The future of physics at particle accelerators
(INFN/CSN1 preparations beyond HL-LHC)

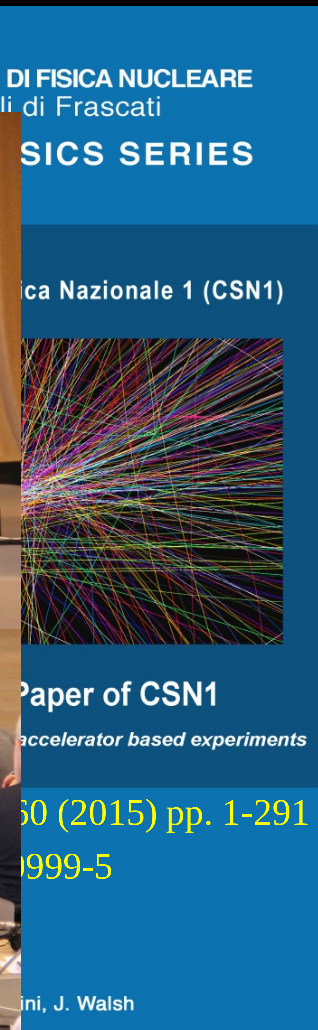
F. Bedeschi
INFN-Pisa,
Giugno 2017

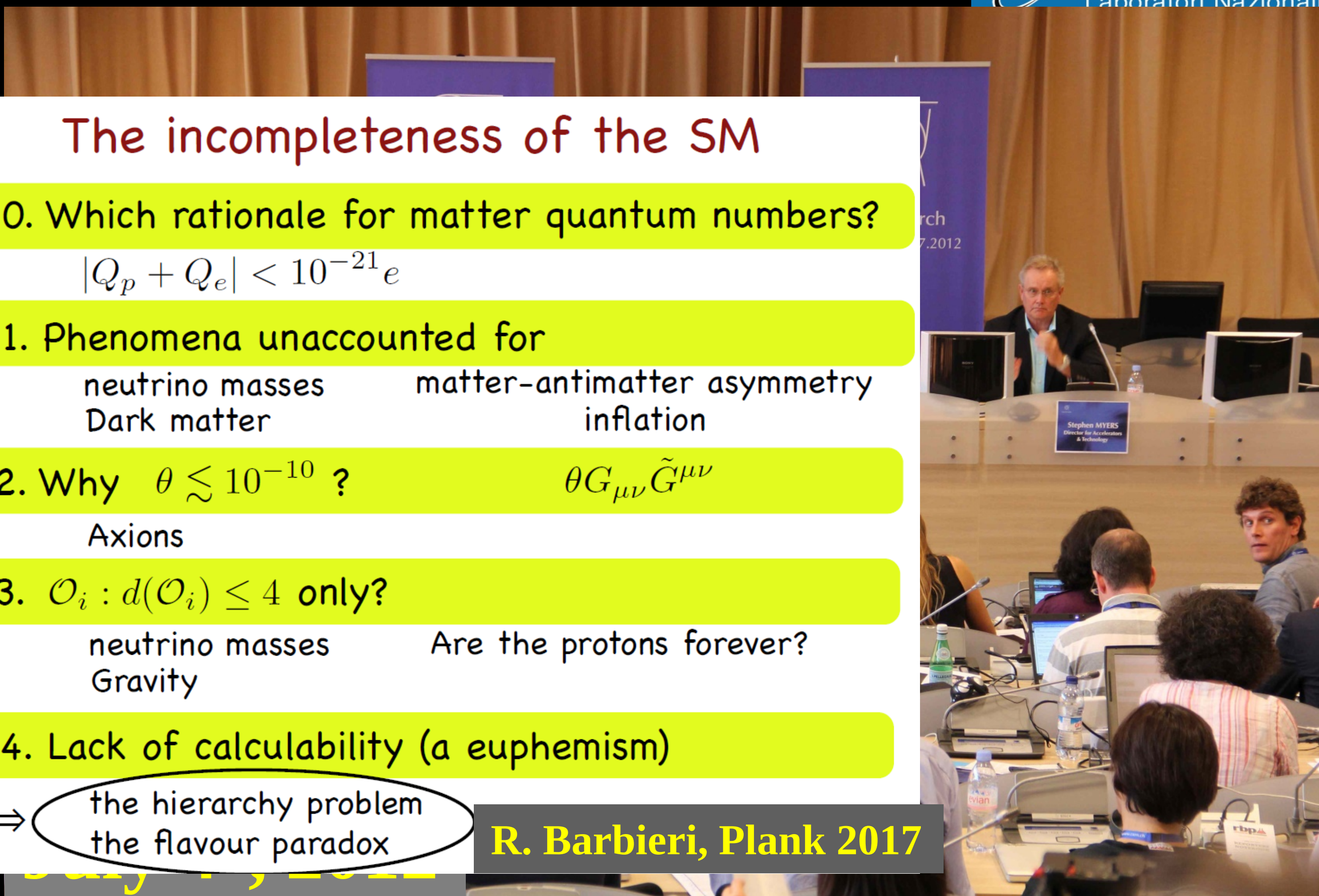
OUTLINE

- Some recent history
- Present status of HEP
- Potential of future machines
- What is on the table?
  - What could we build? Now, later, far future?
- Related INFN/CSN1 activity

What Next

- After the Higgs … what next?
-





The incompleteness of the SM

0. Which rationale for matter quantum numbers?

$|Q_p + Q_e| < 10^{-21} e$

1. Phenomena unaccounted for

neutrino masses — matter-antimatter asymmetry
Dark matter — inflation

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$

Axions

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses — Are the protons forever?
Gravity

4. Lack of calculability (a euphemism)

$\Rightarrow$ the hierarchy problem
the flavour paradox

R. Barbieri, Plank 2017

Recommendations

- Some key recommendations from CSN1 White Paper

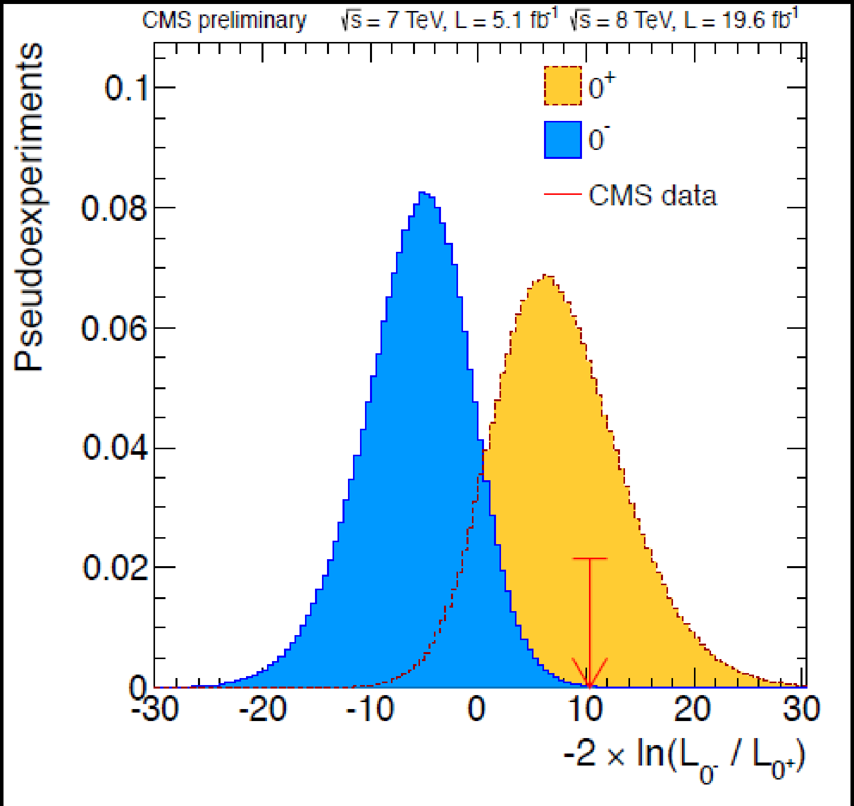
  - CSN1 urges INFN to continue and strengthen its support of R&D for the development of new high field magnets and conventional or un-conventional accelerator structures

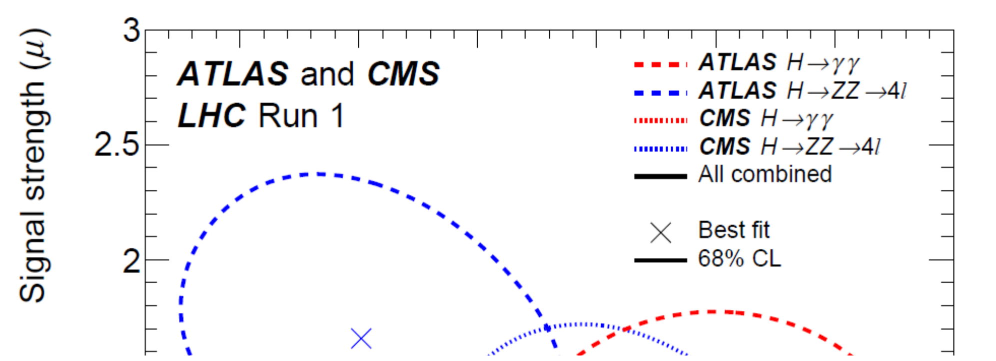
  - CSN1 supports INFN participation in studies and R&D related to the future colliders. **Our community must be part of the planning of the future.**

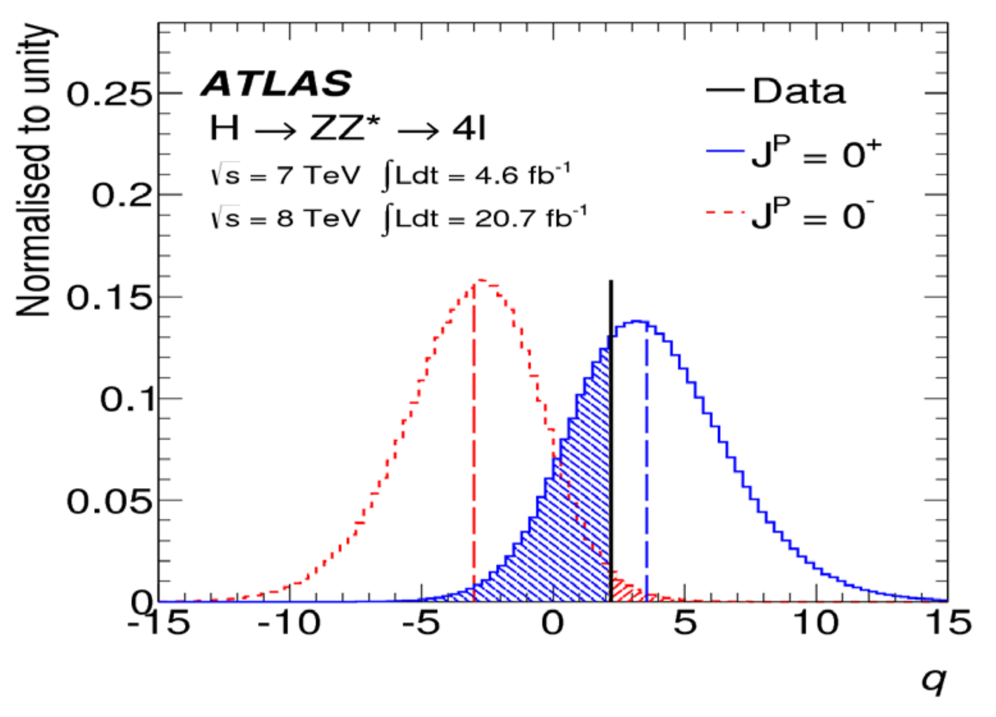
Present status

LHC → Great Success SM! (1)

- Higgs discovered!
  - Couplings ~ SM
  - Quantum numbers ~ SM

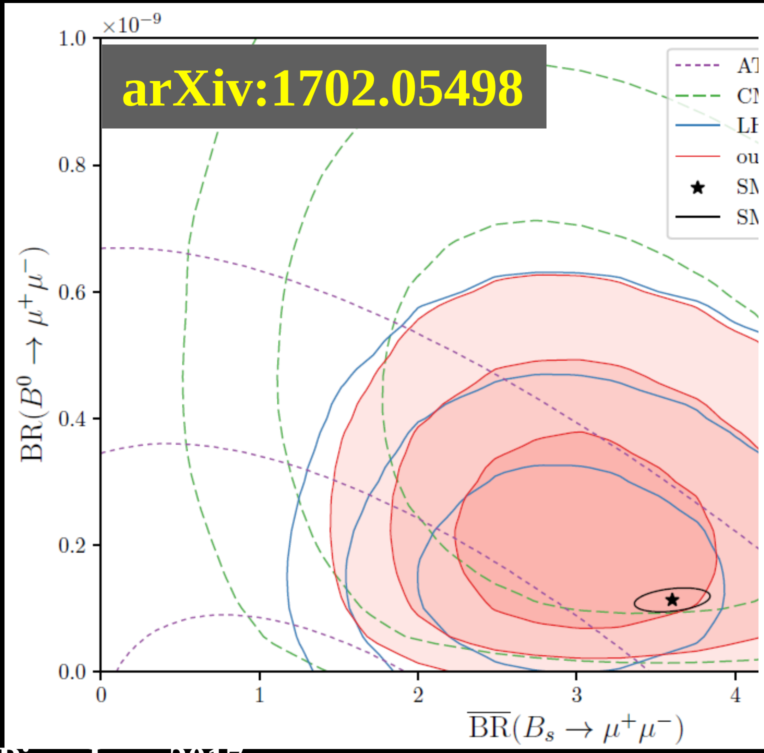


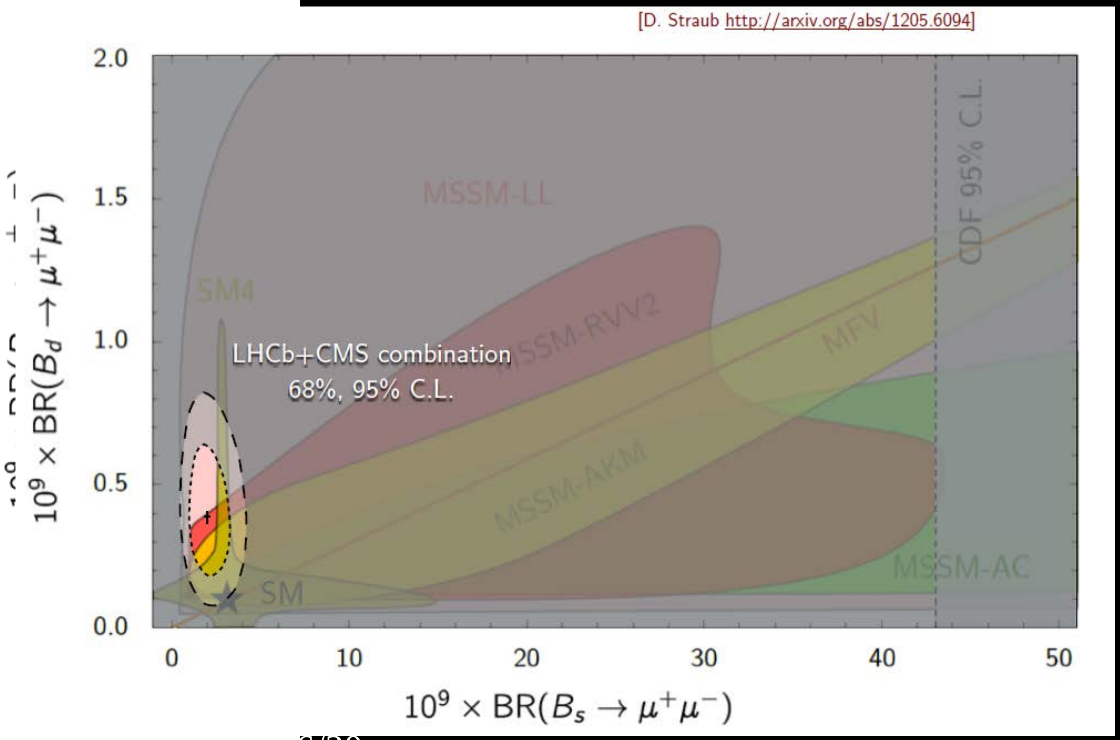




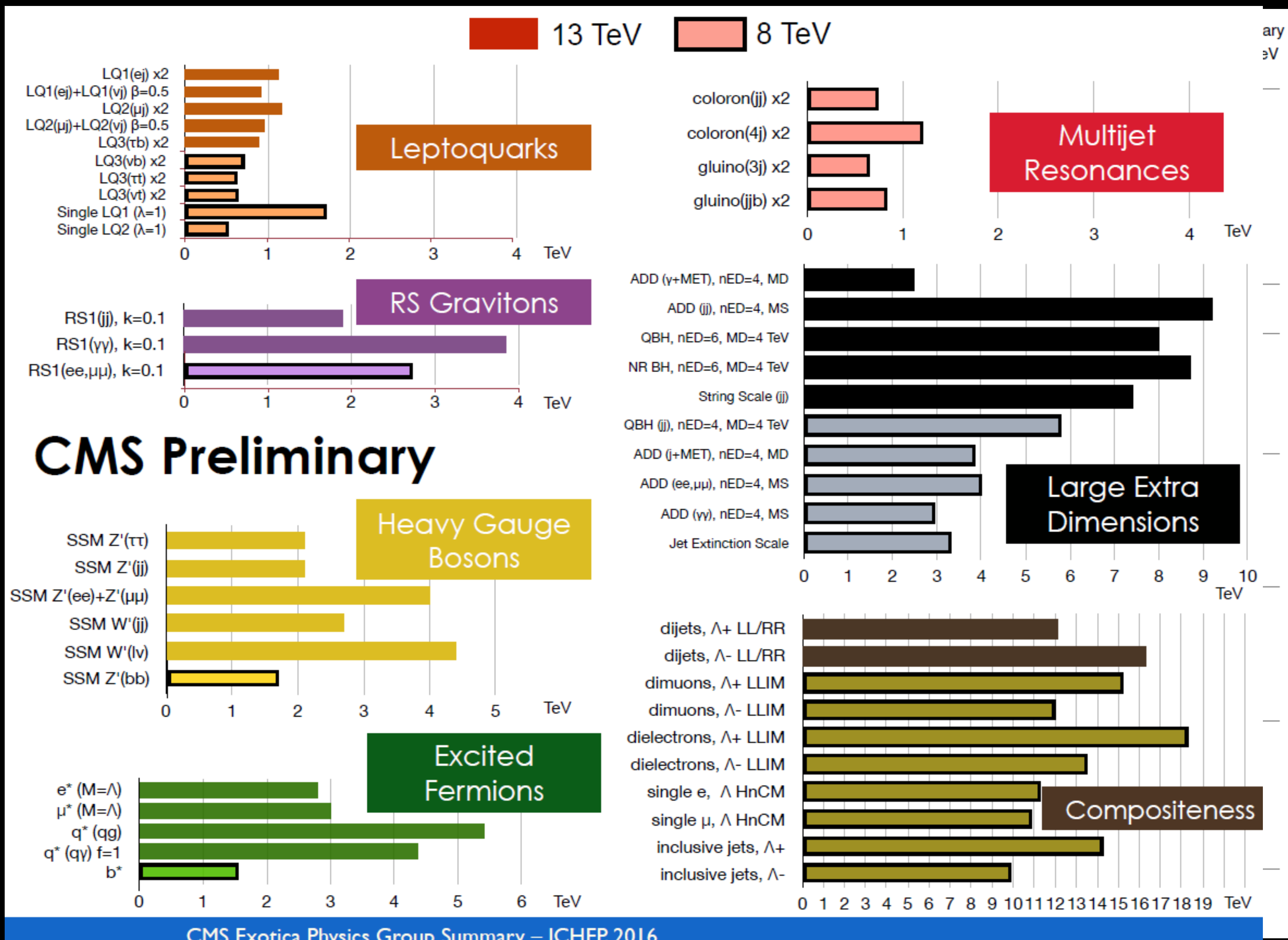
LHC → Great Success SM! (2)

- Also indirect measur. sensitive to radiative corrections
  - Mtop, Mw, M_H
  - Br ($B \rightarrow \mu\mu$)
  - Stronger constraints on new physics





