

# ESUPP discussion: CERN Future Circular Collider

<http://cern.ch/fcc>

## DIS 2018

Kobe, 17<sup>th</sup> April 2017

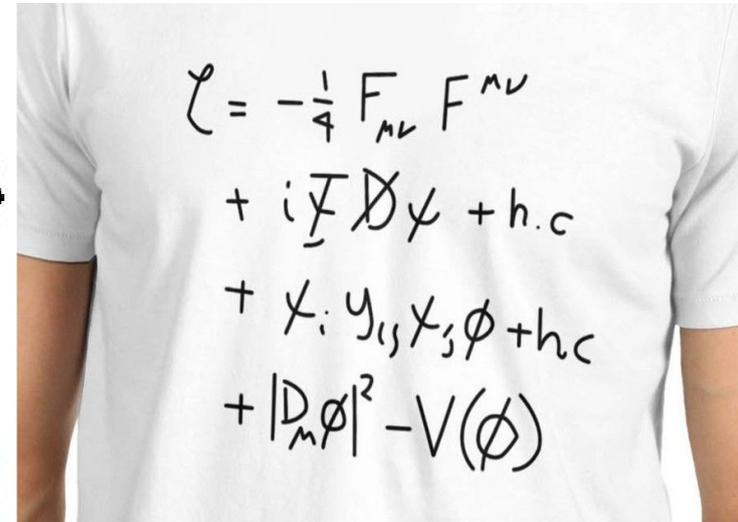
David d'Enterria

CERN



- We have a mathematical theory (SM) that describes with great precision all experimental measurements of the fundamental particles & their interactions carried out for over ~45(!) years (incl. the predicted Higgs boson...)

***So, what is the problem...?***



- ✗ Light-masses generation: 1<sup>st</sup>-gen. fermion (and all v's) masses Yukawas?
- ✗ Higgs potential: Higgs triple & quartic Higgs self-couplings to be measured
- ✗ Fine-tuning: Higgs mass virtual corrections «untamed» up to Planck scale
- ✗ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✗ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)
- ✗ Others: Strong CP, quantum gravity, cosmological constant, dark energy, inflation,...

**Some/Most(?) of these key questions will not be fully answered at the LHC**

# Future Circular Collider: Genesis

- Outcome of the **European Strategy for Particle Physics in May 2013**:

- ◆ **From CERN Council official documents:**

<https://cds.cern.ch/record/1567258/>

To stay at the forefront of particle physics, Europe needs to be in a position to propose an **ambitious post-LHC accelerator project at CERN by the time of the next Strategy update**, when physics results from the LHC running at 14 TeV will be available.

*CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.*

**CLIC**

*[...] coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, [...]*

<https://cds.cern.ch/record/1567295/>

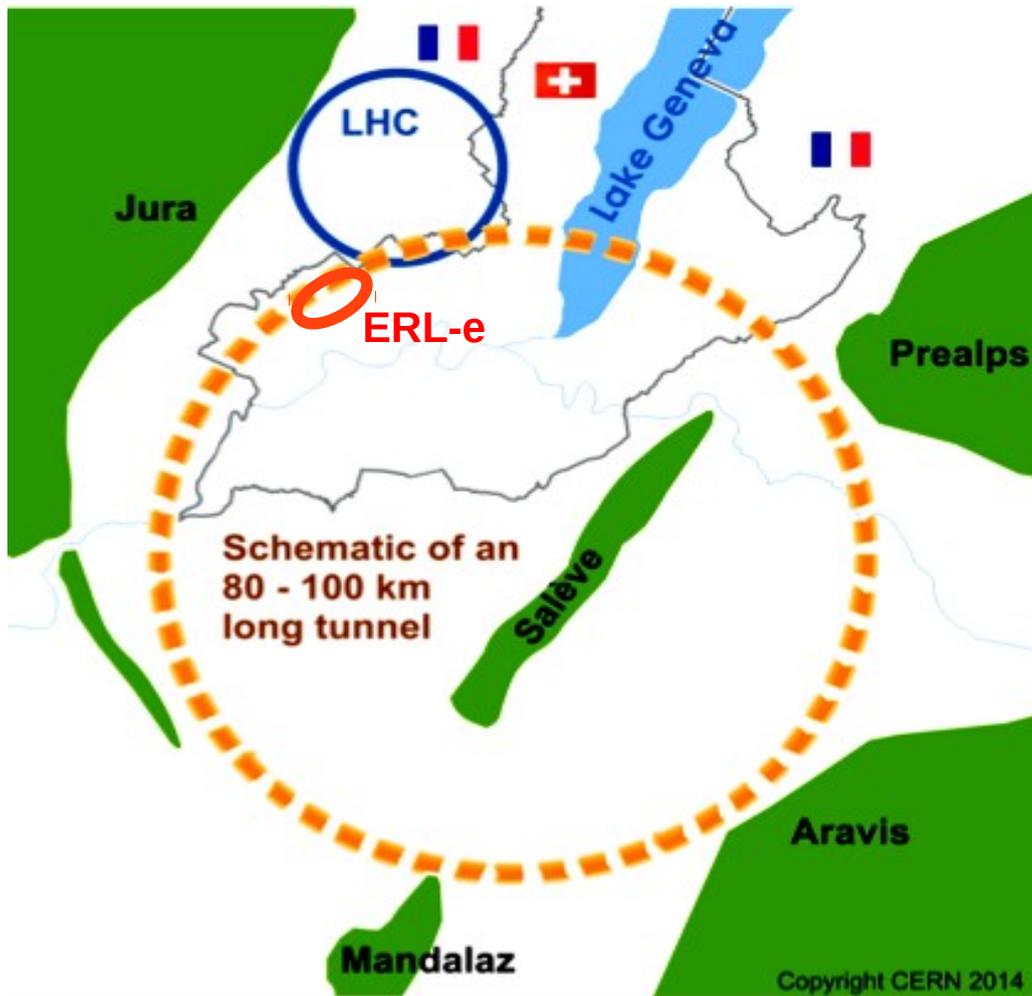
**Possible proton-proton machines of higher energy than the LHC include HE-LHC, roughly doubling the centre-of-mass energy in the present tunnel, and V-LHC, aimed at reaching up to 100 TeV in a new circular 80km tunnel. A large tunnel such as this could also host a circular electron-positron machine (TLEP) reaching energies up to 350 GeV with high luminosity.**

**FCC !**

- Ongoing preparation of **many Conceptual Design Reports for 2019** discussion

# CERN Future Circular Collider

- FCC: Post-LHC collider with  $R=98$  km ( $h=-300$ m) & 16 T  $Nb_3Sn$  dipoles to achieve p-p collisions at  $\sqrt{s} = 100$  TeV with up to  $L_{int} \sim 2$   $ab^{-1}/year$  ( $\sim 20$   $ab^{-1}$  over 20 years).

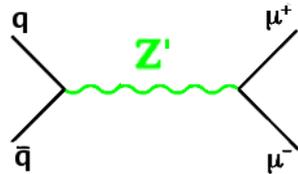


- Initial phase with  $e^+e^-$  collisions at unprecedented energies & lumis:
  - $e^+e^-(Z, 91$  GeV),  $L_{int} \sim 150$   $ab^{-1}/4$  yrs
  - $e^+e^-(WW, 160$  GeV),  $L_{int} \sim 10$   $ab^{-1}/yr$
  - $e^+e^-(HZ, 240$  GeV),  $L_{int} \sim 5$   $ab^{-1}/3$  yrs
  - $e^+e^-(tt, 350$  GeV),  $L_{int} \sim 2.5$   $ab^{-1}/5$  yrs
- Heavy-ions with pPb, PbPb colls. at never-reached energies & lumis:
  - pPb(63TeV),  $L_{int} = 30$   $pb^{-1}/year$
  - PbPb(39TeV),  $L_{int} = 110$   $nb^{-1}/year$
- DIS collisions (ep, eA) with ERL-e:
  - e-h(3.5 TeV),  $L_{int} \sim 2$   $ab^{-1}/20$  years
  - e-Pb(1–3 TeV),  $L_{int} \sim 1$   $fb^{-1}/yr.$

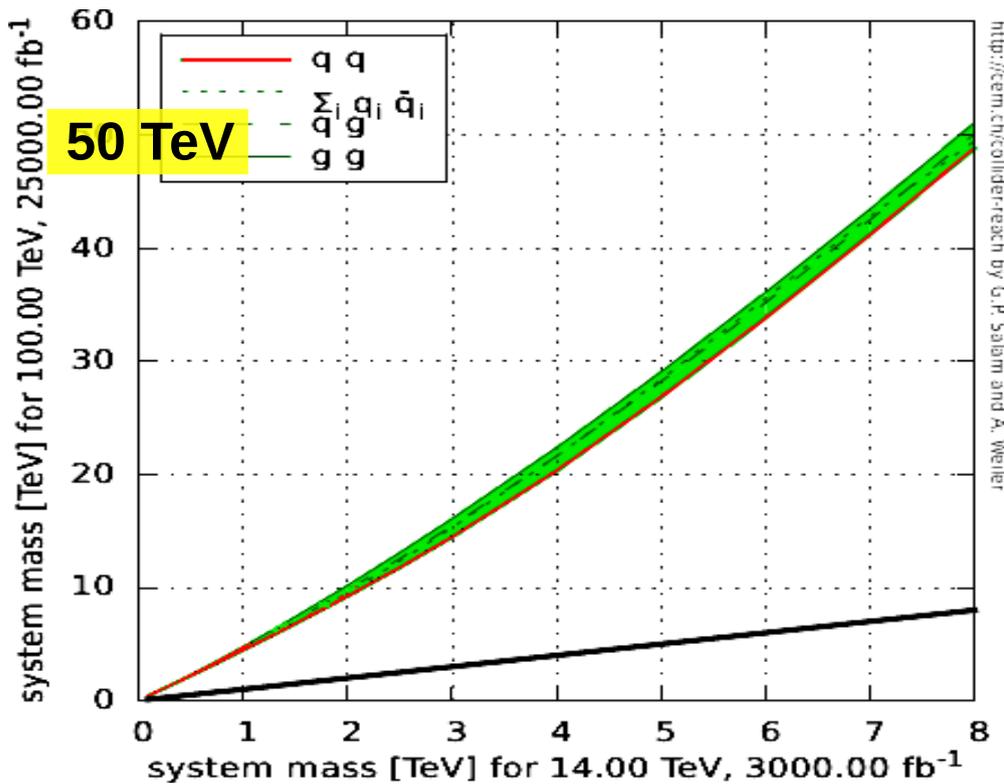
**Goals:** pp,ep: Direct BSM up to  $\sim 50$  TeV with about  $\times 10$  more  $\sqrt{s}$  and  $L_{int}$  than LHC.  
 ee,ep: High-precision SM (uncert.:  $< 1\%$  Higgs,  $< 10^{-5}$  EWK): Indirect BSM up to 50 TeV

# BSM physics reach at FCC

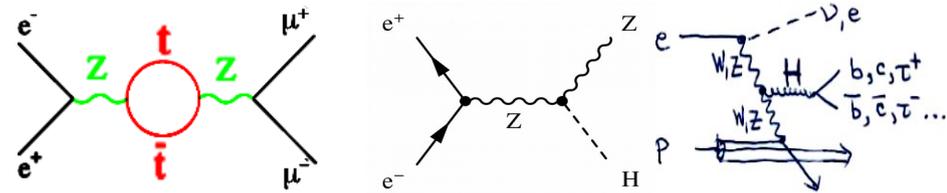
- FCC-pp: **Direct** production of **new heavy particles up to ~50 TeV** (~8 TeV at LHC):



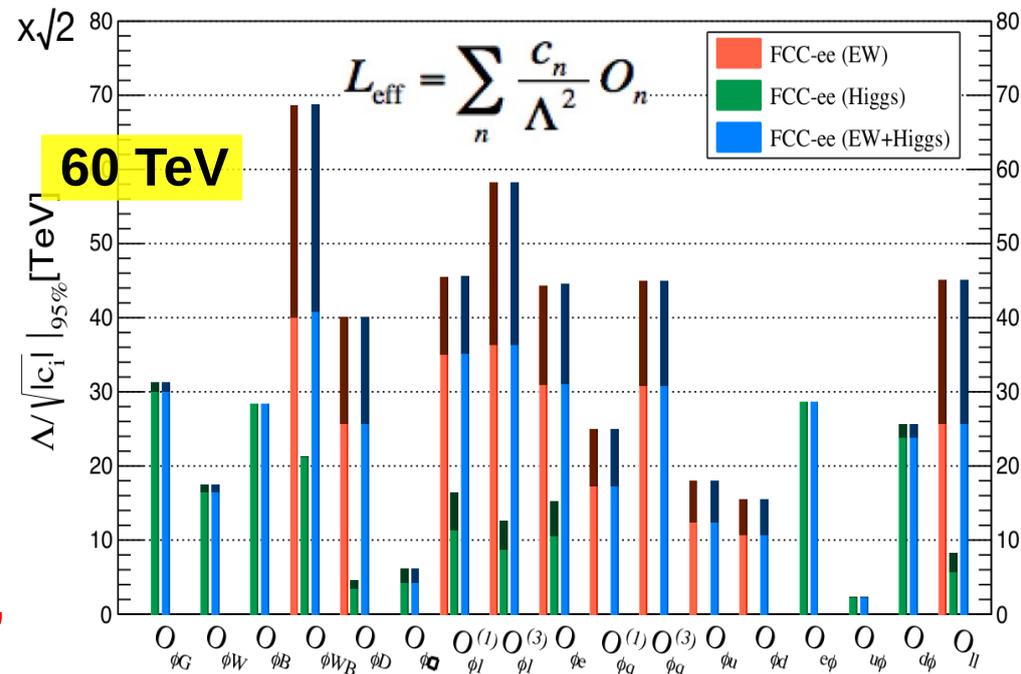
Parton-parton **masses**: FCC vs. LHC



- FCC-ee,eh: **Indirect** sensitivity to **virtual corrections up to ~60 TeV** (~3 TeV at LEP for EWK sector):

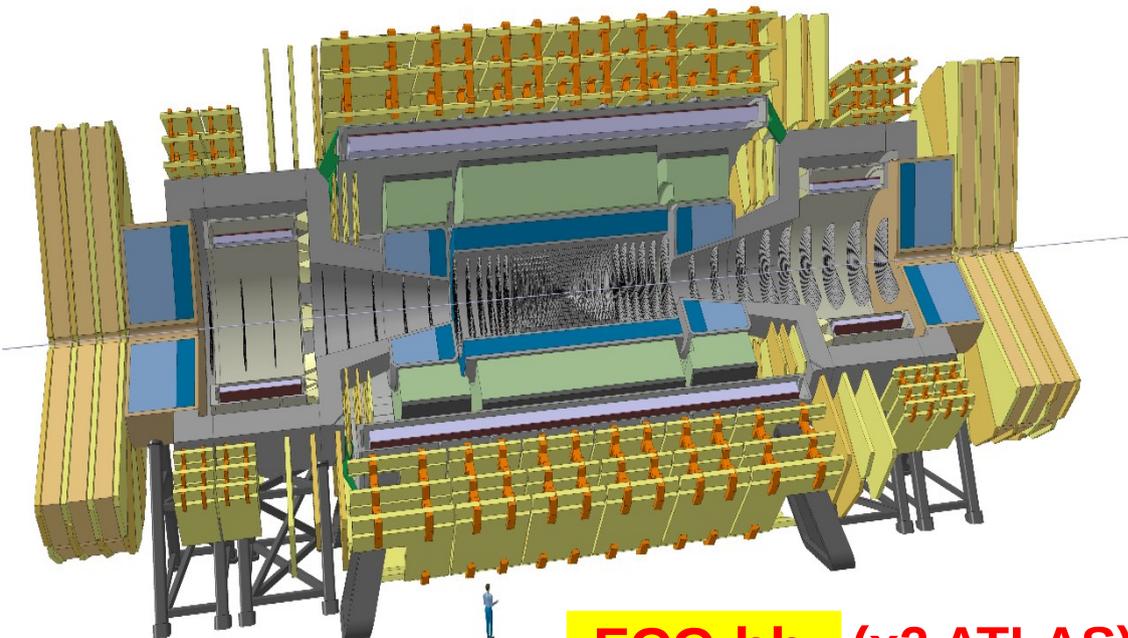


**SM-EFT limits** from EWK ( $\delta X < 10^{-5}$ ) and Higgs ( $\delta g_H < 1\%$ ) observables uncertainties:



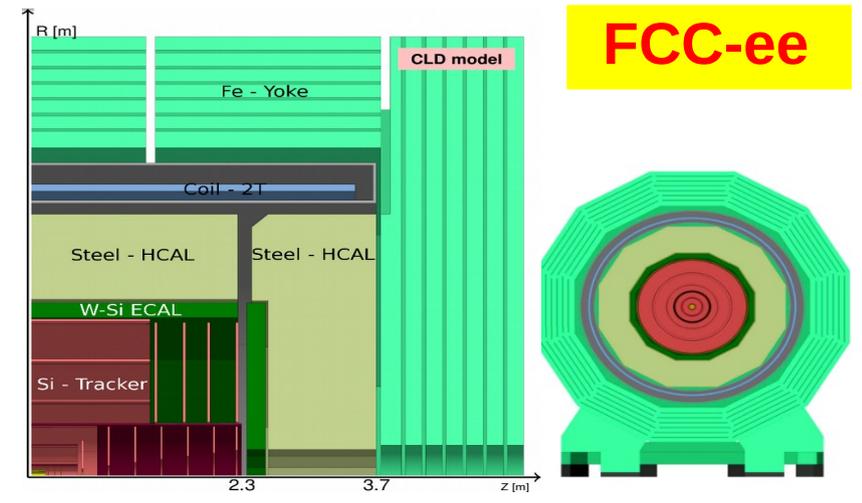
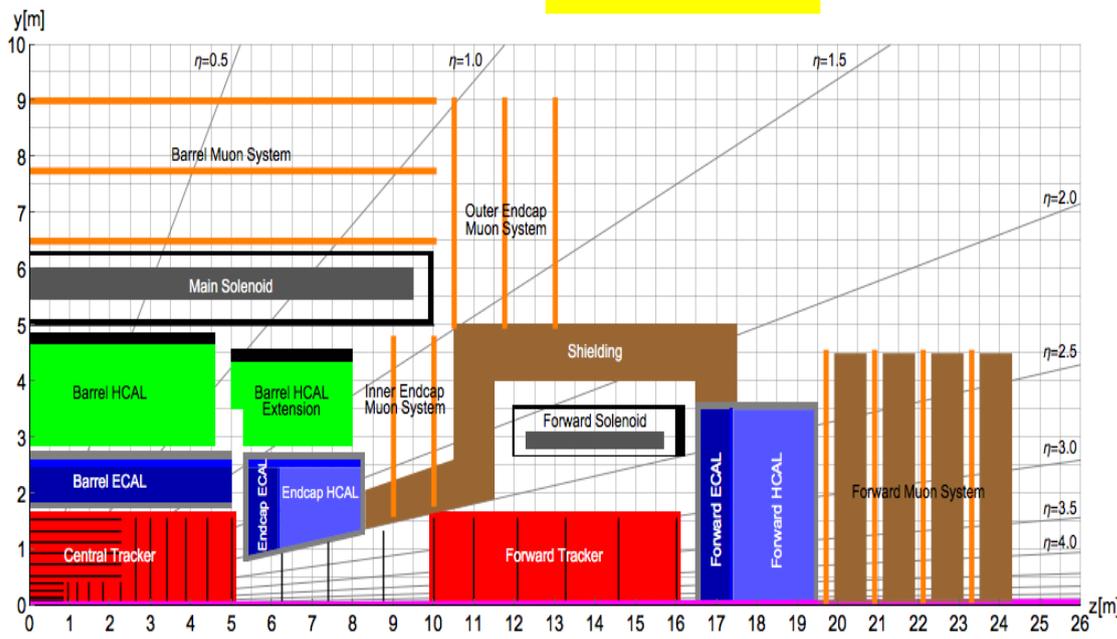
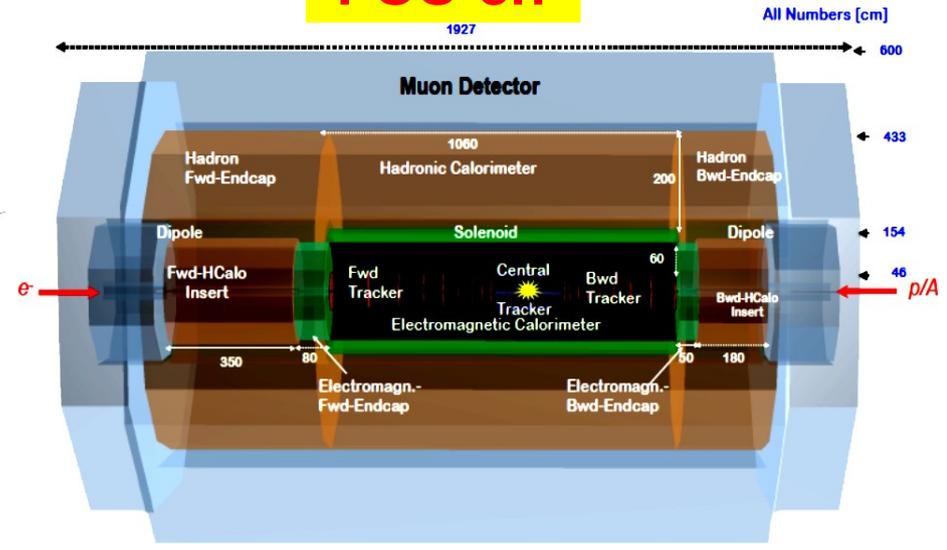
- Plus many more: **Higgs self-coupling, TeV- $p_T$  W,Z,H,t; WW scatt., DM,...**

