Future facilities in high energy frontier and flavour physics

Open Symposium - European Strategy Preparatory Group

Krakow. 10th September 2012

Terry Wyatt.
University of Manchester.

Overview

- Introduction
- High energy frontier physics
  - Summary of main proposed future facilities
  - Physics reach
    - Pick on a few key specific physics questions and measurements
      - in which areas are possible future facilities competitive/complementary?
  - Concluding remarks on high energy frontier physics
- Heavy flavour physics
  - Summary of main proposed future facilities
  - Physics reach
  - Concluding remarks on heavy flavour physics

  - N.B. Future prospects for EDM, charged LFV, K decay, etc, have been covered in talks by Frederic Teubert and Gino Isidori

  - N.B. Many issues relevant to “future facilities” will be covered in the Tuesday afternoon sessions “Accelerator Science and Technology” and “Instrumentation, Computing and General Infrastructure”

Proton-proton colliders

Facility	Years	Ecm [TeV]	Luminosity [10^{34} $cm^{-2}s^{-2}$]	int Luminosity [fb^{-1}]	Comments
nominal LHC	2014-2021	14	1-2	300	
HL-LHC	2023-2030	14	5	3000	luminosity levelling
HE-LHC	>2035	26-33	>2	100-300 / yr	dipole fields 16-20 T
V-LHC		42-100			new 80 km tunnel

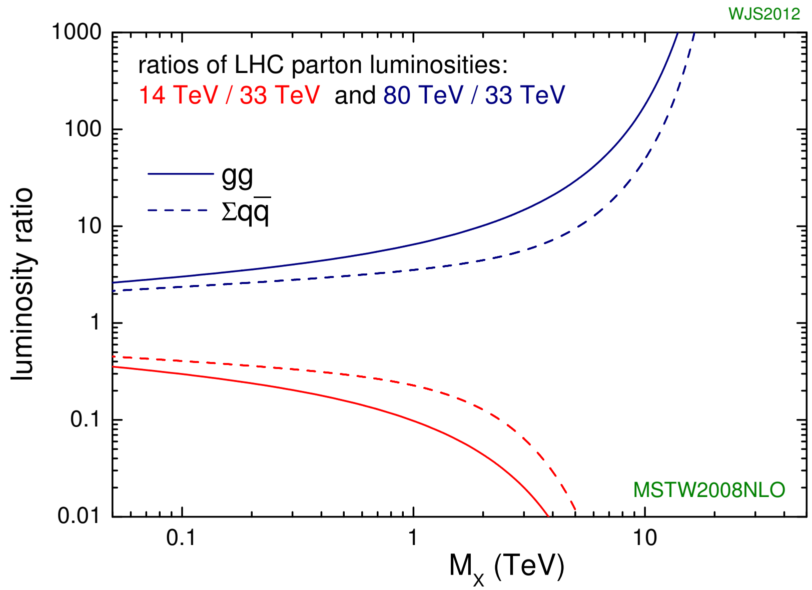
c.f. previous steps in √s at hadron colliders

$Sp\bar{p}S$ ➔ Tevatron ➔ LHC
0.63 ➔ 2 ➔ 14 TeV

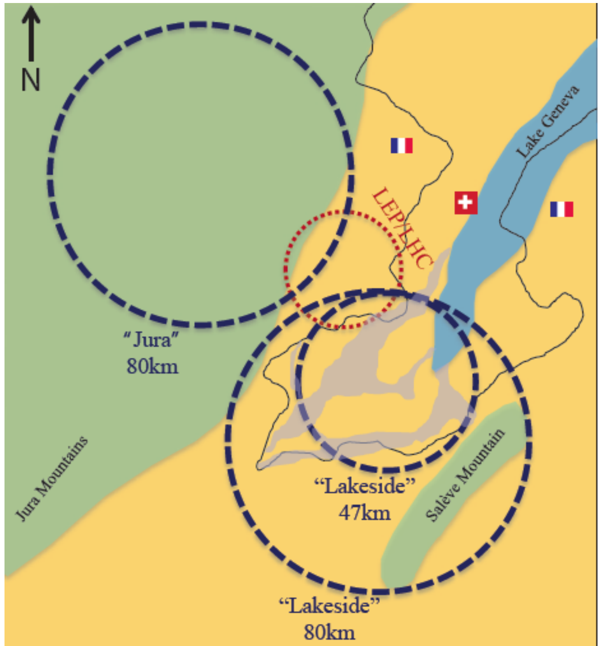
N.B. Very significant challenges to operate trigger/detector and do physics at very high luminosity/high pile-up at HL-LHC and beyond

Possible future high energy proton-proton collider

- Gain a factor of >100 in luminosity for parton-parton collisions of mass
  - at 4-5 TeV for 33 TeV relative to 14 TeV
  - at 10-15 TeV for 80 TeV relative to 33 TeV
    - Plot: thanks to James Stirling (private communication)

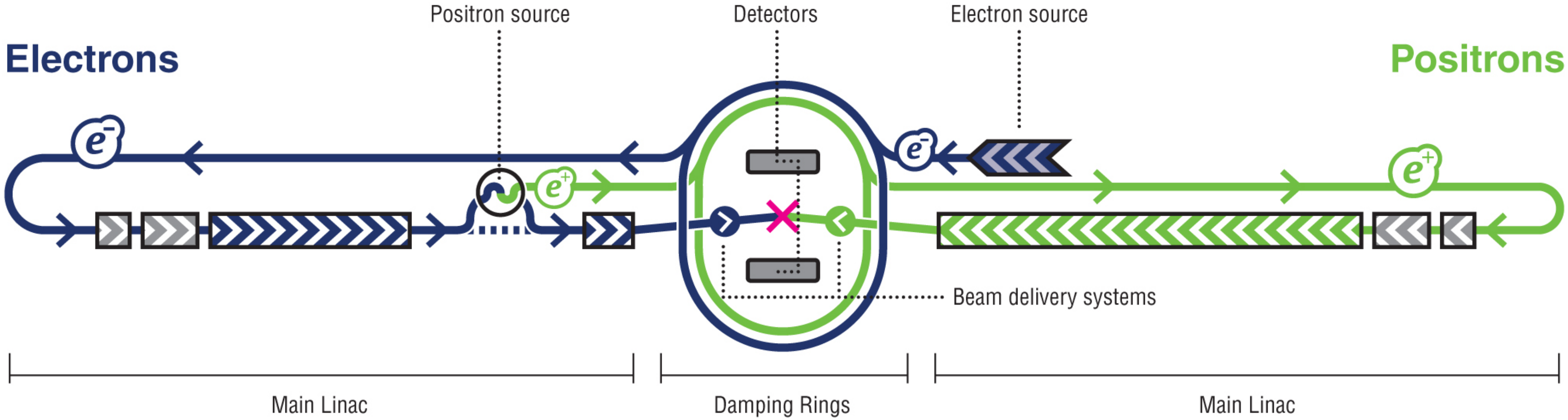


- First geological feasibility studies for 80 km ring at CERN carried out
- High field dual beam dipoles are very large
  - Ideal tunnel diameter needs to be larger than for LHC
  - Reinvestigate proton-antiproton!?
    - Single beam pipe
    - but could enough antiprotons ever be produced?



ILC

Two single-beam linacs with superconducting RF accelerating cavities ~40 MV/m



Schematic layout of the ILC complex

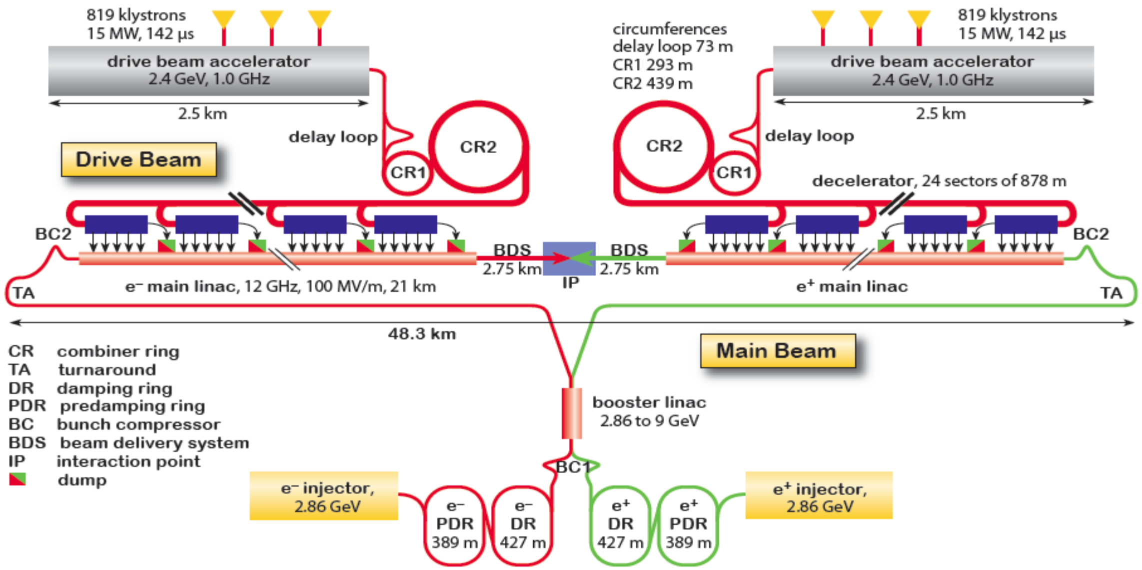
- For √s = 500 GeV total length of facility ~30 km
- Established technology
  - Industrial production of high field superconducting cavities now well established

