Top reconstruction and tagging at future colliders

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CERN

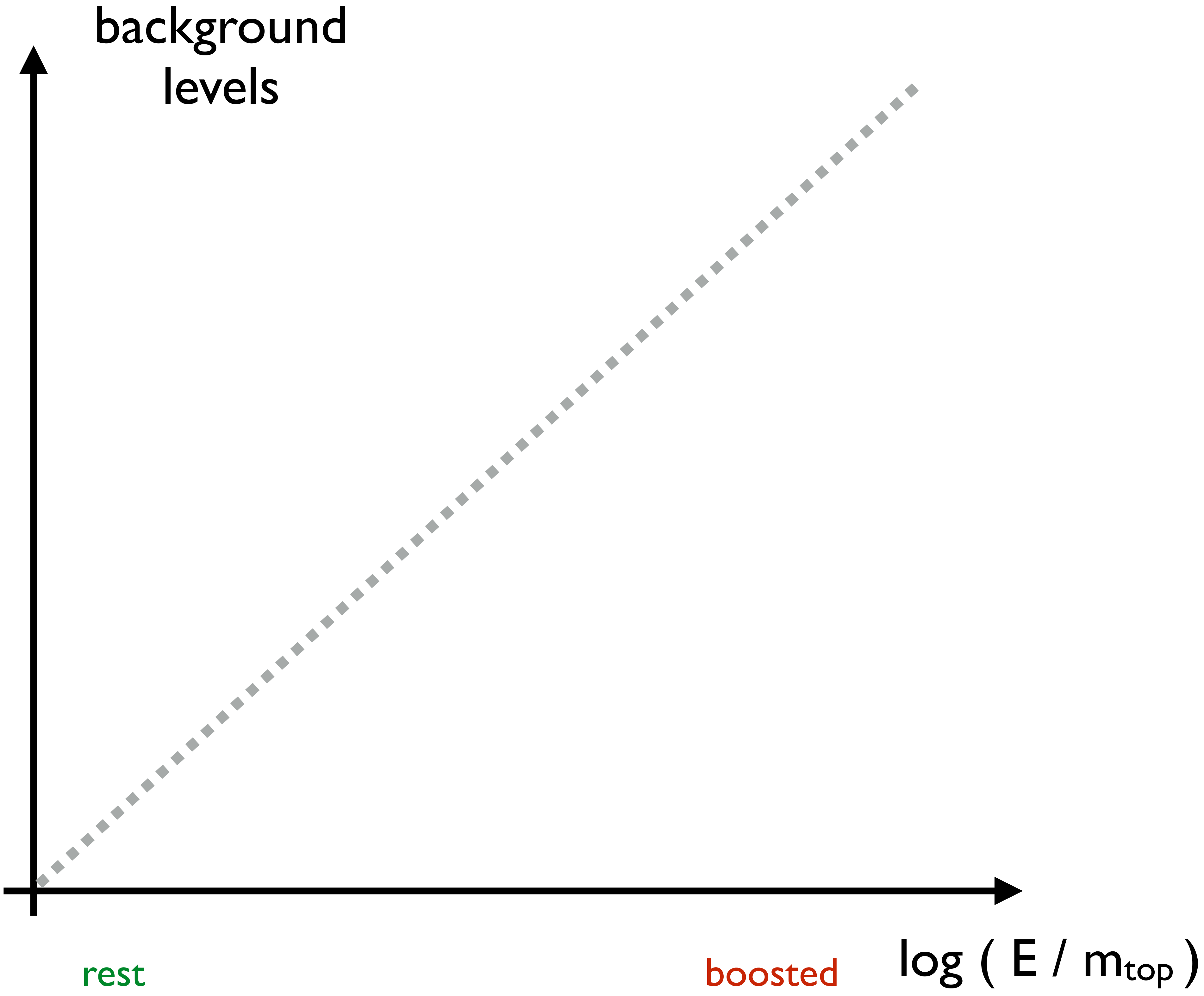
Top 2021

Boost vs exp. backgrounds

pile-up

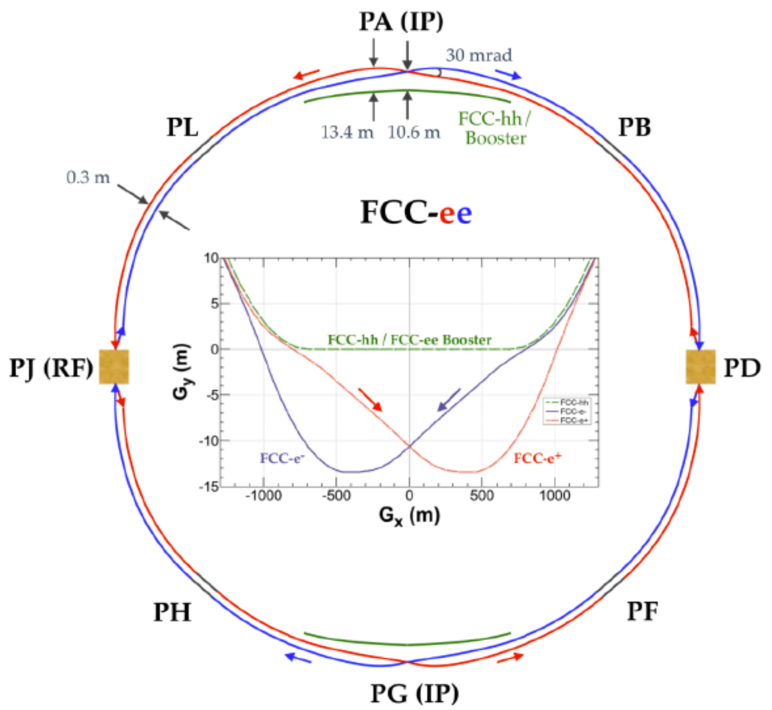
BIB

γγ→had

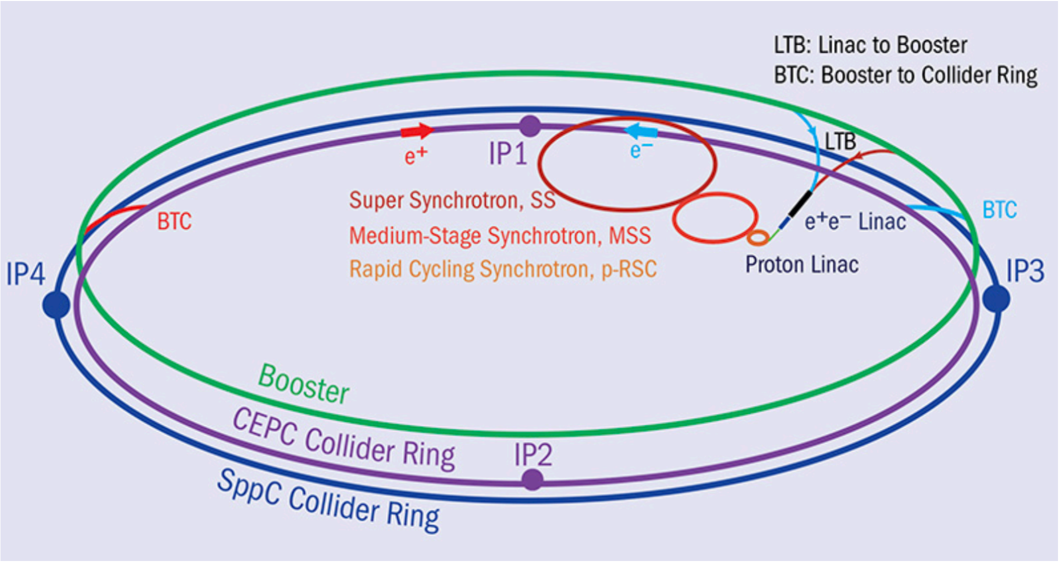


FCC-ee / CEPC

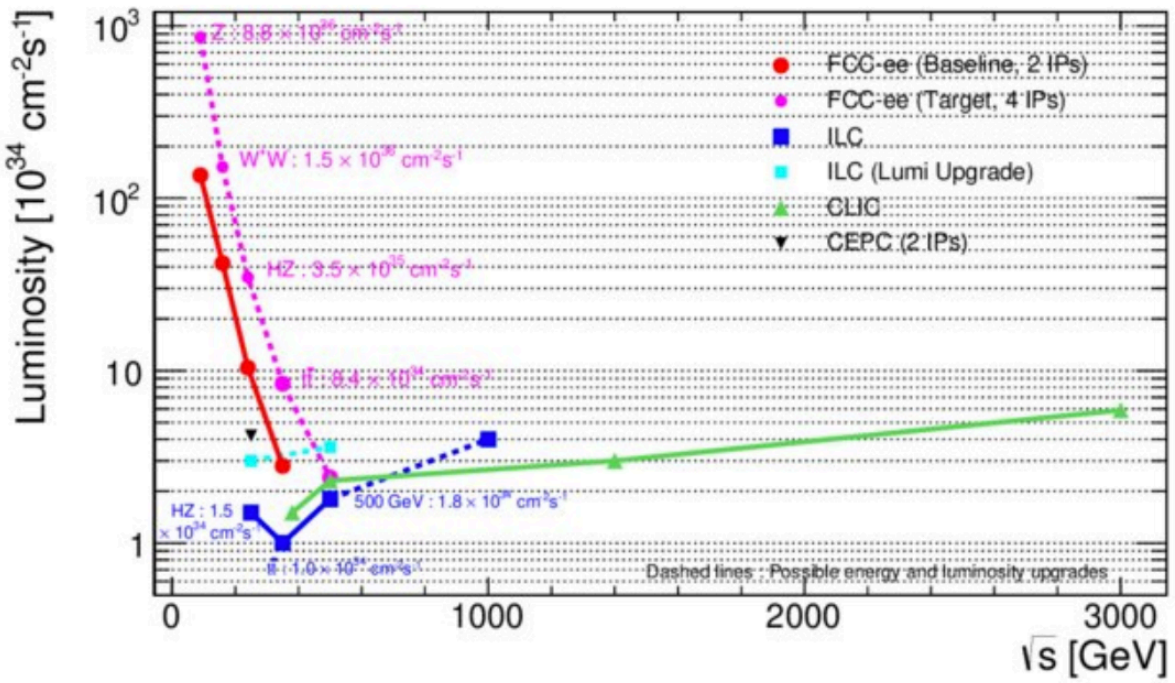
FCC-ee



CEPC



- Maximum E_{CM} ~ 350 GeV (limited by synchrotron radiation)
- Very high luminosity at low energy (Z > W > H > t)
- Benefits:
  - Clean environment , allow for multiple experiments



