Hadronic Physics up to 100 TeV

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New facilities goals

What we cannot deliver:

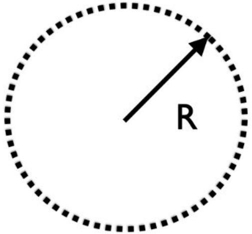
- explore all new physics directions/mass couplings scale
- guarantee discovery

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

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



Pros:

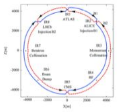
- relatively democratic initial states, strong and electro-weak force
- high center of mass, thanks to ~ small synchrotron power loss $(m_e/m_p)^4$
    - caveat: at 100 TeV it becomes significant!
- high luminosity up to high energy

Cons:

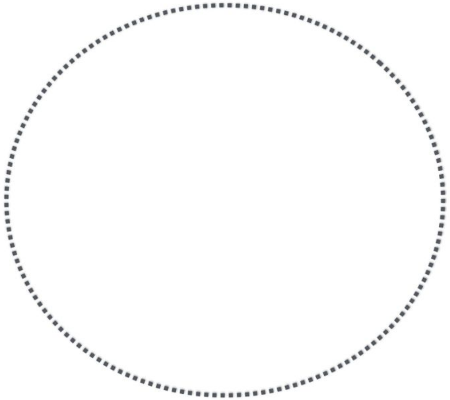
- large backgrounds compared to lepton machines ($\alpha_S > \alpha_{EM,W}$), from
    - high Q2 physics (di-jet, ttbar …)
    - “simultaneous” p-p collision (pile-up)

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

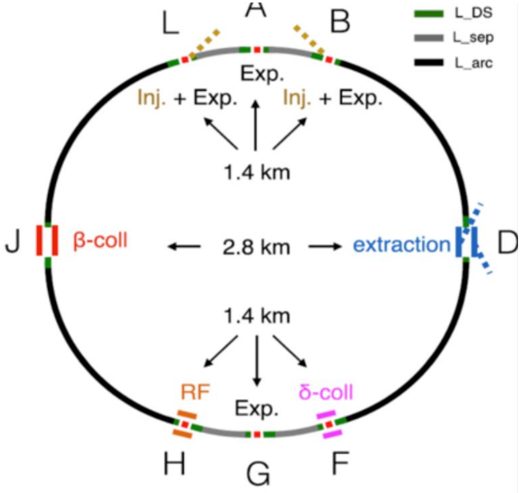
Variants



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

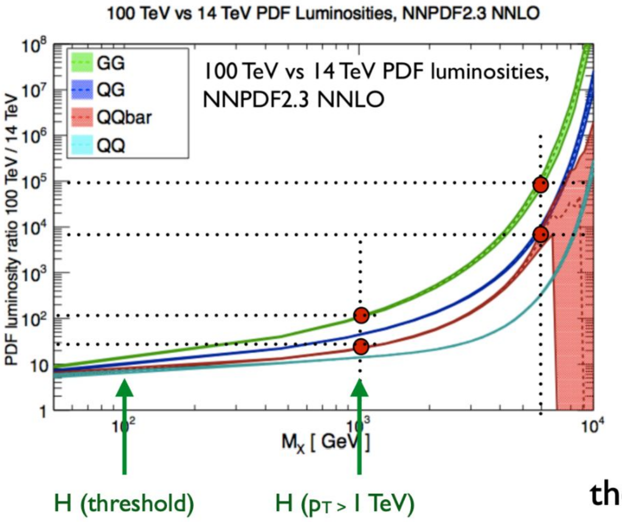
Main challenge: high field superconducting > 14 T magnets , high PU

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

$$\frac{\text{cross-section } (\sqrt{s} = 100\text{ TeV})}{\text{cross-section } (\sqrt{s} = 14\text{ TeV})} \approx L_1 / L_2 \approx (s_2 / s_1)^a \approx (100 / 14)^{2a}$$

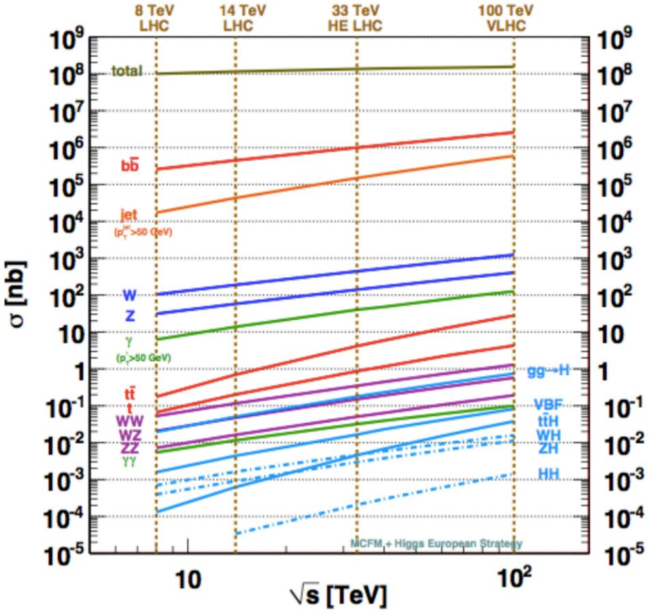


	σ(100)/σ(14)
ggH	15
HH	40
ttH	55
H (p_T > 1 TeV)	400

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



MCFM + Higgs European Strategy

- 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 !

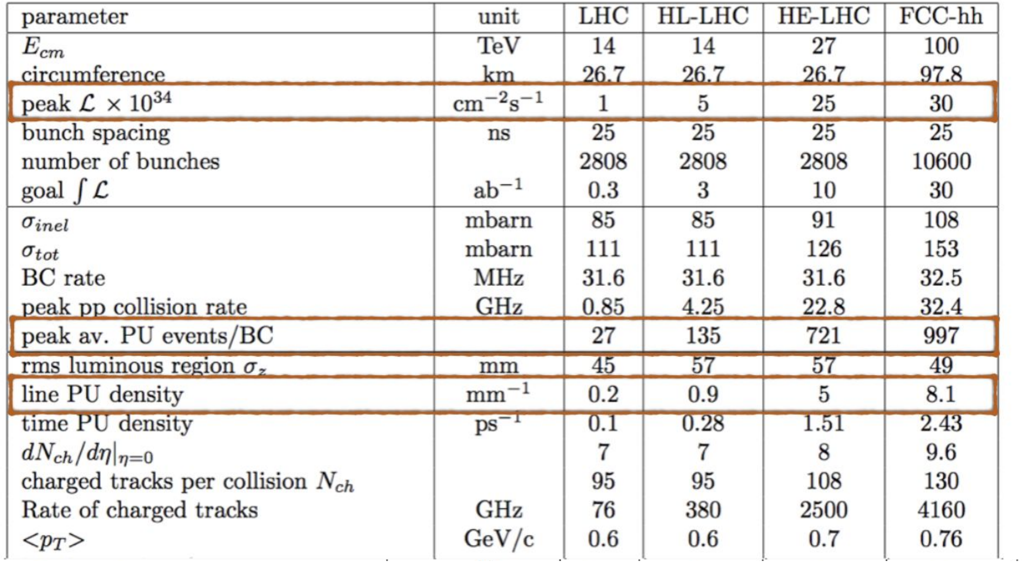
Rate of increase from 14 TeV to 100 TeV:

- ggH x15
- HH x40
- ttH x55

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

Hadron Machines specs and detector requirements

lumi & pile-up



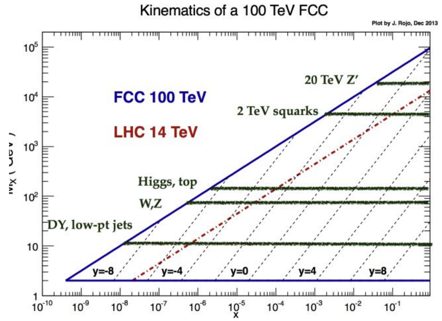
parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	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
$dN_{ch}/d\eta \vert_{\eta=0}$		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