CLIC

Two double-beam linacs

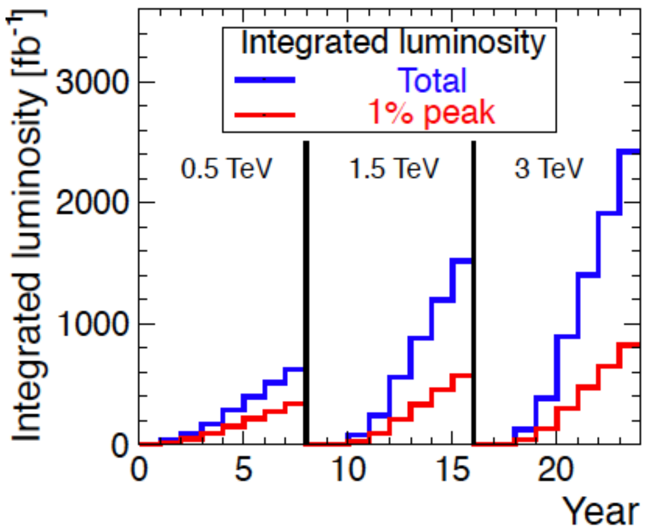
- Low energy, high current drive beam powers ~100 MV/m RF cavities in main linac

Overview of the CLIC layout at √s = 3 TeV

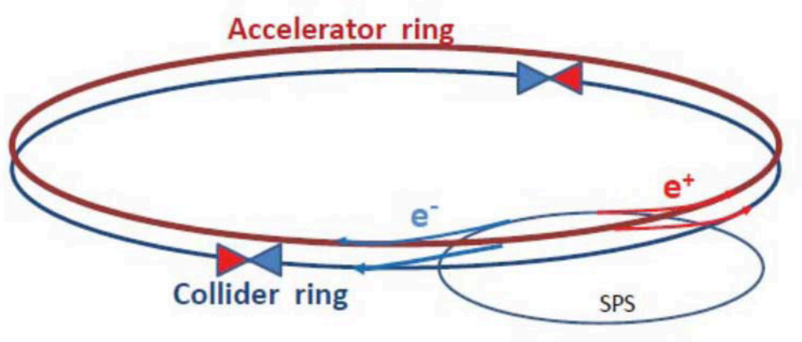


- Two scenarios considered for staged construction of machine
- Scenario A employs higher aperture cavities for 500 GeV running:
  - allows higher beam current and factor 2 increase in luminosity above 99% of √s
  - but these cavities must be replaced for 3 TeV running
- Scenario B employs nominal aperture cavities throughout the programme to minimize overall cost

Projected integrated luminosity for CLIC “scenario B”



Circular e^+e^- colliders



E.g., LEP3:

- $\sqrt{s}$ = 240 GeV in the LHC tunnel to produce $e^+e^- \rightarrow ZH$ events
- Short beam lifetime (~16 mins) requires two ring scheme
  - Top up injection from 240 GeV "accelerator ring"
  - "Collider ring" supplying 2-4 interaction points L = 10^{34} $cm^{-2}s^{-1}$ per IP
    - Re-use ATLAS and CMS and/or install two dedicated LC-type detectors
- Current design uses arc optics from LHeC ring
  - Dipole fill factor 0.75 (smaller than for LEP)
  - increased synchrotron energy loss (7 GeV per turn)
  - redesign possible?
- $e^{\pm}$ polarization probably not possible at $\sqrt{s}$ = 240 GeV
- In principle space is available to install compact e^+e^- facility on top of LHC ring
  - Is this really feasible?
  - Alternatively wait until completion of LHC physics programme and removal of LHC ring?
- SuperTRISTAN is a proposal for a similar machine in Japan

E.g., TLEP:

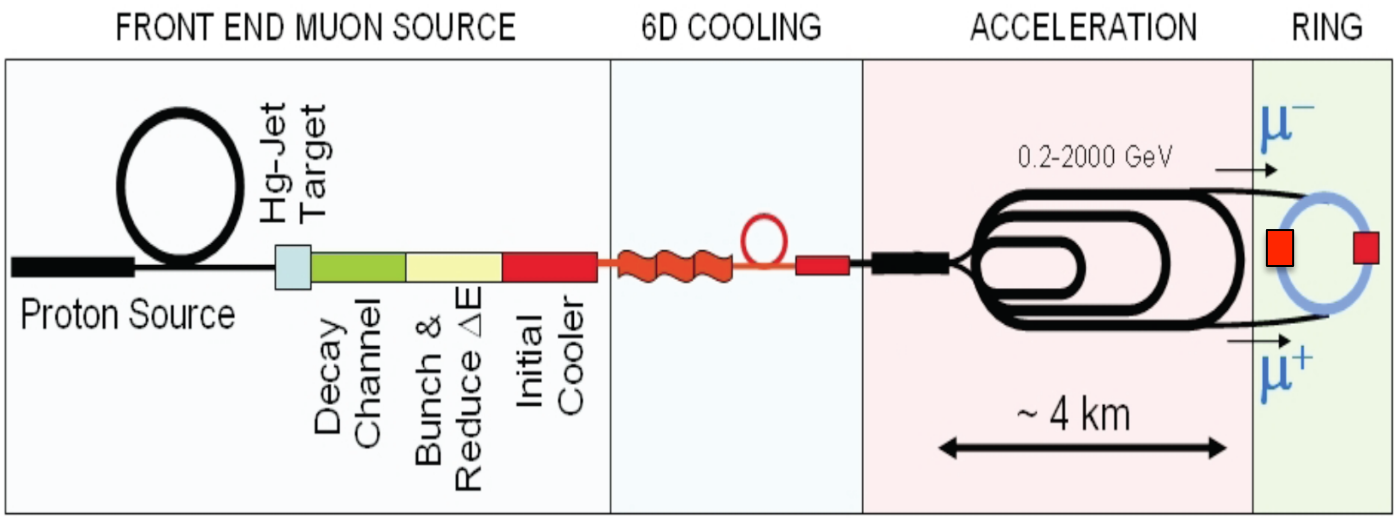
- $\sqrt{s}$ = 350 GeV in 80 km LHC tunnel to reach thresholds for top pair and $e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu H$

e^+e^- collider summary

	ILC	ILC	ILC	CLIC	CLIC	CLIC	LEP3
√s [GeV]	250	500	1000	500	1500	3000	240
Luminosity [10^{34} $cm^{-1}s^{-1}$]	0.75	1.8	4.9	1.3	3.7	5.9	1 per IP
>0.99 √s fraction	87%	58%	45%	54%	38%	34%	100%
polarization e^-	80%	80%	80%	80%	80%	80%	-
polarization e^+	30%	30%	20%	>50%?	>50%?	>50%?	-
beam size σ_x [nm]	729	474	335	100	60	40	71000
beam size σ_y [nm]	7.7	5.9	2.7	2.6	1.5	1	320
Power [MW]	128	162	300	235	364	589	200

- Both ILC and circular e^+e^- machines offer the option of "GigaZ"
  - Collect 10^9 (ILC) to 10^{11} (LEP3, with 80% $e^\pm$ polarization) Z events in one year at E_{cm} = 91 GeV
  - Improve by an order of magnitude or more on the precision of the LEP/SLC measurements of Z couplings
- Also running at WW threshold to improve m_W