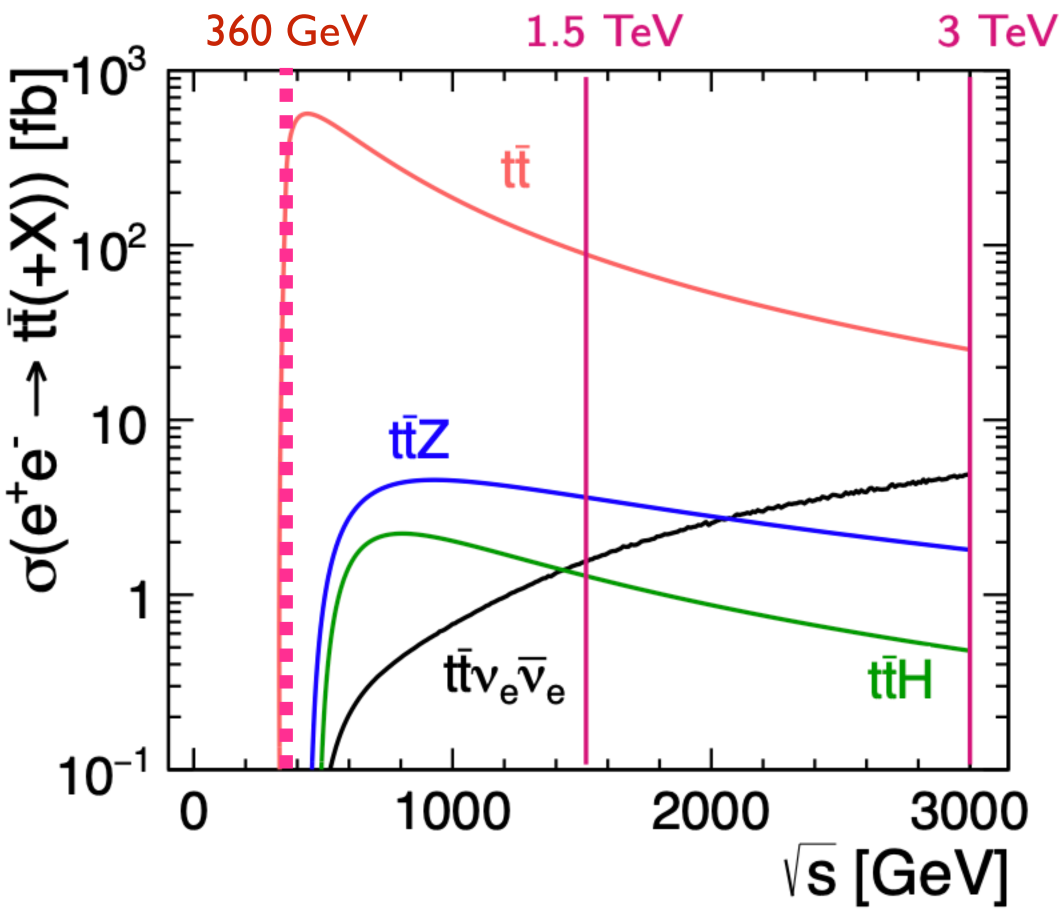
Parameter	Z	W	H	t
Cm E [GeV]	91.2	160	240	350
FCC-ee				
L [10^{34} cm^{-2}s^{-1}]	200	28	8.5	1.8
Years op.	4	2	3	5
Int. L / 2 IP [ab^{-1}]	150	10	5	1.5
CEPC				
L [10^{34} cm^{-2}s^{-1}]	32	10	3	
Years op.	2	1	7	
Int. L / 2 IP [ab^{-1}]	16	2.6	5.6	

FCC-ee / CEPC

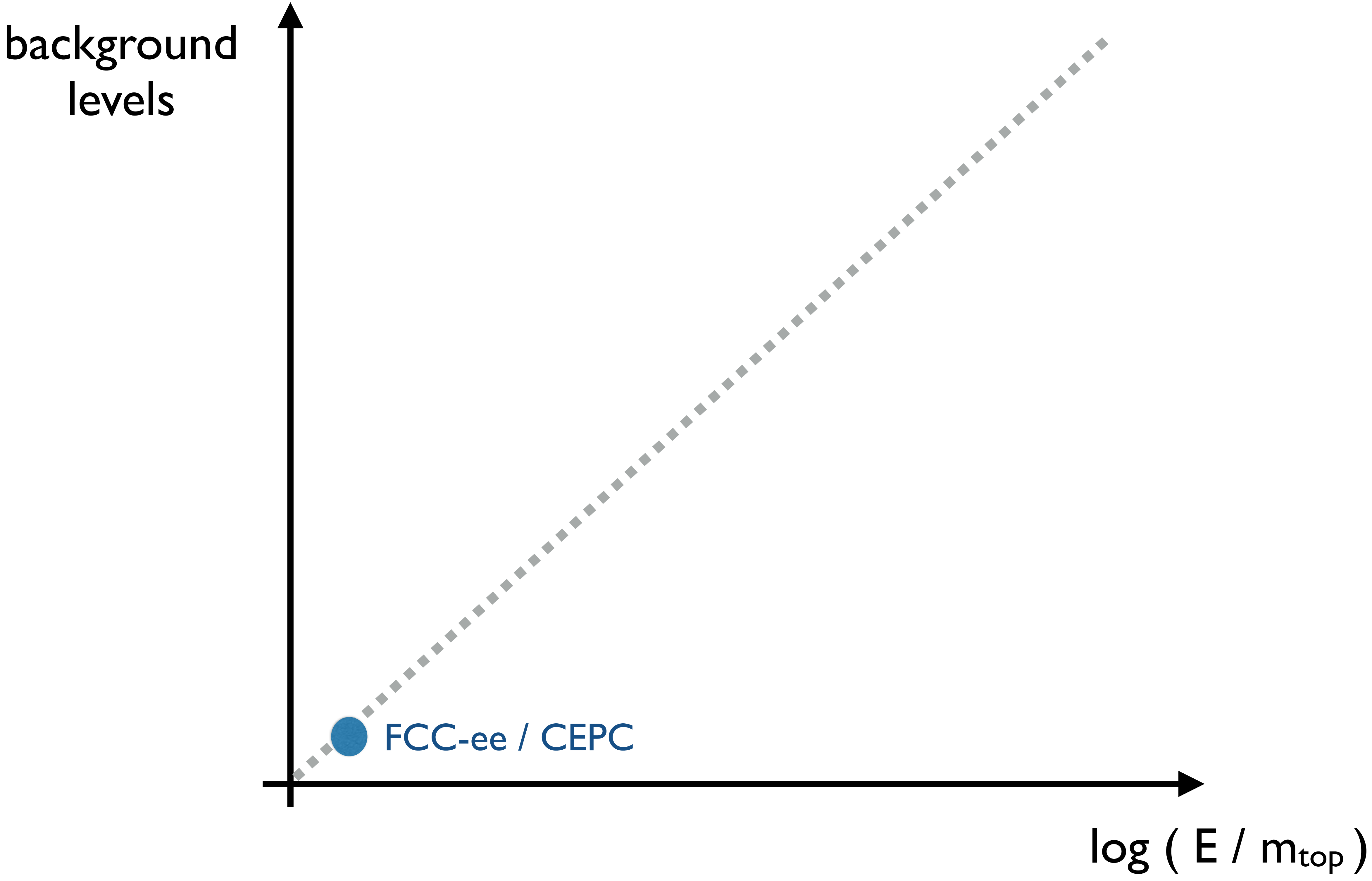
Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold	365 GeV
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	8.1 ab^{-1}	1.95 ab^{-1}	0.22 ab^{-1}	0.39 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4

- 1 M tops FCC-ee:
  - top mass threshold
  - ttZ/ttɣ coupling
  - FCNCs , (V_{ts} ?)

