Summary for FCC-eh
work and thoughts in progress

Max Klein
U Liverpool and CERN
for the FCC-he/LHeC Study Group

FCC-eh Baseline
New Physics
Detector and IR
Directions of Work

Rome, 15th of April, 2016

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Summary of the FCC-eh Parallel Sessions at the Annual FCC Workshop, Rome 11-15.4.16
Presentations on FCC-eh This Week

Monday Plenary Opening

Uta Klein : Physics and Experiment

Tuesday: Pheno+Thy Session

Chen Zhang: Higgs Physics in ep
Nestor Armesto: Electron-Ion Scattering
Voica Radescu: PDFs and QCD

Thursday 2 Parallel Sessions

Oliver Bruening: Status of the LHeC
Daniel Schulte: FCC-eh Parameters
Alessandro Polini: Detector Development
Saleh Sultansoy: High Energy lh Colliders
Charlie Cook: Civil Engineering
Emilia Cruz: Interaction Region Design
Max Klein: New Physics with eh
Nestor Armesto: Low x Physics in ep

FCC-eh was discussed much informally and also in other sessions (hh, RF..)

Thanks to all speakers and contributors,
Thanks to the LHeC/FCC-eh study group,
to the FCC coordination, ee/hh colleagues and to the CERN directorate for support.
## Organisation

