FCC-hh studies status and work ahead

Michele Selvaggi (CERN)

LNF 2024

Outline:

- Recap results for the CDR - 100 TeV
  - Benchmark studies and detector requirements
  - New projections - HH
- What is missing? Ideas for future studies
  - Physics ←→ Detectors/reconstruction
- How to get started?

New facilities goals

What we cannot deliver:

- explore all new physics directions/mass couplings scale
- guarantee discovery

What we can deliver:

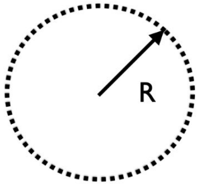
- precision
- sensitivity to new as many as possible scenarios of new physics
    - clear yes/no answers to concrete scenarios

High energy hadron machines

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

p [TeV/c] = 0.3 B [T] R [km]

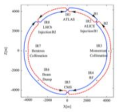


Cons:

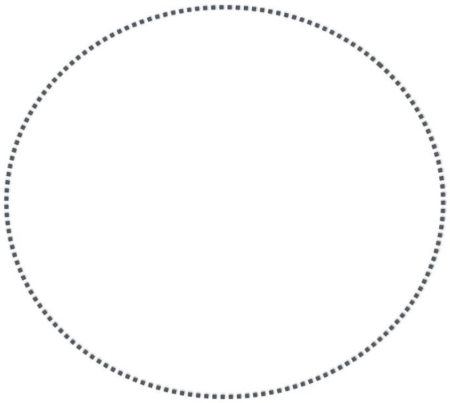
- large backgrounds compared to lepton machines ($\alpha_S > \alpha_{EM,W}$), from
    - high Q2 physics (di-jet, ttbar …)
    - “simultaneous” p-p collision (pile-up)

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

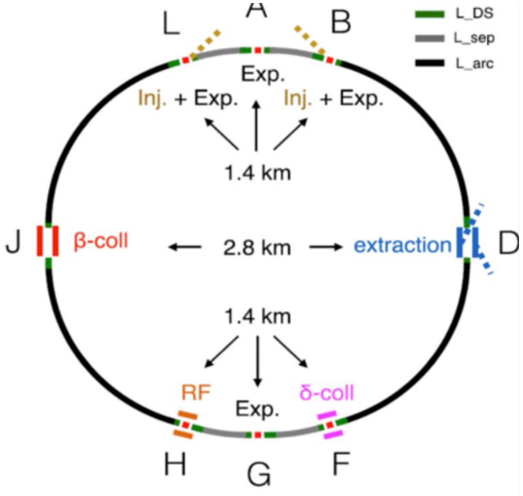
Variants



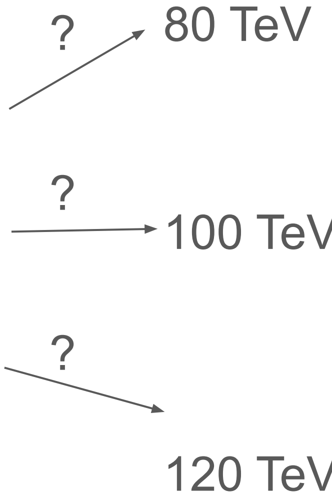
HE-LHC



LE-FCC



FCC-hh



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

More variants

name	F12LL	F12HL	F12PU	F14	F17	F20
√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 ~ $\sqrt{s}^{\,4}$

High energy hadron machines

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

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

dimensional analysis

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

$1/\tau^{a}$

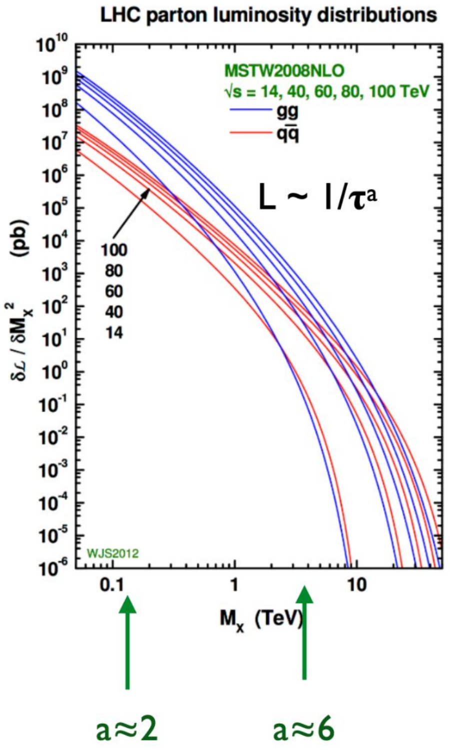
$\tau = x_1 x_2 = M^2 / s$

$1/M^2$

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:

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

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

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

≈ 1

assumes:

- large a
- large luminosity

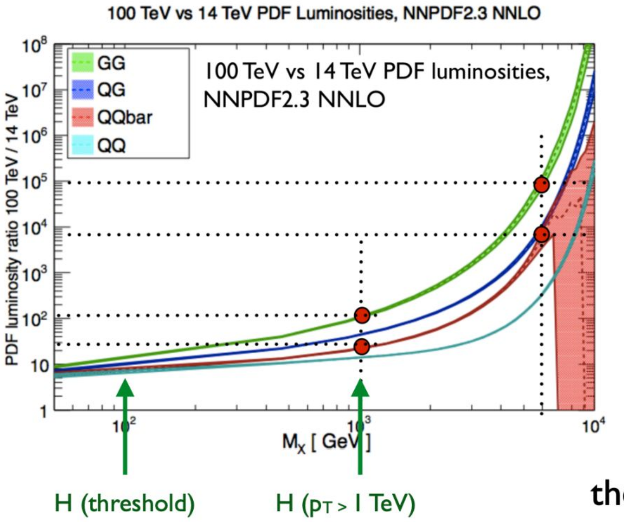
As expected, mass reach scales linearly with $\sqrt{s}$

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

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

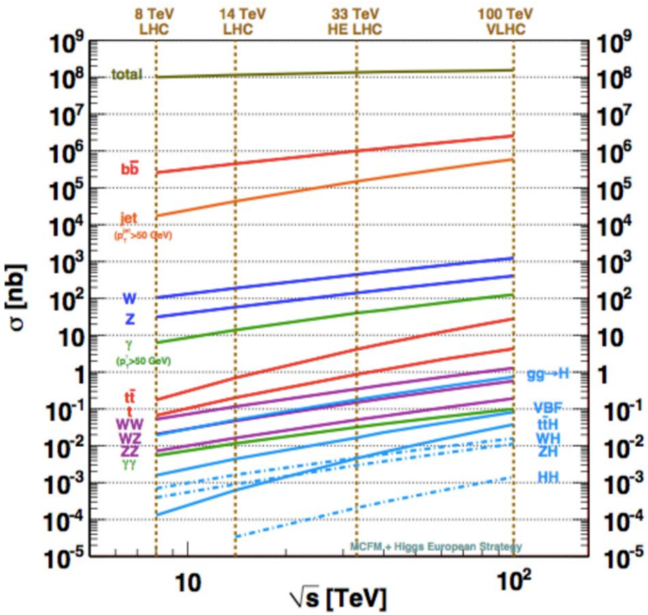


	σ(100)/σ(14)
ggH	15
HH	40
ttH	55
H (p_T > 1 TeV)	400

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

Hadron Machines specs and detector requirements

lumi & pile-up

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

→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

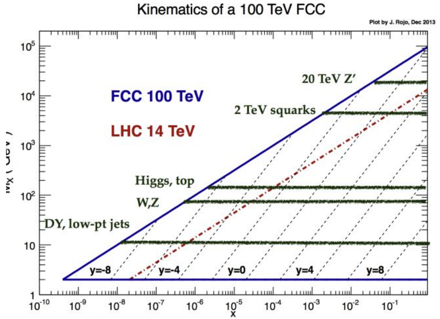
Physics at threshold

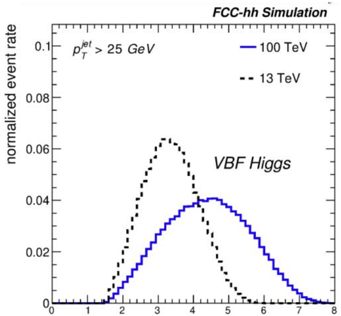
$$x_1 * x_2 * s = M^2$$

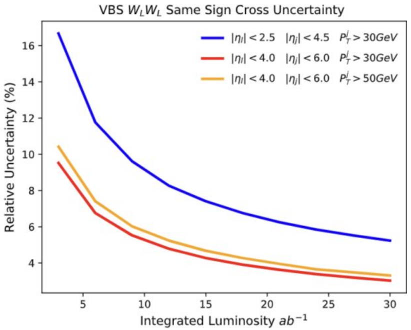
SM Physics is more forward @100TeV

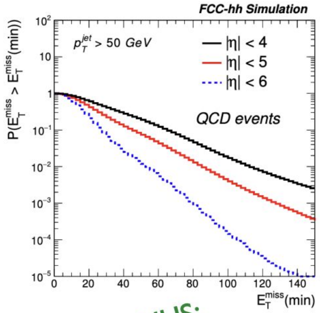
- If we want to maintain **high efficiency in states produced at threshold** need **large rapidity** (with tracking) and **low p_T** coverage

→ highly challenging levels of radiation at large rapidities









Tracking and calorimetry needed up to |η| < 6 for ~. VBF signatures

BONUS: Hermeticity E_T^{miss} resolution

Boosted topologies at multi-TeV energies

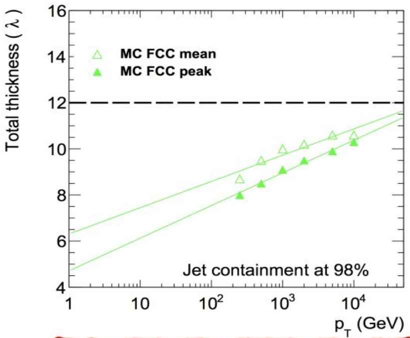
The boosted regime:

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

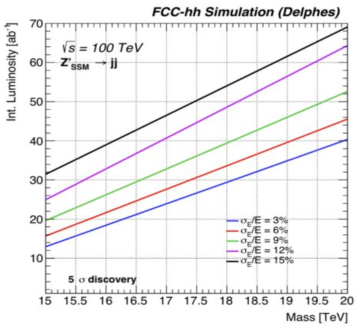
Tracking: $$\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$$

