Electrons for the LHC:
The LHeC Project

Christian Schwanenberger

Deutsches Elektronensynchrotron (DESY)

Future of Particle Physics:
A Quest for Guiding Principles

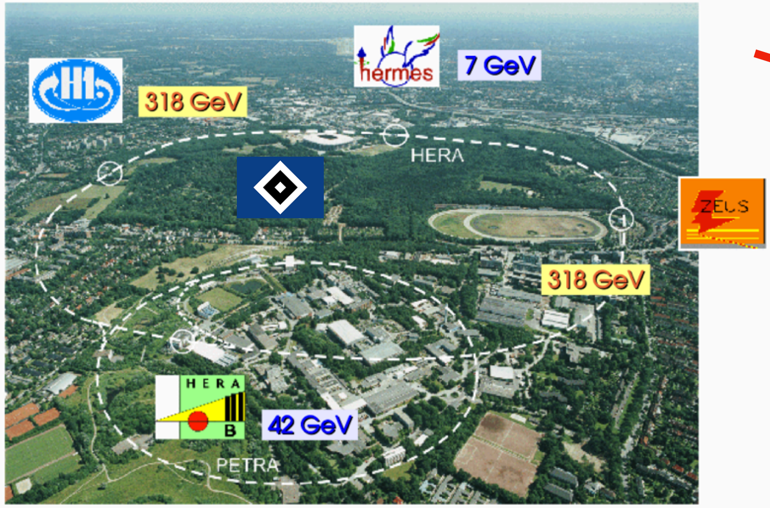
Karlsruhe Institute of Technology (KIT)

01 October 2018

High Energy Colliders: past

HERA

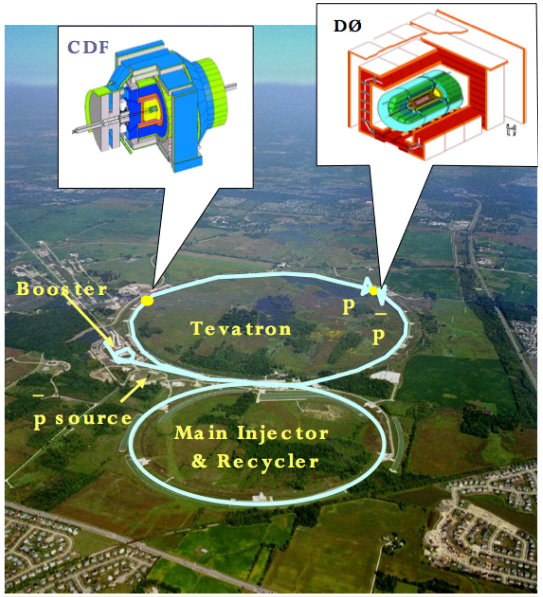
ep



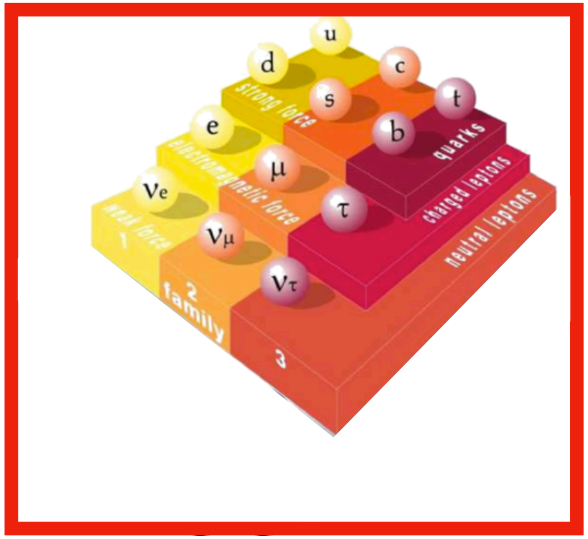
1992–2007

Tevatron

$p\bar{p}$



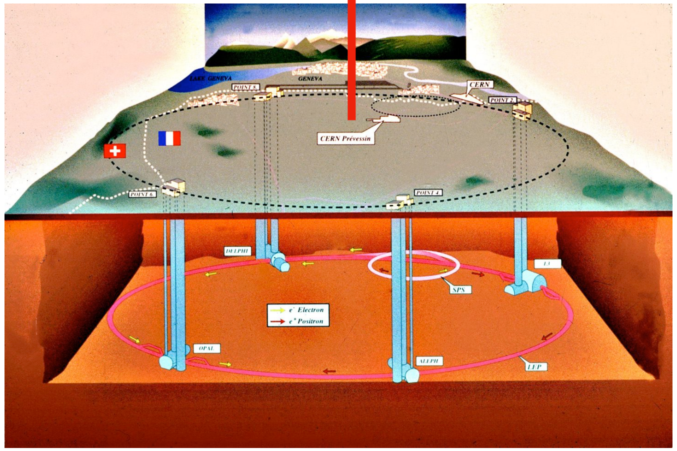
1983–2011



SLC

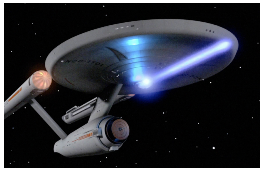
B-factories

ee



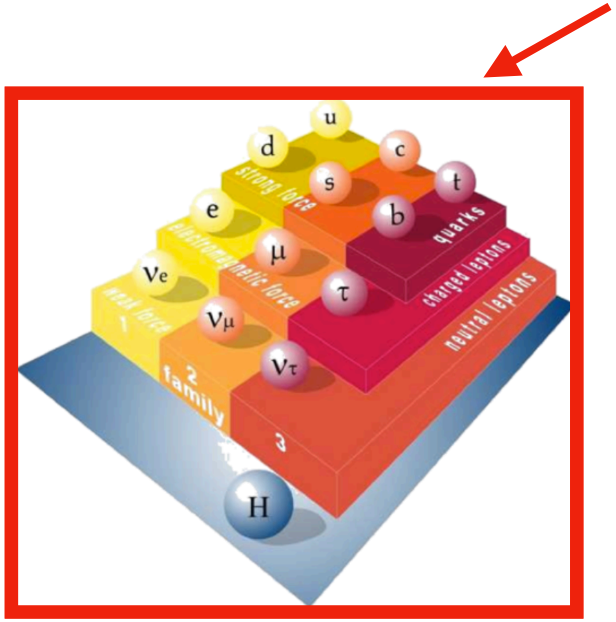
LEP

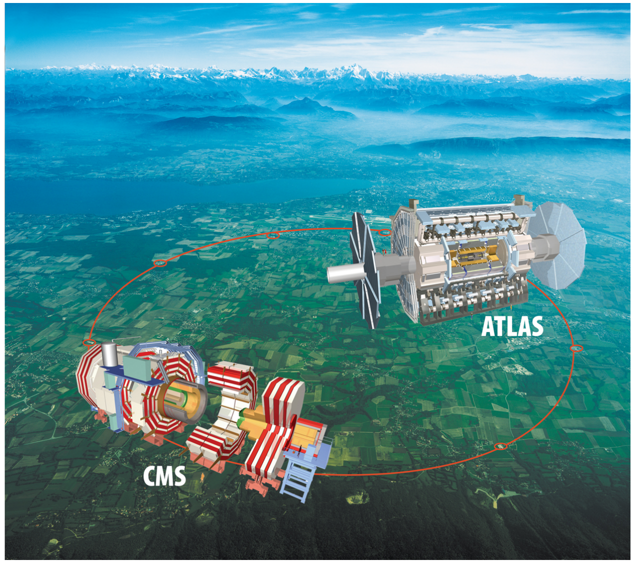
1989–2000



High Energy Colliders: present

LHC(b) **pp**

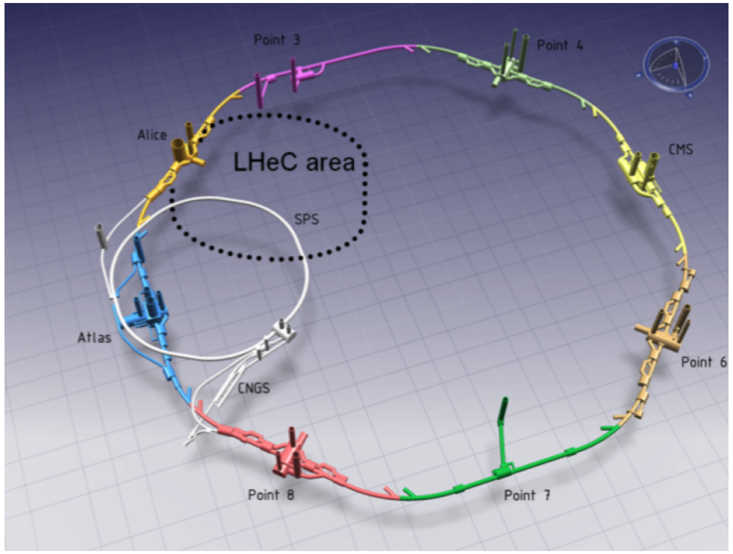




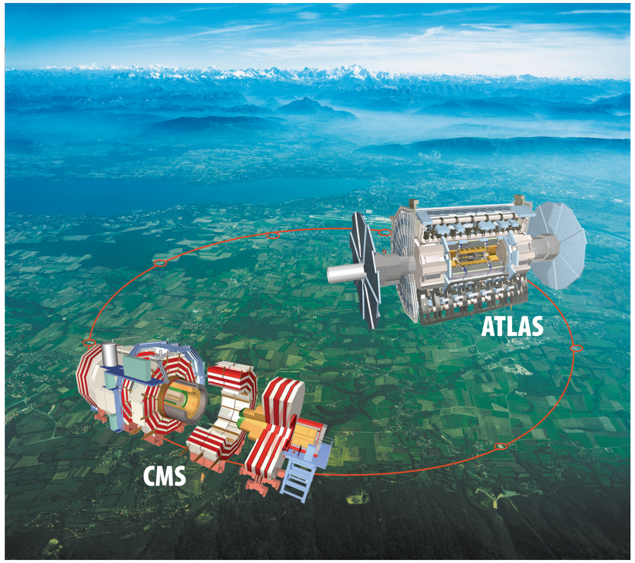
since 2008

High Energy Colliders: next generation

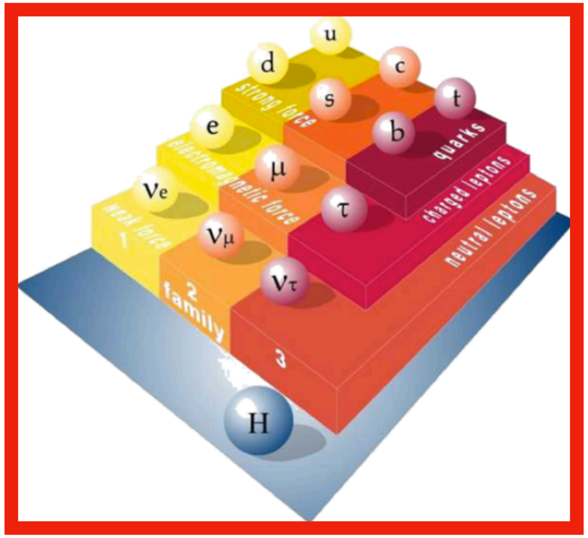
LHeC **ep**



LHC(b) **pp**



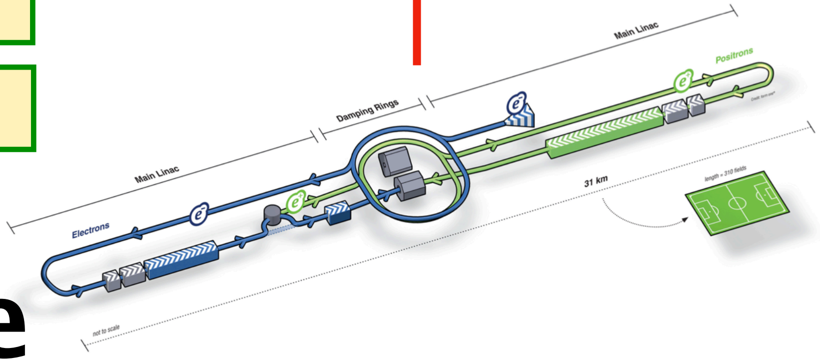
since 2008



SuperB

CepC

ee

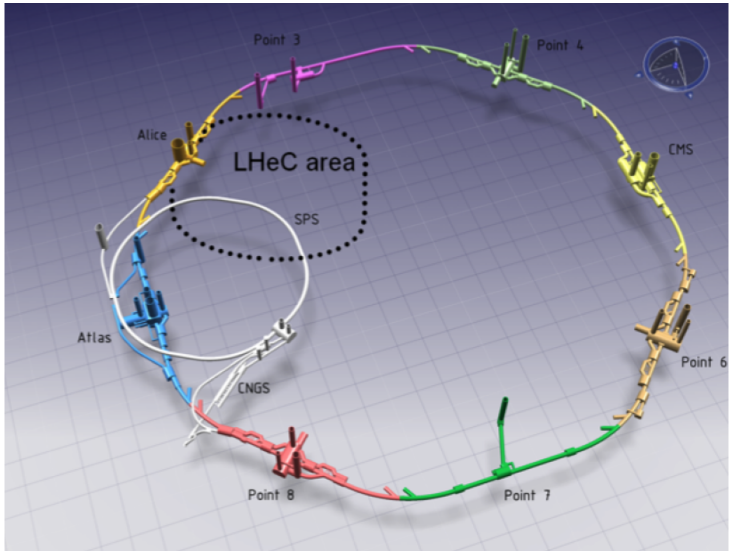


CLIC

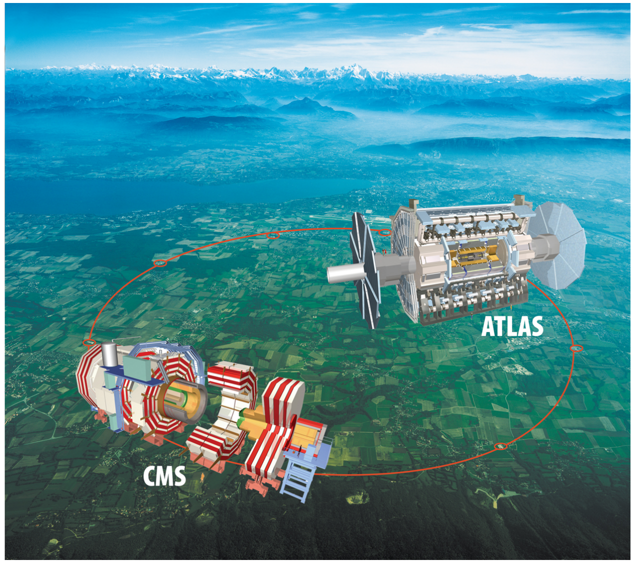
ILC

High Energy Colliders: next generation

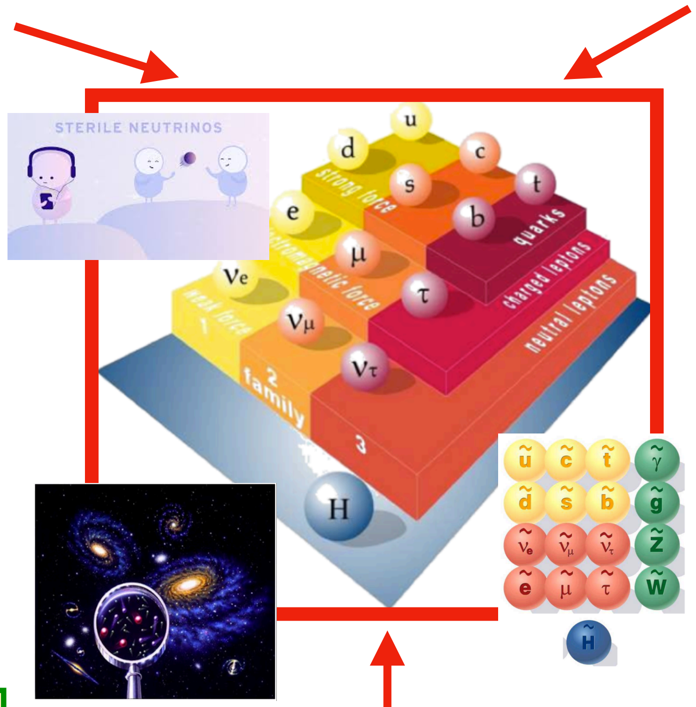
LHeC **ep**



LHC(b) **pp**



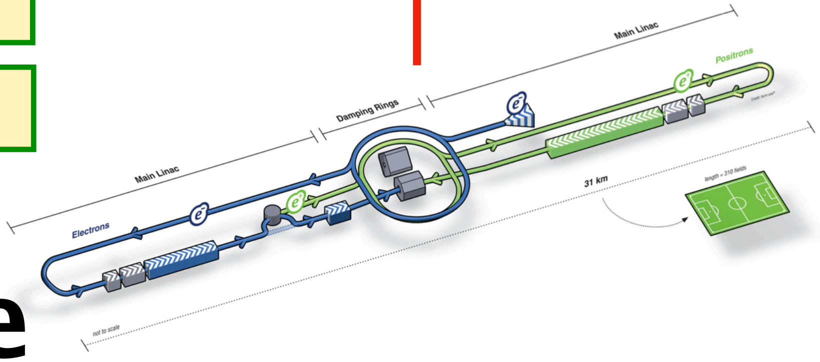
since 2008



SuperB

CepC

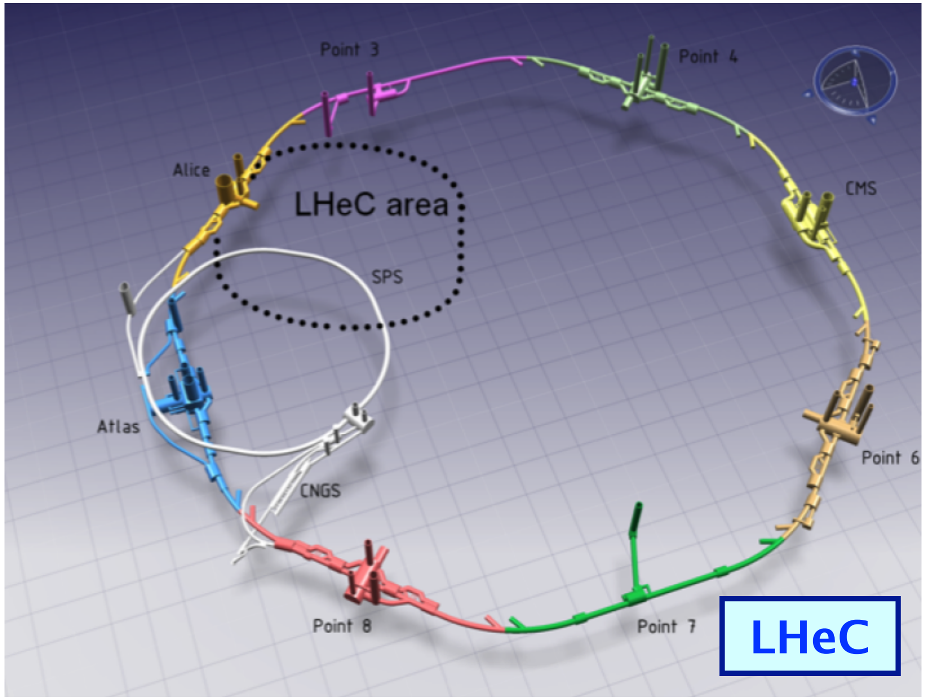
ee



CLIC

ILC

Linac-Ring Collider, LHeC and FCC-eh

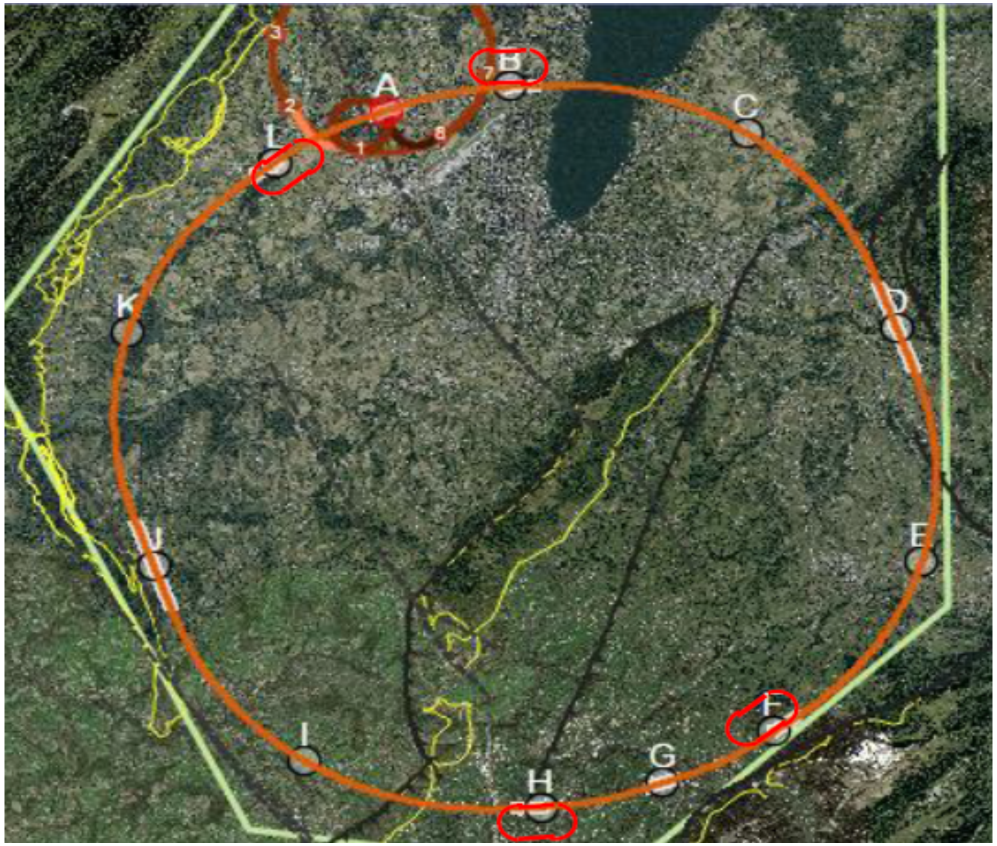


Energy Recovering Linac

$e^{\pm}$ beam: 60 GeV

L_{int} = 1-3 ab^{-1} (1-3k HERA!)

FCC-ep



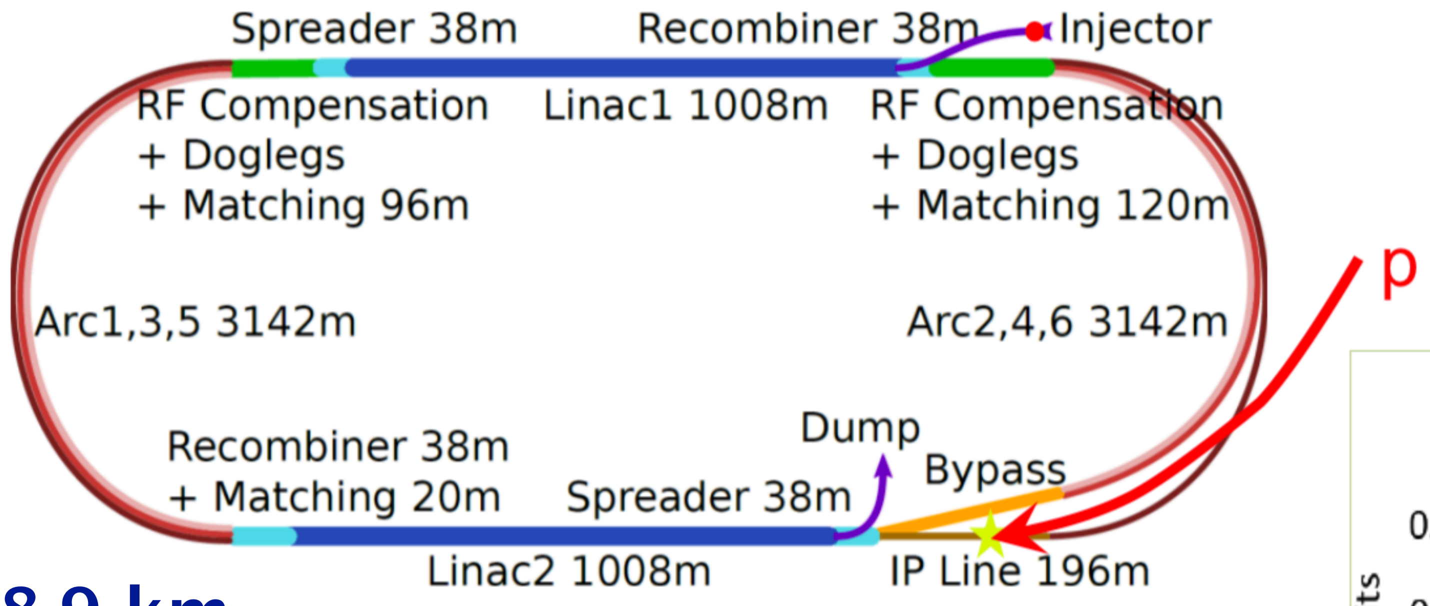
operated synchronously

- **with HL-LHC:**
  p beam: 7 TeV, $\sqrt{s}$=1.3 TeV
- **with HE-LHC:**
  p beam: 13.5 TeV, $\sqrt{s}$=1.8 TeV
- **or later with FCC-hh:**
  p beam: 50 TeV, $\sqrt{s}$=3.5 TeV

Energy Recovering Linac

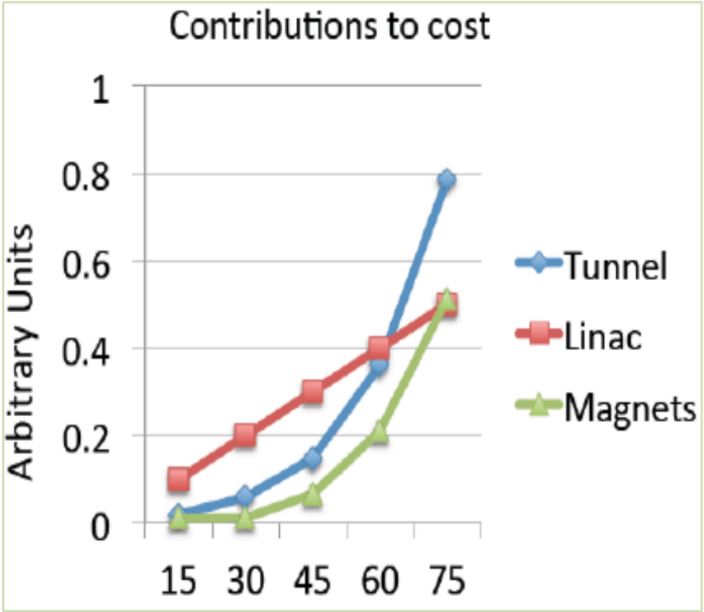
Energy Recovering Linac (ERL):

E_e=60 GeV



8.9 km

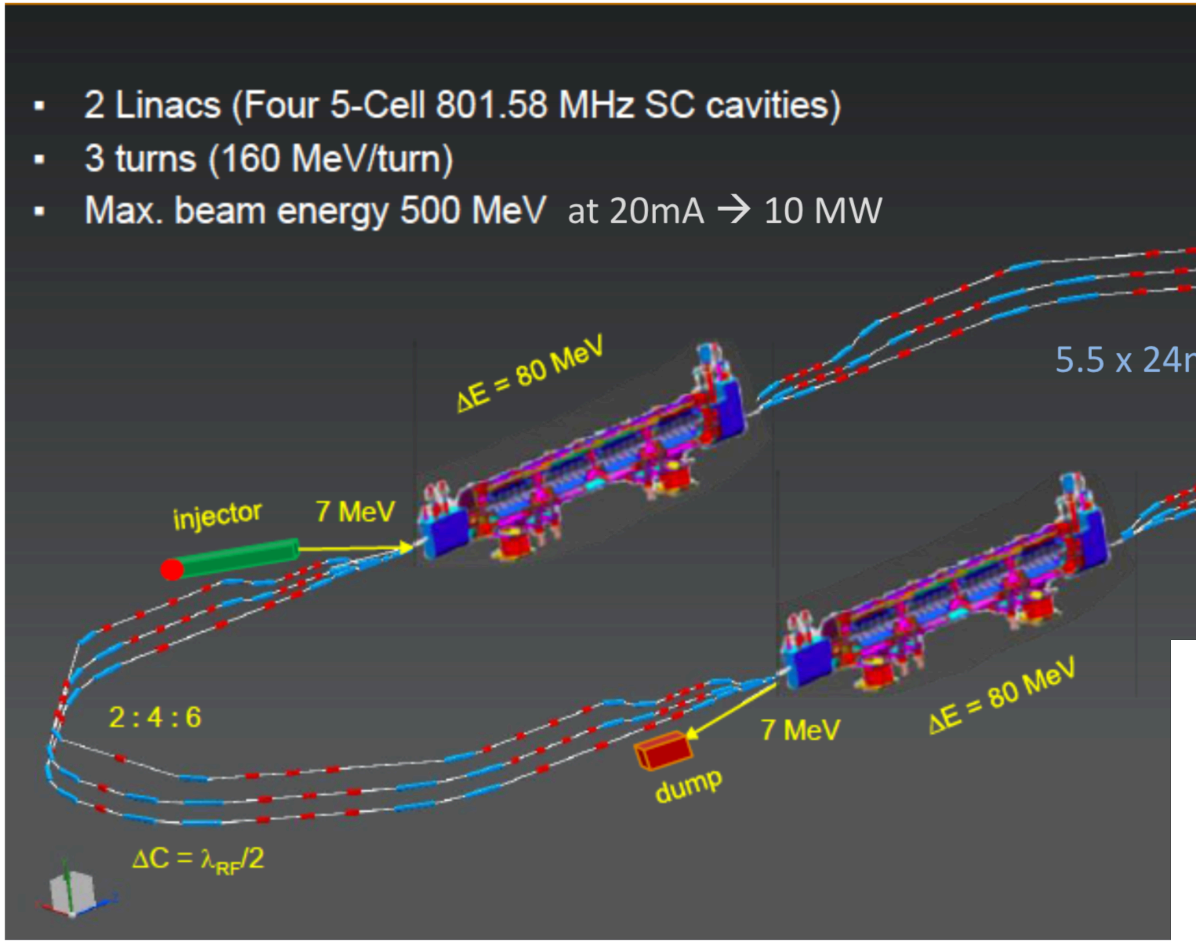
- power limit: 100 MW
- luminosity: 10^{34} cm^{-2} s^{-1}
- factor of 15/120 (LHeC/FCC-eh) extension of Q^2, 1/x reach



M. Klein, F. Zimmermann

Initial, tentative, rough scaling estimate of basic cost (tunnel, linac (XFEL), magnets

Powerful ERL for Experiments (PERLE)



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

cf Walid Kaabi at Amsterdam FCC

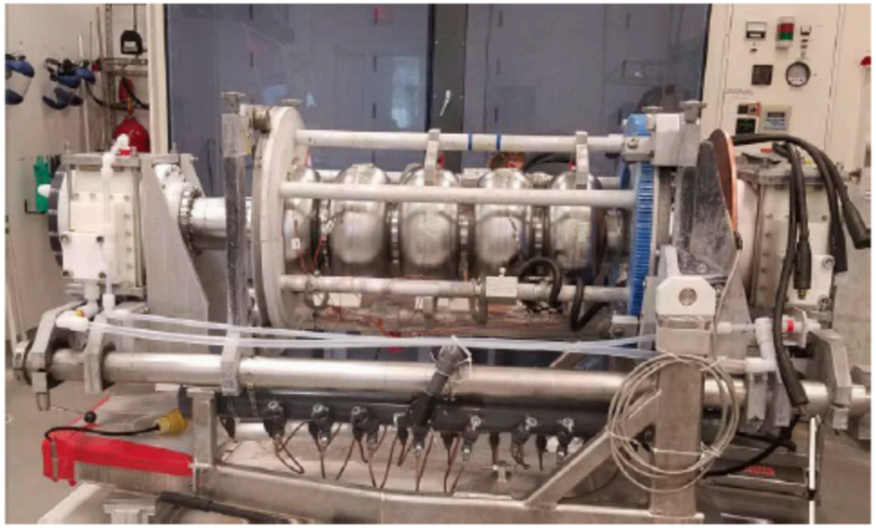
in Orsay

- BINP
- CERN
- Daresbury/Liverpool
- Jlab
- Orsay

→ CDR 1705.08783 [J. Phys G]

→ TDR in 2019

First 802 MHz cavity successfully built (Jlab)



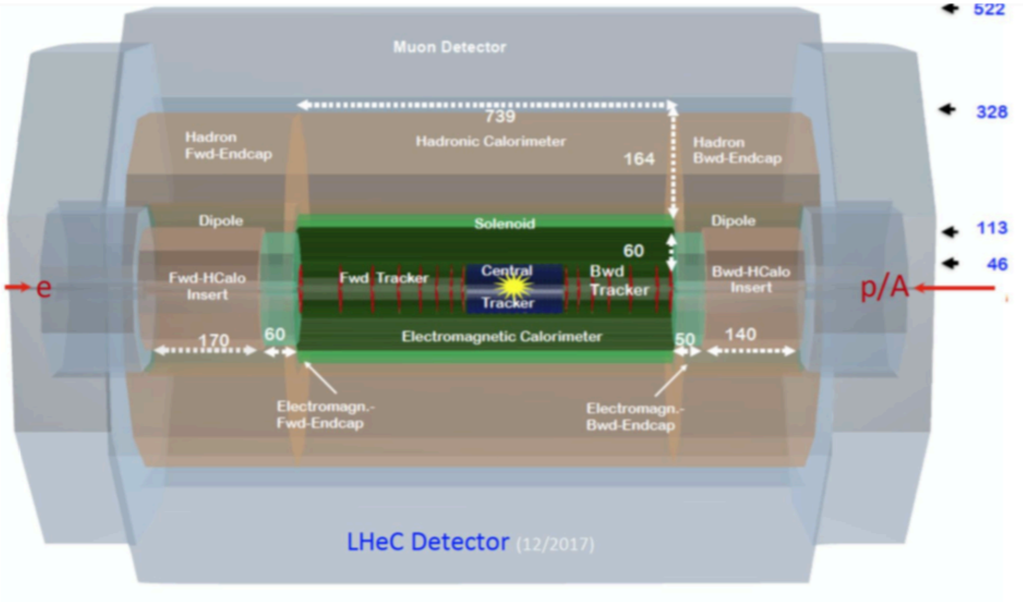
→ **ERL demonstrator**

→ **O(10 MeV) physics**

LHeC Detector Layout

- Cross section with MadGraph5
  - tree-level Feynman diagrams using p_T of scattered quark as scale for ep processes
  - Fragmentation & hadronisation uses ep-customised Pythia.
- DELPHES Fast Detector Simulation
  - ‘Standard’ GPD LHC-detectors
    - Optimising vertex resolution a la ATLAS IBL of ~ 5 μm
    - ATLAS b-tagging efficiencies
    - Using state-of-the art hadronic and el.mag. Resolutions
  - Considering displaced vertices and impact parameter distributions

[arXiv:1802.04317]



Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)
ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

Object	Acceptance
Electrons	$\|\eta\|<4.7$
Muons	$\|\eta\|<4.7$
Jets	$\|\eta\|<5$
b-tagging	$\|\eta\|<3.5$

Slide: M. Schott

DIS 2018 International Workshop, Kobe

Daibutsu (Great Buddha) statue, Nara

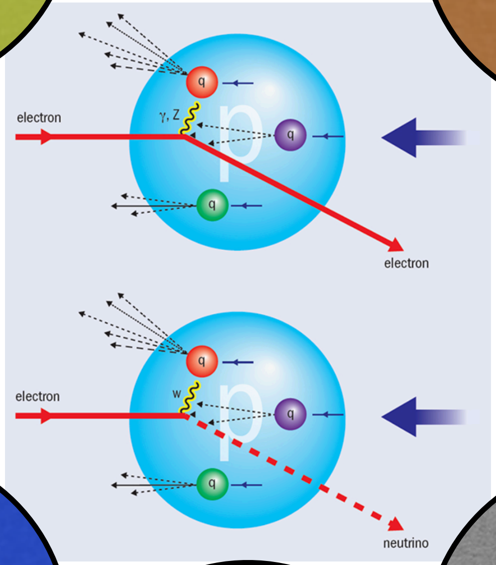
The eight fold path

High Energy Frontier in DIS

EWK

QCD

Higgs



small x

Top

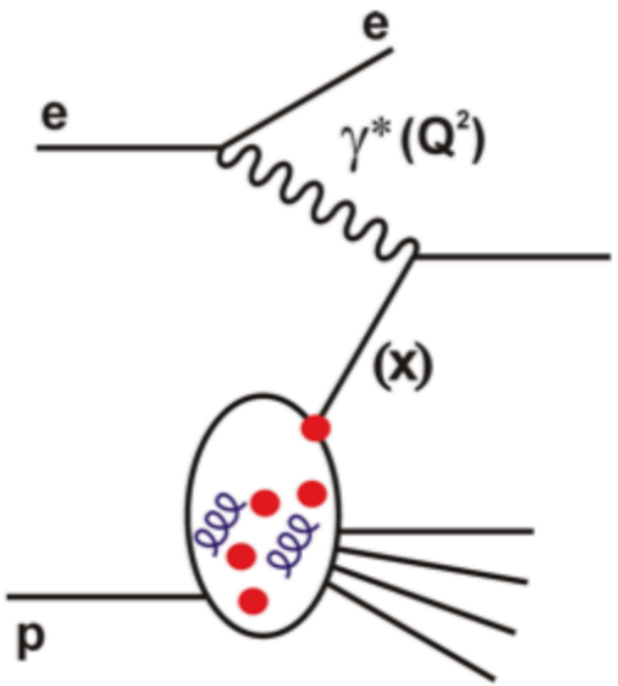
nucl. PDF

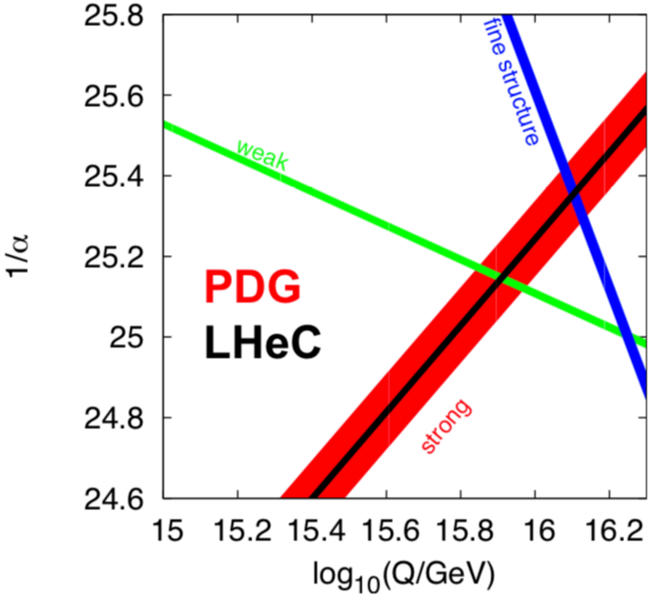
BSM

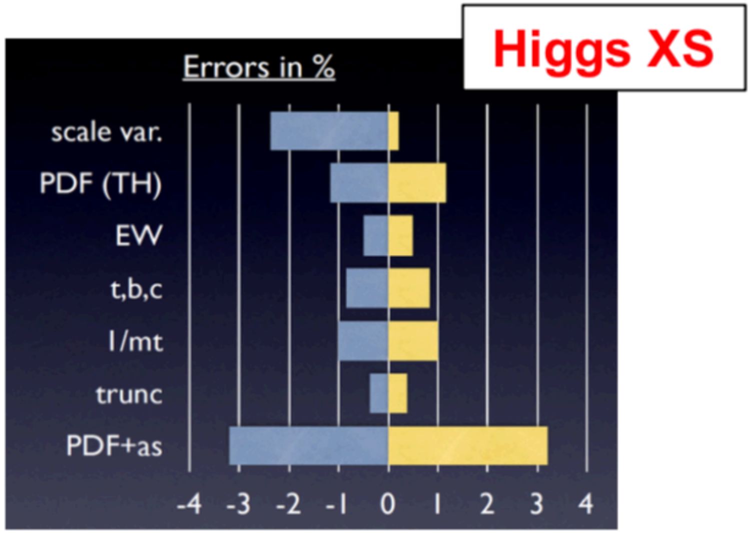
PDF

Determination of Strong Coupling

QCD







(G. Zanderighi, Moriond16;
from C. Anastasiou et al, arXiv:1602.00695)

- α_s is least known coupling constant: important to constrain GUT scenarios, Higgs cross section, …
- perform QCD fit of inclusive NC and CC DIS

→ per mille level precision!