# FCC reference detectors



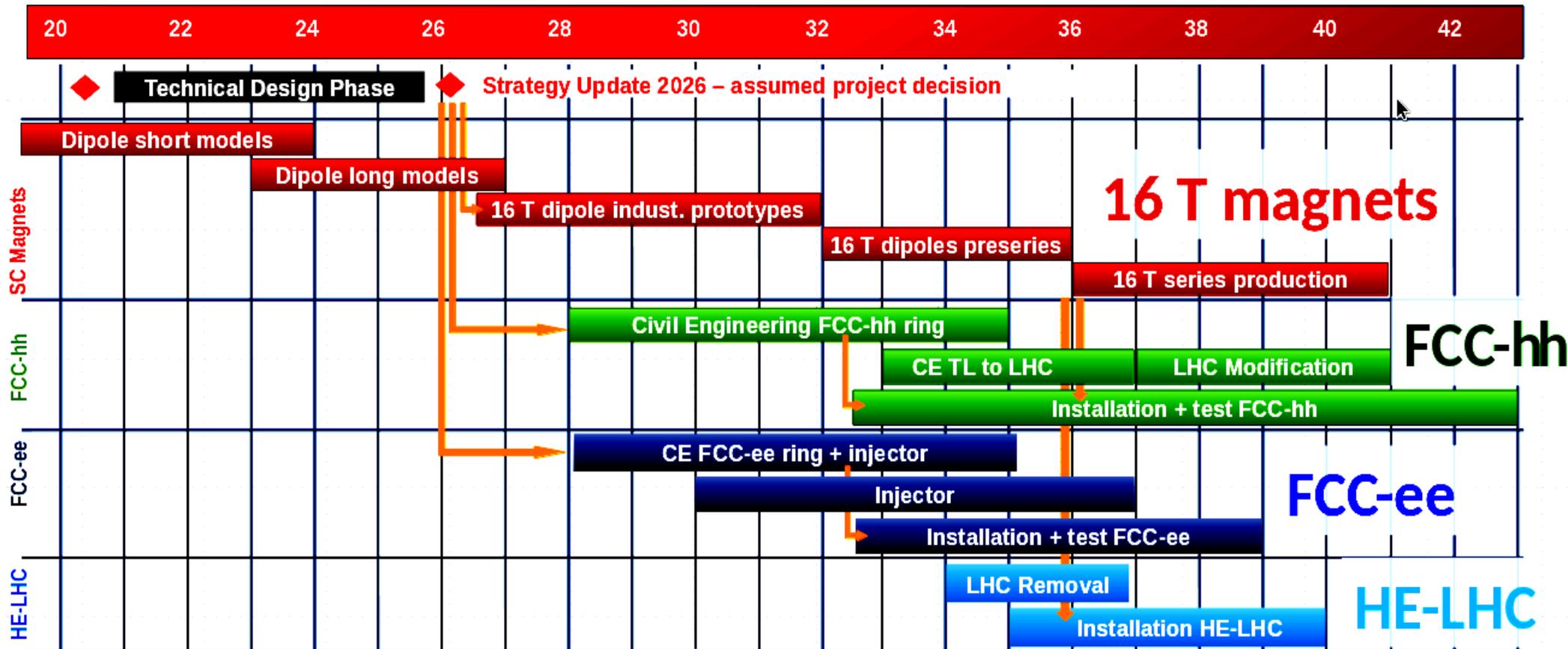
**FCC-hh (x2 ATLAS)**

**FCC-eh**



**FCC-ee**

# FCC Schedule



**Schedule constrained by 16-T magnet development & production**

Earliest possible physics starting dates (~20-25 years from DIS'18):

▶ **FCC-ee: 2039**

▶ **FCC-hh: 2043**

(**HE-LHC: 2040**, with HL-LHC stop LS5 / 2034)



# QCD is key for all FCC-ee,eh,hh physics

- ▶ Though QCD is *not per se* the main driving force behind FCC, **QCD is crucial for many FCC measurements** (signals & backgrounds):
  - **High-precision  $\alpha_s$** : Affects SM fits/tests, all hadronic cross sections & decays
  - **$N^{\text{n}}\text{LO}+N^{\text{n}}\text{LL}$  corrections**: Needed for all x-sections with initial/final hadrons
  - **Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...**: Needed for all precision measurements & BSM searches with jets.
  - **High-precision (n)PDFs**: In h-h collisions, affects all precision W,Z,H (mid-x) measurements, all BSM searches (high-x), & beyond-DGLAP (low-x) studies.
  - **Semihard QCD**: low-x **gluon saturation, multiple hard** parton interactions, ...  
Note:  $Q_0 \sim 10(!)$  GeV at 100 TeV.
  - **Many-body QCD**: **Partonic collective behaviour** in high particle-density systems, **Colour reconnection** in “central” h+h collisions; impact on fundamental quantities in jetty final-states ( $m_W, m_{\text{top}}$  extractions,...),
  - **Non-pQCD**: Control of **hadronization+diffraction+...** is basic at FCC-pp with  $\mathcal{O}(1.000)$  pileup, backgds,...



# QCD at FCC: Unparalleled potential

Flash just a few examples...

- (1) QCD coupling** (FCC-ee, FCC-eh, FCC-pp)
- (2) Proton parton densities** (FCC-ep, FCC-pp)
- (3) Nuclear parton densities** (FCC-eA, FCC-pA)
- (4) Beyond DGLAP** (FCC-eh, FCC-hh)
- (5) QCD thermodynamics** (FCC-AA)

# (1) QCD coupling $\alpha_s$ importance

Impacts all QCD x-sections, Higgs decays, precision top & EWPO:

Process	$\sigma$ (pb)	$\delta\alpha_s$ (%)	PDF + $\alpha_s$ (%)	Scale (%)
ggH	49.87	$\pm 3.7$	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	$\pm 3.0$	$\pm 8.9$	-9.3 + 5.9

Channel	$M_H$ [GeV]	$\delta\alpha_s$ (%)	$\Delta m_b$	$\Delta m_c$
H $\rightarrow$ $c\bar{c}$	126	$\pm 7.1$	$\pm 0.1\%$	$\pm 2.3\%$
H $\rightarrow$ gg	126	$\pm 4.1$	$\pm 0.1\%$	$\pm 0\%$

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\text{SD-low}})^{\text{exp}}$	$(\delta M_t^{\text{SD-low}})^{\text{theo}}$	$(\delta \bar{m}_t(\bar{m}_t))^{\text{conversion}}$	$(\delta \bar{m}_t(\bar{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 - 23 MeV	70 MeV

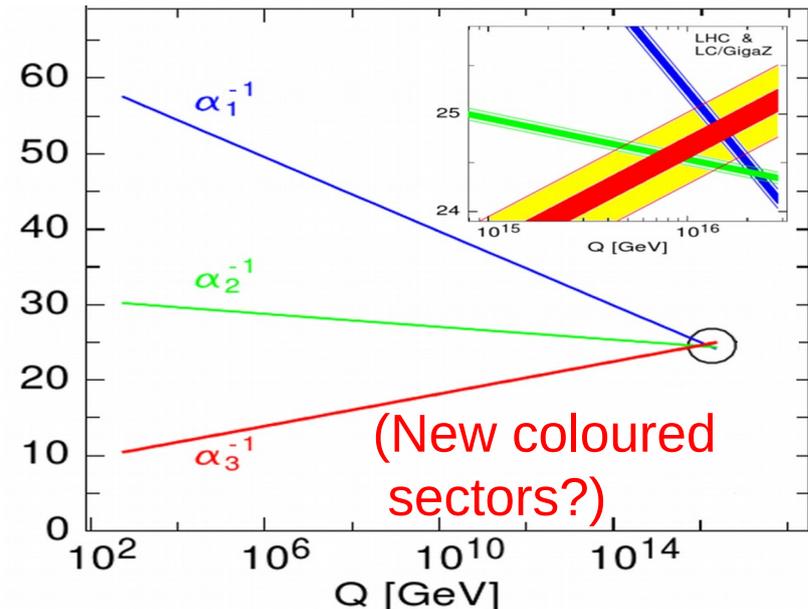
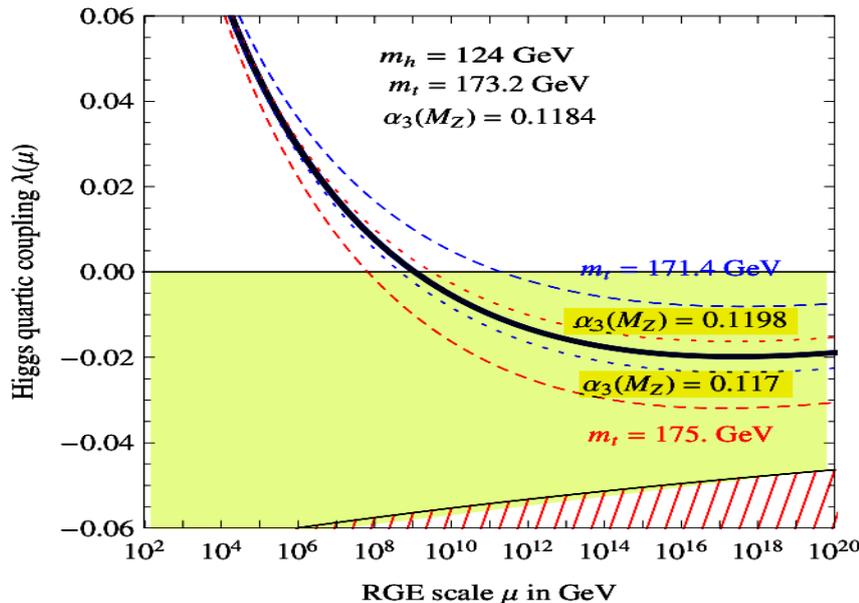
$\Rightarrow$  improvement in  $\alpha_s$  crucial  $\delta\alpha_s(M_Z) = 0.001$

Summary of future parametric uncertainties:

Quantity	FCC-ee	future param.unc.	Main source
$\Gamma_Z$ [MeV]	0.1	0.1	$\delta\alpha_s$
$R_b$ [ $10^{-5}$ ]	6	< 1	$\delta\alpha_s$
$R_\ell$ [ $10^{-3}$ ]	1	1.3	$\delta\alpha_s$

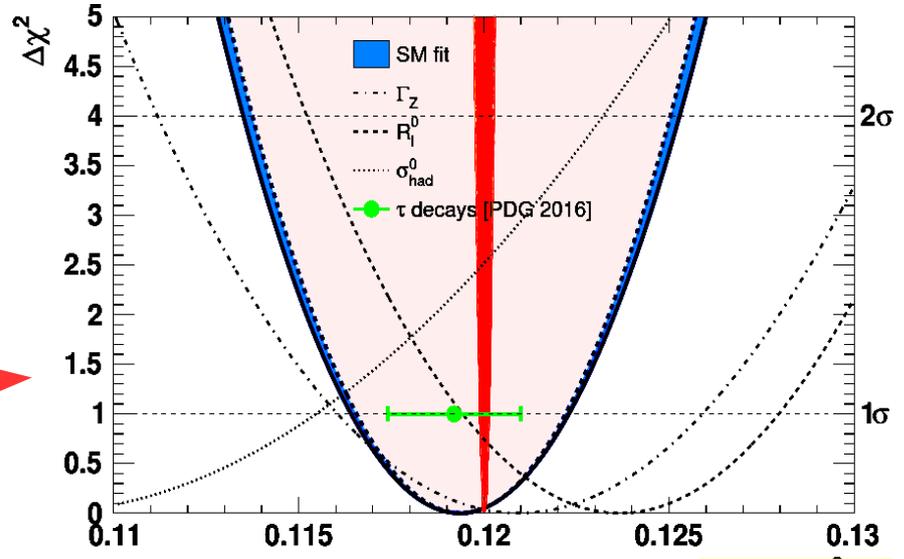
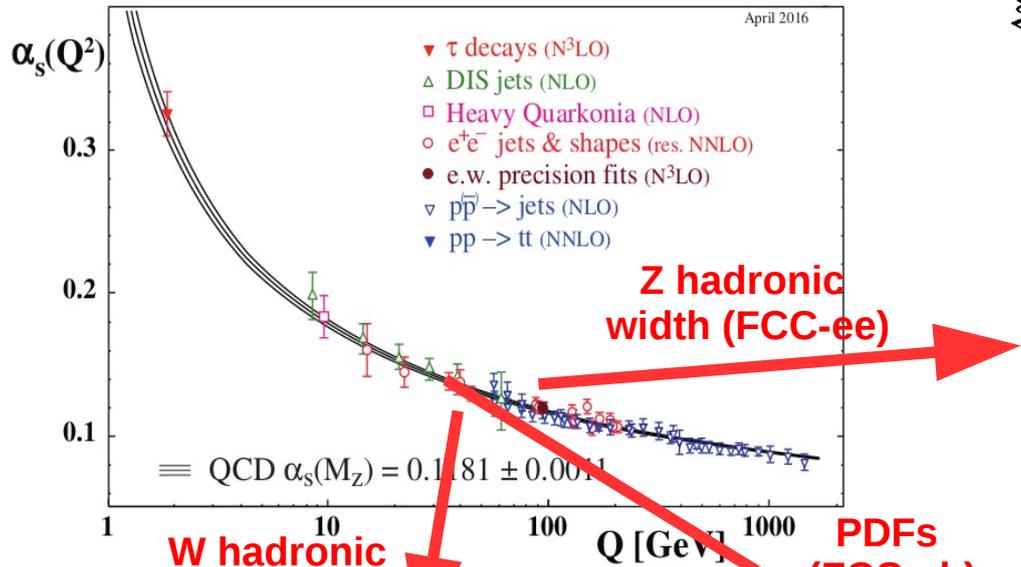
Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

Impacts physics approaching Planck scale: EW vacuum stability, GUT

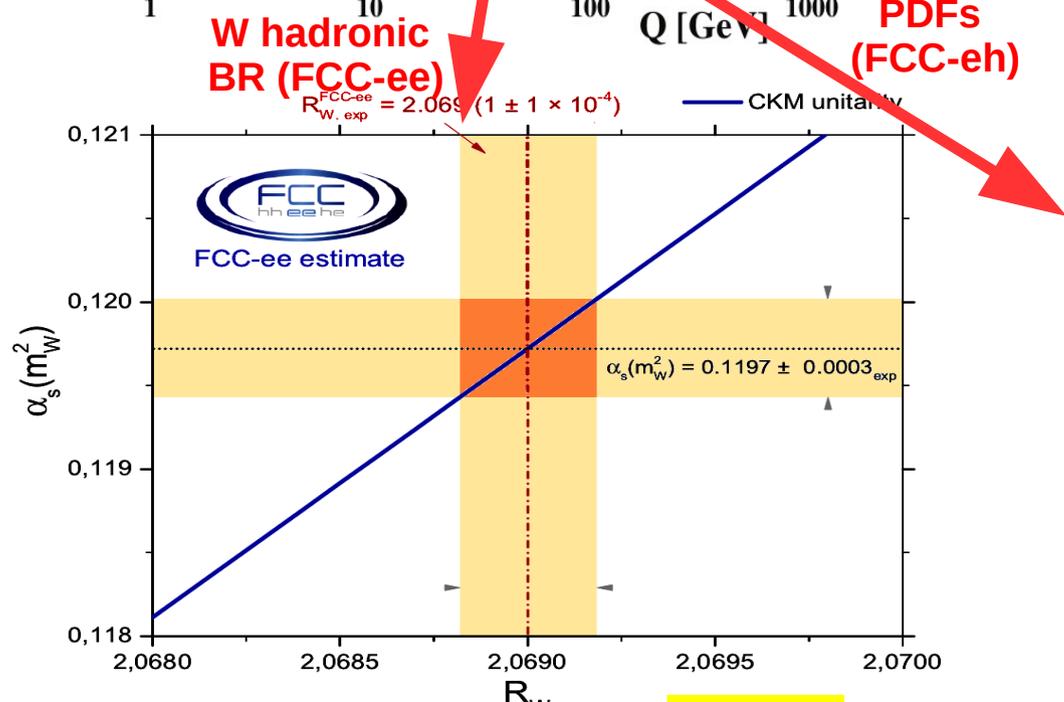




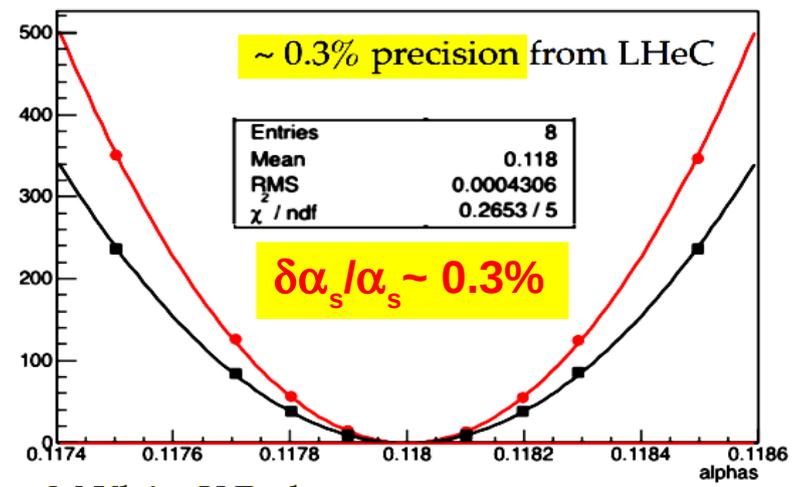
# (1) FCC-ee,eh: $\alpha_s$ extraction



LEP:  $\alpha_s(M_Z) = 0.1196 \pm 0.0030$  ( $\pm 2.5\%$ )  
 Z stats ( $\times 10^5$  LEP) will lead to:  $\delta\alpha_s/\alpha_s < 0.2\%$



