Future Circular Colliders

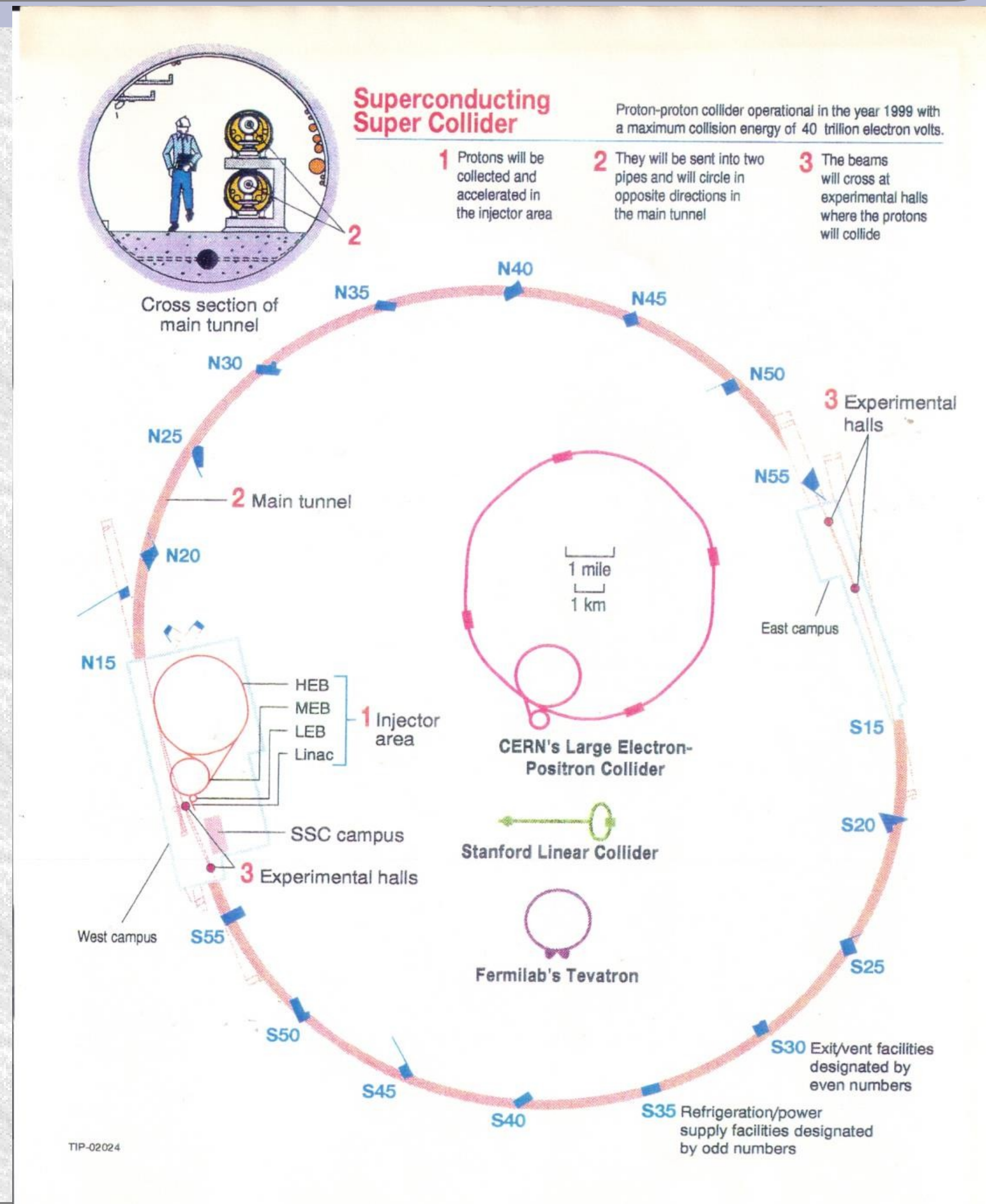
W. Murray, Warwick/STFC-RAL

Birminham 27th Nov 2019

Fcc-ee, CepC, Fcc-hh, CppC

The SSC

- 40 TeV ‘Throw Deep’ pp collider sited in Texas
- Cost estimates:
  - 1982: $1-3 Billion
  - 1983: $1.4-2.2 B
  - 1986: $3.01 B
  - 1987: $4.5 B
  - 1989: $5.9 B
  - 1991: $8.25 B
  - 1993: $9.94 B
  - 1993’: $10.45 B – Cancel
- US ‘vanity’ project
  - Cold war ended...



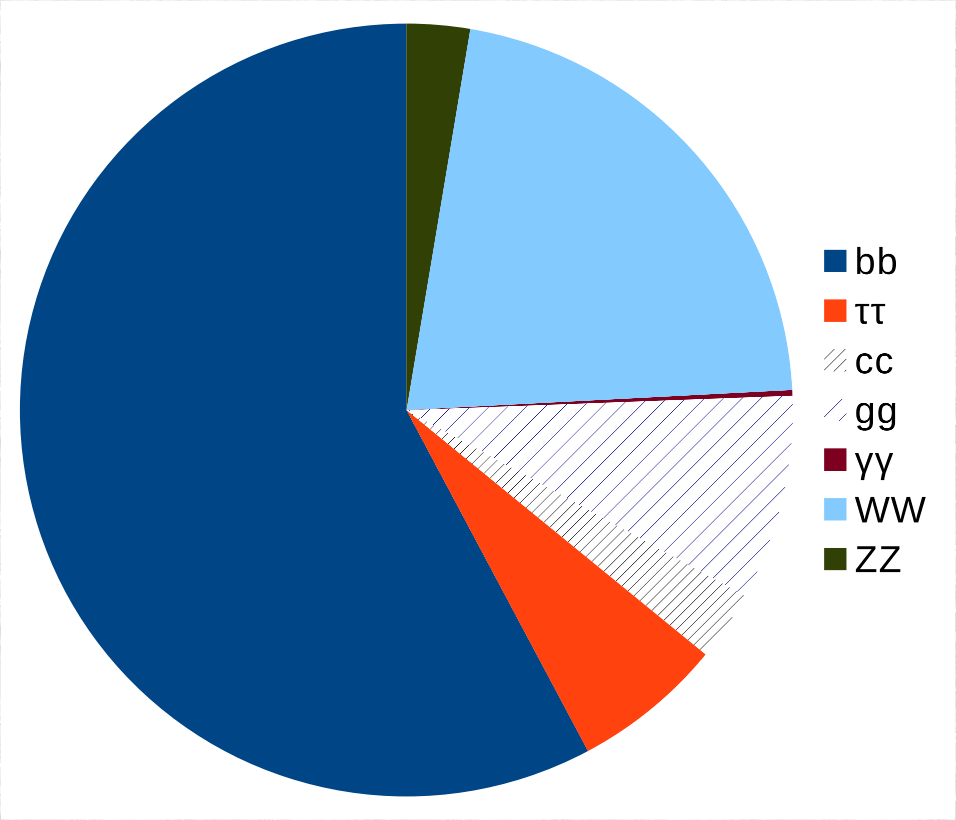
Cancelled: with a lot spent

North Campus

Tunnel

The Higgs Boson

- The defining discovery of the LHC – so far
  - It completed a picture imagined in 1964
- The mass of 125 GeV allows many observations:
  - Decay to ZZ, γγ, WW, ττ, bb all observed at 5σ
  - Same for ggH, VBF, VH and ttH production
- Expected CP-even scalar fits observations well
- Mass is measured to 0.2%
- Job done?



Problems facing the SM

- Gravity
  - We do not have a working theory of quantum gravity
- Neutrino Mass
  - Neutrinos have mass – but how? We do not know
- Dark matter
  - Most matter in the Universe is something unknown
- Dark energy
  - What accelerates the Universe expansion?
- Matter-antimatter asymmetry
  - Where did the antimatter go after the big bang?
- The hierarchy or naturalness problem
  - Why is the Higgs so light?
- **HL-LHC & Future colliders might answer any**

Future colliders..why?

- Juegen D'hondt, ECFA Chair:

Towards new discoveries via the Higgs sector

- No clear indication where new physics is hiding, hence experimental observations will have to guide us in our exploration.
- One of the avenues is to explore as fast as possible, and as wide as possible, the Higgs sector.
  - Yukawa couplings
  - Self-couplings (HHH and HHHH)
  - Couplings to Z/W/γ/g
  - Rare SM and BSM decays (H→Meson+γ, Zγ, FCNC, μe/$\tau\mu$/τe, …)
  - CP violation in Higgs decays
  - Invisible decay
  - Mass and width
  - …
- Important progress will be made on Higgs physics with the LHC and the HL-LHC.
- To discover new physics inaccessible to the (HL-)LHC, future colliders will be complementary.

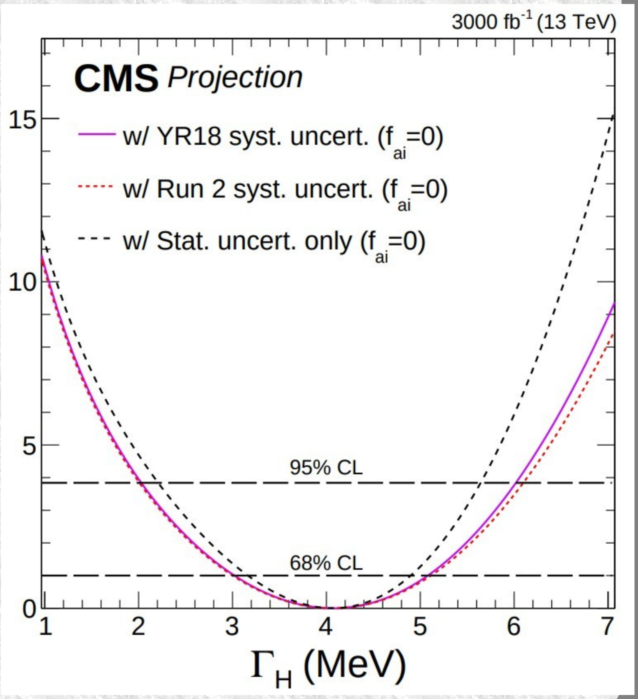
- Whatever further is discovered at LHC:
  - We will want to pursue this list

Expected Background

- How far will HL-LHC take us?

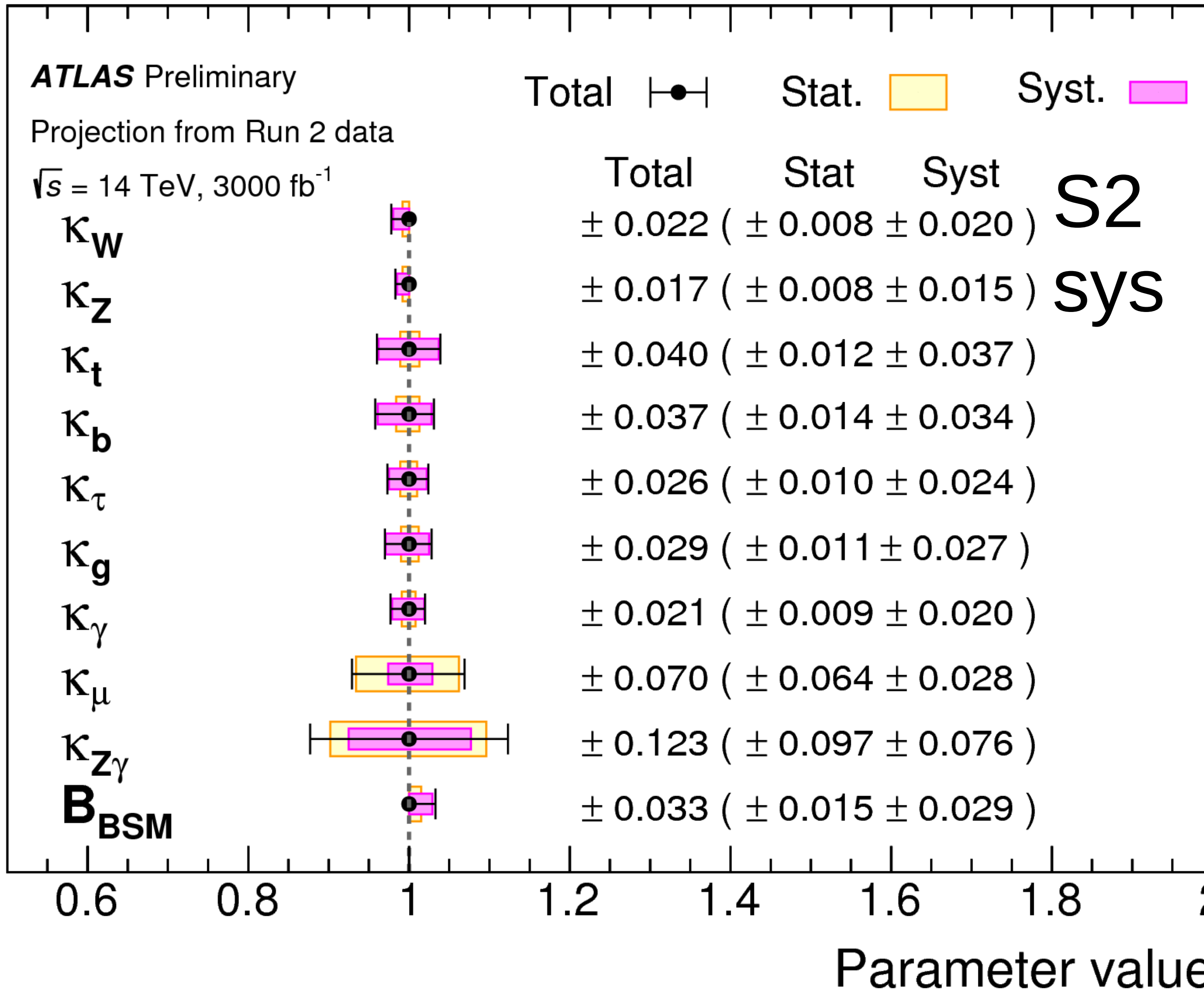
Higgs mass and width

- Higgs mass in 4-lepton from will improve
  - ATLAS currently 240 MeV error
  - 52 MeV if no improvements made
  - 47 MeV if ITk yields 30% resolution improvement
  - 33-38 MeV If also scale uncertainty reduced 50-80%
  - *No current theory need for better*
- $H \rightarrow \gamma\gamma$ systematics more important
- Width from off-shell couplings
  - CMS project range 2-6 MeV @95%CL
    - S1/S2 similar here
    - Statistics are important



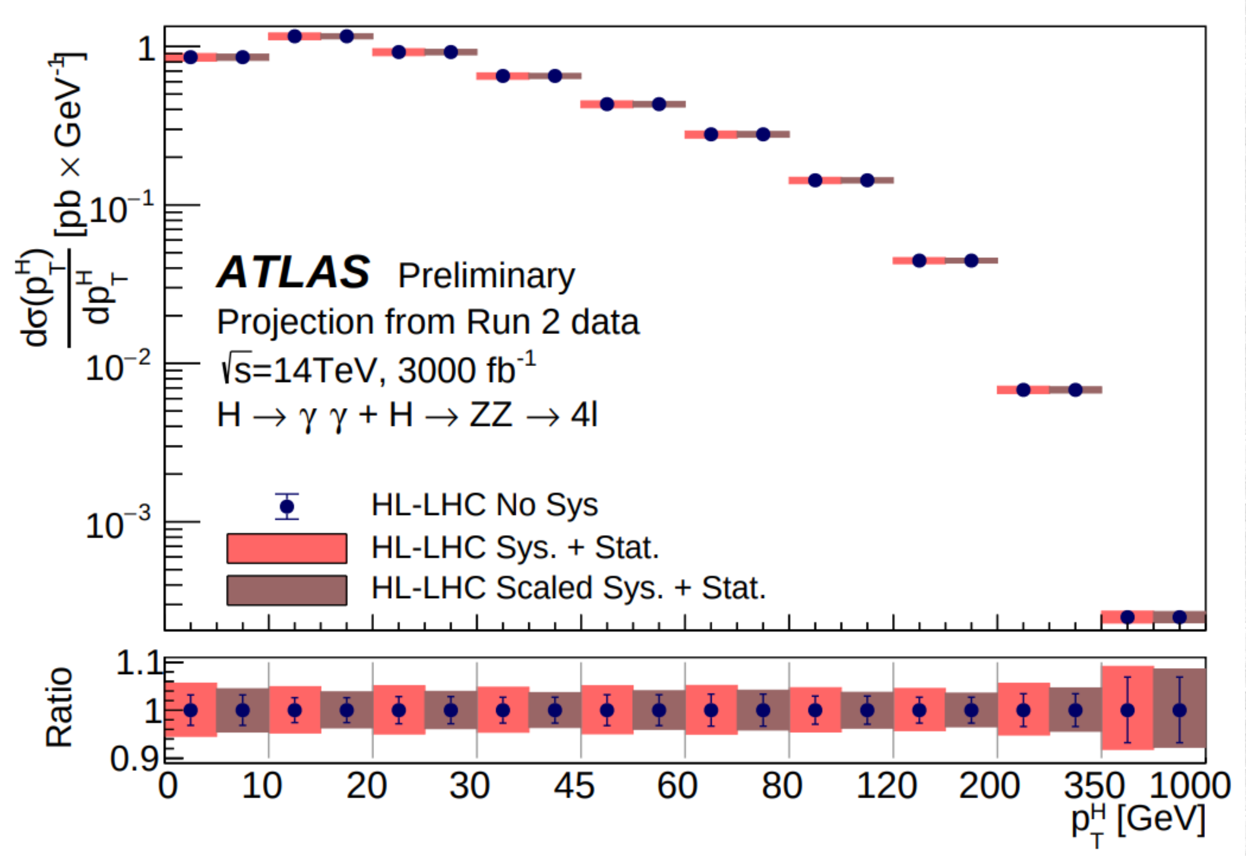
Extracted couplings

- 10 parameter general fit
  - Imposing UL on W,Z
- Gives 2-4% precision
  - Except μ & Zγ
- 3.3% limit on non-SM decays, e.g. DM

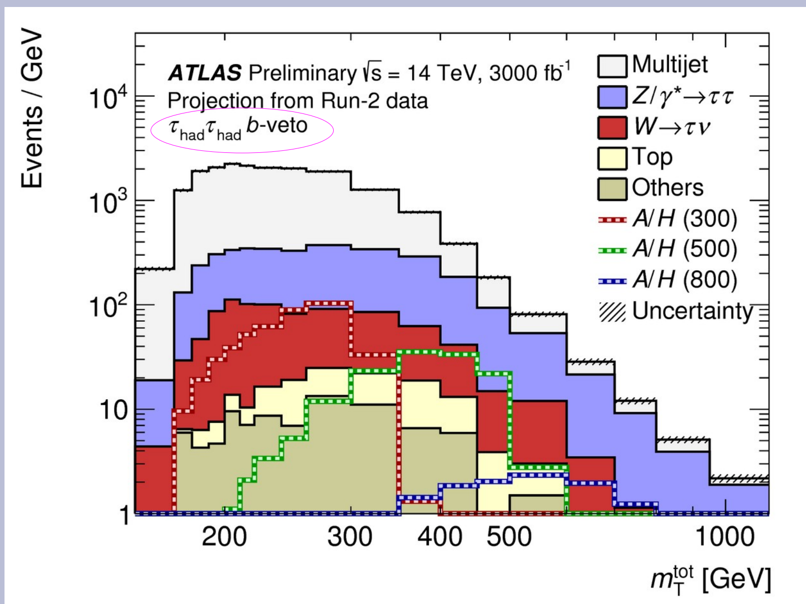


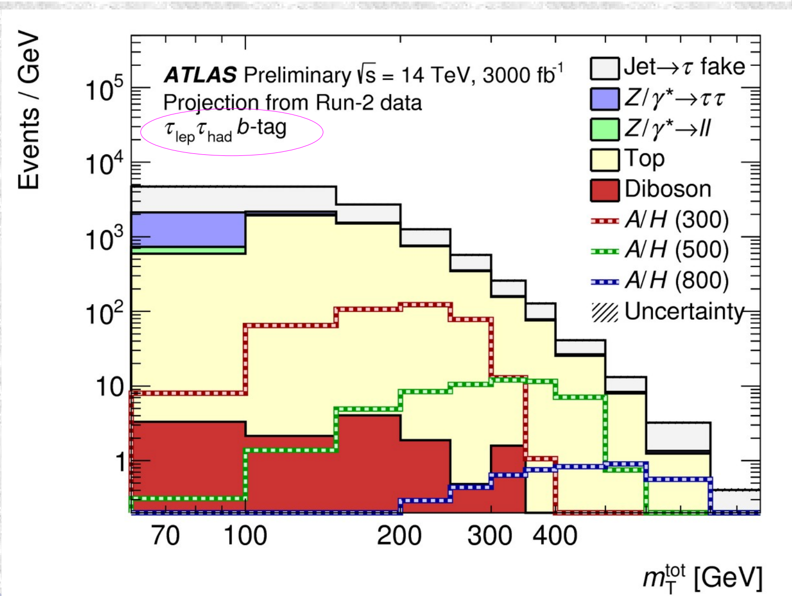
Differential distributions: ZZ+γγ

- Higgs p_T up to 1 TeV 10% precision or better
  - Statistics important
- High-pT bin can be divided
- May add $H \rightarrow \tau\tau$ & $H \rightarrow bb$ at high p_T.
- Some BSM operators are enhanced at high p_T

