

Turning the LHC into a powerful Higgs Facility

Uta Klein

Speaker's affiliations :



CDR “A Large Hadron Electron Collider at CERN”

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913]

“On the Relation of the LHeC and the LHC” [arXiv:1211.5102]

ISSN 0954-3899

Journal of Physics G Nuclear and Particle Physics

LHeC CDR : About 200 experimentalists and theorists from 69 institutes working for 5 years based on series of yearly workshops since 2008

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for
Machine and Detector
LHeC Study Group



iopscience.org/jphysg

IOP Publishing

<http://cern.ch/lhec>

International referees invited by CERN

Ring Ring Design

Kurt Huebner (CERN)

Alexander N. Skrinsky (INP Novosibirsk)

Ferdinand Willeke (BNL)

Linac Ring Design

Reinhard Brinkmann (DESY)

Andy Wolski (Cockcroft)

Kaoru Yokoya (KEK)

Energy Recovery

Georg Hoffstaetter (Cornell)

Ilan Ben Zvi (BNL)

Magnets

Neil Marks (Cockcroft)

Martin Wilson (CERN)

LHeC and FCC-he
High-energy frontier e-p and e-A
colliders to follow HERA with factor
1000 higher luminosity running
simultaneously with HL-LHC / FCC-hh.

Gian Giudice (CERN)

Michelangelo Mangano (CERN)

Precision QCD and Electroweak

Guido Altarelli (Roma)

Vladimir Chekelian (MPI Munich)

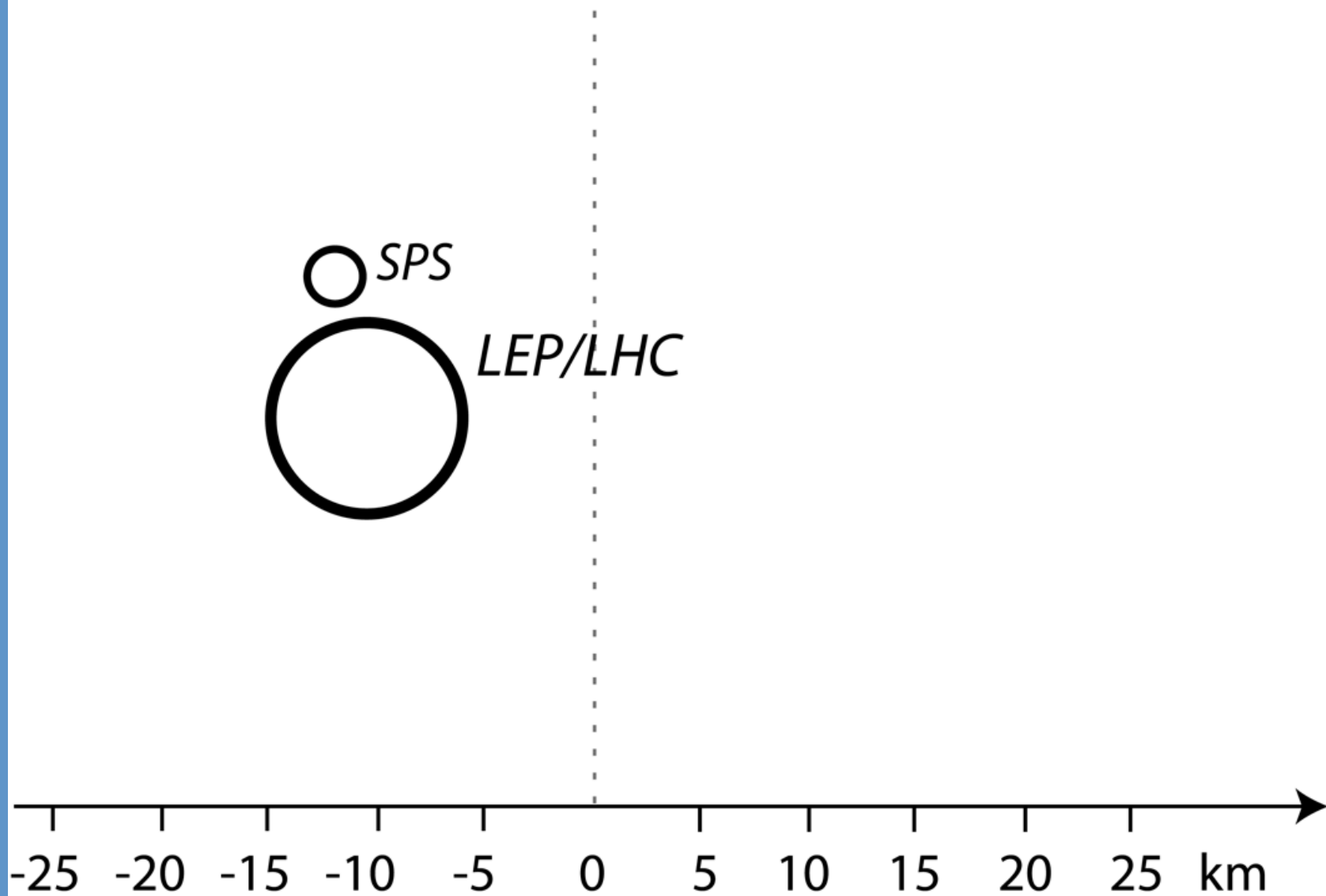
Alan Martin (Durham)

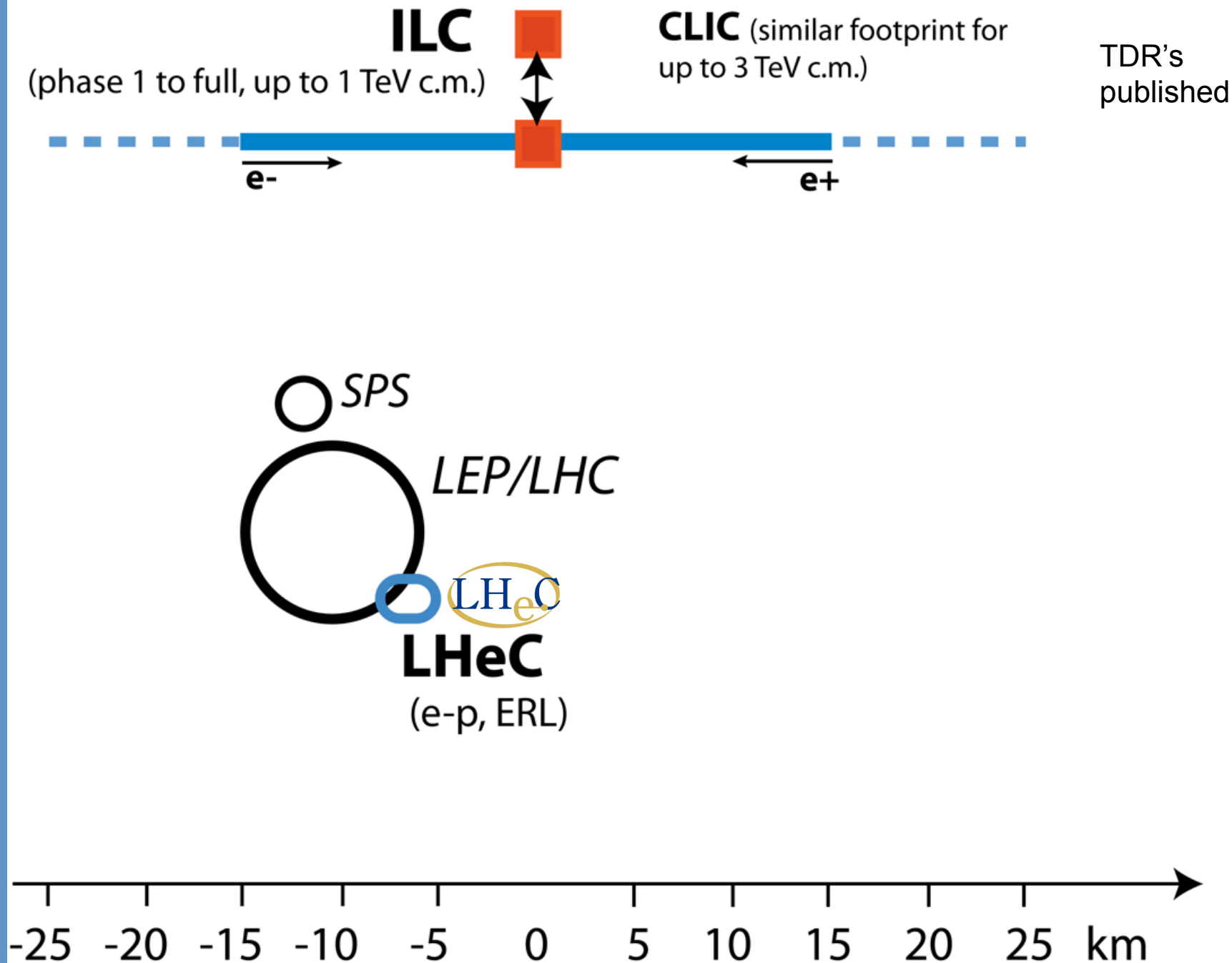
Physics at High Parton Densities

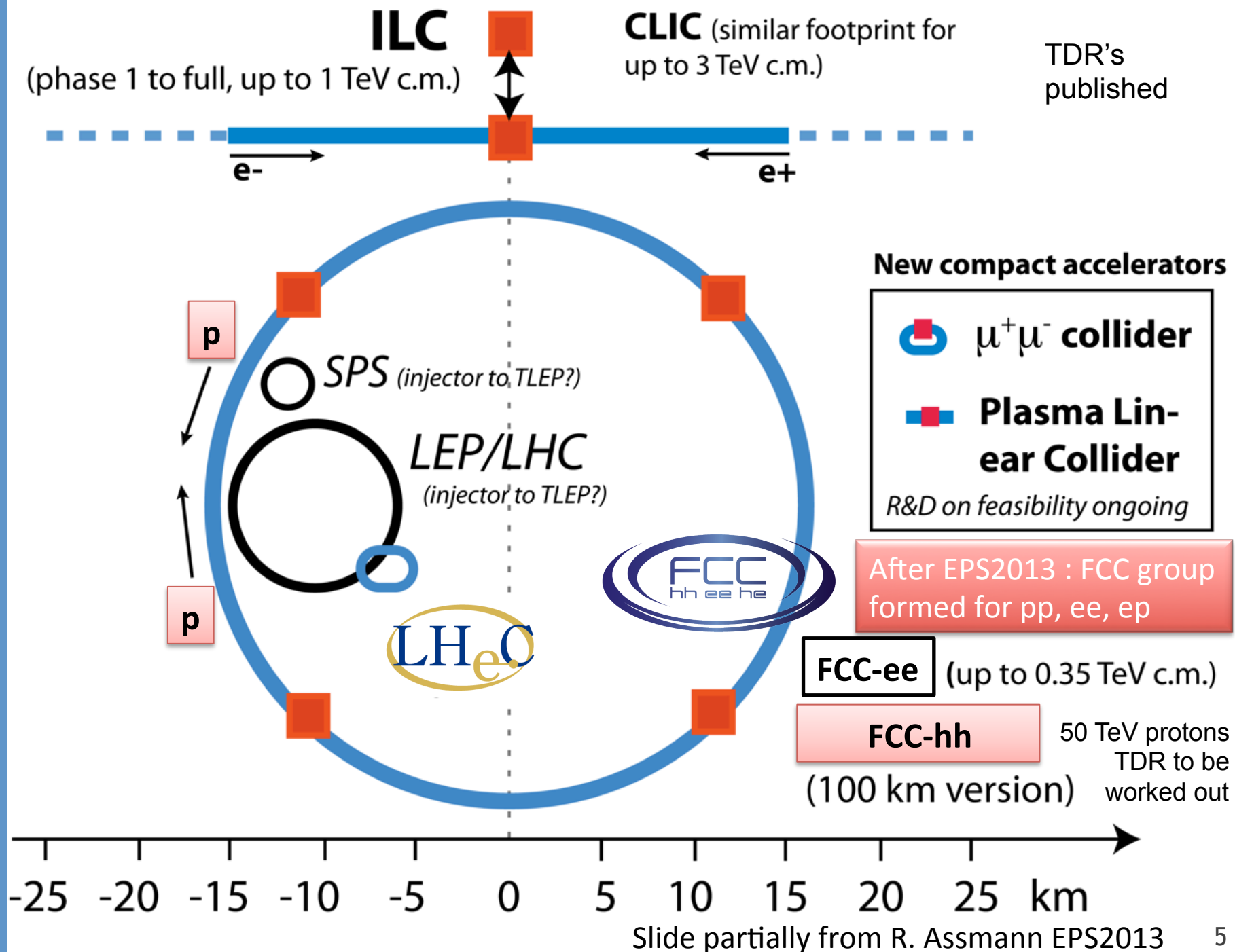
Alfred Mueller (Columbia)

Raju Venugopalan (BNL)

Michele Arneodo (INFN Torino)





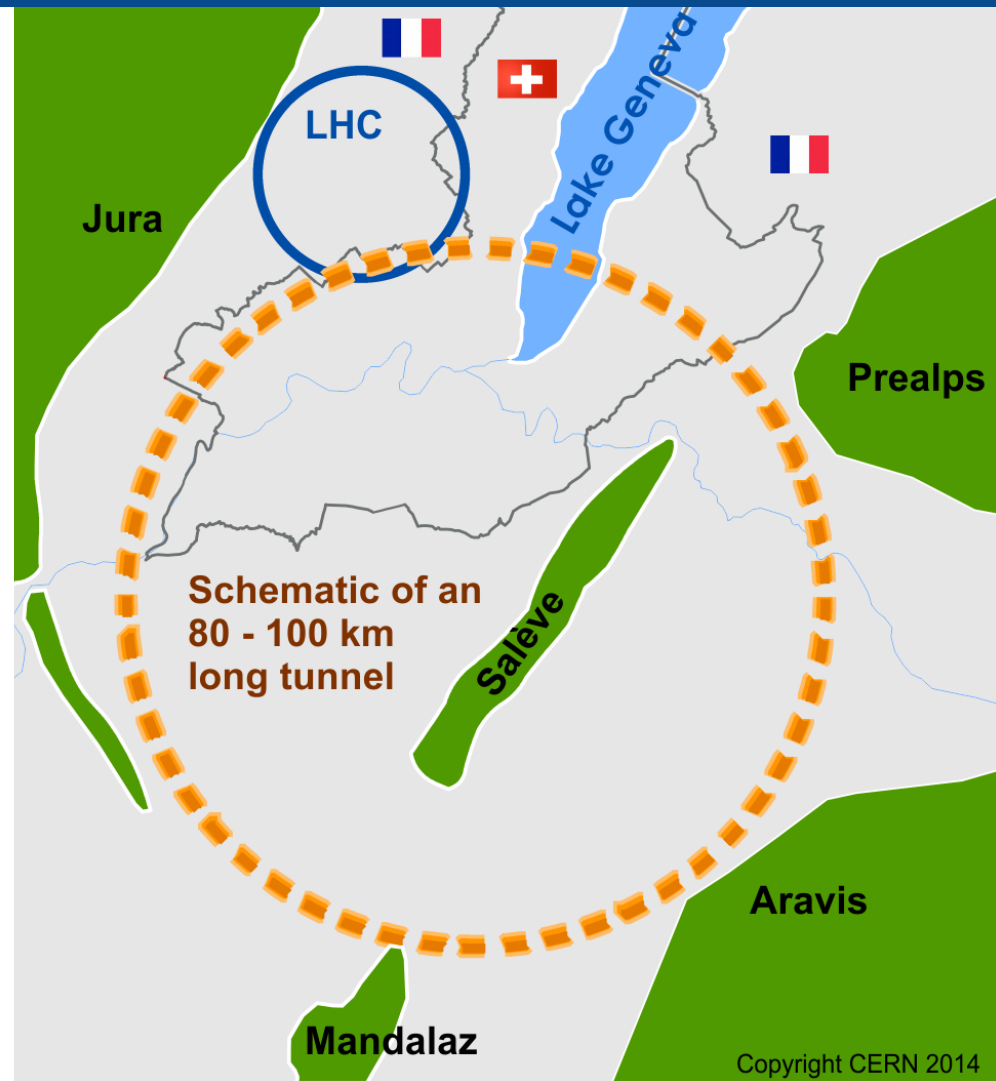


Future Circular Collider Study

Goal: CDR for European Strategy Update 2018/19

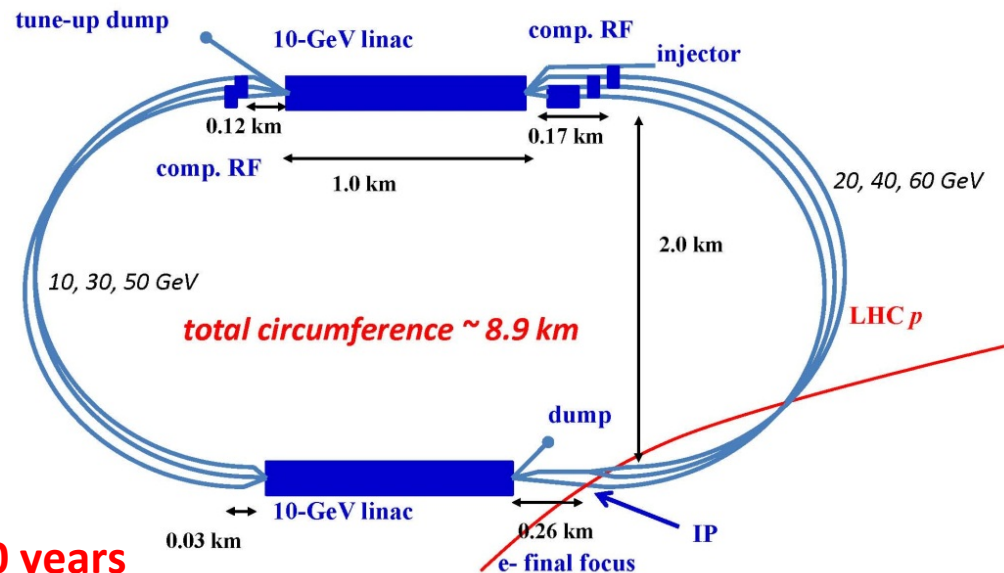
International FCC collaboration
(CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
→ main emphasis, defining infrastructure requirements
 $\sim 16\text{ T} \Rightarrow 100\text{ TeV } pp \text{ in } 100\text{ km}$
- **80-100 km tunnel infrastructure**
in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*)**,
as potential first step
- ***p-e* (*FCC-he*) option**,
integration one IP, *FCC-hh* & ERL
- **HE-LHC** with *FCC-hh* technology



Baseline : Electron Linac - LHC Ring

- Design constraint: power consumption < 100 MW, $E_e = 60$ GeV
- Two 10 GeV electron **Linacs** with $I_e > 6$ mA and high electron polarisation of 80-90%
- 3 return arcs, 20 MV/m
- Energy recovery in same structure
- **Installation fully decoupled from LHC operation!**

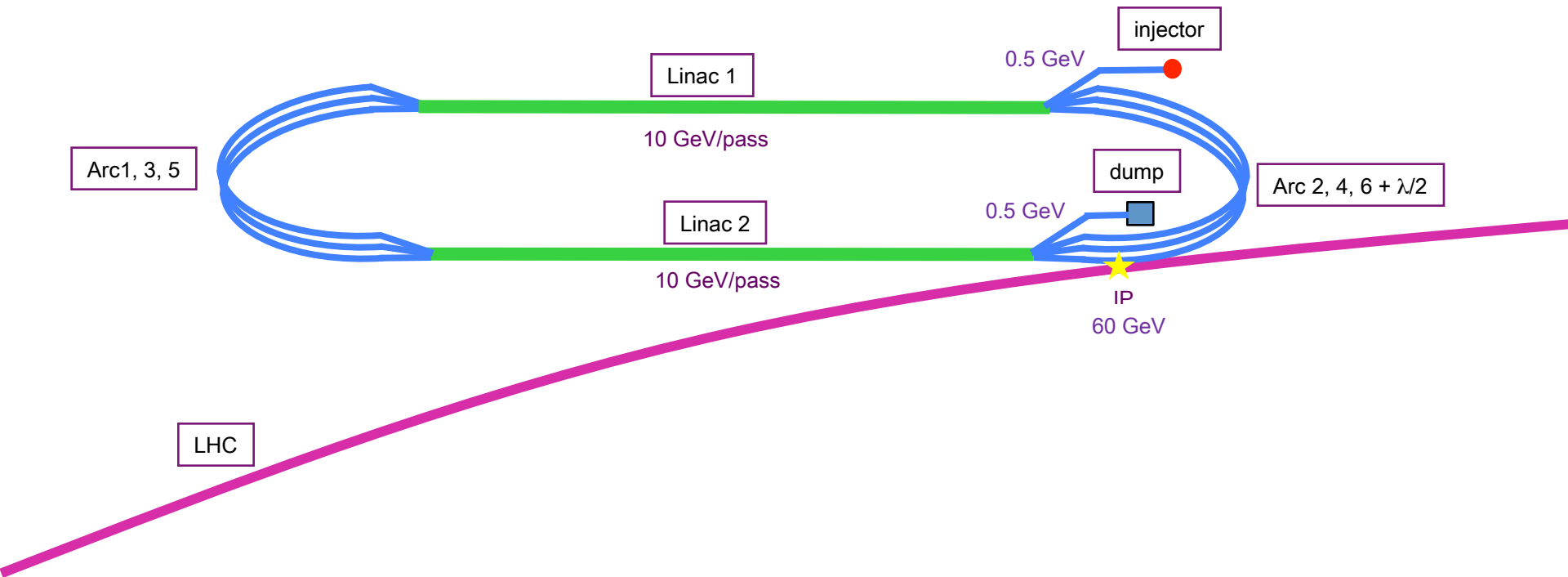


- ep Lumi $10^{33} - 10^{34} \text{ cm s}^{-2} \text{ s}^{-1} **$
- 10 - **100 fb⁻¹ per year**
- 100 fb⁻¹ – **1000 fb⁻¹ total collected in 10 years**
- eD and eA collisions have always been integral to programme
- eA luminosity estimates $\sim 10^{32} \text{ cm s}^{-2} \text{ s}^{-1}$ for eD (ePb)

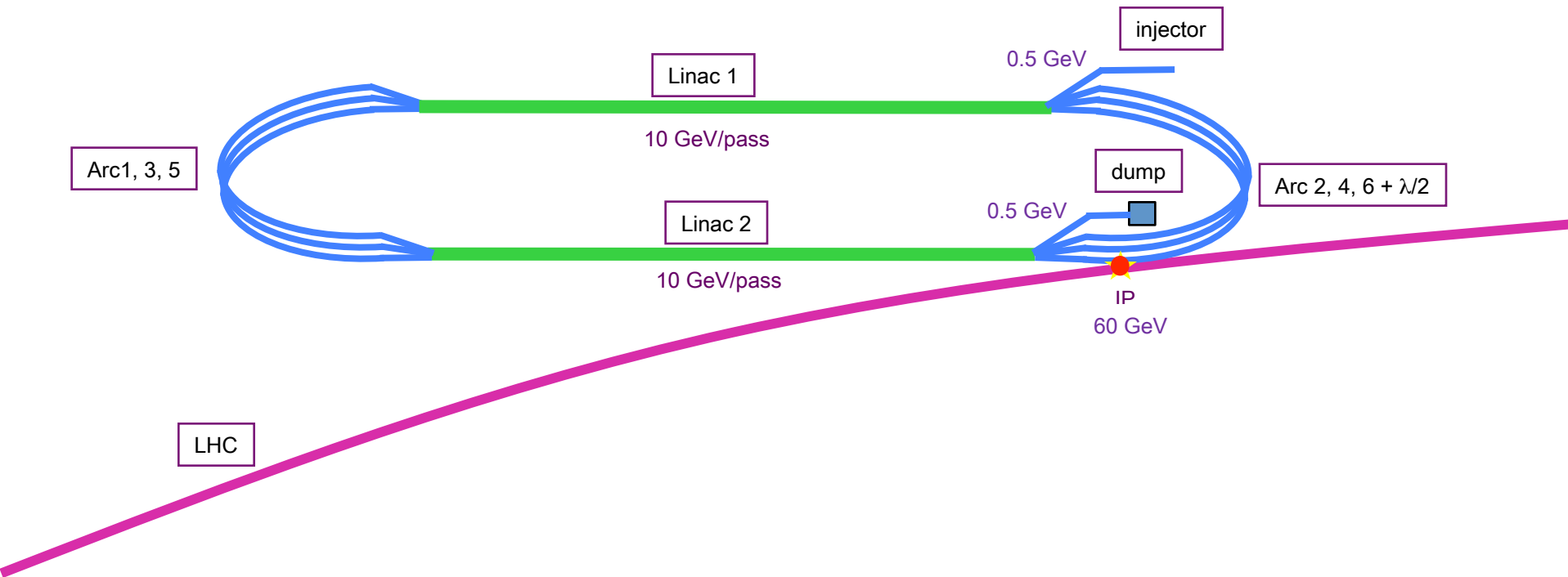
** based on existing HL-LHC proposal

Using material from Oliver Bruning, FCC kickoff, Geneva 2014,
<https://indico.cern.ch/event/282344/session/15/contribution/96/material/slides/1.pdf>

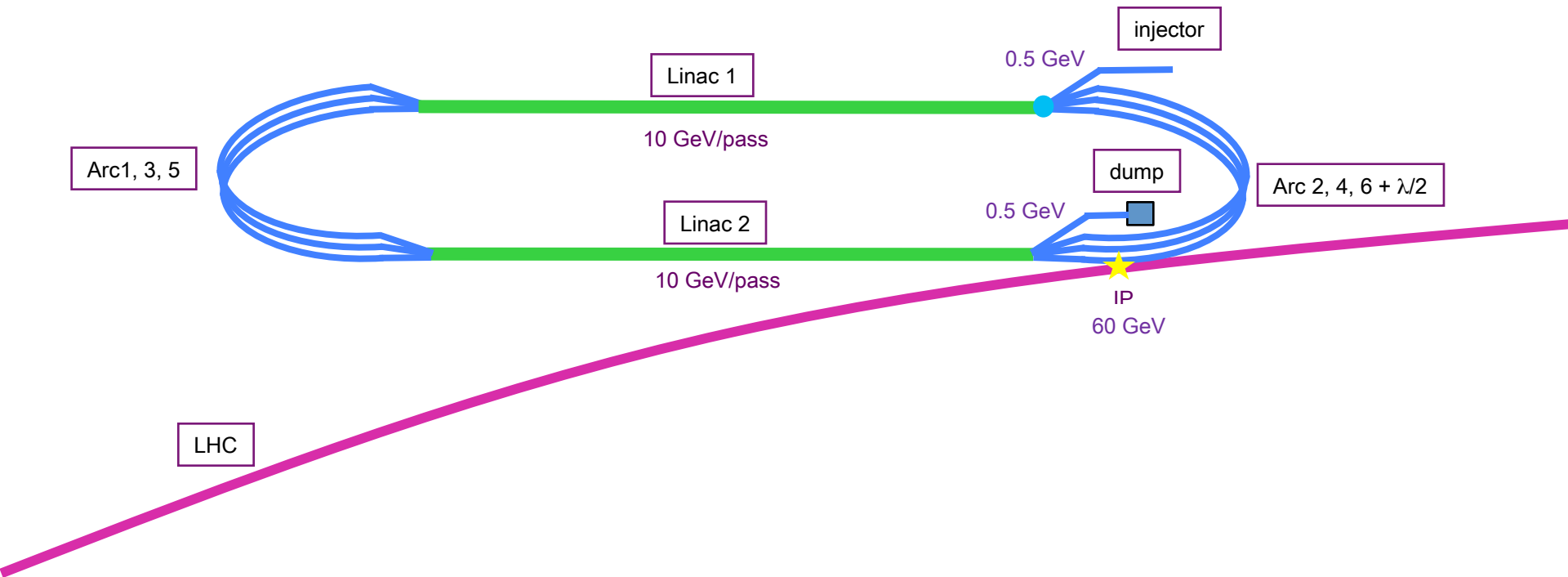
LHeC Recirculator with Energy Recovery



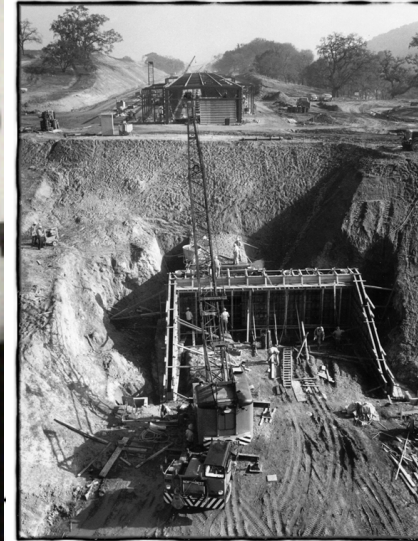
LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



can one build a 2 km long linac?