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

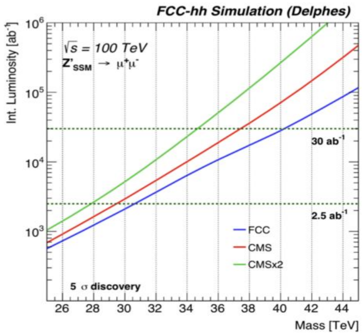
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets

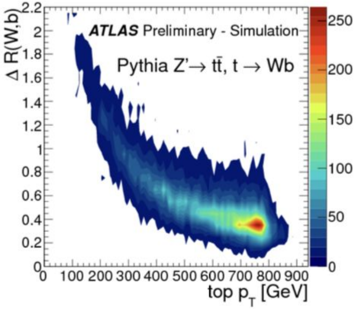


high p_T muons

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 → $\Delta R \sim 0.002$
ECAL → $\Delta R \sim 0.02$
HCAL → $\Delta R \sim 0.1$

High p_T flavor tagging

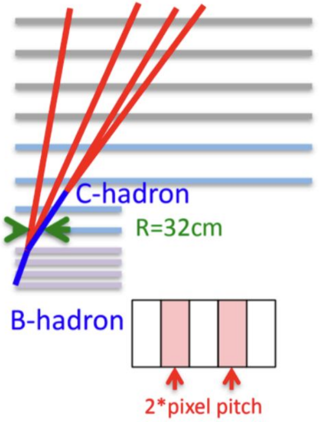
- **The boosted regime:**
  → measure b-jets, taus from multi-TeV resonances

- 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

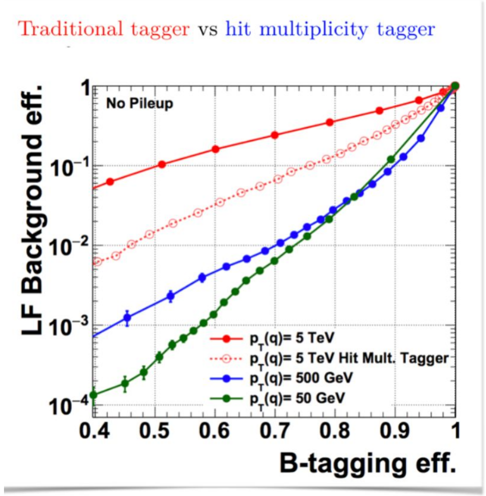
→ re-think reconstruction algorithms:
  - hard to reconstruct displaced vertices
  - **exploit hit multiplicity discontinuity**



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

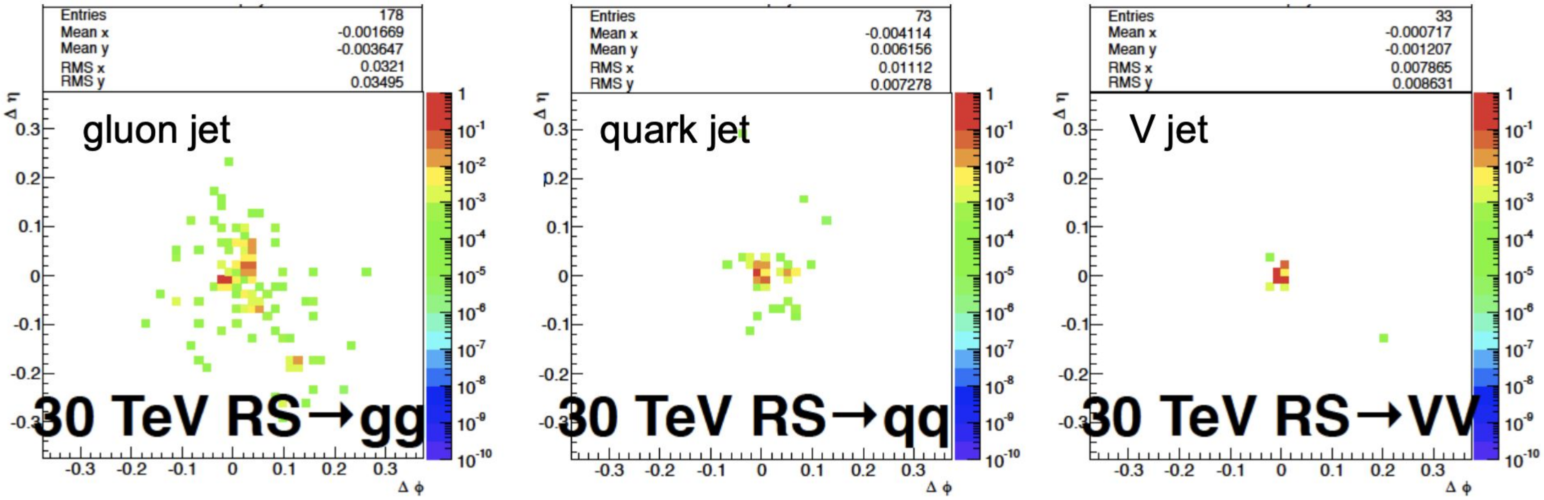
- displaced vertices

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



Color Singlets (W/Z/H)

[Pierini]

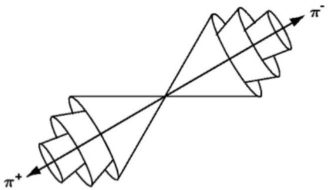


- **Gluon/quark** jet looks the same at 50 GeV and 5 TeV (**QCD is ~ scale invariant**)
- **Color Singlets** look like taus (do not radiate, a part from occasional QED/EWK shower)
  - **high mass, highly isolated, highly collimated tracks**

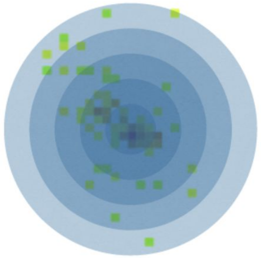
Boosted Color Singlet ID

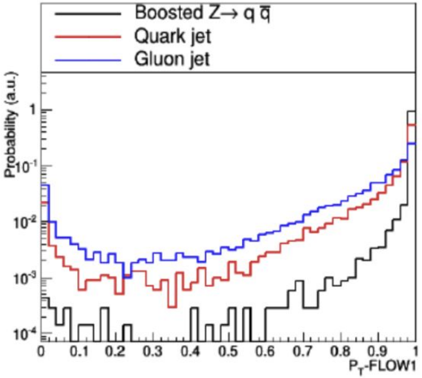
[Pierini]

~ isolation variable



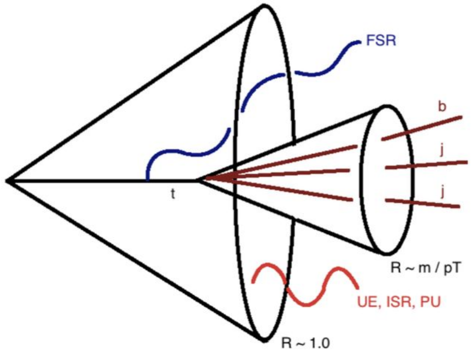
$$p_T^i(flow) = \frac{\sum\limits_{p \epsilon C_i} p_T^p}{p_T^{jet}}$$



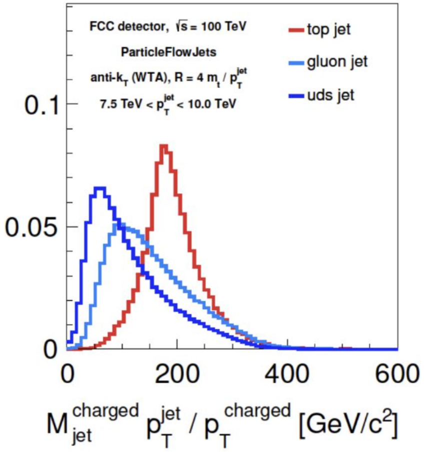


Loss in performance, but no show stoppers
Very simple heuristic based , can probably do much better with today's techniques

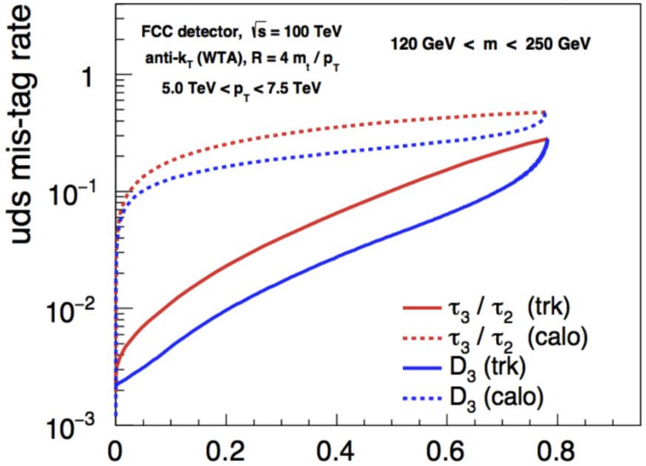
Boosted Colored Resonances



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

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

	HL-LHC	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–
$\delta g_{HHH} / g_{HHH}$ (%)	**50**	40
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**

Need to improve (rows $\delta g_{H\mu\mu}$ to δg_{HHH})

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:

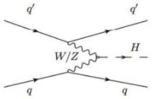
$$BR(H\rightarrow XX) / BR(H\rightarrow ZZ) \approx g_X^{\,2} / g_Z^{\,2}$$

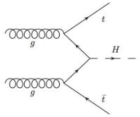
← from e^+e^-

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

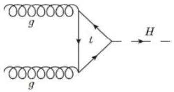
→ synergy between lepton and hadron colliders

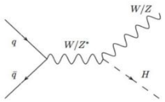
Higgs production in hadron machines





	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

$N_{100} = \sigma_{100\,TeV} \times 20\ ab^{-1}$
$N_{8} = \sigma_{8\,TeV} \times 20\ fb^{-1}$
$N_{14} = \sigma_{14\,TeV} \times 3\ ab^{-1}$

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

Factor: 1/100 1/10

reduction in stat. unc.

