2
			$-4/3$	$e_L^- d_L \to \ell^- d$	$-\sqrt{2}\lambda_L$	1
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \to \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$	$e_R^- u_L \to \ell^- u$	λ_R	1
			$-4/3$	$e_R^- d_L \to \ell^- d$	λ_R	1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \to \ell^- u$	λ_L	1
V_0^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	λ_L	1/2
				$e_R^+ d_L \to \bar{\nu}_\ell u$	λ_L	1/2
V_0^R	1	0	$+2/3$	$e_L^+ d_R \to \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \to \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	$-\lambda_L$	1/2
				$e_R^+ d_L \to \bar{\nu}_\ell u$	λ_L	1/2
			$+5/3$	$e_R^+ u_L \to \ell^+ u$	$\sqrt{2}\lambda_L$	1
$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \to \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$	$e_L^+ d_L \to \ell^+ d$	$-\lambda_R$	1
			$+5/3$	$e_L^+ u_L \to \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \to \ell^+ d$	λ_L	1

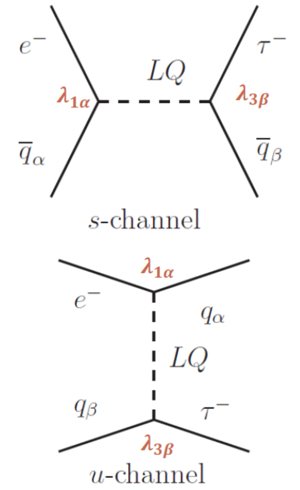
Charged lepton flavour violation (CLFV)

Neutrino oscillation means lepton flavour violations in the neutrinos.
→ Why not in the charged lepton?

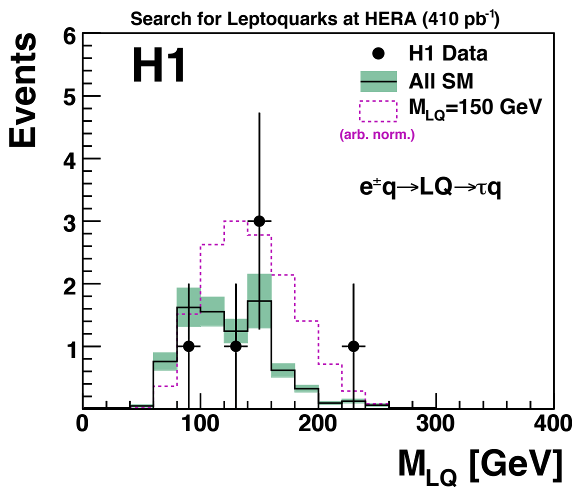
ep colliders can search for CLFV (1,3) in DIS from $ep \to \tau X$

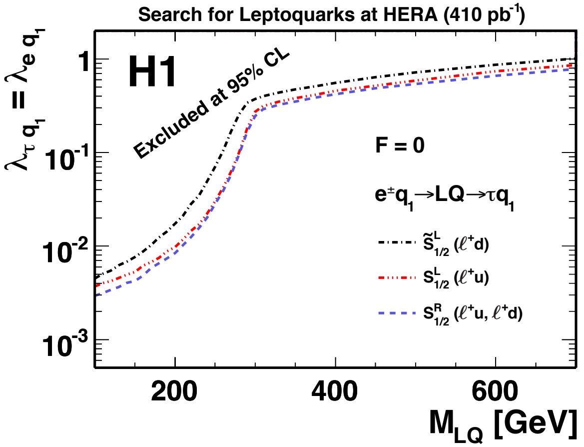
- Much less background compared to $ep \to eX$
- Less constraint compared to CLFV (1,2). cf $\mu \to e\gamma$

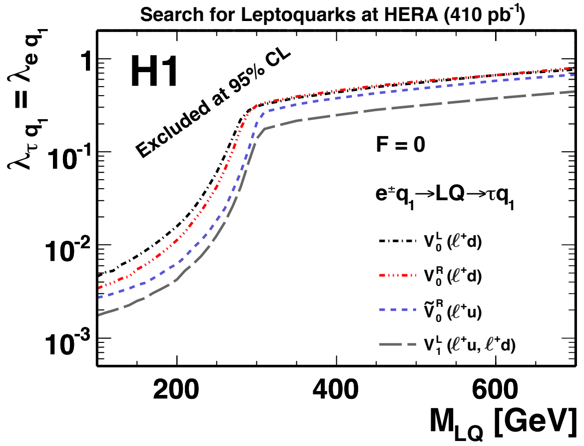
$ep \to \tau X$ can be interpreted as a process via leptoquarks.