it has been done before



Post-CDR: LHeC Baseline Parameter

→ for first time a realistic option of an 1 ab^{-1} electron-proton collider also due to excellent performance of LHC; ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$]	16	16	1	1
Normalized emittance $\gamma \epsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Function $\beta_{x,y}^*$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma_{x,y}^*$ [μm]	4	4	7	7
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40	70	58
Beam Current [mA]	1112	25	430 (860)	6.6
Bunch Spacing [ns]	25	25	25 (50)	25 (50)
Bunch Population	$2.2 \cdot 10^{11}$	$4 \cdot 10^9$	$1.7 \cdot 10^{11}$	$(1 \cdot 10^9) \ 2 \cdot 10^9$
Bunch charge [nC]	35	0.64	27	(0.16) 0.32

Operation concurrent with
HL-LHC *pp* data taking

ep : Some Basics

The only ep collider so far : **HERA @ DESY**

with a **c.m.s.** energy of **0.32 TeV** using

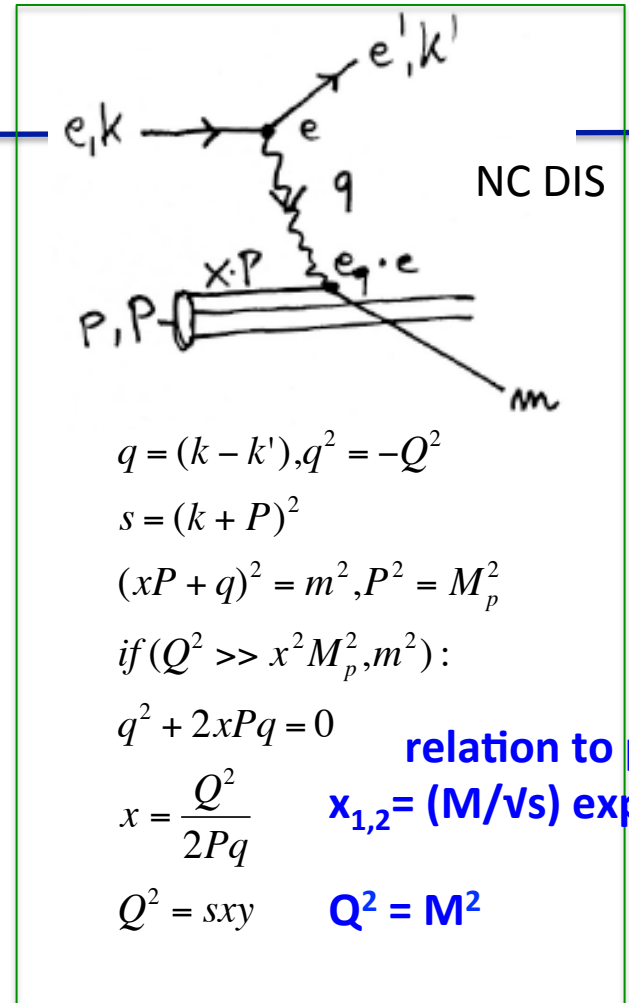
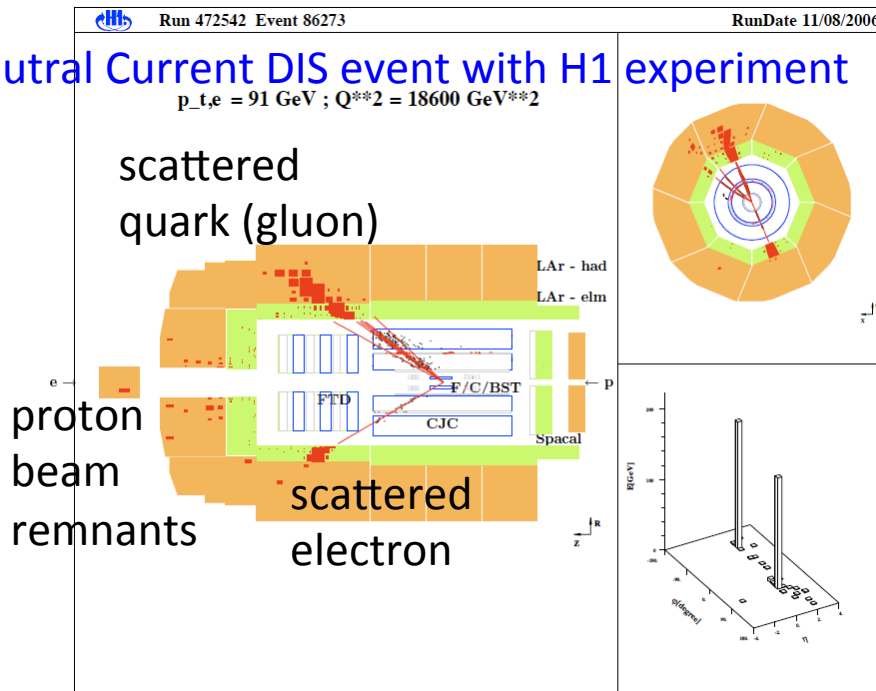
electrons/positrons with $E_e = 27.6$ GeV

protons with $E_p = 0.92$ TeV [like Tevatron protons]

Precise probe of proton structure using Deep Inelastic Scattering (DIS) in a new kinematic range

with a resolution up to 10^{-18} m : ep = Supermicroscope

Neutral Current DIS event with H1 experiment



$$q = (k - k'), q^2 = -Q^2$$

$$s = (k + P)^2$$

$$(xP + q)^2 = m^2, P^2 = M_p^2$$

$$\text{if } (Q^2 \gg x^2 M_p^2, m^2):$$

$$q^2 + 2xPq = 0$$

$$x = \frac{Q^2}{2Pq}$$

$$Q^2 = sxy$$

relation to pp

$$x_{1,2} = (M/\sqrt{s}) \exp(\pm y)$$

$$Q^2 = M^2$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{e^4 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \left[W_2(q^2, W) + 2W_1(q^2, W) \tan^2(\theta/2) \right]$$

SLAC-PUB-642

August 1969

@SLAC: birth of DIS, 50 years ago.

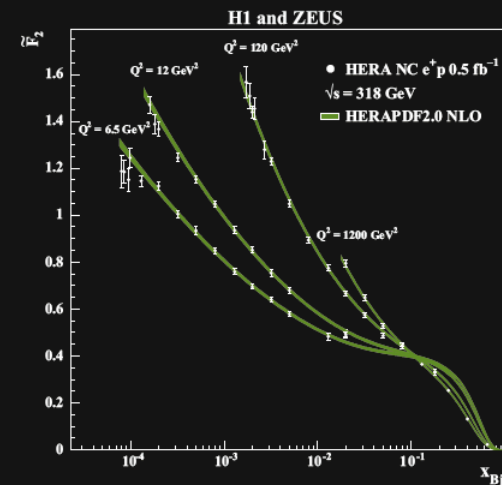
HERA Run 2



→ **Mandatory input for our currently best knowledge about the quark-gluon dynamics of the proton**, e.g. LHC Higgs cross section predictions.

“Limitations” of HERA

- Luminosity $1\text{--}4 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
- No eA collisions
- No polarised protons



The structure function F_2 as extracted from the measured reduced cross sections for four values of Q^2 together with the predictions of HERAPDF2.0 NLO. The bands represent the total uncertainty on the predictions. From H1 and ZEUS Collaborations: Combination of measurements of inclusive deep inelastic e^+p scattering cross sections and QCD analysis of HERA data.

Standard Model Particles & QCD

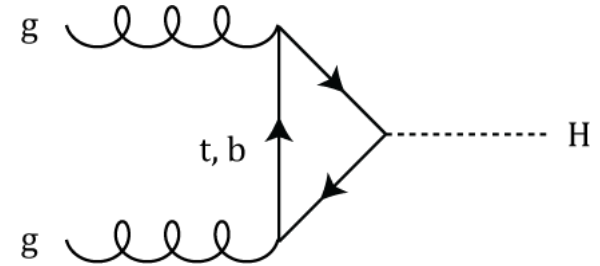
mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS

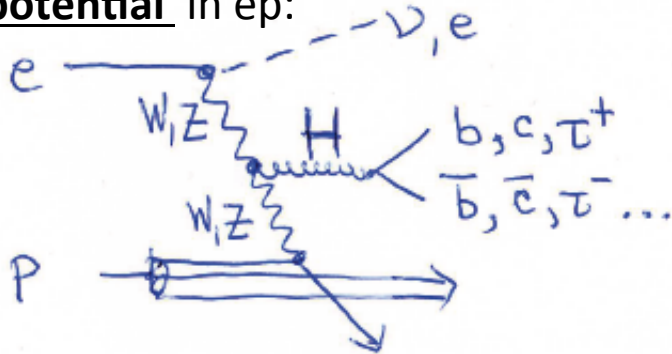
LEPTONS

GAUGE BOSONS

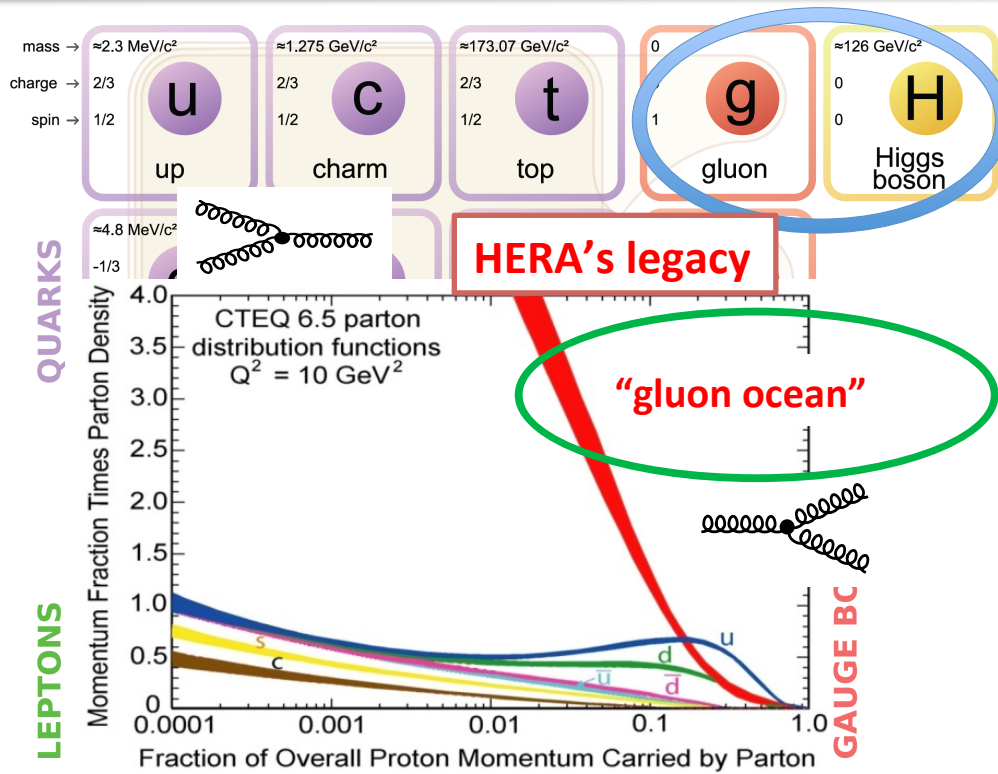
Higgs discovery at LHC via
gluon-gluon fusion



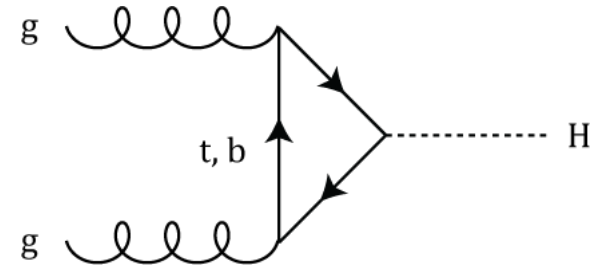
Higgs potential in ep:



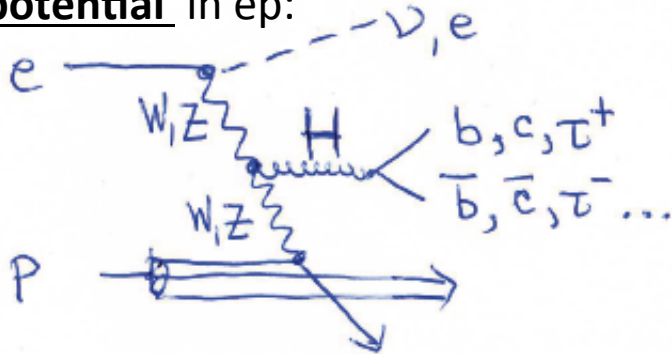
Standard Model Particles & QCD



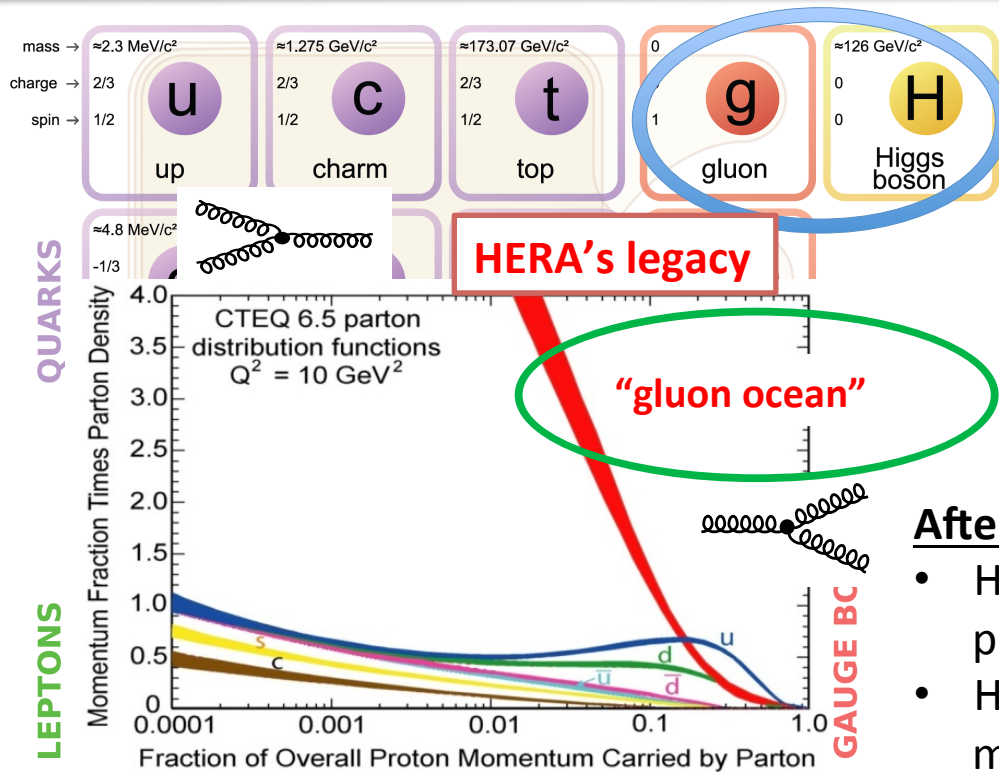
Higgs discovery at LHC via gluon-gluon fusion



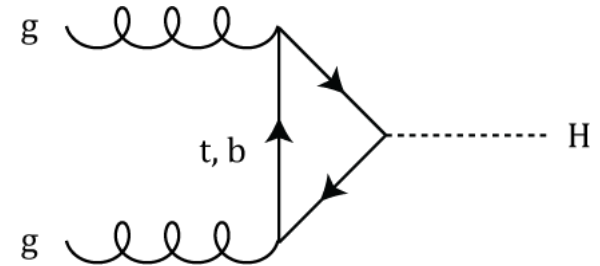
Higgs potential in ep:



Standard Model Particles & QCD



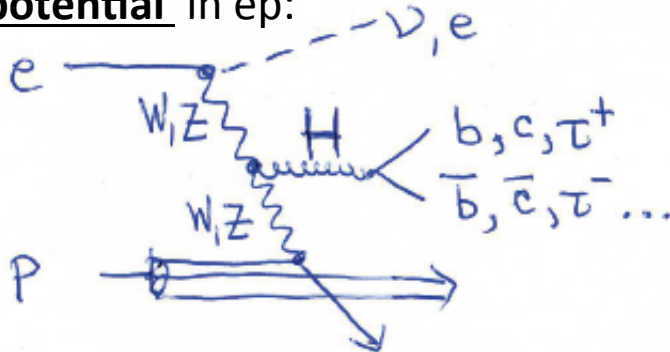
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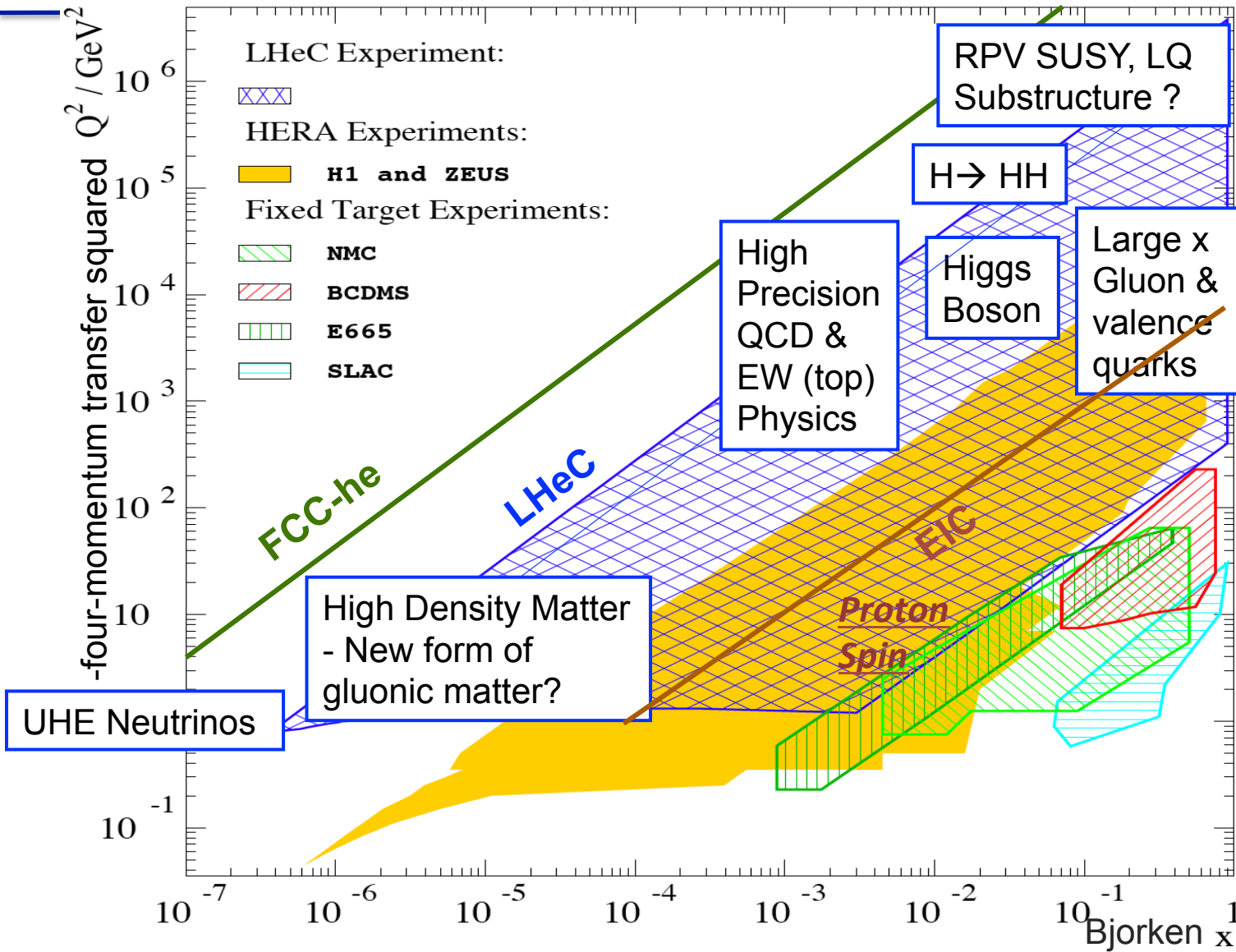
After the Higgs discovery:

- How can we reach a best understanding Higgs properties / EW symmetry breaking?
- How can we exploit best our highest energy machines for finding new physics/new particles?
- ✓ ep : Precision quark-gluon dynamics for sensitive searches; top & Higgs physics
- ✓ **Concurrent running of pp and ep :**
Compelling synergy for exploring the EW and QCD sector to unprecedented precision.

Higgs potential in ep:



The ep Physics at the Energy Frontier



HERA established the validity of pQCD down to $x > 10^{-4}$ (DGLAP) due to a very high lever arm in Q^2 .

Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

Relation to pp : $x_{1,2} = (M/v_s) \exp(\pm y)$ & $Q^2 = M^2$

Neutrino-Nucleon Cross Section at UHE

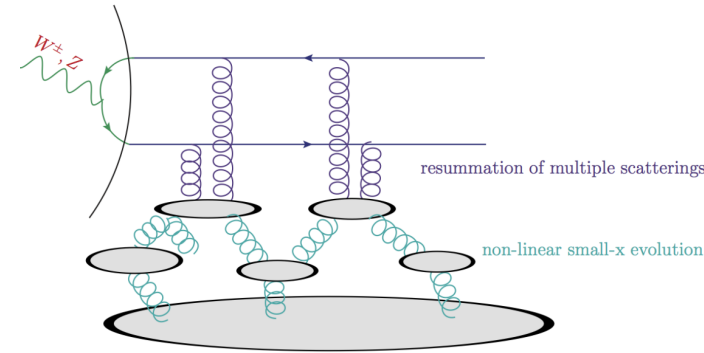
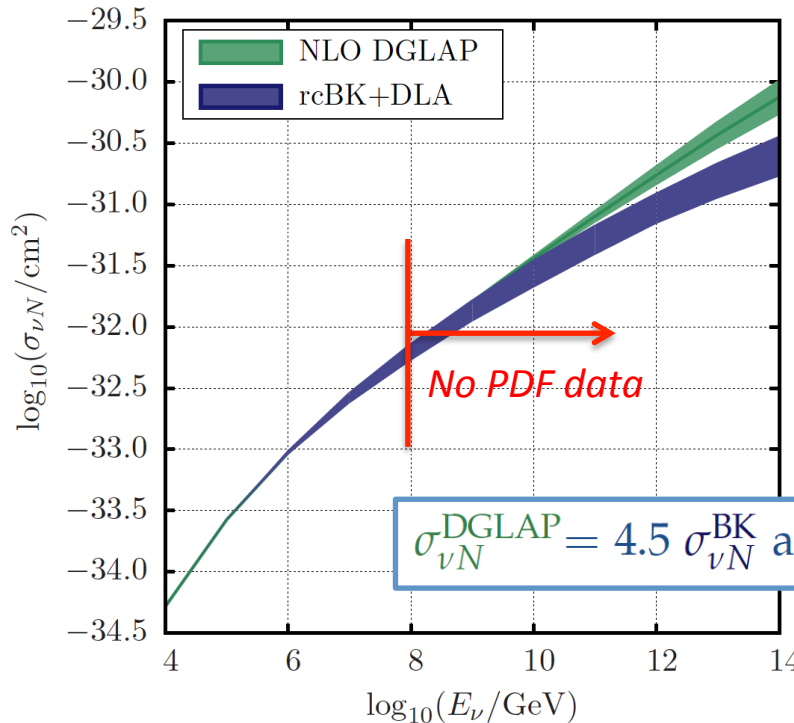
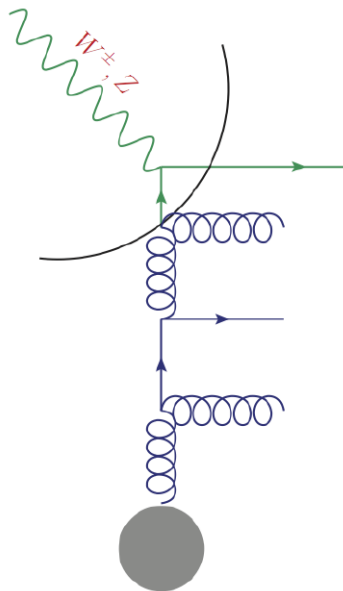
& its *astrophysical* Implications

Alba SOTO ONTOSO,
@POETIC VI
PRD 92, 014027 (2015)

DGLAP approach
($\alpha_s \ln(Q^2/Q_0^2) \sim 1$)

$$\sigma_{\nu N} \sim \underbrace{\left(\begin{array}{c} \text{Probability of} \\ \text{finding a quark/gluon} \\ \text{in nucleon} \end{array} \right)}_{\text{Low energy QCD}} \otimes \underbrace{\sigma^{q/g-\nu}}_{\text{Perturbative}}$$

À la BK ($\alpha_s \ln(x_0/x) \sim 1$)



$$\sigma_{\nu N}^{\text{DGLAP}} = 4.5 \sigma_{\nu N}^{\text{BK}} \text{ at } E_\nu = 10^{14} \text{ GeV.}$$

Limits on astrophysical ν fluxes

... have a **much larger uncertainties** than currently assumed :

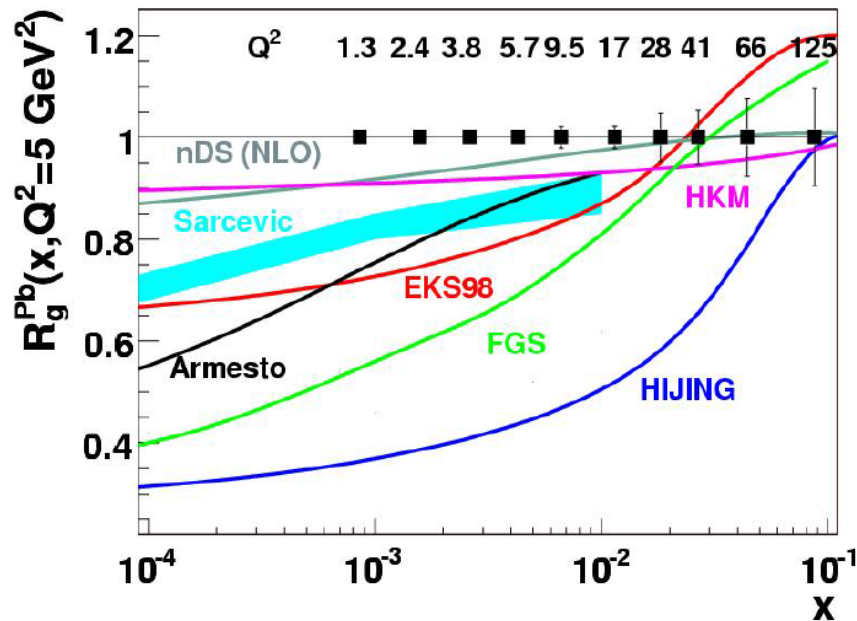
factors 1.4 to 4.5 for $10^9 < E_\nu < 10^{14}$ GeV.