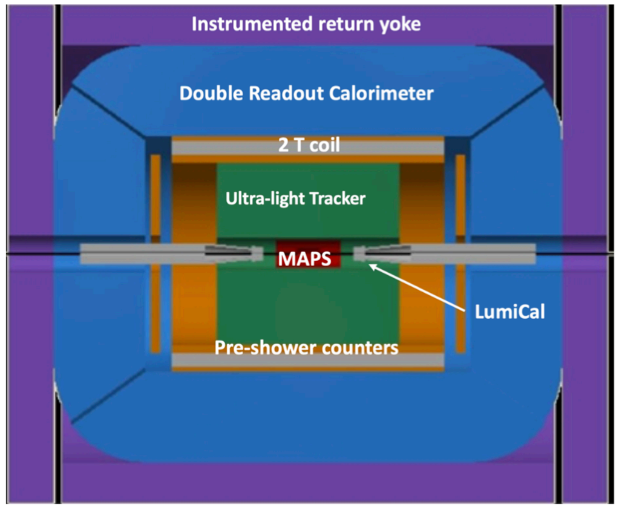
Tops produced at threshold,
with ~low statistics



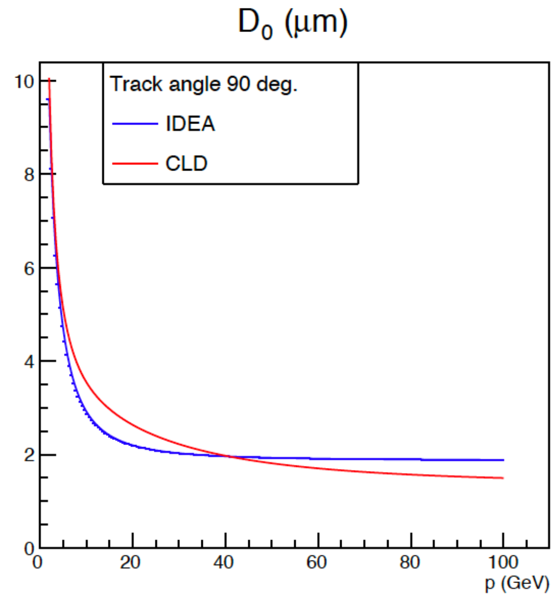
Boost vs exp. backgrounds



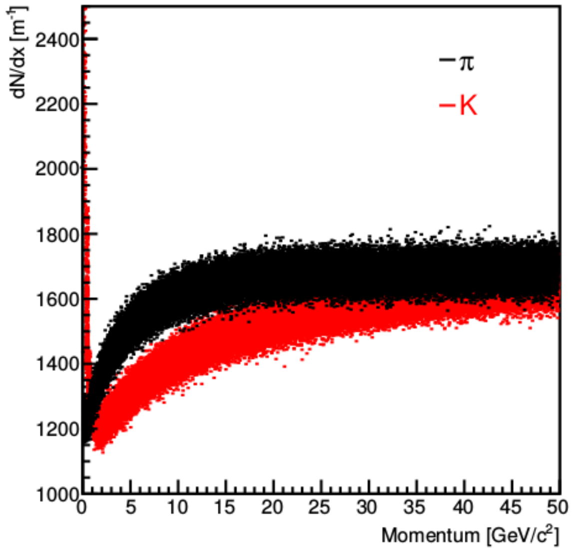
Detector for flavour tagging (IDEA - FCCee)



- To extract the most:
  - electron/tau final state (low mass tracker)
  - excellent jet energy resolution
  - excellent jet flavour tagging capabilities

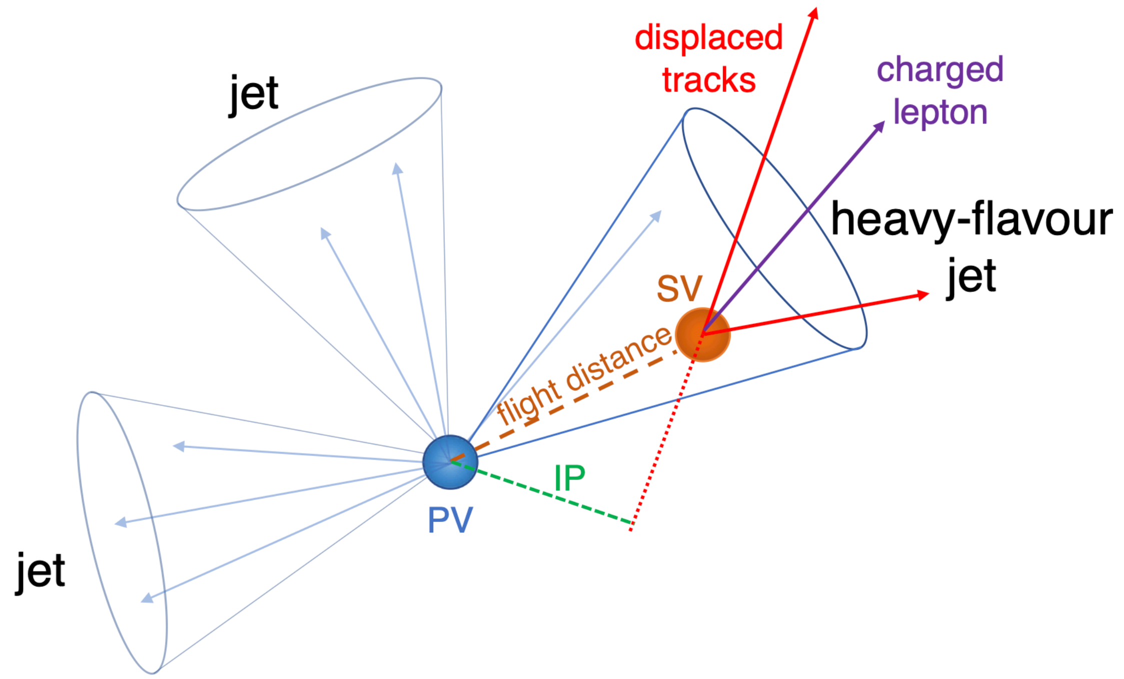


- Impact parameter resolution
  - Low material budget tracker (minimise multiple scattering)
    - 2 µm resolution (CMS/ATLAS ~ 20 µm)
  - Small beam-pipe 1.5 cm -- investigating 1 cm



- PID capabilities
  - dEdx (Si tracker) -- Cluster counting (Drift)
  - Time of flight -- timing layer

Jet Flavour (b,c)



- Large lifetime
  - b (c) lifetime ~ps (~0.1ps)
  - b (c) decay length: ~5 (2-3) mm for ~50 GeV boost
- Displaced vertices/tracks
  - Large impact parameters
  - Tertiary vertices when B hadron decays to C hadron
- Large track multiplicity
  - ~5 (~2) charged tracks/decay
- Non-isolated e/μ
  - ~20 (10)% in B (C) decays

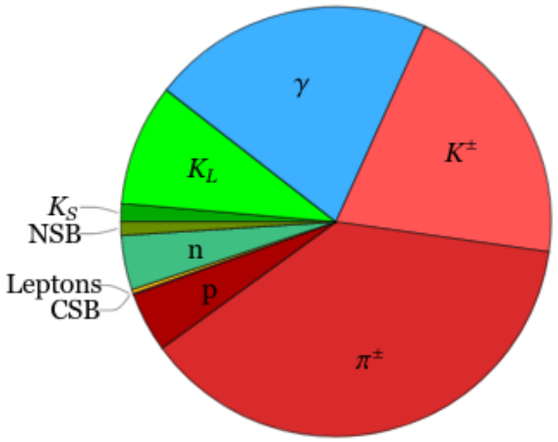
Detector constraints:

Need pixel/tracking detectors

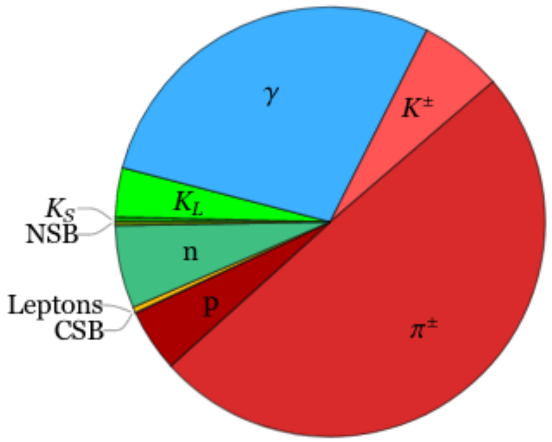
- Good spatial resolution
- As little material as possible
- Precise track alignment

Jet Flavour tagging (strange)

- Large Kaon content
  - Charged Kaon as track:
    - K/pi separation
      - TOF
      - dEdx/dNdx
  - Neutral Kaons:
    - $K_s \to \pi\pi$
      - Displaced 2 track vertex
      - 4 photons