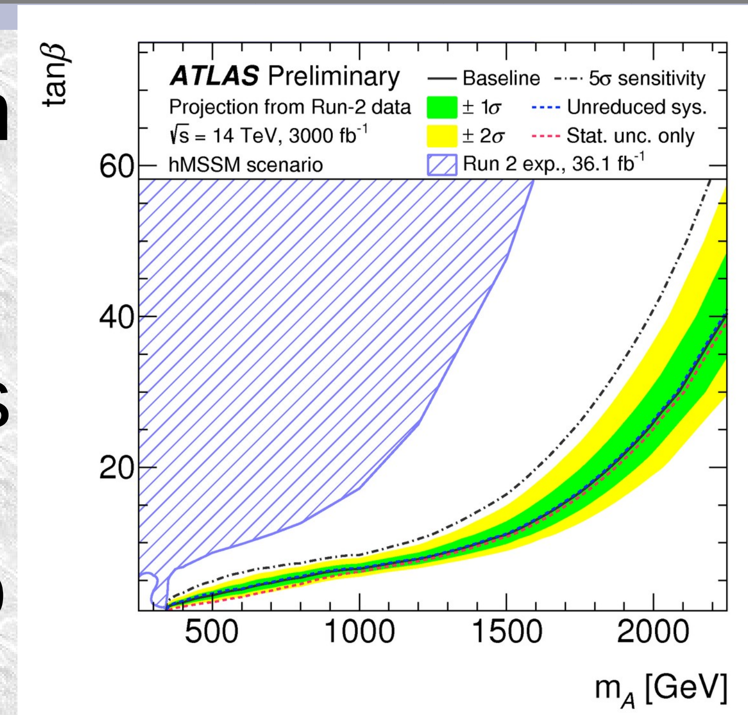


Searches continue: h/A to ττ





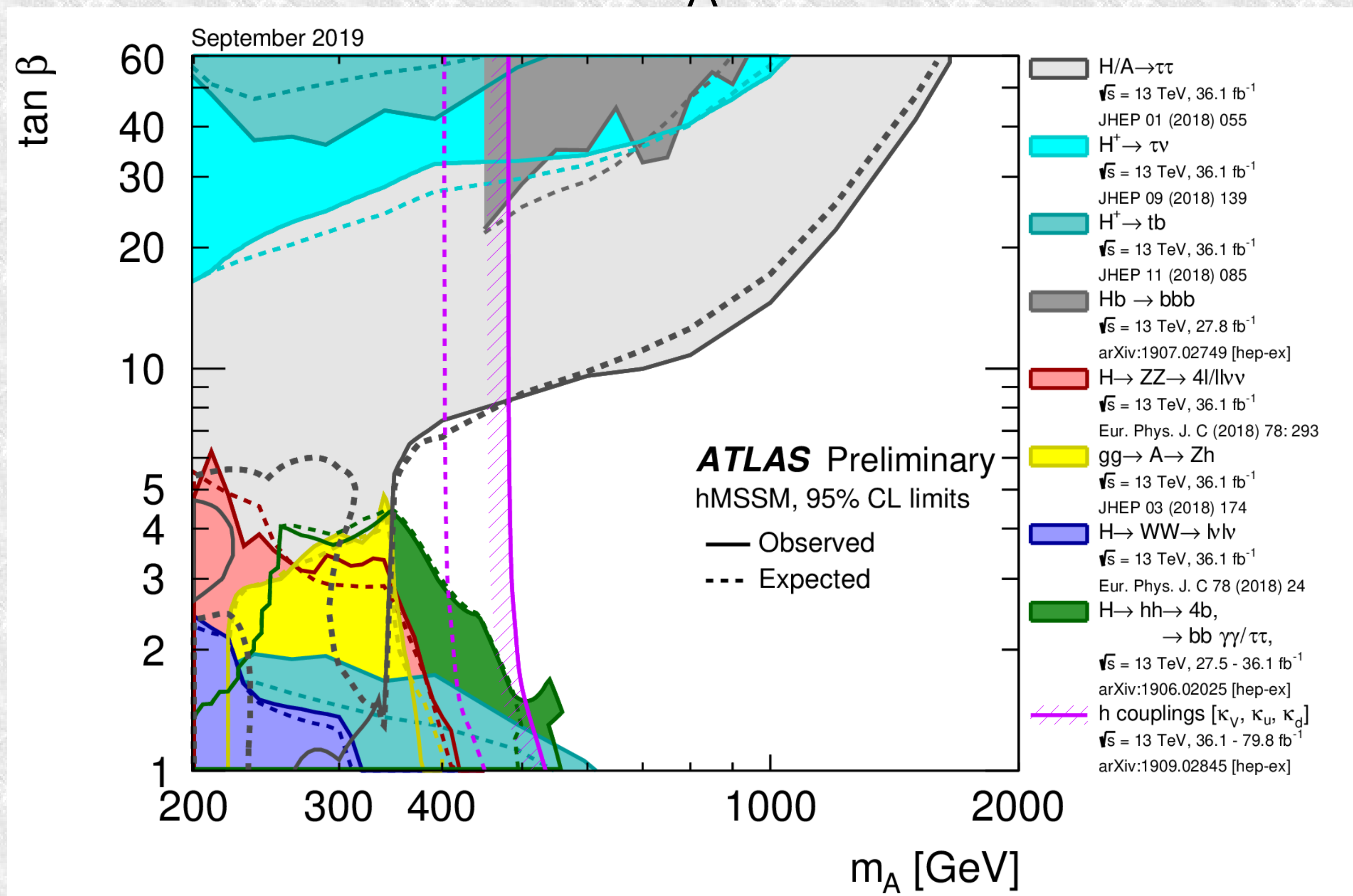
- Tau pair in l-h and h-h channels
- with b-tag or b-veto



- Expect to be sensitive to tan β>12 for m_A<1.5TeV in hMSSM
- Best channel for high tan β

Direct v Indirect studies

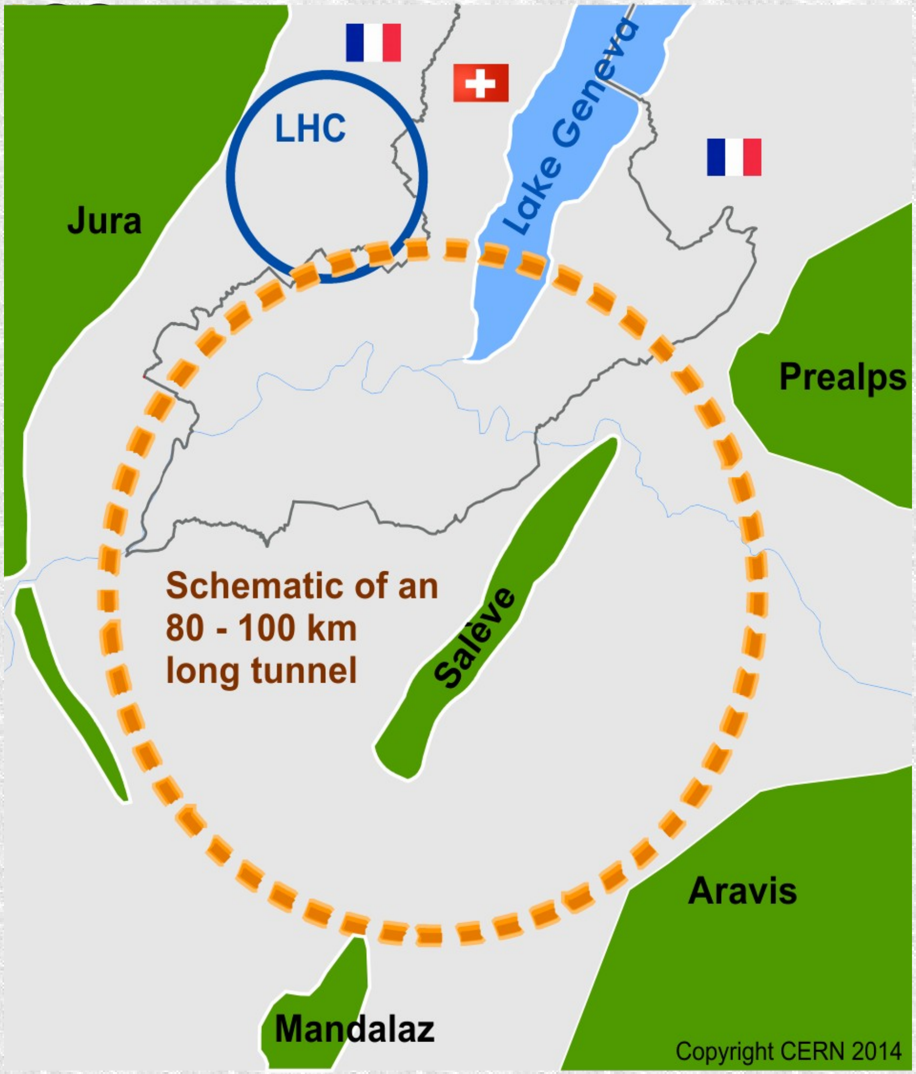
- Example: SUSY Higgs sector, m_A and tan β
- Direct searches (solid) and indirect (purple line) have comparable reach
- We learn a lot from Higgs couplings



Four 100km machines

- ee collider
  - 90 GeV- 240/365 GeV (Z, WW, HZ, tt)
  - Clean, Precision Higgs and EW physics
  - Little R&D to do
- pp collider
  - ~100 TeV
  - Deep search, some fantastic precision, κ_λ (HHH)
  - Technologically & financially more challenging
- CERN
  - Established facilities, track record, excellent working model
- China
  - Potential new entry in high-energy frontier

Where?



7 sites considerd – detailed work ongoing

First: ee

- Design clearer
- Less technological challenges

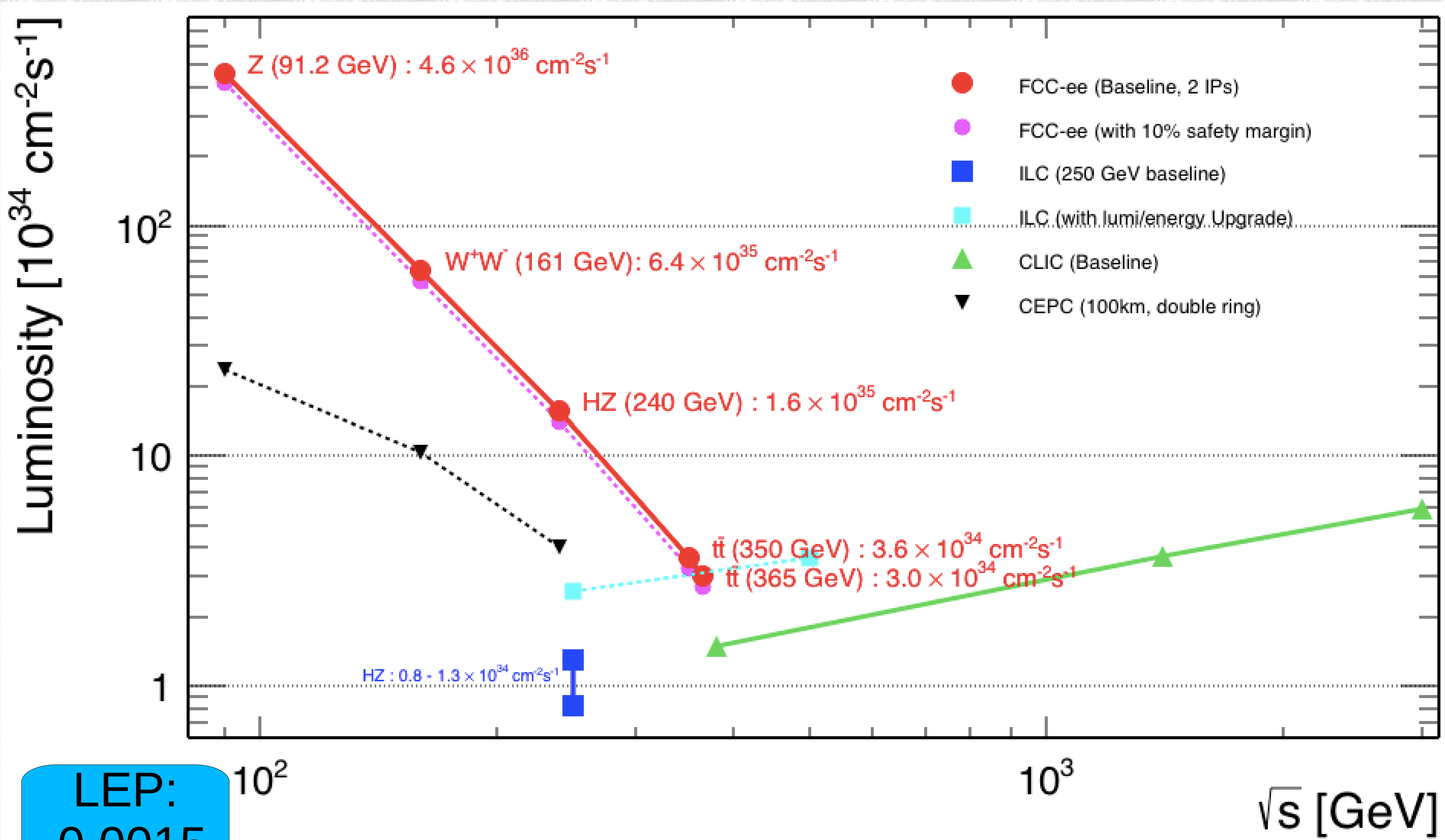
A reminder of brehmstrahlung

- Electron synchrotron’s energy is limited by brehmstralung losses
  - Proportional to E^4/r^2
- LEP at 103 GeV/beam had 18 MW of synchrotron radiation
  - It needed 3.6 GV acceleration,
- Double LEP’s energy would have needed 288 MW
  - 57 GeV lost per turn for 206 GeV beams
    - Its approaching a linear accelerator
    - But without the tiny spot sizes
- But with 100km tunnel power is divided by 16

So why circular ee?

- LEP, 207 GeV, was seen as last big circular ee collider
- Focus was on 500-1000+ GeV as target energy
  - This is the regime of linear colliders
- Change of perspective came from low Higgs mass
  - ZH production rate peaks at 240 GeV
    - Only 15% above LEP's limit
  - Suddenly interest in circular ee revived
- Focus shifted to luminosity:
  - Higgs production at ee is far below pp rates
- Maximise luminosity with continuous top-up
  - 2-ring machine, one collider and one accelerator
- Plus larger ring minimises power bill for luminosity

Luminosity v energy



LEP: 0.0015

Fcc ee (CepC) parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390 (460)	147 (88)	29 (17)	5.4
no. bunches/beam	16640 (12000)	2000 (1524)	393 (242)	48
bunch intensity [10^{11}]	1.7 (0.8)	1.5 (1.2)	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)	0.2 (0.36)	0.3 (0.36)	1
vertical beta* [mm]	0.8 (1.5)	1 (1.5)	1 (1.5)	1.6
horiz. geometric emittance [nm]	0.27 (0.18)	0.28 (0.54)	0.63 (1.21)	1.46
vert. geom. emittance [pm]	1.0 (4)	1.7 (1.6)	1.3 (3.1)	2.9
bunch length with SR / BS [mm]	3.5 / 12.1 (2.4)	3.0 / 6.0 (3.0)	3.3 / 5.3 (2.7)	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230 (16/32)	28 (10)	8.5 (2.9)	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

Run strategy

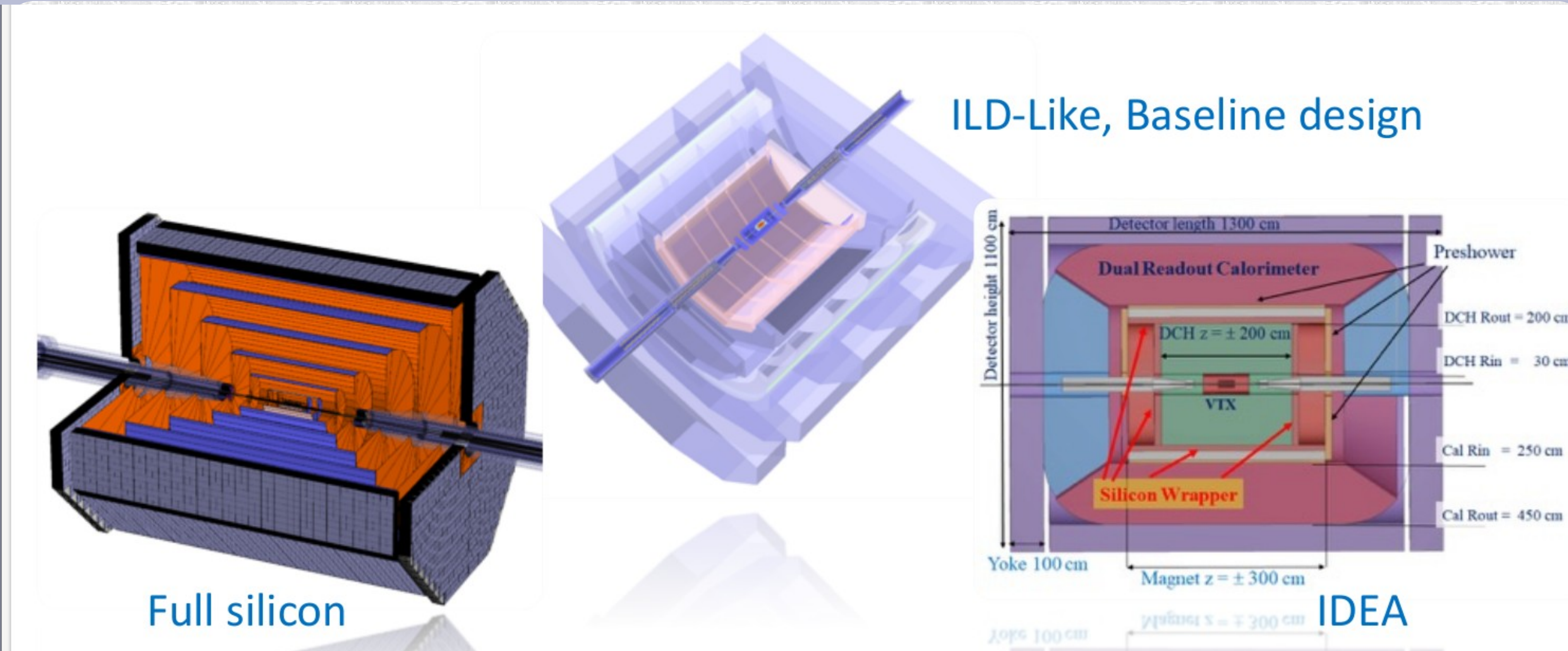
	Fcc-ee	CepC
Z	4 years	2 years
WW	2 years	1 year
ZH	3 years	7 years
tt	5 years	n/a

- Clearly these can change
  - But they reflects the priorities of the proposers

Commentary:

- FCC-ee is proposing ultimate ee collider ring
  - Covering Z peak to tt and preforming exquisite measurements at each
  - Designed by LEP experts who have seen it done once and now want to do it best
- CepC is proposing minimal Higgs-factory
  - Power budget limits luminosity and energy range
  - The aim is an affordable design for China
  - But if others join, and pay, these parameters can improve
- But the designs converge
  - CepC undoubtedly employs good features from Fcc-ee
  - But recently idea flow has been two-way

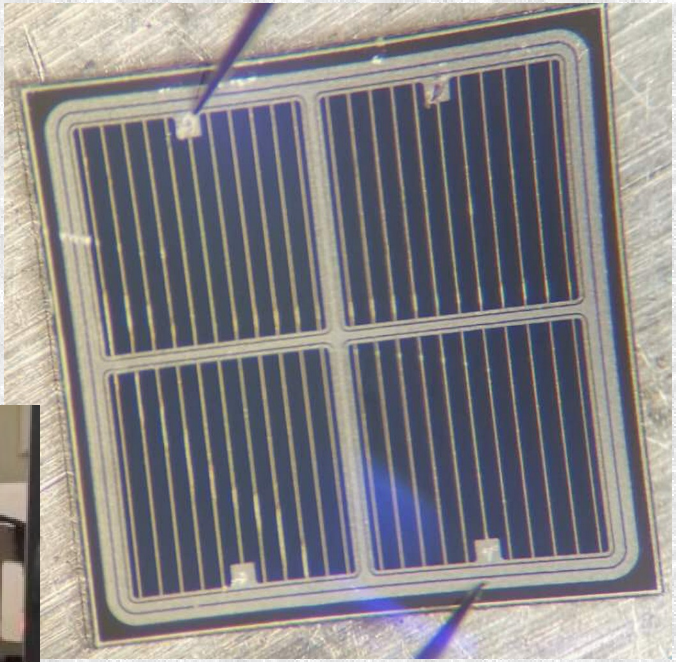
CepC detectors

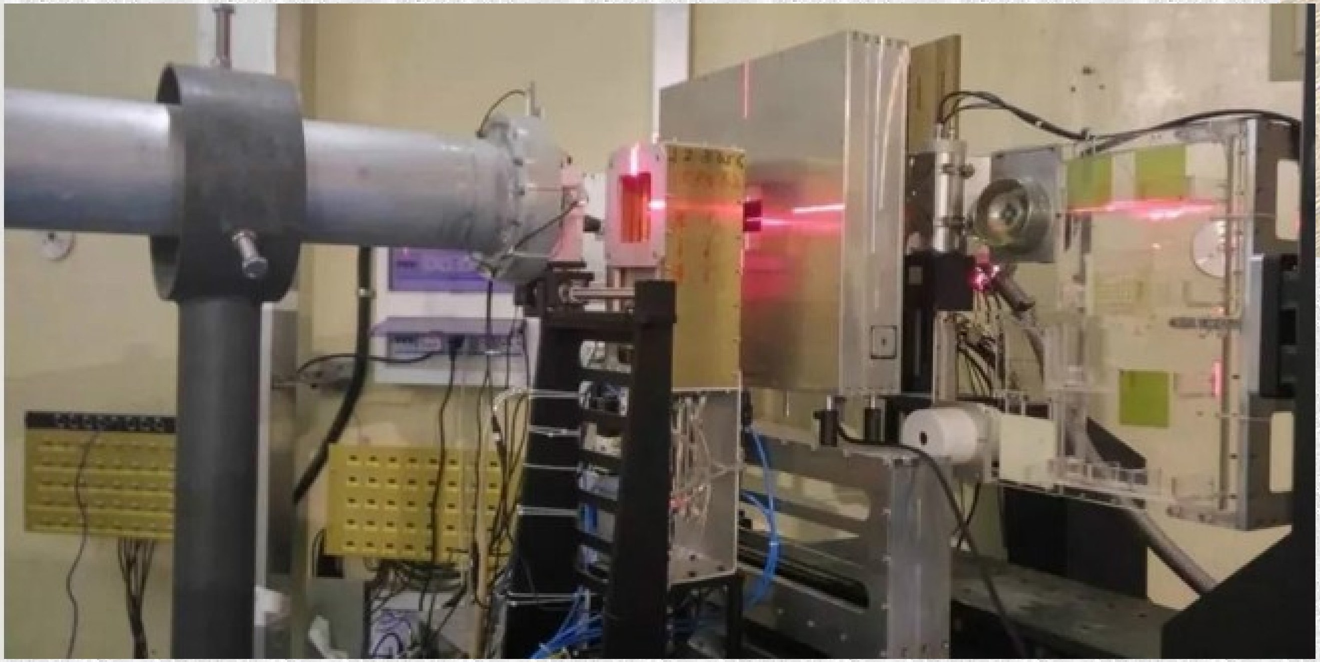


- Borrowing from ILC work heavily
  - Calorimeters scaled down for lower energy
  - But continuous operation challenges silicon readout