Partons in Nuclei

What do we know about gluons in a nucleus?

NOTHING!

Data fits: Ratio of gluons in lead to deuterium

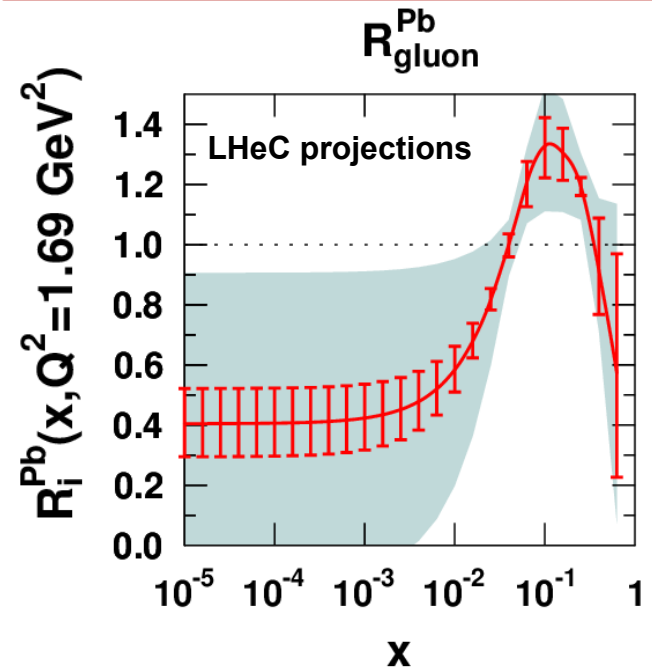


$$Q_s^2(eA) \propto Q_s^2(ep) A^{1/3}$$

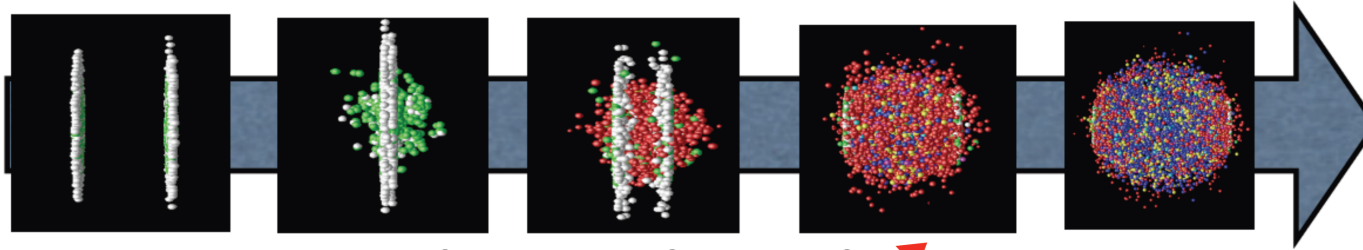
Precision measurements of gluon distribution essential for quantitative studies of onset of **saturation** as a **high density** (small x in ep) and **matter** ($A^{1/3}$) effect.

LHeC will measure all nuclear PDFs for the first time and in an unprecedented kinematic range. Quarks through NC and CC DIS (flavour separation).

Gluons accessed through $dF_2/d\ln(Q^2)$ (large range in Q^2)



Synergy : eA and AA



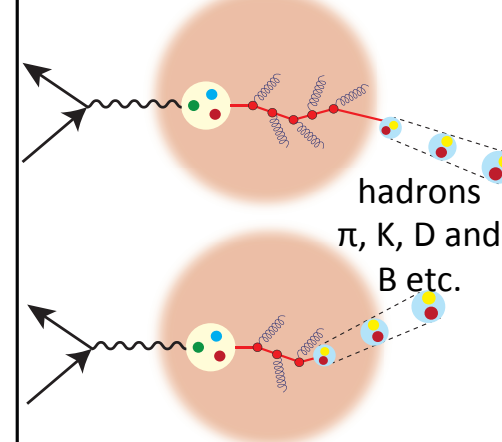
Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x : **nuclear structure functions.**

- Particle production at the very beginning: **which factorisation in eA?**
- How does the system behave as $\sim$ isotropised so fast?: **initial conditions for plasma formation to be studied in eA.**

- Probing the medium through energetic particles (jet quenching etc.): **modification of QCD radiation and hadronization in the nuclear medium.**

eA: measure in semi-inclusive DIS modification of fragmentation/hadronisation in dense nuclear medium



The LHeC-eA will explore a region overlapping with the LHC-AA

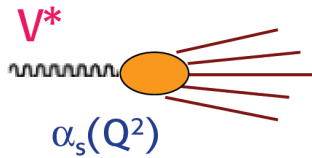
→ in a cleaner experimental setup;

→ on firmer theoretical grounds.

LHeC-eA explores 2 orders of magnitude higher in Q^2 and $1/x$ compared to US-EIC.

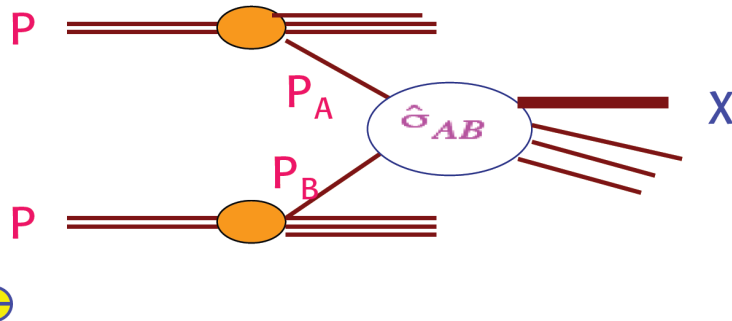
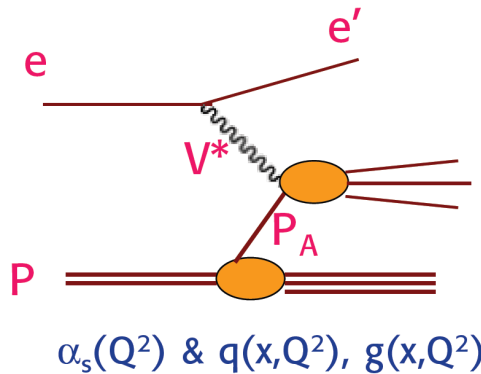
On the Synergies of ep and pp

Guido Altaralli
Cern 6/2015



The basic experimental set ups for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)



The pdf are defined in DIS

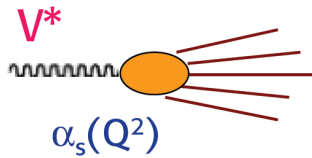
The theory of inclusive DIS is crystal clear

Thru the factorization

“theorem” the pdf’s and α_s determine the hadron collider rates

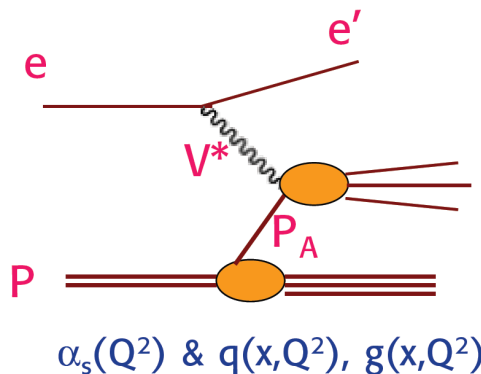
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The pdf are defined
in DIS

The theory of inclusive DIS
is crystal clear

We often hear the statement that all the relevant info on pdf's
can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision
One example:

The factorization "theorem" is essential.

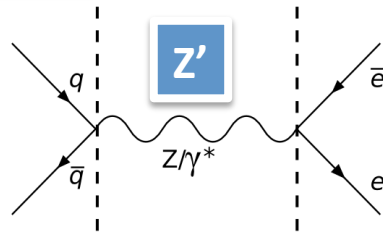
Not fully proved theoretically (beware of non pert. effects)

[nearly complete arguments only for Drell-Yan & similar]

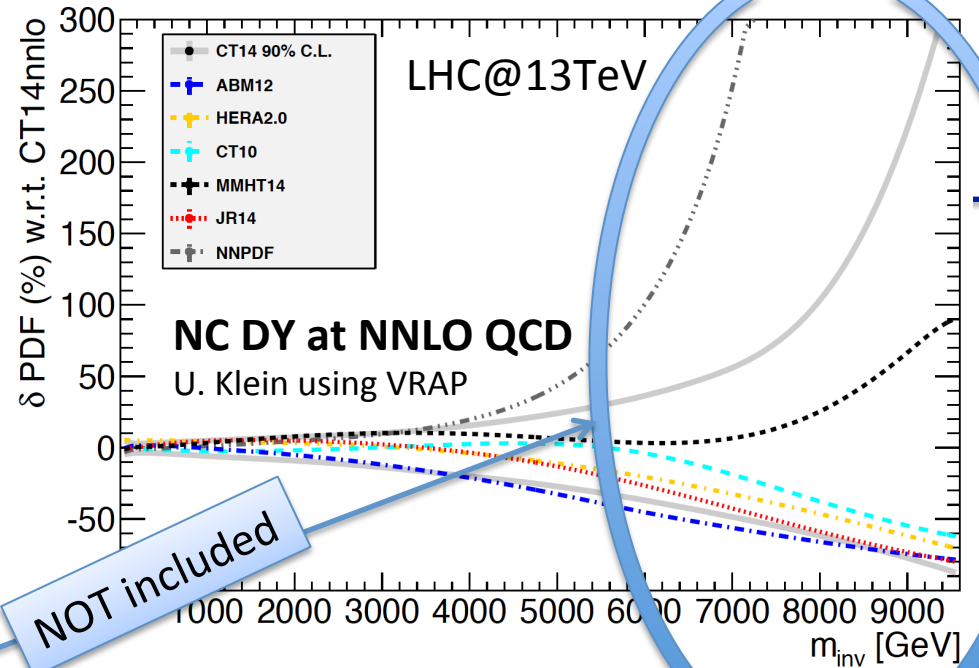
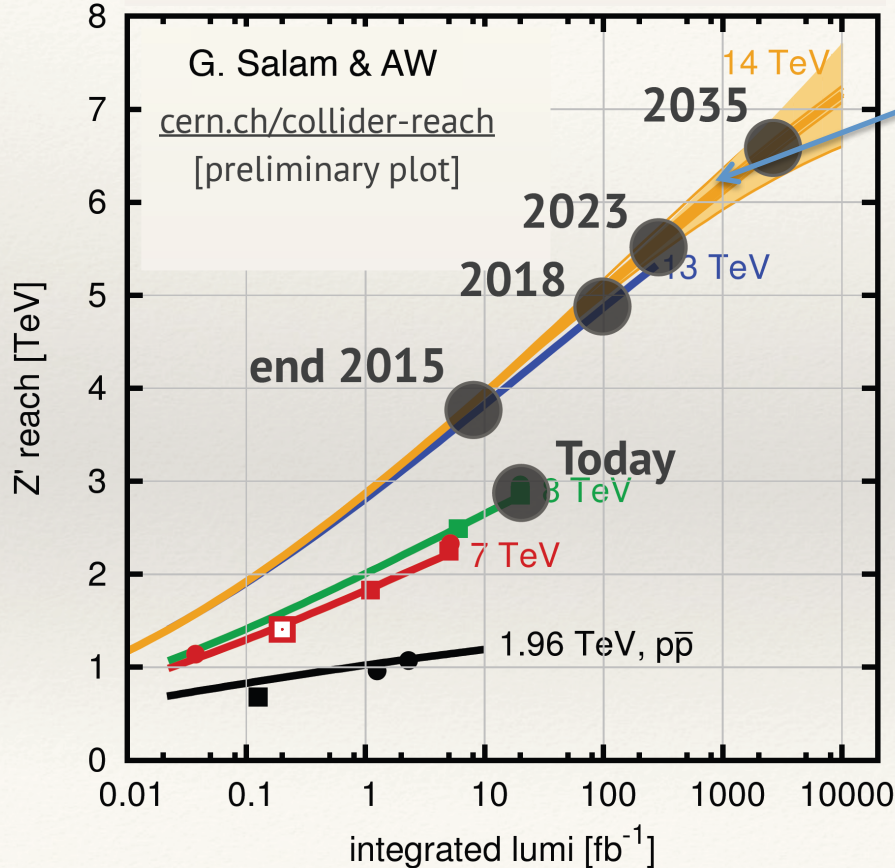
Should finally be experimentally tested with precision



Searches and PDF Uncertainties @ LHC



Z' exclusion reach v. lumi



By the end of the year, most searches will beat 8 TeV results

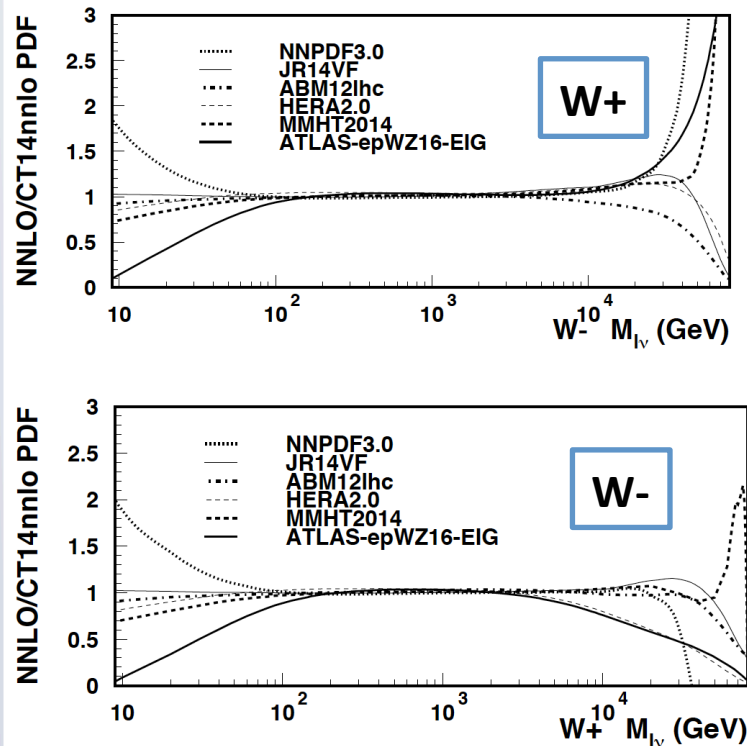
[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb^{-1}]

A. Weiler@EPS2105

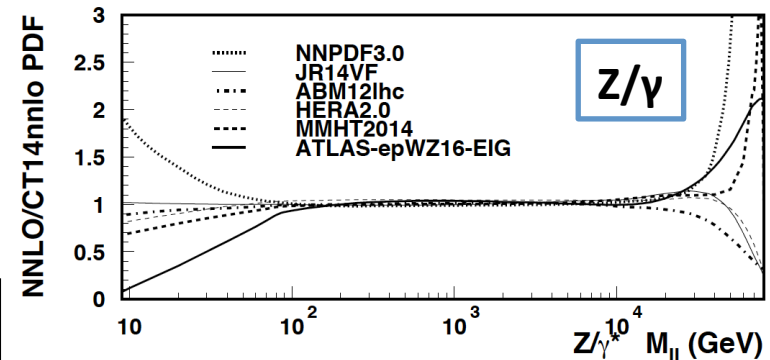
We do NOT know the structure of the proton at high x (high masses)

Impact of PDF: High mass Drell-Yan

- Non resonant searches for ED (interference) sensitive to tails of DY distributions thus to PDF. Predominantly q-qbar



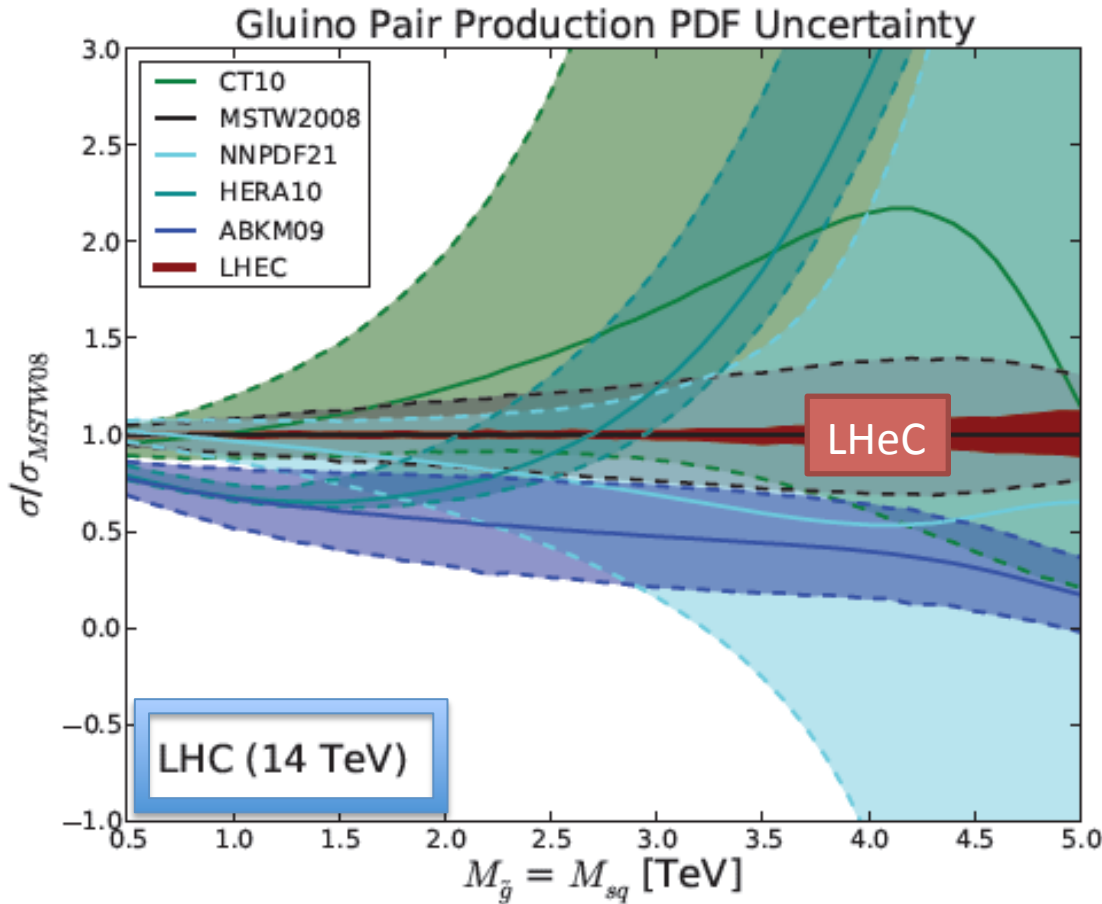
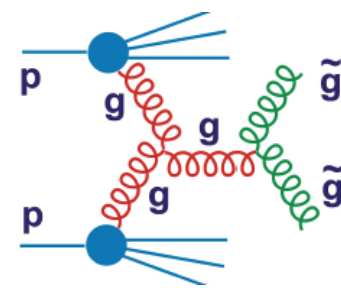
Uta Klein
VRAP 0.9 for NNLO QCD



“Troubles” at low and high x

FCCeh (and before, LHeC) can improve low and high M_{ll} and $M_{l\gamma}$ precision for standard candle measurements and searches for new physics

Precision Gluons for SUSY



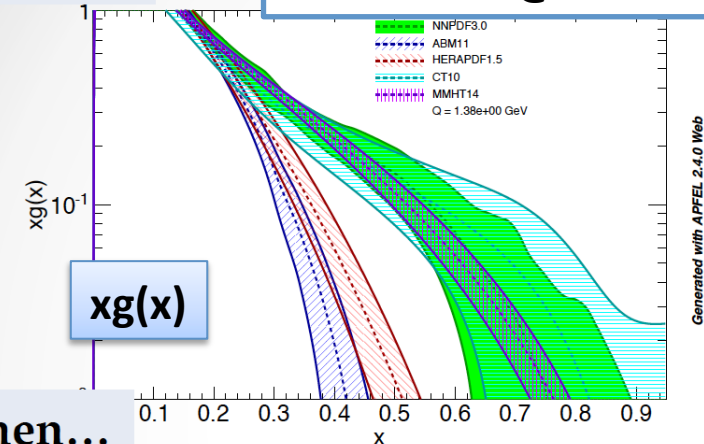
Using 2012 NLO PDFs

LHeC Note 2012-005 [arXiv:1211.5102]

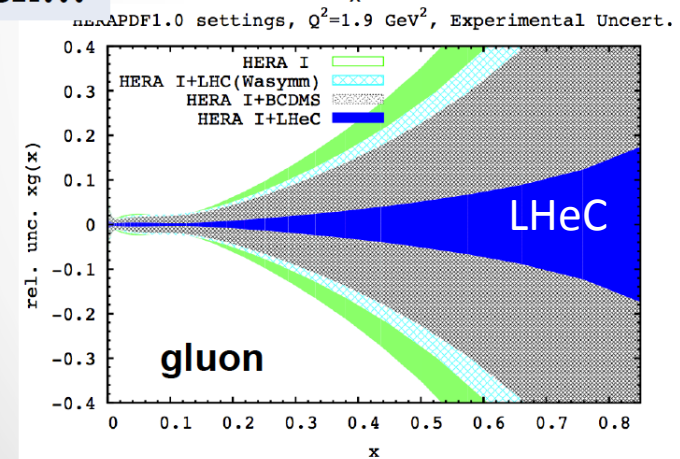
LHeC-PDF uncertainties accessible via LHAPDF

now...

C. Gwenlan @DIS2015

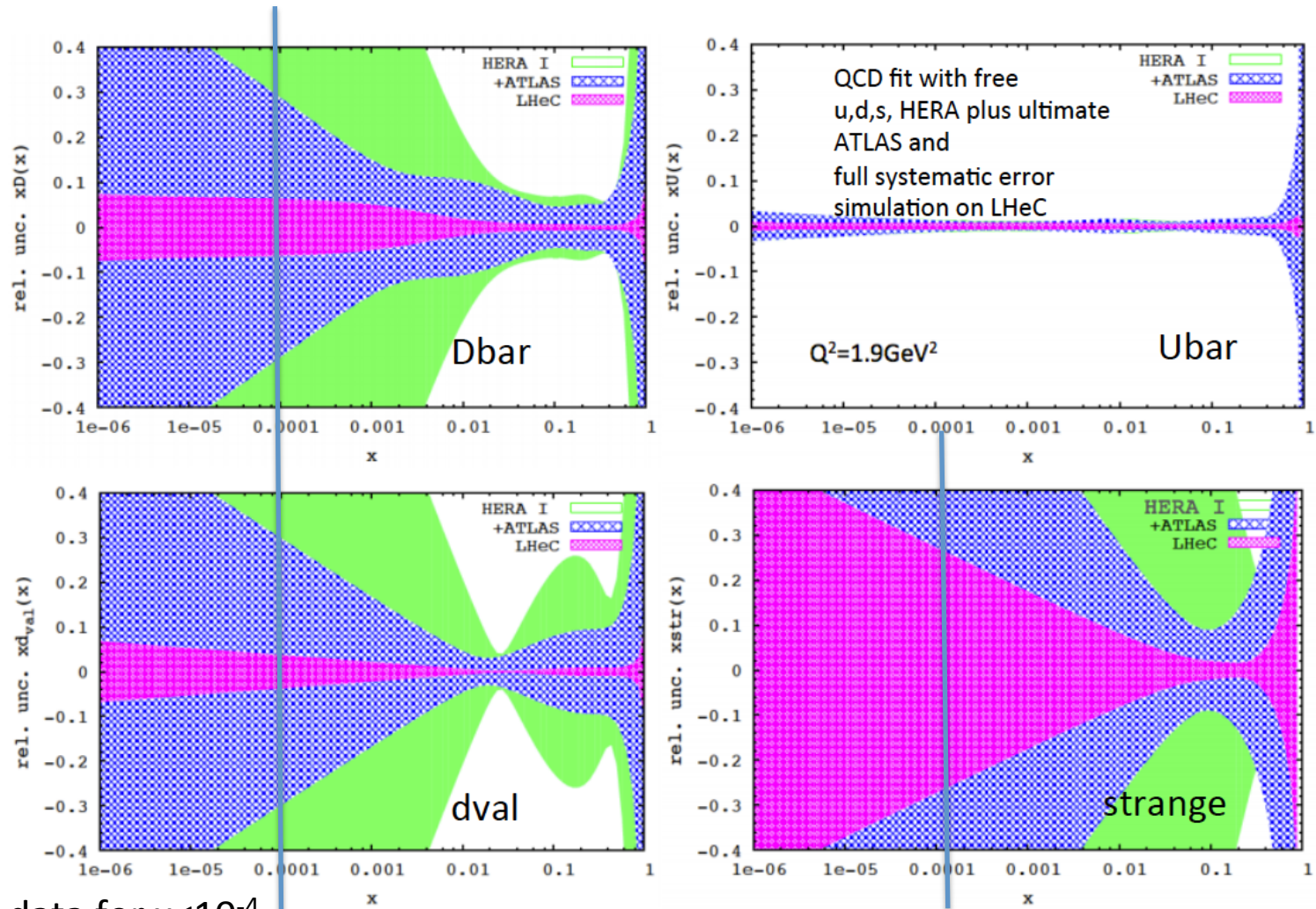


then...



