XII Quark Confinement and the Hadron Spectrum Conference (Conf12) -

Satellite Workshop: *Accelerators Revealing the QCD Secrets*, Thessaloniki, 3-5 September 2016

Future Circular Collider Study

Frank Zimmermann

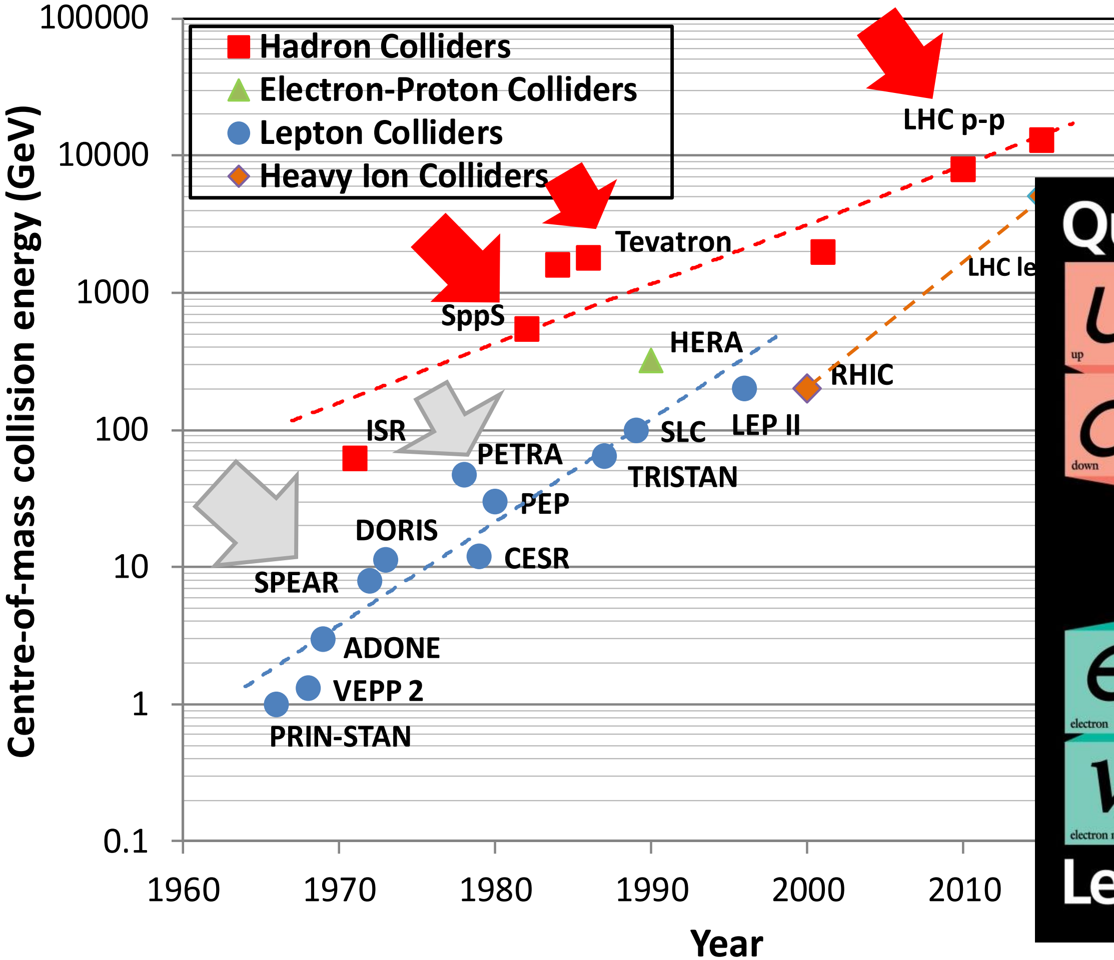
gratefully acknowledging input from FCC coordination group the global design study team and all contributors

http://cern.ch/fcc

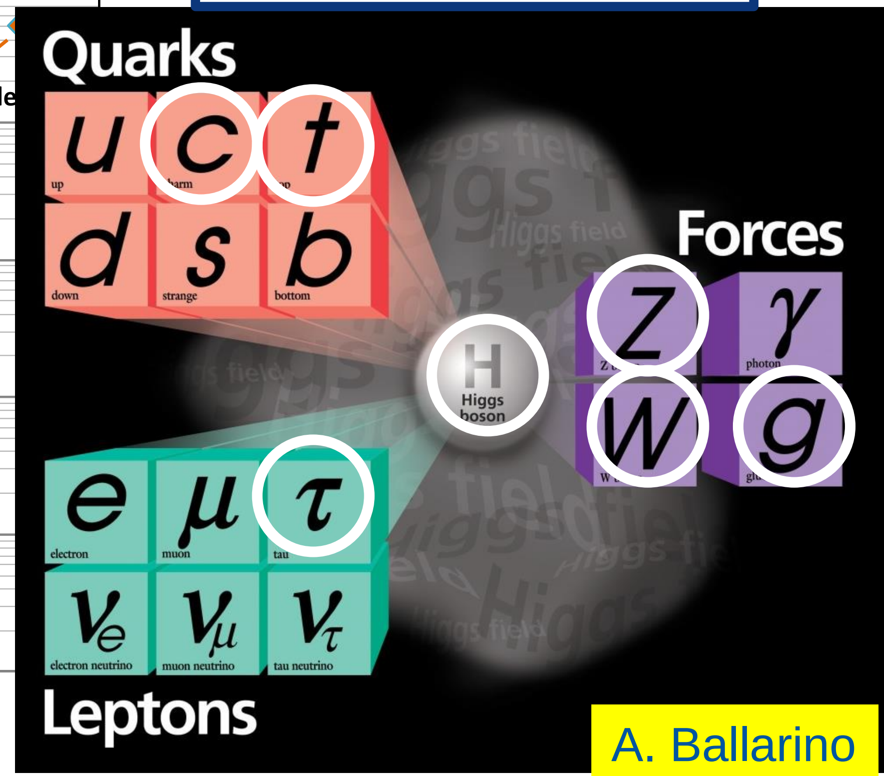
*Work supported by the **European Commission** under Capacities 7th Framework Programme project EuCARD-2, grant agreement 312453, and the HORIZON 2020 project EuroCirCol, grant agreement 654305*

J. Wenninger

colliders and discoveries



Standard Model Particles and forces



A. Ballarino

powerful instruments for discovery and precision measurement

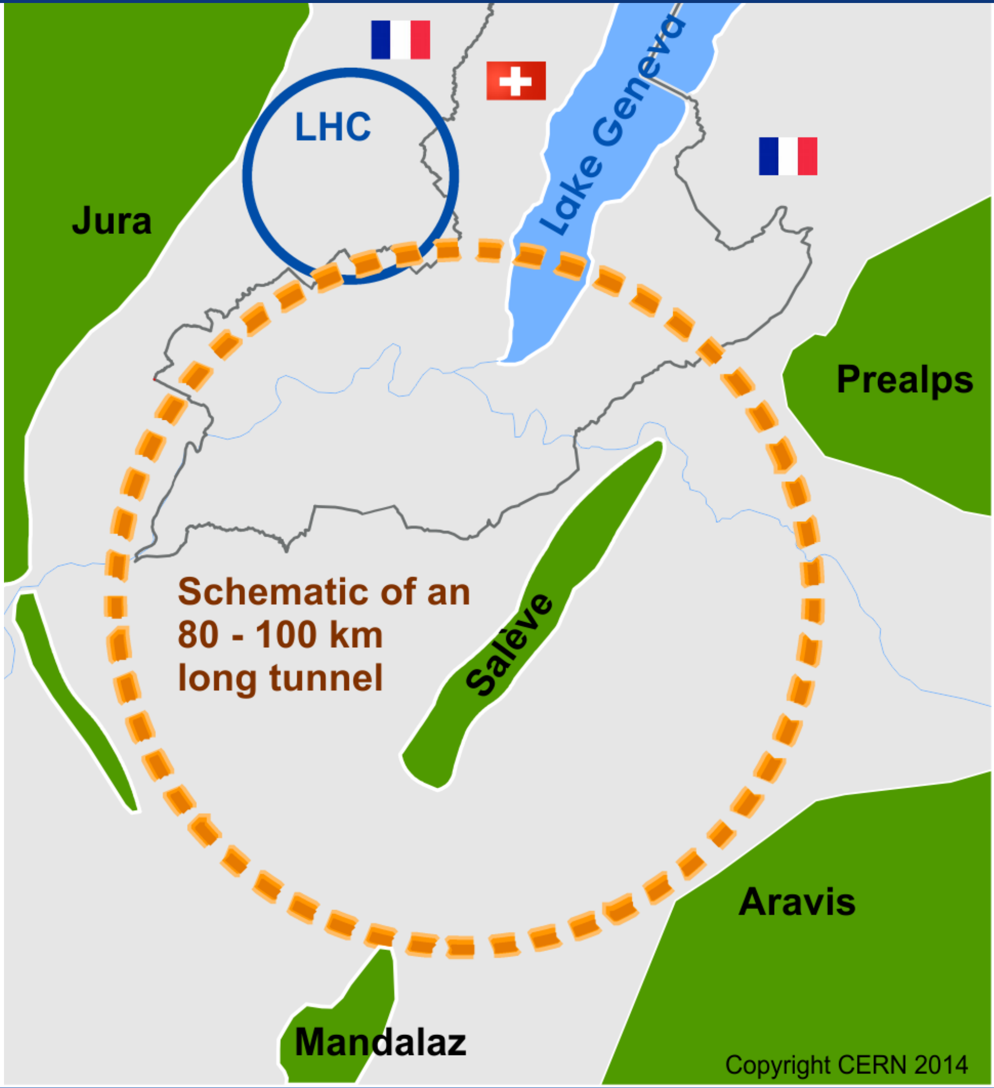
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

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

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

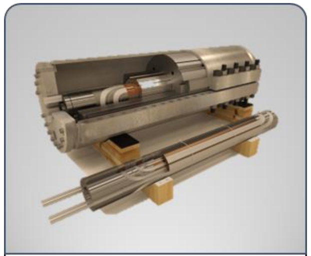
- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



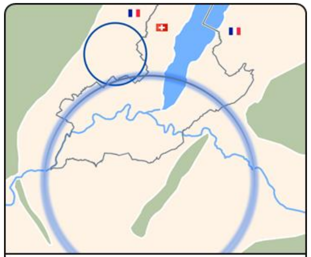
FCC Scope: Accelerator and Infrastructure

Collider Designs

FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
HE-LHC: **based on FCC-hh technology**

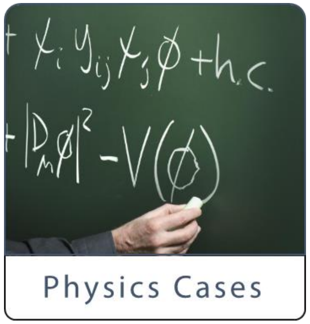

R&D Programs

key enabling technologies
pushed in dedicated R&D programmes, e.g.
16 Tesla magnet program, cryogenics, SRF technologies and RF power sources

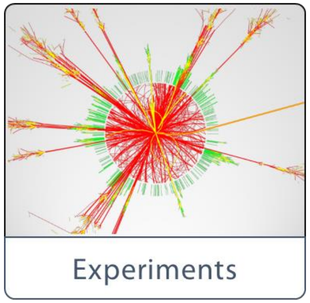

Infrastructures

tunnel infrastructure in Geneva area, linked to CERN accelerator complex;
site-specific, as requested by European Strategy

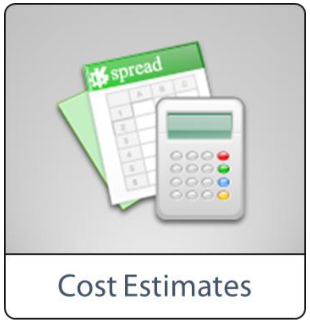
FCC Scope: Physics & Experiments



elaborate and document
- **physics opportunities**
- **discovery potentials**

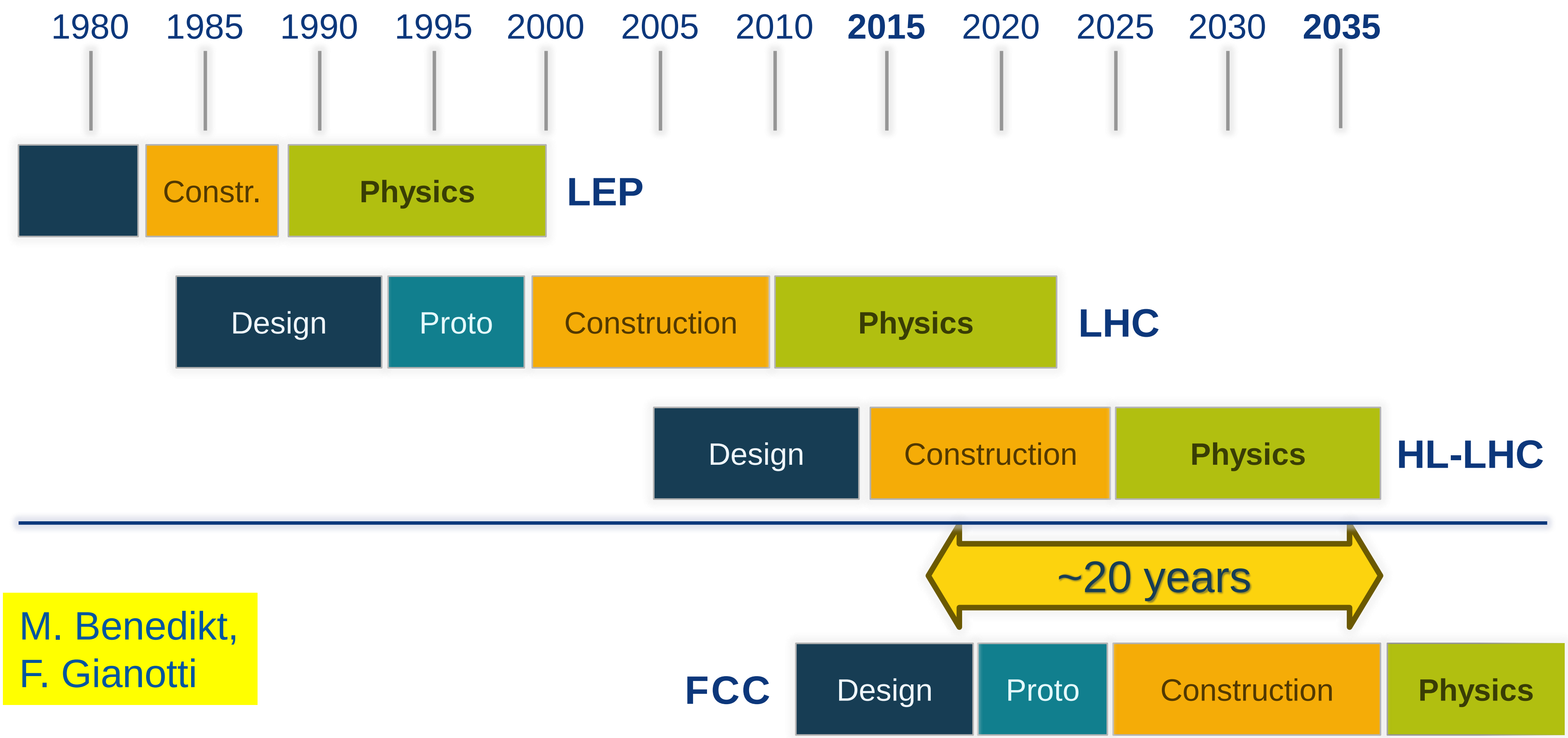


experiment concepts for hh, ee and he
Machine Detector Interface (MDI) studies
R&D needs for **detector technologies**



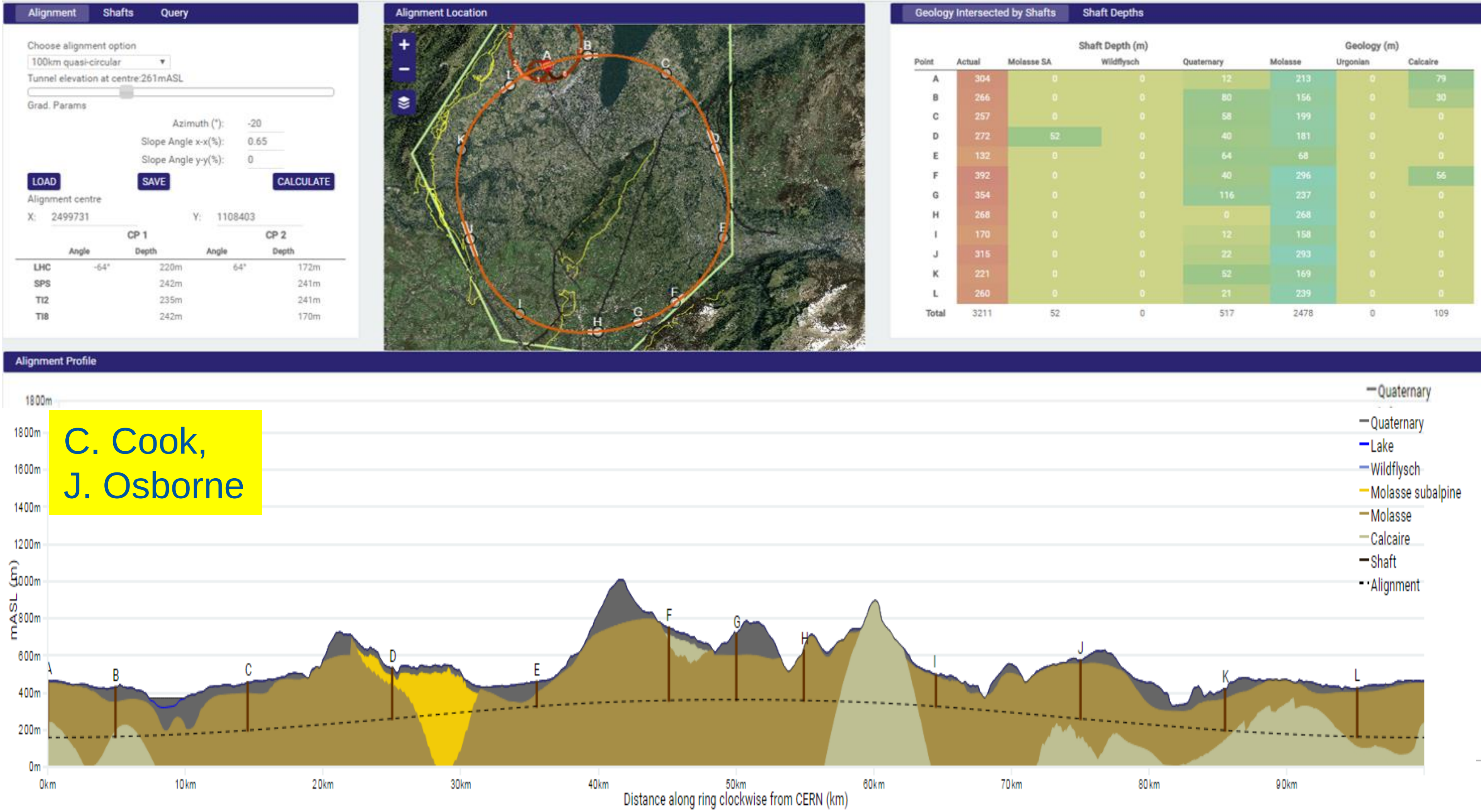
overall **cost model for collider scenarios** including infrastructure and injectors
develop **realization concepts**
forge **partnerships with industry**

CERN circular colliders & FCC



must advance fast now to be ready for the period 2035 – 2040; goal of phase 1: CDR by end 2018 for next update of European Strategy

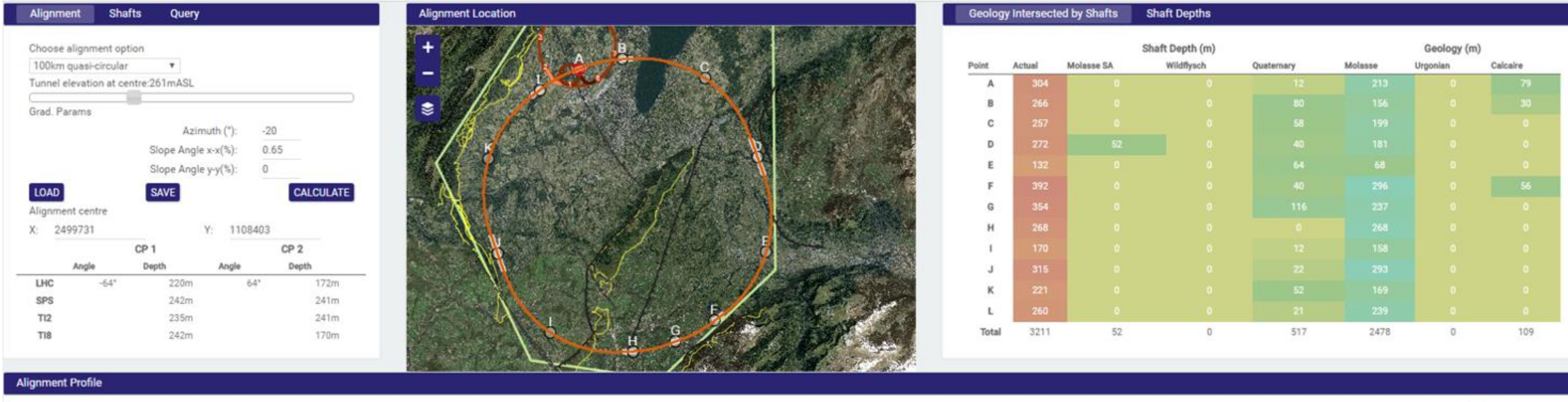
site investigations



	Shaft Depth (m)			Geology (m)			
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