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



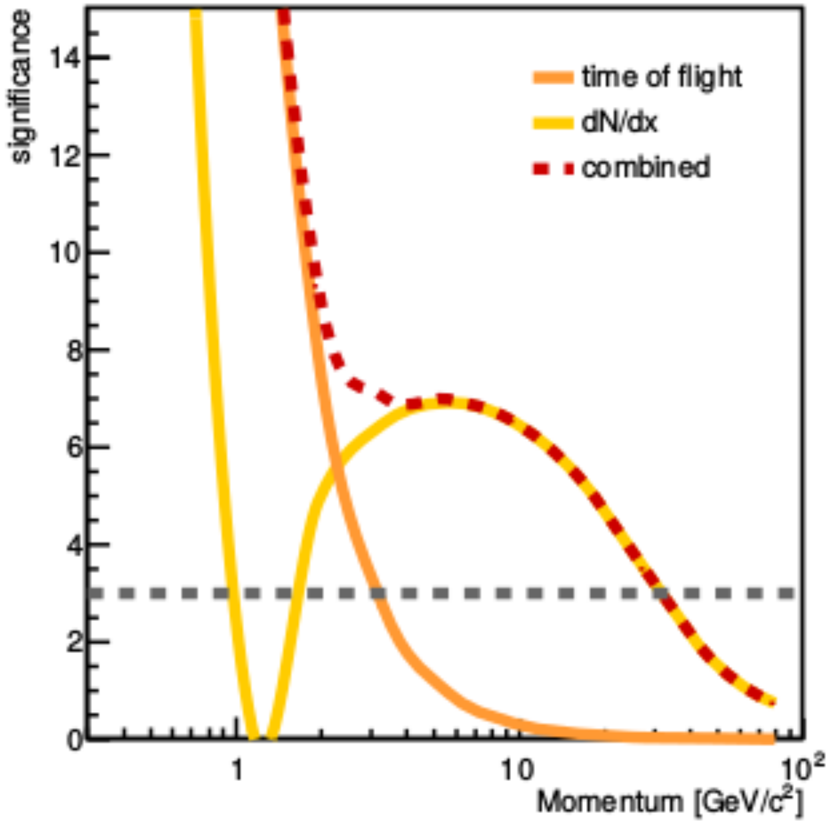
Down $p_T = 45\,\mathrm{GeV}$

Detector constraints:

Need power pixel/tracking detectors

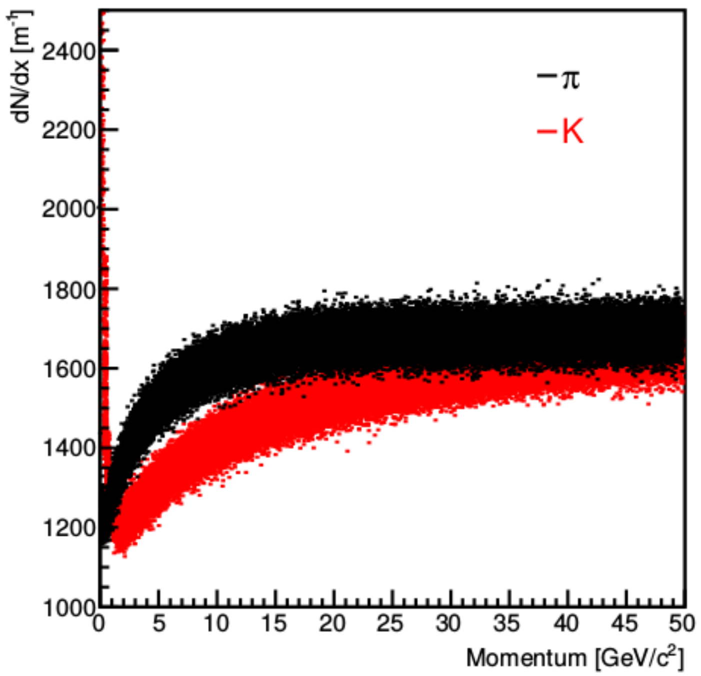
- good spatial resolution
- timing detectors
- charged energy loss (gas/silicon)

[Bedeschi, Gouskos, MS , in prep.]



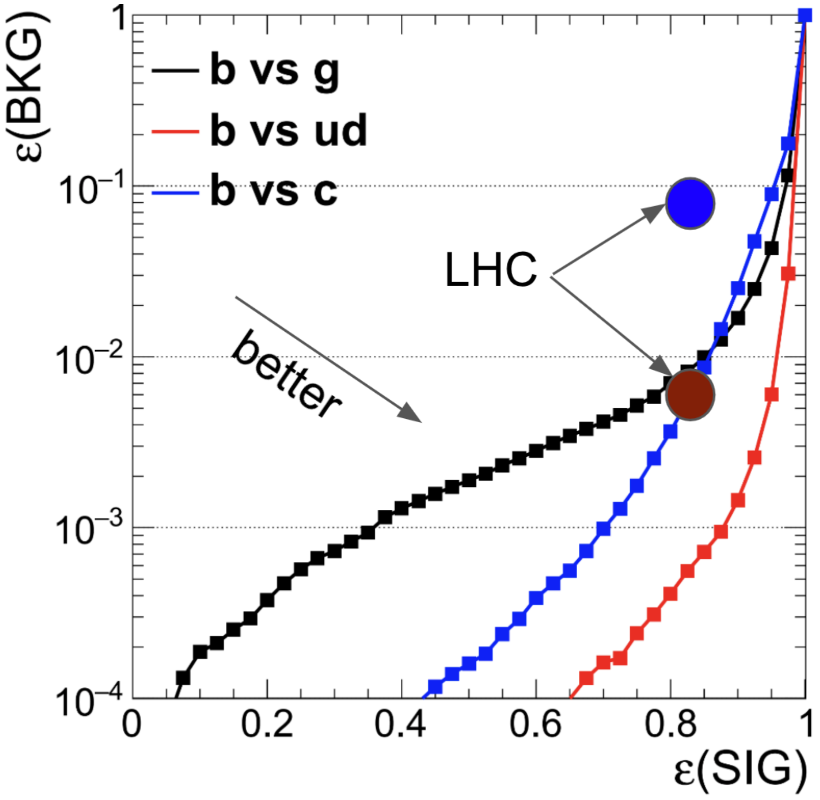
IDEA detector:

90% He / 10 % Isobutane

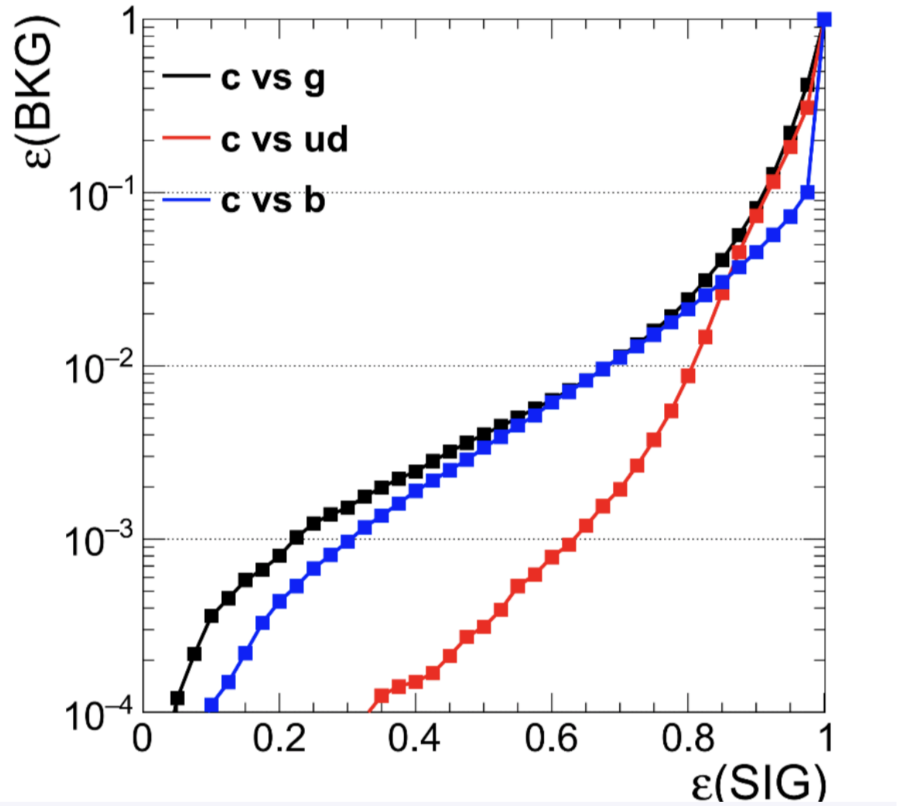


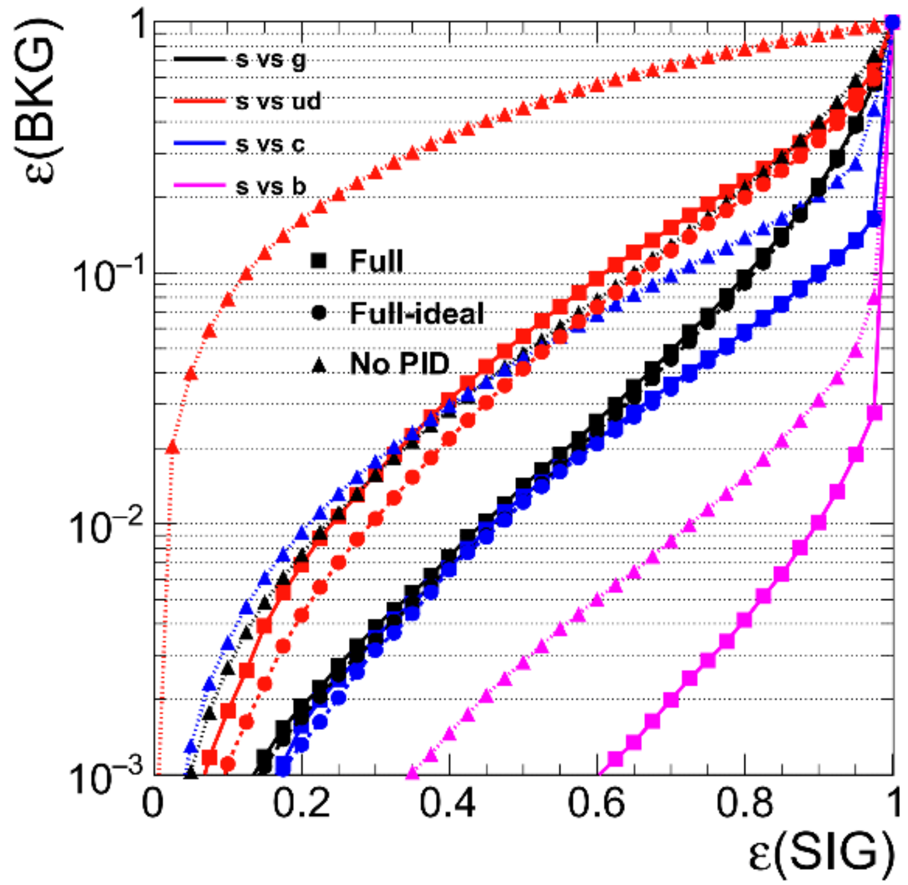
Jet flavour tagging (b,c,s)

[Bedeschi, Gouskos, MS , in prep.]