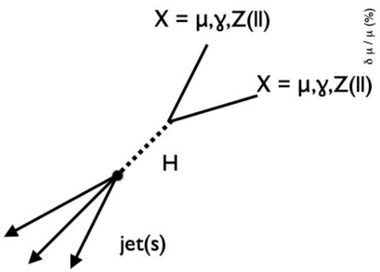
Large statistics will allow:

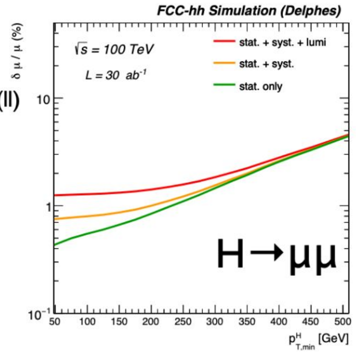
- for **% - level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

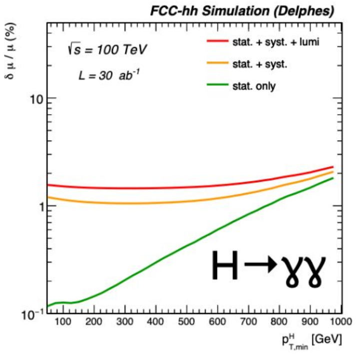
Higgs rare decays

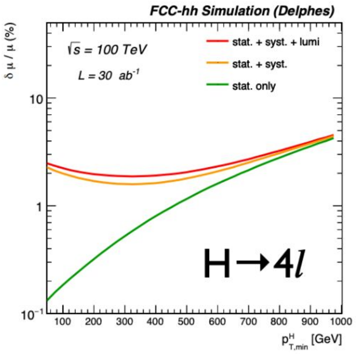
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \to \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \to \infty$

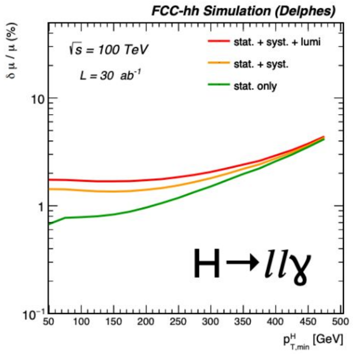
- study sensitivity as a function of **minimum p_T(H)** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** p_T(H): **large statistics** and **high syst**. unc.
- **large** p_T(H): **small statistics** and **small syst**. unc.
- **O(1-2%) precision on BR** achievable up to very high p_T (means 0.5-1% on the couplings)







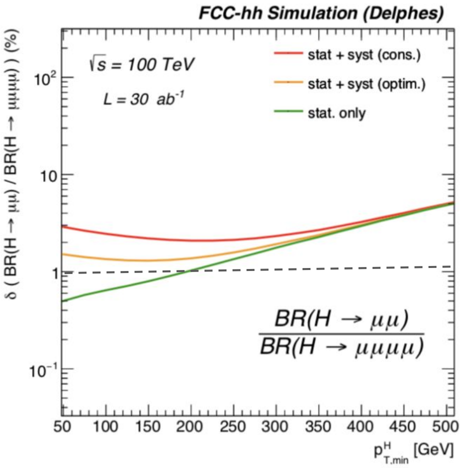


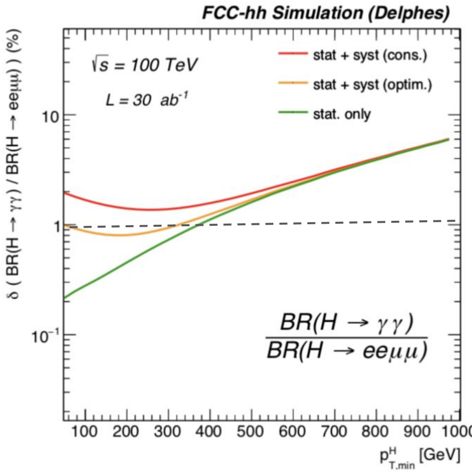


BR ($\mu\mu$,γγ,Zγ) / BR(H→ZZ)

- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)
- Becomes **absolute precision** measurement in particular if combined with **H→ZZ** measurement from e^+e^- (at 0.2%)

1% precision





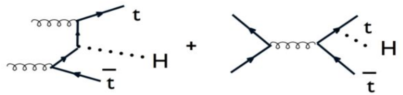
Top Yukawa , H→bb boosted

- 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

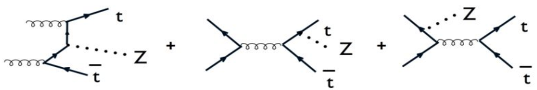
- assuming g_{ttZ} and κ_b known to 1% (from FCC-ee),

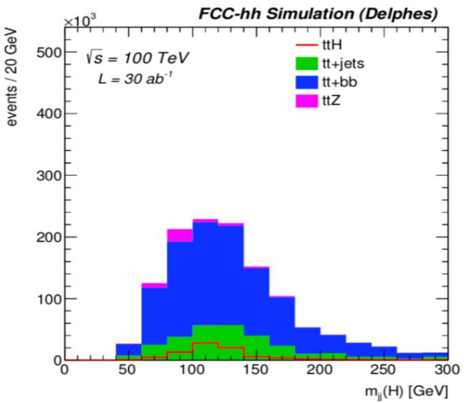
  → measure y_t to 1%

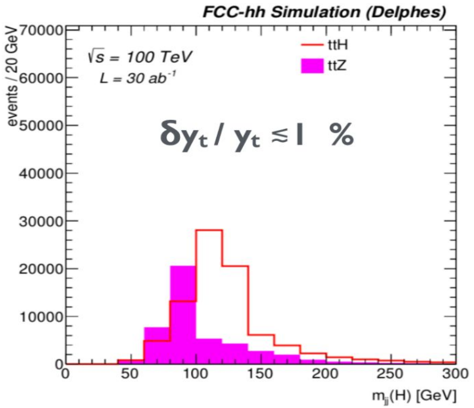
ttH



ttZ



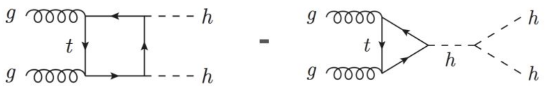




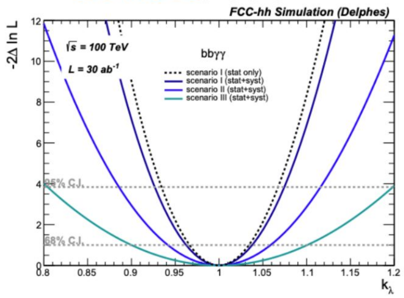
complement using Hττ

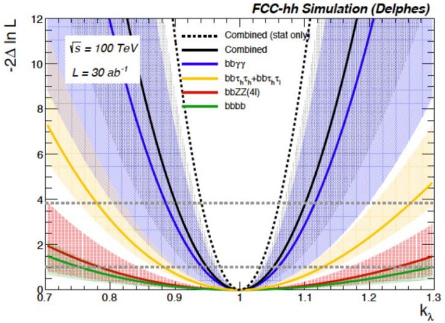
Higgs self-coupling

- σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
- x400 in event yields and x20 in precision



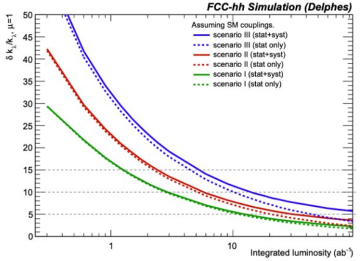
2004.03505 [hep-ph]



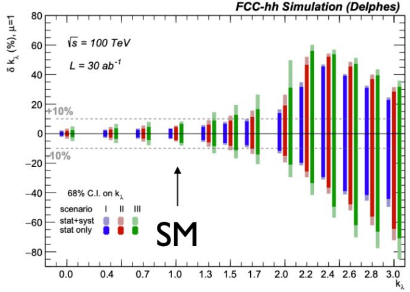


- Expected precision:

@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8

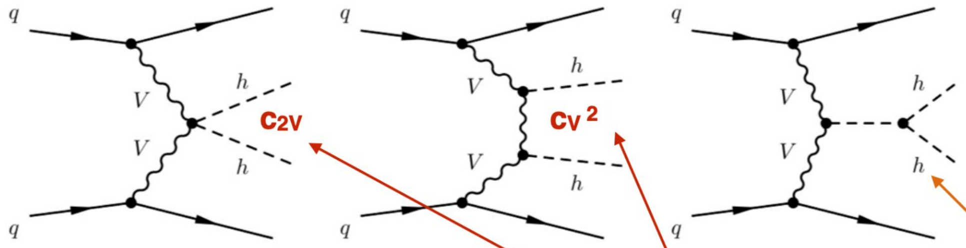


- Combined precision:
  - 3.5-8% for SM (3% stat. only)
  - 10-20% for $\lambda_3 = 1.5 * \lambda_3^{SM}$



HHVV coupling

Bishara, Contino, Rojo

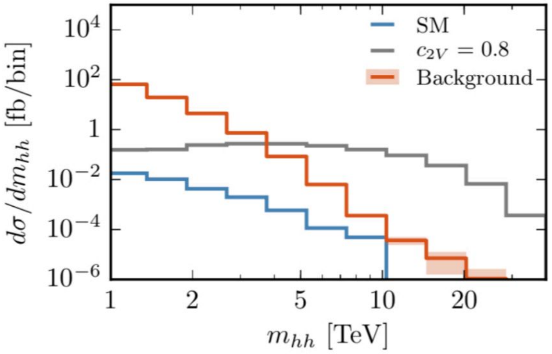


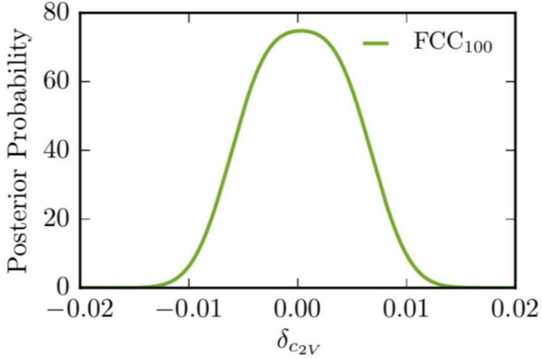
negligible at large m_{HH}

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

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, $\delta c_{2V} < 1\%$

Summary Higgs measurements

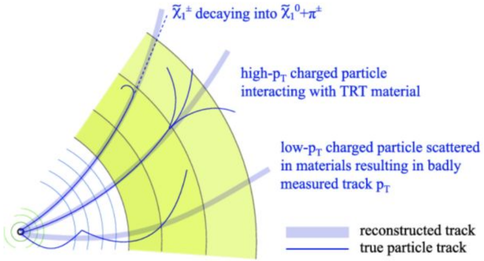
	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.91 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

