VBS @ Future Hadron Colliders (HE-LHC, FCC-hh)

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Pushing the energy frontier

- A very large circular hadron collider seems the only approach to reach 100 TeV c.m. collision energy in coming decades
- It allows access to direct production of new particles in the few TeV to 30 TeV mass range, far beyond LHC reach.
- Much-increased rates for phenomena in the sub-TeV mass range. This means an increased precision w.r.t. LHC and possibly ILC (on some statistically limited processes)
- The name of the game of a hadron collider is energy reach

$$E \propto B_{dipole} \times \rho_{bending}$$

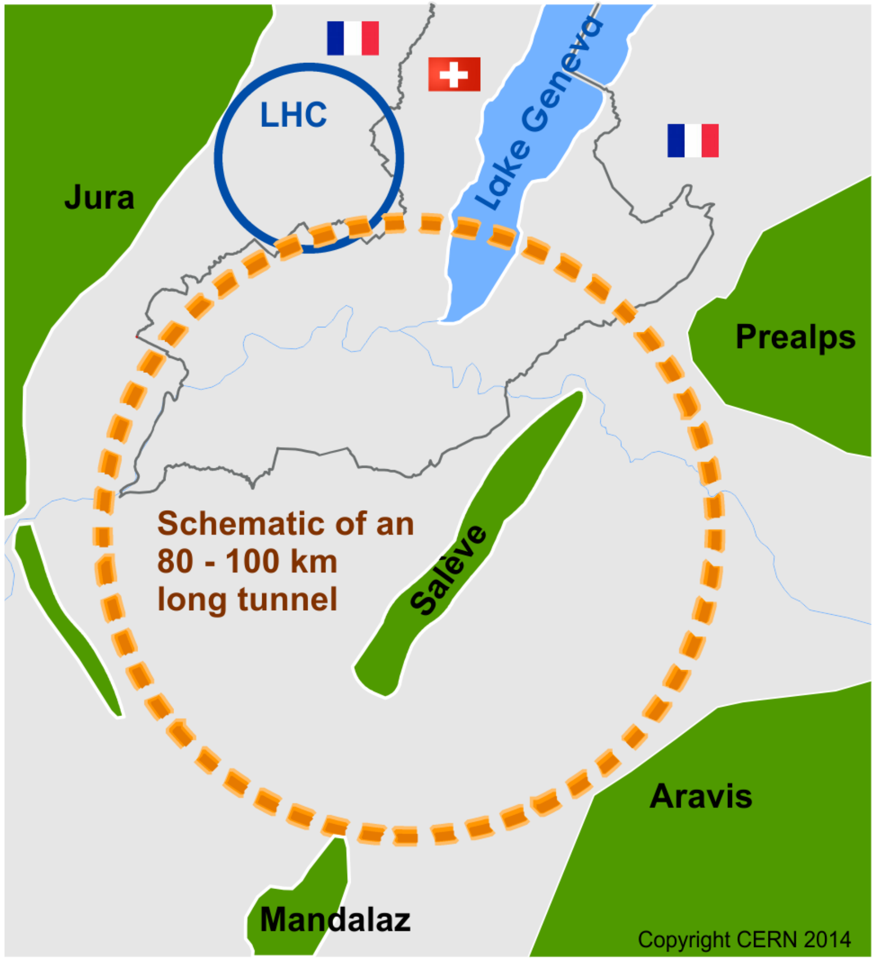
- Comparing with the LHC: FCC-hh provides a factor ~4 in radius, factor ~2 in field, factor O(10) in E_{cms}

FCC Project Study

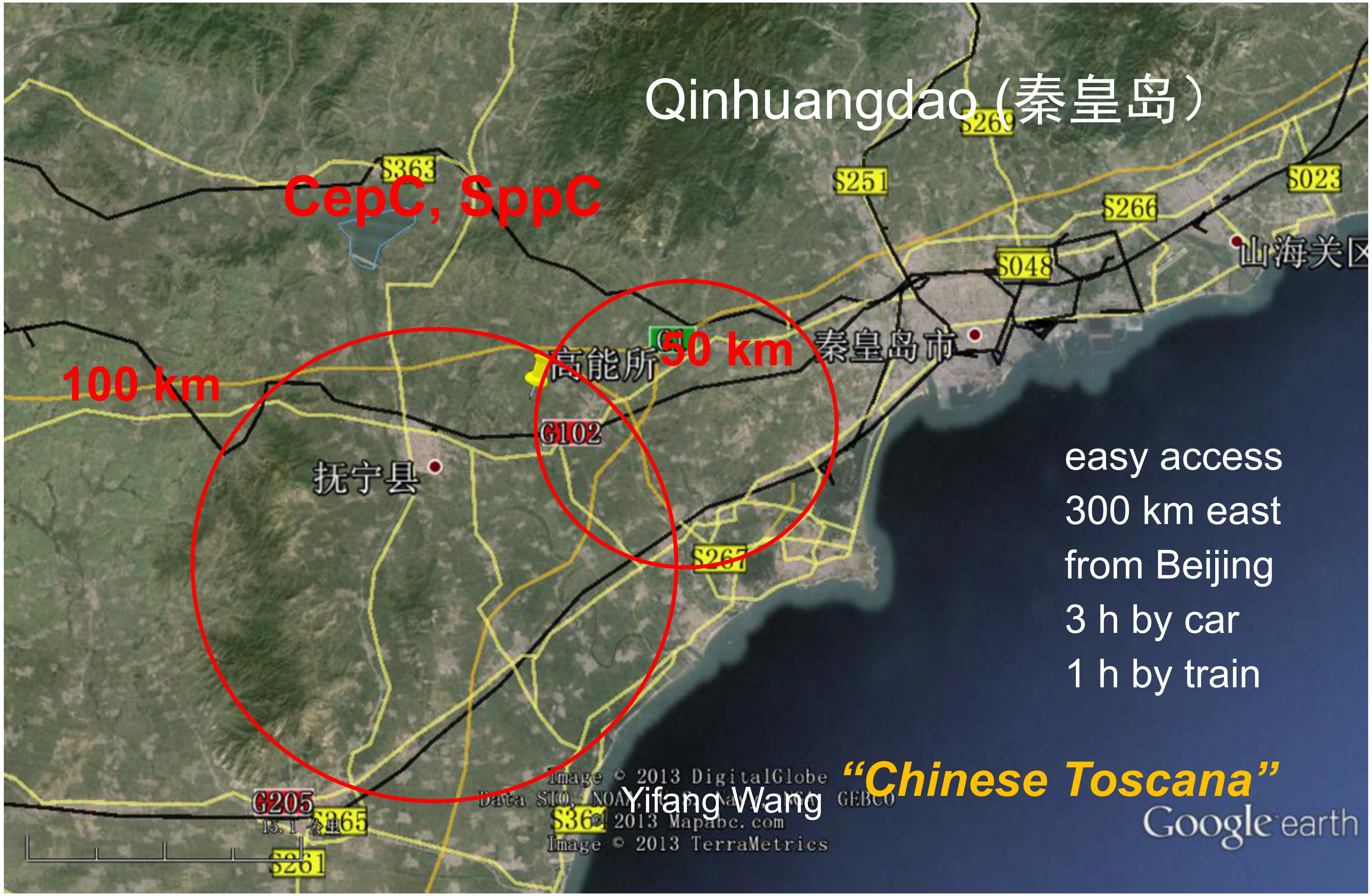
- International FCC collaboration (CERN as host lab) to study:
- pp-collider (FCC-hh): current main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- 80-100 km tunnel infrastructure in Geneva area
- e+e- collider (FCC-ee) as first step
- p-e (FCC-he) option
- Considering also the option of a HE-LHC with FCC-hh technology



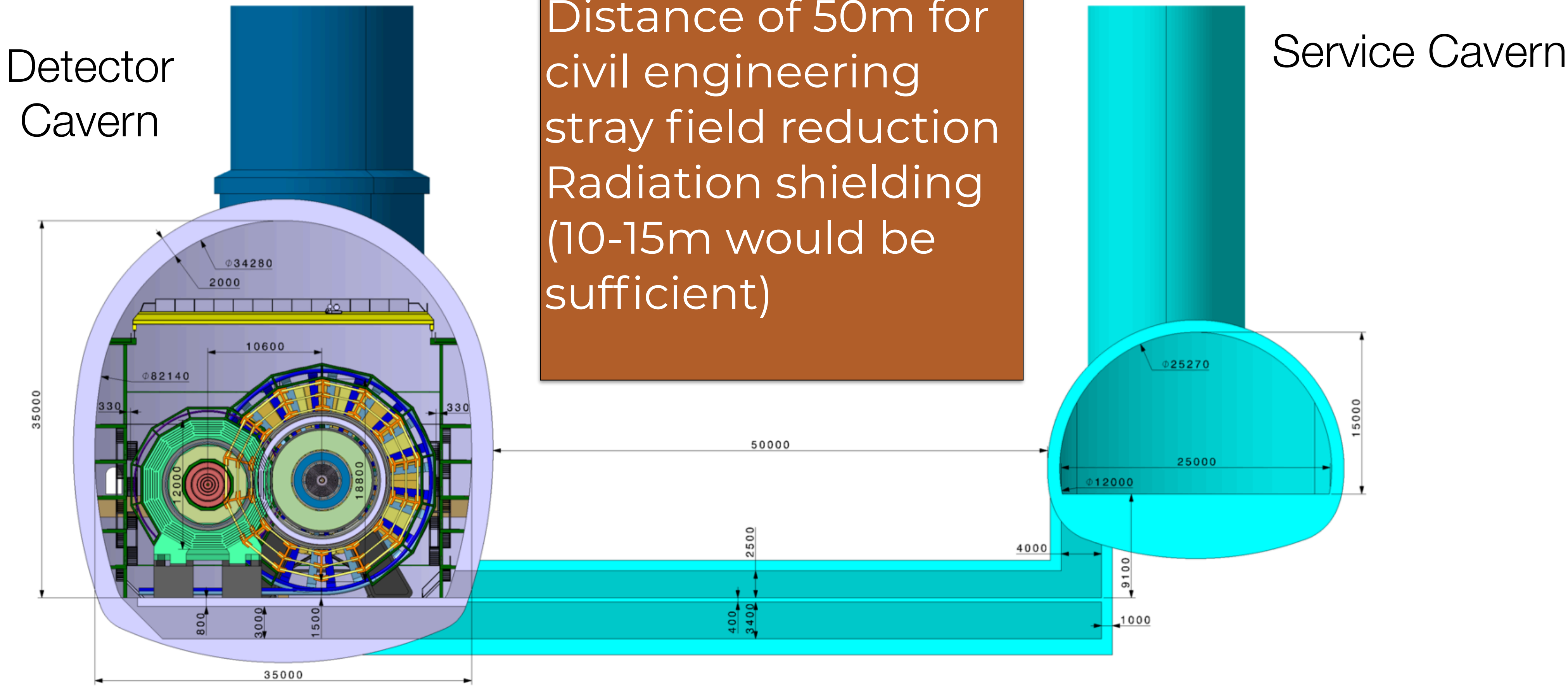
CEPC-SPPC study (similar parameters, aggressive timeline)