DISCLAIMER:
FastSimulation (Delphes)

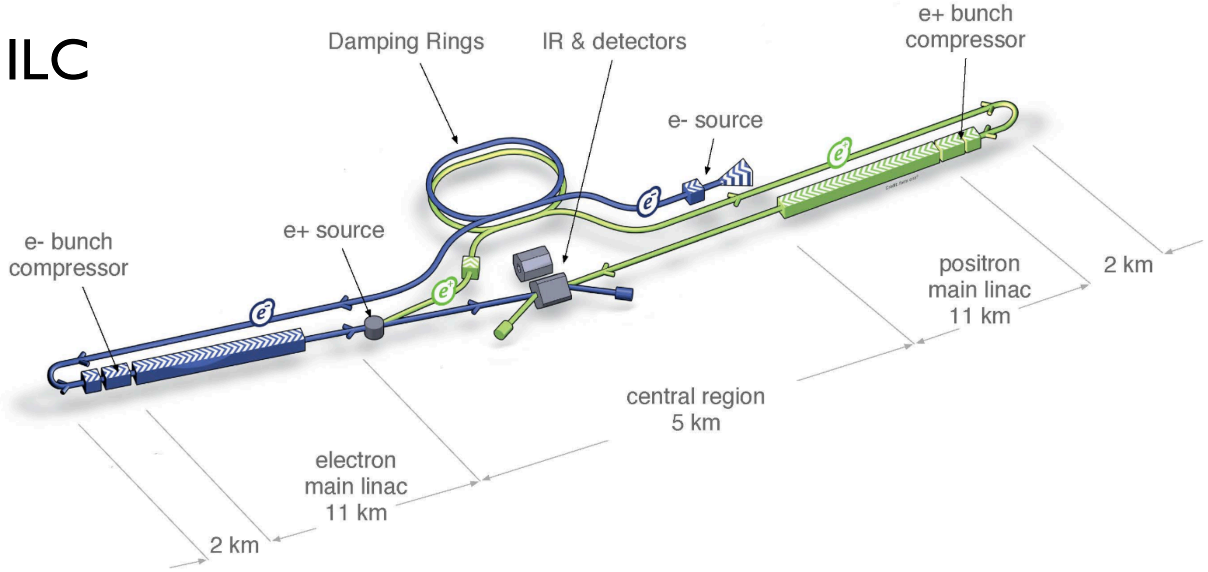




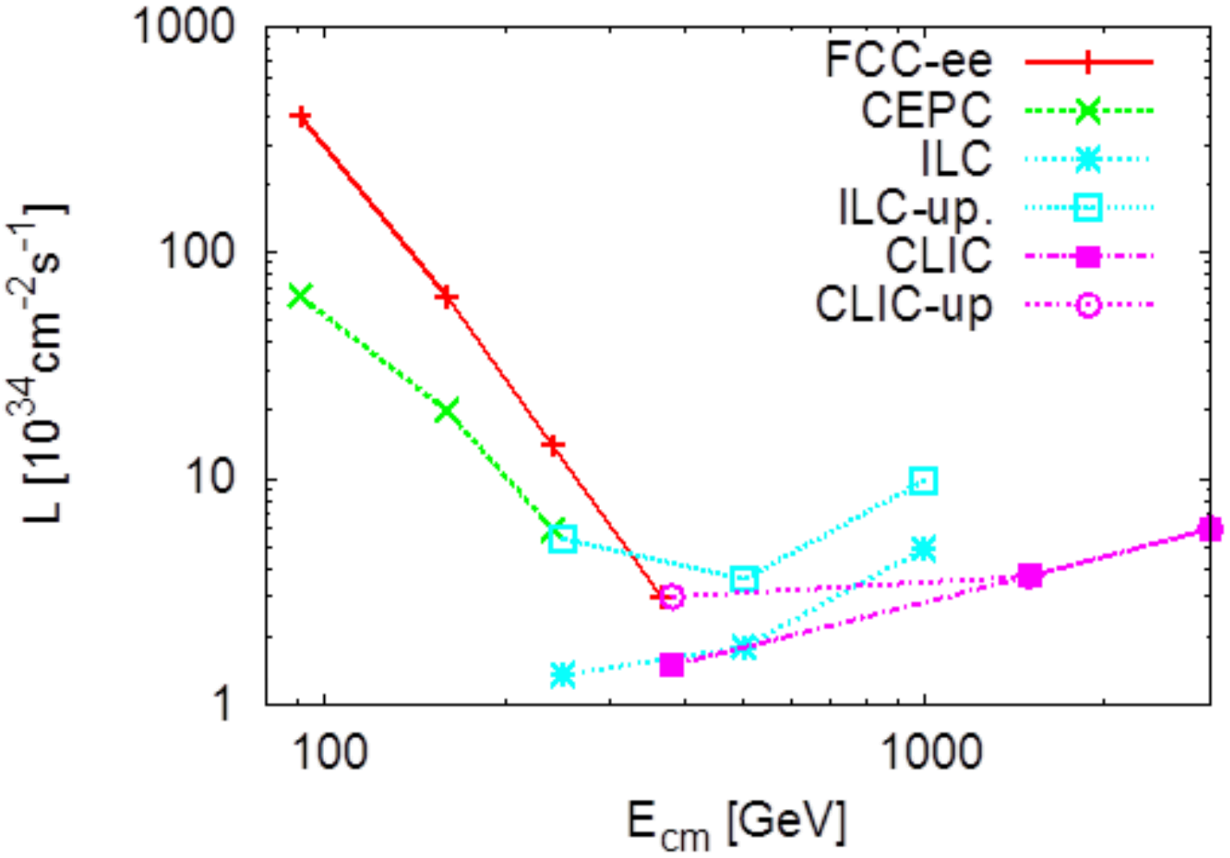
- Clean experimental conditions can drastically improve top identification capabilities
  - 1 order of magnitude improvement in background rejection for b/c tagging
  - Strange tagging

