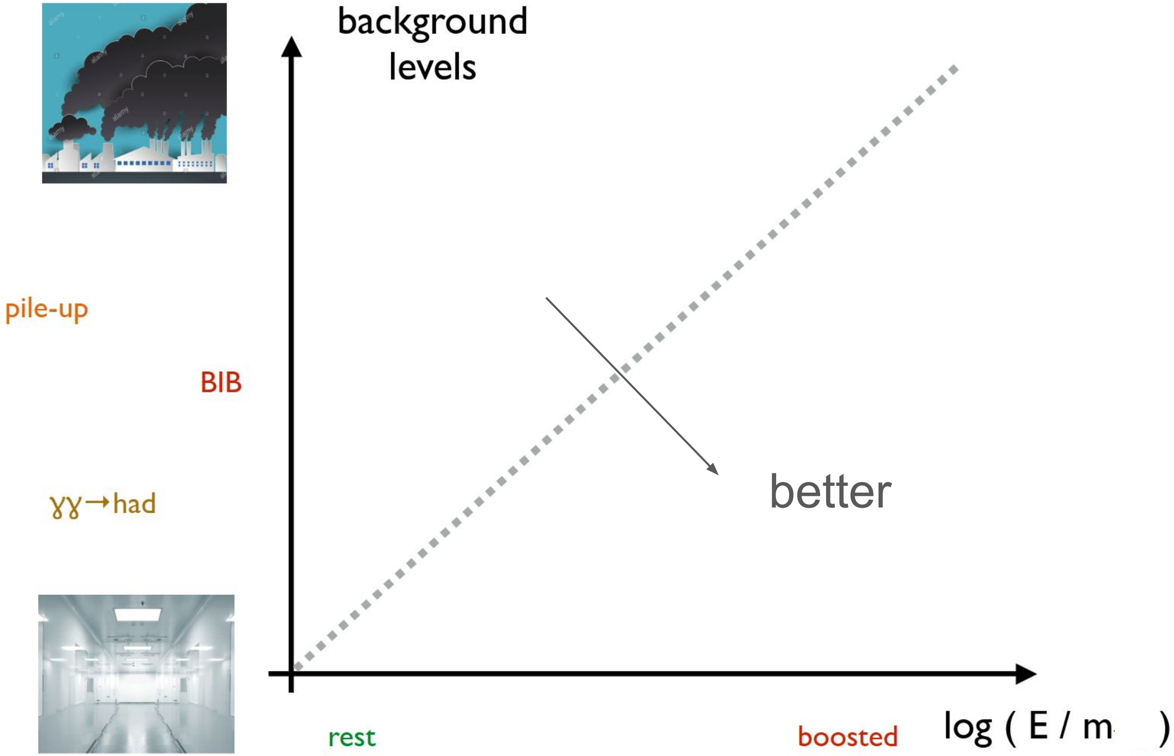
Jets at Future Colliders

Michele Selvaggi (CERN)

Boost 2024

Collider phase space



background levels

pile-up

BIB

γγ→had

better

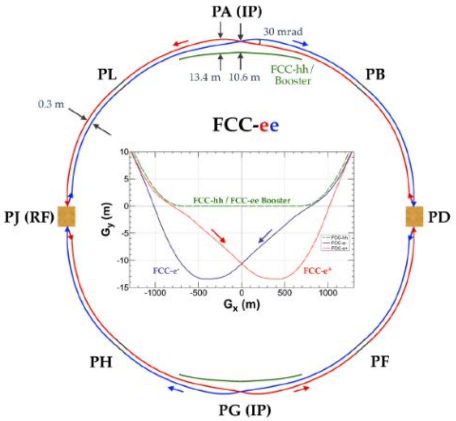
rest

boosted

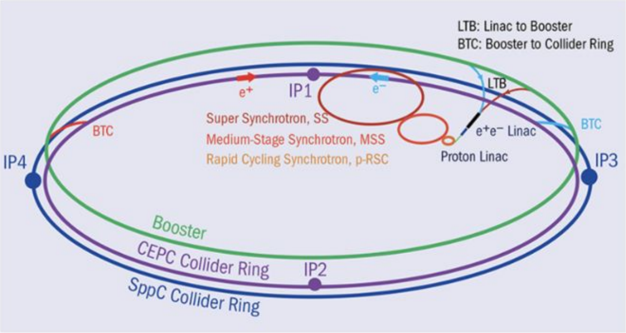
log (E / m)

FCC-ee/CEPC

FCC-ee



CEPC



91 km storage ring

e^+e^- collisions

Higgs/EWK/Top factory

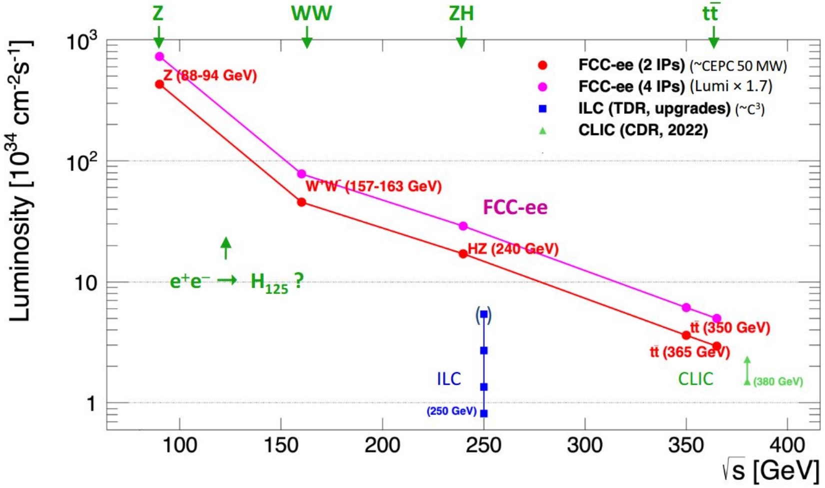
15 (20?) years of operations

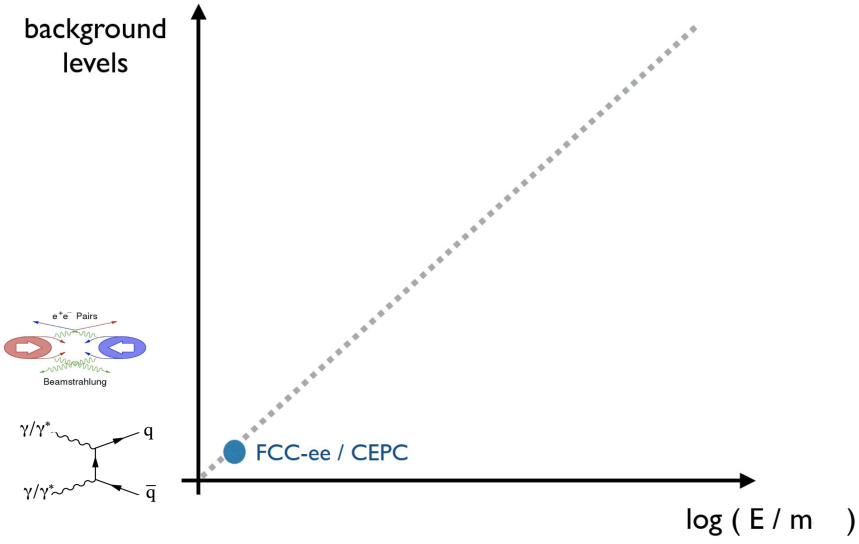
	Z pole	**? H pole ?**	**WW**	**ZH**	**ttbar**
√**s** [GeV]	88 - 91 - 94	125	157 - 161	240	350 - 365
Lumi / IP $[10^{34}\ \mathrm{cm}^2\ \mathrm{s}^{-1}]$	182	80	19.4	10.8	1.33
Int. lumi / 4IP $[\mathrm{ab}^{-1}$ / yr]	87	38	9.3	5.2	0.65
$\mathbf{N_{years}}$	**4**	**5**	**2**	**3**	**5**
$\mathbf{N_{events}}$	**8 Tera**	**8 K**	**300 M**	**2.2 M**	**2 M**

FCC-ee/CEPC

Exquisite luminosity allows for ultimate precision:

- ○ 100K Z bosons / second
  - ■ LEP dataset in 1 minutes
- ○ 10k W boson / hour
- ○ 2k Higgs bosons / day
- ○ 3k tops / day





- small backgrounds (mostly forward)
  - ■ Beamstrahlung
  - ■ Incoherent pair production
  - ■ γγ→hadrons

- small boost
  - ○ E_j ~ 50 GeV

Physics landscape at the FCC-ee/CEPC

Higgs
factory

m_H, σ, Γ_H
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..
self-coupling

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

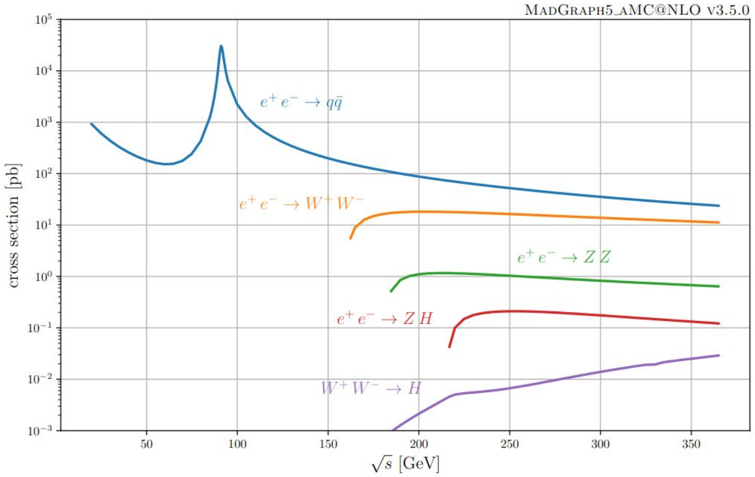
FCC-ee/CEPC

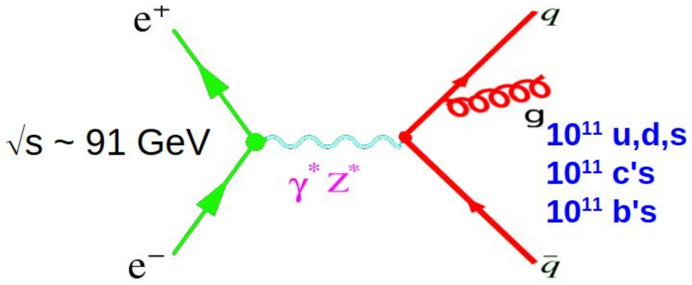
A clean jet factory:

- 10^{12} jets at the Z pole
  - 10^{11} b,c,s,u,d, tau jets
  - 10^{10} gluons in 3 jet events
- 10^{8} at the WW threshold
- 10^{6} at the ZH and ttbar thresholds
  - 10^{5} H→gg events

- Advantages compared to p-p collisions:
  - QED initial-state with **known kinematics**
  - QCD radiation only in final-state
  - well-defined heavy-Q, quark, gluon jets
  - no PDFs, no QCD “underlying event”,…

- Direct clean parton fragmentation & hadroniz.