### International Advisory Committee

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Guido Altarelli (Rome) + Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
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Leonid Rivkin (Lausanne)
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Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)
```

### Coordination Group

#### Accelerator+Detector+Physics

- Nestor Armesto
- Oliver Brüning – Co-Chair
- Stefano Forte
- Andrea Gaddi
- Erk Jensen
- Max Klein – Co-Chair
- Peter Kostka
- Bruce Mellado
- Paul Newman
- Daniel Schulte
- Frank Zimmermann

5(11): members of the FCC coordination team

OB+MK: FCC-eh responsibles

### Working Groups

#### PDFs, QCD
- Fred Olness,
- Voica Radescu

#### Higgs
- Uta Klein,
- Masahiro Kuze

#### BSM
- Georges Azuelos,
- Monica D’Onofrio

#### Top
- Olaf Behnke,
- Christian
- Schwanenberger

#### eA Physics
- Nestor Armesto

#### Small x
- Paul Newman,
- Anna Stasto

#### Detector
- Alessandro Polini
- Peter Kostka

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April 2016
A Baseline for the FCC-he

Oliver Brüning¹ Max Klein¹,², Daniel Schulte¹, Frank Zimmermann¹
¹ CERN, ² University of Liverpool
March 3rd, 2016

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>$E_e$ [GeV]</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\sqrt{s}$ [TeV]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.9</td>
<td>3.5</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>protons per bunch [$10^{11}$]</td>
<td>1.7</td>
<td>2.2</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>$\epsilon_p$ [$\mu$m]</td>
<td>3.7</td>
<td>2</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>electrons per bunch [$10^9$]</td>
<td>1</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>electron current [mA]</td>
<td>6.4</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>IP beta function $\beta^*_p$ [cm]</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>hourglass factor</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>pinch factor</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>luminosity [$10^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>1.3</td>
<td>10.1</td>
<td>15.1</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Synchronous ep and pp (eA and AA) operation

4.3.2016   - work in progress   Study value of dedicated operation $O(10^{35}$ cm$^{-2}$s$^{-1}$), also eA
14.4.: Presentation of Daniel Schulte (400 fb$^{-1}$ in 5 years with 25ns, 150 fb$^{-1}$ with 5ns only)
Beam Dynamics and ‘front-end’ Simulations:

Key Studies (performed with PLACET2 code from CLIC):

- Synchrotron radiation
  bunch shape and acceptance for deceleration and dump

- Beam-beam interaction
  bunch shape and beam stability

- RF Wakefields and HOM
  beam stability

- Recombination patterns
  beam stability (filling of the RF buckets can be controlled by tuning the arc lengths)

- Cavity alignment requirements
  orbit and emittance control

LHeC is a well developed baseline, but:
- It needs “proofs” for $10^{34}$ luminosity
- needs integration study into FCCpp/AA

Oliver Bruening 14.4.16
Choice of Baseline Configuration = $f(\text{cost}, E_e, s)$

- Cost strongly rising with tunnel circumference. Presently stick to LHeC default.
- Maximise independence of ring installation, design for synchronous ep and pp OP
Choice of the Electron Beam Energy

Stick to 60 GeV but consider reducing it keeping H, top, low x physics and stay open to go up

Major changes of lepton beam concept not in practical reach: LC, muon collider, PWA ..
Simultaneous installation and operation of e and p beams in the FCC tunnel is not considered, for reasons of power and logistics and complexity of installation. It is considered for Beijing.
Circus Nero:
Begun 37AD by Caligula and finished by Claudius. Site of games, races and of the first, state sponsored martyrdoms of Christians in 65, including St Peter (in 67).
**ERL Demonstrator**

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

\[ E_e = 200 \ (400) \ \text{MeV with} \ 1(2) \ \text{module} \]

A.Valloni 2/16

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Dipoles per arc</td>
<td>3/4</td>
</tr>
<tr>
<td>Dipole length</td>
<td>50 cm</td>
</tr>
<tr>
<td>Max B Field</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Quadrupoles per arc</td>