C. Cook,
J. Osborne

site investigations



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L	260	0	0	21	239	0	0
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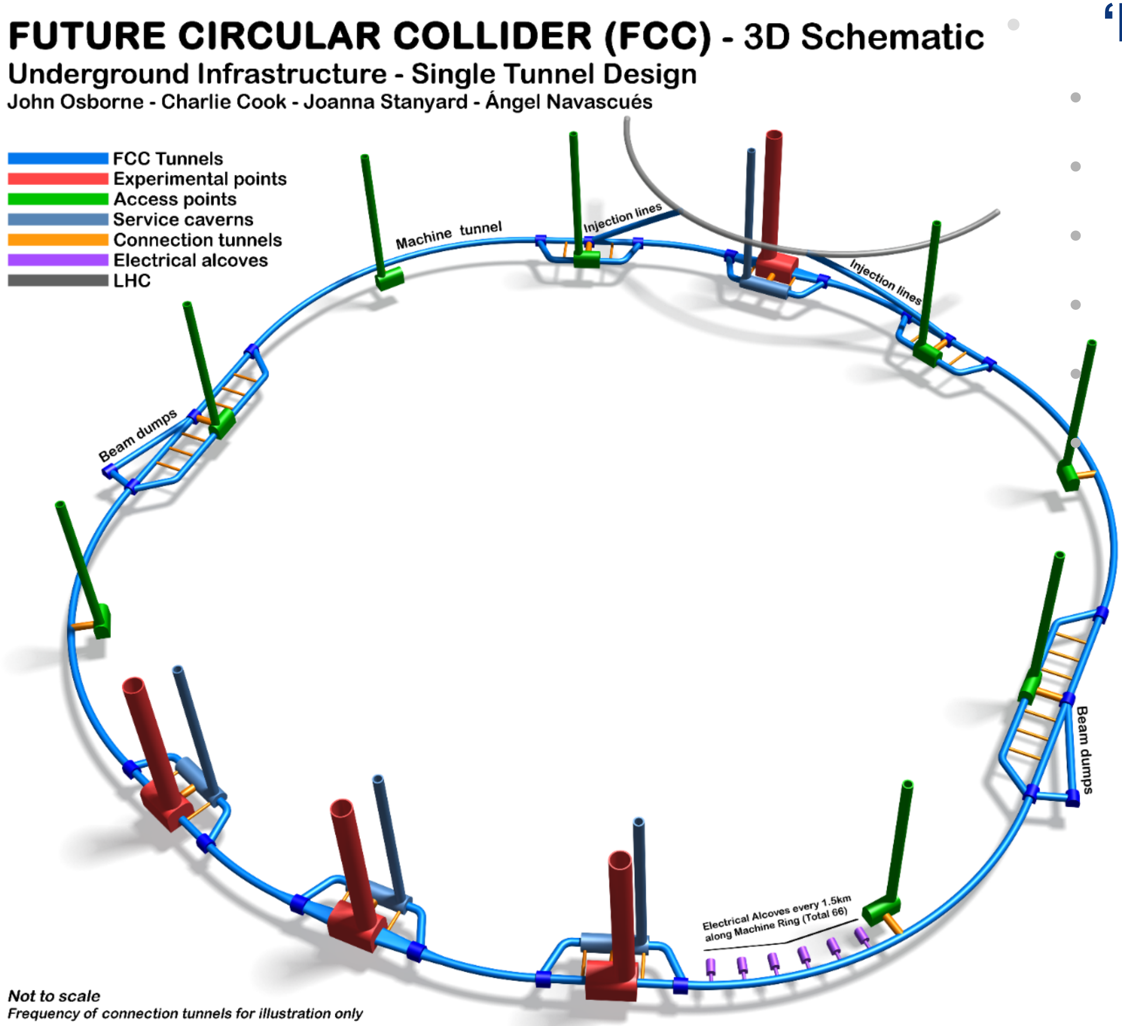
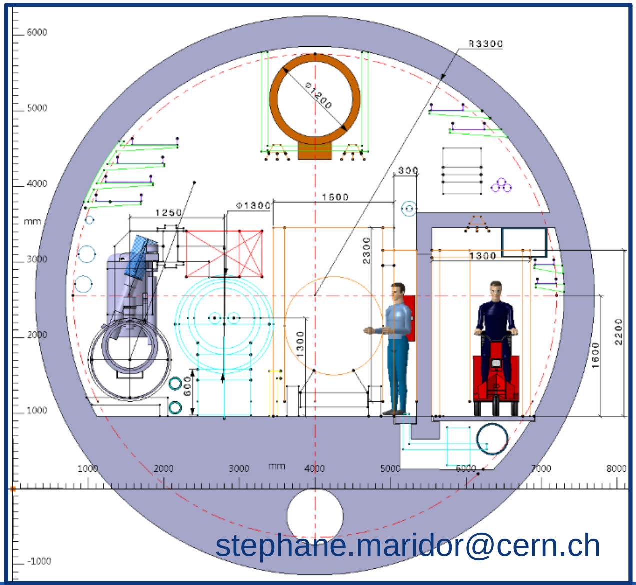
- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- the 100 km version, intersecting LHC, is now being studied in more detail

FCC tunnel layout



'baseline' layout

- 100 km tunnel 6 m inner diameter
- 4 large experimental caverns
- 8 service caverns for infrastructure
- 12 & 4 vertical shafts (3 km integral)
- 2 transfer tunnels (10 km)
- 2 beam dump tunnels (4 km)

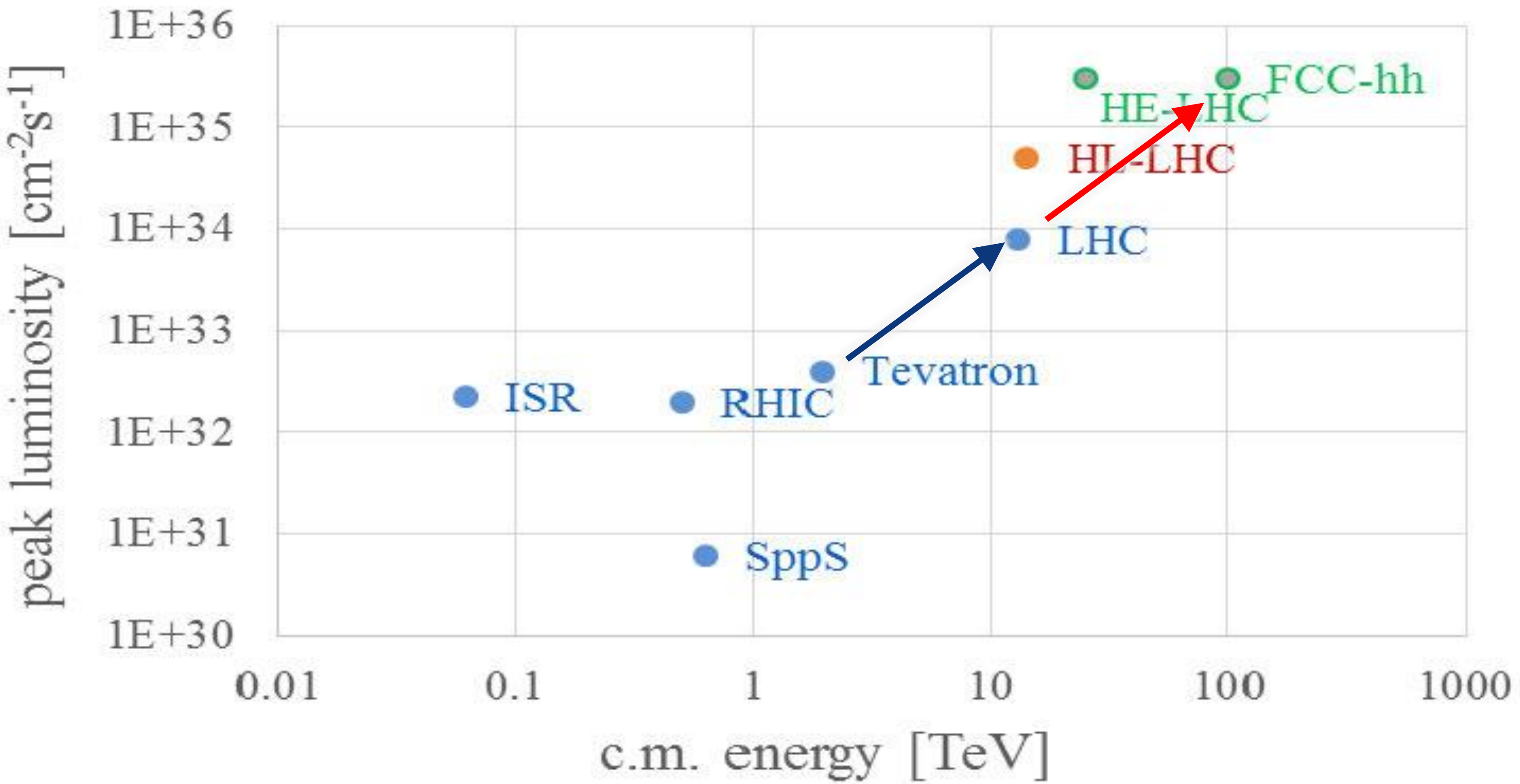


hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC*	(HL) LHC
collision energy cms [TeV]	100		25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.27	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.2)	1 (0.2)	2.5	(2.2) 1.15
bunch spacing [ns]	25 (5)	25 (5)	25 (5)	25
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	34	(5) 1
peak #events/bunch crossing	170	1020 (204)	1070 (214)	(135) 27
stored energy/beam [GJ]	8.4		1.4	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		4.1	(0.35) 0.18
transv. emit. damping time [h]	1.1		4.5	25.8
initial proton burn off time [h]	17.0	3.4	2.3	(15) 40

*tentative

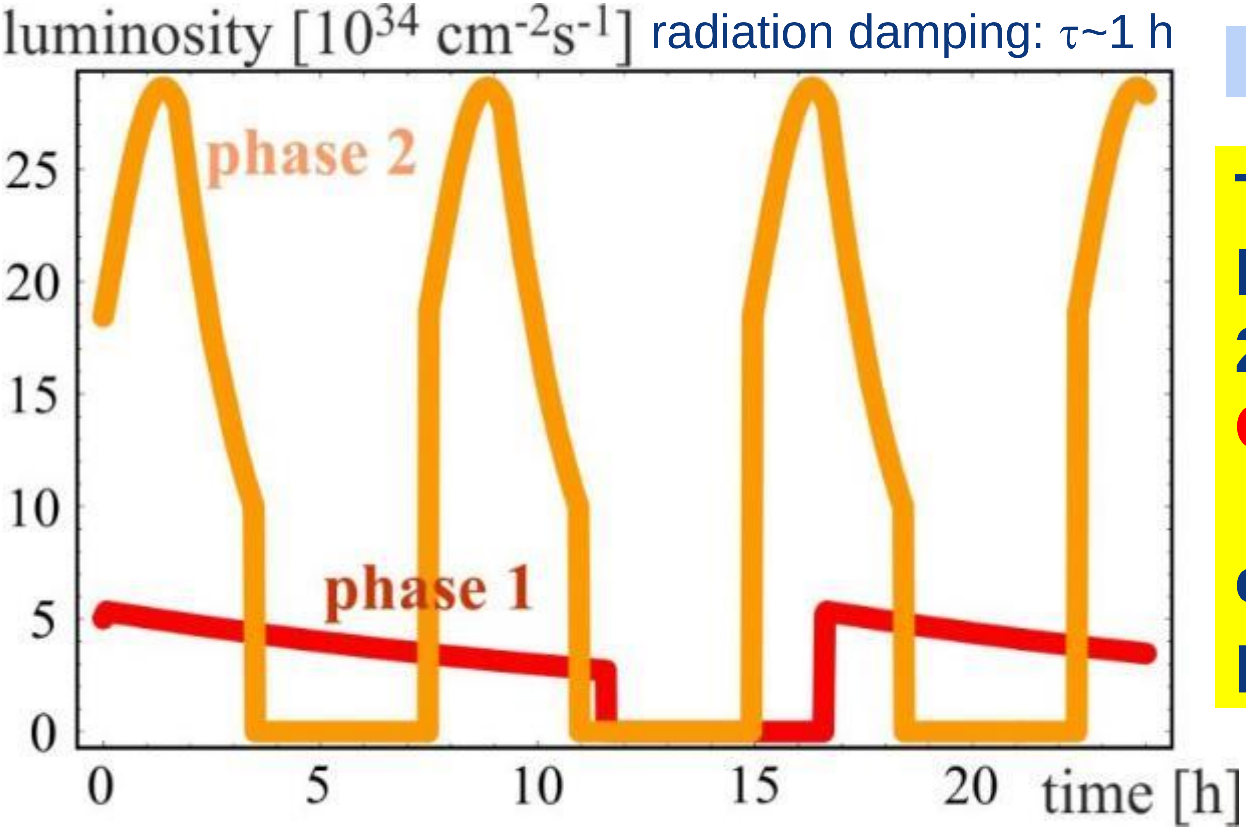
pp/p-pbar in the *L-E* plane



FCC-hh luminosity phases

phase 1: β*=1.1 m, $\Delta Q_{tot}=0.01$, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β*=0.3 m, $\Delta Q_{tot}=0.03$, t_{ta}=4 h, 1 ab^{-1} / year

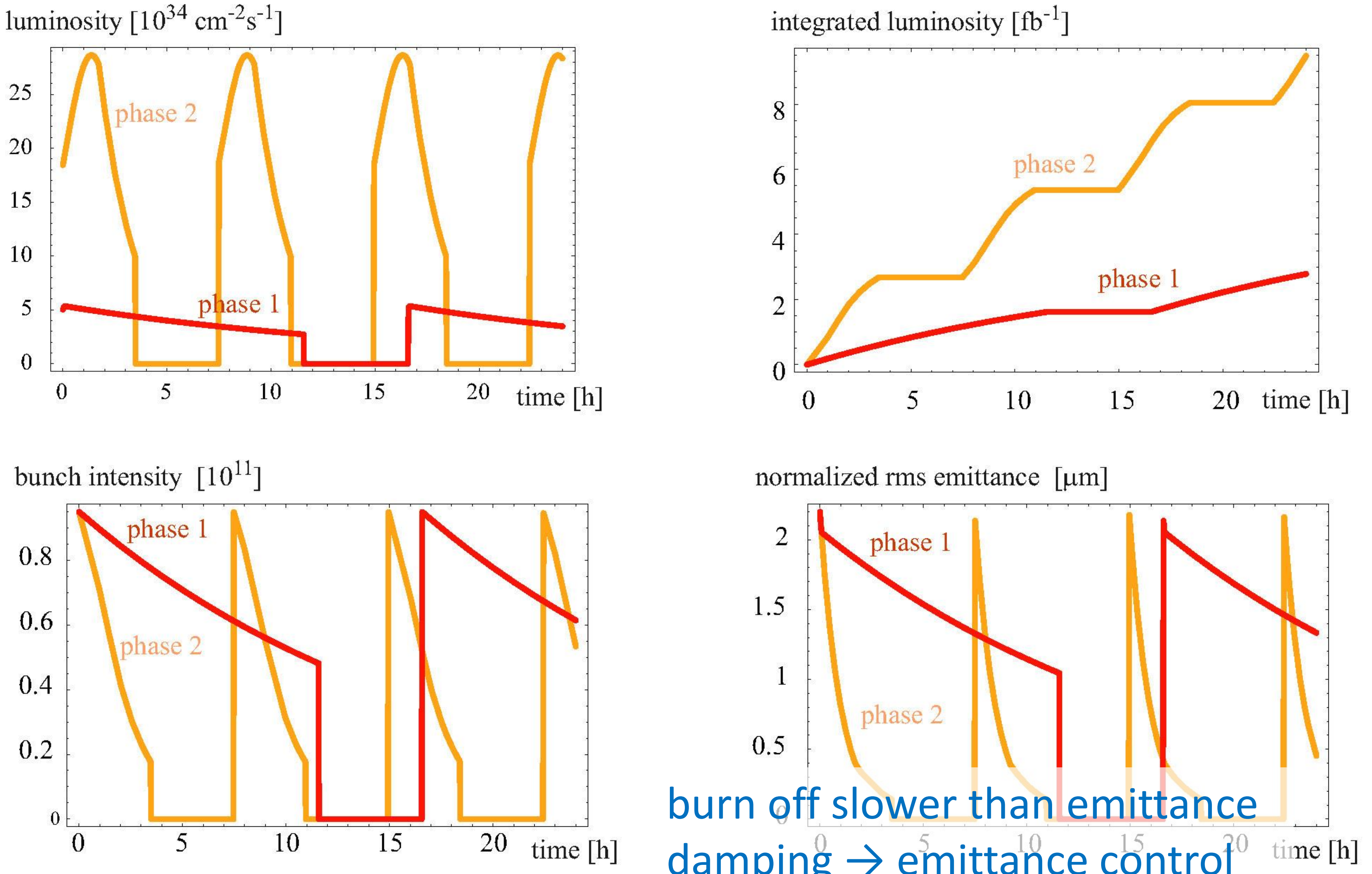


PRST-AB 18, 101002 (2015)