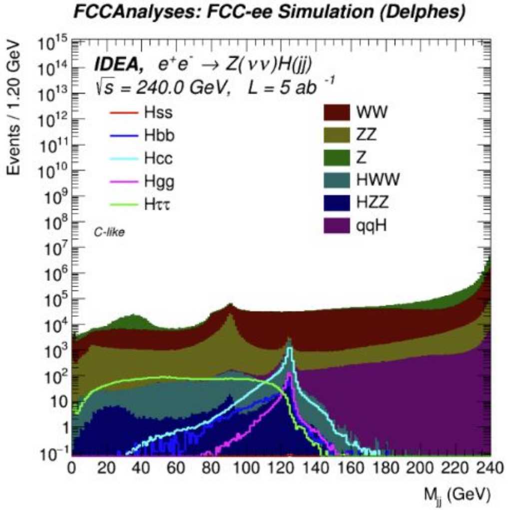
Perfect lab to **study QCD** (α_S, fragmentation, jet substructure)

See for a review:
[d'enterria FCC week]

Higgs (Factory)

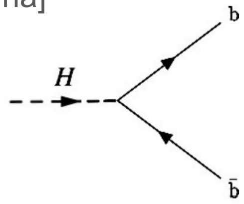
[del Vecchio, Gouskos, Iakovidis, Marchiori, MS]

- Most **Higgs** decays are **hadronic**
- FCC-ee produces ~ 2M (mostly from ZH),
  - crucial to **exploit all of them** for maximal statistical precision!
  - **2j** and **4j** final states modes
- For rare channels (**H→cc**, **H→ss**) need:
  - excellent visible mass resolution
    - sensitivity ~ $\sqrt{\sigma}(m_{vis})$
  - high tagging efficiency



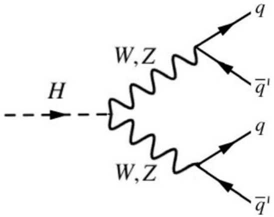
[d’Enterria]

$\mathcal{B}$=57.7%



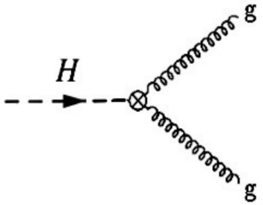
N(H)≈1.e6 @FCC-ee

$\mathcal{B}$=11%



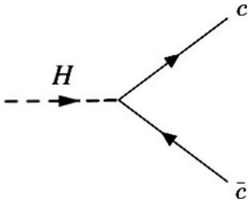
N(H)≈2.e5 @FCC-ee

$\mathcal{B}$=8.6%



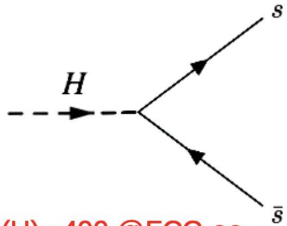
N(H)≈1.5e5 @FCC-ee

$\mathcal{B}$=2.9%



N(H)≈5.e4 @FCC-ee

$\mathcal{B}$=0.024%



N(H)≈400 @FCC-ee

Jet Clustering at lepton colliders

[Cacciari, Salam, Soyez]

- **spherical** symmetry
- beam direction “z” not special
  - (as opposed to LHC where long. boost invariance along beam axis)
- distance measure should use
  - $\mathbf{E_i, \theta_{ij}}$
- relative **absence** of machine **backgrounds**
  - every hadron should be clustered in a jet

baseline: Durham k_T algorithm:

$$d_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$$

Jet Clustering at lepton colliders

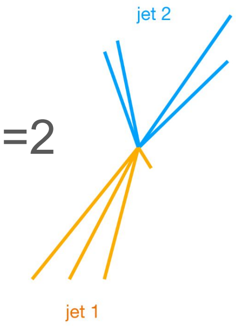
[Cacciari, Salam, Soyez]

N=4 exclusive

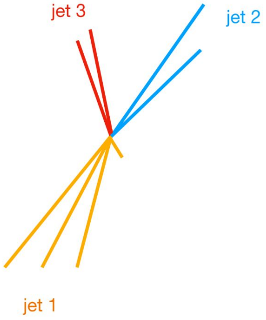
virtually no ISR (only QED):

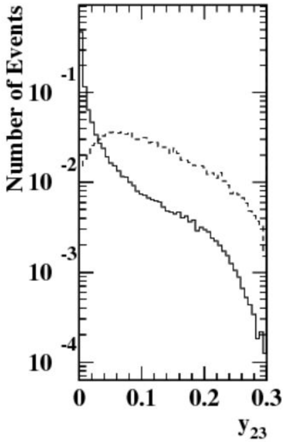
- **number of jets** in the final states well known both for signal and backgrounds
- baseline: **exclusive clustering** N mode:
    - **stop** when **number of required jets reached**
    - store merging distances d_{ij} for further background discrimination

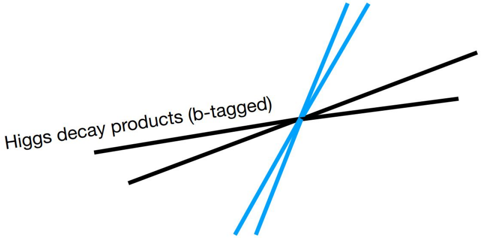
N=2



N=3

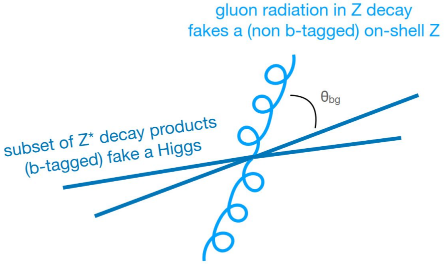






SIGNAL ZH

$d_{34(23)}$ (ZH→jjjj) >> $d_{34(23)}$ (Z→jj)



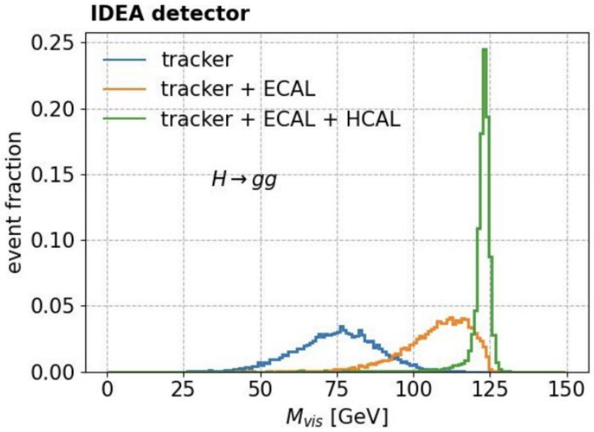
BACKGROUND (Z* → hadrons)

Particle Flow and detector requirements

- **To maximise visible energy/mass resolution:**
  - **every final state particle should be reconstructed**

$$\sigma^2_{\mathrm{PF}}(E) = \sum_{i\in\mathrm{tracks}} \sigma^2_{\mathrm{track}}(E_i) + \sum_{i\in\gamma} \sigma^2_{\mathrm{E}}(E_i) + \sum_{i\in\mathrm{had}} \sigma^2_{\mathrm{H}}(E_i)$$

60% 30% 10%



Requirements:

- hadron energy resolution
- **100% tracking eff.**, photon, neutral hadrons reco. (n, KL) efficiency
  - **low mat budget** in front of calo, low noise
  - excellent **granularity** for optimal **charged component** and **neutral hadron identification**

Ideal PF

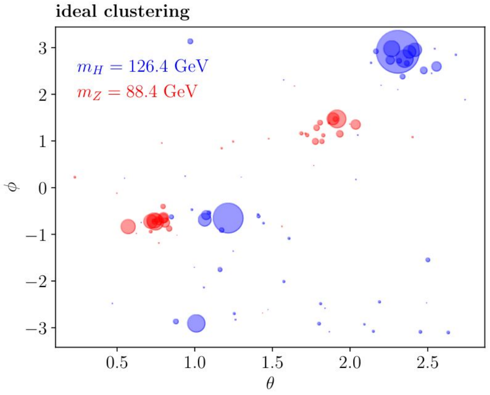
Resolution [GeV]	Crystal Cu/Brass (CMS)	LAr TileCal (ATLAS)	Dual Readout	Dual Readout +Crystal
S_{ECAL}	5%	10%	10%	5%
S_{HCAL}	100%	50%	30%	30%
σ_{ECAL}	0.3 GeV	0.6 GeV	0.6 GeV	0.3 GeV
σ_{HCAL}	3.7 GeV	1.8 GeV	1.1 GeV	1.1 GeV
σ	3.7 GeV	1.9 GeV	1.2 GeV	1.1 GeV

Color Singlet Clustering (FCC-ee)

[Garcia, Gergaud, MS]

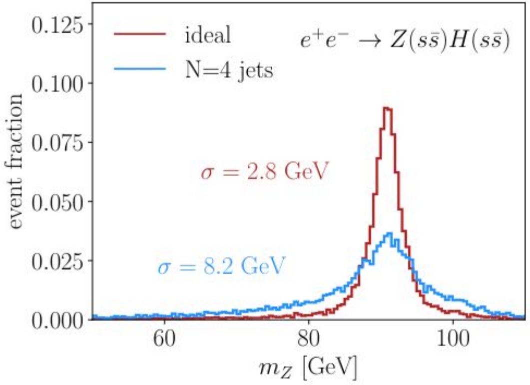
- **boosted** resonances are “easy”:
    - jet substructure techniques
- resolved multi-resonance events are harder (e.g. ZH → jjjj):
    - jet clustering mixes decay products from the two resonances
    - ad-hoc criteria to producing pairings from N=4 jets to N=2 singlets
        - standard heuristics pairs of jets that match singlets mass
            - risk of sculpting backgrounds

$$\chi^2 = \left(\frac{m_{i_1 i_2} - m_{S_1}}{\sigma_{S_1}}\right)^2 + \left(\frac{m_{i_3 i_4} - m_{S_2}}{\sigma_{S_2}}\right)^2 ,$$

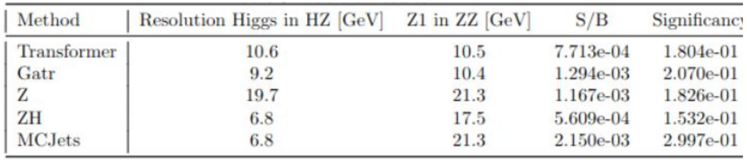


(a)

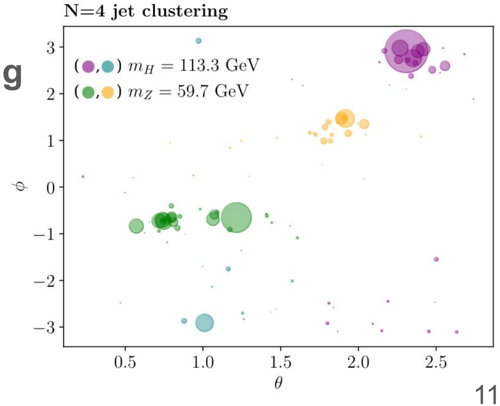
significant resolution loss



→ **supervised (resolved) color singlet clustering**

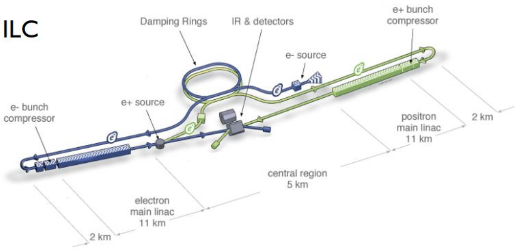


Method	Resolution Higgs in HZ [GeV]	Z1 in ZZ [GeV]	S/B	Significanc
Transformer	10.6	10.5	7.713e-04	1.804e-01
Gatr	9.2	10.4	1.294e-03	2.070e-01
Z	19.7	21.3	1.167e-03	1.826e-01
ZH	6.8	17.5	5.609e-04	1.532e-01
MCJets	6.8	21.3	2.150e-03	2.997e-01