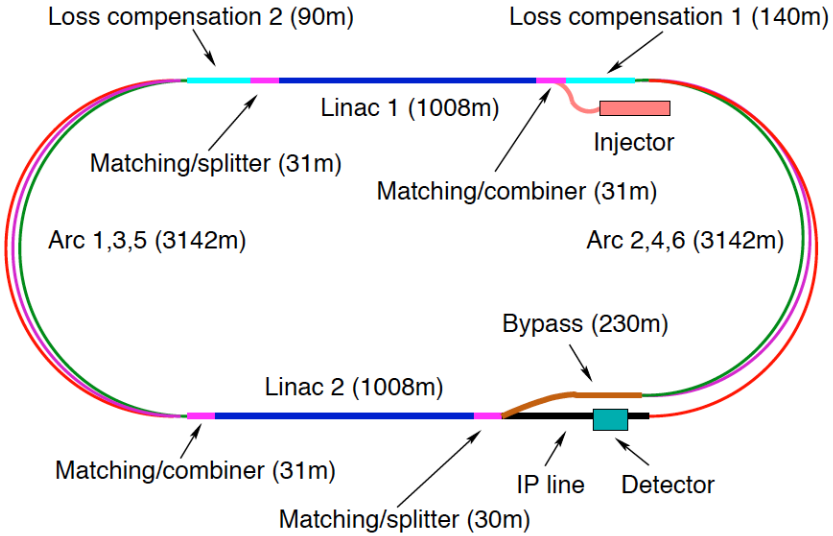
Muon collider



- Potential advantages wrt. e^+e^-
- Smaller facility size
  - Synchrotron radiation losses ~ E^4/m^4r
- Smaller energy spread
  - Beamsstrahlung ~ E^4/m^4
- s-channel Higgs production ~m^2

- Target L = 10^{34} $cm^{-2}s^{-1}$ per IP
- Many technical challenges to be faced
  - Intense proton source
  - Muon cooling
  - Can detectors survive muon decay rate and still do the physics?
- Could be a follow-on from (or precursor to) a ν-factory

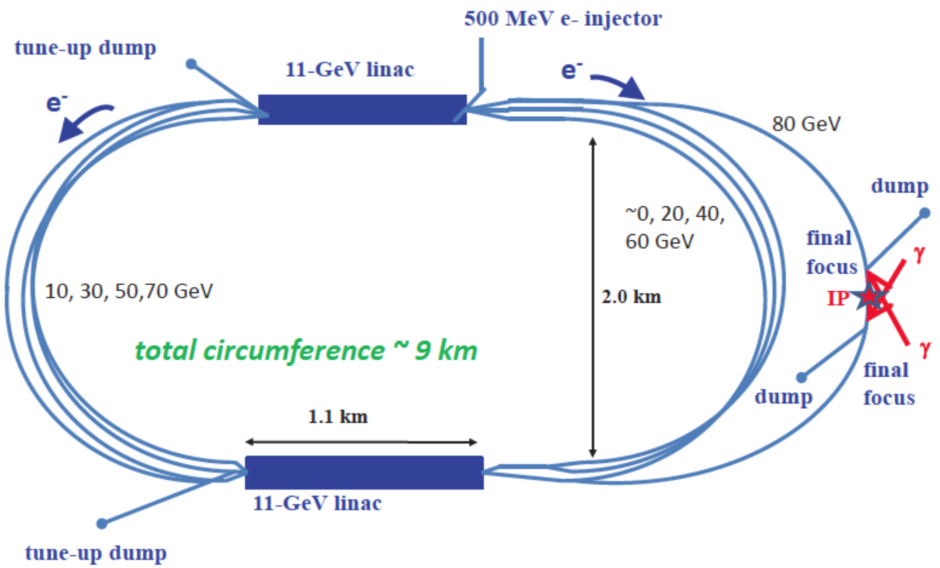
electron-proton collider (LHeC)



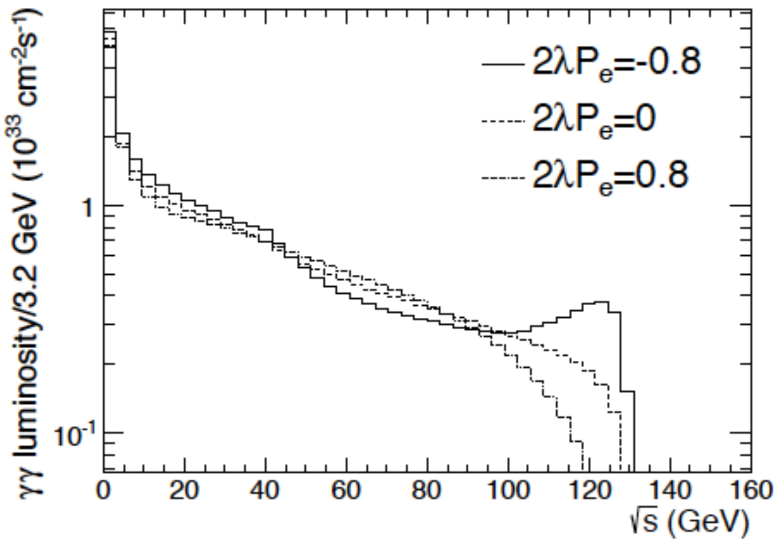
- Double ("race-track") linear accelerator option now preferred
- 10 x 2 x 3=60 GeV $e^{\pm}$ beam
- Unused beam returned from IP to recover energy

- Q^2_{max} ~ 1 TeV
- Luminosity 10^{33} $cm^{-2}s^{-1}$ (e^-p), 10^{32} $cm^{-2}s^{-1}$ (e^+p)
- Integrated luminosity aim ~100 fb^{-1}
- e^- polarization ~ 90%
  - Q^2_{max} and luminosity are factors of around 30 and 100, respectively, higher than at HERA
- N.B. precise QCD (PDFs, α_s, MC, etc) is very important for HEF programme at LHC!
  - In addition, some particular HEF reach
  - e^-N collisions also possible

Photon-photon colliders



$\gamma\gamma$ luminosity as function of √s for different polarization of laser photons (λ) and electrons (P_e)



- Photon-photon collisions at √s = 125 GeV for $\gamma\gamma \rightarrow$ H (s-channel)
- E.g., SAPPHiRE:
- Pair of recirculating linacs similar in design to those proposed for the LHeC
  - E_{beam} = 80 GeV
- Laser back-scatter system peak power 6 x 10^{21} Wm^{-2}
  - Needs R&D!
- $\gamma\gamma$ Luminosity ~0.3 x 10^{34} $cm^{-2}s^{-1}$ for √s ≈ 125 GeV
- Some advantages over e^+e^- for Higgs
  - Lower beam energy
  - Do not need positron source

Physics reach of future high energy frontier facilities

Define "benchmark" set of energy frontier physics questions/measurements:

- Measurement of Higgs-like particle properties
  - mass, spin, couplings
- Measurement of gauge boson pair scattering at high energies
- Other precise EW measurements
  - W mass, $\sin^2\theta_W$, etc.
    - Give access to new physics through quantum effects
- Measurement of top quark properties
  - mass, couplings, spin correlations, W helicity, tt resonance search, etc.
- Generic cases of sensitivity of searches for massive particles/new interactions

Caveat emptor

- Different studies are currently at very different levels of sophistication/ realism
  - Full Geant-level MC with pile-up vs. parameterized MC (of varying levels of sophistication) vs. extrapolations from current performance vs. "back of envelope" estimates
  - Currently running detectors vs. experience from similar past machines vs. "guesswork”
  - Difficult to predict improvements in theory uncertainties
    - In most projections theory uncertainties ignored or quoted separately
    - A huge effort will be needed to ensure that the theoretical interpretation will match the precision of the improved experimental measurements
  - I'll try to point out some specific caveats in the following

- For almost any past facility in particle physics, compare actual physics achieved with that predicted before turn on!
  - E.g., EW precision at LEP
  - E.g., The recent "Higgs" discovery came at half the LHC design energy, much more severe pileup, and one-third of the integrated luminosity than expected
  - Actual start date compared to that advertised when it was being "sold"?

- Nevertheless, we have to try to estimate physics reach as a guide in making rational decisions about future directions
  - which R&D to pursue, ultimately which facility to build?