However ...New physics? ... Not yet

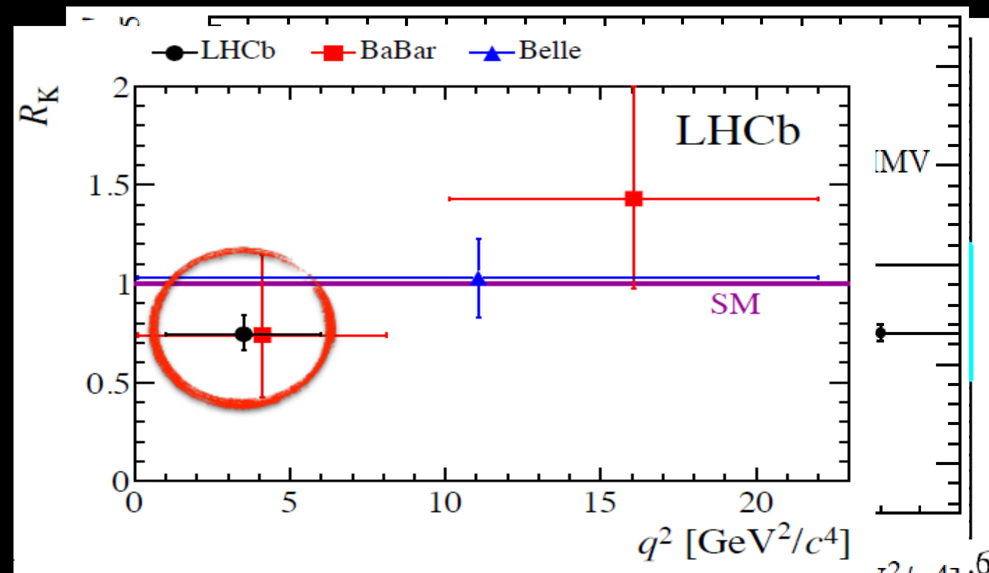


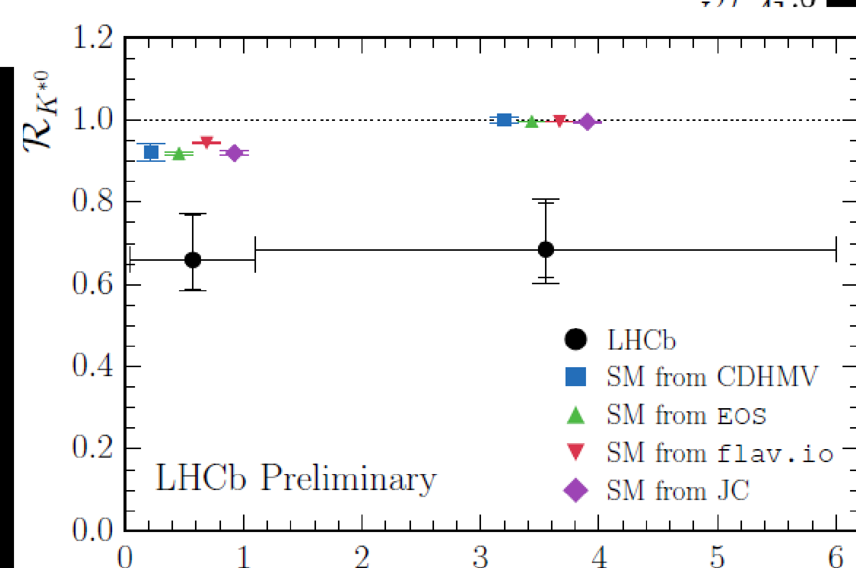
Hints? (....weak)

- ~~Di-photons 2016?~~
  - ~~Atlas: 3.6/1.8 σ~~
  - ~~CMS: 2.9/>1 σ~~
- Flavor:
  - R(D*) vs R(D)
    - ~3.9 σ

$R(D^{(*)}) = BR(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}) / BR(\bar{B} \rightarrow D^{(*)} l \bar{\nu})$

  - LHCb:
    - Bd→K*^{0}μμ
    - R(K) = B→Kμμ/B→Kee
    - R(K*) = B→K*μμ/B→K*ee





However .....

Many of our past expectations have been shattered

Naturalness as guiding principle

G. Giudice, FCC meeting, Rome 2016

Technicolor → no fundamental Higgs — No!

Supersymmetry → $m_h \lesssim 120$ GeV, $\tilde{m}_t \lesssim 300$ GeV, $\tilde{m}_g \lesssim 1$ TeV — No!

Extra dimensions → hell breaks loose at TeV — No!

Composite Higgs → $\Delta BR_h \sim O(1)$ — No!

Change of paradigm?

Directions?

- “Confusion is the best moment in science”
  - G. Giudice: FCC week, Rome, April 2016

- the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field:
  - M. Mangano: 98° ECFA meeting, Nov. 2015

Directions?

- Proposed criteria to evaluate future facilities (MLM):
  - Guaranteed deliverables
  - Exploration potential
    - Target broad well justified BSM scenarios
  - Potential to provide conclusive answers to relevant broad questions

- Additional practical criteria apply
  - When will the technology needed to build it be available?
  - Are the expected construction and operation costs acceptable?

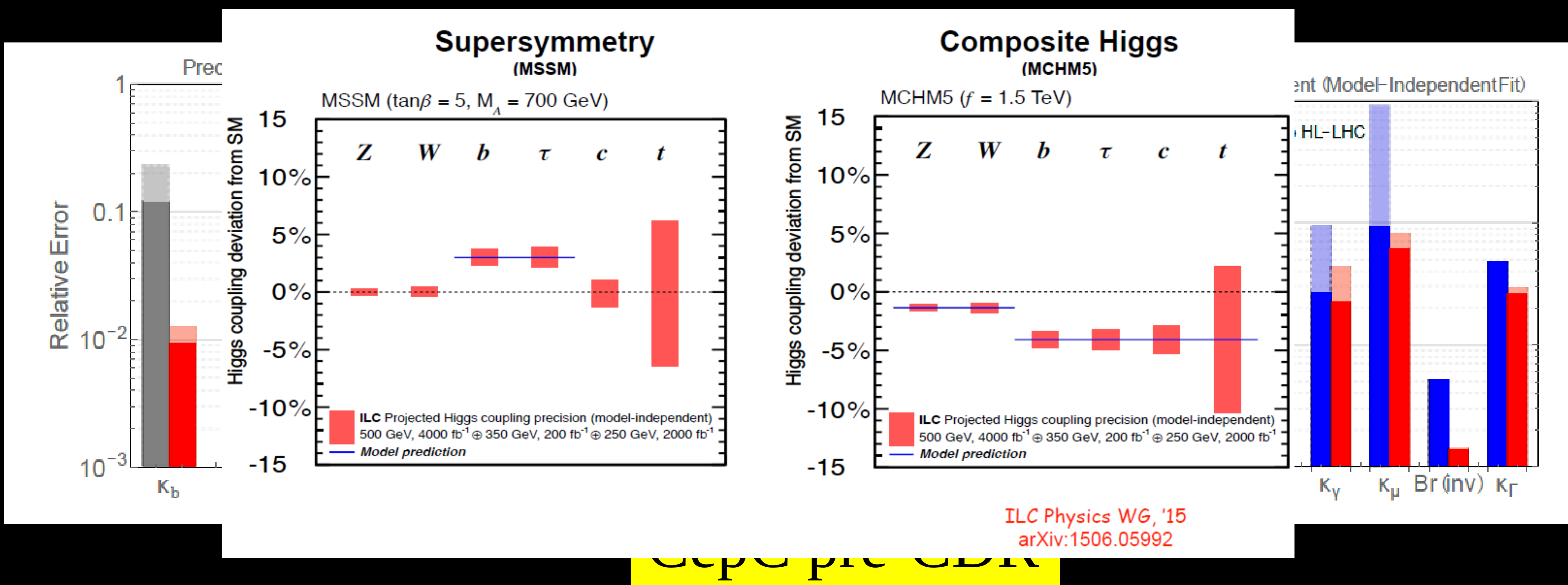
Combined potential of future facilities ee, μμ, hh

Guaranteed deliverables

- Detailed study of Higgs boson
  - Higgs is VERY special
  - Need beyond HL-LHC precision
- Extreme precision physics
  - EWK sector
  - Heavy Flavor sector

Higgs couplings

- Deviation from SM: $\delta \sim v^2/M^2$ $v = 246$ GeV
  - M scale of new physics
  - $M \sim 1 - 10$ TeV → $\delta \sim 6 - 0.06\%$
  - Need < ~ % sensitivity → beyond HL-LHC



Higgs couplings

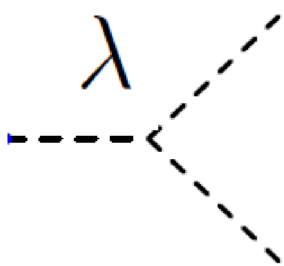
David d'Enterria: arXiv:1701.02663v1 [hep-ex] 10 Jan 2017

50 km version

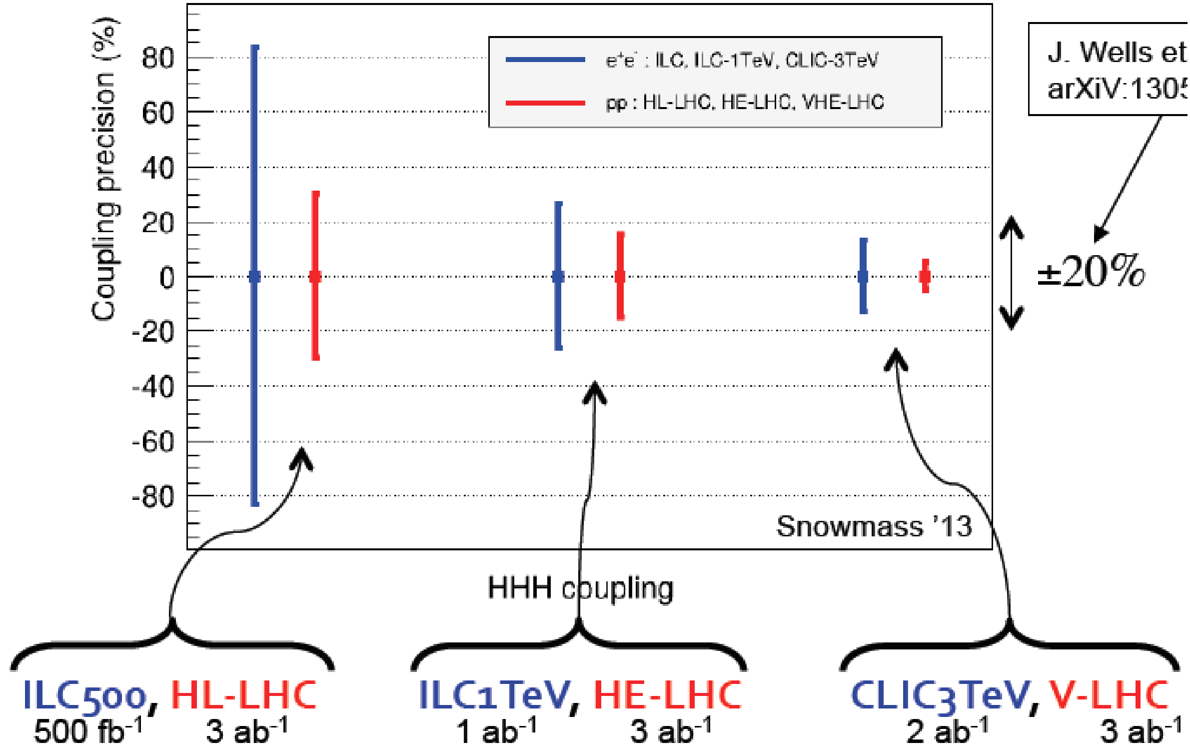
Parameter	Current* 7+8+13 TeV $\mathcal{O}$ (70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
σ(HZ)	–	–	0.4%	0.7%	0.5%	1.6%
g_{ZZ}	10%	2–4%	0.15%	0.3%	0.25%	0.8%
g_{WW}	11%	2–5%	0.2%	0.4%	1.6%	0.9%
g_{bb}	24%	5–7%	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_{gg}	–	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%
Δm_H	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
Γ_H	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
Γ_{inv}	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

Higgs self-couplings

- in the SM : $V(H$
- m_H d



- needs
  in fina



Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of $\%$
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

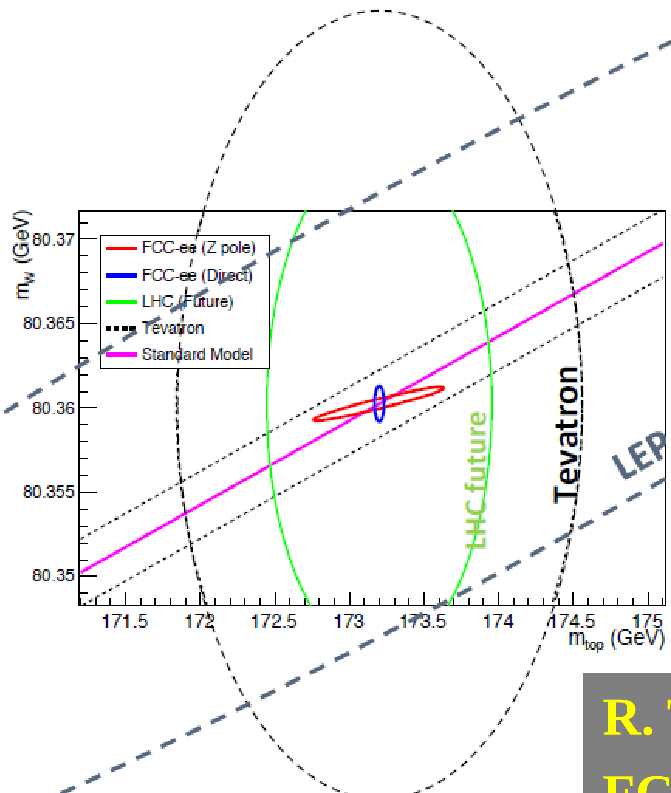
Gupta et al, arXiv:1305.6397

- BSM : Max λ deviations compatible with no other BSM observation: few % to ~20%

➜ target for both TH and EXP accuracies !

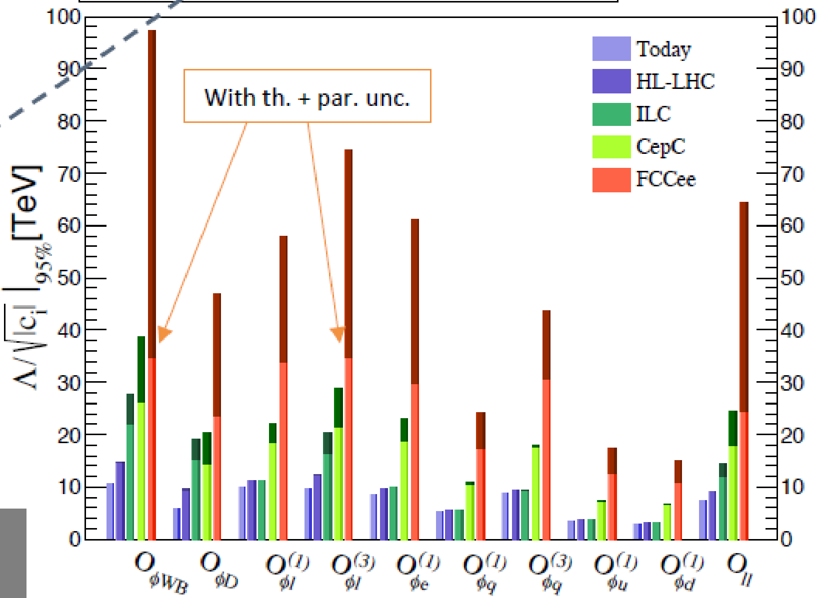
New physics indirect constraints in EFT

Global ewk fit and sensitivity to new physics



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

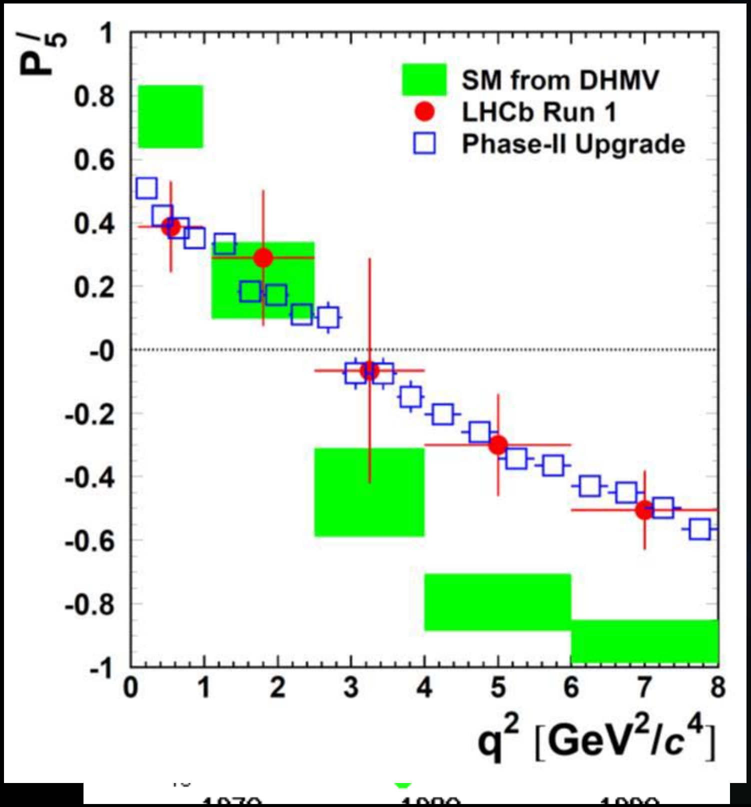
Jorge de Blas
LHCP 2017

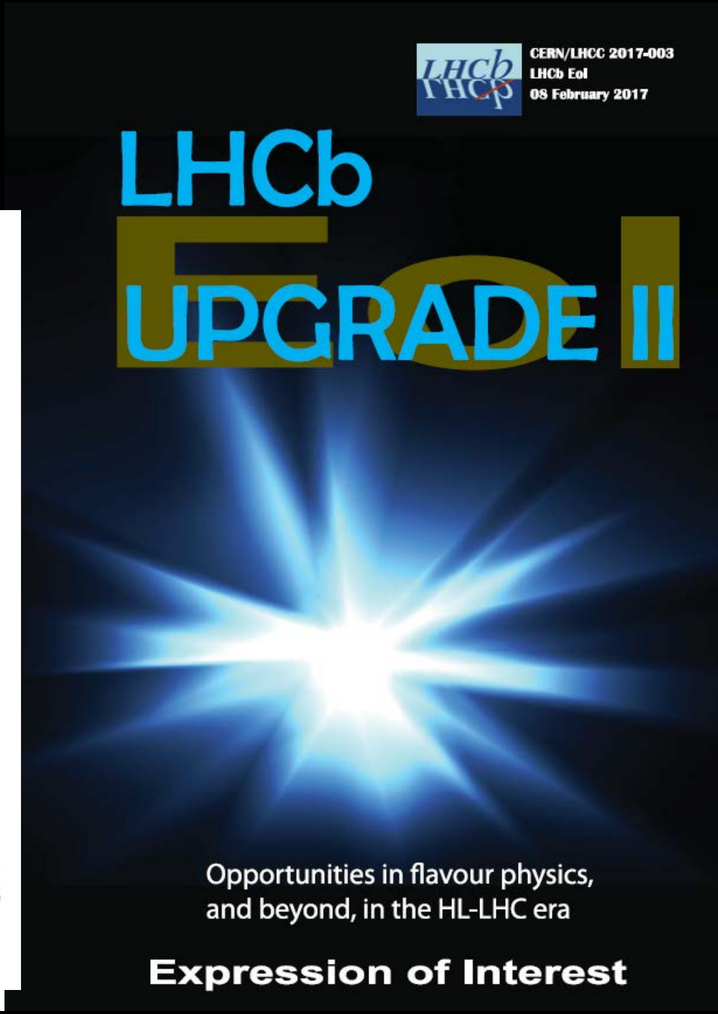


R. Tenchini
FCC week, 2017

Heavy flavors (1)