Using 2014 NNLO PDFs

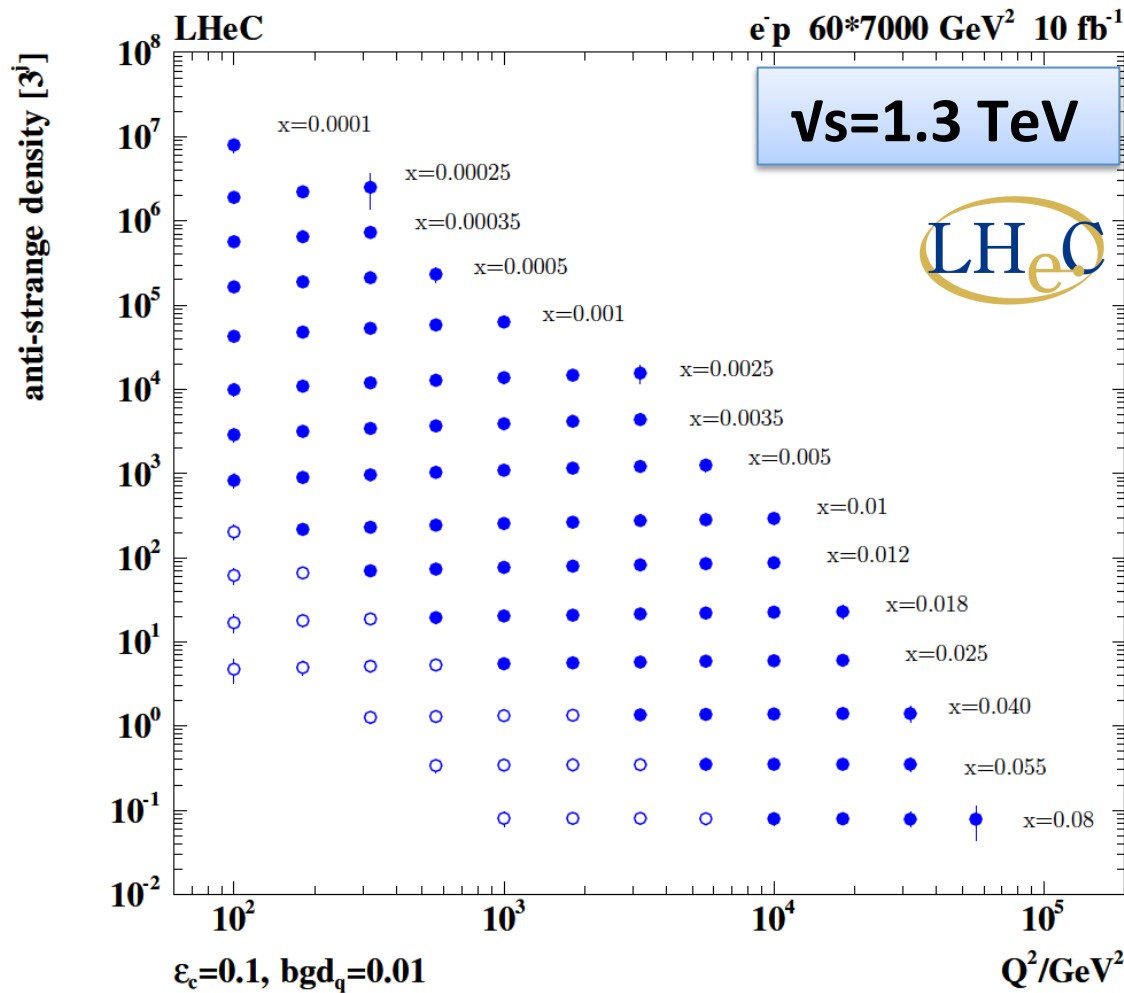
ep + pp and free fit to u,d,s



no HERA data for $x < 10^{-4}$

→ adding e.g. high precision ATLAS W,Z data give some constraints in particular for strange at medium x

Precision **Strange** Quark Distributions



- ✓ High luminosity
 - ✓ High Q^2 lever arm
 - ✓ Small beam spot
 - ✓ Modern Silicon detectors
 - ✓ NO pile-up, no DPS ...
 - ✓ similar new measurements for charm and beauty
- δM_c reduced from 60 to 3 MeV → α_s precision

→ First (x, Q^2) measurement of the (anti-)strange density (even intrinsic charm?) over large phase space

$x = 10^{-4} \dots 0.05$

$Q^2 = 100 - 10^5 \text{ GeV}^2$

LHeC : Complete unfolding of the flavour structure of the proton for the first time.

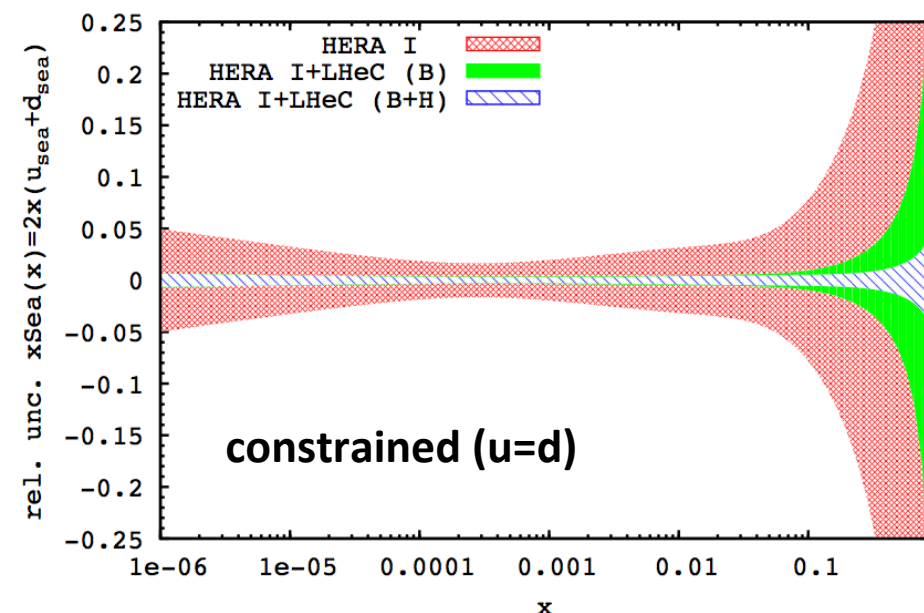
Resolving Partonic Structure

free of symmetry assumptions

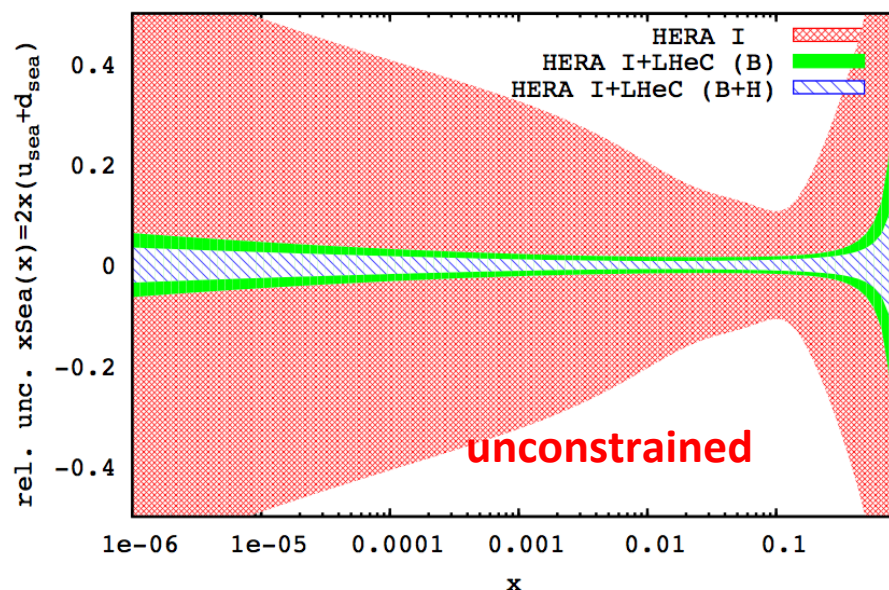
Voica Radescu &
Max Klein, 2014



HERAPDF1.0 settings, $Q^2=1.9 \text{ GeV}^2$, Experimental Uncert



Unconstrained sea Fit, $Q^2=1.9 \text{ GeV}^2$, Experimental Uncert.

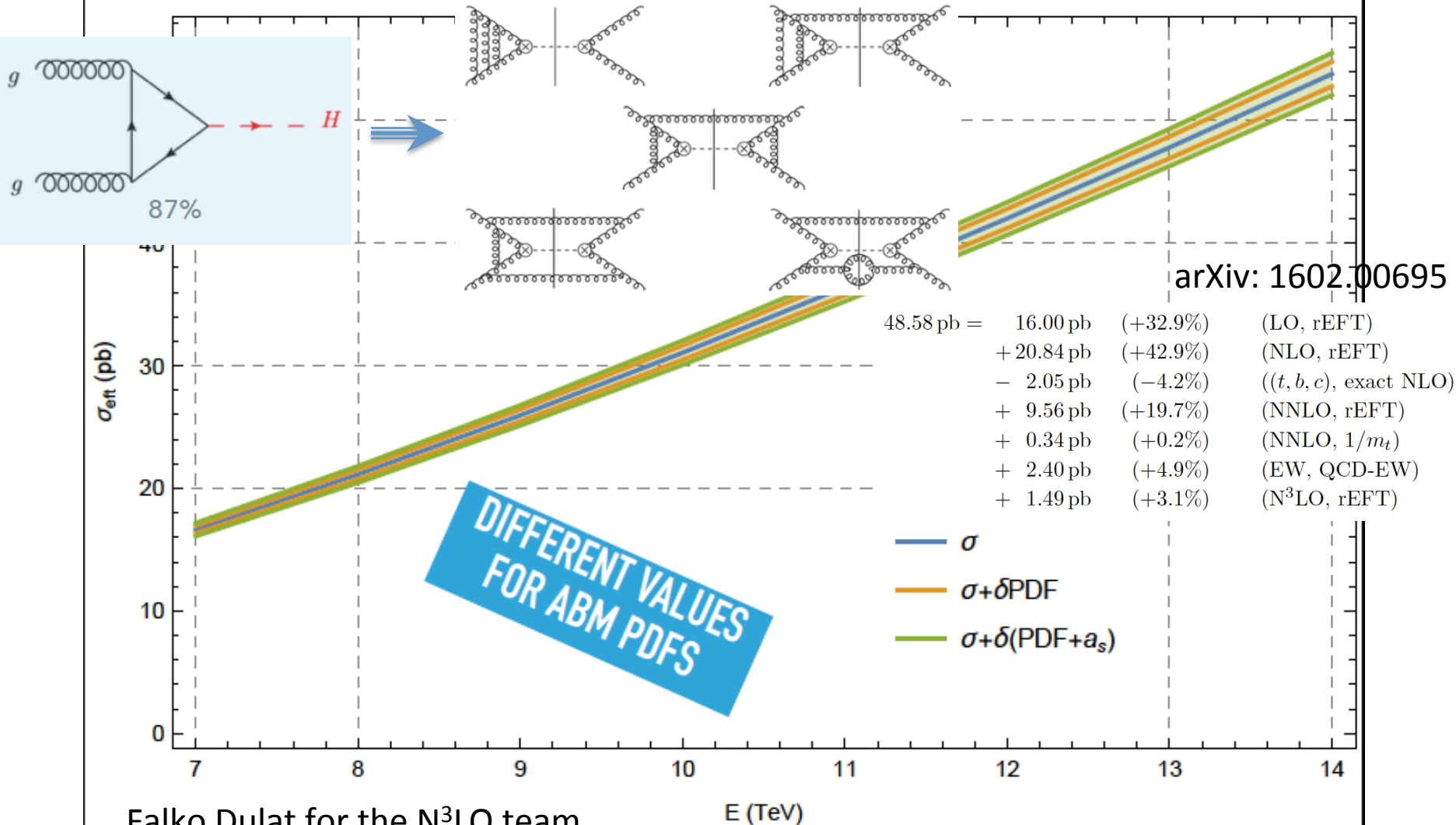


- One can see that for HERA data, if we relax the low x constraint on u and d , the “PDF errors” are increased tremendously!
- However, when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
- Further important cross check comes from the **deuteron** measurements, with tagged spectator and controlling shadowing (small x partons) with diffraction...
- **All parton distribution functions of the proton at N³LO !**

LHC : Total Higgs Cross Sections @ N³LO

PDF + ALPHAS UNCERTAINTY

52

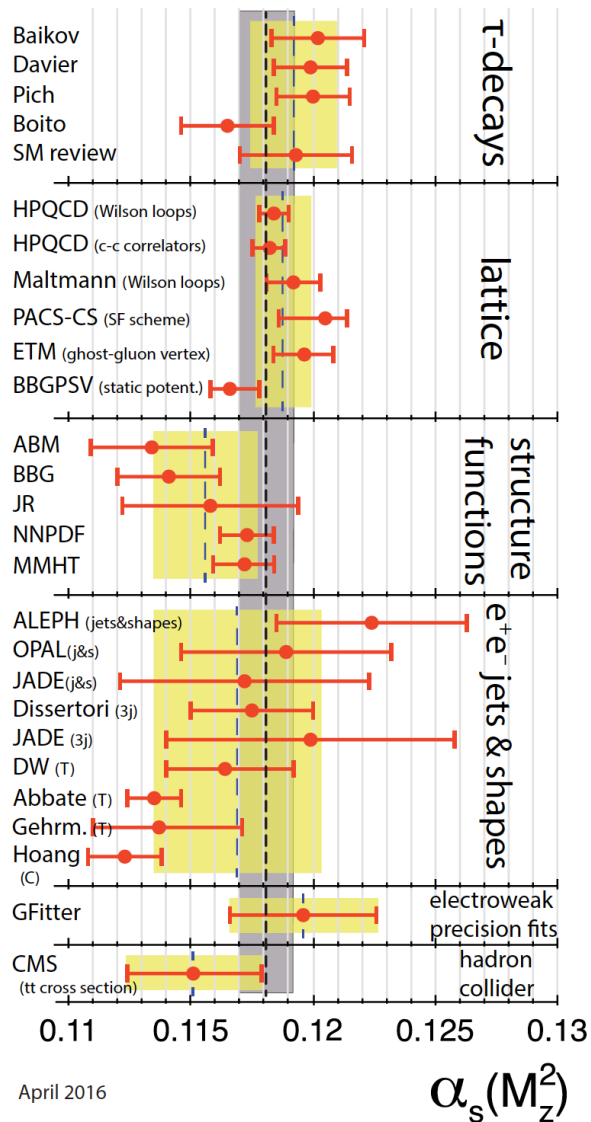


Falko Dulat for the N³LO team.

CERN seminar 11.12.2015 <https://indico.cern.ch/event/462111/>

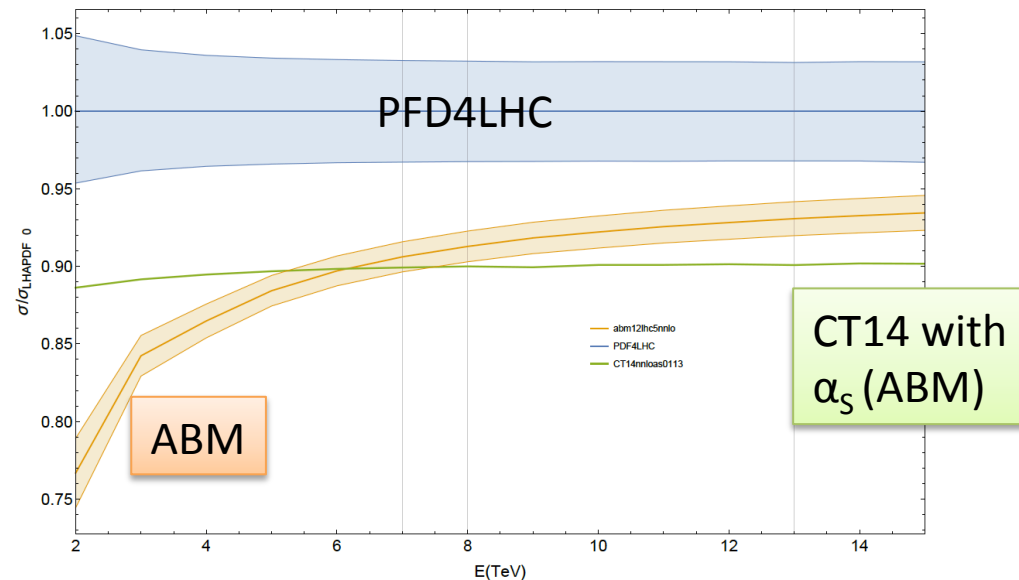
Tensions : α_s and $\sigma^{\text{tot}}_{\text{Higgs}}$ @ 13 TeV

C.Anastasiou et al,
arXiv: 1602.00695



April 2016

PDG 2016



Recommendation using PDF4LHC and 68% CL

$$\sigma = 48.58 \text{ pb}^{+2.22 \text{ pb} (+4.56\%)}_{-3.27 \text{ pb} (-6.72\%)} (\text{theory}) \pm 1.56 \text{ pb} (3.20\%) (\text{PDF} + \alpha_s).$$

ABM prediction

$$\sigma_{\text{ABM12}} = 45.07 \text{ pb}^{+2.00 \text{ pb} (+4.43\%)}_{-2.88 \text{ pb} (-6.39\%)} (\text{theory}) \pm 0.52 \text{ pb} (1.17\%) (\text{PDF} + \alpha_s). \quad (8.3)$$

The significantly lower central value is mostly due to the smaller value of α_s , which however is also smaller than the world average.

Strong Coupling Constant

- α_s least known of coupling constants

Grand Unification predictions need smaller $\delta\alpha_s$

- Is $\alpha_s(\text{DIS})$ lower than world average (?)

- LHeC: per mille - independent of BCDMS!

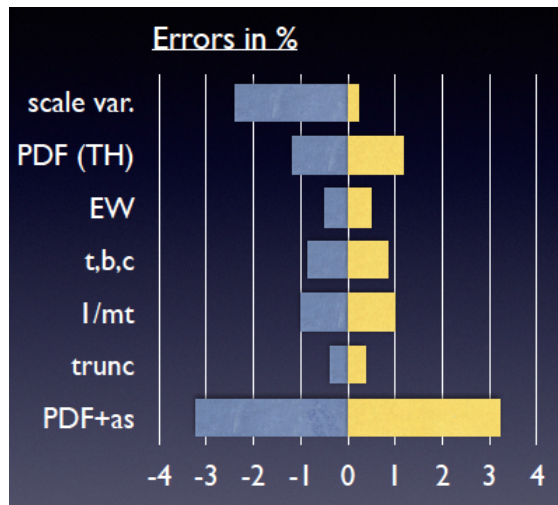
- High precision from inclusive data – $\alpha_s(\text{jets})$
 → for HERA : now NNLO calculations available

- Challenge lattice QCD

LHeC simulation, NC+CC inclusive, total exp error

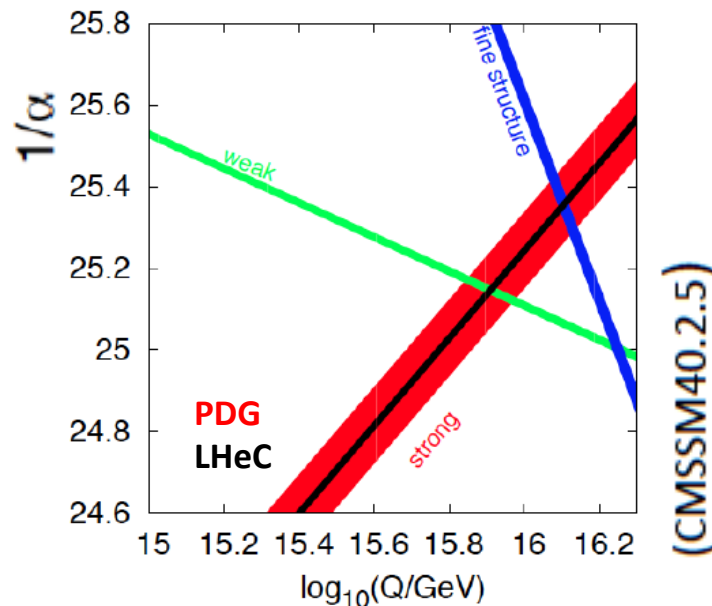
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Two independent QCD analyses using LHeC+HERA/BCDMS



Uncertainty on Higgs cross section

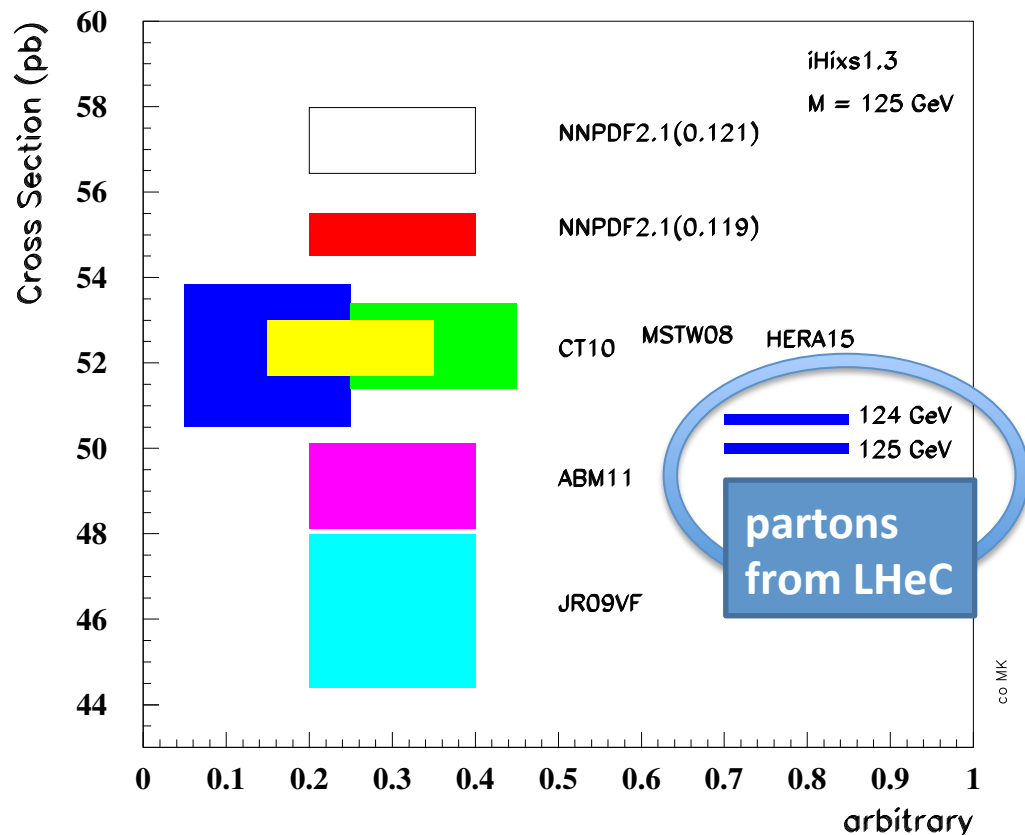
Giulia Zanderighi, Vietnam 9/16,
 from C.Anastasiou et al, 1602.00695
 who also discuss the ABM α_s .



LHeC Precision Partons for Higgs@LHC

- Using LHeC input: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and α_s** is strongly reduced to **$\sim 0.4\%$**
- *clear theoretical path to determine N^3LO PDFs*
- Similar conclusions and relations expected for FCC-hh and LHeC/FCC-he

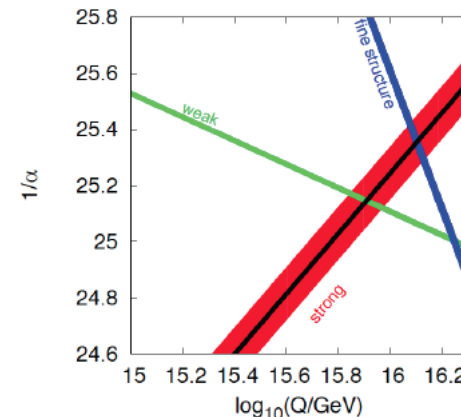
NNLO pp-Higgs Cross Sections at 14 TeV



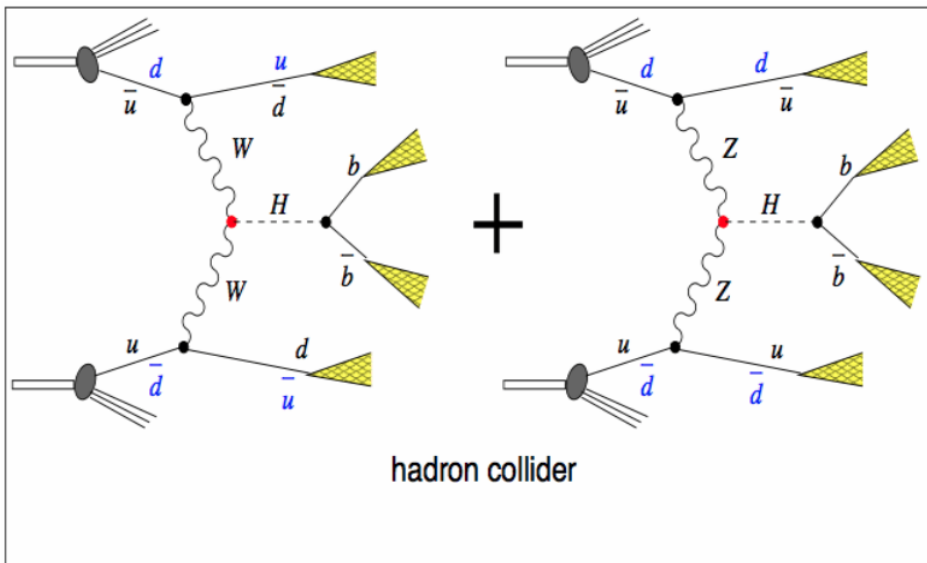
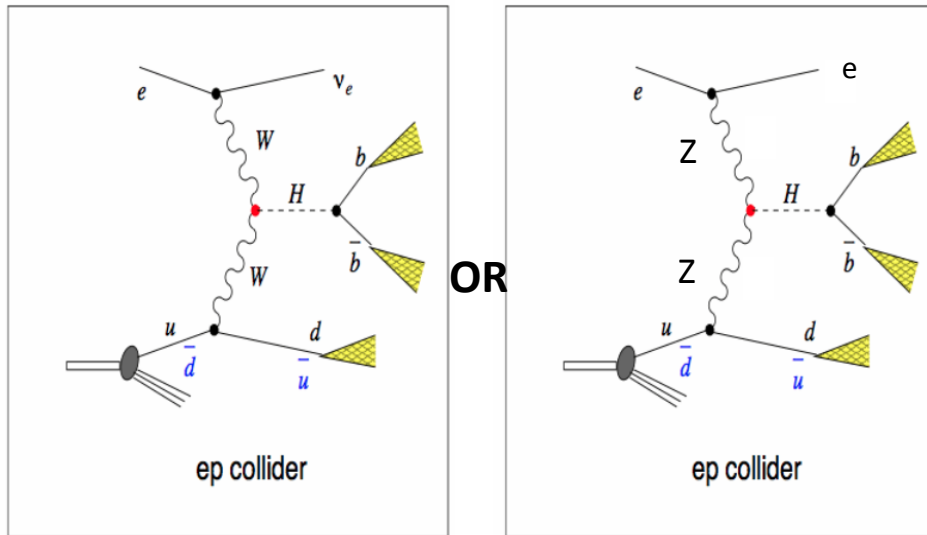
α_s = underlying parameter relevant for uncertainty ($0.0015 \rightarrow 2.6\%$)
@ LHeC: measure to permille accuracy (0.0002)

→ **precision from LHeC can add a very significant constraint on the Higgs mass** *but also:*

Study unification of couplings



VBF Higgs Production in ep (top) and pp (bottom)



ep: Higgs production in ep comes uniquely from either CC or NC

Pile-up in ep at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is 0.1@25ns
Clean bb final state, S/B ~ 1

e-h Cross Calibration $\rightarrow$ Precision

ep:

Clean, precise reconstruction and easy distinction of WWZ and WWH without pile-up ($< \sim 0.1$ events)

VBF: Small theoretical uncertainties!

pp: Higgs production in pp comes predominantly from $gg \rightarrow H$

VBF cross section about 200 fb (about as large as at the LHeC).