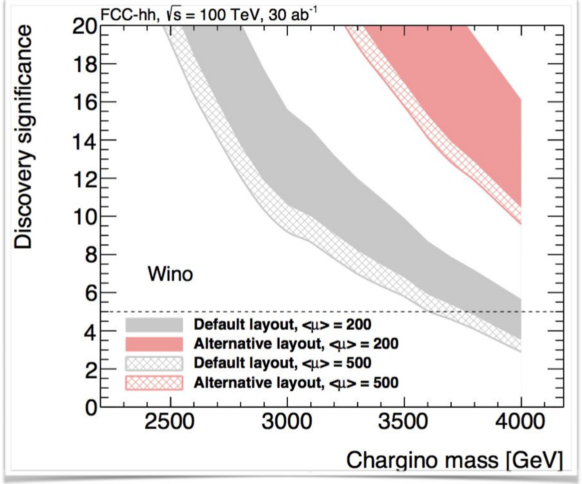
* From BR ratios wrt B(H→4l) @ FCC-ee

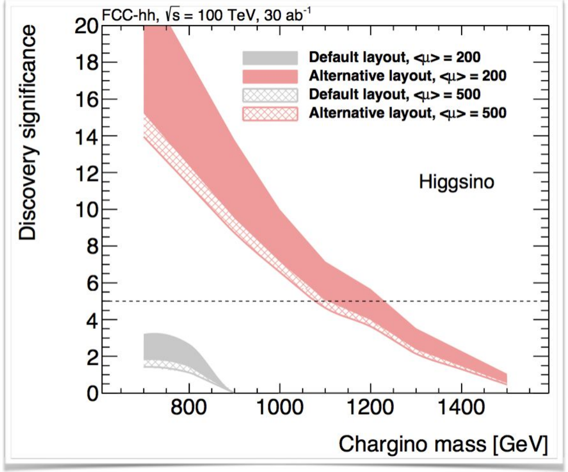
** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

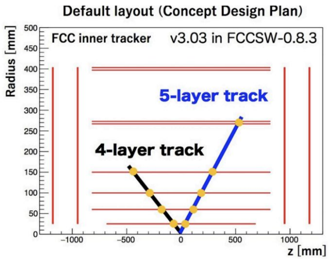
WIMP dark matter - disappearing track analysis

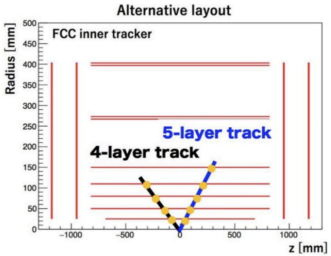
Nearly degenerate chargino-LSP









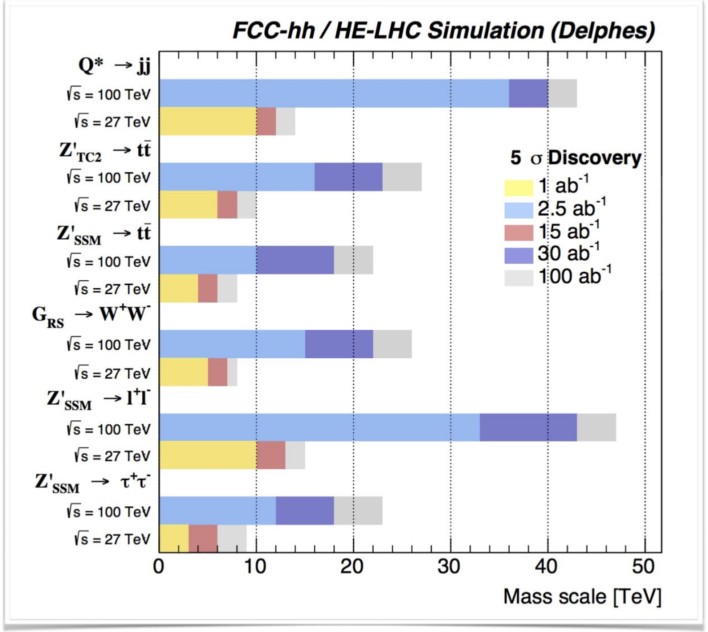


observed relic density

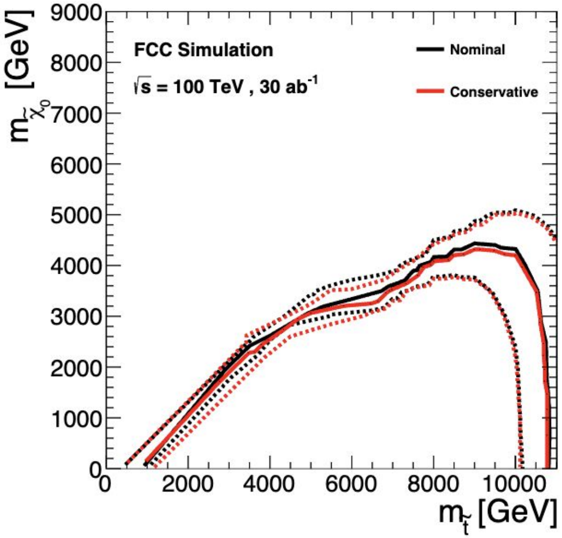
- M = 1 TeV Higgsino can be discovered
- M = 3 TeV Wino can be discovered

The energy frontier

High mass resonances



stops



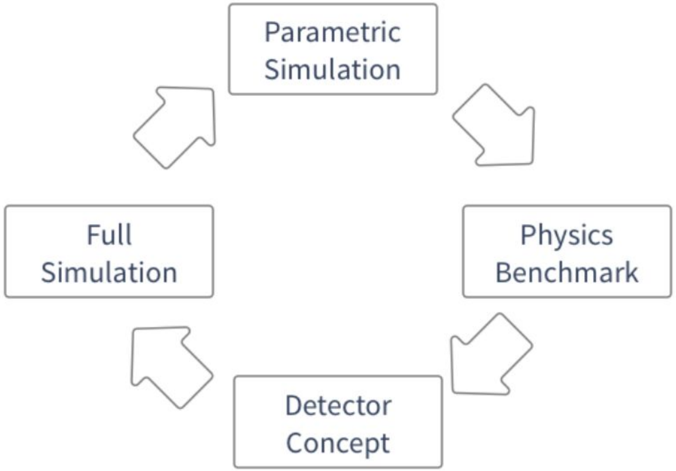
<u>Challenges:</u> multi-TeV collimated top, W, τ highly collimated.

Tracking is the key highly segmented calorimetry

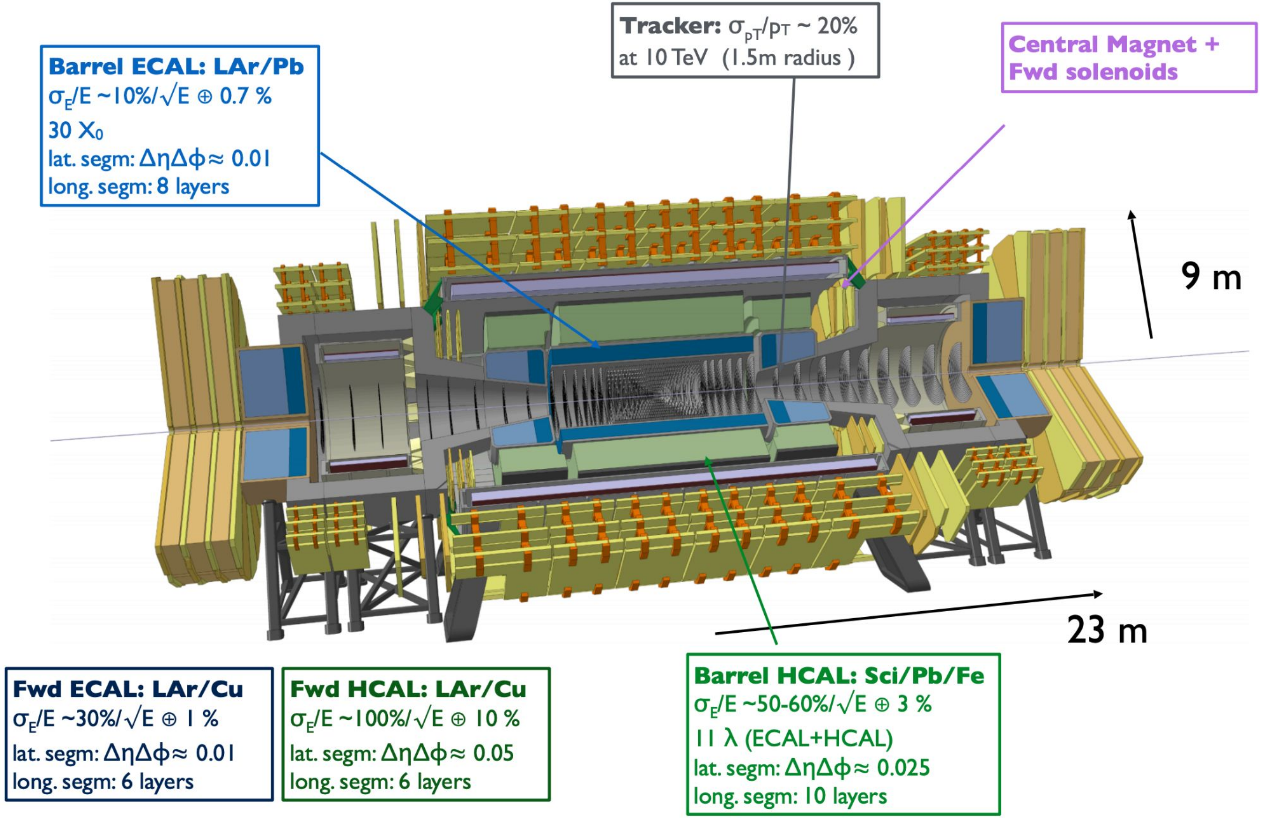
Work ahead

Recap, how we proceeded for the CDR

- Baseline detector concept in Delphes
- Physics benchmarks
  - Higgs and SM
  - BSM
- Refined detector requirements
- Implementation on detector concept in full simulation
  - Study performance in full sim
- Improve detector parameterisation in Delphes
  …



A detector concept that does the job …



More variants

name	F12LL	F12HL	F12PU	F14	F17	F20
√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 ~ $\sqrt{s}^{\,4}$

Wishlist

- Using the various benchmarks, explore impact of different:
  - c.o.m. energies 80-100-120 TeV
  - luminosities
    - and corresponding trade-offs and detector design implications
      - 80 TeV with 2x nominal luminosity or
      - 120 TeV with 0.5x nominal luminosity ?
    - beyond σ vs. $\mathscr{L}$ considerations (500PU vs 3000PU !!)