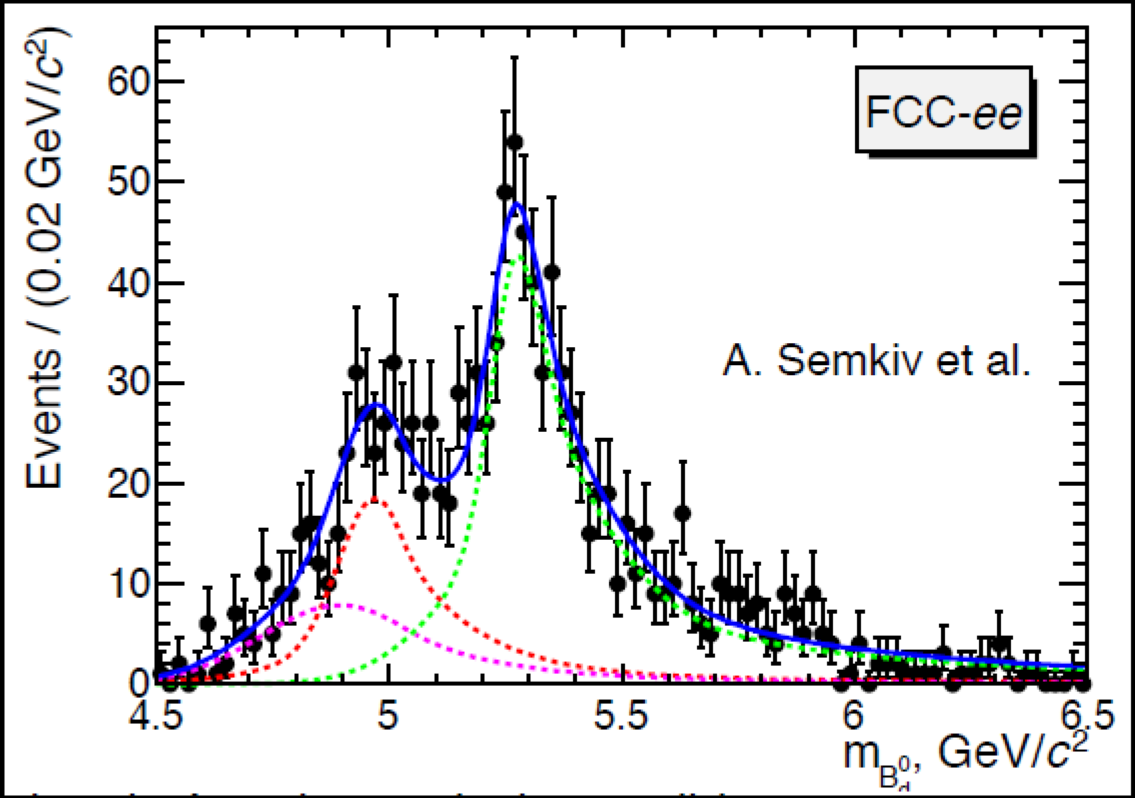
- Large potential at existing machines
  - SuperKEKB x40-80 KEKB/PEP-II
  - LHCb phase 2 → 10^{14} b, 10^{15} c …. if possible





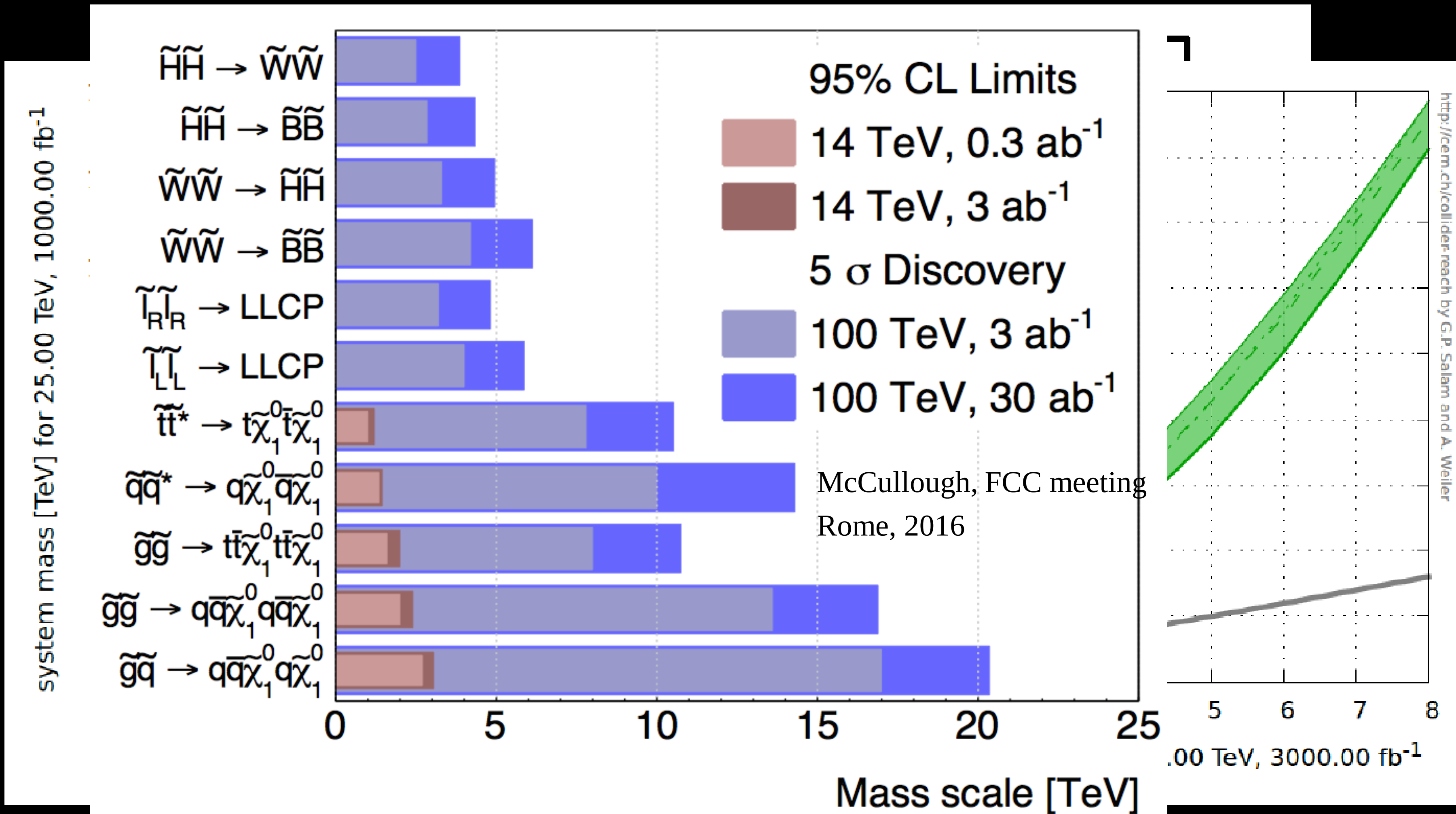
Heavy flavors (2)

- Full potential of e+e- on Z still being understood
  - E.g. $B^0_d \rightarrow K^{*0}\tau^+\tau^-$
  - ~1000 events@10^{36}



Exploration potential

- Search reach scaled for HL-LHC (2-3 TeV for SUSY)

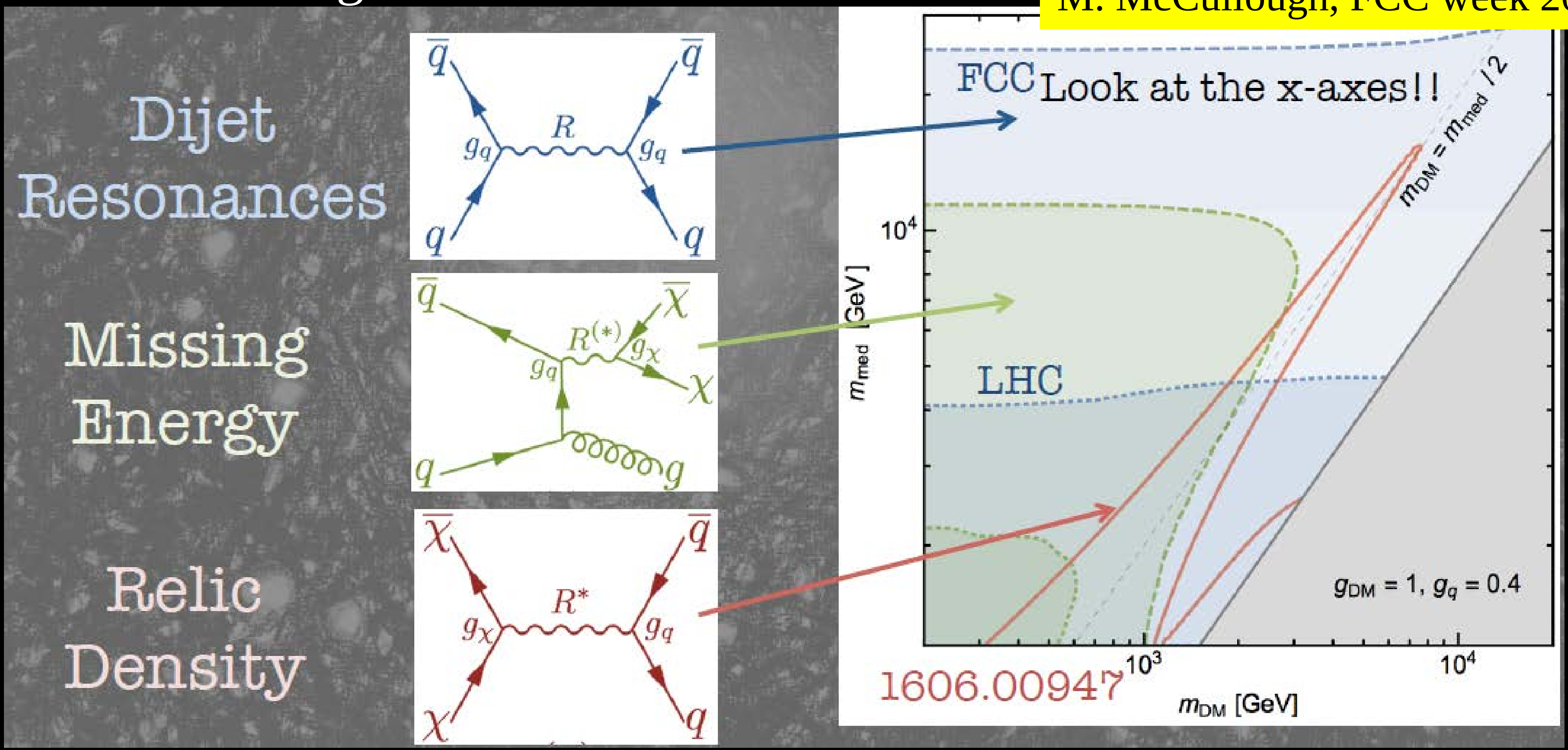


McCullough, FCC meeting Rome, 2016

Conclusive answers?

- Dark matter (simplified models)
  - 100 TeV pp could cover all parameter space allowed by cosmological bounds

M. McCullough, FCC week 2017



Summary of potential physics

- ....assuming we build everything:
  - Detailed Higgs studies and precision EWk physics are guaranteed deliverables

m 2-3

y not

arios

R. Barbieri, Plank 2017

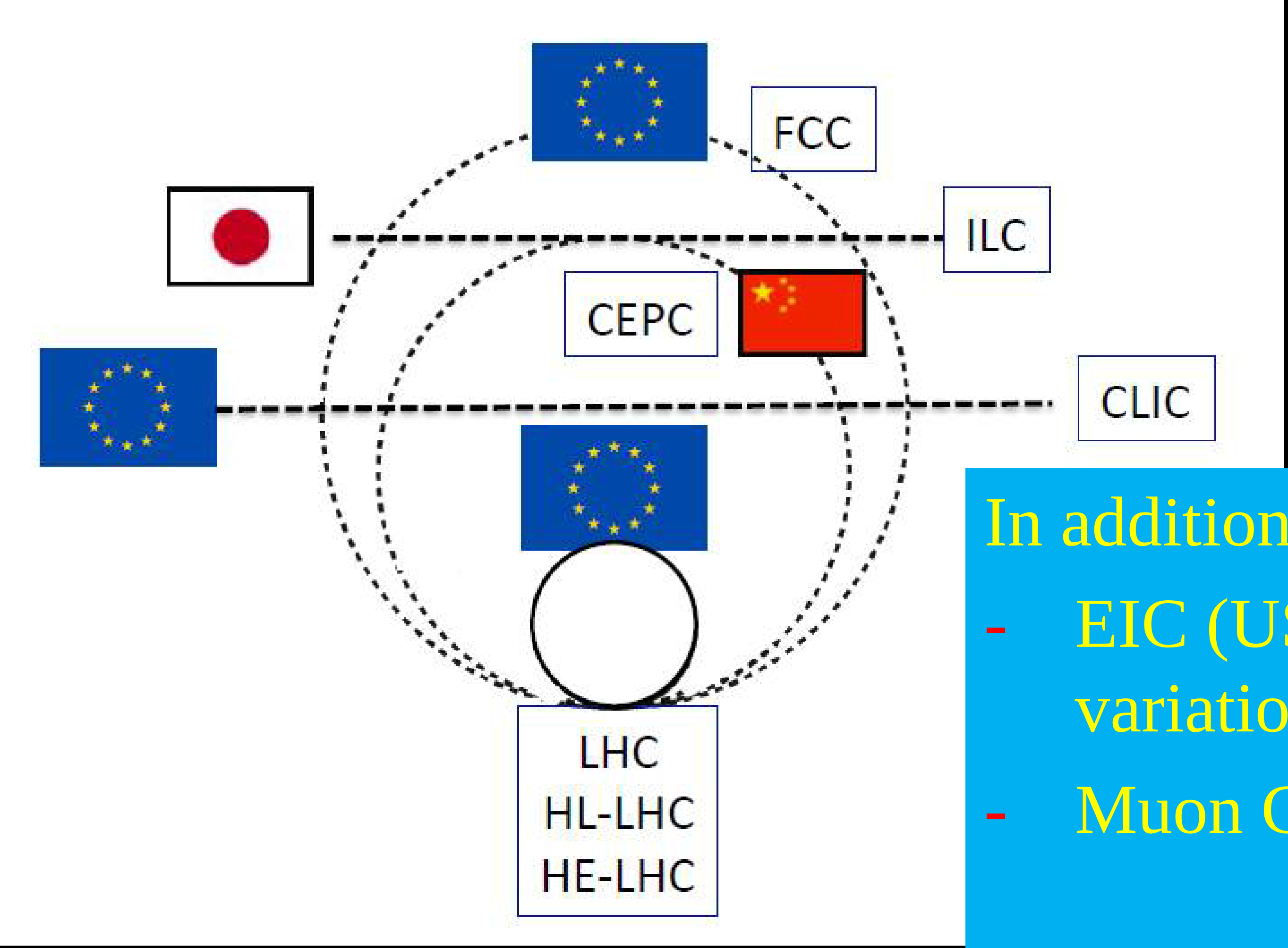
Conclusions

The Standard Model is **NOT** a complete story (although any deeper theory will include it as a relevant limit)

Precision in Higgs and flavour physics is a must

Pictures that go **Beyond the SM** are not lacking, but - fair to say - we don't know which one is right

What is on the table?

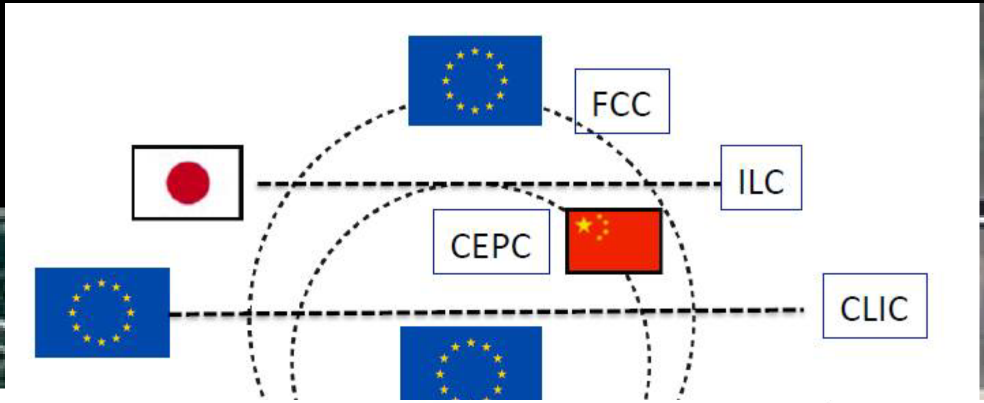


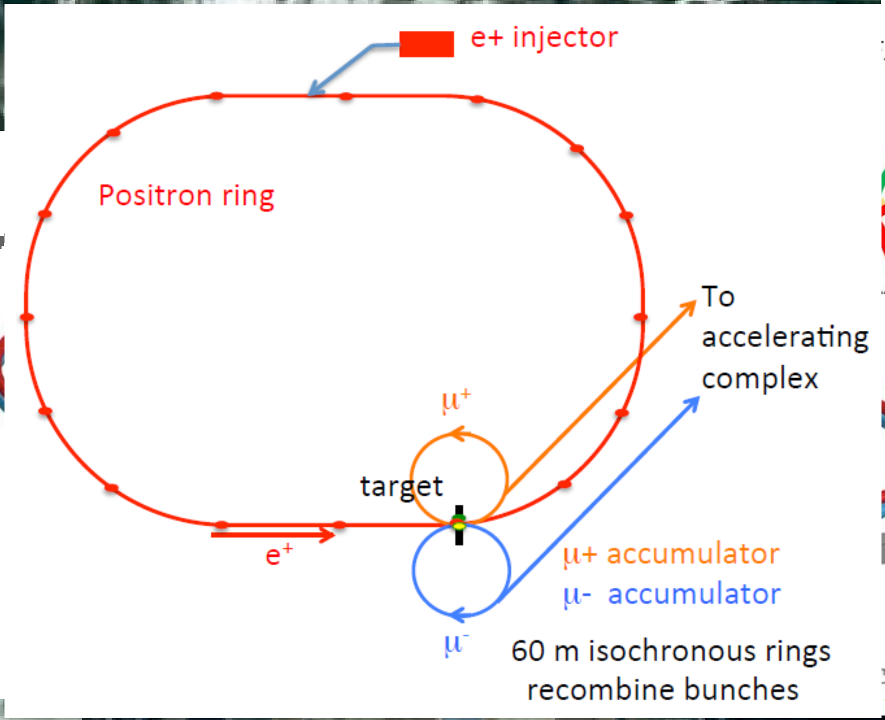
In addition:

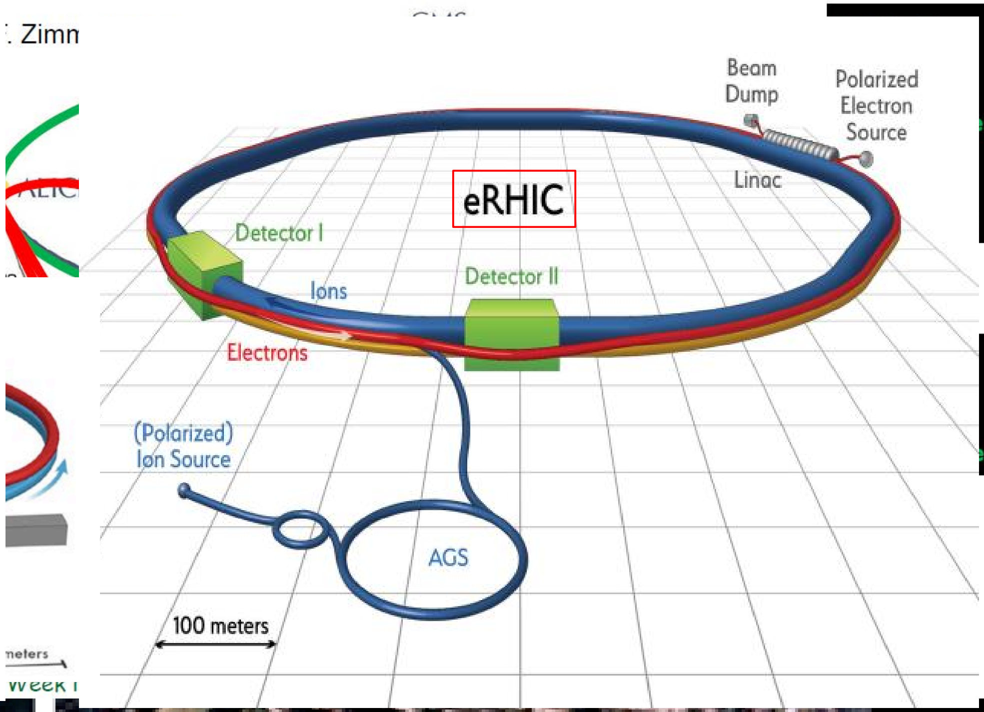
- EIC (USA) and variations on ep
- Muon Colliders

Old and new machines

- Future in EU and Asia
- In addition:
  - **Electron-hadron colliders**
  - **Muon colllider**





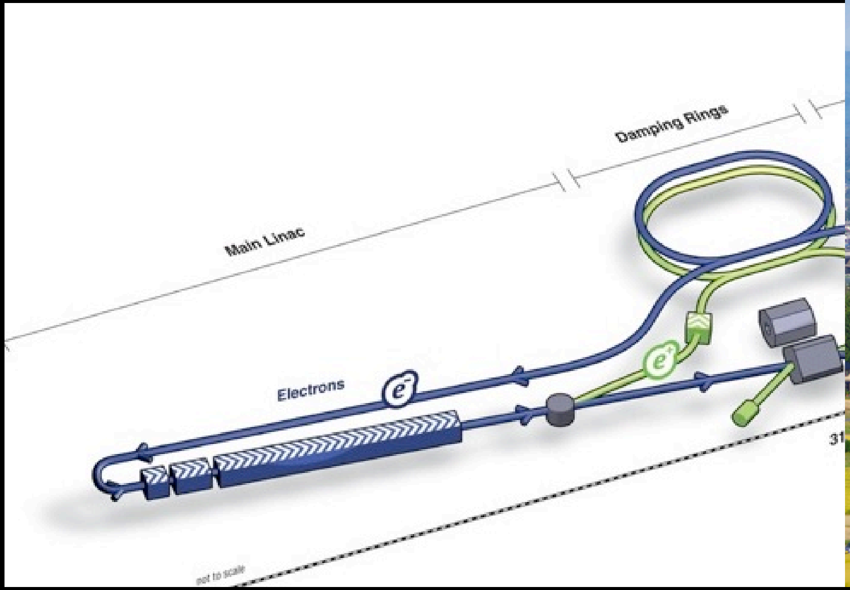


Build what?