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

(**LHeC**: NC+CC incl.; total exp. uncerts; independent of BCDMS)

PDF

Unpolarised PDFs

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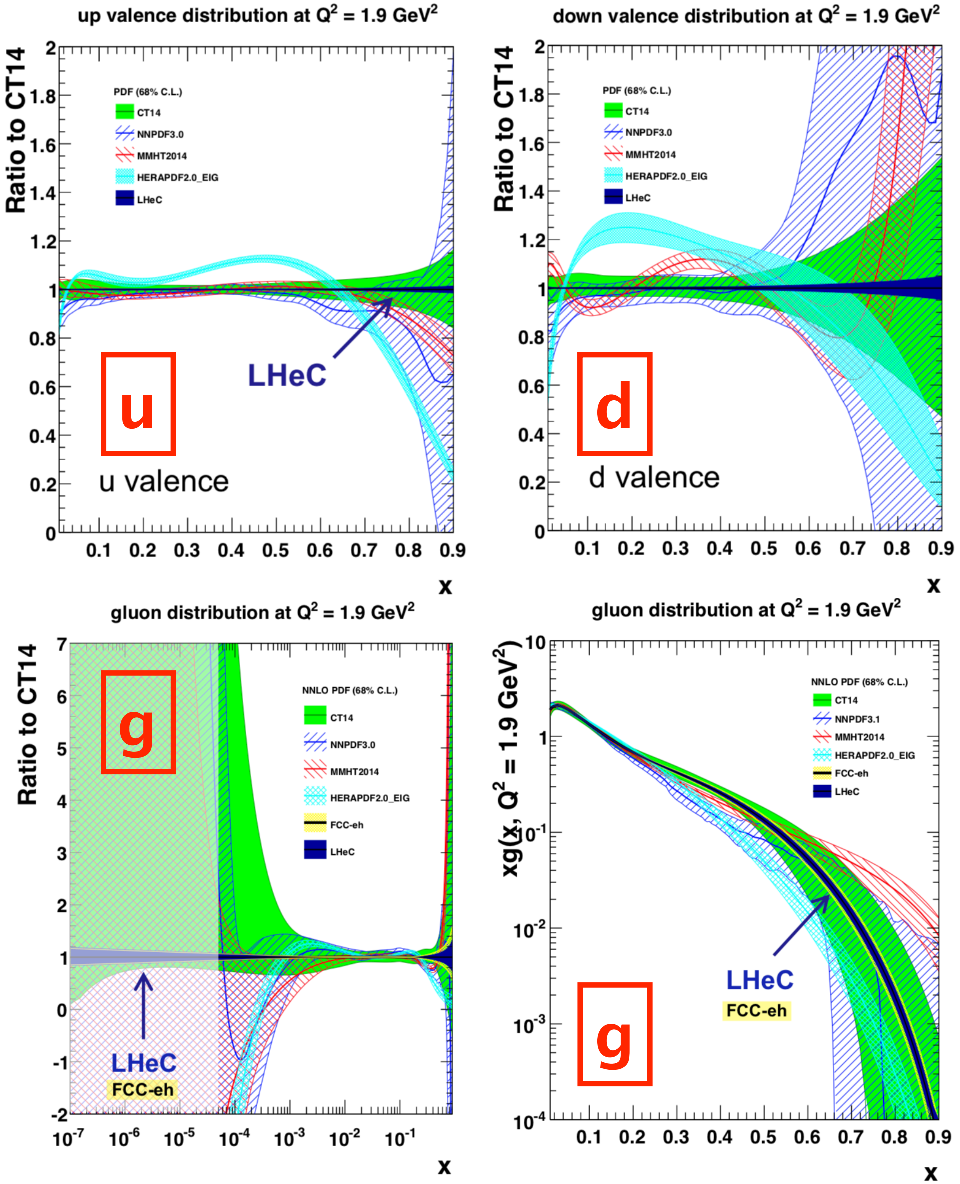

→ **huge improvements**

PDF

Unpolarised PDFs

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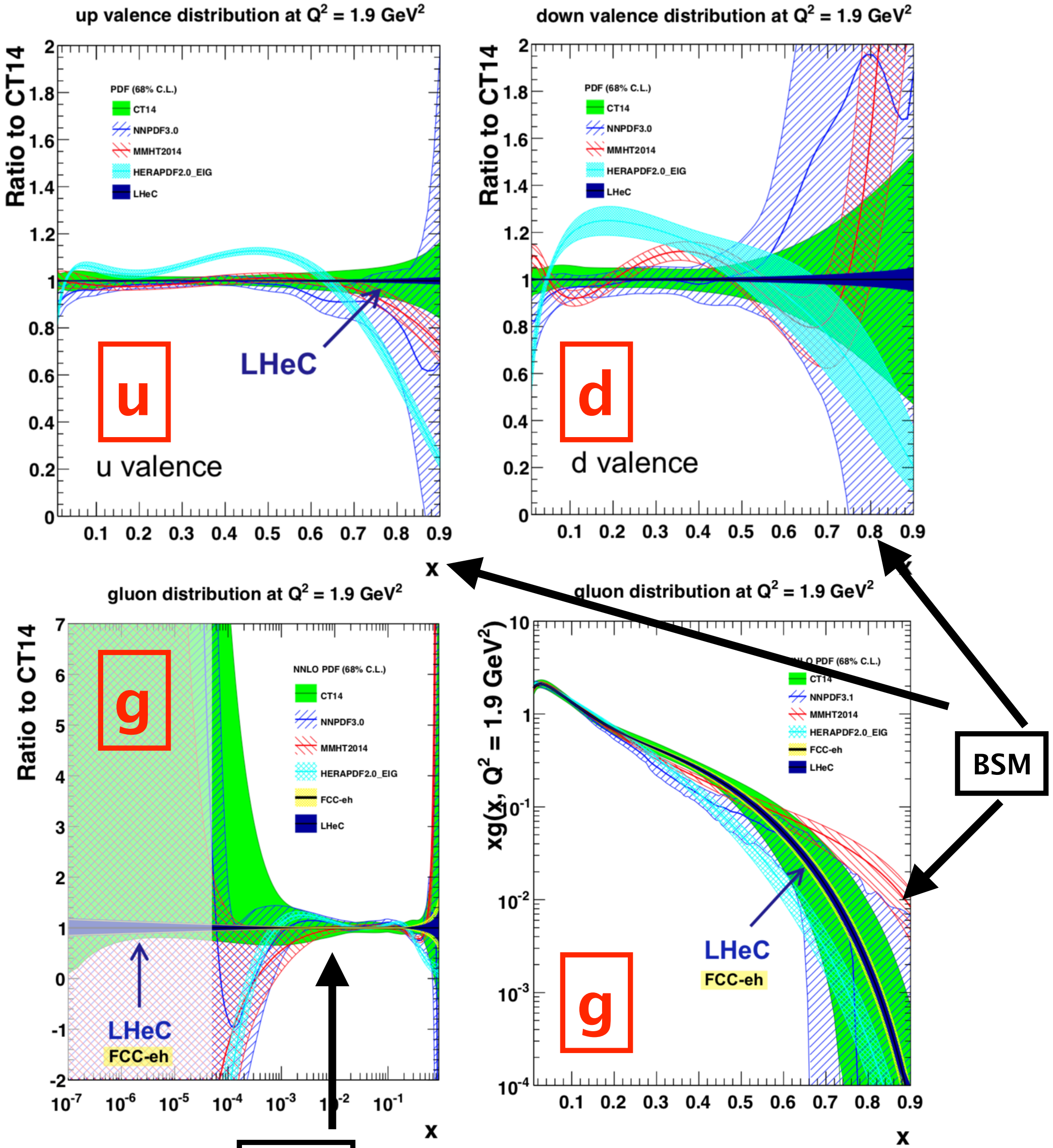
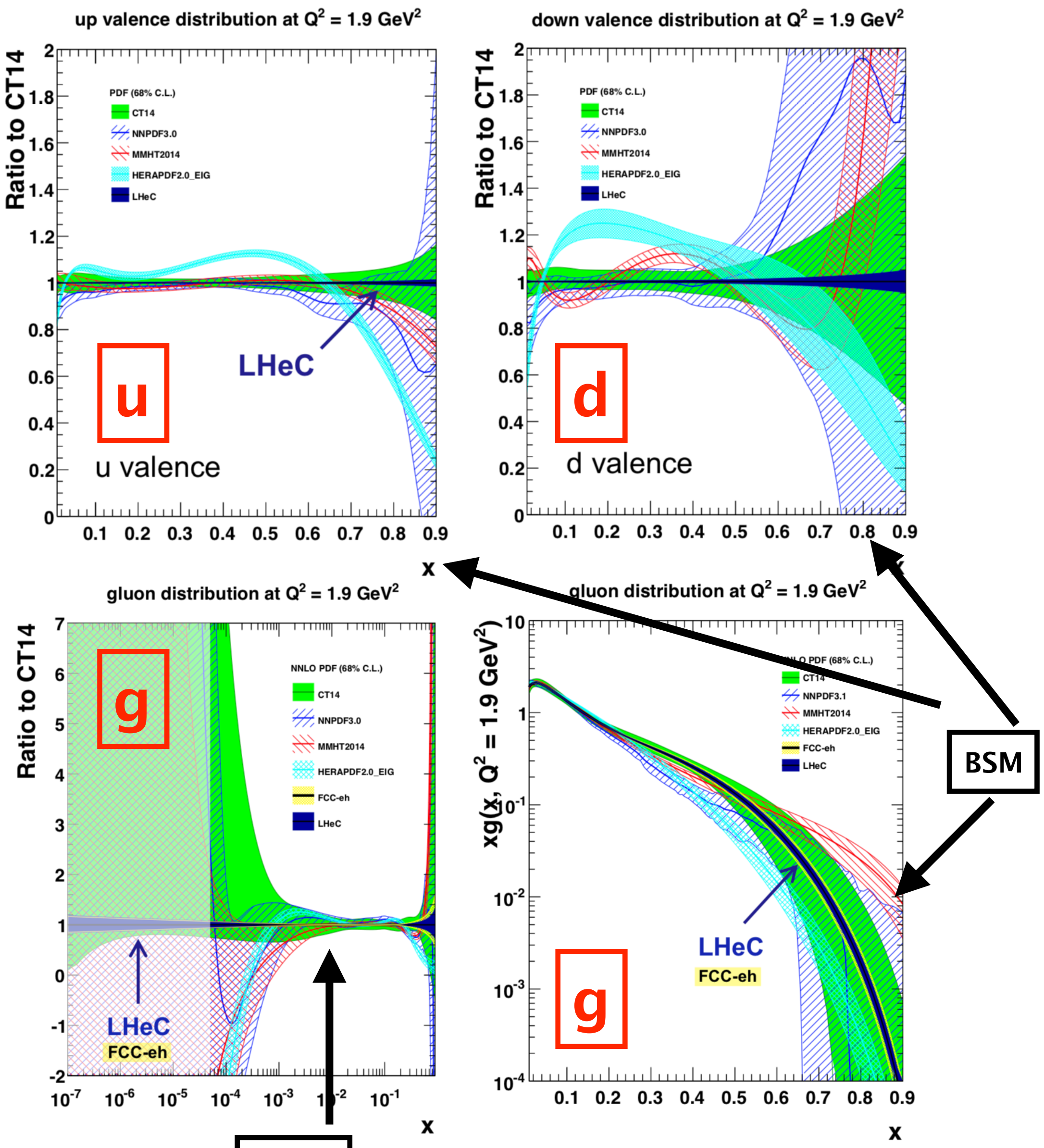
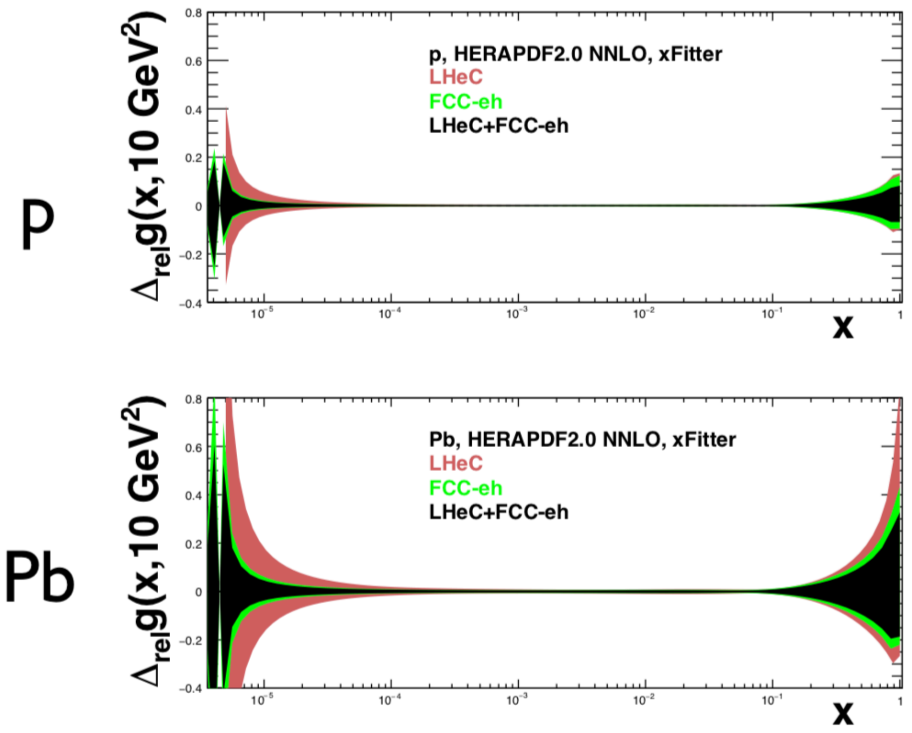


Higgs → **huge improvements**

Unpolarised PDFs



Higgs → **huge improvements**



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Unpolarised PDFs

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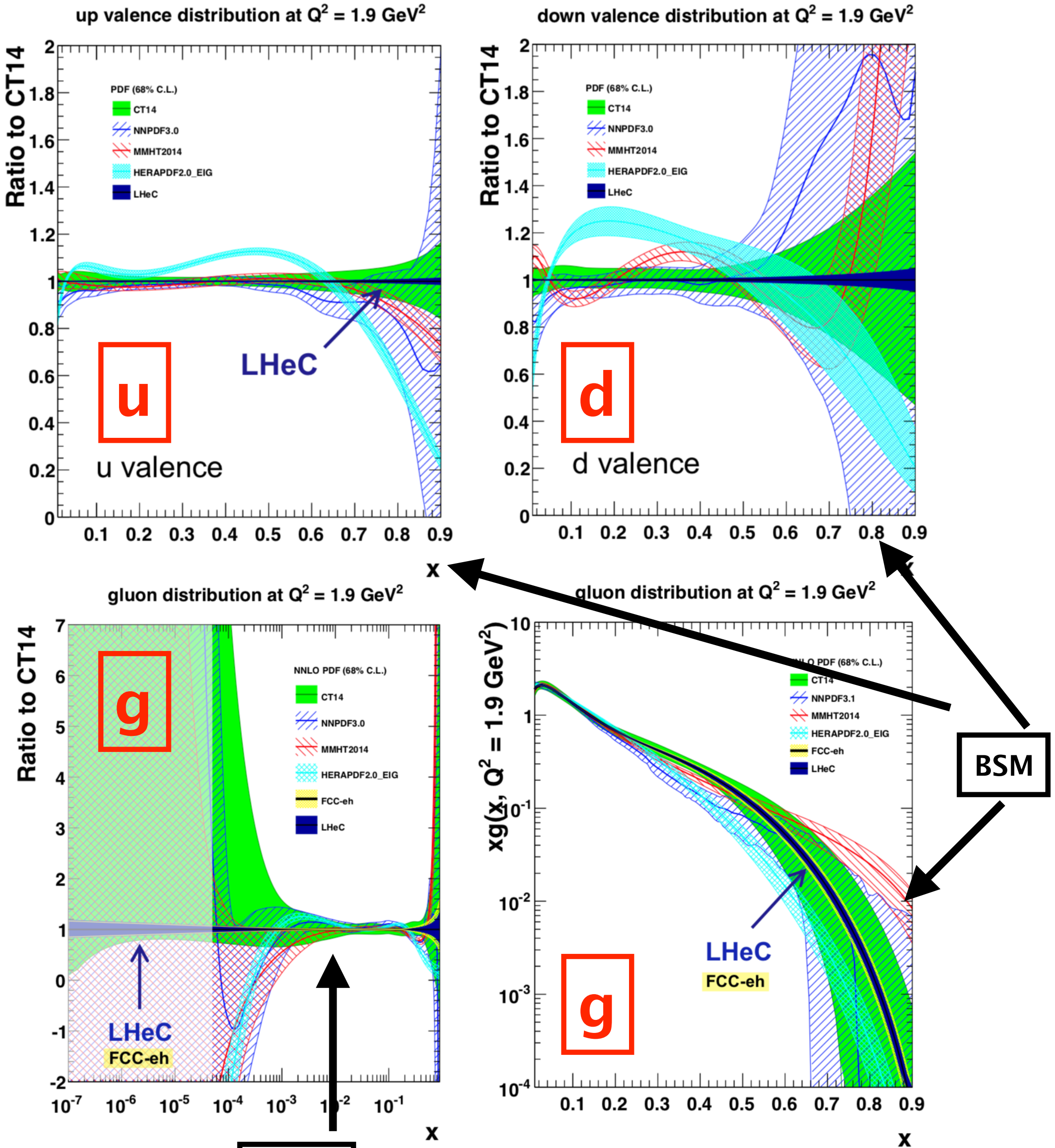
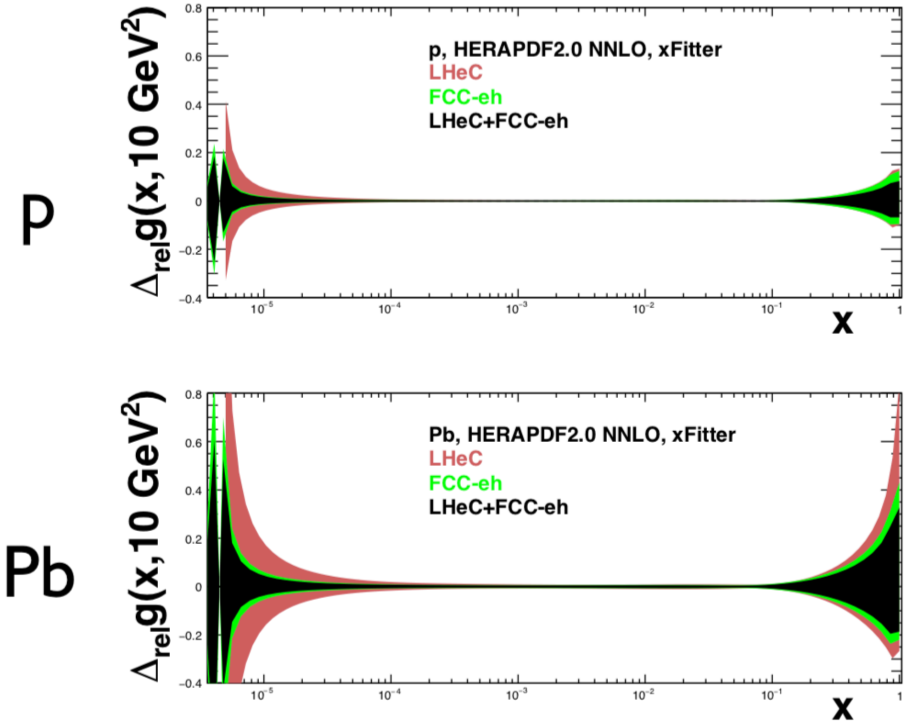
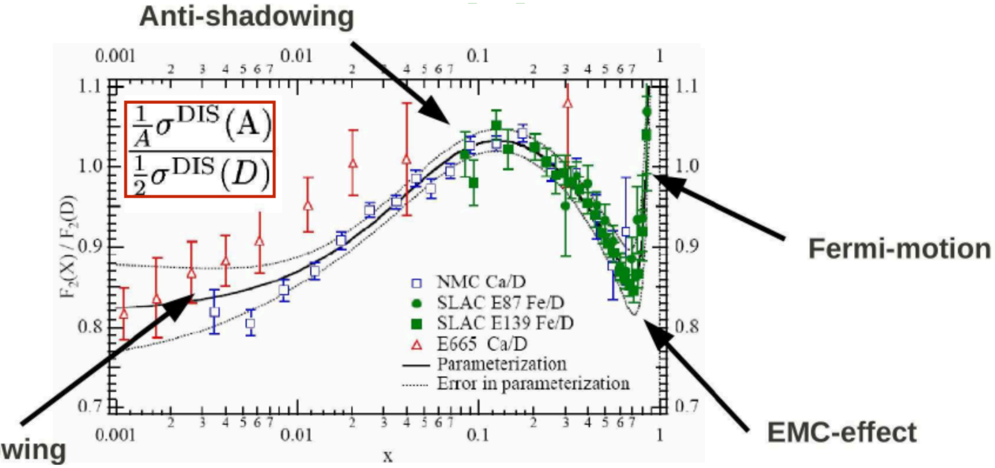


Higgs → **huge improvements**



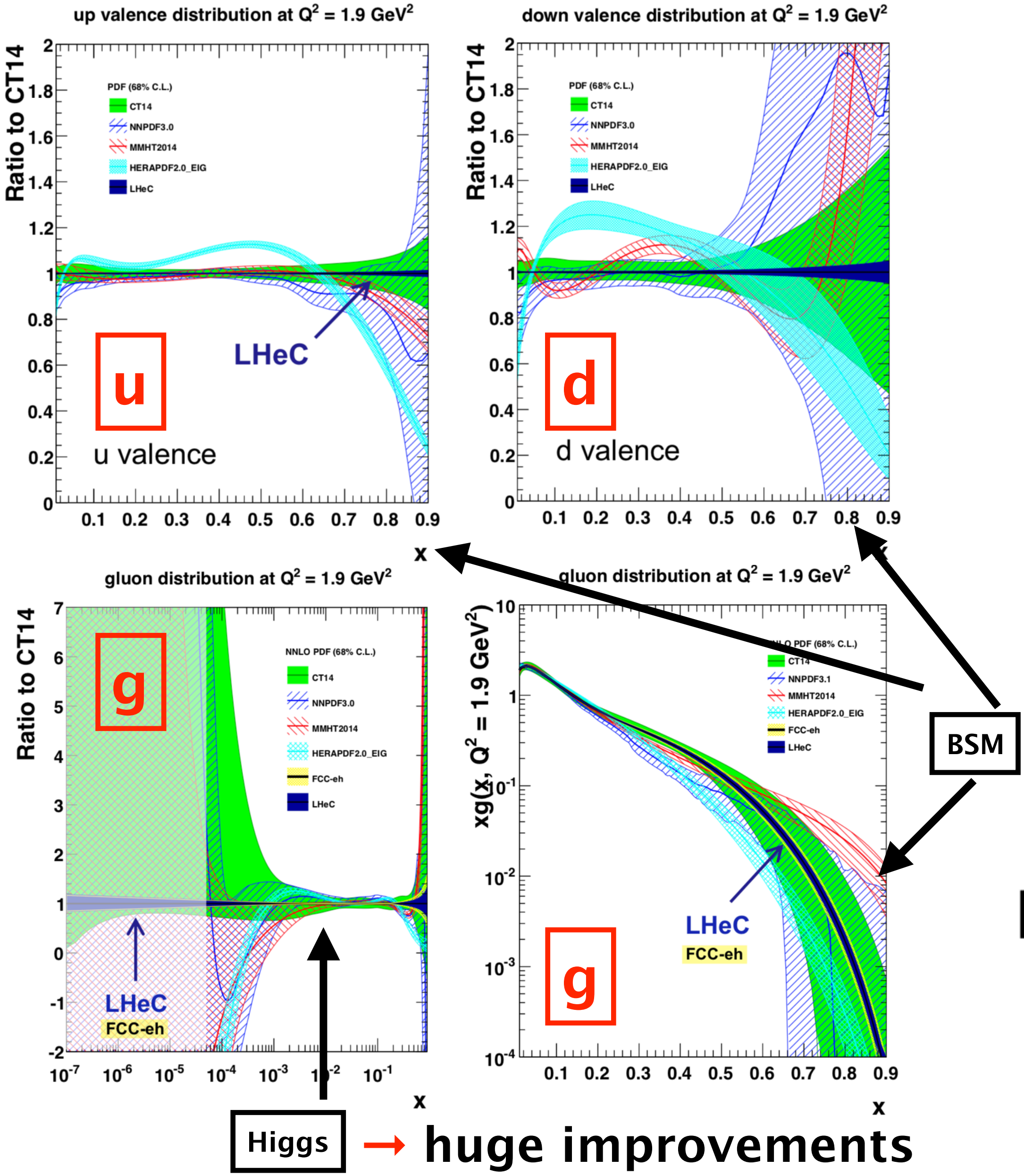


Shadowing

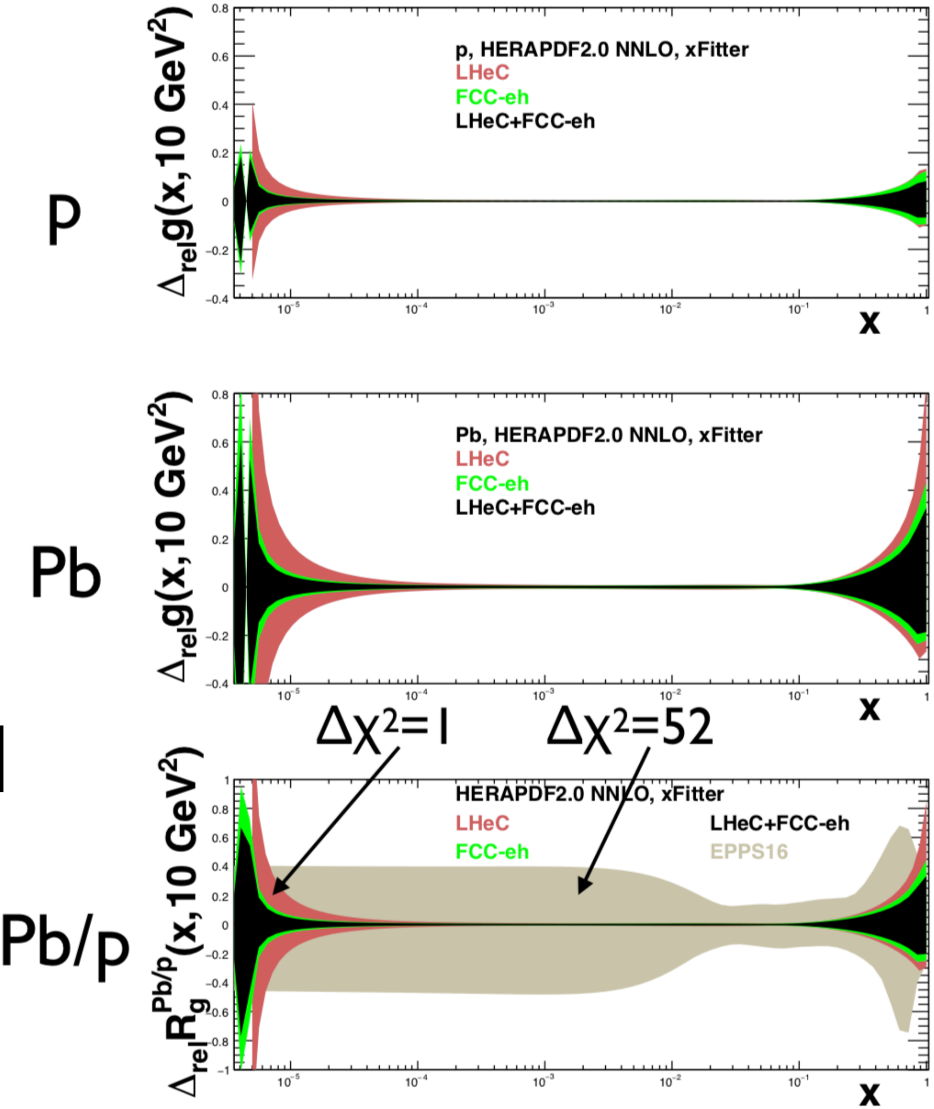
PDF

Unpolarised PDFs

nucl. PDF



→ **huge improvements**

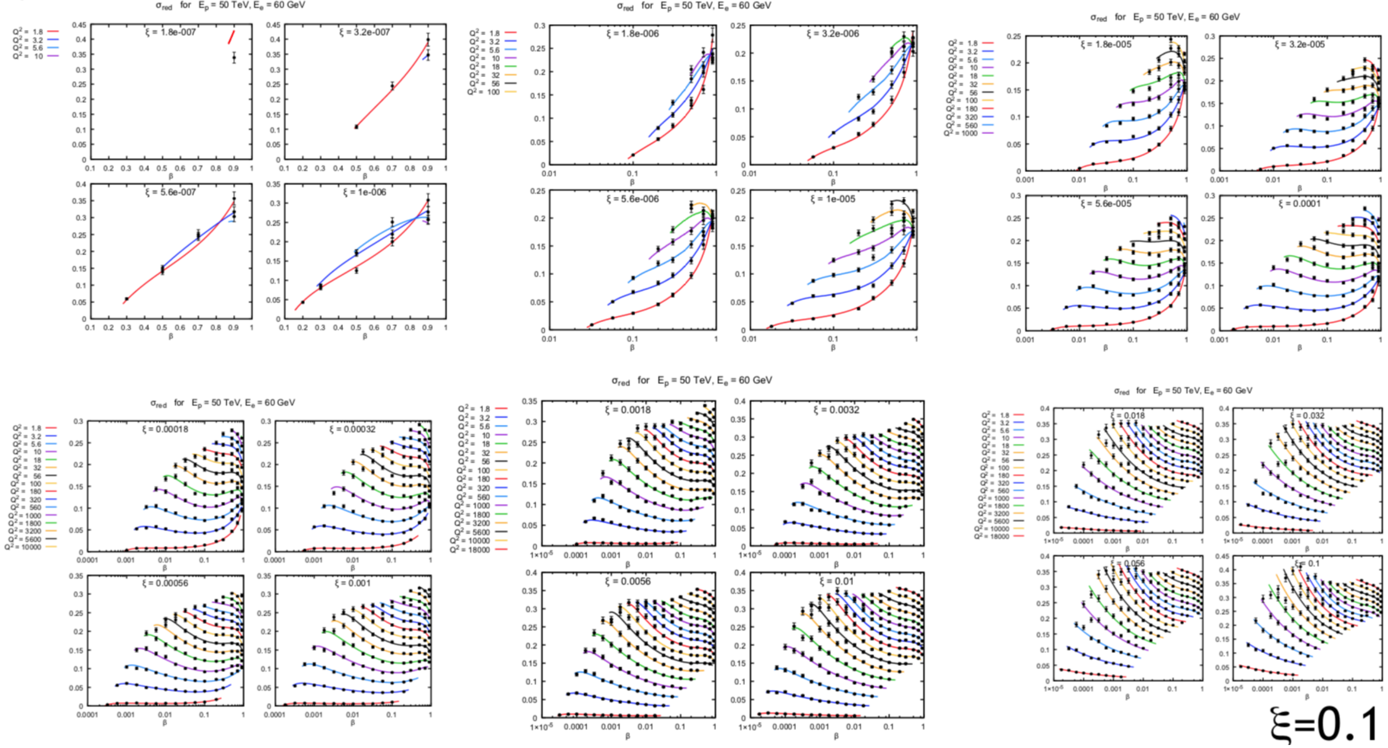


→ **study nuclear effects**
(anti-)shadowing, EMC, Fermi-motion

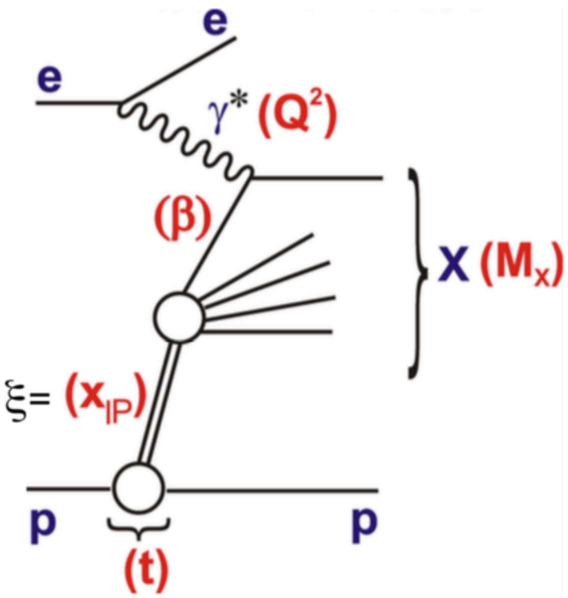
Diffractive Parton Densities

small x

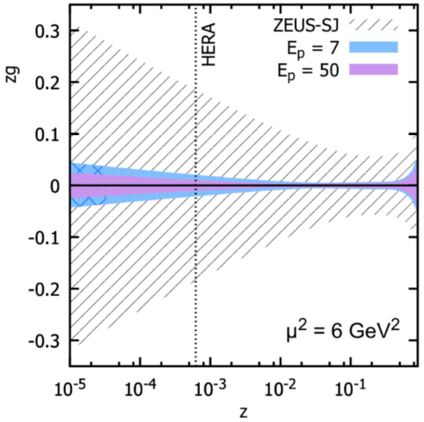
ξ=1.8 x 10^{-7}



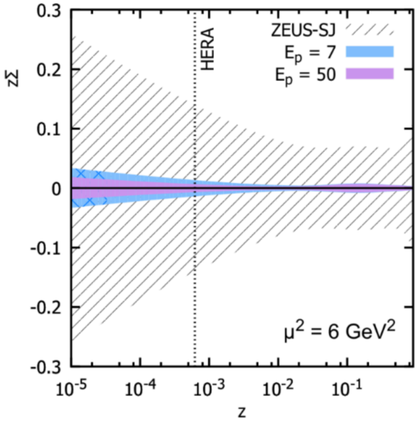
ξ=0.1



Gluons



Quarks

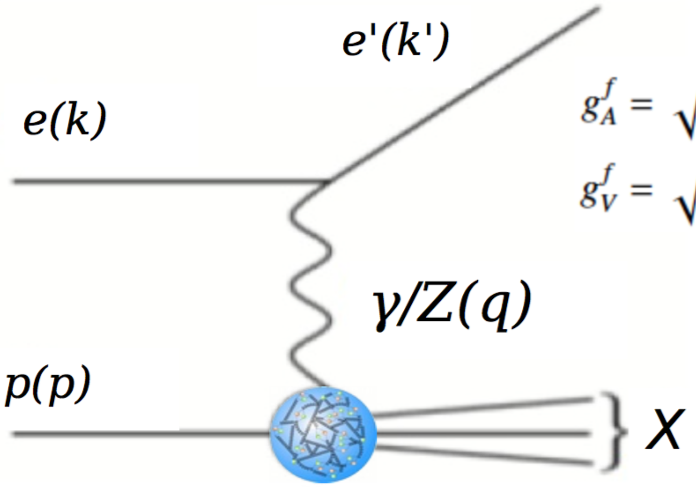


→ **test diffractive factorisation**

→ **test proton vertex factorisation (pomeron structure)**

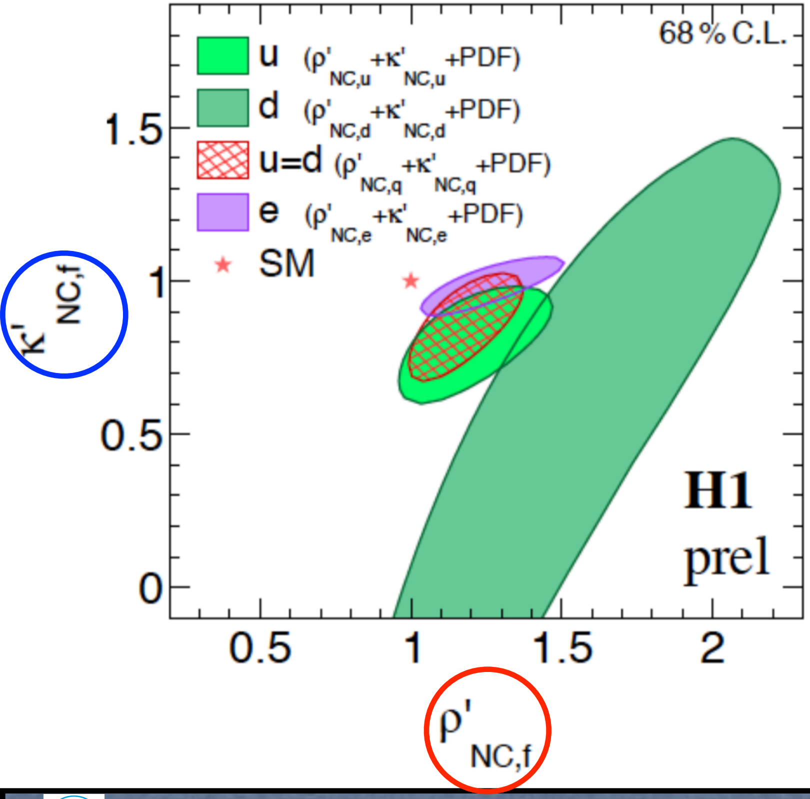
Electroweak Fermion Couplings

EWK



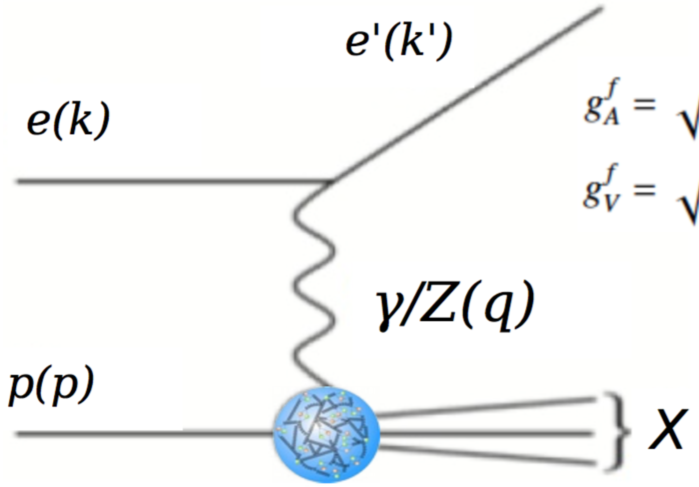
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}\,,$$