<td>5</td>
</tr>
<tr>
<td>Quadrupoles in straight lines</td>
<td>4</td>
</tr>
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<td>Dipole length in Spreader/Combiner</td>
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<td>Dipoles in Spreader/Combiner</td>
<td>3</td>
</tr>
<tr>
<td>Dipoles for Injection-Extraction</td>
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Footprint: 14x5m²

M.Klein, Talk on FCC-eh at Istanbul 2/16

Work in progress
Vatican XV Century - a racetrack must be embedded in something bigger to make sense
FCC-he Civil Engineering

LHeC and FCC-he

LHeC Machine

Independent FCC-he Point L, F, H or B

LHeC / FCC-he LHC P8 & FCC PB

C. Cook

FCC Week, Rome 2016

Thurs 14th April 2016
FCC-he Point H

FCC Long Straight Section H

Tunnel Geology
• Molasse rock (sandstone)

Construction
• Tunnel Boring Machine (TBM) in straight sections
• Roadheader in arcs

Civil Engineering challenges
• Low geological risk
• Interaction with main FCC tunnel(s)

CE favoured site is point H
LHeC/FCC-he Civil Engineering

LHC Point 8 & FCC Long Straight Section L
Further Study

TO BE STUDIED
FCC-he Detector Study

- Very preliminary FCC detector design: extension of LHeC baseline detector
- Dimensions 20 x 12 m, transverse and longitudinal (fwd) sizes scaled w.r.t. LHeC
- Assumption of similar electron beam steering dipoles as in LHeC baseline design

Note added: LHeC → HE-LHC → FCC-he: 1 → 1.4 → 2 scaling the fwd dimension

Alessandro Polini 14.4.
First FCC-eh Simulations

50 TeV p vs 60 GeV $e^{-}$
$H \rightarrow bb$

April 14 2016
Principal solutions exist from LHeC. However, the IR is the most challenging part and more dedicated study is required. Collaboration with ‘sweet’ B.Parker, R.Tomas et al

Fcc-eh design presents some advantages:

1. IR can be design to be adapted to luminosity requirements (Not on a previous design).
2. More relaxed $\beta^*$ (15 cm instead of 10 cm)

Comparison with FCC-hh:

On-going work for $\beta^*$ below 20 cm. FCC-he might provide more flexibility in L* (FCC-hh detector requires L*>45m)
some bits of physics

Gluon in many facettes
PDFs in ep and eA
top
Higgs
BSM Higgs
Low x
Heavy Neutrinos...
..

Deep Inelastic Scattering at the Energy and Intensity Frontier is a unique lab for PP
Fluctuations of the Gluon Field - Instantons?

The Standard Model of particle physics contains certain anomalous processes induced by instantons which violate the conservation of baryon and lepton number \((B + L)\) in the case of electroweak interactions and chirality in the case of strong interactions [1, 2]. In quantum chromodynamics (QCD), the theory of strong interactions, instantons are non-perturbative fluctuations of the gluon field. They can be interpreted as tunnelling transitions between topologically different vacua. Deep-inelastic scattering (DIS) offers a unique opportunity [3] to discover a class of hard processes induced by QCD instantons.

NEW:
H1: DESY 16-150
March 16
O(3) pb xsection limits

Max Klein, 14.4.
Gluon at High x and Universality.

HERA and ABM gluons are much steeper at large x than those of MMHT, CT, NNPDF
→ Can we trust factorisation, how do we test it
Gluon at large x become very small and are hugely uncertain. But $M_x^2 = s x_1 x_2$ ..
Gluon-Gluon, luminosity

Current status of gluon-gluon sub-cross section uncertainty at FCC (hh) vs mass produced
Expected gluon-gluon sub-cross section uncertainty at FCC (eh) vs mass produced.

Needs extension of grid beyond $Q^2=10^8$ GeV$^2$..

V. Radescu
Remarks on Precision Higgs Physics in ep

The Higgs is produced in ep predominantly via $WW \rightarrow H$ in $ep \rightarrow \nuHX$

The cross section at the LHeC is $\sim 200\text{fb}$, i.e. very similar to that of $Z^* \rightarrow ZH$ in $ee$

With $1\text{ab}^{-1}$ integrated luminosity from $10^{34}$ one reaches 1% precision on $bb$ and 7% on $cc$ and corresponding numbers on other channels still to be studied. These LHeC numbers will be better at HE-LHC and FCC-eh (1% $\rightarrow$ 0.4% $\rightarrow$ 0.3% for $bb$)

At the FCC-eh the cross section is almost 1pb. Therefore, statistically, FCC-ee, with 4 $10^{34}$ luminosity at ZH and FCC-eh with $10^{34}$ luminosity are about comparable, subject also to the running times: ee at ZH plans 3 years, ep with pp plans $O(10)$.