Example R&D

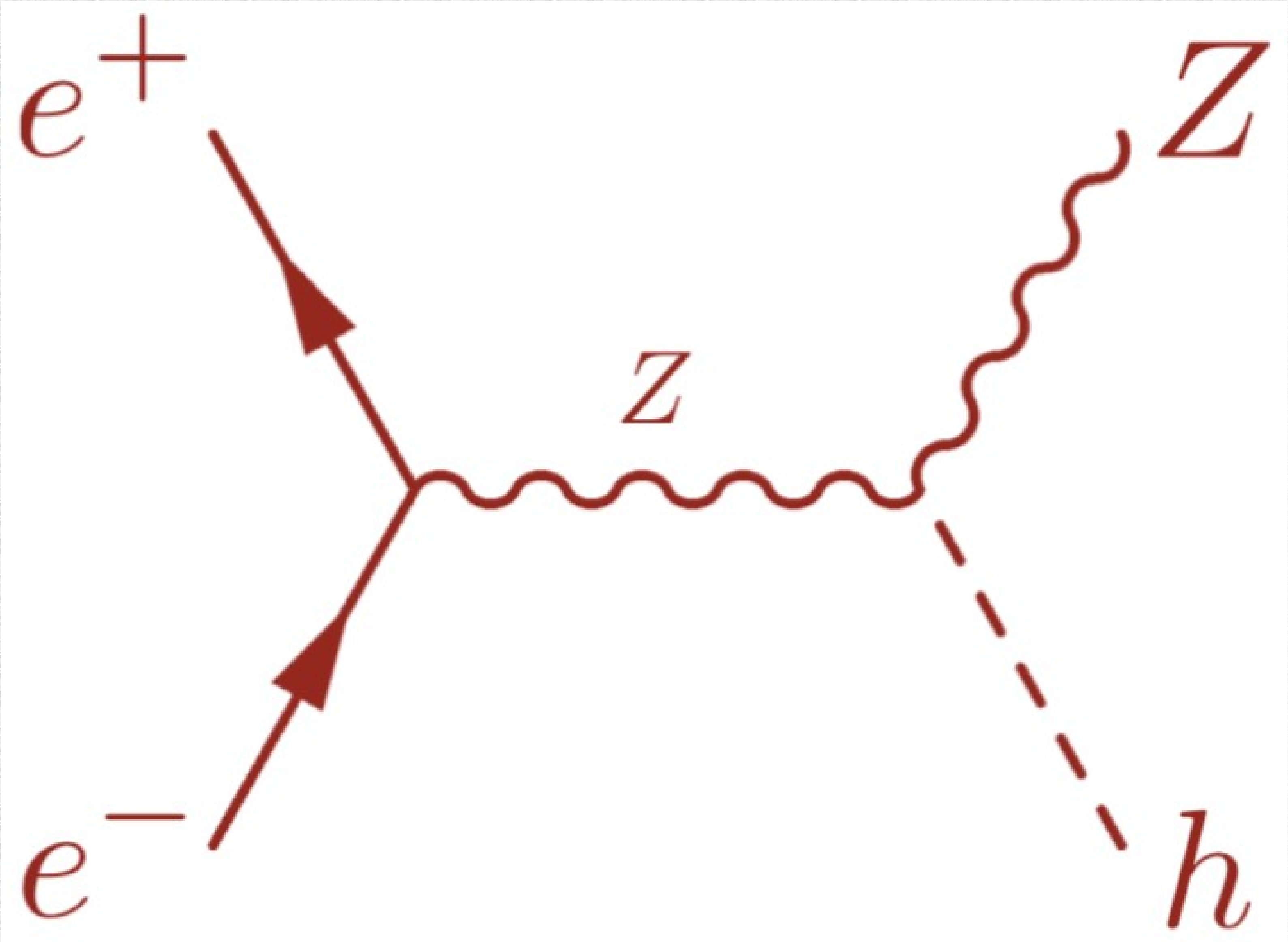
- New LGAD foundry: NDL in Beijing Normal University
  - Started 2019
- First sensors meet 30ps timing
- Radiation testing ongoing





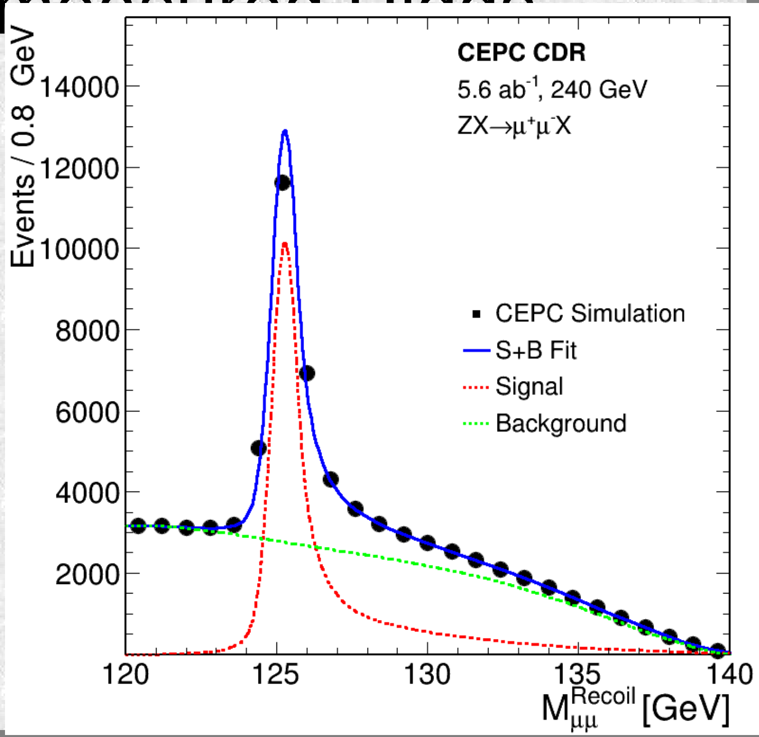
- Could be used for particle ID

ee collider H target

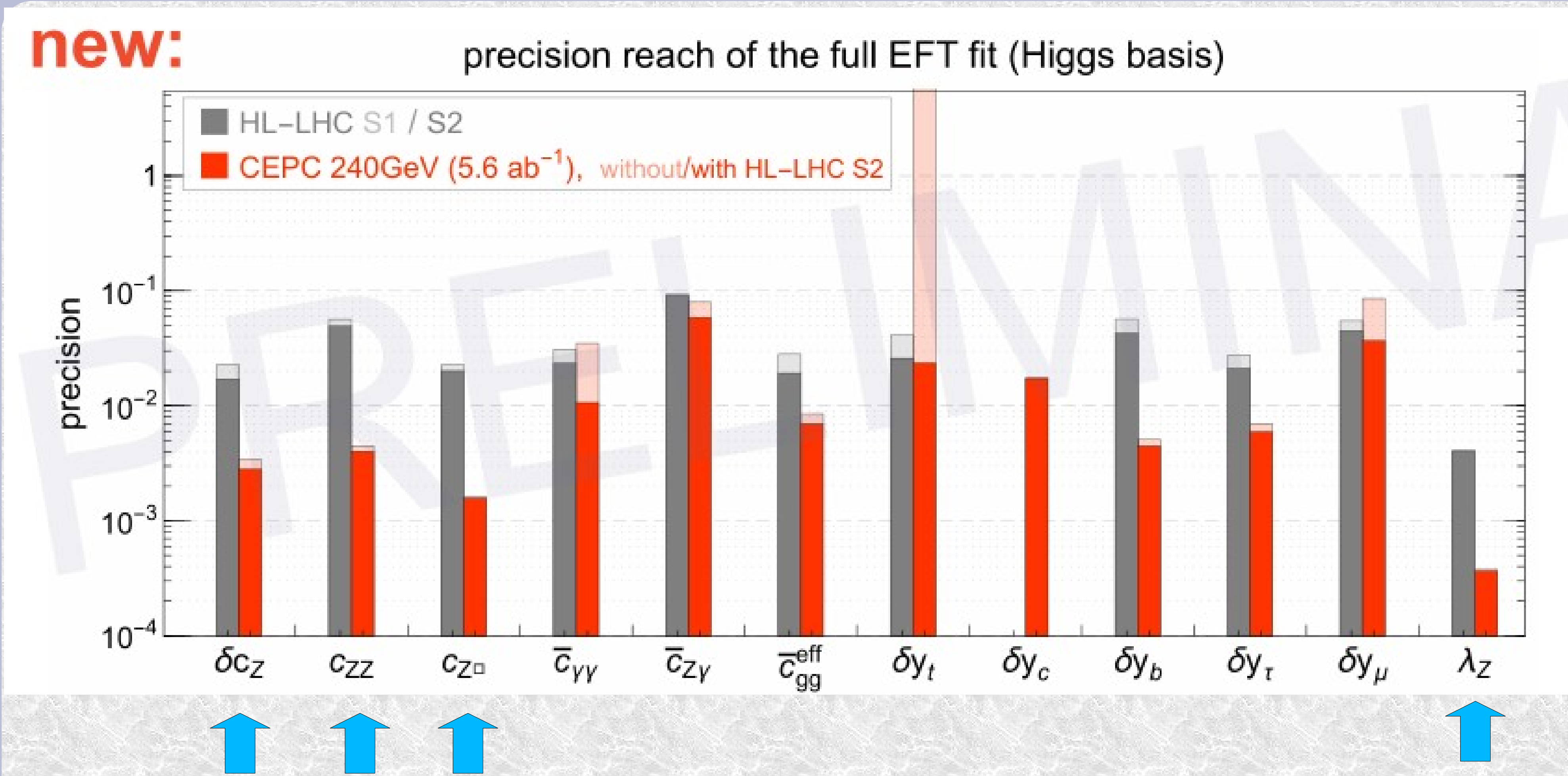


The method

- The Higgs-strahllung from known initial state is the unique and best feature of the Higgs factory
  - Higgs-tagging from the Z
    - Leptonic and hadronic z decays to maximise rate
  - Total width can be extracted
  - The result is g_{HZZ} is much the best measured Higgs coupling at ee ring
- Many Higgs decays are accessible in clean ee environment

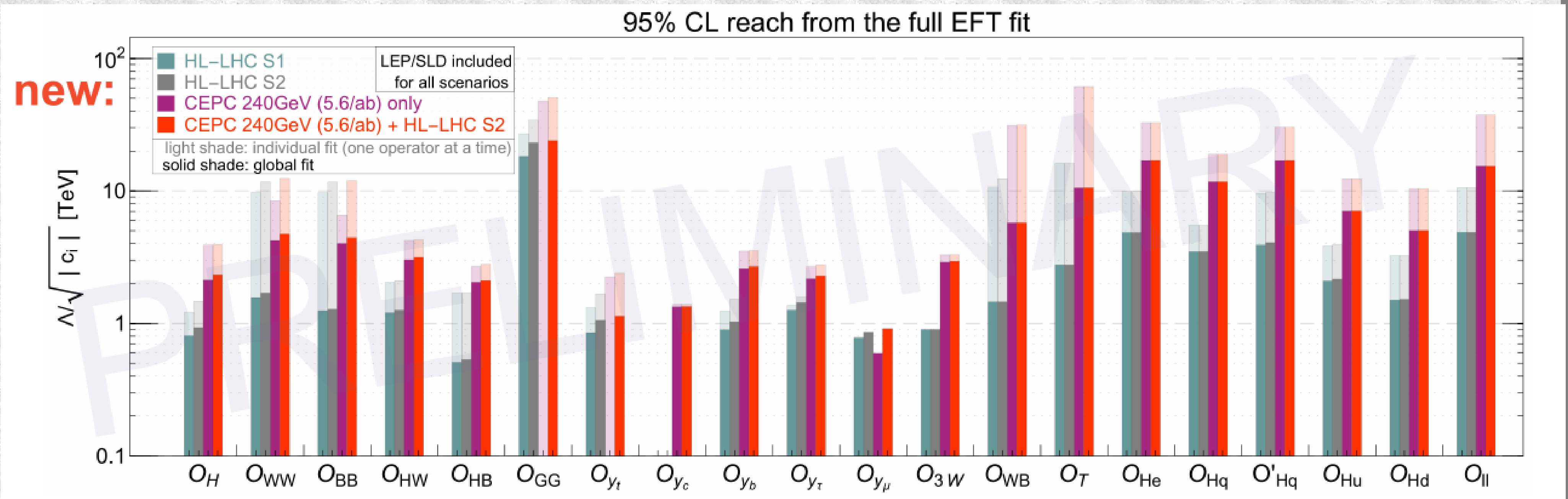


Higgs couplings precision



- Big gains expected
  - Especially on Z couplings & b/c interactions

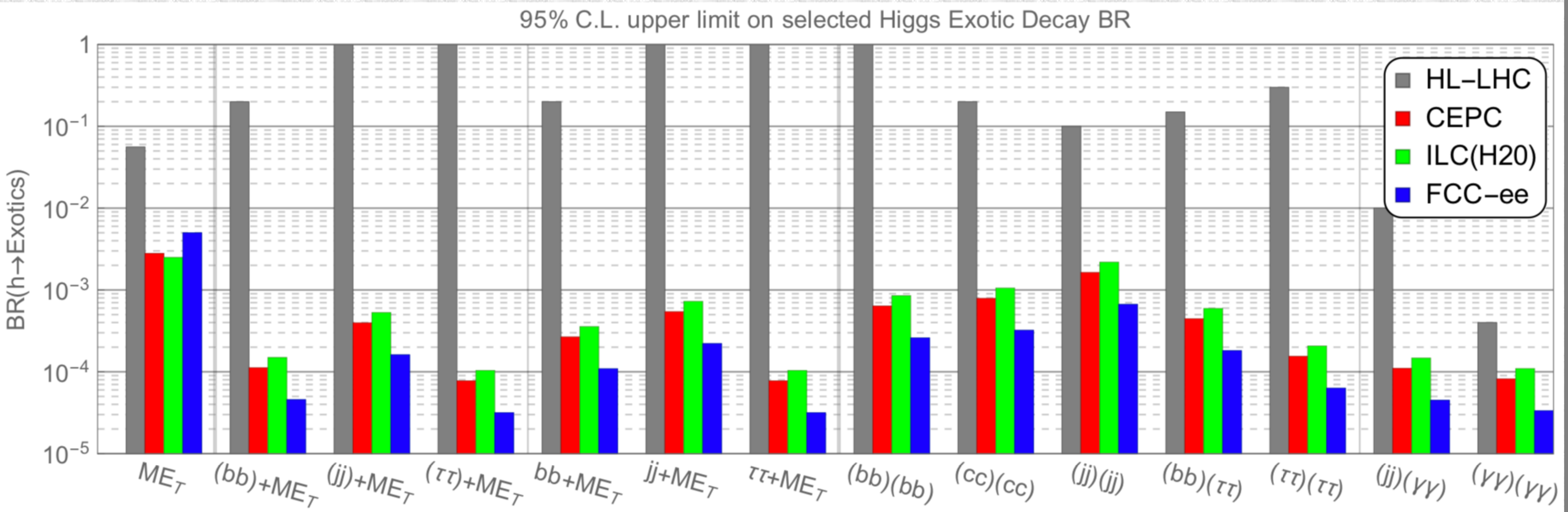
Searching for new physics



- The CepC adds nearly a factor 4 in most operators
  - Searching deep into the unknown

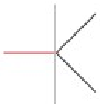
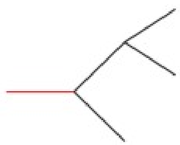
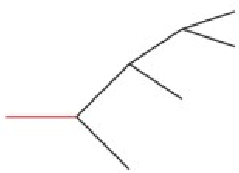
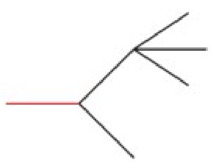
Exotic Higgs decays

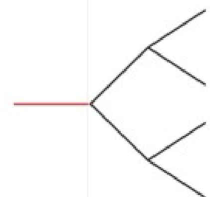
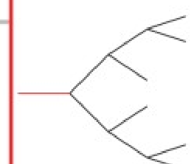
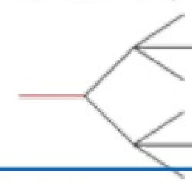
- Huge potential for unexpected Higgs decay modes



- Electron colliders deliver up to 10^4 over LHC
- This is testing the couplings/mixings of the only fundamental scalar
- There are similar gains in rare Z decays

Even more expanded list

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

Strong areas of Higgs factories

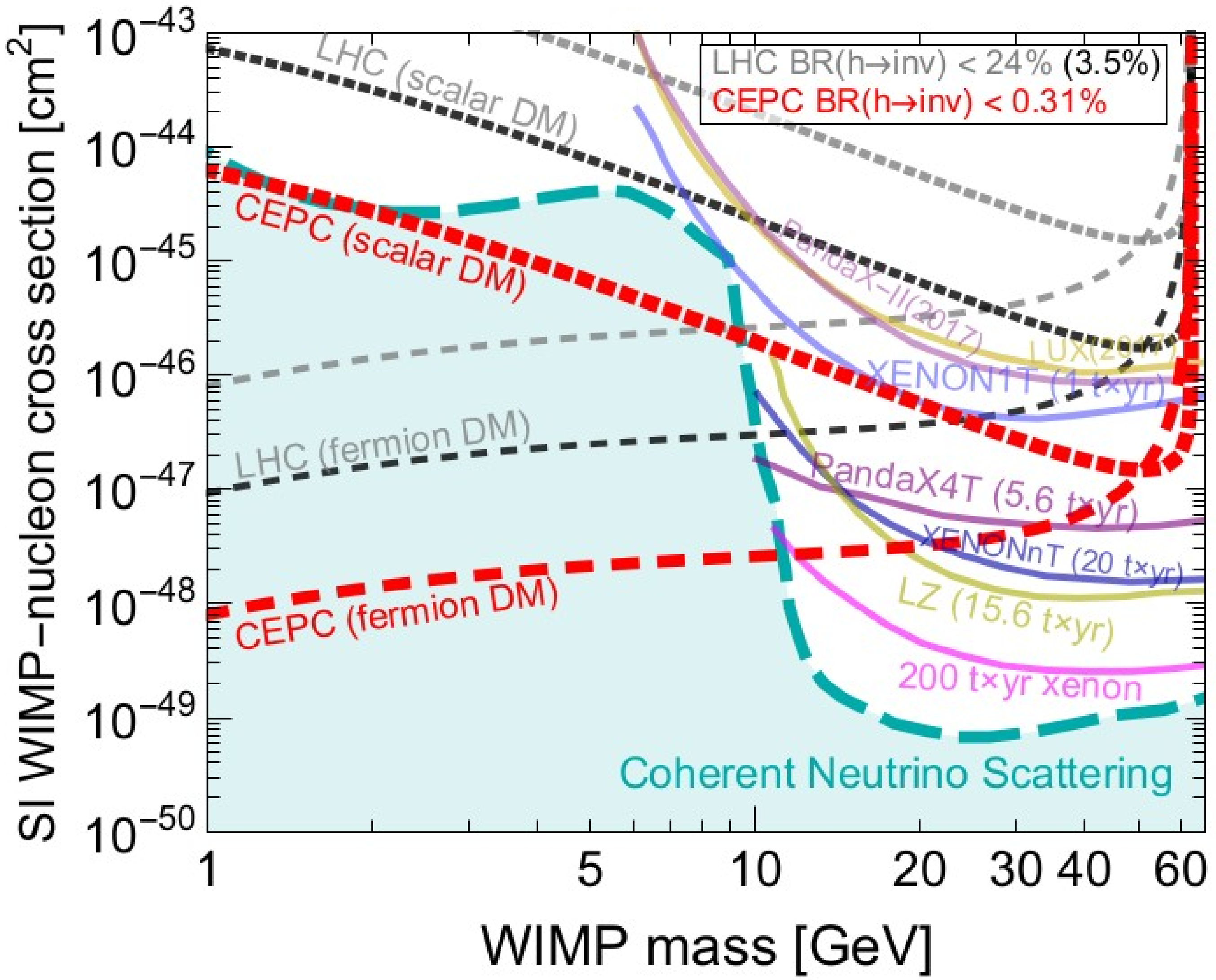
More hadronic

With MET, less lepton

Great sensitivity from the LHC

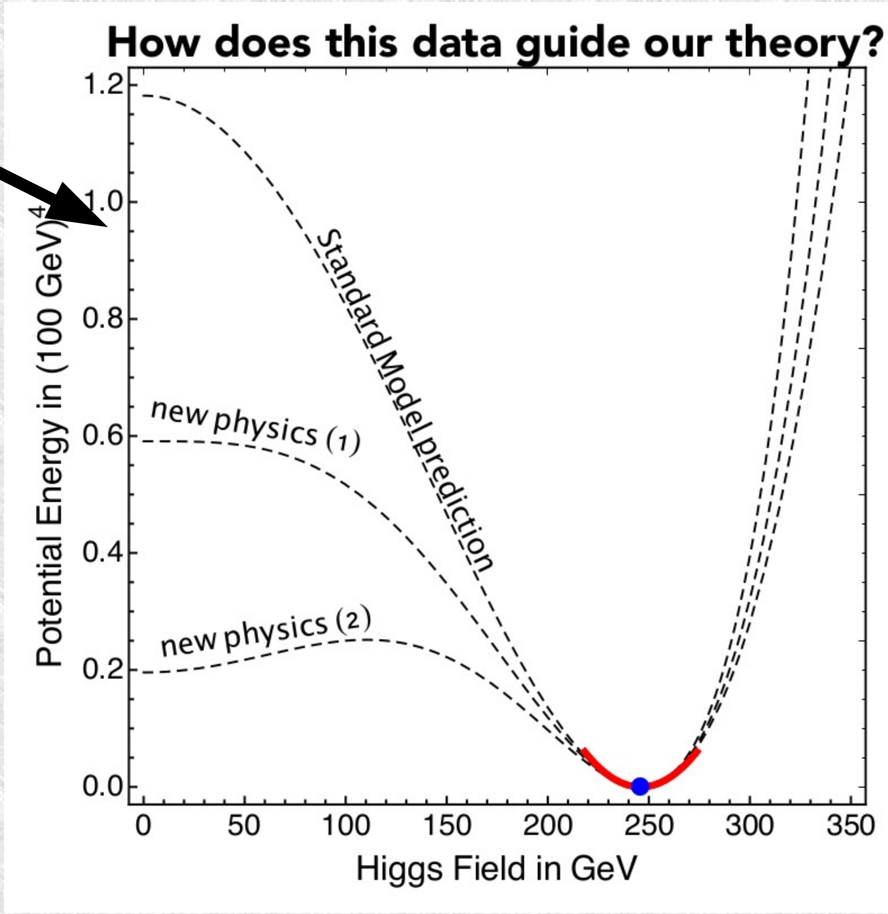
Higgs to MET

- Higgs to dark matter is 100% invisible
- e+e- offers an order of magnitude increase in sensitivity
  - Especially useful at low mass