Accelerator parameters comparison

	LHC / HL-LHC	HE-LHC (tentative)	FCC-hh Initial	FCC-hh Ultimate
Cms energy [TeV]	14	27	100	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1 / 5	28	5	20-30
Machine circumference	27	27	97.75	97.75
Arc dipole field [T]	8	16	16	16
Bunch charge	1.15 / 2.2	2.2	1	1
Bunch distance [ns]	25	25	25	25
Background events/bx	27 / 135	800	170	<1020
Bunch length [cm]	7.5	7.5	8	8

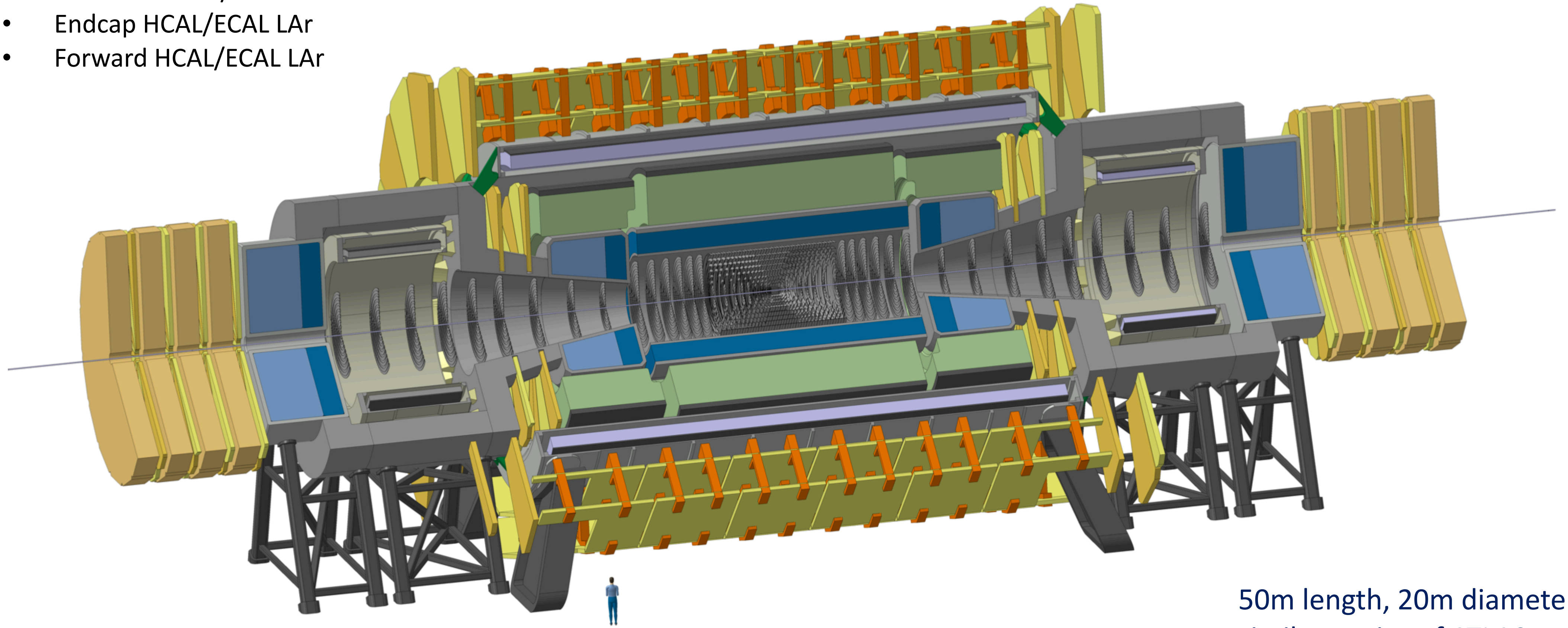
FCC-hh reference Detector Cavern



Distance of 50m for civil engineering stray field reduction Radiation shielding (10-15m would be sufficient)

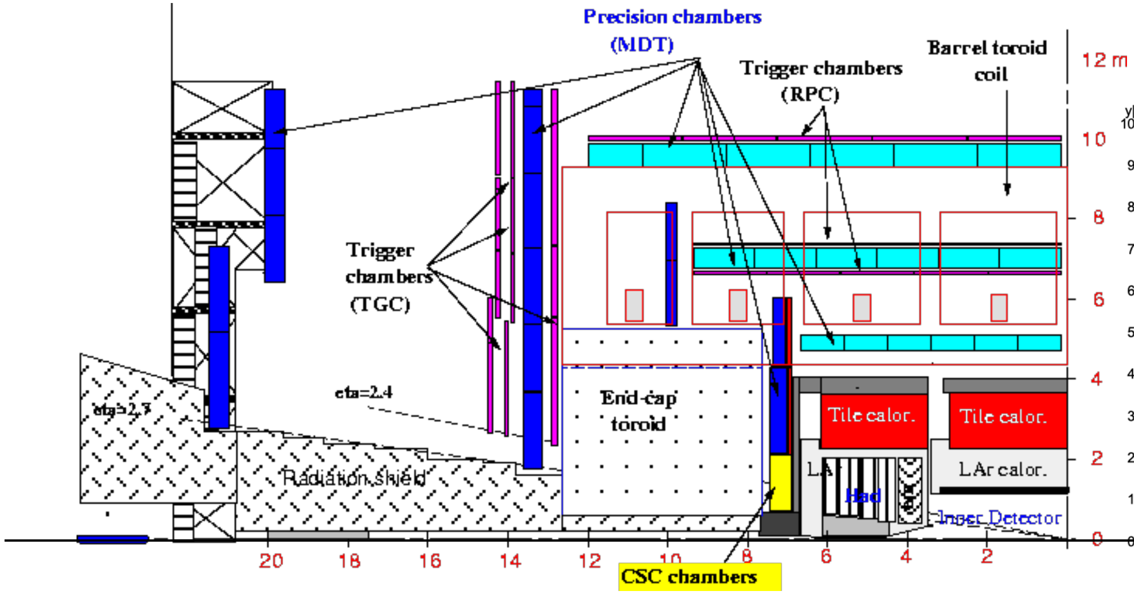
FCC-hh Reference Detector

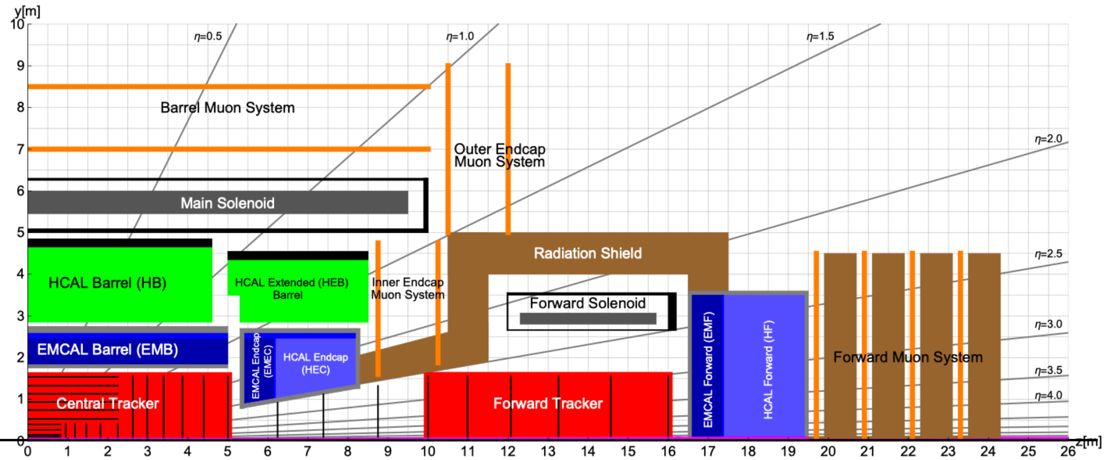
- 4T, 10m solenoid, unshielded
- Forward solenoids, unshielded
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