Total integrated luminosity over 25 years operation O(20) ab^{-1}

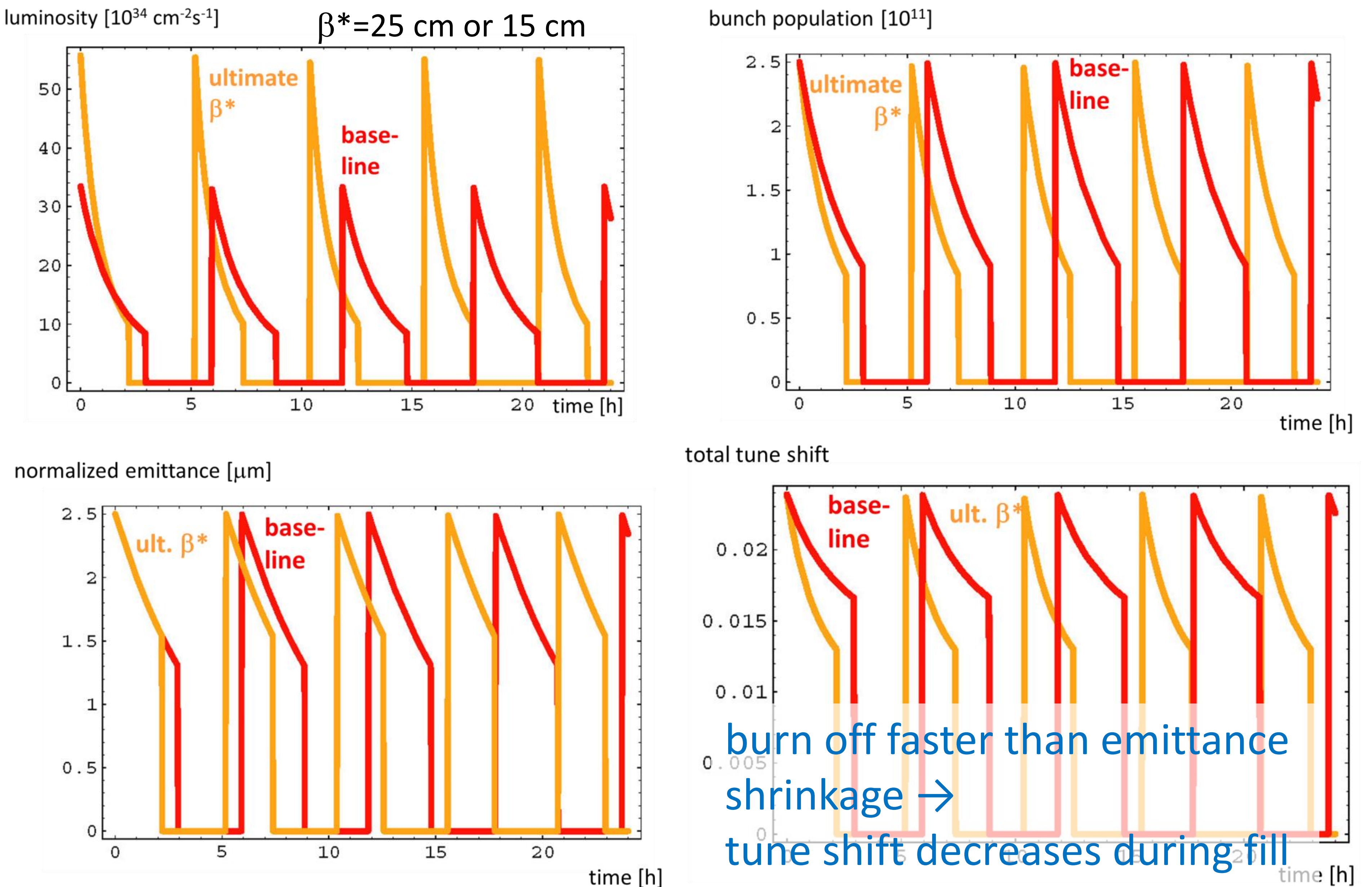
consistent with physics goals

FCC-hh - 100 TeV c.m., 25 ns



burn off slower than emittance damping → emittance control

HE-LHC - 25 TeV c.m., 25 ns

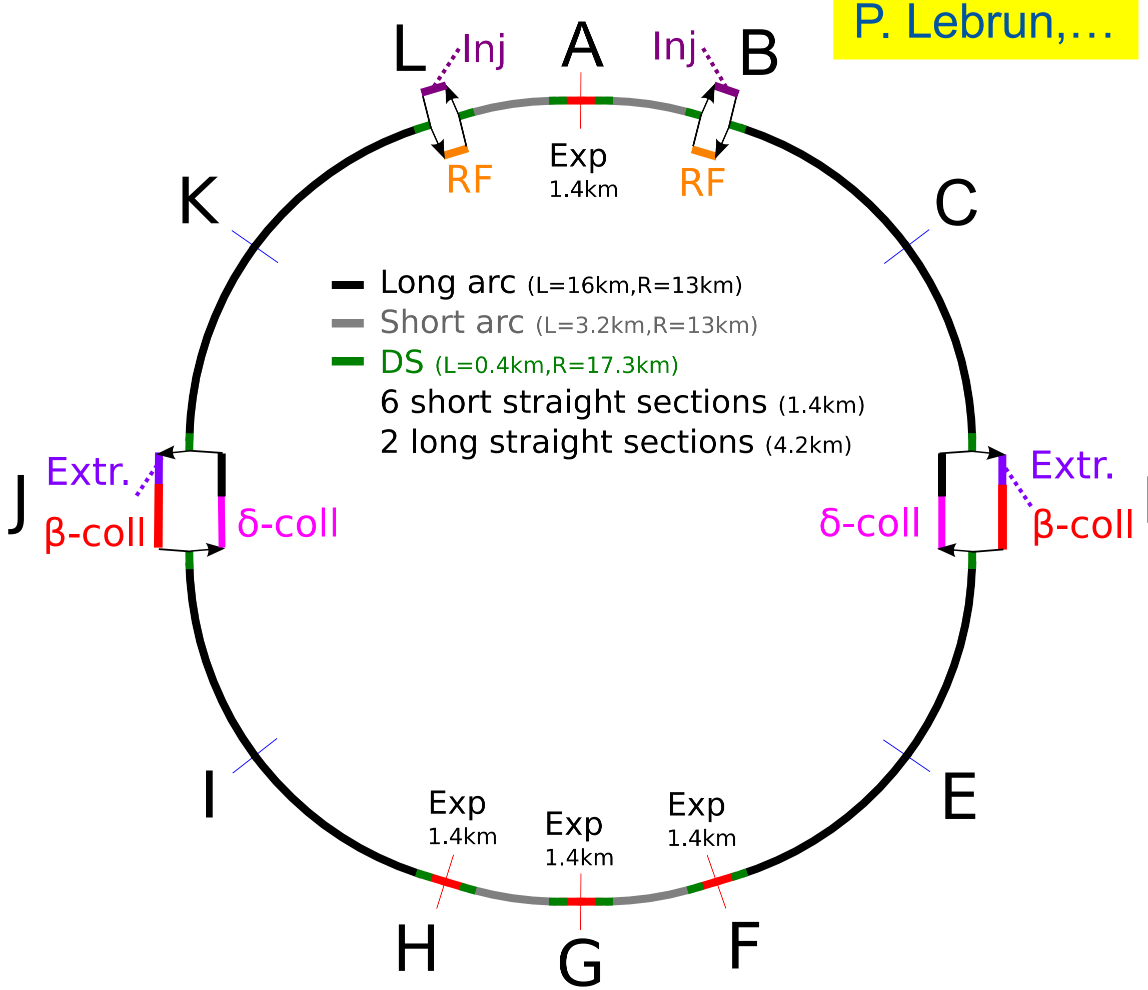


burn off faster than emittance shrinkage →
tune shift decreases during fill

FCC-hh layout

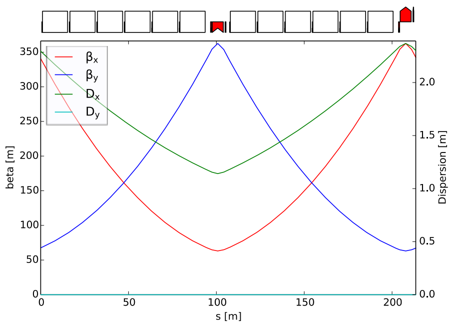
D. Schulte, P. Lebrun,…

- integrated lattice exists;
  - recent designs:
    - energy collimation
    - extraction
    - experiment
    - betatron collimation
    - injection
- first results on:
  - dynamic aperture
  - tolerances and alignment
  - detailed magnet specifications

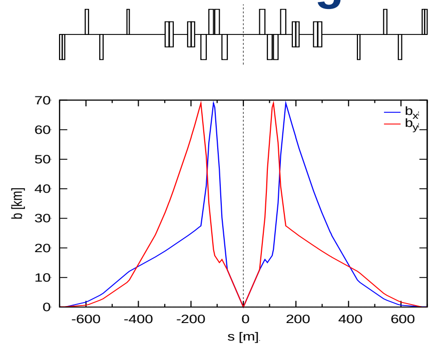


FCC-hh full-ring optics

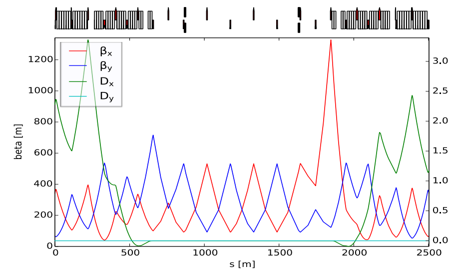
regular arc cell



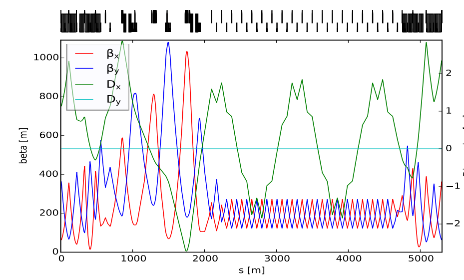
interaction region



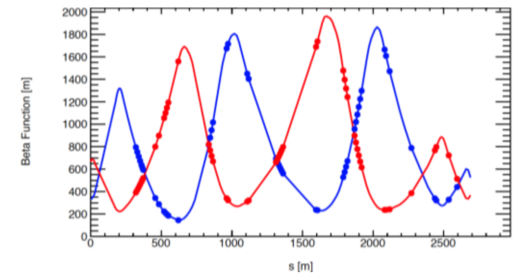
injection with RF



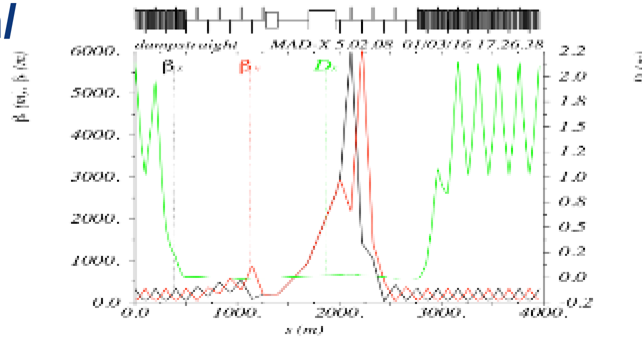
momentum collim.



betatron collimation



extraction/ dumping



full ring lattice permits:

- beam dynamics studies
- optimisation of each insertion
- definition of system specifications (apertures, etc.)
- improvement of baseline optics and layout

D. Schulte, B. Holzer, R. Haerer, A. Seryi, et al.

key technologies for FCC-hh

16 T arc dipole magnets based on Nb_3Sn

- conductor development, magnet design
- ***highest priority!*** (talk by Gijs de Rijk)

arc beam screen

cryogenics system

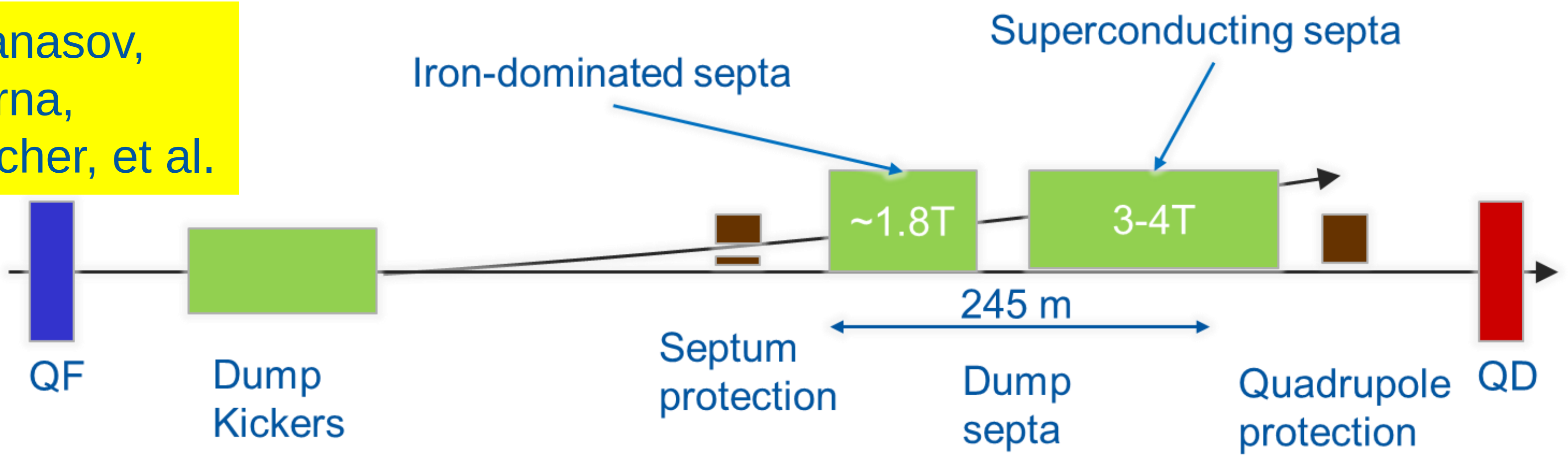
SC septa

SC detector magnets

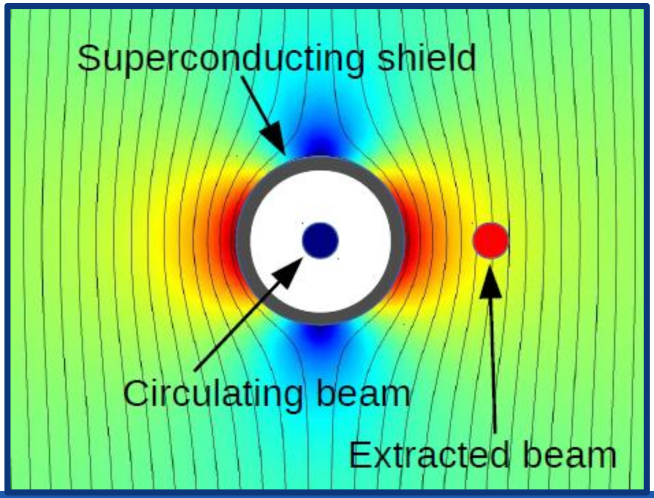
R&D on superconducting septa

need extraction system for safely removing beam from collider;
hybrid system: short overall length with high robustness & availability

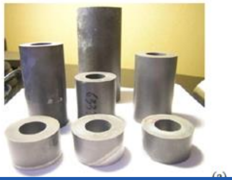
M. Atanasov,
D. Barna,
E. Fischer, et al.



SuShi concept:
SC shield creates field-free region inside strong dipole field



3 candidate technologies:
(1) NbTi/Nb/Cu multilayer sheet
(2) HTS tape
(3) Bulk MgB_2



synchrotron radiation - beam screen prototype

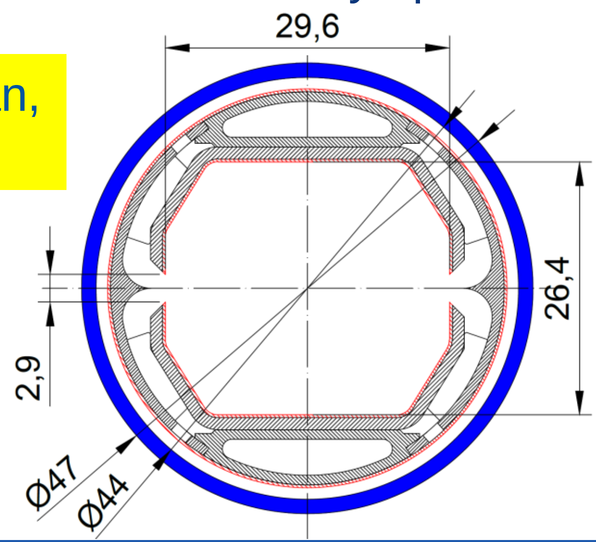
high synchrotron radiation load of proton beams @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!!!)**

new beam screen with ante-chamber

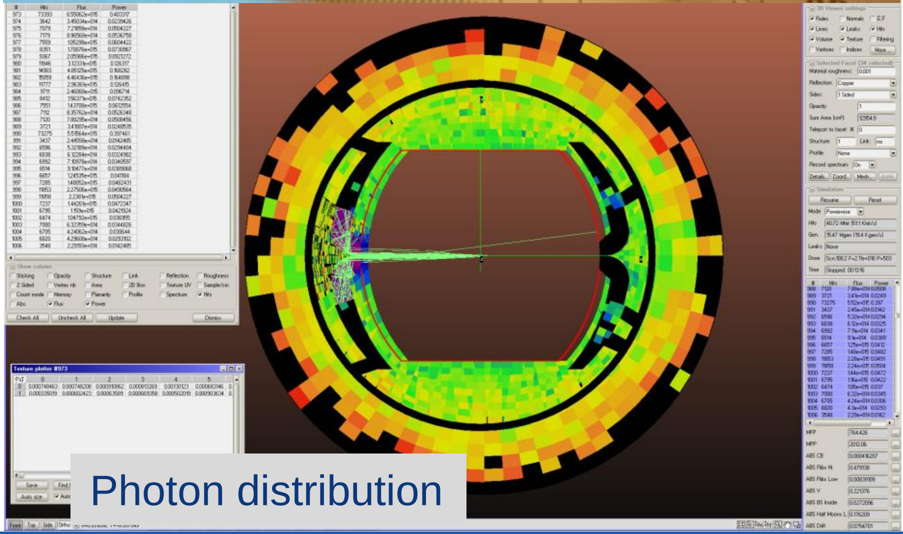
- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of cryo power

R. Kersevan,
C. Garion



First FCC-hh beam screen prototype

Testing 2017 in ANKA within EuroCirCol



Photon distribution

HTS coating for beam screen

S. Calatroni,
G. Stupakov

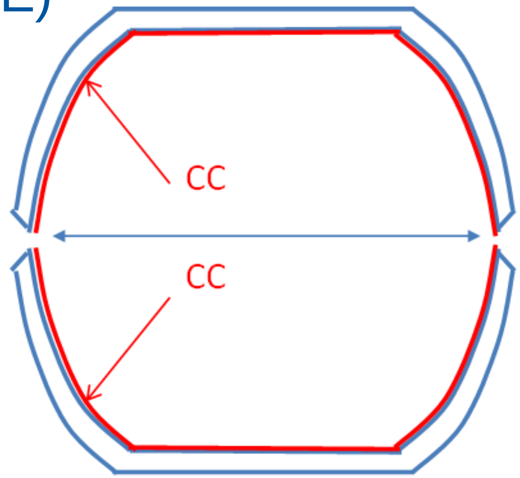
goals: - drastically lower FCC-hh beam impedance
- allow for (even) higher beam-screen temperature

candidate materials:

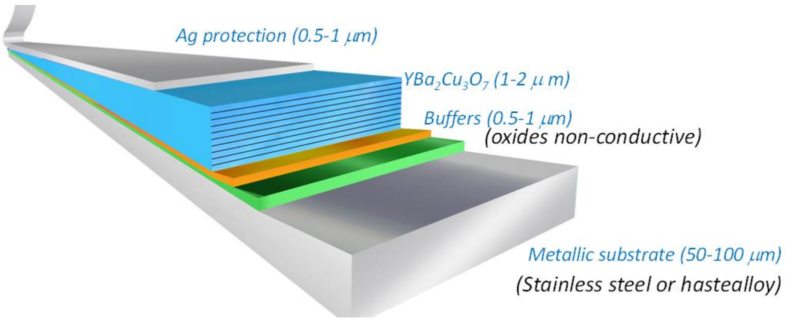
Tl-1223 (promising performance, opens up >100 K temperature window, scalable coating, R&D with CNR-SPIN and TU-Vienna)

YBCO (proven performance, requires forming technology, R&D with ICMAB-ALBA-IFAE)

HTS can have surface resistance lower than Cu at T< 77 K and f < 10 GHz

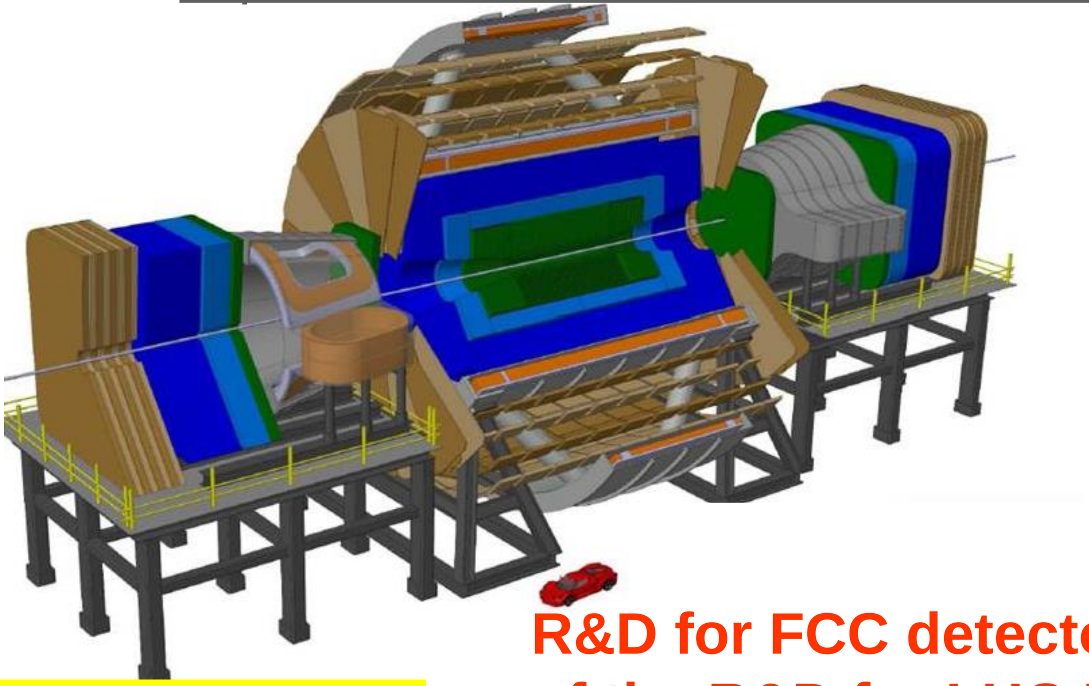


CC: coated conductor



detector concepts for 100 TeV pp

- a B=6 T, R=6 m solenoid with shielding coil and 2 dipoles has been engineered in detail; alternative magnet systems are being studied
- parametrized detector performance model (DELPHES) is available and integrated in FCC software framework for physics simulations
  - https://twiki.cern.ch/twiki/bin/view/FCC/FccPythiaDelphes



H. ten Kate, W. Riegler et al.

some design challenges:

- large η acceptance
- radiation levels of >50 x LHC Phase II
- pileup of ~1000

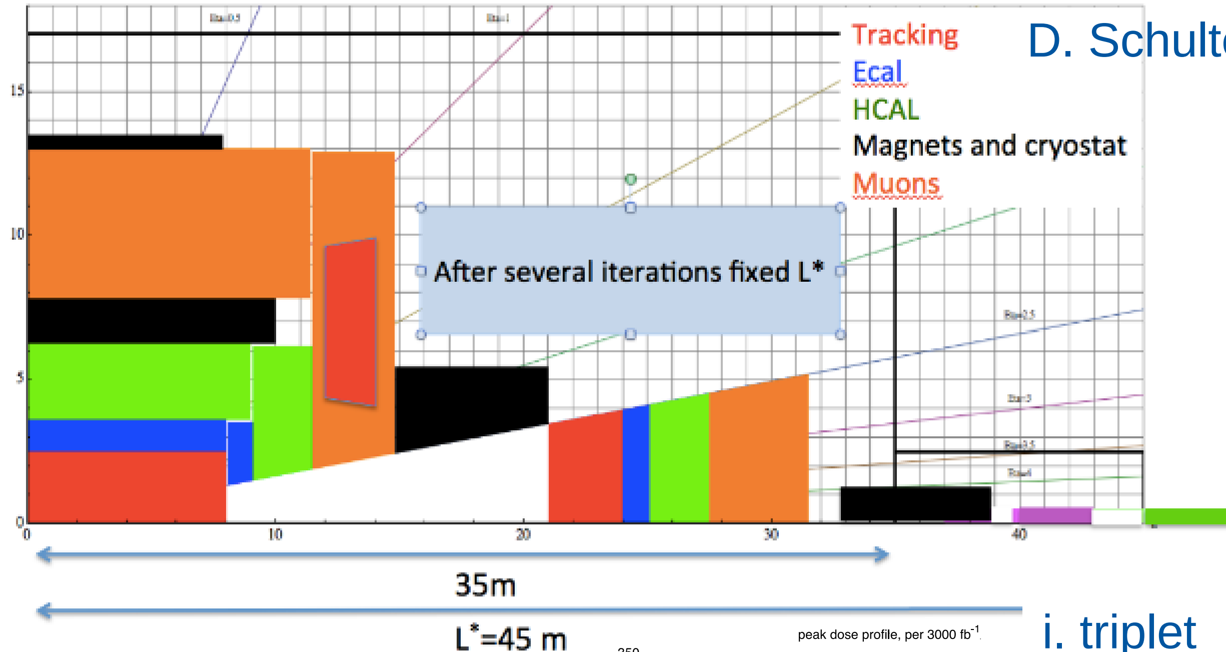
R&D for FCC detectors is a natural continuation of the R&D for LHC Phase II upgrade