- Review physics benchmarks and corresponding objects most affected by machine conditions in view of recent LHC experience
  - HH, ttH, VBS
    - identification: b/τ-tagging, forward jet tagging, photon fake-rate
    - resolution: m_{bb}, $m_{\tau\tau}$, $m_{\gamma\gamma}$, E_T^{miss}
    - triggering
  - High p_T:
    - τ, W, H substructure vs extreme PU/collimation

Wishlist/open questions

- Explore novel calibration/reconstruction/pu subtraction techniques
  - identify clean control samples with large stats to calibrate critical objects and reduce systematics (e.g. ɣ-id with Z→ μμɣ samples) for robustness
  - jet flavor tagging in extreme pile-up, impact of tracking geometry
  - 5D Particle-Flow reconstruction and PU subtraction (p,E,t)
    - conventional/AI based

- Explore new detector designs/ technologies, e.g:
  - ambitious technologies (LXe/LYSO calorimetry, MAPs, quantum sensors, ..)
    - for some far from rad. hardness/cost requirements
      - but R&D should be pursued with such goals in mind
  - new designs:
    - low PU detectors targeting low p_T physics
    - ATLAS without Toroid, muon det. simply to tag
      - enough selectivity with track triggering at L1?

Wishlist (single H)

- Add “missing” physics channels, exploring new ideas to reduce dependence on detector assumptions and systematics:
  - $H \to WW$, bb, cc, $\tau\tau$
  - 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:

- $WH(\gamma\gamma) / ZH(\gamma\gamma) \sim \kappa_{W,Z}$
- $WH(\gamma\gamma) / WZ(ee) \sim \kappa_W$
- $WH(bb,cc,\tau\tau) / WZ(bb,cc,\tau\tau) \sim \kappa_W$
- $ZH(bb,cc,\tau\tau) / ZZ(bb,cc,\tau\tau) \sim \kappa_{b,c,\tau}$
- $ttH(bb,\tau\tau) / ttZ(bb,\tau\tau) \sim \kappa_t$

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

Wishlist (HH)

- Self-coupling HH
  - Focus on most sensitive channels bbγγ, bb$\tau\tau$
    - κ_λ sensitivity vs c.o.m / luminosity / detector assumptions (being covered)
    - (κ_λ , κ_t) scan with/without input from ttH/ttZ
    - (κ_V , κ_{2V}) sensitivity from VBF - HH (4b) ?
  - production mode dependent categorisation
  - boosted regime to be revisited (bbbb, bb$\tau\tau$)
  - bbZZ, bbWW
  - γγ$\tau\tau$, .. ? unexplored

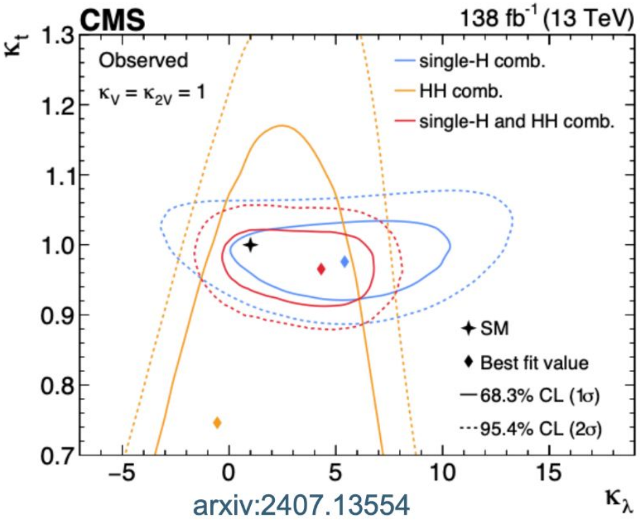
Plenty of space to contribute …

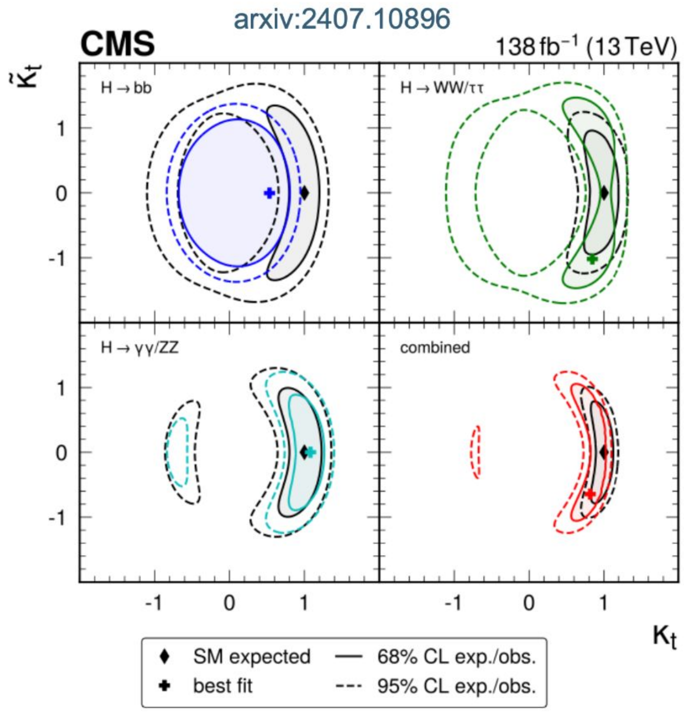
Wishlist (HH)

Daina Leyva (DESY), Aliya Nigamova (UHH)

FUTURE CIRCULAR COLLIDER

- The objective: improve constraints from in κ_λ - κ_t plain with single Higgs channels