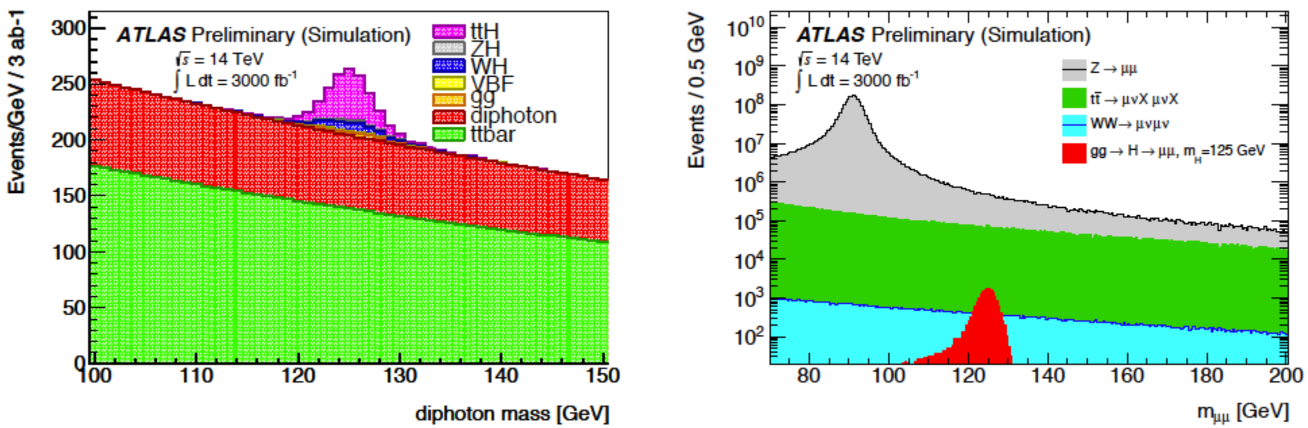
Higgs

- Many extensions to SM have a “light”, “SM-like”, “Higgs-like” particle
- Important to measure couplings as precisely as possible
- m_H= 125 GeV is “ideal” since it provides non-negligible Br to many final states

Higgs at the LHC

- In pp many possible H decays are for practical purposes "invisible"
- Can measure only ratios of couplings

$\sigma_i \cdot \mathrm{BR}_j$ is assumed to be proportional to $\Gamma_i \cdot \Gamma_j / \Gamma_H$ with $i = g, W, Z, t$ and $j = W, Z, \gamma, \mu, \tau$.

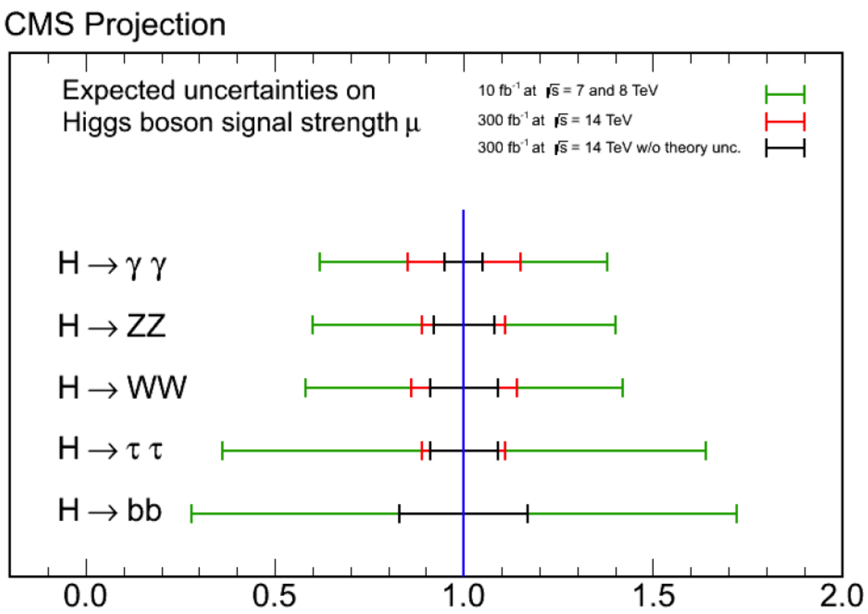


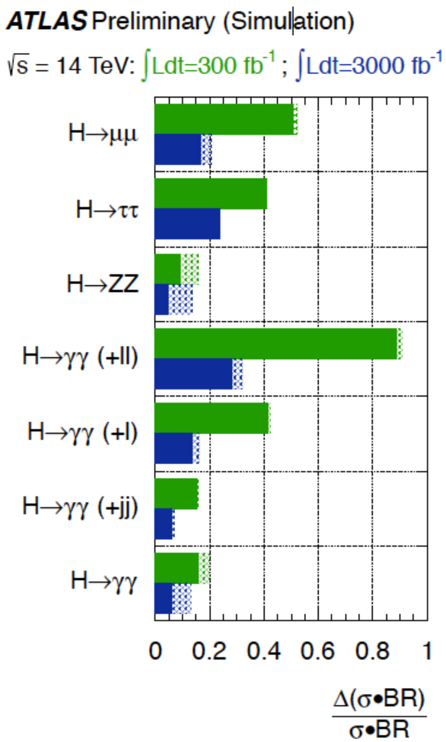
(a) (b)

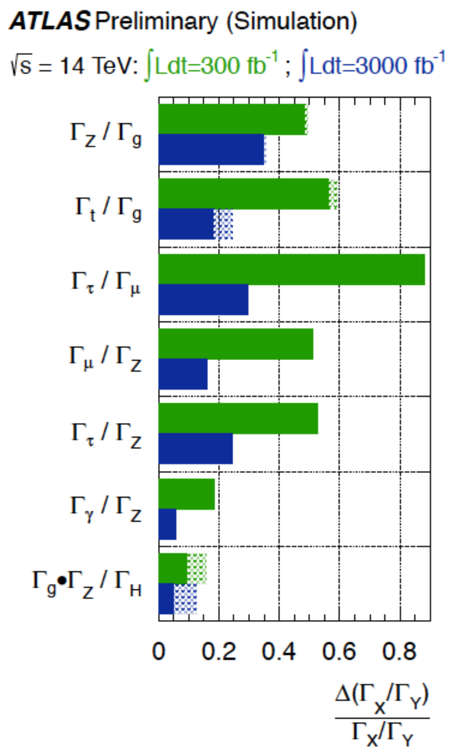
Figure 1: Expected invariant mass distribution for (a) $t\bar{t}H, H \to \gamma\gamma$ in the 1-lepton selection and (b) the inclusive $H \to \mu\mu$ channel, for an assumed integrated luminosity of $3000\,\mathrm{fb}^{-1}$

ATLAS and CMS Higgs couplings

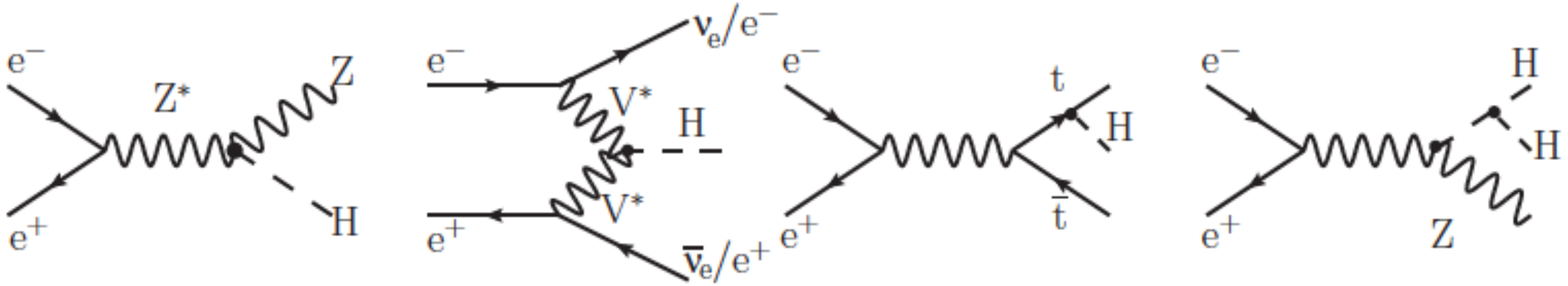
- ATLAS has studied expected degradation in detector performance using full Geant MC with pile up (up to μ~70)
  - Extrapolate to μ~140 and input to parameterized MC
  - Projections for 300 fb^{-1} and 3000 fb^{-1}
- CMS extrapolates to 300 fb^{-1} assuming current detector performance can be maintained
  - No projections currently for 3000 fb^{-1}
- Differences in projected performance at 300 fb^{-1} understood at some level as coming from different methodologies
  - E.g. $\gamma\gamma$ signal strength precision 10±5% for 300 fb^{-1} (ATLAS estimate 15%, CMS estimate 5%)
- Much to be done to refine these projections
  - But the experiments have understandably had other priorities in this area recently ;-)
- Significant gain in precision expected between 300 and 3000 fb^{-1}
  - Uncertainties <5% look likely for H➔γγ , H➔ZZ