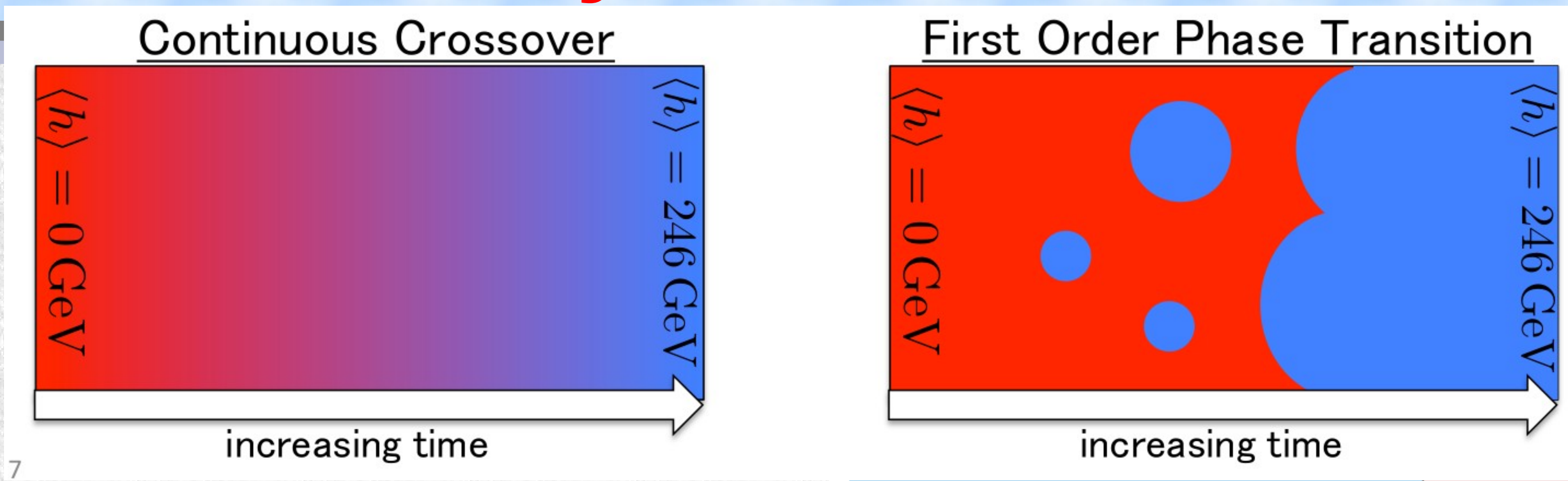
First order phase transition

- So far we probe the Higgs potential near 250GeV
- There could be a barrier between the origin and vacuum?
- If so the symmetric vacuum is meta-stable
- Universe does not smoothly evolve to the observed Higgs VeV
- But will start from local fluctuations which spread

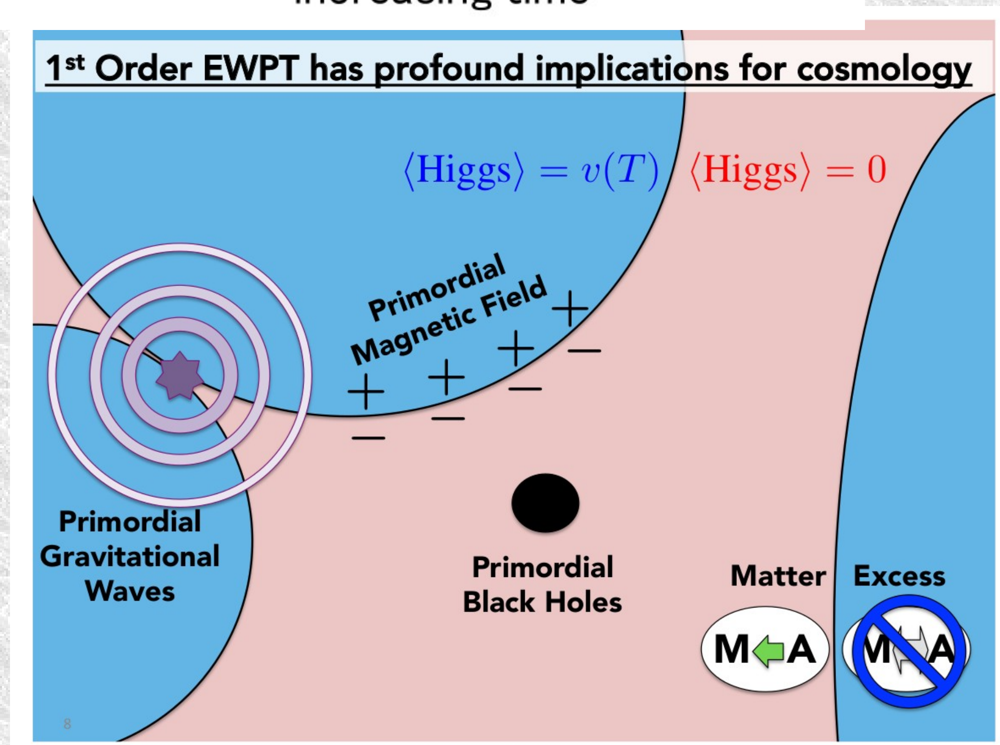


Long

Why do we care?

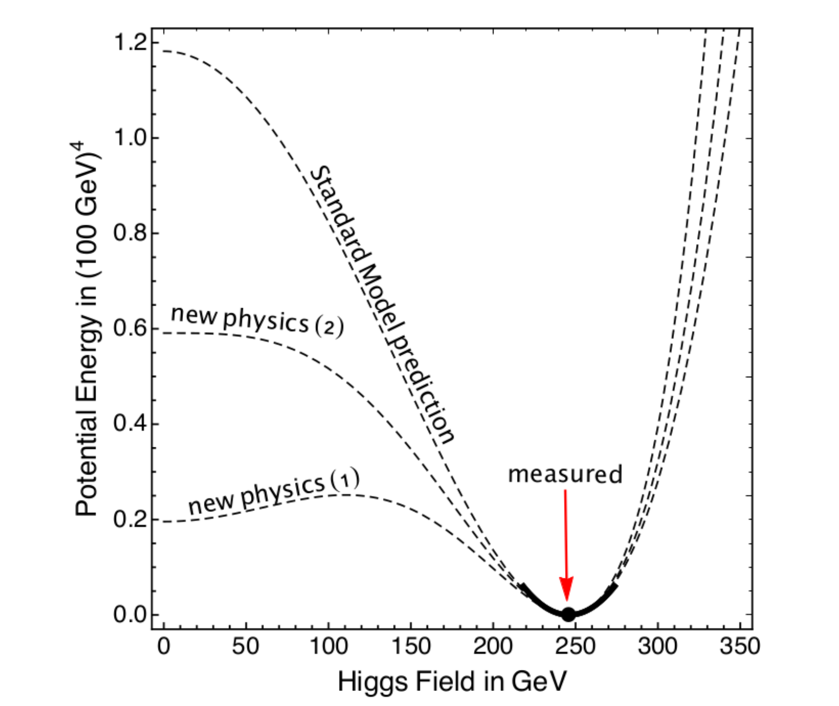


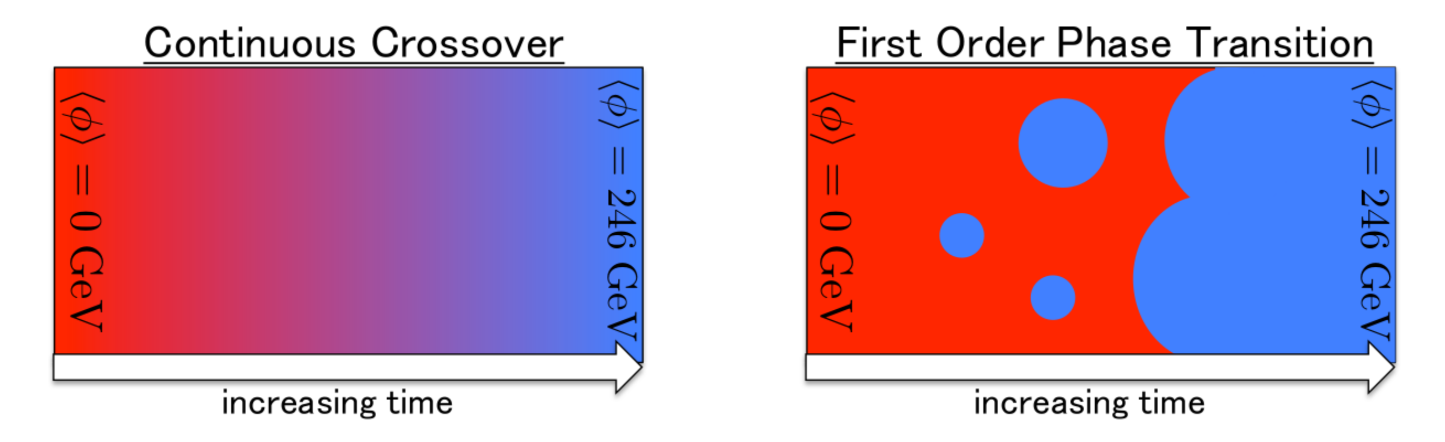
- The inhomogeneities associated could drive matter asymmetry,
- create gravitational waves
- Or seed primordial black holes



Higgs couplings and CPV

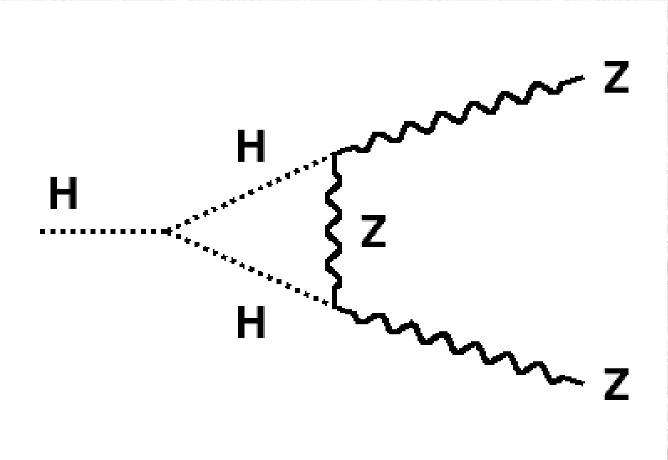
- The Higgs potential may not be simple $-m\varphi^2+\varphi^4$
- Add a singlet and you can deform the potential
- If the potential is metastable then phase transition is first order
  - Bubbles of expanding real vacuum
- This can yield matter domination!

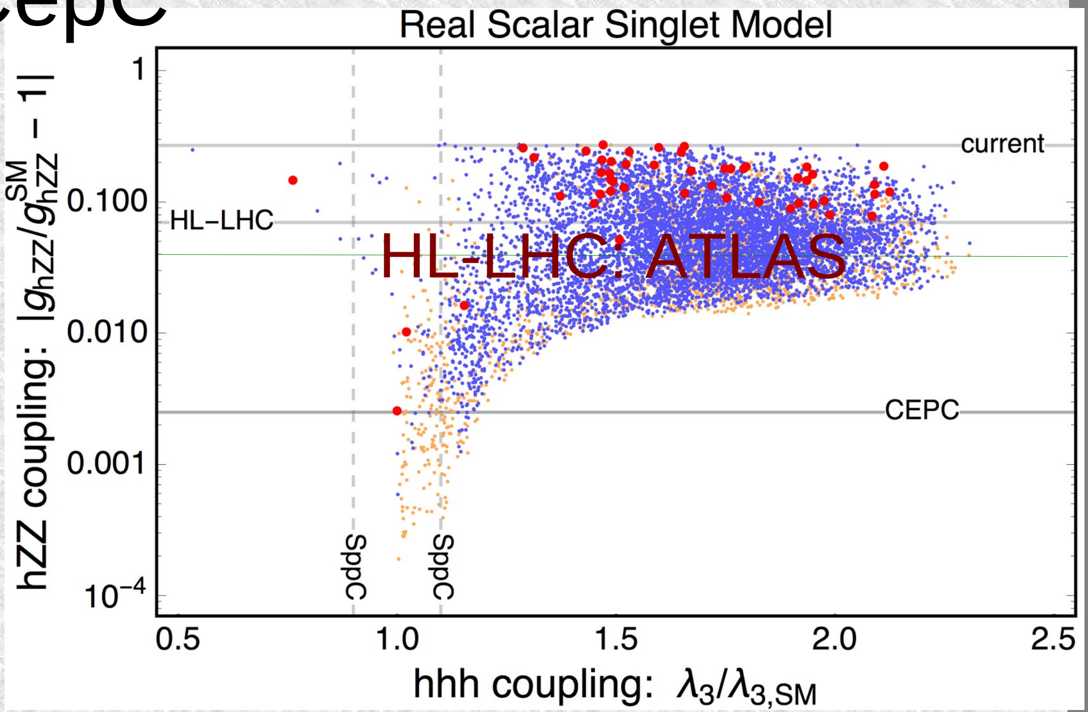




What do couplings teach?

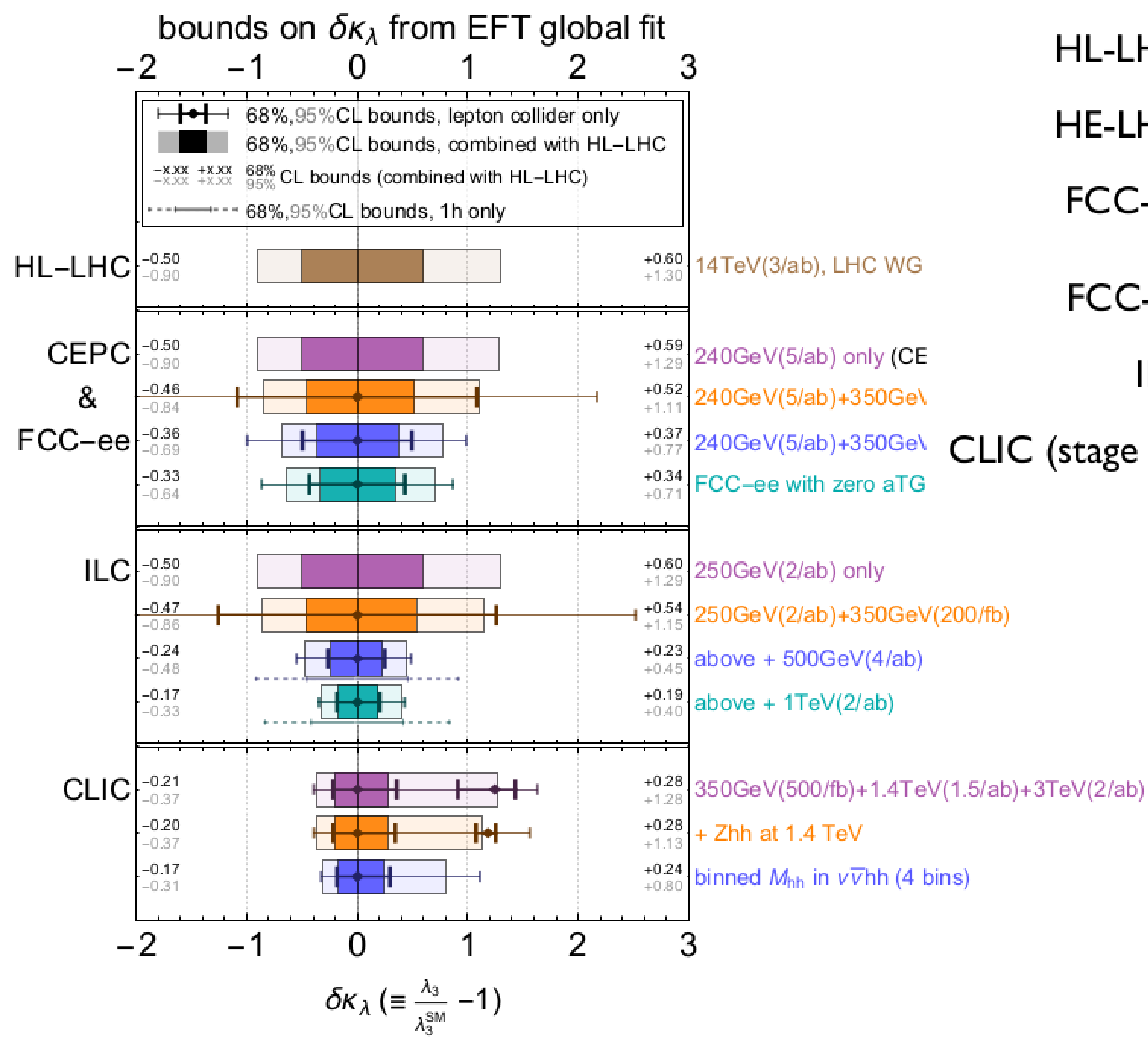
- Vertex corrections mix HHH and ZZH couplings real vacuum
- Large distortions to the triple coupling will shown up in g_{hZZ}
- Bottom right plot (from CepC CDR) shows much of parameter space accessible
- HL-LHC may find hints to origin of Universe