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\kappa'_{\mathrm{NC},f}\sin^2\theta_W\right)$$



Electroweak Fermion Couplings

EWK



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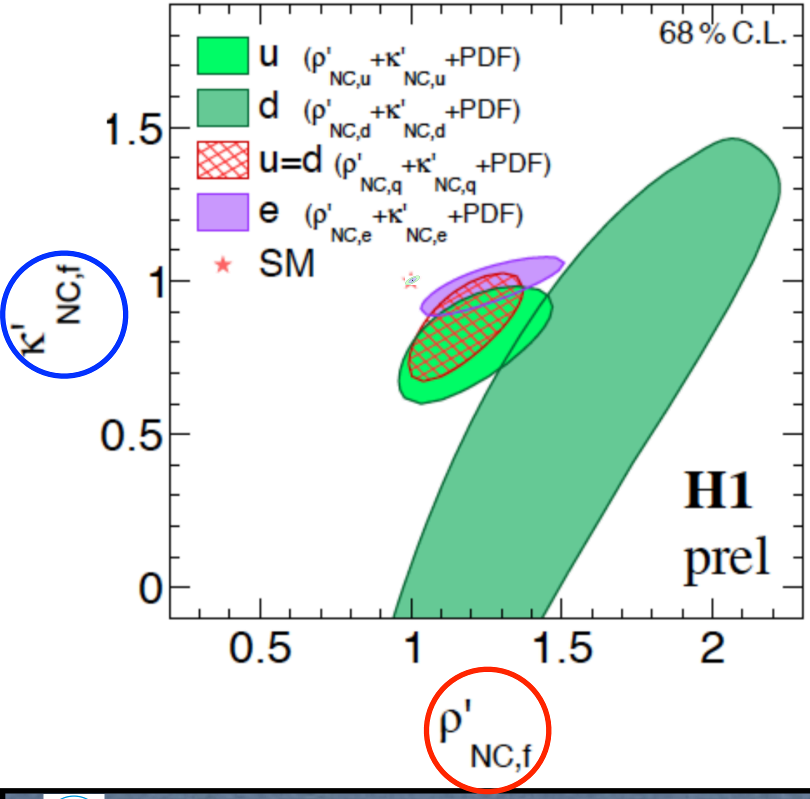
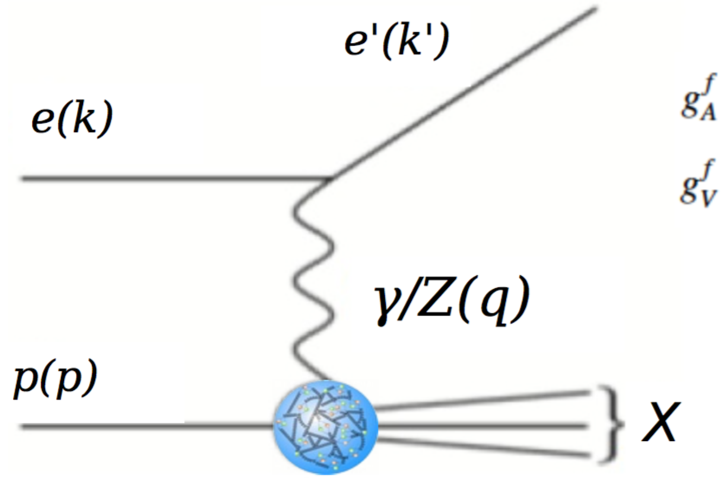


Electroweak Fermion Couplings

EWK



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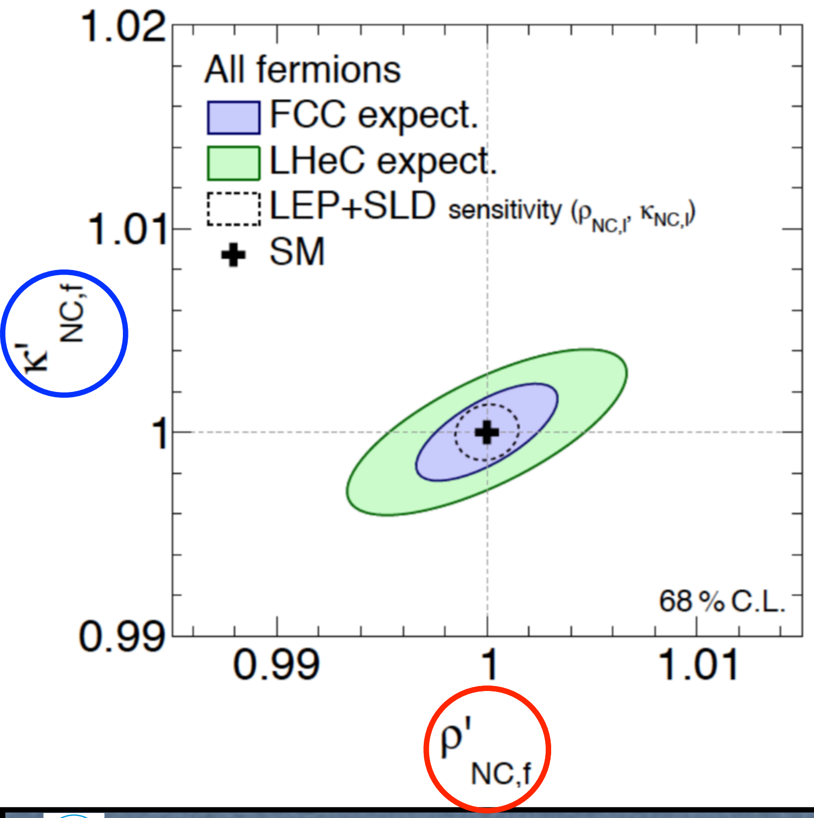
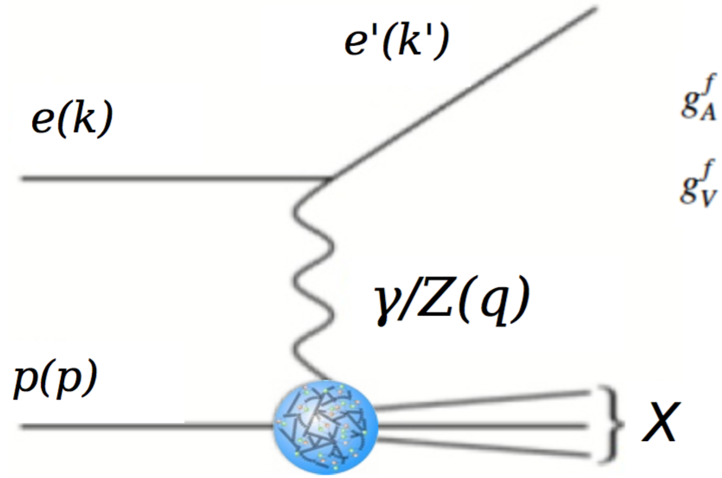


→ **precision < 1%**

Electroweak Fermion Couplings

EWK



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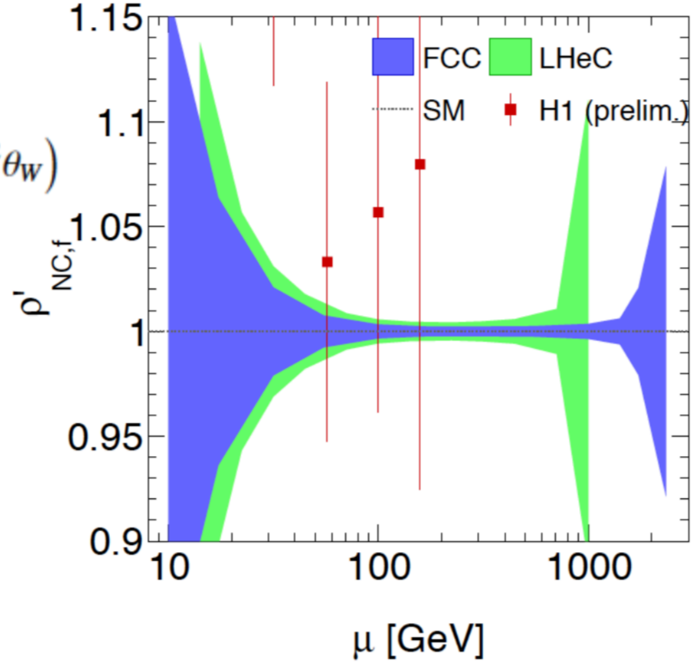
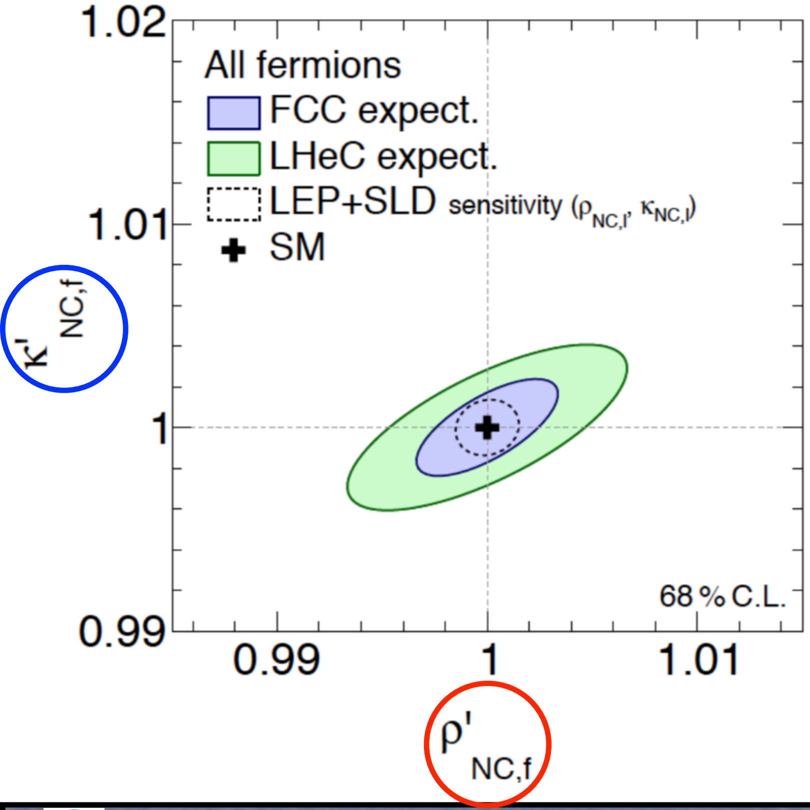
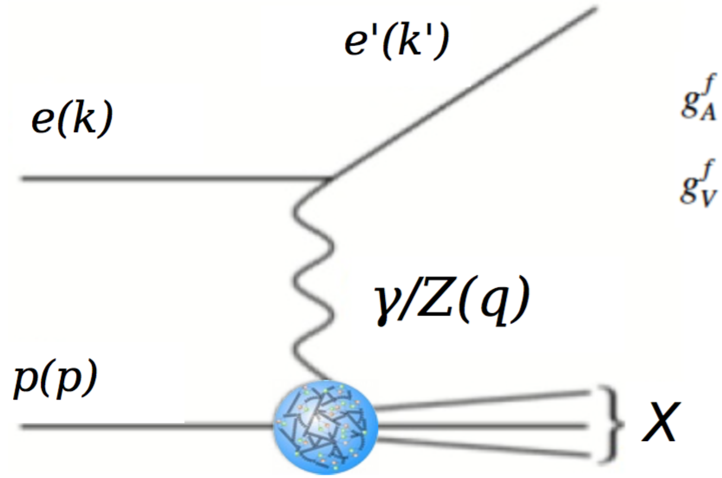


- → **precision < 1%**
- → **scale dependence**



Electroweak Fermion Couplings

EWK



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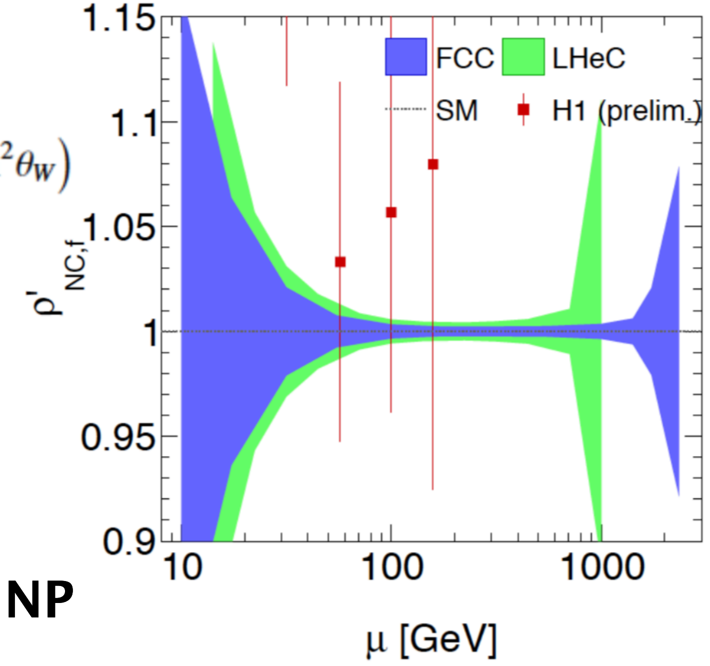
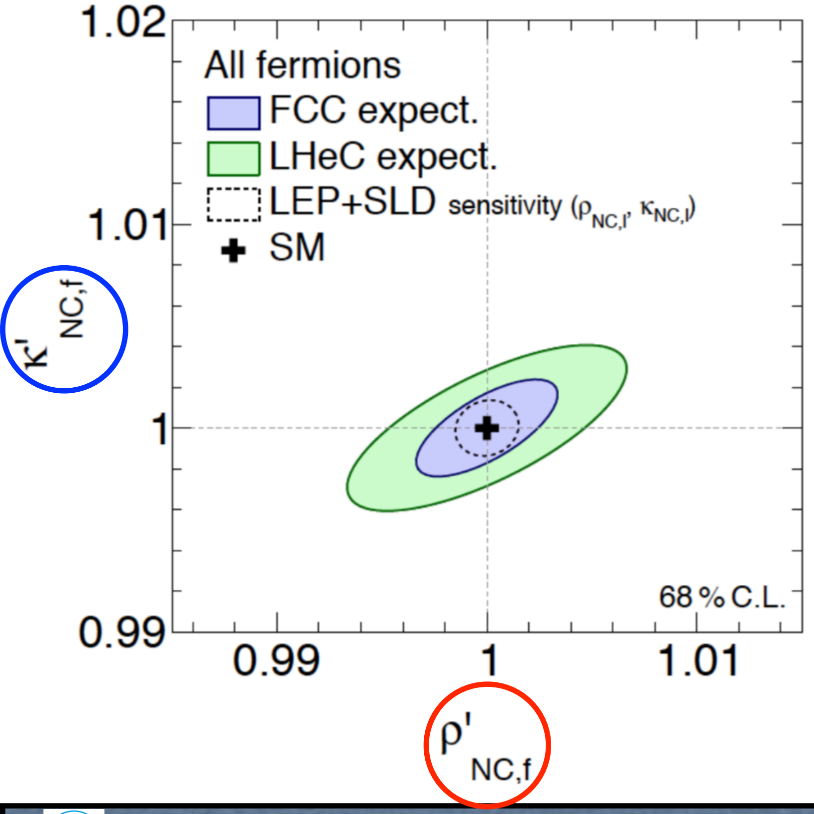
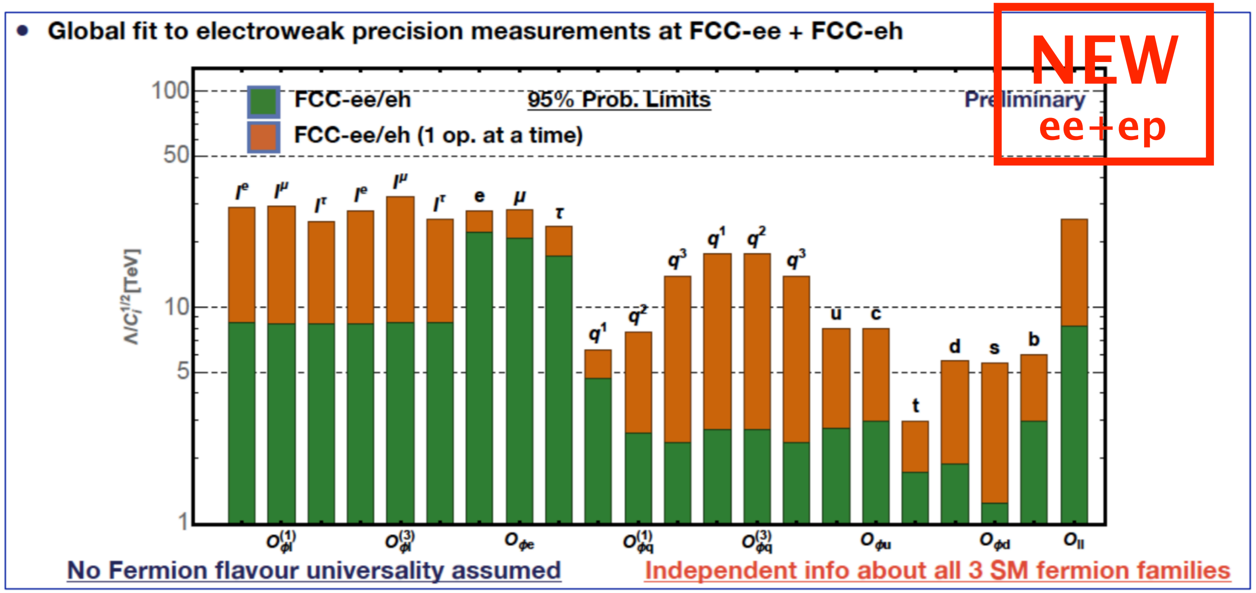




→ **precision < 1%**
→ **scale dependence**
→ **high sensitivity to NP**



- **Global fit to electroweak precision measurements at FCC-ee + FCC-eh**

No Fermion flavour universality assumed

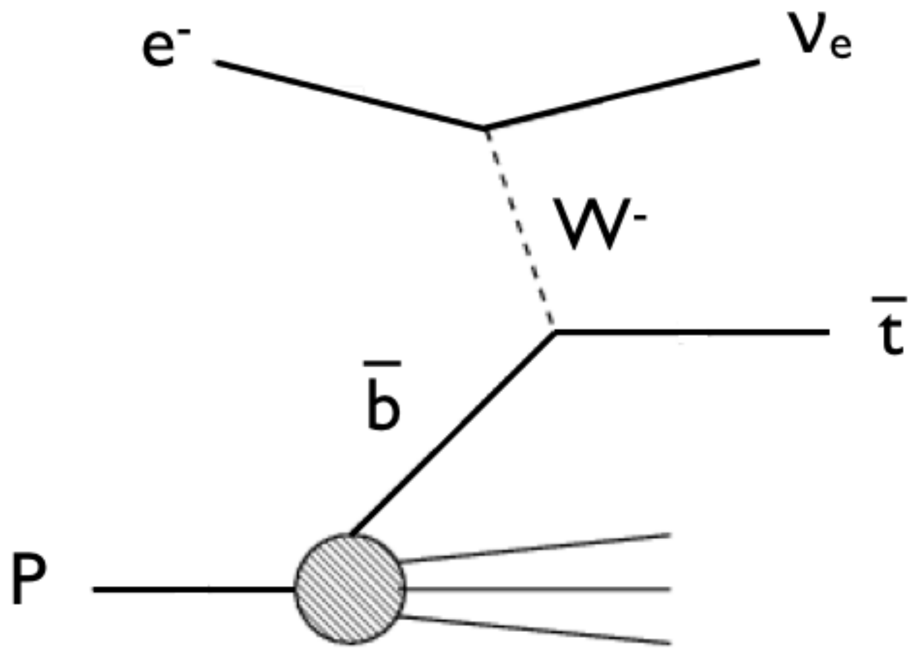
Independent info about all 3 SM fermion families

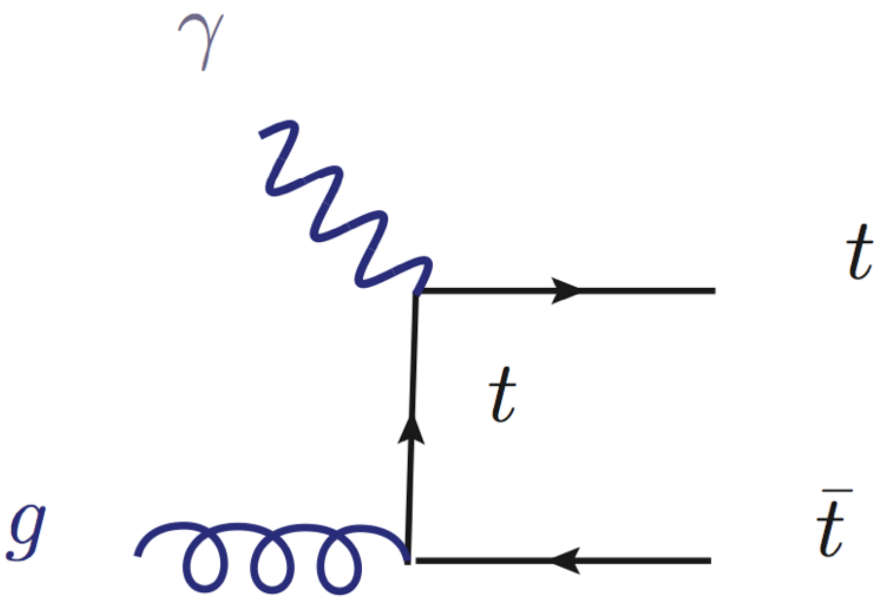
SM Top Quark Production

Top

CC DIS top production

NC top photoproduction





σ=1.73pb @ LHeC

σ=15.3pb @ FCC-ep

E_e=60 GeV

σ=0.05pb @ LHeC

σ=1.14pb @ FCC-ep

→ **future ep collider is ideal to study EWK interactions of the top quark**

Signal and Backgrounds

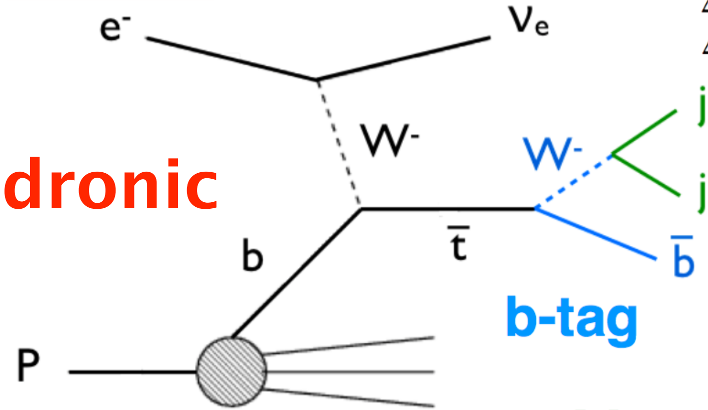
Top

signal

background

Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577

hadronic



$\not{E}_T \geq 25$ GeV

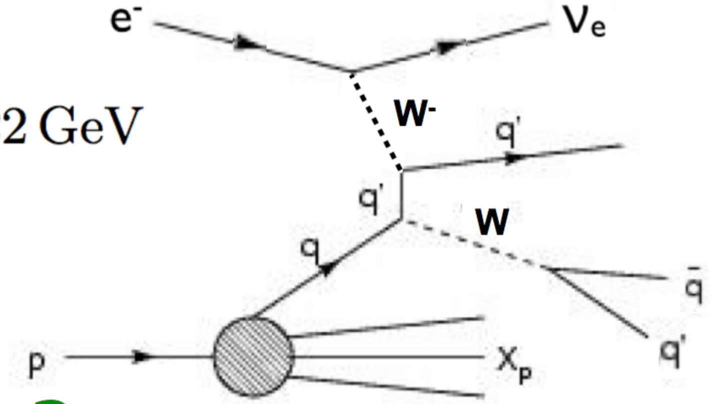
$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$

$|m_{j_1 j_2} - m_W| \leq 22$ GeV

$p_{T\,j,b} \geq 20$ GeV

$|\eta_j| \leq 5, |\eta_b| \leq 2.5$

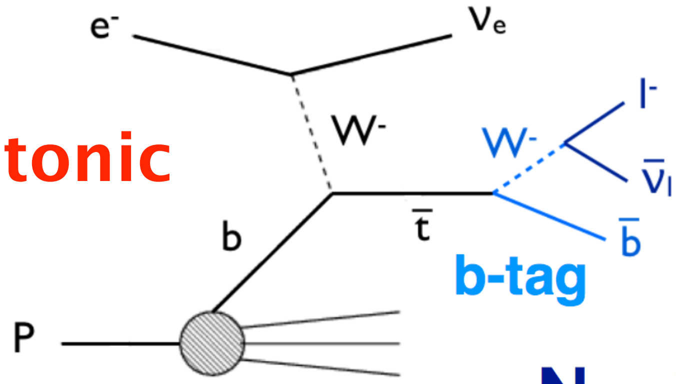
$\Delta R_{j,b/j} \geq 0.4$



N_t=220k, s/b=1.2

e beam: 60 GeV
1000 fb^{-1}

leptonic



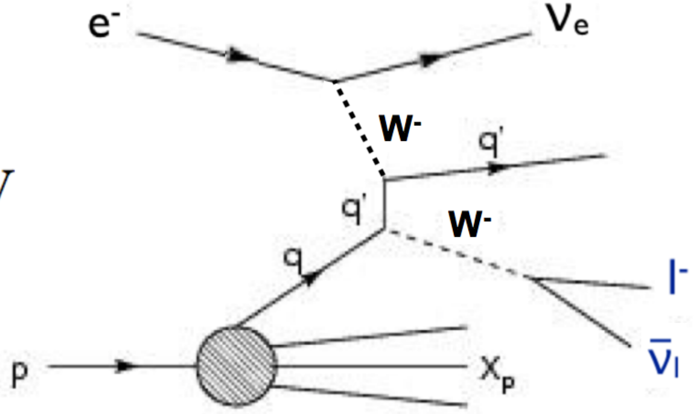
$\not{E}_T \geq 25$ GeV

$\Delta\Phi_{\not{E},j} \geq 0.4$
$\Delta\Phi_{\not{E},b} \geq 0.4$
$\Delta\Phi_{\not{E},l} \geq 0.4$

$p_{T\,j,b,l} \geq 20$ GeV

$|\eta_j| \leq 5,\ |\eta_{b,l}| \leq 2.5$

$\Delta R_{j,b/j} \geq 0.4$



N_t=110k, s/b=11

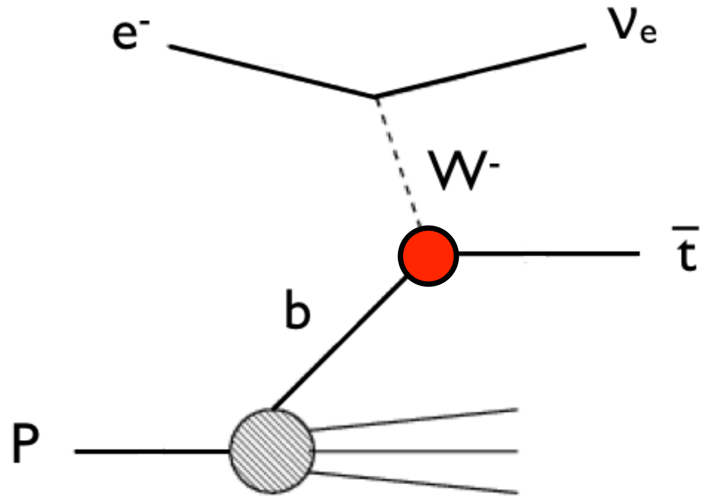
→ **top quark factory (with low backgrounds)**

Limits on Anomalous Wtb Couplings

Top

= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(\boxed{f_V^L} P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$



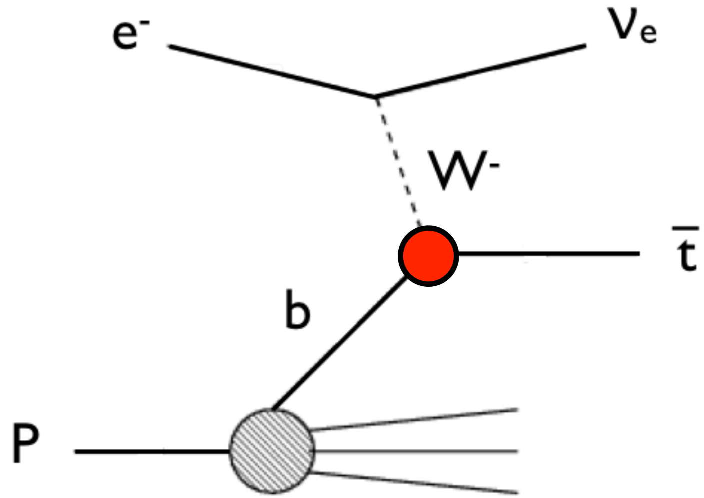
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Limits on Anomalous Wtb Couplings

Top

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

= 1 in SM



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

Limits on Anomalous Wtb Couplings

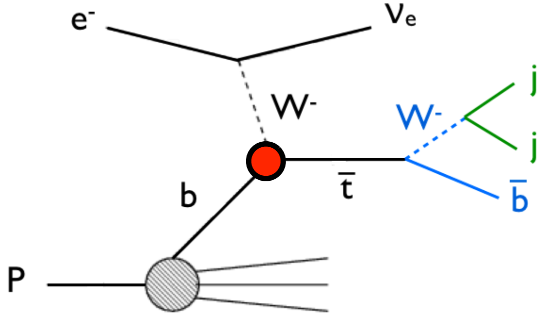
Top

Dutta, Goyal, Kumar,
Mellado, Eur. Phys. J.
C75 (2015) no.12, 577
Kumar, Ruan, to be publ.

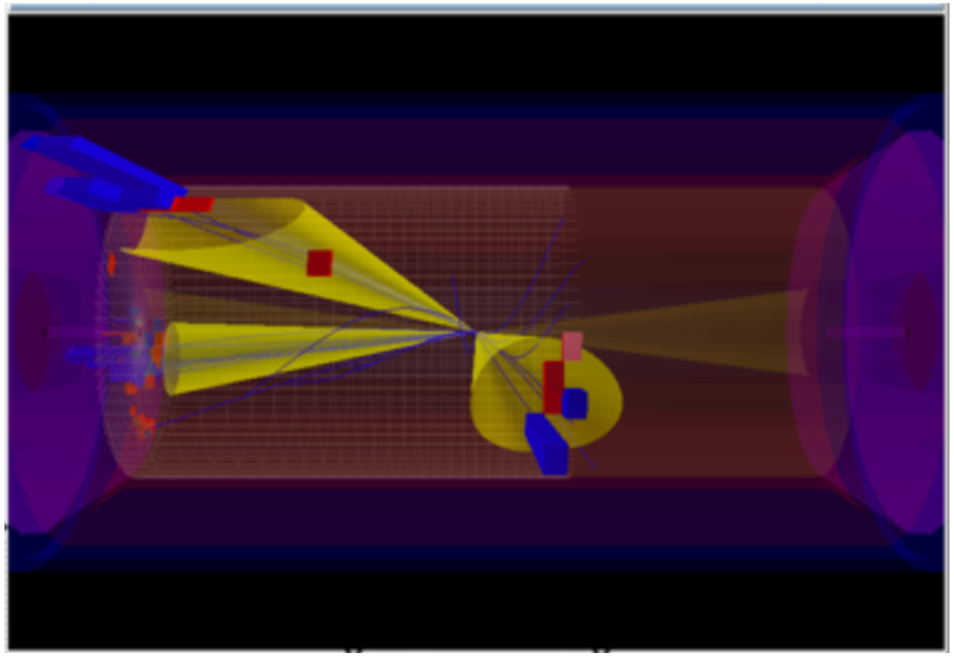
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

= 1 in SM



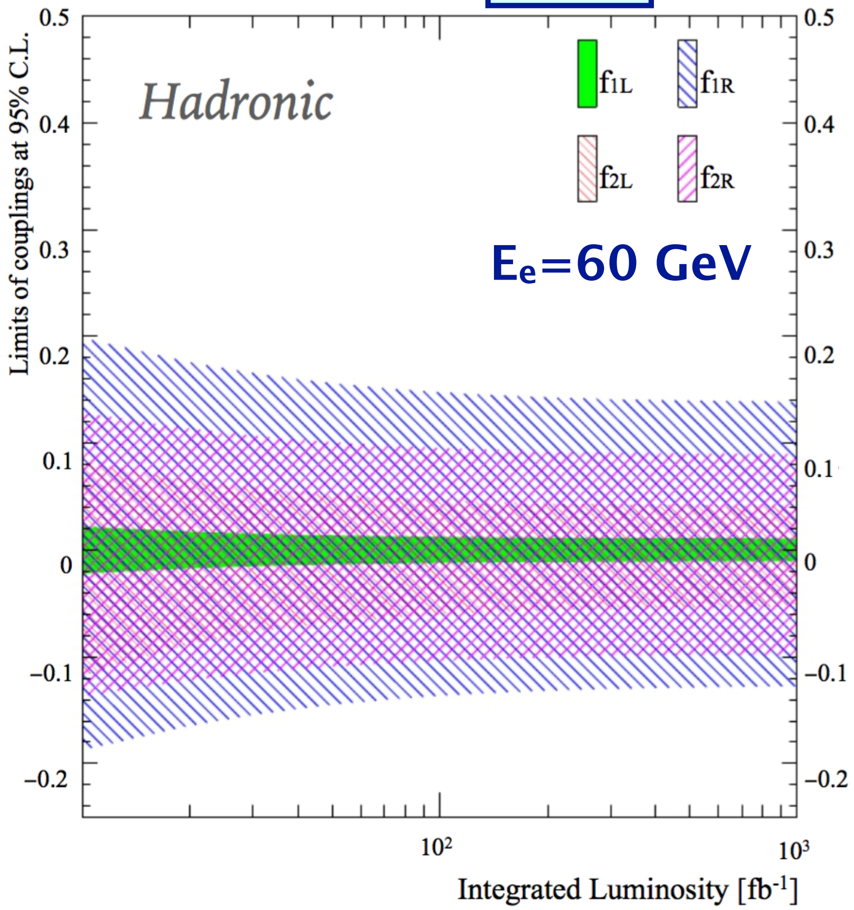
DELPHES



including detector simulation (Delphes)

LHeC

95% C.L.