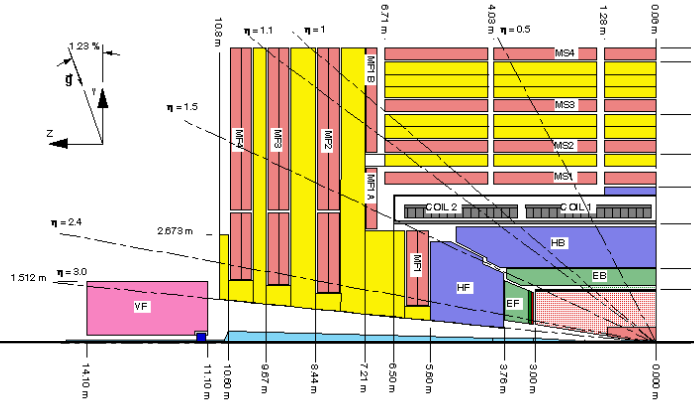


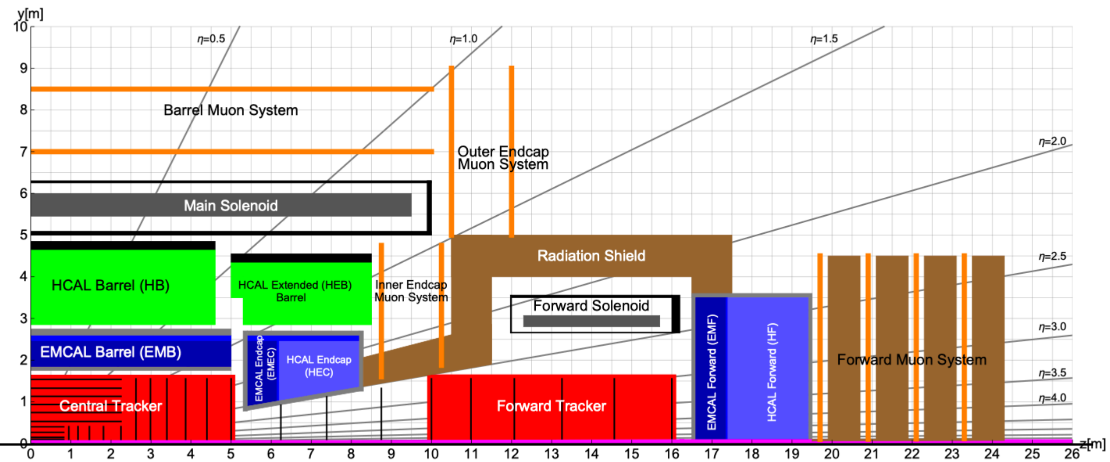
50m length, 20m diameter
similar to size of ATLAS

Comparison to ATLAS & CMS

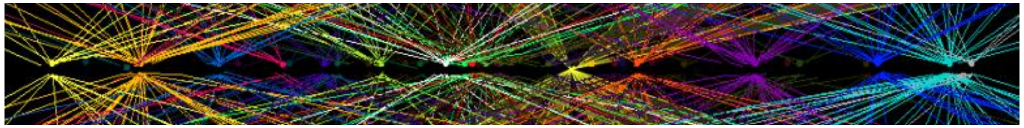


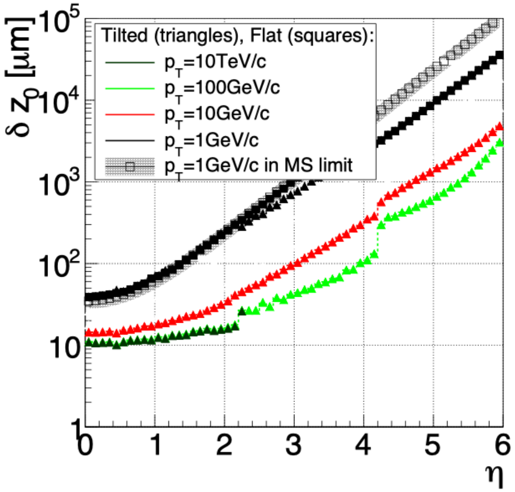


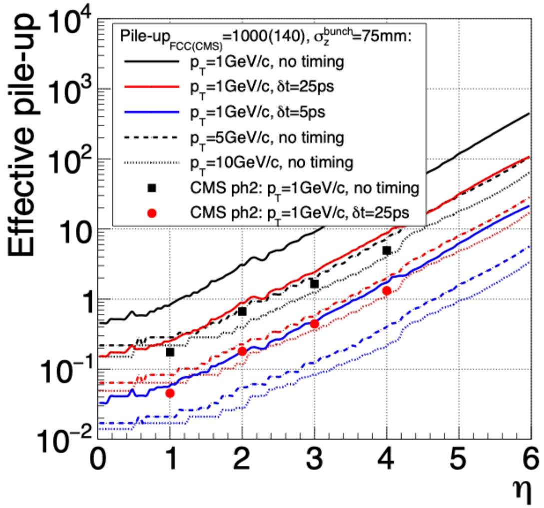


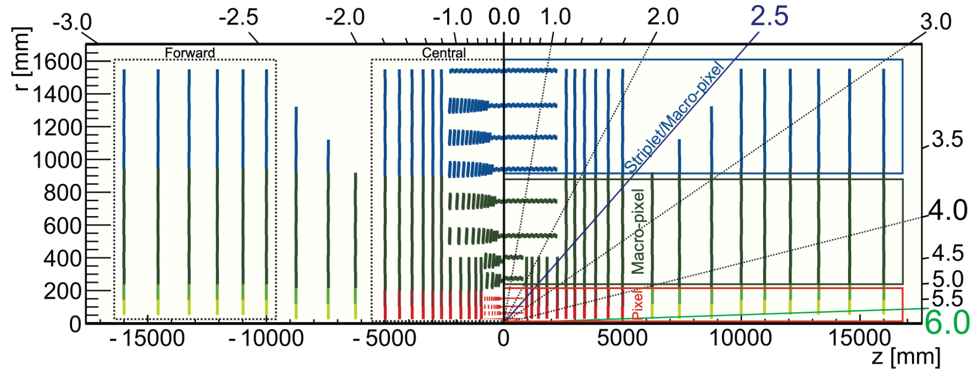


Pileup









- Average distance between vertices at z=0:
  - 1mm for HL-LHC (140 pileup)
  - 125um for FCC-hh (1000 pileup)

- As for HL-LHC, timing can help for vertex identification
- Effective pileup: Number of vertices that a track of a given pT is compatible with at 95% CL.
  - For a time resolution of 25ps, CMS can get to an effective pileup of 1 for 1 GeV/c tracks at η = 4.
  - For an FCC detector the time resolution has to be at a level of 5ps to get to similar numbers.

- The impact of pileup on a given physics analysis depends very much on the specific channels.

Remarks

- Higher statistics shifts the balance between systematic and statistical uncertainties.
  - It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the « systematics wall » of Low-stat measurements.
- We often talk about « precise » Higgs measurements.
  - What we actually aim at is « sensitive » tests of the Higgs propertie, where sensitive refers to the ability to reveal a BSM behaviour
- Sensitivity may not require extreme precision. Going after « sensitivity » rather than just precision opens itself new opportunities…

  - For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

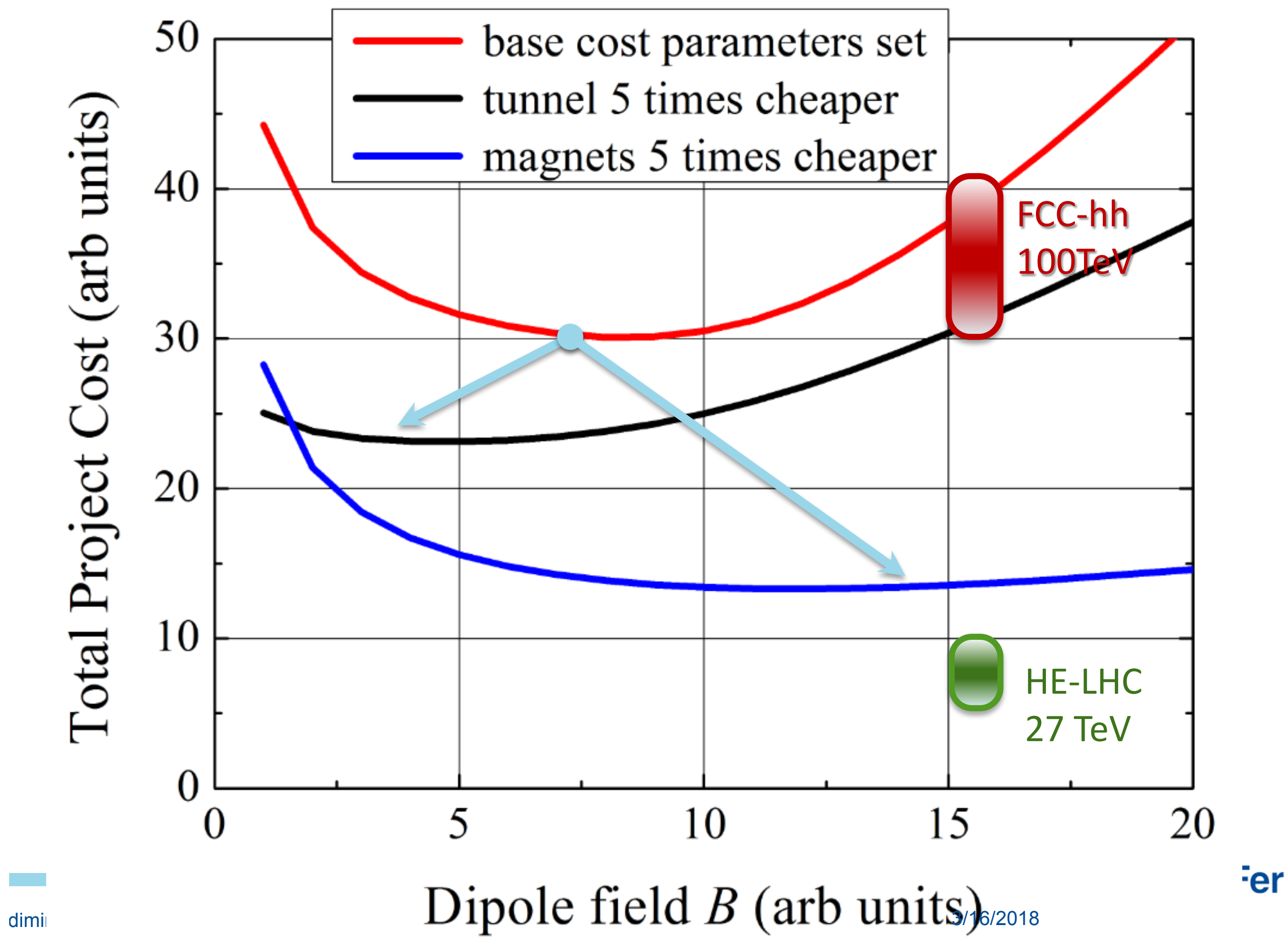
BR measurement: $\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$ ⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

$\sigma(p_T > X)$: $\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$ ⇒ **kinematic reach** probes large Λ

e.g. $\delta O = 15\%$ at $Q = 1$ TeV $\Rightarrow \Lambda \sim 2.5$ TeV

Why proposing HE-LHC?



