Future Hadron colliders Detector and Physics from 100 TeV to PeV energies

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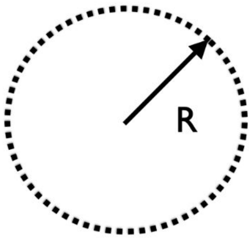
Physics at the highest energies - GGI

31/07/2025

High energy hadron machines

$p\,[\,\mathrm{TeV}/c\,] = 0.3\,B\,[\,\mathrm{T}\,]\,R\,[\,\mathrm{km}\,]$



Pros:

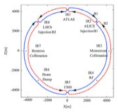
- relatively democratic initial states, strong and electro-weak force
- high center of mass, thanks to ~ small synchrotron power loss $(m_e/m_p)^4$
  - caveat: at 100 TeV it becomes significant!
- high luminosity up to high energy

Cons:

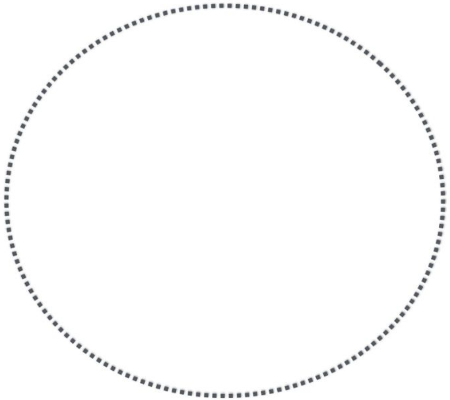
- large backgrounds compared to lepton machines ($\alpha_S > \alpha_{EM,W}$), from
  - high Q2 physics (di-jet, ttbar …)
  - “simultaneous” p-p collision (pile-up)

- Discovery machines for heavy new states
- Also suited for precision (thanks to high rates)

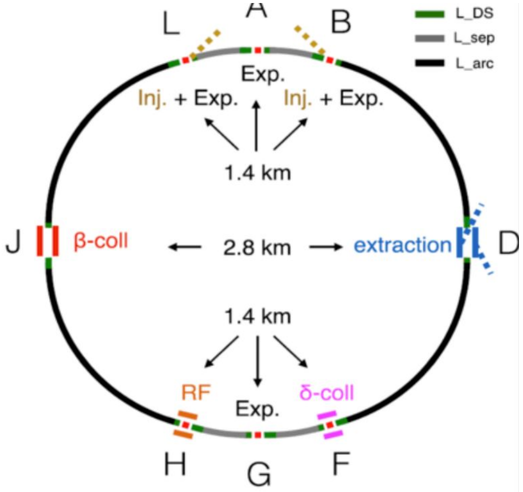
Variants



HE-LHC



LE-FCC



FCC-hh

? → 80 TeV

? → 100 TeV

? → 120 TeV

sqrt(s)	27 TeV
Lumi	15 ab^{-1}
B	16 T
circ.	27 km

sqrt(s)	37 TeV
Lumi	15 ab^{-1}
B	6 T
circ.	100 km

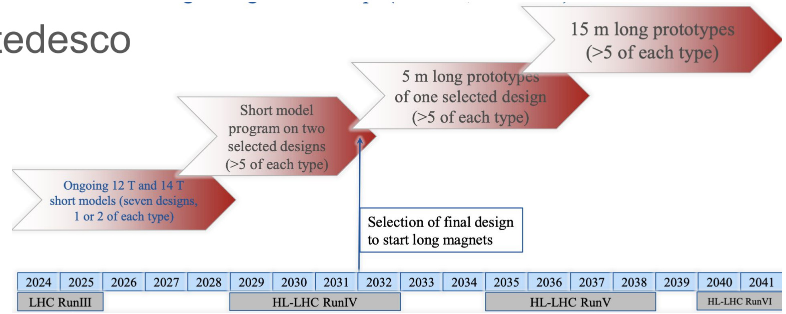
sqrt(s)	100 TeV
Lumi	30 ab^{-1}
B	16 T
circ.	100 km

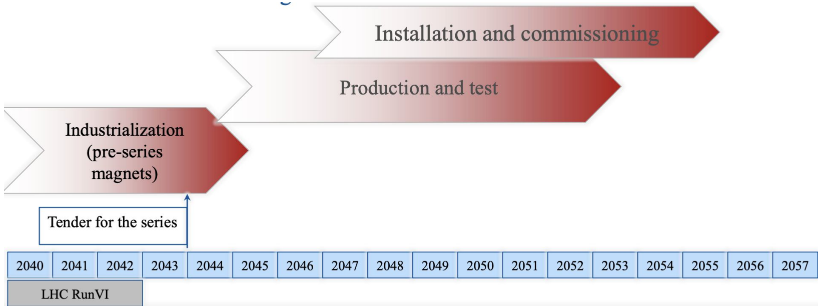
Main challenge: high field superconducting > 14 T magnets , high PU
FCC-hh cost: 18 BCHF (24 BCHF if standalone)

Magnet challenge

- Baseline FCC-hh design: B = 14 T ($\sqrt{s}$ = 84 TeV)
- New conductor Nb_3Sn supports higher fields due to its larger critical current density and critical field
  - HTS ? far from required specs still … → needed for higher energy (120 TeV)
- Wider coils (50–55 mm vs. 30 mm in LHC dipoles) are needed to maintain a conservative 400 A/mm² overall current density.
- This design demands 2–2.5 times more conductor material than in LHC dipoles.
  - 4.7k magnets (cost will be addressed in the ESPPU ~ 10 BCHF)
- Still intense R&D required to reach 15-16 T (including safety margin)

Ezio tedesco





High energy hadron machines

To compute reach, we assume we need to observe given number of events:

$$N = \sigma \mathscr{L}$$

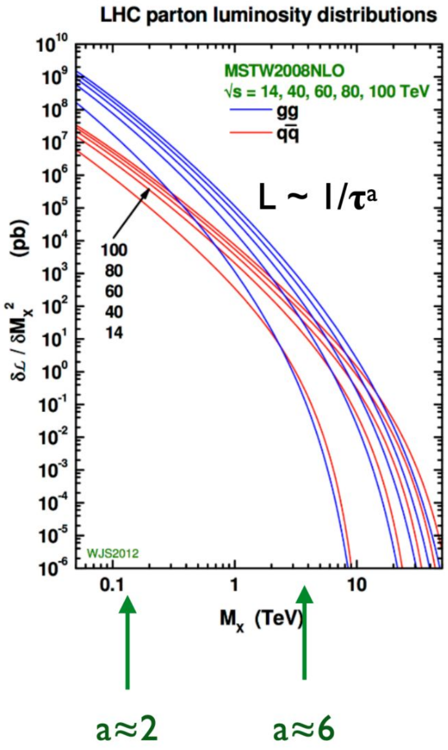
dimensional analysis

$$\sigma \sim L_{parton}(\tau) \cdot \sigma_{partonic}$$

$1/\tau^{a}$ $\quad$ $1/M^2$

$\tau = x_1 x_2 = M^2/s$

assumes mostly produce at threshold



$\mathscr{L}$: integrated luminosity

L_{parton} : parton luminosity

Mass reach scaling

How does the reach for observing a a new state of mass M (e.g BSM Higgs, …) **scale** from 14 TeV to 100 TeV ?

Assume we need the same number of events at 14 TeV and 100 TeV to claim discovery:

$$\#\ \text{events}\ (\sqrt{s_2} = 100\ \text{TeV}) \approx\ \#\ \text{events}\ (\sqrt{s_1} = 14\ \text{TeV})$$

$$(M_2 / M_1) \sim (s_2 / s_1)^{1/2}\ [(s_1/s_2)(\mathscr{L}_2/\mathscr{L}_1)]^{1/(2a+1)}$$

$$M_{100\,\text{TeV}} / M_{14\,\text{TeV}} \approx 7$$

$[(s_1/s_2)(\mathscr{L}_2/\mathscr{L}_1)]^{1/(2a+1)} \approx 1$

assumes:
- large a
- large luminosity

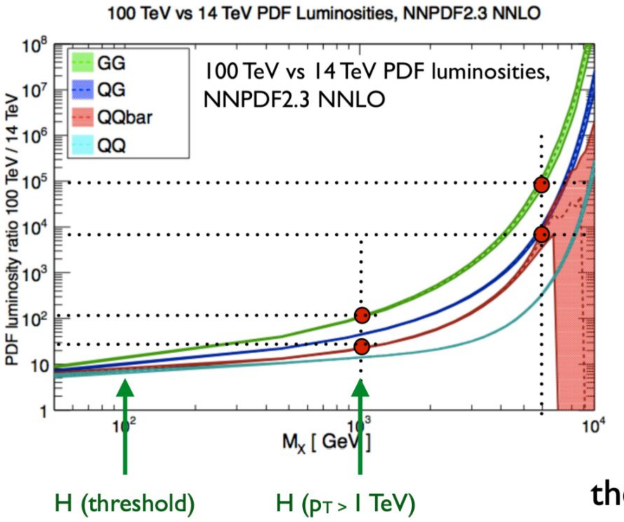
As expected, mass reach scales linearly with $\sqrt{s}$

Cross section scaling

How does the rate of a **given process** (e.g. single Higgs production) scale from 14 TeV to 100 TeV

parton luminosities

$$\frac{\text{cross-section } (\sqrt{s} = 100\text{ TeV})}{\text{cross-section } (\sqrt{s} = 14\text{ TeV})} \approx L_1 / L_2$$

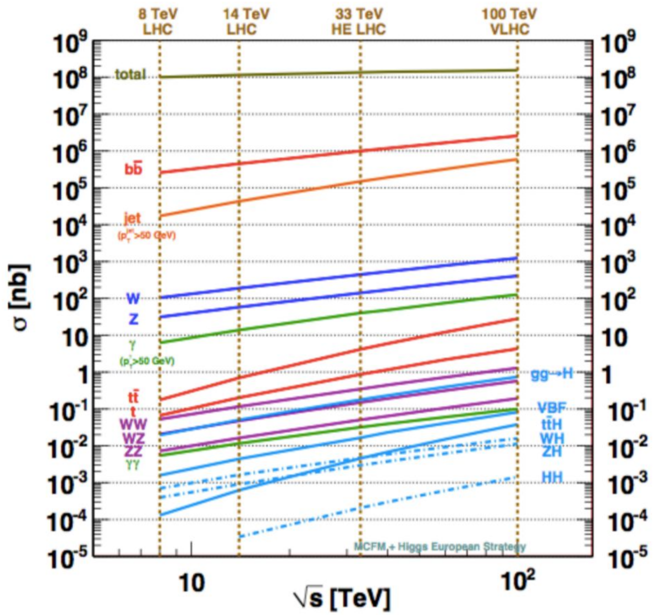


	σ(100)/σ(14)
ggH	15
HH	40
ttH	55
H (p_T > 1 TeV)	400

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)

High energy hadron machines



- Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

→ Levels of pile-up will scale basically as the instantaneous luminosity.

- Cross-section for relevant processes shows a significant increase.

→ interesting physics sticks out more !

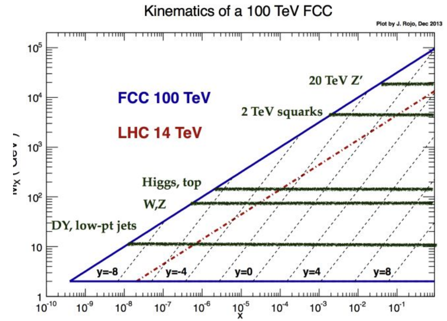
Rate of increase from 14 TeV to 100 TeV:

- ggH x15
- HH x40
- ttH x55

→ reduction of **x10-20** statistical uncertainties

Physics at threshold

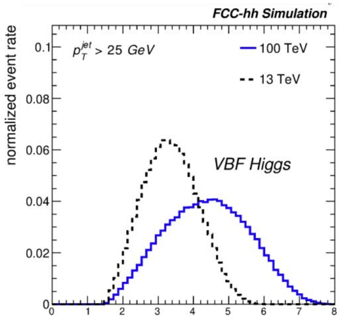
$x_1 * x_2 * s = M^2$

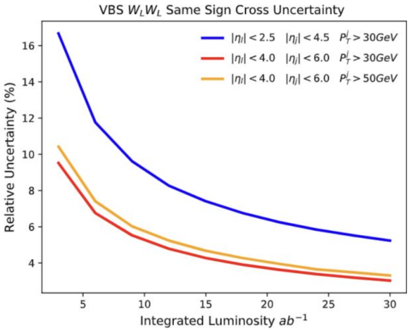


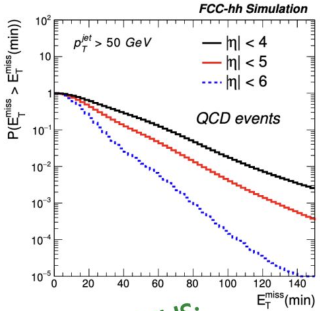
SM Physics is more forward @100TeV

- If we want to maintain **high efficiency in states produced at threshold** need **large rapidity** (with tracking) and **low p_T** coverage

→ highly challenging levels of radiation at large rapidities







Tracking and calorimetry needed up to $|\eta| < 6$ for ~. VBF signatures

BONUS: Hermeticity E_T^{miss} resolution

Boosted topologies at multi-TeV energies

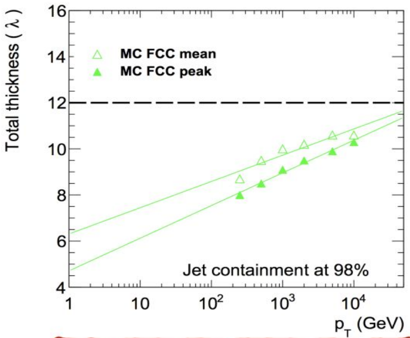
The boosted regime:

→ measure leptons, jets, photons, muons originating ~ 40-50 TeV resonances

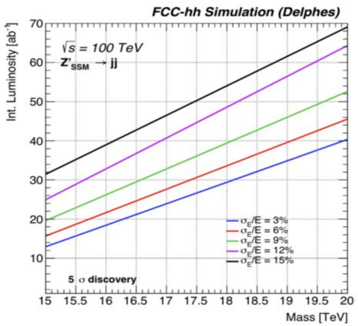
Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

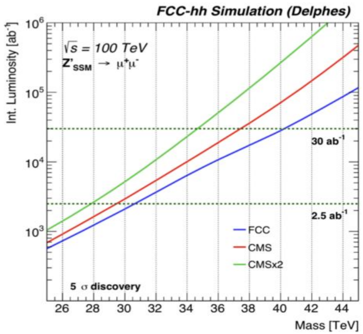
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets

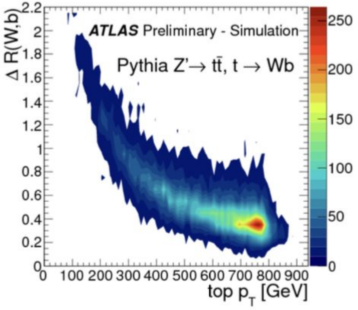


high p_T muons

Boosted topologies at multi-TeV energies

min. distance to resolve two partons

$$\Delta R \approx 2\,m / p_T$$



ex for top:

p_T = 200 GeV → R ~ 2
p_T = 1 TeV → R ~ 0.4
p_T = 10 TeV → R ~ 0.05

- At 10 TeV whole jet core within 1 calo cell
  - neutrals possibly un-resolvable
    - B field "helps" with charged
  - PF reconstruction will be severely affected
    - Total jet energy OK, calo does good job
    - reed to be studied and rethought for

- Naive approach:
  - use calo for energy measurement
  - tracking for substructure identification

in CMS:

Tracking → ΔR ~ 0.002
ECAL → ΔR ~ 0.02
HCAL → ΔR ~ 0.1

High p_T flavor tagging

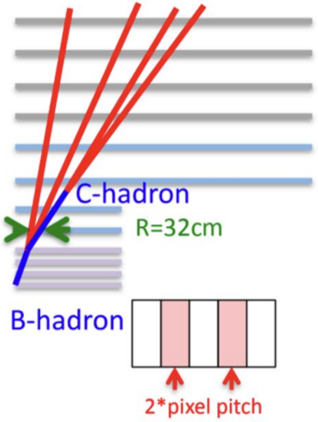
- **The boosted regime:**
  → measure b-jets, taus from multi-TeV resonances

- Long-lived particles live **longer**:

  ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
  5 TeV **tau lepton** travels **10 cm** before decaying

  → extend pixel detector further?
  - useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)
  - number of channels over large area can get too high

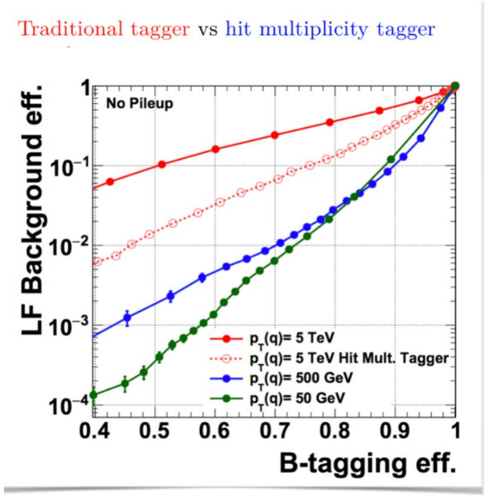
  → re-think reconstruction algorithms:
  - hard to reconstruct displaced vertices
  - **exploit hit multiplicity discontinuity**



Only 71% 5 TeV b-hadrons decay < 5th layer.

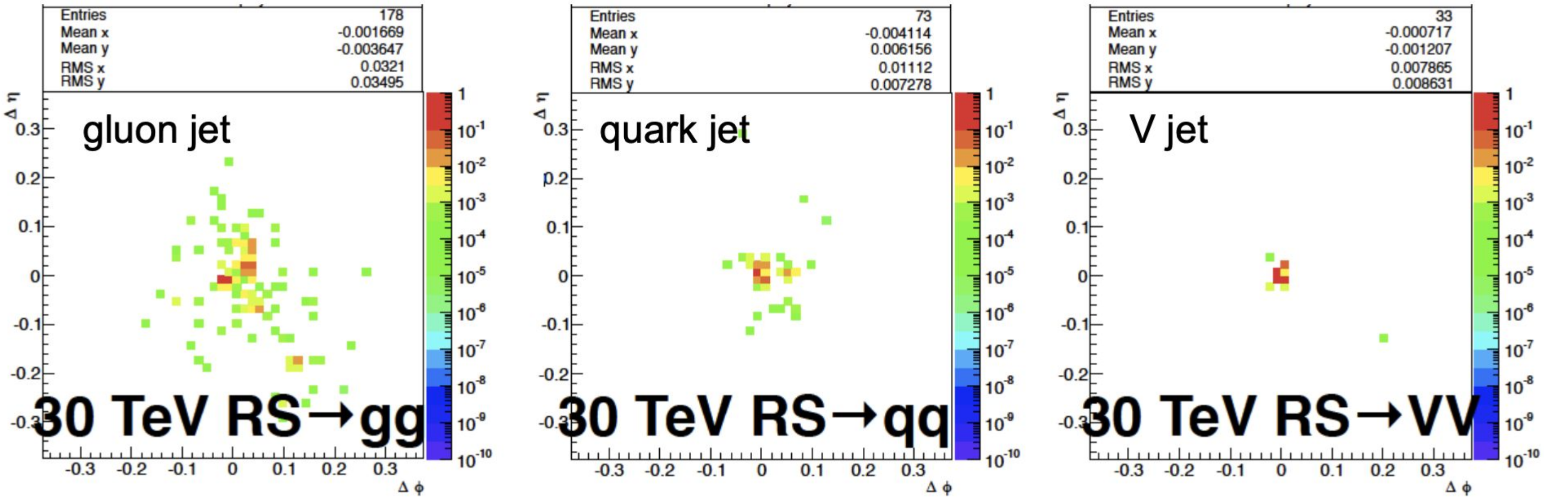
- displaced vertices

Perez Codina, Roloff [CERN-ACC-2018-0023]



Color Singlets (W/Z/H)

[Pierini]

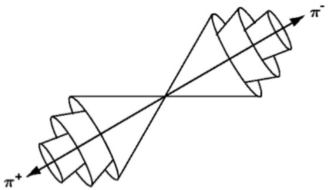


- **Gluon/quark** jet looks the same at 50 GeV and 5 TeV (**QCD is ~ scale invariant**)
- **Color Singlets** look like taus (do not radiate, a part from occasional QED/EWK shower)
    - **high mass, highly isolated, highly collimated tracks**

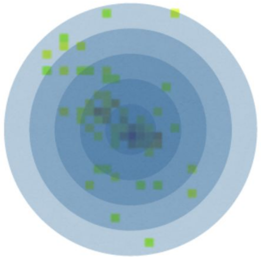
Boosted Color Singlet ID

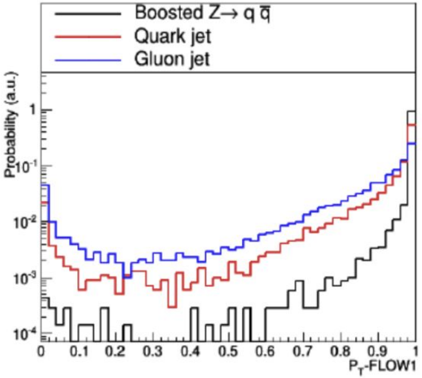
[Pierini]

~ isolation variable



$$p_T^i(flow) = \frac{\sum\limits_{p \epsilon C_i} p_T^p}{p_T^{jet}}$$

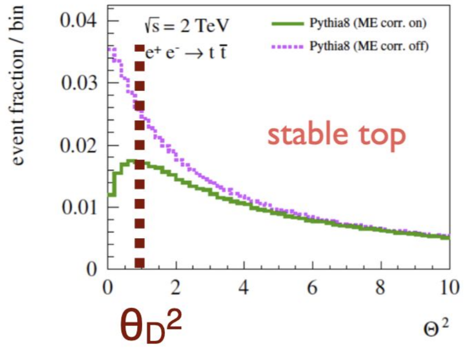




Loss in performance, but no show stoppers
Very simple heuristic based , can probably do much better with today's techniques

The deadcone effect for massive colored res.

Maltoni, MS, Thaler [1606.03449]

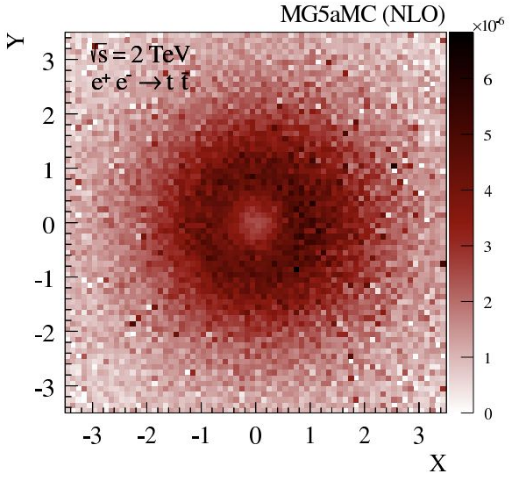


FSR in soft and collinear limit :

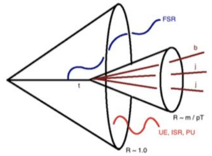
$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}z\,\mathrm{d}\theta^2} \simeq \frac{\alpha_S}{\pi} C_F \frac{1}{z}\frac{\theta^2}{(\theta^2+\theta_D^2)^2}$$

$$\theta_D \equiv \frac{m_q}{E_q}$$

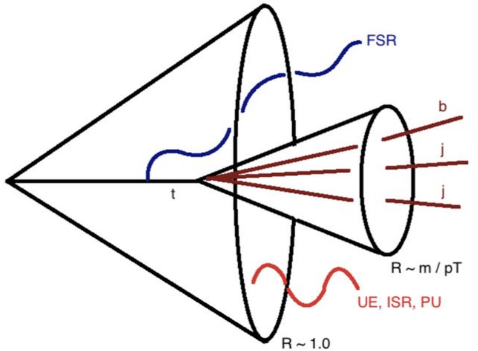
- effect can be observed at HL-LHC
- rather than treated as a nuisance can be exploited for top tagging at multi TeV energies



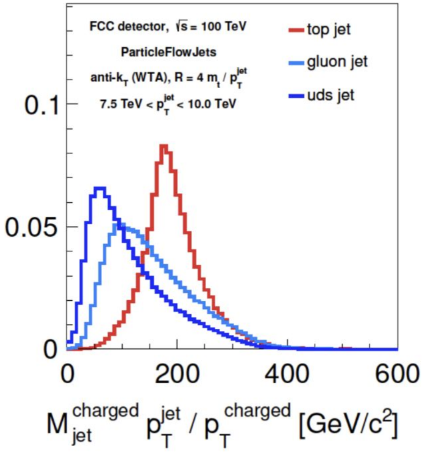
for the top can be pretty large angle



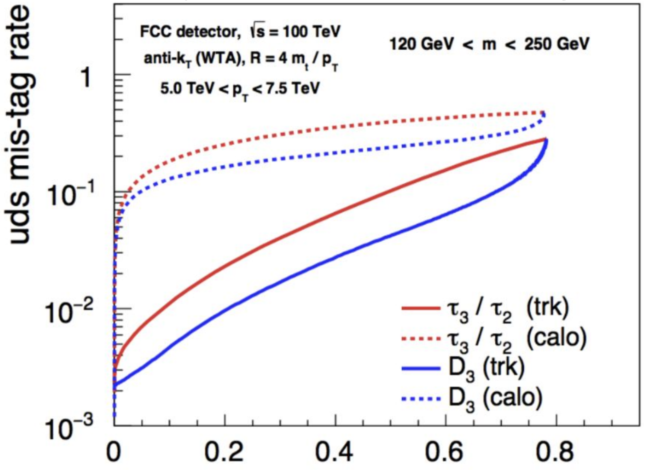
Boosted Colored Resonances



Track- based jet Mass



Very simple heuristic algo



- Multi TeV top radiates FSR at a typical scale angular scale ~ m / pT (deadcone)
- Large cone FSR can spoil mass by adding $\Delta m \sim m_{top}$ even for 1 GeV emission
  - → use shrinking cone algo by reclustering with R ~ 4m/pT
  - use tracking for substructure

Challenges

LHC → boost / M_x

SM precision (Higgs, ..)