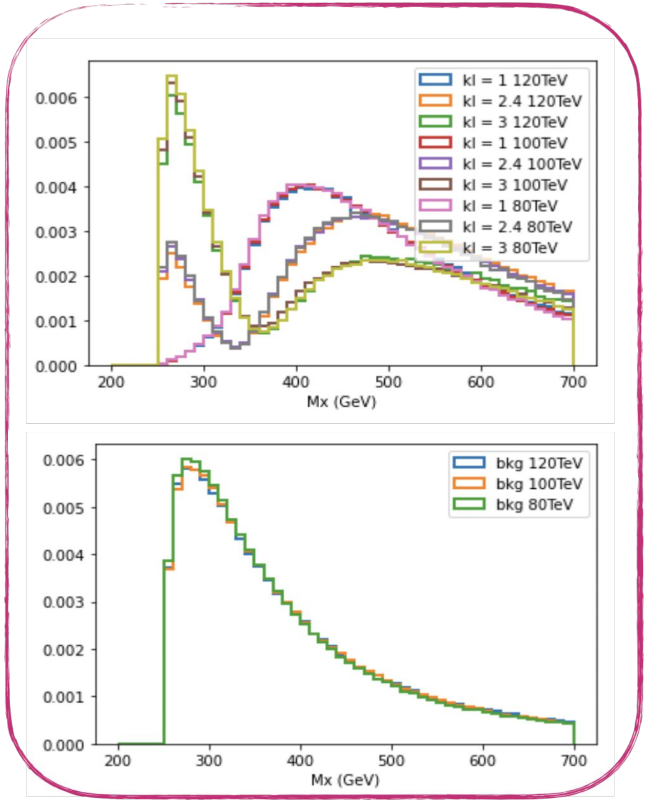


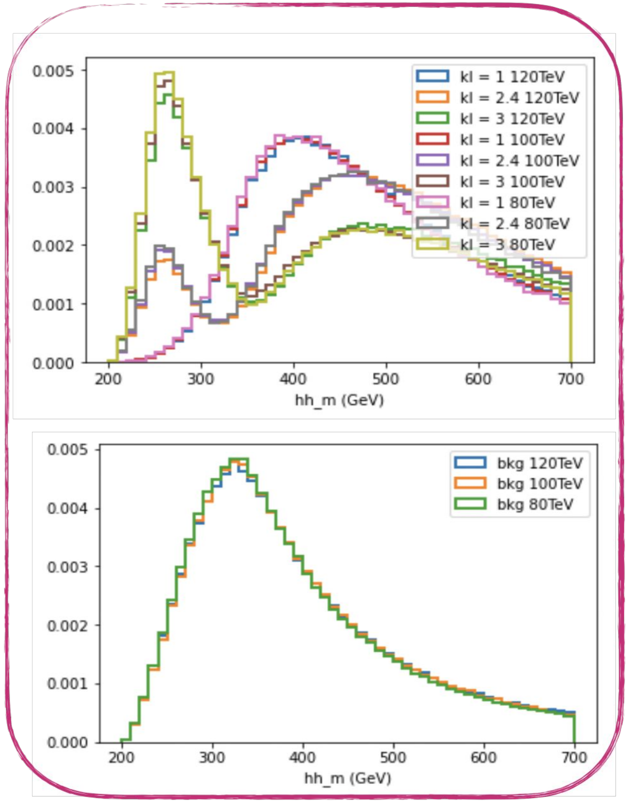


- The best channel: ttH, with $H \rightarrow \gamma\gamma$ decay

Maybe taking advantage of ttH(γγ)/ttZ(ee) for cancelling correlated systematics

$HH \rightarrow \bar{b}b\gamma\gamma$ analysis: center of mass energy scan



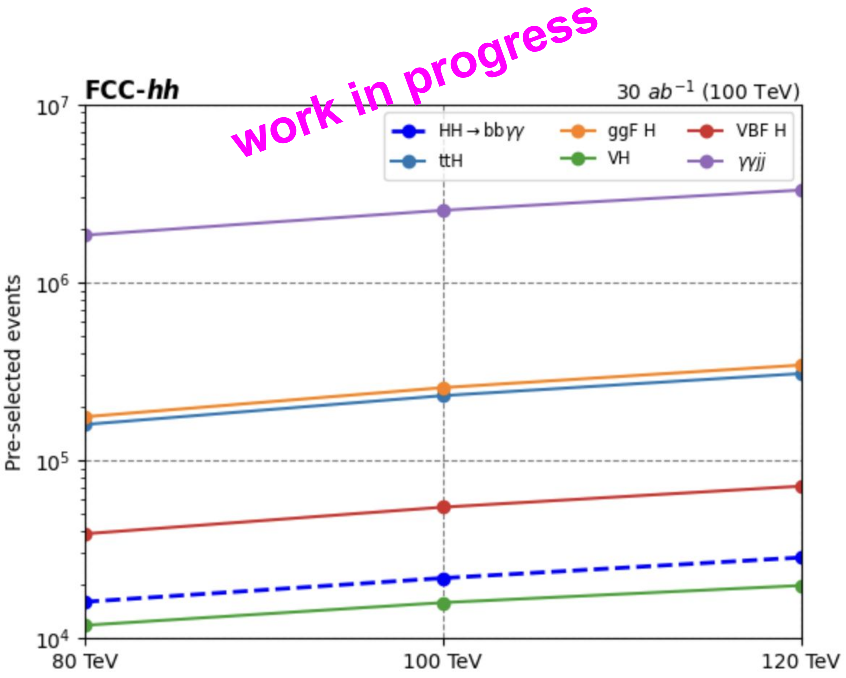


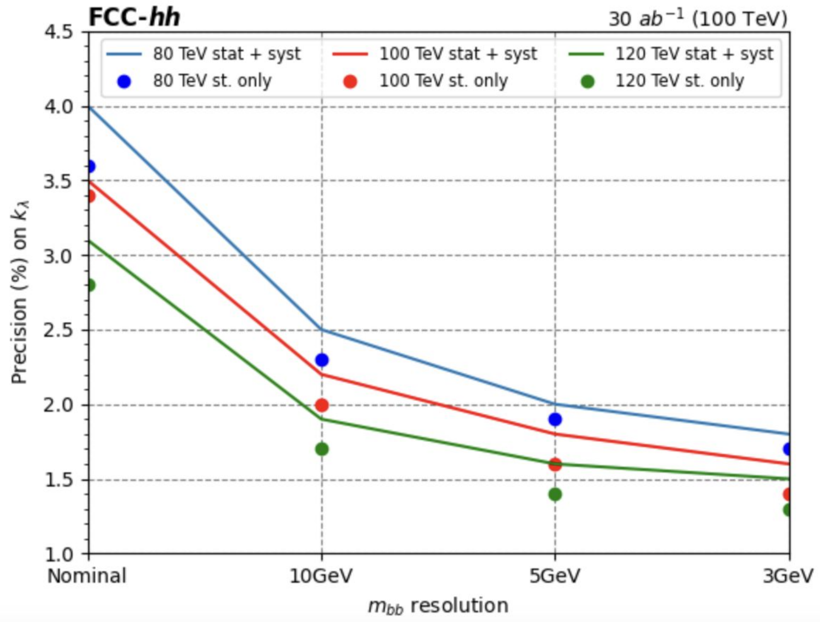
We produced samples for the 80,100,120 TeV scenarios as well

Mastrapasqua, Taliercio, Stapf

Recent highlights: HH → bbγγ

Mastrapasqua, Taliercio, Stapf

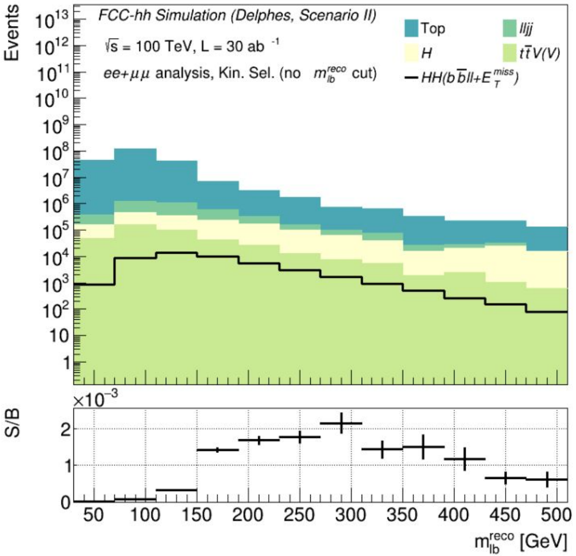




$80 < m_{bb} < 200$ GeV
$100 < m_{\gamma\gamma} < 180$ GeV

Recent highlights: HH → bbWW, bbττ

Stapf, Gallo, Tackman



Case	$\delta\kappa_\lambda$ (68% CL)
Scen I, stat. only	22.4%
Scen II, stat. only	25.8%
Scen II, syst. 1	30.7 %
Scen II, syst. 2	36.1 %
Scen II, syst. 3	42.7 %

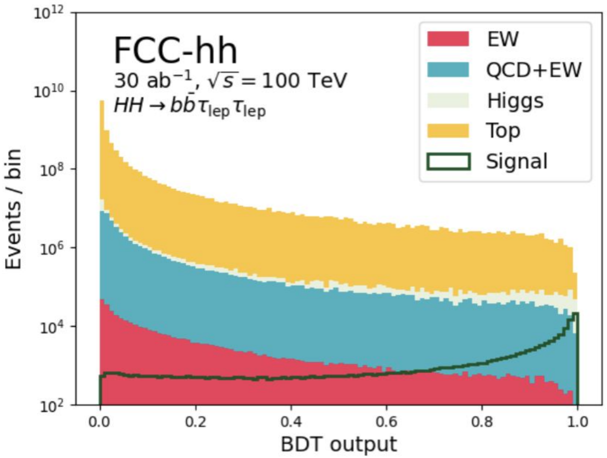
work in progress

Improved precision w.r.t to previous studies

To do:

- e.c.m /lumi/syst. variations
- combination with bbγγ

Sam Valentine, Cristiano Sebastiani, Jordy Degens, Monica D'Onofrio, Carl Gwilliam

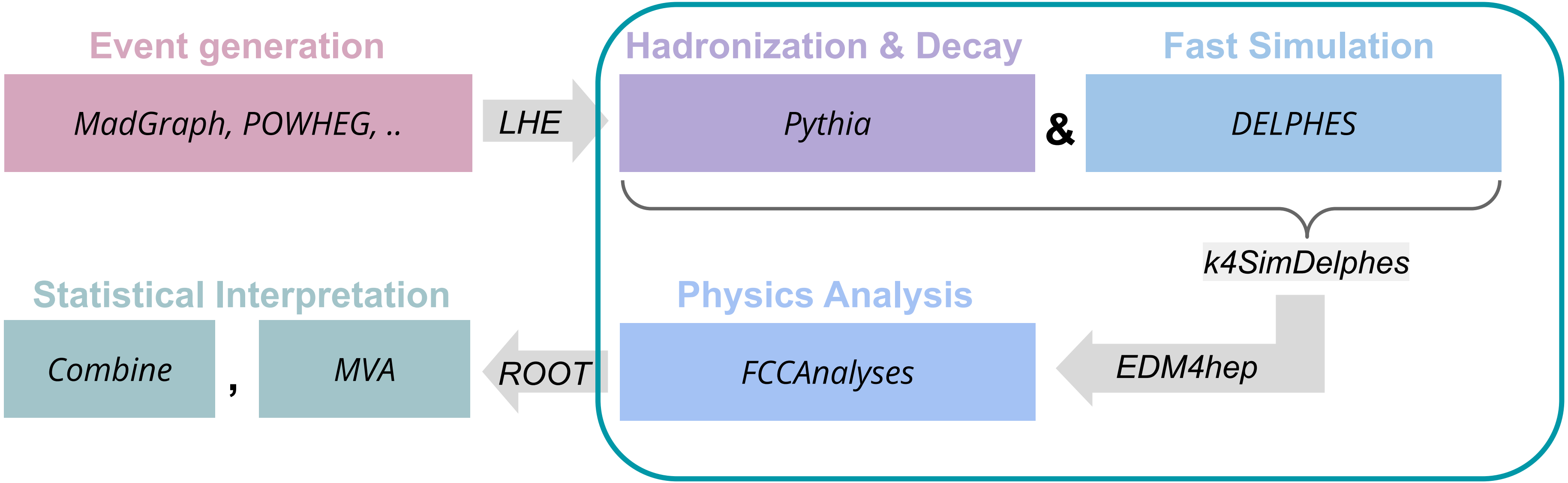


	HH+jet study	WIP study
	Yield [fb^{-1}]	
Signal	0.14	1.22
Background	0.96	38.94
	$S/\sqrt{B}$	
$\tau_\ell\tau_h$	24.97	32.32

$b\bar{b}\tau_\ell\tau_h$ comparison

In practice

Overview of technical workflow



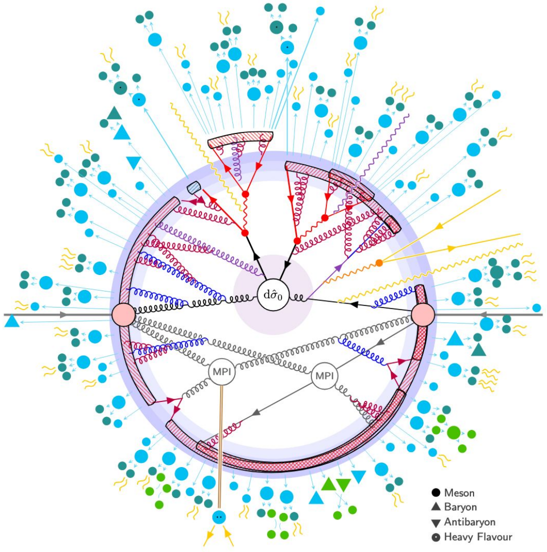
Rely on the key4hep project

Same approach as for FCC-ee studies

- All information for FCC-hh physics & performance studies summarized on this page

Hadronization & fast simulation with k4SimDelphes

- The k4SimDelphes tool allows us to run Pythia8 and Delphes in one step (and converts to EDM4hep format)



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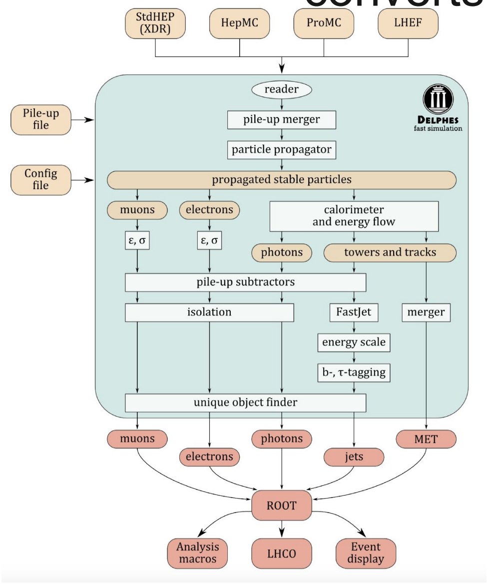
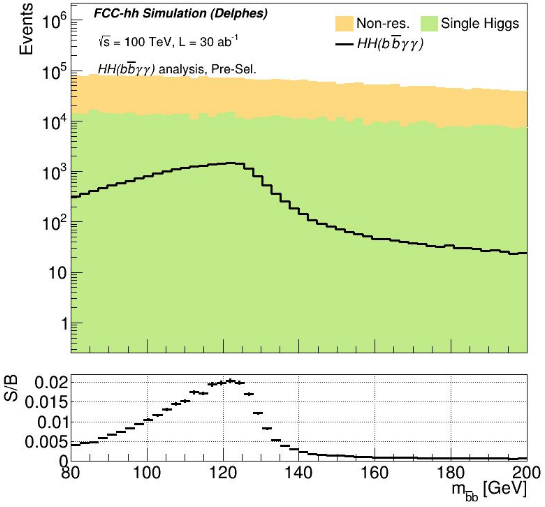


=



Event generation

- Typically use MadGraph and Powheg for FCC-hh studies with PDF sets from LHAPDF
  - Produced with common FCC framework: EventProducer
- Database

FCC | FCC-hh | Gen | Les Houches | About

FCC-hh | Gen | Les Houches Samples

Additional stats about the production can be found here.