HE-LHC design goals and basic choices

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$)

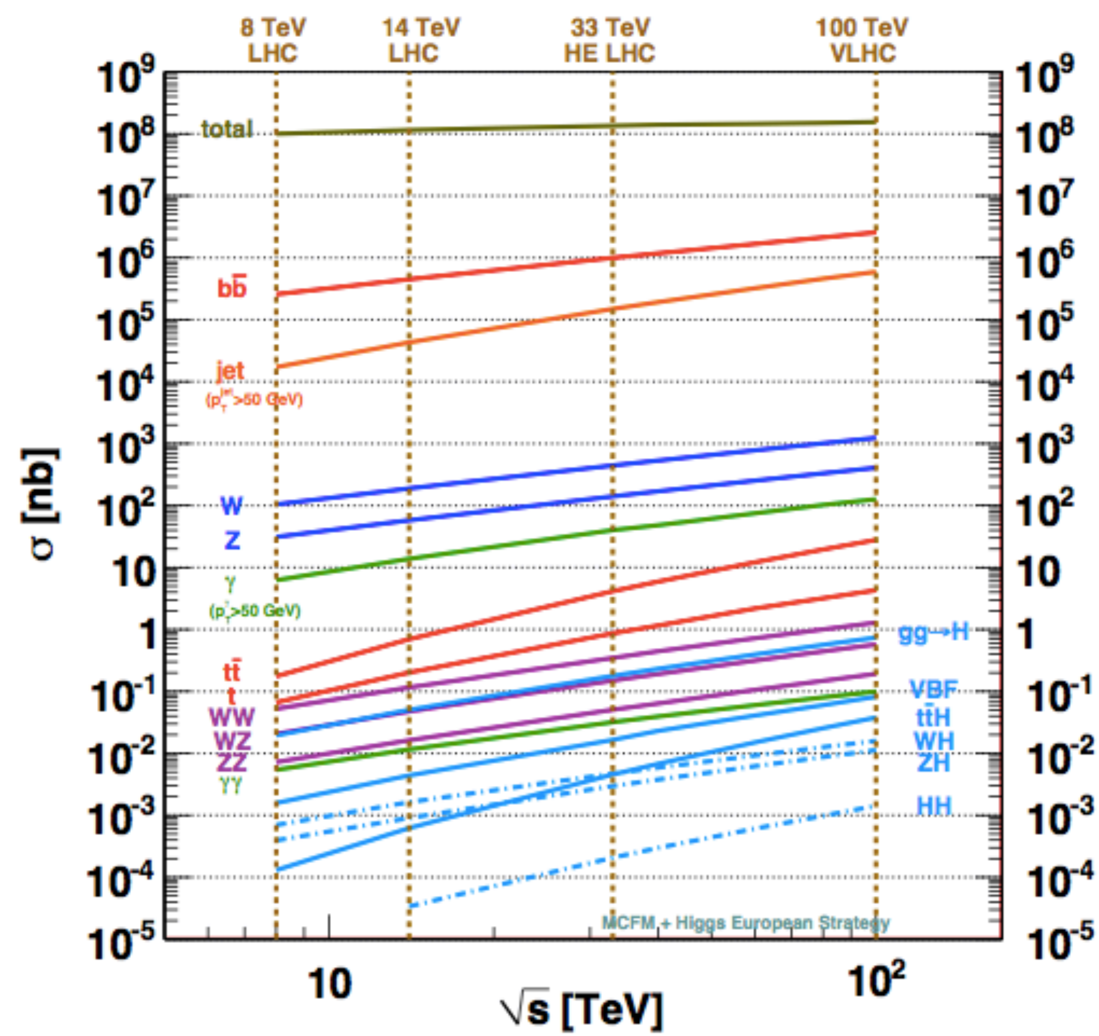
key technologies:

- FCC-hh magnets (curved!) & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

beam:

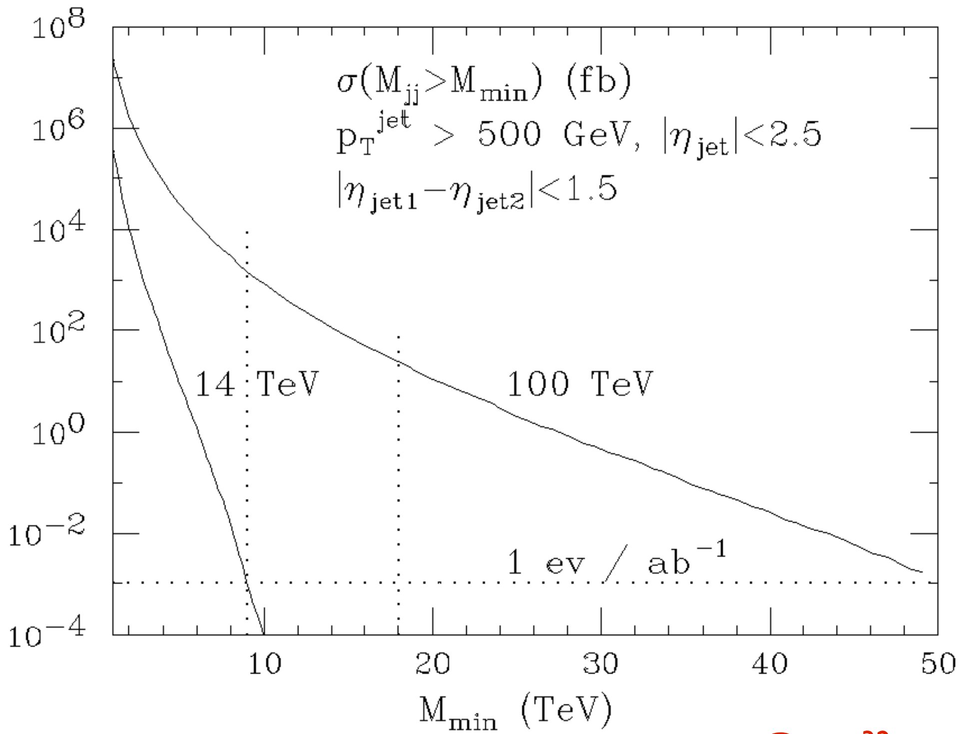
- HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)

The scale of FCC-hh - Cross sections for SM particles



final state	$N_{ev}/10ab^{-1}$
W	10^{13}
t tbar	3×10^{11}
H	10^{10}
HH	10^{6}
jets (p_T>5 TeV)	10^{6}
jets (p_T>10 TeV)	10^{4}

Di-jet production at large mass



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}
- 1fb^{-1} to 3x the sensitivity of HL-LHC ⇒< 1 year @ 2x10^{32}

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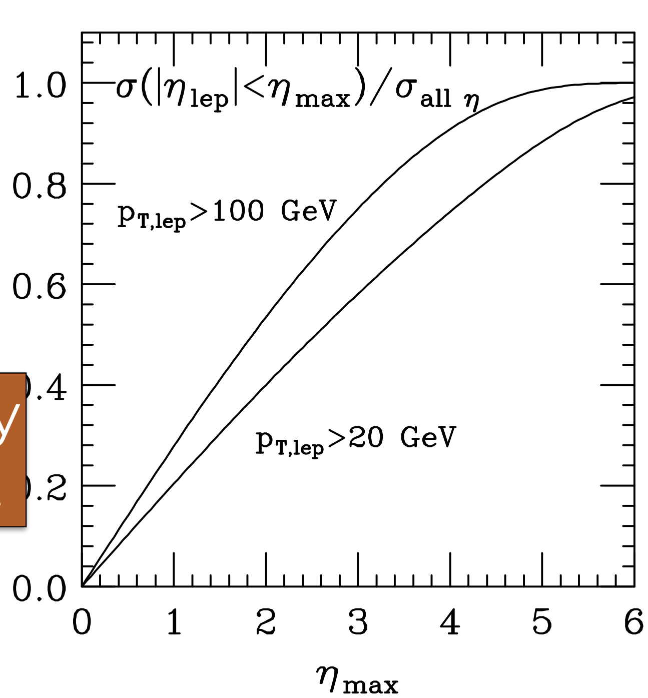
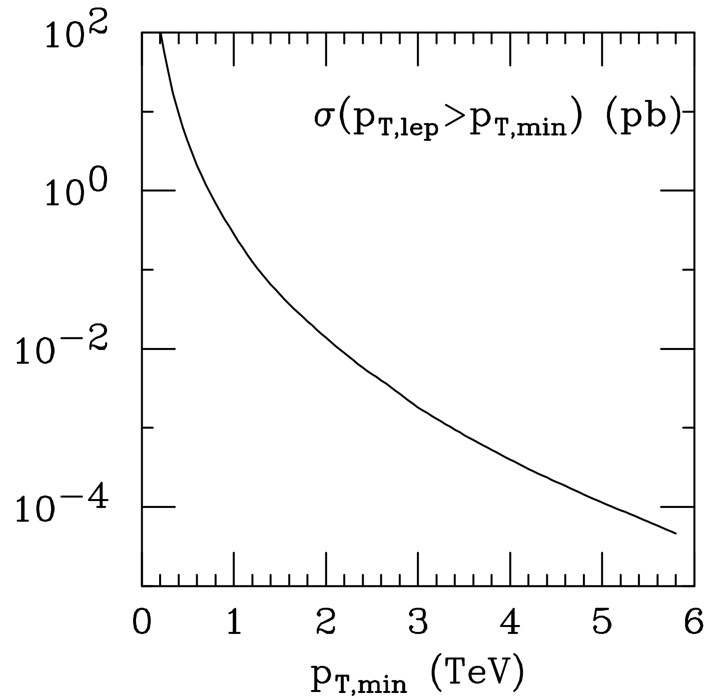
W and Z production at FCC-hh

- Production of W and Z bosons is an extremely important probe of EW and QCD dynamics
- The production rate of $W^{\pm}(Z0)$ bosons at 100 TeV is about 1.3(0.4)μb. This corresponds to $O(10^{11})$ leptonic decays per ab^{-1}.