<0.14

<0.09

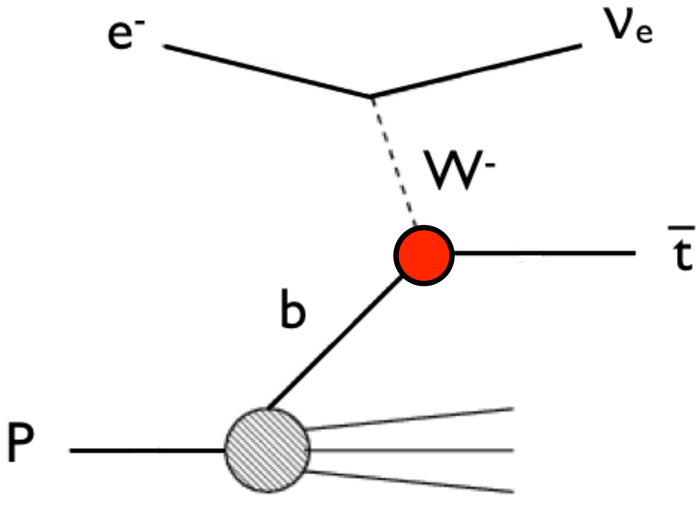
<0.04

<0.01

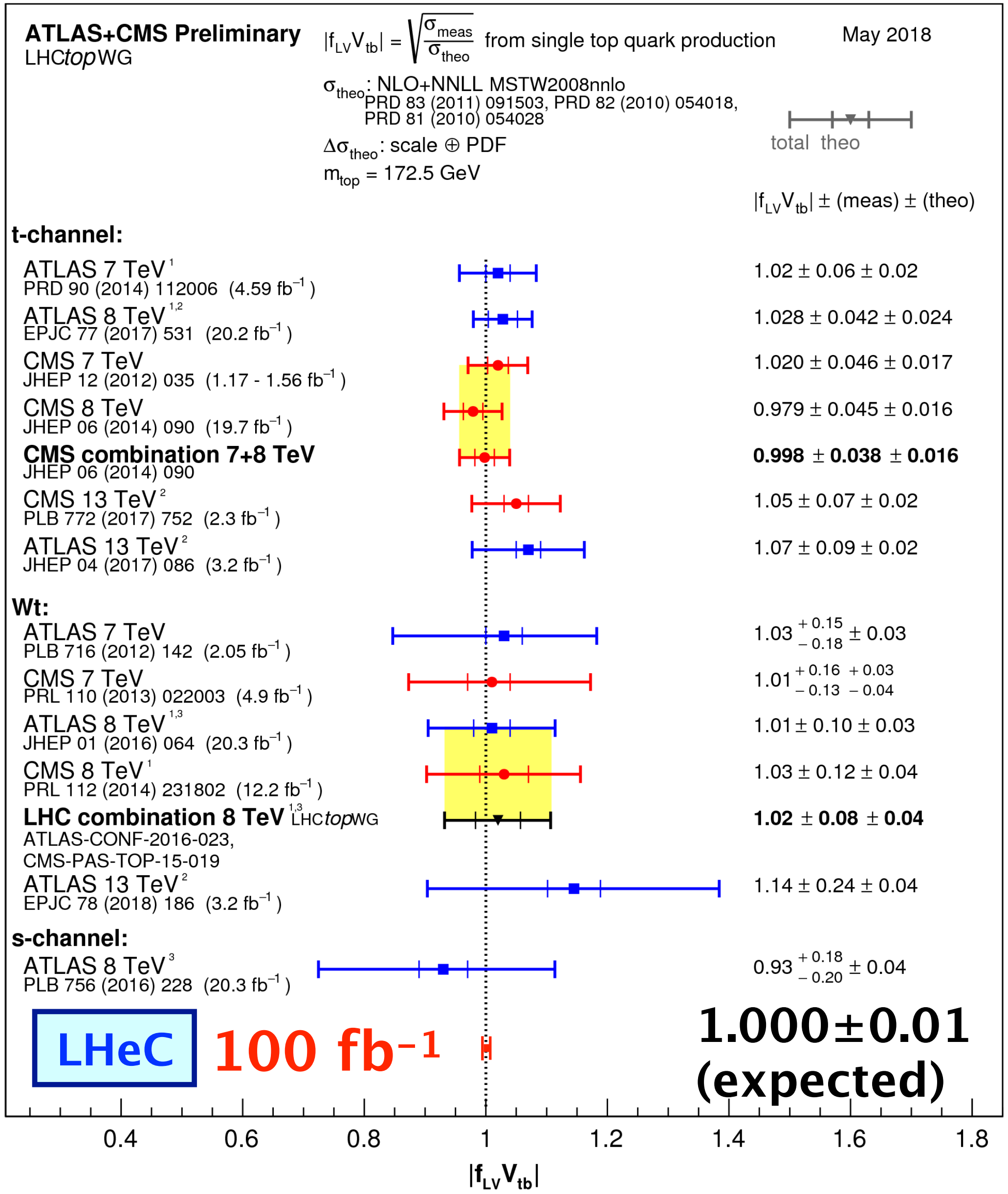
Direct Measurement of $|V_{tb}|$

Top

[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO PDF4LHC11 NPPS205 (2010) 10, CPC191 (2015) 74
[3] including beam energy uncertainty



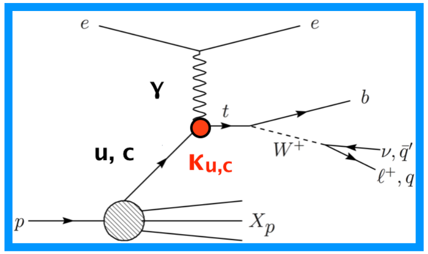
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

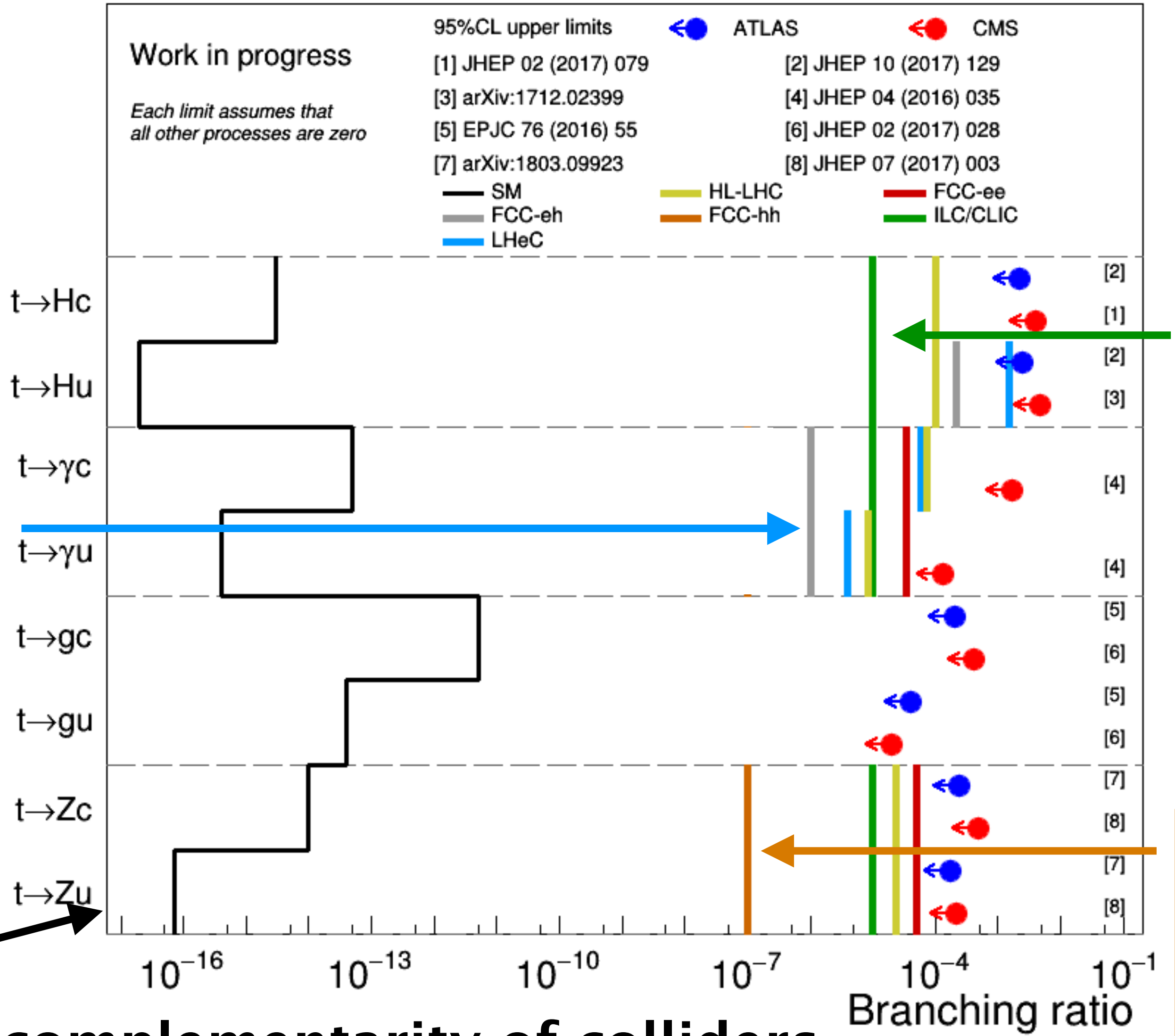


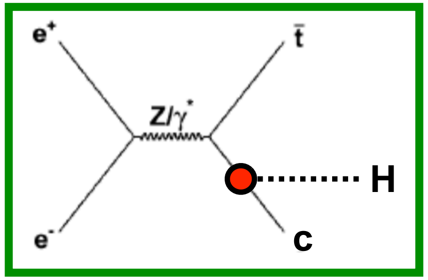
FCNC Top Quark Couplings

Top

LHeC **FCC-ep**

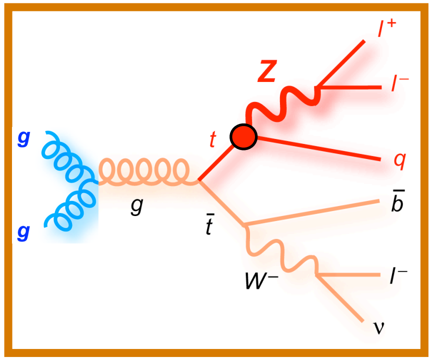


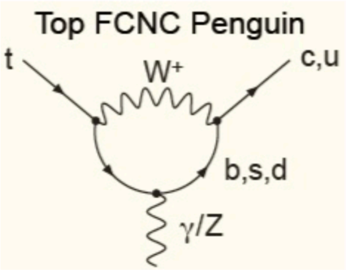




CLIC **FCC-ee**

FCC-pp



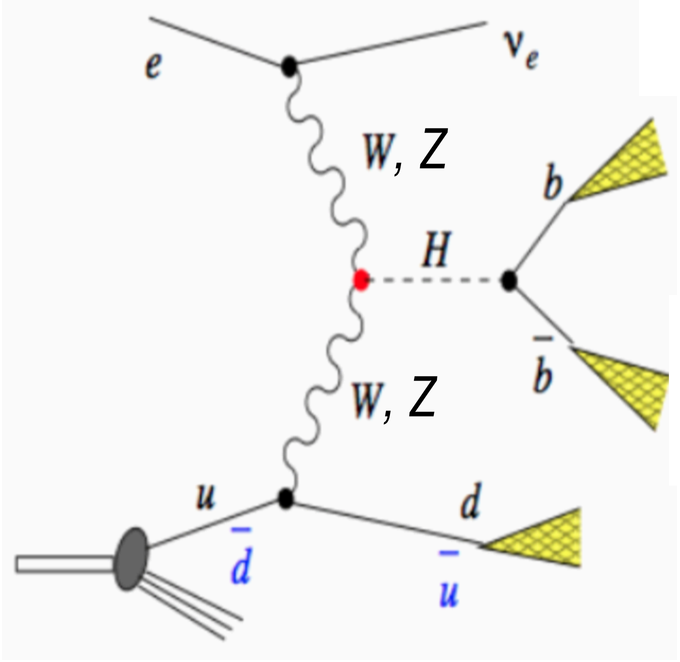


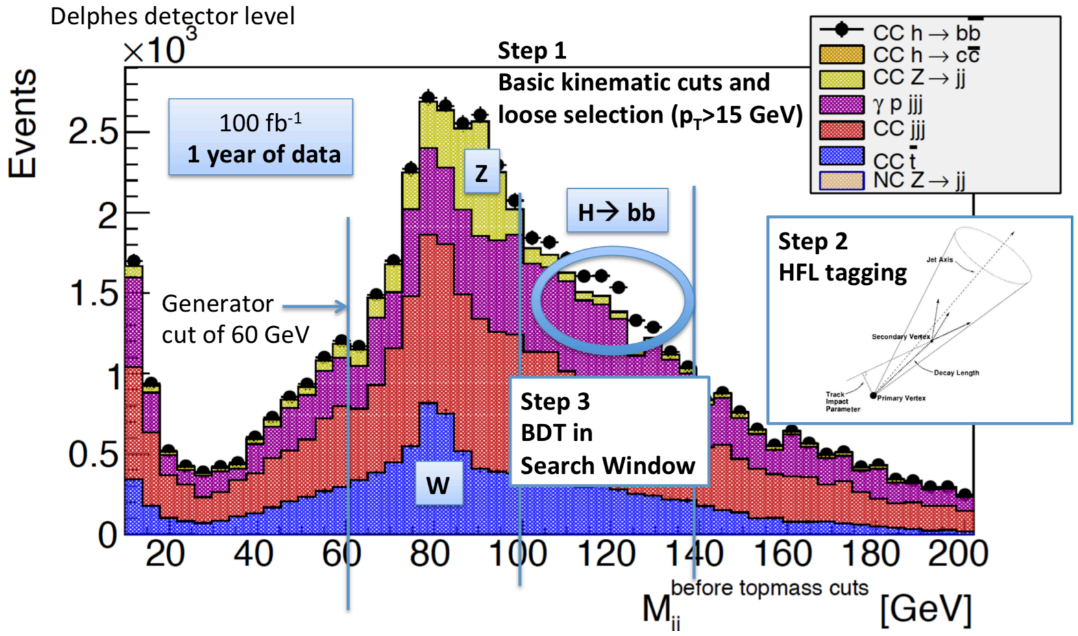
→ **complementarity of colliders**

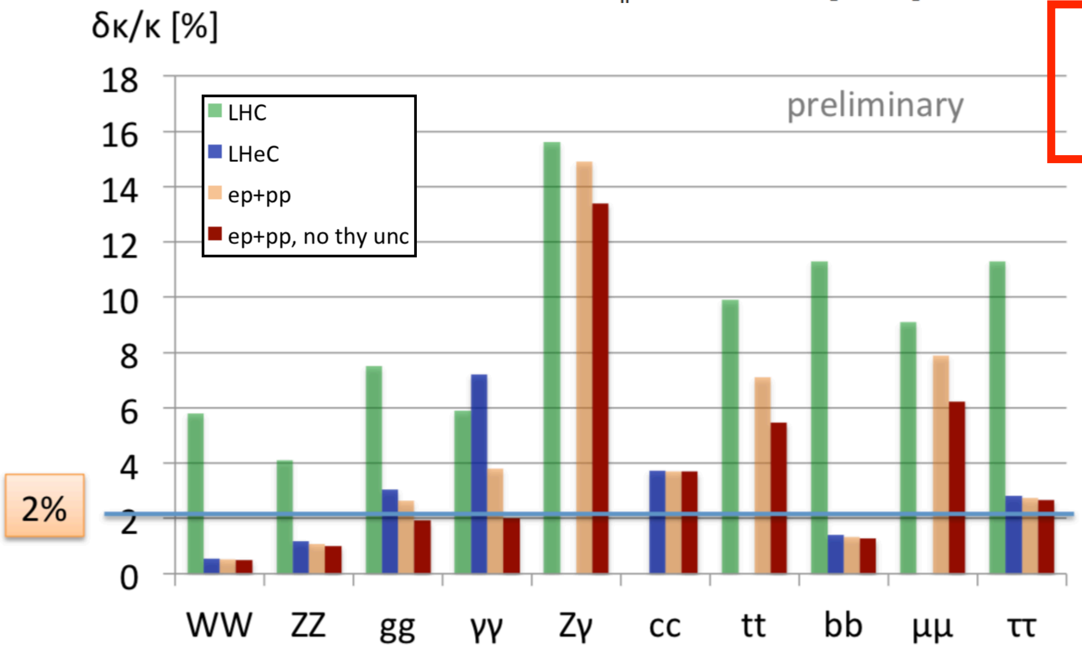
→ **test little Higgs, SUSY, technicolor, …**

Higgs Couplings

CC(e^-p): 196 pb (LHeC)





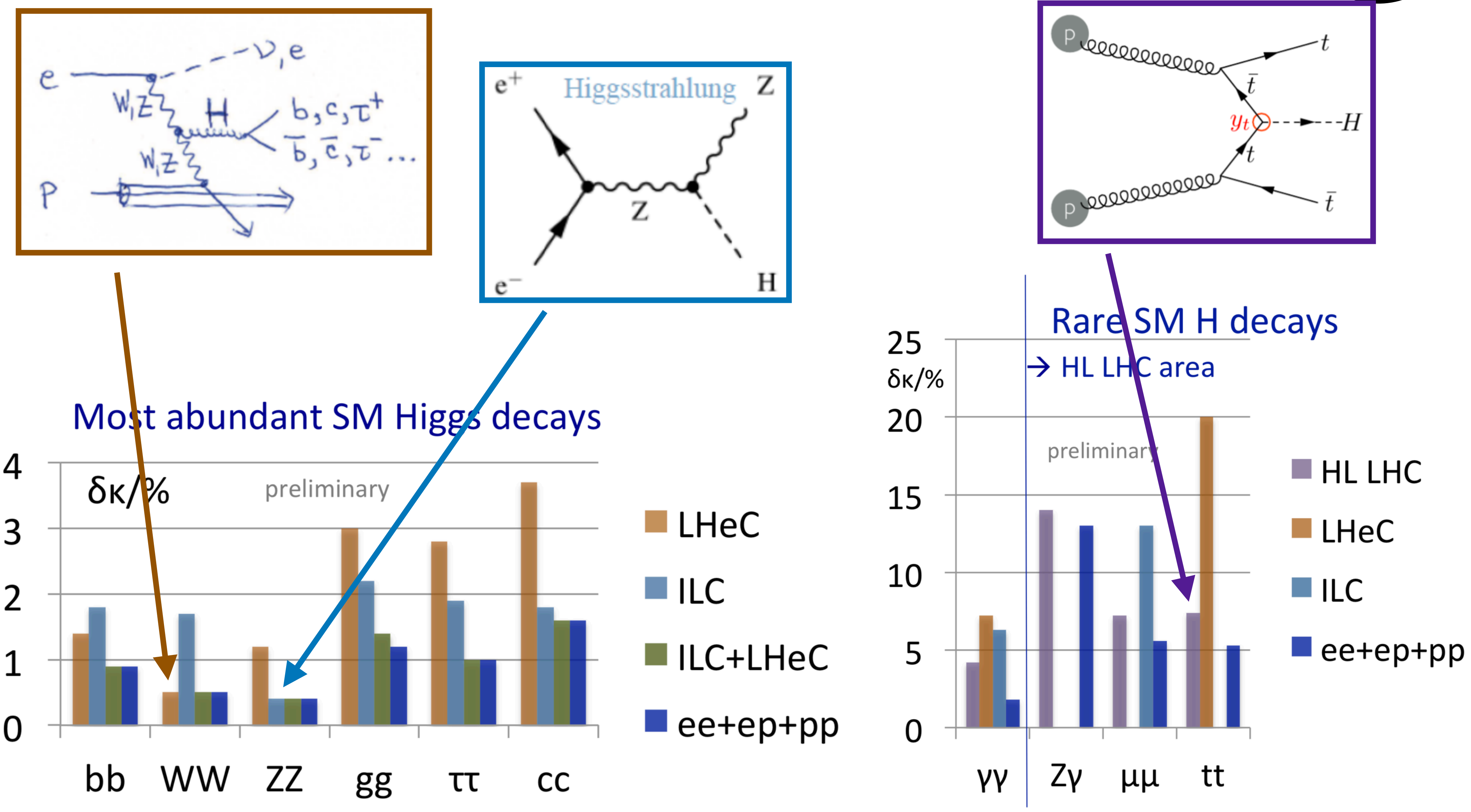


NEW
ep+pp

→ adding electrons makes the LHC a Higgs precision facility

Higgs Couplings

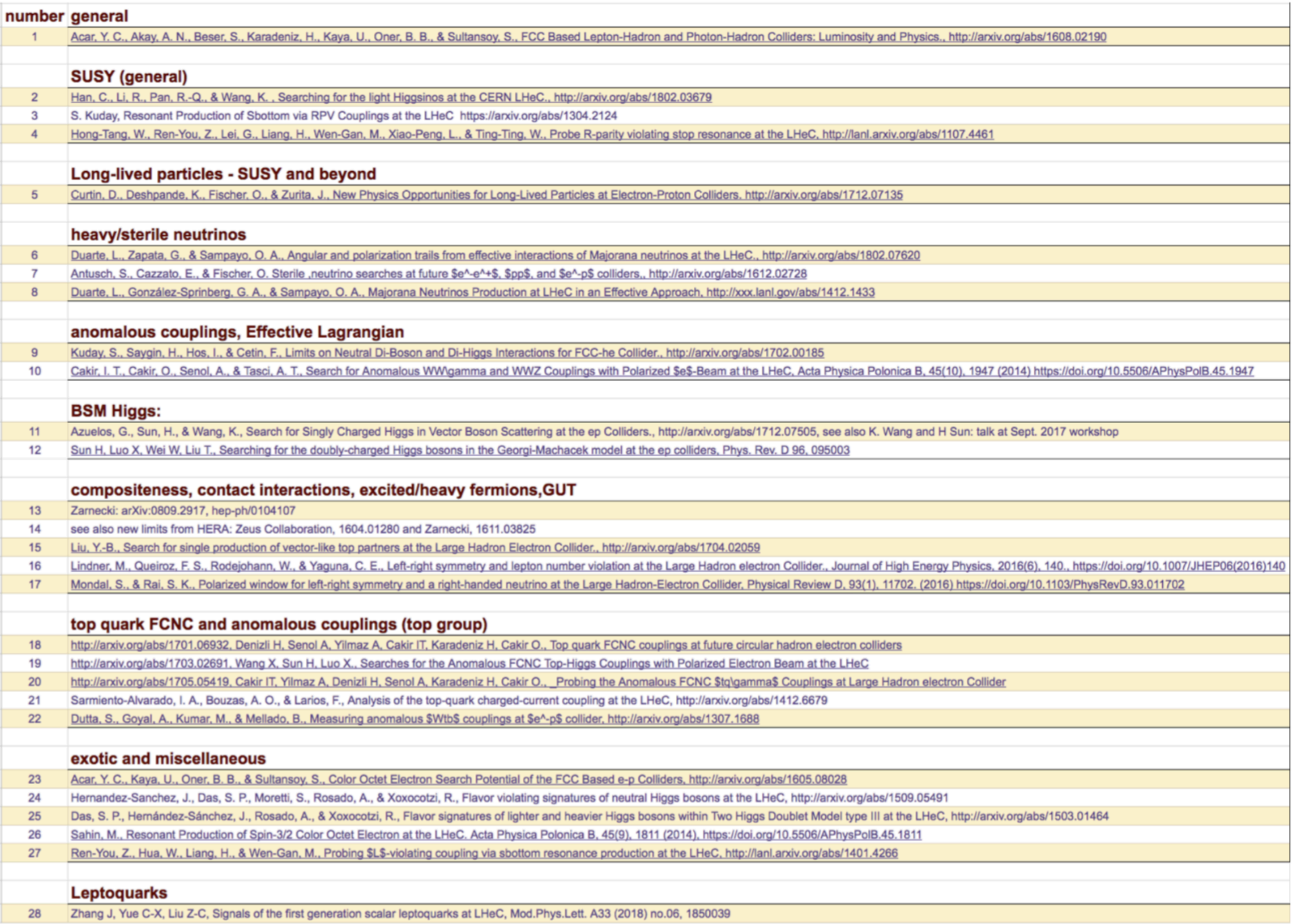
Higgs



→ **complementarity of colliders**

Searches for New Phenomena

BSM



number	general
1	Acar, Y. C., Akay, A. N., Beser, S., Karadeniz, H., Kaya, U., Oner, B. B., & Sultansoy, S., FCC Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics., http://arxiv.org/abs/1608.02190
	SUSY (general)
2	Han, C., Li, R., Pan, R.-Q., & Wang, K. , Searching for the light Higgsinos at the CERN LHeC., http://arxiv.org/abs/1802.03679
3	S. Kuday, Resonant Production of Sbottom via RPV Couplings at the LHeC https://arxiv.org/abs/1304.2124
4	Hong-Tang, W., Ren-You, Z., Lei, G., Liang, H., Wen-Gan, M., Xiao-Peng, L., & Ting-Ting, W., Probe R-parity violating stop resonance at the LHeC, http://lanl.arxiv.org/abs/1107.4461
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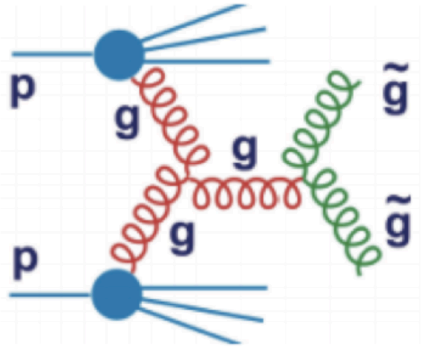
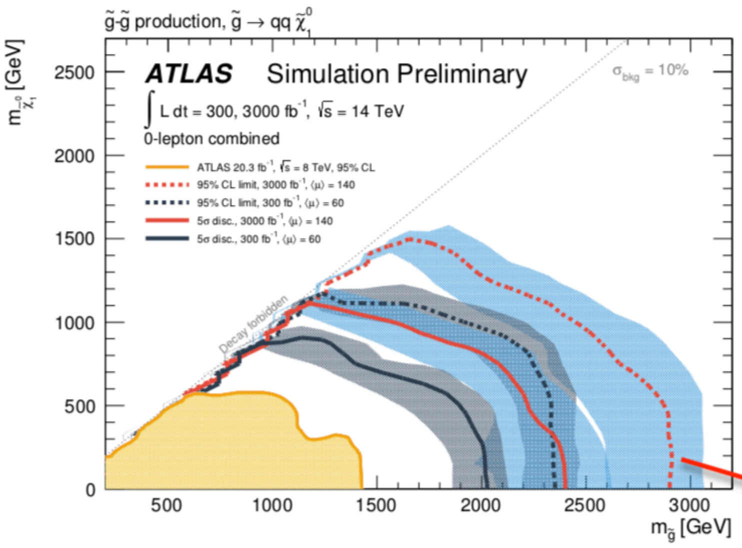
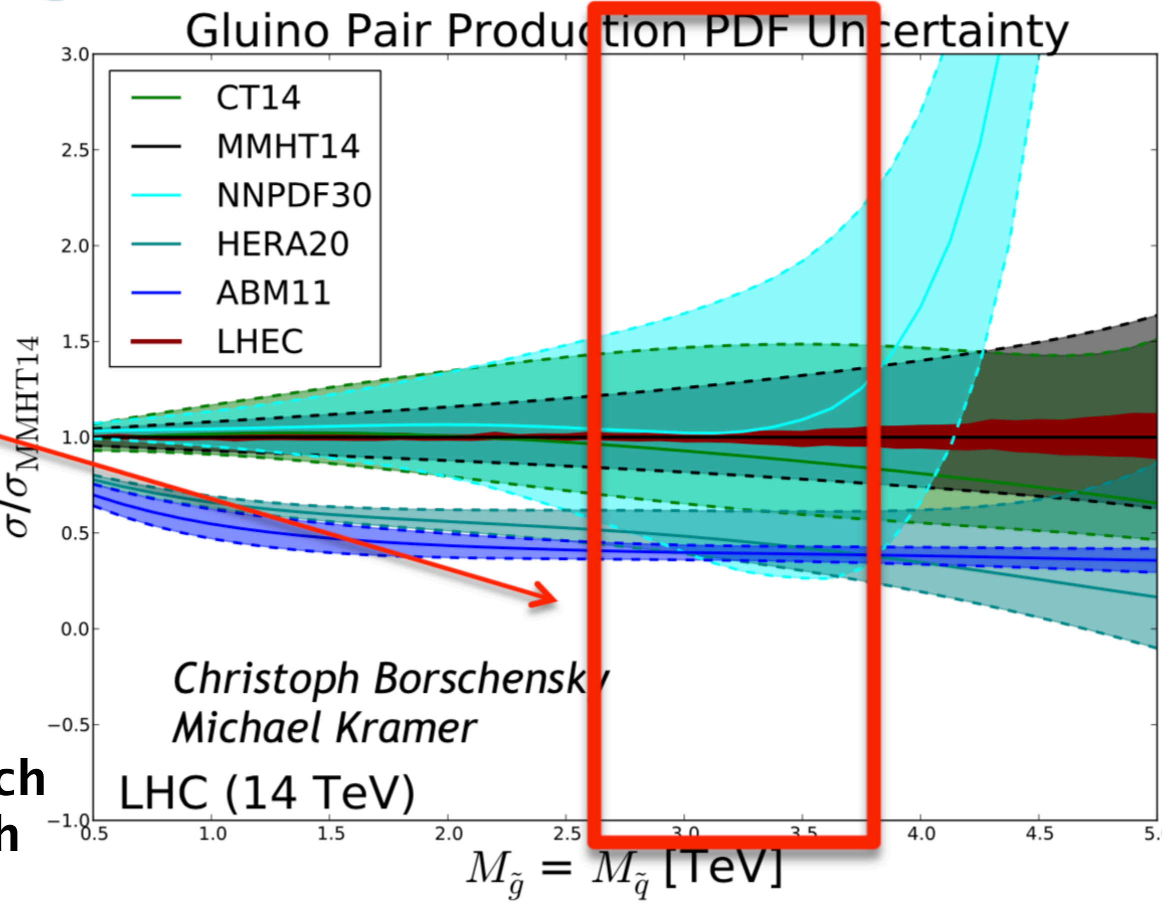
5	Curtin, D., Deshpande, K., Fischer, O., & Zurita, J., New Physics Opportunities for Long-Lived Particles at Electron-Proton Colliders, http://arxiv.org/abs/1712.07135
	heavy/sterile neutrinos
6	Duarte, L., Zapata, G., & Sampayo, O. A., Angular and polarization trails from effective interactions of Majorana neutrinos at the LHeC., http://arxiv.org/abs/1802.07620
7	Antusch, S., Cazzato, E., & Fischer, O. Sterile ,neutrino searches at future e^-e^+, pp, and e^-p colliders,, http://arxiv.org/abs/1612.02728
8	Duarte, L., González-Sprinberg, G. A., & Sampayo, O. A., Majorana Neutrinos Production at LHeC in an Effective Approach, http://xxx.lanl.gov/abs/1412.1433
	anomalous couplings, Effective Lagrangian
9	Kuday, S., Saygin, H., Hos, I., & Cetin, F., Limits on Neutral Di-Boson and Di-Higgs Interactions for FCC-he Collider., http://arxiv.org/abs/1702.00185
10	Cakir, I. T., Cakir, O., Senol, A., & Tasci, A. T., Search for Anomalous WW\gamma and WWZ Couplings with Polarized e-Beam at the LHeC, Acta Physica Polonica B, 45(10), 1947 (2014) https://doi.org/10.5506/APhysPolB.45.1947
	BSM Higgs:
11	Azuelos, G., Sun, H., & Wang, K., Search for Singly Charged Higgs in Vector Boson Scattering at the ep Colliders., http://arxiv.org/abs/1712.07505, see also K. Wang and H Sun: talk at Sept. 2017 workshop
12	Sun H, Luo X, Wei W, Liu T., Searching for the doubly-charged Higgs bosons in the Georgi-Machacek model at the ep colliders, Phys. Rev. D 96, 095003
	compositeness, contact interactions, excited/heavy fermions,GUT
13	Zarnecki: arXiv:0809.2917, hep-ph/0104107
14	see also new limits from HERA: Zeus Collaboration, 1604.01280 and Zarnecki, 1611.03825
15	Liu, Y.-B., Search for single production of vector-like top partners at the Large Hadron Electron Collider., http://arxiv.org/abs/1704.02059
16	Lindner, M., Queiroz, F. S., Rodejohann, W., & Yaguna, C. E., Left-right symmetry and lepton number violation at the Large Hadron electron Collider., Journal of High Energy Physics, 2016(6), 140., https://doi.org/10.1007/JHEP06(2016)140
17	Mondal, S., & Rai, S. K., Polarized window for left-right symmetry and a right-handed neutrino at the Large Hadron-Electron Collider, Physical Review D, 93(1), 11702. (2016) https://doi.org/10.1103/PhysRevD.93.011702
	top quark FCNC and anomalous couplings (top group)
18	http://arxiv.org/abs/1701.06932, Denizli H, Senol A, Yilmaz A, Cakir IT, Karadeniz H, Cakir O., Top quark FCNC couplings at future circular hadron electron colliders
19	http://arxiv.org/abs/1703.02691, Wang X, Sun H, Luo X., Searches for the Anomalous FCNC Top-Higgs Couplings with Polarized Electron Beam at the LHeC
20	http://arxiv.org/abs/1705.05419, Cakir IT, Yilmaz A, Denizli H, Senol A, Karadeniz H, Cakir O., _Probing the Anomalous FCNC $tq\gamma$ Couplings at Large Hadron electron Collider
21	Sarmiento-Alvarado, I. A., Bouzas, A. O., & Larios, F., Analysis of the top-quark charged-current coupling at the LHeC, http://arxiv.org/abs/1412.6679
22	Dutta, S., Goyal, A., Kumar, M., & Mellado, B., Measuring anomalous Wtb couplings at e^-p collider, http://arxiv.org/abs/1307.1688
	exotic and miscellaneous
23	Acar, Y. C., Kaya, U., Oner, B. B., & Sultansoy, S., Color Octet Electron Search Potential of the FCC Based e-p Colliders, http://arxiv.org/abs/1605.08028
24	Hernandez-Sanchez, J., Das, S. P., Moretti, S., Rosado, A., & Xoxocotzi, R., Flavor violating signatures of neutral Higgs bosons at the LHeC, http://arxiv.org/abs/1509.05491
25	Das, S. P., Hernández-Sánchez, J., Rosado, A., & Xoxocotzi, R., Flavor signatures of lighter and heavier Higgs bosons within Two Higgs Doublet Model type III at the LHeC, http://arxiv.org/abs/1503.01464
26	Sahin, M., Resonant Production of Spin-3/2 Color Octet Electron at the LHeC. Acta Physica Polonica B, 45(9), 1811 (2014), https://doi.org/10.5506/APhysPolB.45.1811
27	Ren-You, Z., Hua, W., Liang, H., & Wen-Gan, M., Probing L-violating coupling via sbottom resonance production at the LHeC, http://lanl.arxiv.org/abs/1401.4266
	Leptoquarks
28	Zhang J, Yue C-X, Liu Z-C, Signals of the first generation scalar leptoquarks at LHeC, Mod.Phys.Lett. A33 (2018) no.06, 1850039

Impact of PDF @ High x

BSM





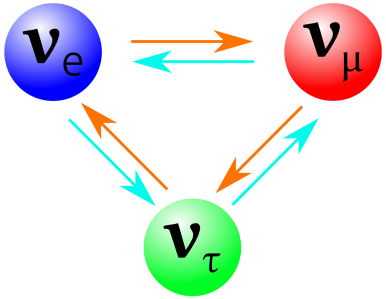


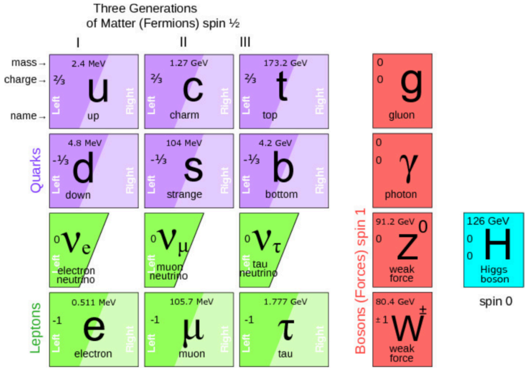
- Studies updated with modern PDF sets!
  - M(squark)=M(gluino)=μ_R=μ_F
  - LHeC PDF uncertainties unchanged
  - Normalized to MMHT14

→ **needs to be quantified by how much HL-LHC analyses would improve with PDFs being measured at LHeC**