Pile-up in pp at $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is 150@25ns
S/B very small for bb

Precision needs accurate PDFs & α_S

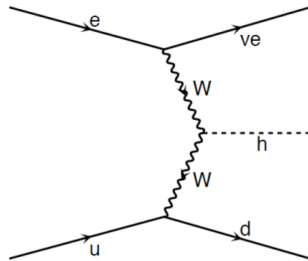
Light SM Higgs Production in ep

CC

LO SM Higgs Production

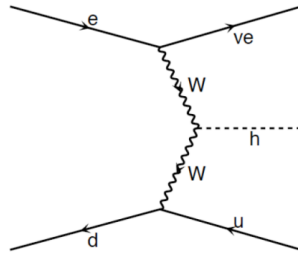
e-p (swap charges for e+p)

$e^- u^- \rightarrow \nu_e h d^-$



around 90-80%

$e^- d^- \rightarrow \nu_e h u^-$



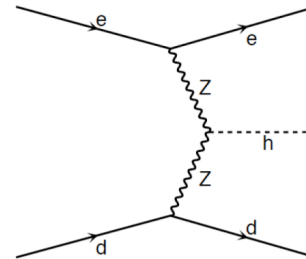
around 10-20%

NC

LO SM Higgs Production

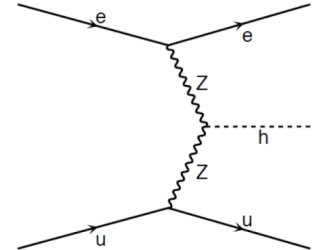
e-p (swap charges for e+p)

$e^- d^- \rightarrow e^- h d^-$



around 1/3

$e^- u^- \rightarrow e^- h u^-$



around 1/3

Light SM Higgs Production in ep

CC : LO SM Higgs Production

e-p (swap charges for e+p)

e- u -> ve h d

e- d -> ve h u

electrons →

E_T^{miss}

WWH

LHC protons →

Fwd jet

around 90-80%

around 10-20%

NC : LO SM Higgs Production

e-p (swap charges for e+p)

e- d -> e- h d

e- u -> e- h u

electrons →

FS electron

ZZH

LHC protons →

Fwd jet

around 1/3

around 1/3

$E_e = 60 \text{ GeV} : \sqrt{s} = 1.3 \text{ TeV}$

→ In ep, direction of quark (FS) is well defined.

$M_H = 125 \text{ GeV}$

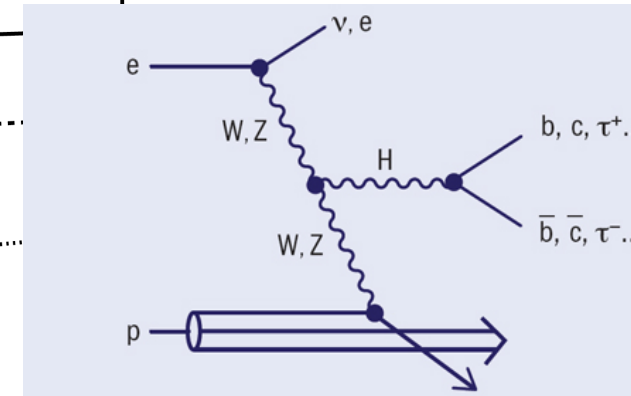
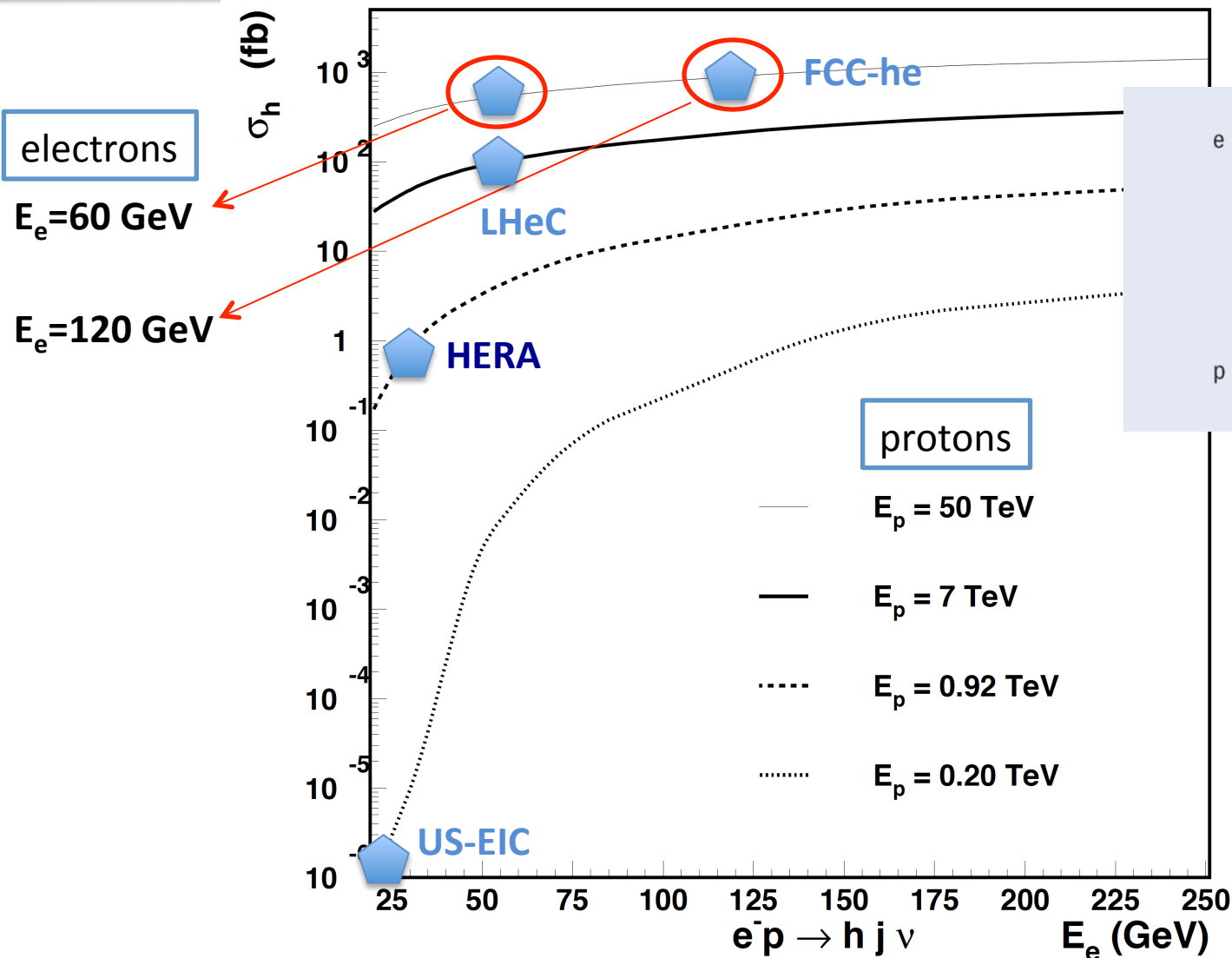
Electron beam energy	CC e-p	CC e+p	NC e-p
cross section [fb]	109	58	20
polarised cross section [fb] P=-80%	196	N.A.	25

- Scale dependencies of the LO calculations are in the range of 5-10%.
- NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.

[J. Blumlein, G.J. van Oldenborgh, R. Ruckl, Nucl.Phys.B395:35-59,1993] [B.Jager, arXiv: 1001.3789]

SM Higgs in ep

U. Klein,
@DIS2015



LHeC / FCC-he: Sizeable charged current (CC) DIS unpolarised ep cross sections

Analysis Framework & New Developments

Event generation

- SM / BSM Higgs production
 - CC & NC background
- by MadGraph5/MadEvent



- Fragmentation
- Hadronization

by PYTHIA (modified for ep)



Fast detector simulation

by PGS (LHC-style detector)



$H \rightarrow b\bar{b}$ (any decay) selection

- Calculate cross section with tree-level Feynman diagrams using pT of scattered quark as scale ($\sqrt{s}$) for ep processes like single t, Z, W, H

→ Standard HERA tools can NOT to be used !

- **NEW:** full update for Madgraph5 (CDR MG4)
- **Higgs mass 125 GeV as default for sm and sm-full** (for Hcc) → **BR corrected to 'best' HDECAY**
- Fragmentation & hadronisation uses ep-**customised Pythia**.
- **Interface to Delphes 'detector' → displaced vertices and signed impact parameter distribution analysis for Hcc!**

→ powerful method to optimise detector tuning and S/N for various Higgs decays

Valid for ep only. Any other model can be easily tested → non-SM higgs, SUSY etc.

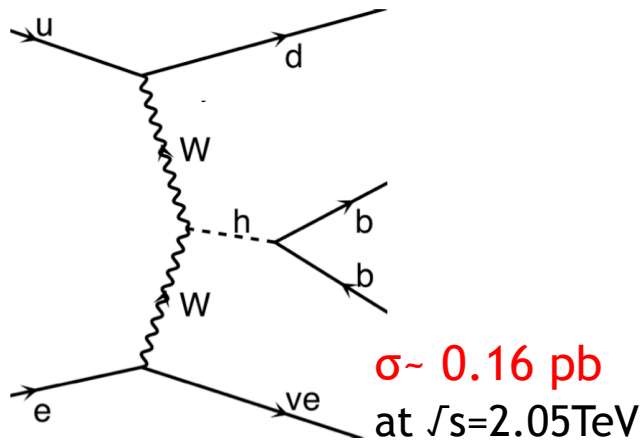
[eA needs modelling of nuclear fragmentation]

Examples: Generated Samples

Graphs by MadGraph

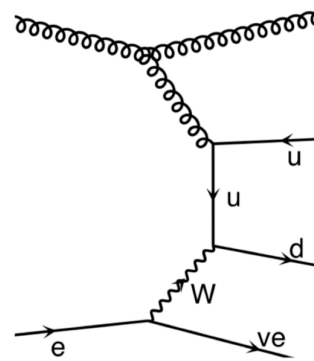
Signal

CC: $H \rightarrow \bar{b}b$ (BR ~ 0.7 at $M_H=120\text{GeV}$)

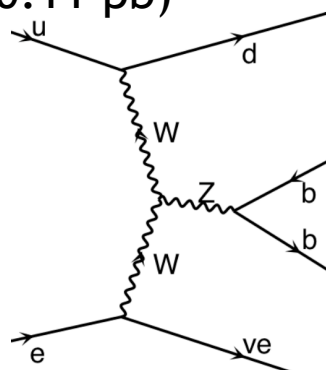


Background (examples)

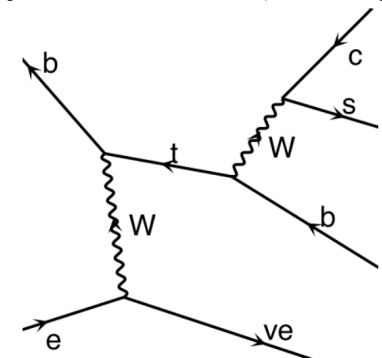
CC: 3 jets ($\sim 57 \text{ pb}$)



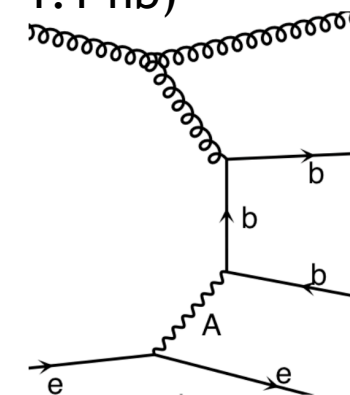
CC: Z production ($\sim 0.11 \text{ pb}$)



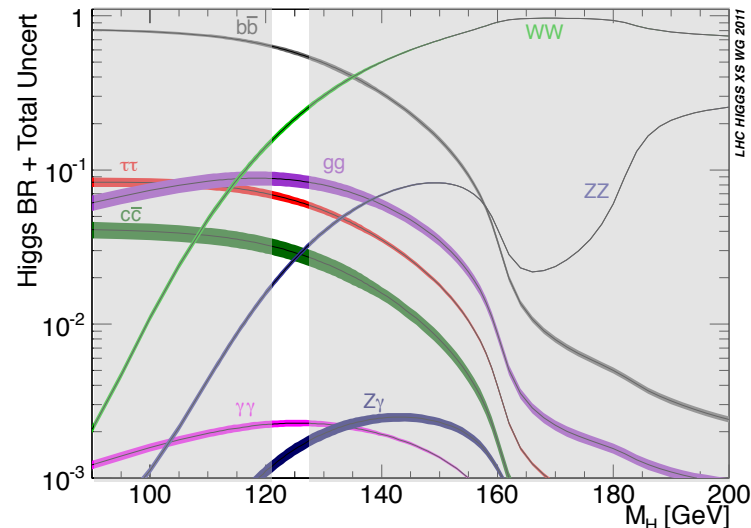
CC: single top production ($\sim 4.1 \text{ pb}$)



NC: b pair production ($\sim 1.1 \text{ nb}$)



NOTE: Background sample cross sections are after pre-selection in generator and for $E_e=150 \text{ GeV}$



CDR : Selection of $H \rightarrow b\bar{b}$

[before Higgs discovery $M_H = 120$ GeV, $E_p = 7$ TeV, $E_e = 150$ GeV]

■ NC DIS rejection

- Exclude electron-tagged events
- $E_{T,miss} > 20$ GeV
- $N_{jet} (p_T > 20 \text{ GeV}) \geq 3$
- $E_{T,total} > 100$ GeV
- $y_{JB} < 0.9$, $Q^2_{JB} > 400 \text{ GeV}^2$

■ b-tag requirement

- $N_{b-jet} (p_T > 20 \text{ GeV}) \geq 2$

■ Higgs invariant mass

- $90 < M_H < 120$ GeV

$\Rightarrow$ 44% of remaining BG is single-top...

■ Single top rejection

- $M_{jjj,top} > 250$ GeV
- $M_{jj,W} > 130$ GeV

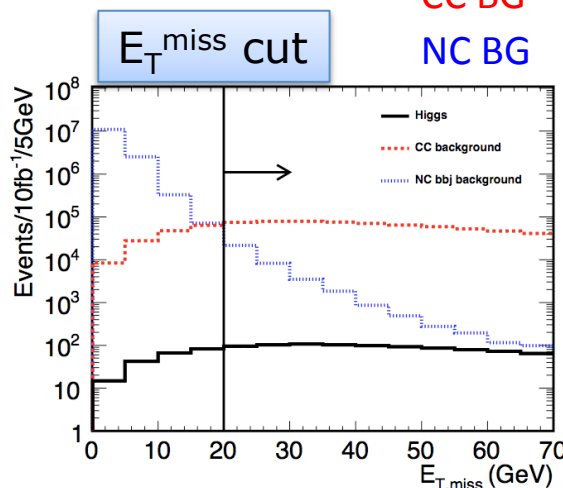
**CDR: A Large Hadron
Electron Collider at CERN**

J. Phys. G: Nucl. Part. Phys.
39 (2012) 075001

$H \rightarrow b\bar{b}$

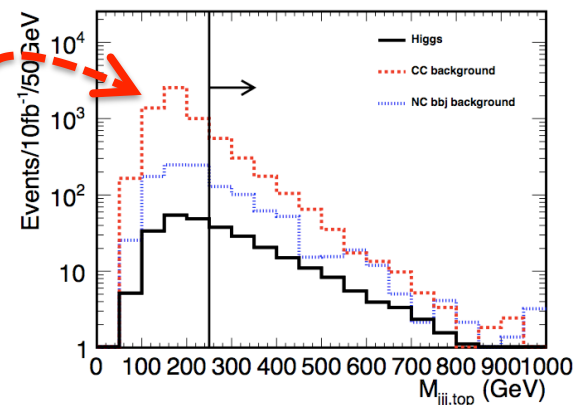
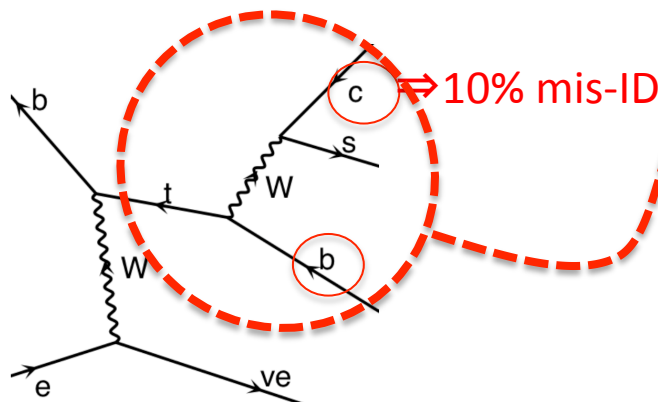
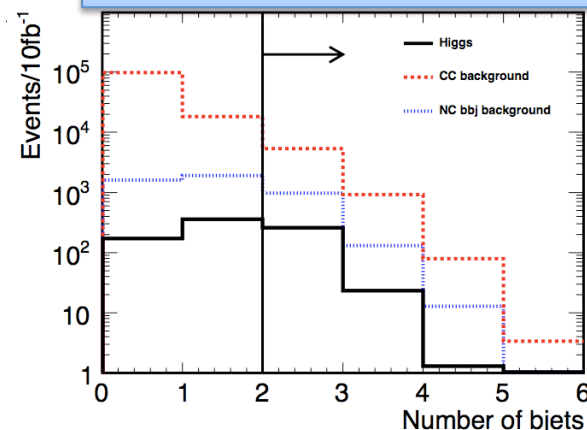
CC BG

NC BG



b-tag requirement

Flat efficiency for $|\eta| < 3$
of 60% (c:10%, lq,g:1%)



CDR : $H \rightarrow b\bar{b}$ Results

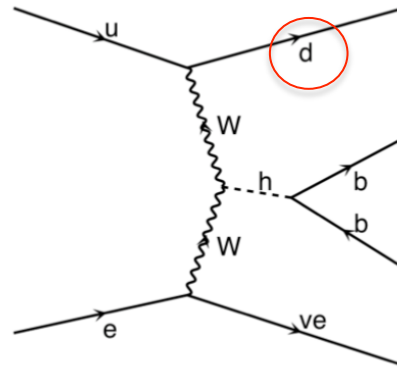
[before Higgs discovery $M_H=120$ GeV, $E_p=7$ TeV, $E_e=150$ GeV]

- Forward jet tagging
 - $\eta_{\text{jet}} > 2$ (lowest η jet excluding b-tagged jets)

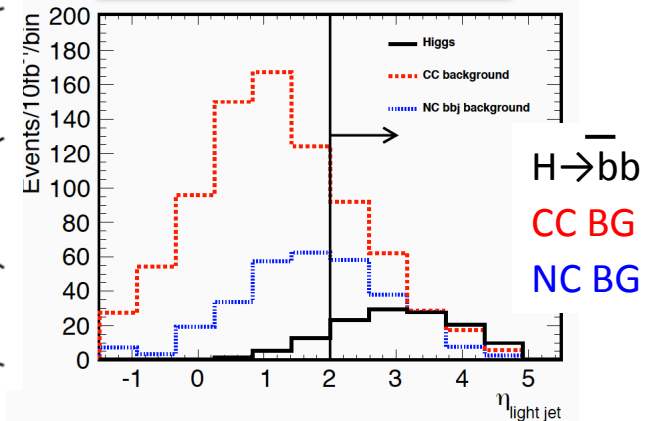
Coordinate:

Fwd: +z-axis along proton beam

$H \rightarrow b\bar{b}$ signal

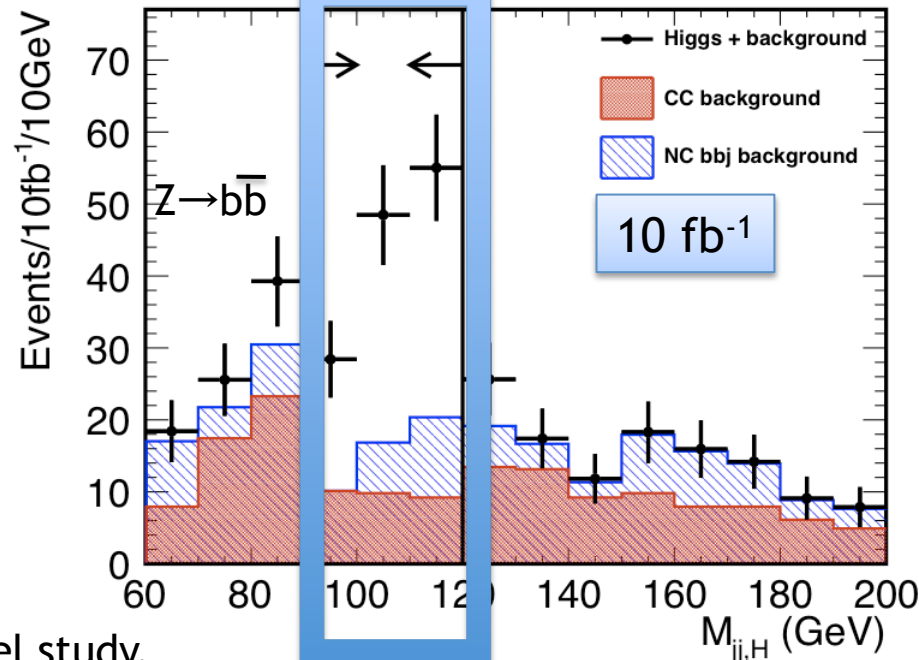


Forward jet η tag



- Higgs invariant mass after all selection

	$E_e = 150$ GeV (10 fb ⁻¹ , P=0)
$H \rightarrow b\bar{b}$ signal	84.6
S/N	1.79 (4.7*)
S/√N	12.3



Clear signal
obtained with
just cut based
analysis already!

*parton-level study.

Measure CP Properties of Higgs

[CDR before Higgs discovery $M_H=120$ GeV, $E_p=7$ TeV]

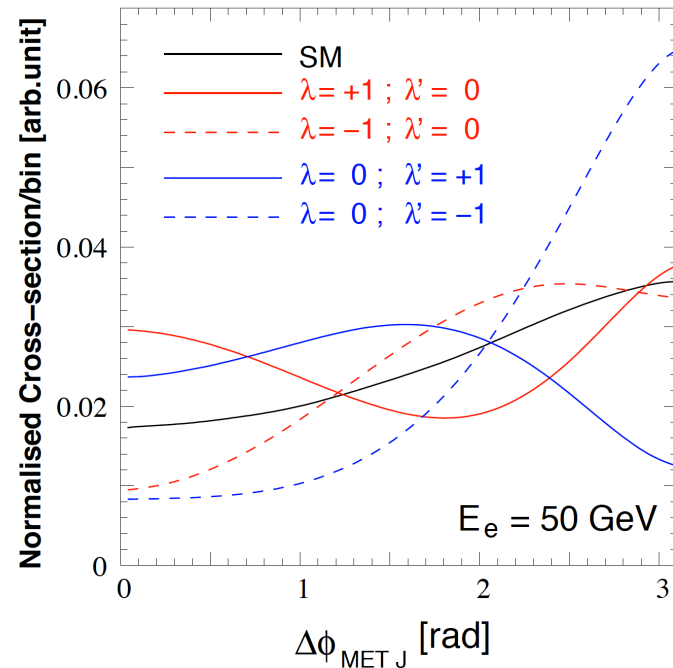
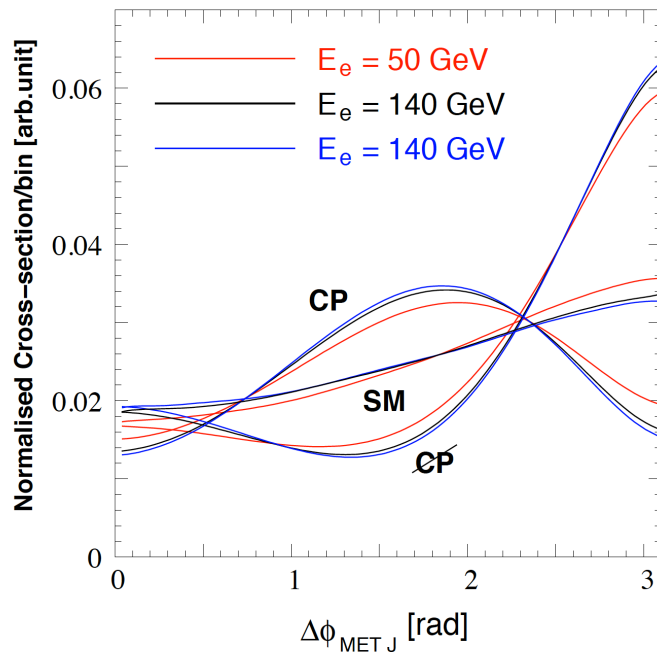
- Higgs couplings with a pair of gauge bosons (WW/ZZ) and a pair of heavy fermions (t/b/ τ) are largest.
- Higgs@LHeC allows uniquely to access HWW vertex $\rightarrow$ explore the CP properties of HVV couplings: BSM will modify CP-even (λ) and CP-odd (λ') states differently

$$\Gamma_{(SM)}^{\mu\nu}(p, q) = g M_W g^{\mu\nu}$$



$$\Gamma_{\mu\nu}^{(BSM)}(p, q) = \frac{-g}{M_W} [\lambda (p \cdot q g_{\mu\nu} - p_\nu q_\mu) + i \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma]$$

- Study **shape changes** in DIS normalised CC Higgs $\rightarrow$ bb cross section versus the azimuthal angle, $\Delta\phi_{MET,J}$, between $E_{T,miss}$ and forward jet.