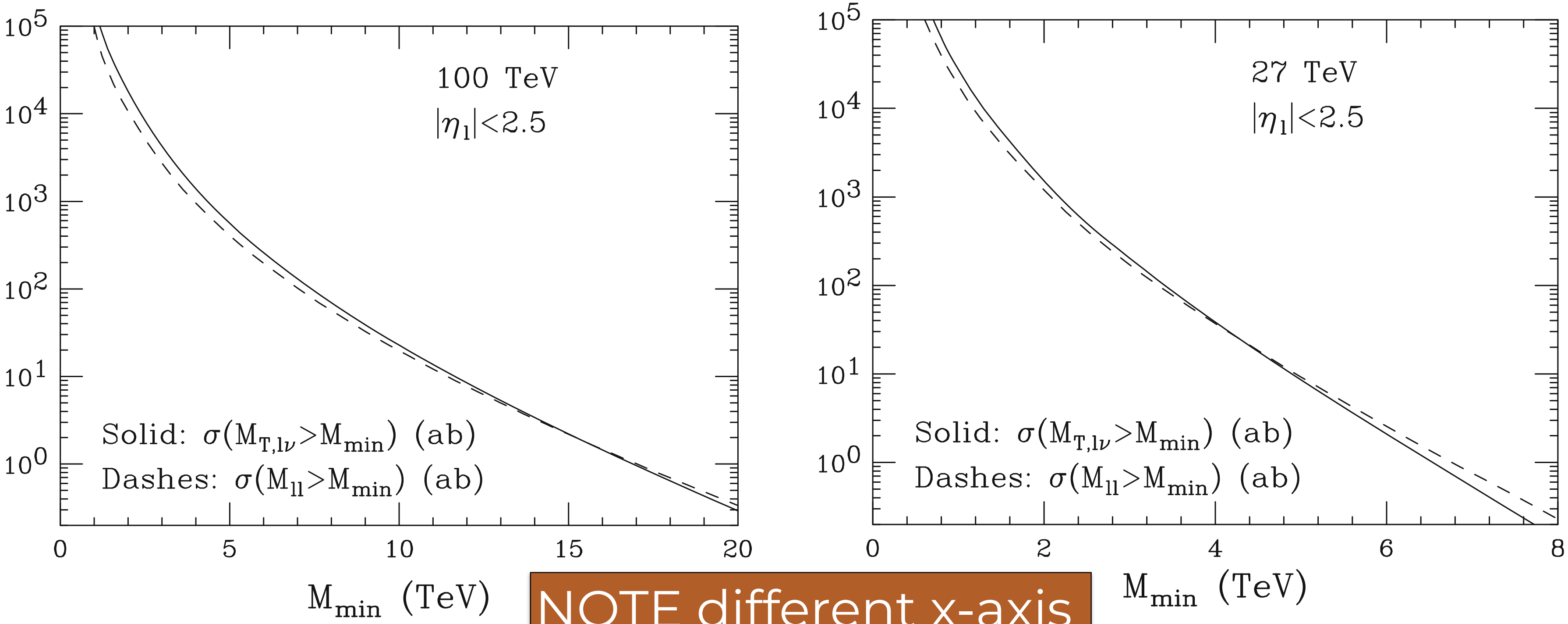


large rapidity distribution!



large p_T

High pt dilepton comparison with HE-LHC

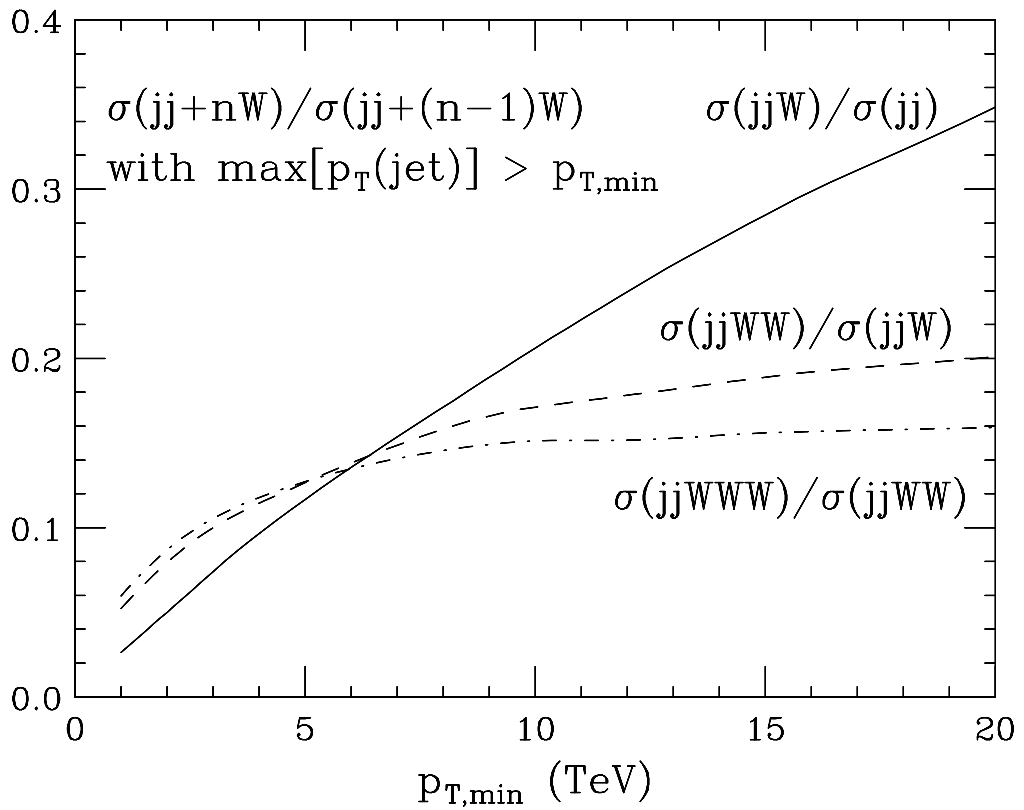


NOTE different x-axis

Fig. 3.3 Integrated lepton transverse (dilepton) mass distribution in pp $\to$ W* $\to$ $\ell\nu$ (pp $\to$ Z^*/γ^* $\to$ $\ell^+\ell^-$), at 100 and 27 TeV. One lepton family is included, with $|\eta_\ell| < 2.5$

Production of gauge boson by « radiation »

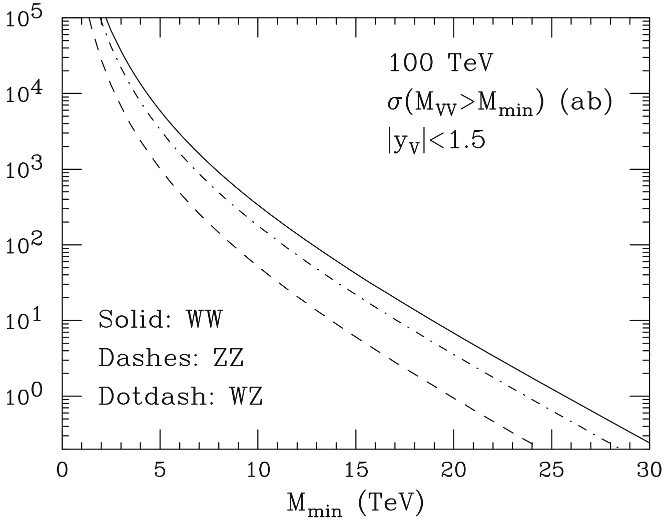
- **New phenomenon!**
- Most likely mechanism to produce gauge boson in final states with multi-TeV jets is NOT LO QCD process of V recoiling against the jet: $qg \rightarrow qV$
- It is a higher order process where another jet recoiling radiates off a V $qq \rightarrow qqV$
- Emission probability can be enhanced by 10%!

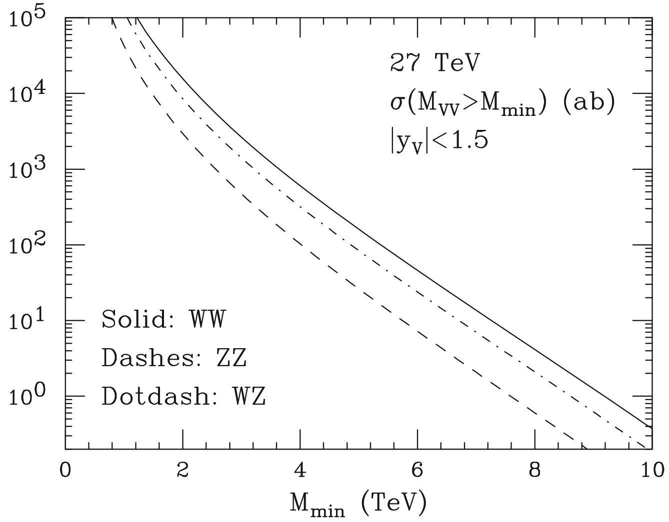


ïg. 37: Emission probability for additional W bosons in dijet events at large p_T.