- Could build now ... almost
  - ILC/CepC/FCC-ee
  - LHeC
- Need more R&D
  - HE-LHC, FCC-hh/SppC
  - CLIC
- Not yet demonstrated
  - PWFA = «Plasma WakeField Acceleration»
  - Muon collider
- Potential extensions
  - ILC/CLIC → PWFA
  - CepC/FCC-ee/LHeC → Muon collider

Machines with known technology

- ILC: linear e+e- collider
  - SC Linac 500 GeV (→1 TeV)
  - Detailed TDR/Engineering
  - Site chosen/Review by MEXT
  - Govnmt negotiation 2-3 yr

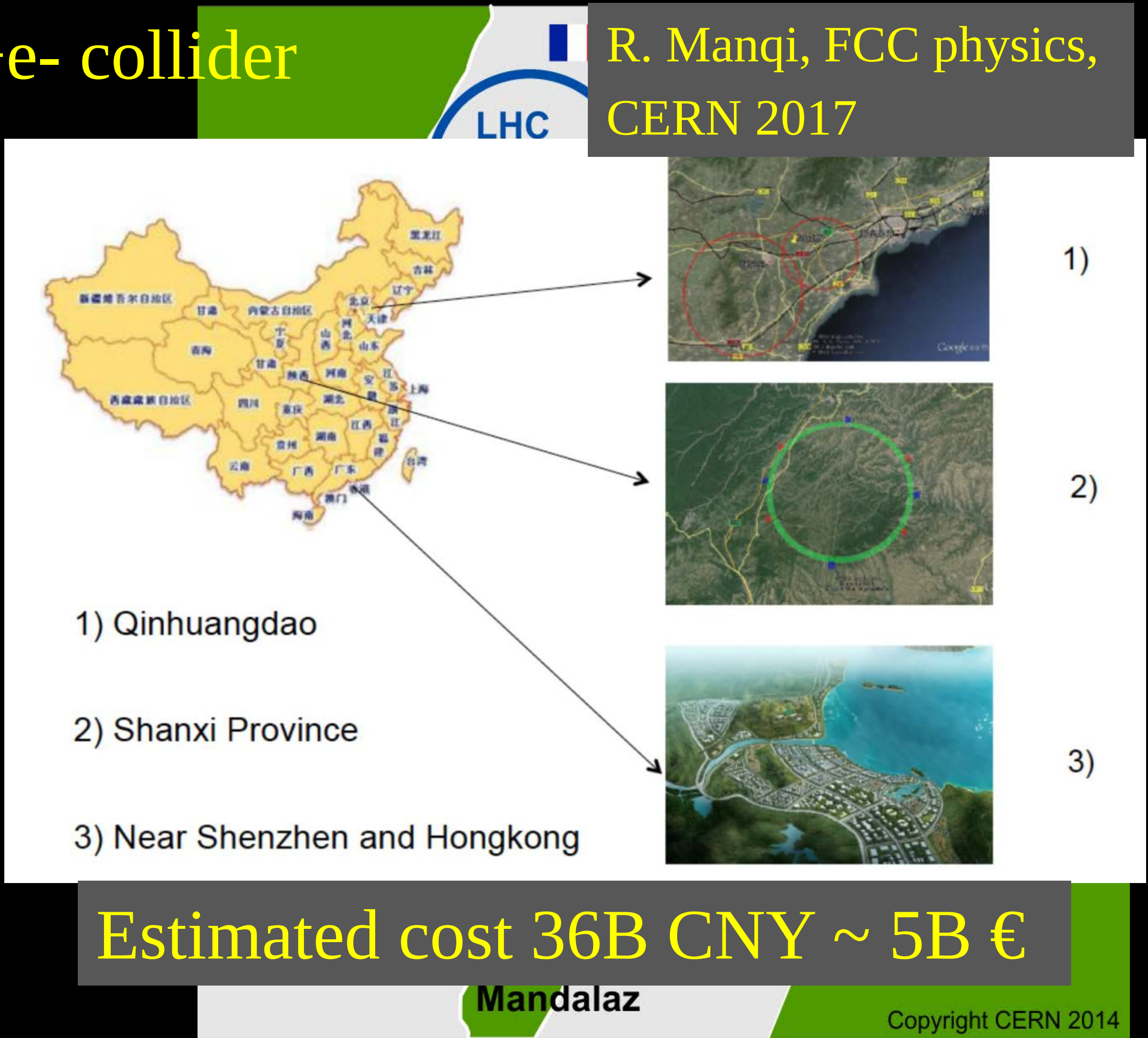


In progress study of:

cost reduction and staging options

Machines with known technology

- FCC-ee: circular e+e- collider
  - ~100 km tunnel
  - → 350 GeV
  - CDR by 2018
  - Beam 2039?
- CepC: circular e+e-
  - 100 km tunnel
  - 240-350 GeV
  - Pre-CDR finished
  - CDR by 2017
  - Beam 2028-30?

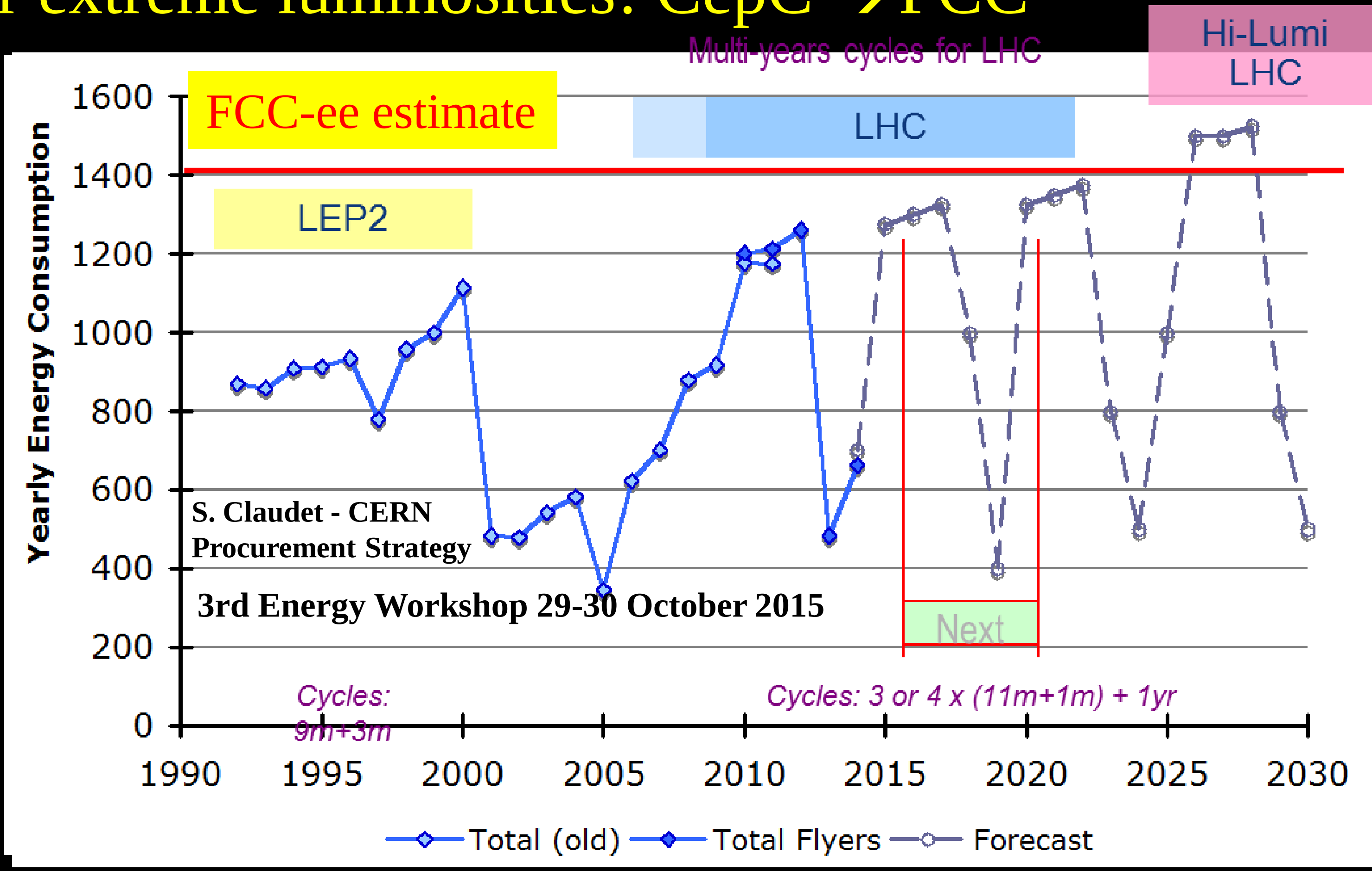


R. Manqi, FCC physics, CERN 2017

Estimated cost 36B CNY ~ 5B €

e+e- luminosity comparison

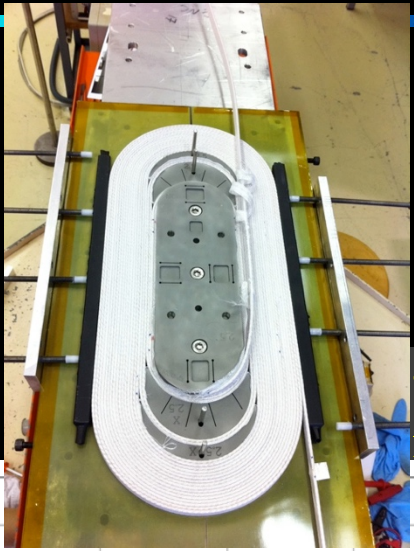
- Planning for extreme luminosities! CepC →FCC
- Reference:
  - LEP1:
    - 3.4×10^{31}
  - LEP2:
    - 1×10^{32}
- Power OK



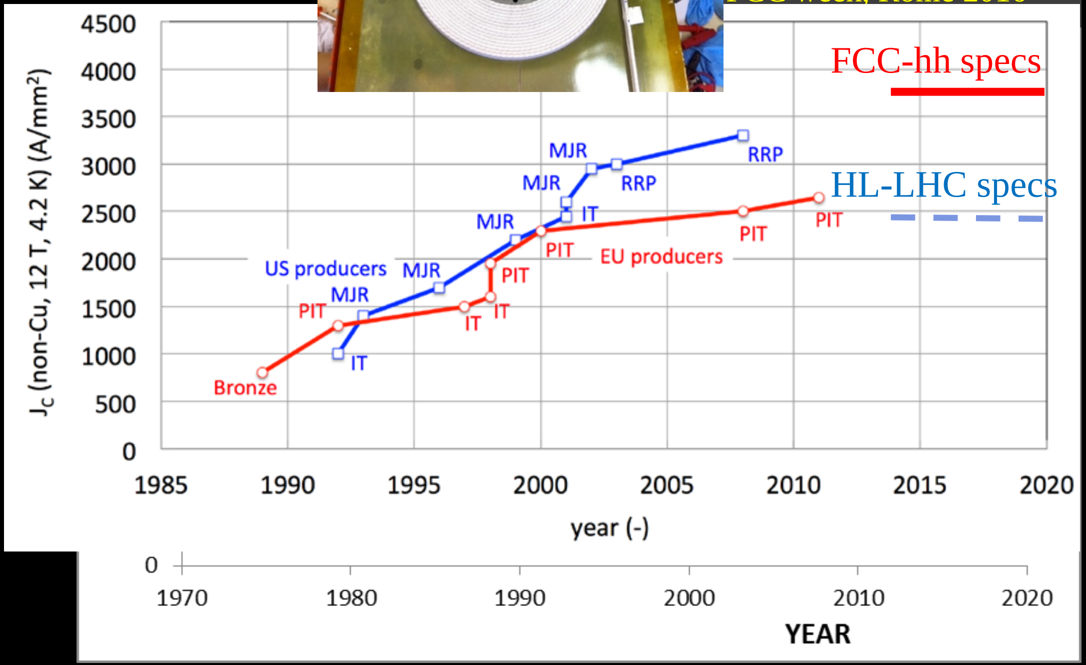
- Much activity on future circular colliders in
  - EU
  - China

Machines needing R&D

- HE-LHC/FCC-hh/SppC:
  - Share tunnels with LHC, FCC-ee, CepC
- Need high field Nb_3Sn magnets
  - 8 T (LHC) → 16 T
    - 20 T with HTS
  - Conductor
  - Complex construction



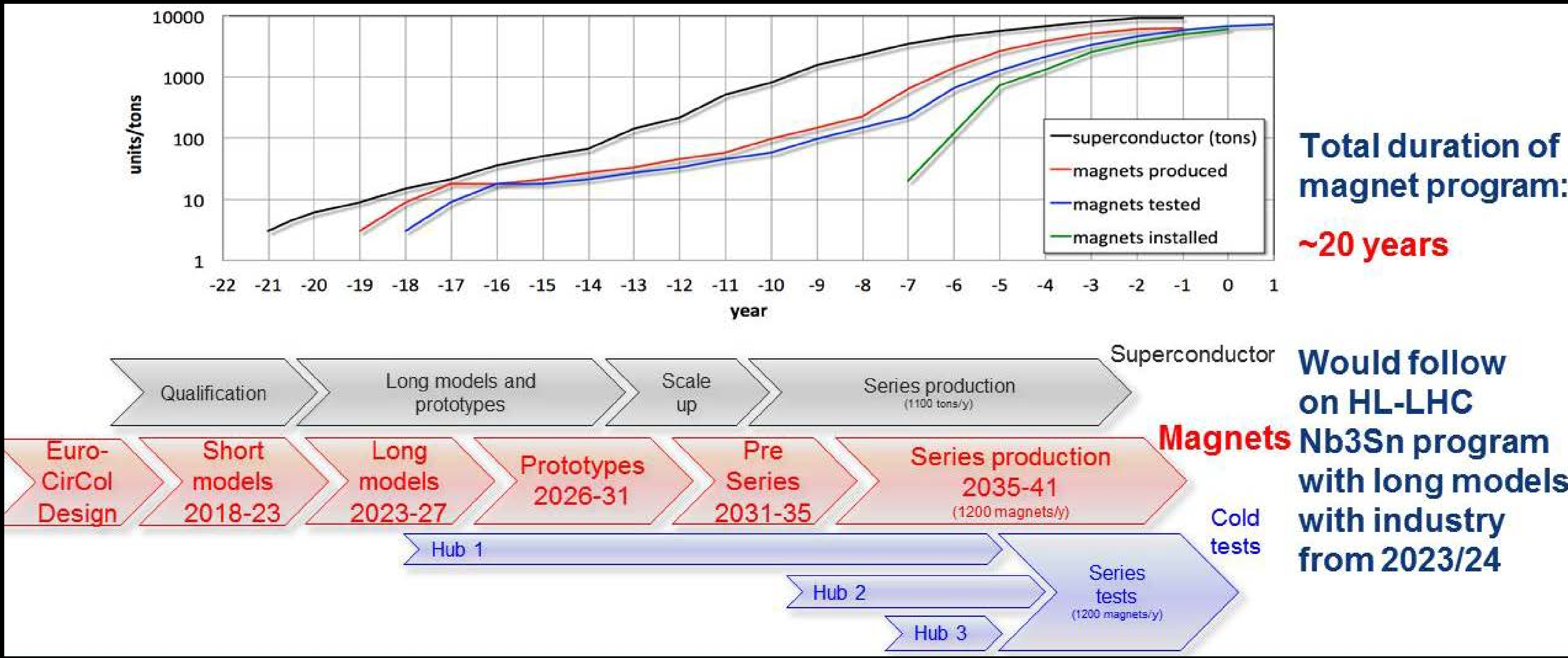
Courtesy of Gijs de Rijk, FCC week, Rome 2016