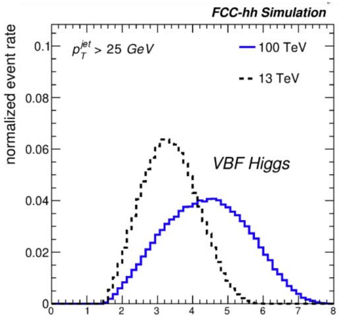
$$x_1 * x_2 * s = M^2$$

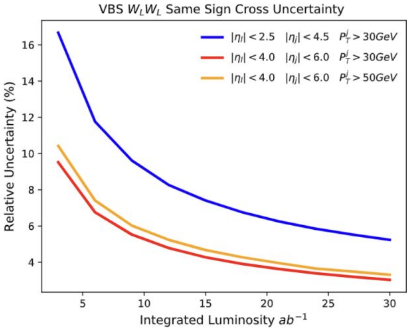


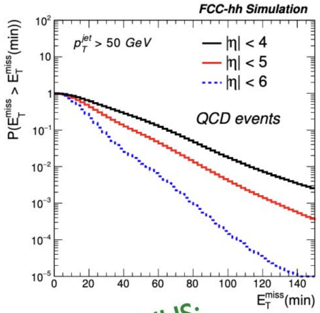
SM Physics is more forward @100TeV

- 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 $|\eta| < 6$ for ~. VBF signatures

BONUS:
Hermeticity
E_T^{miss} resolution

Boosted topologies at multi-TeV energies

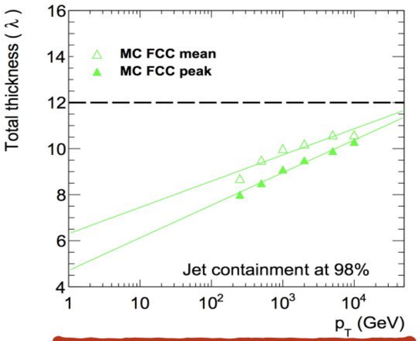
The boosted regime:

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

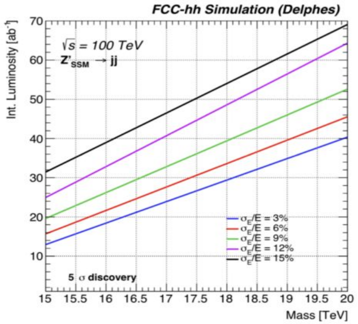
Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$

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

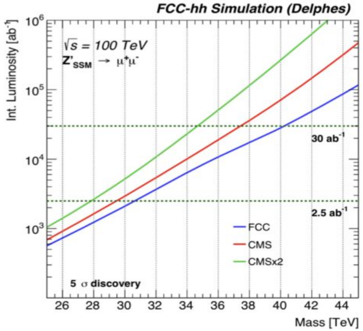
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets

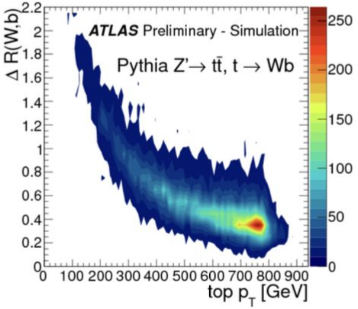


high p_T muons

Boosted topologies at multi-TeV energies

min. distance to resolve two partons

$$\boxed{\Delta R \approx 2\,m / p_T}$$



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

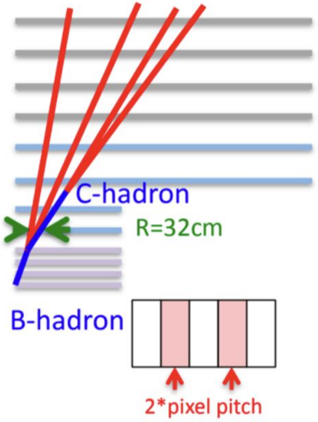
- The boosted regime:
  → measure b-jets, taus from multi-TeV resonances

- 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

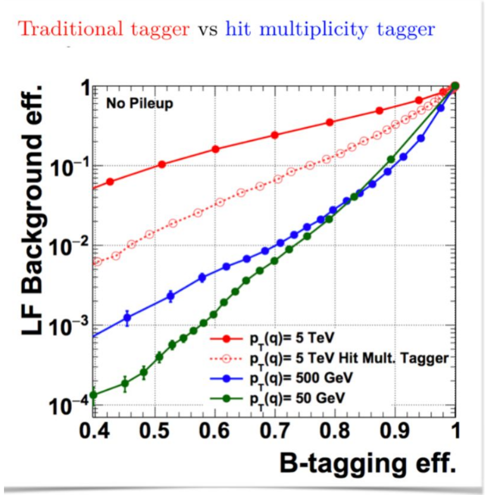
→ re-think reconstruction algorithms:
- hard to reconstruct displaced vertices
- **exploit hit multiplicity discontinuity**



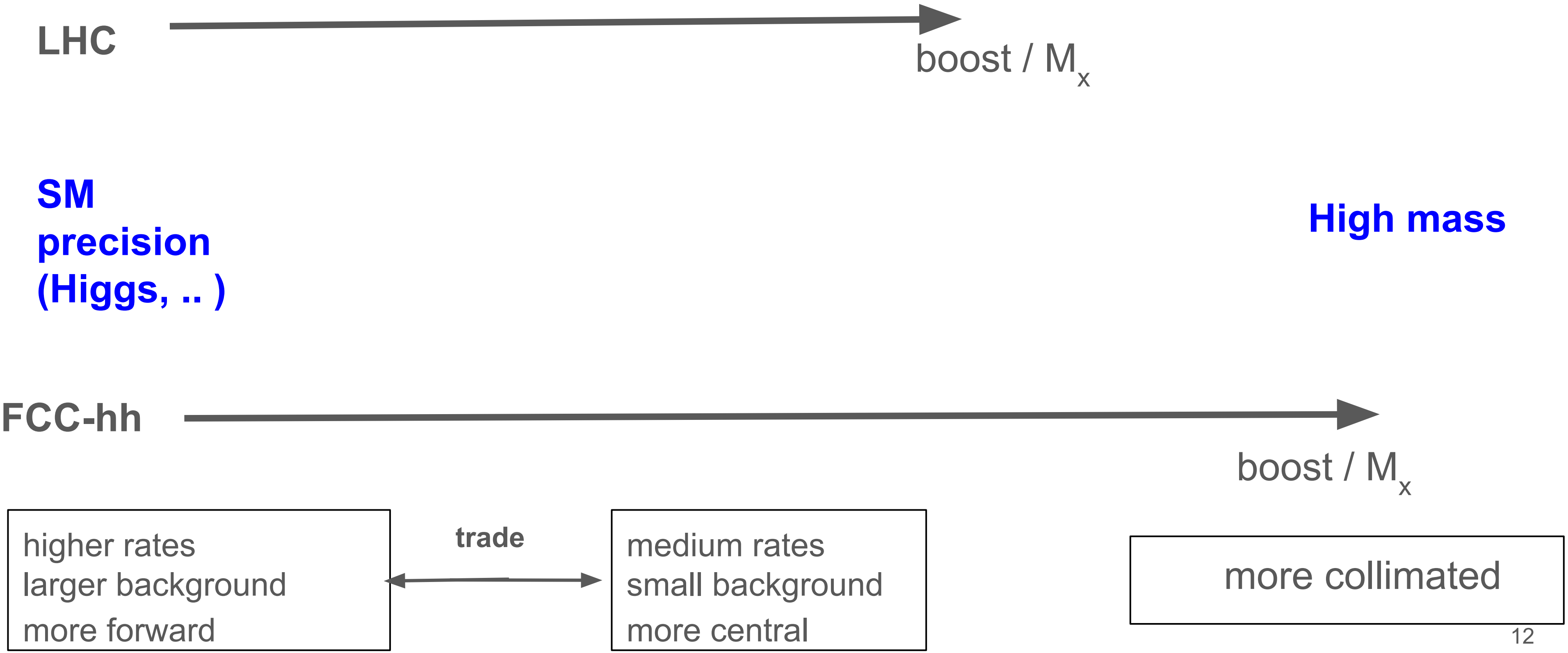
Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices

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



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

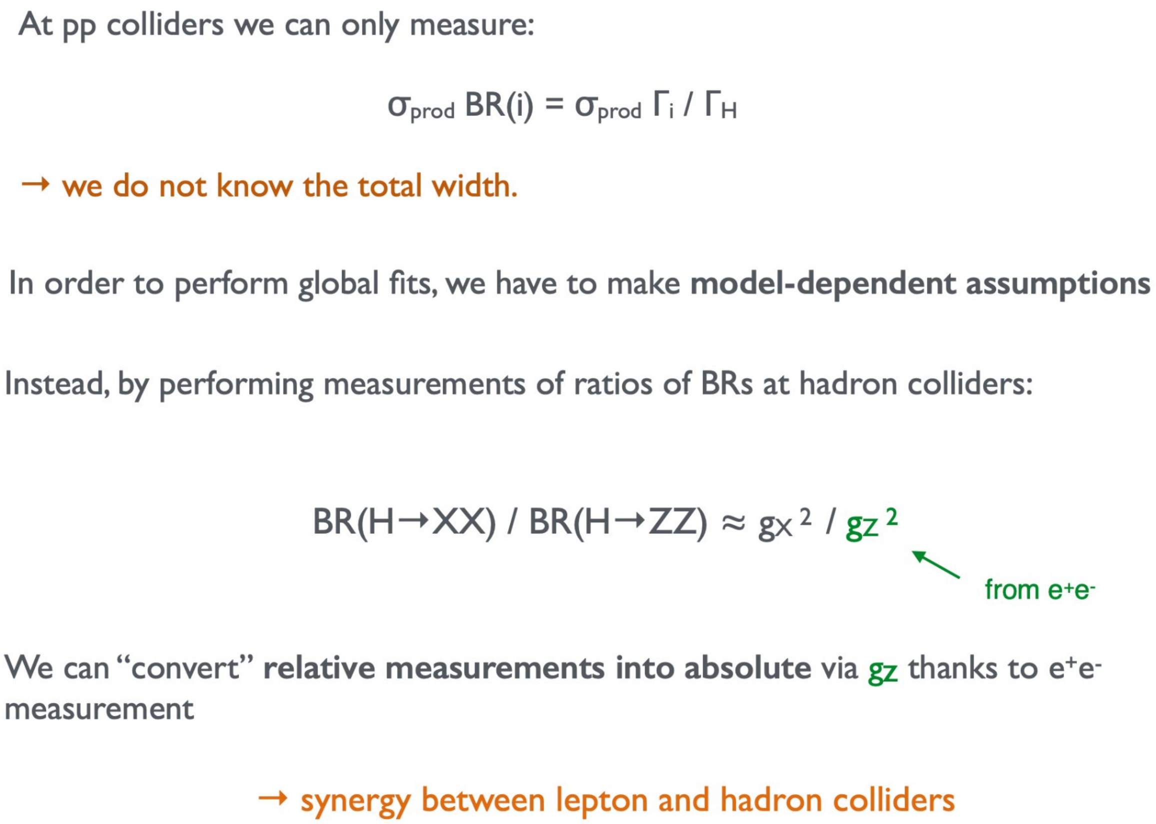
	HL-LHC	**FCC-ee**
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	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

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:

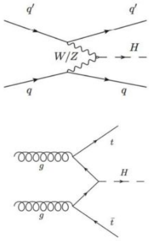
$$BR(H\rightarrow XX) \,/\, BR(H\rightarrow ZZ) \approx g_X{}^2 \,/\, g_Z{}^2$$

from e^+e^-

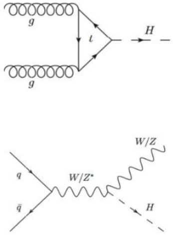
We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

→ 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

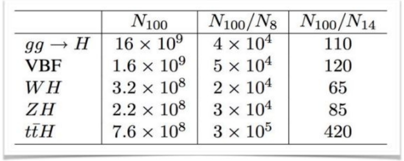


30M Higgs pairs

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

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



	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.

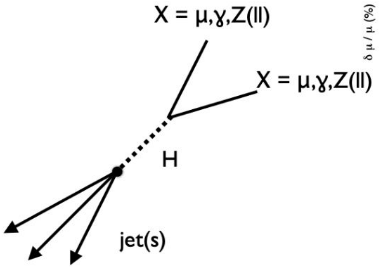
Large statistics will allow:

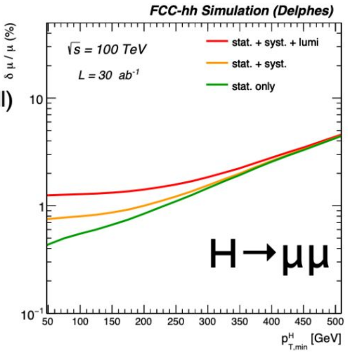
- for **% - level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channel, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

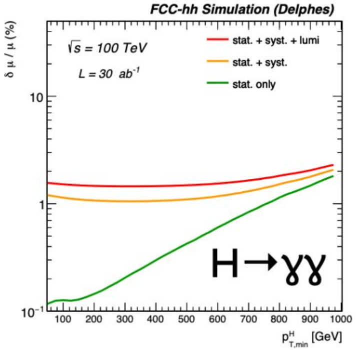
Higgs rare decays

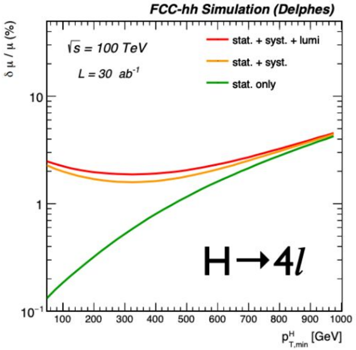
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \to \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \to \infty$

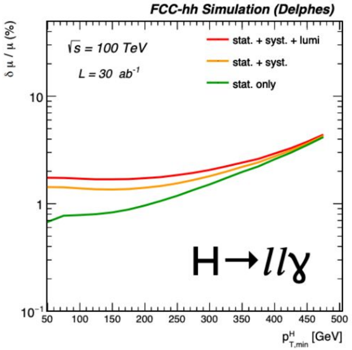
- study sensitivity as a function of **minimum p_T(H)** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** p_T(H): **large statistics** and **high syst.** unc.
- **large** p_T(H): **small statistics** and **small syst.** unc.
- **O(1-2%) precision on BR** achievable up to very high p_T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







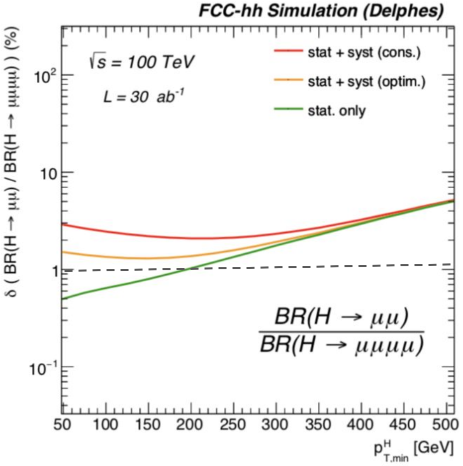


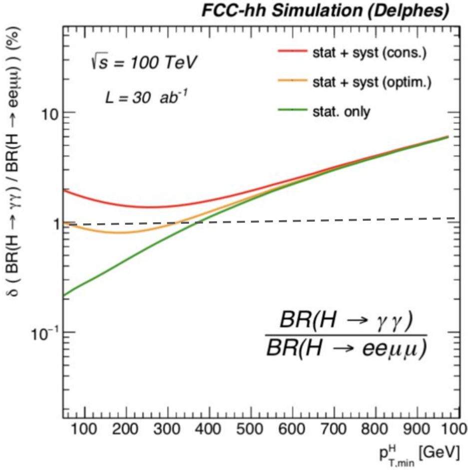


BR ($\mu\mu$,γγ,Zγ) / BR(H→ZZ)

- 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





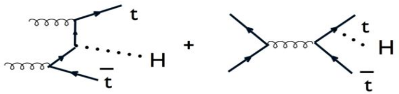
Top Yukawa , H→bb boosted

- production ratio **$\sigma(ttH)/\sigma(ttZ)$** ≈ **$y_t^2\ y_b^2/\ g_{ttZ}^{\ 2}$**
- 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