High mass

FCC-hh → boost / M_x

higher rates
larger background
more forward

trade ↔

medium rates
small background
more central

more collimated

Machine and detector requirements

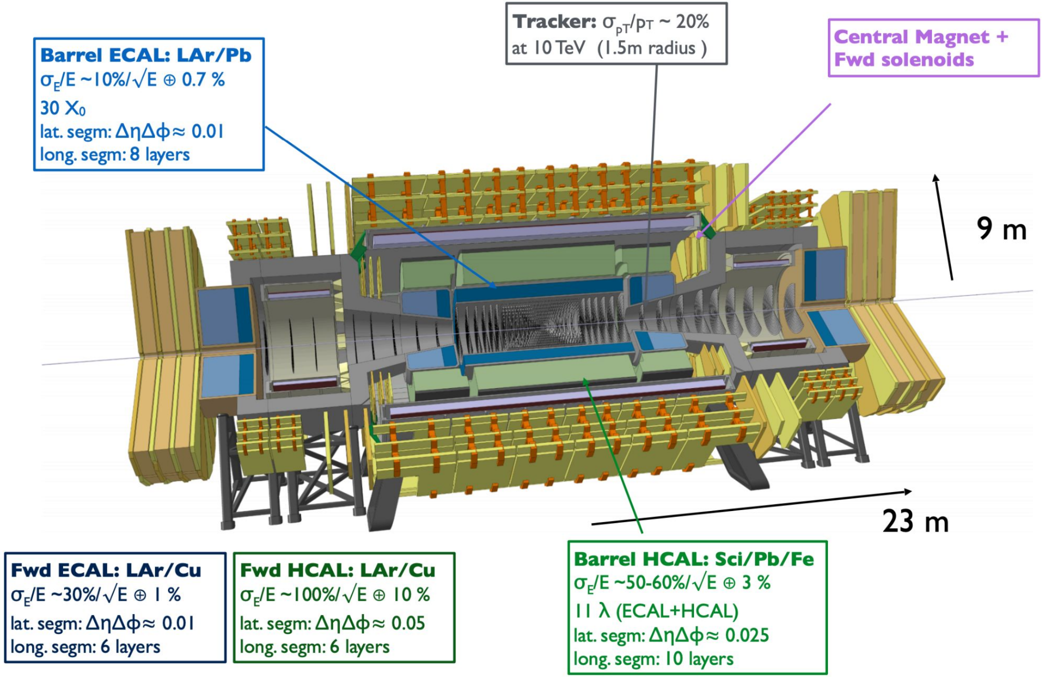
rad. levels

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$cm^{-2}s^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\|_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

→ x50 HL-LHC

10^{18} cm^{-2} MeV-neq @ 2.5 cm !!

A detector concept that does the job …

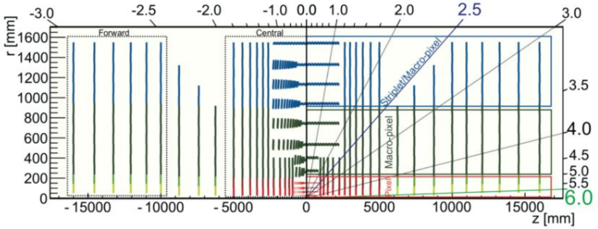


Challenges

- Large dynamic range
- High occupancy (1000 PU)
  - Timing (3 ps resolution)
- High data rates
  - 10x data vs HL-LHC
- High radiation
  - $3x10^{18}$ 1MeV neq / cm2

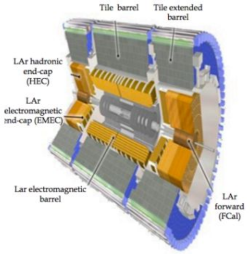
R&D should continue after HL-LHC

A detector concept that does the job …



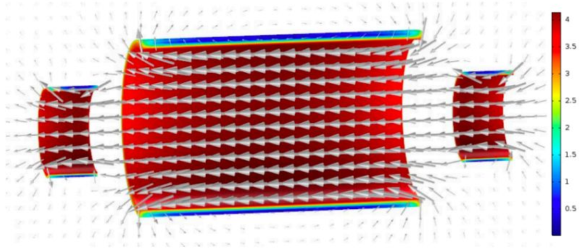
Tracker

- -6 < η < 6 coverage, 20-40% total X/X_0
- pixel : $\sigma_{r\phi}$ ~10μm, σ_Z ~15-30μm, X/X_0(layer) ~ 0.5-1.5%
- outer : $\sigma_{r\phi}$ ~10μm, σ_Z ~30-100μm, X/X_0(layer) ~ 1.5-3%



Calorimeters

- ECAL: LArg , $30X_0$, 1.6 λ, r = 1.7-2.7 m (barrel)
- HCAL: Fe/Sci , 9 λ, r = 2.8 - 4.8 m (barrel)

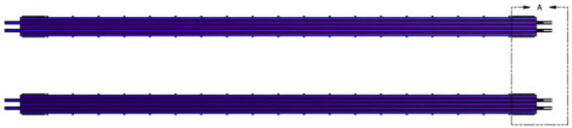


Magnet

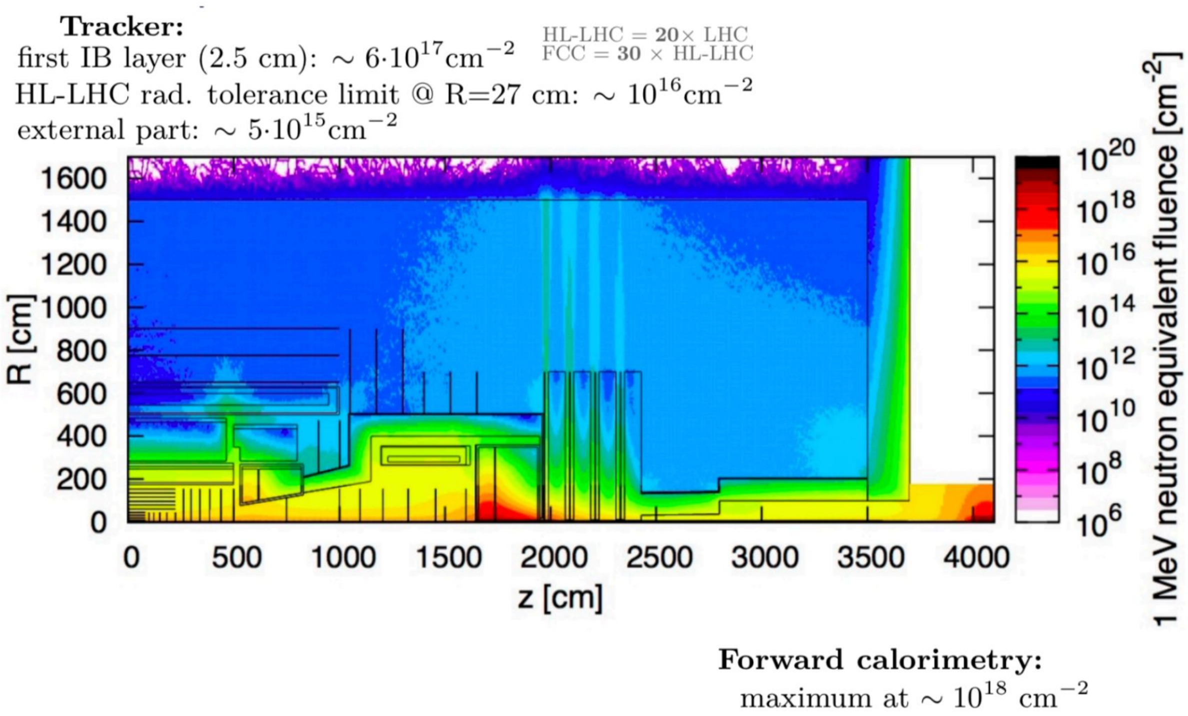
- central R = 5, L = 10 m, B = 4T
- forward R = 3m , L = 3m , B = 3.5T

Muon spectrometer

- Two stations separated by 1-2 m
- 50 μm pos., 70μrad angular



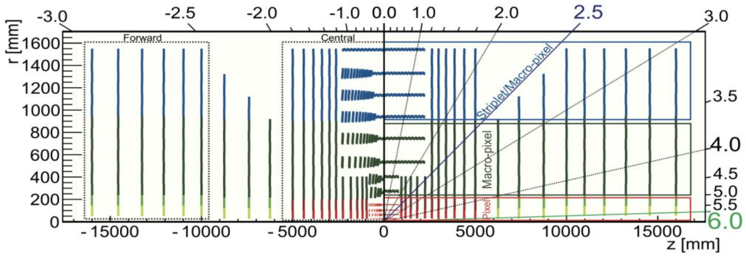
Radiation tolerance



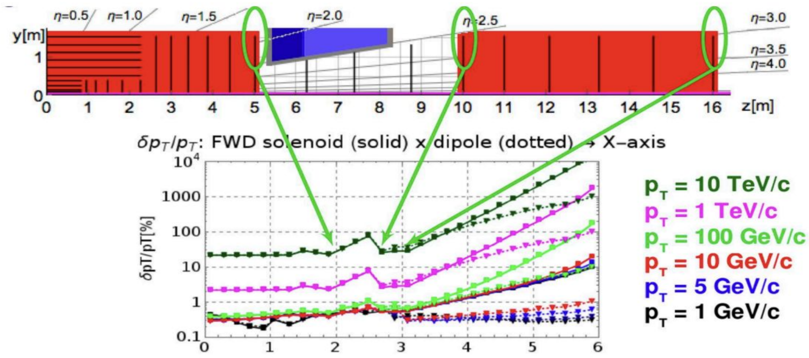
- A hadron fluence > 10^{16} cm^{-2} is very challenging for silicon sensors
- This limit is reached already @ 27 cm from the beam pipe
- Dedicated R&D needed to push the limit of radiation hardness (LHCb Upgrade II)

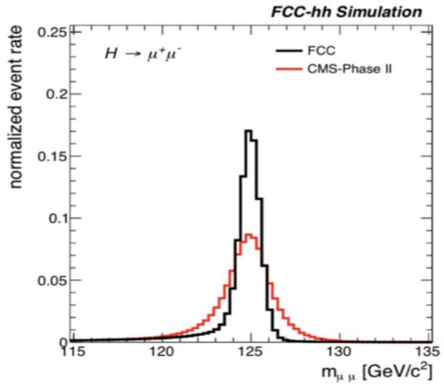
Tracker

- Binary readout
- 16 billions readout channels, x(3-10) phase II detectors)
- Radiation hardness is an issue for innermost layers



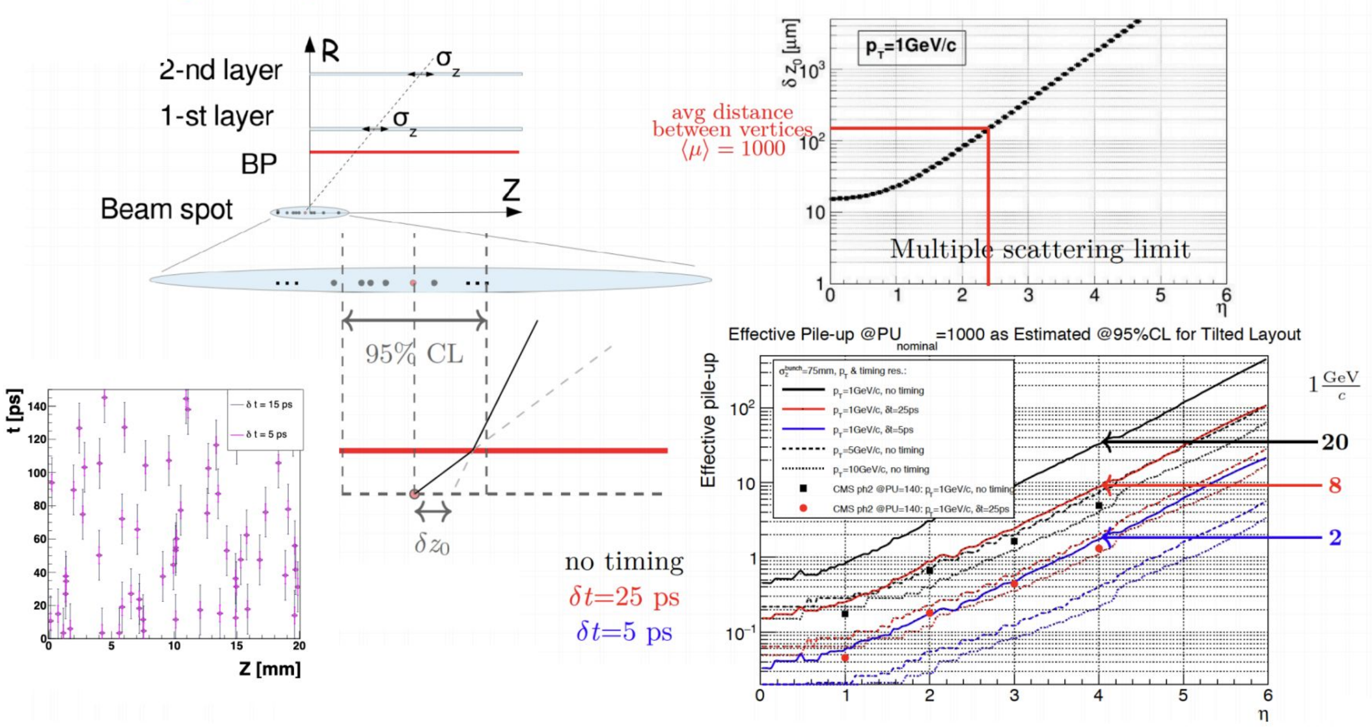
- Tilted geometry with inclined modules:
  - minimize effect of Multiple scattering (low material)
  - helps with pattern recognition





low p_T muons → resolution dominated by MS

Pile-up and timing information

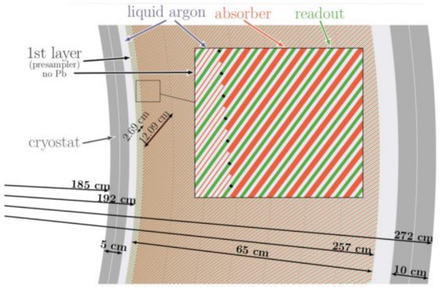


With PU density = 8 mm^{-1} need δz_0 ~ 100 μm resolution in track longitudinal impact parameter

→ at large angles this corresponds to beam-pipe contribution alone !!!