Gauge Boson pair production

- Pair production is the most direct and sensitive probe of triple gauge-bosons interactions (TGCs).
- TGCs strongly constrained by LEP measurements
- Anomalous TGCs violate gauge invariance and its delicate cancellations and give rise to deviation that grow with quadratically with the bosons energy.
- High mass boson pair provide strong constraints on BSM:

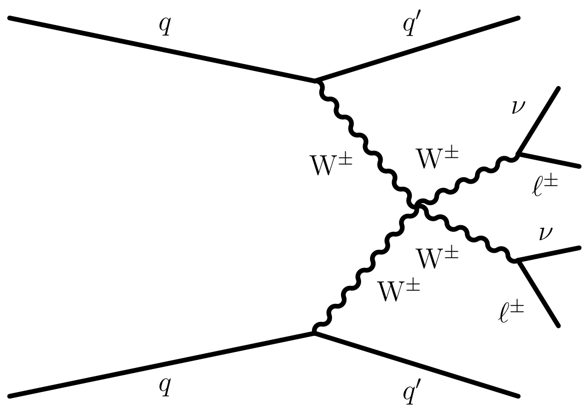


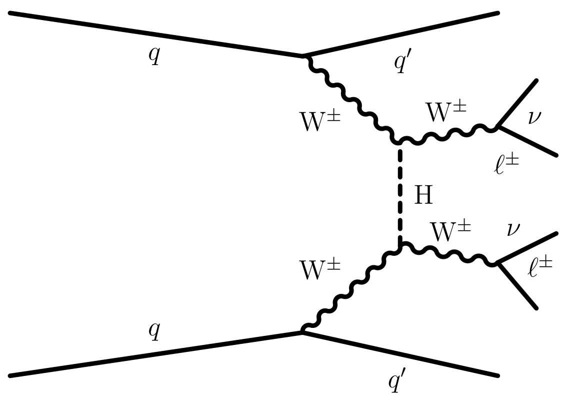


Rate at high mass larger than DY: Comparable reach? Use of hadronic decays with boosted topologies

VBS and VBF production of EWK bosons

- VBF and VBS processes is a key measruement to probe the mechanism of EWK symmetry breaking and test effect of BSM models
- The $V_L V_L \to V_L V_L$ scattering is unitarized by the interference with the H exchange
-





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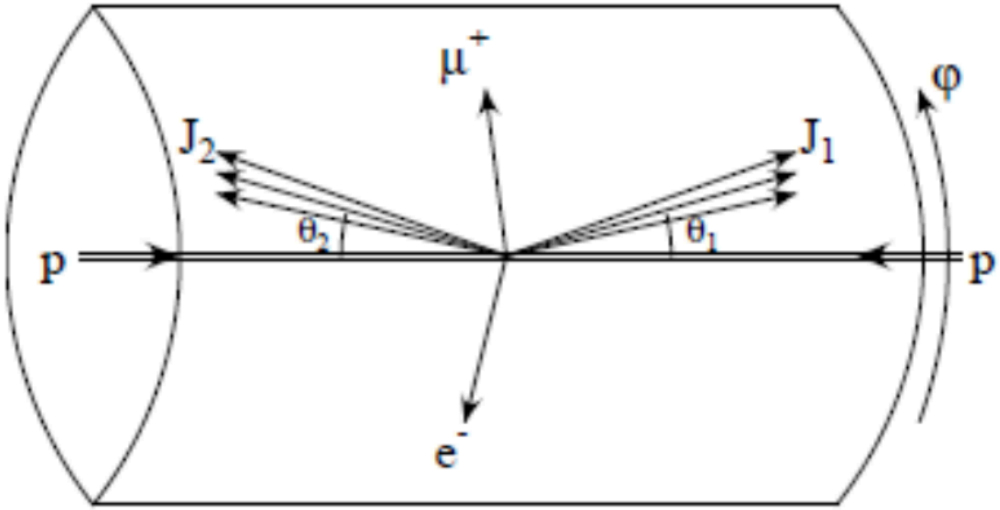
VBS and VBF production of EWK bosons

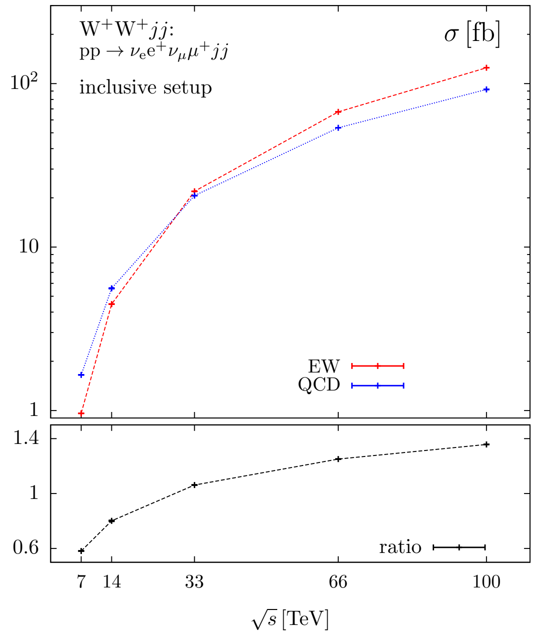
- At hadron collider this happens with (anti)quarks scattering with the exchange of a weak gauge boson in t-channel and then emission of 2 gauge bosons: $pp \to VVjj$
  - The 2 jets are typically in the forward region
  - Little QCD activity in the central region
  - useful to reduce the big QCD background



for 100TeV
1704.0491
1607.01831

VBS @100TeV - Leptonic final state study

- Analysis for leptonic final states of WW, WZ and ZZ
- Study considers EFT Dim-8 operators only affect Quartic Gauge Boson coupling and arise only in VBS processes
- Takes care of unitarity constraint as well



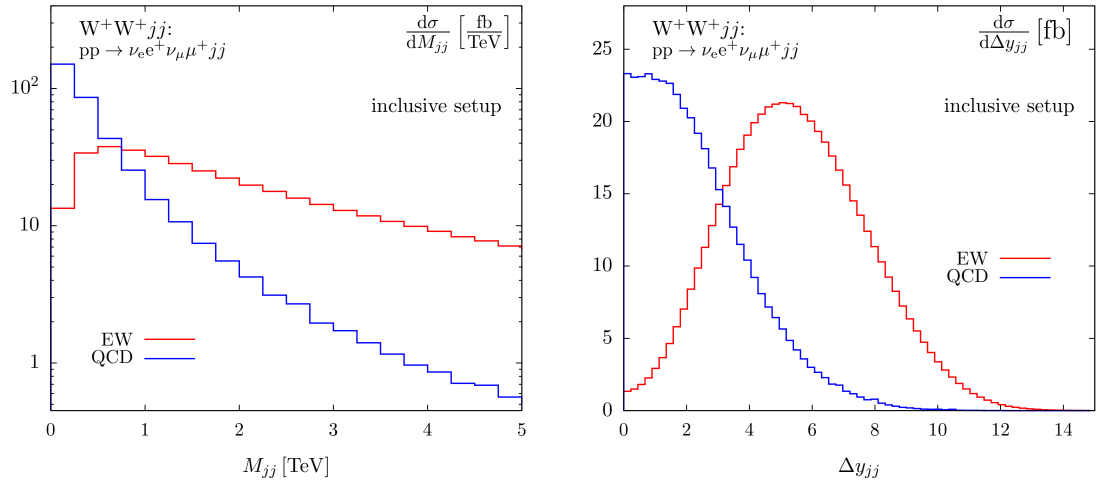


Figure 2: *Invariant mass (l.h.s.) and rapidity separation of the two tagging jets (r.h.s) for the EW-induced (red lines) and QCD-induced (blue lines) contributions to* $pp \to \nu_e e^+ \nu_\mu \mu^+ jj$*, without any selection cuts.*

VBS@100TeV - WWjj Effect of dim-8 operators + unitarity

$p_{T,\mathrm{jet}} \geq 50\mathrm{GeV}$
$y_{j1} \times y_{j2} < 0$
$p_T(l) \geq 20\mathrm{GeV}$
$y(l) \leq 5$
$DR(j,l) \geq 0.4$
$y_{j,\mathrm{min}} < y(l), y_{j,\mathrm{max}}$

$$M_{jj} > 500 \text{ GeV}$$

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 1.5\,,$$

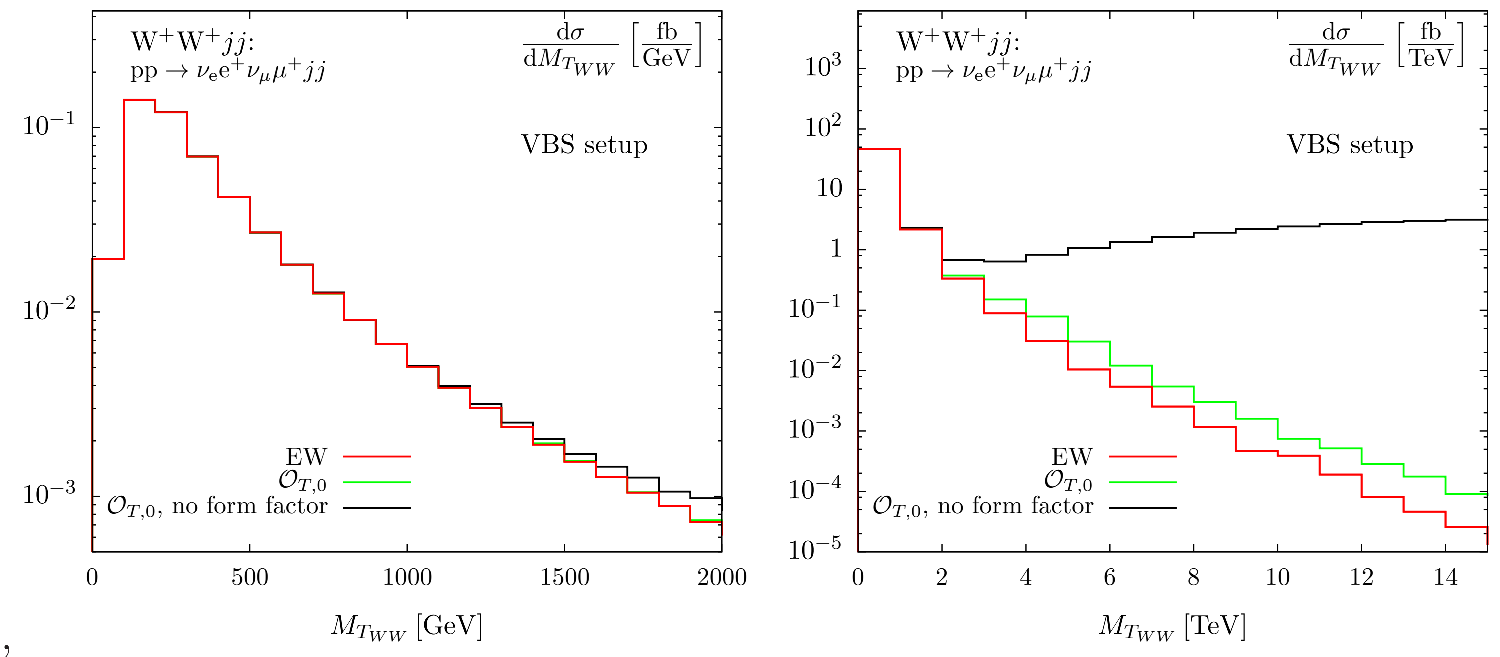


Figure 7: *Transverse-mass distribution of the gauge-boson system for the process* $pp \to \nu_e e^+ \nu_\mu \mu^+ jj$ *in the framework of the SM (red lines) and including the impact of the dimension-eight operator* $\mathcal{O}_{T,0}$ *without (black lines) and with (green lines) the form factor of Eq. (23), in two different plot ranges. The selection cuts of Eqs. (11)–(14) and Eq. (24) are imposed.*