**CDR initial study
of HWW vertex:**

**CP couplings
probed to**

$\lambda \sim 0.05$

$\lambda' \sim 0.2$

based on 50 fb^{-1}

In ep, full
 $\Delta\phi$ range needs to
be explored still.

ep Higgs “Facility” @ 1 ab⁻¹

Post-CDR: for first time a realistic option of an 1 ab⁻¹ ep collider (stronger e-source, stronger focussing magnets) and **excellent performance of LHC** (higher brightness of proton beam)

$\sqrt{s} = 1.3 \text{ TeV}$ → need of different models : cc: ‘sm-full’ gg, $\gamma\gamma$: ‘heft’	LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
	Polarisation		-0.8	-0.8	0
	Luminosity [ab ⁻¹]		1	1	0.1
	Cross Section [fb]		196	25	58
	Decay	BrFraction	$N_{CC}^H e^-p$	$N_{NC}^H e^-p$	$N_{CC}^H e^+p$
	$H \rightarrow b\bar{b}$	0.577	113 100	13 900	3 350
	$H \rightarrow c\bar{c}$	0.029	5 700	700	170
	$H \rightarrow \tau^+\tau^-$	0.063	12 350	1 600	370
	$H \rightarrow \mu\mu$	0.00022	50	5	—
	$H \rightarrow 4l$	0.00013	30	3	—
	$H \rightarrow 2l2\nu$	0.0106	2 080	250	60
	$H \rightarrow gg$	0.086	16 850	2 050	500
	$H \rightarrow WW$	0.215	42 100	5 150	1 250
	$H \rightarrow ZZ$	0.0264	5 200	600	150
	$H \rightarrow \gamma\gamma$	0.00228	450	60	15
	$H \rightarrow Z\gamma$	0.00154	300	40	10

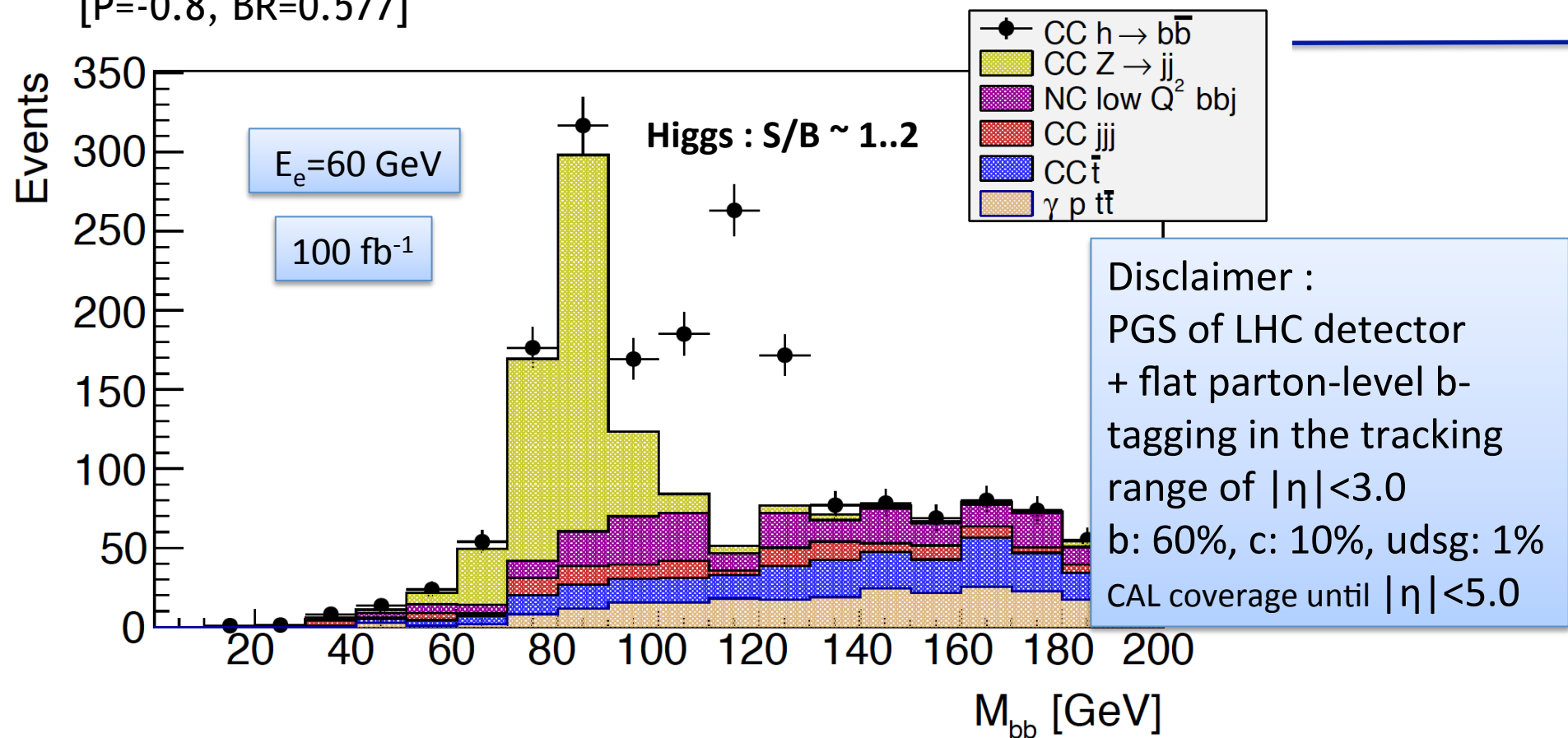
Ultimate polarised e-beam of 60 GeV and LHC 7 TeV p-beams, 10 years of operation

→ Decay to bb is dominating HFL decay modes :

Higgs decay to cc is factor 20 less likely than Hbb
times the ratio of detection efficiencies-squared !

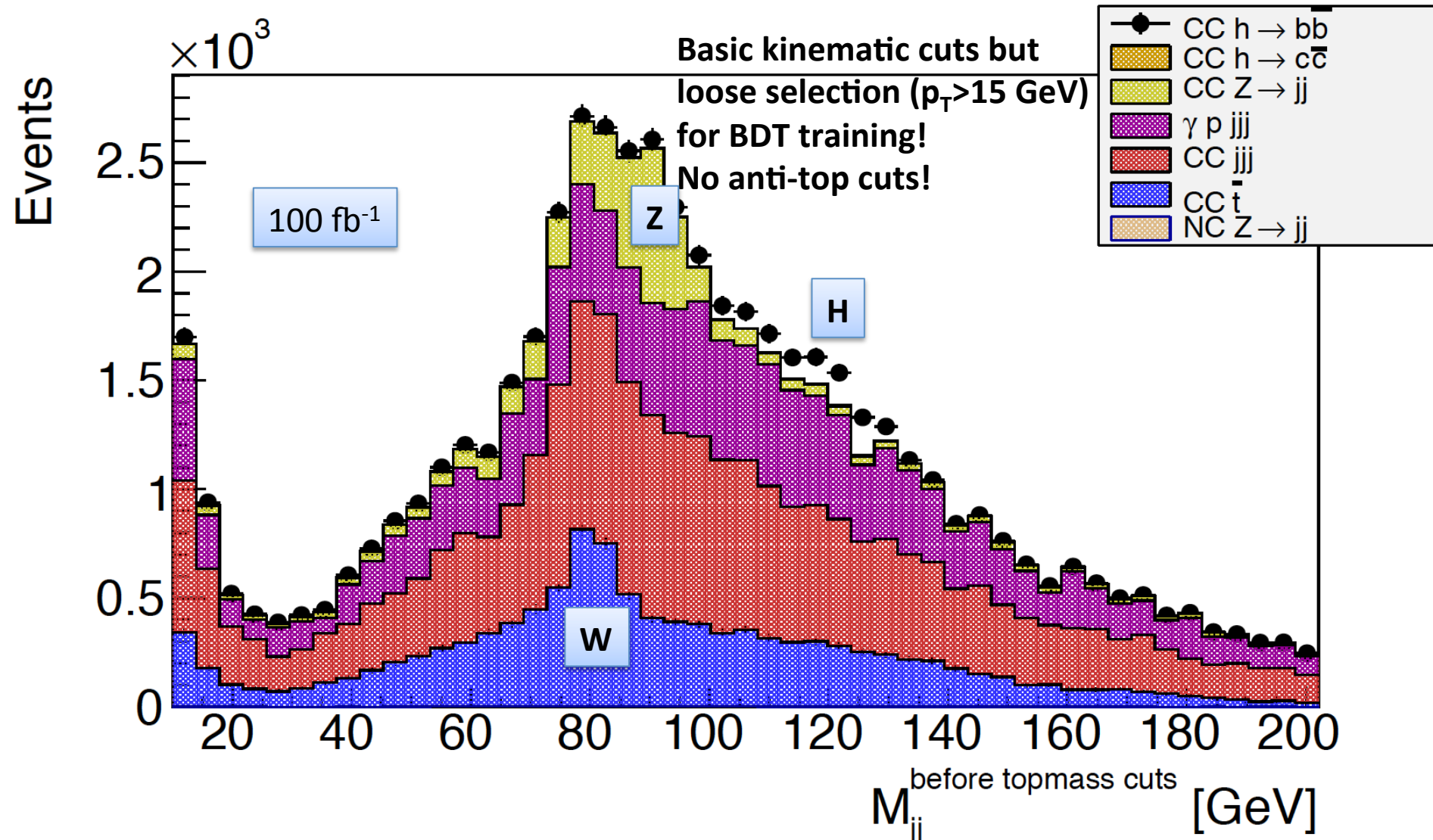
LHeC @ ICHEP14 : $H \rightarrow b\bar{b}$ Updated

[$P=-0.8$, $BR=0.577$]



- Master thesis Ellis Kay, University of Liverpool 2014, together with U. Klein
- Dedicated background sample production including a first emulation of PHP background using either very low Q NC events or a monochromatic Photon beam of $0.8 \cdot E_e$
- **NEW : Using MG 2.1.1 Photoproduction (PHP) background is now produced based on the Weizsacker-Williams approximation**
- **NEW : use a real experimental method for HFL tagging based on jet lifetime probabilities**

Dijet Mass : two lowest eta Jets - *HFL untagged*

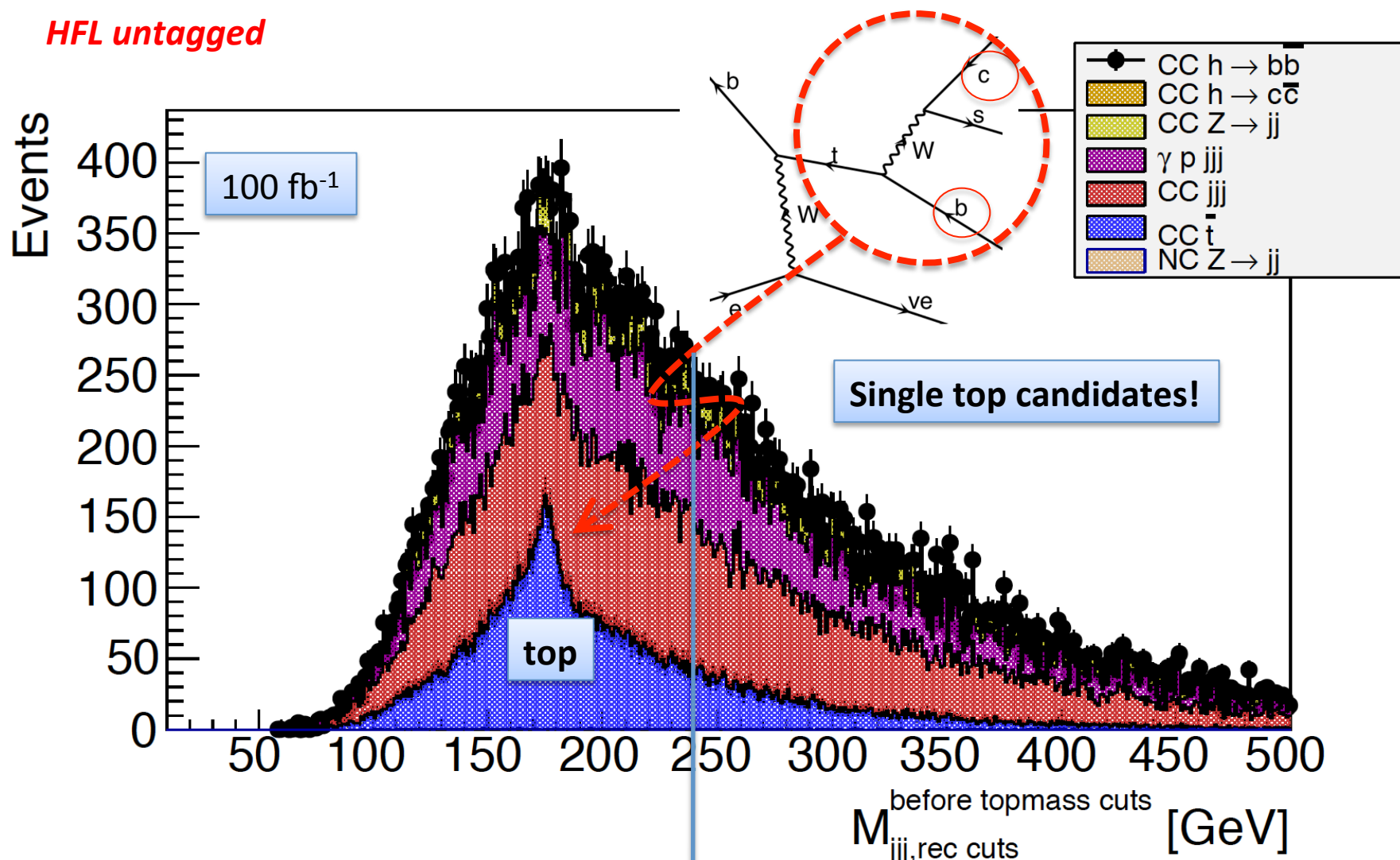


Note : Photoproduction background is assumed to be untagged ('worst' scenario)!

→ addition of small angle electron taggers will reduce the PHP ~1-2%

Top: Mass of three highest p_T Jets

HFL untagged



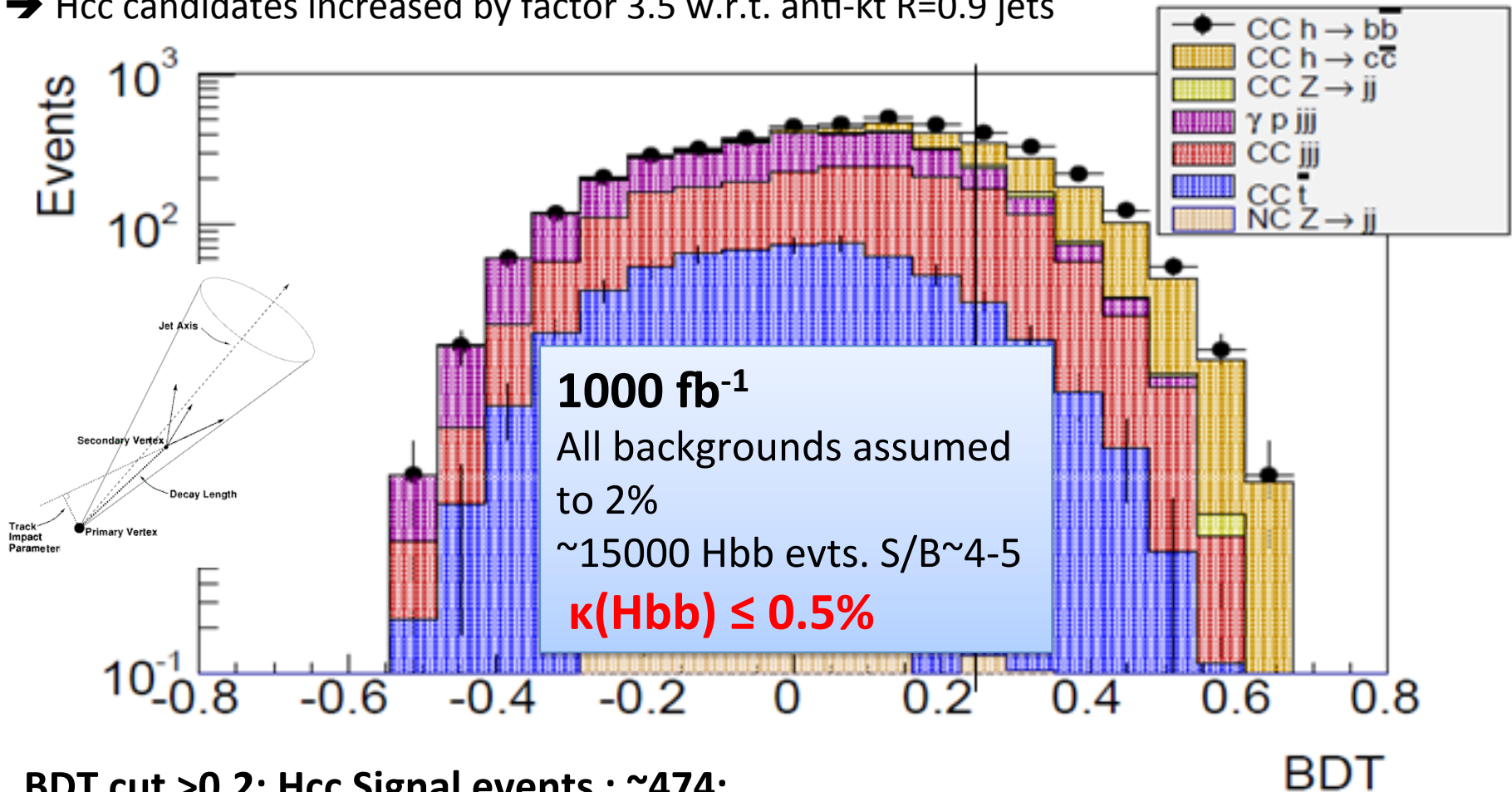
→ usual cut to accept Higgs candidates
BUT on cost of signal efficiency

BDT Result for Higgs $\rightarrow$ cc

Uta Klein &
Daniel Hampson
May 2016

NEW : Using R = 0.5 anti-kt jets and ATLAS IBL vertex resolution (5 μ m)

$\rightarrow$ Hcc candidates increased by factor 3.5 w.r.t. anti-kt R=0.9 jets



BDT cut >0.2: Hcc Signal events : ~474;

S/ $\sqrt{S+B}$ =12.8 $\rightarrow$ **$\kappa(\text{Hcc}) = 4\%$** for
1000 fb⁻¹

**Clear potential to access the Higgs to
charm decay channel at the LHeC.**

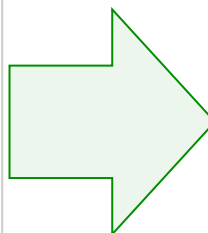
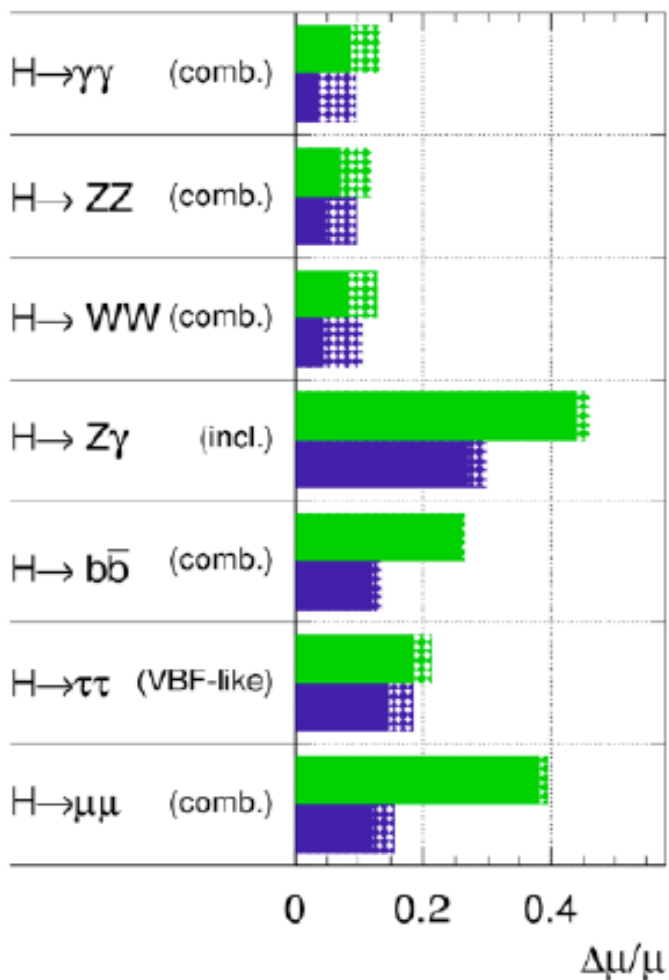
The LHC as ONE Higgs Facility

pp: PDF+ α_s errors
<0.5% with LHeC
input!

HL-LHC

ATLAS Simulation Preliminary

($\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$)

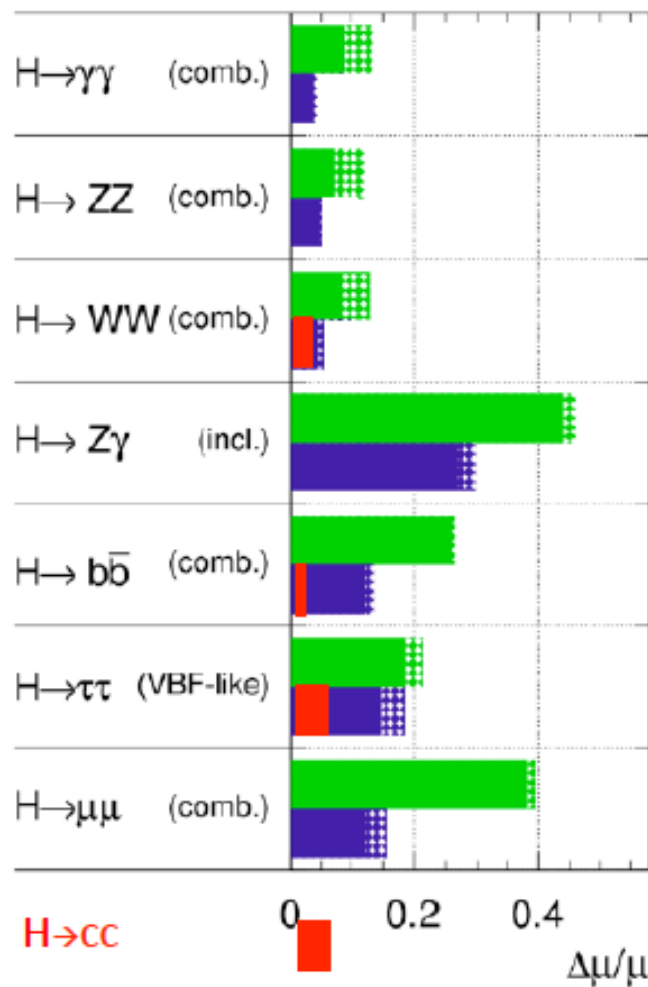


bb and cc so far only worked on !

HL-LHC + LHeC

ATLAS Simulation Preliminary

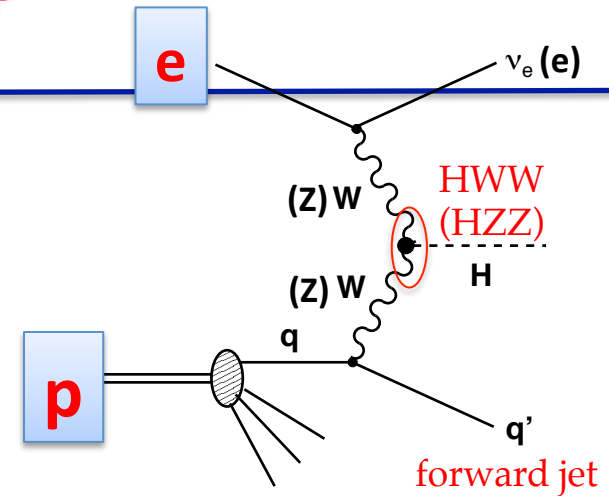
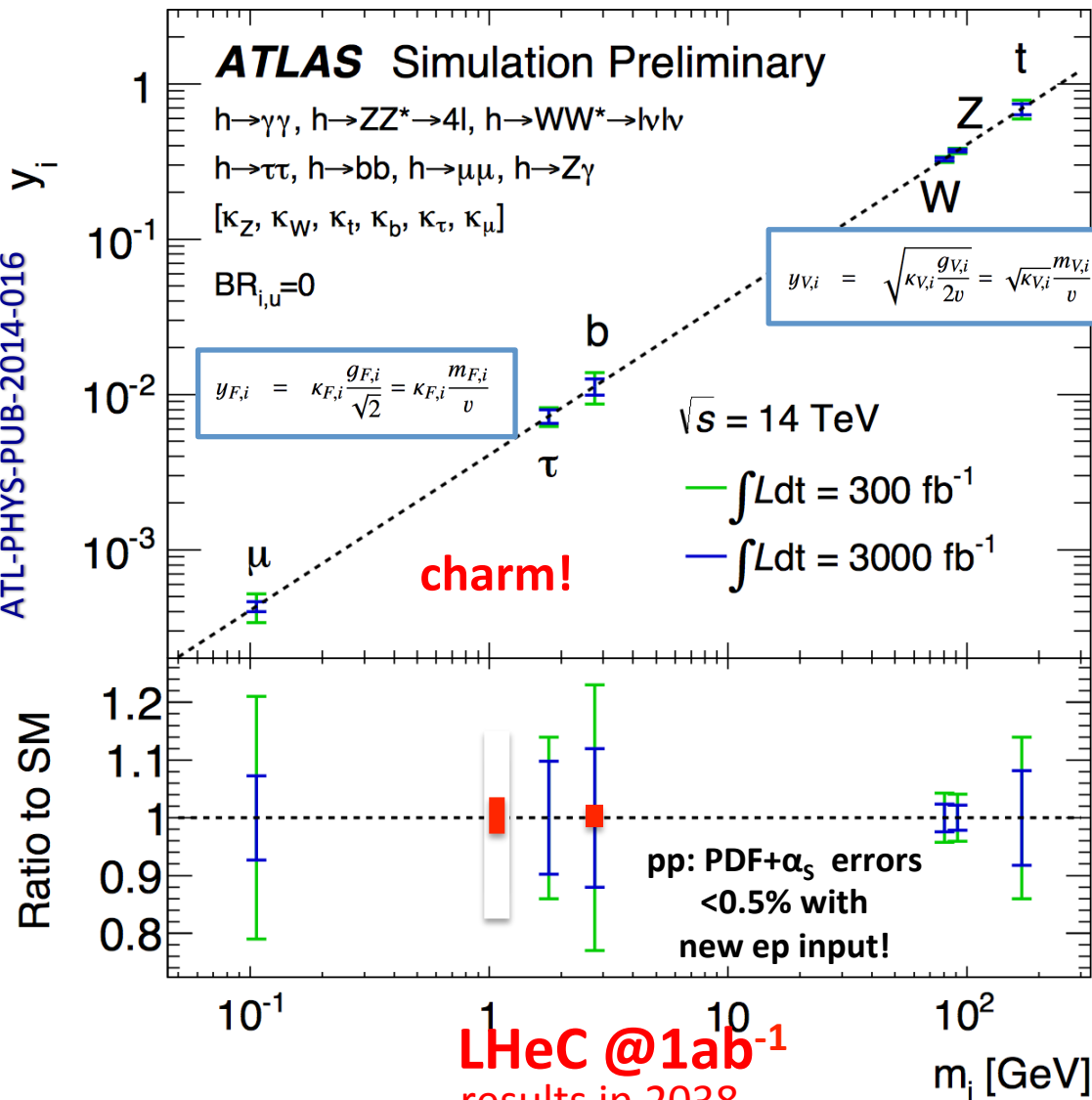
($\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$)



Higgs Couplings at pp + ep

running concurrently

ATL-PHYS-PUB-2014-016



$E_p = 7 \text{ TeV} \quad 14 \text{ TeV} \quad 50 \text{ TeV}$

c.m.s. [TeV]	LHeC 1.3	DLeHC 1.8	FCC-eh 3.5
$\kappa(H \rightarrow bb)$ BR=57%	0.5%	0.3%	0.2%
$\kappa(H \rightarrow cc)$ BR=3%	4%	2.8%	1.8%

→ to be improved further
 → more couplings to come
 → turn pp into ONE powerful
 Higgs facility by adding an
 electron beam

Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

Y.-L. Tang et al.,
arXiv: 1508.01095

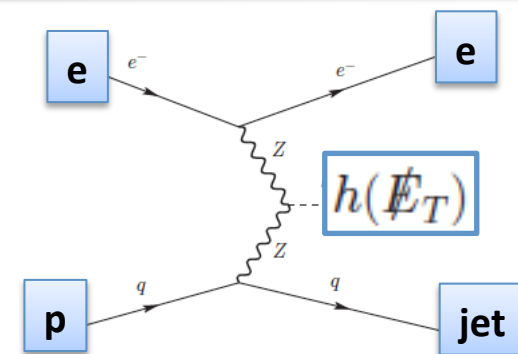
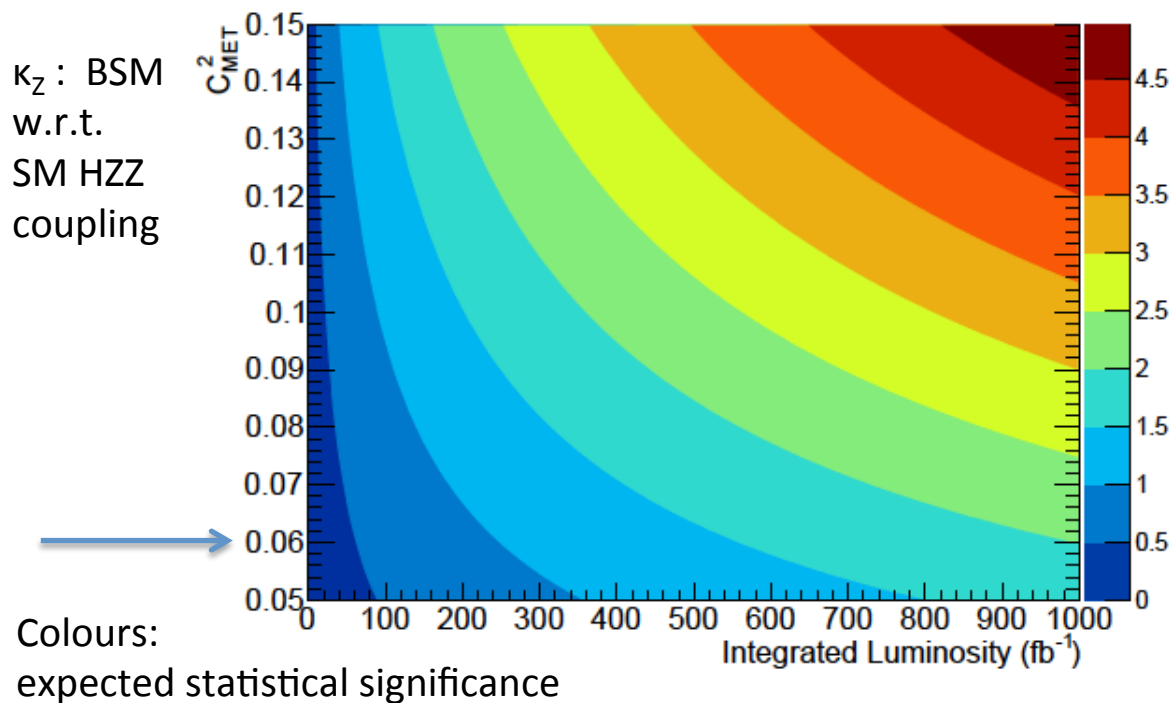
HL-LHC @ 3 ab⁻¹ [arXiv:1411. 7699]

$\text{Br}(h \rightarrow \cancel{E}_T) < 3.5\% \text{ @95\% C.L.}$, MVA based

For **LHeC**, assume : 1ab⁻¹, P_e=-0.9, cut based

$\text{Br}(h \rightarrow \cancel{E}_T) < 6\% \text{ @ 95 \% C.L.}$

$$C_{\text{MET}}^2 = \kappa_Z^2 \times \text{Br}(h \rightarrow \cancel{E}_T)$$



- ➔ NEW studies performed on Delphes detector-level using our Madevent framework
- ➔ potential much enhanced for FCC-eh @ 3.5 TeV and HE-LHC-eh @ 1.8 TeV

Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Values given in case of 2σ

Delphes detectors	LHeC	DLHeC	FCC-eh
	1.3 TeV	1.8 TeV	3.5 TeV
LHC-style	4.7%	3.2%	1.9%
First 'ep-style'	5.7%		2.6%

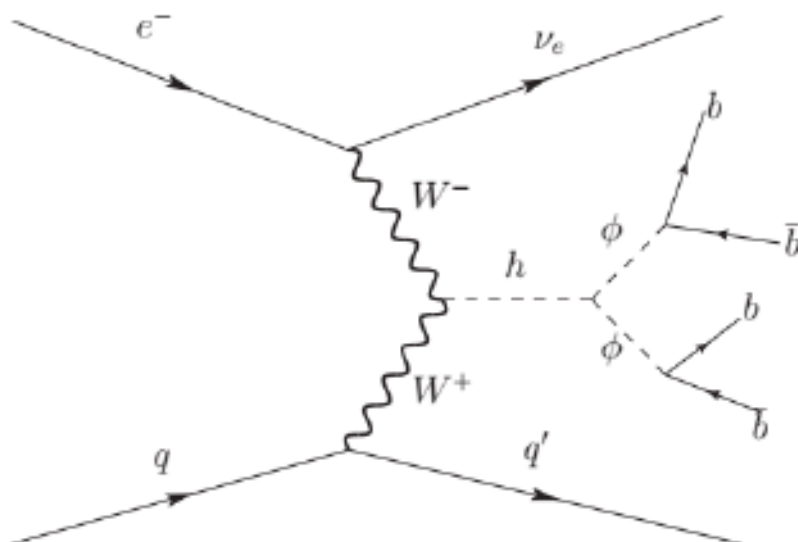
- ✓ **Results look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 2%.**
- ✓ For 2 different detector options we get similar results.
- Certainly : we will use this channel to further optimize analysis strategies (used methods and requirements, e.g. size of jets and electron reconstructions) and to modify our ep-detector
- employ synergies within FCC study group → detector has certainly a significant impact on results

Exotic Higgs Decays

$$h \rightarrow \phi\phi \rightarrow 4b$$

ϕ : a spin-0 particle from new physics.

$$eq \rightarrow \nu_e h q' \rightarrow \nu_e \phi\phi q' \rightarrow \nu_e b\bar{b}b\bar{b}q'$$



$$\mathcal{L}_{eff} = \lambda_h v h \phi^2 + \lambda_b \phi \bar{b} b + \mathcal{L}_{\phi \text{ decay, other}}$$

S. Liu, Y. L. Tang, C. Zhang, S. Zhu, 1608.08458

- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC $t/h/W/Z$ +jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is done at parton level.

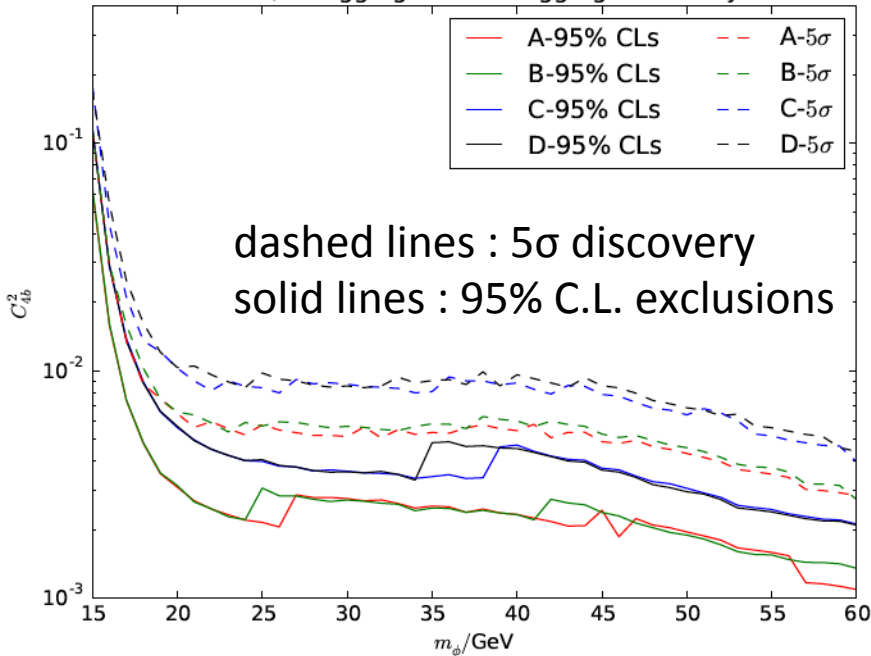
$$C_{4b}^2 = \kappa_V^2 \times \text{Br}(h \rightarrow \phi\phi) \times \text{Br}^2(\phi \rightarrow b\bar{b})$$

ϕ mass range targeted in this study: [20,60]GeV, scanned in 1 GeV step.

Btag
scenarios

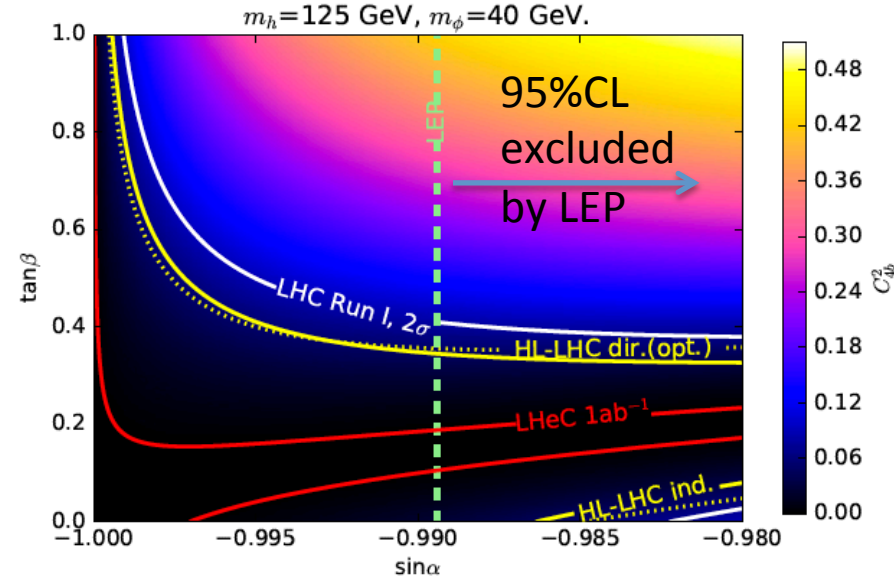
- (A) $\epsilon_b = 70\%$, $\epsilon_c = 10\%$, $\epsilon_{g,u,d,s} = 1\%$
- (B) $\epsilon_b = 70\%$, $\epsilon_c = 20\%$, $\epsilon_{g,u,d,s} = 1\%$
- (C) $\epsilon_b = 60\%$, $\epsilon_c = 10\%$, $\epsilon_{g,u,d,s} = 1\%$
- (D) $\epsilon_b = 60\%$, $\epsilon_c = 20\%$, $\epsilon_{g,u,d,s} = 1\%$

1ab⁻¹, B-tagging and mistagging rates vary.



95% C.L. for m_ϕ of 20, 40, 60 GeV for
 $C^2_{4b} = \kappa_V^2 \times \text{Br}(h \rightarrow \phi\phi) \times \text{Br}^2(\phi \rightarrow b\bar{b})$
 is 0.3%, 0.2% and 0.1%

Sensitivity comparison in Higgs Singlet Model



$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h' + x}{\sqrt{2}} \quad (12)$$

Here $v = 246 \text{ GeV}$ ensures the correct mass generation for W, Z bosons and SM fermions. The gauge eigenstates $\tilde{h}, h'$ can be related to mass eigenstates ϕ, h via an orthogonal rotation

$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix} \quad (13)$$

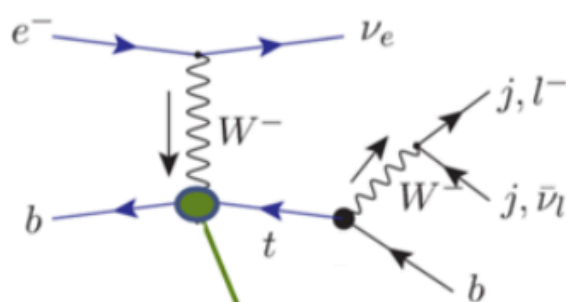
Now it is convenient to parameterize the model in terms of five more physical quantities: (m_ϕ, m_h are masses of ϕ and h respectively)

$$m_\phi, m_h, \alpha, v, \tan \beta \equiv \frac{v}{x} \quad (14)$$

MEASUREMENT OF V_{tb}

- the results can also be applied conservatively to the FCC-ep.

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688 [hep-ph]



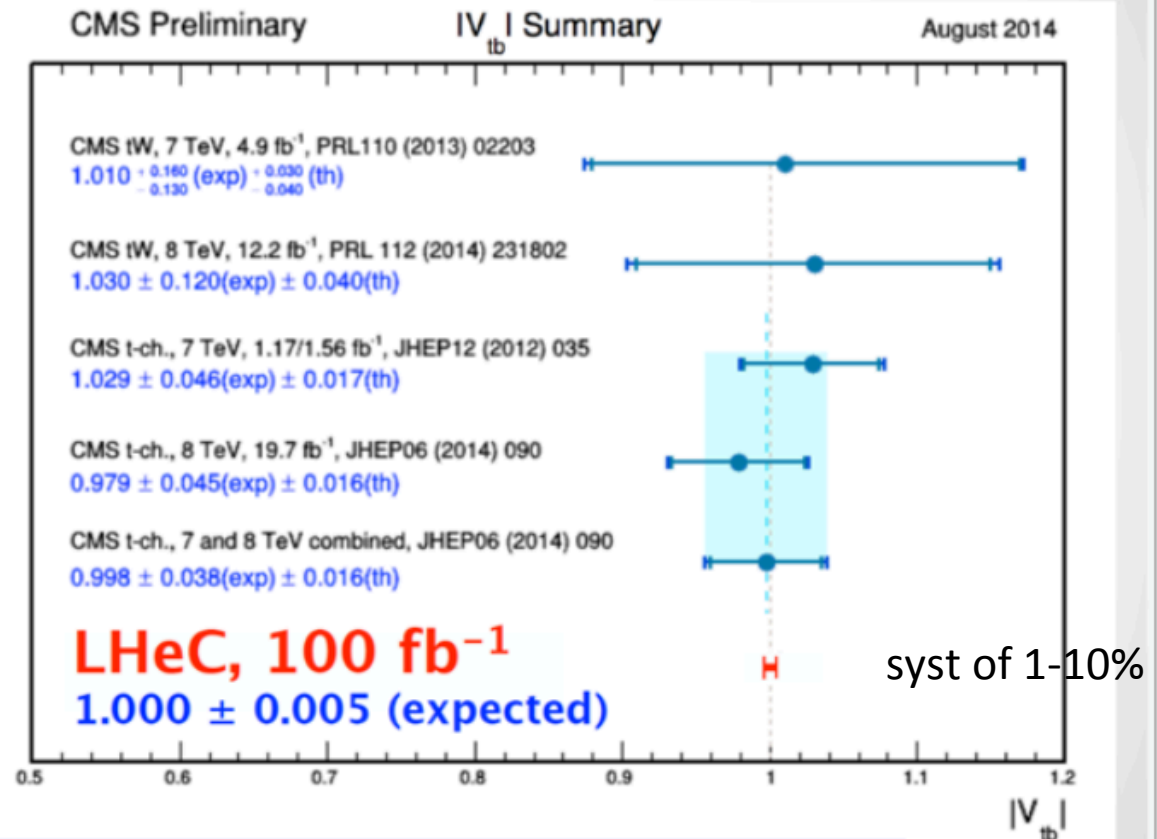
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

e beam: 60 GeV

$\mathcal{L}_{int} = 100 \text{ fb}^{-1}$ and simple cuts:

HAD: $N_t = 22000$, $S/B=1.2$

LEP: $N_t = 11000$, $S/B=11$



LHeC: very high precision measurement

current LHC+Tevatron average: $|V_{tb}| = 1.009 \pm 0.031$

Organisation*)

International Advisory Committee

“..Direction for ep/A both at LHC+FCC”

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

IAC being renewed by new DG
We lost Guido Altarelli.

*)August 2016

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) are members of the
FCC coordination team

OB+MK: FCC-eh responsables
MDO: physics co-convenor

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

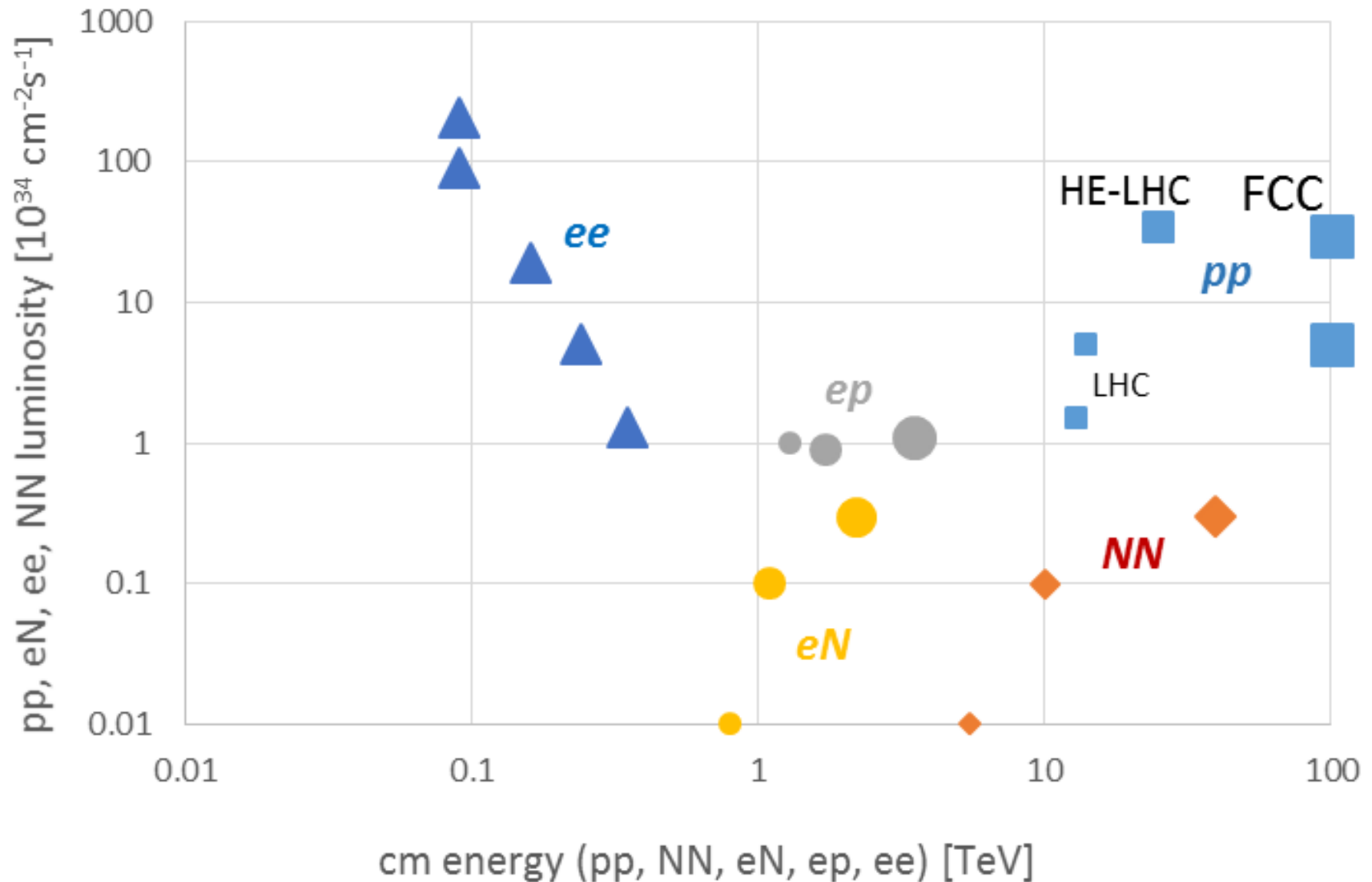
Small x

Paul Newman,
Anna Stasto

Detector

Alessandro Polini
Peter Kostka

luminosity vs energy - most options



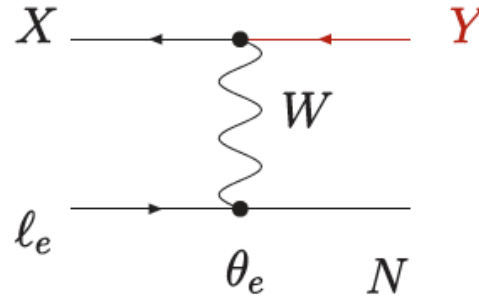
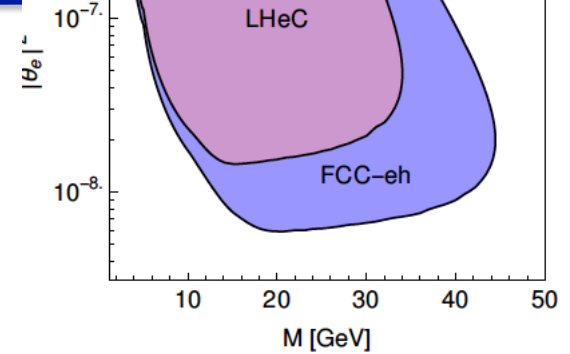
Sterile Neutrino Searches

Oliver Fischer

$$\mathcal{L}_N = - \underbrace{(Y_\nu)_{i\alpha} \bar{\nu}_R^i \tilde{\phi}^\dagger}_{\nu \text{ Yukawa matrix}} L^\alpha - \frac{1}{2} \underbrace{\bar{\nu}_R^i M_{ij} (\nu_R^j)^c}_{\text{sterile } \nu \text{ mass matrix}} + \text{H.c.}$$

ν Yukawa matrix

sterile ν mass matrix



Non-unitarity parameters: $\varepsilon_{\alpha\alpha} = -\theta_\alpha^* \theta_\alpha$

Three Generations of Matter (Fermions) spin 1/2

	I		II		III	
mass	2.4 MeV		1.27 GeV		173.2 GeV	
charge	2/3		2/3		2/3	
name	Left up	Right up	Left charm	Right charm	Left top	Right top
Quarks						
mass	4.8 MeV		104 MeV		4.2 GeV	
charge	-1/3		-1/3		-1/3	
name	Left down	Right down	Left strange	Right strange	Left bottom	Right bottom
Leptons						
mass	0.511 MeV		105.7 MeV		1.777 GeV	
charge	-1		-1		-1	
name	Left electron	Right electron	Left muon	Right muon	Left tau	Right tau

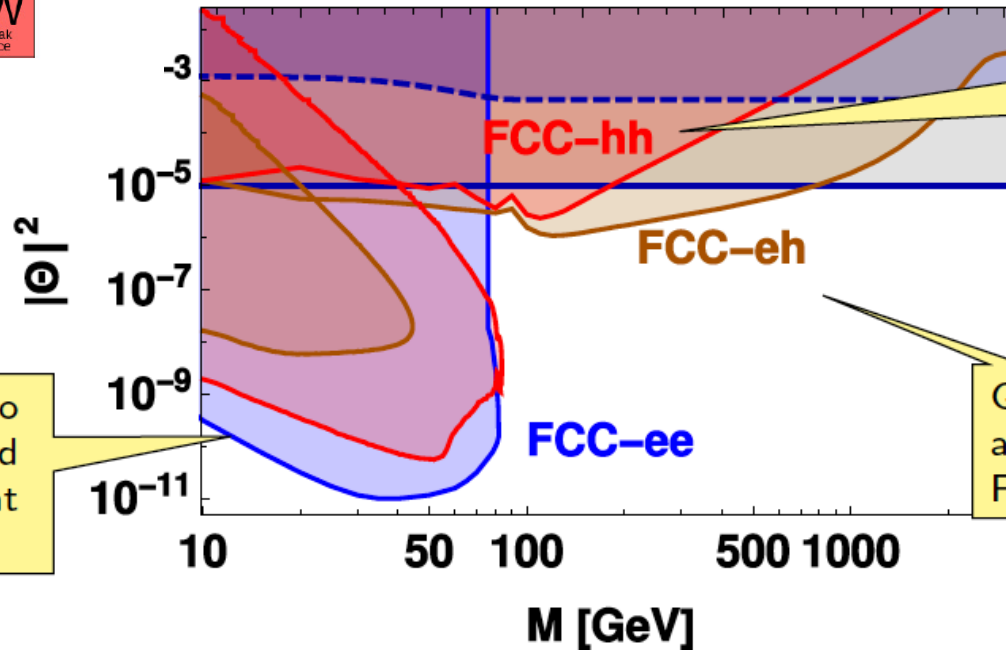
Bosons (Forces) spin 1

0	g
0	gluon
0	γ
0	photon
91.2 GeV	Z^0
0	weak force
126 GeV	H
0	Higgs boson
80.4 GeV	W
± 1	weak force

spin 0

126 GeV	H
0	Higgs boson

Shaposhnikov et al.



Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

FCC-hh able to test all flavour combinations.

Good sensitivity reach from FCC-hh & FCC-eh.

... to take home

- We have a fantastic machine at work – the LHC – let's use it as best as we can.
- We have the big and realistic opportunity to **upgrade** the HL-LHC complex at CERN **with an electron beam** and to found **ONE** powerful '**Higgs facility**' **challenging the QCD and electroweak sector of the SM to a state-of-the art level with an extremely rich physics programme**– all this at moderate cost and **within the next 10 to 25 years**.
- There is plenty of opportunities to contribute, also in the context of exciting new theoretical developments for FCC physics and accelerator developments → LHeC design (1000* HERA Luminosity) rests on high current, multi-turn energy recovery e Linac. ERL test facility: CDR to be published soon. TDR for demonstrator ("PERLE at Orsay"), kickoff collaboration meeting, February 17 in LAL Orsay.
- 'Future of DIS' session at DIS 2017 conference in Birmingham, 3.-7.4.17 <http://www.ep.ph.bham.ac.uk/DIS2017/>
- LHeC/FCC-eh Reports (Physics, Detector, Accelerator) by end of 2018

ep/eA International Advisory Committee

Max Klein ICFA Beijing 10/2014

Guido Altarelli (Rome)⁺
Sergio Bertolucci (CERN)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
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Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – **Chair**
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

IAC Composition June 2014, plus
Oliver Brüning Max Klein ex officio

The IAC was invited in 12/2013 by the CERN DG with the following

Mandate 2014-2018 renewed by new CERN management

Advice to the LHeC Coordination Group and the CERN directorate by following the **development of options of an ep/eA collider at the LHC and at FCC**, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.



Additional Sources & Thanks to

The LHeC/FCC-eh study group, <http://cern.ch/lhec>.