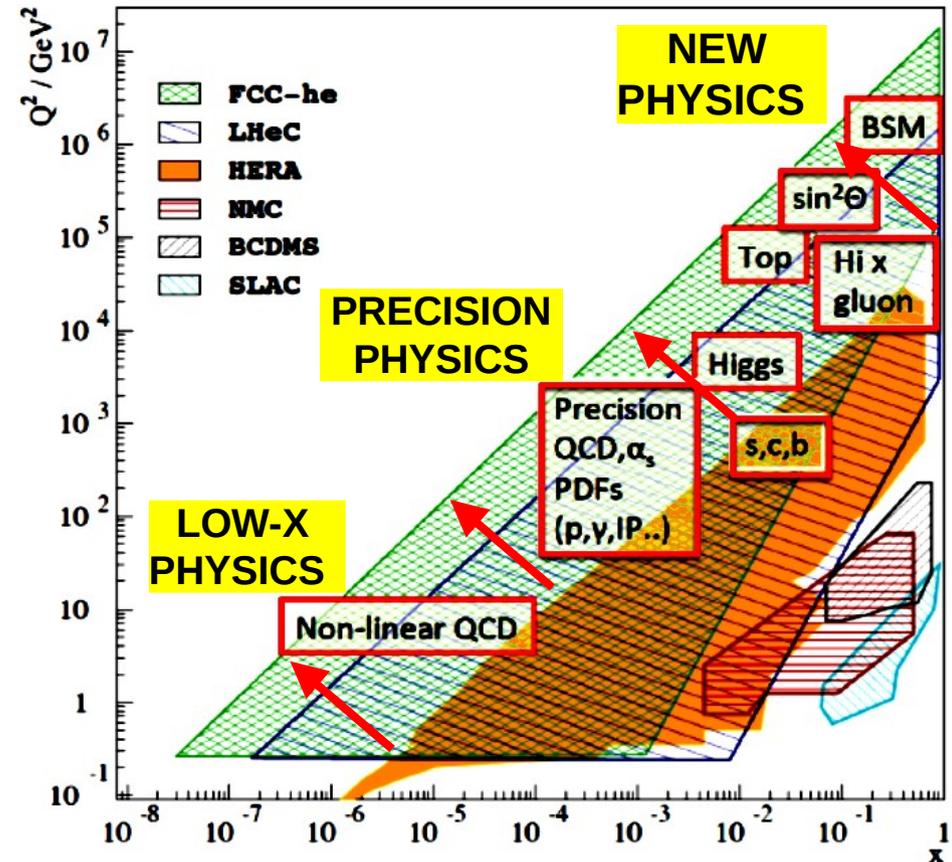
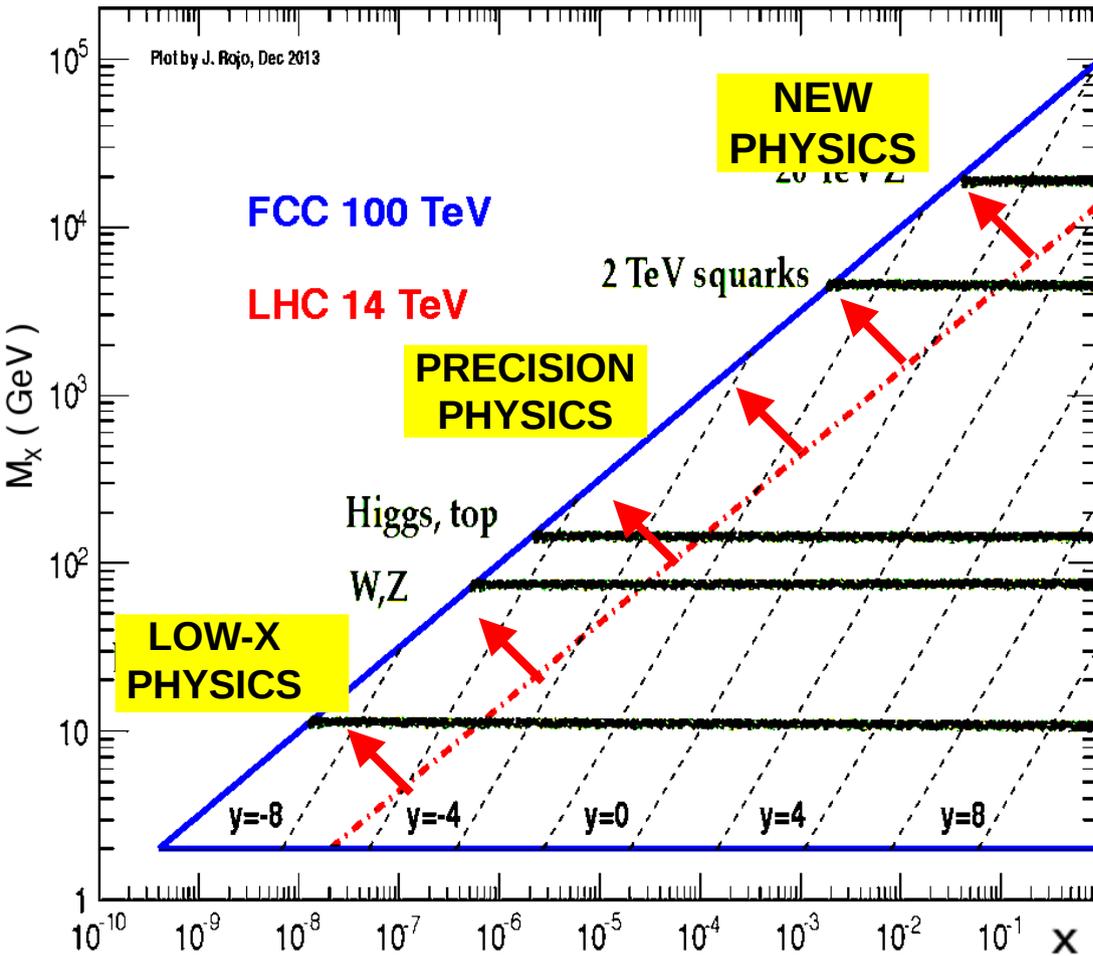
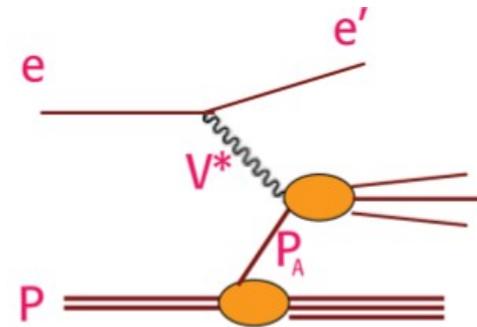
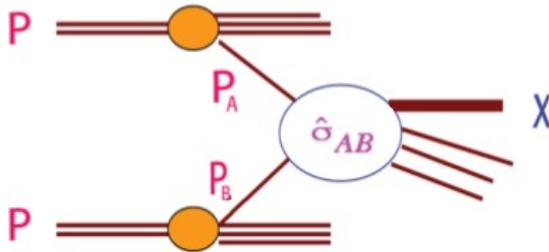
LEP:  $\alpha_s(M_W) = 0.117 \pm 0.040$  ( $\pm 35\%$ )  
 W stats ( $\times 10^4$  LEP) will lead to:  $\delta\alpha_s/\alpha_s < 0.3\%$



M Klein, V Radescu  
 combined fit to PDFs+ $\alpha_s$  using LHeC data

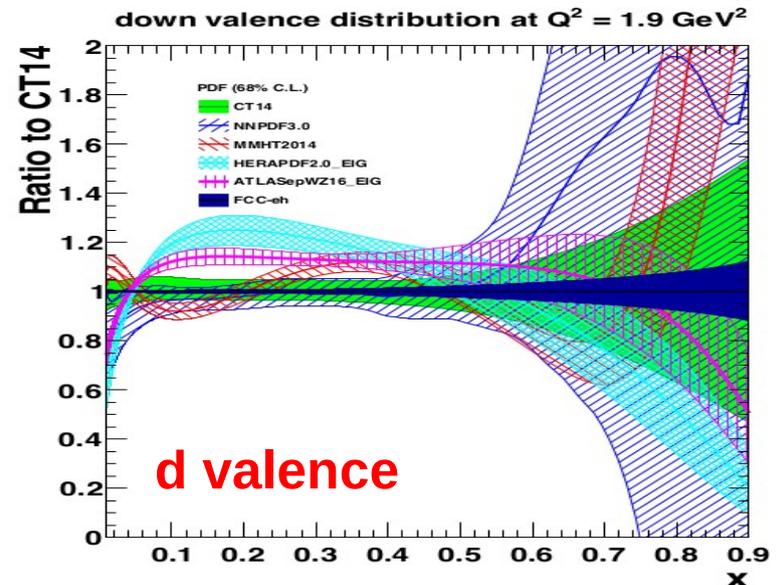
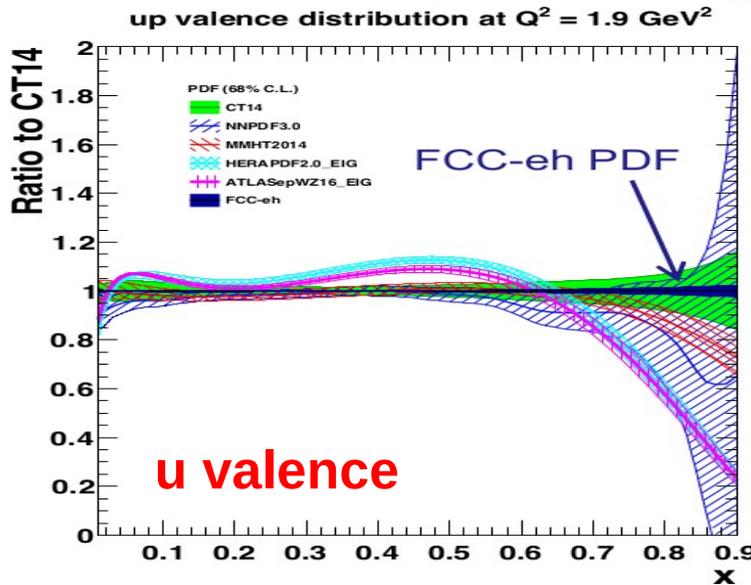
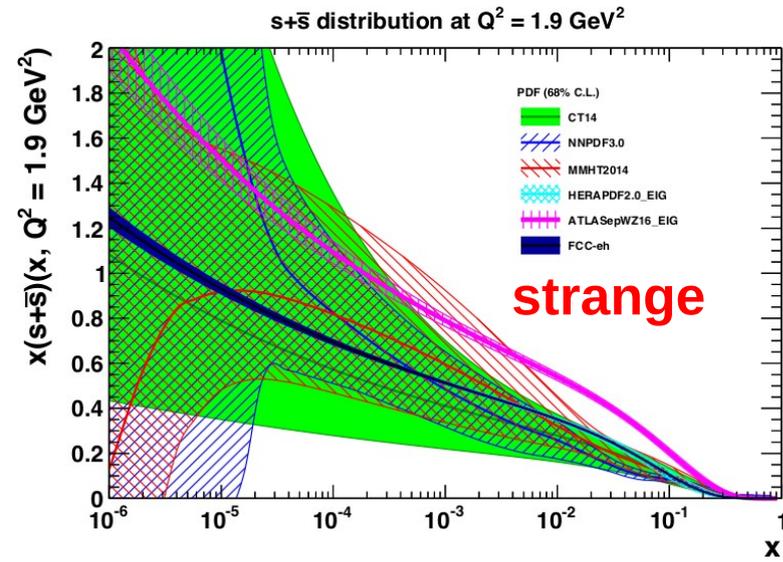
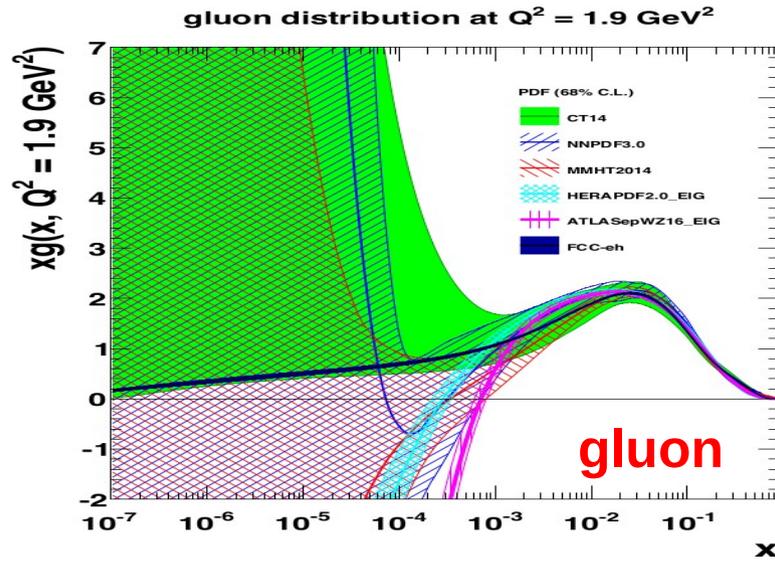
# (2) FCC-pp,ep: PDF kinematic reach

- Unparalleled  $(x, Q^2)$  reach:  $\times 10$  LHC, HERA, down to  $x \sim 10^{-8}$
- Accurate PDF measurements in all key regions: BSM, precision, low- $x$



# (2) FCC-ep: Improved PDFs (all flavours, x)

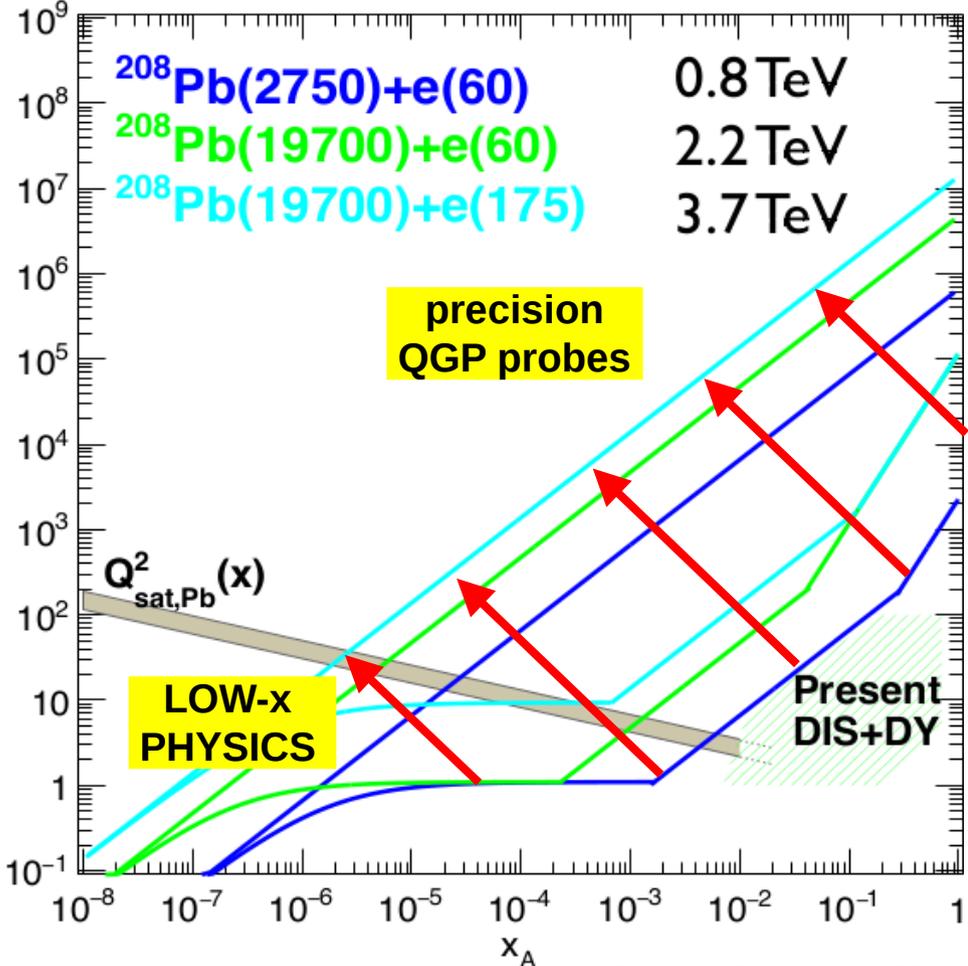
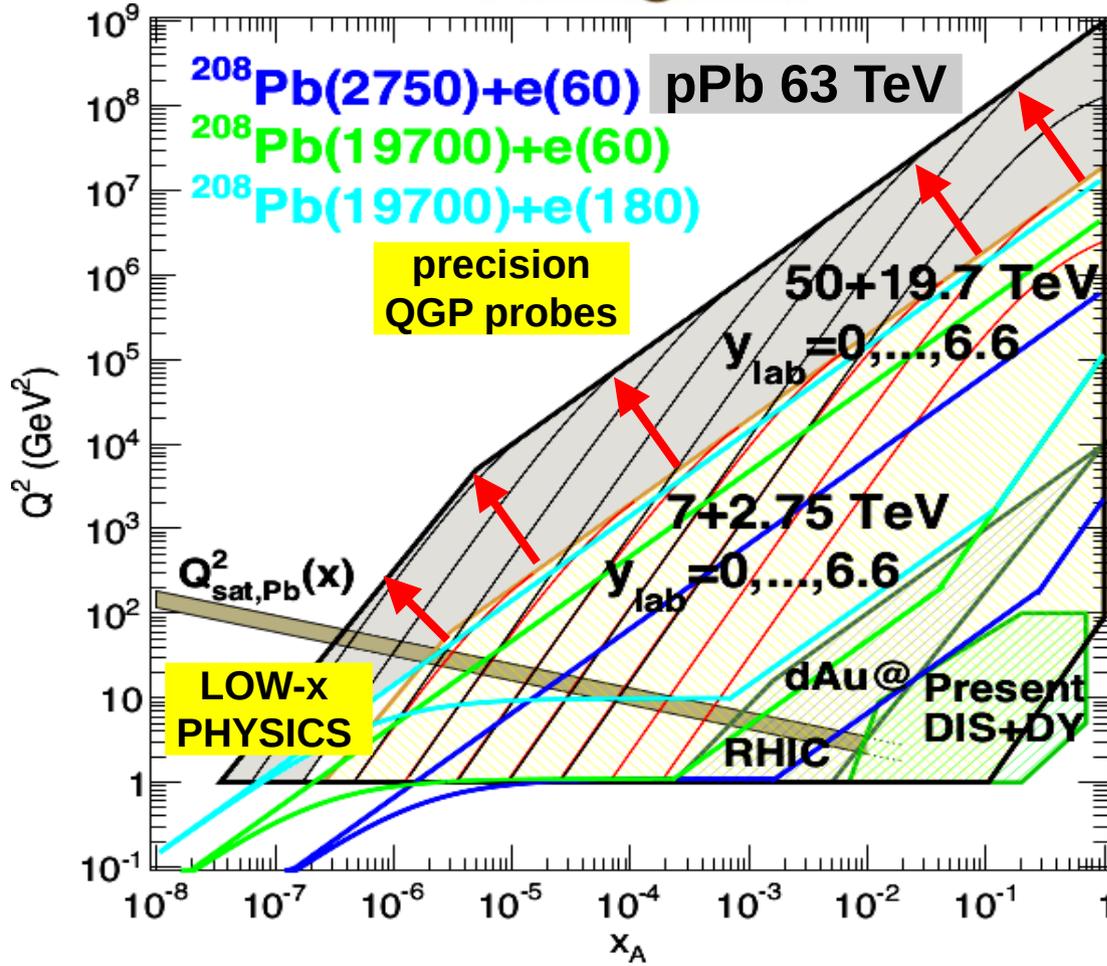
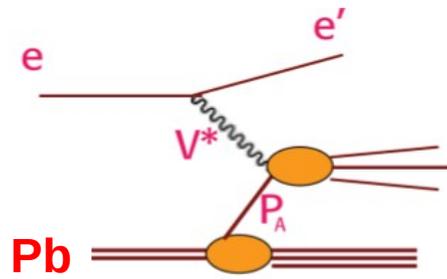
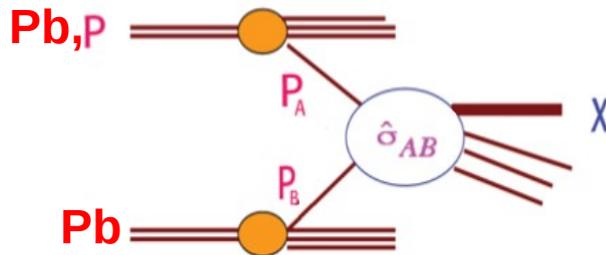
■ e-p (60 GeV+50 TeV) NC&CC pseudo-data  $P=\pm 0.8$