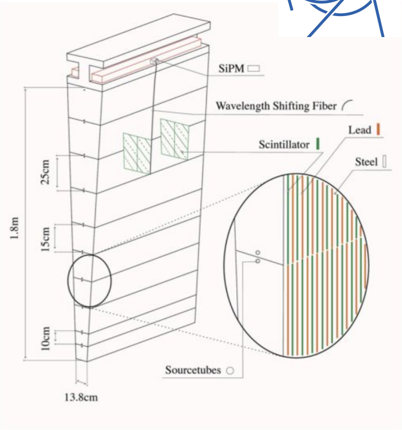
High resolution (~ 5-10 ps) timing information needed !!

Calorimeters



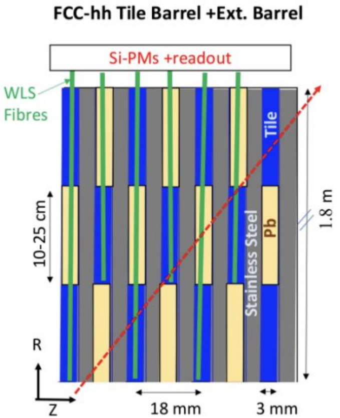
ECAL

HCAL

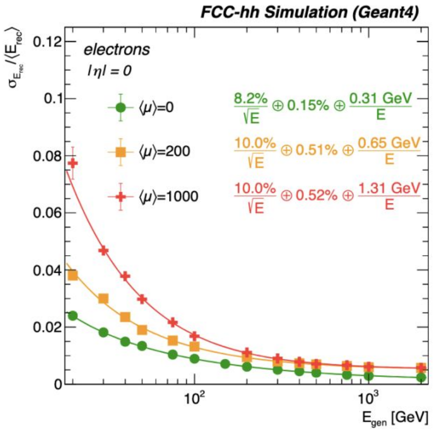


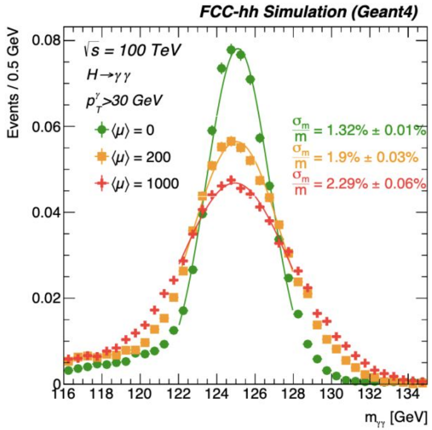
- ECAL: LAr + Pb technology driven by radiation hardness
- HCAL:
  - Organic scintillator + Steel, R/O with WLS fiber + SiPM
  - LAr in the forward (Dose > 10 MGy)

- Design goals:
  - High longitudinal (7+10 layers) + transverse segmentation (x4 CMS and ATLAS)
  - Particle-flow compliant
  - standalone PU rejection

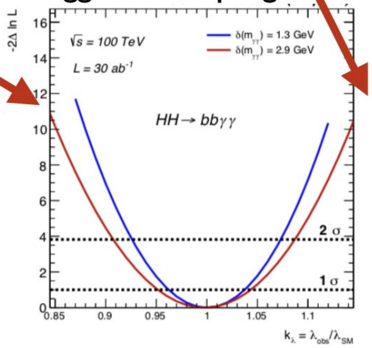


Photon performance





Higgs self-coupling



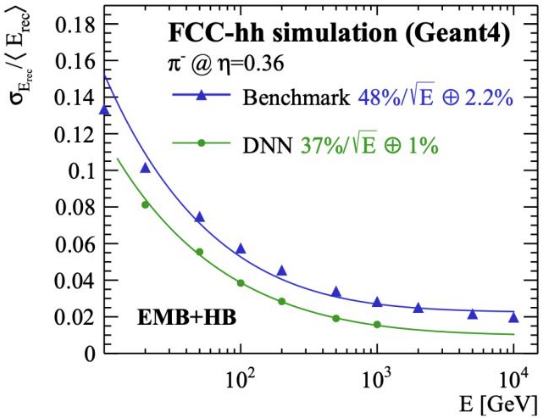
m(γγ) resolution

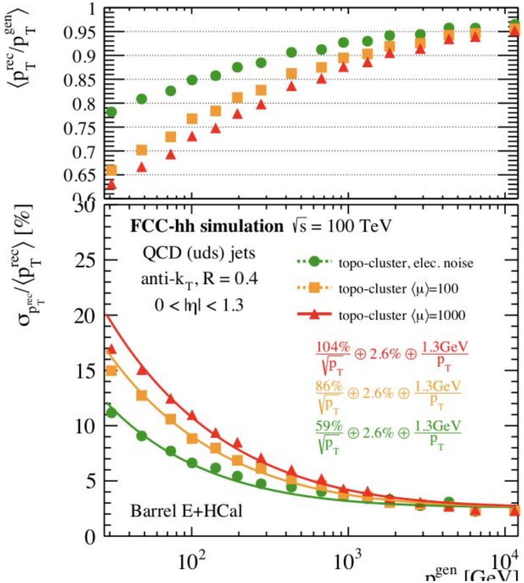
- Target: **σ/m as small as possible for HH→bbγγ**
- **Large impact of in time PU** on the noise term (out of the box with no improvements)!!
- severely **degrades $m_{\gamma\gamma}$** resolution (improving clustering, not sliding windows may help)
- **impacts Higgs** self-coupling precision by **$\delta\kappa_\lambda \approx 1\%$**
- some thought needed (tracking, timing information can help?)

Jet performance

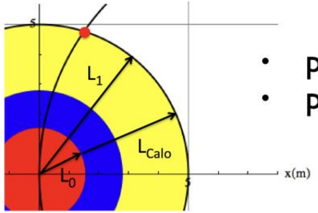
- Excellent resolution up to $p_T = 10$ TeV !!
- Large impact of PU at low p_T (as expected)
  - crucial for low mass di-jet resonances (again, such as HH→**bb**γγ)
  - Further motivation for Particle-flow

→ since charged PU contribution can be easily subtracted (Charged Hadron Subtraction)

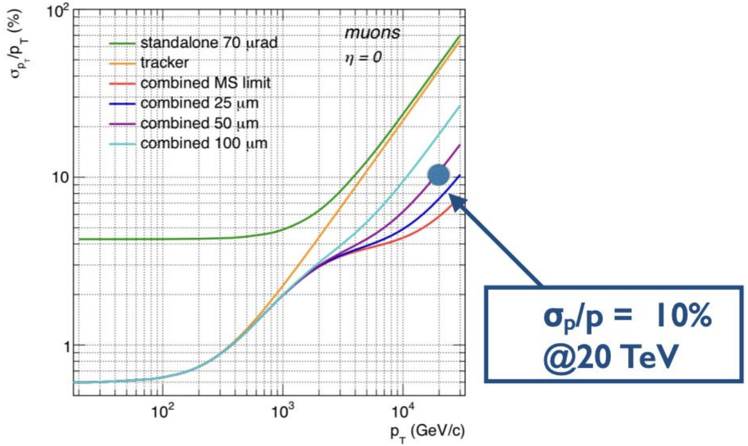


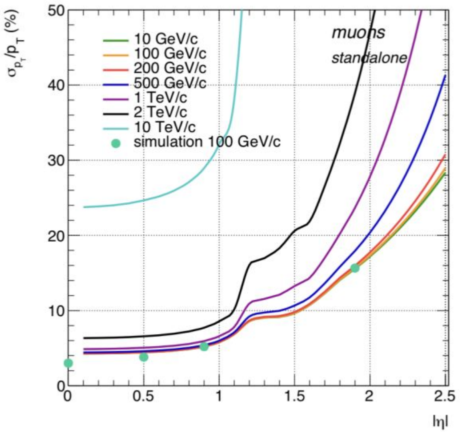


Muons



- pT = 4 GeV muons enter the muon system
- pT = 5.5 GeV leave coil at 45 degrees



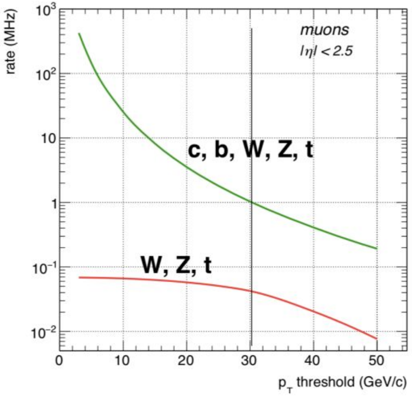


Calo + Coil = 180-280 X_0

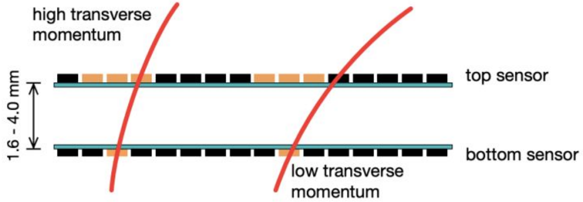
- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 μm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5
- Rates manageable with HL-LHC technology (sMDT)

Data rates

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [341]	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90



- Phase II:
  - ATLAS/CMS readout **calorimeters/muons** @40MHz and send via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions
  - CMS reads out (part of) the tracker at L1 50 Tb/s
  - Full detector readout @1MHz (5Mb/event)
    - @40MHz it would correspond to 200 Tb/s



- FCC-hh:
  - At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
  - However full detector would correspond to 1-2 Pb/s
    - Seems hardly feasible (30 yrs from now)
  - How much data can be transferred out, without spoiling the performance?

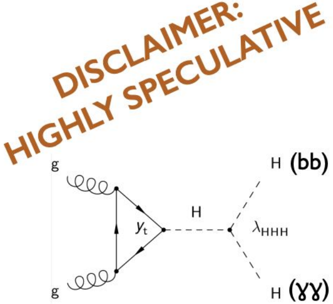
Road to 1% precision on the self-coupling ?

- Photons
  - energy/momentum resolution
    - Homogenous LXe calorimeter ?
      - $M_R \sim 5$ cm, $X_0 \sim 2.5$ cm
      - $3\%/\sqrt{E}$
  - Eff - low misID
    - Pile-up rejection (~ 10 ps timing)
- (B-)jet energy momentum resolution
  - Intrinsic HCAL resolution,
  - Calorimeter segmentation for optimal particle-flow
  - Timing for pile-up rejection
- Flavor Tagging
  - Close to IP (radiation damage !!!) (1/d)
    - ~ @1cm → 1e19 1 MeV neq/cm^2
  - Light vertex detector ($\sqrt{X_0}$)
    - but power/cooling needed to extract data
  - target single point resolution ~ 10 µm x 10 µm

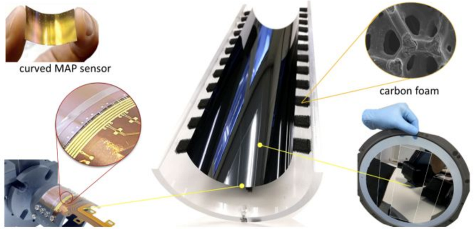
$\delta\kappa_\lambda$ (stat) ~ 2-3%

[MLM, Ortona, MS]

[Taliercio et al.]



XENONnT:



maps ~ 1e15 1 MeV neq/cm^2

Guiding principles for FCC-hh detector

- Guiding principles were machine constraints and physics requirements

- This generic detector serves as a starting point for:
  - benchmarking physics reach of the machine
  - identify: challenges of building such an experiment
  - topics where R&D needed

- Most likely, this is not “THE OPTIMAL” detector.

- Maybe the optimal route will be to have several detectors optimized for specific signatures (low? vs high lumi)

- Also, expected improvements in technology may lead to more ambitious and less-conventional approaches of detector concepts in the future
  - most of the challenges common to any high energy/high luminosity project.

Higgs at 100 TeV vs HL-LHC and FCC-ee

- 100 TeV provides **unique and complementary measurements** to ee colliders:
  - **Higgs self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zɣ), ratios, ..) measurements will be **statistically limited** at FCC-ee

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

need to improve

Large rates for rare modes and HH production at FCC-hh

→ complementary to e^+e^-

Higgs complementarity with lepton machines

At pp colliders we can only measure:

$$\sigma_{prod}\, BR(i) = \sigma_{prod}\, \Gamma_i \,/\, \Gamma_H$$

→ we do not know the total width.