Magnet R&D

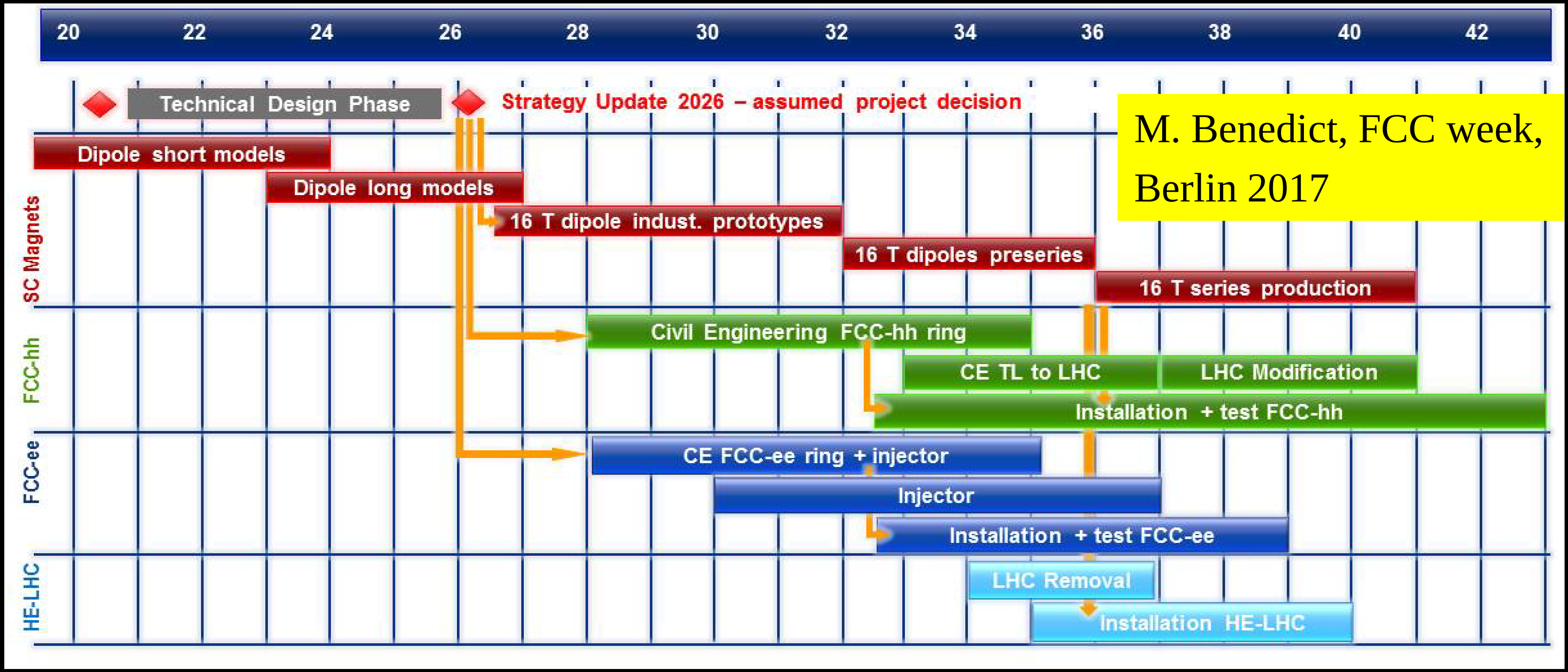
❖ CERN plan for FCC magnets

- 1° 16 T prototype by mid 2020's
- Complete series production 2041



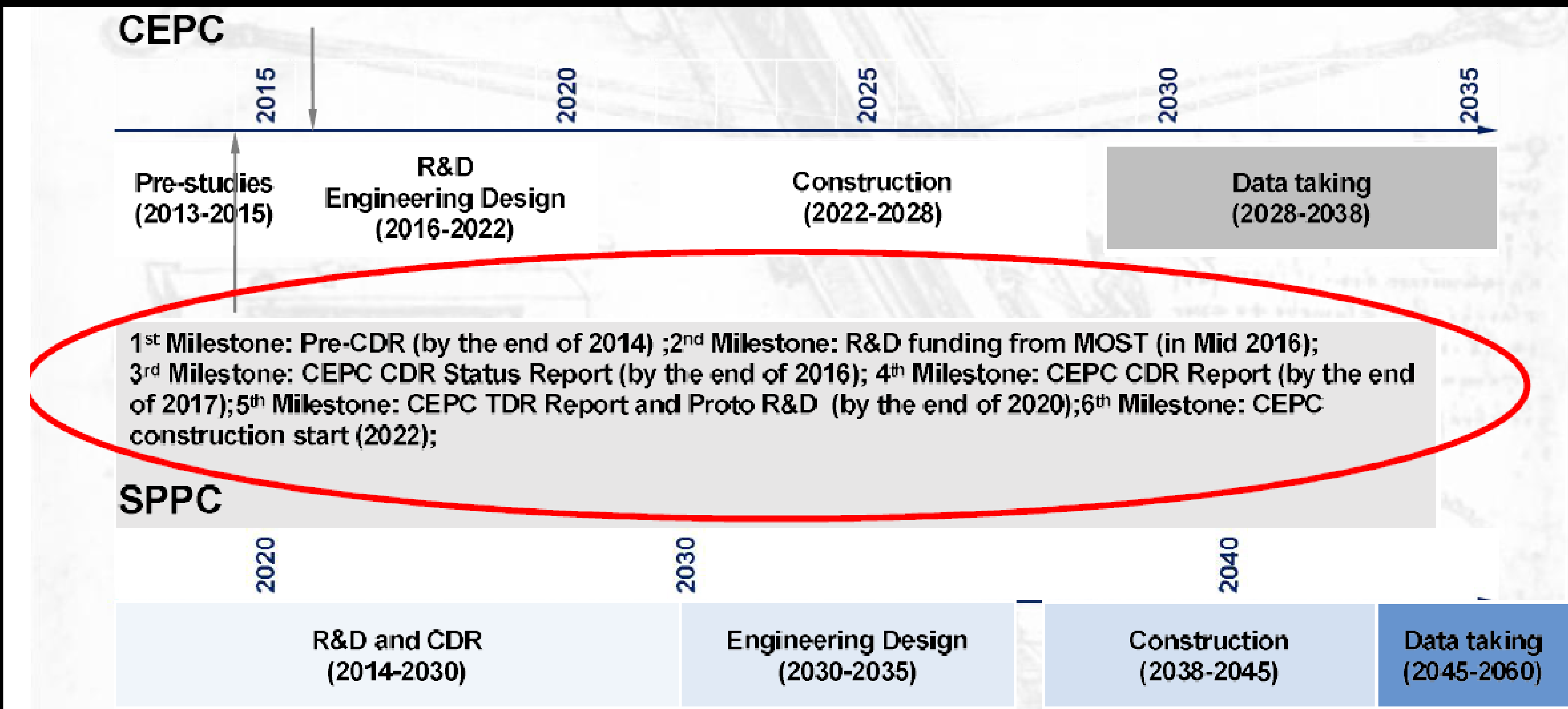
Circular collider schedules (EU)

- CERN-FCC schedule recently presented in Berlin 2017
  - Technically driven schedule – Reality could be worse (F. Gianotti)



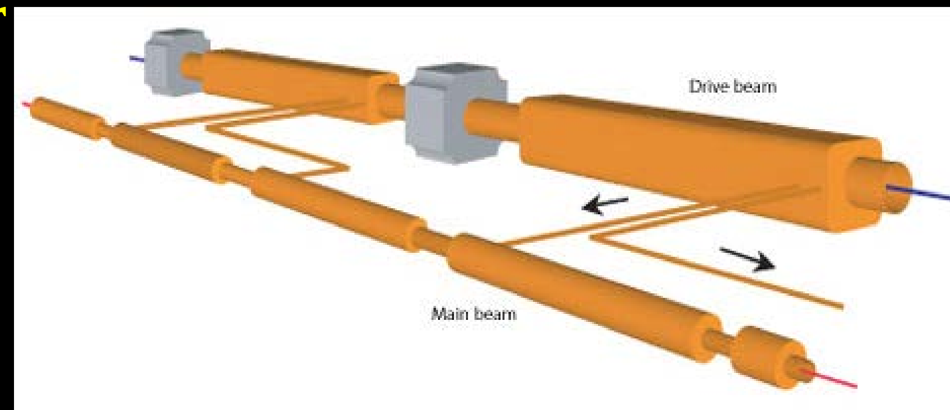
Circular collider schedules (China)

- China-CepC/SppC schedule recently presented IAS conference on HEP, Hong Kong 2017

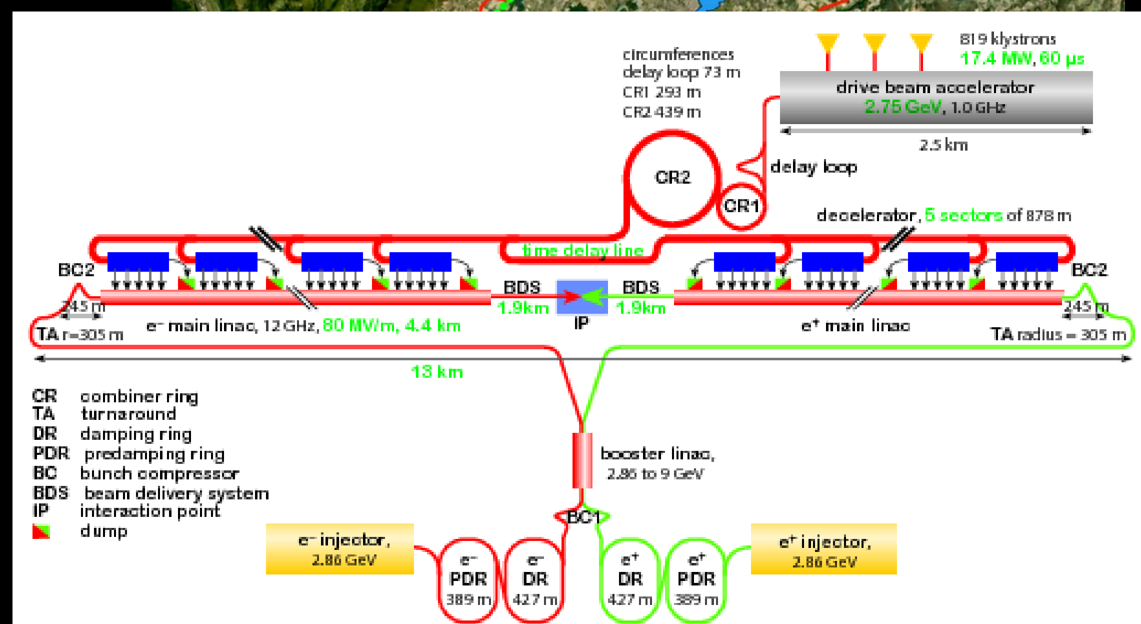


Machines needing R&D

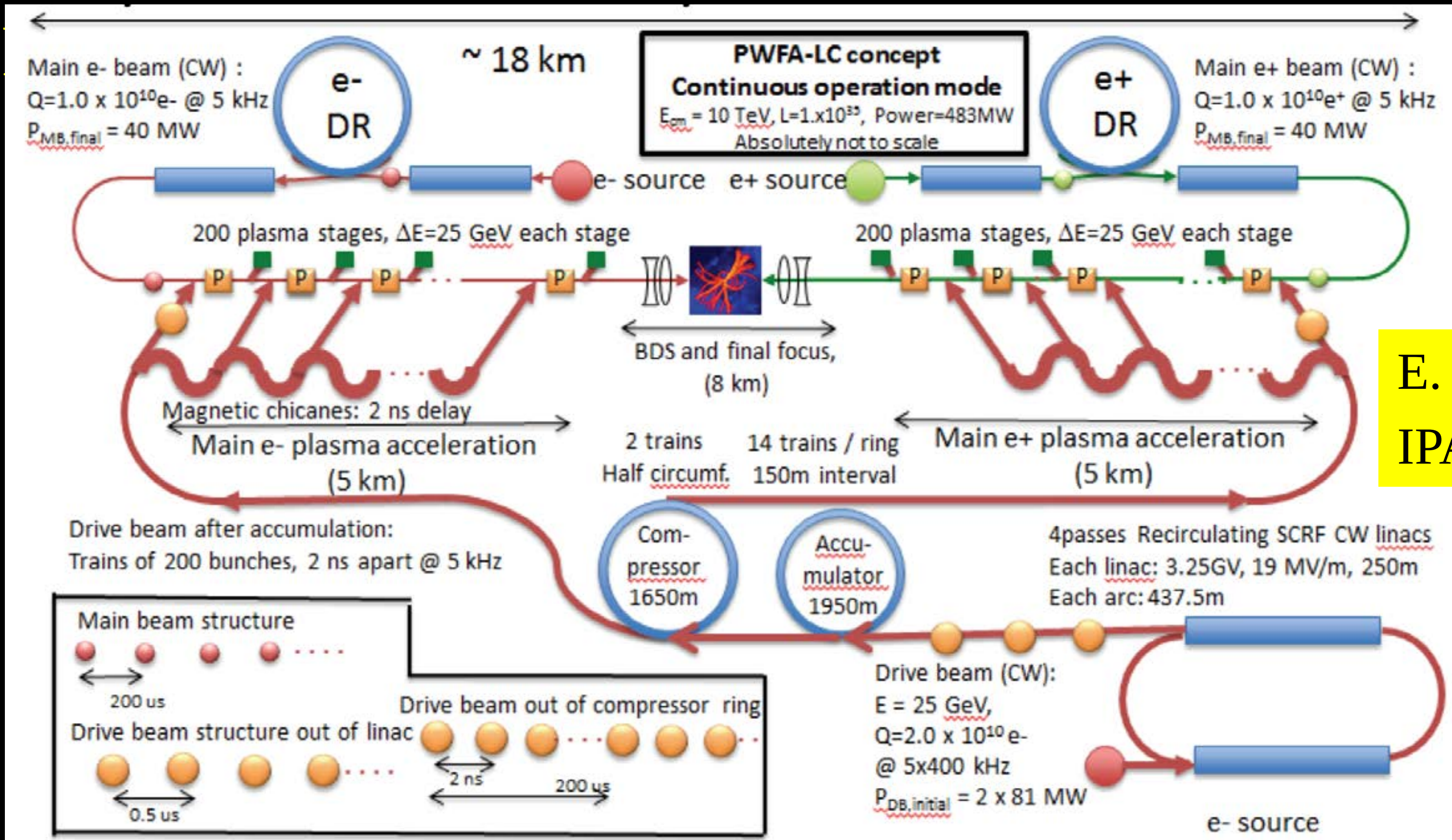
- CLIC: Linear e+e- collider
  - 380 GeV → 3 TeV
  - Room temp. Linac
    - 100 MV/m @ 12 GHz
  - Klystrons→Drive beam

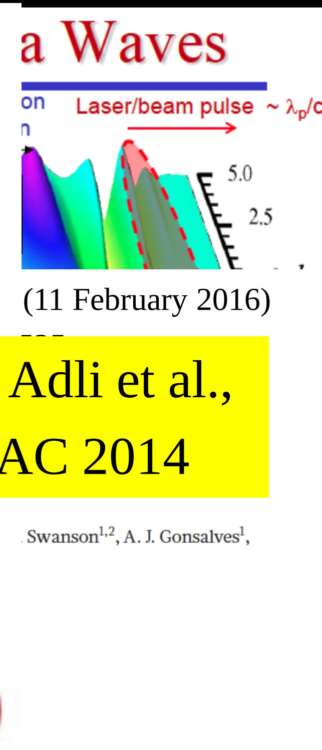


- Challenges:
  - RF breakdown
  - RF power transfer
  - 600 MW @ 3 TeV
  - Final focus
  - Beamstrahlung
  - Alignment



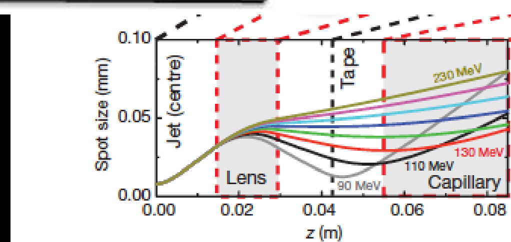
LPA/PWFA

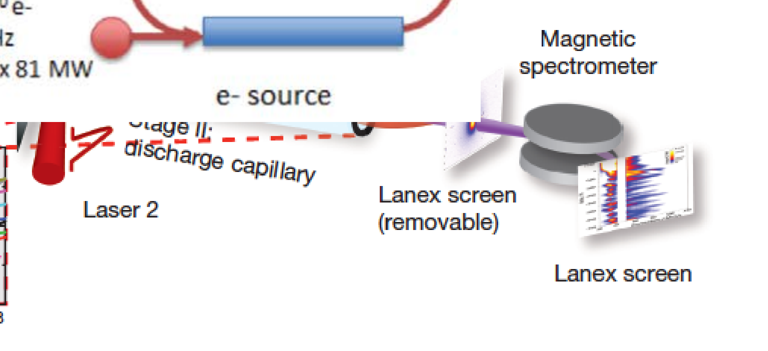




E. Adli et al.,
IPAC 2014

- Linear colliders
  - > 10 TeV

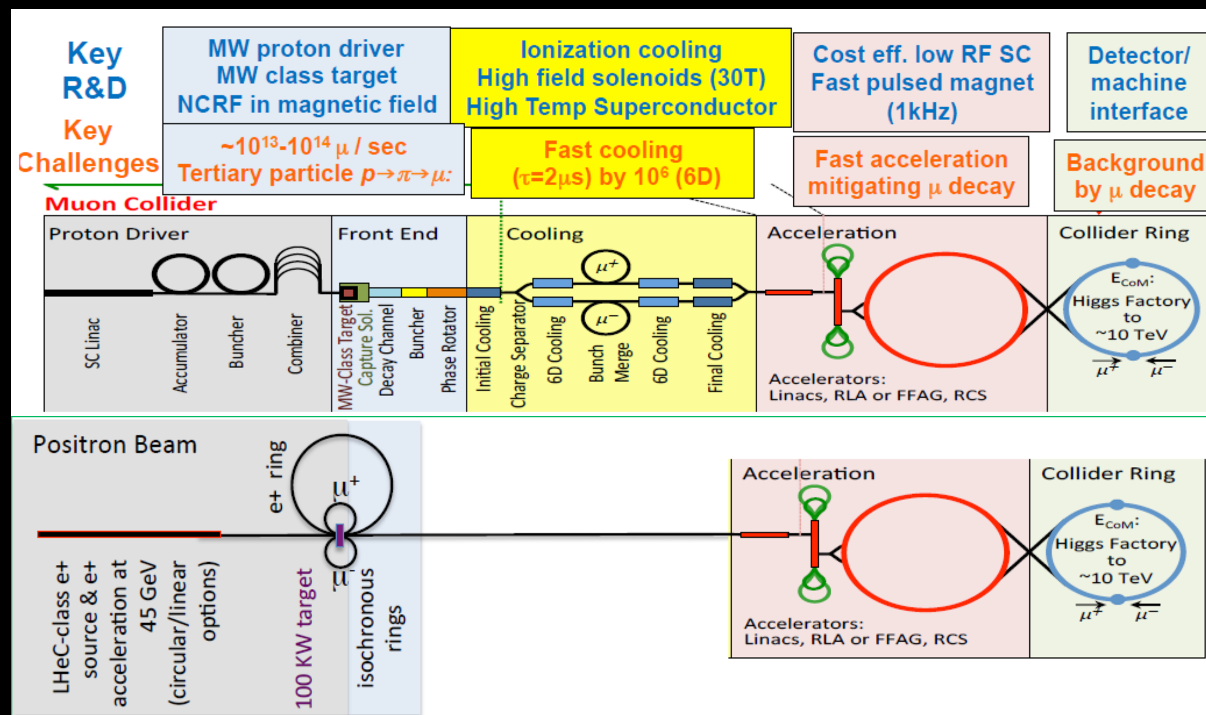




Muon colliders

INFN Istituto Nazionale di Fisica Nucleare

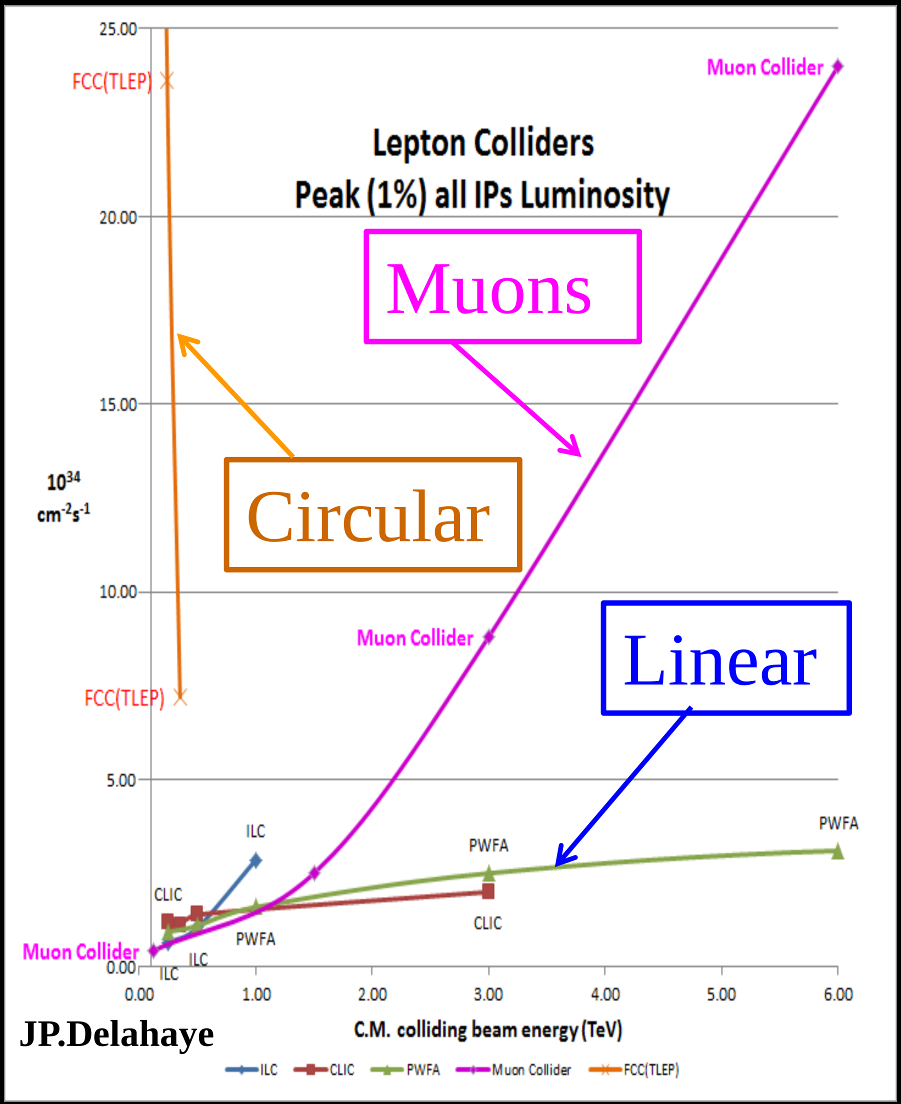
- Circular μ+μ– collider
  - 125 GeV → 10 TeV
  - No beamstrahlung
  - Low power
- Two approaches:
  - Proton prod.
  - Positron prod.
- Challenges:
  - Cooling
  - Targets
  - Backgrounds