PLB 701 (2010) 20







Sensitivities at EIC vs HERA

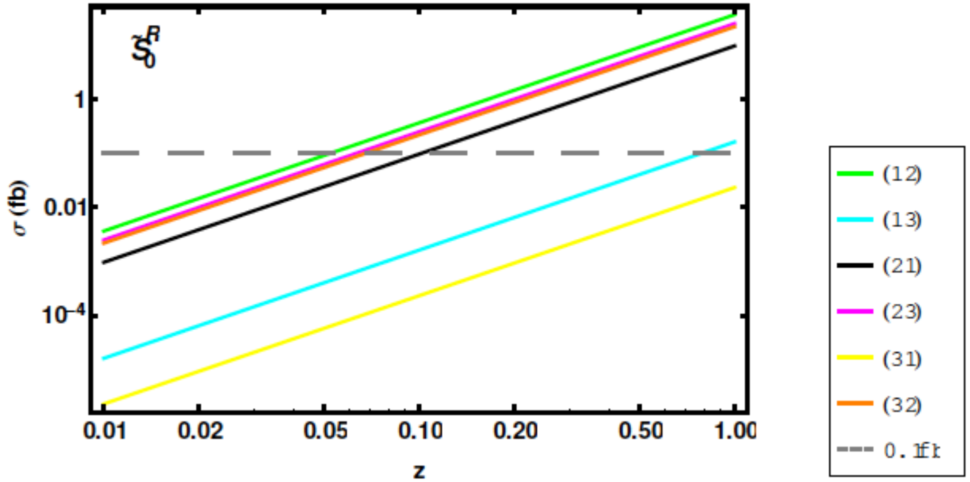
M. Gonderinger, M. J. Ramsey-Musolf
JHEP 05 (2012) 047

EIC@√s=90GeV, compared to HERA*.

*ZEUS EPJC 44 (2005) 463,
H1 EPJC 52 (2007) 833

$$z = \frac{(\lambda_{1\alpha}\lambda_{3\beta})/M_{\mathrm{LQ}}^2}{[(\lambda_{1\alpha}\lambda_{3\beta})/M_{\mathrm{LQ}}^2]_{\mathrm{HERA\ limit}}}$$

Assuming the same acceptance and τ tagging efficiency as HERA.



- With 10 fb^{-1} data, EIC can improve HERA limits, which are stringent for (2,3) and (3,2) in case of $\tilde{S}_0^R$
  - Higher √s gives higher sensitivities.
  - Larger statistics will give further improvement.
  - Polarization of e$^-$/e$^+$ beams can increase or suppress the cross section.
    → Distinguish L vs R.

EIC can take a role in leptoquark searches

Summary

- LHC looks for new physics using pp collisions at √s = 13 TeV. LHC physics require:
  - Better determination of the proton parton distribution functions.
  - Good description of jet production.

- EIC can improve the determination of the parton distribution functions.
  - High-y measurements are very important.
  - F_L can be measured.
  - → Require good measurement of hadrons in the forward region and electrons in the rear side.

- Jet physics at EIC could be also interesting.

- EIC can play a role in the search of leptoquarks, which get particular attention due to the anomalies in B physics.

And a remark…

As you may notice, there are a lot of room for sensitivity studies.

Rik wrote me:

"these kind of HEP oriented studies are somewhat neglected at the EIC"

- A lot of interest for the EIC from the nuclear physics community.
- Less discussion in the HEP community.