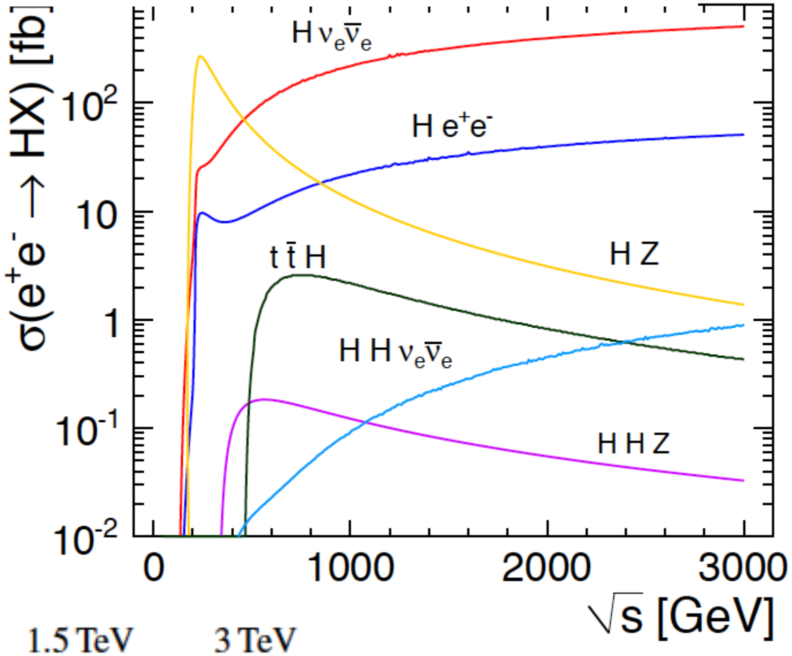






Higgs in e^+e^-





Many studies performed using full Geant-based MC

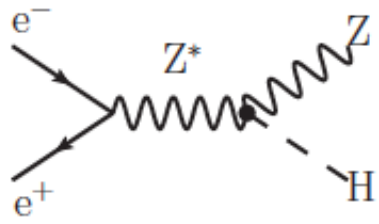
Integrated luminosity and numbers of events expected for initial 5 years running at each value of E_{cm}

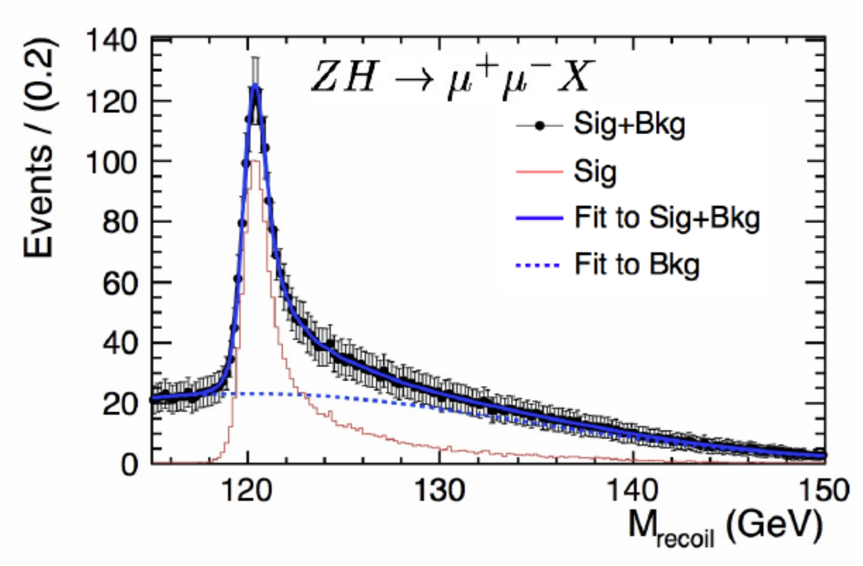
	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

√s ~ 250 GeV ZH

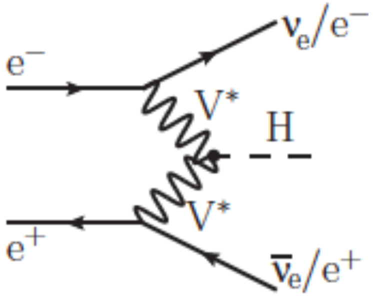
- Recoil mass in l^+l^-X events
  - very powerful
  - σ_{ZH} independent of decay mode
    - including invisible decays

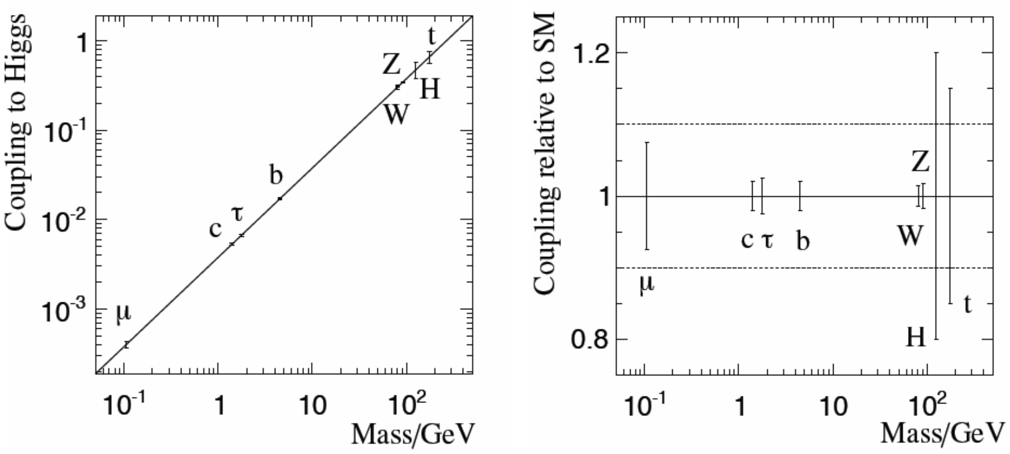
$\sqrt{s}$	250 GeV	350 GeV
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}
$\Delta(\sigma)/\sigma$	3 %	4 %
$\Delta(g_{HZZ})/g_{HZZ}$	1.5 %	2 %





√s > 500 GeV WW and ZZ fusion





e^+e^- precision on Higgs couplings assuming one operating point ~250 GeV and one ~500 GeV

I.e., typical e^+e^- precisions on couplings ~few percent

	250/350 GeV	500 GeV†	3 TeV
$\sigma \times Br(H \to bb)$	1.0/1.0 %	0.6 %	0.2 %
$\sigma \times Br(H \to cc)$	7/6 %	4 %	3 %
$\sigma \times Br(H \to \tau\tau)$	6*/6 %	5 %	?
$\sigma \times Br(H \to WW)$	8/6 %	3 %	?
$\sigma \times Br(H \to \mu\mu)$	−/−	?	15 %
$\sigma \times Br(H \to gg)$	9/7 %	5 %	?

	250/350 GeV	500 GeV†	3 TeV
g_{Hbb}	1.6/1.4 %	?	2 %
g_{Hcc}	4/3 %	2 %	2 %
$g_{H\tau\tau}$	3*/3 %	2.5 %	?
g_{HWW}	4/3 %	1.4 %	< 2 %
$g_{H\mu\mu}$	−/−	−	7.5 %
$\frac{g_{HWW}}{g_{HZZ}}$	?/?	?	< 1 %*
g_{Htt}	−/−	15 %	?

- N.B. Higgs production in WW and ZZ fusion can be studied also at LHeC
  - e.g., σ.Br (H->bb) precision ~4%

Higgs mass and width

- Δm_H ~ 50 MeV
  - From recoil mass at √s = 250 GeV or direct reconstruction
- For m_H = 125 GeV, the total Higgs decay width in the SM is less than 5 MeV
  - Cannot be measured directly
  - Can be determined to ~5% using

$$\Gamma_H = \Gamma(\mathrm{H} \to \mathrm{WW}^*)/Br(\mathrm{H} \to \mathrm{WW}^*)$$