VBS@100TeV - $pp \to ZZjj$

- Sensitive to scalar resonances, background to VBF H production

Final state
fully reconstructable

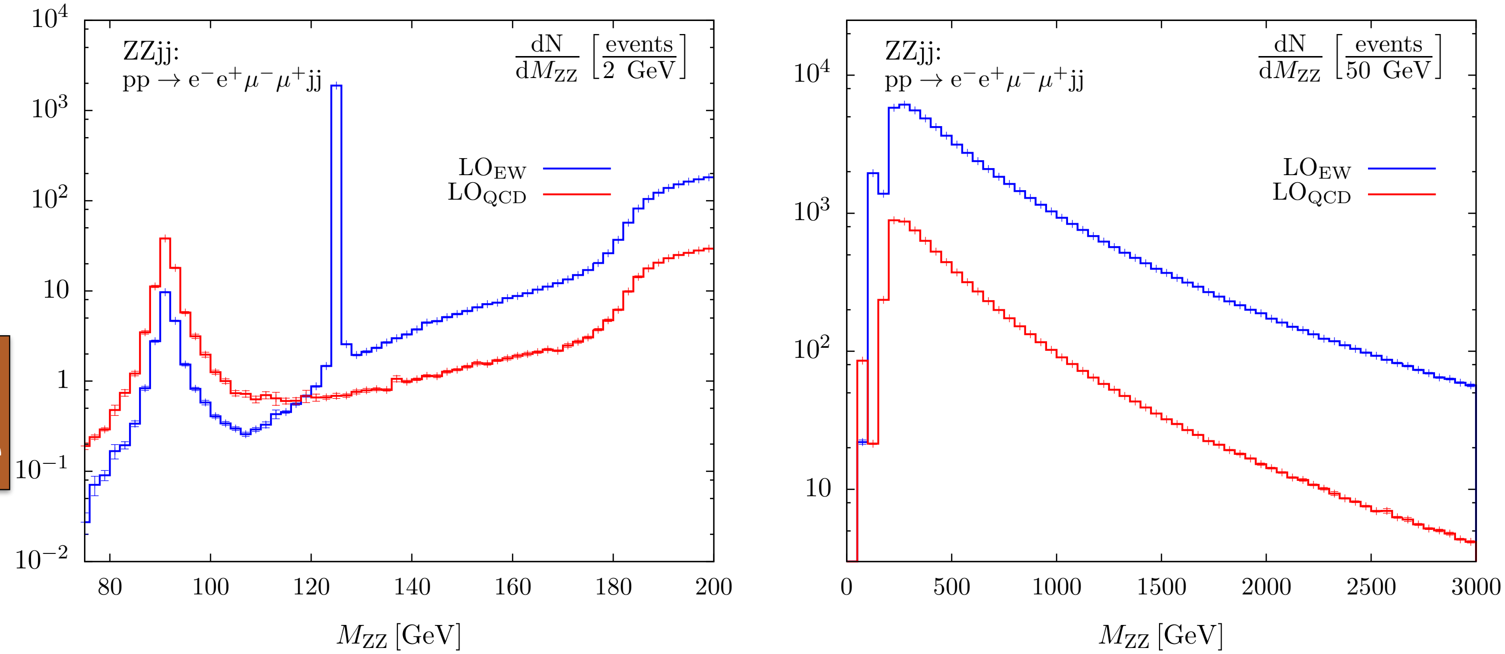


Fig. 95: Invariant-mass distribution of the four-lepton system for two different ranges of the EW-induced (blue line) and QCD-induced (red line) contributions to $pp \to e^-e^+\mu^-\mu^+jj$, within the selection cuts of Eqs. (42)–(46) and Eq. (51). An integrated luminosity of 30 ab^{-1} is assumed.

VBS $pp \to ZZjj$ - Effect of Dim-8 operators

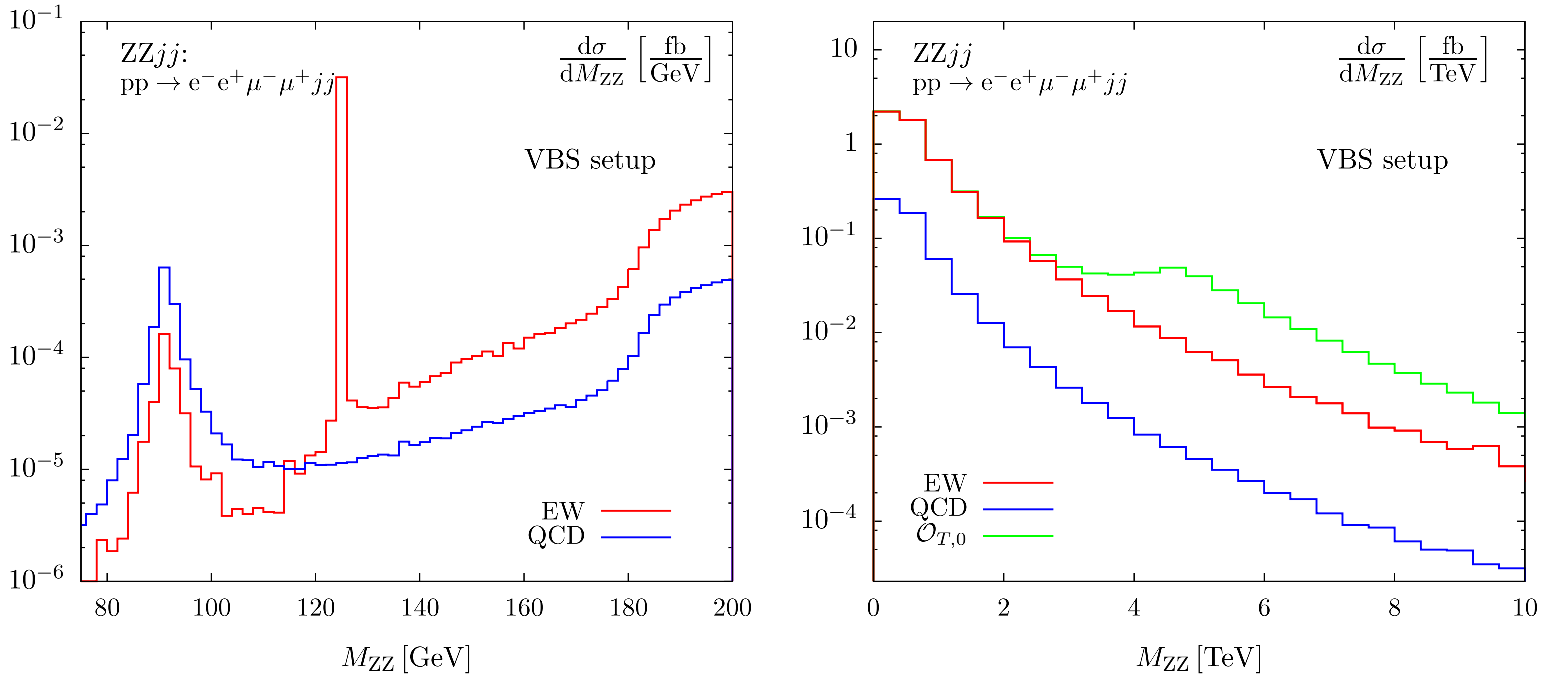
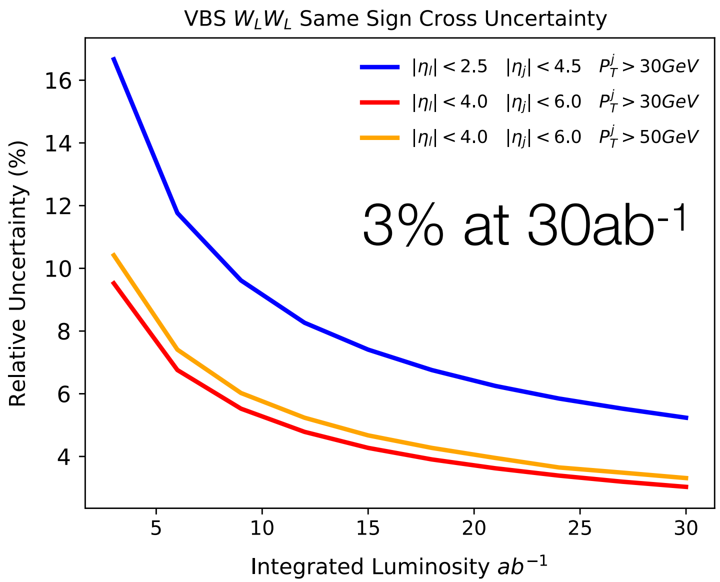
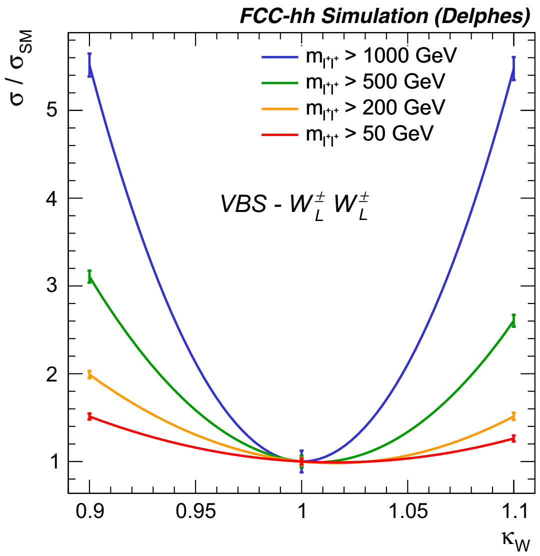
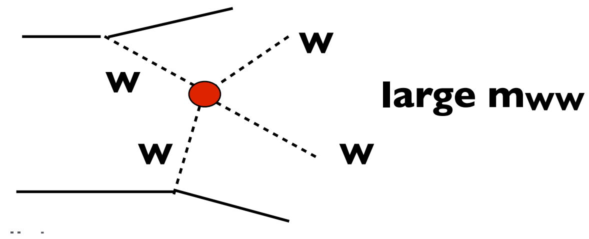