Linear ILC/CLIC

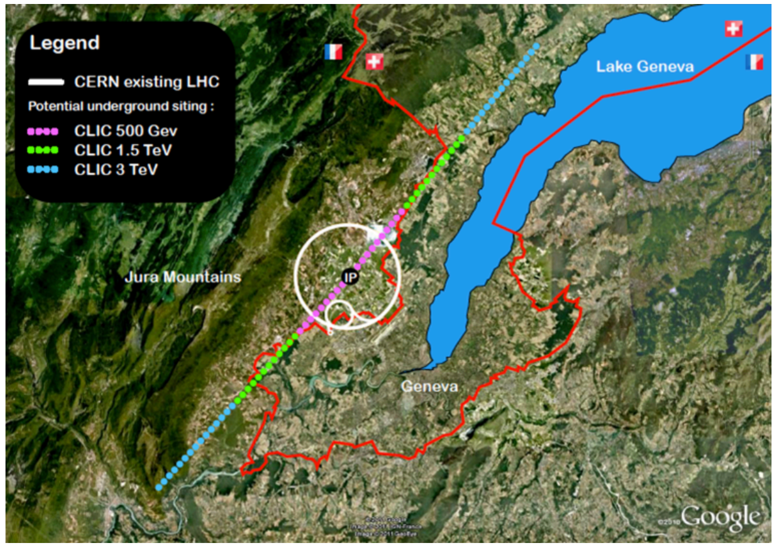
ILC



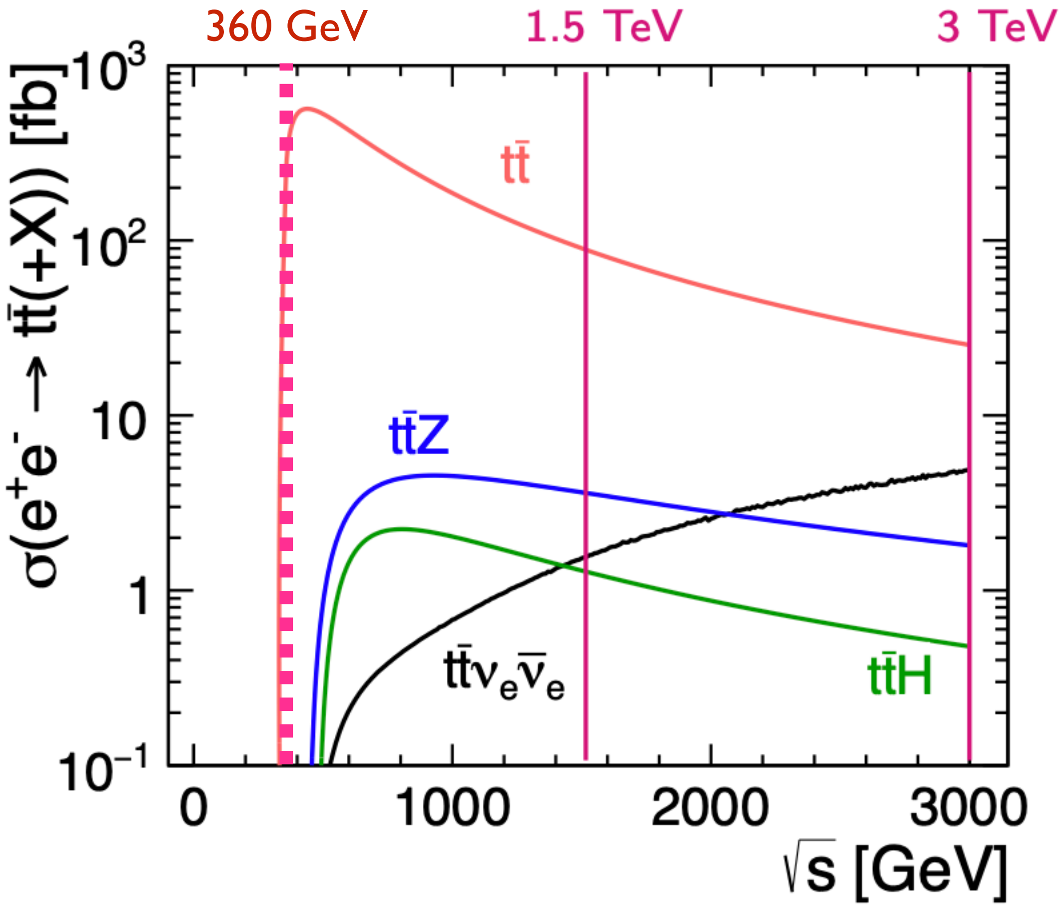
- Can reach high energies
- High lumi at high energies (tt , ttH, HH, H …)



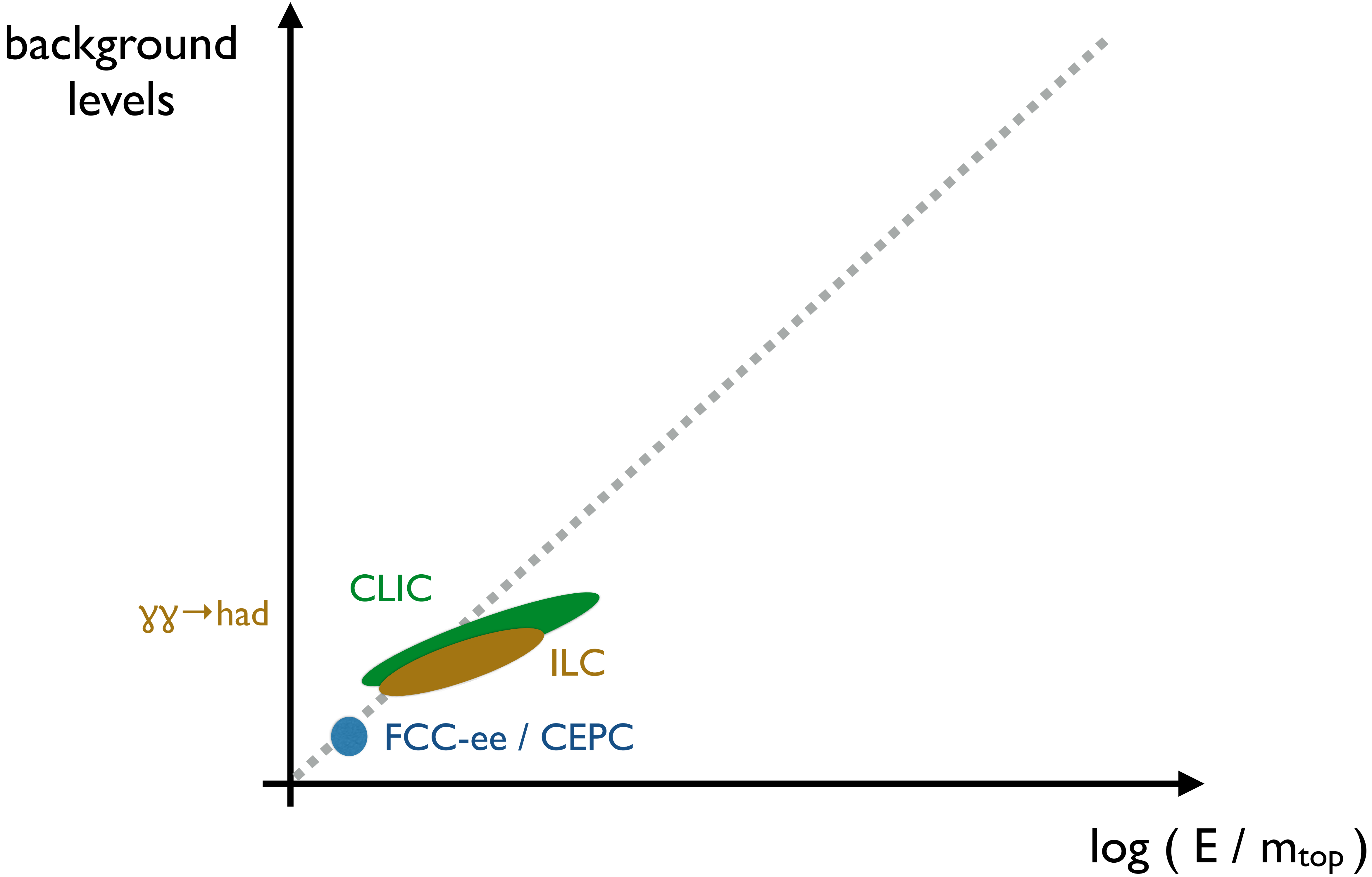
CLIC



Tops quarks produced with moderate boost ɣ ~ 1-10



Boost vs exp. backgrounds



Tops at linear colliders

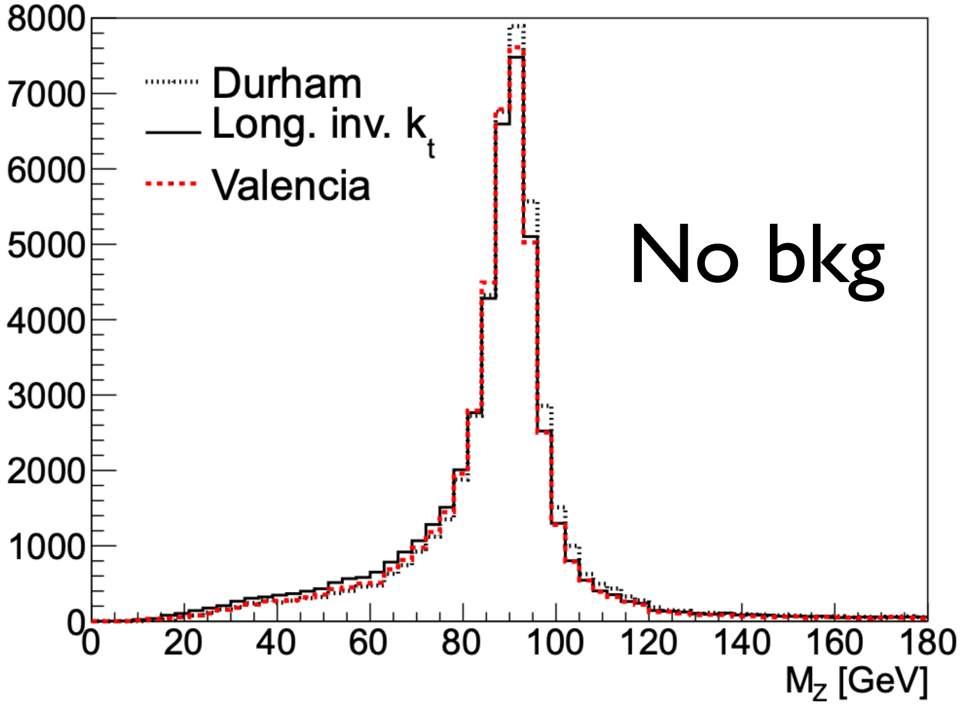
Boronat, Garcia, Vos [1404.4294]