FCC-hh BDS & MDI

design of interaction region

- consistent for machine and detector
  - L^*=45 m
  - integrated spectrometer and compensation dipoles
- optics with long triplet with large aperture
  - helps distributing collision debris
  - more beam stay clear

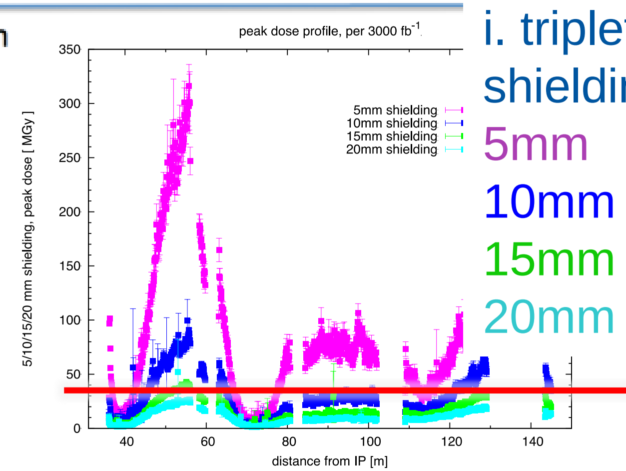
proton losses in dispersion suppressor are an issue



radiation dose for final quadrupoles

dose for 3000 fb^{-1}

30 MGy = present limit



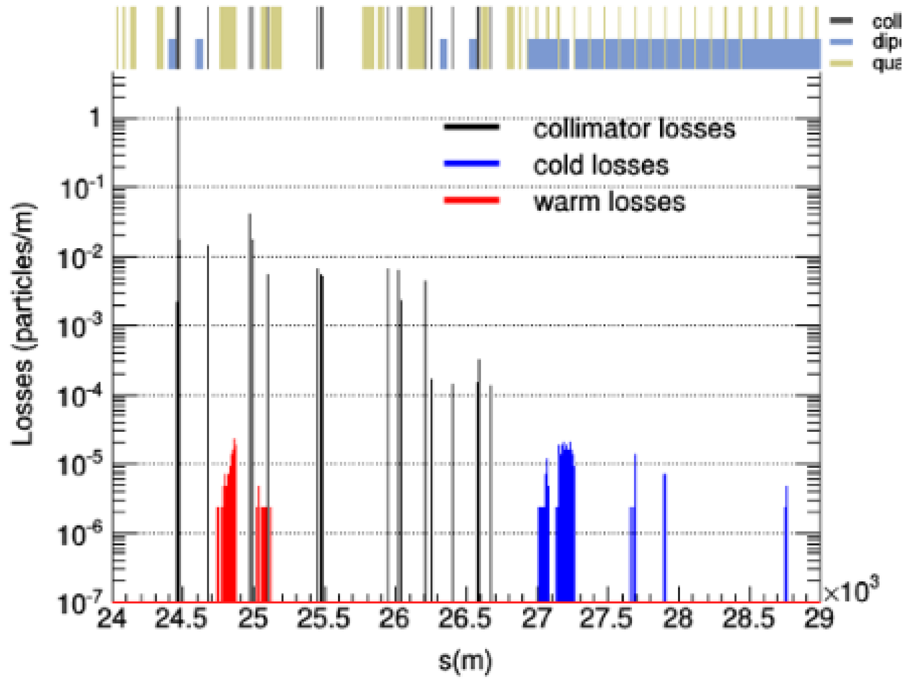
i. triplet shielding
5mm
10mm
15mm
20mm

I. Besana, F. Cerutti, A. Seryi, et al.

FCC-hh collimation

aperture model of machine exists;
system design developed;
first efficiency studies

- high losses in dispersion suppressor
- heat load on primary collimators close to the limit



upcoming:

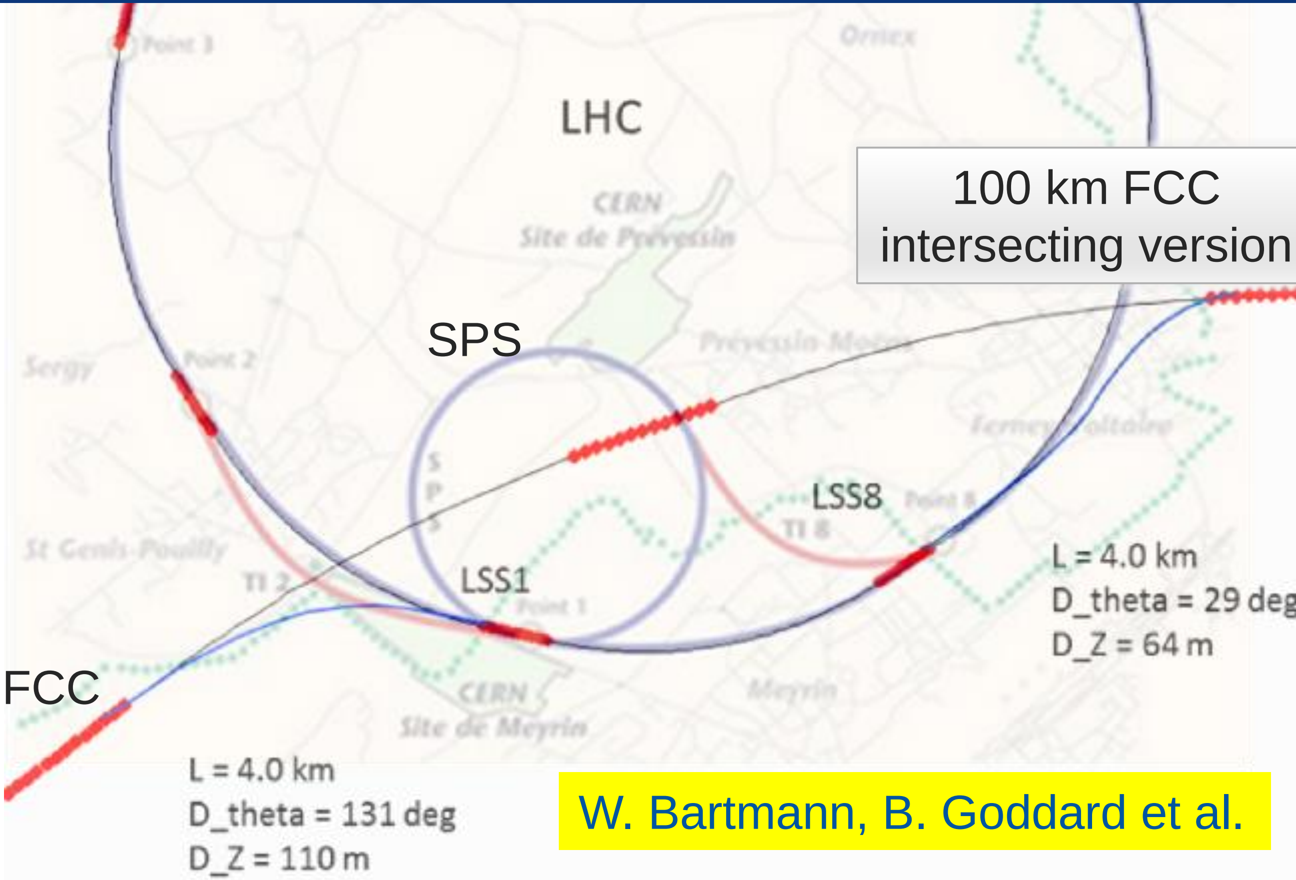
- study load on secondary collimators
- shower simulations
- operational robustness improvements:
  - **crystal collimation?**
  - **hollow electron lens?**
- impact of 5 ns operation on design

M. Fiascaris,
J. Molson,
S. Redaelli,
D. Schulte

FCC-hh injector studies

injector options:

- **SPS → LHC → FCC**
- SPS/SPS$_{upgrade}$ → FCC
- SPS → FCC booster
  → FCC



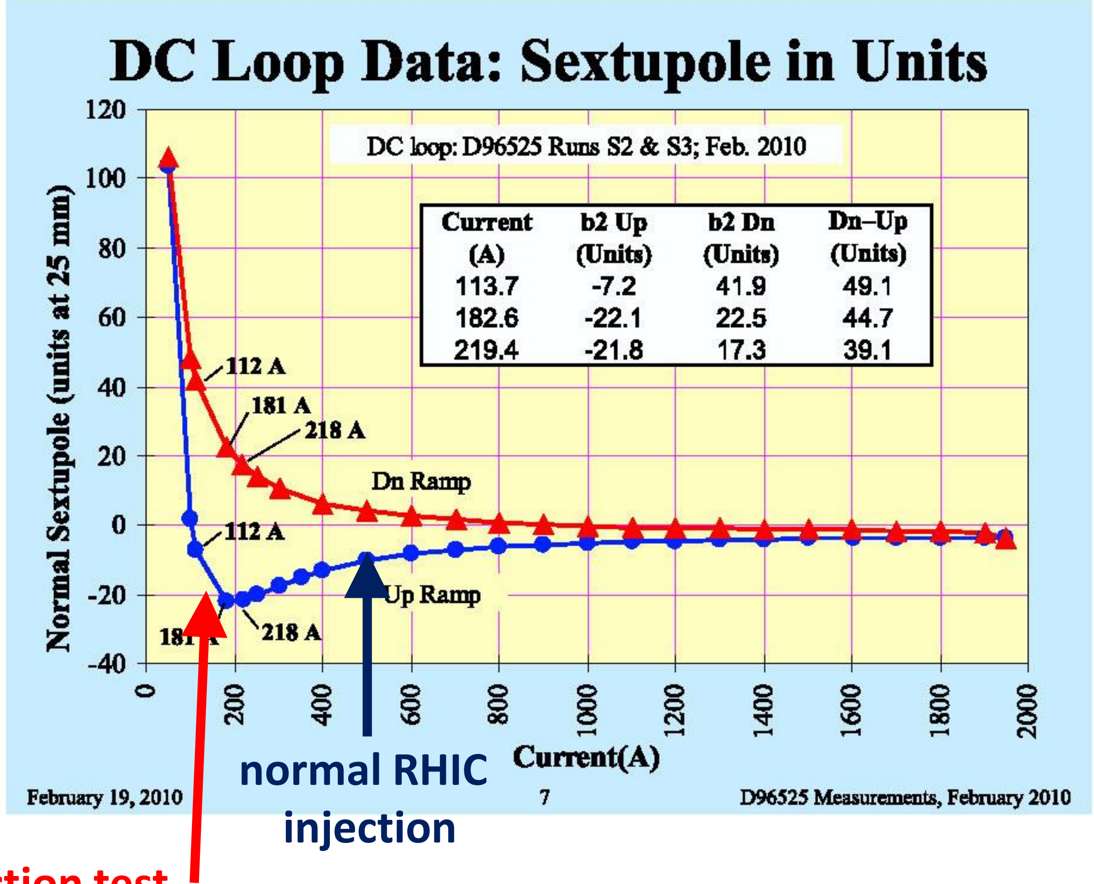
current baseline is to fully re-use the existing CERN accelerator complex

- **injection energy 3.3 TeV from LHC**

injection from SPS tunnel means lower injection energy ~1.5 TeV

lower injection energy (1.5 TeV)?

beam studies proposed at LHC (injection at 225 GeV instead of 450 GeV) and at RHIC (*p* inj. at 7.3 GeV)



C. Montag

FCC-hh as A-A collider

	Pb-Pb	Pb-p
beam energy [TeV]	4100	50
c.m. energy/nucleon pair [TeV]	39.4	62.8
no. bunches / beam	2072	2072
IP beta function [m]	1.1	1.1
long. emit. rad. damping time [h]	**0.24**	0.5
init. luminosity [10^{27} cm^{-2}s^{-1}]	24.5	2052
peak luminosity [10^{27} cm^{-2}s^{-1}]	**57.8**	**9918**

based on existing LHC complex; fast radiation damping; secondary beams from IP require dedicated collimators,…

J. Jowett, M. Schaumann

M. Schaumann, "Potential performance for Pb-Pb, p-Pb, and p-p collisions in a future circular collider, Phys. Rev. ST Accel. Beams 18, 091002 (2015).
A. Dainese et al., "Heavy ions at the Future Circular Collider," contribution to forthcoming CERN Report on Physics at FCC-hh, http://arxiv.org/abs/1605.01389 .

FCC-hh physics prospects

Physics at the FCC-hh

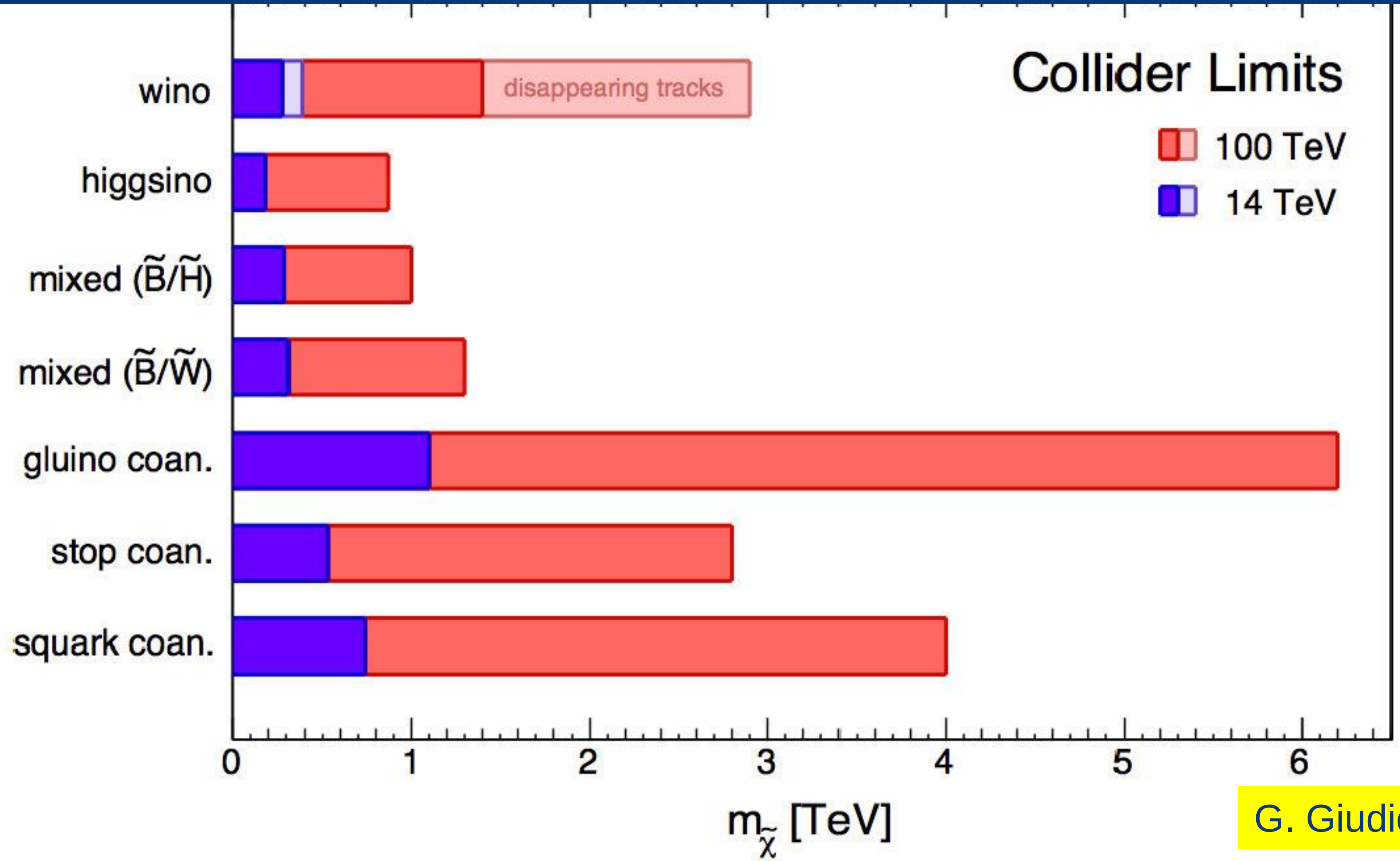
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

M. Mangano et al.

- **Being published as CERN yellow report**

FCC-hh physics perspectives



G. Giudice

FCC-ee physics requirements

- **physics programs / energies:**

  ***Z* (45.5 GeV) *Z* pole,** *'TeraZ' and high precision M_Z & Γ_Z*

  ***W* (80 GeV) *W* pair production** *threshold, high precision M_W*

  ***H* (120 GeV) *ZH* production** *(maximum rate of H's)*

  ***t* (175 GeV): $t\bar{t}$ threshold**, *H studies*

- **beam energy range from 35 GeV to ≈200 GeV**
- **highest possible luminosities** *at all working points*
- possibly ***H* (63 GeV) direct *s*-channel** production with **monochromatization**

  (**c.m. energy spread <6 MeV**, presentation at IPAC'16)

- **beam polarization up to ≥80 GeV** for beam energy calibration

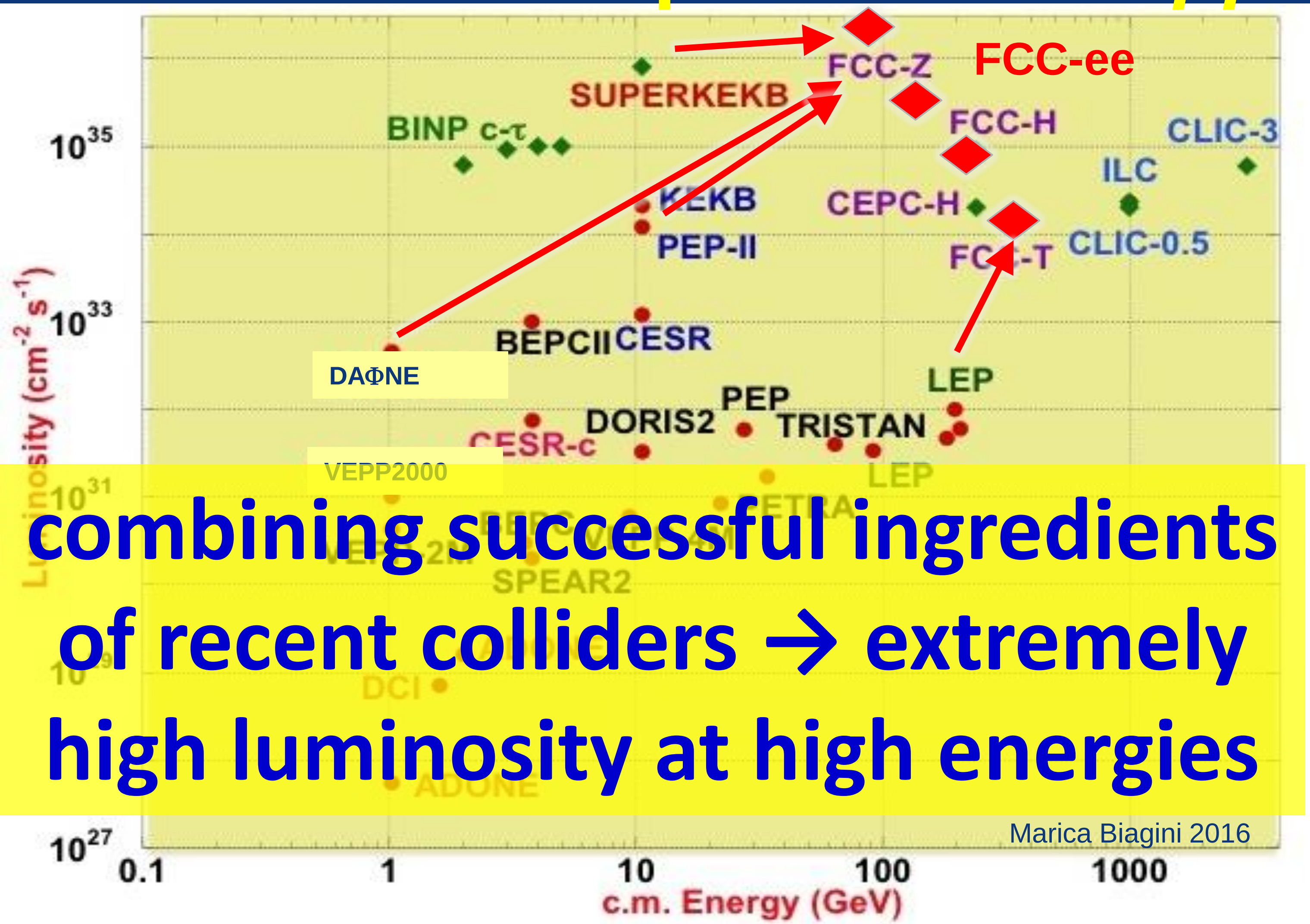
lepton collider parameters

parameter	FCC-ee (400 MHz)					CEPC	LEP2
Physics working point	Z		WW	ZH	tt_{bar}	H	
energy/beam [GeV]	45.6		80	120	175	120	105
bunches/beam	30180	91500	5260	780	81	50	4
bunch spacing [ns]	7.5	2.5	50	400	4000	3600	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	3.8	4.2
beam current [mA]	1450	1450	152	30	6.6	16.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.1	3.34
synchrotron power [MW]	100					103	22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	6.9	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings   CEPC, LEP: single beam pipe

exploiting lessons & recipes from past e^+e^- and *pp* colliders



combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
- high energy
- SR effects