Name: lambda100

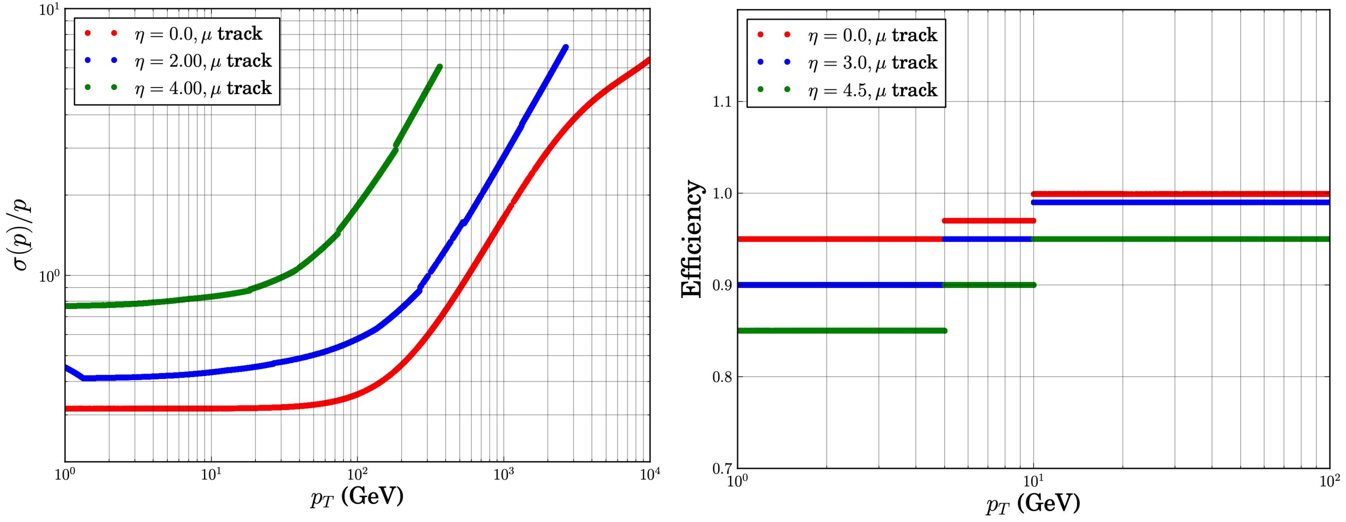
Expand table

No	Name	Nevents	Nfiles	Nbad	Neos	Size [GB]	Output Path	Main Process	Final States	Matching Param	Cross Section [pb]
128	mg_pp_hh_lambda100_5f	15,300,000	1530	0	1530	2.59	/eos/experiment/fcc/hh/generation/lhe//mg_pp_hh_lambda100_5f/	HH, H->bb, H undec., kl = 1.00			1.42752
142	mg_pp_hhj_lambda100_5f	8,750,000	875	0	875	1.25	/eos/experiment/fcc/hh/generation/lhe//mg_pp_hhj_lambda100_5f/	HH + 1 jet, pT(HH) > 200, kl = 1.00	inclusive		0.05644
315	mg_pp_tthh_lambda100_5f	1,000,000	100	0	100	0.17	/eos/experiment/fcc/hh/generation/lhe//mg_pp_tthh_lambda100_5f/	ttHH	inclusive		0.0595724055
375	mg_pp_vbfhh_lambda100_5f	1,000,000	100	0	100	0.17	/eos/experiment/fcc/hh/generation/lhe//mg_pp_vbfhh_lambda100_5f/	VBF HH (qq->jjHH)	inclusive		0.072176497
461	mg_pp_vhh_lambda100_5f	1,000,000	100	0	100	0.14	/eos/experiment/fcc/hh/generation/lhe//mg_pp_vhh_lambda100_5f/	VHH	inclusive		0.01159155
576	pw_pp_hh_lambda100_5f	10,329,977	1033	0	1033	1.64	/eos/experiment/fcc/hh/generation/lhe//pw_pp_hh_lambda100_5f/	gg->HH (NLO)	inclusive		1.13822

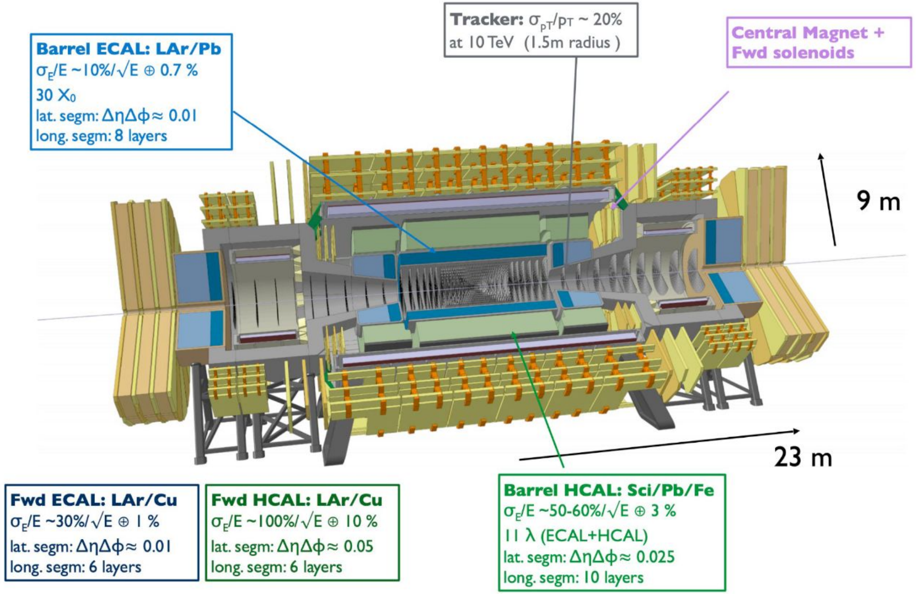
Hadronization & fast simulation with k4SimDelphes

- The k4SimDelphes tool allows us to run Pythia8 and Delphes in one step
- Two current Delphes scenarios for

Example parametrization for muons



Hadronization & fast simulation with k4SimDelphes

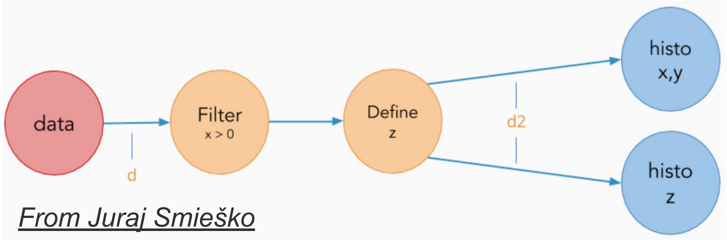


- The k4SimDelphes tool allows us to run Pythia8 and Delphes in one step
- Two current Delphes scenarios for FCC-hh:
  - Scenario I: Idealistic scenario for ultimate precision
  - Scenario II: Baseline scenario based on FCC-hh c

Note: Both scenarios implement fixes w.r.t the original, e.g. bremsstrahlung for electrons, multiple scattering, resolutions in forward region

	Relative p resolution		Efficiency	
	Scenario I	Scenario II	Scenario I	Scenario II
Electrons	0.4-1%	0.8-3%	76-95%	72-90%
Muons	0.5-3%	1-6%	90-99%	88-97%
Medium b-tagging			80-90%	76-86%

FCCAnalyses framework




```
# Mandatory: analyzers function to define the analysis graph, please make
# sure you return the dataframe, in this example it is dframe2
def analyzers(self, dframe):
    '''
    Analysis graph.
    '''

    dframe2 = (
        dframe

        .Define("weight",  "EventHeader.weight")

        ########################################### PHOTONS ###########################################

        .Define("gamma",  "FCCAnalyses::ReconstructedParticle::get(Photon_objIdx.index, ReconstructedParticles)")
        .Define("selpt_gamma", "FCCAnalyses::ReconstructedParticle::sel_pt(30.)(gamma)")
        .Define("sel_gamma_unsort", "FCCAnalyses::ReconstructedParticle::sel_eta(4)(selpt_gamma)")
        .Define("sel_gamma", "AnalysisFCChh::SortParticleCollection(sel_gamma_unsort)") #sort by pT

        .Define("ngamma",  "FCCAnalyses::ReconstructedParticle::get_n(sel_gamma)")
        .Define("g1_e",  "FCCAnalyses::ReconstructedParticle::get_e(sel_gamma)[0]")
        .Define("g1_pt",  "FCCAnalyses::ReconstructedParticle::get_pt(sel_gamma)[0]")
        .Define("g1_eta",  "FCCAnalyses::ReconstructedParticle::get_eta(sel_gamma)[0]")
        .Define("g1_phi",  "FCCAnalyses::ReconstructedParticle::get_phi(sel_gamma)[0]")
        .Define("g2_e",  "FCCAnalyses::ReconstructedParticle::get_e(sel_gamma)[1]")
        .Define("g2_pt",  "FCCAnalyses::ReconstructedParticle::get_pt(sel_gamma)[1]")
        .Define("g2_eta",  "FCCAnalyses::ReconstructedParticle::get_eta(sel_gamma)[1]")
        .Define("g2_phi",  "FCCAnalyses::ReconstructedParticle::get_phi(sel_gamma)[1]")
```

- FCCAnalyses is a common software framework to analyse EDM4hep events using ROOT’s RDataframe
  - Build an “analysis graph” with very simple syntax in python code
  - C++ libraries for the complex computations
  - Examples and tutorials available here
- Additions for FCC-hh analyses to come:
  - Using generator event weights, reading heavy flavour tagging from Delphes

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

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

Backup

High energy hadron machines

- **Ultimate discovery machine**
  - **directly** probe new physics up to **unprecendented** scale
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
      "weak" m(Z') ≈ 40TeV,
    - SUSY m(gluino) ≈ 15 TeV,
      m(stop). ≈ 10 TeV

x7 LHC ?