- Threshold behaviour of cross section gives information on CP

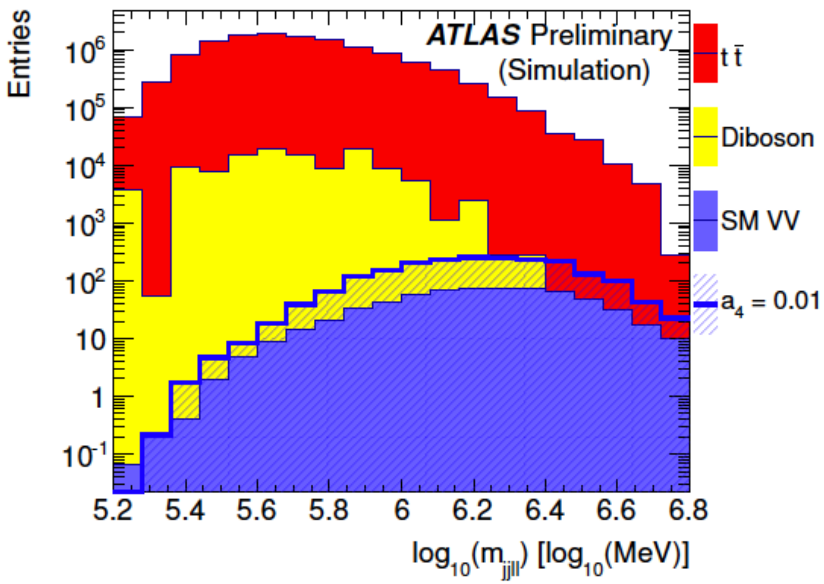
Higgs self-coupling

- Observing HH events: very difficult at the LHC
  - Destructive interference between diagrams involving HHH and gg→HH
    - σ_{HH} = 71, 34, 16 fb for $\lambda_{HHH}/\lambda_{HHH}^{SM}$ = 0,1,2
  - Most promising channels bbγγ, bbττ
  - Maybe ~3σ significance per expt in a few channels?
  - Maybe 30% measurement of λ_{HHH}?
  - At the moment estimates are very vague and based on a large degree of optimism
- This is not easy at LC either!
  - $\sqrt{s}$ = 500 GeV ZHH
  - $\sqrt{s}$ = 1000 GeV ννHH
  - Maybe 20% measurement of λ_{HHH}?

Vector boson scattering at high energy

- Essential component in test of EWSB
- At LHC VBF signature tagged by two forward jets separated by "rapidity gap"

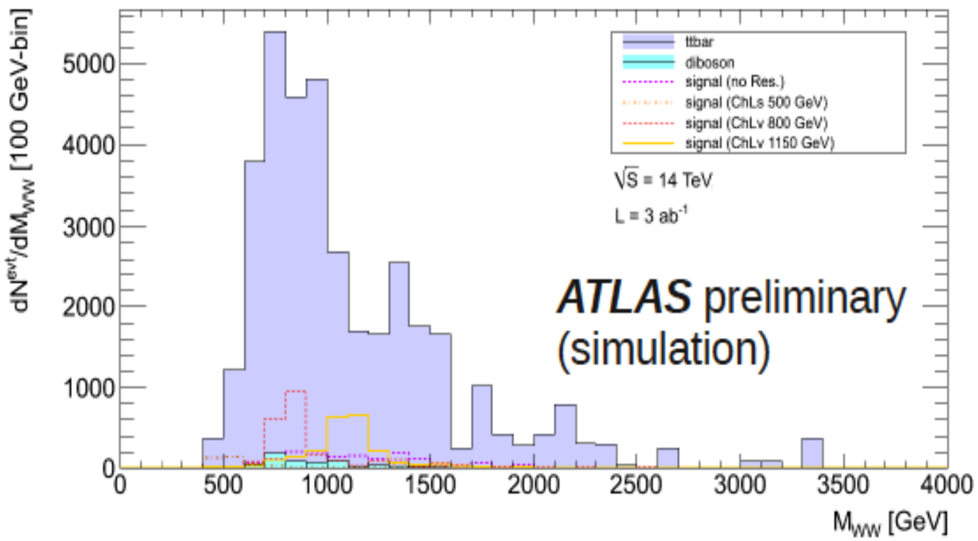
e.g., WW+jj ➔ eνμν+jj
(fully leptonic WW decay)



95% CL limits on parameter a_4 that multiplies example non-SM operator

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
a_4	0.066	0.025	0.016

e.g., WW+jj ➔ lνjj+jj
(semi-leptonic WW decay)



Sensitivity to SM WW and various resonance hypotheses

model	baseline	500 GeV scalar	800 GeV vector	1150 GeVvector
(a_4, a_5)	(0, 0)	(0.01, 0.009)	(0.009, −0.007)	(0.004, −0.004)
S/B	(3.3 ± 0.3)%	(0.7 ± 0.1)%	(4.9 ± 0.3)%	(5.8 ± 0.3)%
$S/\sqrt{B}$ (L = 300fb^{-1})	2.3 ± 0.3	0.6 ± 0.1	3.3 ± 0.4	3.9 ± 0.4
$S/\sqrt{B}$ (L = 3000 fb^{-1})	7.2 ± 0.1	1.6 ± 0.1	10.4 ± 0.7	12.4 ± 0.7

Vector boson scattering at LC

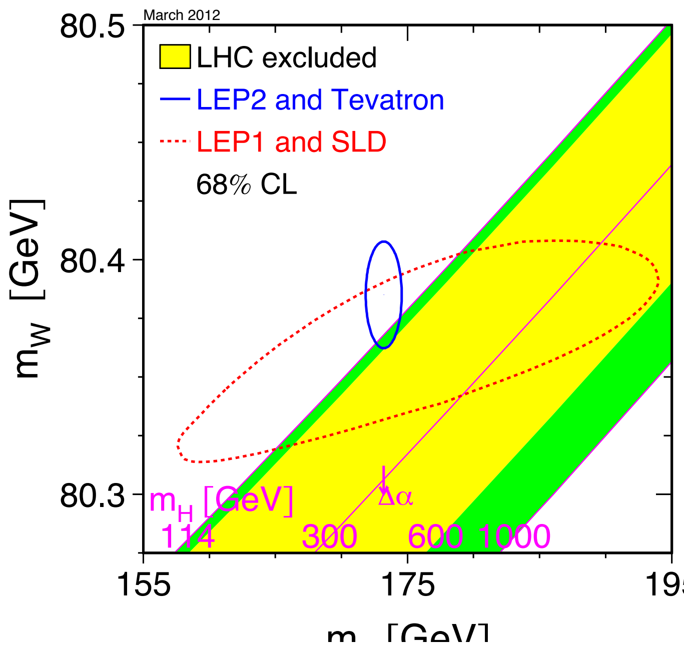
$$e^+e^- \to \nu\overline{\nu}W^+W^-$$
$$e^+e^- \to \nu\overline{\nu}ZZ,$$

- Separating WW and ZZ in the 4-jet final state
  - Requires excellent jet energy resolution
  - Has driven development of highly segmented calorimeters for energy flow
- Sensitivity to anomalous triple and quartic gauge couplings
- High beam polarization and high integrated luminosity would allow very precise tests to be made
  - ~1% precision on each individual contribution to Lagrangian

Other precise EW measurements

- W mass, $\sin^2\theta_W$, etc.
  - Measurements possible at LHC
    - Competitive with the LEP/Tevatron precision
      - but unlikely to make huge gains relative to LEP/Tevatron
- New e^+e^- machines running at $\sqrt{s} = M_Z$ and $\sqrt{s} = 2M_W$
  - could give order of magnitude or more improvements
    - e.g., $\Delta m_W \sim 0.5 - 1.0$ MeV?
    - e.g., $\sin^2\theta_W$ from polarization and forward-backward asymmetries

- $\sin^2\theta_W$ starts to look like the poor relation in this plot!
  - Significant theoretical progress would be required in the interpretation of more precise experimental measurements in this area!

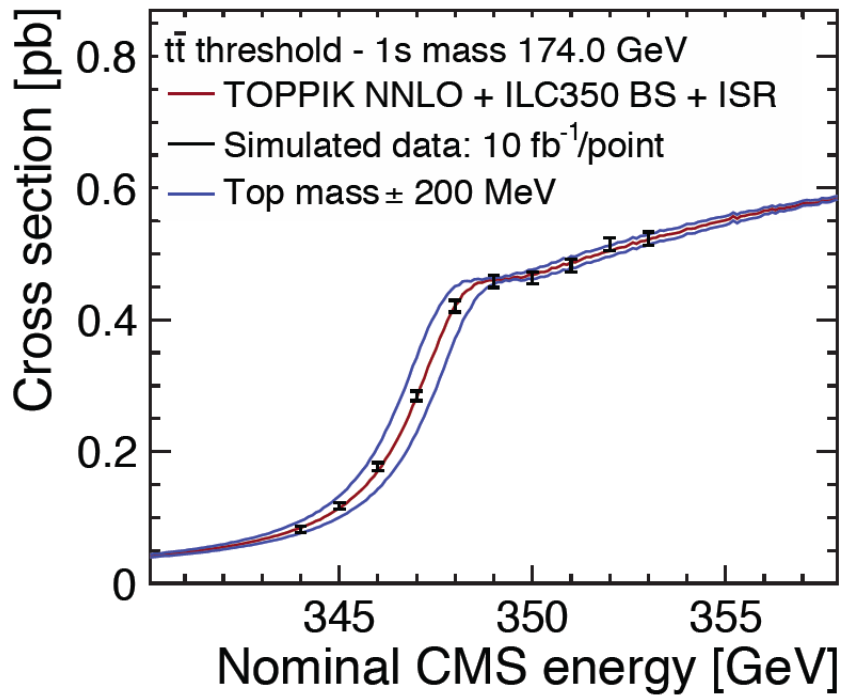


Top physics

- Huge numbers of events with 300 fb^{-1} at LHC
  - ~50M lepton+jet, 10M di-leptons, 15M single top
- Allows many interesting and precise measurements of top quark properties
  - mass, couplings, spin correlations, W helicity, A_{FB}, $t\bar{t}$ resonance search, etc.
- Δm_t ~ 1 GeV from Tevatron
- Hard to imagine a huge improvement at LHC, unless radically new ideas can be exploited?
- Theoretical progress needed in interpretation of experimental result
- Less precise (few GeV) measurement from cross section