■ Strongly reduced PDF uncertainties for all flavours (also charm, bottom, top) at all x (down to  $10^{-8}$ )

# (3) FCC-eA,AA: Nuclear PDF ( $x, Q^2$ ) range

- Unparalleled ( $x, Q^2$ ) reach:  $\times 10$  LHC,  $\times 10^4$  nDIS ( $\times 10^3$  EIC), down to  $x \sim 10^{-6}$
- Accurate nPDF measurements in precision QGP, low-x

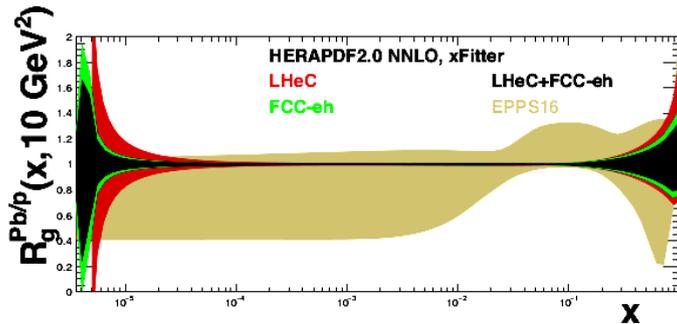


# (3) FCC-eA: Significantly improved nPDFs

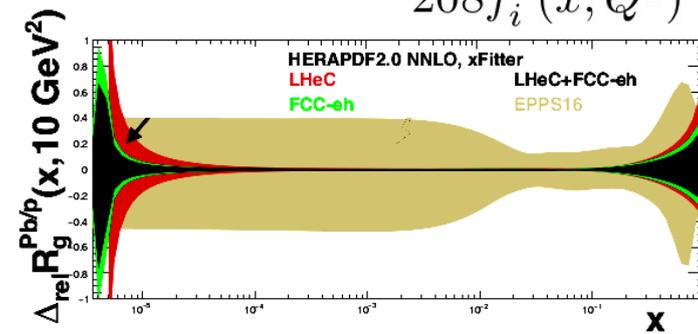
- Very large uncertainties today on nPDFs: Precision study of QGP properties in PbPb jeopardized by initial-state uncertainties.

- ePb (60 GeV+20 TeV) NC&CC pseudo-data:  $R_i^{\text{Pb}}(x, Q^2) = \frac{f_i^{\text{Pb}}(x, Q^2)}{208 f_i^p(x, Q^2)}$ ,  $i = q, \bar{q}, g$

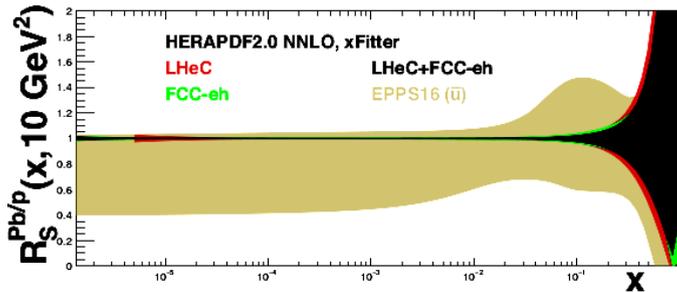
Gluon:



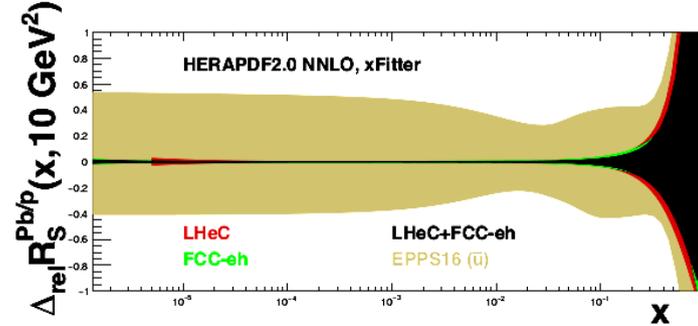
Pb/p



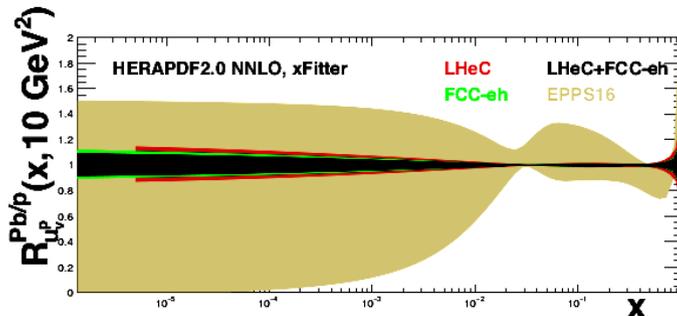
Sea:



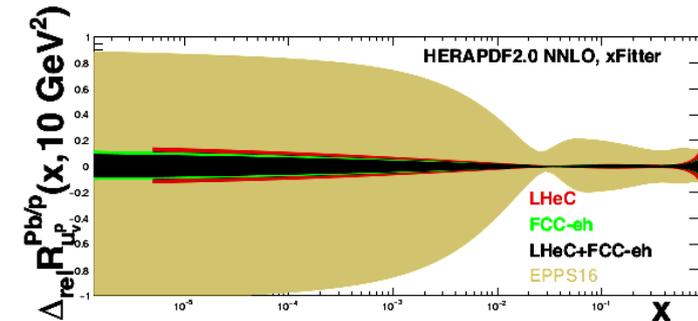
Pb/p



Valence:

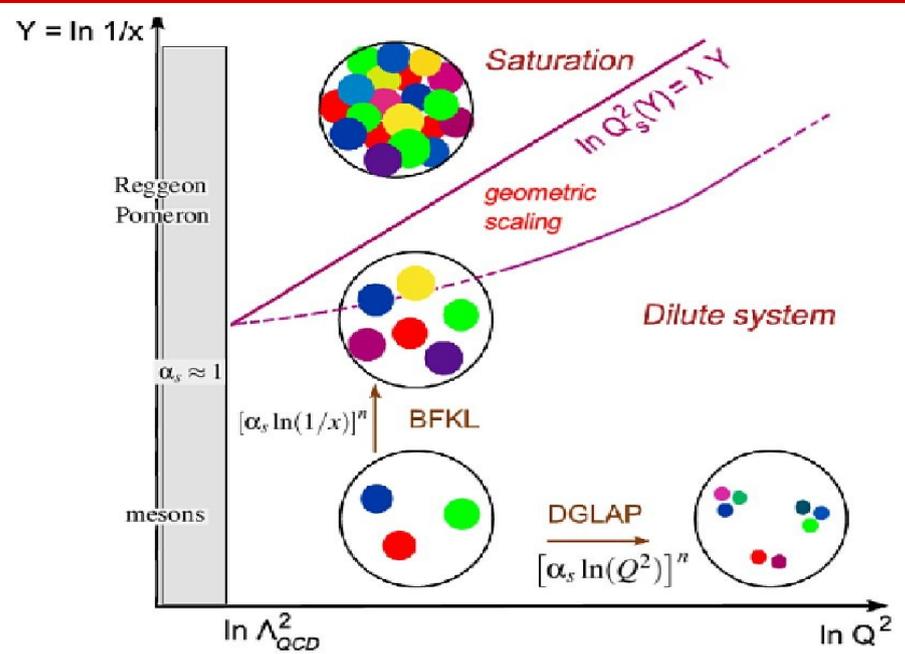


Pb/p



- Hugely reduced PDF uncertainties for all flavours (also strange, charm, bottom) at all x (down to  $10^{-5}$ ) via multiple clean nuclear DIS measurements.

# (4) FCC-ep,eA: Beyond-DGLAP low-x dynamics

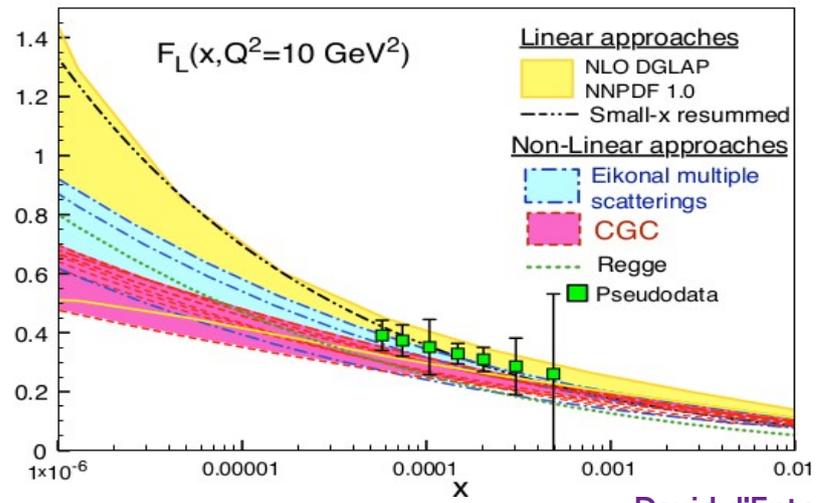
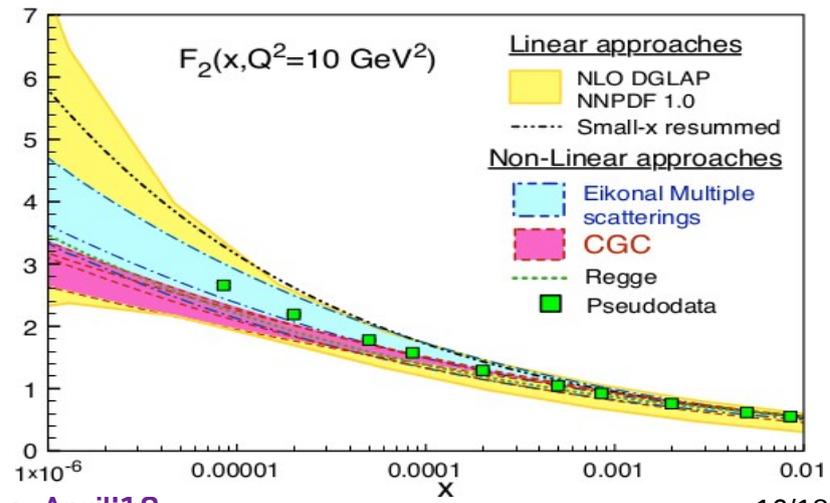


- **DGLAP** eqs. describe parton splittings as a function of  $Q^2$
- At increasing  $\sqrt{s}$ , non-linear QCD evolution will set in at low  $x$ .
- $gg \rightarrow g$  peaks at **perturbative “saturation scale”**  $\mathcal{O}(\text{few GeV})$ .
- Enhanced in nuclei ( $\sim A^{1/3}$ ).

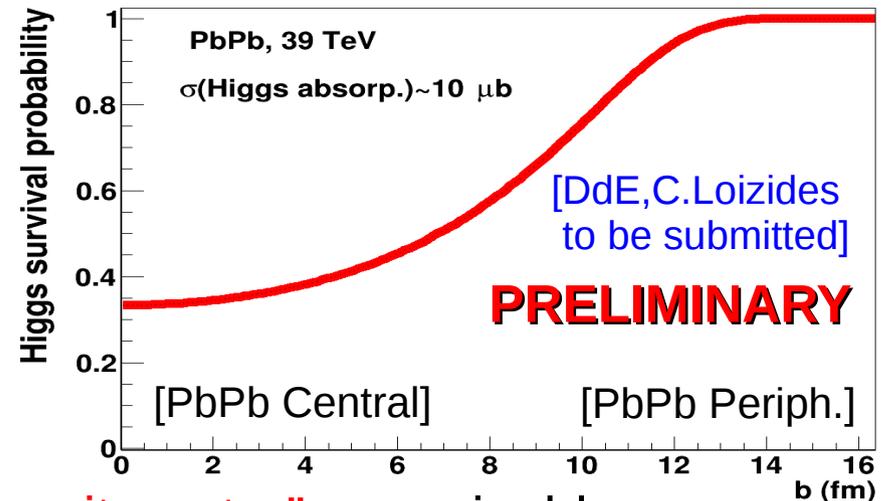
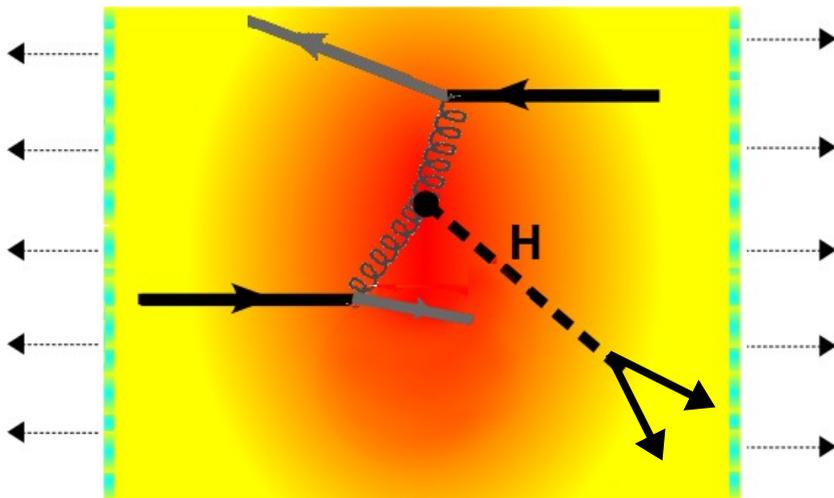
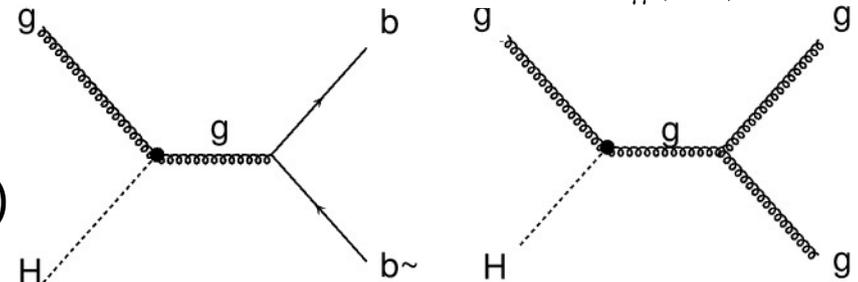
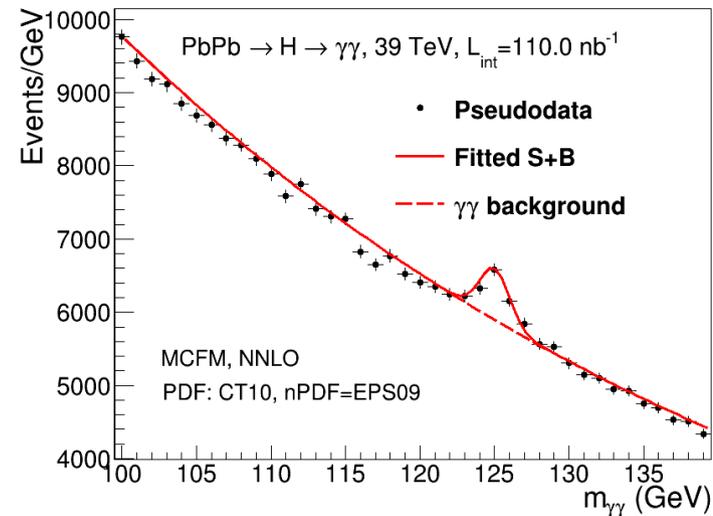
► Multiparton interactions ► Breaking of std. collinear factorization

- **FCC-eh** is an optimal low-x lab ( $x < 10^{-6}$ ): DGLAP fits cannot simultaneously accommodate  $F_2$  &  $F_L$  if gluon saturation present:

[N. Armesto et al.]