“On the Relation of the LHeC and the LHC” [arXiv:1211.5102]

Poetic 2016 Workshop, 14.-18.11.2016, Temple University (USA)

https://phys.cst.temple.edu/poetic-cteq-2016/scientific_program.html

1st FCC Physics Workshop, 16.1.-20.1.2017, CERN

<https://indico.cern.ch/event/550509/>

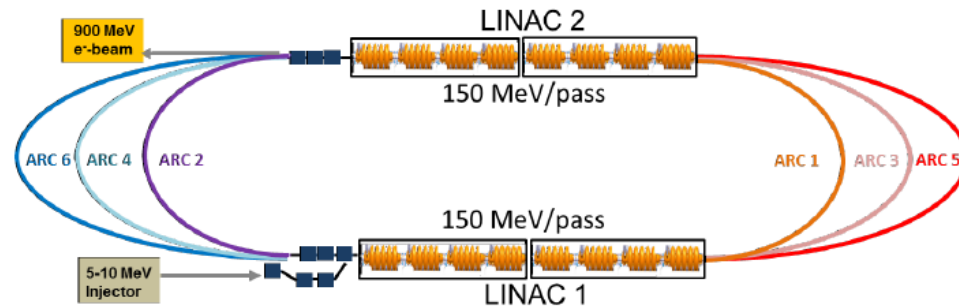
→ see M. Benedikt's and F. Zimmermann's and further eh talks given at this workshop

Special thanks to my colleagues in the LHeC/FCC-eh Higgs group, the project leader Max Klein and our detector expert Peter Kostka.

Additional material



Powerful energy
recovery linac experiments



Conceptual Design Report

Draft 1.3 November 10th, 2016

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and Astec
Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab
Newport News, BINP Novosibirsk, IPNO and LAL Orsay

Physics

ep
 $R(p)$, $\sin^2\theta$
Dark photons
 γp
 $1000 \times L(\text{ELI})$
 $E_\gamma > 30 \text{ keV}$
→ Unique
photo-nuclear
Physics

Technology

High $I_e \sim 10 \text{ mA}$
Multiturn ERL
SC RF
Cryomodules
Operation

Testfacility 1st
Userfacility 2nd

CDR of ERL
demonstrator,
and test facility
with physics
applications
and technology
goals, soon out

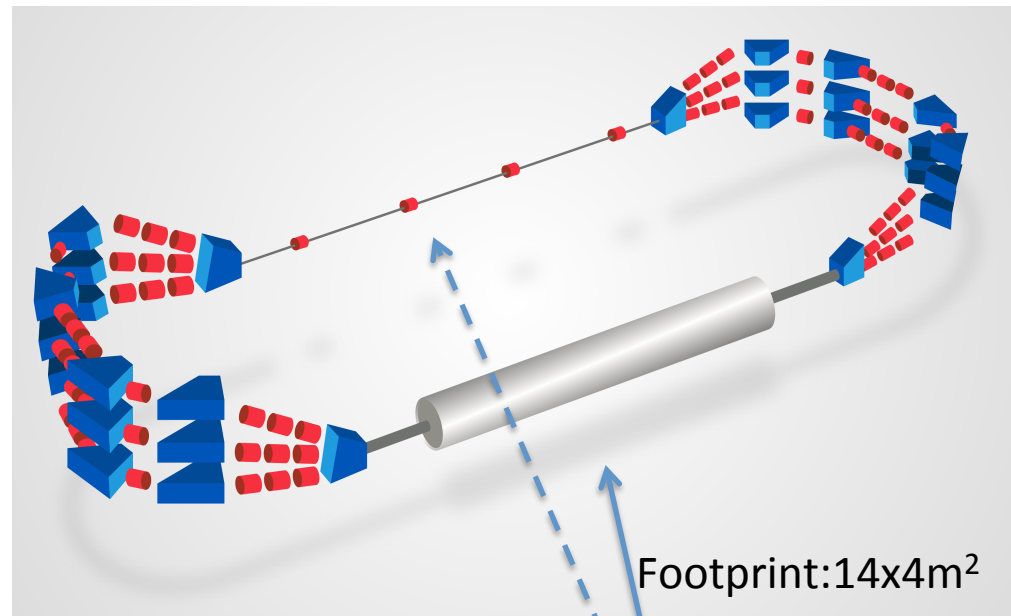
Cf also
ICFA beam
Newsletter 68/2016

ERL Testfacility

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

Test and development of 802MHz
SCRF technology

$E_e = 200$ (400) MeV with 1(2) module
which houses four 5-cell cavities



Parameter	Value
Dipoles per arc	3/4
Dipole length	50 cm
Max B Field	1.1 T
Quadrupoles per arc	5
Quadrupoles in straight lines	4
Dipoles in Spreader/Combiner	1-3
Quads in Spreader/Combiner	3
Dipoles for Injection-Extraction	6

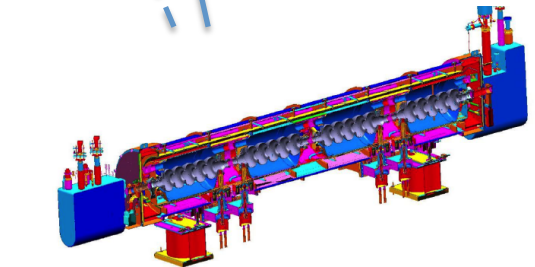


Figure 3.9: SNS high β module adapted to house $\beta = 1$ 5-cell cavities for LHeC.

BINP, CERN, Daresbury, Jlab,
Liverpool, Orsay (LAL/IPN),+

Technical Design as next goal
802 MHz cavity soon produced

“PERLE” CDR to be published, ICFA Beam Newsletter 68 (2016)

802 MHz Cavity Parameters

design to also test FCC-ee

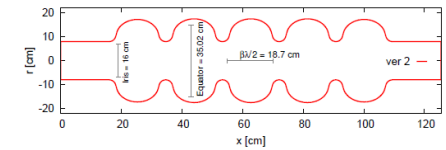


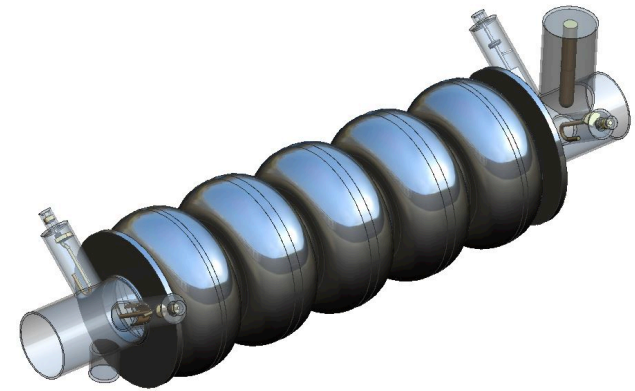
Fig. 6: Envelope of the second version of the five-cell ERL cavity at 802 MHz with 16 cm aperture.

CERN-ACC-NOTE-2015-xxx

28-05-2015

Rama.Calaga@cern.ch

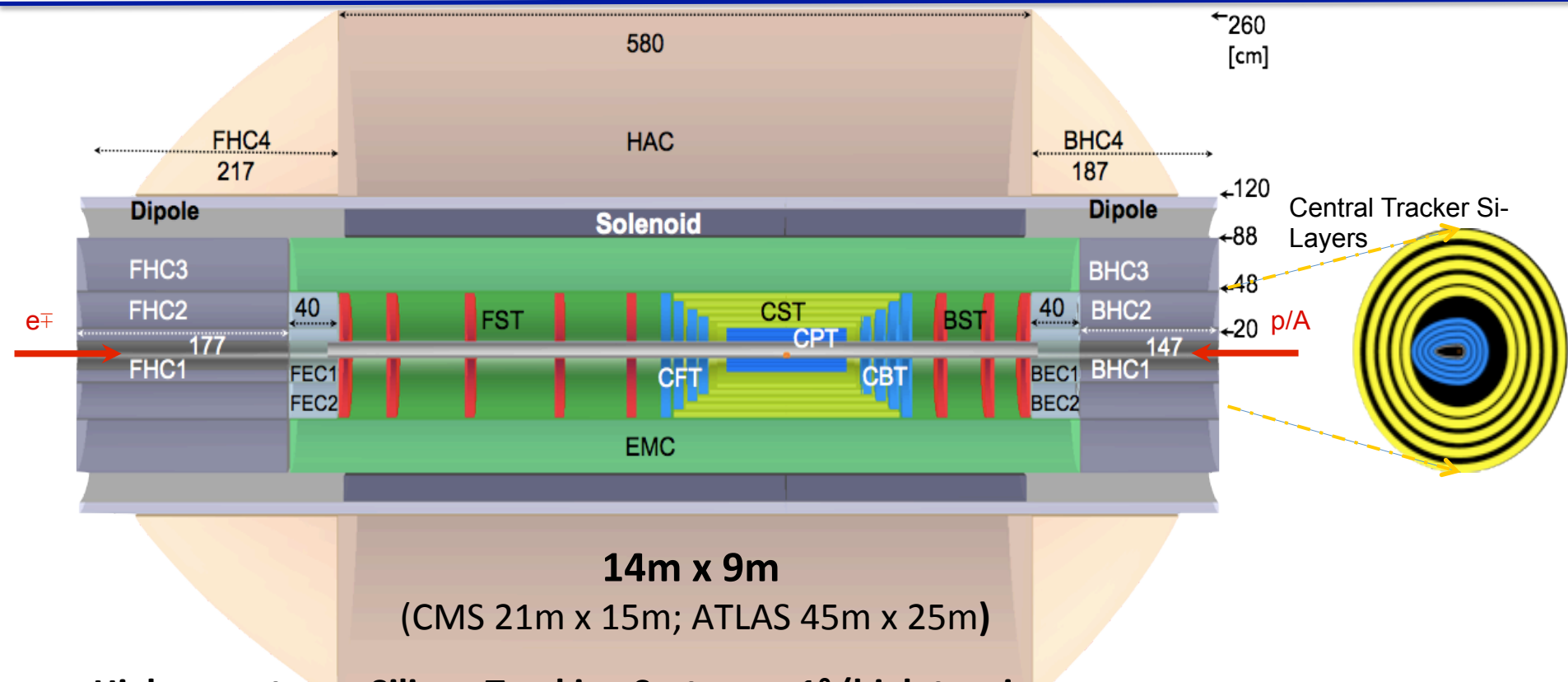
Parameter	Unit	Value	Value	Value		Value	
cavity type		LHeC prototype (2016)	LHeC study (2015)	LHeC study (2015)		LHeC Ver. 1	LHeC Ver. 2
frequency	MHz	801.58	802	802		801.58	801.58
number of cells		5	5	5		5	5
L_{active}	mm	917.91	922.31	922.14		935	935
$R/Q = V_{\text{eff}}^2 / (\omega * W)$	Ω	523.7	580.1	5			3
$R/Q/\text{cell}$	Ω	104.7	116.0	1			6
G	Ω	274.6	273.2	2			3
$R/Q \cdot G/\text{cell}$		28765	31702	3			44
Eq. Diameter	mm	327.95	323.12	3			.2
Iris Diameter	mm	130	115				0
Tube Diameter	mm	130	140				0
Eq./Iris ratio		2.52	2.81				9
Wall angle (mid-cell) deg		0	0				5
$E_{\text{peak}}/E_{\text{acc}}$ (mid-cell)		2.26	2.07				0
$B_{\text{peak}}/E_{\text{acc}}$ (mid-cell)	mT/(MV/m)	4.20	4.00	4.00		4.77	4.52
k_{cc}	%	3.22	2.14	2.14		4.47	5.75
N^2/k_{cc}		7.78	11.71	11.71		5.59	4.35
cutoff TE_{11}	GHz	1.35	1.26	1.53		1.17	1.10
cutoff TM_{01}	GHz	1.77	1.64	2.00		1.53	1.43



Detail end group + flange locations → build

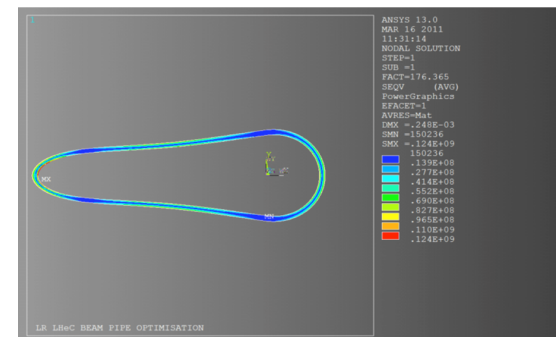
Baseline LHeC Detector Design

A. Polini and P. Kostka



- High acceptance Silicon Tracking System $\sim 1^\circ$ (high tagging capabilities e.g. for b-jets up to $\eta \sim 3$)
- Liquid Argon EM Calorimeter
- Iron-Scintillator Hadronic Calorimeter
- Forward Backward Calorimeters: Si/W Si/Cu
- Taggers for e , γ , p and n

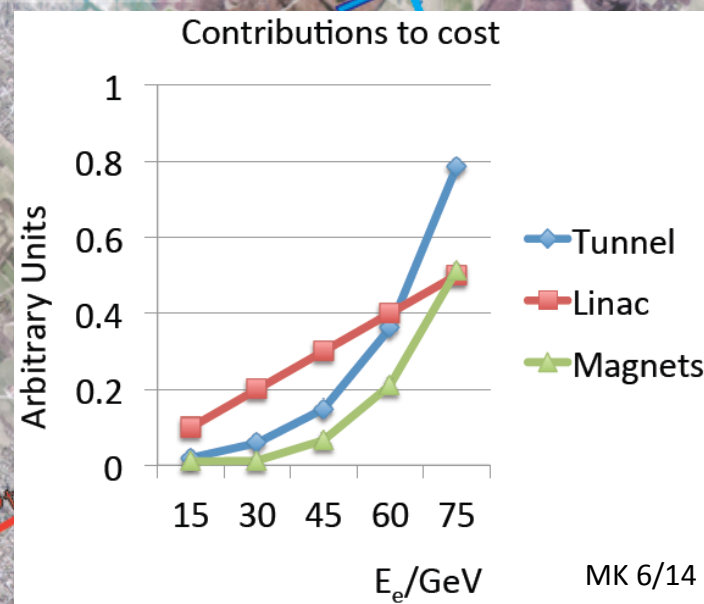
Beam pipe design for 3 beams



Civil Engineering Footprint

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
LHeC construction planning							
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

7 years for 9km
Civil Engineering



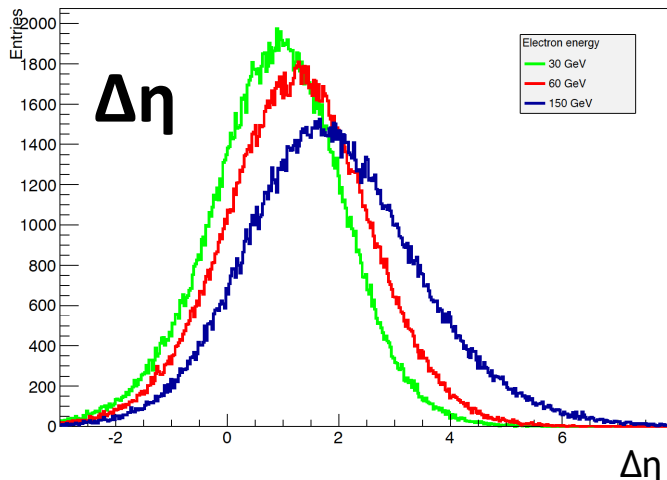
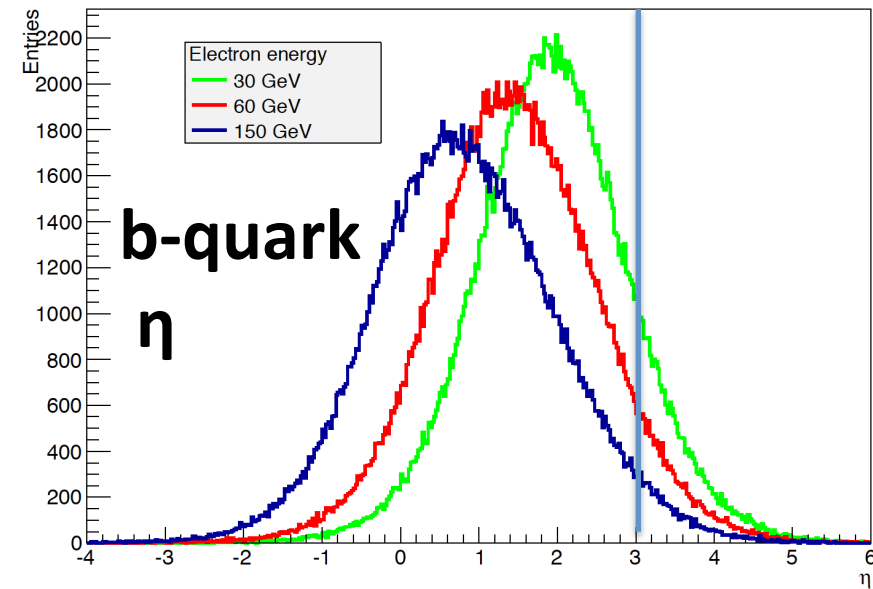
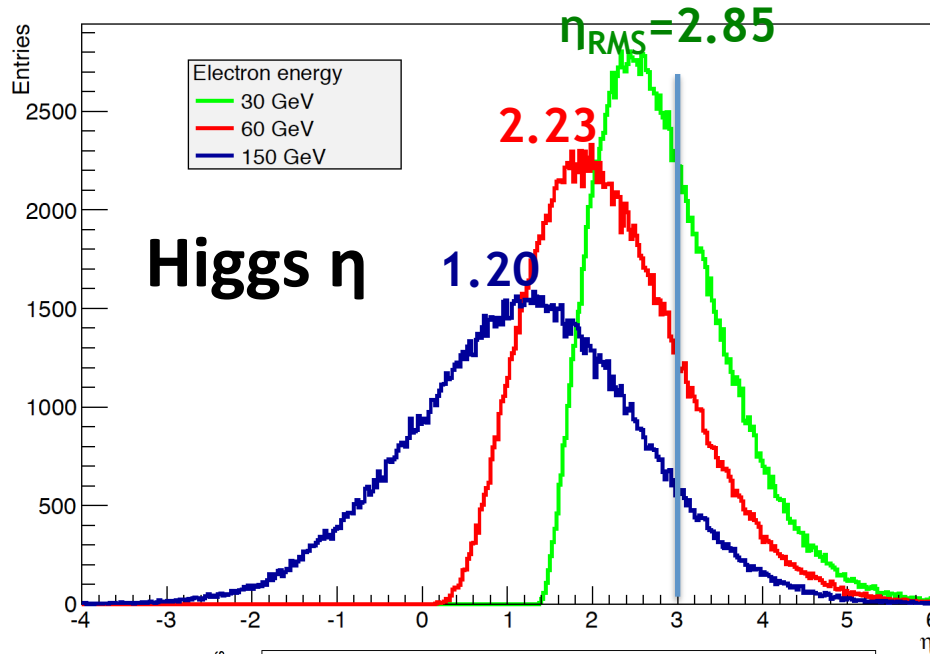
LHeC
Civil Engineering
Different Options
Fraction 1/3-1/4-1/5
Pt2 and Pt8

J.OSBORNE/L.FAISANDEL GS-SE-DOP

Higgs acceptance vs E_e

[after Higgs discovery $M_H=125$ GeV, $E_p=7$ TeV]

[Master thesis by Sergio Mandelli, Liverpool 2013]



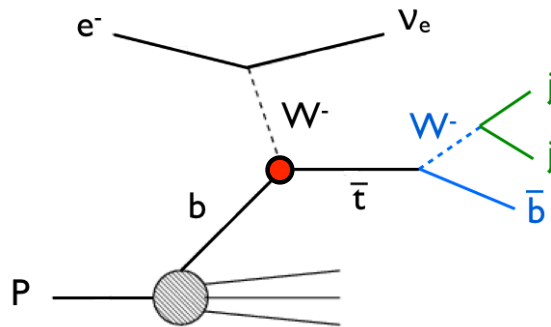
- ➔ lowering of electron beam energy (more cost efficient) will challenge more detector design: worse separation between higgs and forward jet ($\Delta\eta$ shrinks by 1 unit) and b-quarks from Higgs decay are more forward
- ➔ **stick with 60 GeV** E_e : decay products of Higgs scattered at $\sim 28^\circ$ ($\eta \sim 1.4$)

Top Quark & EW in ep

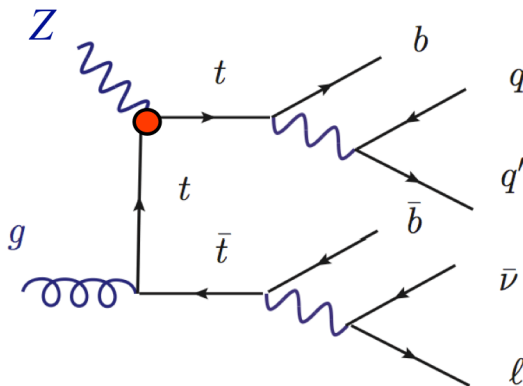
... a few examples only

C. Schwanenberger,
@DIS2015

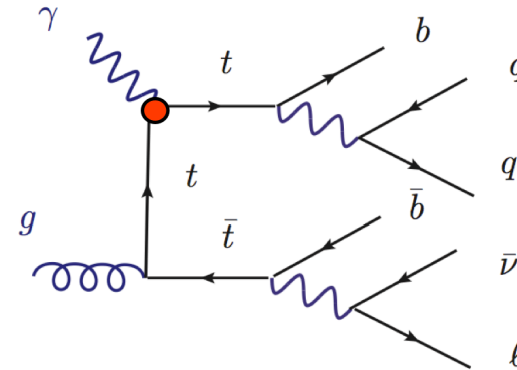
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : top quark expected to be most sensitive to BSM physics, due to large mass



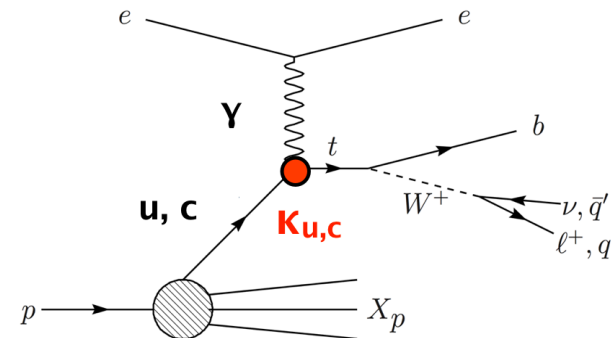
- high precision measurements of V_{tb} and search for **anomalous Wtb** couplings



- measurement of top isospin and search for **anomalous $t\bar{t}Z$** couplings (eg. EDM, MDM)



- direct measurement of top quark charge and search for **anomalous $t\bar{t}\gamma$** couplings (eg. EDM, MDM)



- sensitive search for **FCNC couplings** will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

Pile-up estimate for LHeC

- high luminosity option using $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (LHeC) and $L=5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (HL-LHC) with 150 pile-up events (25 ns)
[calculations by M. Klein]

➔ Pile-up events expected for LHeC $< \sim 0.1$

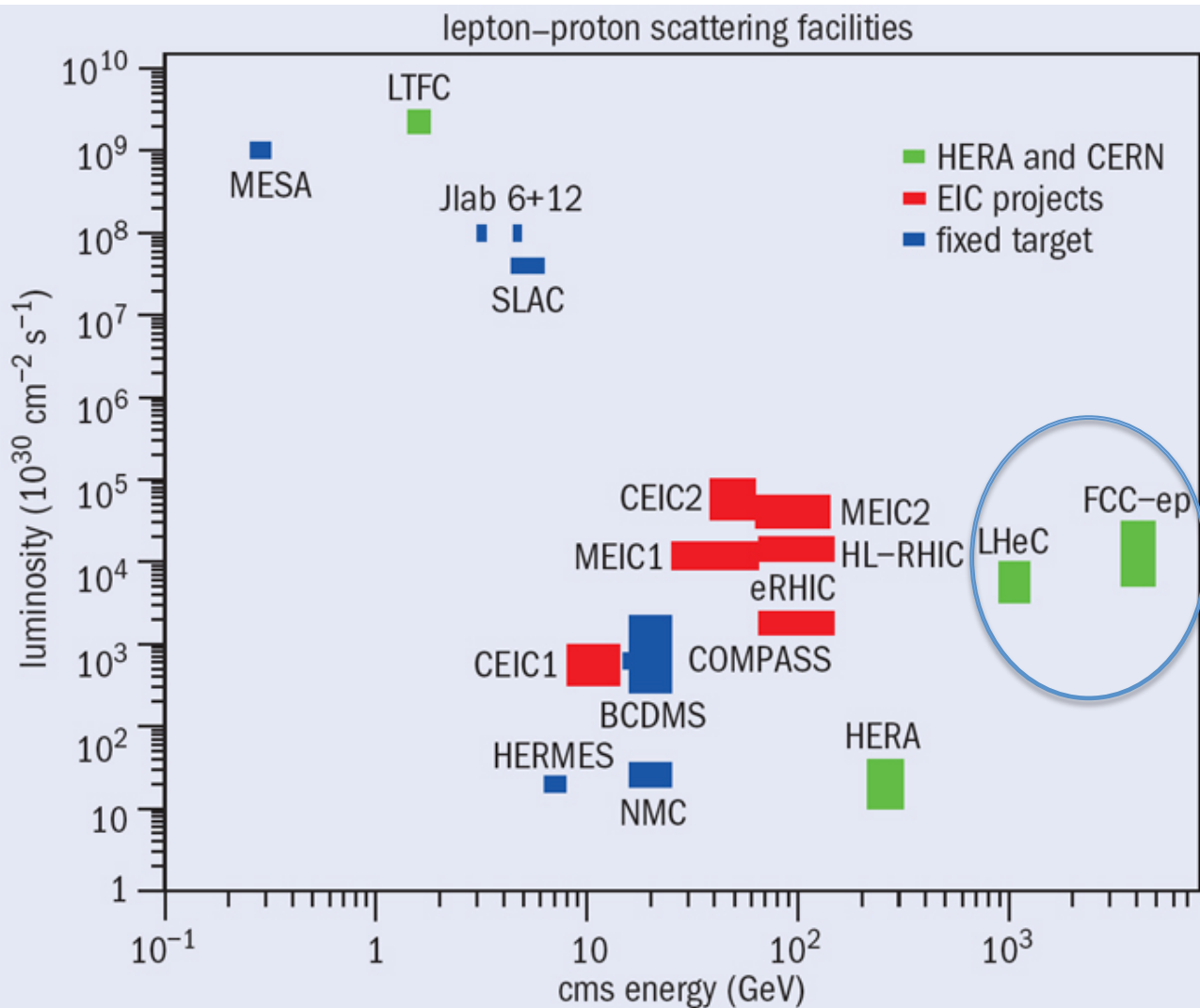
Using pp LHC pile-up estimates

$$\begin{aligned} N(\text{ep}) &= N(\text{pp}) \times s(\text{yp})/s(\text{pp}) \times L(\text{ep})/L(\text{pp}) \\ &= 150 * 0.003 * 0.2 \\ &= 0.1 \end{aligned}$$

Direct calculation using total gamma-proton cross section of $300 \mu\text{b}$

$$\begin{aligned} N(\text{ep}) &= 300 \cdot 10^{-6} \cdot 10^{-24} \text{ cm}^2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \times 25 \cdot 10^{-9} \text{ s} \\ &= 0.075 \end{aligned}$$

The ep Landscape : Luminosity vs $\sqrt{s}$



China

CEIC1 = Chinese version of Electron-Ion Collider
(*"A dilution-free mini-COMPASS"*)

U.S.

MEIC1 = EIC@Jlab

eRHIC = EIC@BNL

Europe

LHeC = ep/eA collider
@ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

} future extensions