Top physics at LC

- Threshold scan allows:
  - Δm_t ~ 20 MeV (expt)
    - with additional ~100 MeV ascribed to theoretical interpretation
  - $\Delta\Gamma_t$ ~ 30 MeV
- Use of polarized beams very powerful in making precise measurements of angular observables



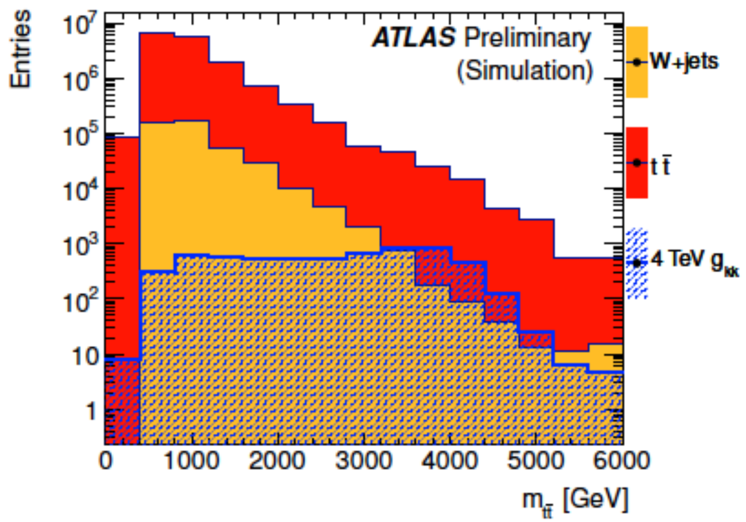
Resonance search in ttbar at LHC

"Benchmark" example of complex final states

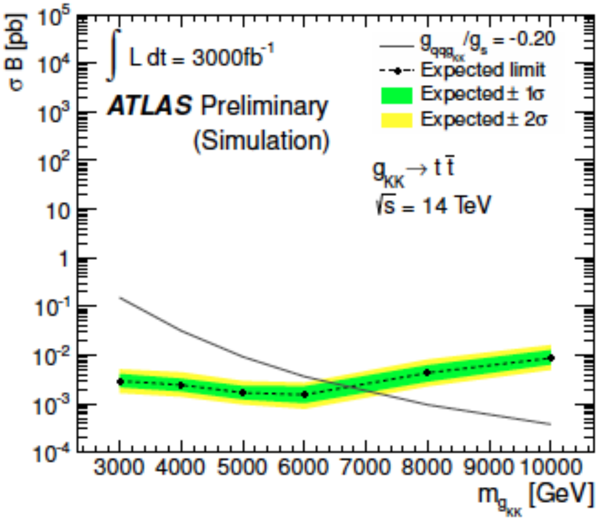
- (multiple) leptons, MET, jets (including b-tag), highly boosted systems

- Compare
  - l+jets: higher Br, higher backgrounds, mass reconstruction possible
  - di-lepton: lower Br, lower backgrounds, no direct mass reconstruction

m_{tt} in lepton+ jets



projected limit on σ.Br gKK➔tt (3000 fb^{-1})



Limits [TeV] from searches in l+jets (di-lepton) stat. uncertainties only

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\text{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

← strong coupling: broad resonance (g_{KK})

← weak coupling: narrow resonance ($Z'_{\text{Topcolour}}$)

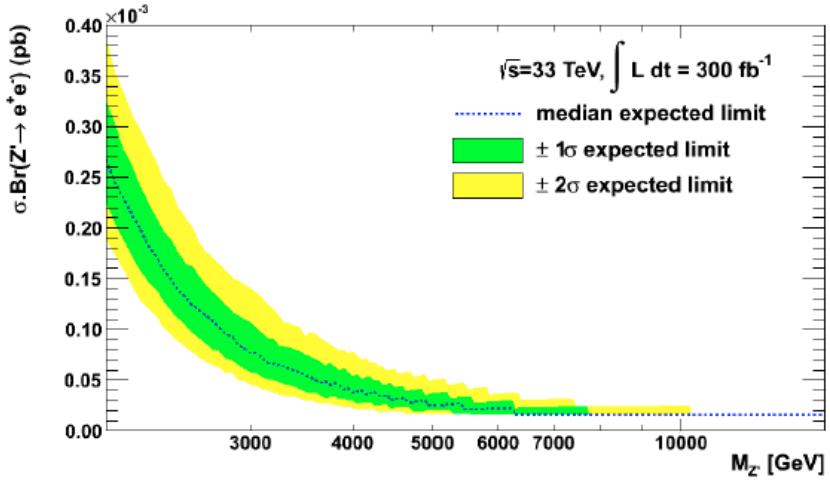
Resonance search in l^+l^- at LHC

- Challenge to maintain electron energy/muon momentum resolution in multi-TeV region
- Background dominated by SM Drell-Yan

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

(stat. uncertainties only)

- Example CMS projection for l^+l^- search at 33 TeV



Summary on direct searches at √s = 14 TeV

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\mathrm{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

- Search sensitivity up to ~8 TeV
- Specific mass values very model dependent + need systematics
- Clear improvement with increasing integrated luminosity

- N.B. clear windows of opportunity for direct and indirect searches at LC and LHeC
  - e.g., interference effects in (polarized) forward-backward asymmetries give sensitivity to scales 10s TeV

Concluding remarks on high energy frontier

Can we think of any scenario in which it would make sense to stop running the LHC in ~2022 (once 300 fb^{-1} has been collected)?

- If we have found new particles
  - Presumably we shall want to study them and search for more at higher mass and/or lower σ.Br ?
- If we have found nothing new (other than SM higgs)
  - Would it make sense to switch off the LHC, when it might still represent the best chance of finding NP at higher mass/lower σ.Br ?
- In addition, there is an important programme of "bread and butter" physics at the LHC that will benefit from increasing the integrated luminosity beyond 300 fb^{-1}
    - Higgs couplings, top properties, vector boson pair scattering at high energies

- Large costs in consolidation of accelerators/detectors are required to enable the LHC to continue to run beyond 300 fb^{-1}
  - even without any upgrade to deliver HL-LHC
- Costs specific to HL-LHC upgrade represent small fraction (~10%?) of total running+consolidation cost of LHC programme for 2022-2030
- Expect HL-LHC upgrade to bring factor ~3 in integrated luminosity
  - 3000 fb^{-1} rather than 1000 fb^{-1} if continue to run until 2030 at ~100 fb^{-1}/year
    - Maybe hard to imagine sustaining a programme at constant luminosity over such a long period

Concluding remarks on high energy frontier

- LHC built to deliver 100s fb^{-1} at 14 TeV
- Currently we have ~20 fb^{-1} at 7-8 TeV
- It is too early to say what discoveries will be made at the LHC
  - In particular, at what mass the first BSM particles will be found
- We should welcome the wealth of possible future options as a strength of our field
  - Possible to imagine scenarios in which just about any of the above-mentioned large facilities might be the best next step
- Too early to decide what the next big machine will be?

- Whilst waiting for the discoveries (or absence thereof) that will shape the future of the field, can we agree on
  - the further studies that need to be made
    - accelerator and detector designs, physics cases
  - the R&D that needs to be made
- so that when we are in a position to take decisions about the next big HEF facility
  - (maybe by the next round of the European strategy process ;-)
- we can make rational, well-informed decisions?