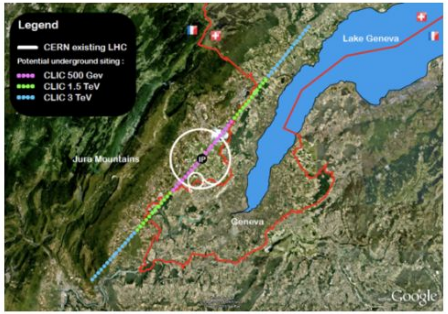


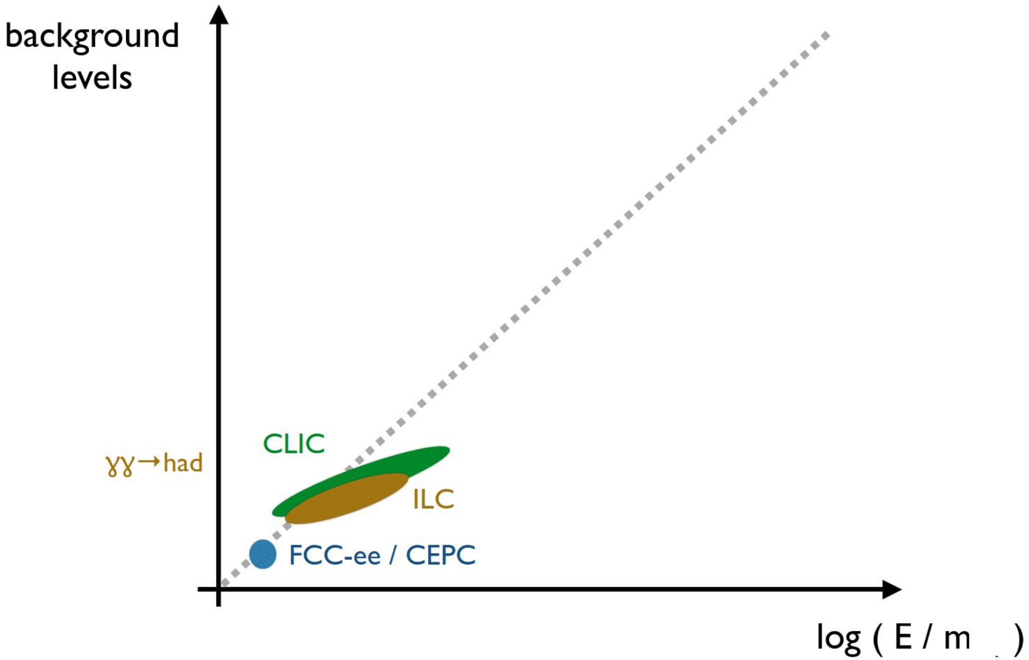
High energy linear colliders

ILC



CLIC





- Linear collider can reach 1-3 TeV
- Gives access to ttH, HH

High energy lepton colliders

[Boronat, Garcia, Vos]

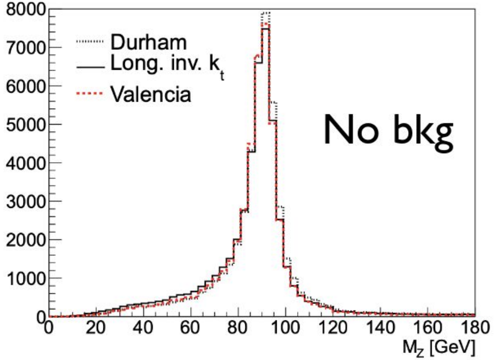
Jet clustering “Valencia Linear Collider” (VLC)

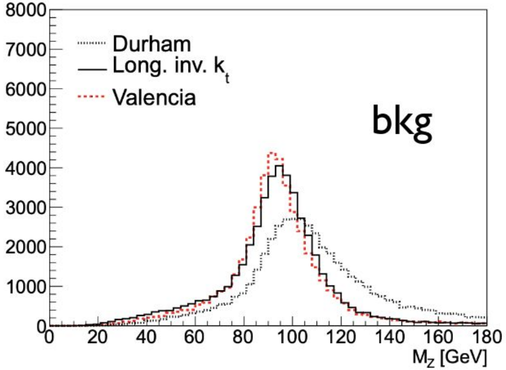
- γγ→hadrons background (isolated energetic, forward)
- beta exponent additional parameter which allows for tuning algorithm
  - governs likelihood of clustering background

$$d_{ij} = min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$

$$d_{iB} = p_T^{2\beta}$$

RMS$_{90}$ [GeV]	E_{4j}	E_W	m_W	E_t	m_t
Durham	23.2	19.6	20.3	19.5	21.4
e^+e^- k_t	25.6	20.8	21.6	20.5	22.8
long. inv. k_t	21.7	18.4	18.9	18.4	20.1
Valencia	21.4	18.0	18.8	18.2	20.0





Kinematic Fit at lepton colliders

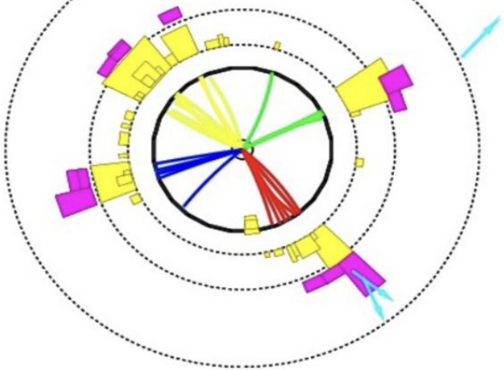
precise **knowledge of center of mass energy**:
→ kinematic fit can be used to improve resolution

e.g for 4 jet final states (ZH, WW, ..), kinematics overconstrained

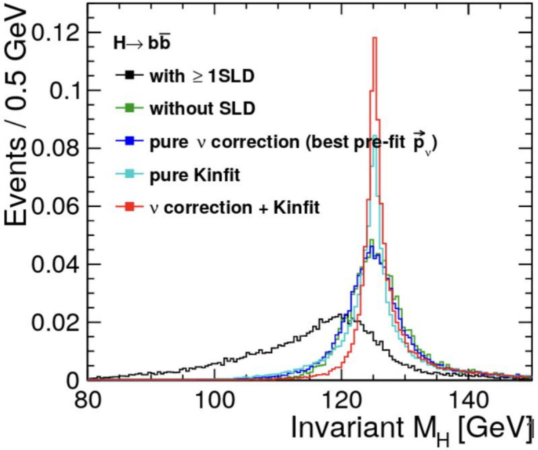
$$\text{for } i = 1, \ldots, N \text{ observed objects, } \sum_i \vec{p}_i = 0 \text{ and } \sum_i E_i = 2E_{beam} = \sqrt{s}$$

Derive covariance matrix C for (p_1,... ,p_4) and minimize with Lagrange multipliers

$$\chi^2(\hat{p}_1, \hat{p}_2, \hat{p}_3, \hat{p}_4) = \sum_{k=1}^{4} \left[\sum_{\alpha\beta} (p_k^\alpha - \hat{p}_k^\alpha)(\mathbf{C}_k^{-1})_{\alpha\beta} \left(p_k^\beta - \hat{p}_k^\beta\right) \right]$$
$$+\lambda_0 \left[\sum_k \hat{E}_k - \sqrt{s} \right] + \sum_{a=1}^{3} \lambda_a \left[\sum_k \hat{p}_k^a \right] + \mu \left[(\hat{E}_a + \hat{E}_b) - (\hat{E}_c + \hat{E}_d) \right]$$



[Einhaus, Radkhorrami]



Jet tagging at FCC

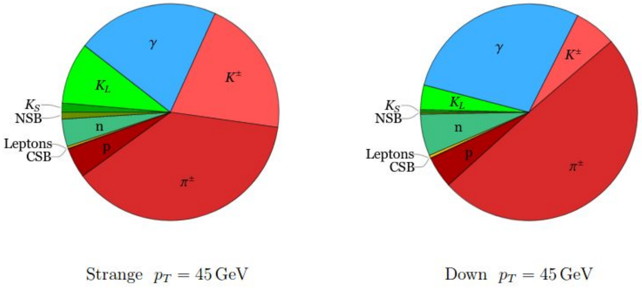
- **b/c-tagging:**
  - Large lifetime, (2-3) mm for ~50 GeV boost
  - Displaced vertices/tracks (Large impact parameters)
  - Large track multiplicity
  - Presence of non-isolated e/μ (20 (10)% in B (C) decays)

- **s-tagging:**
  - Large Kaon content:
    - as tracks (K/pi separation ToF, dEdx, dNdx)
    - Neutral Kaons:
      - K_S 2 tracks
      - K_L ToF vs n

Detector constraints:

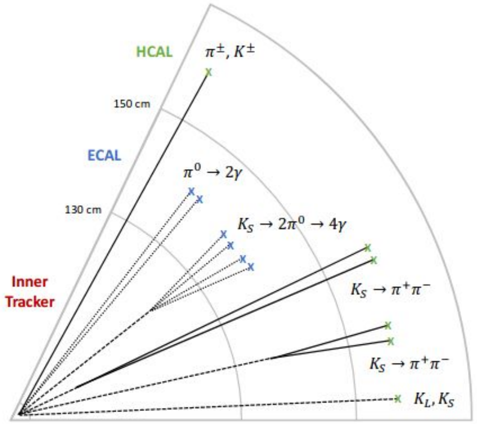
Need power pixel/tracking detectors

- Good spatial resolution
- As little material as possible
- Precise track alignment
- Timing detectors
- Charged energy loss (gas/silicon)



Strange $p_T = 45\,\mathrm{GeV}$ Down $p_T = 45\,\mathrm{GeV}$

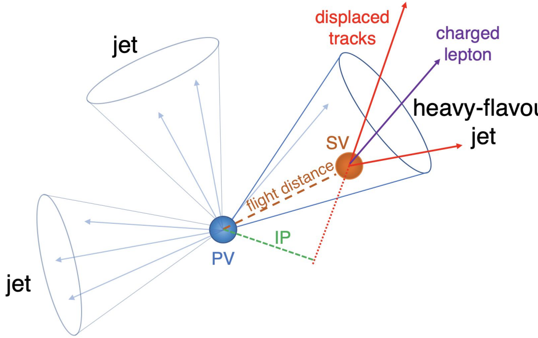
[Nakhai, Shih, Thomas]

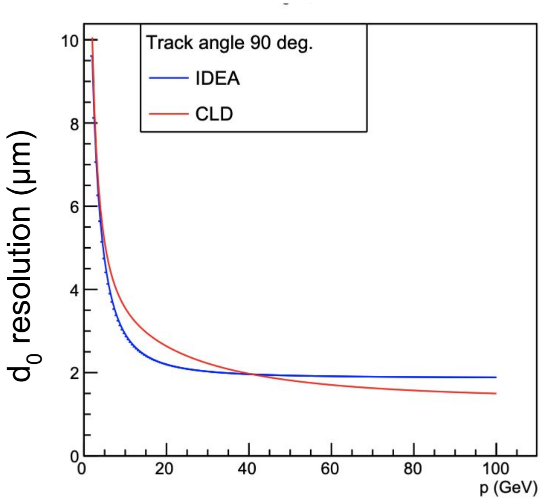


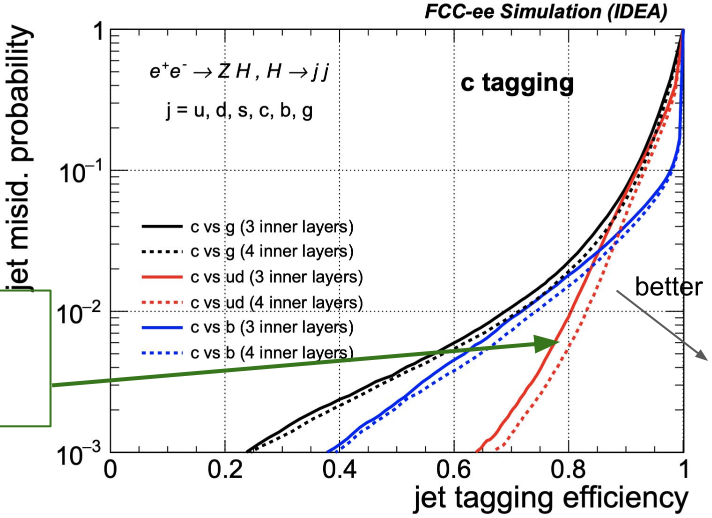
Track impact parameter resolution and vertexing