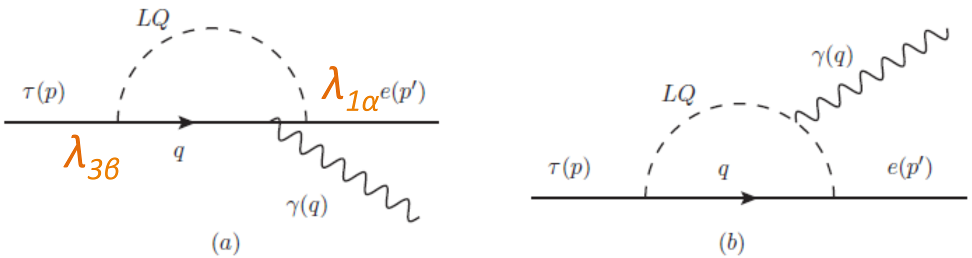
"this is a machine that will run likely concurrently with HL-LHC"

➔ **Good to consider the HEP-oriented possibilities at EIC.**

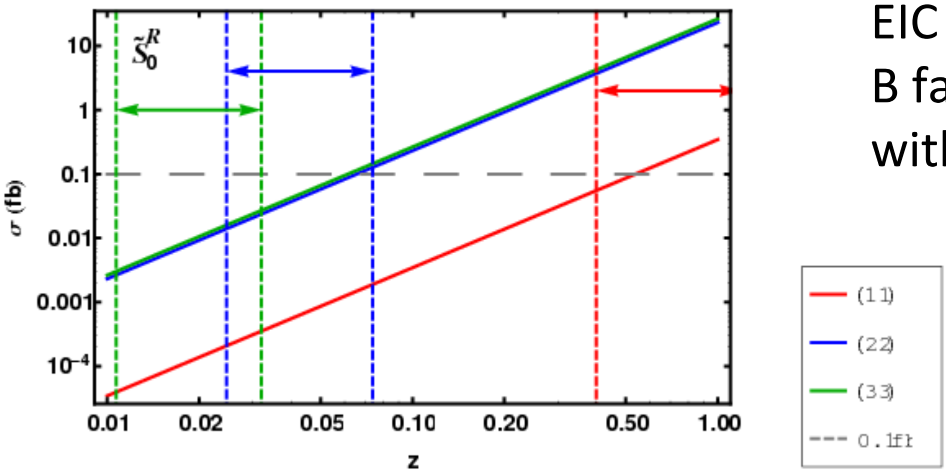
CLFV EIC vs B factory

- Rare decay τ→ eγ at B factories* can set limits for α=β

*Babar PRL104(2010) 021802
Belle PLB 660 (2008) 154



M. Gonderinger, M. J. Ramsey-Musolf
JHEP 05 (2012) 047



EIC could compete with previous B factories for the 1st generation quarks with large statistics.

Not sure wrt Belle II.

Where HERA ep has sensitivities:

PLB701(2010)20

$ep \to \tau X$			**H1**				$F = 0$
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{\mathrm{LQ}}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
q_iq_j	$S^L_{1/2}$ $\ell^-\bar{U}$ ℓ^+U	$S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D	$\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ ℓ^+D	V^L_0 $\ell^-\bar{D}$ ℓ^+D	V^R_0 $\ell^-\bar{D}$ ℓ^+D	$\tilde{V}^R_0$ $\ell^-\bar{U}$ ℓ^+U	V^L_1 $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D
1 1	$\tau \to \pi e$ 0.06 **1.4**	$\tau \to \pi e$ 0.03 **1.2**	$\tau \to \pi e$ 0.06 **2.2**	$\tau \to \pi e$ 0.03 **1.2**	$\tau \to \pi e$ 0.03 **1.3**	$\tau \to \pi e$ 0.03 **0.9**	$\tau \to \pi e$ 0.005 **0.4**
1 2	**1.5**	$\tau \to Ke$ 0.04 **1.2**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.2**	$\tau \to Ke$ 0.02 **1.5**	$\tau \to Ke$ 0.02 **1.6**	**1.2**	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
1 3	*	$B \to \tau\bar{e}$ 0.07 **2.2**	$B \to \tau\bar{e}$ 0.07 **2.2**	$B \to \tau\bar{e}$ 0.03 **1.8**	$B \to \tau\bar{e}$ 0.03 **1.8**	*	$B \to \tau\bar{e}$ 0.03 **1.8**
2 1	**3.4**	$\tau \to Ke$ 0.04 **2.8**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **3.9**	$\tau \to Ke$ 0.02 **1.5**	$\tau \to Ke$ 0.02 **1.6**	**1.2**	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
2 2	$\tau \to 3e$ 0.6 **6.4**	$\tau \to 3e$ 0.9 **4.2**	$\tau \to 3e$ 1.8 **5.0**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.9 **2.8**	$\tau \to 3e$ 0.3 **3.5**	$\tau \to 3e$ 0.2 **1.4**
2 3	*	$B \to \tau\bar{e}X$ 14.0 **5.8**	$B \to \tau\bar{e}X$ 14.0 **5.6**	$B \to \tau\bar{e}X$ 7.2 **3.6**	$B \to \tau\bar{e}X$ 7.2 **4.0**	*	$B \to \tau\bar{e}X$ 7.2 **3.6**
3 1	*	$B \to \tau\bar{e}$ 0.07 **5.3**	$B \to \tau\bar{e}$ 0.07 **4.8**	V_{ub} 0.14 **1.5**	$B \to \tau\bar{e}$ 0.03 **1.7**	*	V_{ub} 0.14 **1.5**
3 2	*	$B \to \tau\bar{e}X$ 14.0 **7.9**	$B \to \tau\bar{e}X$ 14.0 **7.6**	$B \to \tau\bar{e}X$ 7.2 **2.9**	$B \to \tau\bar{e}X$ 7.2 **3.1**	*	$B \to \tau\bar{e}X$ 7.2 **2.9**
3 3	*	$\tau \to 3e$ 0.9 **10.1**	$\tau \to 3e$ 1.8 **9.1**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.9 **4.9**	*	$\tau \to 3e$ 0.2 **4.7**