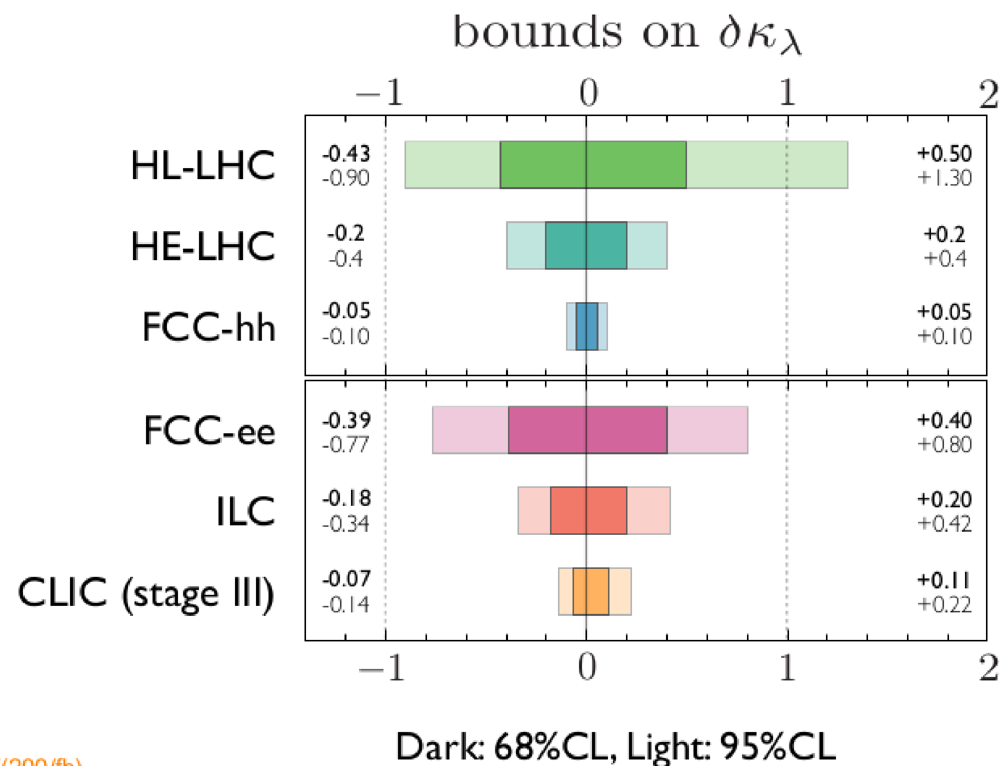




h³ prospects

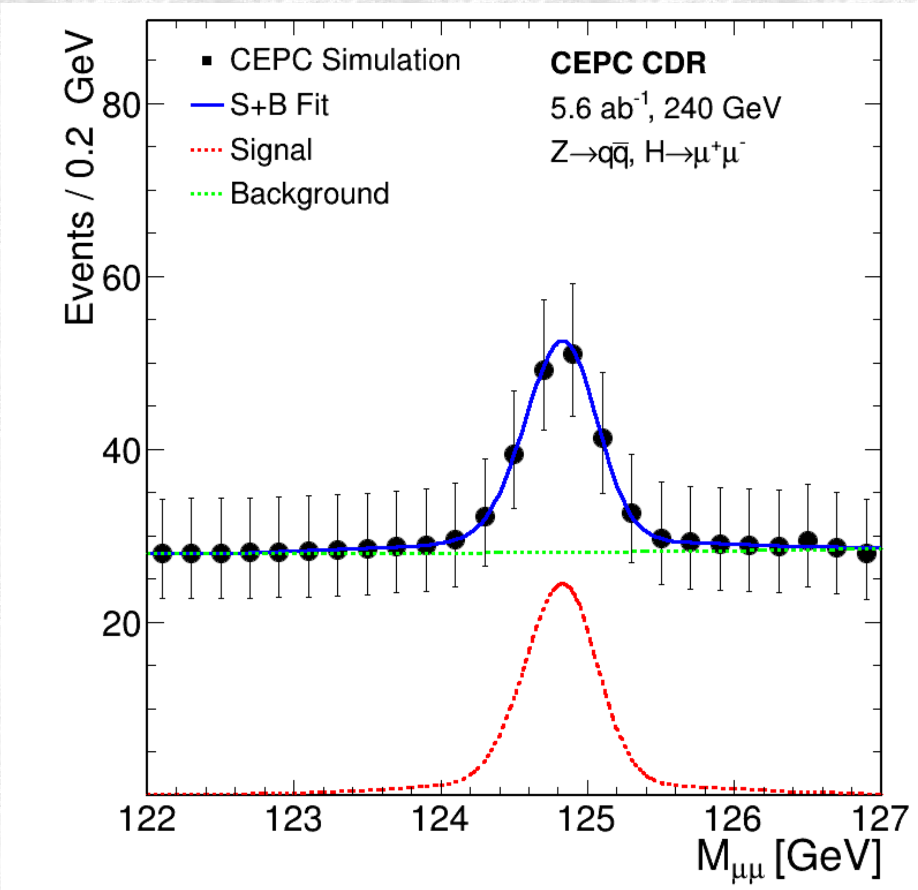
DiVita et al, arXiv: 1711.03978
(updated with latest HL-LHC) projections

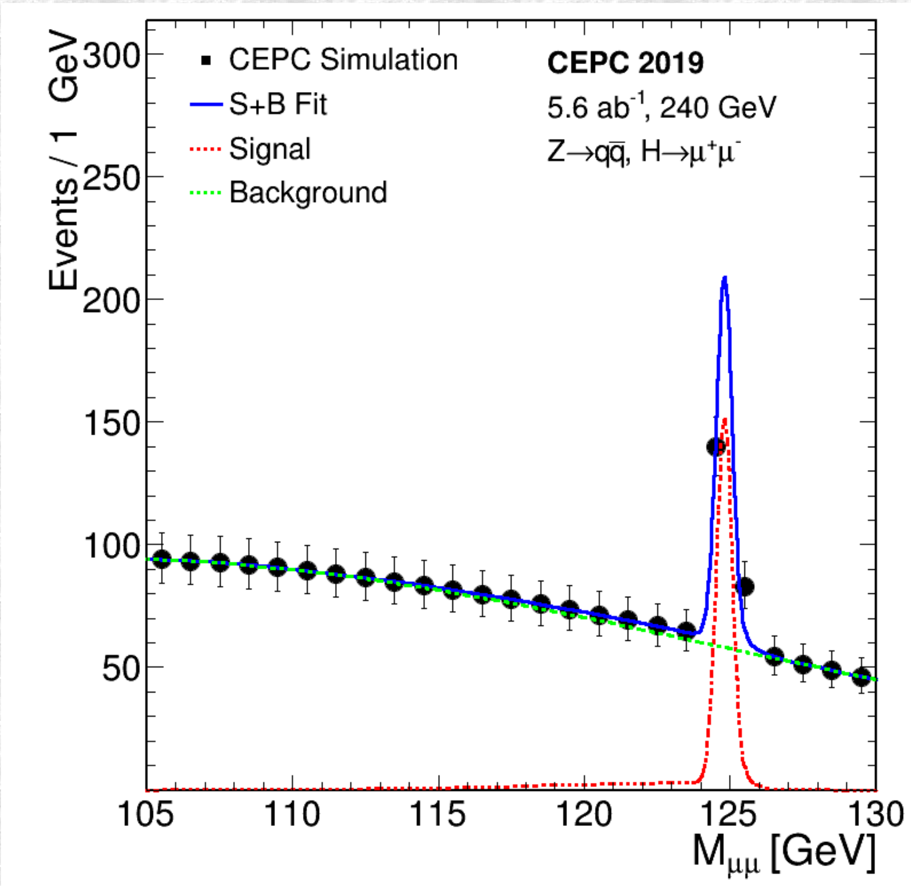




ee colliders
will establish at 95%CL that
the Higgs self-coupling exists
ILC will establish it at 5σ
FCC-hh will probe
the quantum corrections
of the Higgs potential

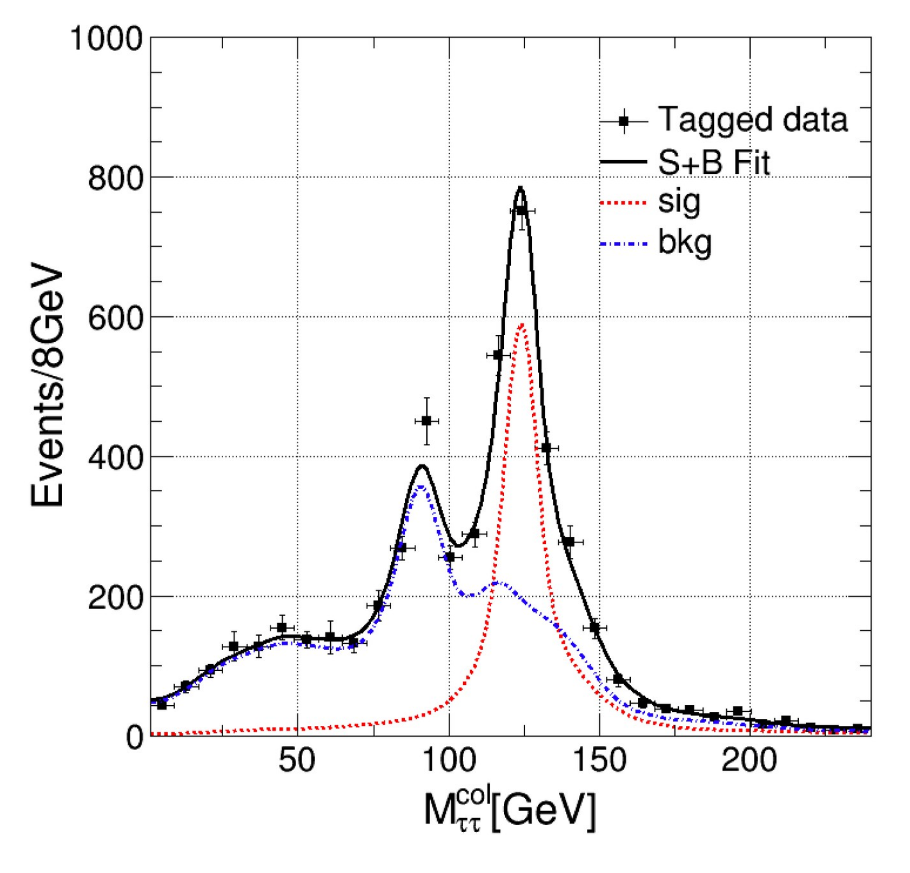
CepC improvements...

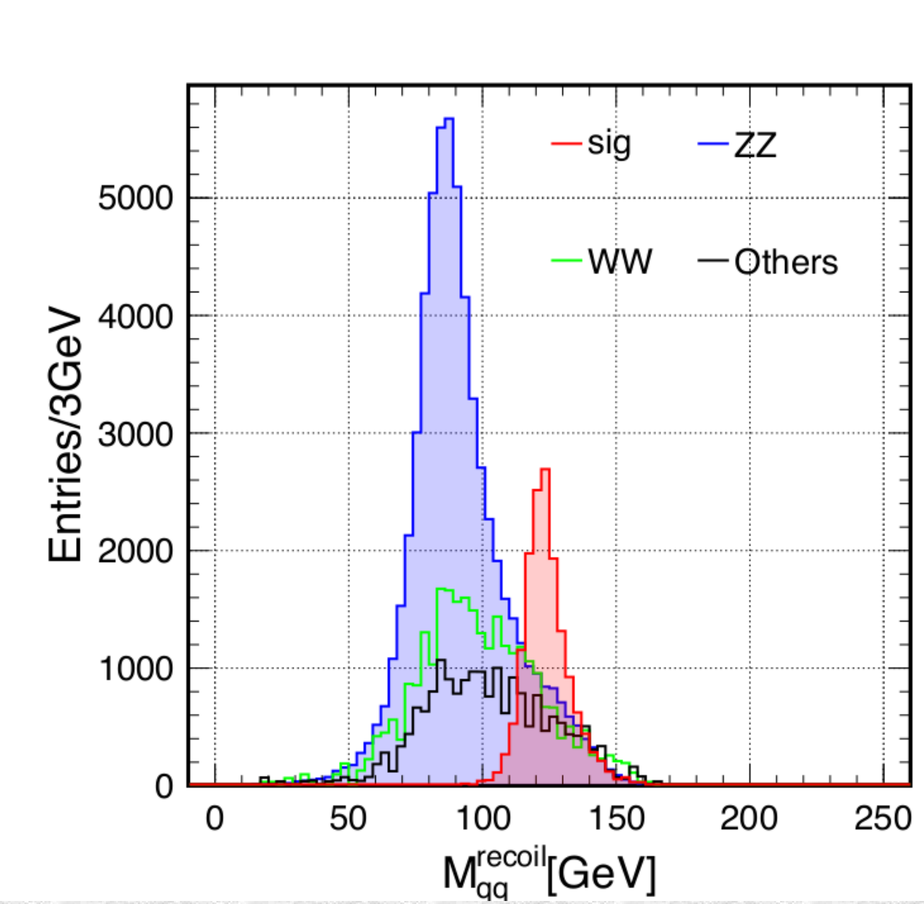




- Improved analysis: precision 17% → 12%
- Also gains in invisible 0.41% → 0.26%

H → ττ

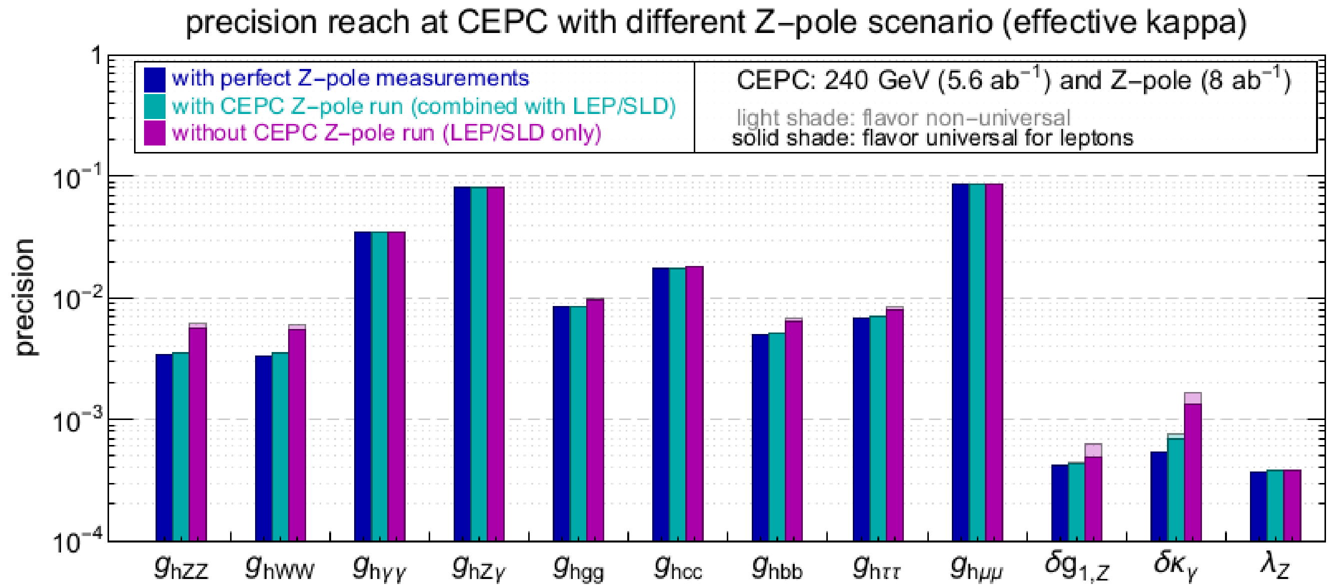




- Left is μμ H, right qqH
- Overall precision 0.8% dominated by qqH channel

EW measurement's impact on Higgs

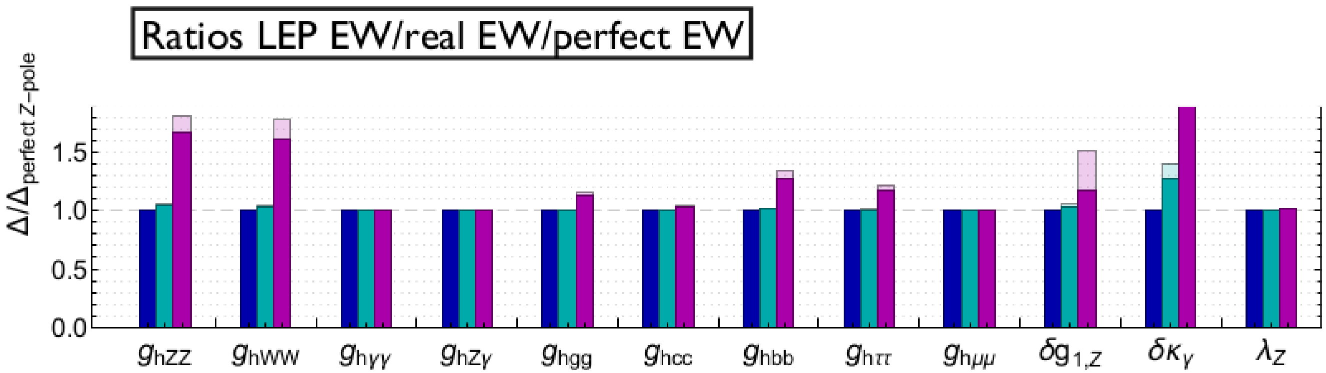
De Blas, Durieux, Grojean, Gu, Paul 'in progress



EFT fit translated into

postdicted Higgs couplings

$(e.g.\ g_{hZZ} \propto \sqrt{\Gamma_{h\to ZZ}})$



✗ CEPC alone

Z-pole run needed
LEP/SLD is not enough
Issue for ILC?

Linear: L ↗ w/ E

Circular: L ↘ w/E

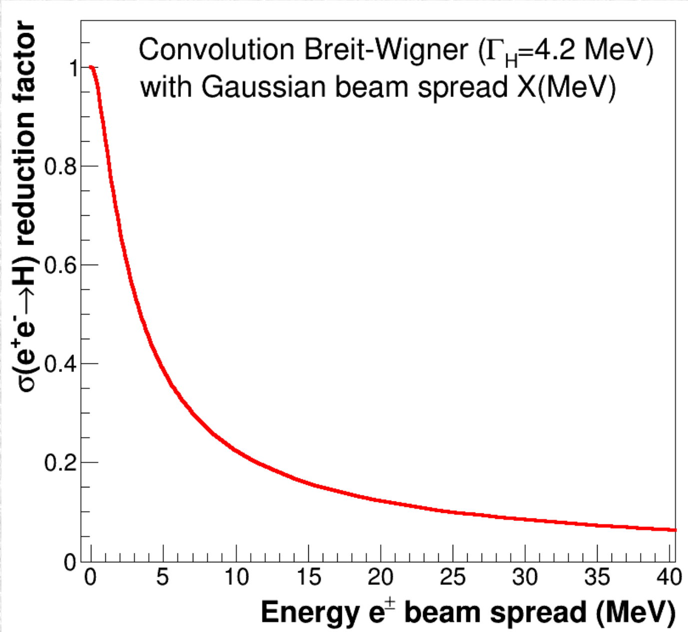
How many Z are needed?
Giga-Z enough?

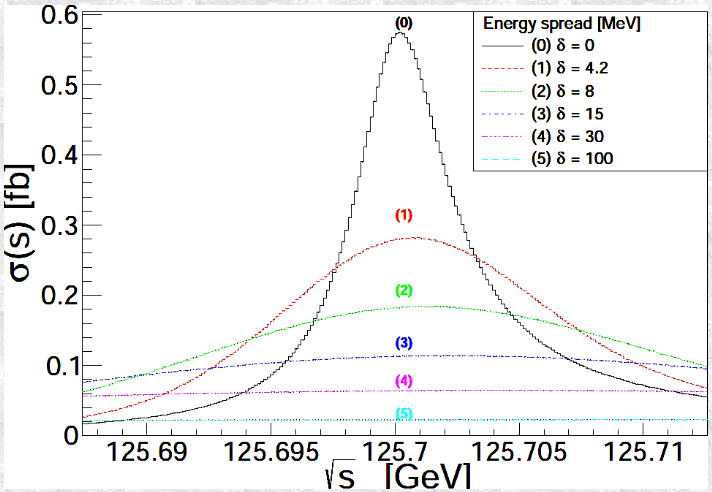
350GeV run & polarisation could help alleviating the need for Z-pole run

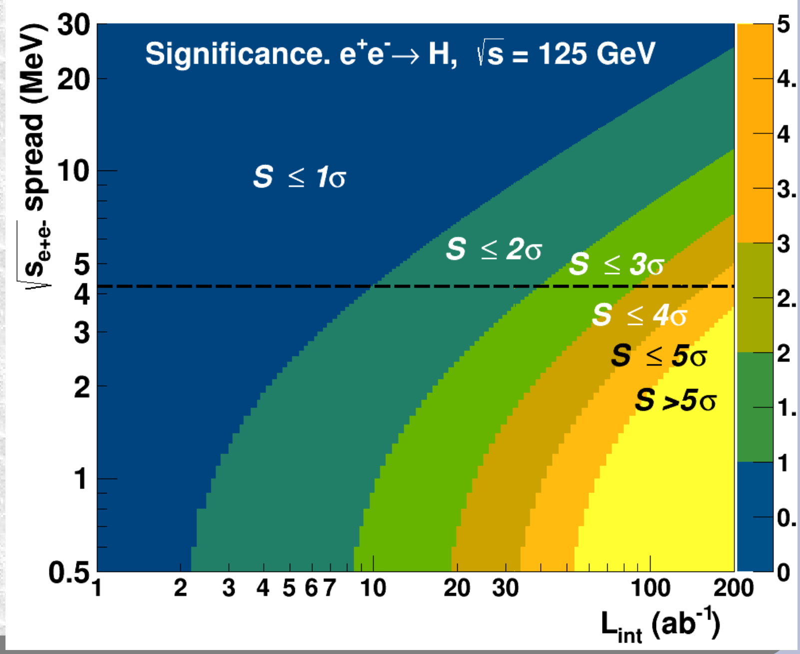
Fcc ee → H

- Can we measure the electron coupling?
  - H → ee is 5 10^{-9} , not possible
- e+e- → H just might be doable
  - If the Fcc beam energy spread is reduced
    - With a luminosity penalty ~ 3
    - L=6 10^{35} cm^{-2} s^{-1}
- It would take years to establish a clear signal
  - But potentially interesting
  - e.g. if 2^{nd} generation couplings look wrong?