Figure 12: *Invariant-mass distribution of the ZZ system reconstructed from the lepton momenta in two different plot ranges for the process $pp \to e^-e^+\mu^-\mu^+jj$ in the framework of the SM (red and blue lines) and including the impact of the dimension-eight operator $\mathcal{O}_{T,0}$ (green line) with the form factor of Eq. (23). The selection cuts of Eqs. (11)–(15) and Eq. (29) are imposed.*

$W_L W_L$ scattering (relevant for VVH coupling) & detector req.







Longitudinal component extracted from angular distribution of the two leptons

Fig. 4.9 Left: precision in the determination of the scattering of same-sign longitudinal W bosons, as function of luminosity, for various kinematic cuts. Right: sensitivity of the longitudinal boson scattering cross section w.r.t. deviations of the WWH coupling from its SM value ($\kappa_W = 1$), for various selection cuts on the final-state dilepton invariant mass. The vertical bars represent the precision of the measurement, for 30 ab^{-1}

Table 4.5 Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_L W_L \to HH$ process

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98, 1.05]	[0.99, 1.04]	[0.99, 1.03]	[0.98, 1.02]

Studies for the HE-LHC

- Studies performed for the YR of the HL/HE-LHC, 1902.04070

process	$\sqrt{S} = 14$ TeV	$\sqrt{S} = 27$ TeV
W^+W^+jj	2.33 fb	8.65 fb
W^+W^+jj ($\lvert\Delta y_{jj}\rvert > 2.4$)	2.49 fb	9.11 fb
W^+Zjj	0.82 fb	3.16 fb
$ZZjj$	0.11 fb	0.44 fb

FULLY LEPTONIC FINAL STATE
Simple scaling for HE-LHC from the HL-LHC results

Table 15: Expected significance and measurement uncertainty for the VBS $Z_L Z_L$ fraction at HL-LHC and HE-LHC with and without systematic uncertainties included.

	significance		precision (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%

Semileptonic VBS at HE-LHC

- Study with Delphes for the HE-LHC focused on the effect of PU reduction

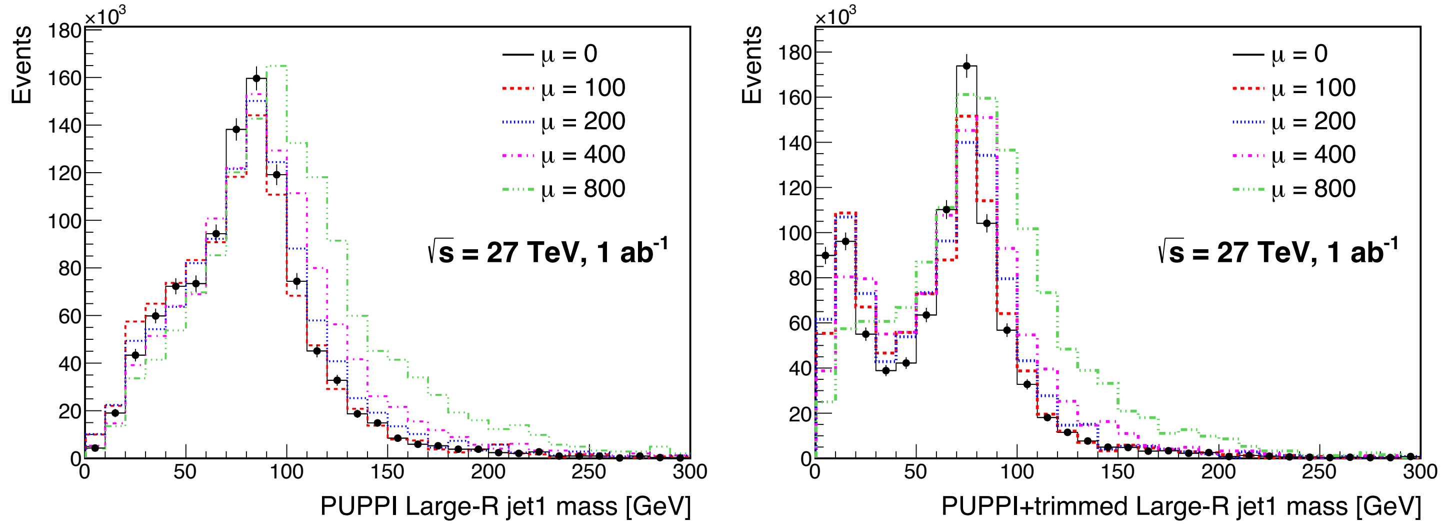


Fig. 32: Leading large-R jet mass (left) after applying the PUPPI algorithm at an integrated luminosity of 1 ab^{-1} at $\sqrt{s} = 27$ TeV with five different pile-up overlay conditions of $\mu_{\text{pileup}} = 0, 100, 200, 400$ and 800. The right plots shows the same distribution but after additionally requiring that the jets are trimmed with the conditions described in the text.

VBS semileptonic @HE-LHC - Significance of EWK signal

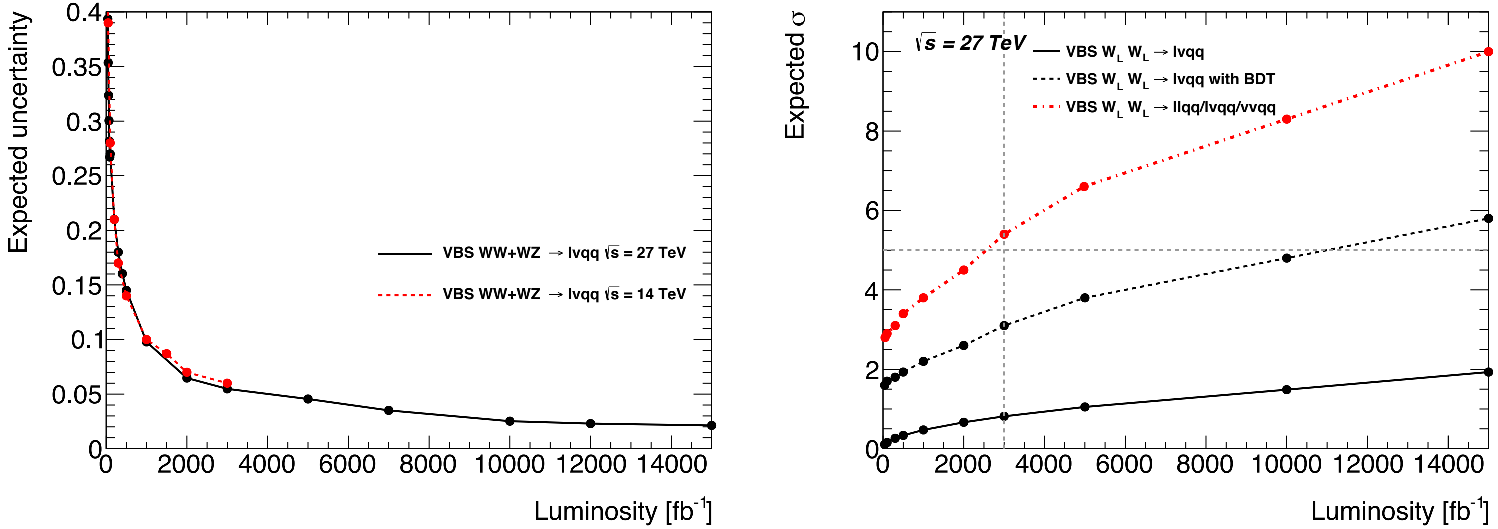


Fig. 33: The expected cross section uncertainty as function of integrated luminosity at 27 TeV compared to the one obtained at 14 TeV (left). Right: Observed significance as a function of the luminosity and expected uncertainty for the EW $W_L W_L$ signal assuming a 10% fraction predicted by MADGRAPH (right). One line shows the results obtained by fitting a single variable, the total invariant mass of the system and the other one shows the expected significance using the BDT. The third line shows the expected significance assuming the combination of all three semi-leptonic channels with the same sensitivity.

Conclusions

- FCC-hh is a great place to study boson processes: the high $\sqrt{s}$ increases the cross section for rare processes, and it also increases the object boost.
  - Large statistics and boosted object allow to trade efficiency for purity in difficult channels
- Analysis very simplistic for the moment, just to set the scale of the reach.
  - technical issues such as PileUp reduction need a much higher level of knowledge of simulation.
  - For now some studies informing the detector requirements
- Important note: much of these measurements rely on the measurement of the previous HL-LHC but also of the FCC-ee for the expected precision