Sterile Neutrinos

BSM

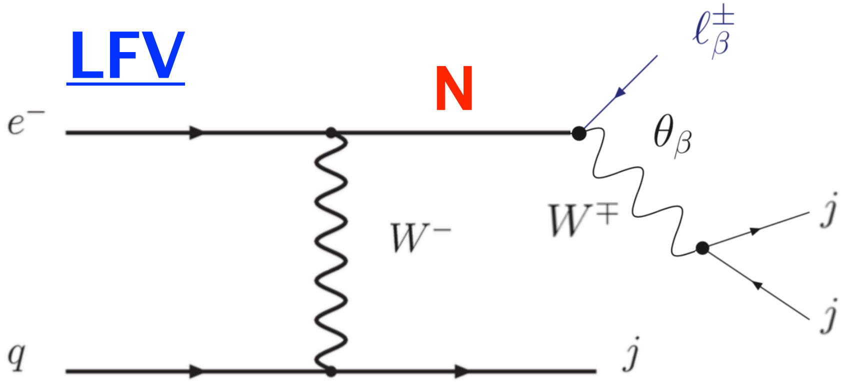




Three Generations of Matter (Fermions) spin ½

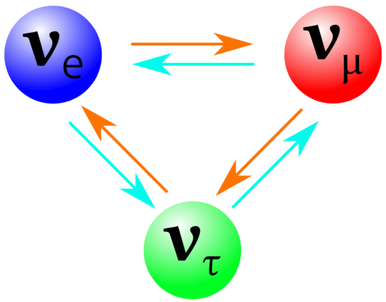
	I	II	III	Bosons (Forces) spin 1	spin 0
mass → charge → name → Quarks	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	173.2 GeV ⅔ t top Left Right	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right	0 0 γ photon	
Leptons	0 ν_e electron neutrino Left	0 ν_μ muon neutrino Left	0 ν_τ tau neutrino Left	91.2 GeV 0 Z^0 weak force	126 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^\pm$ weak force	

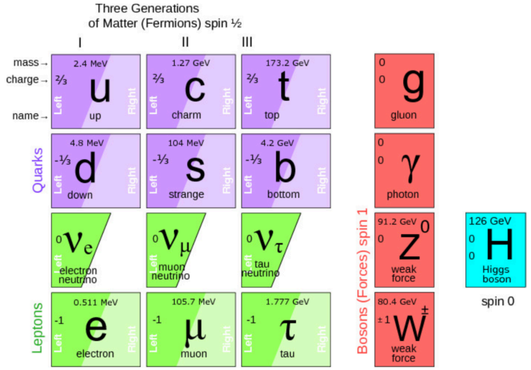
LFV

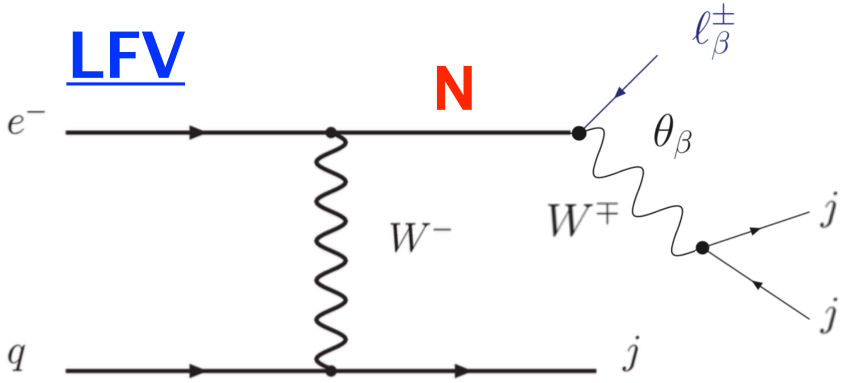


Sterile Neutrinos

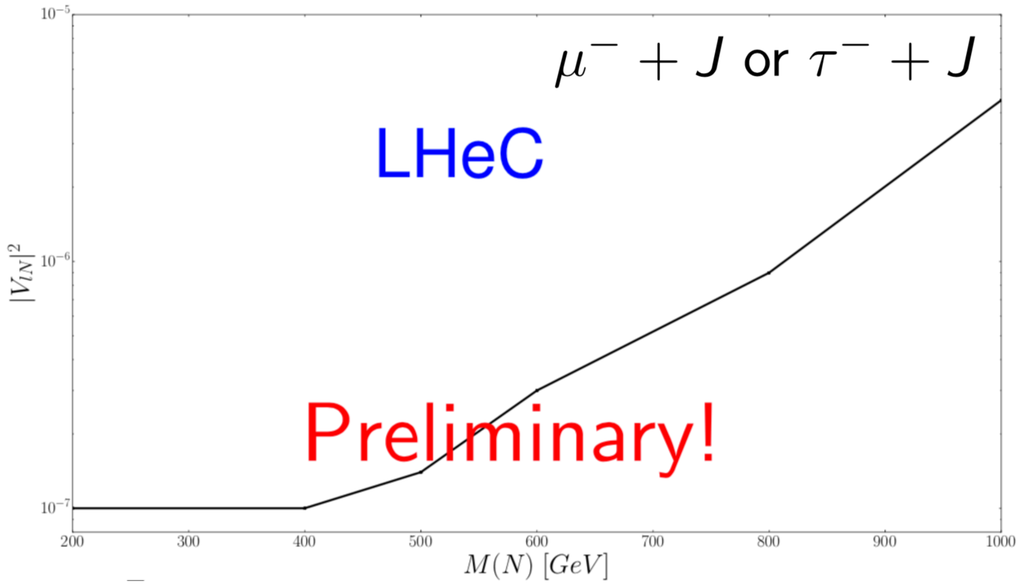
BSM





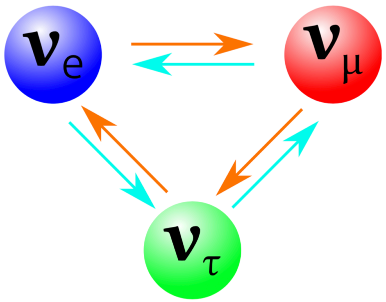


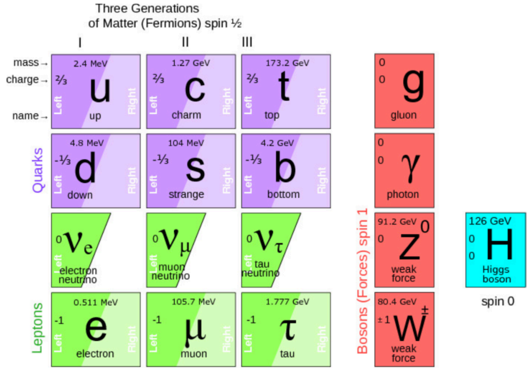
+ **many backgrounds included**



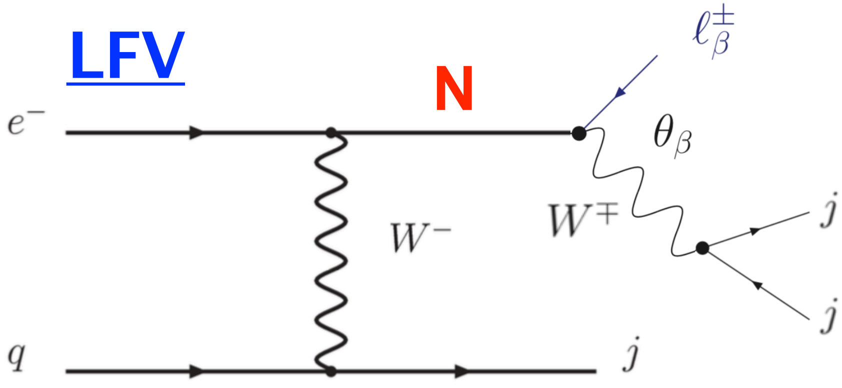
Sterile Neutrinos

BSM

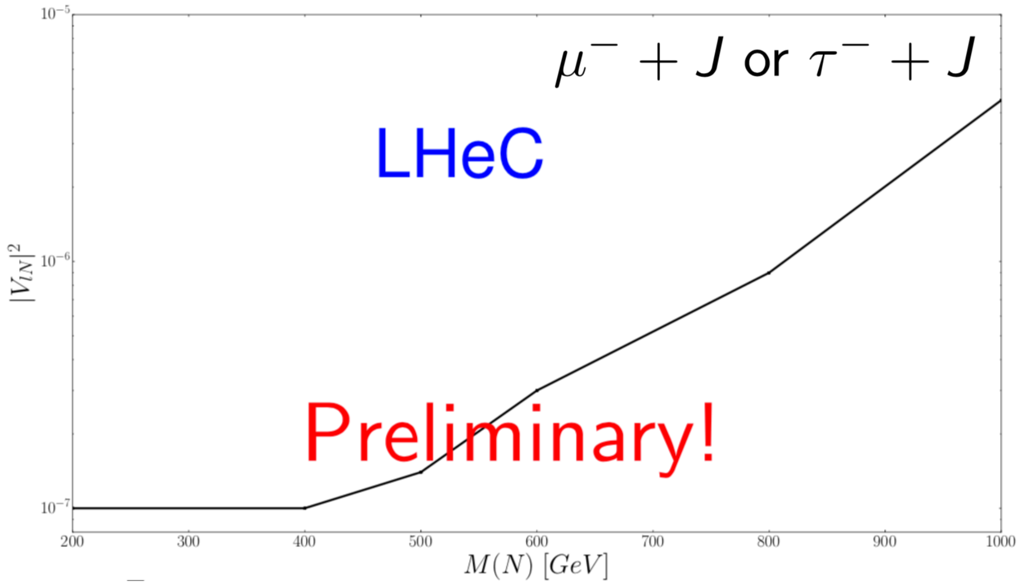


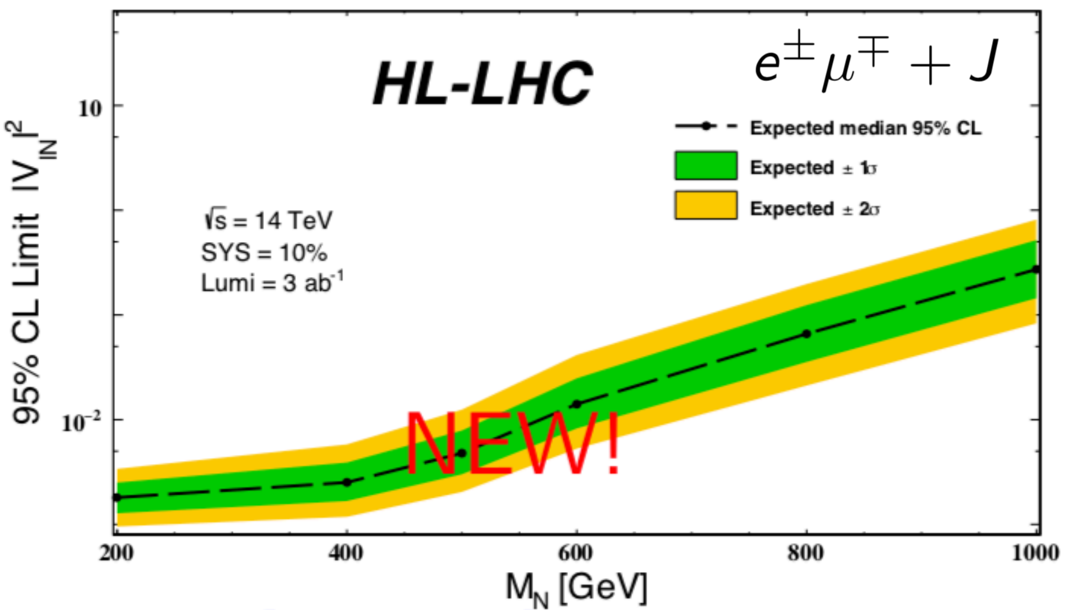


LFV



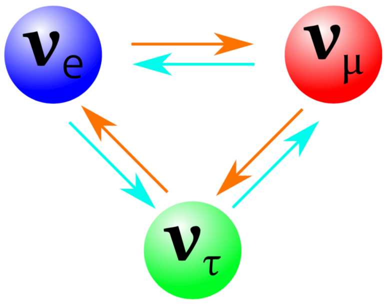
+ **many backgrounds included**

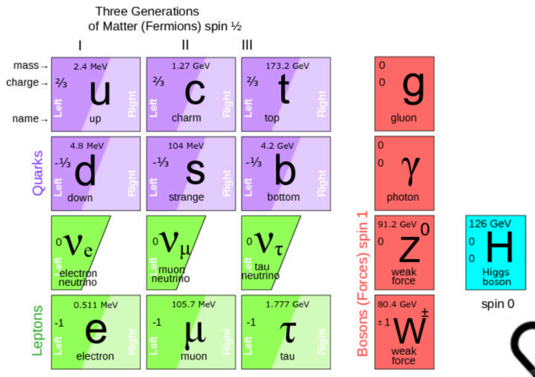




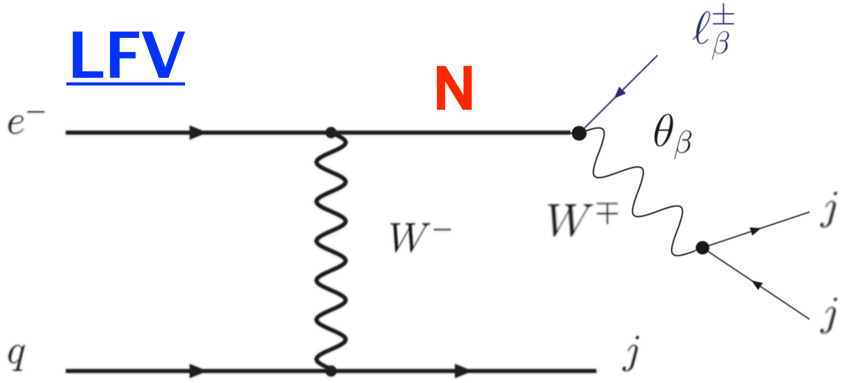
Antusch et al.; [1805.11400]

BSM



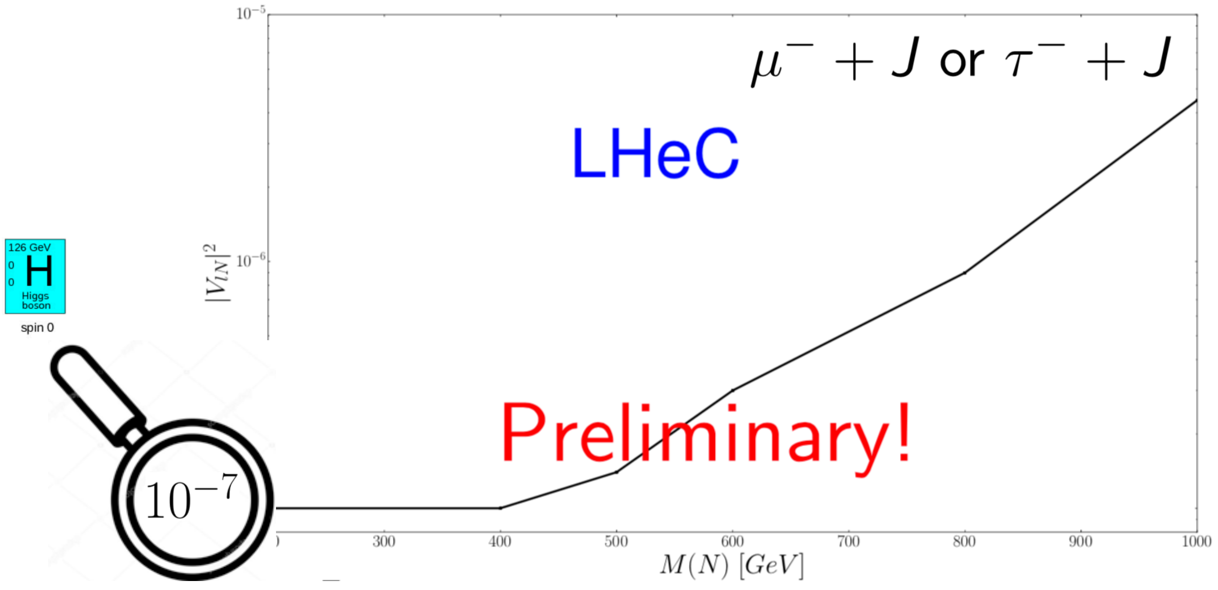


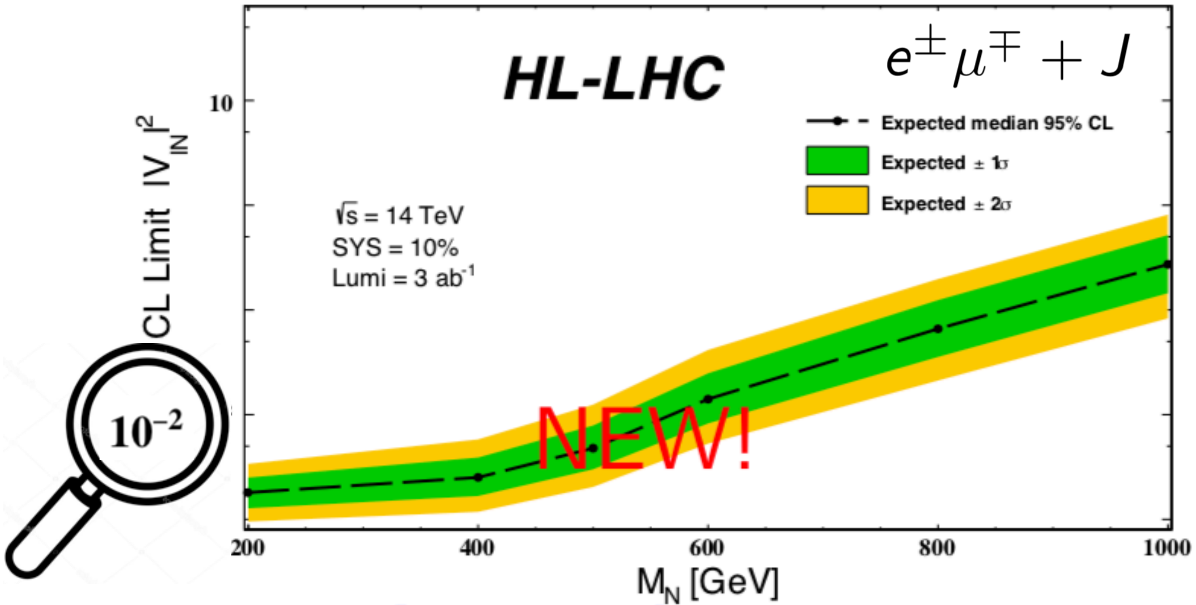
LFV



+ many backgrounds included

→ improves limits considerably

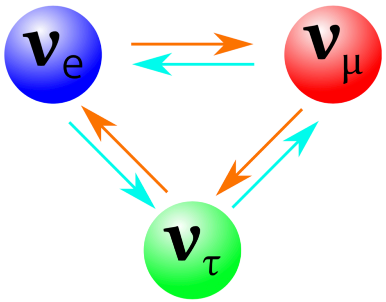


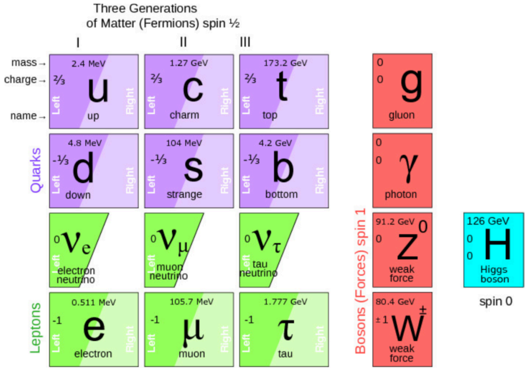


Antusch et al.; [1805.11400]

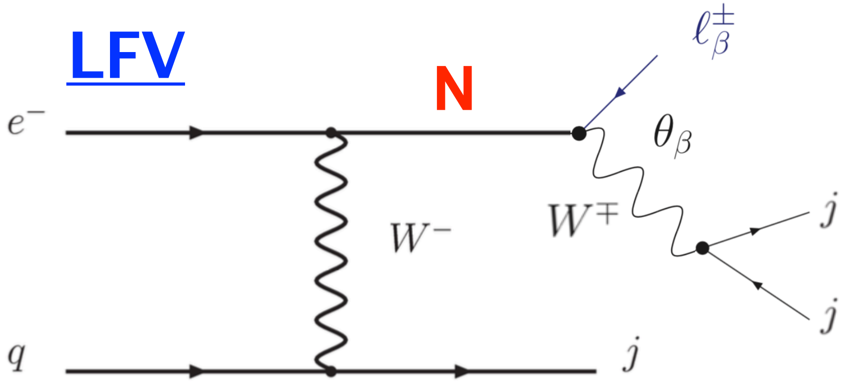
Sterile Neutrinos

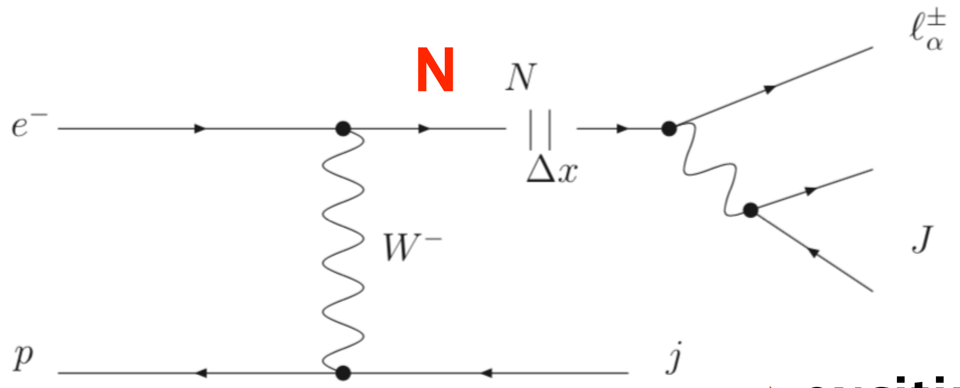
BSM

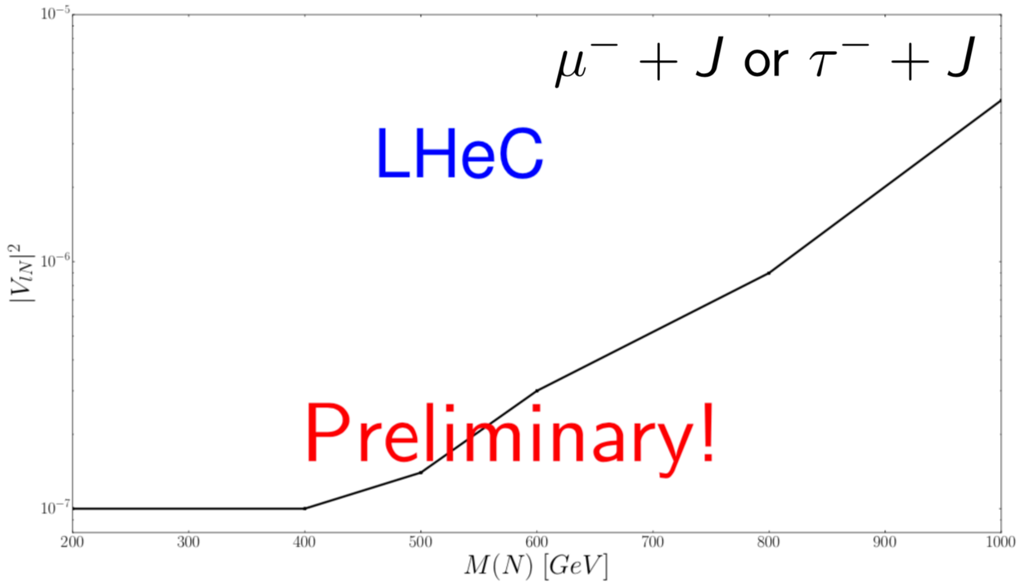


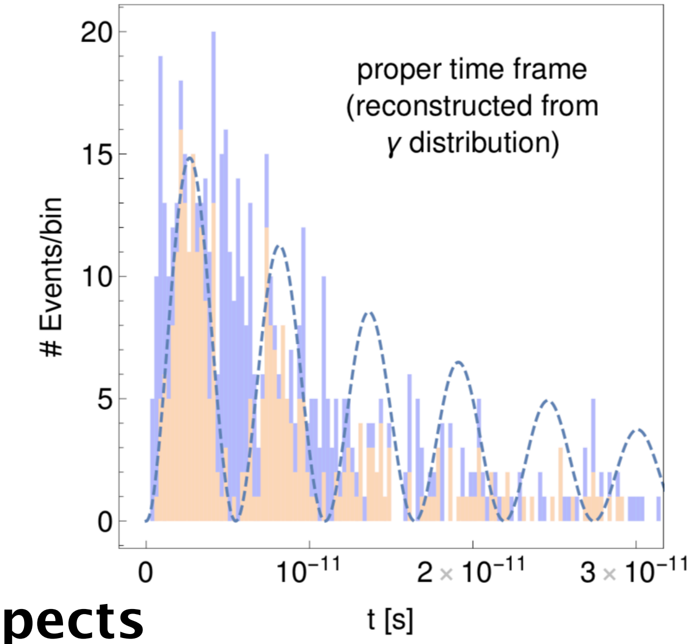


LFV





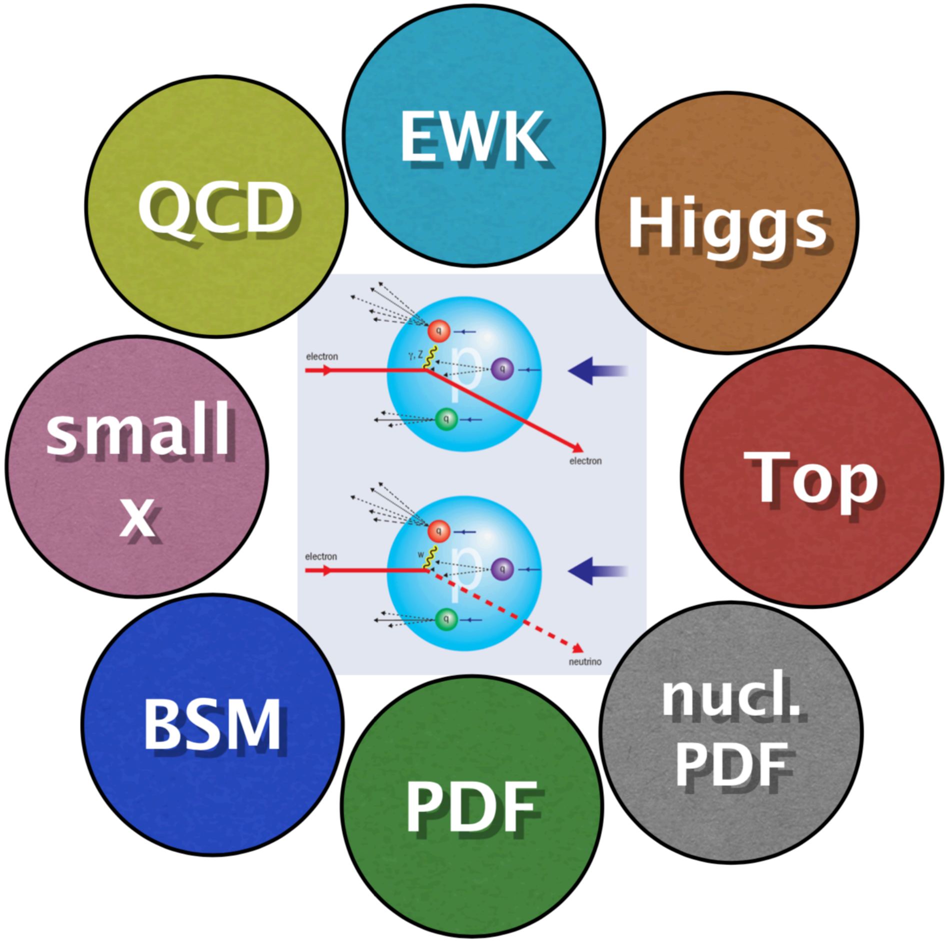




→ **exciting prospects**

Physics Conclusions

- very rich and diverse field of research!
- LHeC will do PDFs important for LHC
- LHeC is high precision facility for EWK, Top, Higgs physics with high sensitivity for BSM physics



→ DIS is unique in studying the inner structure of nature

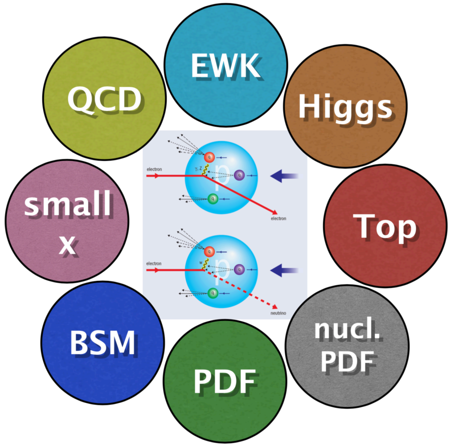
→ DIS is competitive and complementary in performing high precision measurements of particle properties

→ large sensitivities to discover new physics!

3 Raisons d'Être for the LHeC

Physics

- **Microscope**: World's Cleanest High Resolution
- **Empowerment** of the LHC Physics Programme
- **Creation** of a high precision, novel Higgs facility
- **Discovery** Beyond the Standard Model
- **Revolution** of Nuclear Particle Physics



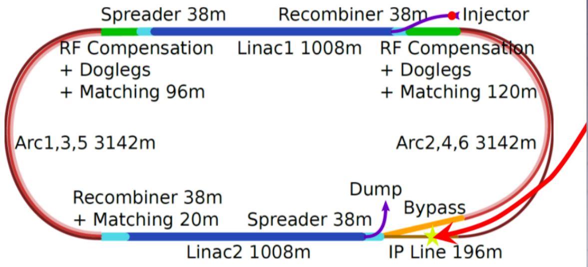
Sustainability and Cost

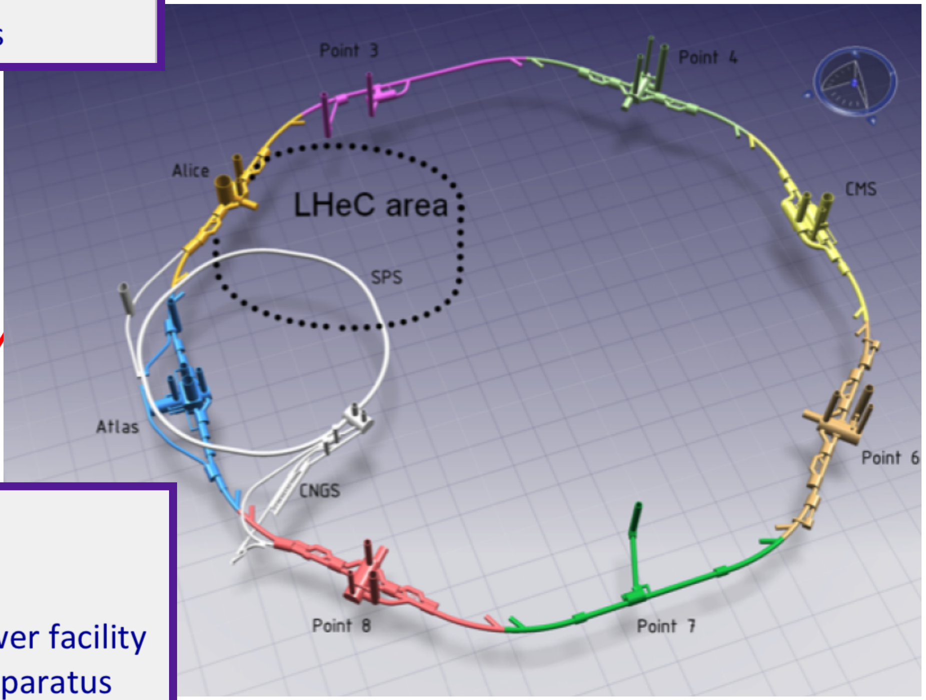
LHC:
- see: SM, Higgs and no BSM
- use: Investment of O(5) BSF
- run: HL LHC until ~2040

LHeC [1206.2913, update 2/19]
- 1.2 TeV ep/A for O(1)BSF

→ Establish novel ep+pp Twin Collider Facility at CERN: sustains HL LHC and bridges to CERN's long term future

For installation during LS4 (2030+) and long term use (HE LHC, FCCeh)

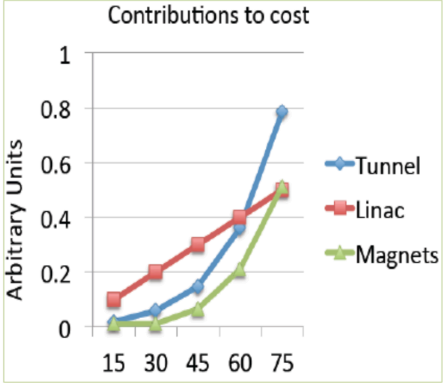




Technology

Accelerator: Novel SRF ERL, green power facility
Detector: Novel high tech (CMOS..) apparatus

→ Keep accelerator and detector base uptodate while preparing for colliders that cost O(10)BSF



→ exciting project!

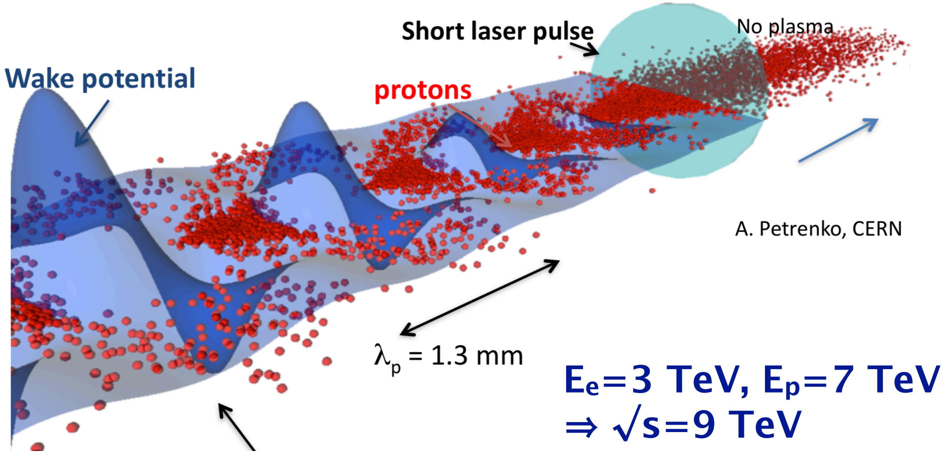
Outlook: Back to the Future

Our future hasn't been written yet.
Our future is whatever *we make it.*
So, let's make it *a good one.*
(Doc Brown)

Backup

High Energy eh Colliders

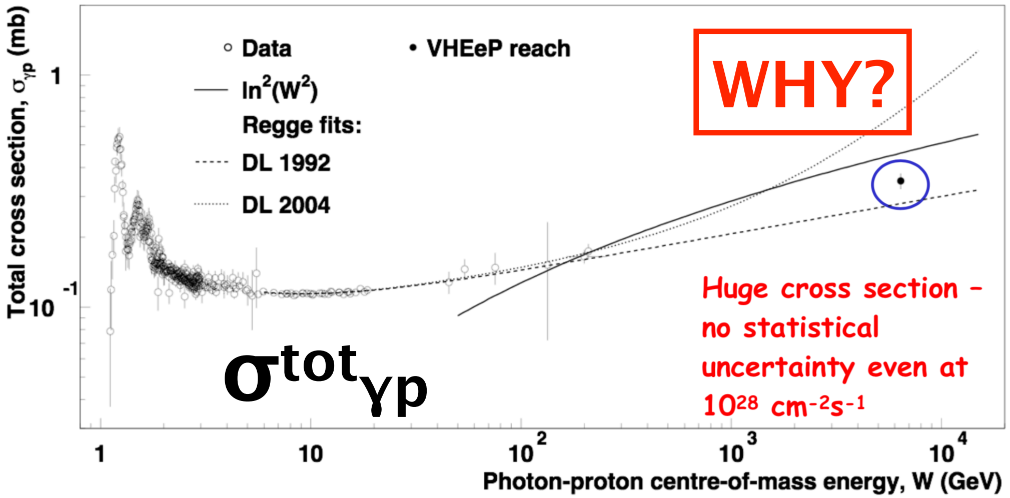
VHEeP (and PEPIC):
Very High Energy eP and eA colliders



A. Petrenko, CERN

E_e=3 TeV, E_p=7 TeV
⇒ $\sqrt{s}$=9 TeV

10^{28}–10^{29} $cm^{-2}s^{-1}$ ⇒ ~1 pb^{-1} p.a.



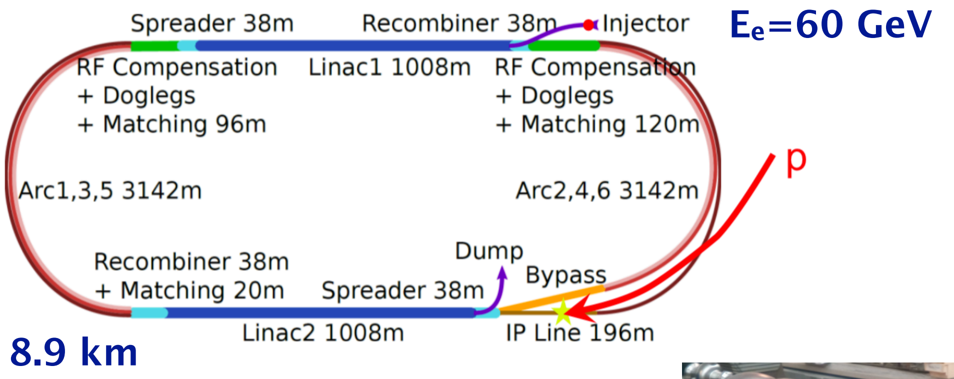
WHY?