In order to perform global fits, we have to make **model-dependent assumptions**

Instead, by performing measurements of ratios of BRs at hadron colliders:

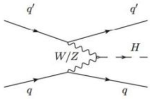
$$BR(H\rightarrow XX) \,/\, BR(H\rightarrow ZZ) \approx g_X{}^2 \,/\, g_Z{}^2$$

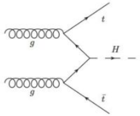
↖ from e^+e^-

We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

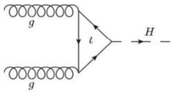
→ synergy between lepton and hadron colliders

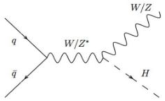
Higgs production in hadron machines





	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55
HH (NNLO)	40 fb	1.2 pb	30





30M Higgs pairs

Expected improvement at FCC-hh:

- **20 billion Higgses** produced at FCC-hh
- **factor 10-50** in cross sections (and Lx10)
- reduction of a **factor 10-20 in statistical** uncertainties

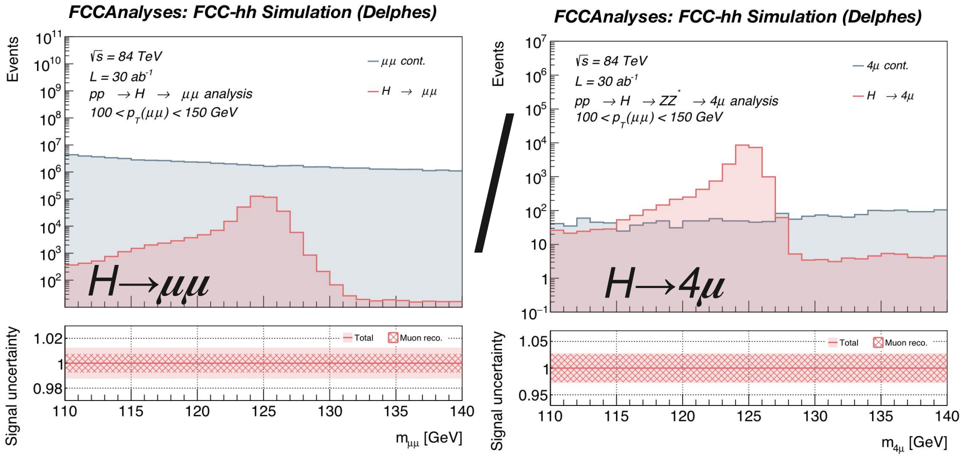
Large statistics will allow:

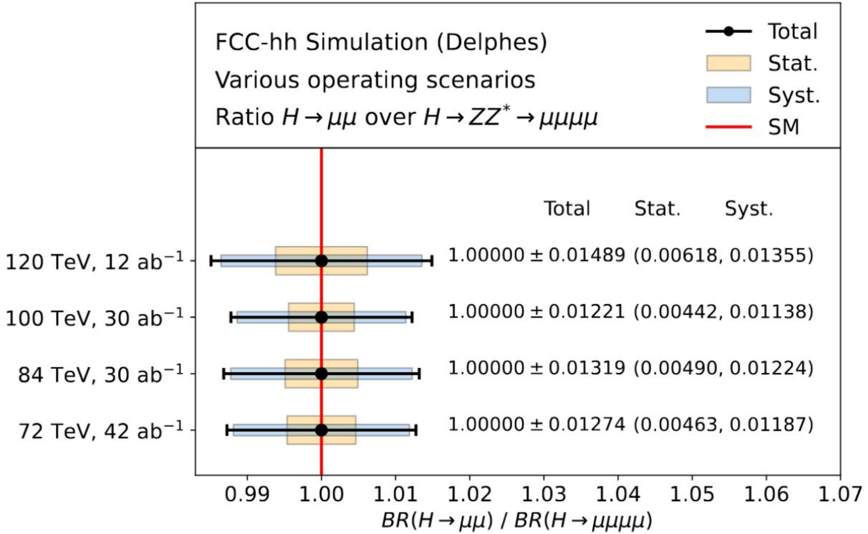
- for **% - level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

> 10M Higgs boson with $p_T(H)$ > 500 GeV

Single Higgs couplings: Ratio $H(\mu\mu)/H(4\mu)$

CDS note
10.17181/sxreb-8h751





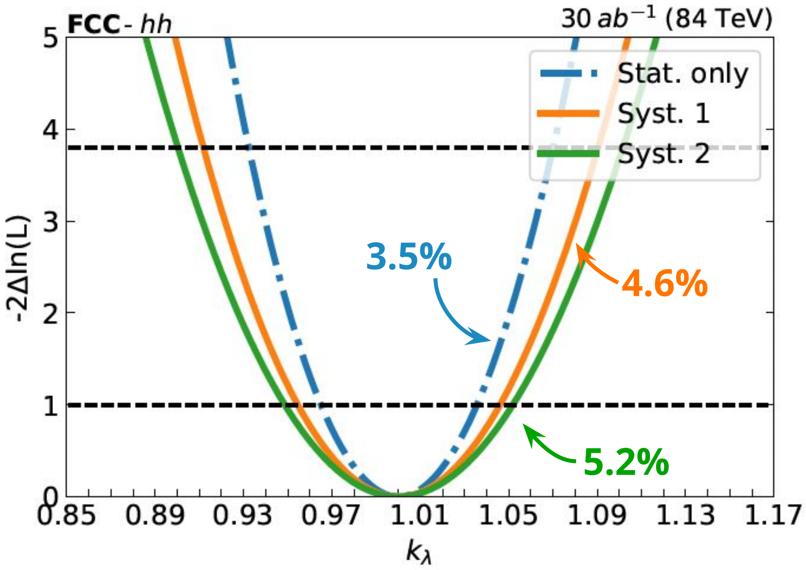
- Benefit from large statistics at high $p_T(H)$, where experimental efficiency systematics are smaller, furthermore focus on ratios of signal strengths to cancel (theory) systematic uncertainties

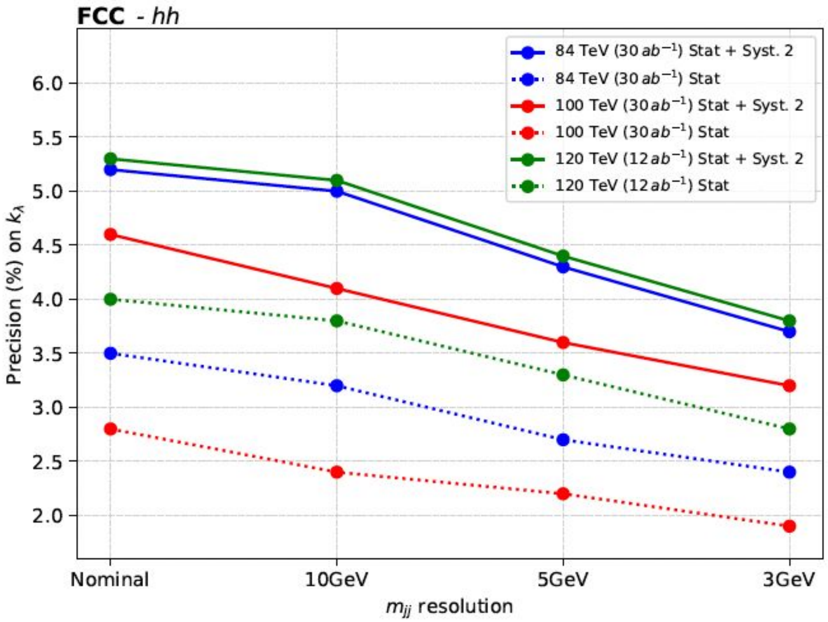
- Updated results from differential fit in $p_T(H)$ bins, for the different operating scenarios

Higgs self-coupling:

See also P. Mastrapasqua's poster

CDS note
10.17181/w6928-gr929





- Re-optimized strategy: Event selection with Deep Neural Network
- Fit invariant di-photon mass in bins of invariant di-jet mass, with different assumptions

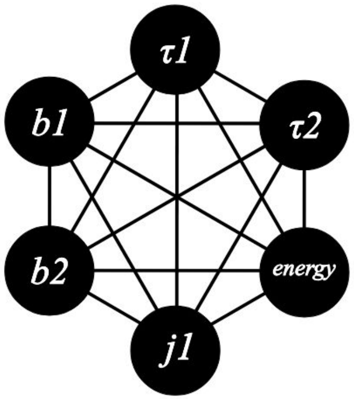
- Consider different energies & resolutions of invariant d-jet mass

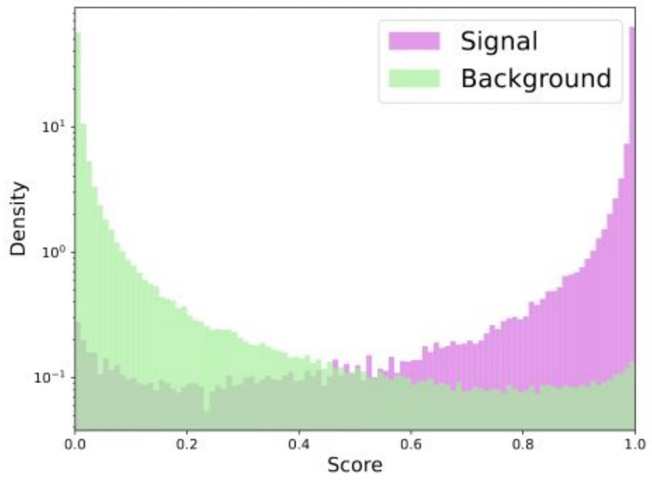
➡ Impact of di-jet resolution is critical

Higgs self-coupling: $\bar{b}b\tau\tau$ analysis

CDS note

10.17181/8cdq9-dj340





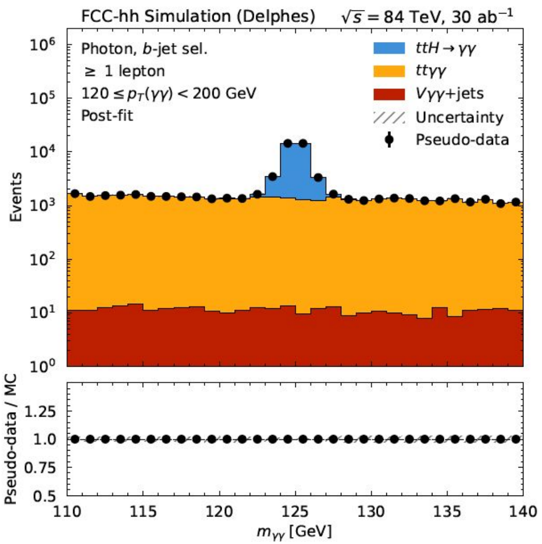
- Focus on channels with hadronic τ decay
- Re-optimized strategy: Event selection with Graph Neural Network: events modelled as fully connected graph

- Working on extraction of κ_λ precision at 84 TeV from fits to GNN score in bins of invariant di-Higgs mass
- Competitive with $\bar{b}b\gamma\gamma$ - combination planned

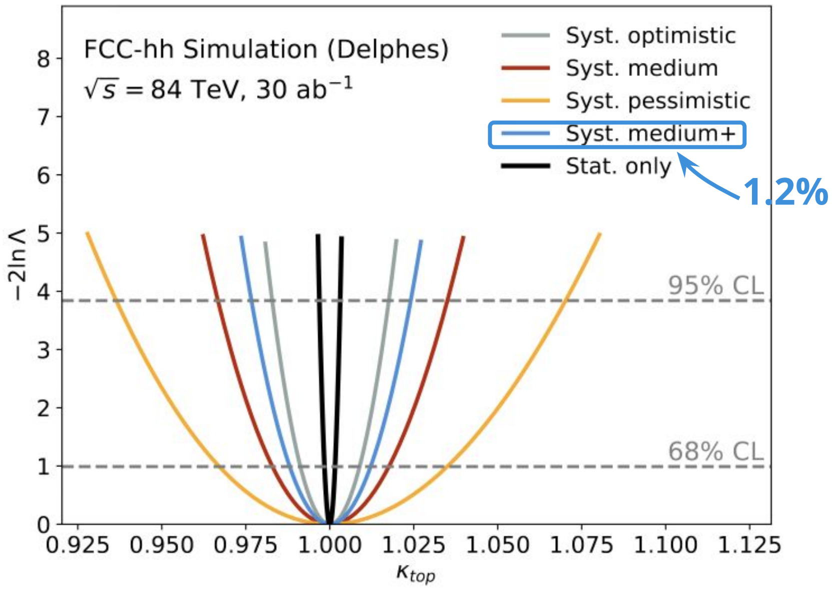
3%(stat) + 3%(syst) on HH(bb$\tau\tau$) cross-section

Single Higgs couplings: $t\bar{t}H(\gamma\gamma)$ analysis

CDS note
10.17181/tr6k7-bm770



- New channel for precision measurement of top Yukawa coupling κ_{top}
- Extract from fits to invariant di-photon mass in $p_T(H)$ bins



- Expected precision for 84 TeV and different assumptions on systematics
- Differential results also provided

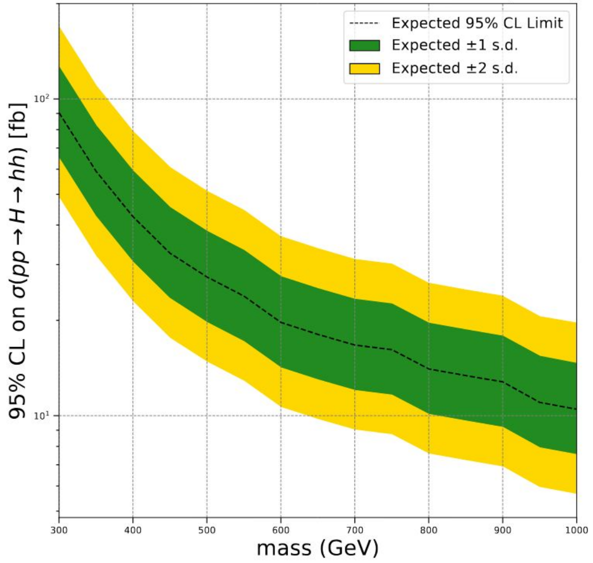
Summary Higgs measurements

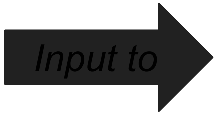
Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