B-factories:
KEKB & PEP-II:
- high beam currents
- top-up injection

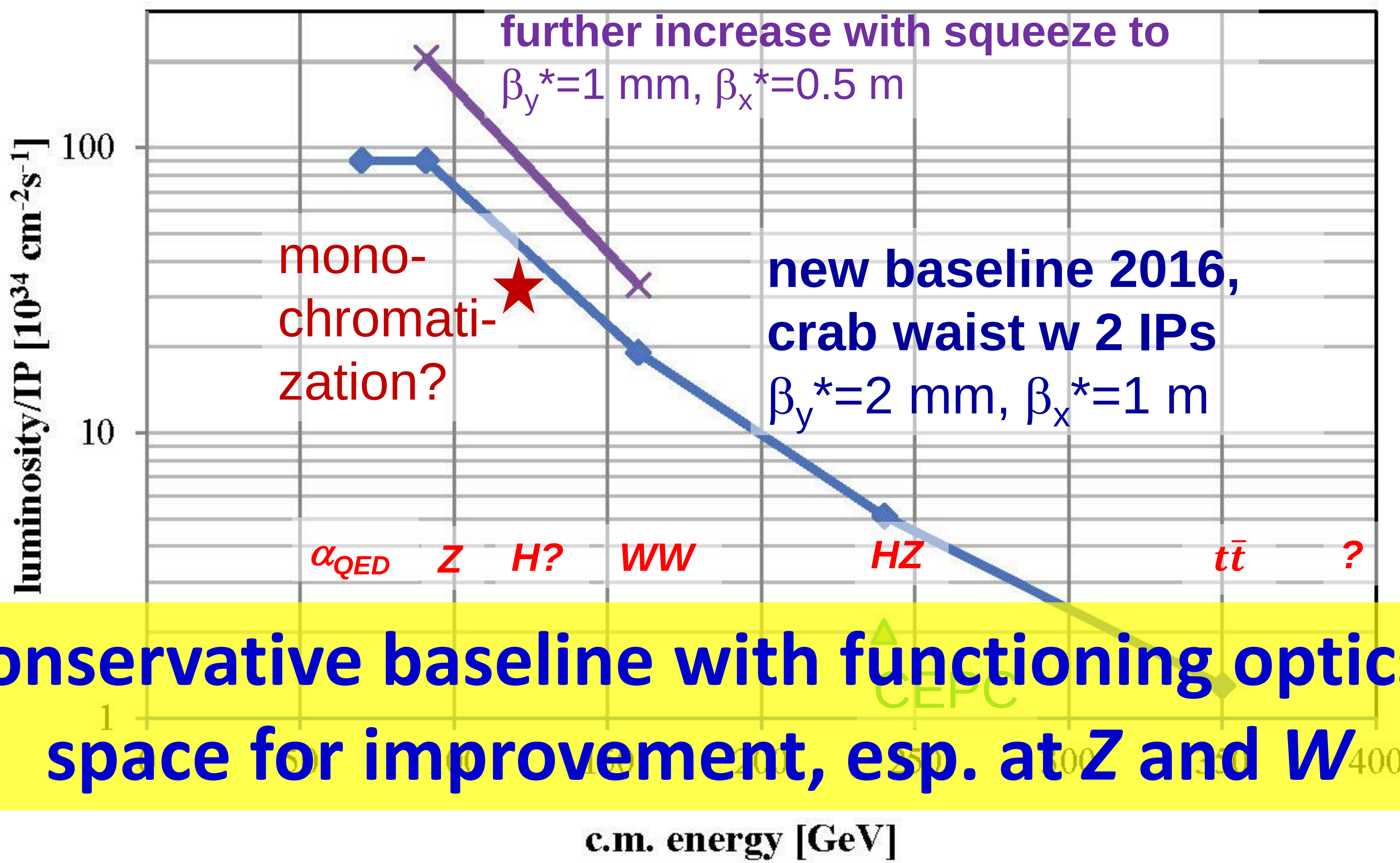
DAFNE: crab waist

Super B-factories
S-KEKB: low β_y^*

KEKB: e^+ source

HERA, LEP, RHIC:
- spin gymnastics

FCC-ee luminosity per IP

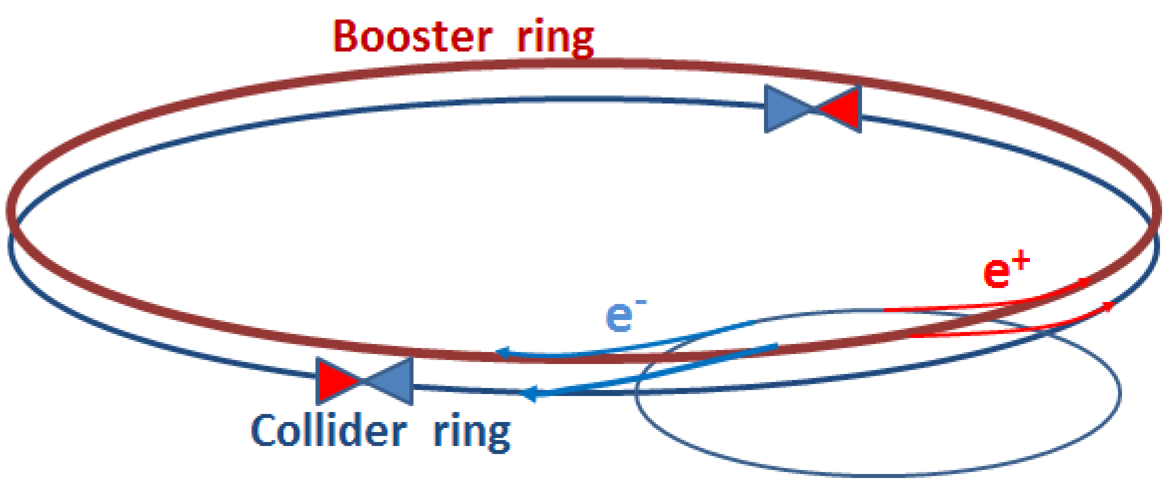


conservative baseline with functioning optics, space for improvement, esp. at *Z* and *W*

FCC-ee top-up injection

beside the collider ring(s), a full-energy booster of the same size (same tunnel) must provide beams for top-up injection to sustain the extremely high luminosity

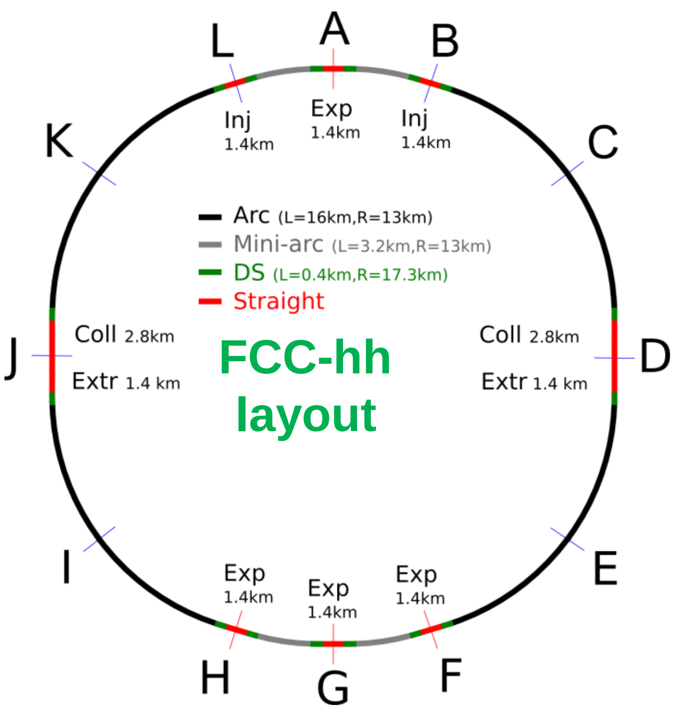
- same size of RF system, but low power (~ MW)
- top up frequency ≈0.1 Hz
- booster injection energy ≈5-20 GeV
- bypass around the experiments

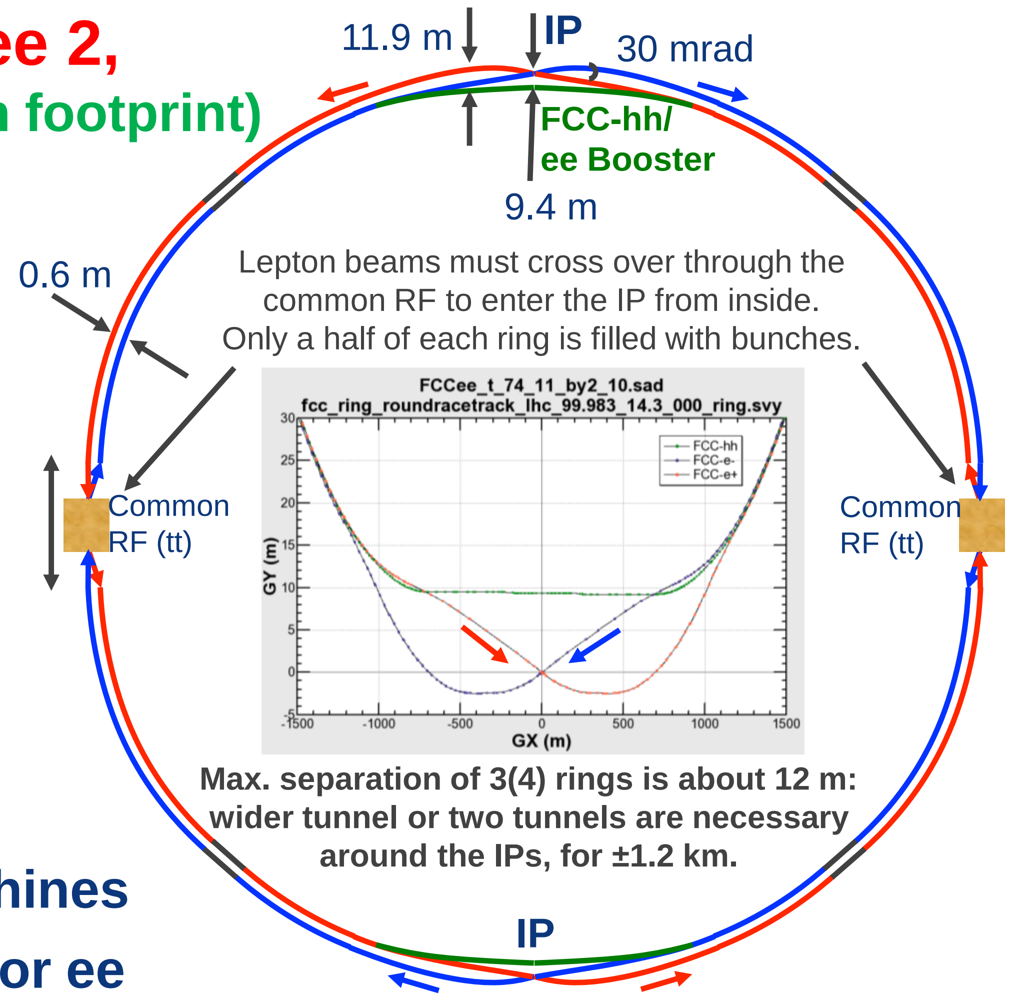


A. Blondel

common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

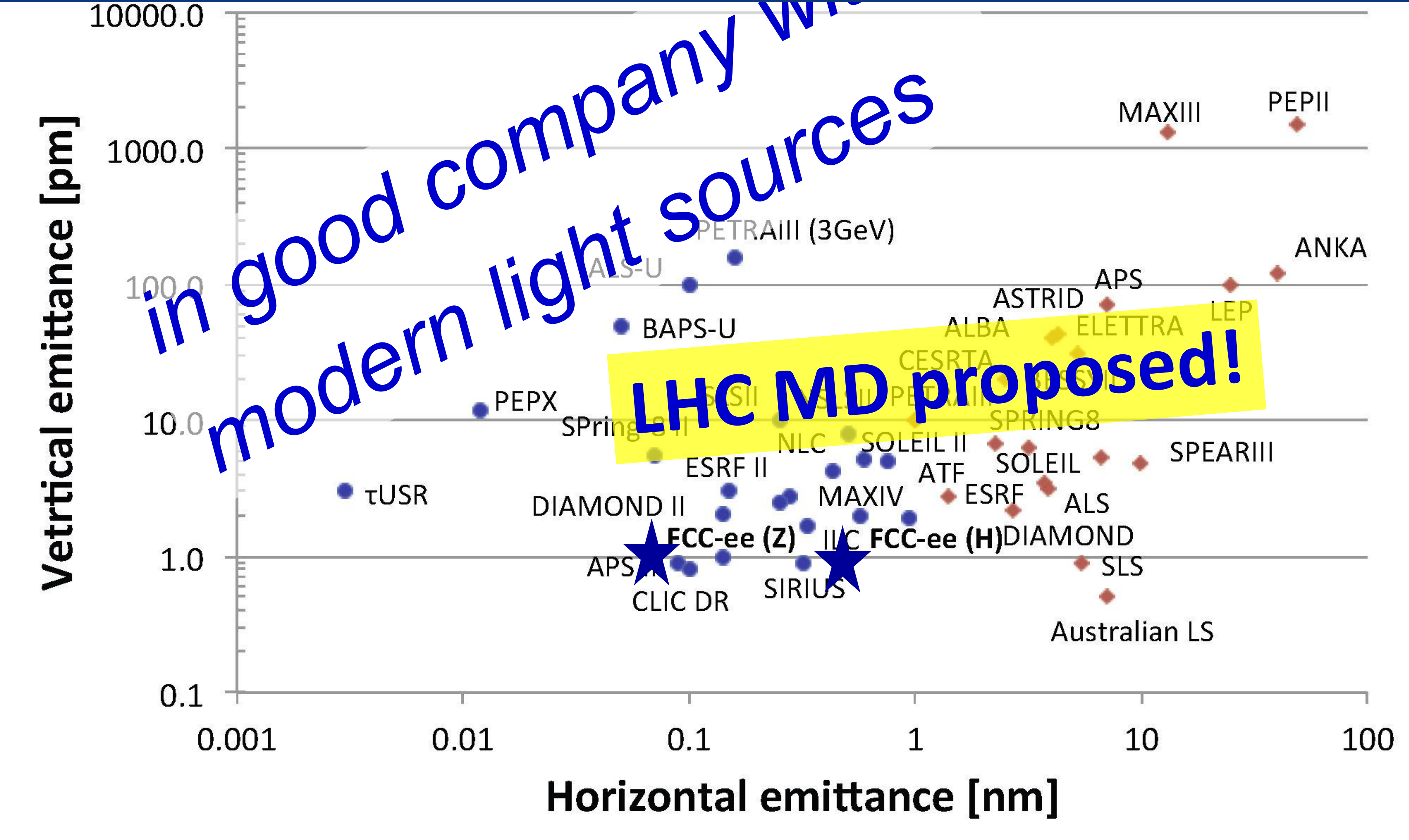




- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

K. Oide, D. Schulte, A. Bogomyagkov, B. Holzer, et al.

transverse emittances



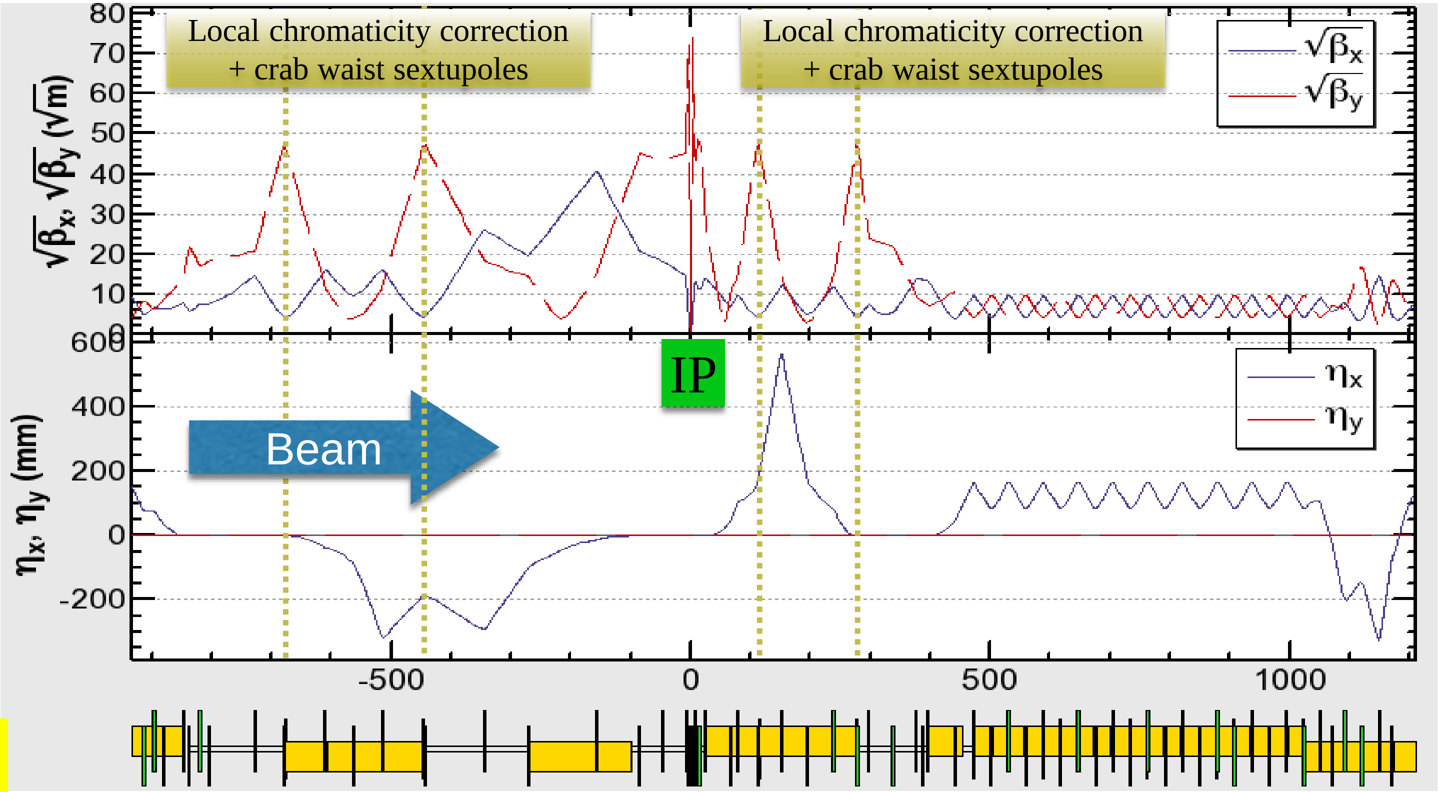
Y. Papaphilippou, J. Wenninger

final-focus optics design

optics design for all working points achieving baseline performance

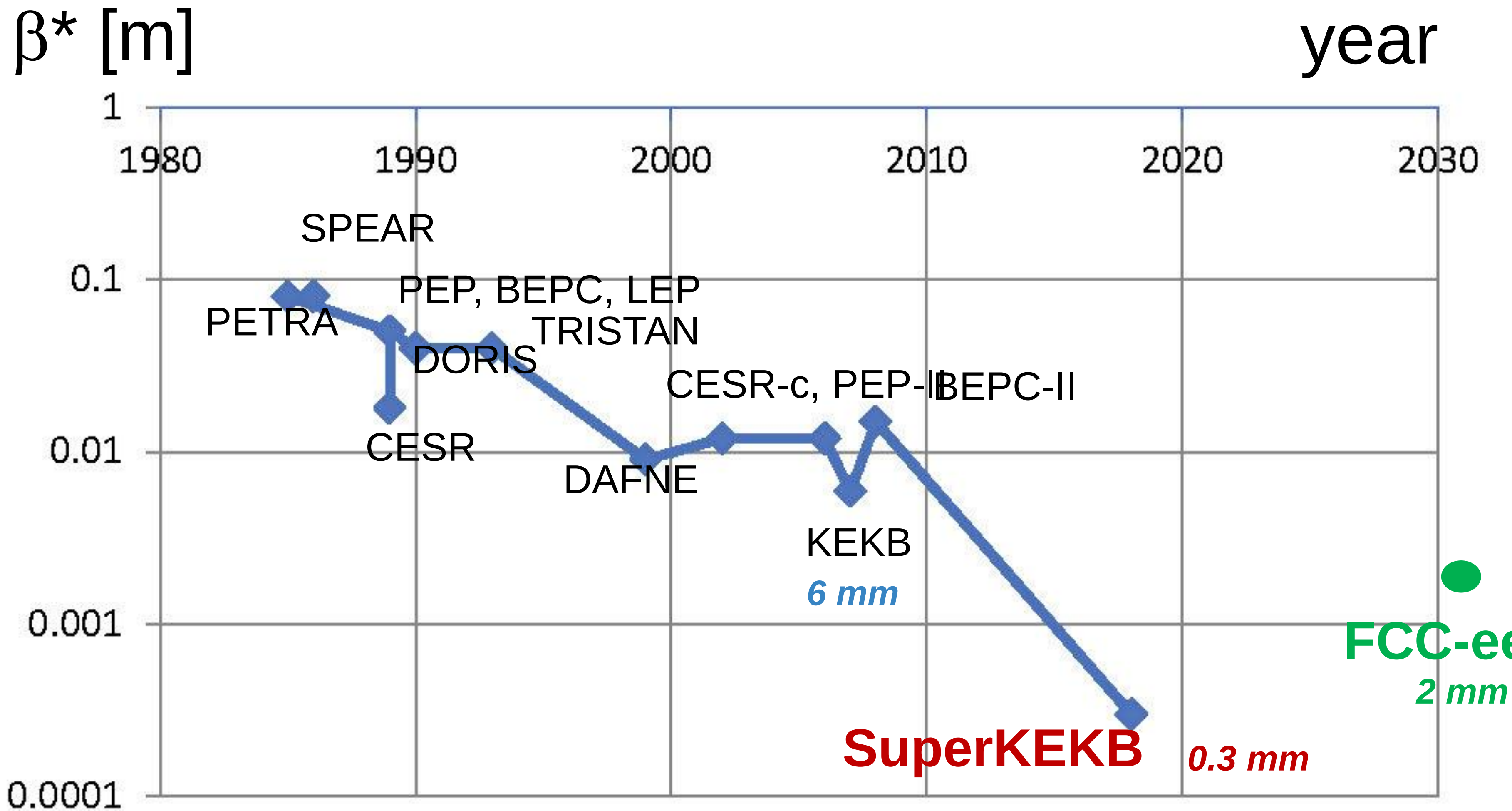
interaction region: asymmetric optics design

- synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- dynamic aperture & momentum acceptance requirements fulfilled at all WPs



K. Oide

β_y^* evolution over 40 years



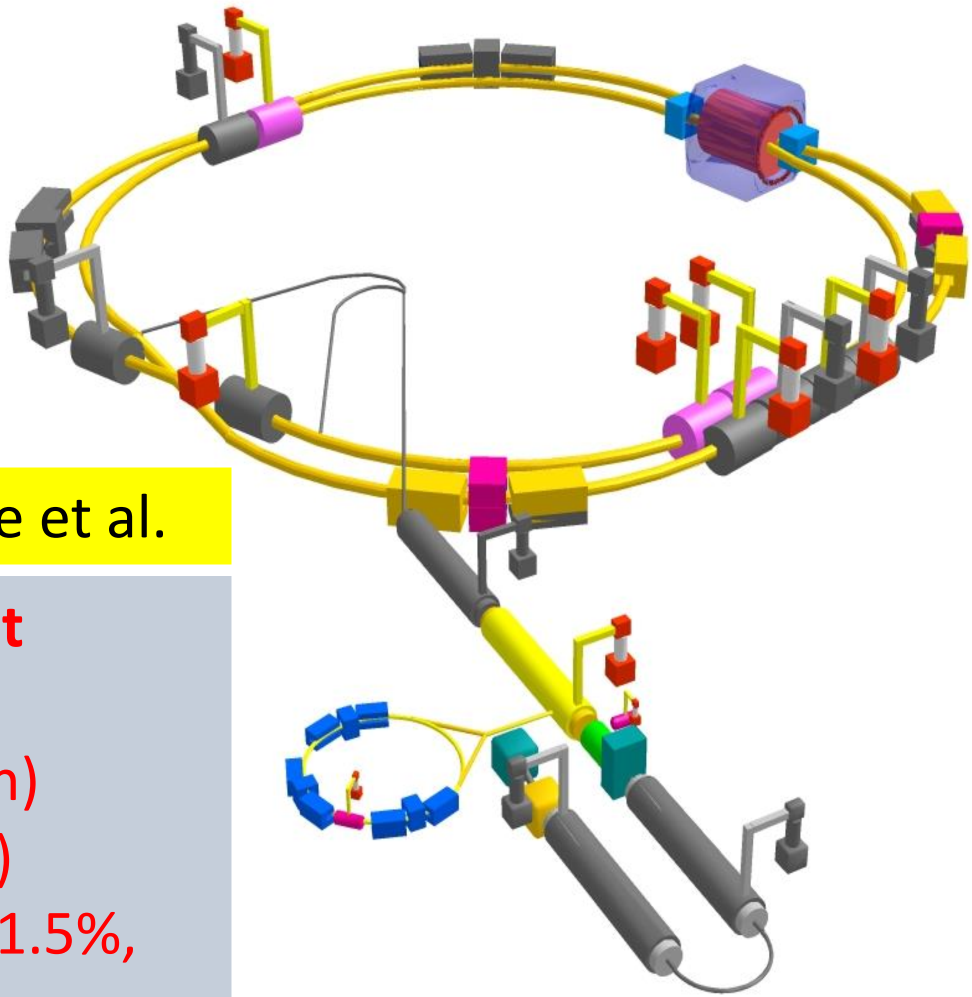
SuperKEKB will pave the way towards $\beta^* \leq 2$ mm

SuperKEKB: ultra-low β*

I_{e+}=3.6 A, I_{e-}=2.6 A

P_{SR} ~ 13 MW
C = 3 km

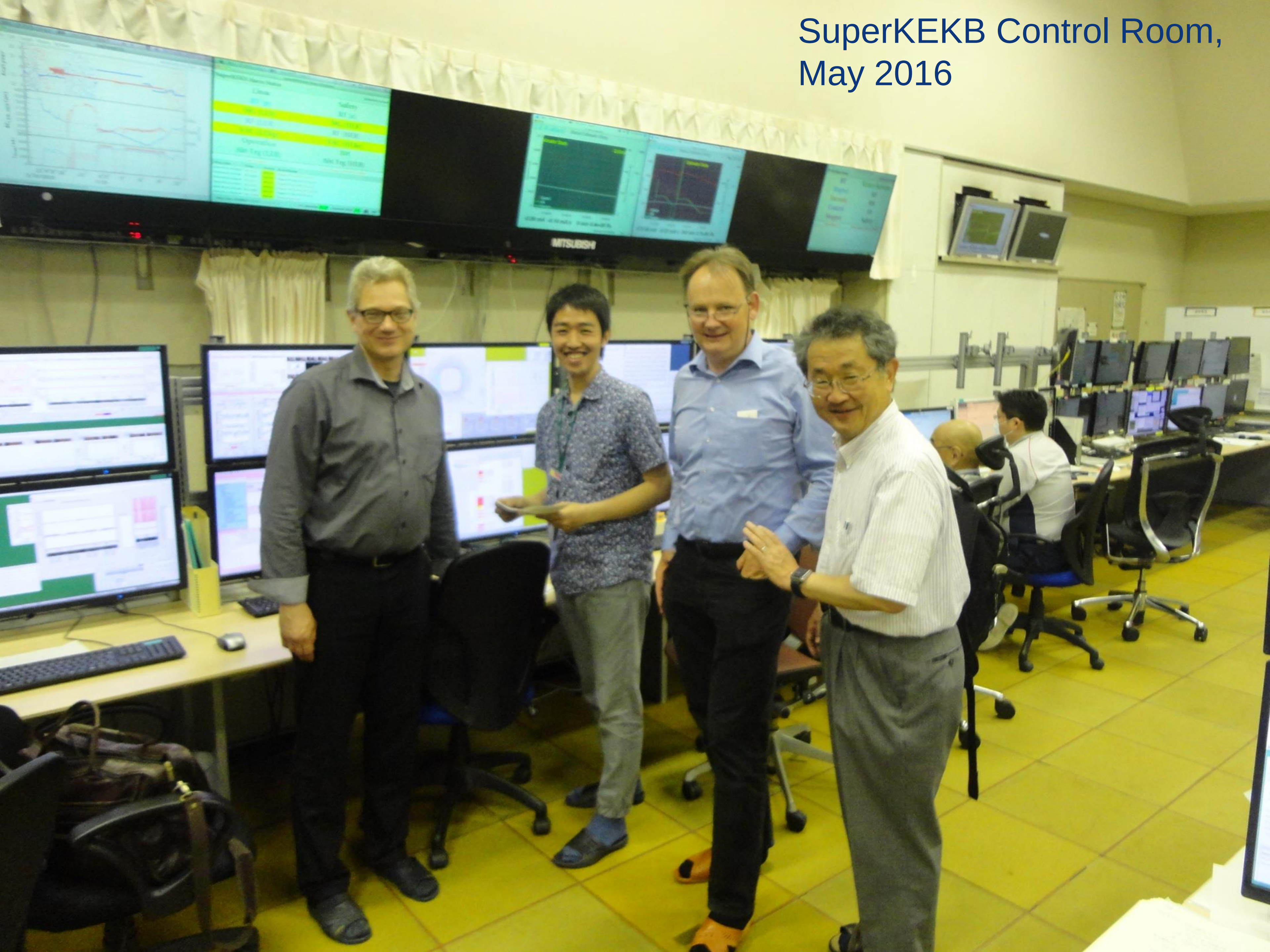
beam commissioning started this year



K. Oide et al.

top up injection at high current
β_y^* =300 μm (FCC-ee: 1 mm)
lifetime 5 min (FCC-ee: ≥20 min)
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)
off momentum acceptance (±1.5%, similar to FCC-ee)
***e*⁺ production rate** (2.5x10^{12}/s, FCC-ee: <1.5x10^{12}/s (*Z* cr.waist)

SuperKEKB goes beyond *FCC-ee*, testing all concept



SuperKEKB Control Room,
May 2016

key technologies for FCC-ee

SC radiofrequency system

efficient RF power sources

vacuum chamber with photon stops
and discrete shielding

low-power low-field arc magnets

final IR quadrupoles

SRF system requirements

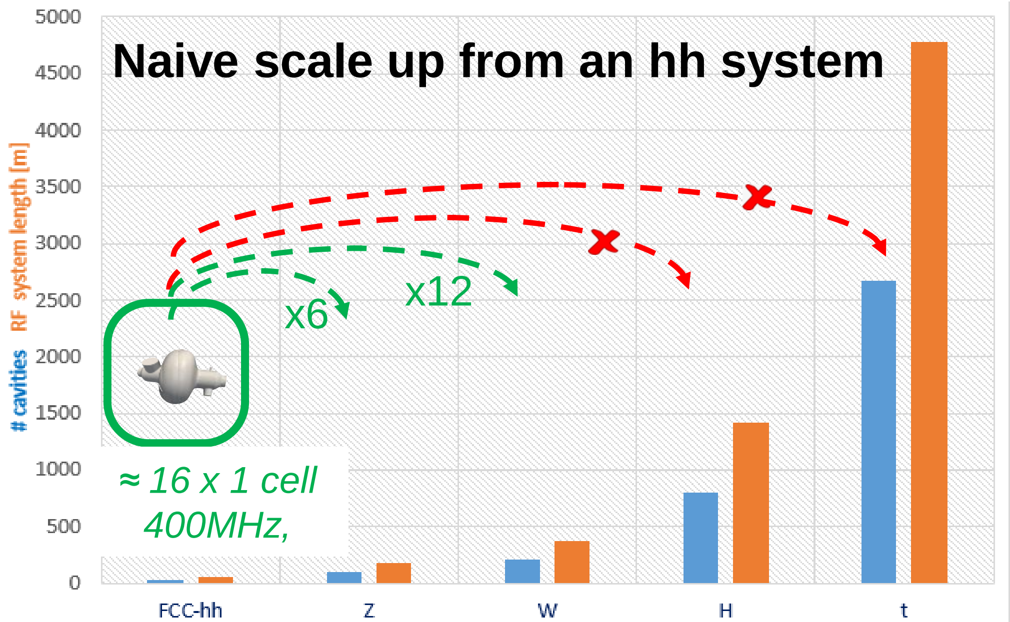
O. Brunner, A. Butterworth
R. Calaga, E. Jensen
S. Aull, N. Schwerg

very large range of operation parameters

“Ampere-class” machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		**500**	
Z	0.4/0.2	30000/90000	**1450**	0.034
W	0.8	5162	152	0.33
H	**5.5**	770	30	1.67
t	**10**	78	6.6	7.55

“high gradient” machines

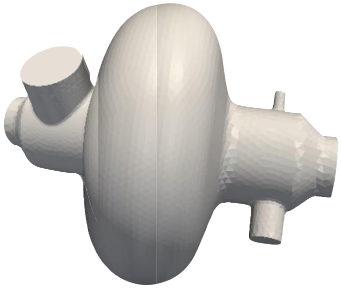


- Voltage and beam current ranges span more than factor > 10^2
- No well-adapted single RF system solution satisfying requirements

SRF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

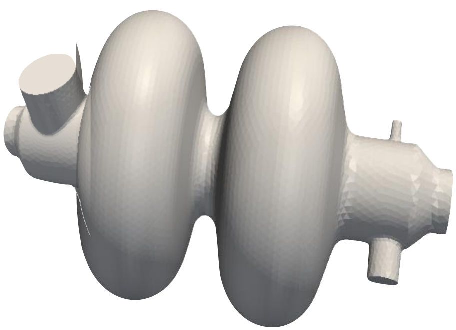
- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)



hh	Z	W
≈ 16 cells per beam	≈ 100 per beam (+ 100 for booster ring)	(≈ 210 per beam (+ 210 for booster ring))

400 or 800 MHz multi-cell cavities preferred for ee-H, ee-tt and ee-W

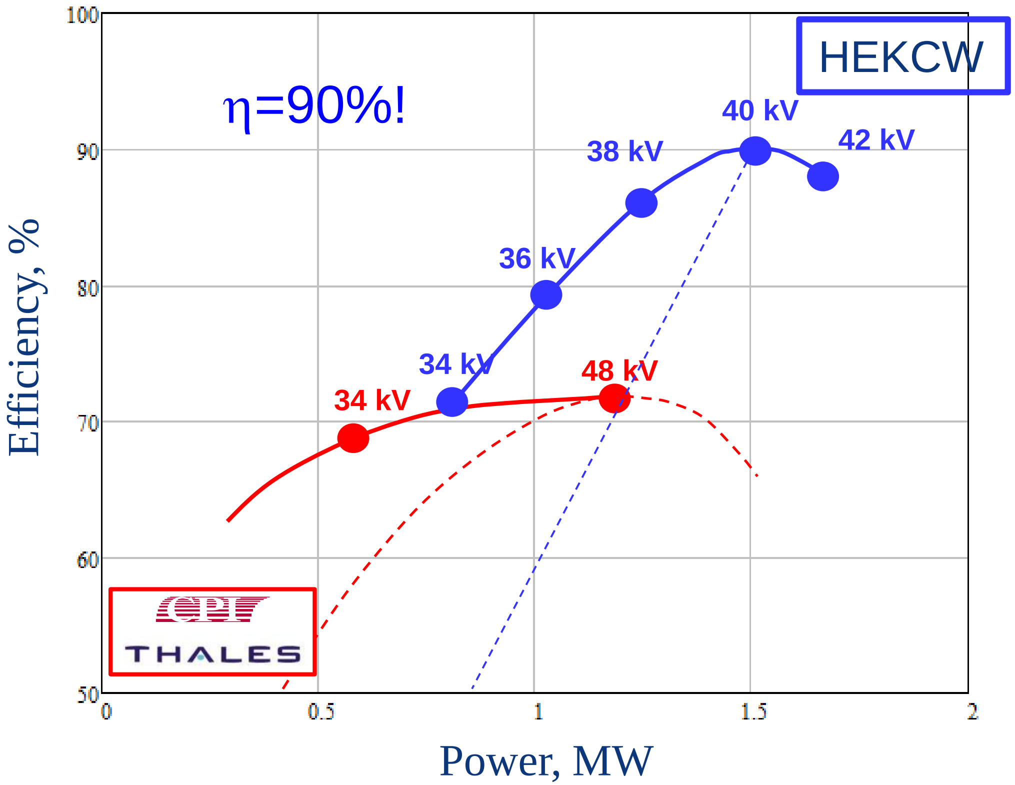
- Baseline options 400 MHz Nb/Cu @4.5 K, ◄—► 800 MHz bulk Nb system @2K
- R&D: High Q_0 cavities, coating, long-term: Nb_3Sn like components



W	H	t
≈ 200 per beam (+ 200 for booster)	≈ 800 per beam (+ 800 for booster)	≈ common 2600 cells for both beams (+ 2600 for booster)

after 80 years a breakthrough in klystron efficiency!

comparing simulated performances of MBIOT and HEKCW MBK

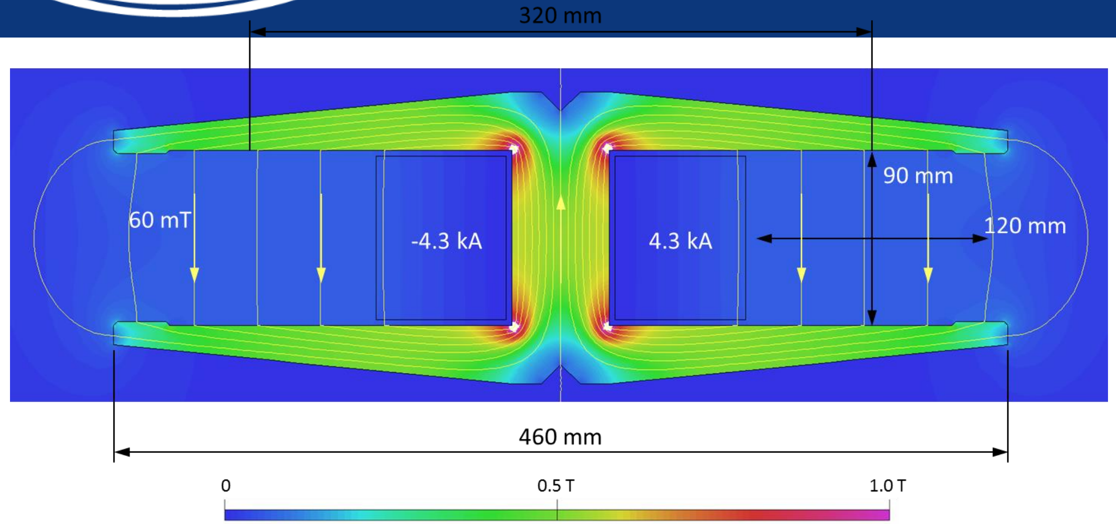


I. Syratchev

A 40-beam prototype "BAC" klystron has been built and successfully tested at VDBT, Moscow, this year!

Dotted lines – only changing P drive
Solid lines – changing P drive and Voltage

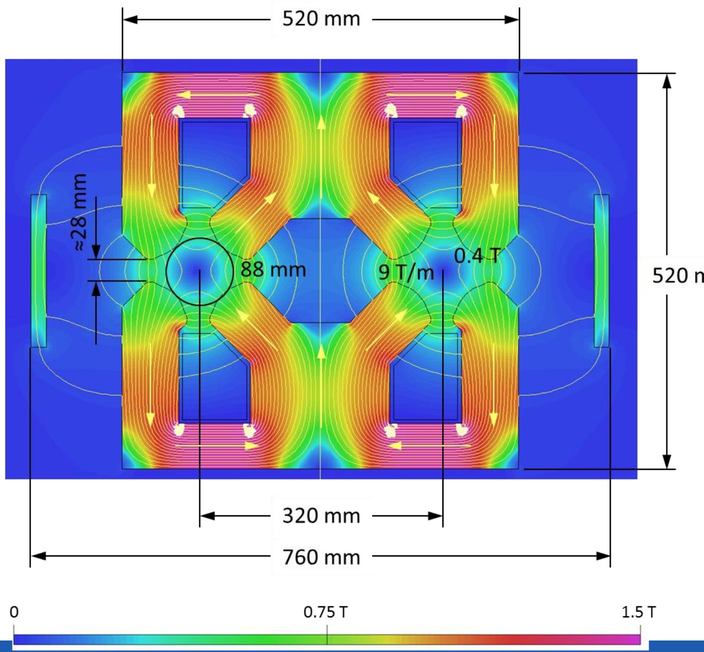
efficient 2-in-1 arc magnets



dipole based on
twin aperture yoke
and single busbars as coils

A. Milanese

twin 2-in-1 quadrupole



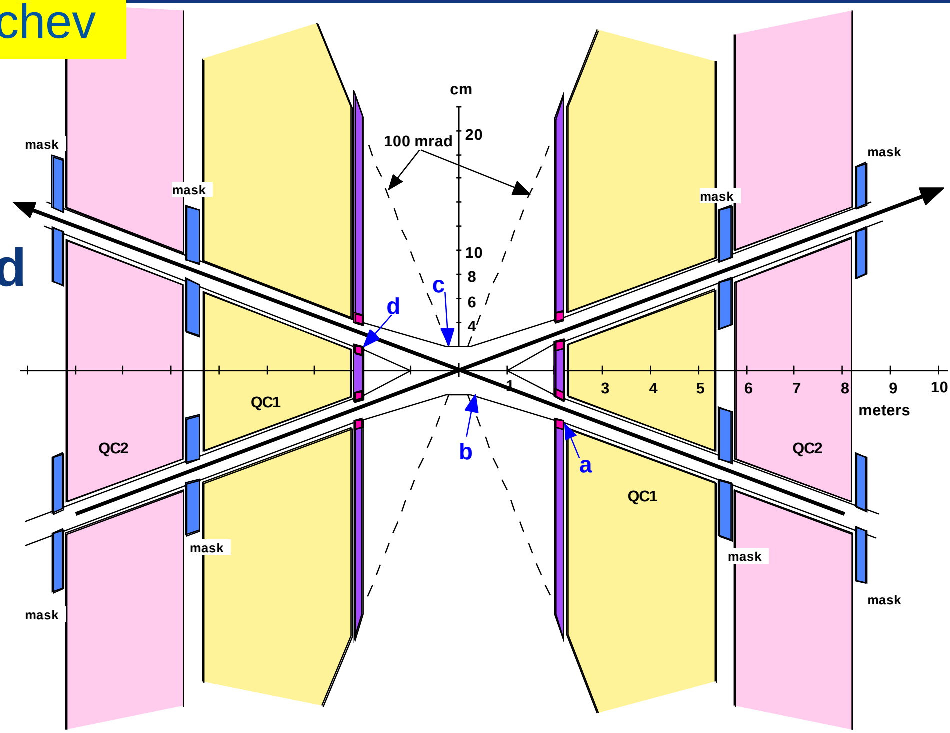
the novel arrangements of the magnetic circuit allow for considerable savings in Ampere-turns and power consumption, less units to manufacture, transport, install, align, remove,…