- **Impact parameter resolution** major driver of jet **charm** and **bottom** jet identification

- precise IP determination driven by:
  - single point resolution
  - **radial distance of first tracking layer** from the interaction point (at large momentum)
    - need small radius beam-pipe
  - material budget X/X_0 (at low p)







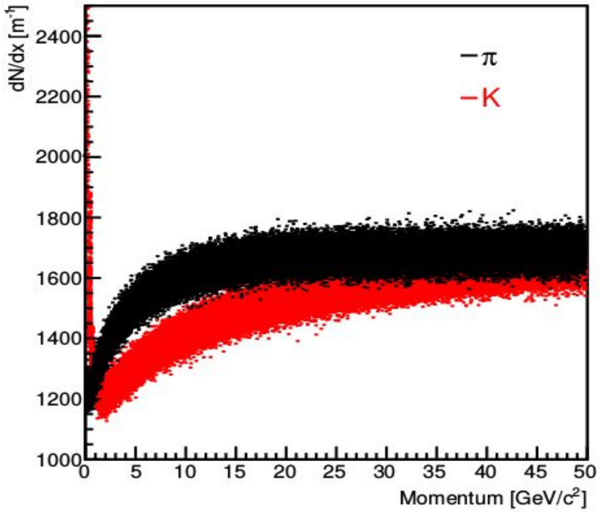
30-40% improvement in bkg rej using :
1st layer at 1 cm

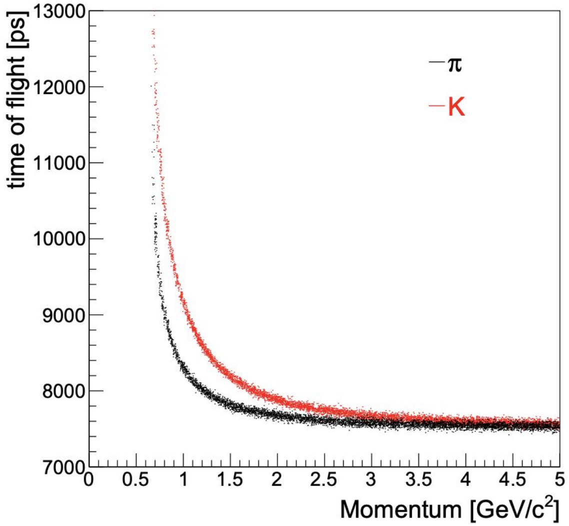
Strange tagging FCC

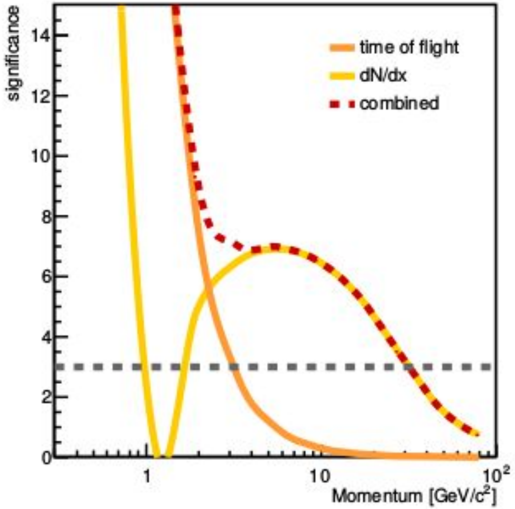
- Kinematic
- Displacement (important for b-tagging)
- Particle Identification:
    - Number of ionization clusters (dN/dx)
    - ToF results in good K/π separation at low-momenta

← input

[Bedeschi, Gouskos, MS]

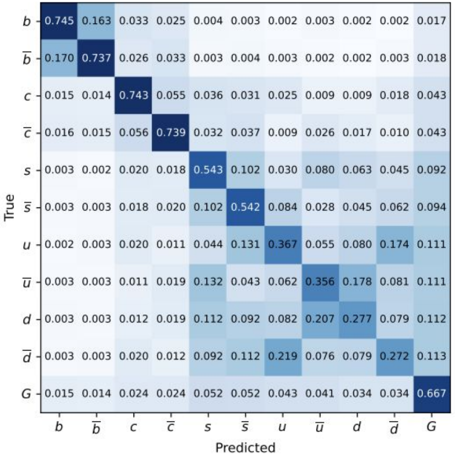






Jet tagging FCC

[Liang, Zhu, Huang, Che, Ruan, Zhou, Qu]



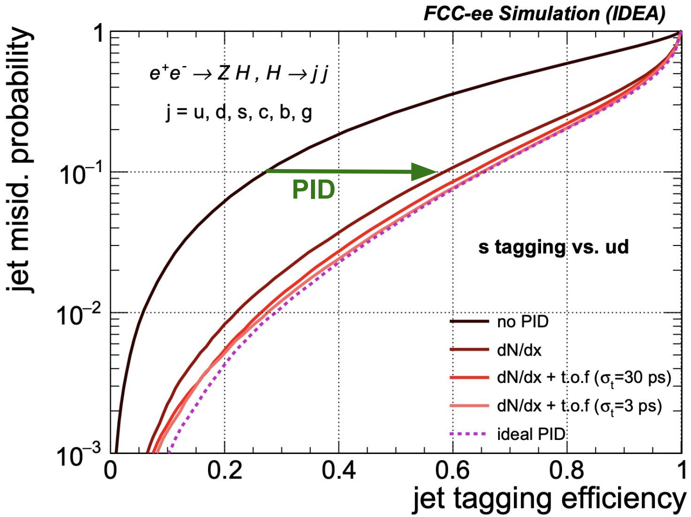
	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.745	0.163	0.033	0.025	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.170	0.737	0.026	0.033	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.014	0.743	0.055	0.036	0.031	0.025	0.009	0.009	0.018	0.043
$\bar{c}$	0.016	0.015	0.056	0.739	0.032	0.037	0.009	0.026	0.017	0.010	0.043
s	0.003	0.002	0.020	0.018	0.543	0.102	0.030	0.080	0.063	0.045	0.092
$\bar{s}$	0.003	0.003	0.018	0.020	0.102	0.542	0.084	0.028	0.045	0.062	0.094
u	0.002	0.003	0.020	0.011	0.044	0.131	0.367	0.055	0.080	0.174	0.111
$\bar{u}$	0.003	0.003	0.011	0.019	0.132	0.043	0.062	0.356	0.178	0.081	0.111
d	0.003	0.003	0.012	0.019	0.112	0.092	0.082	0.207	0.277	0.079	0.112
$\bar{d}$	0.003	0.003	0.020	0.012	0.092	0.112	0.219	0.076	0.079	0.272	0.113
G	0.015	0.014	0.024	0.024	0.052	0.052	0.043	0.041	0.034	0.034	0.667

10.8 ab^{-1} at $\sqrt{s}$ = 240 GeV

Final state	**Comb. [%]**
H → bb	0.22
H → cc	1.70
H → gg	0.9
H → ss	120

[Bedeschi, Gouskos, MS]

s-tagging



strange vs light rejection crucial vs Z(ss)Z(jj) and Z(ss)H(gg) backgrounds

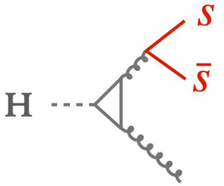
eff = 65% , mistag = 10%

Can approach SM strange Yukawa sensitivity at FCC-ee!

Open questions in Hss and strange fragmentation

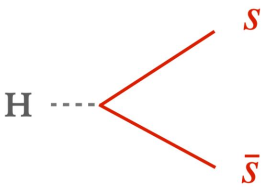
[spira] [salam]

- Dalitz contribution?
  - ○ contamination seems under control since lives in a different phase space
    - ■ H→gg at N^{3}LO required
      - with NLL showers



Dalitz decay ($\alpha_s^3 y_t^2$)

~ α_s suppressed relative to $H \to gg$

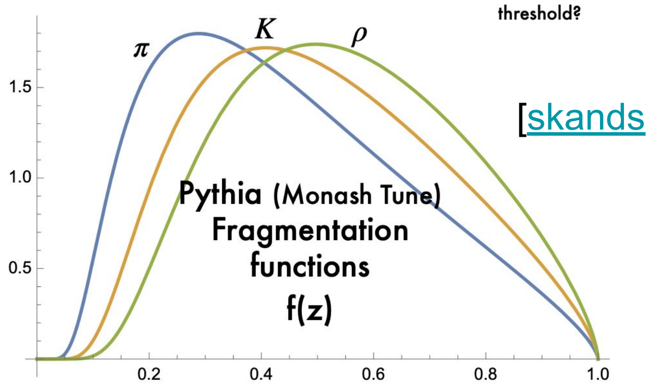


Yukawa decay (y_s^2)

	BR
H → gg	8.1×10^{-2}
H → ss	$\sim 2 \times 10^{-4}$

Ratio is ~ 400

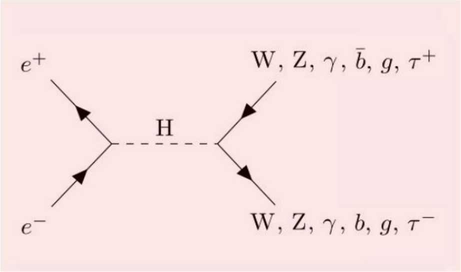
- strange fragmentation functions?
  - ○ used in our taggers
  - ○ average FF well constrained
    - ■ width is not
      - High precision hadron data required
        - ○ 10^{11} Z→qq events !