Preliminary

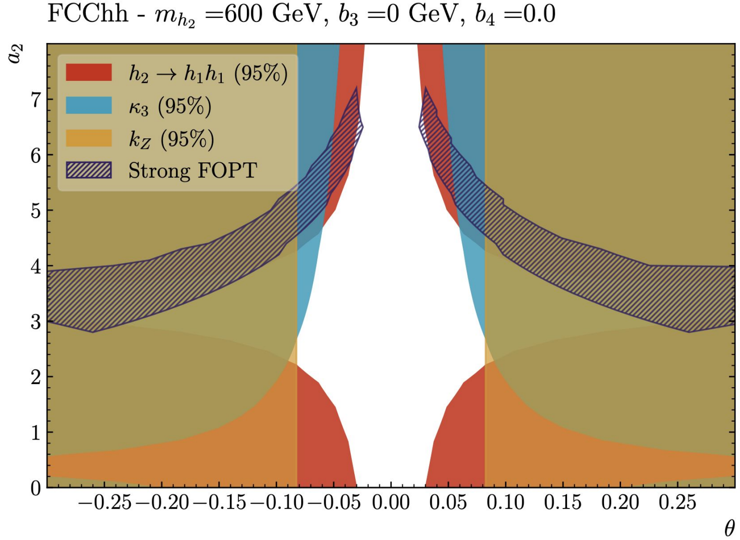
Resonant $\bar{b}b\gamma\gamma$ analysis & singlet interpretation

P. Mastrapasqua et al.



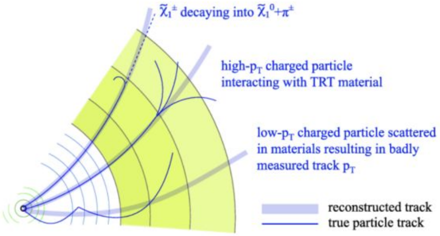


S. Tentori et al.



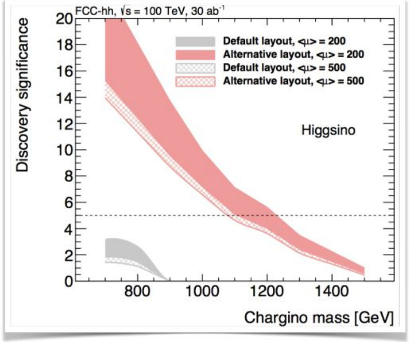
- Follow strategy of self-coupling analysis to derive limits on production of heavy resonance decaying as $H \to hh \to \bar{b}b\gamma\gamma$
- Constraints on parameter space of real singlet extension, where FCC-hh is decisive for full exclusion (or discovery)

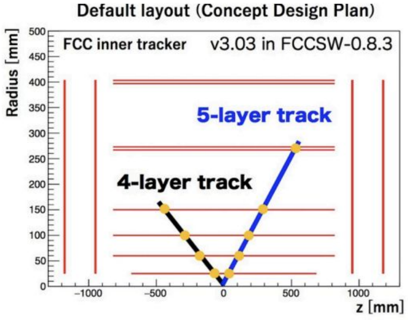
Tracking WIMPs

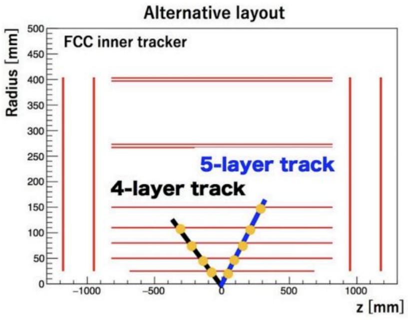


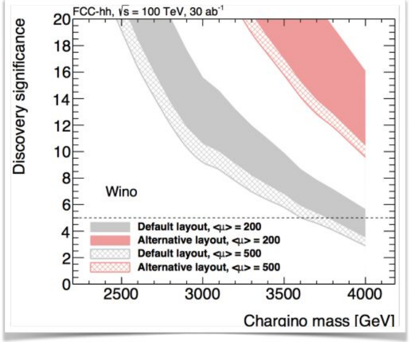
- Observed relic density of Dark Matter Higgsino-like: 1TeV, Wino-like: 3TeV
  - Mass degeneracy: wino 170MeV, Higgsino 350MeV
- Wino/Higgsino LSP meta-stable chargino, $c\tau$= 6cm(wino) 7mm(higgsino)

- Useful tools to optimise detector concepts



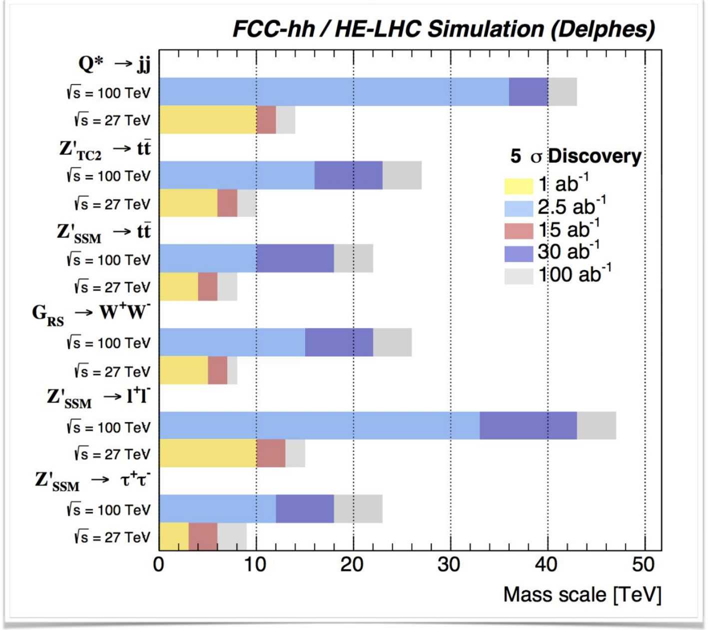




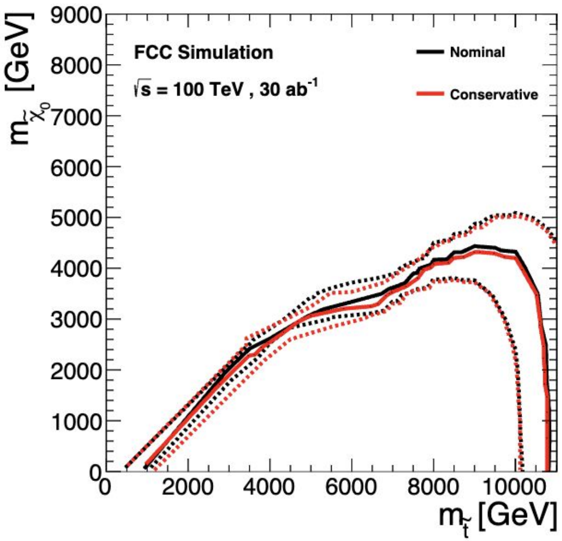


The energy frontier

High mass resonances



stops



Challenges: multi-TeV collimated top, W, τ highly collimated.

Tracking is the key highly segmented calorimetry

Scenarios

name	F12LL	F12HL	F12PU	F14	F17	F20
Dipole Field (T)	12	12	12	14	17	20
√s (TeV)	72	72	72	84	102	120
current (A)	0.5	1.12	1.12	0.5	0.5	0.2
PU	600	3000	1000	600	700	150
SR power (MW) 2 beams	1.3	2.9	2.9	2.4	5.2	4.0
Lumi/yr (ab-1)	1	2	1.3	0.9	0.9	0.35

Limiting factor: 5MW synchrotron power ~ $\sqrt{s}^{\,4}$

Sensitivity to various scenarios

Higgs SM precision

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0	0.8

Higgs self-coupling (scenario I) ~ 3-4%

assuming same detector performances

BSM reach

If there is a cross-over, physics is better at the lower energy collider! (assuming you can handle the pile-up)

Scenario name	Energy	Lumi/year	Cross-over	DM/ Compress EWK 3.0 →	Change in stop mass limit [TeV] 12.5 →	Change in Z' limit [TeV] 40→
F12LL	72 TeV	950 fb^{-1}	~always worse	~2.6	~9.6	~30
F12HL	72 TeV	2000 fb^{-1}	~3 TeV	~3.2	~10.4	~32
F12PU	72 TeV	1300 fb^{-1}	~125 GeV	~2.8	~10.0	~31
F14	84 TeV	950 fb^{-1}	~always worse	~2.8	~10.8	~34
F20	120 TeV	370 fb^{-1}	~25 TeV	~2.5	~12.6	~42

Eliott Lipeles

<u>Preliminary conclusions:</u>

For Higgs physics and lower mass new resonances, luminosity can make up for energy (for the highest energies it is much harder)

WIMP DM still in reach at 80 TeV

100 TeV $\rightarrow$ 1 PeV ?

A 1 PeV p-p collider?

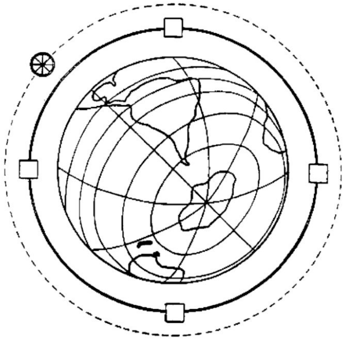
- Assuming 20T magnets, would need 500 km ring.

$$R = \frac{E}{0.3\,B} \implies R \approx \frac{500\,\text{TeV}}{0.3 \times 20\,\text{T}} \approx 8.3 \times 10^4 \text{ m}$$

- For a fixed beam current: $P \propto \frac{E^4}{\rho}$

- Total power for a ring 500 km, assuming FCC-hh luminosity: 20 GW ! → seems unfeasible

- To keep synchrotron radiation at few MW
  - Need x10^4 radius Earth circumference = Fermi Collider
  - Or reduce by 10^3 luminosity



- Only way maybe through a linac (wake field plasma?)
  - 100 MV/m → 5000 km
  - 1 GV/m → 500 km

Acceptance

- Presumably a 1 PeV collider will be built to search for PeV resonances
    - Central physics with “4π” multipurpose detectors
    - “Rare” Higgs physics, HH differential , HHH, …

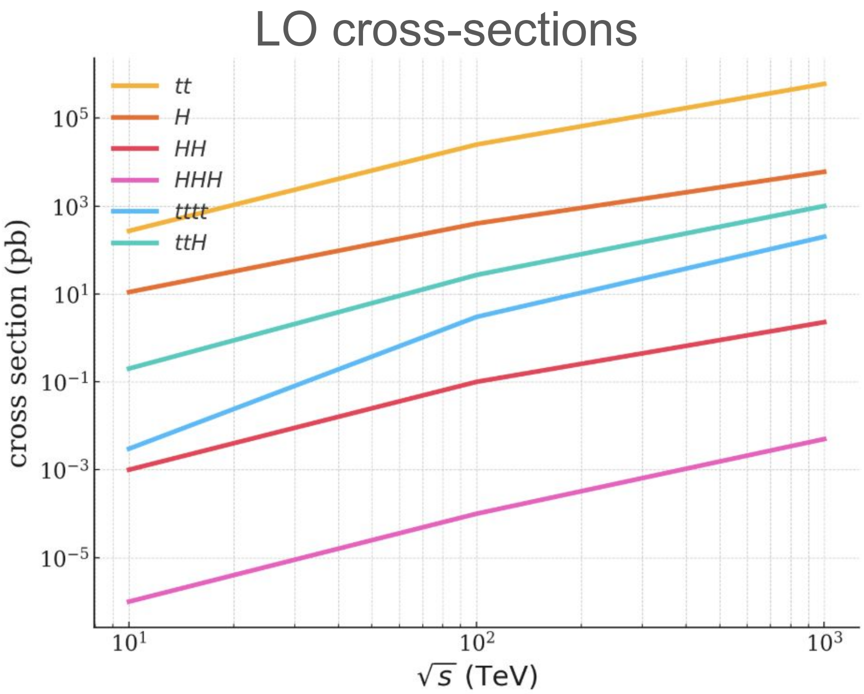
- SM physics will be continued to be measured, but will be produced very forward.
- At the FCC-hh, central spectrometer acceptance limited by the beampipe and VTX placement at eta = 4 → need forward spectrometer (and solenoid)

$\sqrt{s}$ (TeV)	x	$x_{\min}$	$y_{\max}$
10	10^{-2}	2.0×10^{-4}	3.9
100	10^{-3}	2.0×10^{-6}	6.2
1000	10^{-4}	2.0×10^{-8}	8.5

M_x = 100 GeV

- Dedicated Forward Physics Detectors will perform H, Top , and EWK physics
    - Need for flavor facility?
        - LHCb probably last of its kind (for flavor physics)

SM Processes



- tt (x40 vs 100 TeV, x2000 vs 10 TeV)
- H (x20 vs 100 TeV, x600 vs 10 TeV)
- HH (x30 vs 100 TeV, x2000 vs 10 TeV)
- HHH (x50 vs 100 TeV, x5000 vs 10 TeV)
- tttt (x60 vs 100 TeV, x60000 vs 10 TeV)
- ttH (x30 vs 100 TeV, x5000 vs 10 TeV)

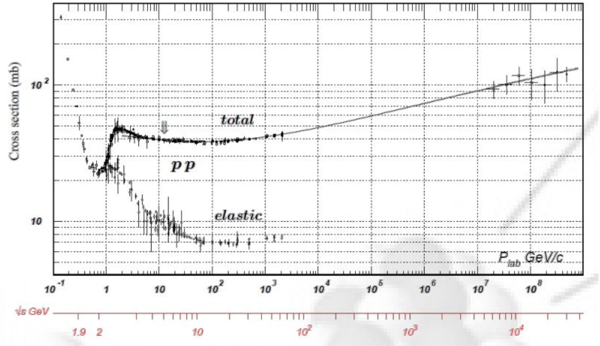
Tracking

- Momentum resolution scales as
- Keeping same target tracking resolu $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$ p = 100 TeV , require:
    - Single point resolution \ 10
        - 2-3 μm , seems feasible (MAPS - modulo radiation hardness …)
    - B x 10
        - 20-40 T magnet very challenging and costly
            - would imply loss of too many low momentum tracks
    - L x 3 , always feasible module cost

        - Detector cost ~ $L^{2\text{-}3}$

    - B = 5T, sigma x = 3x , L = 1.5 m
        - similar performance as FCC-hh

- Nuclear interactions cross-section increases with energy
    - To keep tracking efficiency at same, need lighter tracker
        - Else 20% worse inefficency (1% → 1.2%)
          → acceptable
- Exercise: At which energy hadron nuclear interaction becomes more important than Bremstrahlung?