Huge cross section – no statistical uncertainty even at 10^{28} $cm^{-2}s^{-1}$

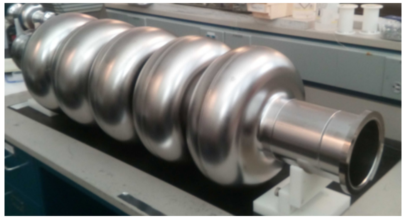
+ many more physics topics

Energy Recovering Linac

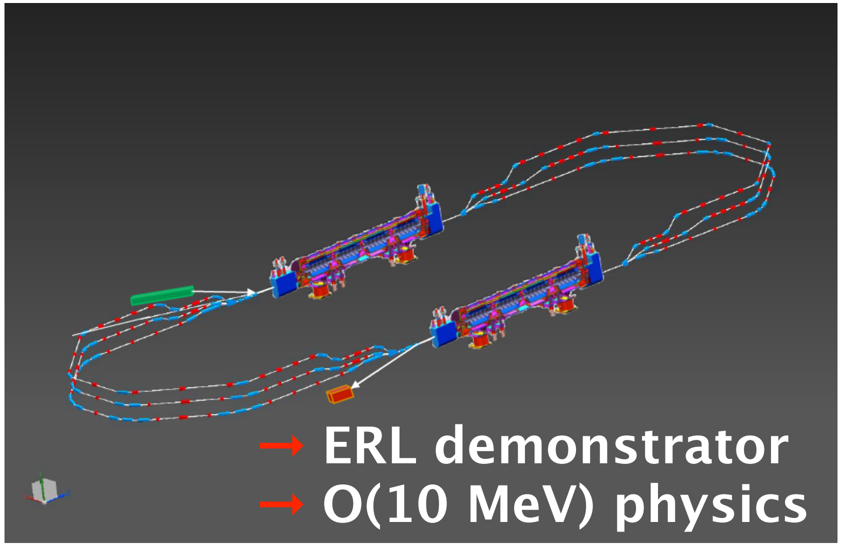
Energy Recovering Linac (ERL):



SC RF cavity prototype:



Powerful ERL for Experiments (PERLE):

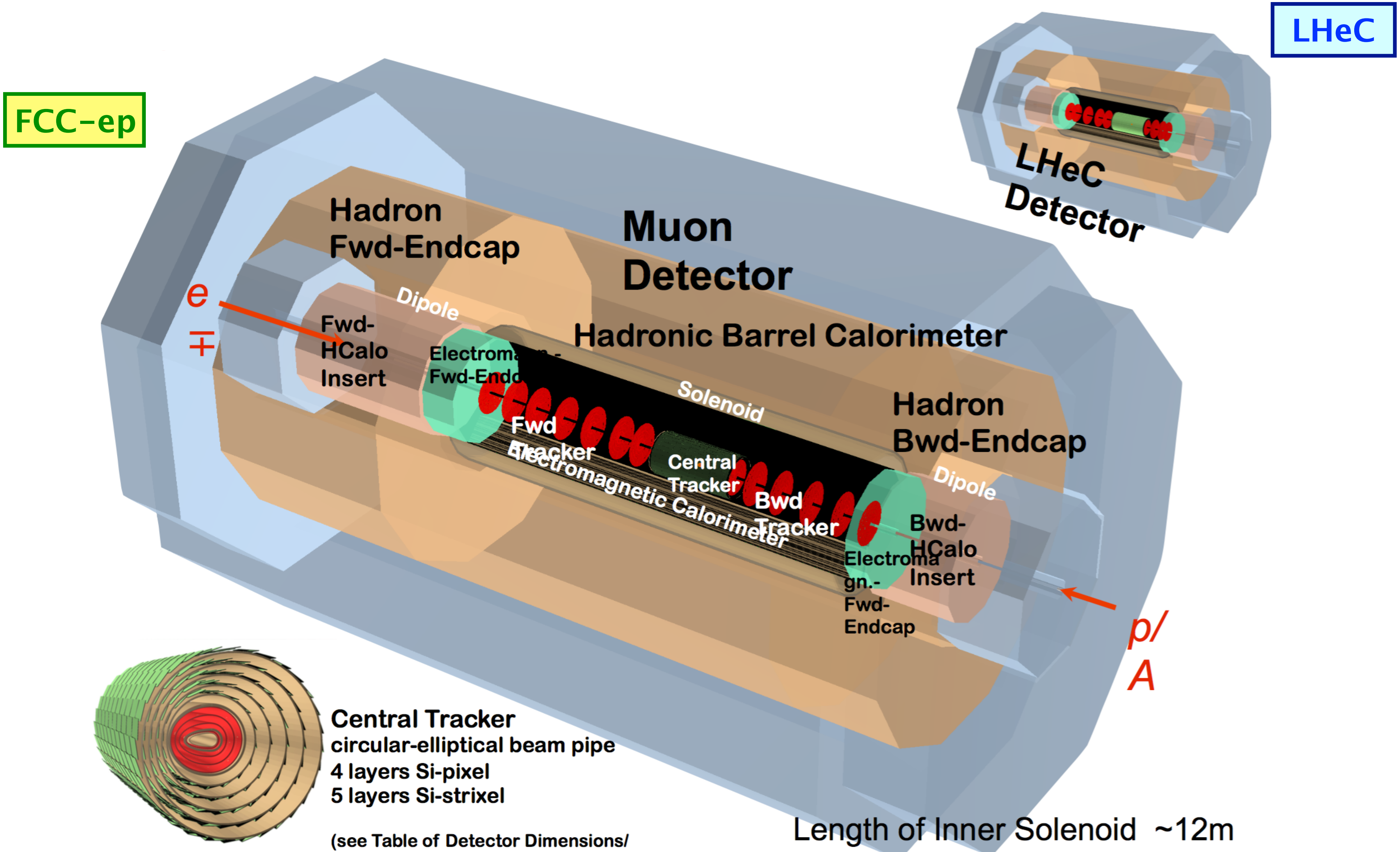


→ ERL demonstrator

→ O(10 MeV) physics

- Electron Energy Recovery Linac (ERL) added to LHC
  - E_e =10-60 GeV
  - E_p =1-7 TeV
    - 13.5 TeV HE-LHC, 50 TeV FCC
  - $\sqrt{s}$=200–1300 GeV
  - Kin.: $0<Q^2<10^6$ GeV^2, $1>x\geq10^{-6}$
    - Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.
  - Electron Polarisation P=±80%.
  - Luminosity: O(10^{34}) cm^{-2}s^{-1}
  - integrated O(1) ab^{-1} for HL LHC
    - 1000 times HERA
    - O(10)fb^{-1} in ePb
  - operated simultaneously to LHC operation (not affected)

LHeC and FCC-eh Detector Layout

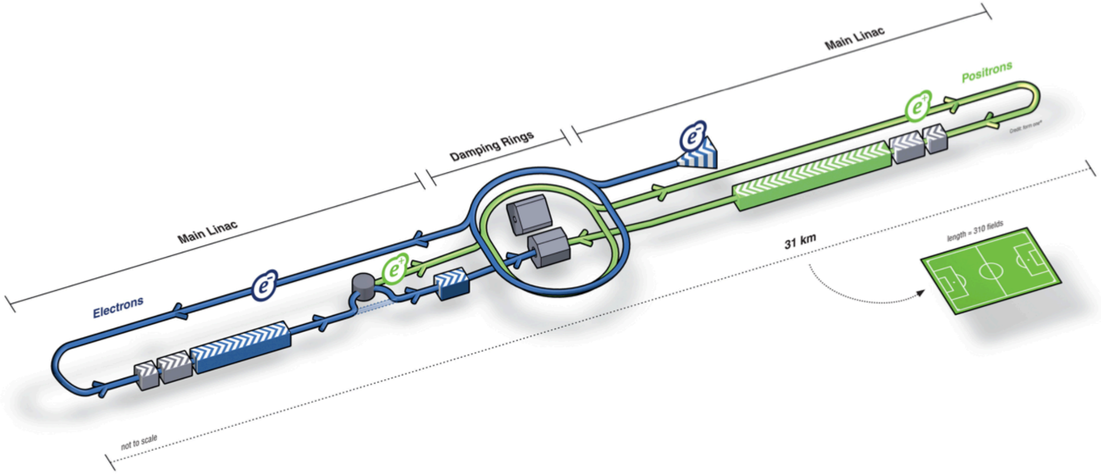


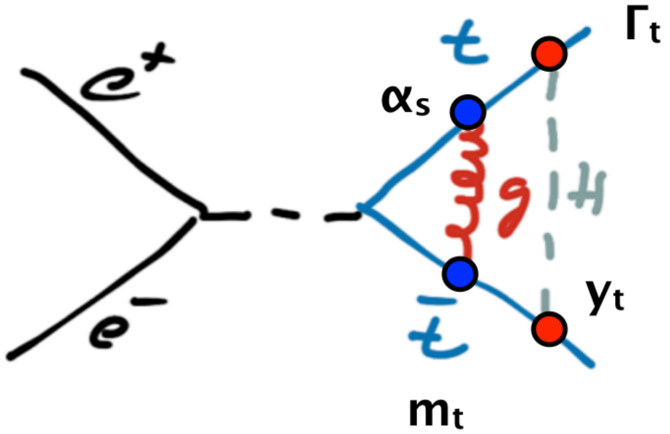
Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

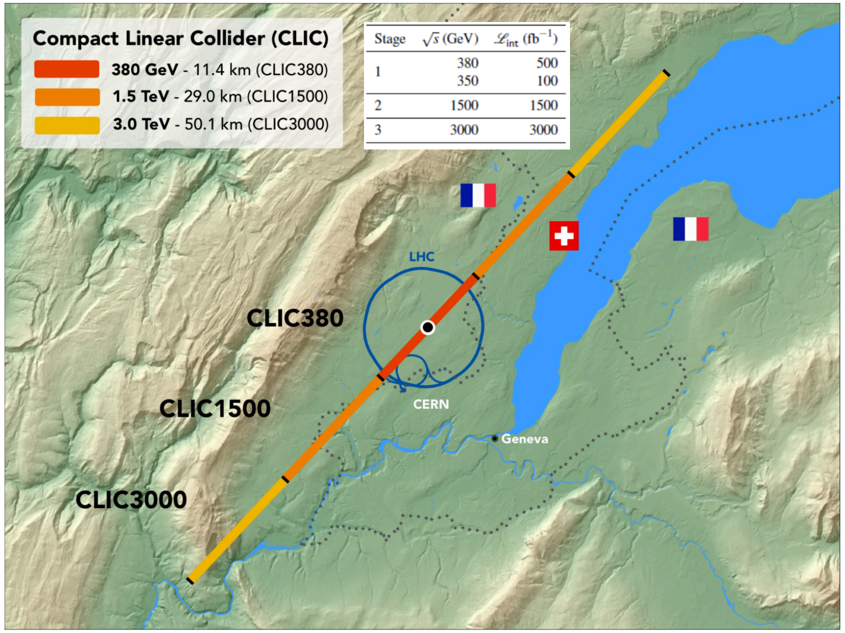
(see Table of Detector Dimensions/ Parameters in backup)

Length of Inner Solenoid ~12m

High Energy e+e− Colliders: ILC, CLIC, FCC



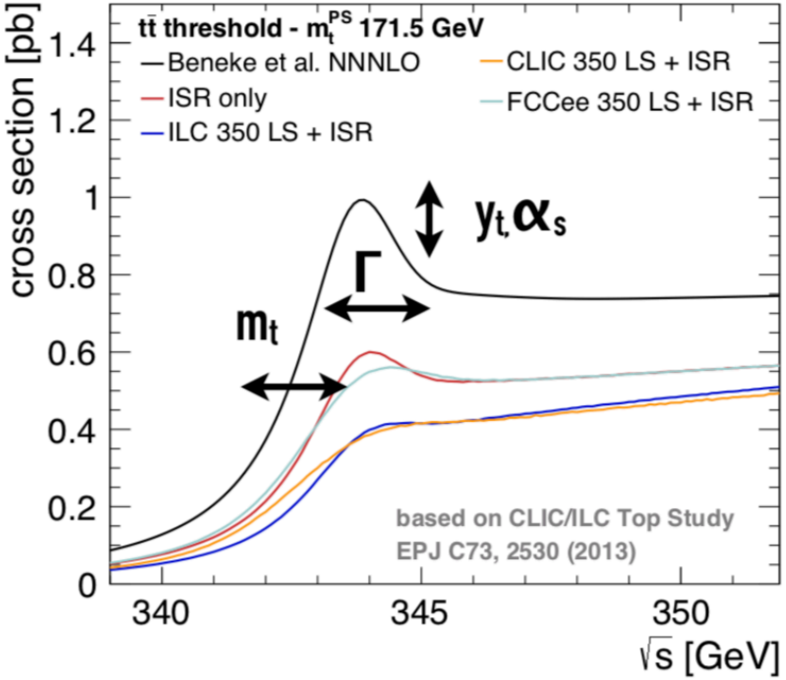




Compact Linear Collider (CLIC)

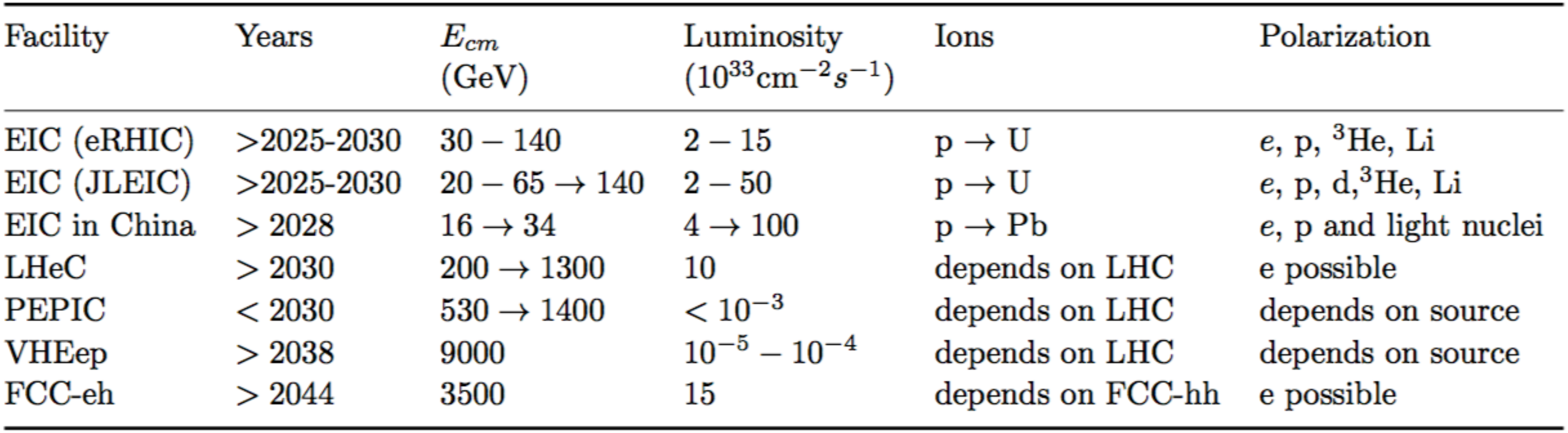
- 🟥 **380 GeV** - 11.4 km (CLIC380)
- 🟧 **1.5 TeV** - 29.0 km (CLIC1500)
- 🟨 **3.0 TeV** - 50.1 km (CLIC3000)

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000



→ **properly defined 1S mass!**

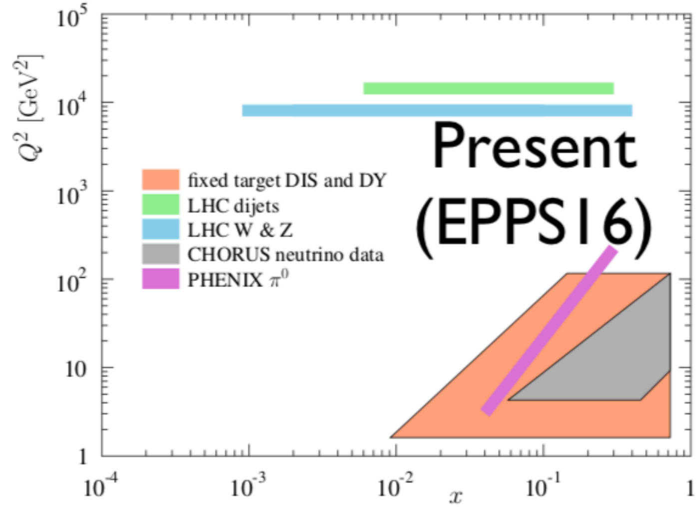
Future DIS colliders

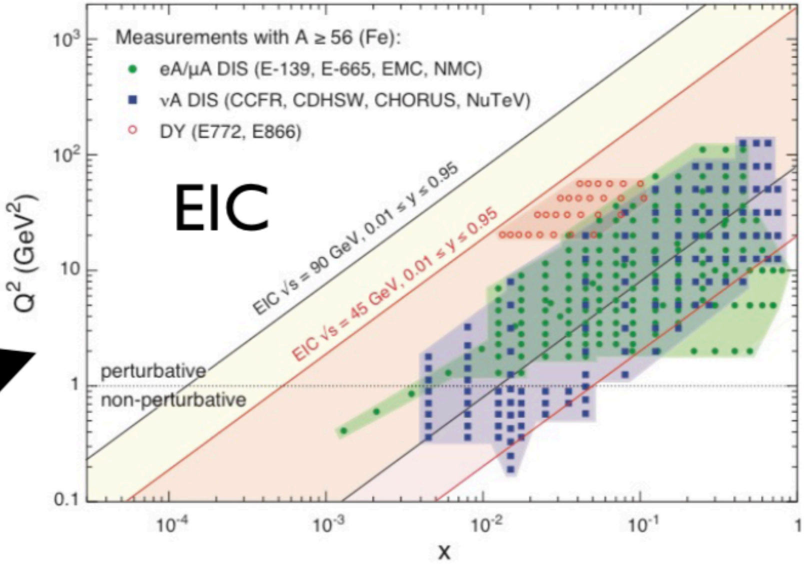


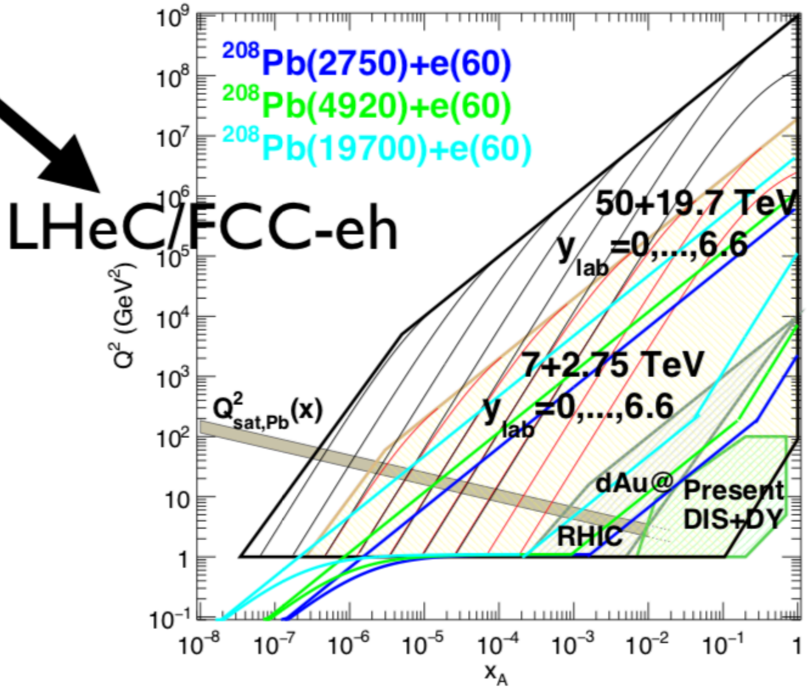
Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33}\mathrm{cm}^{-2}s^{-1}$)	Ions	Polarization
EIC (eRHIC)	>2025-2030	$30 - 140$	$2 - 15$	p → U	e, p, ^{3}He, Li
EIC (JLEIC)	>2025-2030	$20 - 65 \rightarrow 140$	$2 - 50$	p → U	e, p, d,^{3}He, Li
EIC in China	> 2028	$16 \rightarrow 34$	$4 \rightarrow 100$	p → Pb	e, p and light nuclei
LHeC	> 2030	$200 \rightarrow 1300$	10	depends on LHC	e possible
PEPIC	< 2030	$530 \rightarrow 1400$	$< 10^{-3}$	depends on LHC	depends on source
VHEep	> 2038	9000	$10^{-5} - 10^{-4}$	depends on LHC	depends on source
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

Why ep/eA Colliders?

- Kinematical reach:







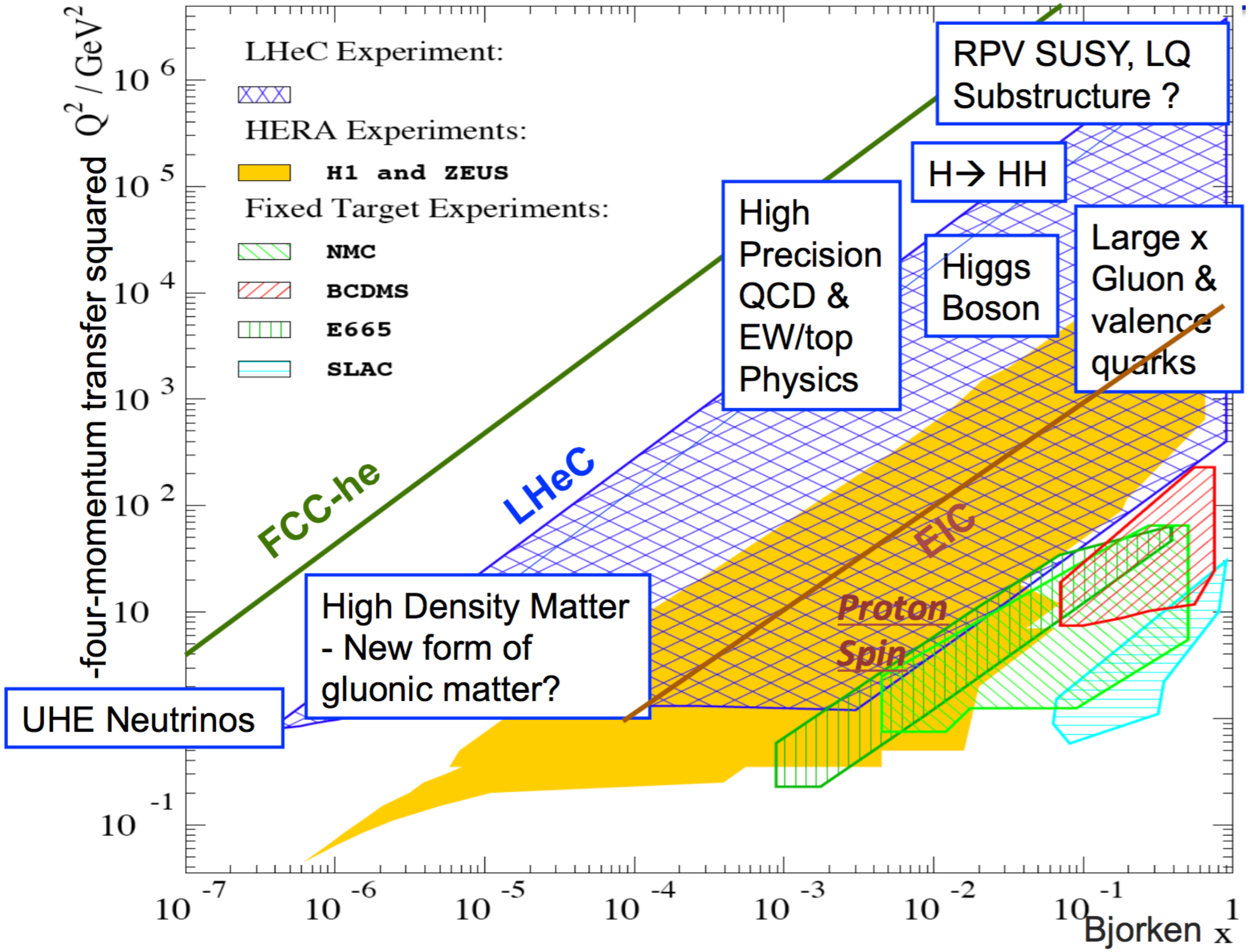
- DIS offers:

➜ a clean experimental environment: lower multiplicity, no pileup, fully constrained kinematics;

➜ A more controlled theoretical setup: most calculations in a dilute-dilute/dense regime.

Slide: N. Armesto

High energy frontier eh physics

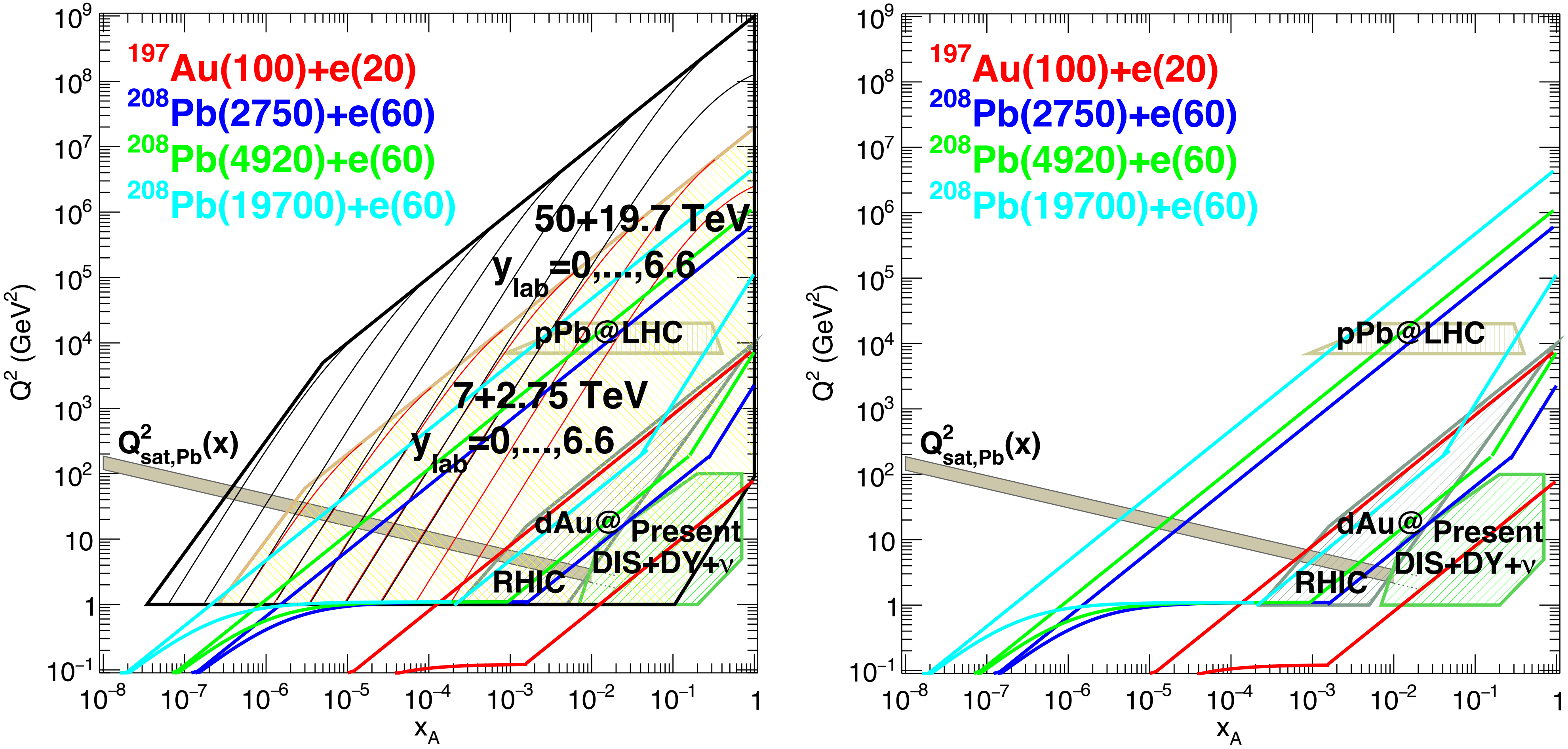


EW symmetry breaking:

- precision EW measurements
- top quark factory: study EW interactions with top quarks
- precision Higgs physics
- search for new physics

→ ep collider excellent to explore QCD and EW theory

Nuclear Physics: Comparison to EIC

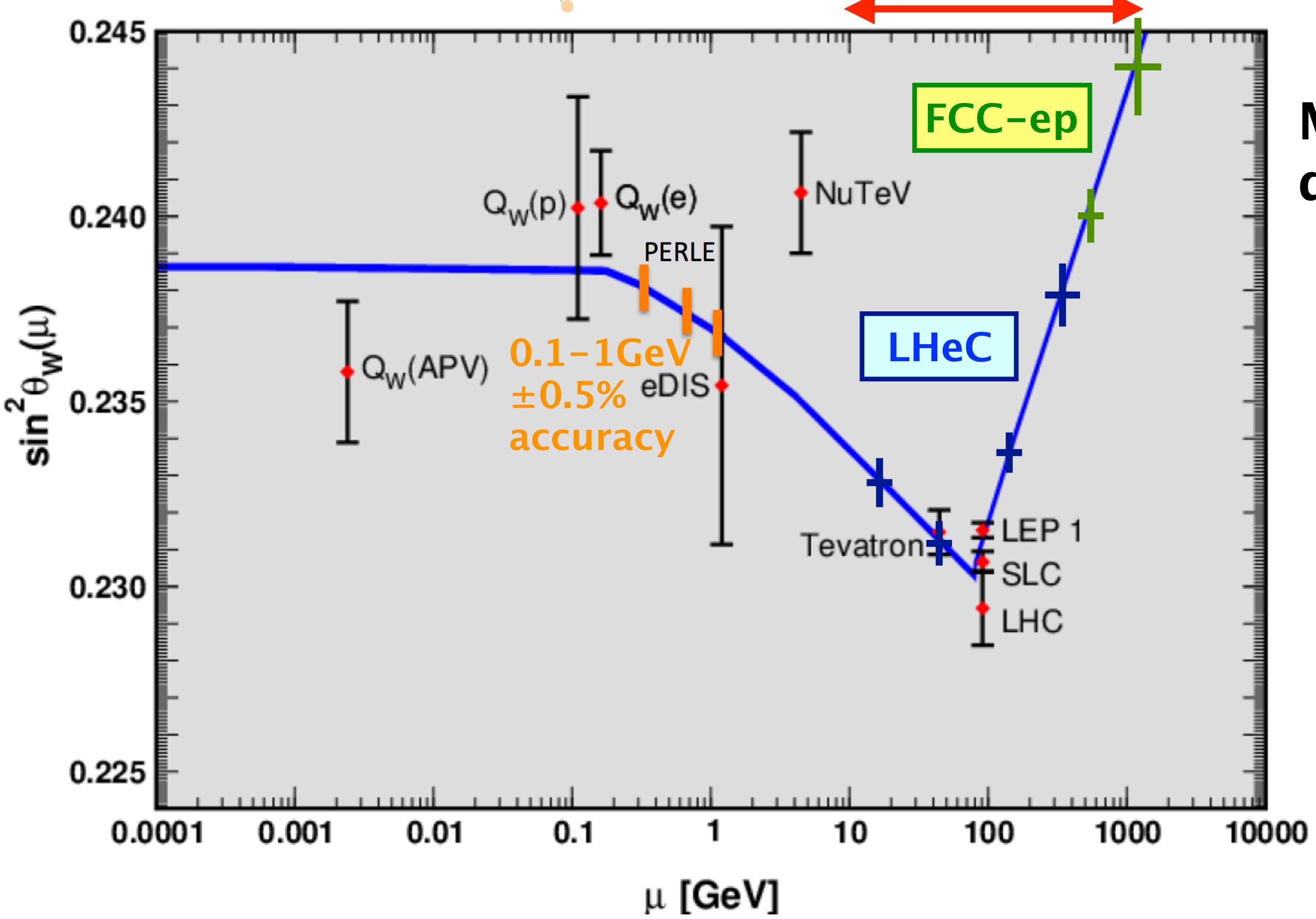


Plots: N. Armesto

Scale Dependence of $\sin^2\theta_W$

PERLE CDR, Arduini et al, to be published
ICFA BeamNewsletter 68 (January 2016)

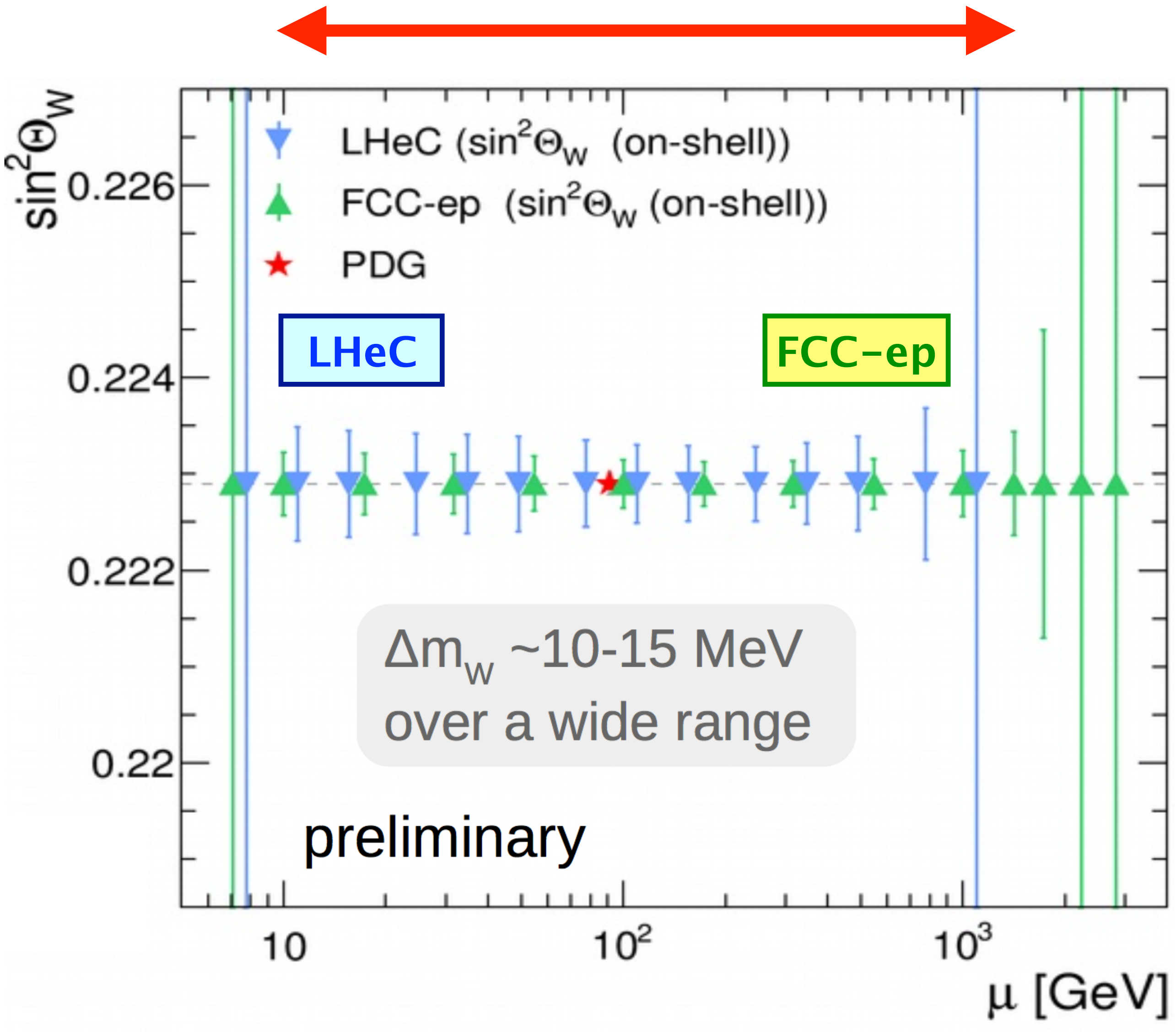
LHeC CDR,
J.Phys. G39,
075001 (2012)



MSbar definition

→ **probe large range of scale dependence**

Scale Dependence of $\sin^2\theta_W$



on-shell definition

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

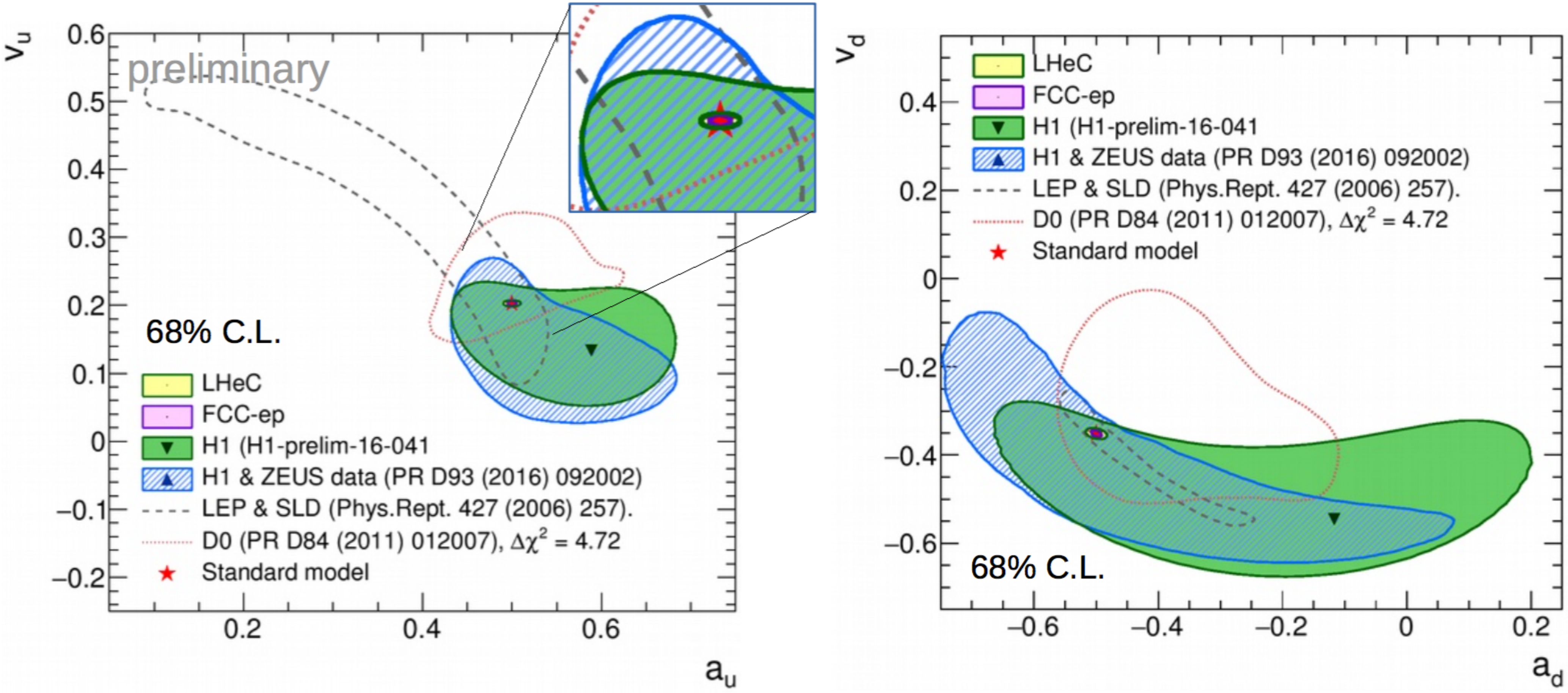
→ **probe large range of scale dependence**