- $gg \rightarrow H$  is the **most precisely known pQCD process:  $N^3LO$** .  
Perfectly visible in PbPb at FCC:  
 $H \rightarrow \gamma\gamma$  (Significance  $\sim 9\sigma$ ) at 39 TeV  
[DdE, arXiv:1701.08047]
- **SM Higgs width:  $\sim 4$  MeV ( $\tau \approx 50$  fm  $\gg \tau_{QGP}$ )**  
**Higgs-gluon scattering absorption cross section:  $\sigma \sim \mathcal{O}(10 \mu b)$** .  
**Medium-induced  $H \rightarrow gg, b\bar{b}$  decays**  
("discovery"  $\gamma\gamma$ , 4leptons decays: depleted)



- Higgs boson: **Most accurate "gluon densitometer" conceivable.**

- 👉 100-km tunnel with 16 T  $\text{Sn}_3\text{Nb}$  magnets.
- 👉 Schedule: Decision ~2026, tunnel (5–7 yrs), magnets (~13 yrs). 1<sup>st</sup> physics~2039
- 👉 Multiple systems with huge lumis:  $e^+e^-$  (90–365 GeV, ~13 yrs, 2–150  $\text{ab}^{-1}$ )  
 $hh, eh$  (3.5–100 TeV; ~20 yrs; 2–20  $\text{ab}^{-1}$ )
- 👉 Direct/indirect **BSM** searches/discovery up to ~50 TeV.
- 👉 **Unparalleled QCD** potential: permille  $\alpha_s$ , ultraprecise PDFs,  $x \sim 10^{-8}$ , Higgs in QGP...
- **Wishful thinking? Look at the past...**

PHYSICS WITH VERY HIGH ENERGY  
 $e^+e^-$  COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,  
 H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,  
 K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,  
 C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

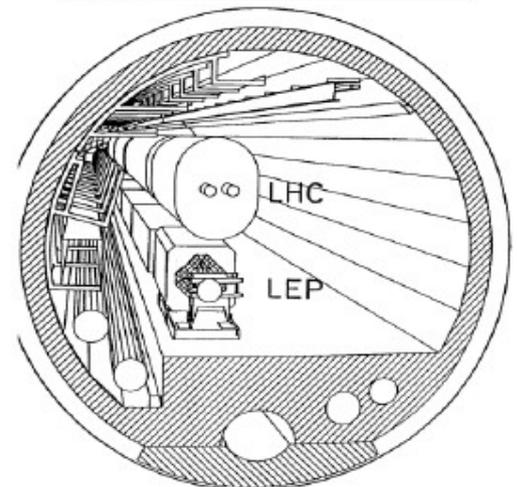
This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

*Did these people imagine that we would be running HL-LHC in the same tunnel almost 60(!) years later?*

CERN 76-18  
 8 November 1976

$e^+e^-$  1989-2000

pp 2010-2035



LARGE HADRON COLLIDER  
 IN THE LEP TUNNEL

# Backup slides



# FCC-pp collider parameters

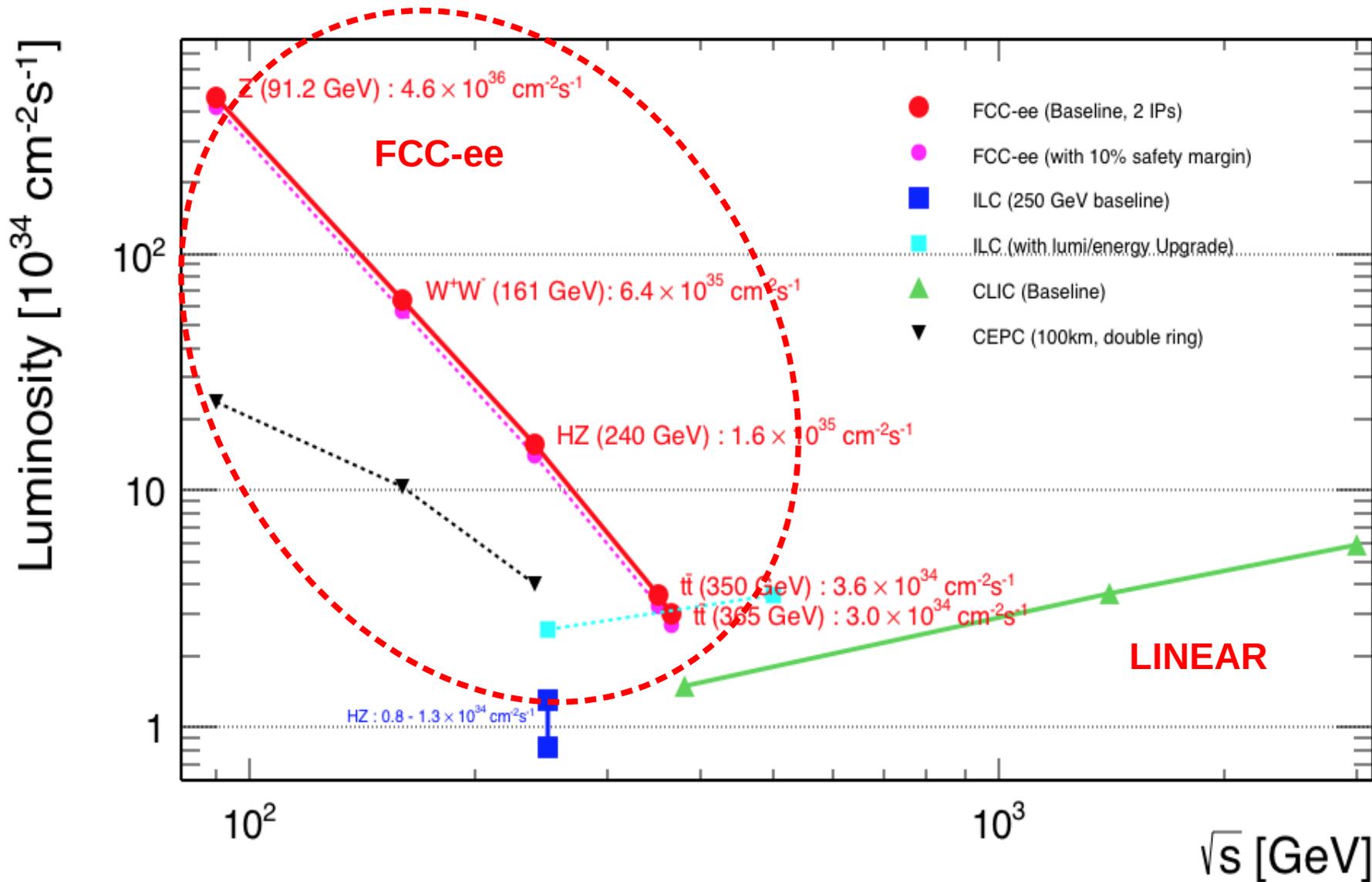
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.1	1.1	0.58
bunch intensity [ $10^{11}$ ]	1	1	2.2	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.15 (min.)	0.55
normalized emittance [ $\mu\text{m}$ ]	2.2		2.5	2.5	3.75
peak luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36



# FCC-ee collider parameters

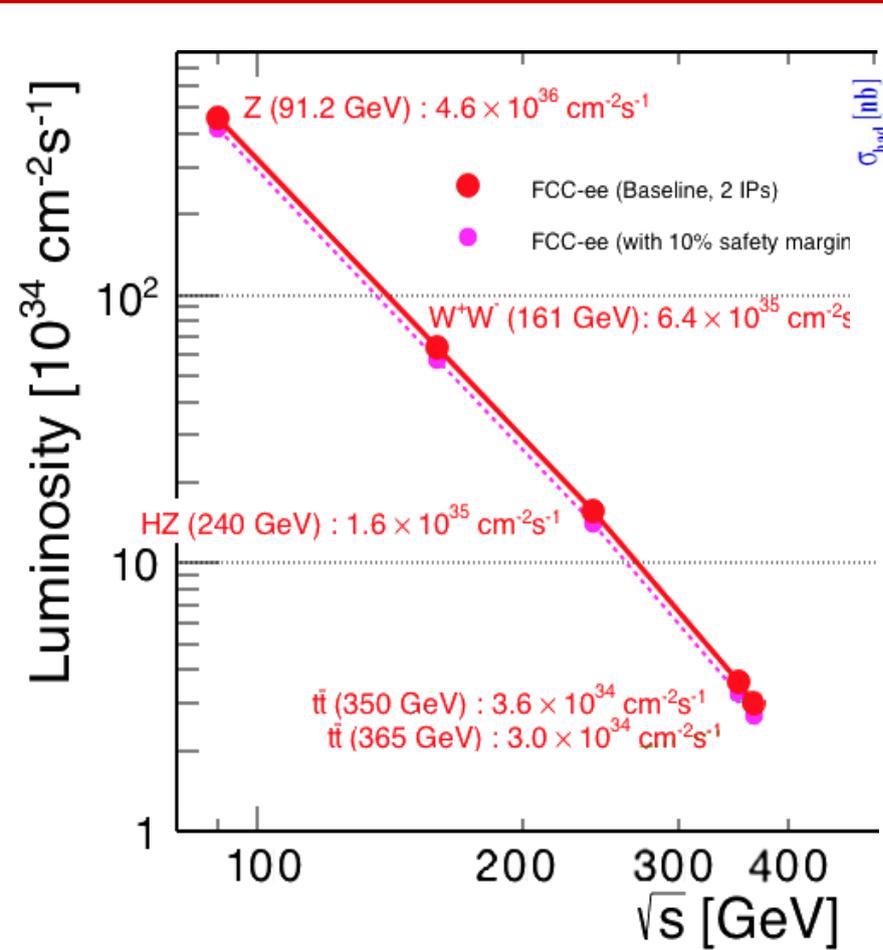
parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [ $10^{11}$ ]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

# FCC-ee: Z( $\times 5 \cdot 10^5$ LEP), W( $\times 10^4$ LEP), H, top factory

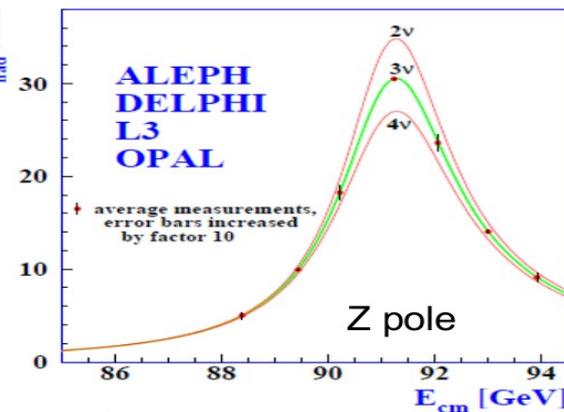


➔ Unique exploration of the 10–100 TeV energy scale through high-precision studies of the 4 heaviest fundamental SM particles: W,Z,H,top

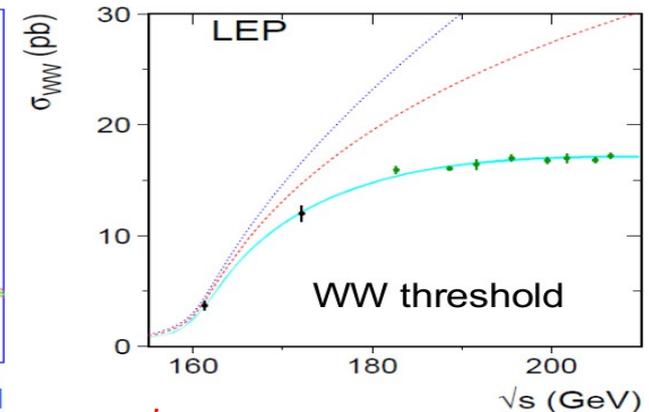
# FCC-ee: Z( $\times 5 \cdot 10^5$ LEP), W( $\times 10^4$ LEP), H, top factory



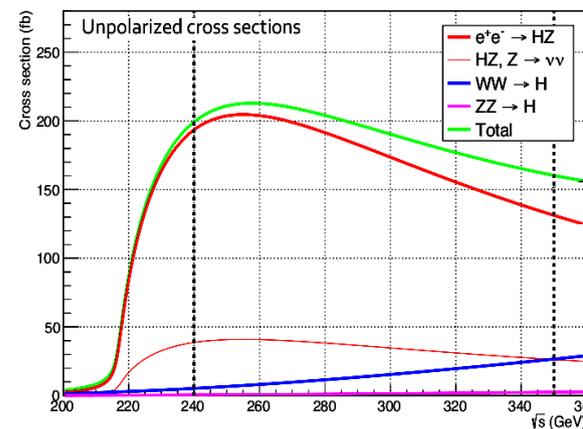
$\sqrt{s}=91 \text{ GeV}, 10^{12} \text{ Z's}$



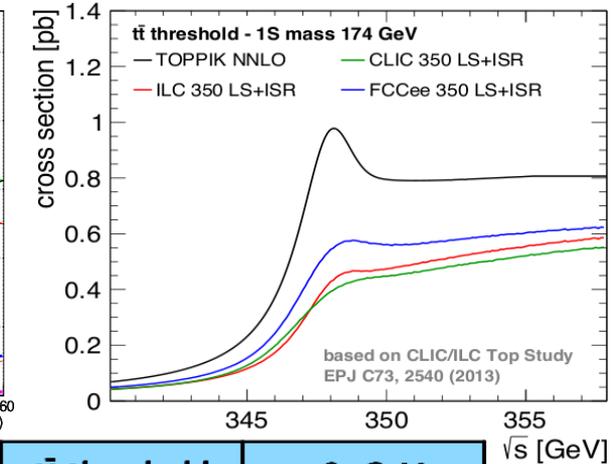
$\sqrt{s}=161 \text{ GeV}, 10^8 \text{ W's}$



$\sqrt{s}=240 \text{ GeV}, 10^6 \text{ H's}$



$\sqrt{s}=350 \text{ GeV}, 10^6 \text{ t's}$



Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold	365 GeV
Lumi/IP ( $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ )	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 $\text{ab}^{-1}$	52 $\text{ab}^{-1}$	8.1 $\text{ab}^{-1}$	1.95 $\text{ab}^{-1}$	0.22 $\text{ab}^{-1}$	0.39 $\text{ab}^{-1}$
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4

■ FCC-ee core physics programme to be completed in  $\sim 13$  years



# FCC-ee: High-precision W, Z, top

■ Exp. uncertainties (stat.uncert. ~negligible) improved wrt. LEP by factors  $\times 20$ :

Z

W

t

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
$m_Z$ (MeV)	Lineshape	$91187.5 \pm 2.1$	0.005	$< 0.1$	QED corr.
$\Gamma_Z$ (MeV)	Lineshape	$2495.2 \pm 2.3$	0.008	$< 0.1$ *	QED / EW
$R_1$	Peak	$20.767 \pm 0.025$	0.001	$< 0.001$	Statistics
$R_b$	Peak	$0.21629 \pm 0.00066$	0.000003	$< 0.00006$	$g \rightarrow bb$
$N_\nu$	Peak	$2.984 \pm 0.008$	0.00004	$< 0.004$	Lumi meast
$\sin^2\theta_W^{\text{eff}}$	$A_{\text{FB}}^{\mu\mu}$ (peak)	$0.23148 \pm 0.00016$	0.000003	$< 0.000005$ *	Beam energy
$1/\alpha_{\text{QED}}(m_Z)$	$A_{\text{FB}}^{\mu\mu}$ (off-peak)	$128.952 \pm 0.014$	0.004	$< 0.004$	QED / EW
$\alpha_s(m_Z)$	$R_1$	$0.1196 \pm 0.0030$	0.00001	$< 0.0002$	New Physics
$m_W$ (MeV)	Threshold scan	$80385 \pm 15$	0.6	$< 0.6$	EW Corr.
$\Gamma_W$ (MeV)	Threshold scan	$2085 \pm 42$	1.5	$< 1.5$	EW Corr.
$N_\nu$	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	$2.92 \pm 0.05$	0.001	$< 0.001$	?
$\alpha_s(m_W)$	$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$	$B_{\text{had}} = 67.41 \pm 0.27$	0.00018	$< 0.0001$	CKM Matrix
$m_{\text{top}}$ (MeV)	Threshold scan	$173340 \pm 760 \pm 500$	20	$< 40$	QCD corr.
$\Gamma_{\text{top}}$ (MeV)	Threshold scan	?	40	$< 40$	QCD corr.
$\lambda_{\text{top}}$	Threshold scan	$\mu = 1.2 \pm 0.3$	0.08	$< 0.05$	QCD corr.
ttZ couplings	$\sqrt{s} = 365$ GeV	$\sim 30\%$	$\sim 2\%$	$< 2\%$	QCD corr

\* work to do: check if we cant improve

■ Theoretical developments needed to match expected experimental uncertainties

- $e^+e^-$  colliders provide **factor > 50 (10) improvement** in precision w.r.t. model-dependent LHC (HL-LHC) expectations:

Parameter	Current* 7+8+13 TeV $\mathcal{O}(70 \text{ fb}^{-1})$	HL-LHC* 14 TeV (3 $\text{ab}^{-1}$ )	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
$\sigma(\text{HZ})$	–	–	0.4%	0.7%	0.5%	1.6%
$g_{ZZ}$	10%	2–4%	0.15%	0.3%	0.25%	0.8%
$g_{WW}$	11%	2–5%	0.2%	0.4%	1.6%	0.9%
$g_{bb}$	24%	5–7%	0.4%	0.7%	0.6%	0.9%
$g_{cc}$	–	–	0.7%	1.2%	2.3%	1.9%
$g_{\tau\tau}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$g_{t\bar{t}}$	16%	6–9%	13%	6.3%	–	4.4%
$g_{\mu\mu}$	–	8%	6.2%	9.2%	17%	7.8%
$g_{e^+e^-}$	–	–	<100%	–	–	–
$g_{\text{EE}}$	–	3–5%	0.8%	1.0%	1.7%	1.4%
$g_{\gamma\gamma}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$g_{Z\gamma}$	–	10–12%	(to be determined)			9.1%
$\Delta m_H$	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
$\Gamma_H$	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
$\Gamma_{\text{inv}}$	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

- Most precise  $g_{ZZ} \sim 0.2\%$  coupling sets limit on new scalar-coupled

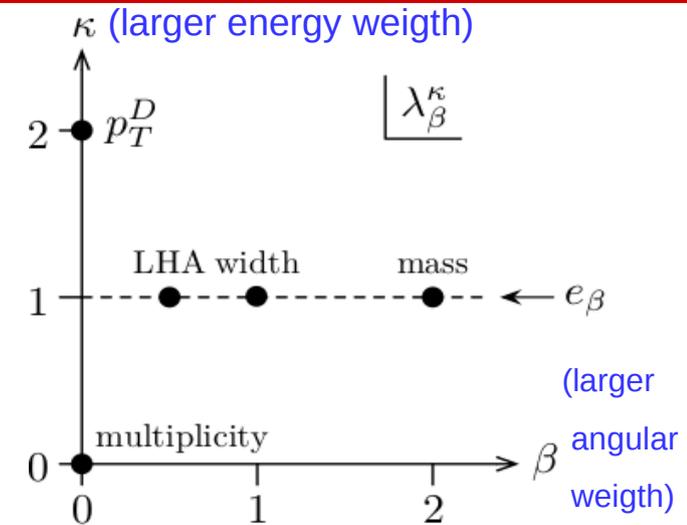
physics at:  $\Lambda \gtrsim (1 \text{ TeV}) / \sqrt{(\delta g_{HXX} / g_{HXX}^{\text{SM}}) / 5\%} \gtrsim 7 \text{ TeV}$

# High-precision jet substructure & flavour tagging

- State-of-the-art jet substructure studies based on **angularities**

$$\lambda_{\beta}^{\kappa} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\beta},$$

(normalized  $E^n \times \theta^n$  products)

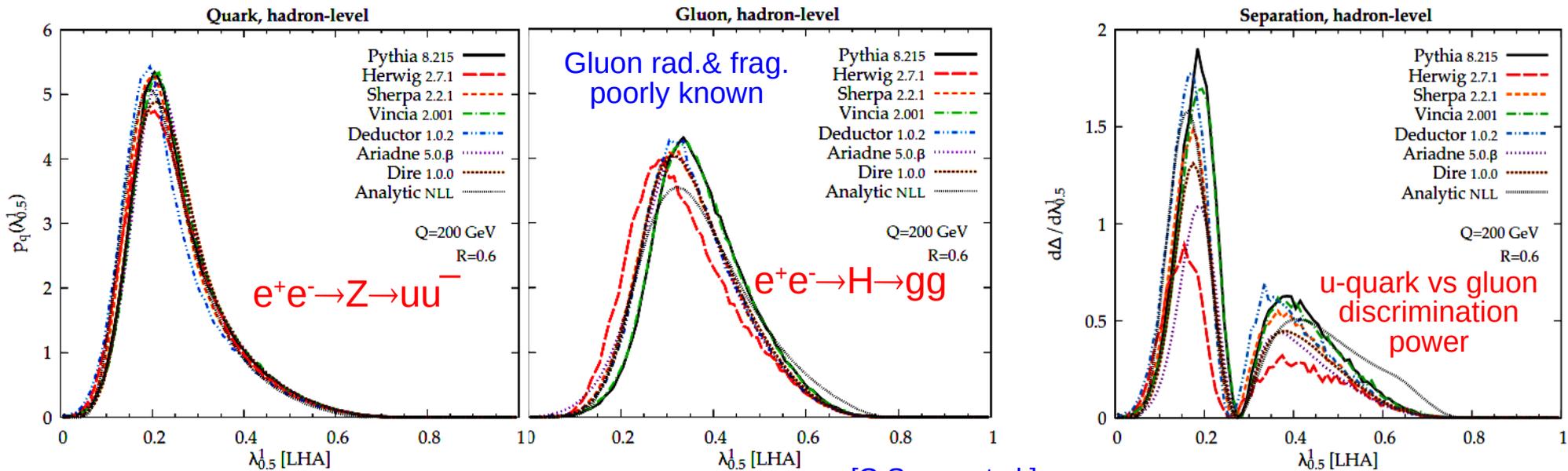


- ("Sudakov"-safe) variables of **jet constituents**: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...

- k=1: IRC-safe** computable (N<sup>n</sup>LO+N<sup>n</sup>LL) via SCET (clean data needed to control non-pQCD corr.)