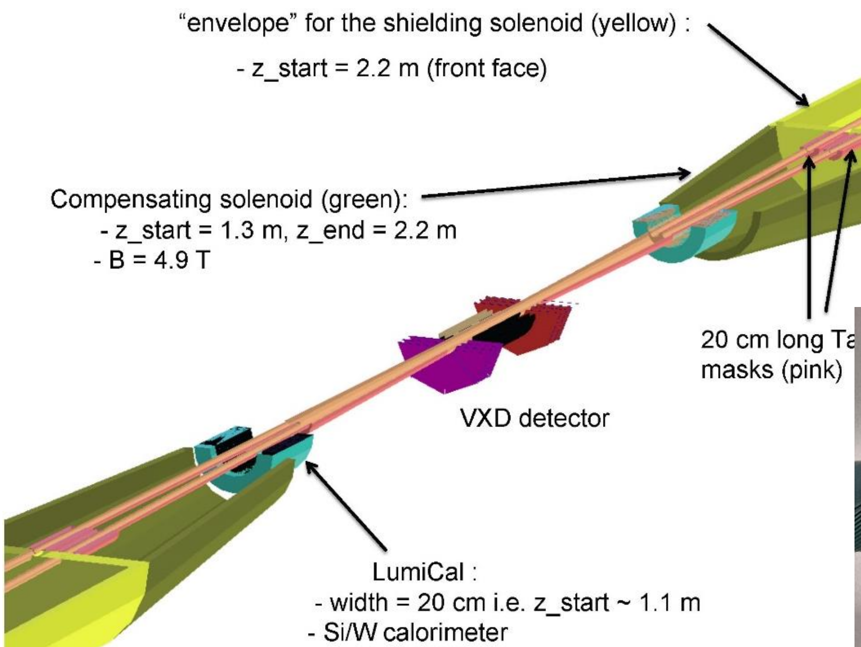
FCC-ee MDI optimisation

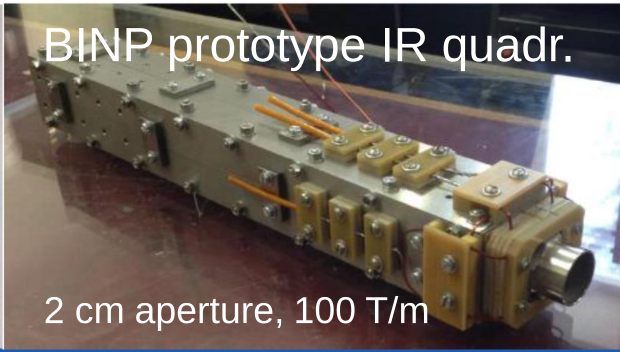
M. Sullivan, A. Kolano, M. Korazinos, E. Levichev

MDI work started with optimization of

- *l**, IR quadrupole design
- compensation & shielding solenoid
- SR masking and chamber layout







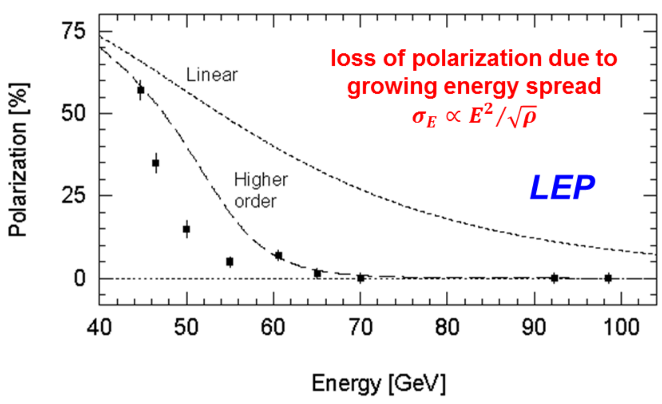
polarization & energy calibration

accurate energy calibration using resonant depolarization ⇒ measurement of M_Z, Γ_Z, M_W – *δM_Z, $\delta\Gamma_Z$ ~ 0.1 MeV, δM_W ~ 0.3 MeV*

physics with longitudinally polarized beams *- transverse polarization must be rotated into the longitudinal plane using spin rotators (see e.g. HERA)*

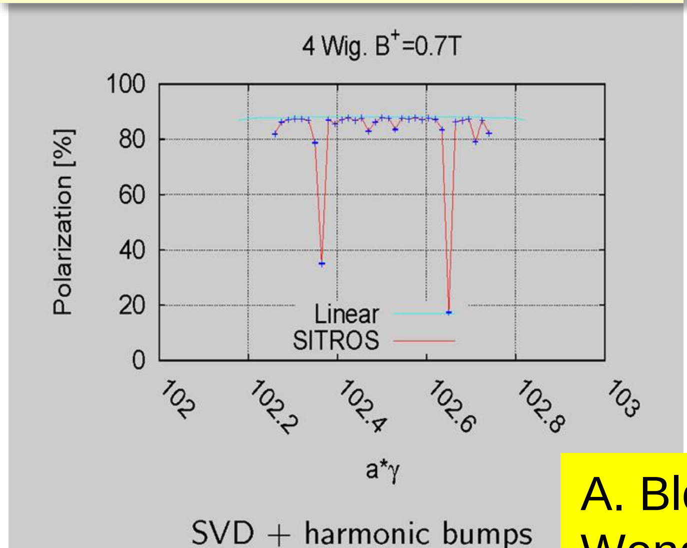
scaling from LEP observations :

polarization expected up to the WW threshold !



simulations for FCC-ee:

high polarization with harmonic spin matching



polarimetry extrapolated from ELSA to FCC-ee:

ΔP~0.1% turn by turn and bunch by bunch using conventional high-power laser

A. Blondel, E. Gianfelice-Wendt, W. Hillert, I. Koop, M. Koratzinos, U. Wienands, J. Wenninger,..

FCC-ee physics

Journal of High Energy Physics

First Look at the Physics Case of TLEP

The TLEP Design Study Working Group
(See next pages for the list of authors)

Journal of High Energy Physics, January 2014, 2014:164

http://link.springer.com/article/10.1007/JHEP01(2014)164

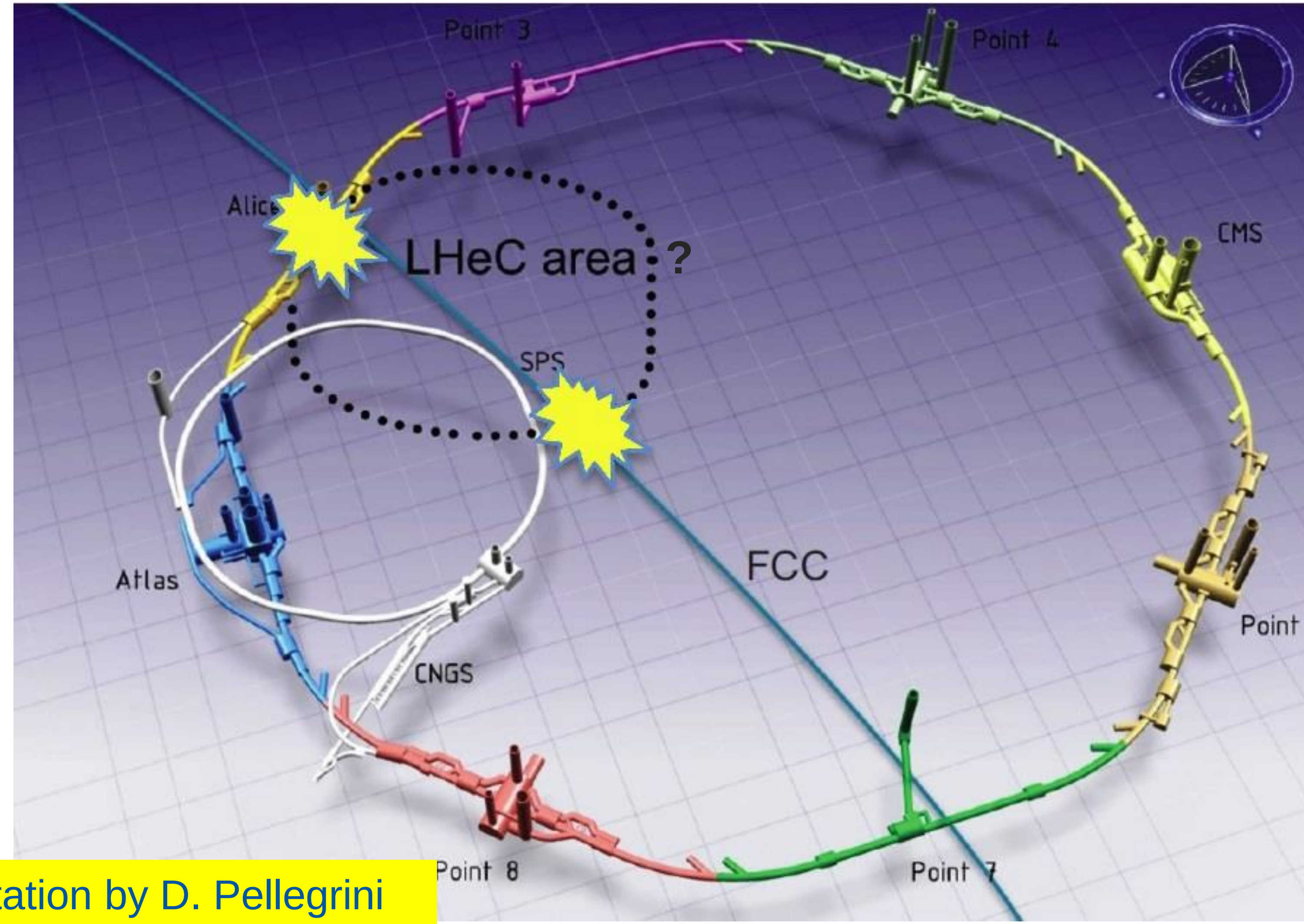
OPEN ACCESS

P. Janot
et al.

lepton-hadron collider FCC-he

FCC-he collides e- from ERL with FCC-hh protons

(same concept as proposed for LHeC; same ERL?)



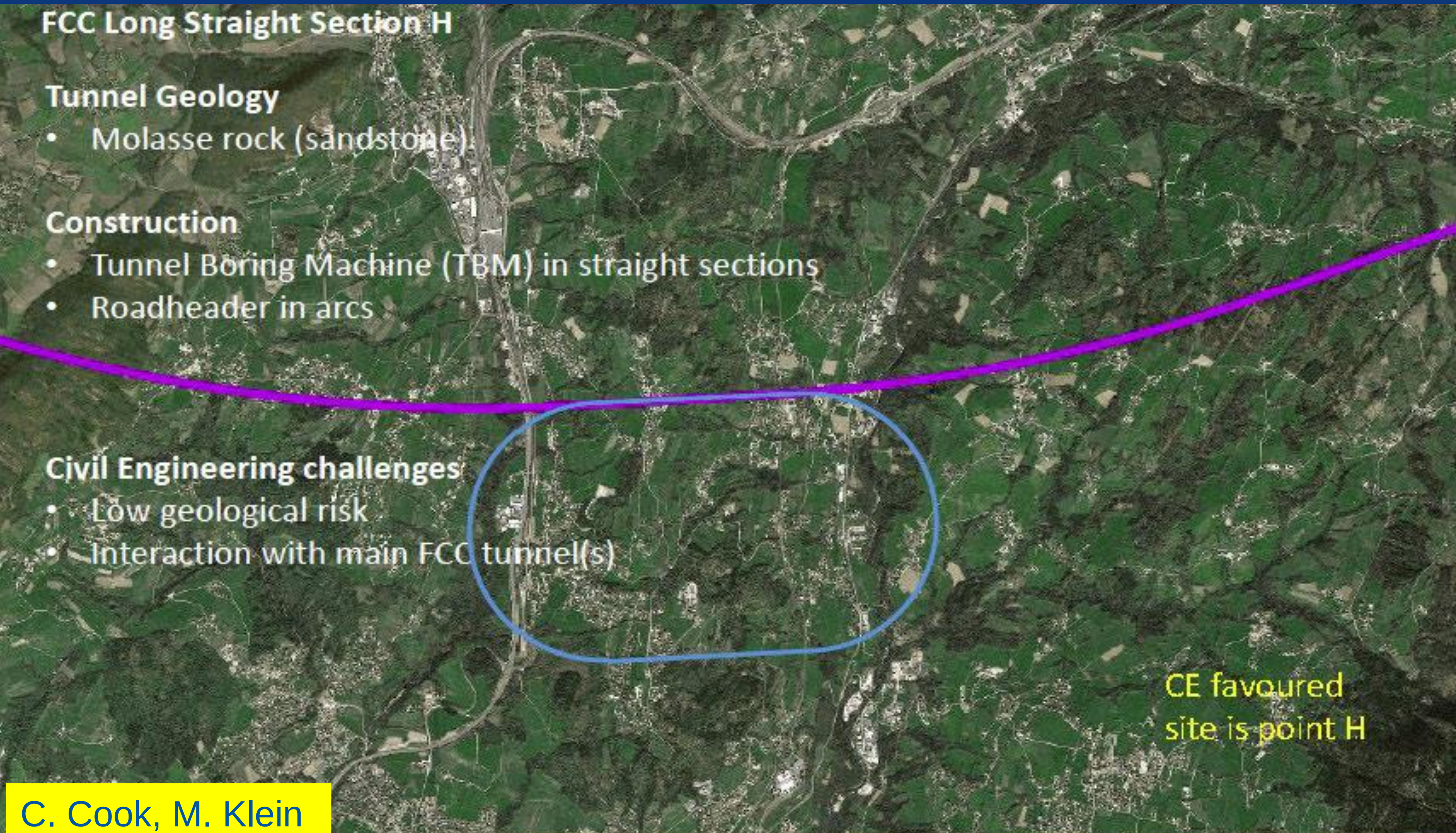
see LHeC presentation by D. Pellegrini

lepton-hadron (*p*) parameters

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	**3.5**
bunch spacing [ns]	25	25	25	25
p/bunch [10^{11}]	1.7	2.2	2.2	1
ε_p [μm]	3.7	2	2	2.2
e^-/bunch [10^9]	1	2.3	2.3	2.3
e^- current [mA]	6.4	15	15	15
β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.2	1.3
luminosity [10^{33} cm^{-2}s^{-1}]	1.3	10.1	15.1	**9.2**

O. Bruning, M. Klein, D. Schulte, F. Zimmermann

FCC-he site studies



FCC-he physics

similar to, and better than LHeC

CDR "A Large Hadron Electron Collider at CERN"

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

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

ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

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

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

http://cern.ch/lhec

International referees invited by CERN

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)

Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

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

M. Klein, U. Klein

unravelling QCD at the FCC

(1) QCD coupling α_s (FCC-ee, FCC-he)

(2) parton densities (FCC-he)

(3) beyond DGLAP (FCC-he)

(4) many-body QCD (FCC-hh, HE-LHC)

numerous synergies between the various FCC colliders!

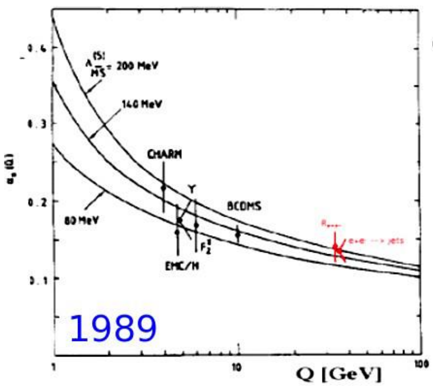
D. d'Enterria, QCD at Future Facilities, QCD@LHC, Zurich, August 2016

QCD coupling α_S

D. d'Enterria

- determines strength of strong interaction between quarks & gluons.
- single free parameter in QCD in the $m_q \rightarrow 0$ limit
- determined at a ref. scale (Q=m_Z)

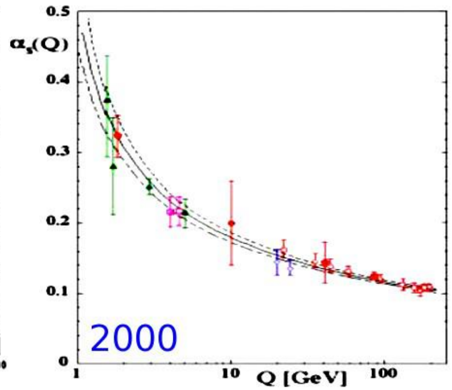
uncert. ~6%



$\alpha_S(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

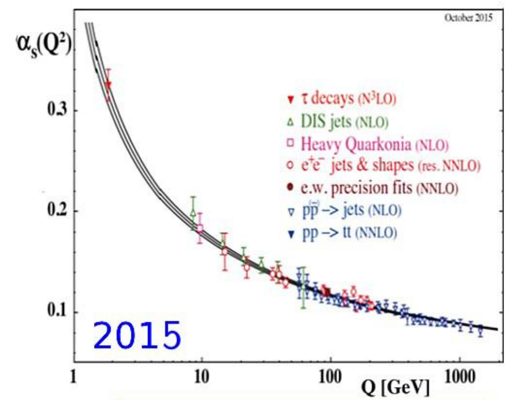
uncert. ~2.5%



$\alpha_S(M_Z) = 0.1184 \pm 0.0031$ (NNLO)

S. B. , J. Phys. G 26, 2000

uncert. ~1.1%



$\alpha_s(M_Z) = 0.1181 \pm 0.0013$ **(NNLO)**

FCC-he: α_S from proton structure function → **$\delta\alpha_S$ <0.3%**

FCC-ee: α_S from e+e- jet event shapes & rates → **$\delta\alpha_S$ <1%**

α_S from hadronic Z decays→ **$\delta\alpha_S$ <0.3%**

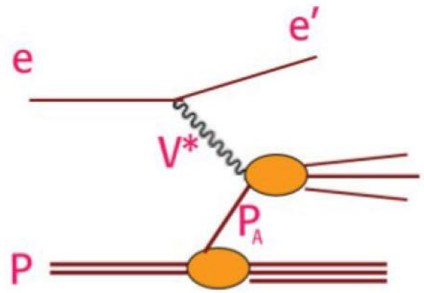
α_S from hadronic W decays→ **$\delta\alpha_S$ <0.3%**

~0.3% α_S precision from high-lumi e^+e^- measurements

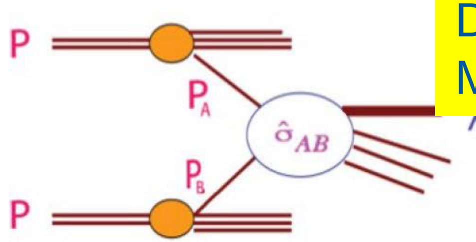
parton kinematics: (x,Q^2)