Fcc ee → H



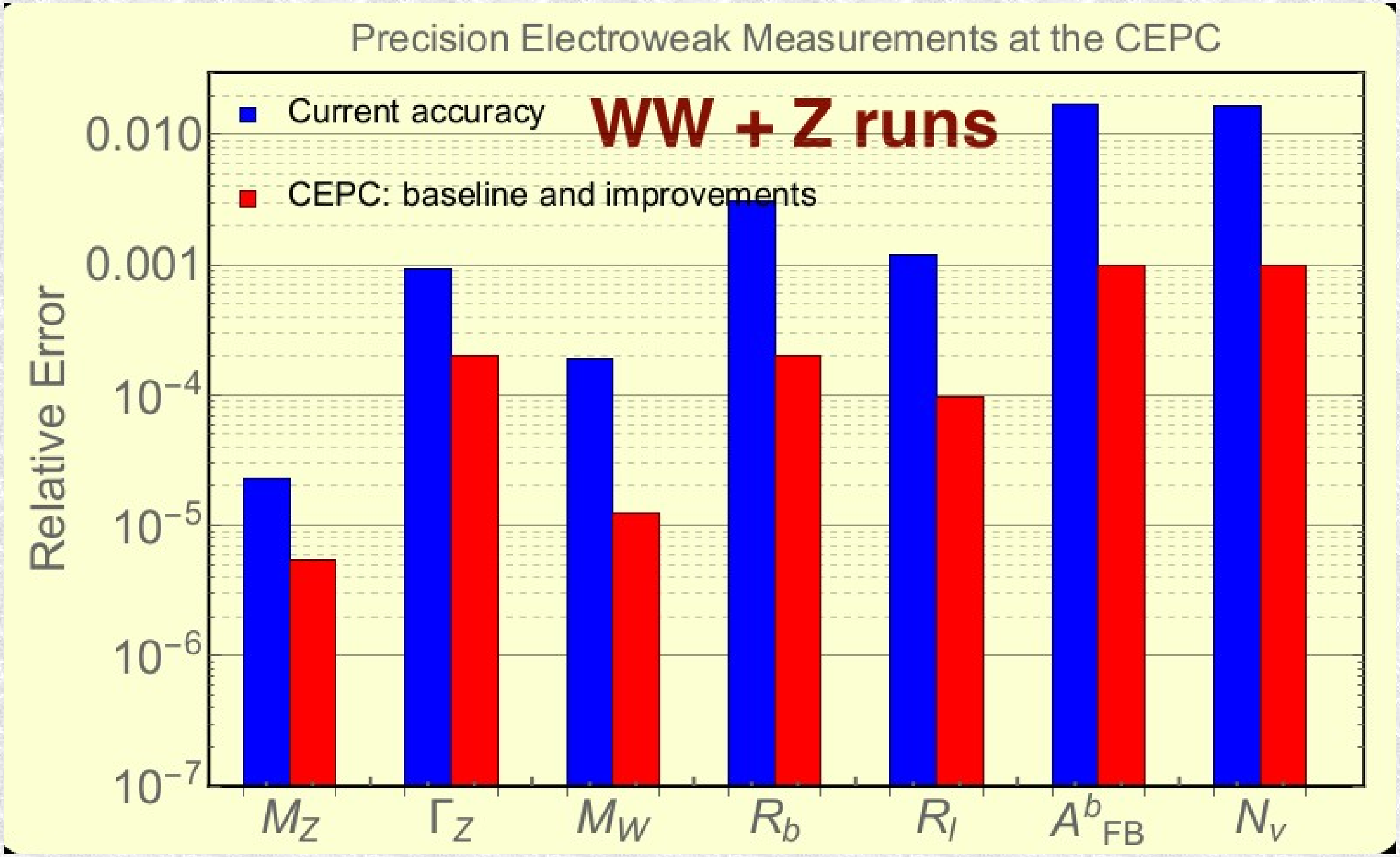




- Would need O(4MeV) beam energy spread
  - To match Higgs width, 4.2 MeV
- H → WW* good s/b
- Estimate 10ab^{-1} per year possible like this...

Electroweak precision

- CepC offers an order of magnitude over LEP in many key electroweak observables
- Fcc-ee is a lot more ambitious

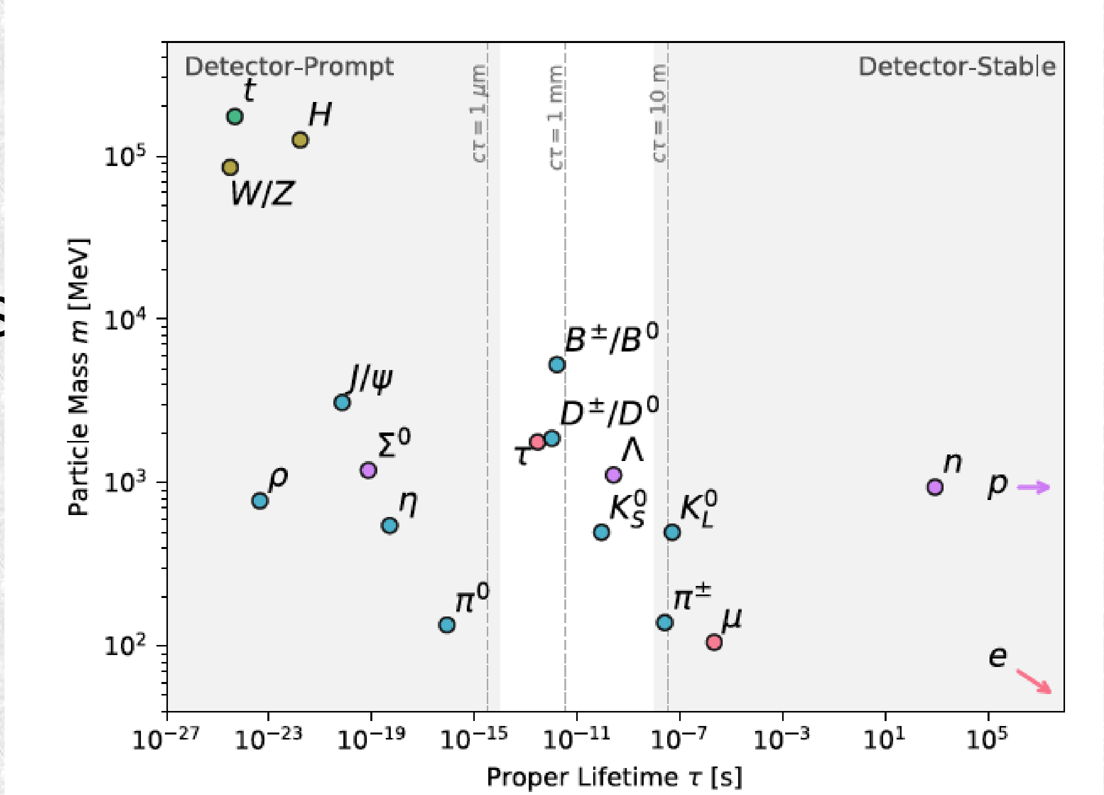


Now turn to other physics..

- There is a lot going on
- These studies are not perhaps the main course
- But the range and variety adds enormously to the community interest
  - Which matters
- And sometimes the sidechannels pay off
  - Kamiokande was designed for proton decay
  - Who remembers that, now the Nobel Prize is in?

Long lived particles

- LHC designed for high mass prompt
  - Searches for long lived need bespoke solutions
- CepC should be ready for long lived
  - Weakly coupled/mass degenerate
  - 3µm resolution allows sub-fs lifetimes to be probed
  - axion: H→Za, with a→ll or γγ could look like a π^0
- Leptogenesis also gives candidates e.g. in Z decay
- Detectors being optimised for this.



B physics at CepC

Altmannshofer & Charles

Beauty hadrons @CEPC

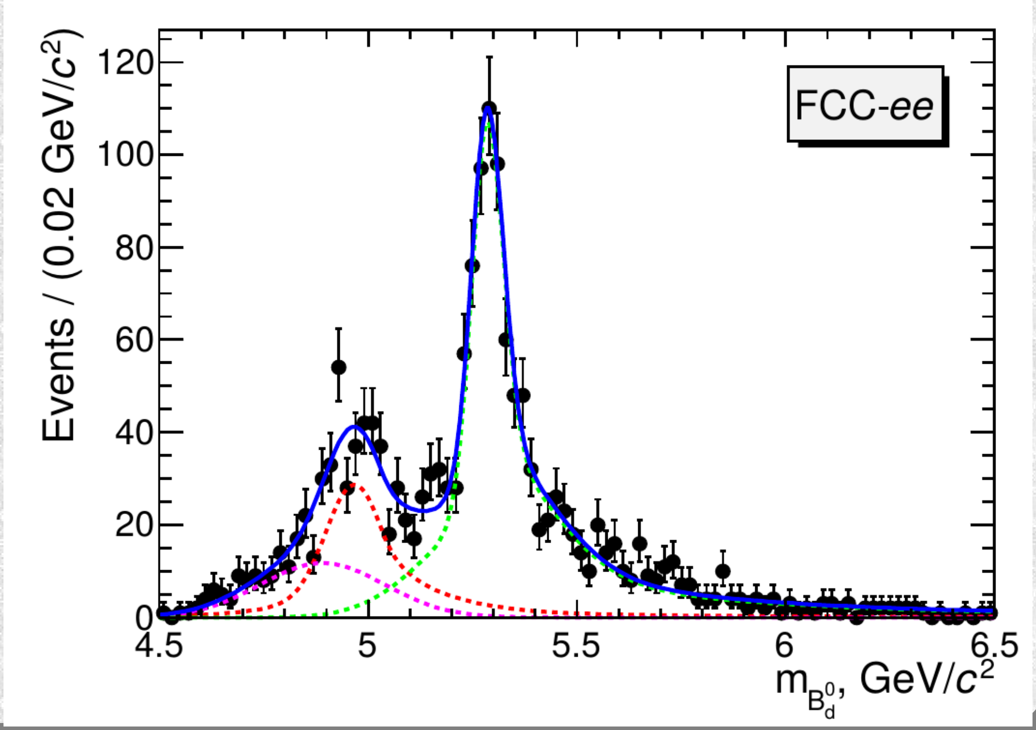
	CEPC (10^{12} Z)	Belle II (50 ab^{-1} @$\Upsilon(4S)$ & 5 fb^{-1} @$\Upsilon(5S)$)	LHCb (50 fb^{-1})
$B^\pm/B^0$	6×10^{10}	3×10^{10}	3×10^{13}
B_s	2×10^{10}	3×10^{8}	8×10^{12}
B_c	10^{8}	-	6×10^{10}
b baryons	10^{10}	-	10^{13}

- Yield matches or exceeds Belle
  - However it is well below LHCb
- But:
  - B's are produced back to back, unlike LHCb
  - With predictable momenta, unlike LHCb

B hadrons

Altmannshofer & Charles

- Tau decay modes might be accessible at CepC?
  - Bs → ττ or B → Kττ
  - The B flavor anomalies make this very interesting
  - B → Kττ with 3-prong tau decays allows 4 vertex positions and thus full mass reconstruction
    - O(100) events seen with CepC?
    - DD background in LHCb
  - Belle-II/LHCb fail here?
- B to Kνν CepC can look for MET+K – promising
- $B_c \rightarrow \tau\nu$ also promising



Charm and more from Z

- Large charm yields; predictable spectra
- 3 10^9 $D^{*+} \rightarrow D^0\pi^+ \rightarrow K\pi\pi^+$ - comparable to LHCb
  - Good π^0 reconstruction would help a lot!
    - EM calorimetry is important
- Possibility to observe CPV in charm baryons?
  - Yield of reconstructed Λ_c 600 times LHCb
- Heavy quark spectroscopy:
  - QCD-stable bb$\overline{\text{ud}}$ tetraquarks predicted
  - should be visible at CepC
- Use radiative return to study lower thresholds
  - Is a dedicated detector needed to study most forward boosted?

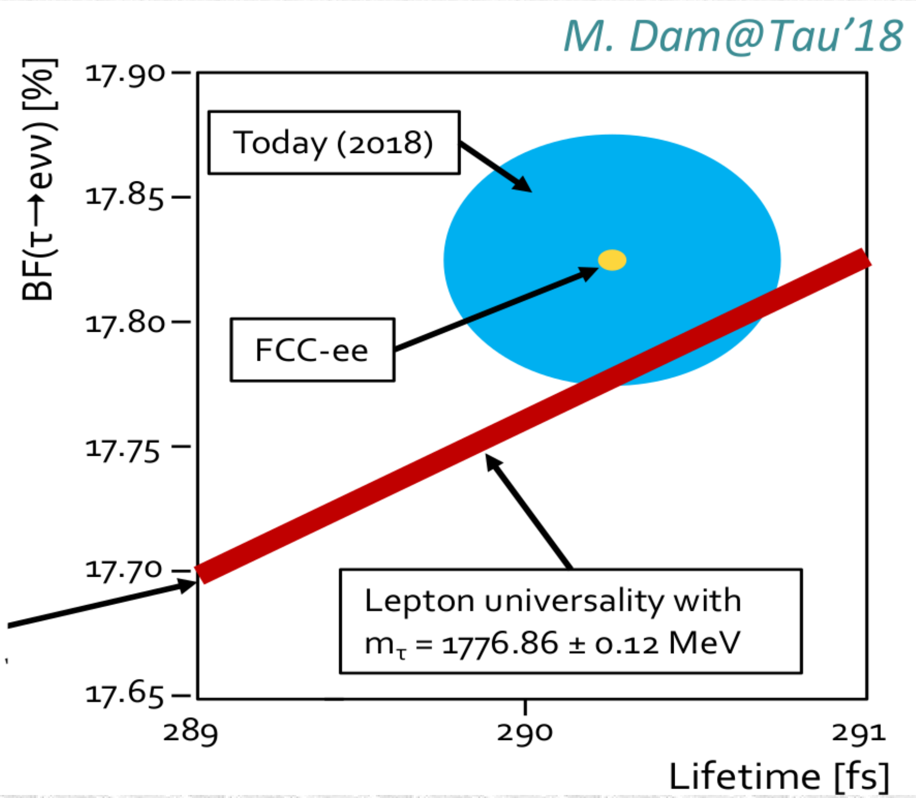
Rare Z decays

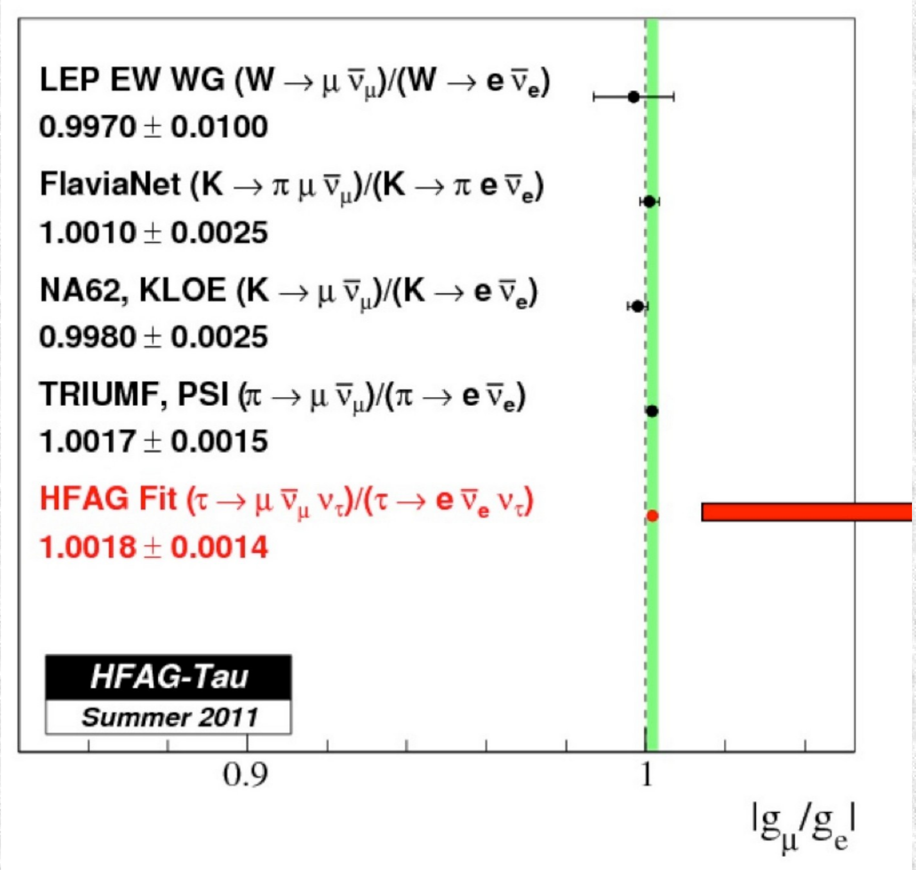
- $Z \rightarrow$ μe, eτ or μτ
  - Sensitivity should be 2 orders of magnitude better than HL-LHC
  - There are constraints from $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ etc
    - Strongly constraining for μe case
    - But not so for decays with taus
- Lepton universality in Z decay
  - ee:μμ:ττ
  - 3 per mille constraints from LEP
  - These are important constraints on the B flavour anomalies
  - CepC will have to understand e/μ/τ efficiencies well
    - Question to experimentalists: What can be achieved here?

Tau working group

Passemar

- In several areas LEP results still dominate
  - Large B-factory tau yields but poor efficiency
- With 10^6 more tau CepC has a rich tau program
- μ/e universality is one key

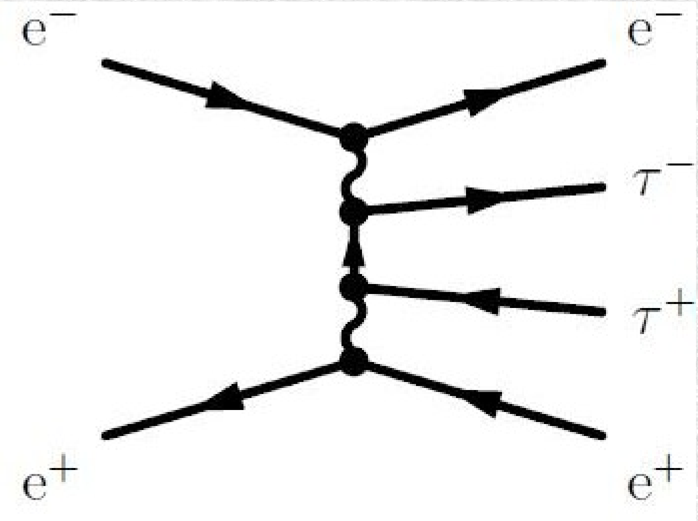


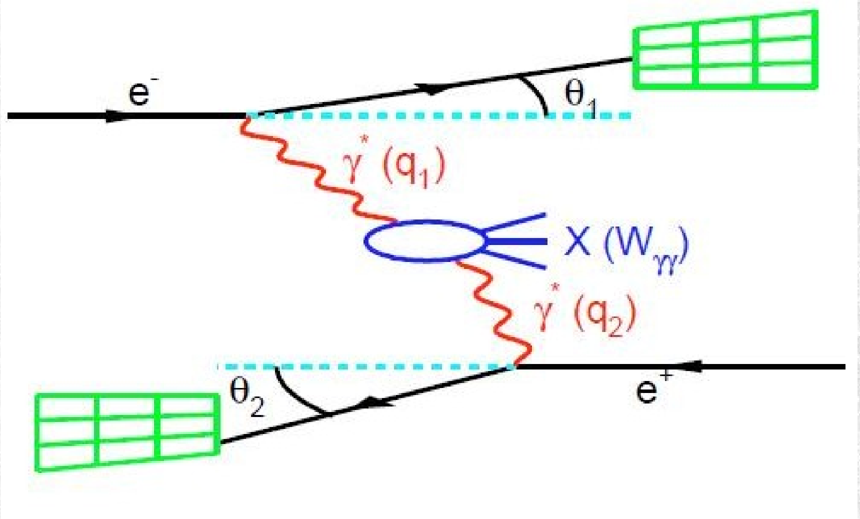


CepC as γγ collider

Boyko

- Two photons processes dominate rate at 240 Gev
- e.g. a_τ was measured best via $\gamma\gamma\rightarrow\tau\tau$ at LEP
  - At 1% level
  - Useful to compare a_e, a_μ
  - Systematics limited but CepC will give major improvement
- Photon structure function can also be improved
- Hadron spectroscopy will be possible too





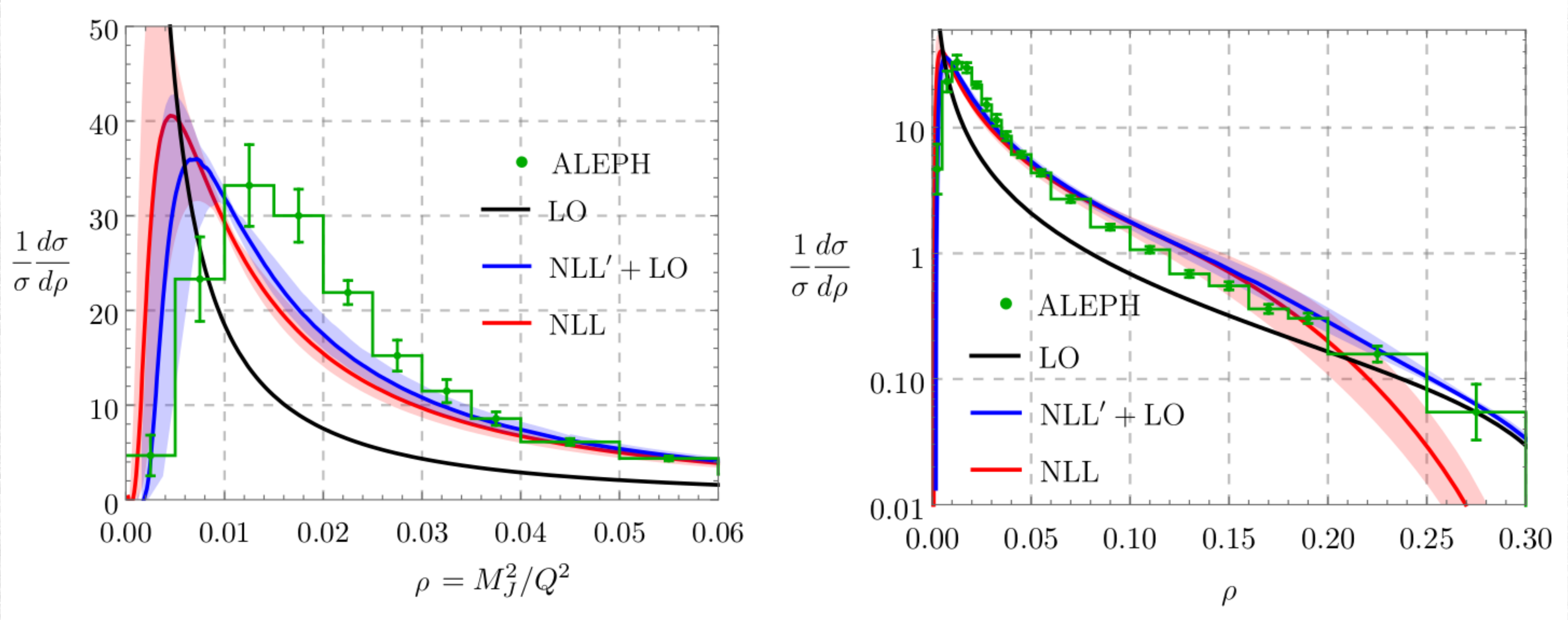
QCD studies

Shao

- α_s measurement
- Non-linear soft gluon evolution & Non-global logs resummation
- Hadronization models & Monte-Carlo tuning
- Fragmentation function
- Interplay with Higgs & Electroweak physics
- Charmonium physics
- Top quark physics