Vector and Axial Vector NC Couplings

LHeC

- simultaneous extraction with PDFs

FCC-ep



→ **high precision measurement of light quark couplings**

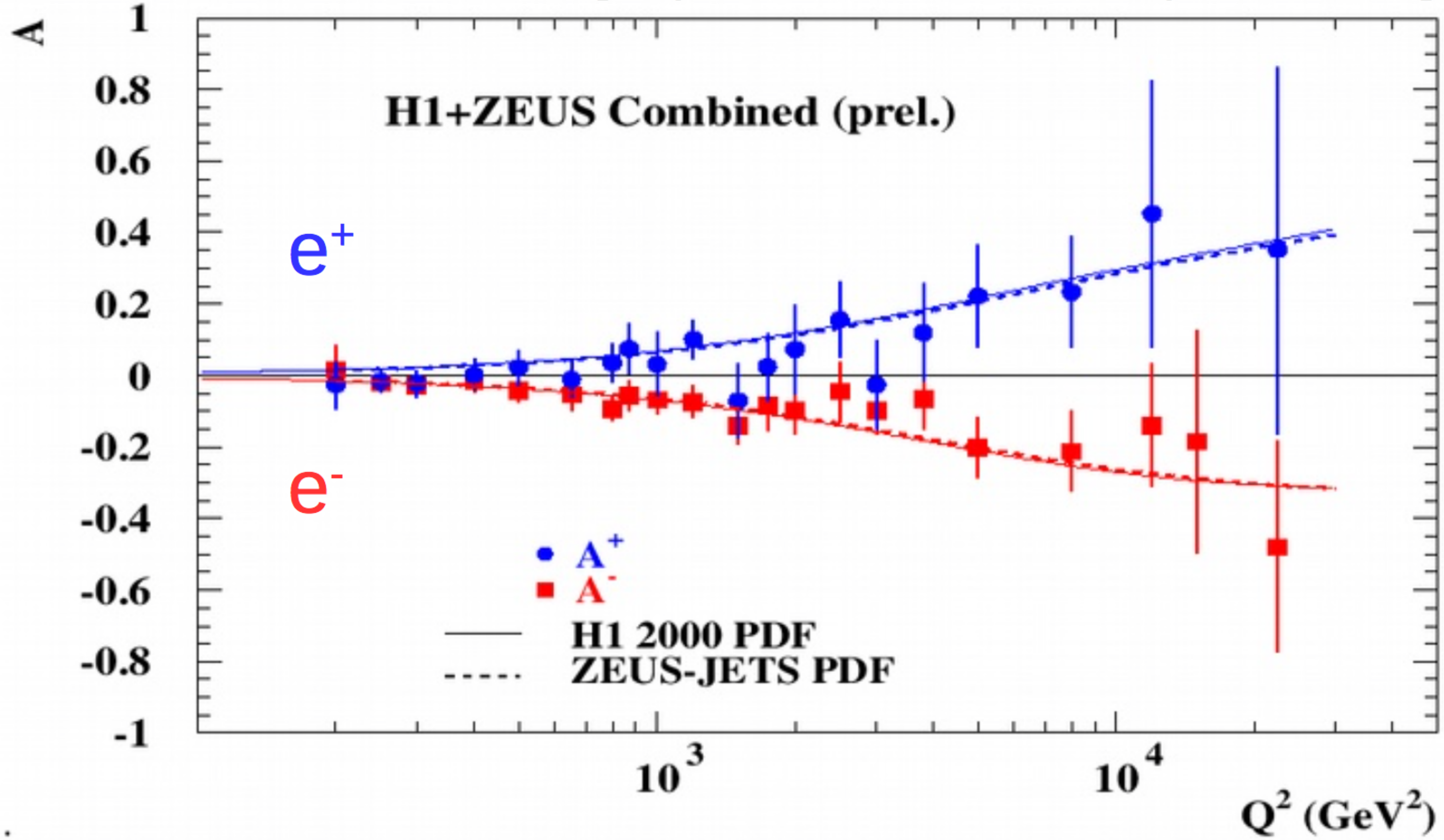
→ **test new physics: Z’ boson, R-parity violating SUSY, leptoquarks**

Asymmetry Measurements

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

- **study P-violation in NC-EW interactions**

H1+ZEUS, [H1prelim-06-142, ZEUS-prel-06-022]



Asymmetry Measurements

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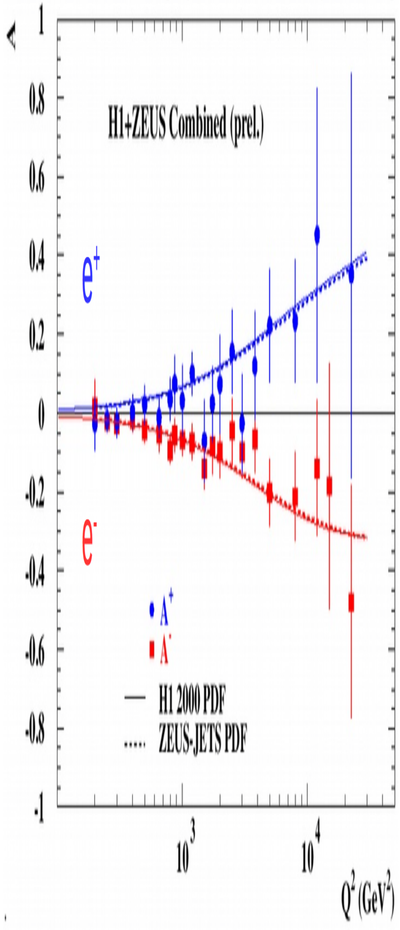
- study P-violation in NC EWK interactions

H1+ZEUS, [H1prelim-08-142, ZEUS-prel-08-022]



Asymmetry Measurements

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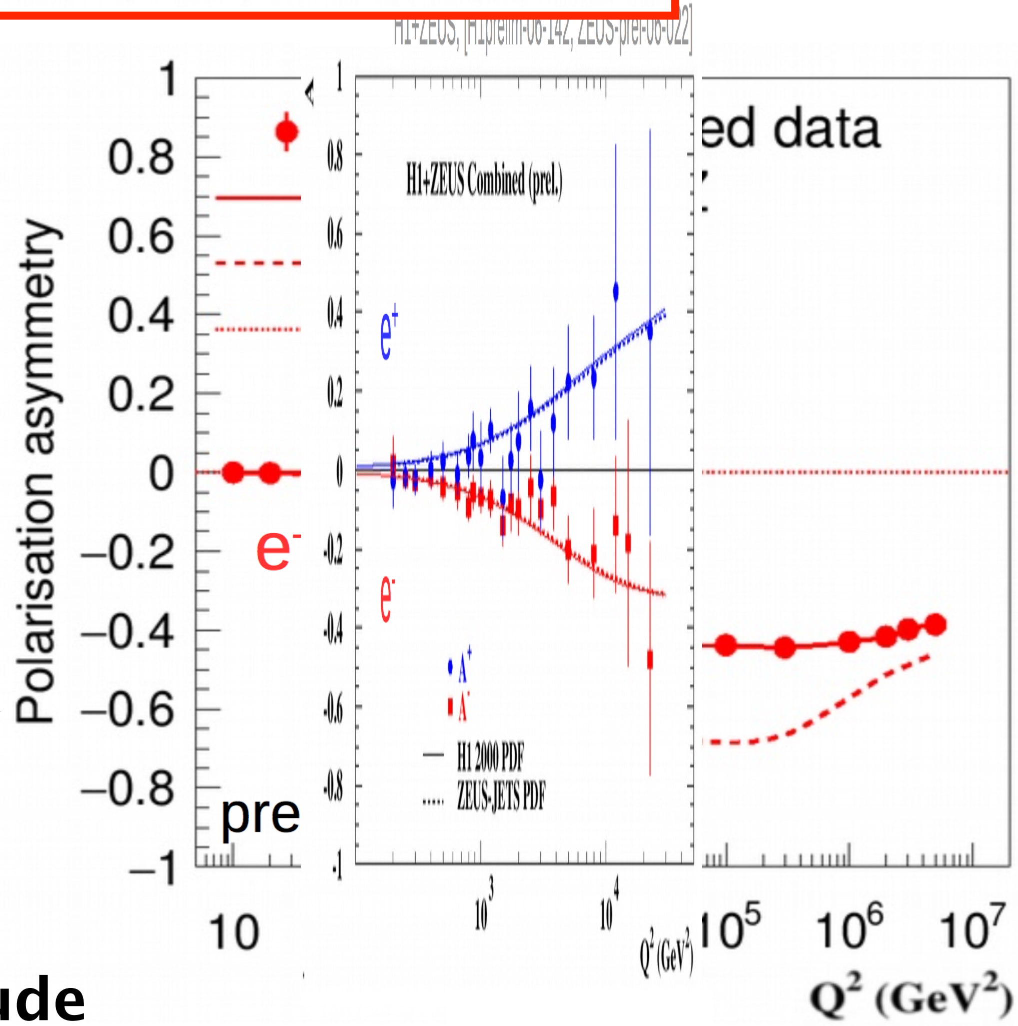
- study P-violation in NC EWK interactions



FCC-ep

- 11 times higher center-of-mass energy
- 100-1000 times higher luminosity
- 2-3 times higher polarisation

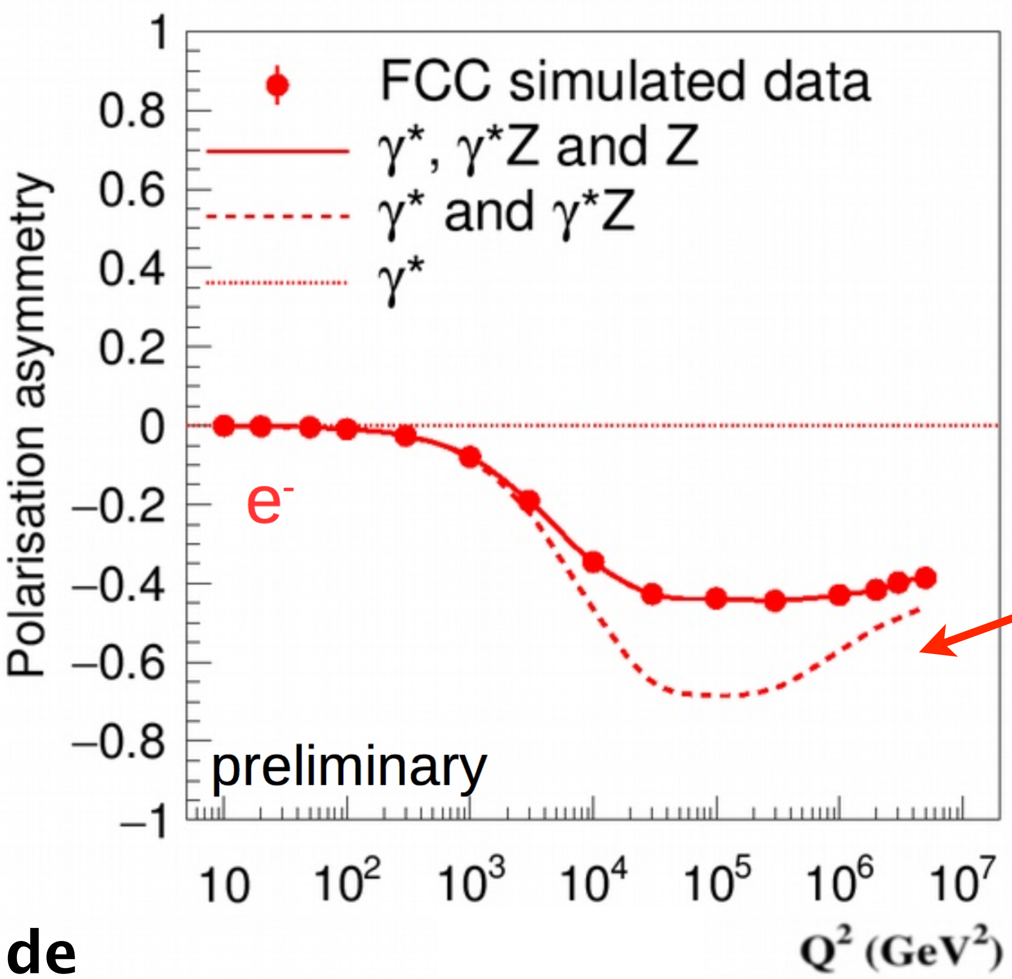
→ extend by 2-3 orders of magnitude

Asymmetry Measurements

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

- **study P-violation in NC EWK interactions**

FCC-ep



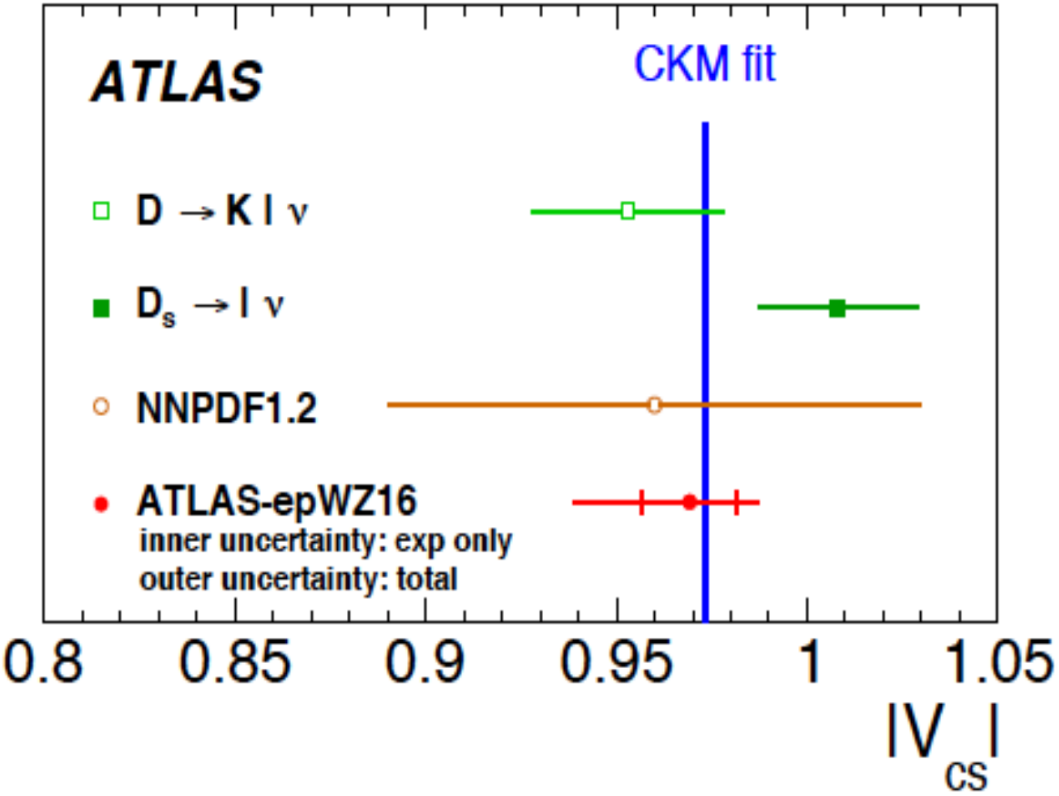
pure Z exchange becomes important

- **11 times higher center-of-mass energy**
- **100-1000 times higher luminosity**
- **2-3 times higher polarisation**

→ extend by 2-3 orders of magnitude

Measurement of $|V_{cs}|$

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



HERA+ATLAS → V_{cs}

Expect LHeC+HL LHC to be 10 x better from +2-3% to surely 0.5% or below

(work in progress)

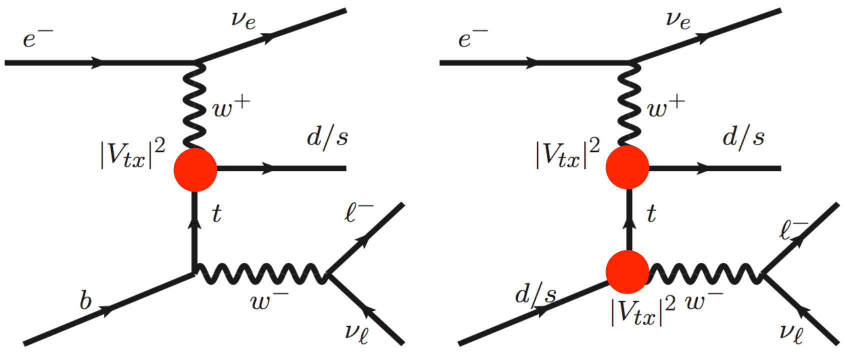
→ **heavy flavour factory**

Measurement of $|V_{td}|$

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

similar

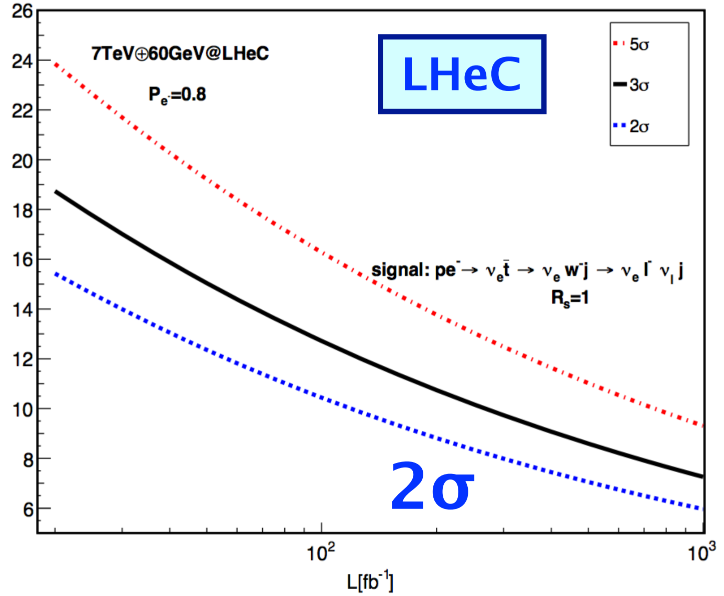
$$|V_{td}^{\mathrm{SM}}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$



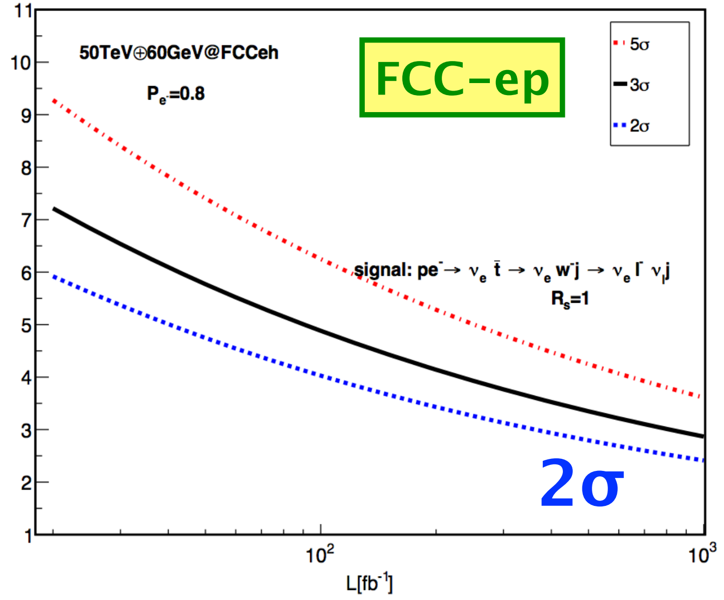
DELPHES

Hao Sun to be publ.

LHC



→ $|V_{td}| < 0.05$



→ $|V_{td}| < 0.02$

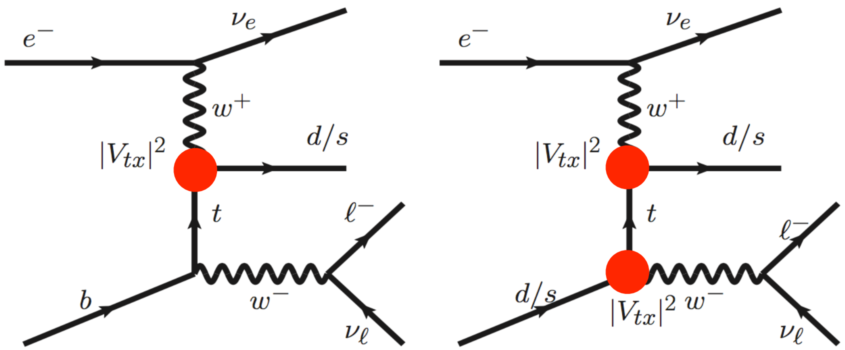
at 2σ C.L.

Measurement of $|V_{td}|$

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

similar

$$|V_{td}^{\mathrm{SM}}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$

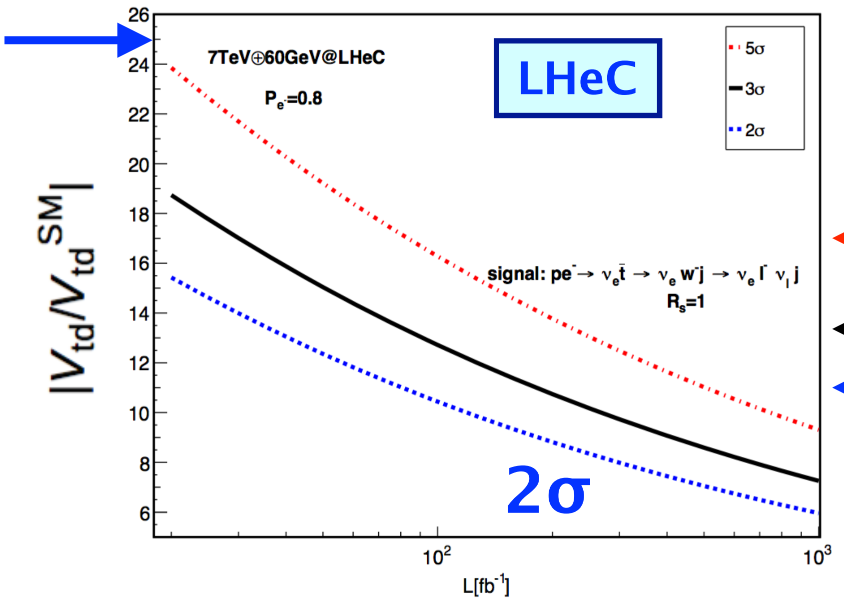


DELPHES

Hao Sun to be publ.

→ **extend HL-LHC limits**

LHC →



LHC, 3000 fb^{-1}@14TeV

HL-LHC

arXiv:1709.07887

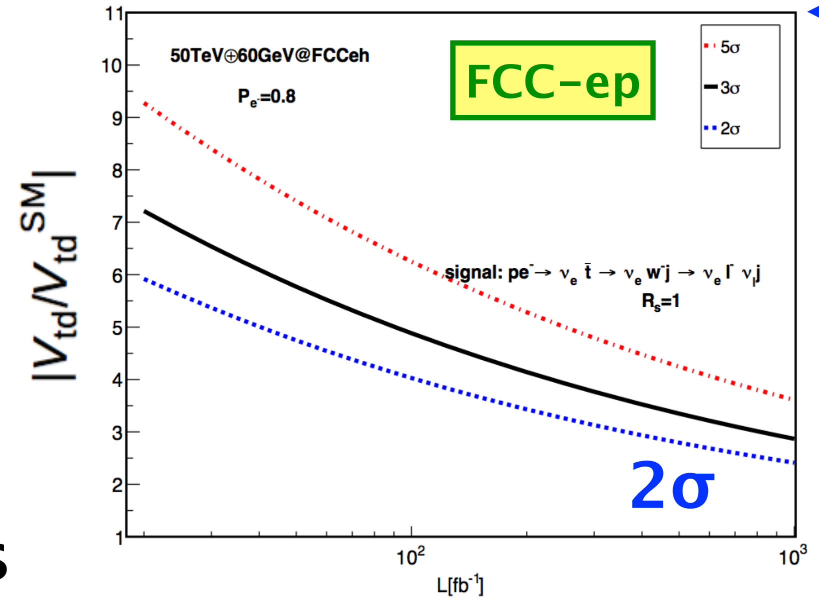
5σ

3σ

2σ

→ $|V_{td}|<0.05$

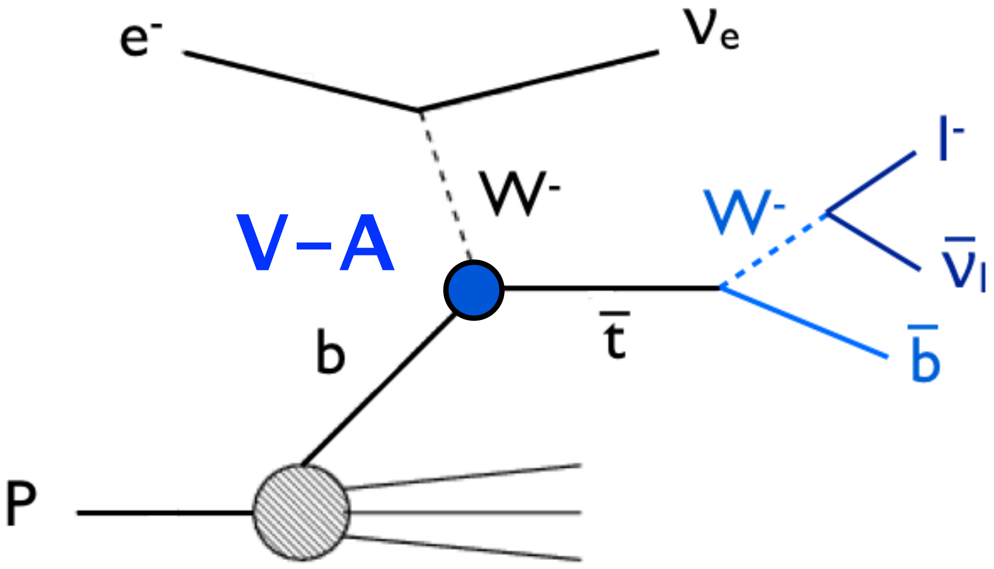
2σ



→ $|V_{td}|<0.02$

at 2σ C.L.

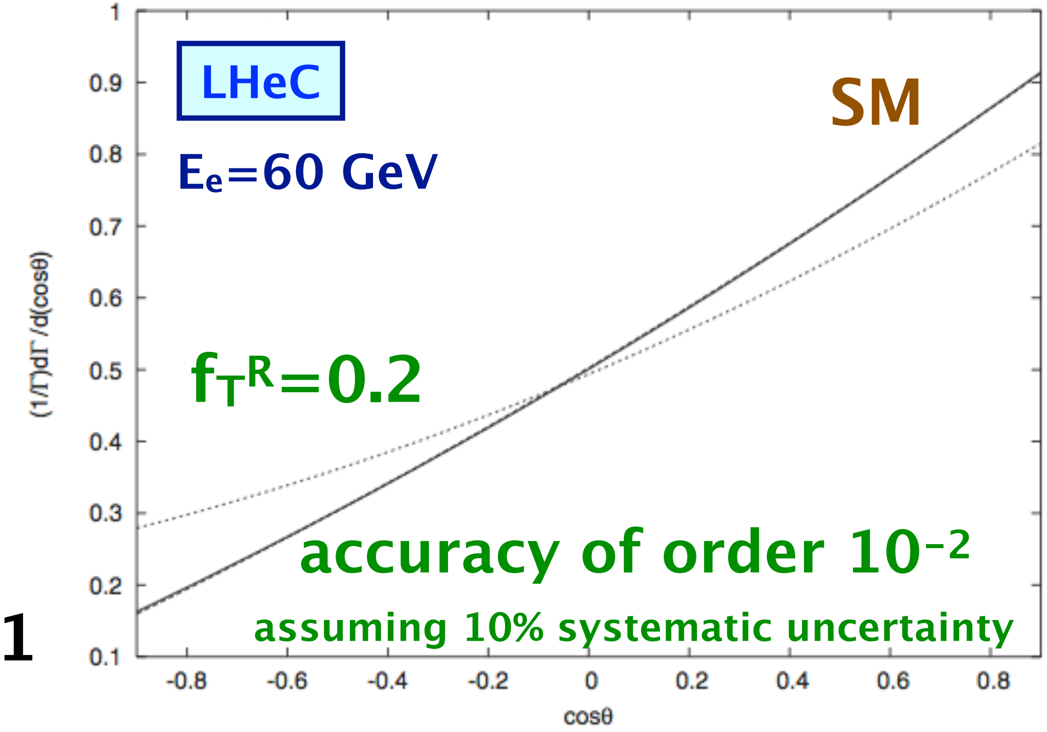
Top Quark Polarisation



Atag, Sahin,
PRD 73, 074001 (2006)

cosθ: angle between charged lepton and spin quantisation axis in top rest frame

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + A_{\uparrow\downarrow}\alpha\cos\theta) \qquad A_{\uparrow\downarrow} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



accuracy of order 10^{-2}

assuming 10% systematic uncertainty

using simply e−beam axis:
polarisation: P_t = 96%

TESLA+HERAp:

$\sqrt{s}$=1.6 TeV
L_{int}=20 fb^{-1}

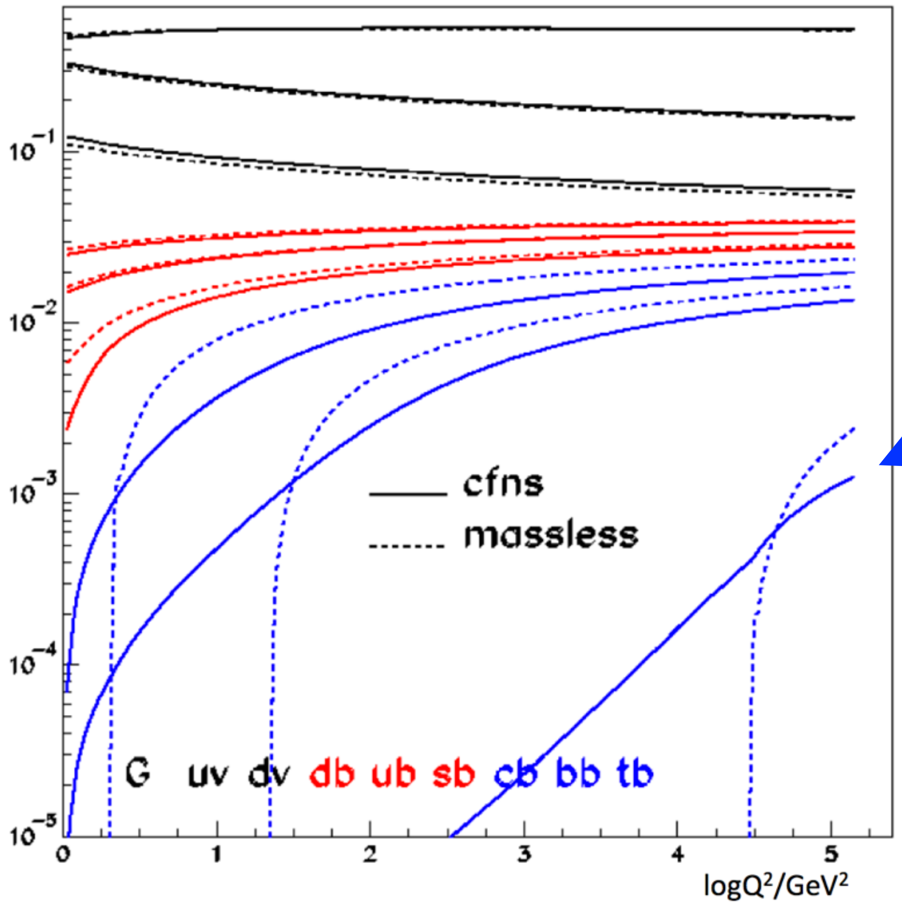
CMS 19.7 fb^{-1}: $A_{\uparrow\downarrow}$ = 0.26±0.11

JHEP 04 (2016) 073

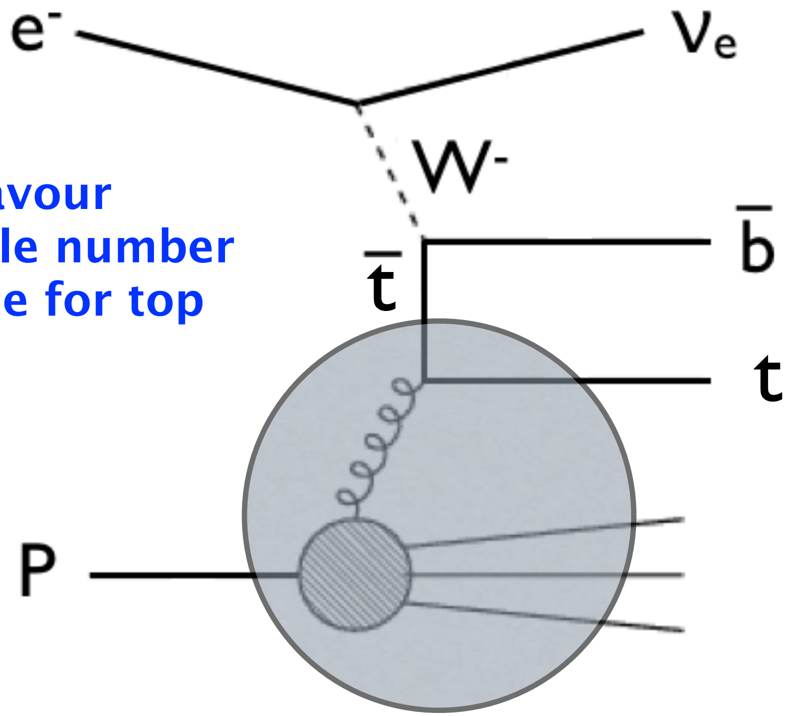
Top Quark Parton Density Function

LHeC CDR, J.Phys. G39, 075001 (2012)

parton momentum fraction



six-flavour variable number scheme for top quark



- in 6 flavour number scheme, top receives at $Q^2 \sim m_t^2$ certain fraction of the proton's momentum
- need to understand what a “top PDF” is in the framework of parton model