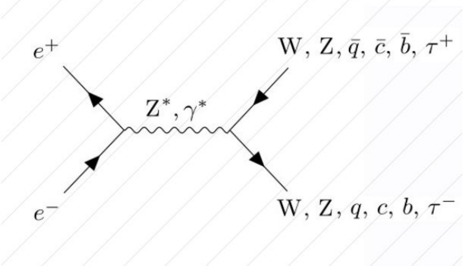


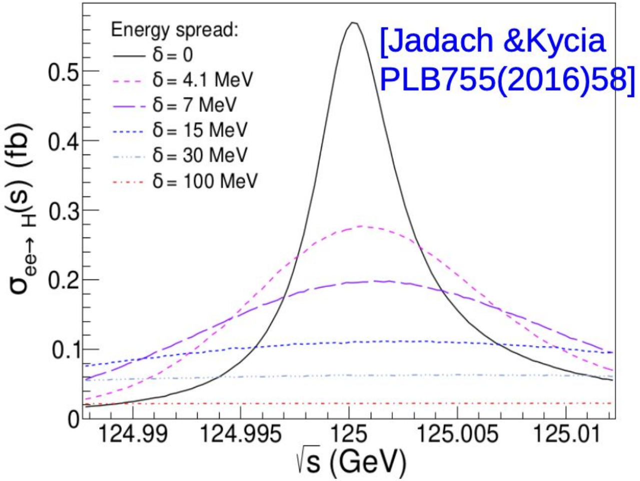
[skands]

H→gg and gluon tagging

- s-channel **ee→H** production provides unique opportunity to **probe electron Yukawa**
- very challenging, even with mono-chromatisation
  - ISR and BES smear the exp. width

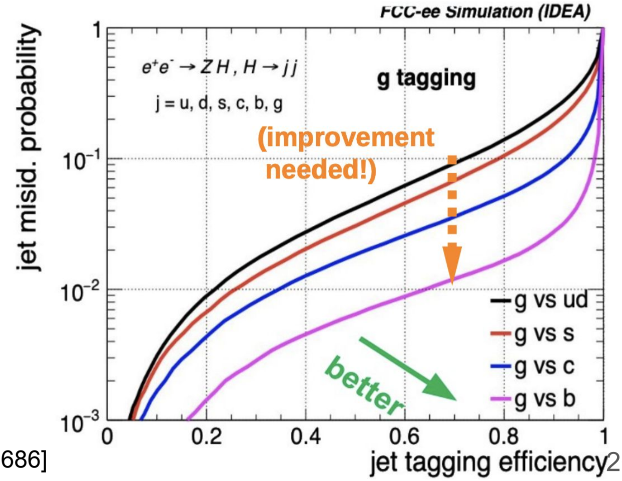






[Jadach &Kycia PLB755(2016)58]

- exploit **H→gg** final state against **Z→qq** background (no prompt gg)
- requires 1% light quark mistag rate in **gluon tagging**
  - 10x light rejection vs state-of-the-art required to approach electron yukawa
    - SM sensitivity in ~ 2 years



d'Enterria [arXiv:2107.02686]

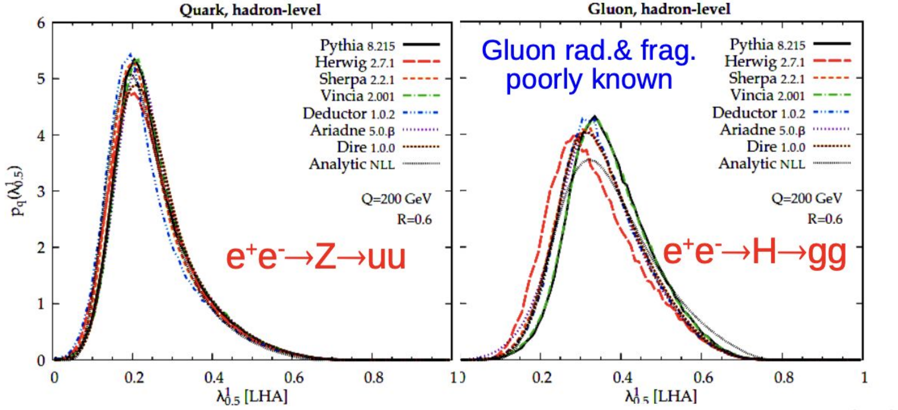
Gluon tagging , open questions

- (g vs q) taggers make use of LL parton showers, that differ substantially from one MC to another, in particular for gluons

- quark showers well constrained from LEP, gluons less-so

Need:

- (N)NLL accurate showers (e.g. Panscale)
- clean data for tuning (in varying kin. regimes exploiting ISR):
  - 10^5 H→**gg** events
  - 10^{11} Z→ bb**g**

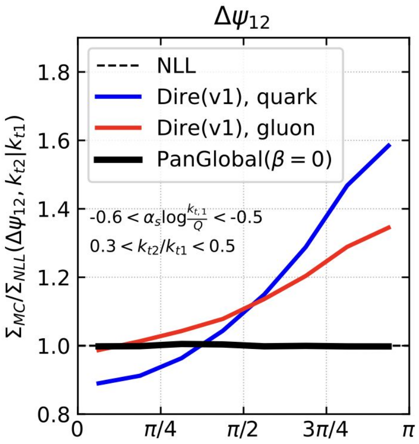


Gluon rad.& frag. poorly known

$e^+e^-\rightarrow Z\rightarrow uu$

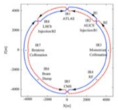
$e^+e^-\rightarrow H\rightarrow gg$

un-physical differences in q vs g in LL shower

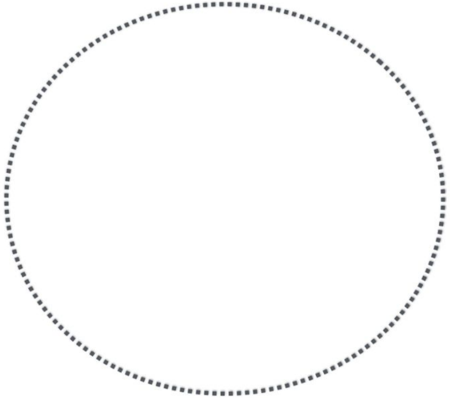


[Soyez]

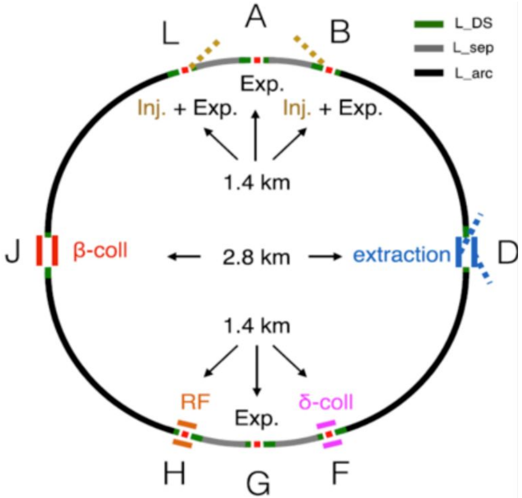
High energy hadron machines



HE-LHC



LE-FCC



FCC-hh

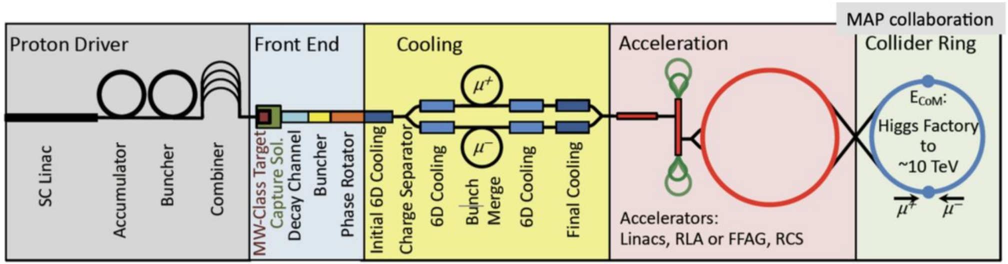
sqrt(s)	27 TeV
Lumi	15 ab^{-1}
B	16 T
circ.	27 km

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

High energy muon collider



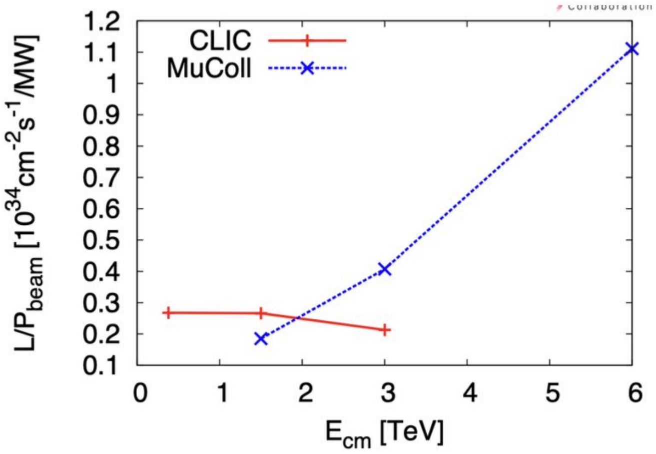
Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision



- only lepton machine capable of reaching **multi TeV energies** in a circular ring
  - electrons radiate too strongly
- many challenges (cooling, neutrino hazard, beam induced background ..)

Processes at FCC-hh

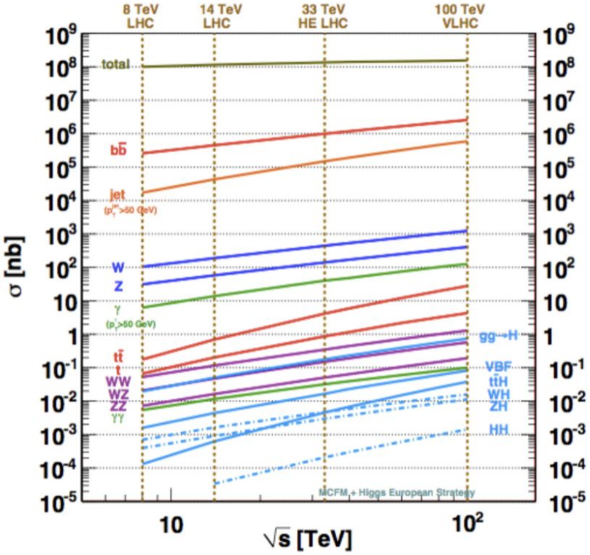
Massive boosted samples (30 ab^{-1}):

10^{12} tops

10^{9} top with p_T > 1 TeV

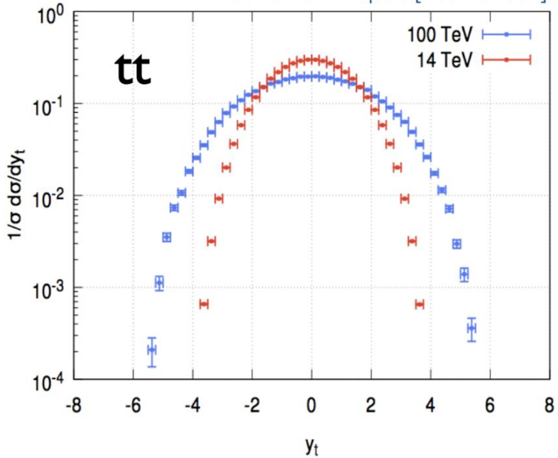
100k top with p_T > 5 TeV

1000 top with p_T > 10 TeV



- Among all SM “backgrounds” , ttbar production gains the most in rate @100 TeV
- tt > HH > VV > H > V