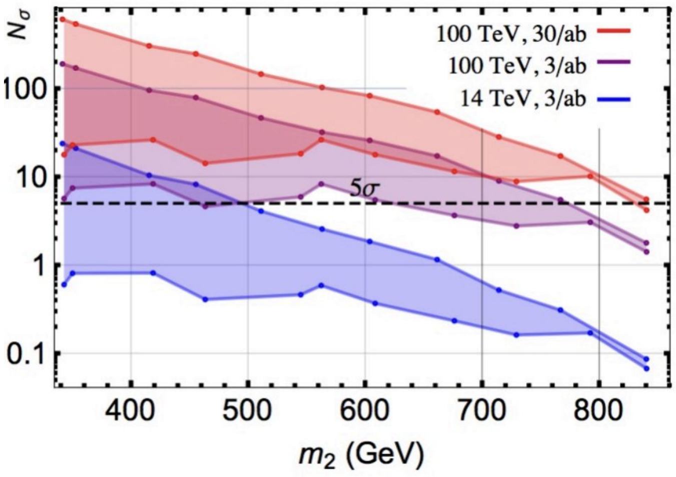
Wino/Higgsino Dark matter (1-3 TeV)

- **Precision machine (Higgs)**
  - probe Higgs **self-coupling** to few % level
  - %-level precision for 3rd generation (top yukawa)
    - and **2nd generation (μμ, cc)**
  - exploit **complementarity with e^+e^-** by probing **high dim.operators** (EFT) in **extreme kinematic** regimes (boosted)

Direct search vs HH

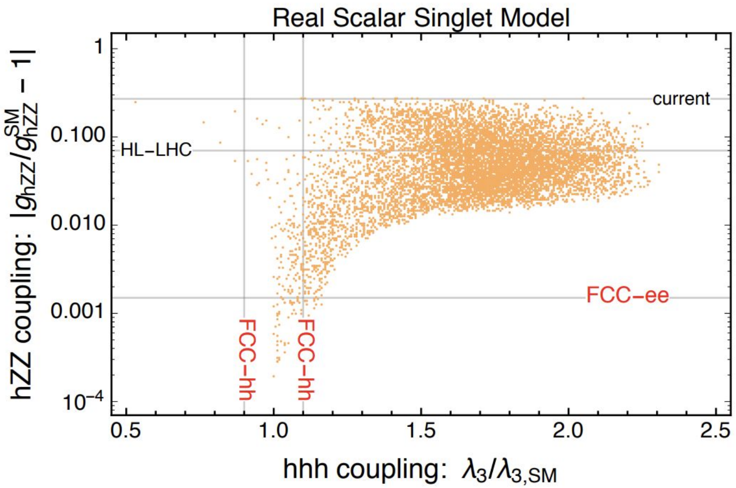
- **Strong 1st order EWPT** needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

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.

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)

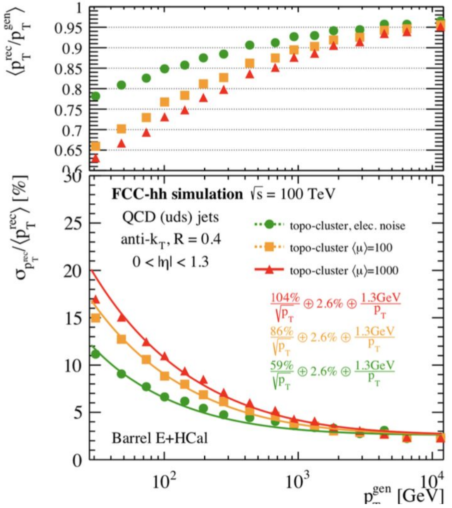
- Also, expected improvements in technology may lead to more ambitious and less-conventional approaches of detector concepts in the future
  - most of the challenges common to any high energy/high luminosity project.

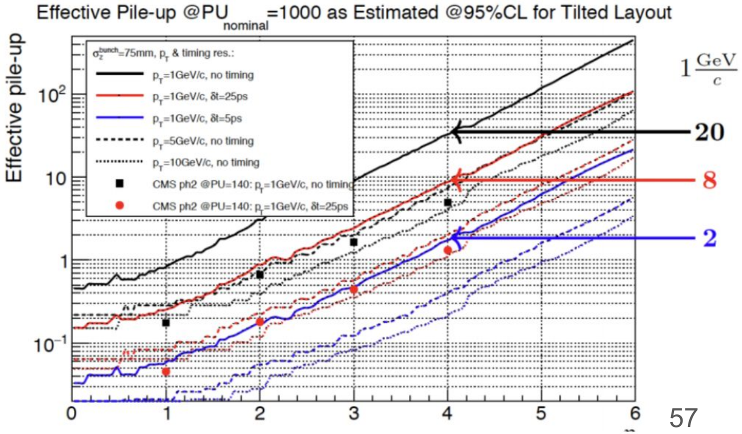
Experimental challenges for jets (at threshold)

- 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

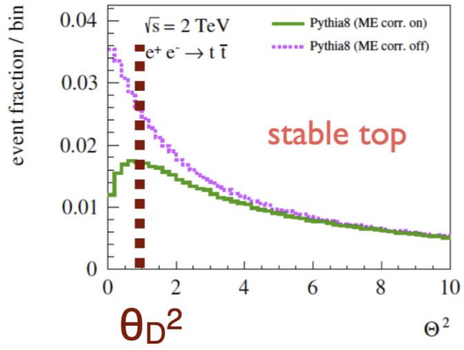
1912.09962





The deadcone effect for massive colored res.

Maltoni, MS, Thaler [1606.03449]

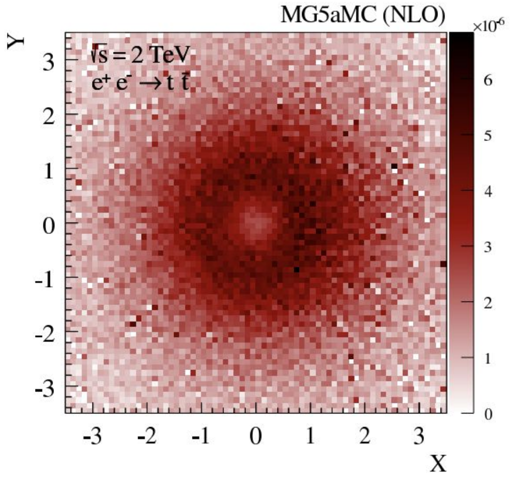


FSR in soft and collinear limit :

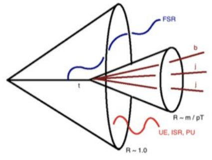
$$\frac{1}{\sigma}\frac{d^2\sigma}{dz\,d\theta^2} \simeq \frac{\alpha_S}{\pi} C_F \frac{1}{z}\frac{\theta^2}{(\theta^2+\theta_D^2)^2}$$

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

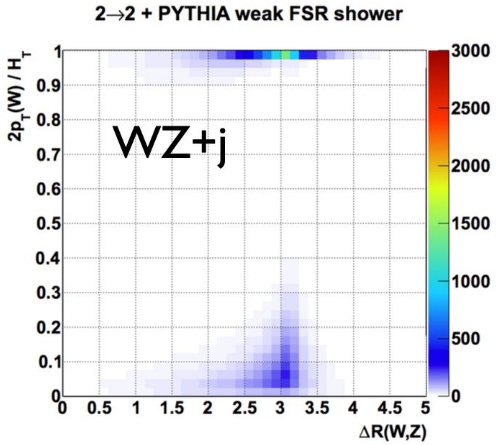
- effect can be observed at HL-LHC
- rather than treated as a nuisance can be exploited for top tagging at multi TeV energies

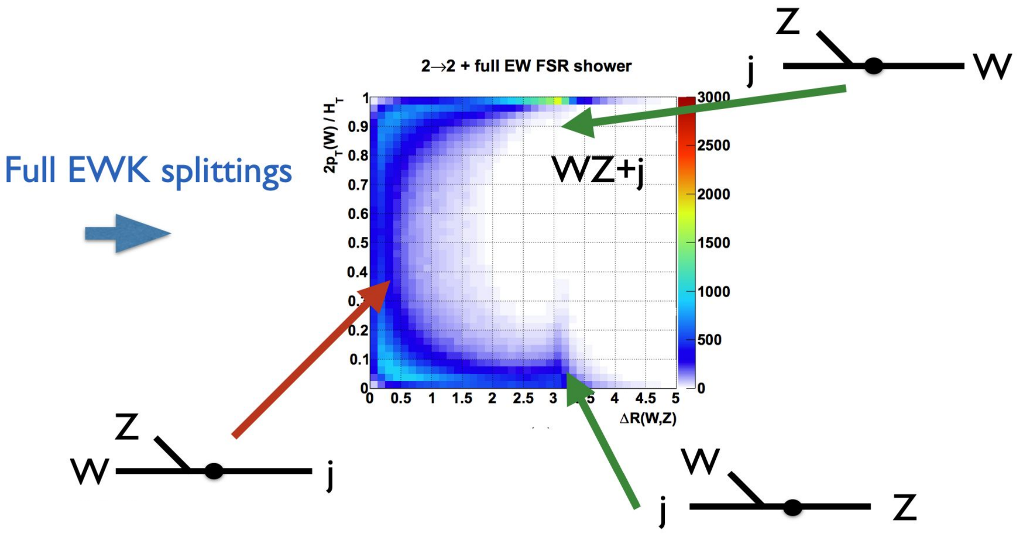


for the top can be pretty large angle

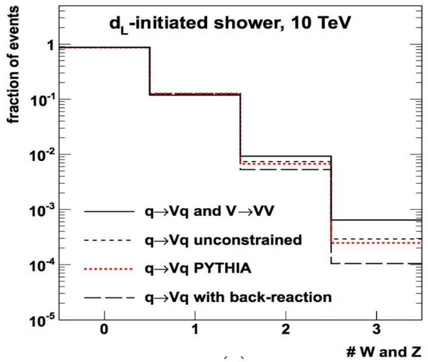


Electroweak showers



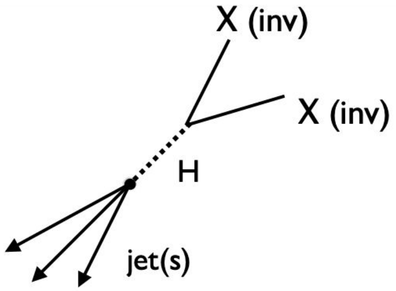


Chen, Han and Tweedie [1611.00788]



- EWK shower become sizeable log-enhanced at multi-TeV energies
  - j → jW can fake a top jet
- can and have to be included and studied in multi-TeV jet tagging
- Neutrino showers?

Higgs invisible



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