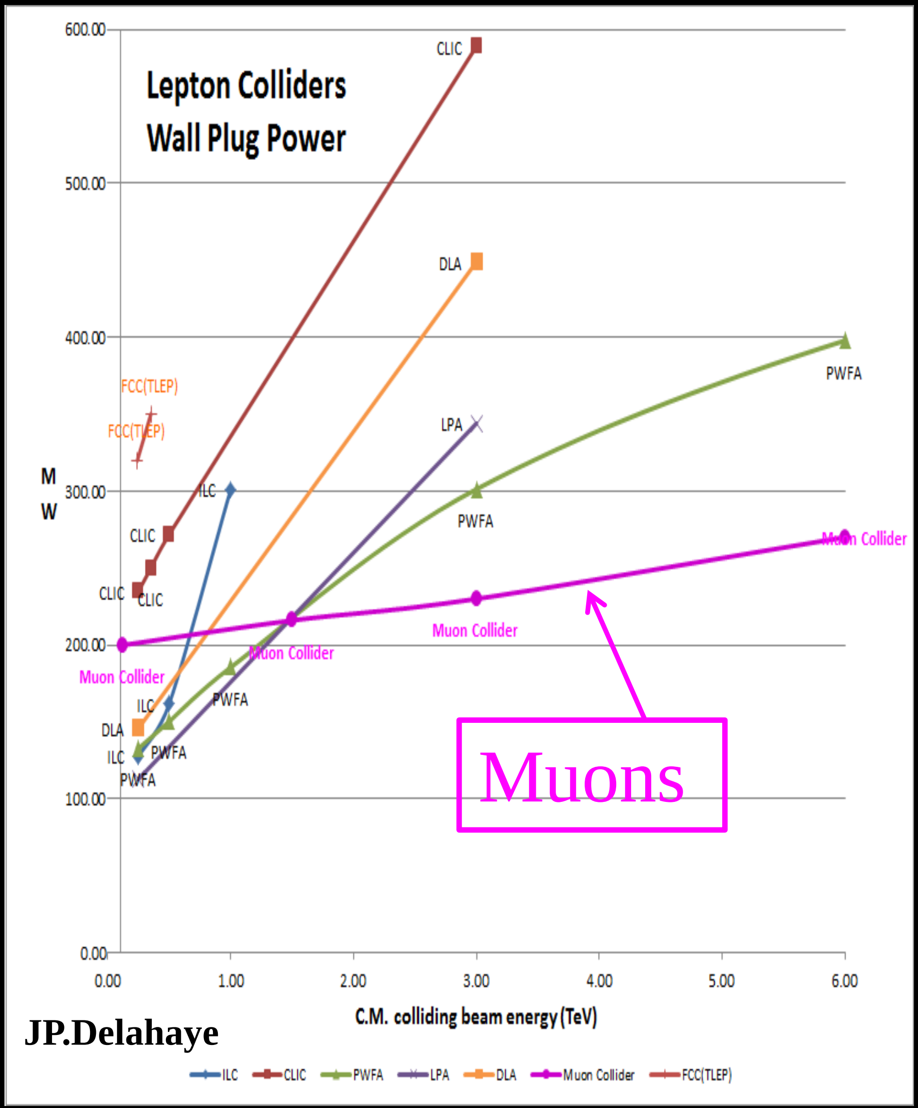


Key Challenges ~10¹¹ μ / sec from e+e-→μ+μ−

Key R&D 10¹⁵ e+/sec, 100 kW class target, NON distructive process in e+ ring

Scaling lepton machines to high energy





Comments

- Hard to stretch HL-LHC much beyond 2035
  - Then FCC-ee or hh?
    - Magnets/money
    - Time gap? How long?
    - Potential time fillers:
      - HE-LHC
        - Down time to replace magnets, expensive, disposal of LHC
      - LHeC
        - Enough interest?
- What could start construction in mid ’20s?
  - ILC/CepC → Could be operational by early/mid ’30s
    - Could speed up FCC-ee?
  - Could complement each other Lumi: CepC/Energy: ILC

Decision times

- ILC:
  - Japan MEXT review completed (2015)
  - Government negotiations for 2-3 years
- FCC:
  - CDR by 2018 – to be discussed at the next European strategy update (2020)
  - Project go ahead decision ~ 2026
- CepC:
  - Pre-CDR done (2015)
  - Machine/detector CDR by end of 2017
  - Project go ahead decision ~ 2020

Related INFN/CSN1 activity

Preparation (2016)

- Follow up from White Paper work
- Bottom up activities:
  - Grants for EIC R&D (INFN-Trieste group)
  - New ideas for positron driven muon coll. (P. Raimondi)
  - Work in FCC R&D groups at CERN
  - Work in CepC R&D groups in China
- Top down:
  - Encouragement from CSN1 president (N. Pastrone)

Consolidation (2017)

- New line of research on future accelerators (RD_FA) created in CSN1
  - Seed money ~ 130 k€
  - Several working groups (13 INFN sections/69 physicists):
    - Physics & simulation
    - MDI
    - Vertex detectors
    - MPGD for RICH/TPC (EIC)
    - Drift chamber
    - MPGD for muon/preshower
    - Silicon Trackers
    - Dual readout calorimetry
    - Muon collider R&D

Consolidation (2017)

- EIC international meeting in Trieste (July 2017)
- Test beam for Muon Collider (CERN July 2017)
- Established contacts for CERN FCC
  - MDI (Bacchetta/PD, Boscolo/LNF are FCC MDI conveners)
  - Physics (INFN theorist group involved: Piccinini, De Curtis, ...)
  - Detector simulation (Azzi/PD, Tenchini/PI)
  - Detector design/R&D (tight cooperation with Rolandi WG11)
- Established contacts for Chinese CepC
  - INFN people participated to several Chinese meetings/events and got involved in planning for CepC:
    - IAS conference on HEP, Hong Kong, January 18-21, 2016
    - CepC-SppC Study Group Meeting, Beijing, September 2-3, 2016
    - IAS conference on HEP, Hong Kong, January 23-26, 2017
    - CepC workshop, Wuhan, April 19-21, 2017

FCC-CepC synergy

- Recent evolution of CepC machine design makes it very similar to FCC-ee → 100 km/ double ring
  - Expect similar performances & problems

- INFN people proposed detector IDEA(*) for FCC-ee and as second detector concept for CepC
  - CERN FCC leaders are aware of this and (so far) encourage cooperation
  - Strong INFN involvement in preparation of FCC and CepC CDRs

(*) IDEA = International Detector for Electron-positron Accelerator

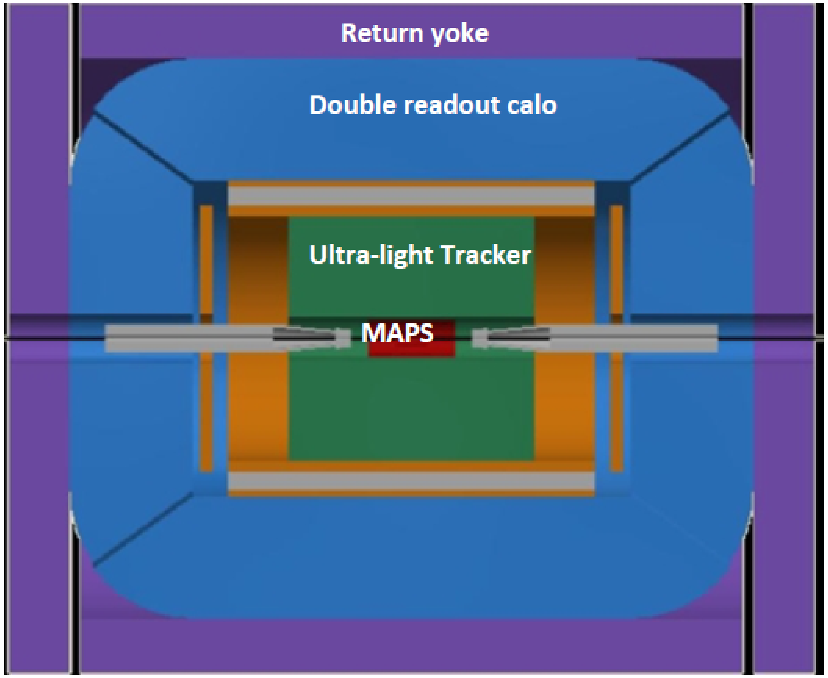
INFN interest in IDEA

Talk of Mogens Dam on Tuesday

the IDEA concept

Two Options: Calorimetry inside or outside coil

- Vertex detector, MAPS (a la ALICE) **MI**
- Ultra-light drift chamber with PID (a la MEG2) **LE**
  - ≈ 0.04 X0 up to the preshower face
- Pre-shower counter **BO, LNF, MI, (PG)**
  - defines acceptance ≈ 10-20 μm precision
- Double read-out calorimetry (RD52 - DREAM) **MI, PI, PV**
- 2 T solenoidal magnetic field
- Possibly instrumented return yoke **BO, LNF**
- Possibly surrounded by large tracking volume (R = 8m) for very weakly coupled (long-lived) particles



R. Tenchini
FCC week, 2017

Conclusions (politically correct)

- The current scenario is very complex, however
  - Options available with high physics potential
- Decisions should be taken by the next EU strategy (2020) to have a future beyond HL-LHC
  - Good measure of realism is important
  - Should absolutely avoid large time gaps with no physics after HL-LHC completes operations
- Limited resources require not only a EU strategy, but also a world strategy → should be very open
- Planning the future takes time and effort
  - All of you should help at some level

Conclusions (what I think...) (1)

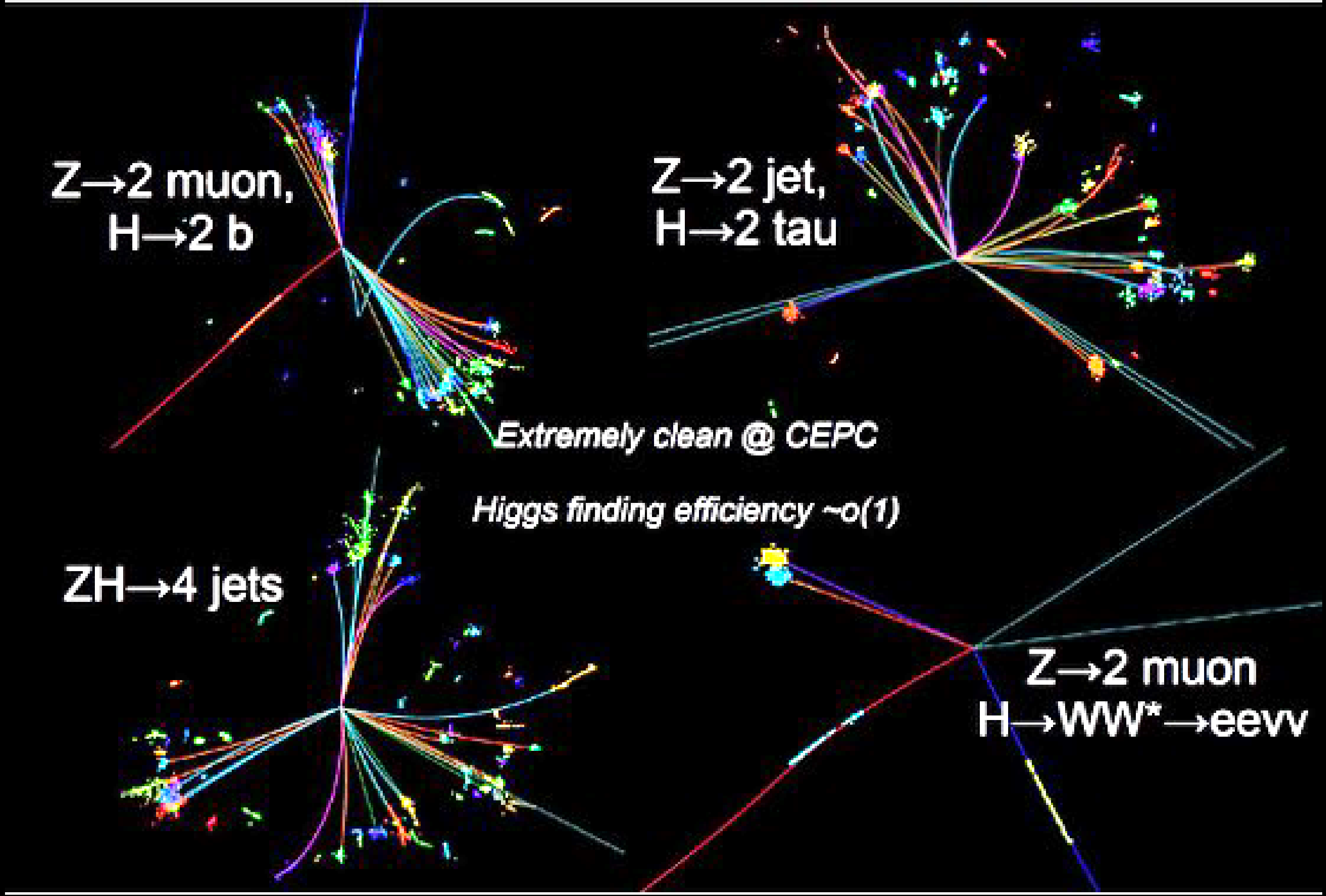
- HE-LHC:
  - Little interest if no strong NP evidence soon
- FCC-hh:
  - Too far away, too expensive; good option for long term future
- ILC:
  - Probably dead, same cost scale as FCC-ee
- FCC-ee:
  - Financially feasible, must speed up agenda
- CepC:
  - Serious competition to FCC-ee, may arrive sooner in spite of limited Chinese expertise ... Then what?

Conclusions (what I think…) (2)

- Tunnel issues at CERN:
  - Cost optimization
  - Authorizations
- LHeC:
  - Could be a low cost time filler as we wait for the big/long hole
    - ERL could be used to make muons for Mu Collider
- Far future:
  - 100 TeV pp after completing exploitation of ee
  - Muon colliders are the most interesting option for very high energy lepton collider up to 10 TeV matching 100 TeV pp
    - Need serious International collaboration to continue R&D or it will never happen