→ **LHeC offers new field of research for top quark PDF**

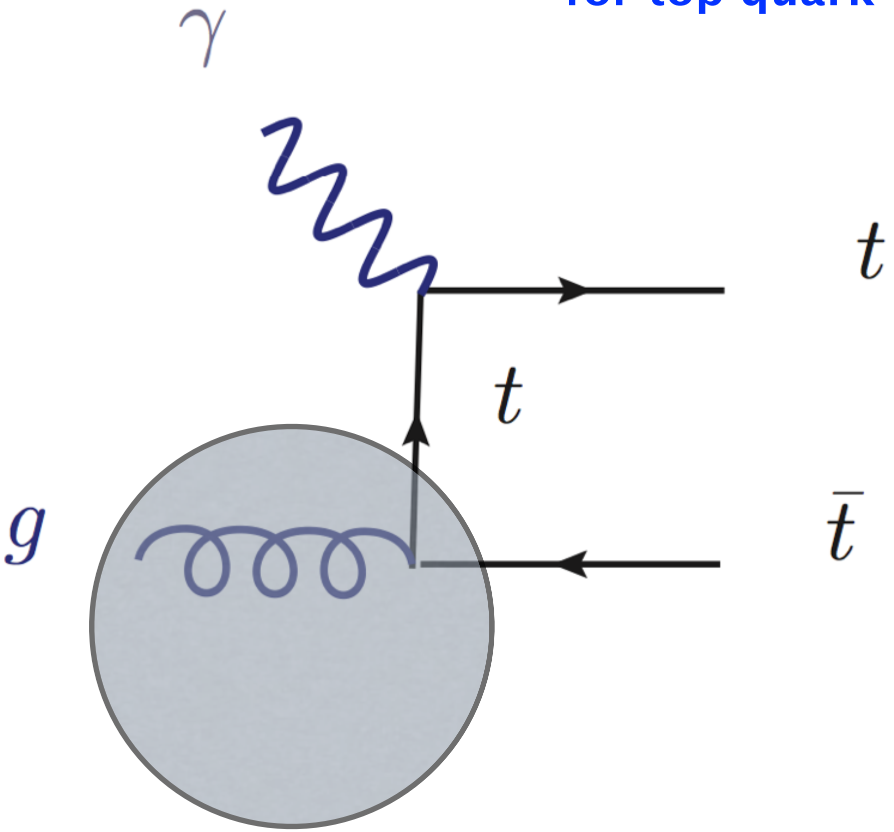
Top Quark Structure Function

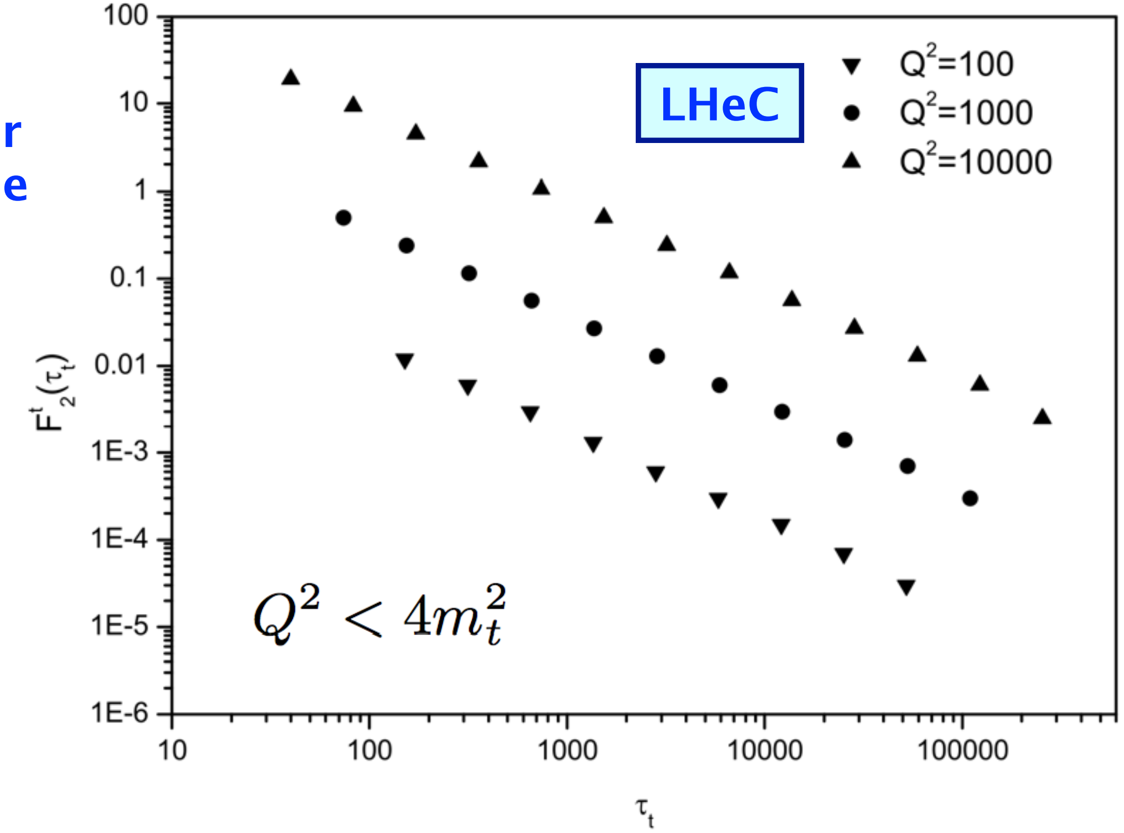
Boroun, Phys. Lett. B744, 142 (2015)

$L_{int}=10\ \mathrm{fb}^{-1}$

$E_e=60$ GeV

variable flavour number scheme for top quark



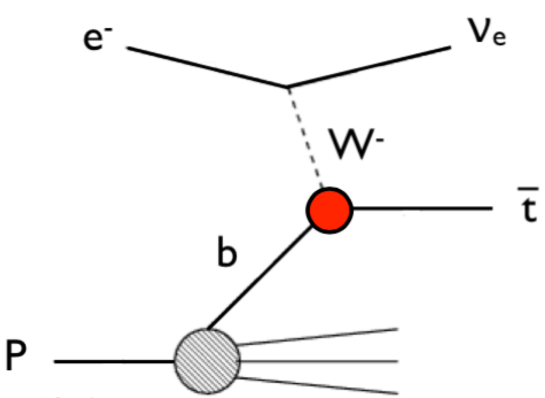


$$\tau_t = (1+\frac{4m_t^2}{Q^2})^{1+\lambda}\frac{Q^2}{Q_0^2}(\frac{x_B}{x_0})^{\lambda}$$

$$x = x_B(1+\frac{4m_t^2}{Q^2})$$

→ **LHeC/FCC-ep opens up a new field of top quark PDFs and to unveil the complete flavour structure of the proton**

Top Quark Anomalous Couplings

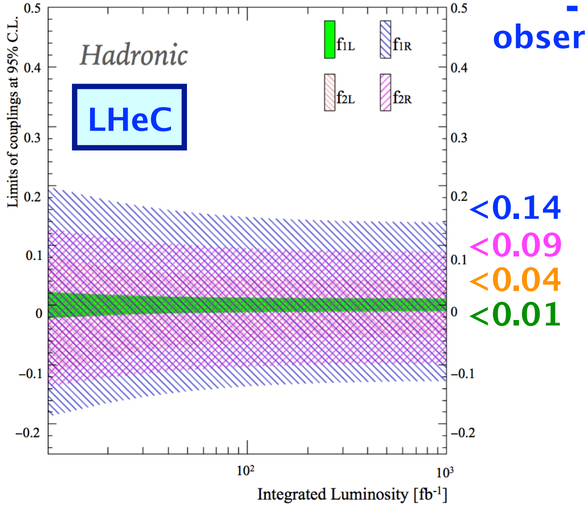


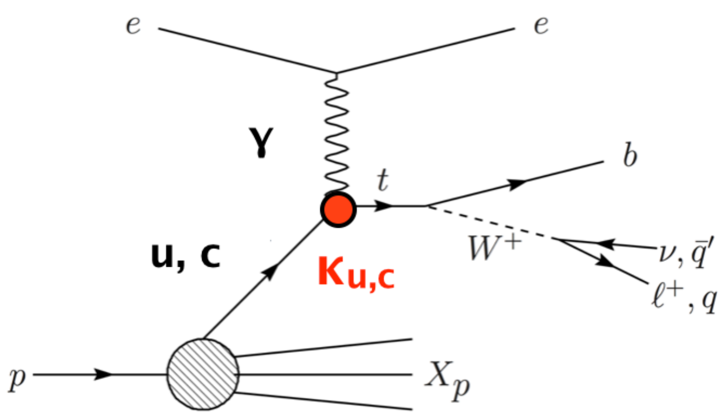
= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L + f_V^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(f_T^L P_L + f_T^R P_R)tW_\mu^- + h.c.$$

DELPHES

Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577
Kumar, Ruan, to be publ.



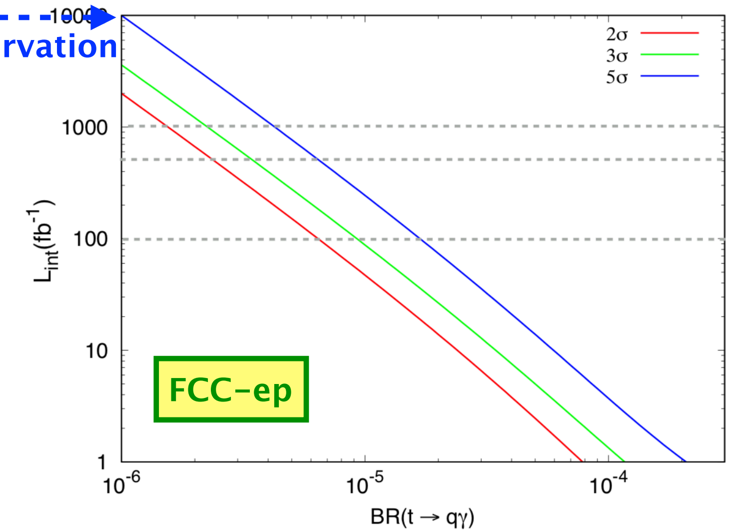


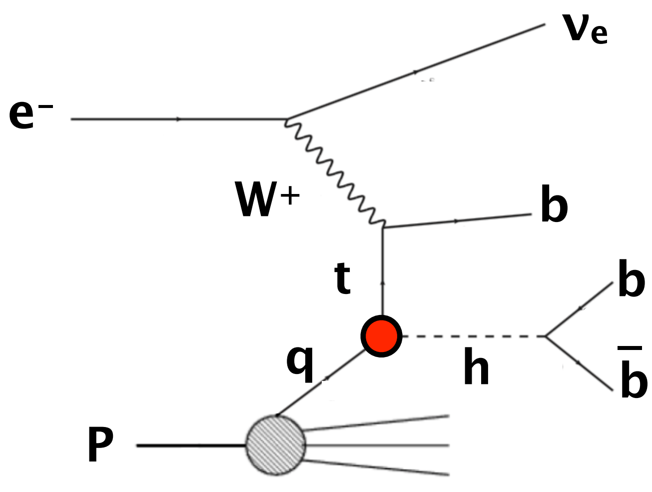
$$L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda}\bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

DELPHES

Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

observation

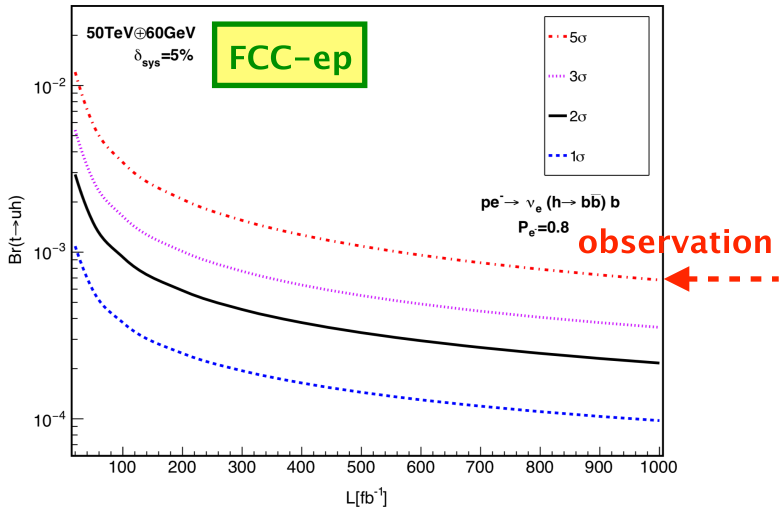




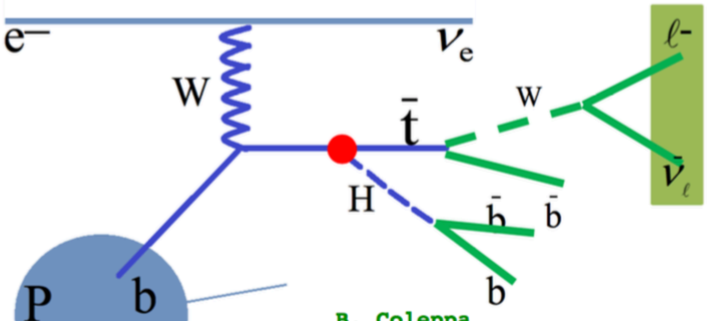
$$\mathcal{L} = \kappa_{tuh}\bar{t}uh + \kappa_{tch}\bar{t}ch + h.c.$$

parametrisation

Sun, Wang, arXiv:1602.04670



CP Nature of Top–Higgs Coupling



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M. Kumar
S. Kumar
B. Mellado

parton level

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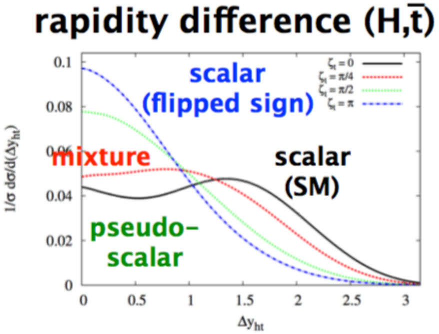
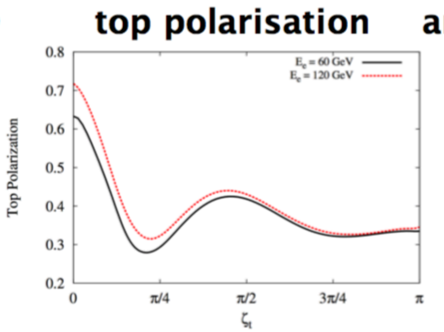
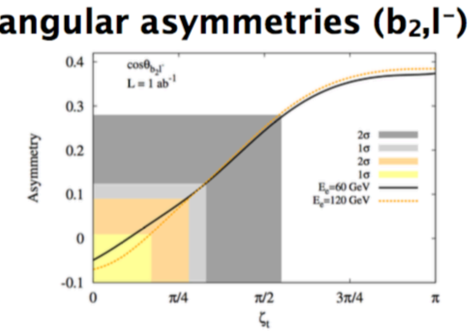

rapidity difference (H,$\bar{t}$)

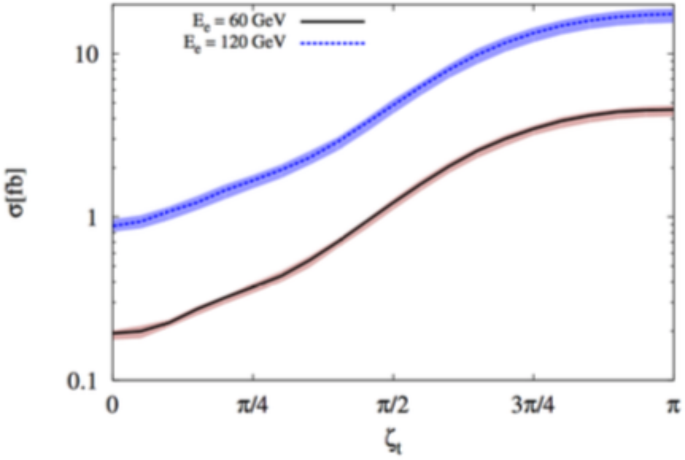

top polarisation


angular asymmetries (b_2,l^-)

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

LHeC

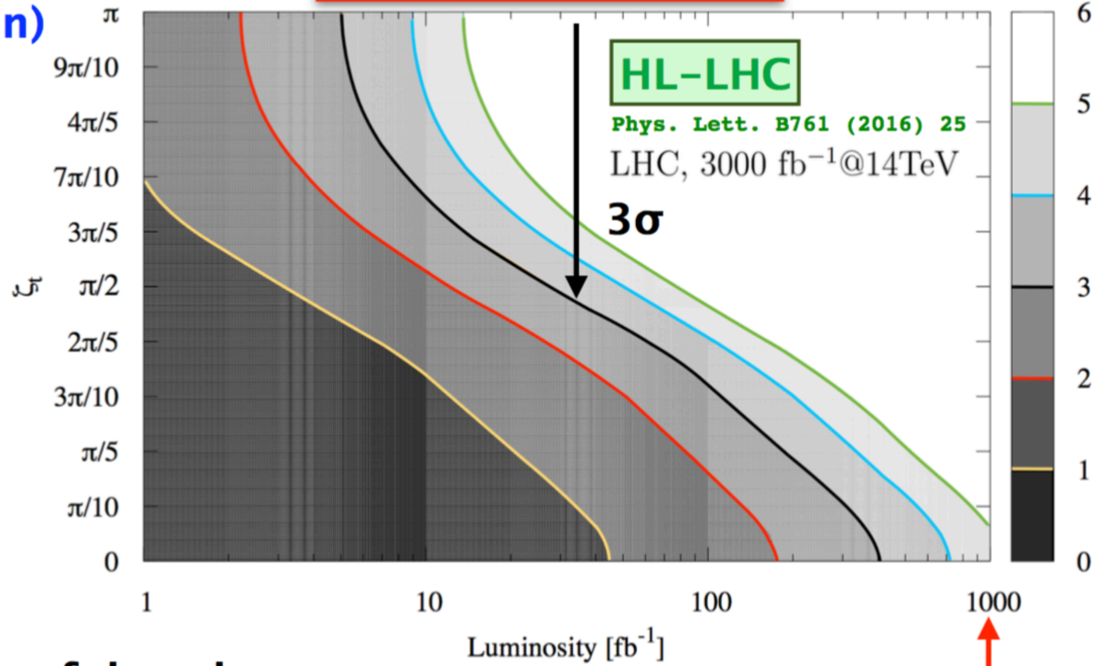
fiducial incl. cross-section



CP-even (flipped sign)

CP-odd

CP-even (SM)

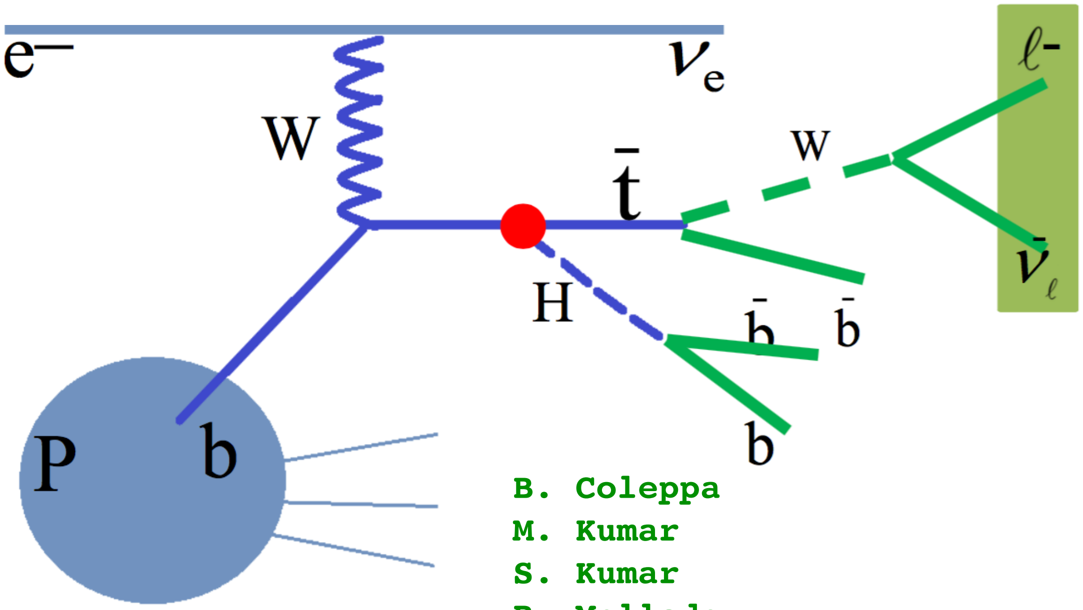


→ **powerful probe of ttH coupling**

10% uncertainty on background yields

$$\kappa = 1.00 \pm 0.17$$

CP Nature of Top-Higgs Coupling



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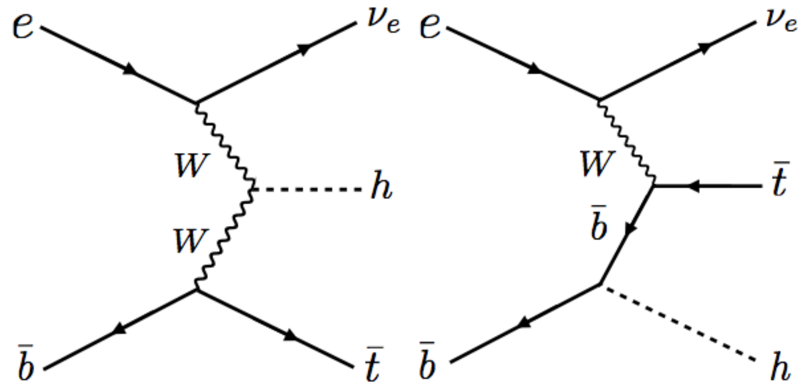
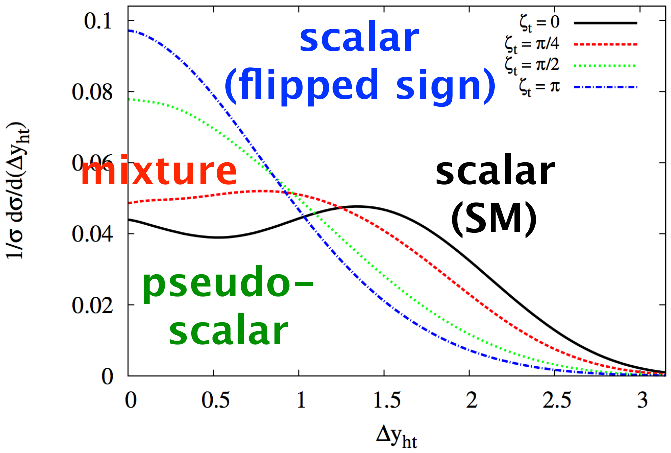
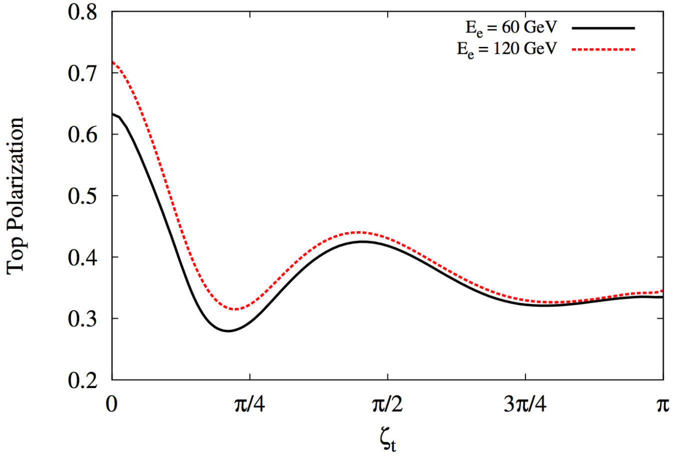


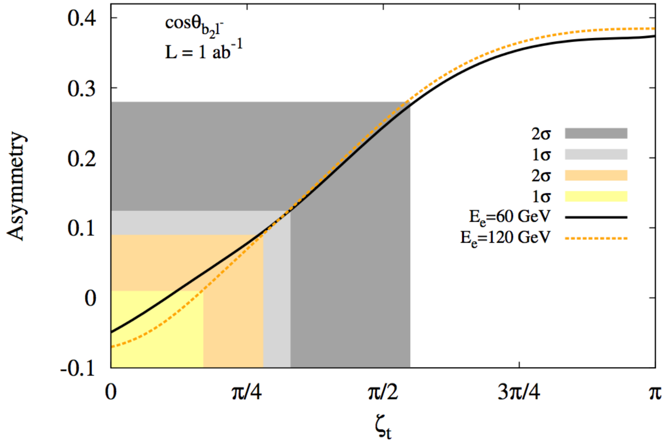
LHeC



rapidity difference $(H,\bar{t})$



top polarisation



angular asymmetries (b_2,l^-)

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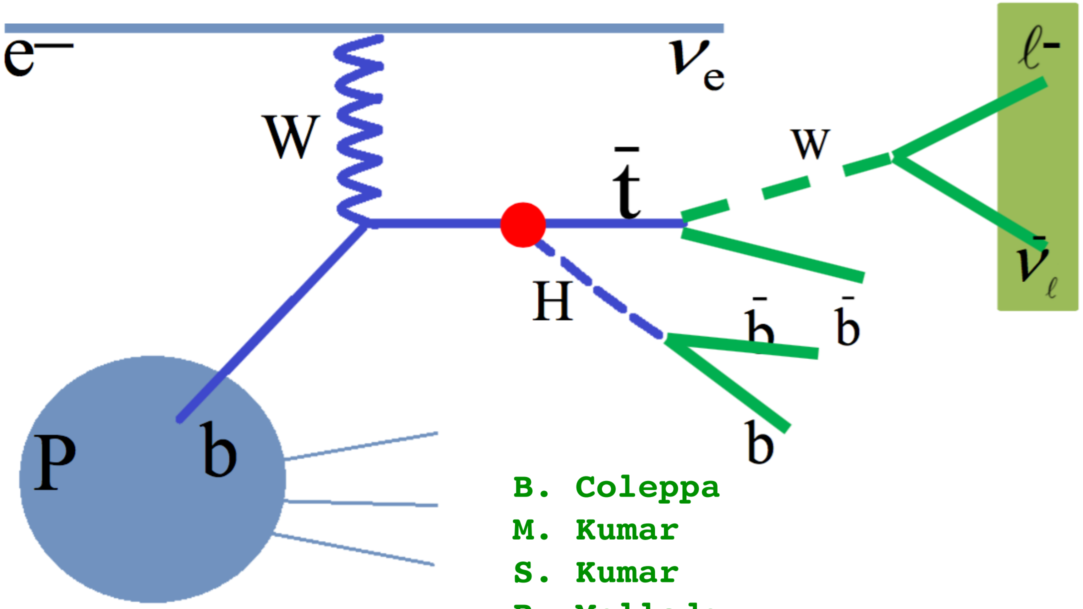

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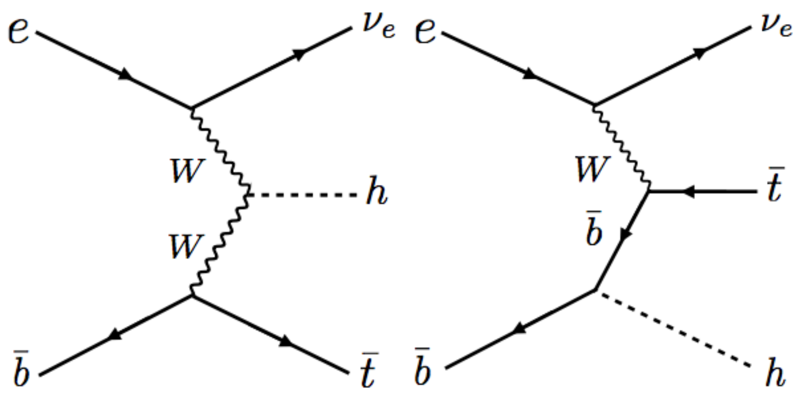
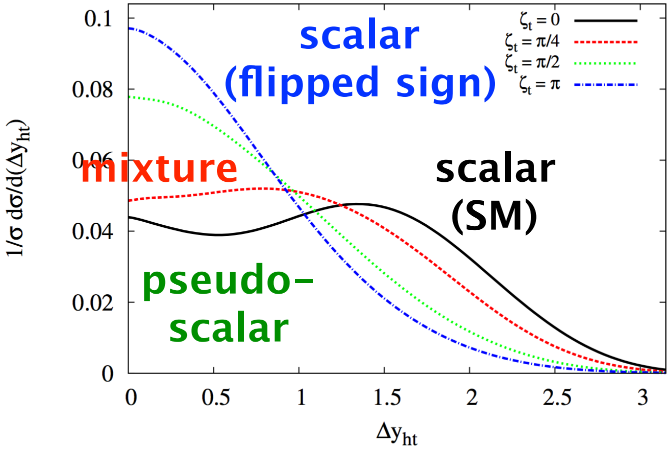


LHeC

rapidity difference (H,$\bar{t}$)



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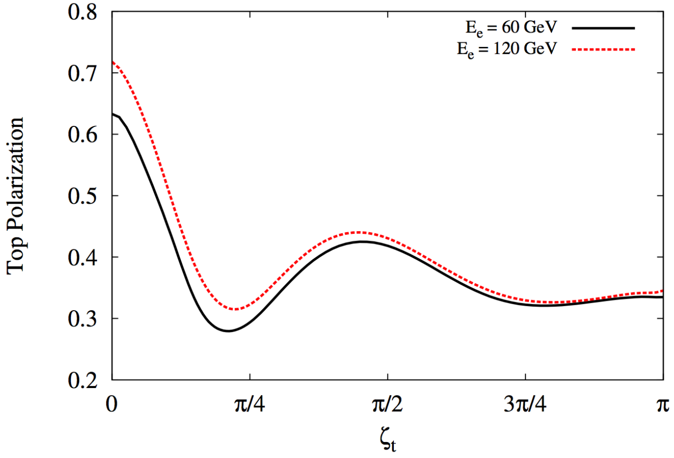
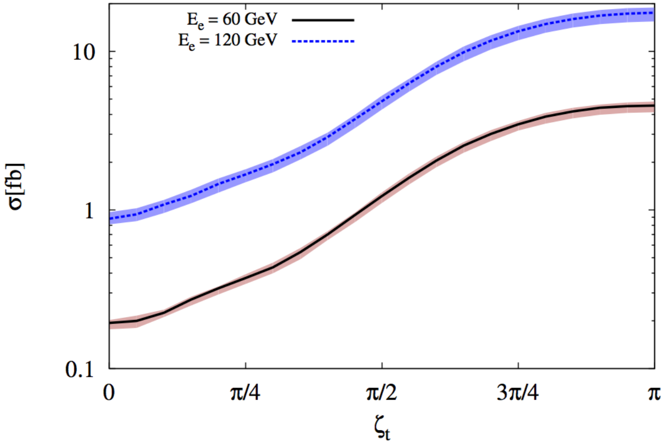


fiducial incl. cross-section



Exclusion Contours (fiducial cross section)

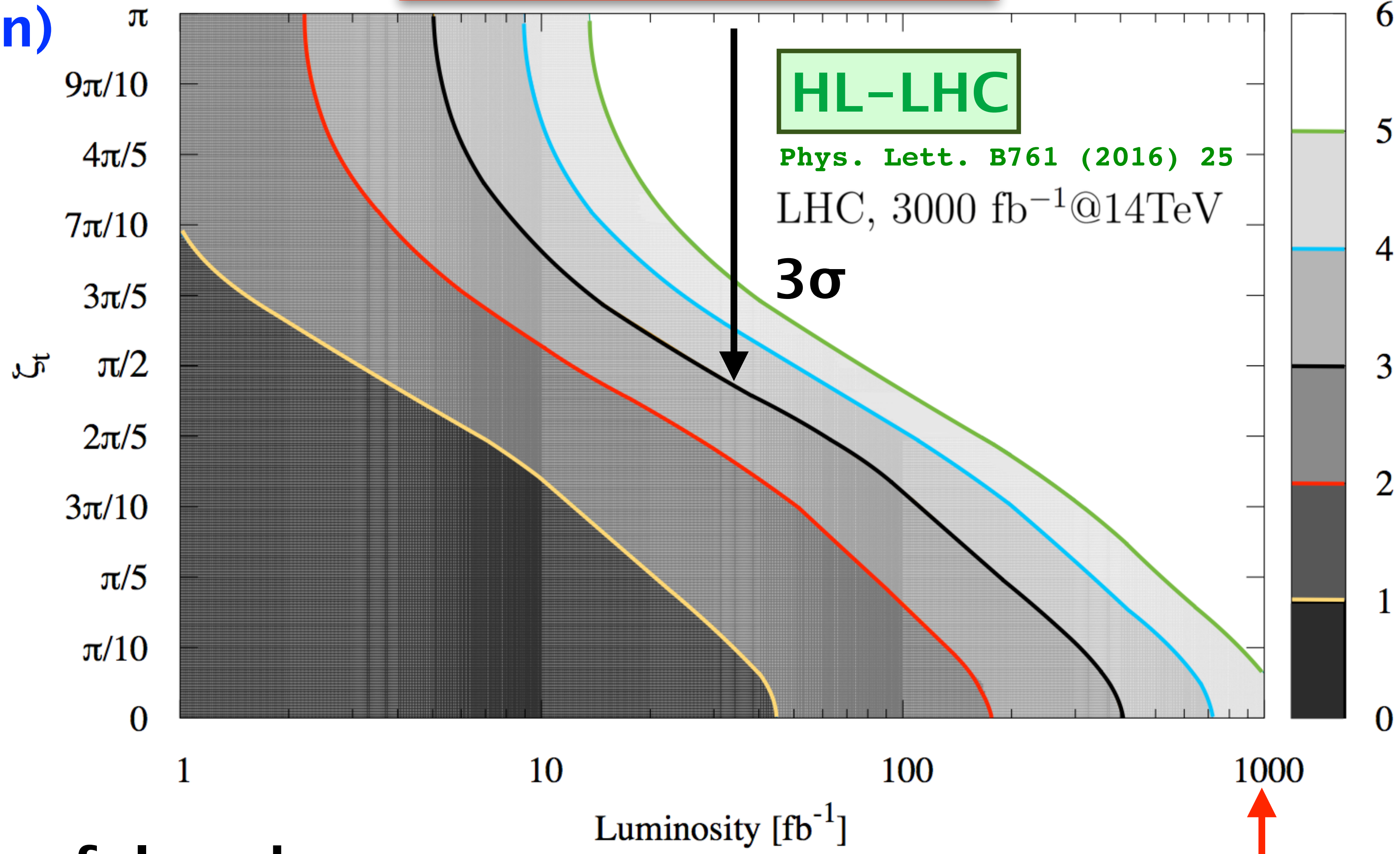
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]t\,h$$

LHeC

CP–even (flipped sign)

CP–odd

CP–even (SM)



→ **powerful probe of ttH coupling**

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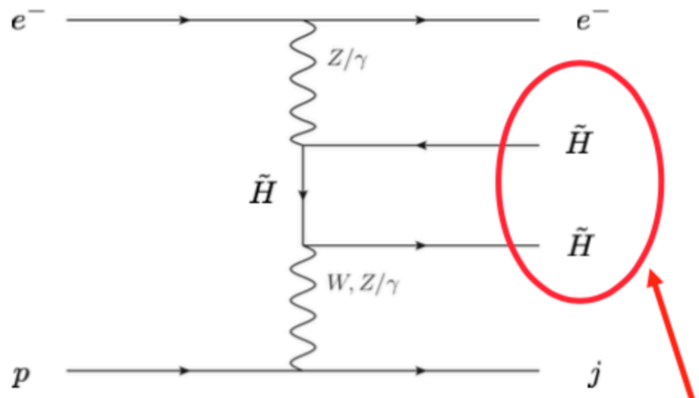
Prompt Higgsino (LSP) Searches

BSM

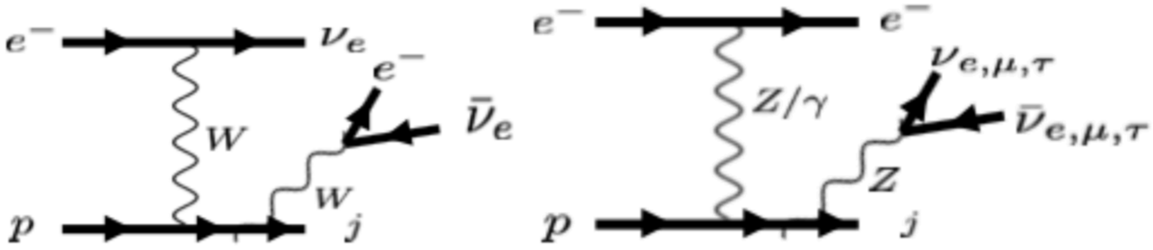
signal

difficult at LHC…

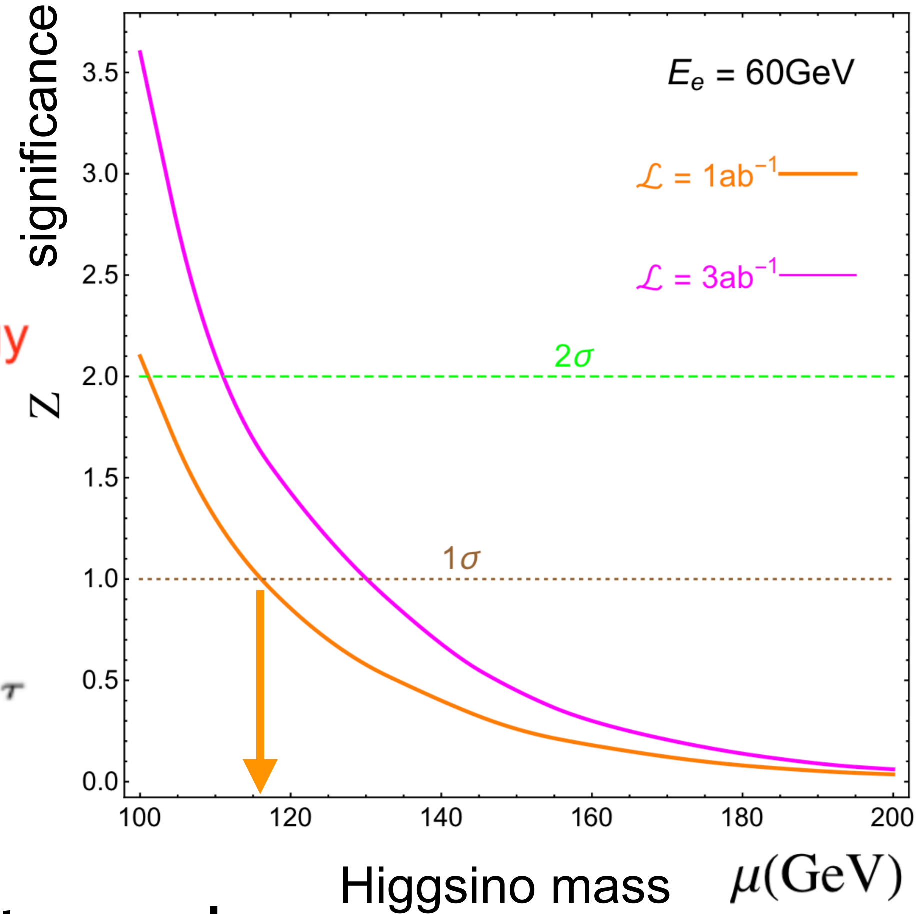


Typical signal: electron + jet + missing energy

background



Han, Li, Pan, Wang, arXiv:1802.03679



→ **many more ideas for sensitive searches to come!**