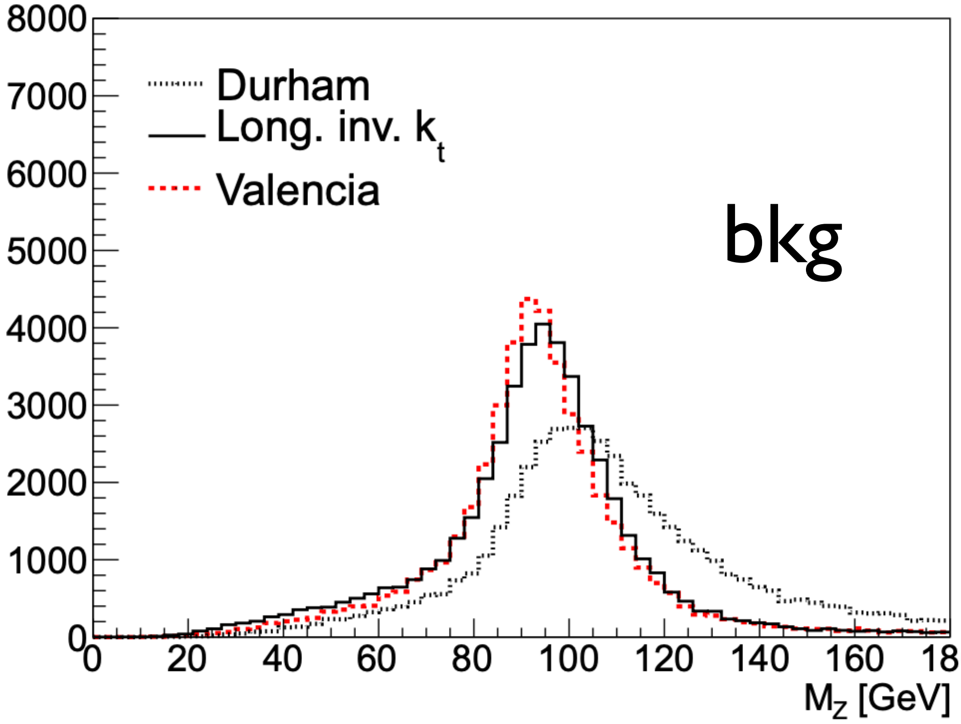
- Jet clustering "Valencia Linear Collider" (VLC)
  - γγ→hadrons background (isolated , energetic, foward)
  - beta exponent additional parameter which allows for tuning algorithm
    - governs likelihood of clustering background