- High-stats & high-precision **jet structure & flavour-tagging at FCC-ee**:

[Larkoski,Salam,Thaler,13]  
[Larkoski,Thaler,Waalewijn,14]



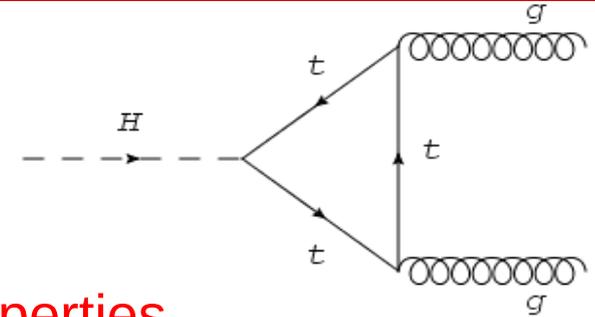
# High-precision gluon-jet studies via $e^+e^- \rightarrow H(gg) + X$

- FCC-ee  $H(gg)$  is a "pure gluon" factory:

$H \rightarrow gg$  (BR~8.1% accurately known) provides

~100.000 extra-clean digluon events:

- High-precision study of gluon radiation & g-jet properties



Handles to split degeneracies

$H \rightarrow gg$  vs  $Z \rightarrow qq$

Rely on good  $H \rightarrow gg$  vs  $H \rightarrow bb$  separation;  
mandated by Higgs studies requirements anyway?

$Z \rightarrow bbg$  vs  $Z \rightarrow qq(g)$

g in one hemisphere recoils against two b-jets in  
other hemisphere: **b tagging**

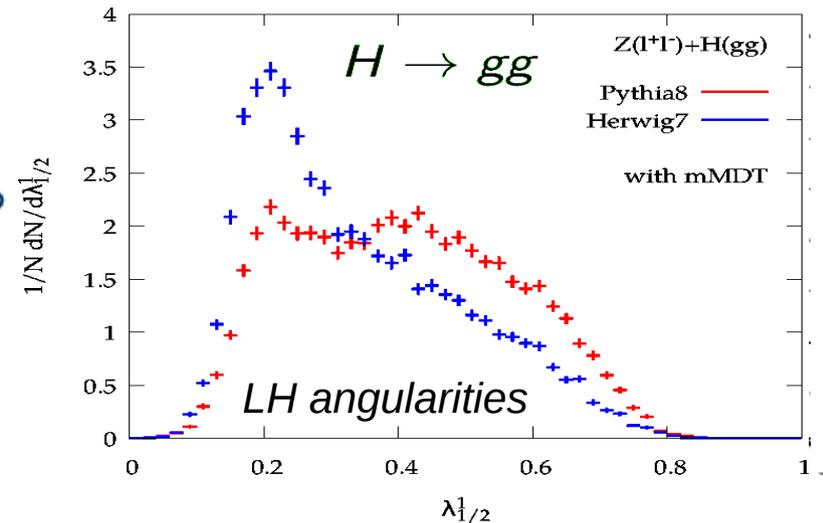
Vary jet radius: **small-R**  $\rightarrow$  **calo resolution**

(R ~ 0.1 also useful for jet substructure)

Vary  $E_{CM}$  range : below  $m_Z$ : radiative events  
 $\rightarrow$  **forward boosted**

(also useful for FFs & general scaling studies);  
Scaling is **slow**, logarithmic  $\rightarrow$  large lever arm

G. Soyez, K. Hamacher, G. Rauco, S. Tokar, Y. Sakaki

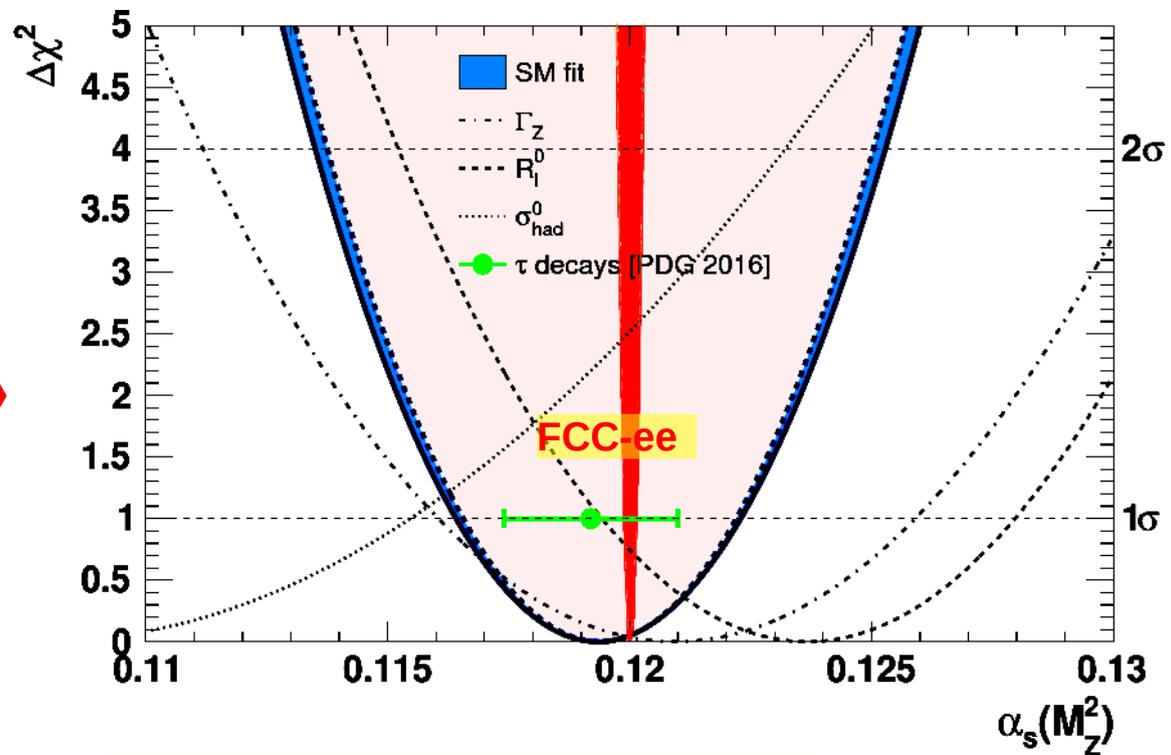
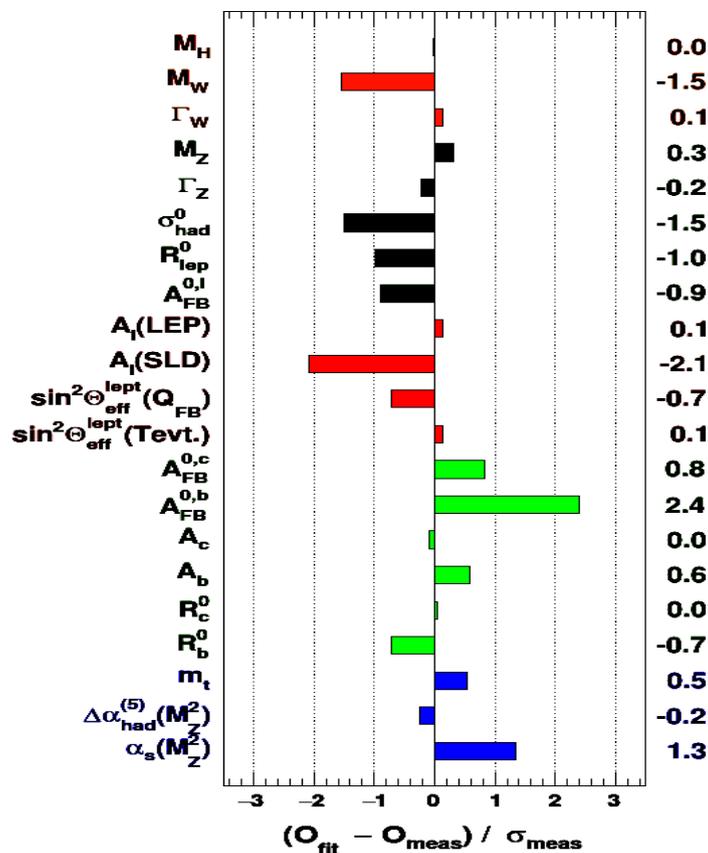


- Check  $N^{\text{th}}$ LO antenna functions
- Improve q/g/Q discrim.tools (BSM)
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs ?
- Leading  $\eta$ 's, baryons in g jets?

# $\alpha_s$ via hadronic Z decays

- Computed at **N<sup>3</sup>LO**:  $R_Z \equiv \frac{\Gamma(Z \rightarrow h)}{\Gamma(Z \rightarrow l)} = R_Z^{EW} N_C (1 + \sum_{n=1}^4 c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_m + \delta_{np})$
- LEP**:  $\Gamma_Z = 2.4952 \pm 0.0023$  GeV ( $\pm 0.1\%$ ),  $R_\ell^0 = \frac{\Gamma_{had}}{\Gamma_\ell}$ ,  $\sigma_{had}^0 = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2}$ ,  $\sigma_\ell^0 = \frac{12\pi}{m_Z} \frac{\Gamma_\ell^2}{\Gamma_Z^2}$

After Higgs discovery,  $\alpha_s$  can be directly determined from **full fit of SM**:



$\alpha_s (M_Z) = 0.1196 \pm 0.0030$  ( $\pm 2.5\%$ )

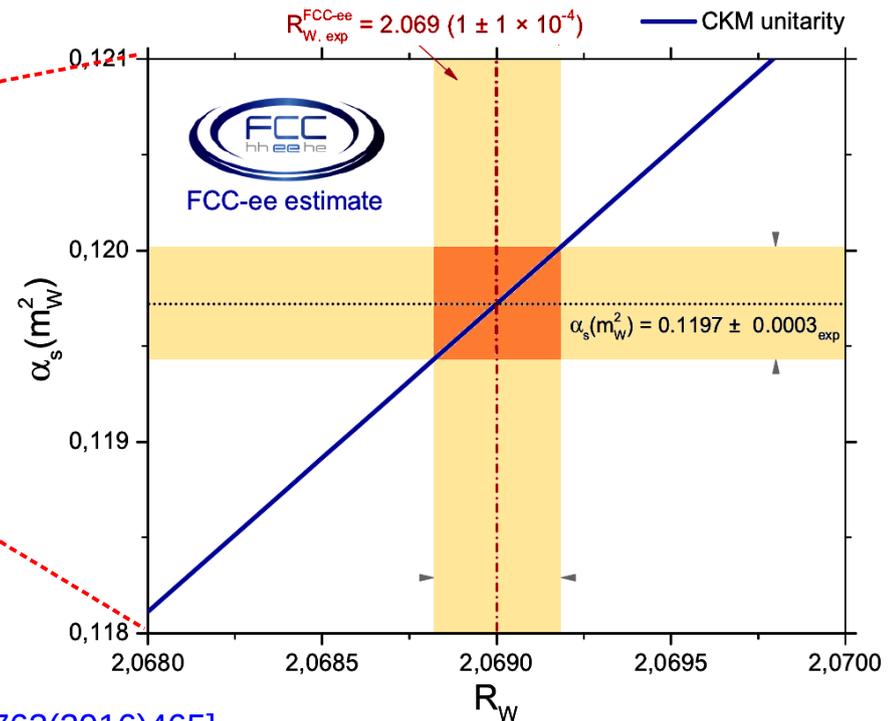
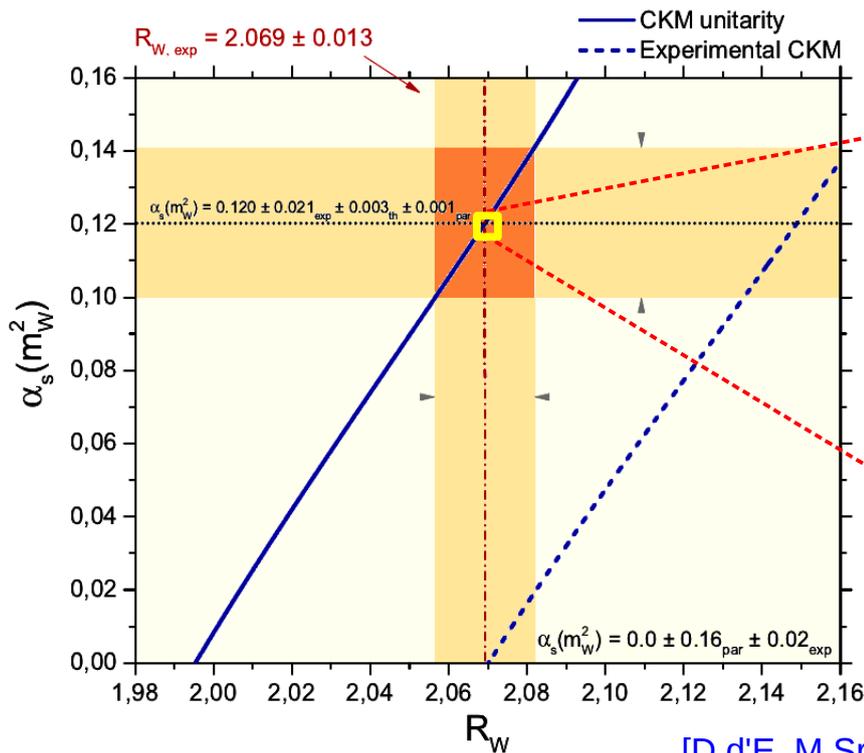
- FCC-ee**:
  - Z stats ( $\times 10^5$  LEP) will lead to:  $\delta\alpha_s/\alpha_s < 0.2\%$
  - TH (parametric) uncertainties:  $\sin^2\theta_{eff}, m_W, m_{top}$

# $\alpha_s$ via hadronic W decays

- Computed at  $N^{2,3}LO$ :  $\Gamma_{W, had} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[ 1 + \sum_{k=1}^4 \left( \frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha\alpha_s) \right]$
- LEP:  $\Gamma_W = 1405 \pm 29$  MeV ( $\pm 2\%$ ),  $BR_W = 0.6741 \pm 0.0027$  ( $\pm 0.4\%$ )

Extraction with large exp. & parametric (CKM  $V_{cs}$ ) uncertainties today:

$$\alpha_s(M_Z) = 0.117 \pm 0.040 \quad (\pm 35\%)$$



- FCC-ee: – Huge W stats ( $\times 10^4$  LEP) will lead to:  $\delta\alpha_s/\alpha_s < 0.3\%$
- TH (param.) uncertainty:  $|\delta V_{cs}|$  to be significantly improved ( $10^{-4}$ )

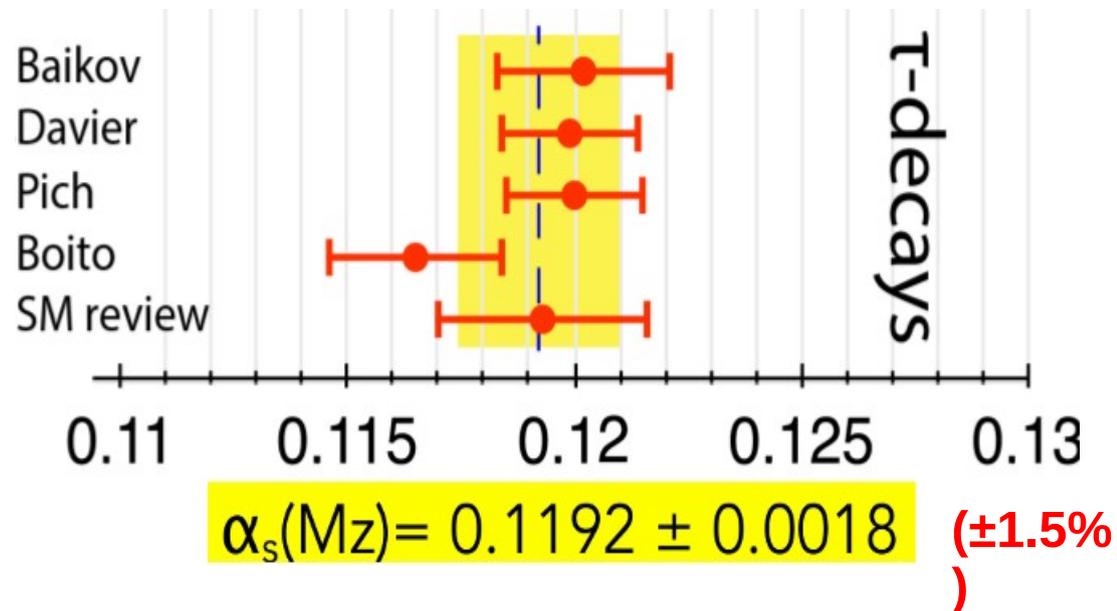
# $\alpha_s$ from hadronic $\tau$ -lepton decays

➔ Computed at **N<sup>3</sup>LO**:  $R_\tau \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \sum_{n=1}^4 c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{np}})$

➔ Experimentally:  $R_{\tau, \text{exp}} = 3.4697 \pm 0.0080$  ( $\pm 0.23\%$ )

➔ Various pQCD approaches (FOPT vs CIPT) & treatment of non-pQCD corrections (note:  $(\Lambda/m_\tau)^2 \sim 2\%$ ), yield different results.