$ep \to \tau X$			**H1**				$F = 2$
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m^2_{\mathrm{LQ}}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
q_iq_j	S^L_0 ℓ^-U $\ell^+\bar{U}$	S^R_0 ℓ^-U $\ell^+\bar{U}$	$\tilde{S}^R_0$ ℓ^-D $\ell^+\bar{D}$	S^L_1 ℓ^-U, ℓ^-D $\ell^+\bar{U}, \ell^+\bar{D}$	$V^L_{1/2}$ ℓ^-D $\ell^+\bar{D}$	$V^R_{1/2}$ ℓ^-U, ℓ^-D $\ell^+\bar{U}, \ell^+\bar{D}$	$\tilde{V}^L_{1/2}$ ℓ^-U $\ell^+\bar{U}$
1 1	G_F 0.3 **1.6**	$\tau \to \pi e$ 0.06 **1.8**	$\tau \to \pi e$ 0.06 **2.6**	$\tau \to \pi e$ 0.01 **1.0**	$\tau \to \pi e$ 0.03 **1.1**	$\tau \to \pi e$ 0.01 **0.7**	$\tau \to \pi e$ 0.03 **0.8**
1 2	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **1.9**	**2.1**	$\tau \to Ke$ 0.04 **2.9**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.1**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.9**	$\tau \to Ke$ 0.02 **1.3**	**1.5**
1 3	*	*	$B \to \tau\bar{e}$ 0.07 **3.0**	V_{ub} 0.3 **1.3**	$B \to \tau\bar{e}$ 0.03 **2.2**	$B \to \tau\bar{e}$ 0.03 **2.4**	*
2 1	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.7**	**2.7**	$\tau \to Ke$ 0.04 **3.5**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.4**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.2**	$\tau \to Ke$ 0.02 **0.7**	**0.9**
2 2	$\tau \to 3e$ 0.6 **6.3**	$\tau \to 3e$ 0.6 **6.8**	$\tau \to 3e$ 1.8 **5.4**	$\tau \to 3e$ 1.5 **2.3**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.5 **2.2**	$\tau \to 3e$ 0.3 **3.4**
2 3	*	*	$B \to \bar{\tau}eX$ 14.0 **5.8**	$B \to \bar{\tau}eX$ 7.2 **2.7**	$B \to \bar{\tau}eX$ 7.2 **3.6**	$B \to \bar{\tau}eX$ 7.2 **4.0**	*
3 1	*	*	$B \to \tau\bar{e}$ 0.07 **4.0**	$B \to \tau\bar{e}$ 0.03 **2.0**	$B \to \tau\bar{e}$ 0.03 **1.2**	$B \to \tau\bar{e}$ 0.03 **1.3**	*
3 2	*	*	$B \to \bar{\tau}eX$ 14.0 **7.9**	$B \to \bar{\tau}eX$ 7.2 **3.7**	$B \to \bar{\tau}eX$ 7.2 **2.9**	$B \to \bar{\tau}eX$ 7.2 **3.1**	*
3 3	*	*	$\tau \to 3e$ 1.8 **10.1**	$\tau \to 3e$ 1.5 **4.6**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.5 **4.9**	*