Concluding remarks on high energy frontier

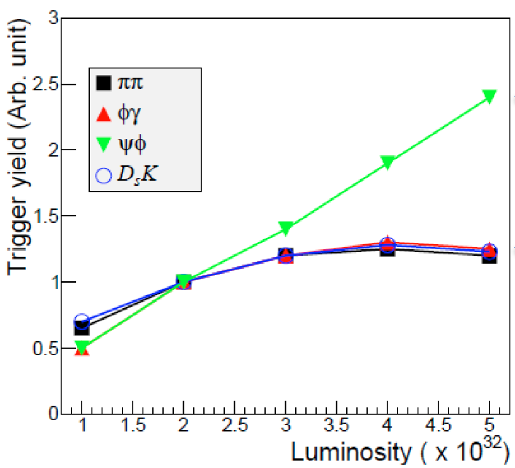
- Discovery of Higgs-like particle with m_H = 125 GeV changes many things
  - A major step forward for the field
  - Measuring its properties a high priority
  - We should be refining/reevaluating all the possible options in this area!
- Let's hope that each major region
  - Will continue to host a vibrant accelerator-based particle physics programme
  - Will attract outside contributions to the facilities it hosts
  - Will be able to contribute to world-class facilities in other regions
    - Maybe too early to say which major future projects will be hosted by which region

Future facilities in heavy flavour physics

- LHCb upgrade
  - In 2012 luminosity levelled at 4 x 10^{32} $cm^{-2}s^{-1}$
    - Mean number of collisions per crossing μ ~ 1.6 (design 0.4)
  - By 2017 can expect to collect total of ~7 fb^{-1}
  - 2018 upgrade
    - Readout entire detector at 40 MHz + software trigger
    - Replace precision tracking detectors
  - 2019 onwards
    - Luminosity levelled at 1-2 x 10^{33} $cm^{-2}s^{-1}$ (μ ~ 2-4)
    - Collect ~5 fb^{-1}/year to achieve total of ~50 fb^{-1}
- Next generation B factory
  - SuperKEKB and Super-B (Frascati)
  - Luminosity ~10^{36} $cm^{-2}s^{-1}$
    - approaching two orders of magnitude increase wrt. first generation B factories
  - Collect ~50 ab^{-1} or more on Υ(4s) and several ab^{-1} on Υ(5s)
  - Substantially improved detectors wrt. first generation
- Many HF observables sensitive to contributions from potential BSM physics
  - e.g., $B_s^0 \rightarrow \mu\mu$, $b \rightarrow s\gamma$, $B^+ \rightarrow \tau^+\nu$ complement SUSY constraints from direct searches at ATLAS/CMS

The LHCb upgrade

- LHCb detector and offline event reconstruction work well even in high pile up environment
  - primary vertices separated by few cm, whereas PV resolution ~60 μm,
- Most important limitation of current LHCb at high luminosity is requirement to limit full detector readout to 1 MHz
  - Currently achieved by L0 trigger (calorimeter + muons)



High efficiency for final states containing muons

Factor ~2 efficiency loss for purely hadronic final states

- Upgrade
  - Enable full detector information to be read out at 40 MHz
  - High Level Trigger (HLT) reduce rate to 10-20 kHz to tape
  - Capable of maintaining high efficiency for hadronic B decays

- LHCb projections assume
  - Detector and reconstruction performance essentially the same as presently achieved
  - At $\sqrt{s}$ = 14 TeV (2014-2017) hadronic triggers will suffer efficiency loss of further factor of 2
  - Factor 4 increase in hadronic trigger efficiency at $\sqrt{s}$ = 14 TeV after upgrade
    - i.e., factor 2 increase relative to current efficiency
  - Observables have central value of current measurements
    - or SM value if there is no measurement yet available

Results of LHCb projections

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [32]	0.045	0.014	~ 0.01
	a^s_{sl}	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [29]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [40, 41]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [63]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

- All measurements show steady improvement with increasing integrated luminosity
- Uncertainties are statistical only
- Systematics most likely to be significant for a^s_{sl}, A_Γ and ΔA_{CP}
- Theory uncertainties will also become significant for a number of observables

Results of LHCb projections

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [32]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %

- $2\beta_s = -\phi_s$ observed in b➔ccs transitions
- $2\beta_s$eff observed in b➔qqs transitions (q = u,d,s)
- a^s_{sl} is CP violation in semileptonic B_s decays
  - Sum of a^d_{sl} and a^s_{sl} observed by DØ deviates from zero with 3.9σ significance

Results of LHCb projections

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [40, 41]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	0.8° [63]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

- Expect to achieve precision in Br($B_s \to \mu\mu$) of ~10% of SM-expected value with 50 fb^{-1} and search for $B_d^0 \to \mu\mu$

- $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

- $A_\Gamma = \Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)$
- Also very interesting to look in other D^0 final states and other charmed hadrons (D^+, D_s^+, Λ_c^+)

Concluding remarks on LHCb upgrade

- LHCb has demonstrated that it is possible to make precise heavy flavour measurements at a high luminosity, high energy hadron collider
  - building on, but in most cases now far exceeding, the pioneering work done at the Tevatron
- LHCb has responded well to challenges/opportunities of much higher luminosity/pile-up than foreseen in the original design
- Sensitive to BSM physics in ways that are complementary to ATLAS and CMS
- Other interesting physics measurements make use of unique geometrical acceptance for LHCb
  - e.g., W and Z at high rapidity,
- Implications for LHC machine of requirement to supply luminosity of 1-2 x 10^{33} $cm^{-2}s^{-1}$ to LHCb during HL-LHC needs careful consideration
- Total cost of LHCb upgrade ~60 MCHF seems modest compared to total cost of LHC programme to 2030

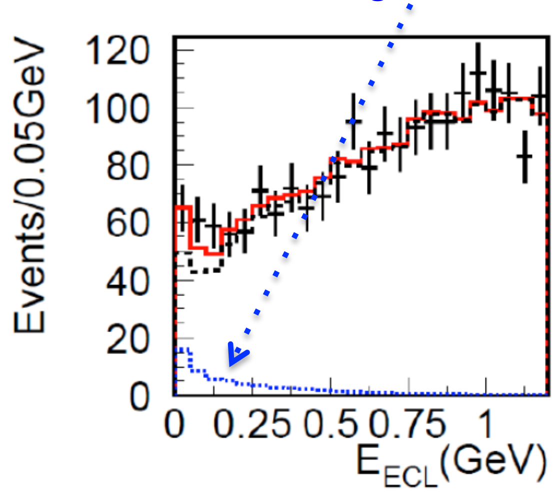
Physics measurements at next generation B factory

"Full reconstruction" or "hadronic tagging"

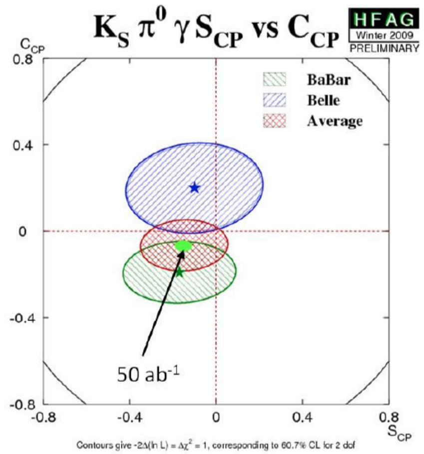
- Fully reconstruct one B decay; the remaining particles must have come from the decay of the other B
- A powerful way to exploit huge numbers of events
  - Decays with invisible particles in the final state
    - e.g., $B^+ \rightarrow \tau^+\nu$, $B \rightarrow K(*)\nu\nu$
  - Decays with neutral particles in the final state
    - e.g., $B \rightarrow K^0_S\pi^0\gamma$
    - *"Don't try these at home"*
      - *if home happens to be a hadron collider!*
  - Inclusive $b \rightarrow s\gamma$

Energy in EM calorimeter in hadronic tagged events:

$B \rightarrow \tau\nu$ signal events



Direct and indirect CPV parameters in $B \rightarrow K^0_S\pi^0\gamma$



Summary by Belle II collaboration demonstrating complementarity of next generation B factory and LHCb

Assumed integrated luminosities:

Belle II: 50 ab^{-1}

LHCb: 10 fb^{-1}

Theoretical uncertainties and "gold-plated" tests of SM:

What is the quality of the gold-plating?

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

Concluding remarks on heavy flavour

- LHCb upgrade and next generation B factory physics programmes are largely complementary
  - LHCb dominates most measurements with B_s, b-baryons, decays to final states consisting entirely of charged particles
  - Next generation B factory dominates measurements in final states containing invisible or neutral particles
- Both are likely to make important contributions

- Physics programme of next generation B factories consists largely of refining measurements and searches for rare decays
  - No guarantee of BSM effects – maybe results will be "only" improved limits?
  - Motivation for two facilities (SuperKEKB and Super-B)?
    - C.f. when the first generation B factories were proposed
    - A major new observation was expected (CPV in B^0)
      - Natural to have two experiments to confirm discovery and cross check subsequent measurements

Let the discussion begin!