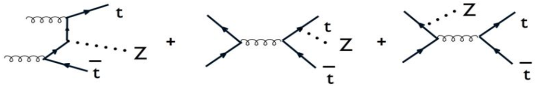
- assuming **g_{ttZ}** and **κ_b** known to 1% (from FCC-ee),

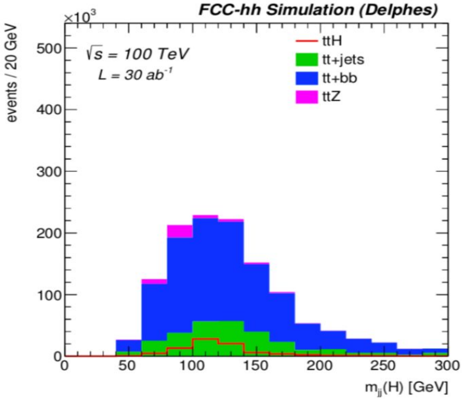
→ measure **y_t** to 1%

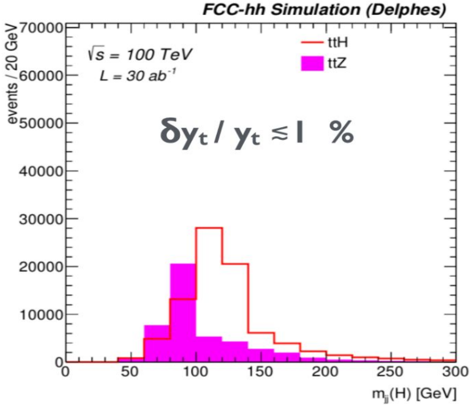
ttH



ttZ







complement using Hττ

New possible studies

- Exploring new ideas to reduce dependence on detector assumptions and systematics:
  - H→WW, bb, cc, **ττ**
  - 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:

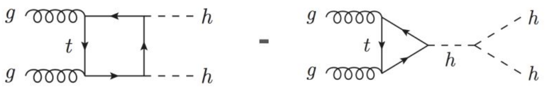
$$\frac{H(bb,cc,\tau\tau)/Z(bb,cc,\tau\tau)}{H(\mu\mu,\ 4\ell)/Z(\mu\mu,\ 4\ell)} \sim \kappa_{b,c,\tau} / \kappa_{\mu,Z}$$

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

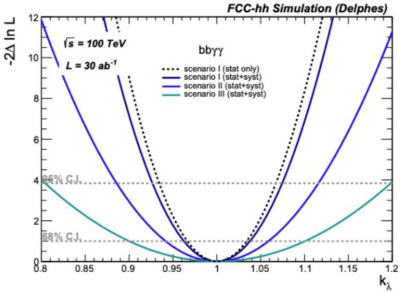
exploit absolute model independent κ_Z , ttZ measurements from FCC-ee

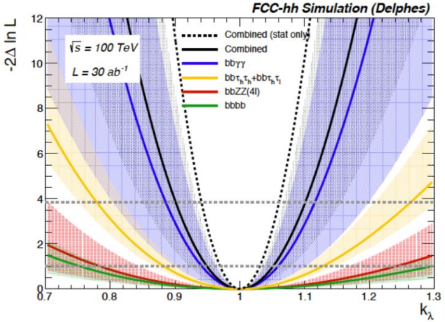
Higgs self-coupling

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



2004.03505 [hep-ph]

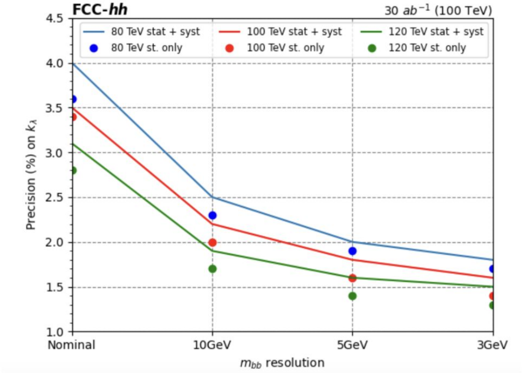


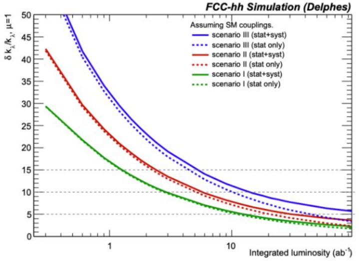


- Expected precision:

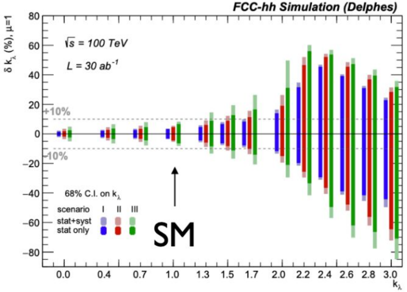
@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8

Mastrapasqua, Taliercio, Stapf





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

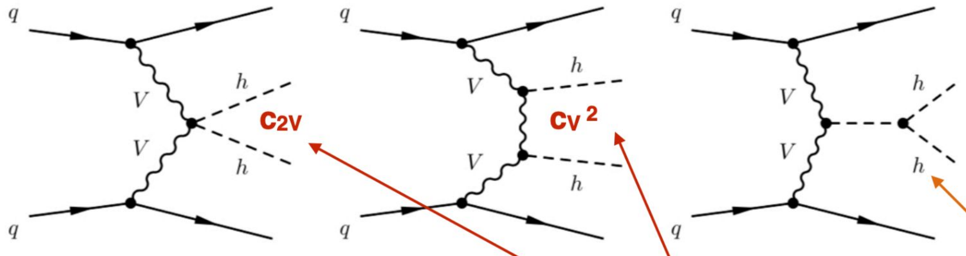


new studies on-going !

exploring more detctor/sqrt(s) variations

HHVV coupling

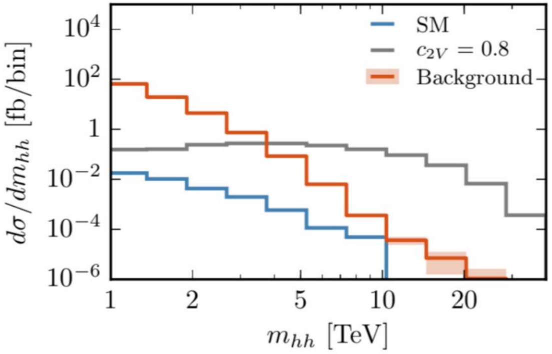
Bishara, Contino, Rojo

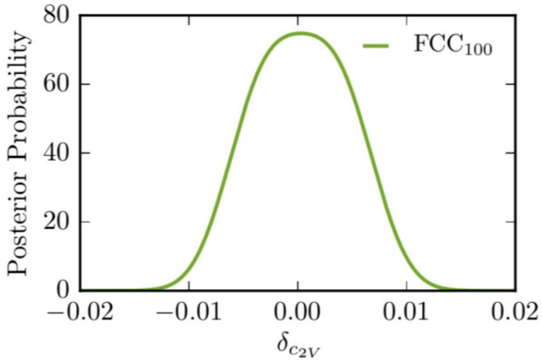


negligible at large m_{HH}

$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}\underbrace{(c_{2V} - c_V^2)}_{\text{0 in the SM}} + \mathcal{O}(m_W^2/\hat{s}),$$

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

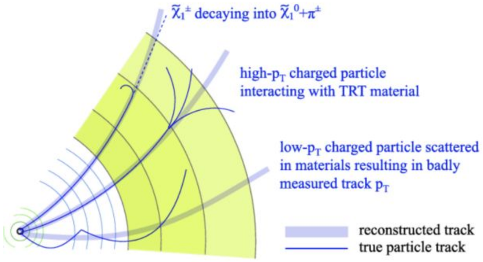
	HL-LHC	**FCC-ee**	**FCC-hh**
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (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%**	**$BR_{inv} < 0.025\%$**