QCD studies: example

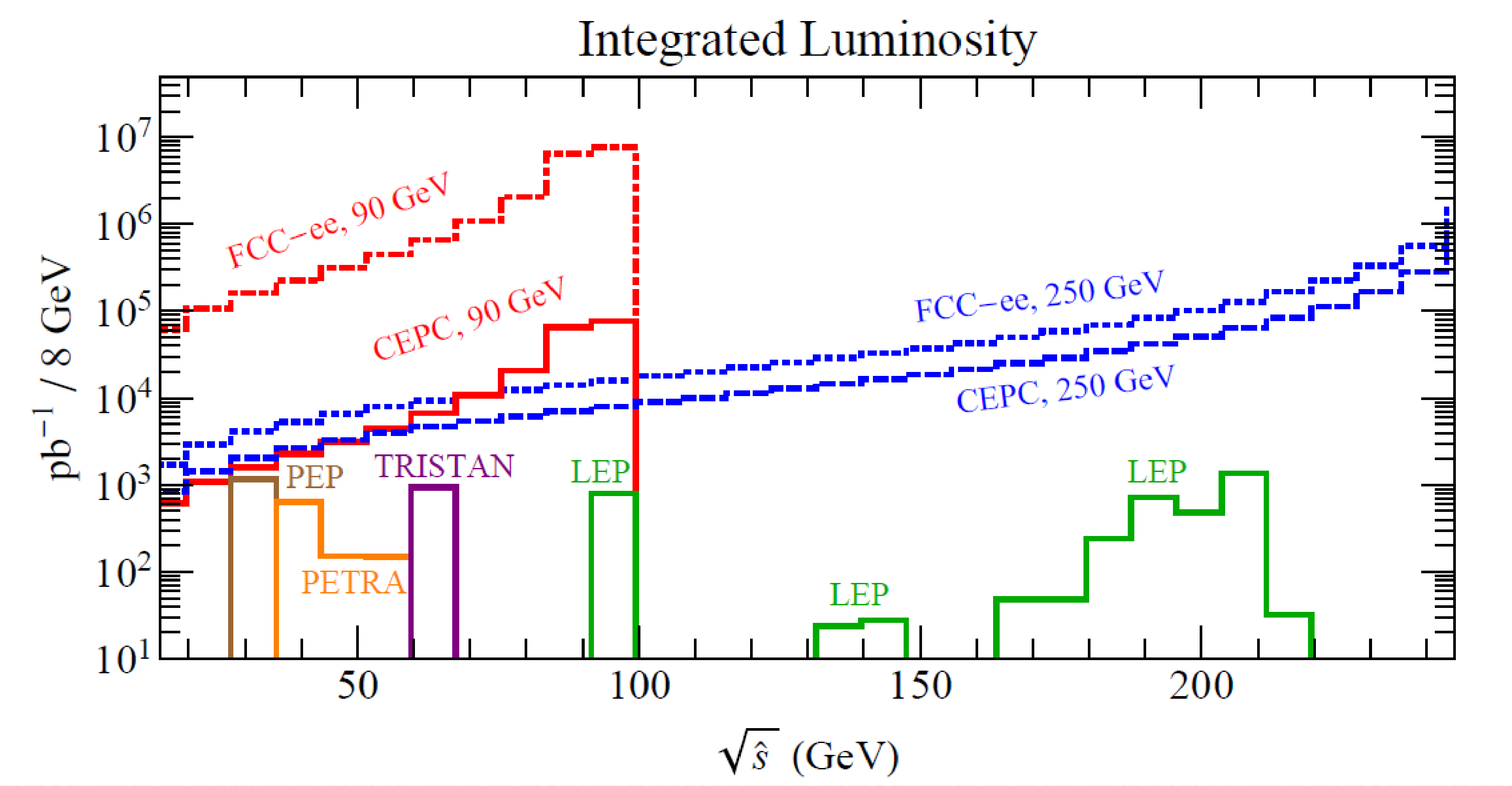
- Non-linear soft gluon evolution & Non-global logs resummation
  - Extending jet mass calculation beyond NLL
  - Important e.g. when separating quark states from hadronic boson decays



Radiative return

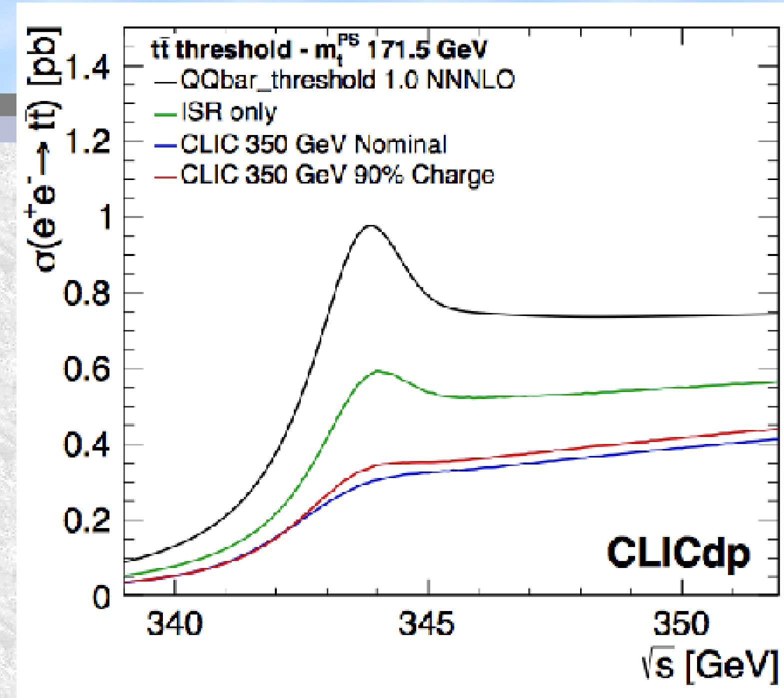
Karliner, Cheng & Rosner

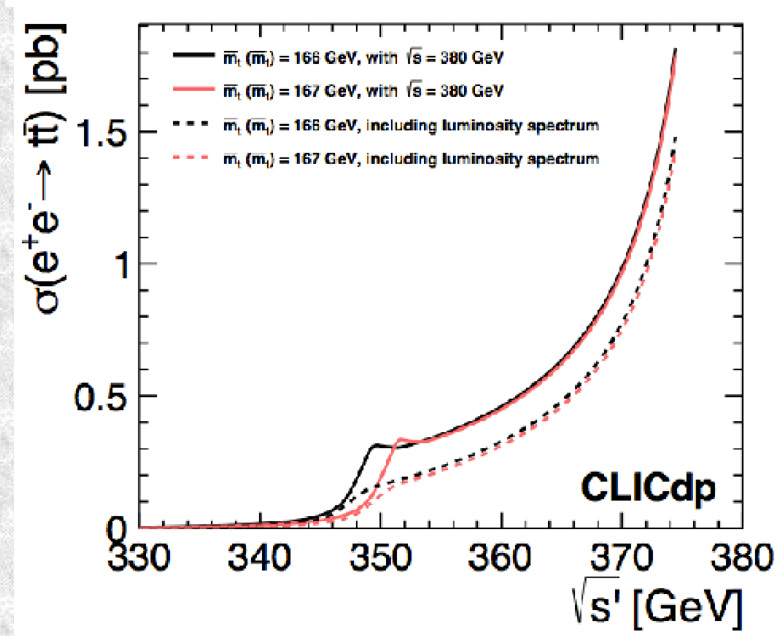
- Many thresholds unexplored. e.g.
  - $B_c\bar{B}_c$ @ 12.551GeV, $\Xi_{bb}\,\Xi_{bb}$ @ 20.3GeV
  - Is a dedicated detector needed to study most boosted?



Dreaming of top

- Fcc-ee (& ILC, CLIC) plan top threshold scan
- m_t errors:
  - 20-30 MeV statistical
  - 25-50 MeV systematic
  - 40MeV theoretical
- Autoscan – radiative return
  - 100 MeV stat
  - 100 MeV theoretical
- Top polarization is a sensitive measurement too
- CepC does not have energy reach….or does it?





CepC status XinChou Lou plenary

- Chinese Government:"actively initiating major-international science project..."
- 国发〔2018〕 5 号 (2018.3.14)
  http://www.gov.cn/zhengce/content/2018-03/28/content_5278056.htm
- focuses on "frontier science, large-fundamental science, global focus, international collaboration, ..."
- by year 2020,3-5 projects will be chosen to go into "preparatory stage", among which 1-2 projects will be selected. More projects will be selected in later years.
- The task of selecting the projects, and develop them further falls on the Ministry of Science and Technology (MOST)
- MOST committees formed, are writing the guidelines
- This is a likely path to realize CEPC. We are paying close attention to this opportunity
  - CEPC team is in regular contact with MOST expert committee
  - Selection criteria seem to be in place, but selection process is not clear, expect to be rather volatile
  - CEPC is focusing on working, & making progress according to the roadmap-schedule

Cultivation of CepC

积极牵头组织国际大科学计划和大科学工程项目培育建议书

项目名称： 环形正负电子对撞机培育

所属领域： 物质科学

申报单位： 中国科学院高能物理研究所 （公章）

项目负责人： 王贻芳

Suggested large international Science & Engineering project for cultivation

Cultivation of CepC

Host: IHEP
PI: Yifang Wang

13th Nov 2019

Proton colliders

- The beam energy is limited by ∫B.dl
- Length: 100km offers factor 4 over LHC
- Field:
  - 8.3T LHC magnets (still not at design) NbTi
  - Nb_3Sn 12T magnets used to save space in HL-LHC
    - 16T prototypes exist
  - HTS (YbaCuO?) could offer 20T
    - But ceramic mechanical properties not ideal.
  - Fe-based super-conductors (≤24T?) still far off
    - Possibly offer 150 TeV collider?

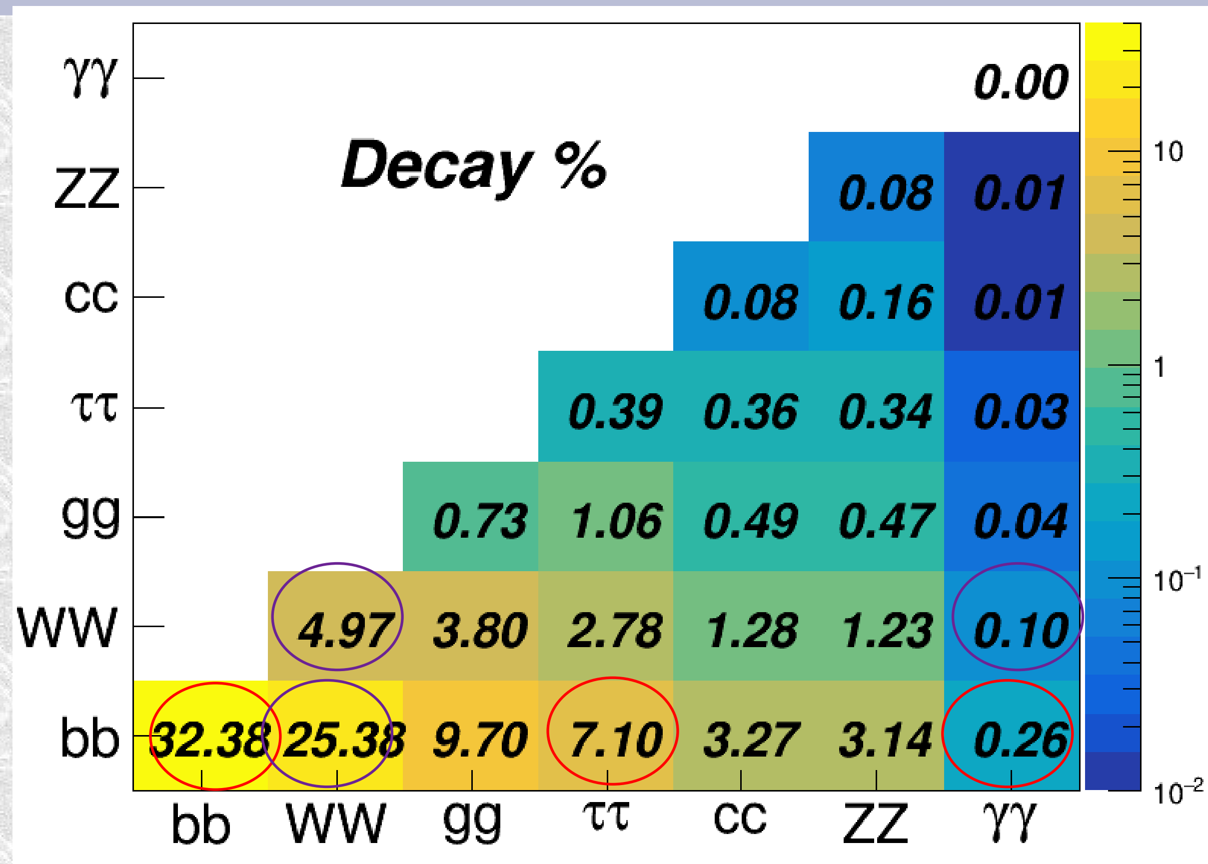
Specifications?

- ddd

	HL-LHC	Fcc-hh	CppC- TDR	CppC-Ultimate
Circumference	27km	100km	100km	100km
CM energy	14TeV	100 TeV	75 TeV	125-150 TeV
IPd	4	4	2	2
Luminosity	$0.5\ 10^{35}$	$0.5\text{-}3\ 10^{35}$	$1.2\ 10^{35}$	$1.2\ 10^{35}$
Current	1.1A	0.5A	0.7A	
Bunch spacing	25ns	25ns	25ns	25ns
Bunch intensity	$2.2\ 10^{11}$	$1\ 10^{11}$	$1.5\ 10^{11}$	
Target dataset		$20ab^{-1}$		
Stored energy	0.7 GJ	8.4GJ		
Pileup	200	170 / 1000	400	

Di Higgs production

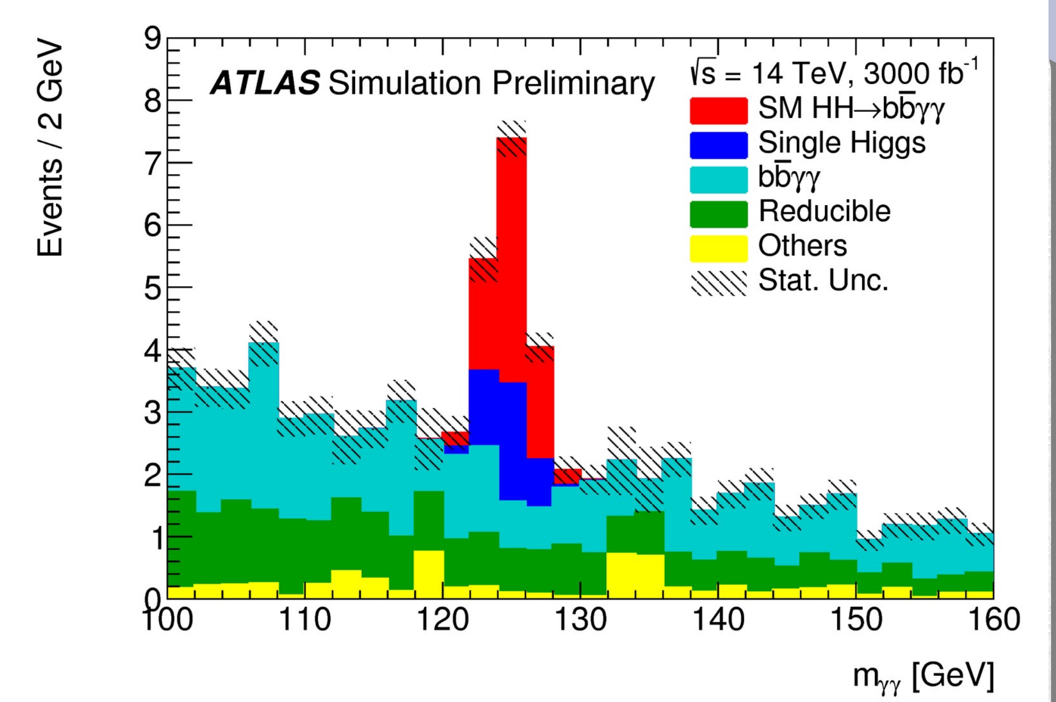
- Right:Branching ratios of various decay modes
- Red circled channels have ATLAS projections
- Purple have results at 13 TeV



- Many weak channels are not exploited – some gain possible

L-LHC: HH → bbγγ

- H → γγ has good resolution & triggering; H → bb is high rate,
- Use BDT to separate from background
- Two comparable backgrounds:
  - Continuum (sidebands)
    - 3.7 in 123-127
  - Single Higgs peaking
    - 3.2 in 123-127 (50% ttH)
- Signal 6.5 expected
- Expected UL 1.2xSMσ



Dominant systematics	Signal	H Background
Photon energy resolution	14%	14%
Jet Energy Resolution	2.9%	7.8%
QCD scale	2.5%	~11%