100 TeV SM Report [1607.01831]

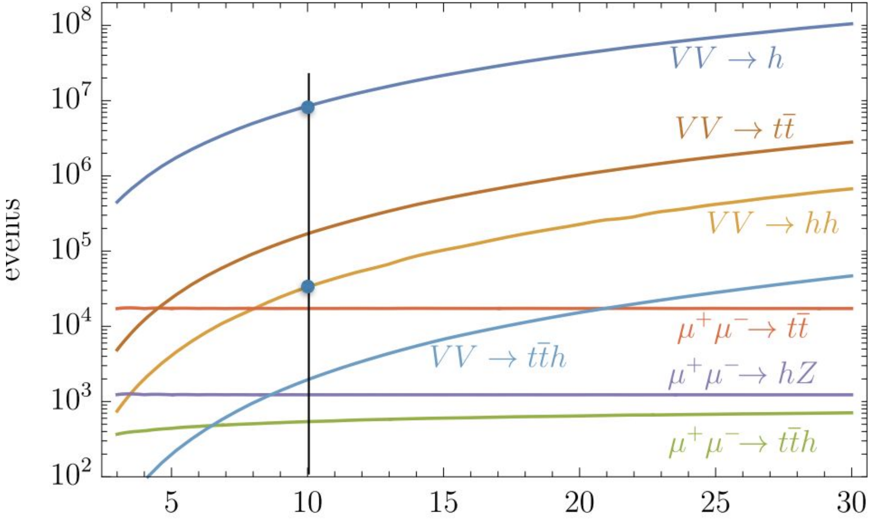


Physics at threshold goes forward

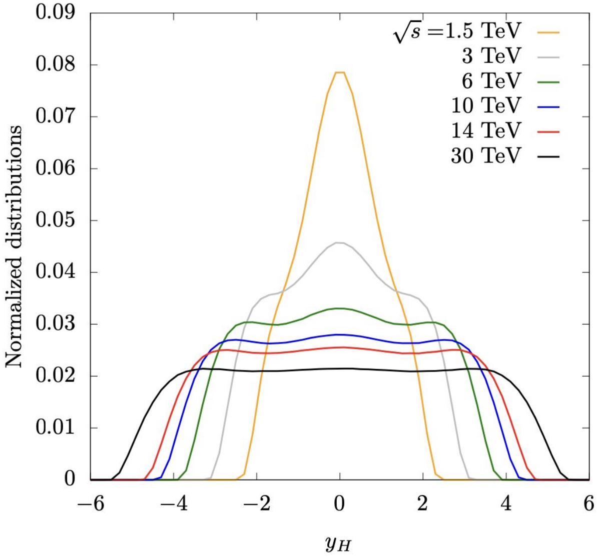
- need more coverage

FCC-hh physics benchmarks with jets : HH→bbXX, ttH, ttZ, ..

Processes at Muon collider



[Maltoni et al.]



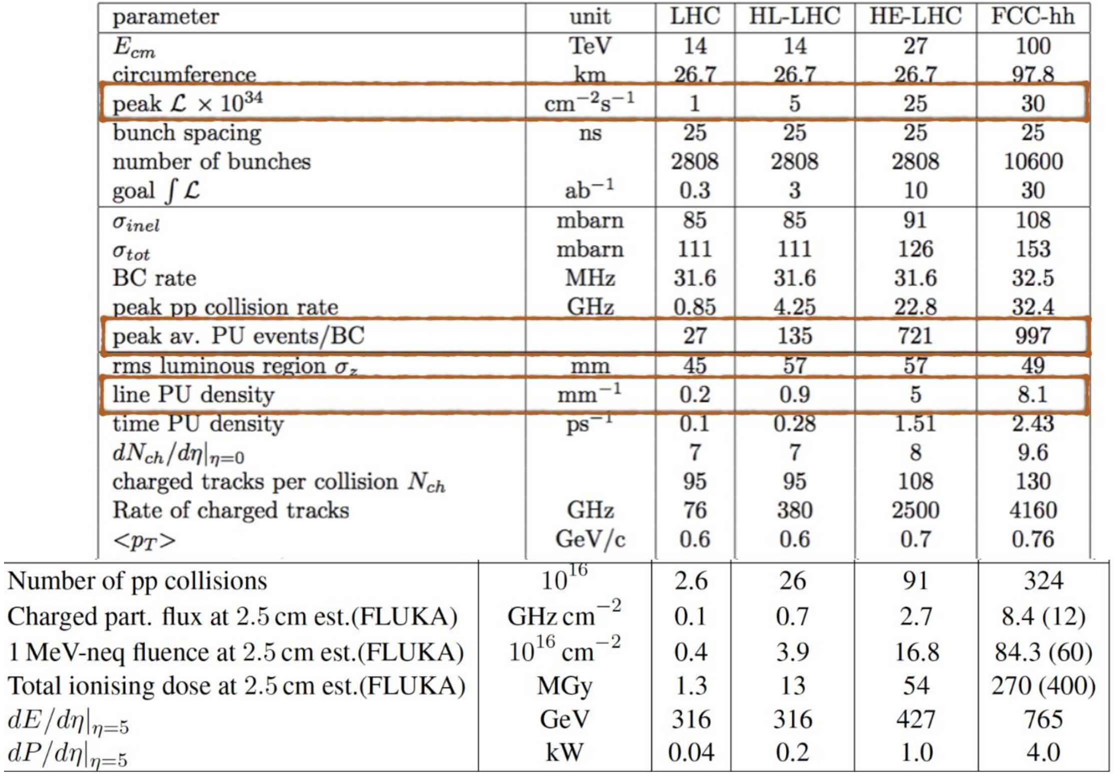
Physics at threshold goes forward

- Production modes:
  - direct mass BSM via s-channel (plus recoil eventually)
  - Weak boson fusion

Muon physics benchmarks with jets : H, HH, HHH, EWK multiplets

Hadron Machines specs and detector requirements

lumi & pile-up



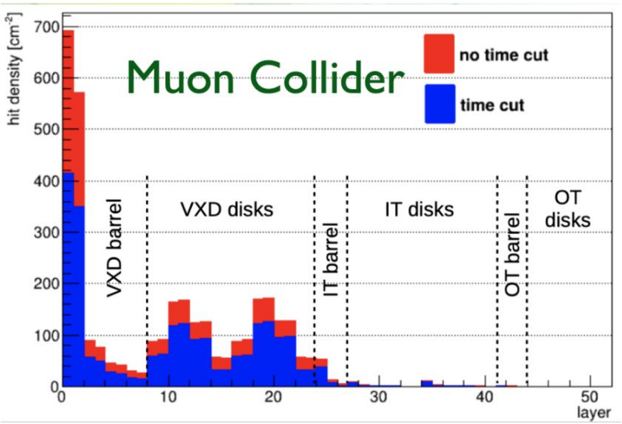
parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$cm^{-2}s^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
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
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

→ x6 HL-LHC

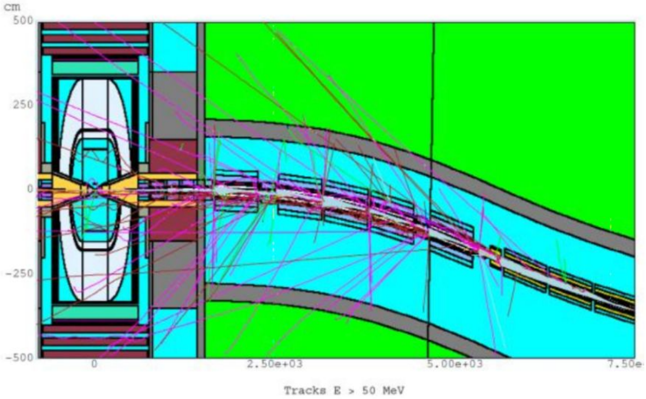
LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

but also x10 integrated luminosity w.r.t to HL-LHC

Muon collider machine specs

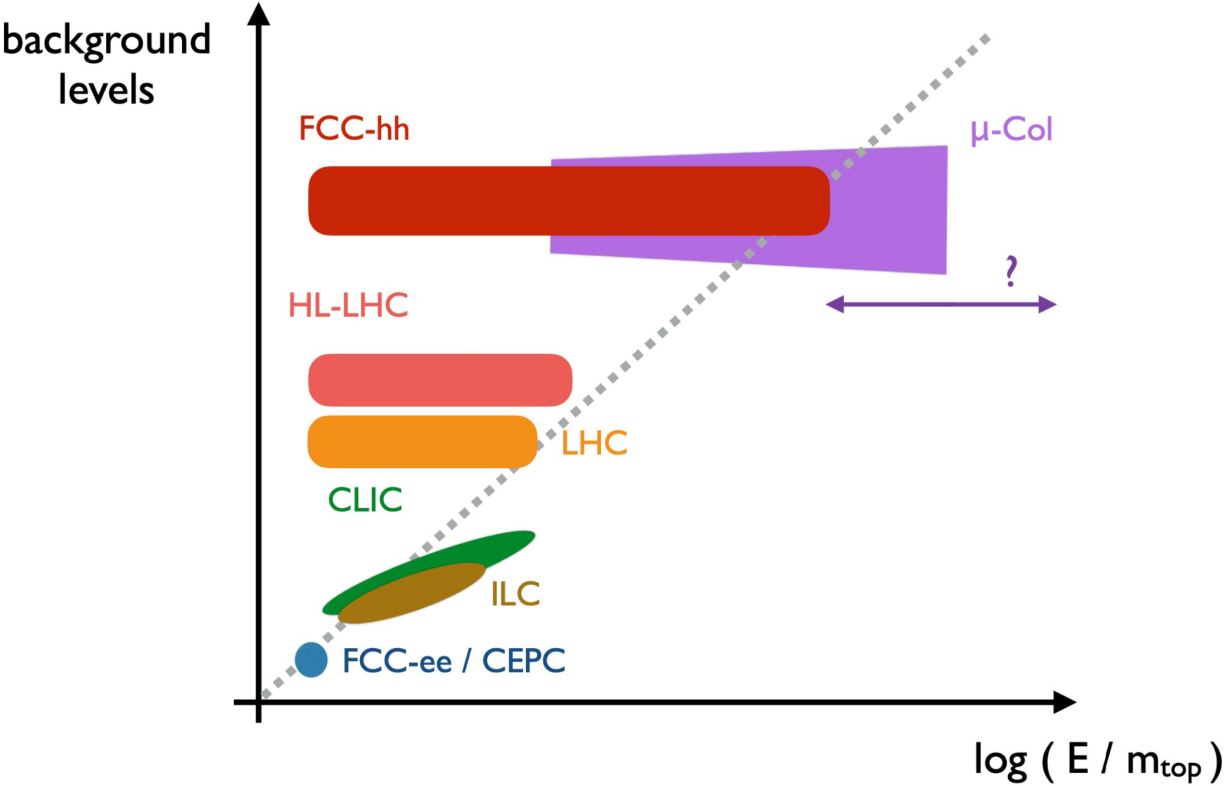


charged fluence: 400-700 (cm^{-2} / BX)