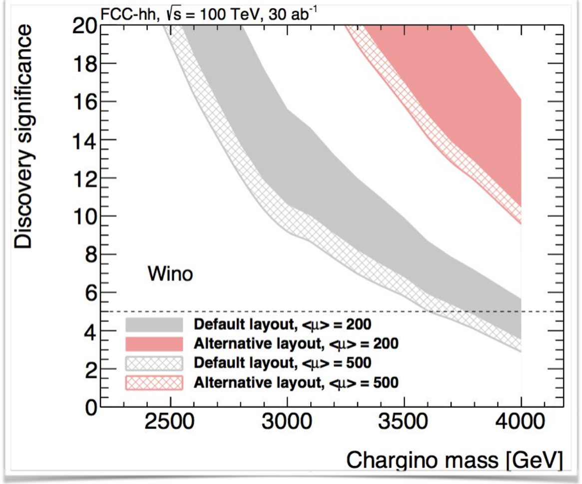
* From BR ratios wrt B(H→4l) @ FCC-ee

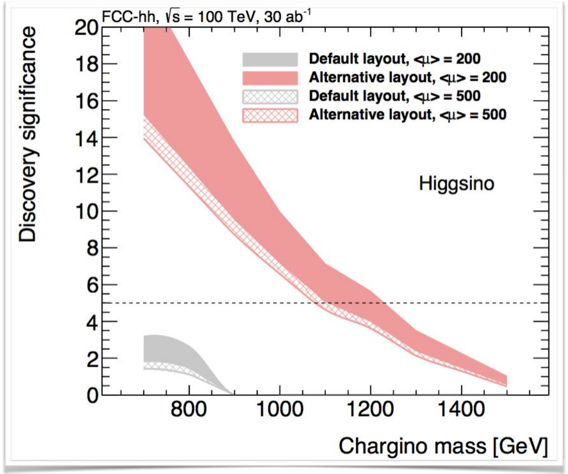
** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

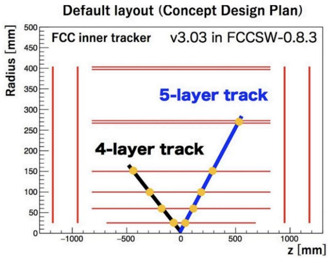
WIMP dark matter - disappearing track analysis

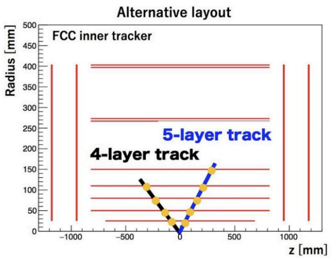
Nearly degenerate chargino-LSP









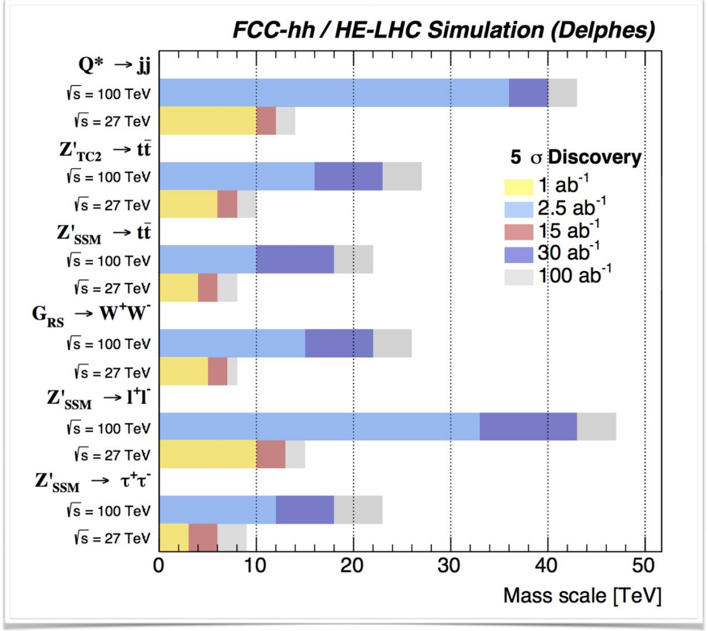


observed relic density

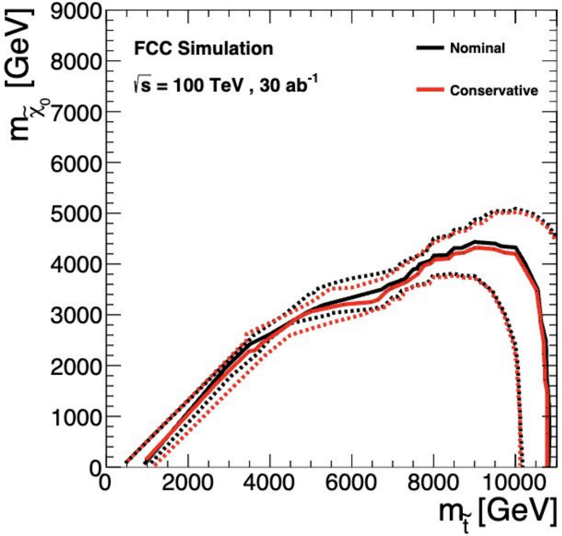
- M = 1 TeV Higgsino can be discovered
- M = 3 TeV Wino can be discovered

The energy frontier

High mass resonances



stops



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

Tracking is the key highly segmented calorimetry

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

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

High energy hadron machines

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

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

dimensional analysis

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

$\swarrow$ $1/\tau^{a}$

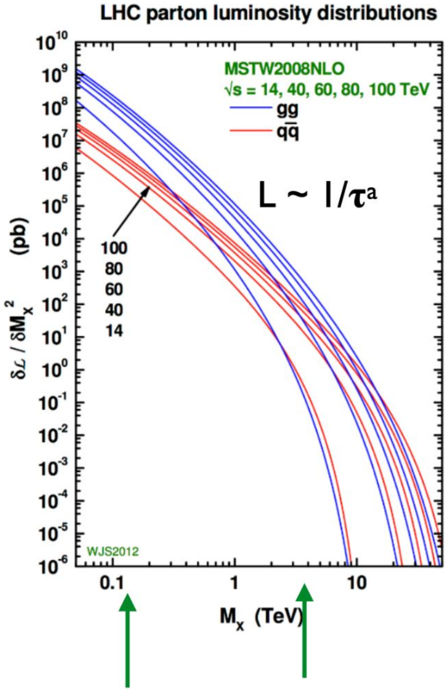
$\tau = x_1 x_2 = M^2/s$

$\searrow$ $1/M^2$

assumes mostly produce at threshold

$\mathscr{L}$: integrated luminosity

L_{parton} : parton luminosity



$a \approx 2$ $a \approx 6$

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:

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

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

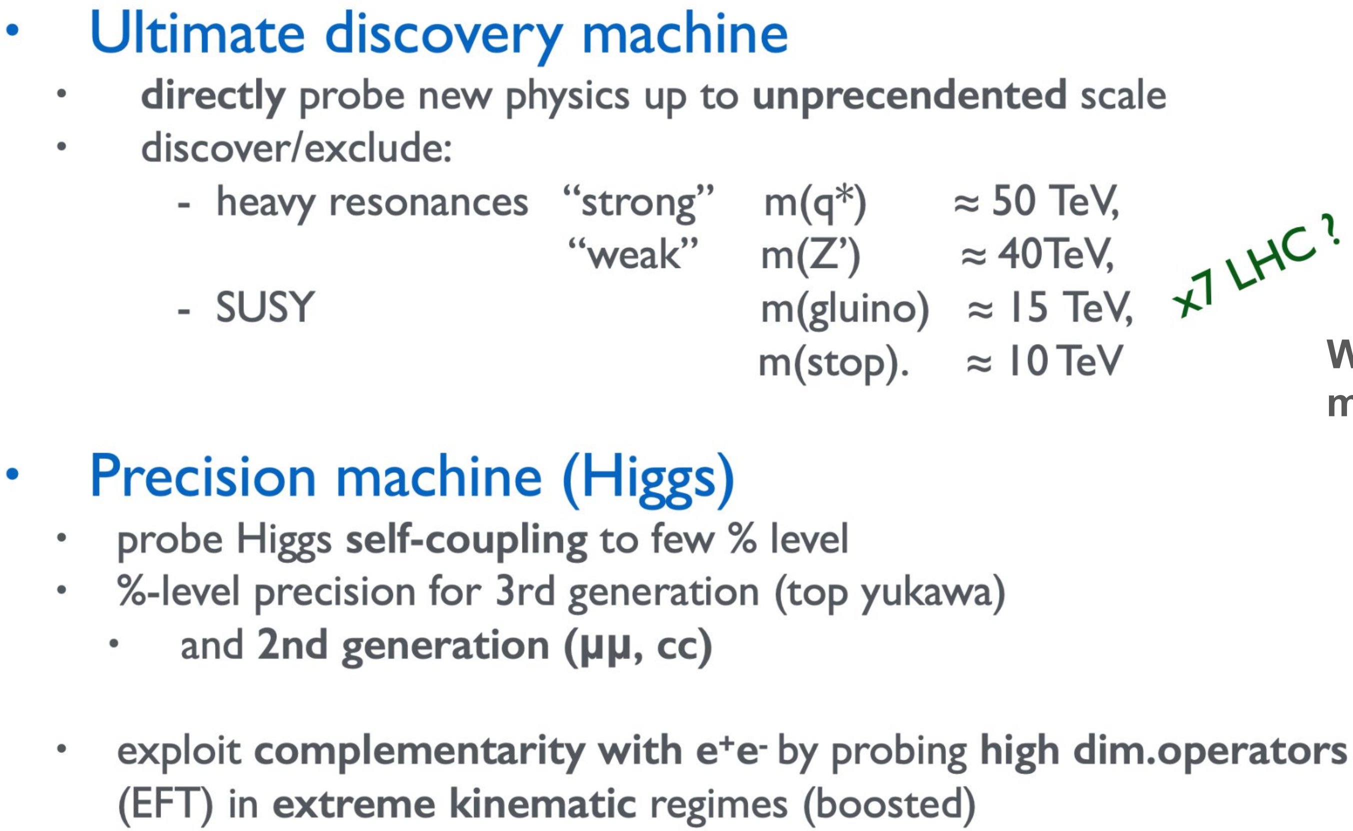
$$M_{100\,\text{TeV}} / M_{14\,\text{TeV}} \approx 7$$

≈ 1

assumes:
- large a
- large luminosity

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

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 ?

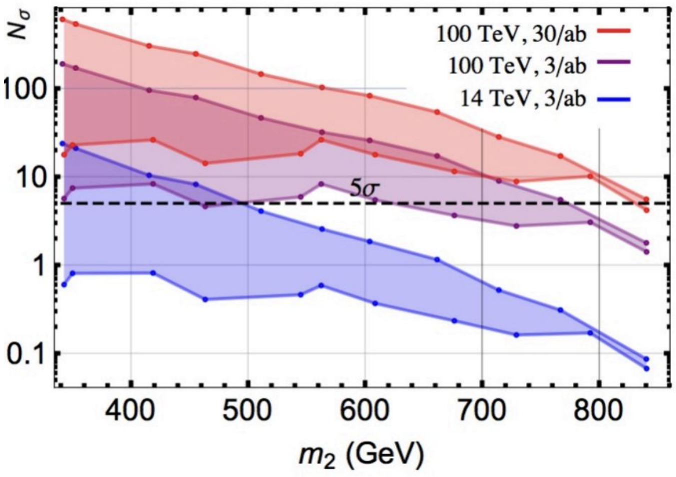
Wino/Higgsino Dark matter (1-3 TeV)

- **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

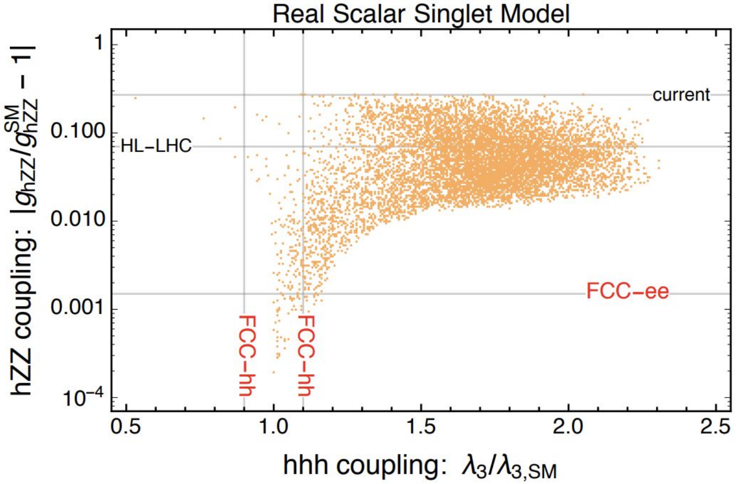
- **Strong 1st order EWPT** needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

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

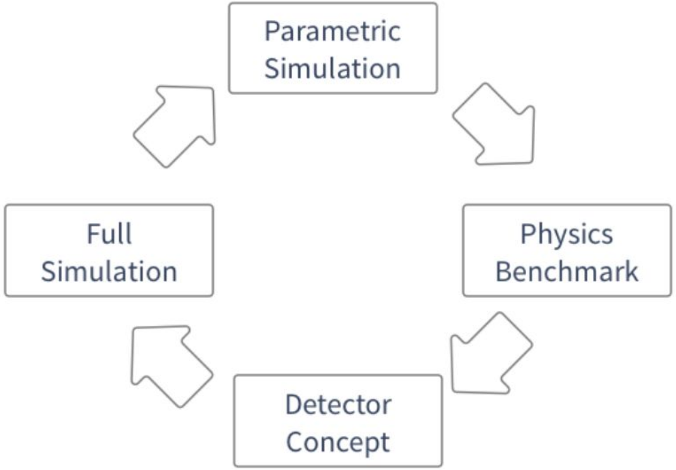


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

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

…

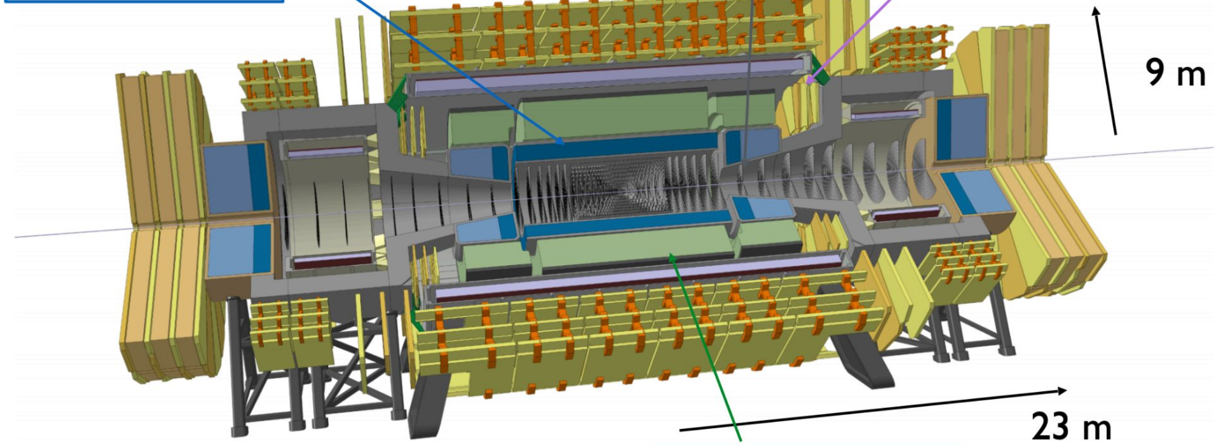


A detector concept that does the job …

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
$30\ X_0$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Tracker: $\sigma_{p_T}/p_T \sim 20\%$
at 10 TeV (1.5m radius)

Central Magnet +
Fwd solenoids



Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

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.