Both ee and ep thus provide high precision measurements on Higgs, much complementary wrt each other AND to pp: for example
- ee uses mostly $Z \rightarrow ZH$, eh uses mostly $WW \rightarrow H$
- ee provides measurement of the Higgs boson width (to be studied in $ZZ \rightarrow H$ at ep)
- ep provides $N^3\text{LO}$ PDFs as are crucial for understanding the $gg \rightarrow H$ production it also provides prediction of Higgs mass with 100 MeV error (cf top mass and cross section physics)
- ep also provides sensitive measurement of $HHH,WWHH$ (arXiv:1509.04016)

Prior to FCC: LHeC and HL-LHC are an exciting couple for precision Higgs physics at LHC
**HIGGS PHYSICS AT THE LHeC**

**SUMMARY**

- **GLUON FUSION AND W FUSION** ⇒ $PDF + \alpha_s$ UNCERTAINTY REMOVED (hatched bands)

- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;

- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

Turn LHC into precision

Higgs facility: add PDFs
add ep channels ($bb, cc$)

S.Forte ECFA 9/15
The Phenomenological Higgs Landscape (Revisited)

Future ep colliders could make important contribution to Higgs physics!

- Mass
- Width \textit{(via VV scattering)}
- Spin-Parity
- Coupling
  - $hVV$, $hff$
  - $3h, 4h, hhVV$
  - FCNC coupling
- Exotic Higgs Decay
  - $h$ to invisible
  - $h$ to $4b$
  - ...  
  - Reducing PDF \& $\alpha_s$ uncertainties in Higgs measurements

See talk given by Voica Radescu

See also:
M. Kumar et al., 1509.04016
U. Klein, talk given at LHeC Workshop 2015

Acceptance of a 750 GeV Ghost S

For $x < 10^{-3}$ no (average) energy deposition exceeding the electron beam energy.
Three Generations of Matter (Fermions) spin $\frac{1}{2}$

<table>
<thead>
<tr>
<th>Generation</th>
<th>Mass (MeV)</th>
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<th>Name</th>
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<td>2.4</td>
<td>$\frac{2}{3}$</td>
<td>up (Left)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>II</td>
<td>1.27</td>
<td>$\frac{2}{3}$</td>
<td>charm (Left)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>III</td>
<td>173.2</td>
<td>$\frac{2}{3}$</td>
<td>top (Right)</td>
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<td></td>
<td></td>
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<table>
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<th>Quarks</th>
<th>Mass (MeV)</th>
<th>Charge</th>
<th>Name</th>
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<tr>
<td>d</td>
<td>4.8</td>
<td>$-\frac{1}{3}$</td>
<td>down (Left)</td>
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<tr>
<td>s</td>
<td>104</td>
<td>$-\frac{1}{3}$</td>
<td>strange (Left)</td>
</tr>
<tr>
<td>b</td>
<td>4.2</td>
<td>$-\frac{1}{3}$</td>
<td>bottom (Right)</td>
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<table>
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<th>Mass (MeV)</th>
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<th>Name</th>
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<tr>
<td>$\mu$</td>
<td>105.7</td>
<td>-1</td>
<td>muon (Left)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.777</td>
<td>-1</td>
<td>tau (Left)</td>
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</table>

<table>
<thead>
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<th>Bosons (Forces)</th>
<th>Mass (MeV)</th>
<th>Spin</th>
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</thead>
<tbody>
<tr>
<td>$Z^0$</td>
<td>91.2</td>
<td>1</td>
</tr>
<tr>
<td>$W^\pm$</td>
<td>80.4 ± 1</td>
<td>0</td>
</tr>
<tr>
<td>$H$</td>
<td>126</td>
<td>0</td>
</tr>
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Oliver Fischer  Rome Talk on Sterile Neutrinos
Heavy Neutrino Search at FCC ($ee, hh, eh$)

Oliver Fischer
Rome Talk
Sterile Neutrinos

⇒ The FCCs provide great prospects for discovering the origin of neutrino masses.

► Future electron-proton colliders provide significant gain in mass reach and fairly “stable” production cross sections.
Discussed intimate relation of eA and AA physics, also the question of integrating HI detection into GPDs.
Some Remarks on Physics and Detector

The ep configuration has much to offer by itself and in complementarity to ee and pp. For the FCC-eh, more studies are under way and need to be pursued.