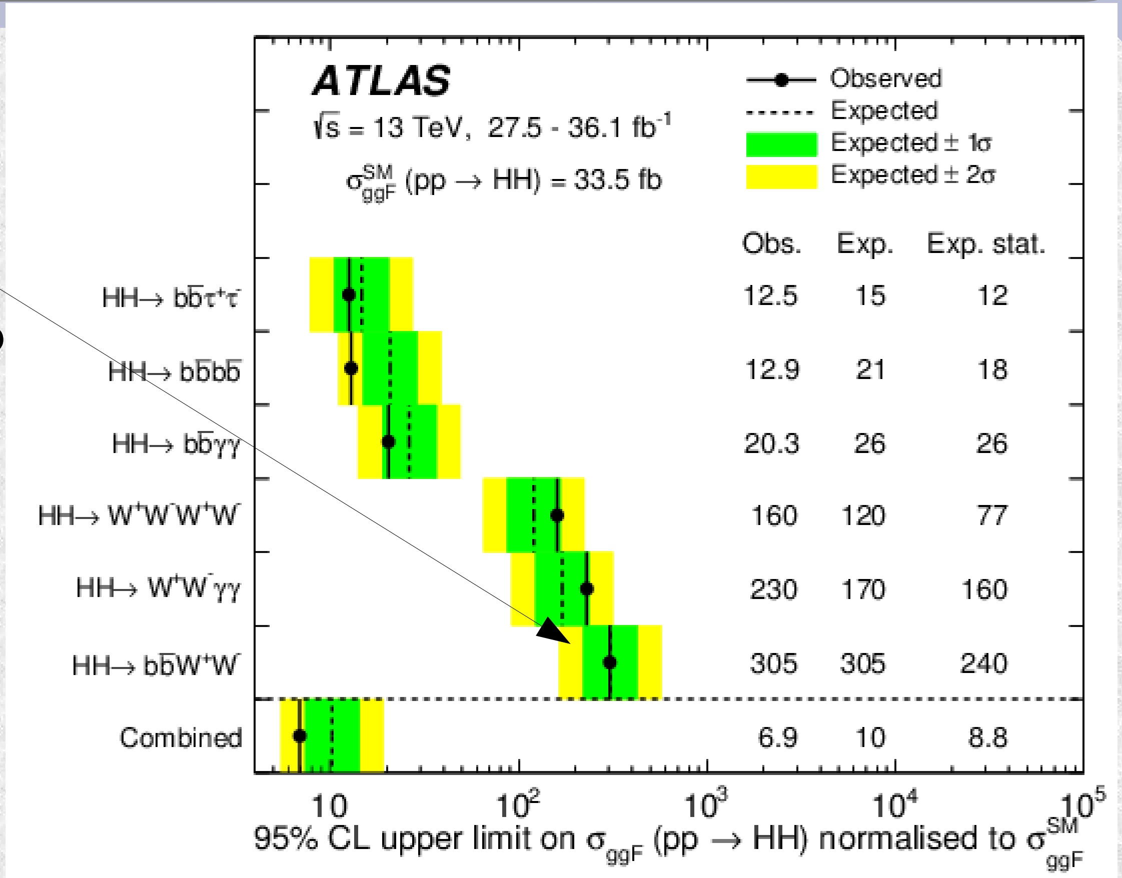
HL-LHC sensitivity to HH

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

- The fitted HH signal strength can be extracted with about a 40% error

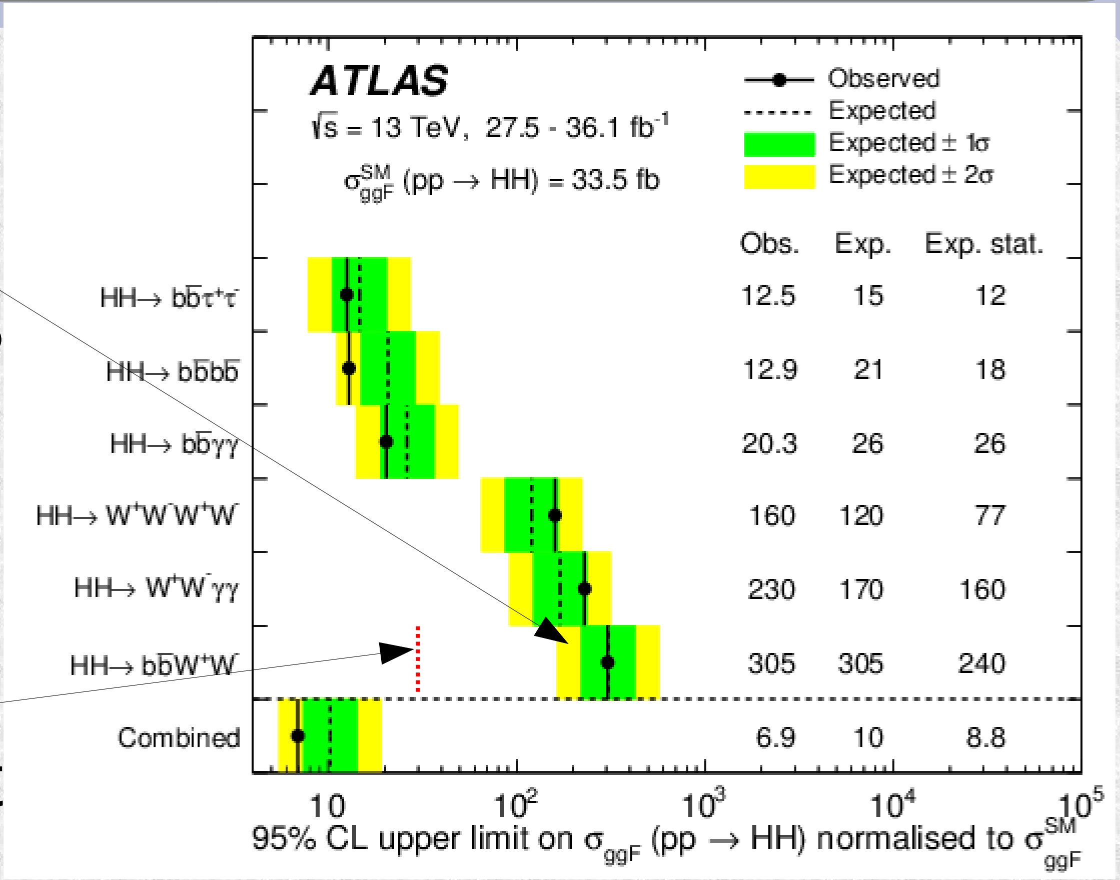
Caution on predictions

- ATLAS 36fb^{-1} HH summary
  - bbWW at 305 x SM!
  - Looks pretty hopeless?



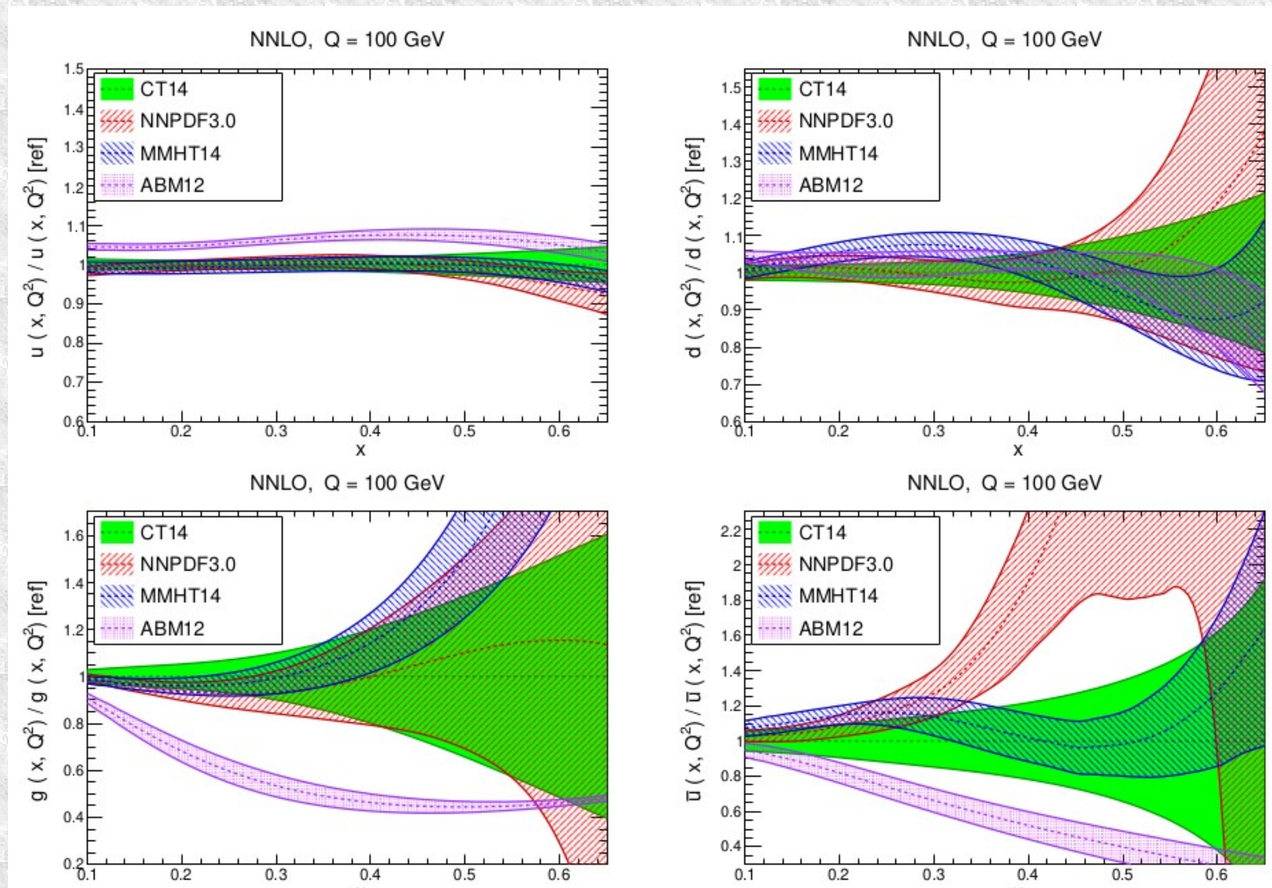
Caution on predictions

- ATLAS 36fb^{-1} HH summary
  - bbWW at 305 x SM!
  - Looks pretty hopeless?
- But 139fb^{-1} bbWW
  - Dileptonic; previous was single-lepton
  - Expected limit 29xSM
  - Factor 10 improvement
- Good ideas and hard work can still improve all the results
  - Especially at pp collider?



PDFs

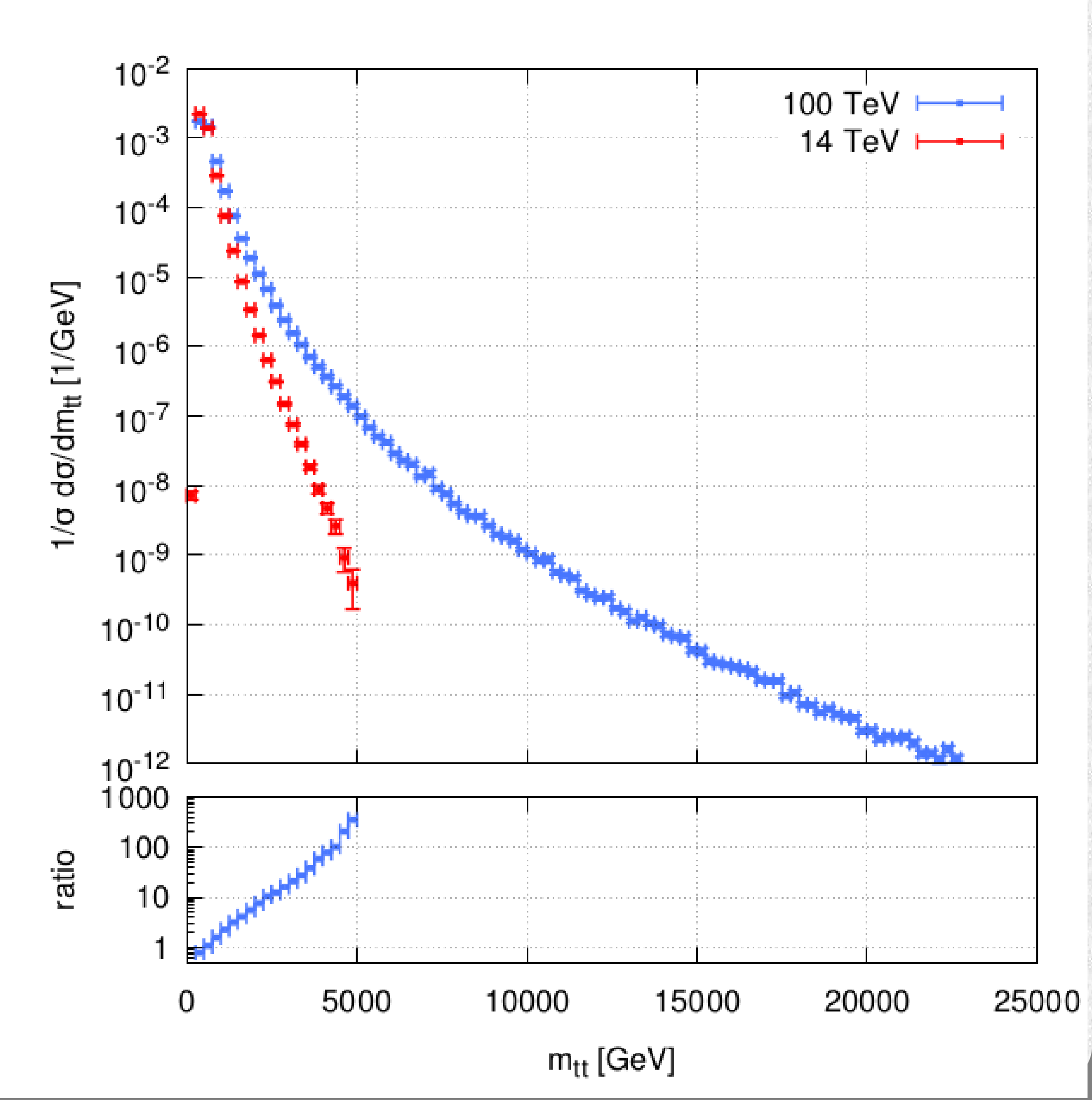
- Knowledge of the parton luminosity is important
- u, d, $\bar{u}$ and gluon from CT14, NNPDF, MMHT and ABM →
- pp data will help
- But an e-h collider could be important



- Precision measurements usually use ratios of σs

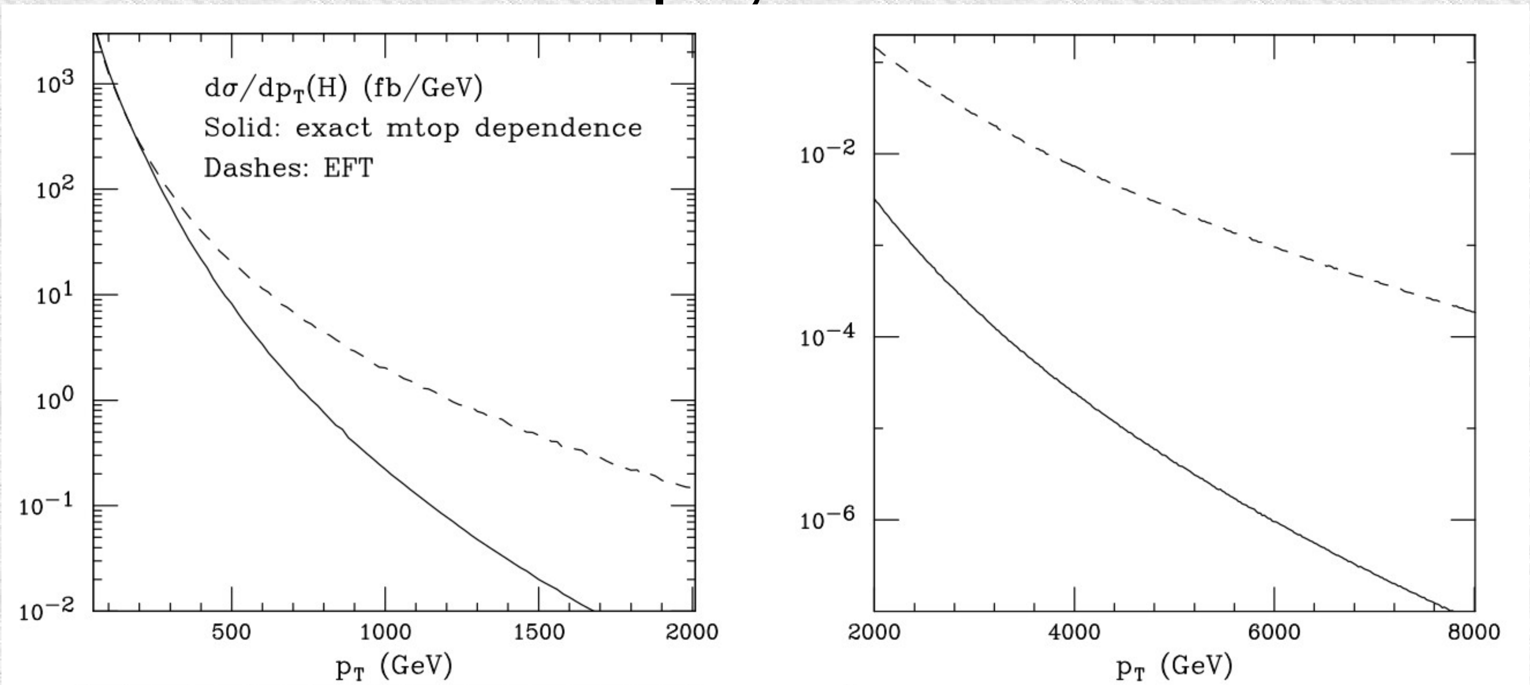
Top at 100 TeV

- Total cross-section 35nb (cf 0.8 at 14 TeV)
- Significant rate of 5 TeV p_T tops
  - ΔR ~ 0.03 requires detector granularity



Higgs at 100 TeV

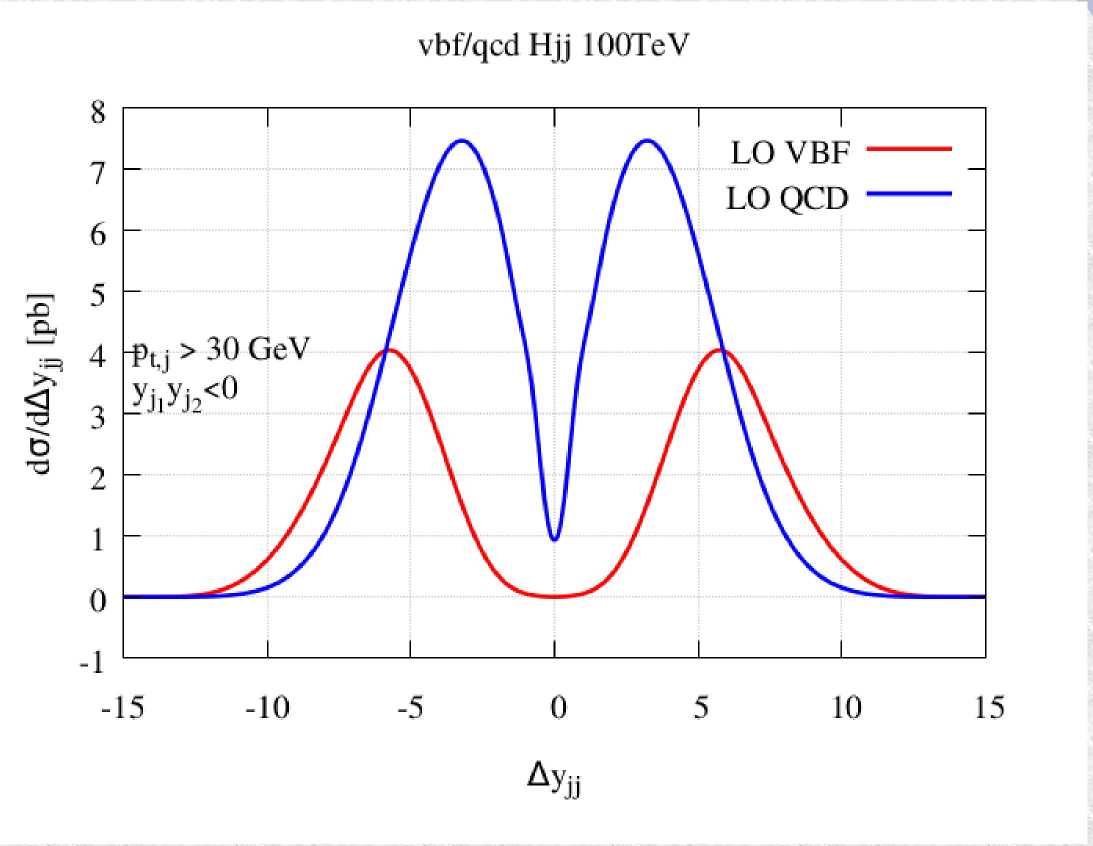
- Total cross-section 900pb, 16x 14 TeV



- Tail of p_T spectrum measurable to ??
- Impact of top loop dramatic
  - Heavier particle (large yukawa) would give strong deviations

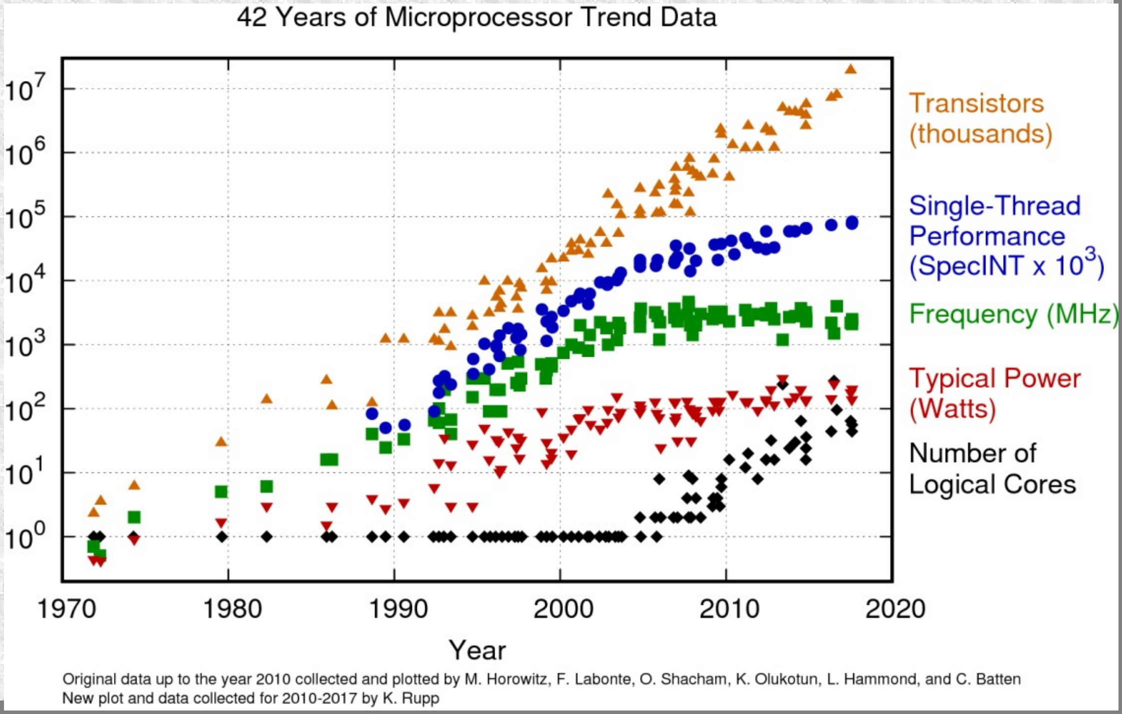
VBF v gluon-fusion jjH

- jjH derived from ggF is always a background for VBF Higgs
  - Shame, as VBF itself is well predicted
- Good acceptance for |Δη| >> 5 required
  - Detectors close to those beams working well!



UK perspective

- A lot of work done on linear colliders over the years
- And we have LHC experience to draw on
- If any of these are built we will want to join
- But we should focus on strengths
  - Silicon tracking
  - DAQ
- e.g. Study application of FPGAs and GPUs to processing needs



Conclusions

- HL-LHC programme holds exciting opportunities
  - But we need to plan beyond
- The 100km circular collider programme has enormous physics potential
  - With electron and proton machines offering complementary physics
  - There are no gauranteed discoveries
- We need to have an ongoing R&D programme
  - High field magnets
  - Detector R&D
- This requires small-scale physics opportunities
  - And a vision for the longer term