Collider options

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	0.4

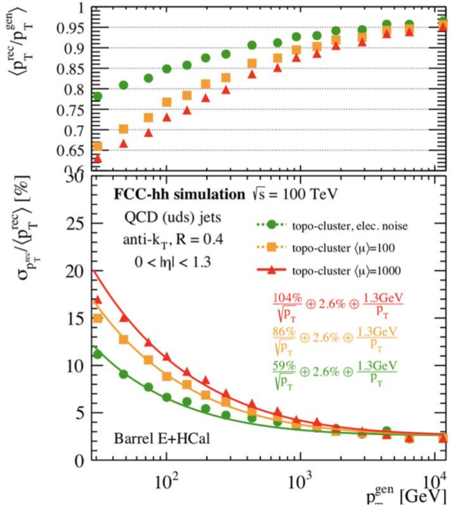
Limiting factor: 5MW synchrotron power ~ $\sqrt{s}^4$

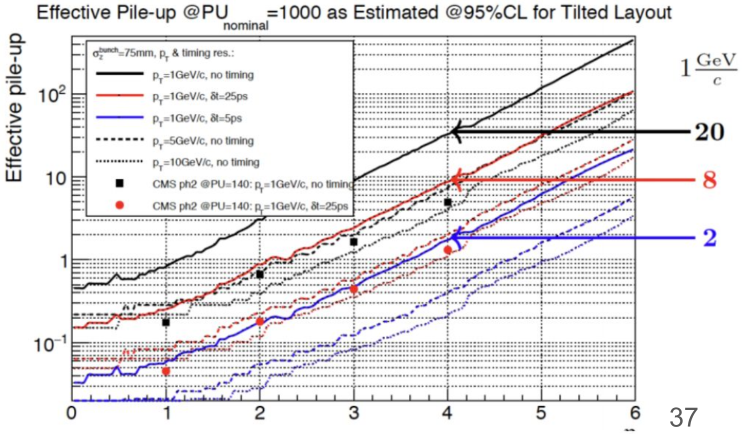
Experimental challenges for jets
(at threshold)

- 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

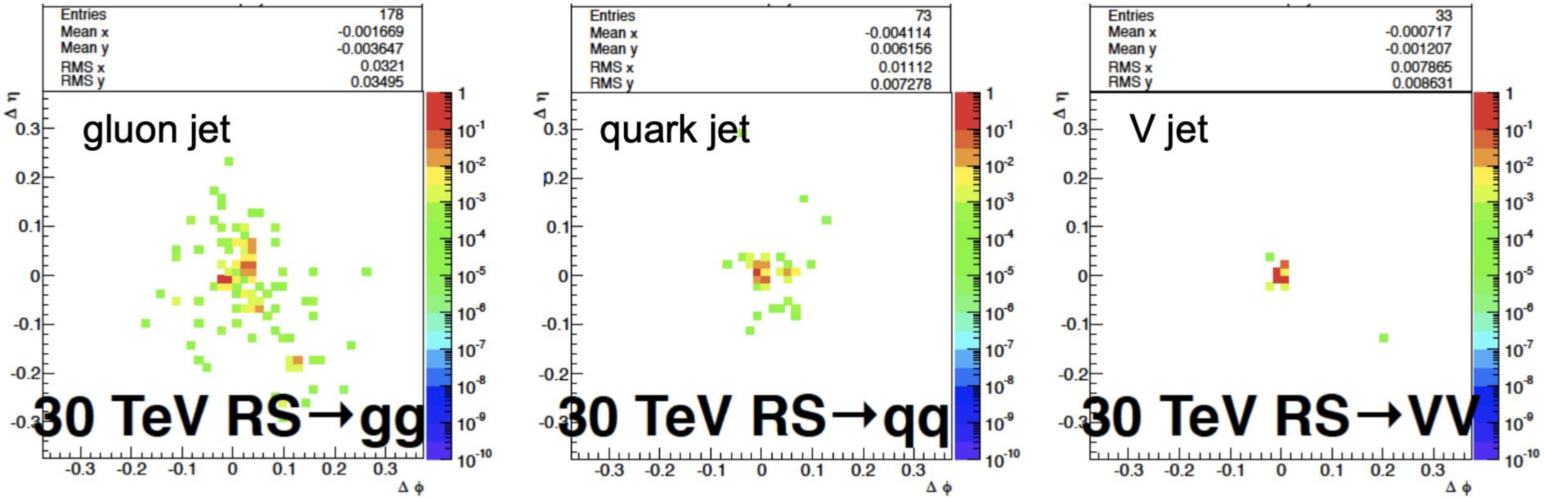
1912.09962





Color Singlets (W/Z/H)

[Pierini]

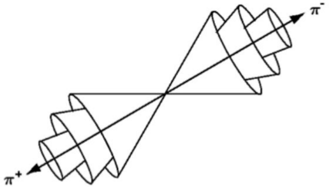


- **Gluon/quark** jet looks the same at 50 GeV and 5 TeV (**QCD is ~ scale invariant**)
- **Color Singlets** look like taus (do not radiate, a part from occasional QED/EWK shower)
  - **high mass, highly isolated, highly collimated tracks**

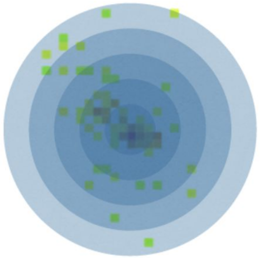
Boosted Color Singlet ID

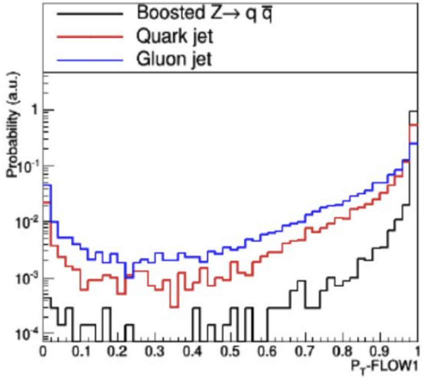
[Pierini]

~ isolation variable



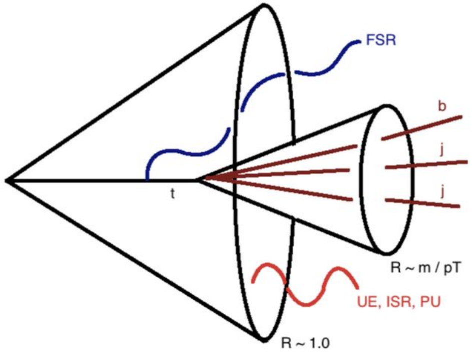
$$p_T^i(flow) = \frac{\sum\limits_{p \epsilon C_i} p_T^p}{p_T^{jet}}$$



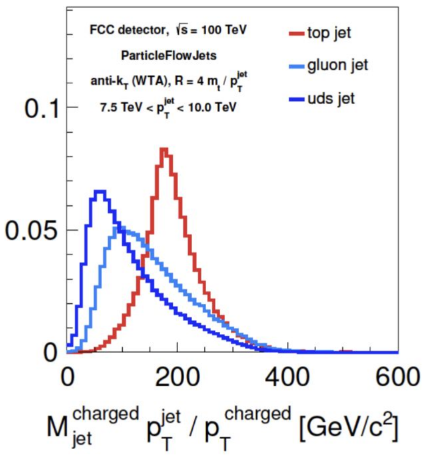


Loss in performance, but no show stoppers
Very simple heuristic based , can probably do much better with today’s techniques

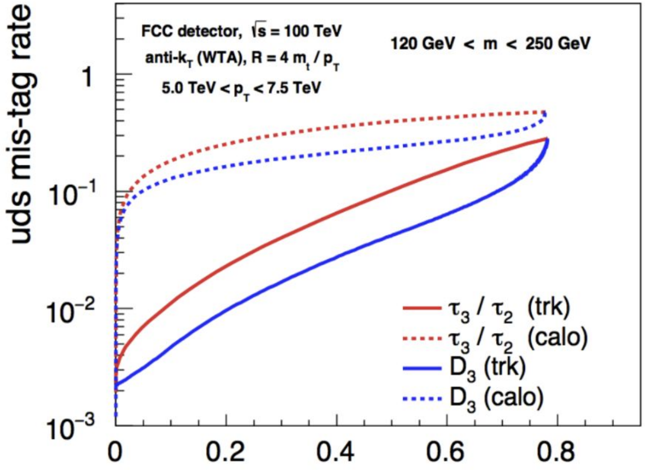
Boosted Colored Resonances



Track- based jet Mass



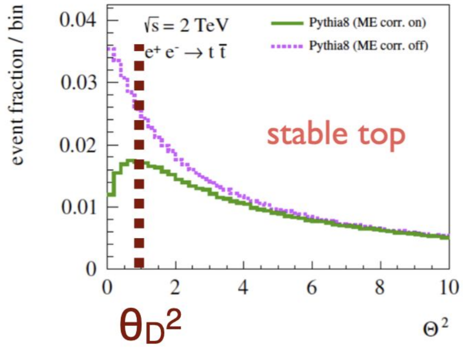
Very simple heuristic algo



- 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

The deadcone effect for massive colored res.