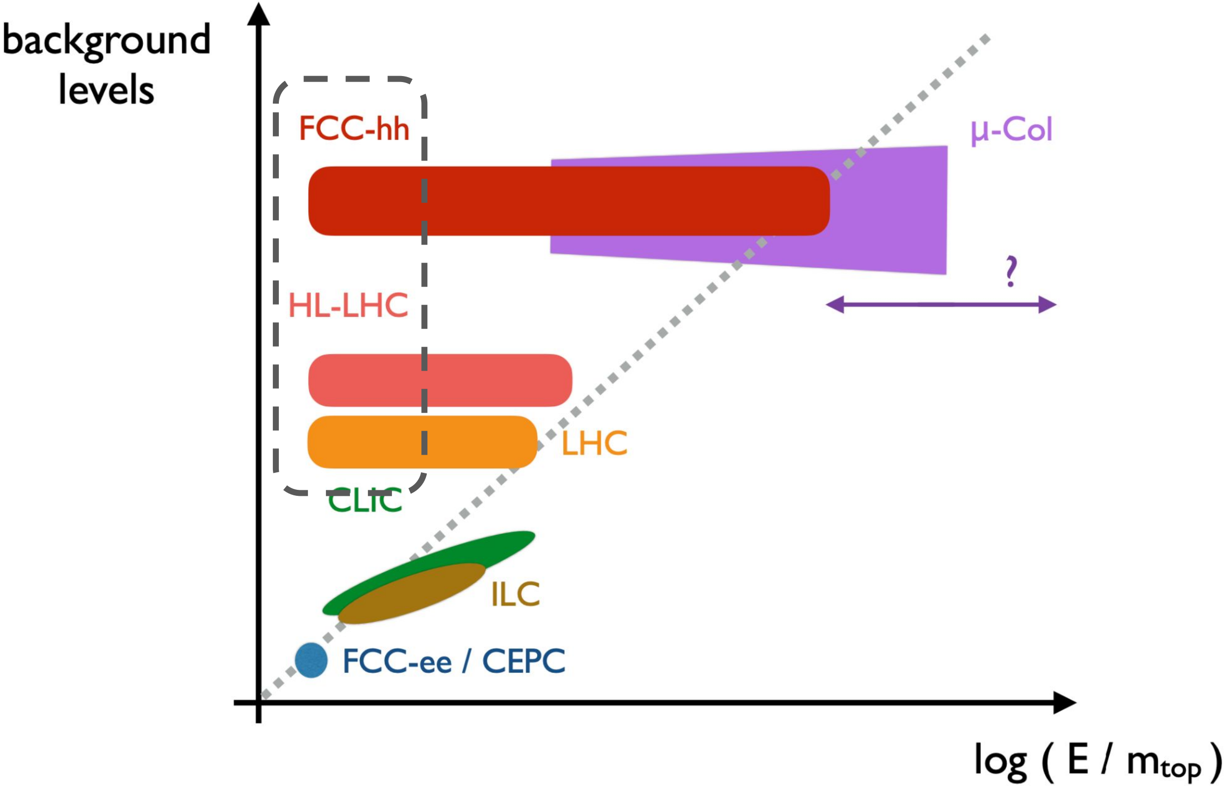


- high occupancy (HL-LHC < muCol < FCC-hh), but low collision rate (~ 50 kHz vs 40 MHz)
- at threshold (or low energy) jet reconstruction will suffer from similar limitations as the FCC-hh (large PU → large Beam induced background)
  - despite some conceptual differences (directionality, energy … → timing cuts)
  - jet definition: probably Valencia like algorithm in exclusive mode since BIB (but no ISR, no UE)

Future high energy facilities



Muon colliders

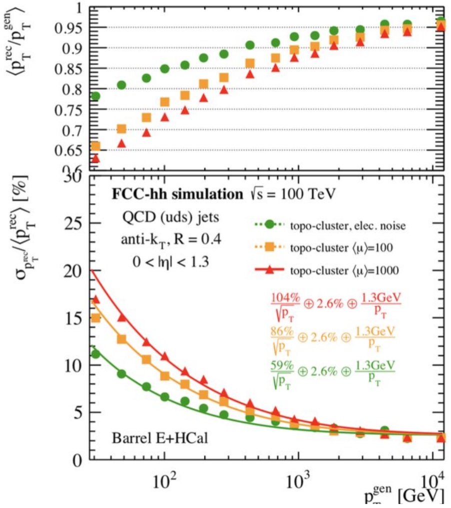


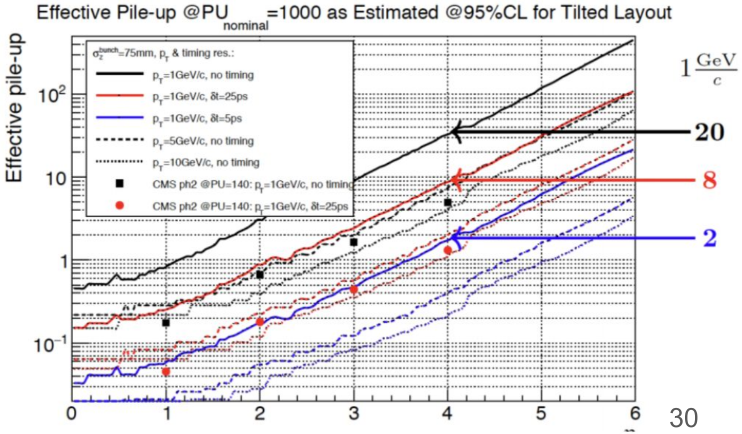
Experimental challenges for jets (at threshold)

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

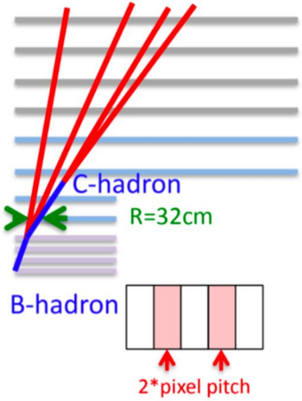
- PU subtraction techniques
  - charged hadron subtraction
    - **timing information (5-10 ps resolution)**
      - **forward!**
  - Residual:
    - area-subtraction
    - PUPPI reconstruction
    - advanced graph based-ML

1912.09962





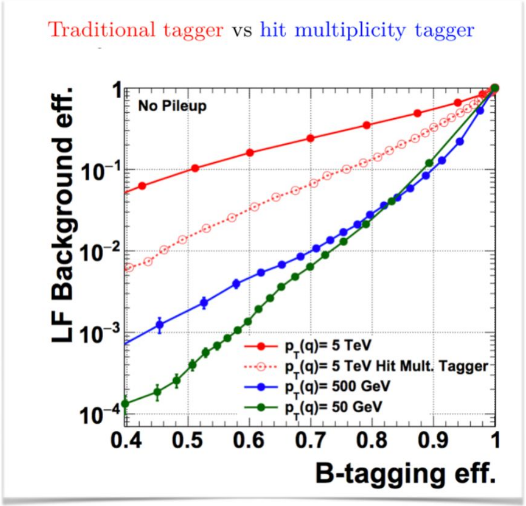
High pT flavor tagging

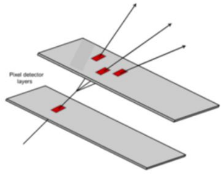


Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices

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





arXiv:1701:06832

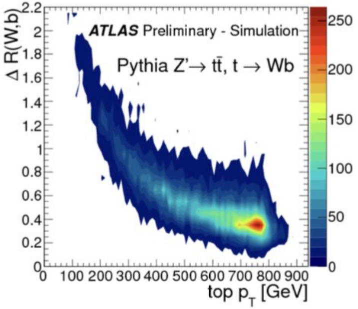
To be verified in high pile-up environment.

- Change in paradigm: heavy flavour tagging
- **multi-TeV b-Hadrons** decay **outside the pixel volume** ($p_T(b) = 2$ TeV → $\gamma c\boldsymbol{\tau} = 50$ cm)
- Need to adapt identification algorithms for identifying multi-TeV tops

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

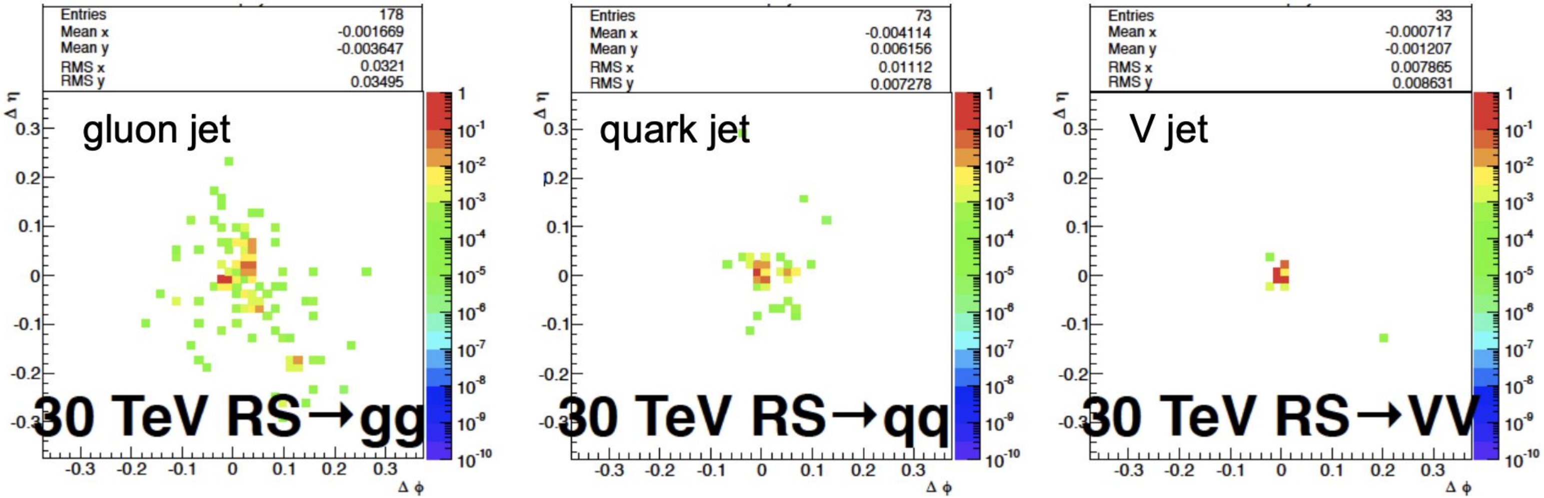
- Naive approach:
  - use calo for energy measurement
  - tracking for substructure identification

in CMS:

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

Color Singlets (W/Z/H)

[Pierini]

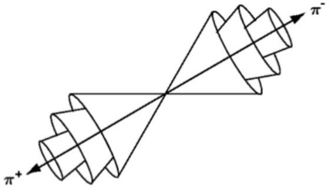


- **Gluon/quark** jet looks the same at 50 GeV and 5 TeV (**QCD is ~ scale invariant**)
- **Color Singlets** look like taus (do not radiate, a part from occasional QED/EWK shower)
    - **high mass, highly isolated, highly collimated tracks**

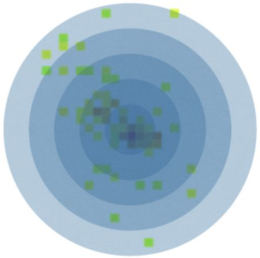
Boosted Color Singlet ID

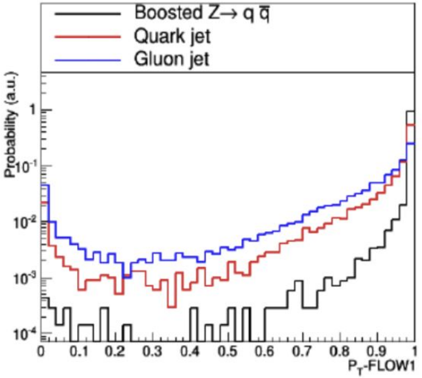
[Pierini]

~ isolation variable



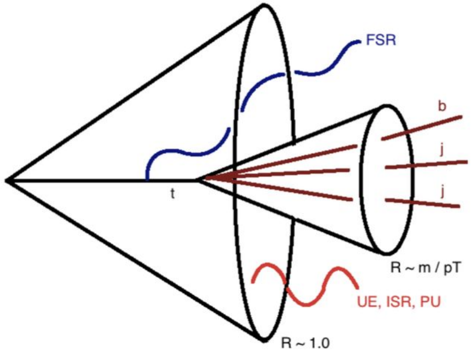
$$p_T^i(flow) = \frac{\sum\limits_{p\epsilon C_i} p_T^p}{p_T^{jet}}$$