The LHeC Study has been the base for FCC-eh also, and time and energy order need to be imposed by us in order to have clearer what can be gained where. This will also need to include the HE-LHC configuration which looks good to eh.

Basically: high x may be done by LHeC, but low x and high masses (equivalent) require FCC-ep

Areas of further study: top, Higgs, BSM

Areas of renewed study: low x, PDFs, ions

Areas of new directions: Heavy neutrinos, BSM Higgs, 750 (if)

Much effort has been put in the detector software and design which needs to be coupled closer to the physics analyses.

→ Lots to be done for CDR on LHeC \(10^{34}\) and ‘eh’ or ‘he’ for FCC, while eh physics remains fascinating to some of us and useful to everybody
... to take home

- Integrating a ‘green’ electron recovery LINAC into LHC-pp and FCC-pp allows to challenge the QCD and electroweak sector of the SM to a state-of-the art level – all this at moderate cost and simultaneously → turning our big investments to the powerful and sustainable ‘Higgs and search facilities’.
- There is a unique discovery potential in ep and eA.
- The value of the eh configuration at the energy frontier and its physics and technologies challenges deserve further study and support.

It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.

R.P. Feynman
Jan Mateiko, “Sala Sobieski”, King of Poland frees Vienna 1683
ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, Paris, France

G. PARISI ***
Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

A novel derivation of the $Q^2$ dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inelastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.

$$
\frac{dq^j(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{q_i q^j} \left( \frac{x}{y} \right) + G(y, t) P_{q_i G} \left( \frac{x}{y} \right) \right],
$$

$$
\frac{dG(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{G q^j} \left( \frac{x}{y} \right) + G(y, t) P_{G G} \left( \frac{x}{y} \right) \right].
$$

Collider Physics within the Standard Model: a Primer
arXiv:1303.2842

Guido Altarelli ¹ (1941-2015)
4.2

6 + 8 = 14

\( \frac{1}{2} \times 16 = 8 \)

Max 7.4.16
Valence quarks

\[ \text{Related to DY, W mass etc} \]

Recall \( xq_v \sim (1-x)^3 \)

\( d/u \to 1 \) a classic question

C. Gwenlan+M. Klein, ATLAS, Lecce 6.10.15
Current status of quark-antiquark sub-cross section uncertainty at FCC (hh) vs mass produced.
LHeC - hadronic final state kinematics

\[ Q^2 = W^2 \frac{t}{x} + M_p^2 \]

\[ W^2 = Q^2 \frac{t}{x} \]

\( x \ll 1 \): \( Q^2 = \frac{W^2}{s} \)

\( W^2 = s'y \)

\( y \geq \left( \frac{750}{s} \right)^2 / 2 \overline{s_{GW}} \)

\( = 0.33 \text{ LHeC} \)

\( 0.047 \text{ FCCeh} \)

\( E_p = 7000 \text{ GeV} \)

\( E_\gamma = 60 \text{ GeV} \)
Increasing Energy without or with ERL

Figure 7.8: Pulsed single straight 140-GeV linac for higher-energy ep collisions.

Figure 7.9: Highest-energy high-luminosity ERL option based on two straight linacs and multiple 10-GeV energy-transfer beams [725].

Pulsed: high cost, low luminosity. ERL: high cost → ERL racetrack was chosen as baseline.
Invisible Higgs@LHeC
relating the Higgs and the ‘dark’ sectors

HL-LHC @ 3 ab\(^{-1}\) [arXiv:1411.7699]
\[ \text{Br}(h \rightarrow \not{\!\! E}_T) < 3.5\% \text{ @90\% C.L., MVA based} \]
For LHeC, assume : 1ab\(^{-1}\), \(P_e=-0.9\), cut based
\[ \text{Br}(h \rightarrow \not{\!\! E}_T) < 6\% \text{ @ 2\sigma level} \]
\[ C^2_{\text{MET}} = \kappa^2_Z \times \text{Br}(h \rightarrow \not{\!\! E}_T) \]

\(\kappa_Z\): BSM
w.r.t.
SM HZZ
coupling

Potential much enhanced for
FCC-eh @ 3.5 TeV and HE-LHC-eh

Colours:
expected statistical significance

FCNC Top and Higgs couplings:
H. Sun [arXiv:1602.04670]
New study for HE-LHC
14 TeV \(p \times 150\text{ GeV e}\)
\[ \text{BR}(t \rightarrow qh) < 0.23\% \]
@ 95\% C.L. and 100 fb\(^{-1}\)
Understanding the High Mass region

Very High Mass Dell Yan 13 TeV - $\sigma$(PDF)/$\sigma$(CT14)

$\delta$ PDF (% w.r.t. CT14nnlo) vs. $m_{inv}$ [GeV]

Graph shows the comparison of various PDF sets with respect to CT14nnlo in the high mass region. The x-axis represents the invariant mass $m_{inv}$ [GeV], and the y-axis represents the difference in PDFs as a percentage. The graph includes data from CT14 90% C.L., ABM12, HERA2.0, CT10, MMHT14, JR14, and NNPDF.

VRAP calculation, U.Klein