Maltoni, MS, Thaler [1606.03449]

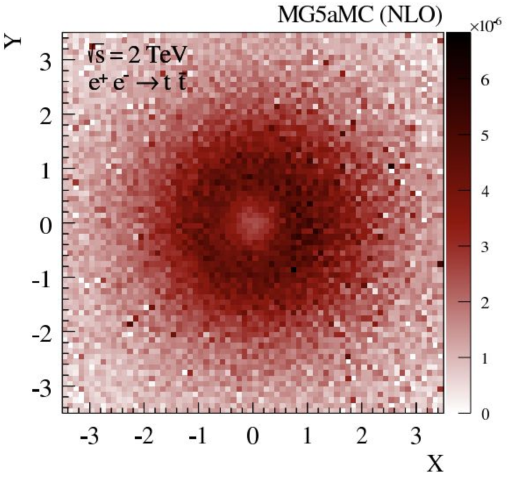


FSR in soft and collinear limit :

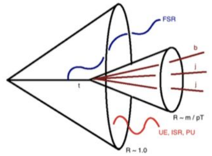
$$\frac{1}{\sigma}\frac{d^2\sigma}{dz\,d\theta^2} \simeq \frac{\alpha_S}{\pi} C_F \frac{1}{z}\frac{\theta^2}{(\theta^2+\theta_D^2)^2}$$

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

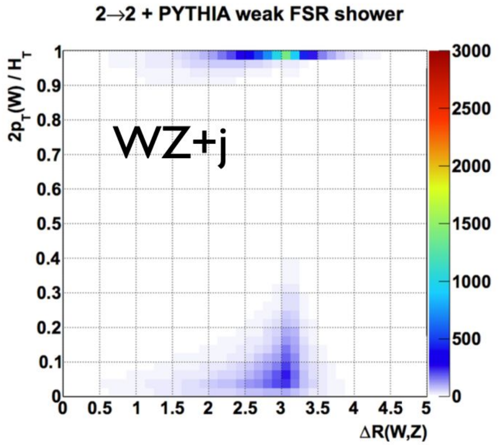
- effect can be observed at HL-LHC
- rather than treated as a nuisance can be exploited for top tagging at multi TeV energies



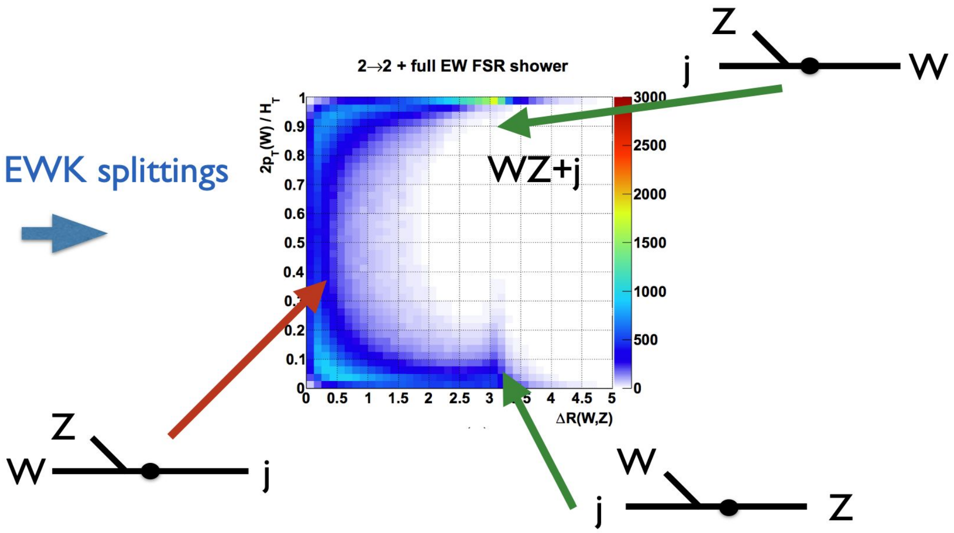
for the top can be pretty large angle



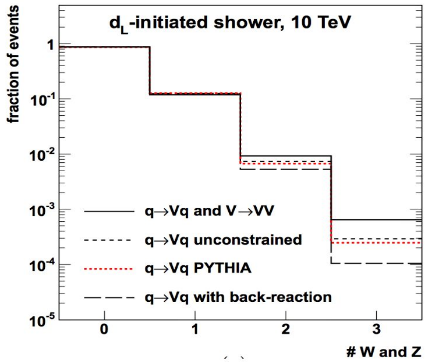
Electroweak showers



Full EWK splittings



- 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?



Chen, Han and Tweedie [1611.00788]

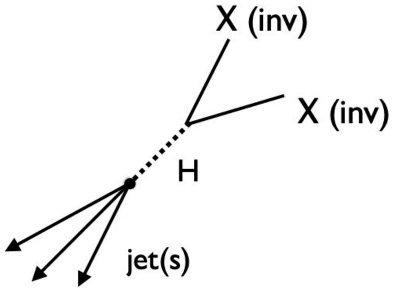
Summary

- Circular ee (FCC-ee/CEPC)
    - small boost, small background, well known initial state
    - Huge statistics 10^{12} jets of any flavor (including tau's)
        - study jets (Q vs G), HF jets and calibrate taggers in data

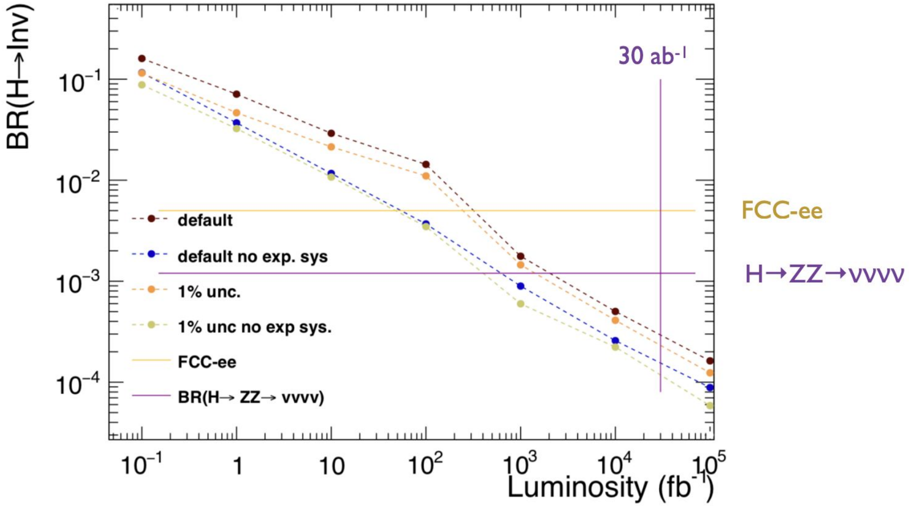
- Linear ee machines (ILC/CLIC)
    - Low to moderate boost/backgrounds

- High energy lepton (μ-Col) and hadron collider (FCC-hh)
    - at threshold:
        - SM Physics is forward, challenging machine backgrounds (PU, BIB)
            - precise tracking/timing
    - Hyper boosted regime ($p_T > 10$ TeV)
        - calorimeters cannot resolve substructure
        - tracking is key
        - new handles:
            - Isolation for color singlets
            - deadcone radiation

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) $\lesssim 2.5\ 10^{-4}$



Conclusion

- Many interesting topics to contribute
    - 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
    - radiation hardness, amount of data real challenge
    - it will be the next generation hadron machine, R&D should not stop after HL-LHC

- Subscribe to **fcc-ped-hh-espp25** and **fcc-ped-hh-physicsperformance-espp25**, mailing lists for more info to come:
    - monthly general meeting
    - focused analysis meeting, tutorials