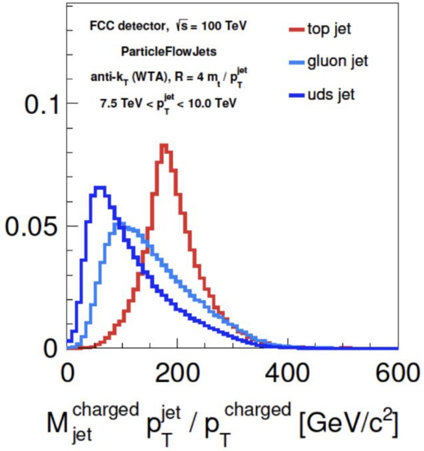


Loss in performance, but no show stoppers
Very simple heuristic based , can probably do much better with today's techniques

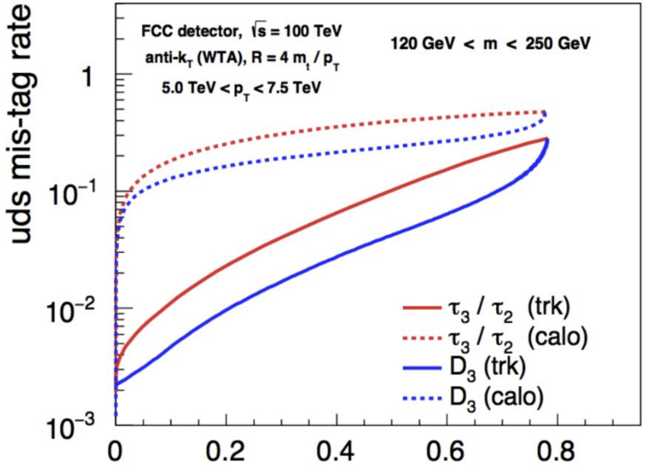
Boosted Colored Resonances



Track- based jet Mass



Very simple heuristic algo



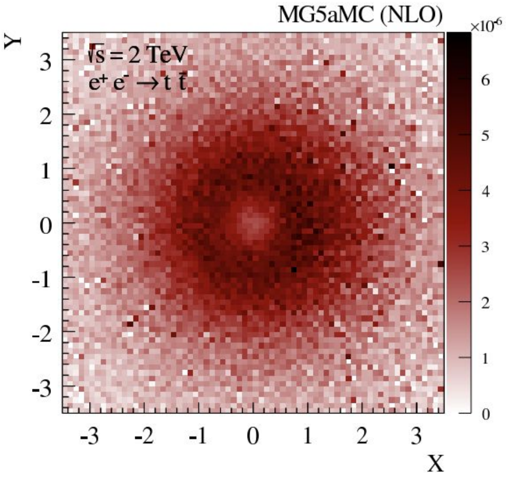
- Multi TeV top radiates FSR at a typical scale angular scale ~ m / pT (deadcone)
- Large cone FSR can spoil mass by adding $\Delta m \sim m_{top}$ even for 1 GeV emission
  - → use shrinking cone algo by reclustering with R ~ 4m/pT
  - use tracking for substructure

The deadcone effect for massive colored res.

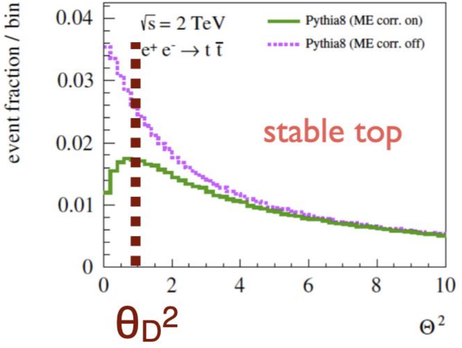
FSR in soft and collinear limit :

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

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

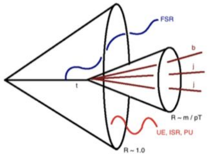


Maltoni, MS, Thaler [1606.03449]

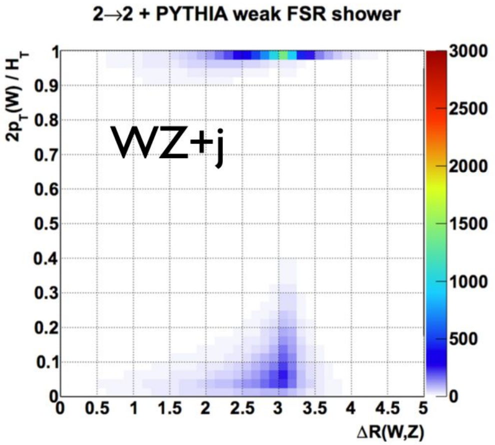


$$\boxed{\theta_D \equiv \frac{m_q}{E_q}}$$

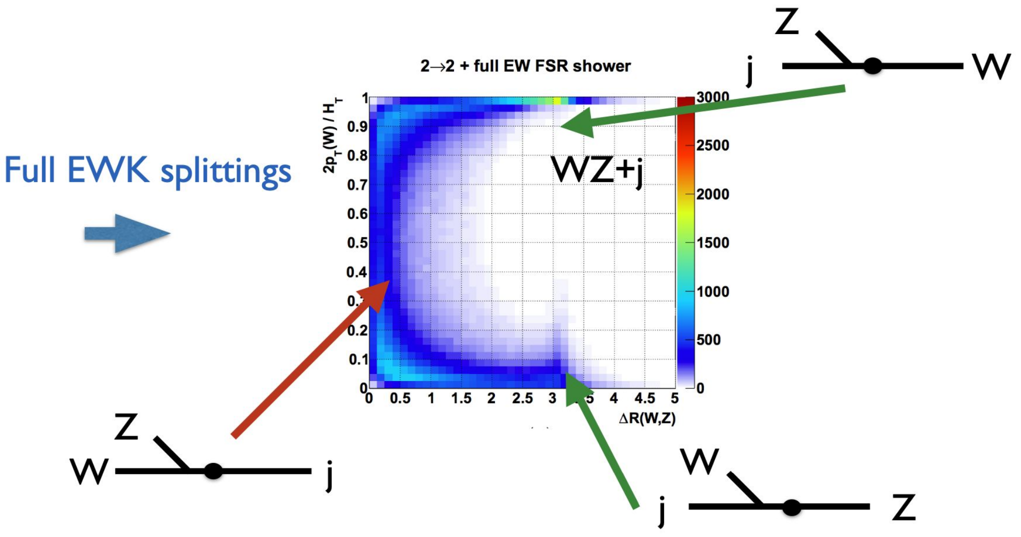
for the top can be pretty large angle



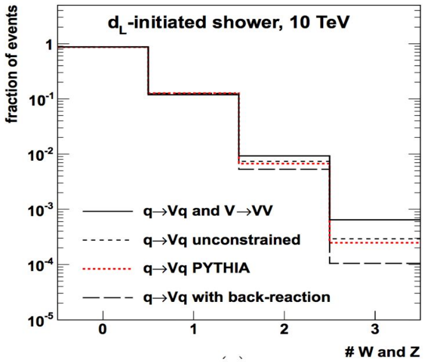
Electroweak showers



Full EWK splittings



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?

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

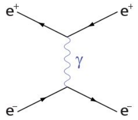
- High energy lepton (μ-Col) and hadron collider (FCC-hh)
    - at threshold:
        - SM Physics is forward, challenging machine backgrounds (PU, BIB)
            - precise tracking/timing
    - Hyper boosted regime (p_T > 10 TeV)
        - calorimeters cannot resolve substructure
        - tracking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

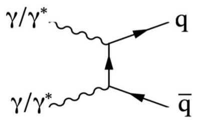
FCC-ee Detector requirements - general considerations

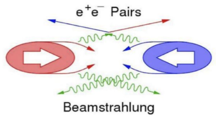
- Requirements for Higgs and above have been studied to some extent by LC:
    - we want a detector that is able to withstand a **large dynamic range**:
        - in energy (√s = 90 - 365 GeV)
        - in luminosity (L = 10^{34} - 10^{36} cm^2/s)

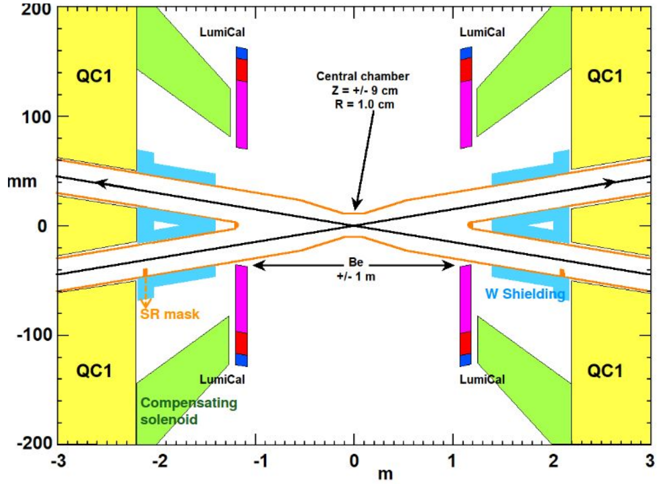
- most of the **machine induced limitations are imposed by the Z pole run**:
    - large collision rates ~ 33 MHz and continuous beams
        - no power pulsing possible
    - large event rates ~ 100 kHz
        - **fast detector response / triggerless** design challenging (but rewarding)
        - **high occupancy** in the inner layers/forward region (Bhabha scattering/γγ hadrons)
    - beamstrahlung

- **complex MDI:** last focusing quadrupole is ~ 2.2m from the IP
    - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical emittance/inst. Lumi via SR)
        - **limits the achievable track momentum resolution**
    - “anti”-solenoid
        - limits the acceptance to ~ 100 mrad



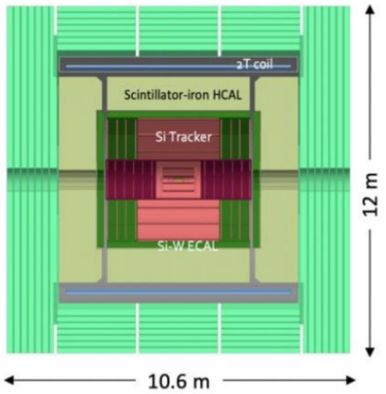






FCC-ee Detector Benchmarks

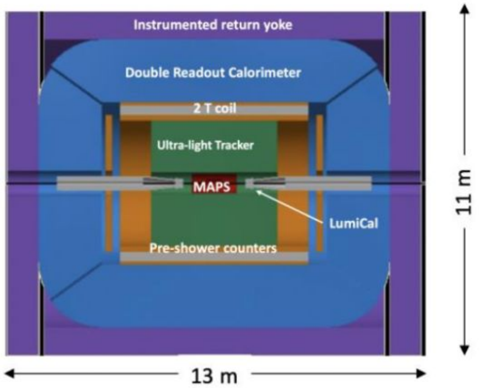
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

CDR

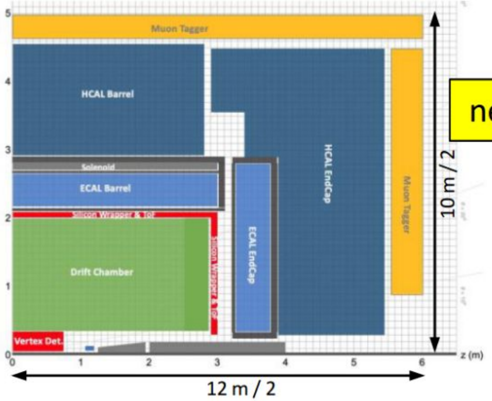
IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

new



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

Physics landscape at the FCC-ee/CEPC

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/***τ*** factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, ***τ*** pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Detector requirements at the FCC-ee/CEPC

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
“boosted” B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

Momentum resolution

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

impact parameter resolution for large displacement

timing

triggerless