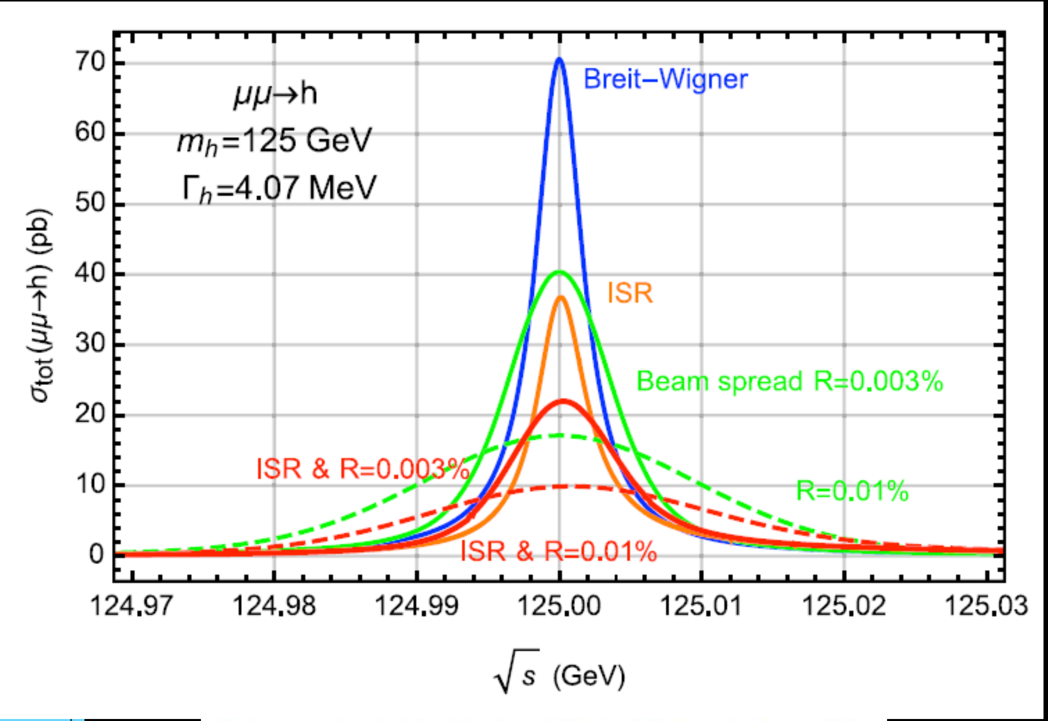
ADDITIONAL SLIDES

ZH in e+e- simulations

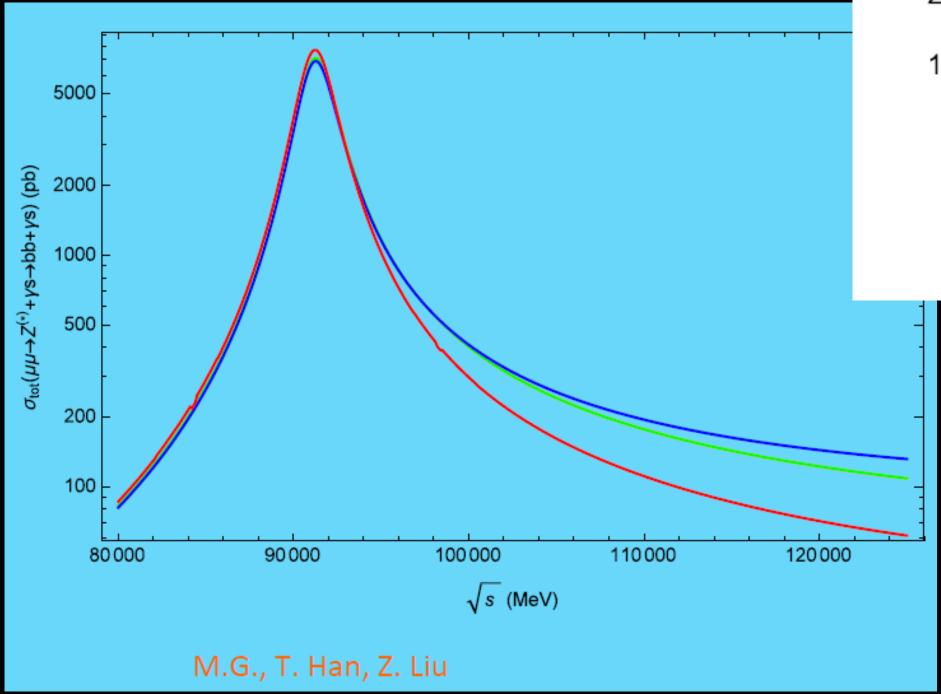


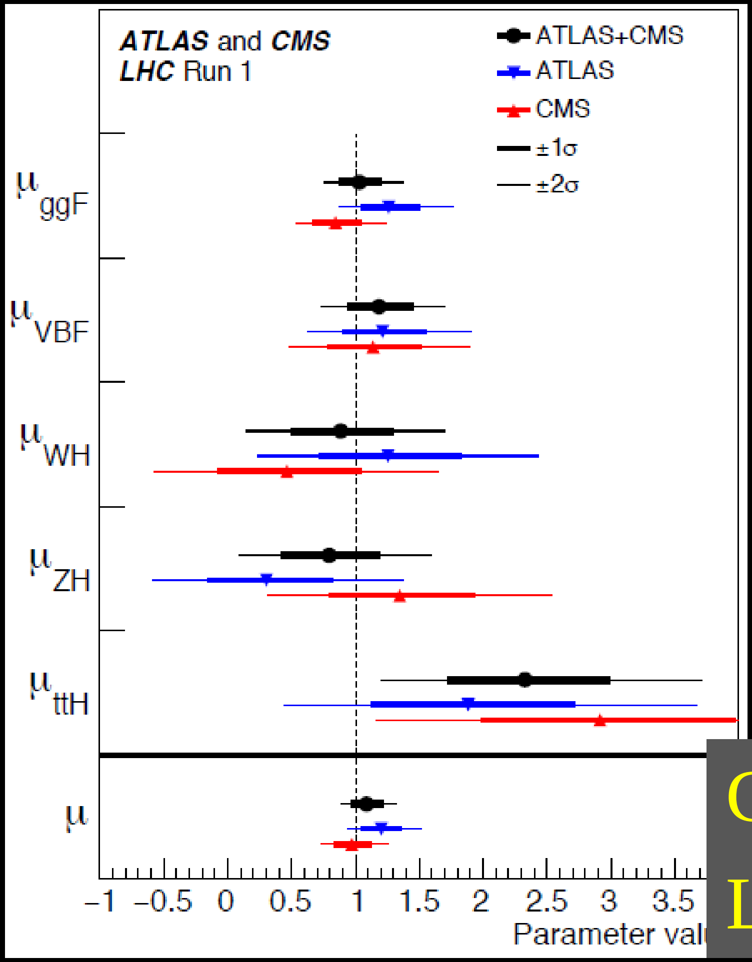
Muon collider on Higgs energy

- S/N not optimal
  - $\sigma_H \sim$ 5-15 pb
  - $Z+Z\gamma \sim$ 300 pb



Physics Letters B 763 (2016) 409–415



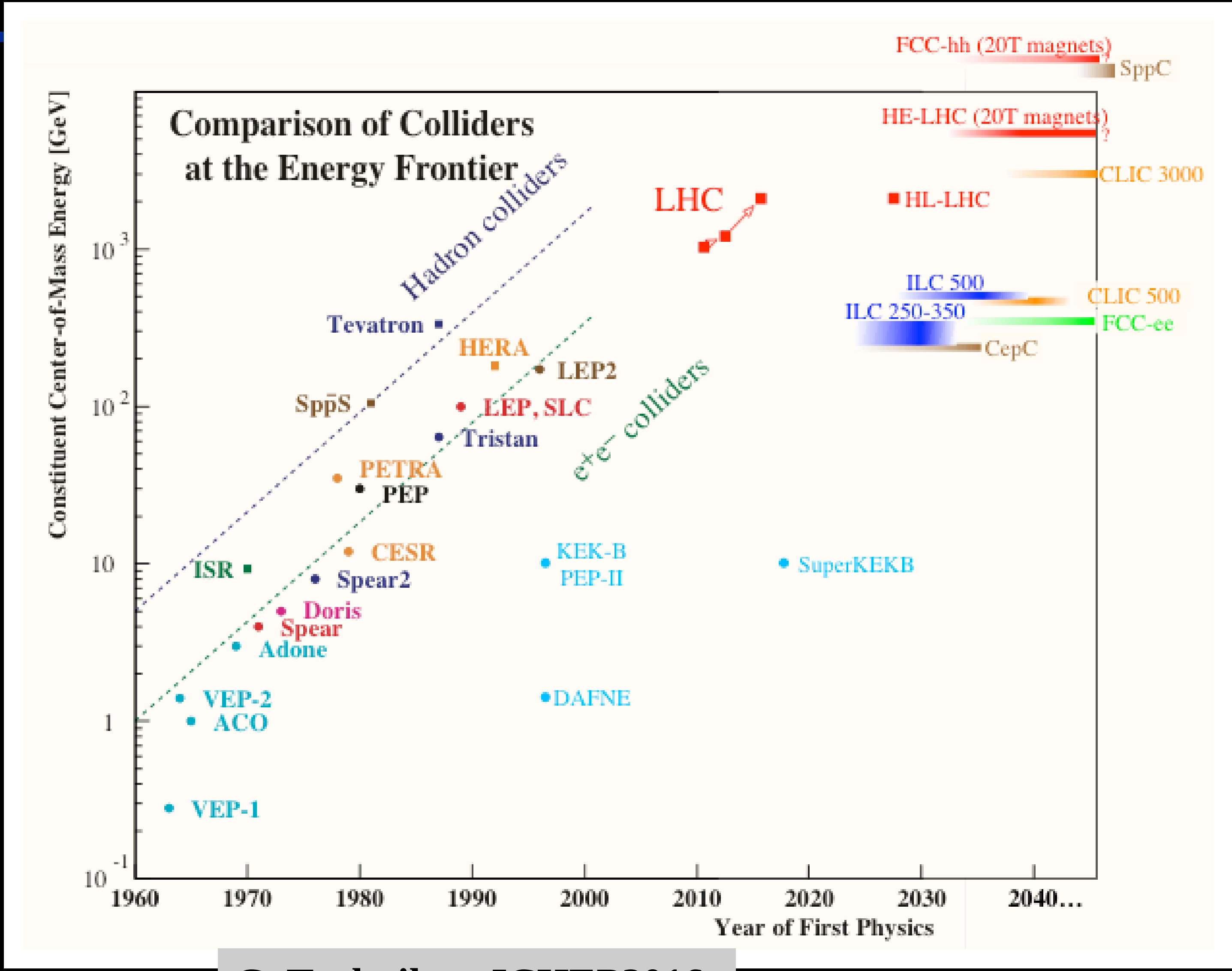


Courtesy of G. Ortona
Lake Louise 2017

CepC funding status

- From R. Manqi presentation at CERN FCC physics week, January 2017

- R&D issues identified & funding request underway
  - IHEP **seed** money: 12 M CNY/3 years
  - MOST: 35 M/5 yr **approved**, ~ 40 M to be asked next year
  - NCDR (13th 5 year plan): ~ 0.8 B/5 yr, **failed** in voting process
  - CAS & CNSF: **under discussion**, hopefully ~ 50 M/y



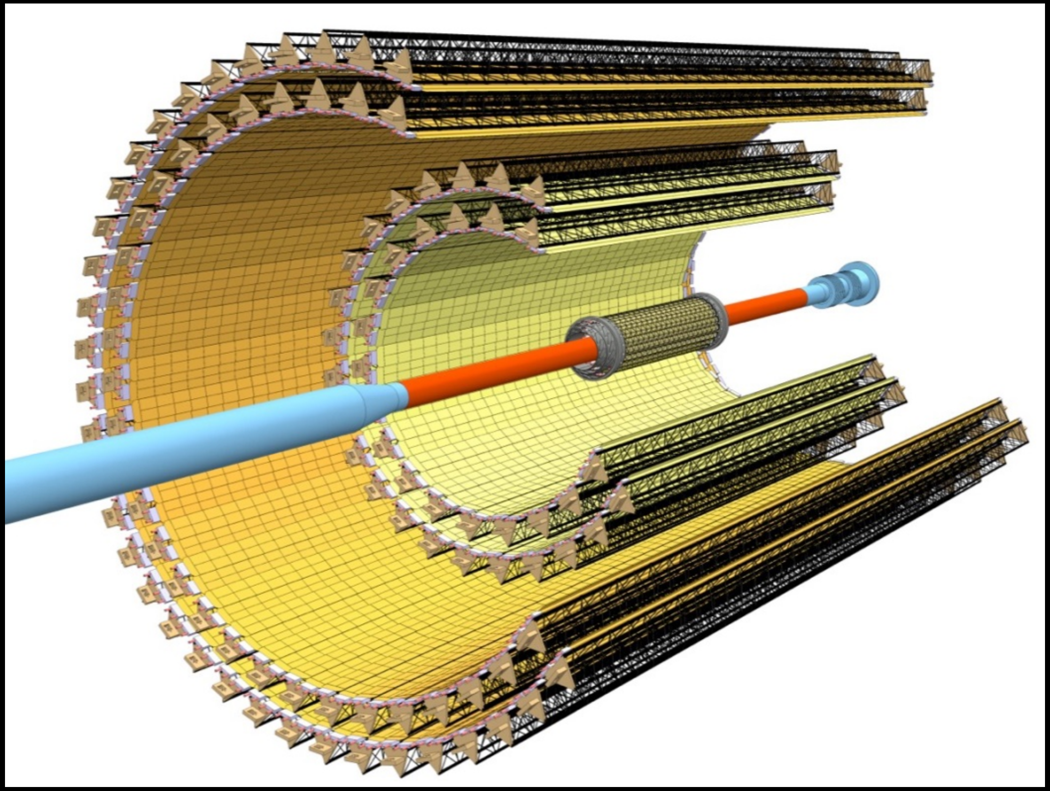
G. Trubnikov, ICHEP2016

IDEA

- International Detector for Electron-positron Accelerator
- Basic concepts:
  - Low field magnet (2T) → can be thin < 1 X_0
    - No compensation problems
    - Low field → small yoke for muon system
  - Fast signal collection: TPC → Drift Chamber (150 ns max d.t.)
  - Si/MPGD based preshower for excellent acceptance determ.
  - Calorimetry outside magnet
    - No compromises on shower containement
    - Maintain large tracking volume

Vertex detector

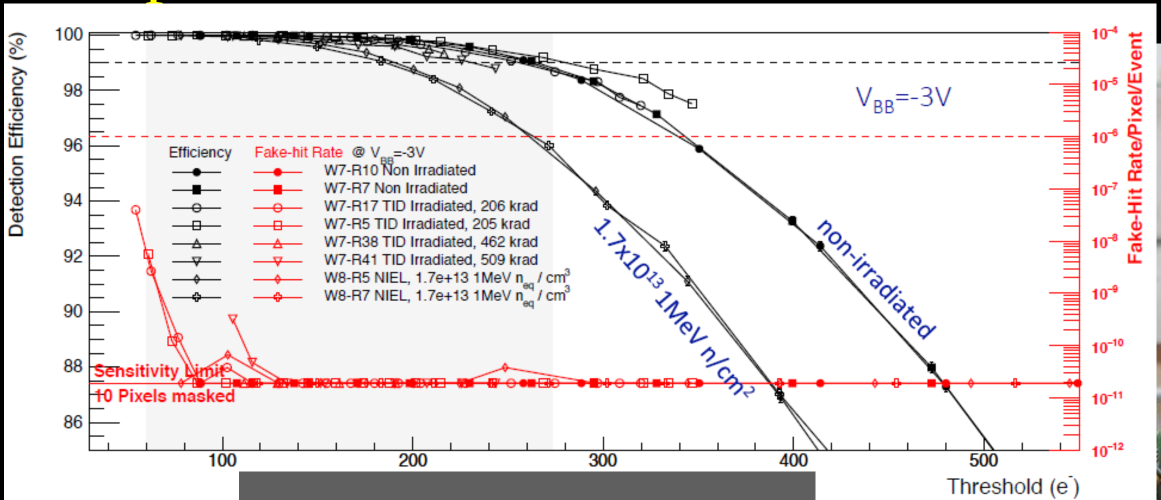
- Build on ALICE ITS technology
  - 30x30 μm MAPS
  - %X0
    - 0.3-1.0% (in-out)
  - Power:
    - 41-27 mW/cm2 (in-out)
  - Radiation hard
  - >100 kHz readout



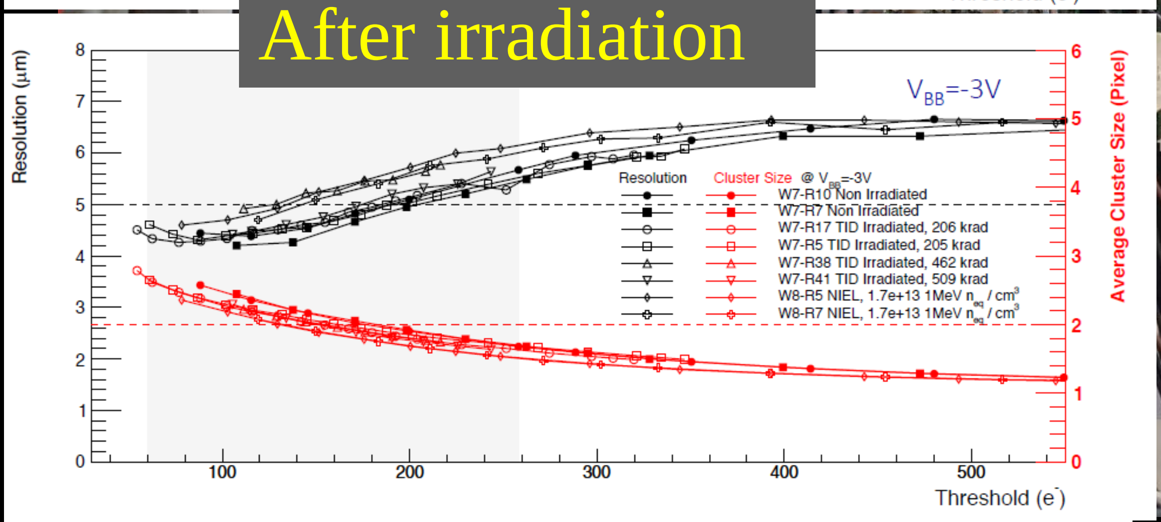
- To be optimized
  - Excellent work by Chinese groups

Vertex detector

❖ Impressive recent test beam results



After irradiation



Courtesy of ALICE J.W. van Hoorne

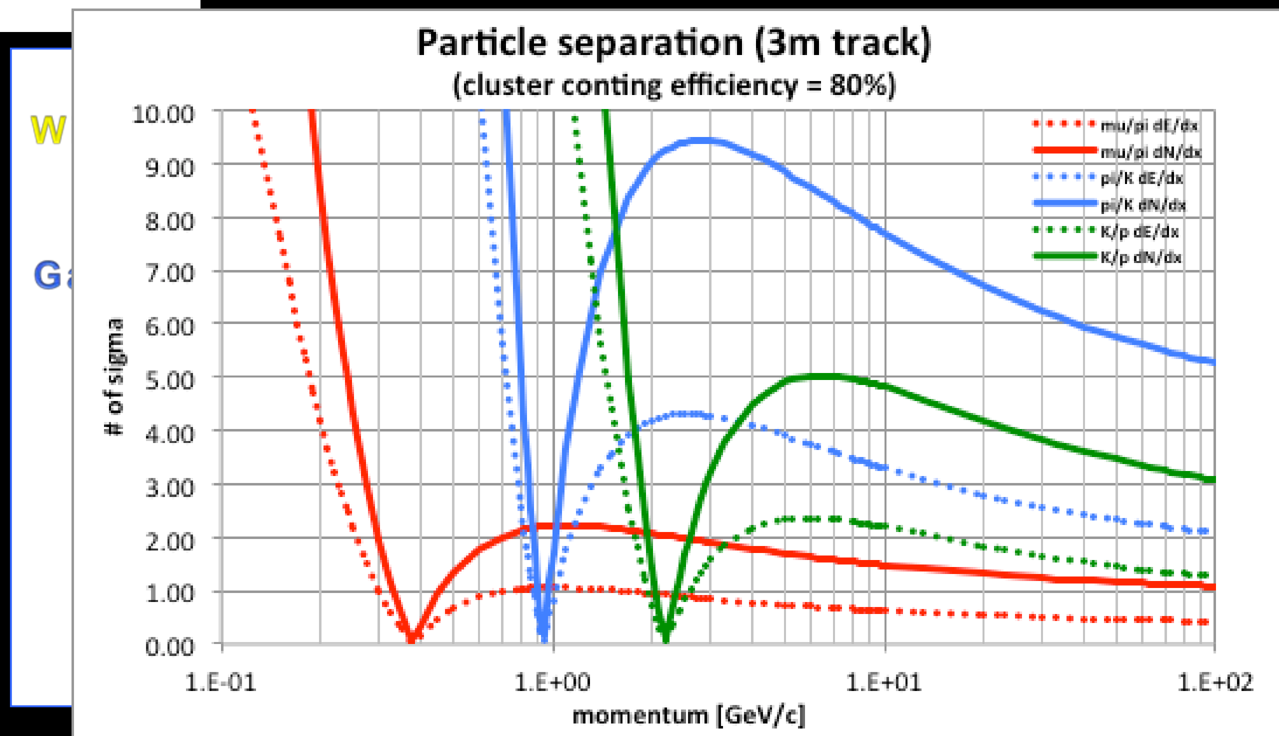
Tracker

- Drift Chamber: fast, small ion buildup, good dE/dx
  - Ultralight chamber (<1% X_0) – gas: He 90% - iC_4H_{10} 10%
  - 4 m long, drift length ~1 cm, drift time ~150ns, σ_{xy} < 100 μm

$$\frac{\Delta p_\perp}{p_\perp} = \frac{8\sqrt{5}\sigma}{.3BL^2\sqrt{n}} p_\perp = 7.1\times10^{-5} p_\perp [GeV/c]$$

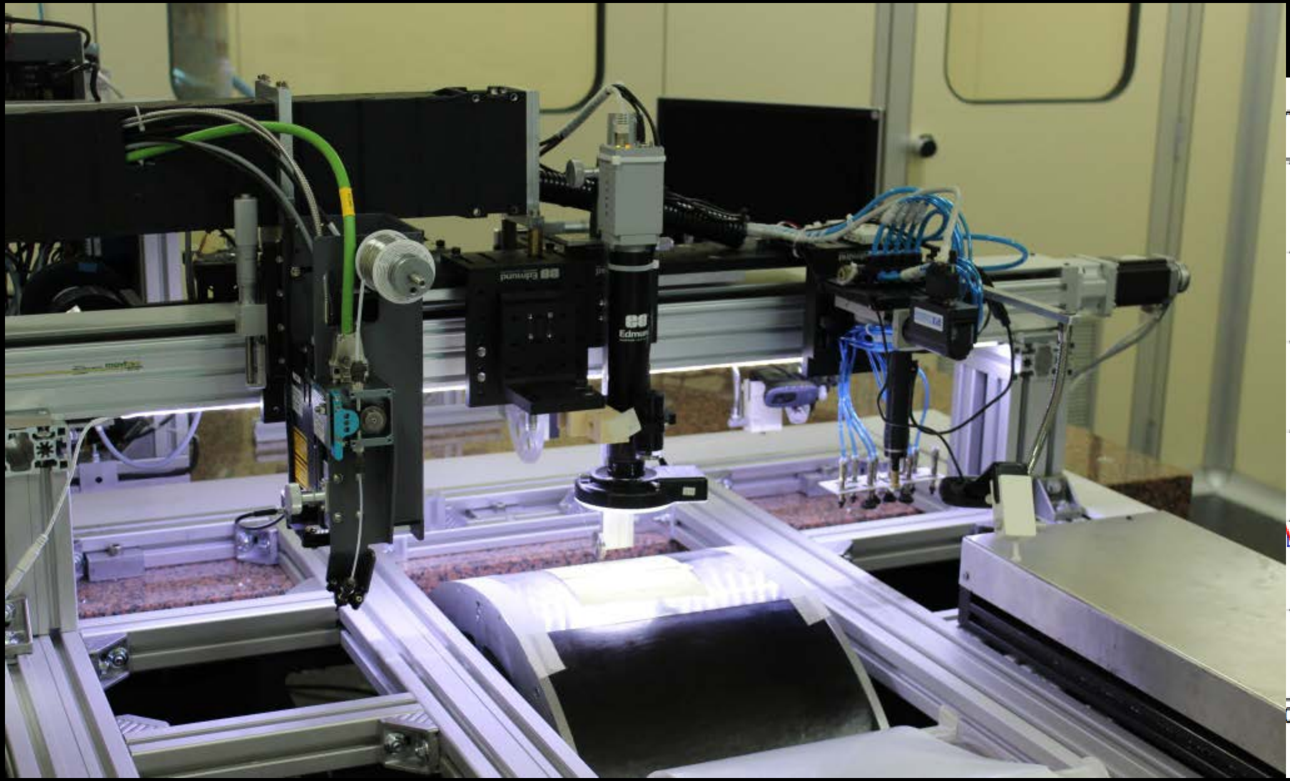
- B = 2 T
- L = 2 m
- N = 112

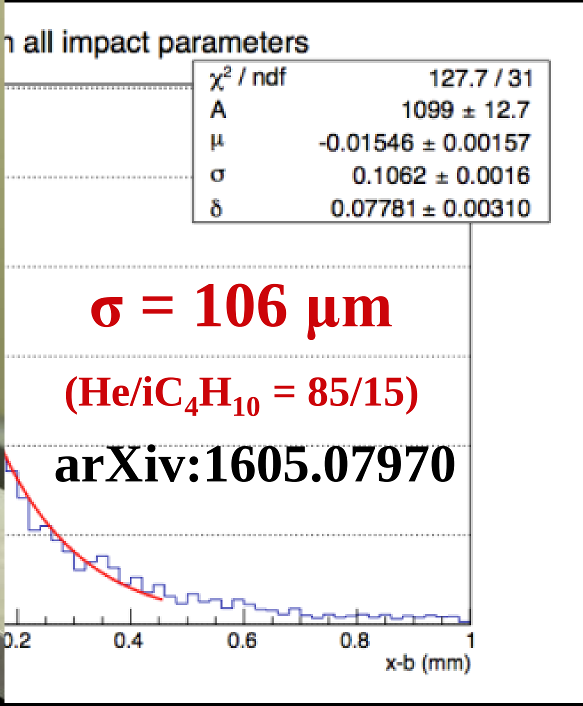
  - dE/dx ~ 4%
  - dN/dx ~ 2%



Tracker

- Minimal performance established (MEG-II prototype)
- Technical solutions engineered (MEG-II)
  - E.g. Wire stringing and soldering machine

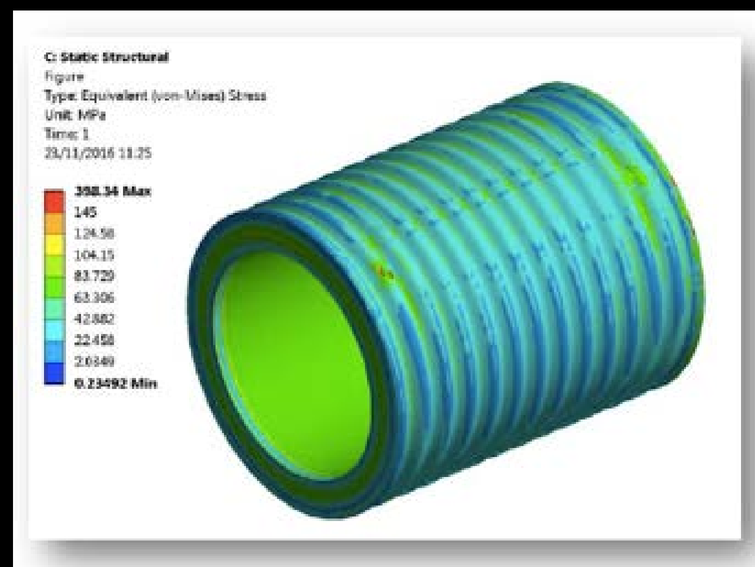




2T solenoid

- Two options:
  - Large bore (R=3.7 m) – calorimeter inside
  - Smaller bore (R=2.2 m) – calorimeter outside
    - Preferred: simpler/ Extreme EM resolution not needed
      - Thick calorimeter/ Coil is part of preshower absorber
    - Thin (30 cm): total = $0.74\ X_0$ ($0.16\ \lambda$) at $\theta = 90^{\circ}$