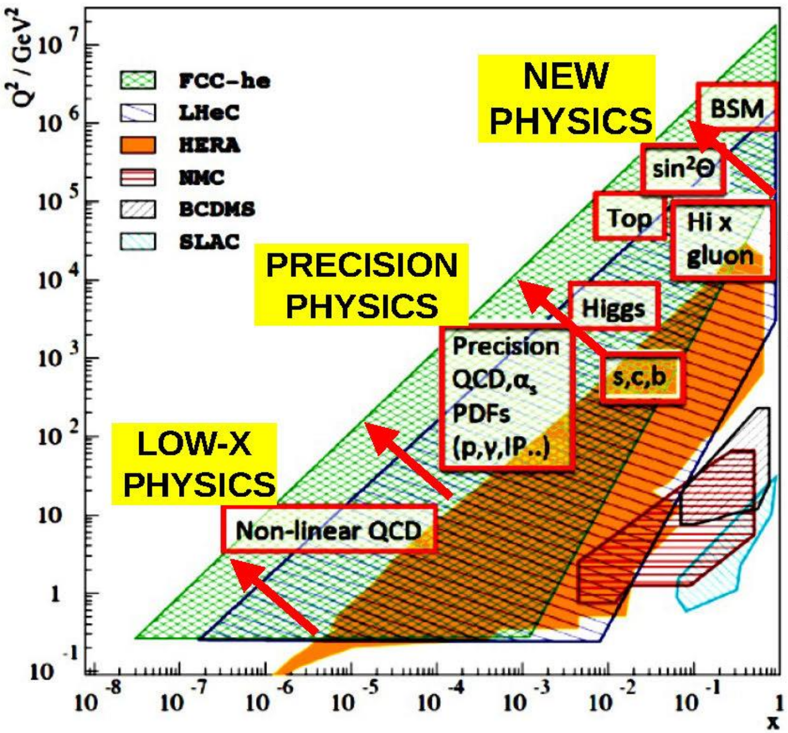
D. d'Enterria, M. Klein

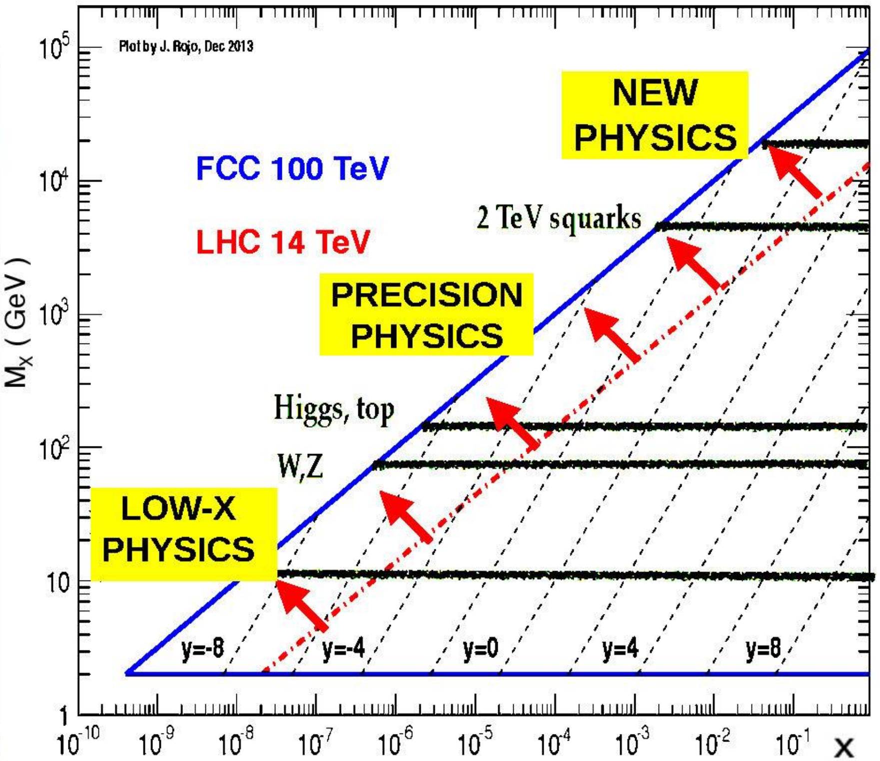
FCC-he (*pe*)



FCC-hh (*pp*)



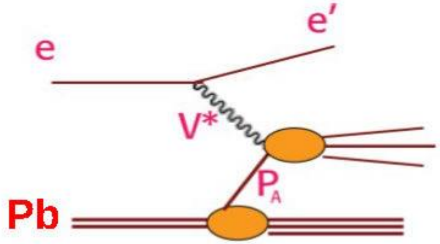




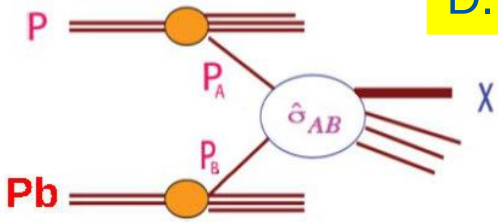
parton kinematics: (x,Q^2) - 2

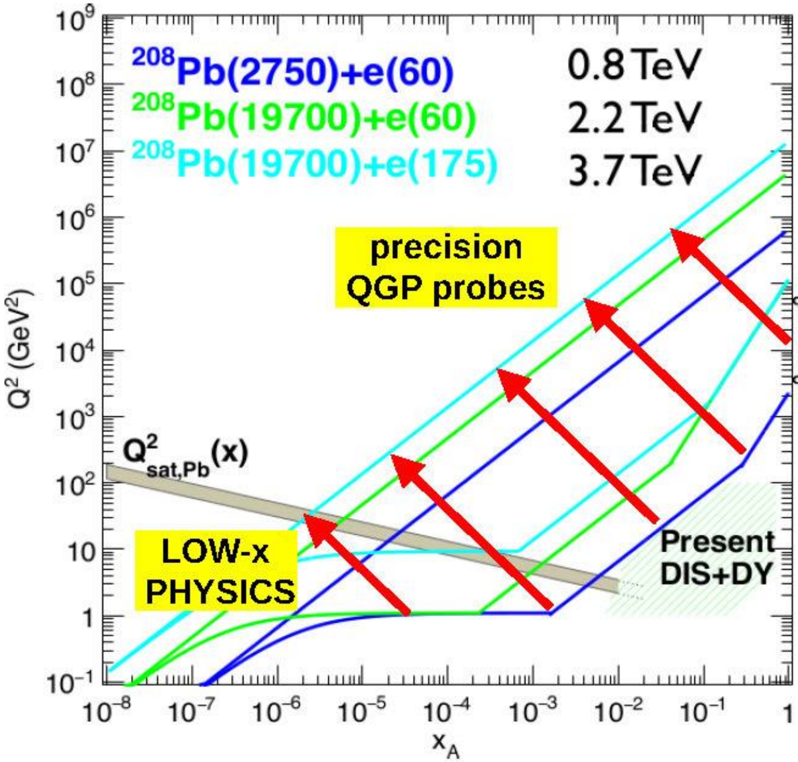
D. d'Enterria

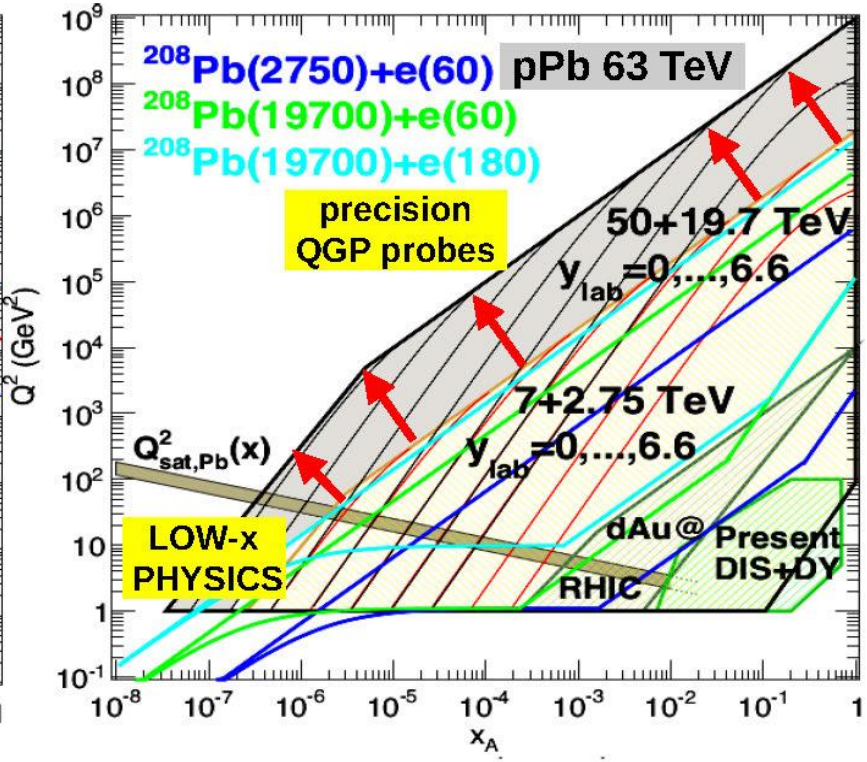
FCC-*he* (*Ae*)



FCC-*hh* (*AA*)







parton distribution functions

D. d'Enterria

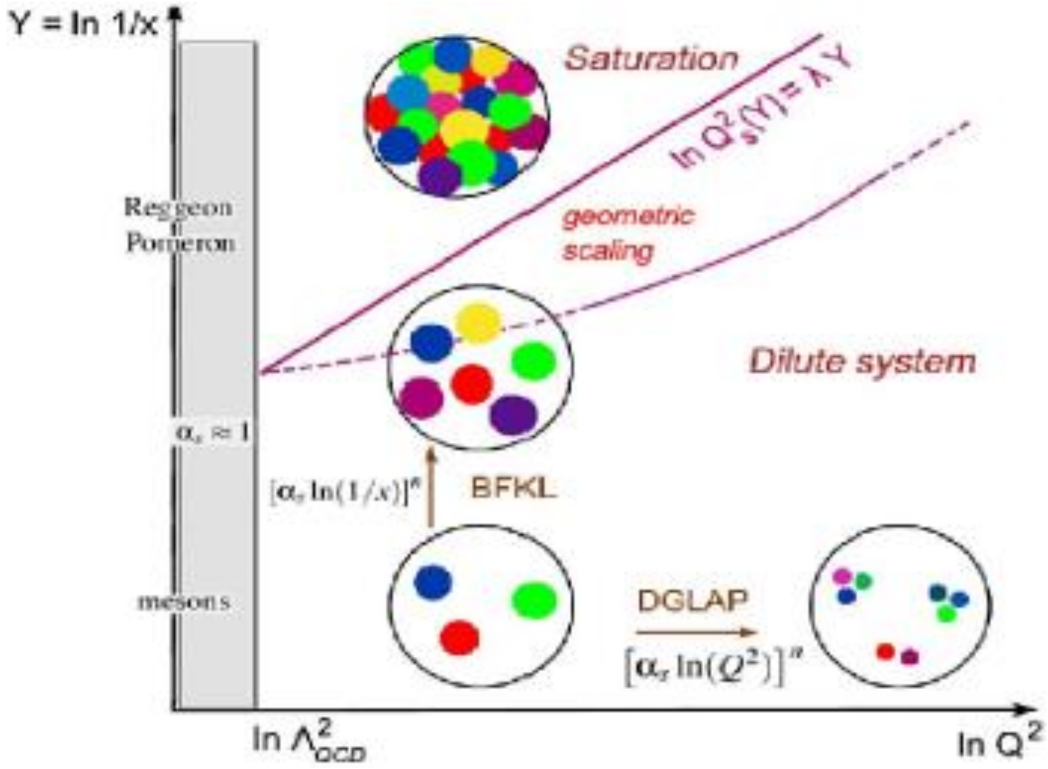
FCC-pp: ~10% PDF uncertainty at *H*, *Z* scales

FCC-he lowers FCC-pp PDF uncertainty to <1% at *H*, *Z* scales and strongly reduces parton uncertainties between 10 GeV and 10 TeV, for all flavors

<1% PDF precision at FCC-hh from high-energy e-p collider (FCC-he)

few % nuclear PDF precision from high-energy e-A collider (FCC-he)

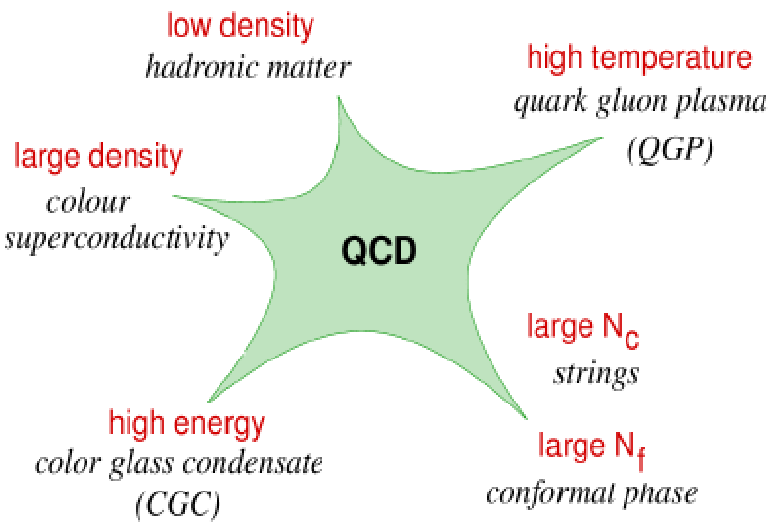
beyond DGLAP

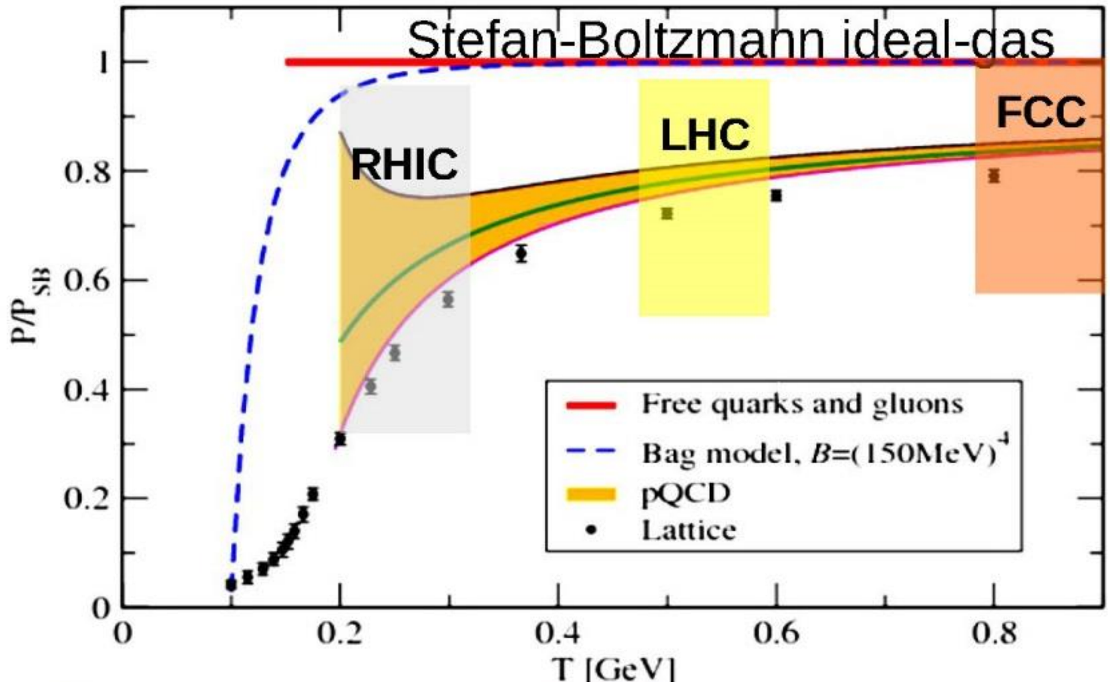


non-linear evolution at low *x*, gluon splitting, gluon recombination multiparton interactions, ...

FCC-he (*pe*, *Ae*) will probe nonlinear QCD

many-body QCD





FCC-hh (*AA*) studying QGP at TeV/fm^3

what will FCC do for QCD?

(1) permil α_s precision (FCC-ee, FCC-he)

(2) sub-% PDF precision (FCC-he)

(3) nonlinear QCD limit (FCC-he)

(4) TeV/fm^3 QCD thermodynamics (FCC-hh, HE-LHC)

FCC = the perfect accelerator complex to reveal the QCD secrets

D. d'Enterria

FCC International Collaboration

- 87 institutes
- 28 countries + EC

Status: August, 2016

FCC Collaboration Status

87 collaboration members + EC + CERN as host

ALBA/CELLS, Spain
Ankara U., Turkey
Aydin U, Istanbul, Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
Cinvestav, Mexico
CNRS, France
CNR-SPIN, Italy
Cockcroft Institute, UK
U Colima, Mexico
UCPH Copenhagen, Denmark
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
DOE, Washington, USA
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
UT Enschede, Netherlands
ESS, Sweden
U Geneva, Switzerland
Giresun U. Turkey

Goethe U Frankfurt, Germany
GSI, Germany
GWNU, Korea
U. Guanajuato, Mexico
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
ISMAB-CSIC, Spain
IFAE, Spain
IFIC-CSIC, Spain
IIT Kanpur, India
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Isik U., Turkey
Istanbul University, Turkey
JAI, UK
JINR Dubna, Russia
Jefferson LAB, USA
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
KU, Seoul, Korea

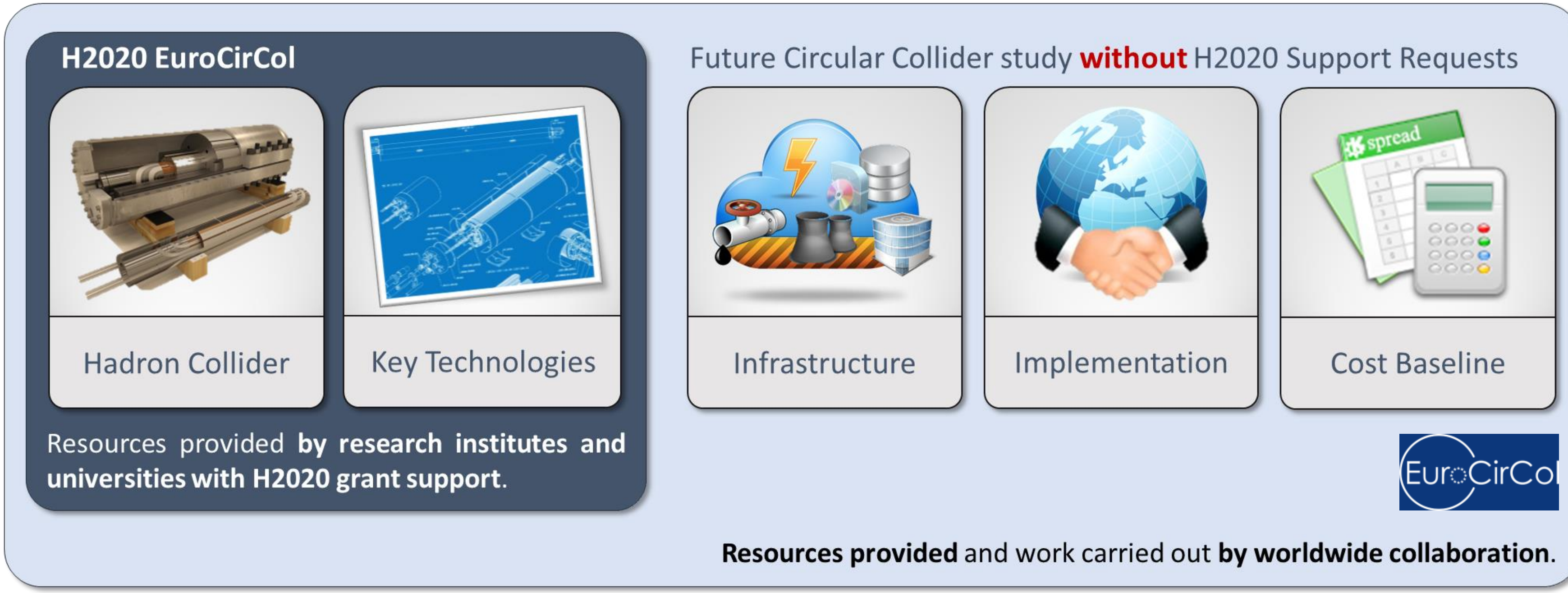
Korea U Sejong, Korea
U Liverpool, UK
U Lund, Sweden
U Malta, Malta
MAX IV, Sweden
MEPhI, Russia
UNIMI, Milan, Italy
MIT, USA
Northern Illinois U, USA
NC PHEP Minsk, Belarus
OIU, Turkey
Okan U, Turkey
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
RTU, Riga, Latvia
UC Santa Barbara, USA
Sapienza/Roma, Italy
U Siegen, Germany
U Silesia, Poland
Stanford U, USA
U Stuttgart, Germany
TAU, Israel
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland

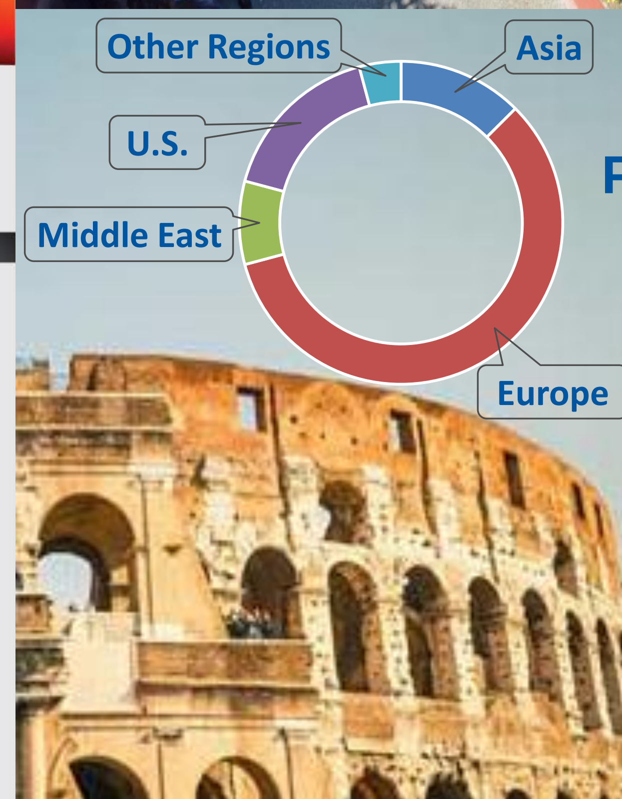
status 29 August 2016

EuroCirCol EU Horizon 2020 Grant

EC contributes with funding to FCC-hh study

- **EuroCirCol H2020 Design Study**, launched in June 2015, is in full swing now and makes essential contributions to the FCC-hh work packages:
- **arc & IR optics, 16 T dipole design, cryogenic beam vacuum system**





468
Participants

168
Institutes

24
Countries

summary

- **FCCs' ee/pp/AA/pe/Ap/Ae collisions will explore uncharted regions in energy, luminosity, polarization, *x* and Q^2**
  - ✓ novel challenges and new opportunities
  - ✓ innovative technological approaches
- **FCC Study aims at cost-effective design with maximum performance**
- **rapidly growing global FCC collaboration (now nearly 100 institutes), more contributors welcome - *especially from Greece*!**
- **Next milestone: FCC Week 2017**


FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch
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