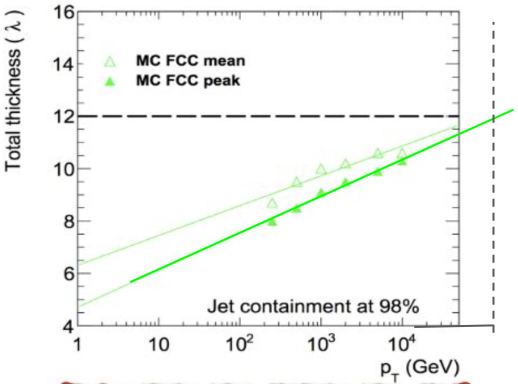
Calorimetry

- Energy resolution scales as $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

- At high energy, resolution becomes better, provided shower can be fully contained
  - hence keeping constant term small
  - Shower max (and containment) grow logarithmically with energy
- Merely a 20% increase in detector size → 12-13 lambdas
  - Or heavier absorbers Pb → W
  - R solenoid outside if cost is too large à la ATLAS

$$L_{95}(E) \approx \lambda_I \left[A + B \ln(E/\mathrm{GeV})\right]$$

100 GeV	$\sim 7\,\lambda_I$
1 TeV	$\sim 8.5\,\lambda_I$
10 TeV	$\sim 10\,\lambda_I$
100 TeV	$\sim 11.5\,\lambda_I$



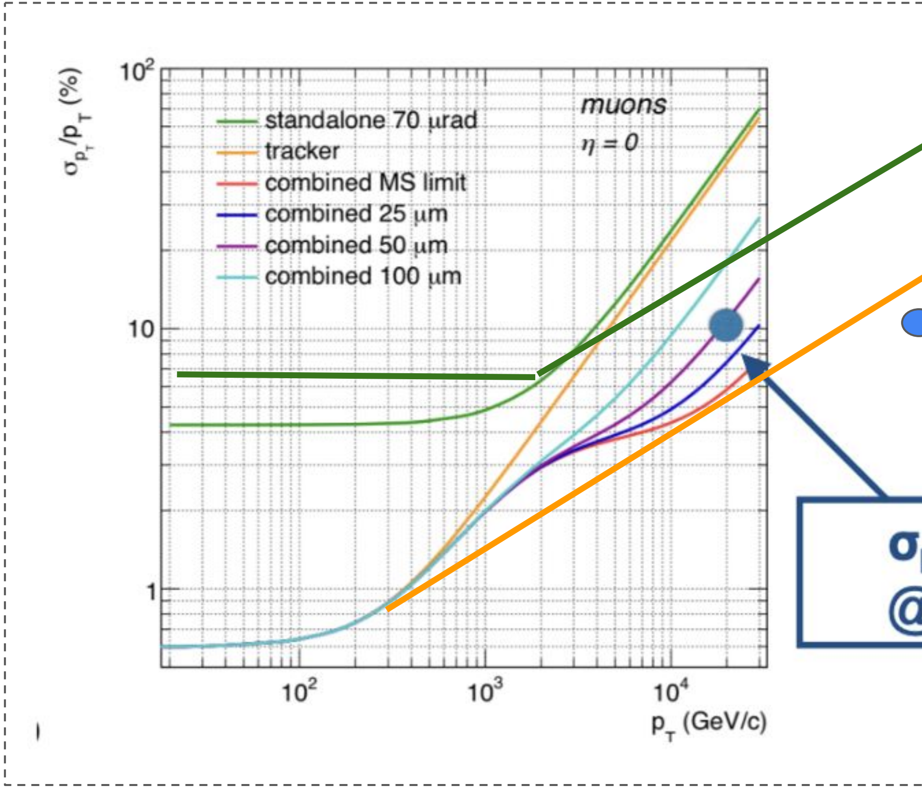
Muons

- Assume standalone muon momentum measurement performed via angle of incidence
- With 50% larger tracker, 20% larger calo
  - Angle proportional to ∫Bdl → x1.5
  - Multiple scattering → / sqrt(1.5)

- Muon brehmstrahlung in calorimeter

  - dE/dX ~ E/X_0
    - Constant fraction of energy loss
    - 100 TeV muon
      → 20 GeV energy loss

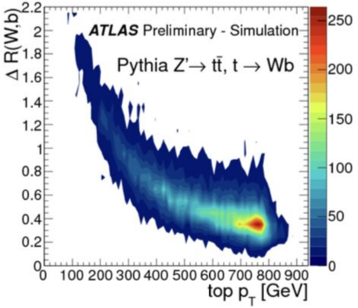
- No impact on momentum measurement



Boosted topologies at PeV energies

min. distance to resolve two partons

$$\Delta R \approx 2\, m / p_T$$

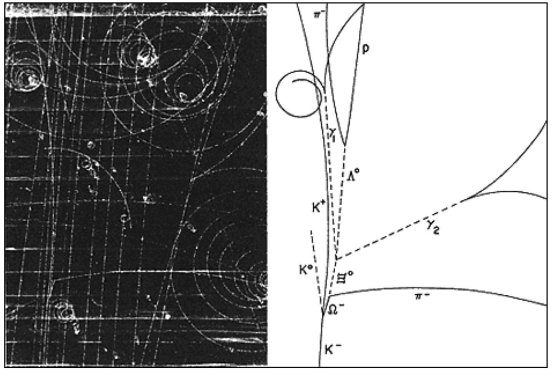


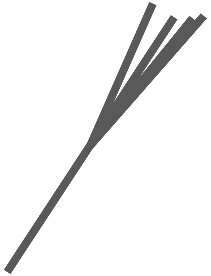
- 100 TeV W/H boson: decay products all contained within
  - R = 0.005
    - W ~ tau
    - H ~ pi0
- At 100 PeV whole jet core within 1/10 calo cell
  - fixed moliere radius, neutrals are un-resolvable
    - B field “helps” with charged
  - PF reconstruction will be severely affected
    - Total jet energy OK, calo does good job
    - reed to be studied and rethought for
- Naive approach:
  - use calo for energy measurement
  - tracking for substructure identification
    - 2,3 prongs should still be resolvable with tracking with 10^{-3} angular separation

Flavor Tagging and Exotic Topologies

50 TeV B/D/tau hadrons

- B: 5m lifetime
  - ~ K_L , charged pion
- D/tau: 1.5m lifetime
  - ~ K_L , charged pion , K_S or Sigmas …
    - Secondary vertex might be resolvable
    - BUT maybe not decay products
      - Kinked tracks
      - Track “jet” ~ nuclear interaction





Weak Showers

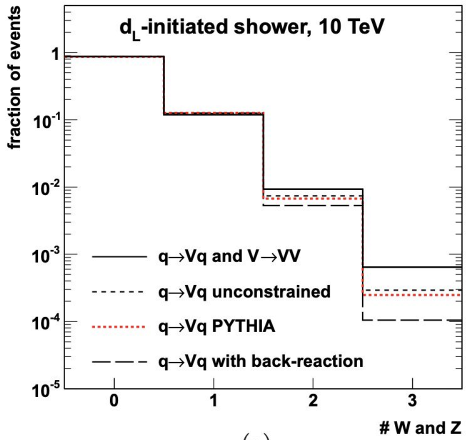
At multi- 100 TeV energies electro-weak showers become important

- Quarks radiate W, Z, H
  - e.g q → qW could become a problem for top ID
  - enrich lepton content in jets
    - problem for b-jet identification?
      - Not displaced (unless taus), so probably not much a pb..

- Neutrinos shower W and Z
  - In turns produce jets and leptons and taus
  - may become visible
    - Improve neutrino direction determination

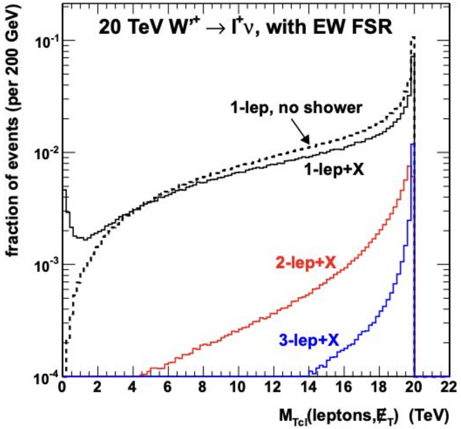
- Photons “convert” in the vacuum to W+W- pairs

…



(a)

Chen, Han, Tweedie



Conclusion

- High energy proton colliders are very “inclusive” facilities for physics
  - probes many different initial states, both for both EWK, colored particles
  - measurements at threshold and beyond thanks to large rates, high mass exploration

- Key physics benchmarks channels studied set the requirements for detector design
  - physics reach
  - detector design and technologies, R&D
  - optimisation of the machine layout
  - reconstruction , object identification, PU removal
  - software, AI …

- FCC-hh is an order of magnitude more complex than HL-LHC
  - main challenges identified, most likely will be overcomed given timescale
    - radiation hardness, amount of data real challenge
    - it will be the next generation hadron machine, **BUT** R&D should not stop after HL-LHC
      - synergetic with other proposed future facilities
- PeV collisions will present yet new challenges (collider related), but also new opportunities

Organisation

- General group: **fcc-ped-hh-espp25**

  → main group, general monthly meetings announcements

  Coordinators:
  Christophe Grojean (DESY/CERN), Michelangelo Mangano, Matthew McCullough, Michele Selvaggi (CERN)

- Physics analysis group: **fcc-ped-hh-physicsperformance-espp25**

  → physics analysis focussed monthly meetings (will be announced soon)

  Coordinators:
  Birgit Stapf (CERN), *Angela Taliercio (NorthWestern)*, Sara Williams *(Cambridge)*

Useful references

Physics at the FCC-hh CERN-2017-003-M

FCC-hh CDR CERN-ACC-2018-0058

FCC-hh Yellow Report (extended CDR) CERN-2022-002

Physics potential of a low-energy FCC-hh CERN-FCC-PHYS-2019-0001

Higgs Physics Potential of FCC-hh Standalone CERN-FCC-PHYS-2019-0002

FCC-hh Detector Requirements CERN Seminar

Backup

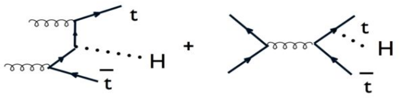
Top Yukawa , H→bb boosted

- production ratio **$\sigma(ttH)/\sigma(ttZ) \approx y_t^2\ y_b^2/\ g_{ttZ}^{\ 2}$**
- measure **$\sigma(ttH)/\sigma(ttZ)$** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

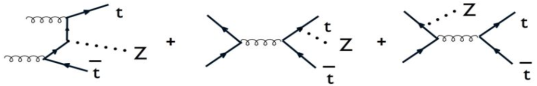
- assuming **g_{ttZ}** and **κ_b** known to 1% (from FCC-ee),