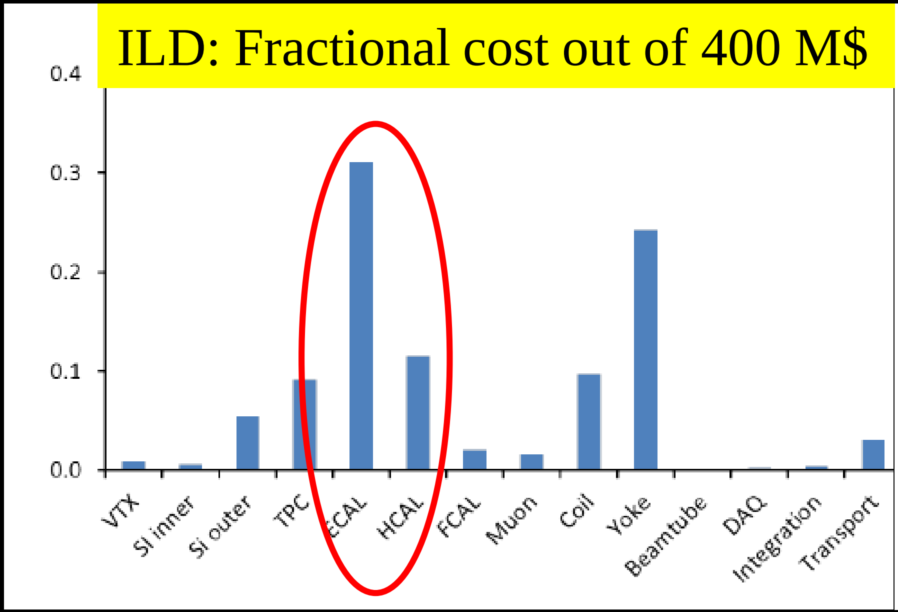
Property	Value
Magnetic field in center [T]	2
Free bore diameter [m]	4
Stored energy [MJ]	170
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6

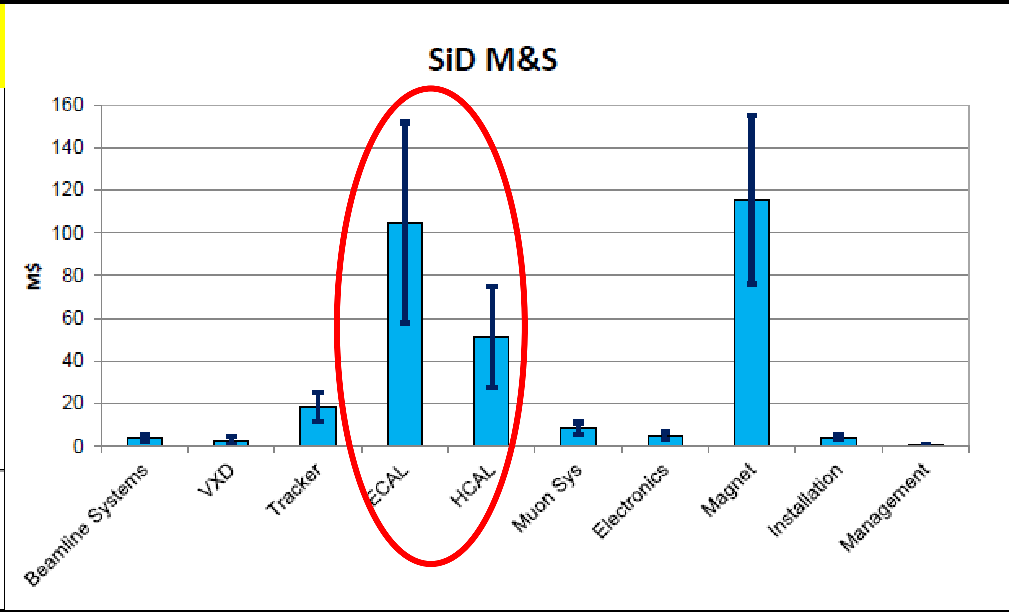


Courtesy of H. ten Kate et al.

Calorimeter

- Particle flow calorimeters are extremely expensive!
- Similar (or better) performances with dual readout
  - EM and HAD in same calorimeter
  - High transverse granularity

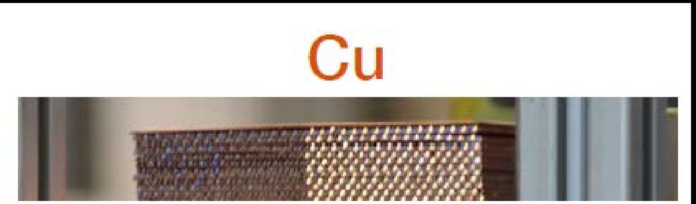


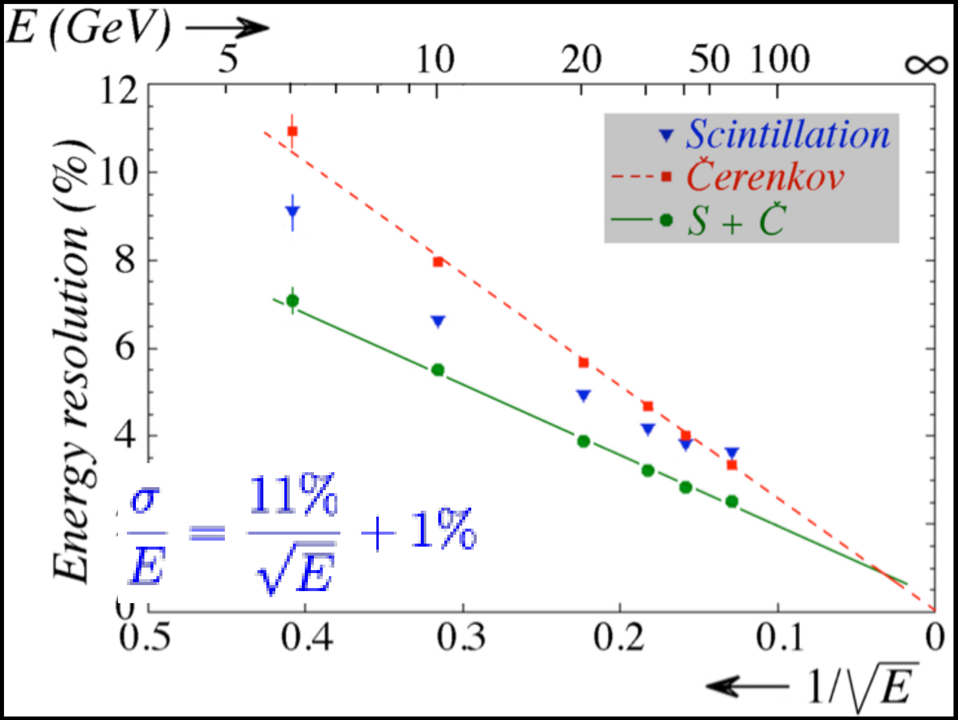


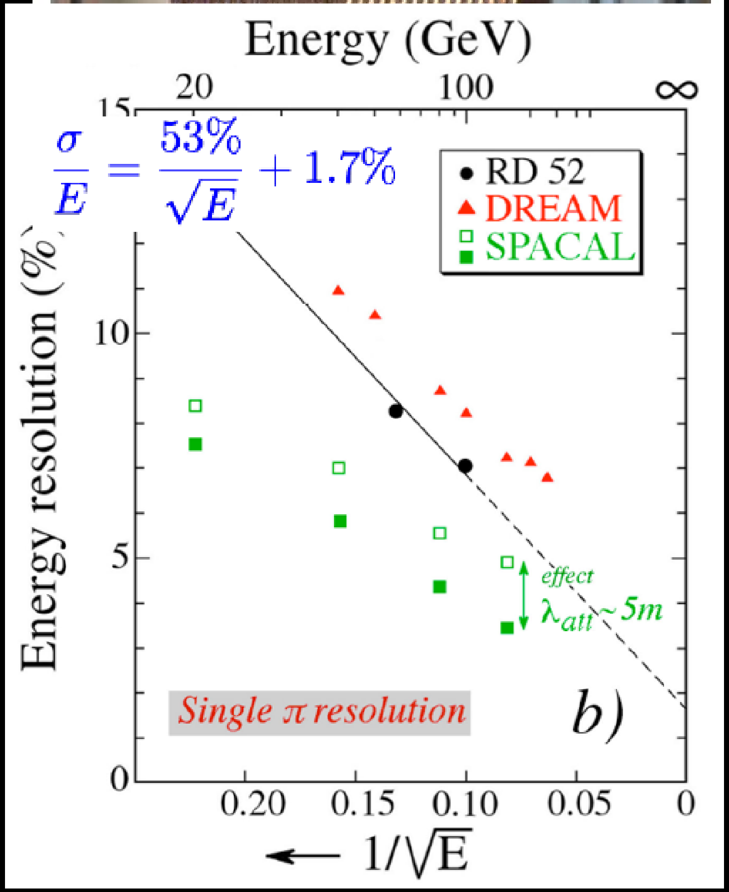
Calorimeter

- Copper dual readout calorimeter
  - Demonstrated EM resolution
  - Observed Had resolution dominated by lateral leakage (~6%)

Courtesy of DREAM/RD52

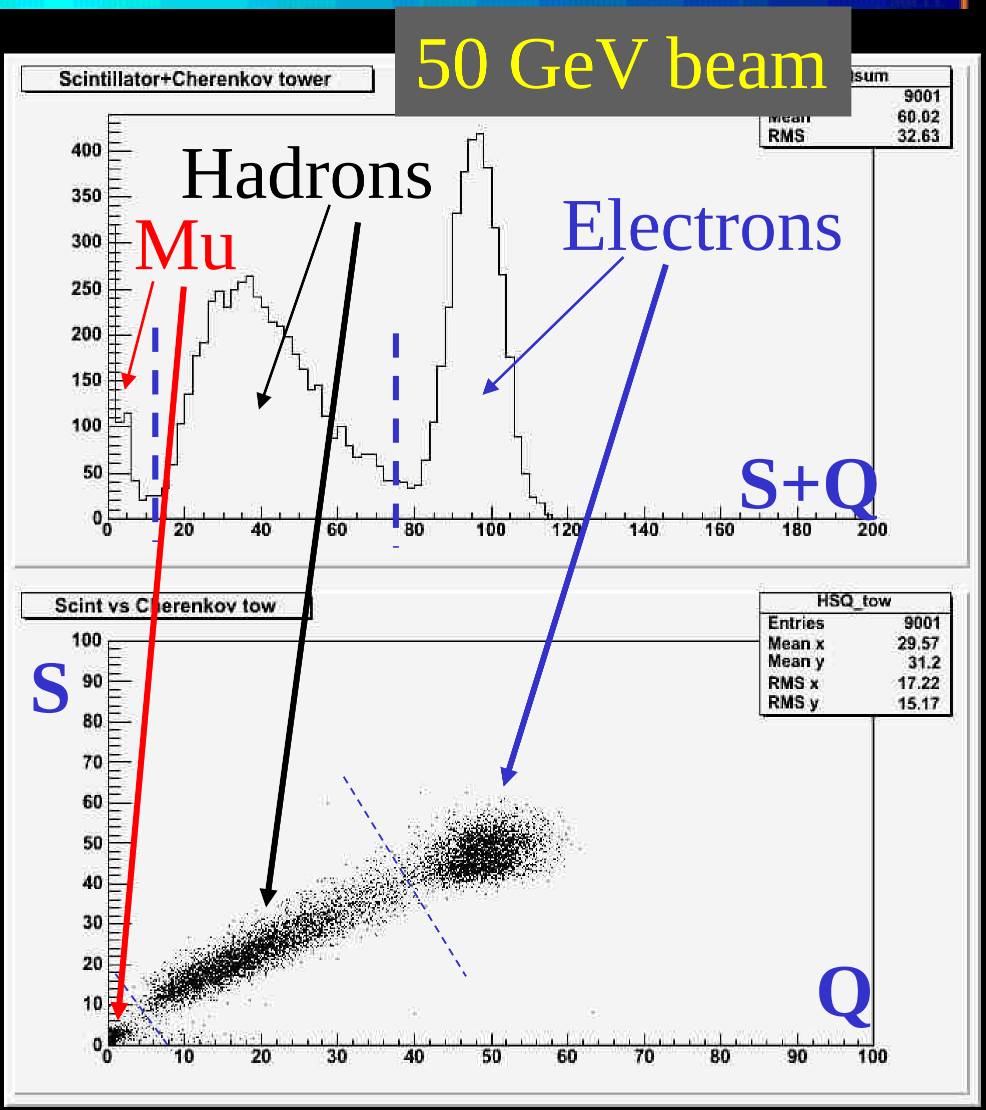






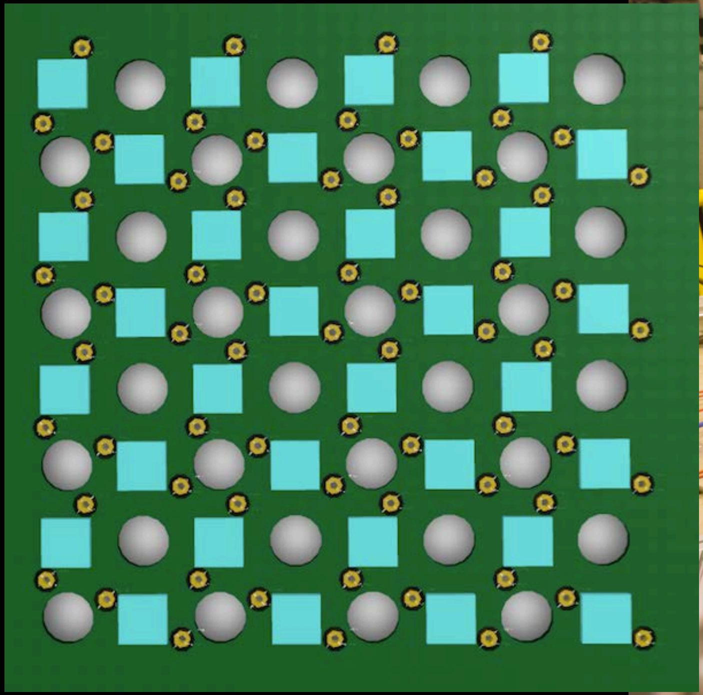
Calorimeter

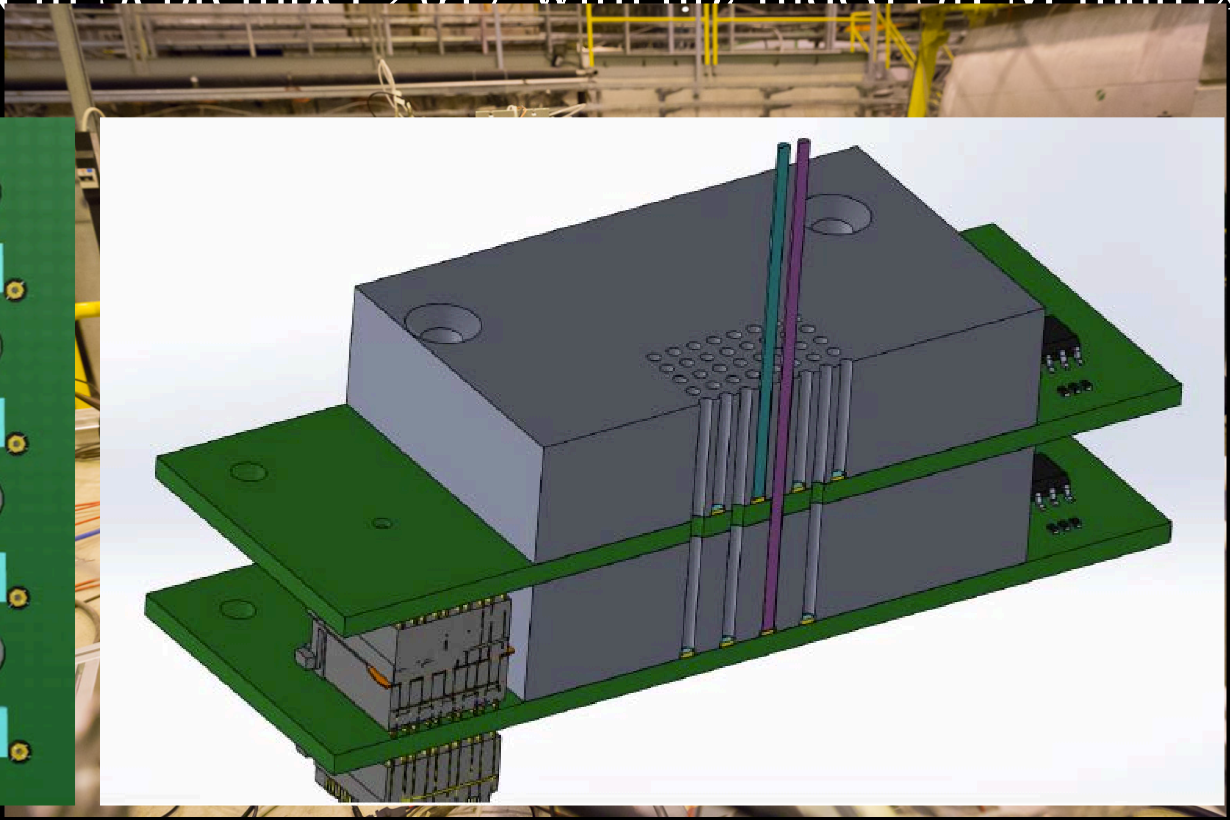
- Potential resolution in jets
  - ~ 30-40%/$\sqrt{E}$
    - (see 4° detector concept LOI)
- Natural μ/π/e separation
  - Can improve with timing and lateral shape cuts
    - ε_{el} > 99%, <0.2% π mis-ID
- Preshower (~2 X_0)
  - Acceptance determination
  - e/γ /π^0 separation
    - Si or MPGD
      - Synergy with part. flow



Calorimeter R&D

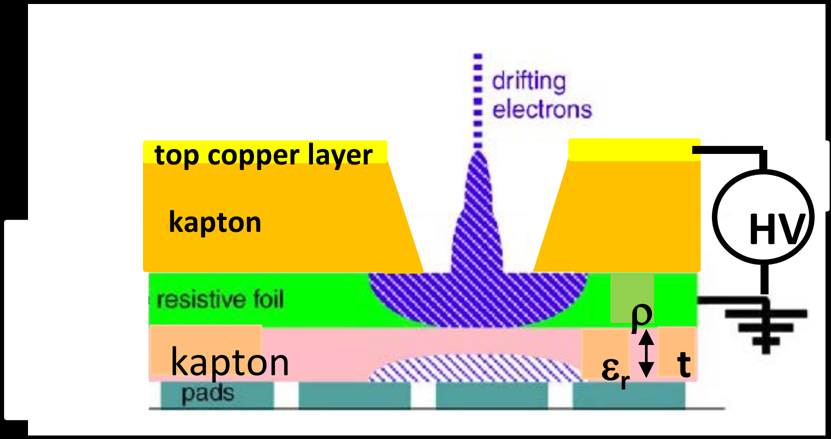
- SiPM readout studies in progress
  - Test beam@CERN in June 2016
  - Test beam@CERN in September 2017 with upgraded SiPM matrix





Muons

- Momentum measurement
  - Vertex+DCH: ~ 0.5% @ 100 GeV
- Better muon ID:
  - More filter behind calorimeter
    - Iron yoke (~50 cm Fe)
  - Followed by additional chambers
    - μ-RWELL low-cost technology already proven for low rate applications (CMS/SHiP)



Summarizing ....

- Beam pipe (R~1.5 cm)
- VTX: 4-7 MAPS layers
- DCH: 4 m long, R 40-200 cm
- 2 T, R~2 m SC Coil
- Preshower (1-2 X_0)
- DR calorimeter (2 m/8 λ_{int})
- (yoke) muon chamber