Uncertainty slightly increased:  
2013 ( $\pm 1.3\%$ )  $\rightarrow$  2017 ( $\pm 1.5\%$ )



➔ Future prospects:

- Better understanding of FOPT vs CIPT differences.
- Better spectral functions needed (high stats & better precision):  
B-factories (BELLE-II)
- High-stats:  $\mathcal{O}(10^{11})$  from  $Z(\tau\tau)$  at FCC-ee(90) :

$$\delta\alpha_s/\alpha_s < 1\%$$

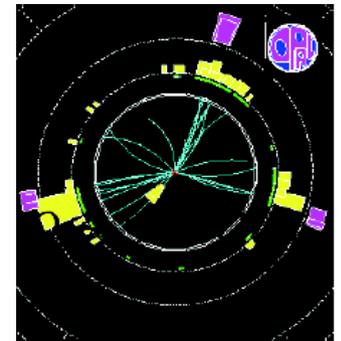
# $\alpha_s$ from $e^+e^-$ jet event shapes & rates

- ➔ Computed at  $N^{2,3}LO+N^{(2)}LL$  accuracy.
- ➔ LEP data for thrust, C-parameter, jet shapes, 3-jet x-sections

Results sensitive to non-pQCD (hadronization) accounted for via MCs or analytically:

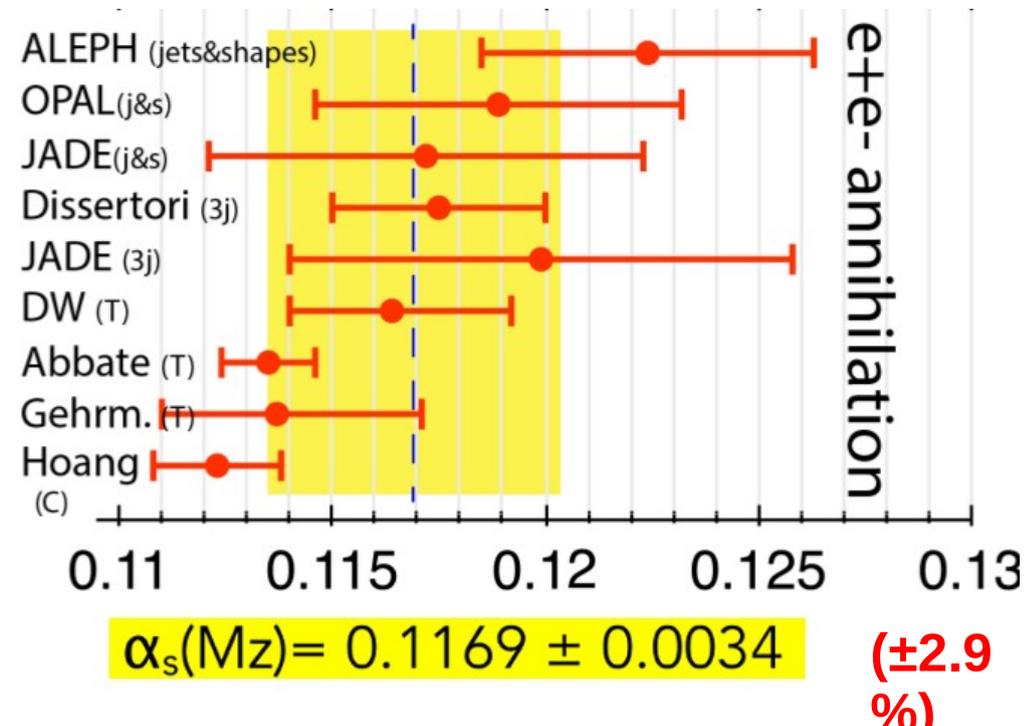
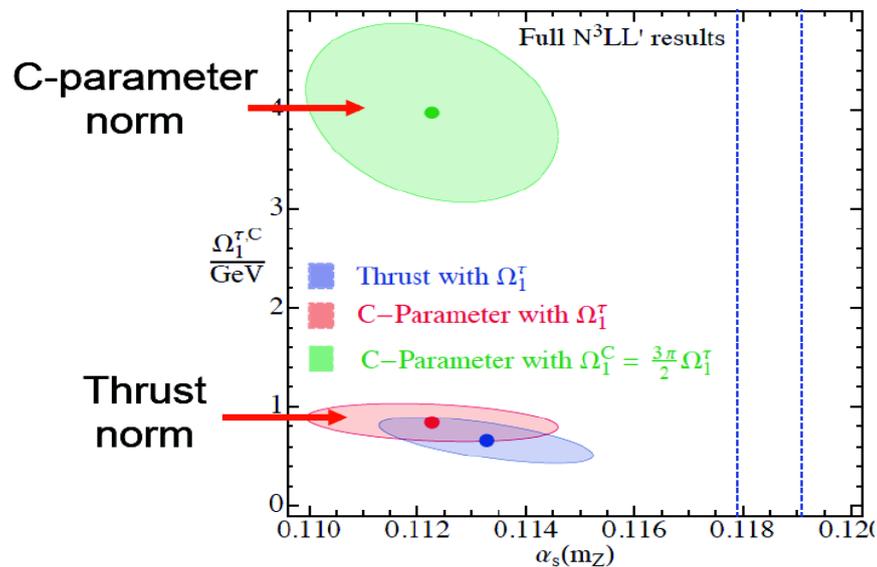
$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i| |\vec{p}_j| \sin^2 \theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$



OPAL 3 jet event

[S.Kluth et al., A.Hoang et. al.]



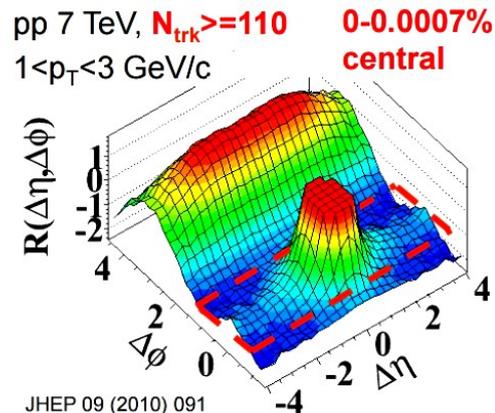
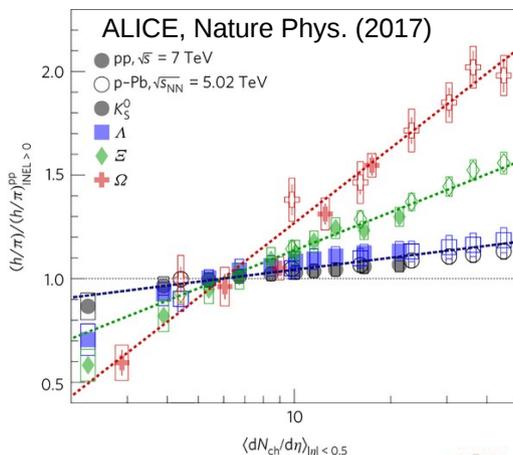
## ➔ FCC-ee:

– Higher- $\sqrt{s}$  data needed for rates (lower- $\sqrt{s}$  for shapes):

– TH: Improved ( $N^{2,3}LL$ ) resummation for rates, hadroniz. for shapes

$$\delta\alpha_s/\alpha_s < 1\%$$

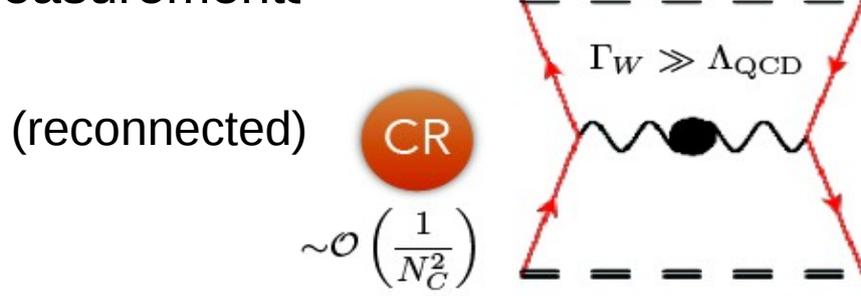
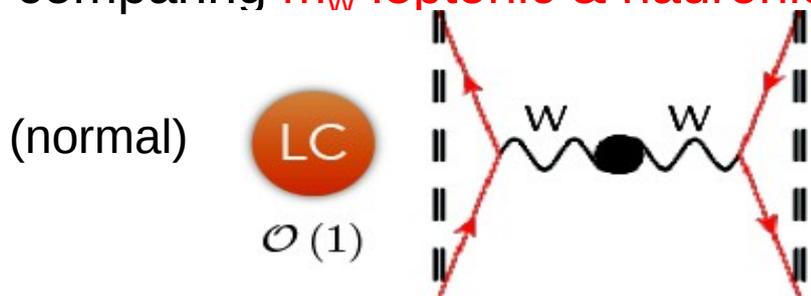
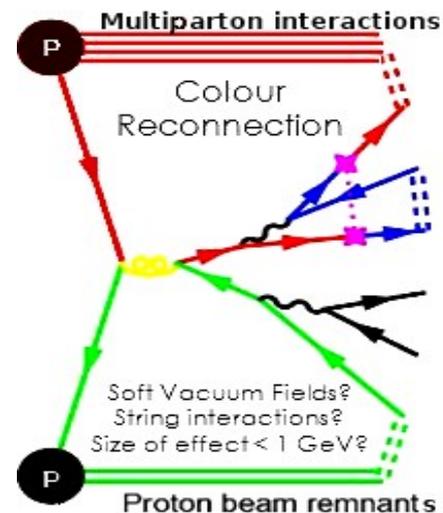
- Hadron production in LHC  
 "central" pp (pA,AA) collisions  
 shows **large final-state**  
**partonic interactions: s-quark**  
**enhancement, collective flow,...**  
 (Likely more enhanced at FCC-hh)



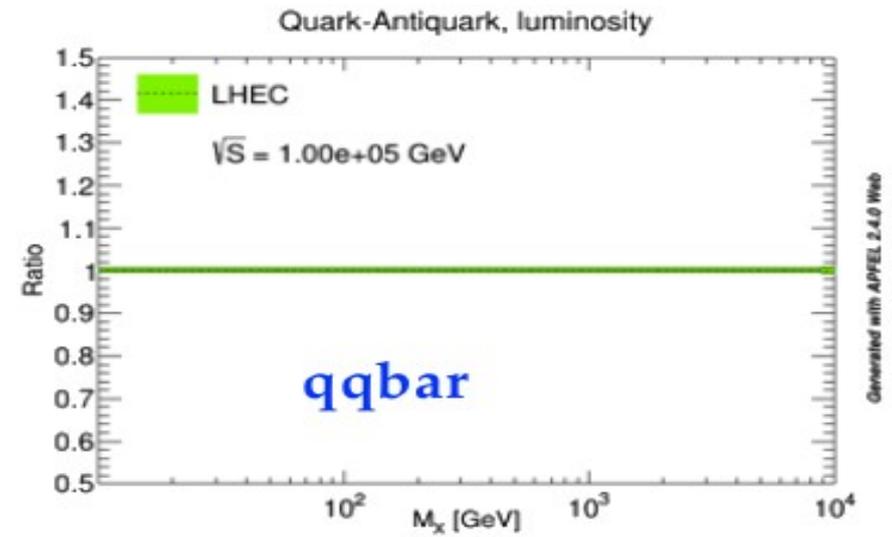
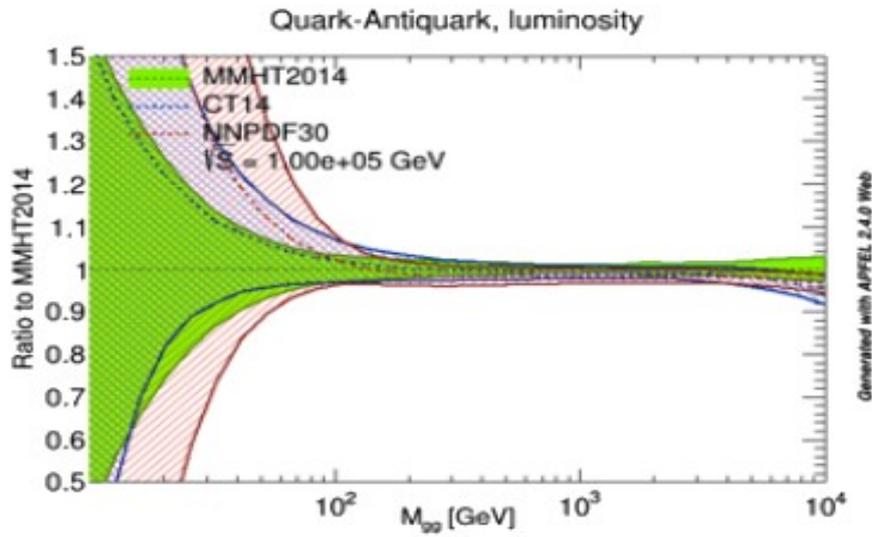
- **Colour reconnection** among partons in pp  
 is source of **uncertainty** in  $m_W$ ,  $m_{top}$  extractions:

👉 **FCC-ee** provides huge W stats ( $\times 10^4$  LEP)

to **cleanly constrain CR** in hadronic WW by  
 comparing  $m_W$  **leptonic & hadronic** measurements\*

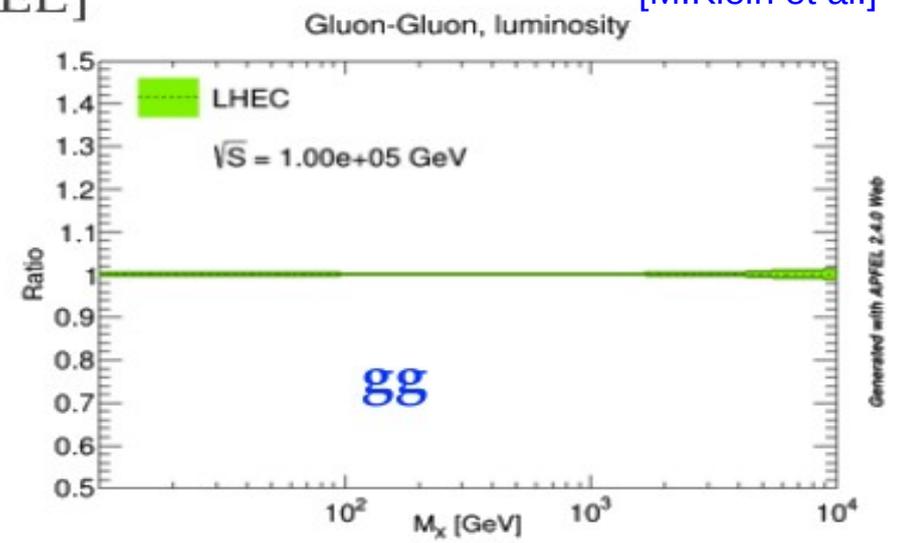
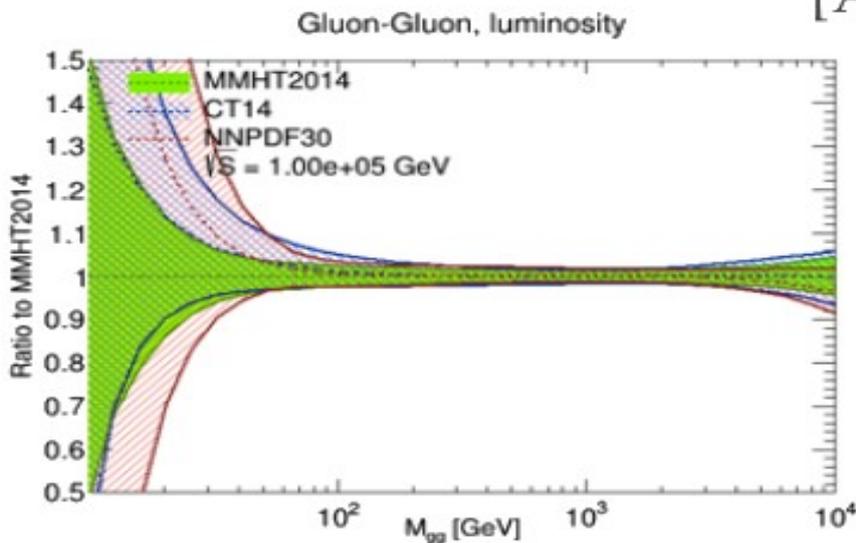


- Strongly reduced **parton luminosity uncertainties** for  $m_x = 10 \text{ GeV} - 10 \text{ TeV}$



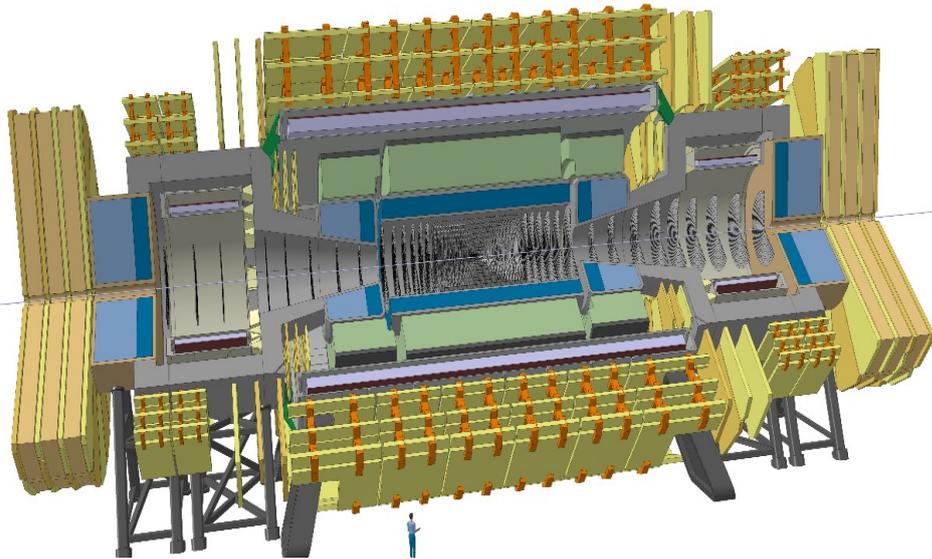
[APFEL]

[M.Klein et al.]



- FCC-ep needed to get  **$O(1\%)$  PDF uncertainty** for  $\sigma(W,Z,H)$  at FCC-pp  
(LHC likely to improve PDFs before, but by factor  $\times 2(?)$ , not  $\times 5-10$ )

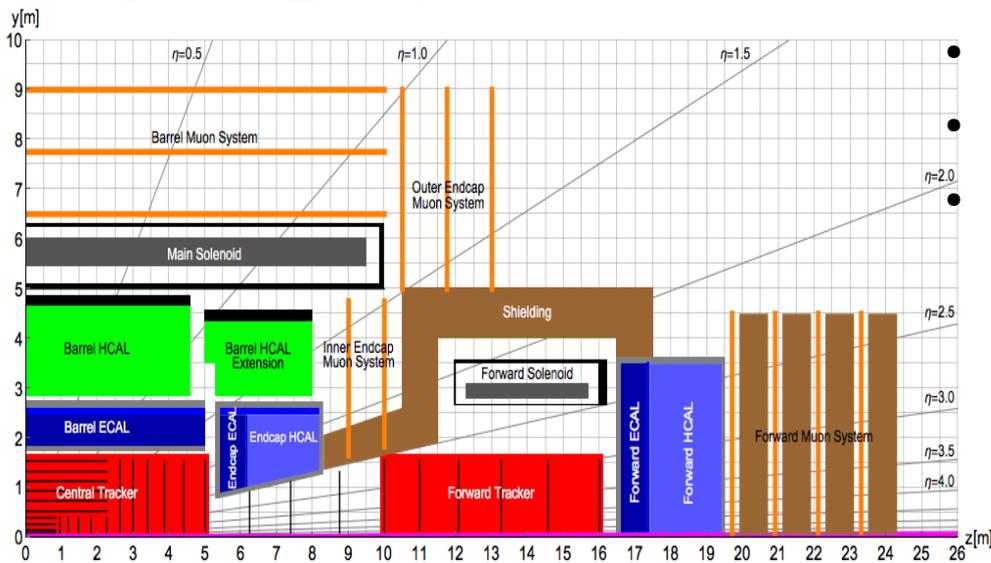
# FCC-hh reference detector



- **Size:**
- **Central Solenoid, 4T, 10m free bore, unshielded**
- **Forward Solenoids, 4T, 5m free bore, unshielded**
- Silicon Tracker 400m<sup>2</sup> total surface up to  $|\eta|=6$
- Precision momentum measurement up to  $|\eta|=4$
- ECAL & HCAL up to  $|\eta|=6$
- Granularity about  $4 \times$  ATLAS/CMS
- Muon system for trigger, identification, momentum

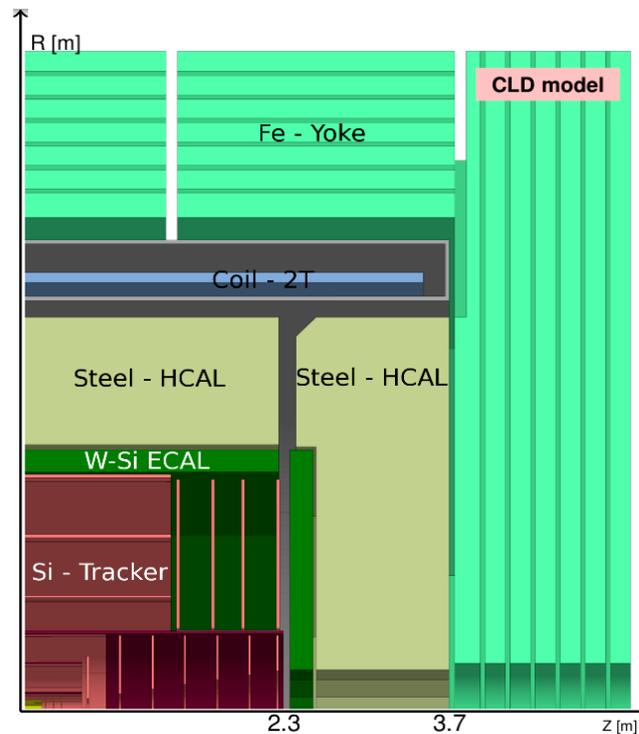
## Challenges:

- Pileup of 1000 vs. 140 at HL-LHC
- Radiation levels up to  $10^{18}$  cm<sup>-2</sup> 1MeV neutron equivalent vs.  $10^{16}$  cm<sup>-2</sup> at HL-LHC
- Total data rate of 1-1.5 PByte/s
- Integration, opening and maintenance scenarios



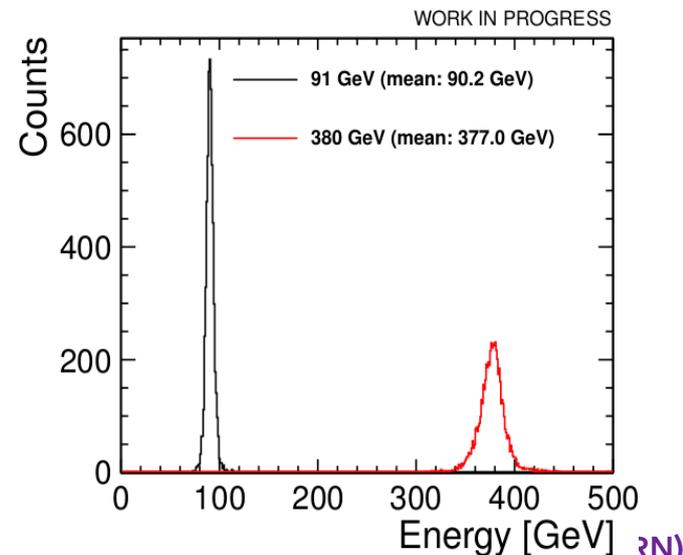
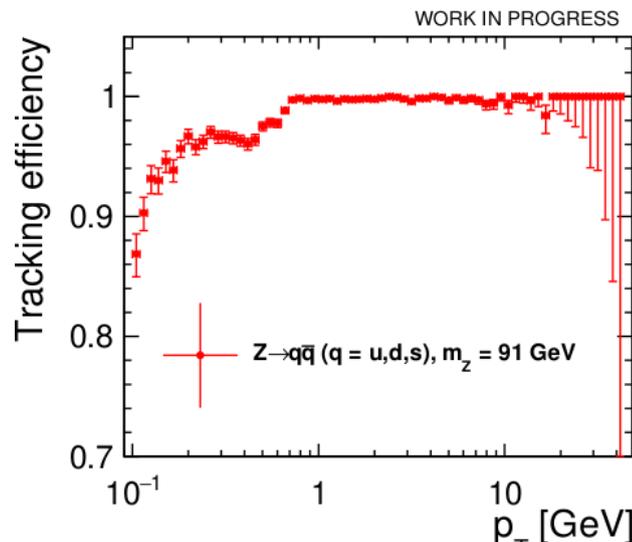
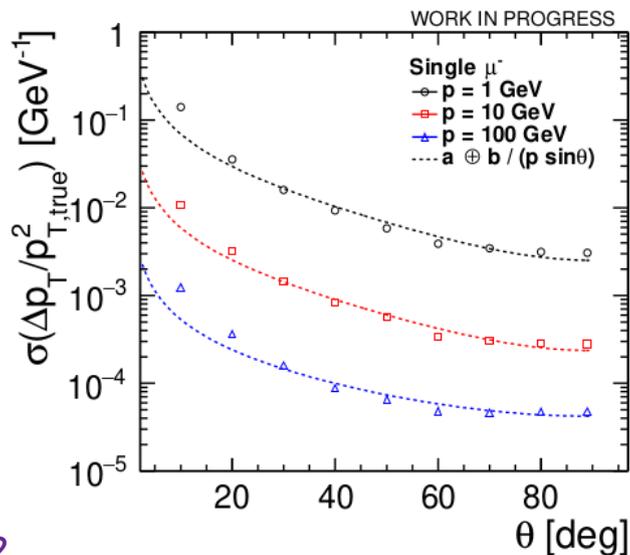
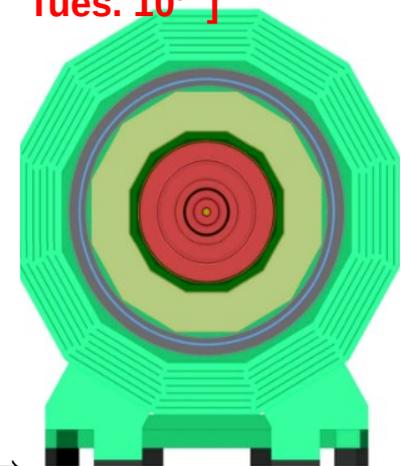
■ CLD (L=10.6 m) **inspired in CLIC/ILC** detectors & optimized for FCC-ee conditions:

- ▶ Beam pipe: ~1.5 cm (0.5%  $X_0$ )
- ▶ **Vertex** detector: **Si** pixels  
3x2 double-layers (1%  $X_0$ ). Point resol.:  $3\mu\text{m}$
- ▶ **Tracker** detector: **Si** pixels & microstrips  
6 layers (8%  $X_0$ ). Point resol.:  $7\times 90\mu\text{m}$
- ▶ **EM & HCAL Calorimeters**:  
Si-W sampling calo ( $22 X_0$ ,  $1\lambda_{\text{int}}$ )  
Sci/Steel sampling calo ( $5.5 \lambda_{\text{int}}$ )
- ▶ B-field: **2 T** (superconducting coil)
- ▶ **Muon system**: 6 RPCs
- ▶ Forward region (<150 mrad): MDI & **LumiCal**

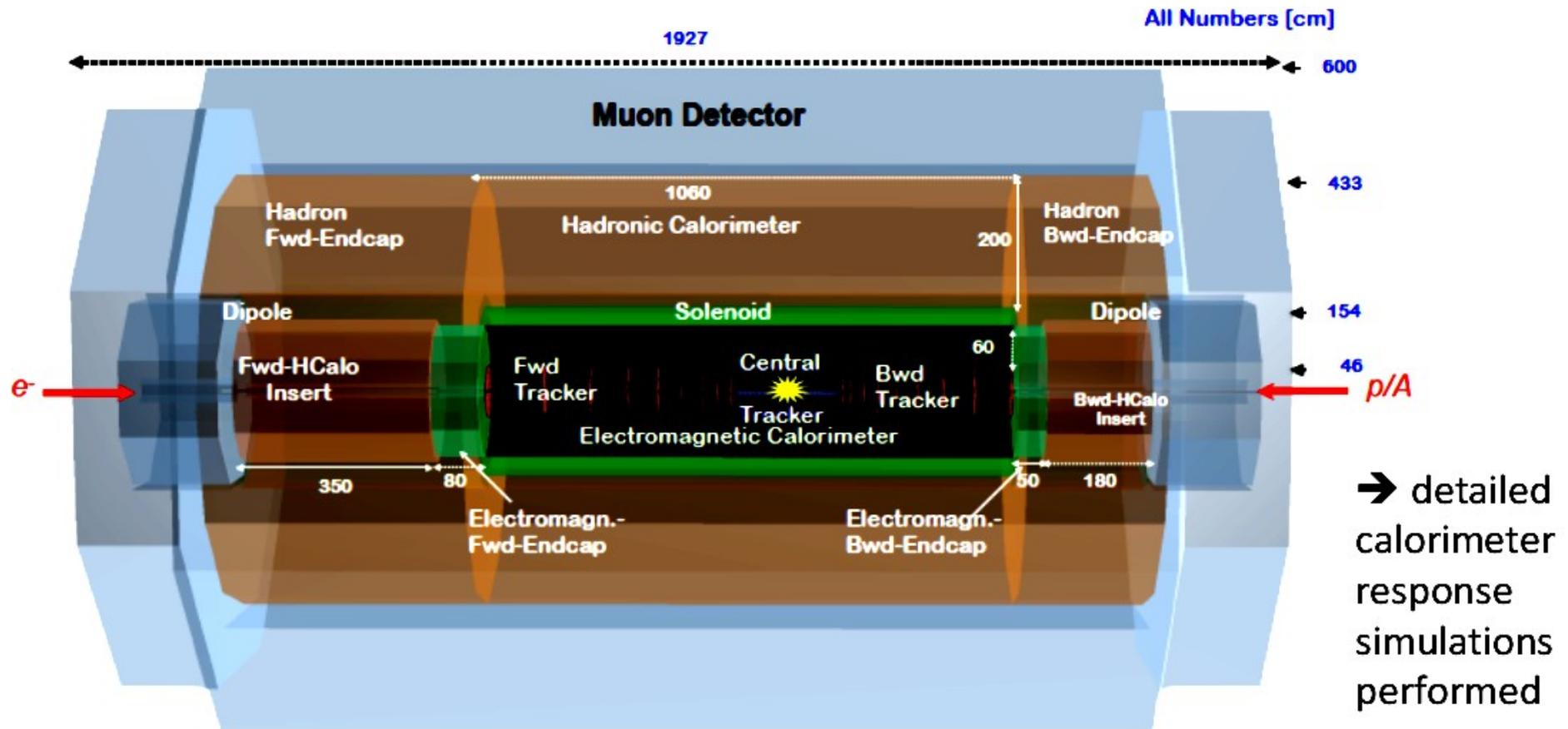


*Proven concept,  
Performances from  
full simulation*

**[See O.Viazlo,  
Tues. 10<sup>th</sup>]**



# FCC-eh reference detector



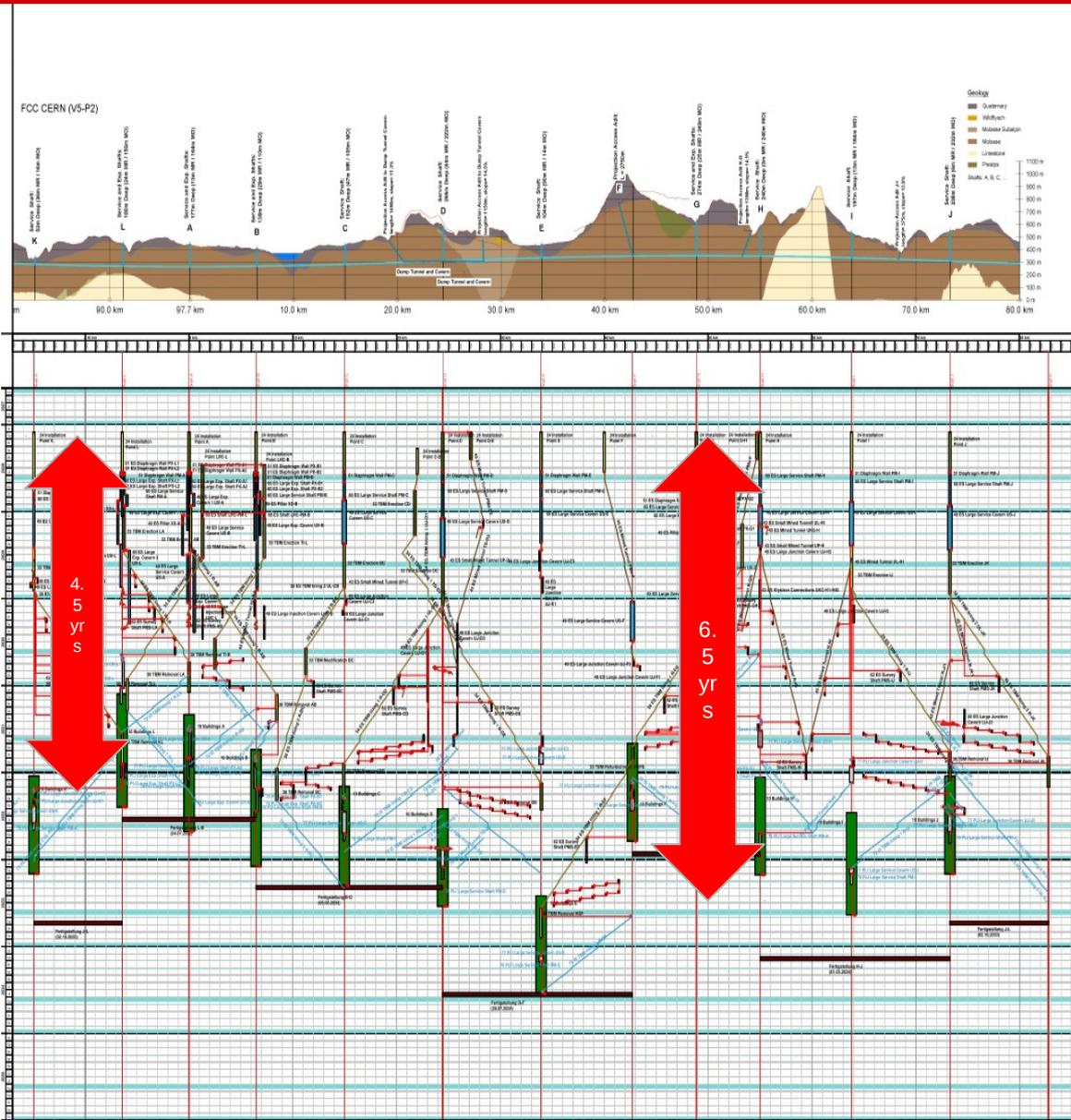
Based on the LHeC design; Solenoid&Dipoles between Electromagnetic Calorimeter and Hadronic Calorimeter. Length of Solenoid ~11m. detector setup in DD4hep.

<https://dd4hep.web.cern.ch/dc>

Discussion of ep solenoids by H ten Kate, see CERN March 2018: **No R&D needed**

<https://indico.cern.ch/event/696066/>

# CE schedule studies



## Excavated Spoil Schedule

Extraction Site	Volume (m³)			Total
	Soft Ground	Limestone	Molasse	
Shaft at LHC1	11,031	0	133,735	144,765
Shaft at LHC2	0	0	202,589	202,589
Shafts at Point A	26,469	0	791,948	818,417
Shafts at Point B	35,161	0	326,482	361,643
Shaft at Point C	181,807	0	385,920	567,727
Construction Tunnel at Point D	0	0	709,452	709,452
Shaft at Point D	15,992	8,806	668,961	693,760
Construction Tunnel at Point D	0	0	235,355	235,355
Shaft at Point E	6,528	0	174,792	181,320
Tunnel at Point F	0	1,206	375,414	376,621
Shaft at Point G	33,086	0	471,215	504,301
Tunnel at Point H	0	244,081	750,620	994,701
Shaft at Point H	0	7,329	421,401	428,730
Shaft at Point I	6,528	0	796,634	803,161
Shaft at Point J	6,528	0	805,629	812,157
Shaft at Point K	13,381	0	610,972	624,353
Shafts at Point L	29,990	0	671,700	701,690
<b>Total Spoil Volume</b>	<b>366,500</b>	<b>22</b>	<b>8,532,821</b>	<b>9,160,743</b>

## Study of excavation material management

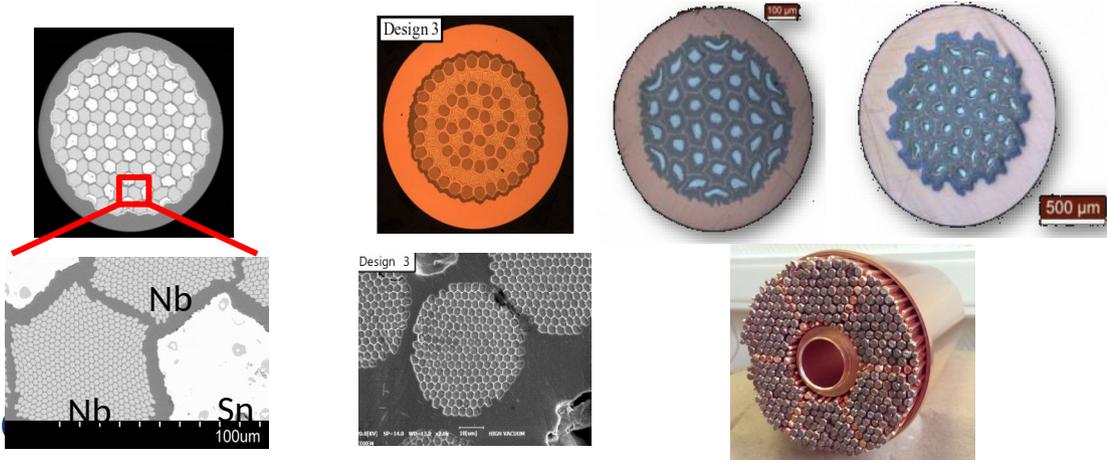
- Total of 9 million m³ to dispose
- Reuse of molasse?

- Detailed study confirmed 2017 numbers
- Construction duration 5 – 7 years



# Global Nb<sub>3</sub>Sn wire development program

- After one year development, prototype Nb<sub>3</sub>Sn wires achieving the HL-LHC performance (~1000 A/mm<sup>2</sup>) already produced by several industrial partners.
- **Impressive progress** for companies starting production of internal-tin high field wire
- **Innovative wire layouts** proposed and produced
- **Strong motivation of industrial partners and confidence on achieving performance and cost.**



Jastec - Japan

Kiswire KAT - Korea

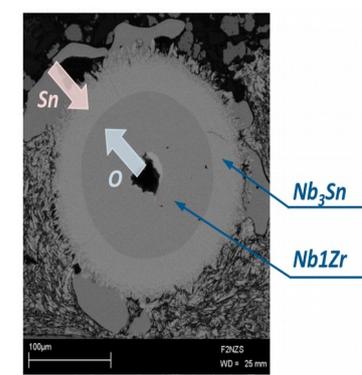
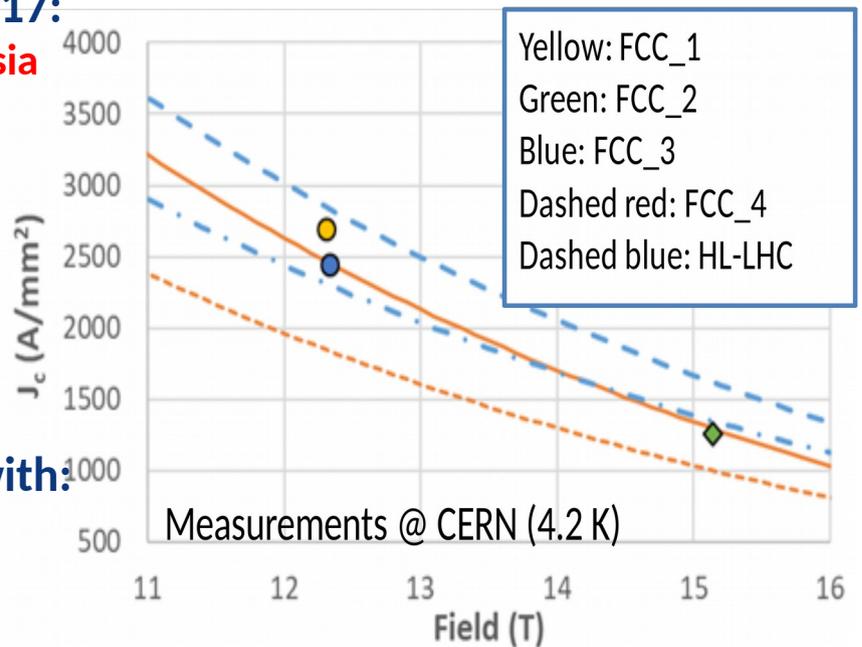
Bochvar/TVEL - Russia

## Conductor activities for FCC started in 2017:

- **Bochvar Institute** (production at TVEL), **Russia**
- **KEK (Jastec and Furukawa)**, **Japan**
- **KAT**, **Korea**
- **Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy**
- **University of Freiberg**, **Germany**

## In addition, being finalized agreements with:

- **Bruker (Germany)**
- **Luvata Pori (Finland)**



Internal oxidation  
Unige