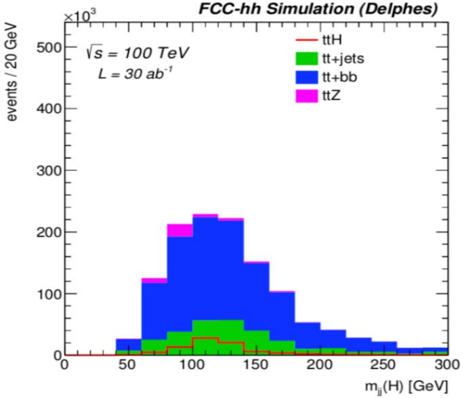
  → measure **y_t** to 1%

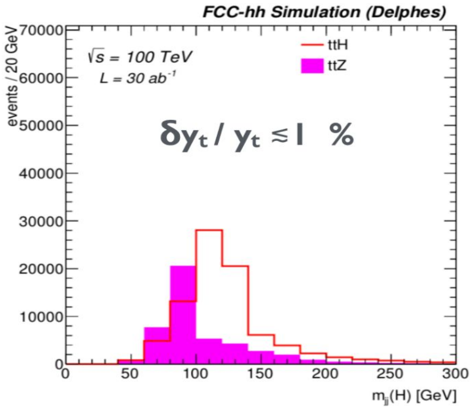
ttH



ttZ





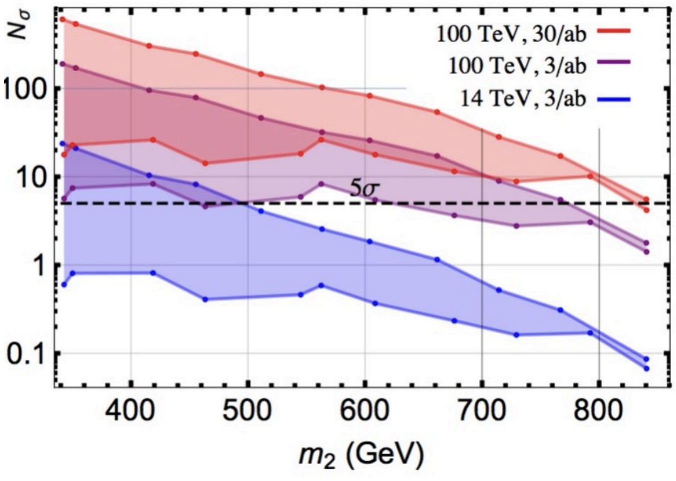


complement using Hττ

Direct search vs HH

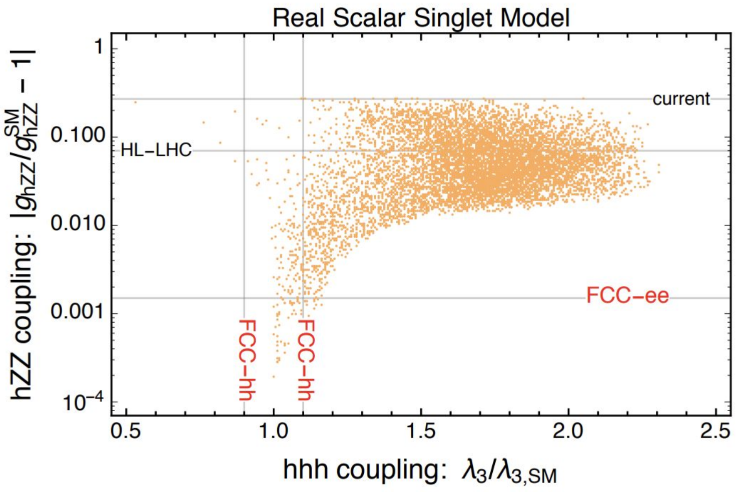
- **Strong 1st order EWPT** needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

New possible studies

- Exploring new ideas to reduce dependence on detector assumptions and systematics:
  - H→WW, bb, cc, $\boldsymbol{\tau\tau}$
  - use ratios/double ratios
    - focus on boosted regime/similar production modes
      - For rate, object, lumi (partial or total) cancellations
  - study tradeoff between boost (syst) and statistics

Single ratios:

- WH(γγ) / ZH(γγ) ~ $\kappa_{W,Z}$
- WH(γγ) / WZ(ee) ~ κ_W
- WH(bb,cc,$\boldsymbol{\tau\tau}$) / WZ(bb,cc,$\boldsymbol{\tau\tau}$) ~ κ_W
- ZH(bb,cc,$\boldsymbol{\tau\tau}$) / ZZ (bb,cc,$\boldsymbol{\tau\tau}$) ~ $\kappa_{b,c,\tau}$
- ttH(bb,$\boldsymbol{\tau\tau}$) / ttZ(bb,$\boldsymbol{\tau\tau}$) ~ κ_t

double-ratio:

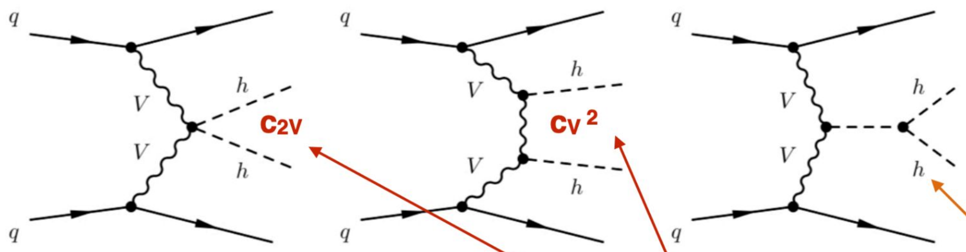
$$\frac{H(bb,cc,\tau\tau)/Z(bb,cc,\tau\tau)}{H(\mu\mu,\,4\ell)/Z(\mu\mu,\,4\ell)} \sim \kappa_{b,c,\tau} / \kappa_{\mu,Z}$$

in ggH, VH? $p_T(H)^{min}$?

exploit absolute model independent κ_Z , ttZ measurements from FCC-ee

HHVV coupling

Bishara, Contino, Rojo

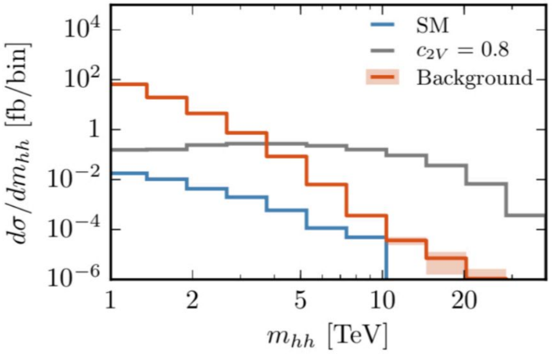


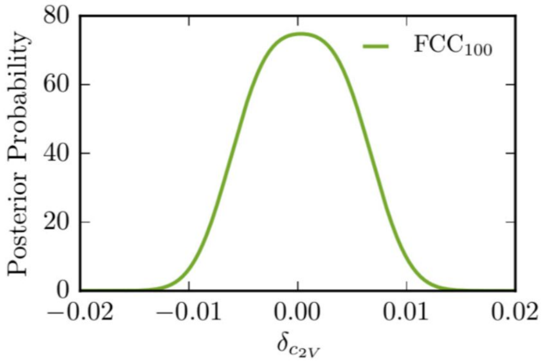
negligible at large m_{HH}

$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}),$$

0 in the SM

high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E





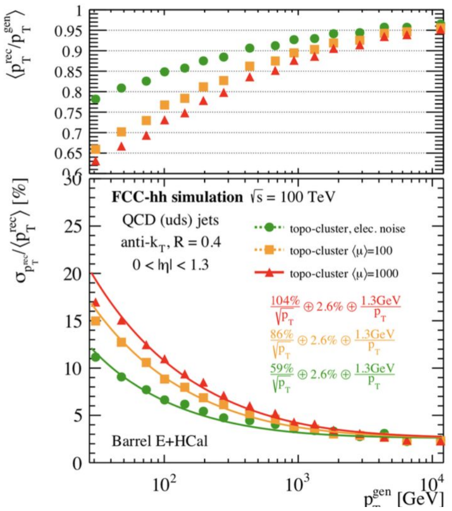
With c_V from FCC-ee, $\delta c_{2V} < 1\%$

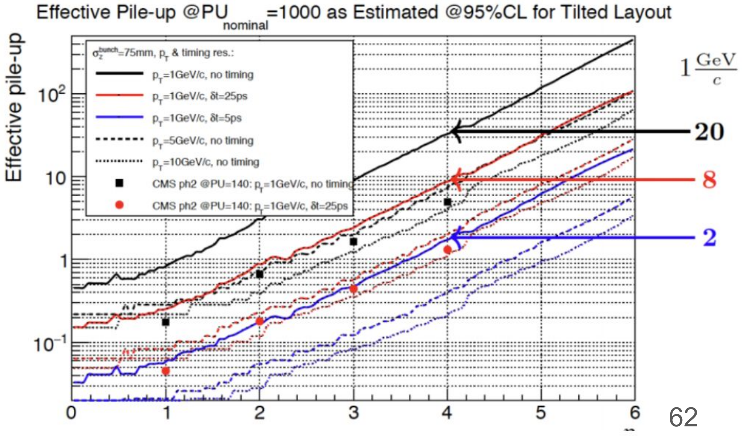
Experimental challenges for jets (at threshold)

- relative impact of PU is large on:
  - jet energy resolution and scale
  - HF-tagging (b/c-tagging)

- PU subtraction techniques
  - charged hadron subtraction
    - **timing information (5-10 ps resolution)**
      - **forward!**
  - Residual:
    - area-subtraction
    - PUPPI reconstruction
    - advanced graph based-ML

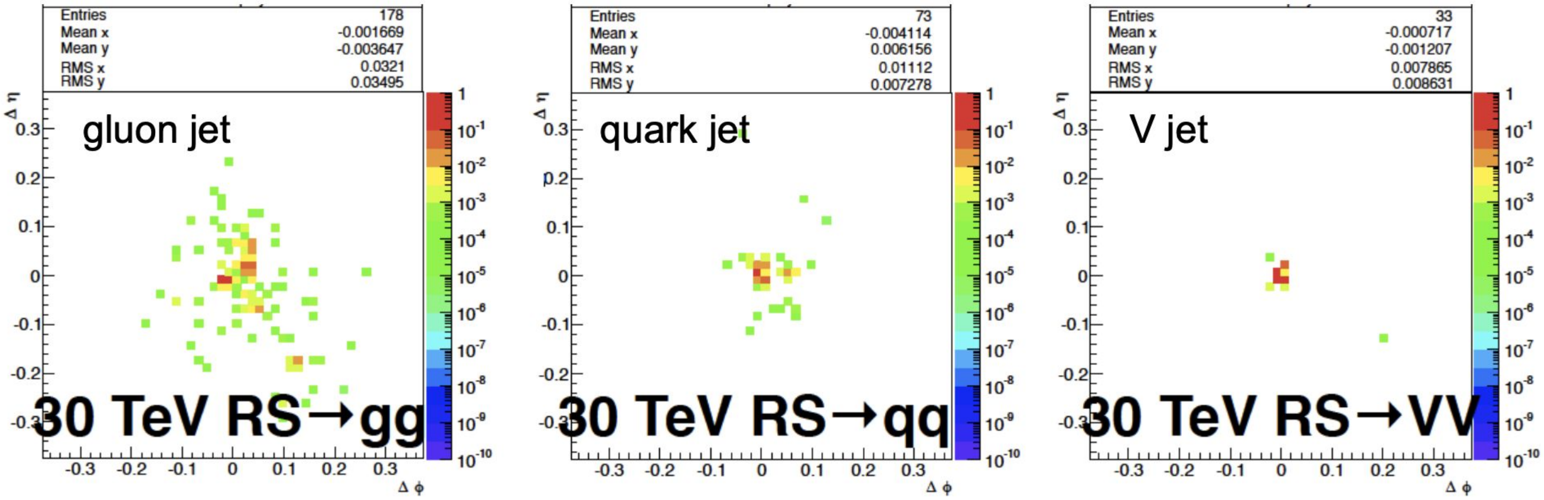
1912.09962





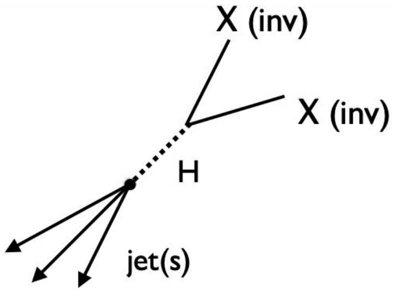
Color Singlets (W/Z/H)

[Pierini]

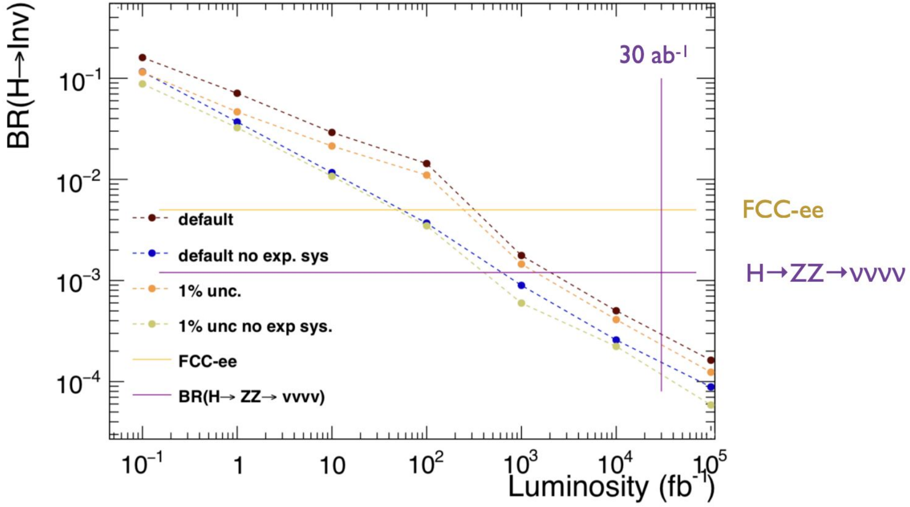


- **Gluon/quark** jet looks the same at 50 GeV and 5 TeV (**QCD is ~ scale invariant**)
- **Color Singlets** look like taus (do not radiate, a part from occasional QED/EWK shower)
    - **high mass, highly isolated, highly collimated tracks**

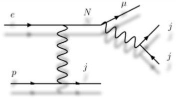
Higgs invisible

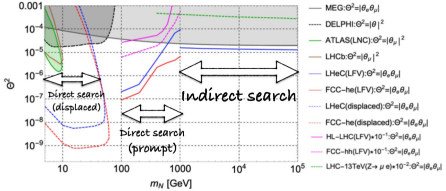


- Measure it from H + X at large p_T(H)
- Fit the E_T^{miss} spectrum
- Estimate Z→νν from Z→ee/μμ control regions
- Constrain background p_T spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z,W and γ spectra
- BR(H→inv) ≲ 2.5 10^{-4}



LHeC/FCC-eh (BSM)





Highest reach for Heavy Neutral lepton searches (HNLs):
- long-lived
- prompt

- Rich BSM physics programme for FCC-eh
  - Lepton-quarks
  - LFV processes
  - Anomalous couplings
  - Contact interactions ….