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

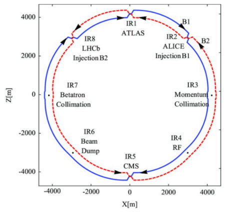
$$d_{iB} = p_T^{2\beta}$$

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

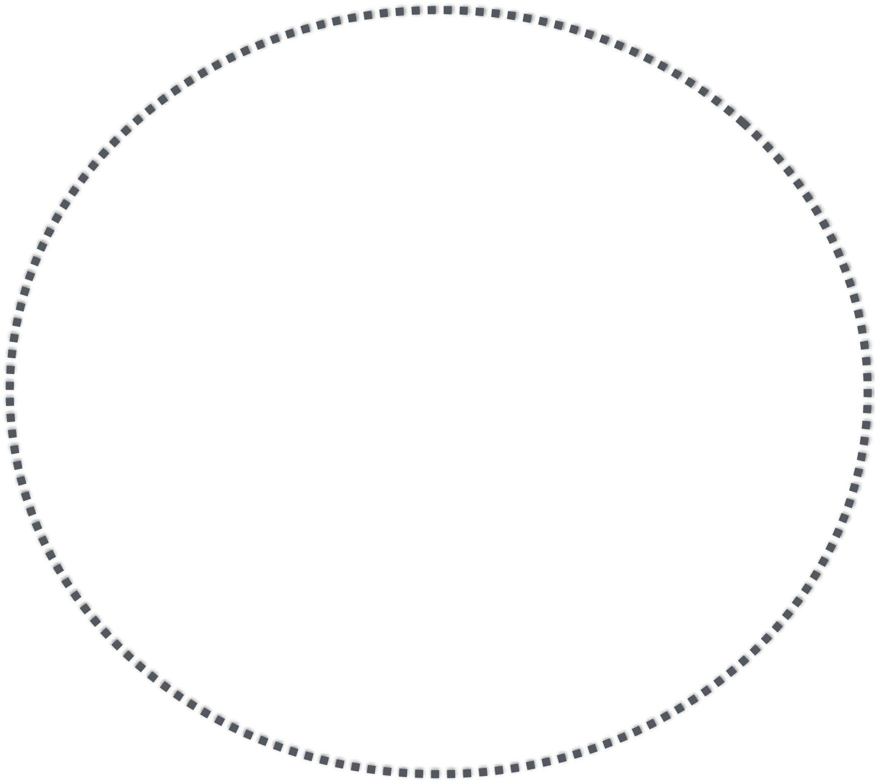




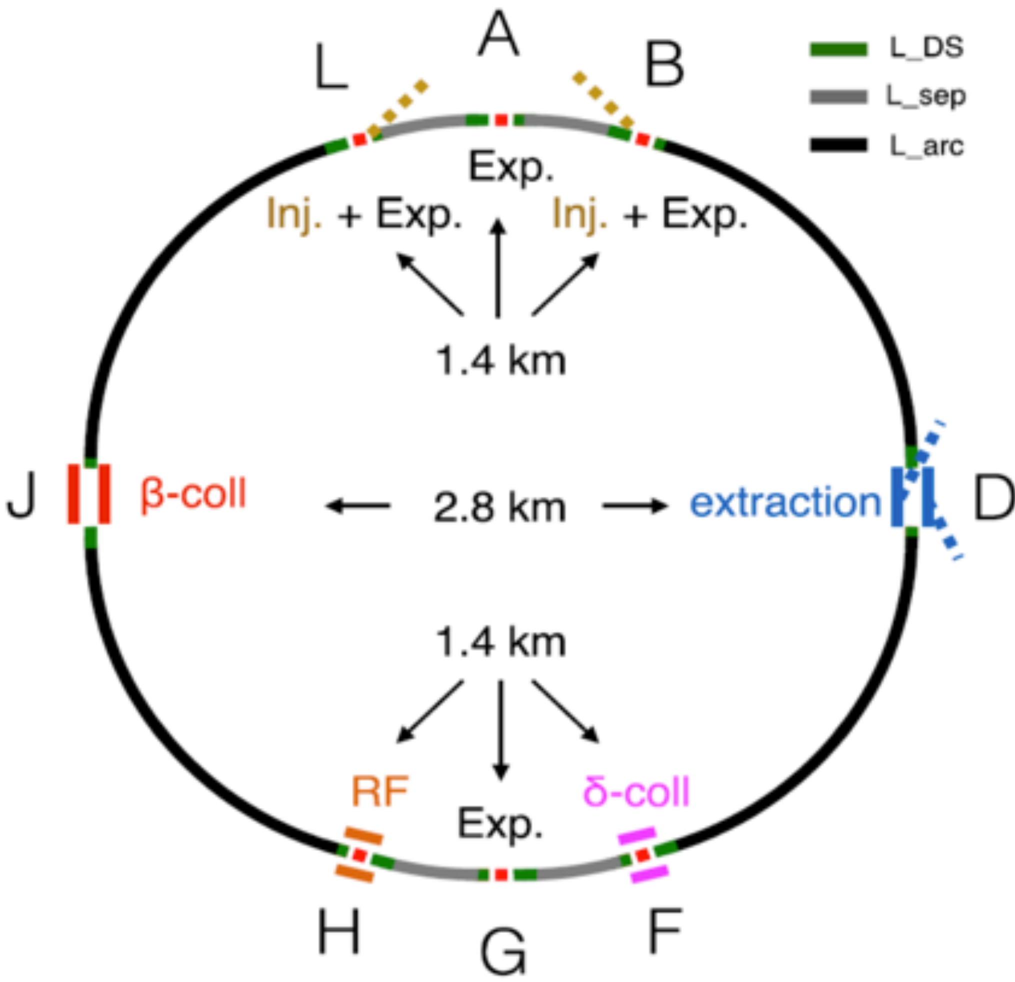
High energy hadron machines



HE-LHC



LE-FCC



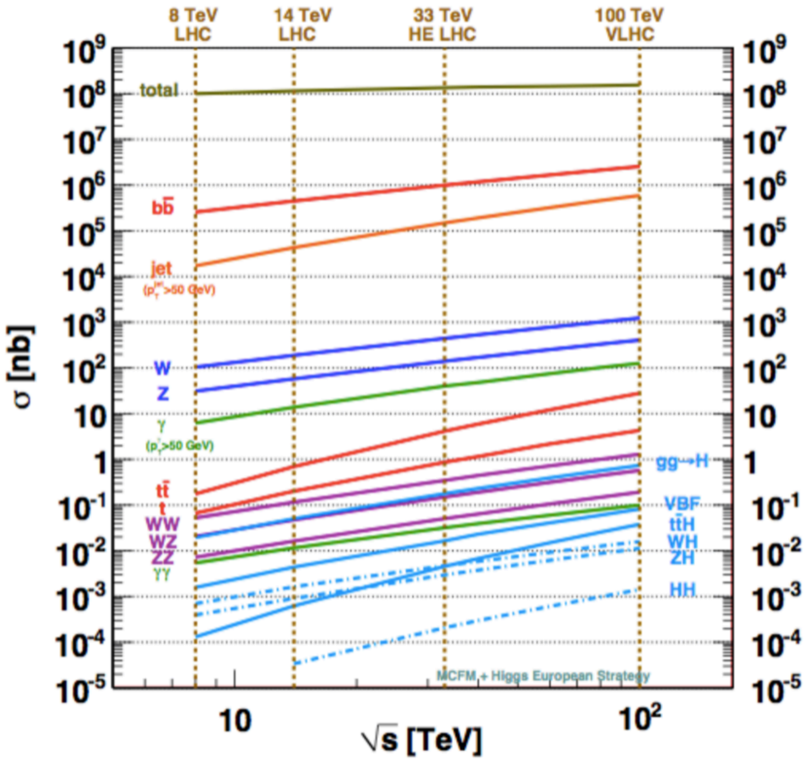
FCC-hh

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

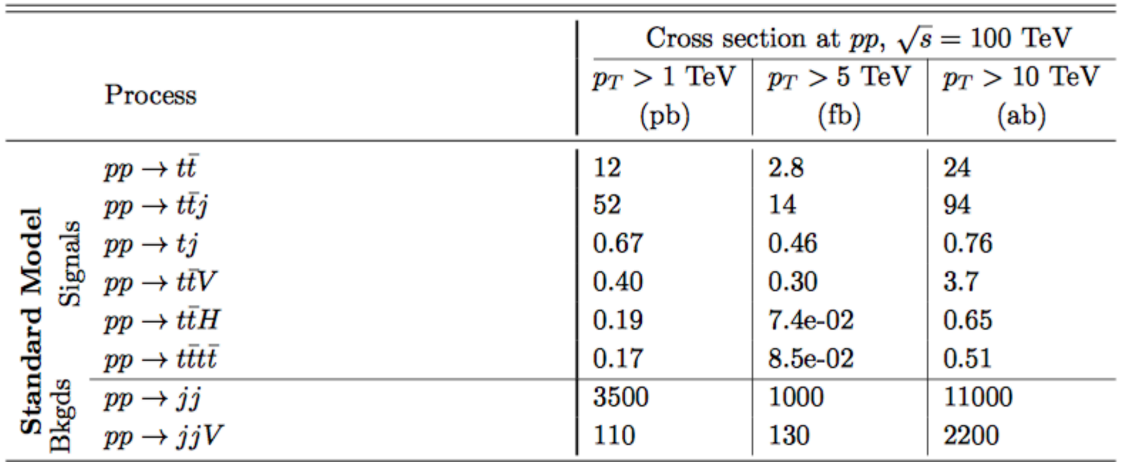
sqrt(s)	37 TeV
Lumi	15 ab^{-1}
B	6 T
circ.	100 km

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

How many tops @FCC-hh ?



[1503.03347]



	Process	Cross section at pp, $\sqrt{s} = 100$ TeV		
		$p_T > 1$ TeV (pb)	$p_T > 5$ TeV (fb)	$p_T > 10$ TeV (ab)
Standard Model Signals	$pp \to t\bar{t}$	12	2.8	24
	$pp \to t\bar{t}j$	52	14	94
	$pp \to tj$	0.67	0.46	0.76
	$pp \to t\bar{t}V$	0.40	0.30	3.7
	$pp \to t\bar{t}H$	0.19	7.4e-02	0.65
	$pp \to t\bar{t}t\bar{t}$	0.17	8.5e-02	0.51
Standard Model Bkgds	$pp \to jj$	3500	1000	11000
	$pp \to jjV$	110	130	2200

With 30 ab^{-1}

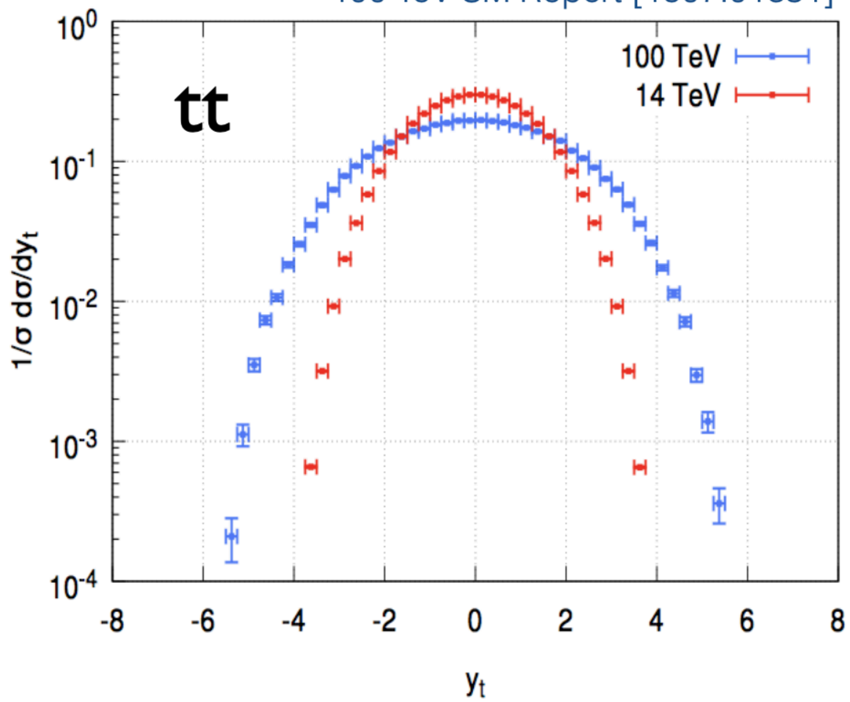
10^{12} tops

10^9 top with p_T > 1 TeV

100k top with p_T > 5 TeV

Among all SM "backgrounds" , ttbar production gains the most in rate @100 TeV

100 TeV SM Report [1607.01831]

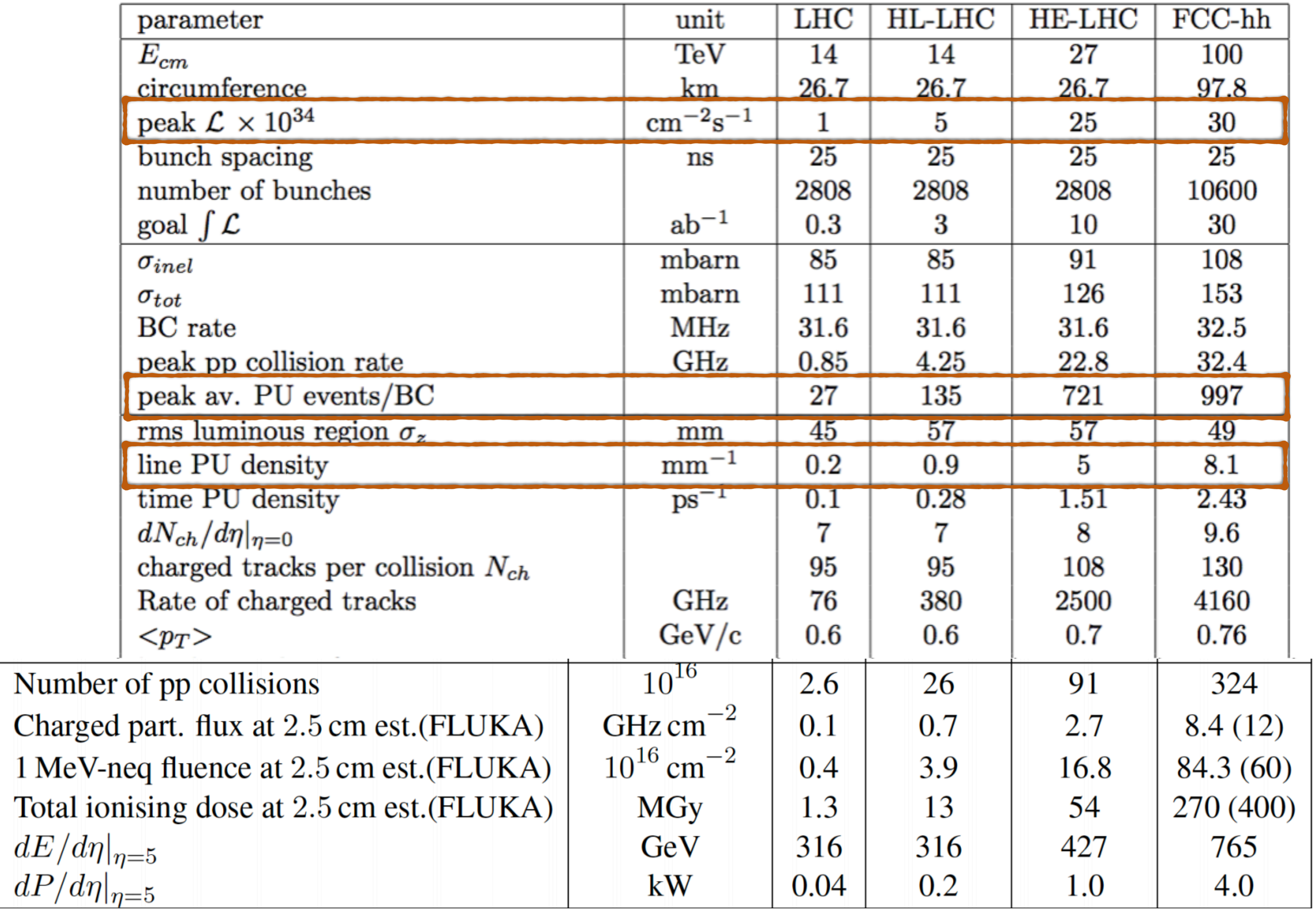


In addition, threshold production occurs more forward

→ crucial to instrument the forward region

Machine 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

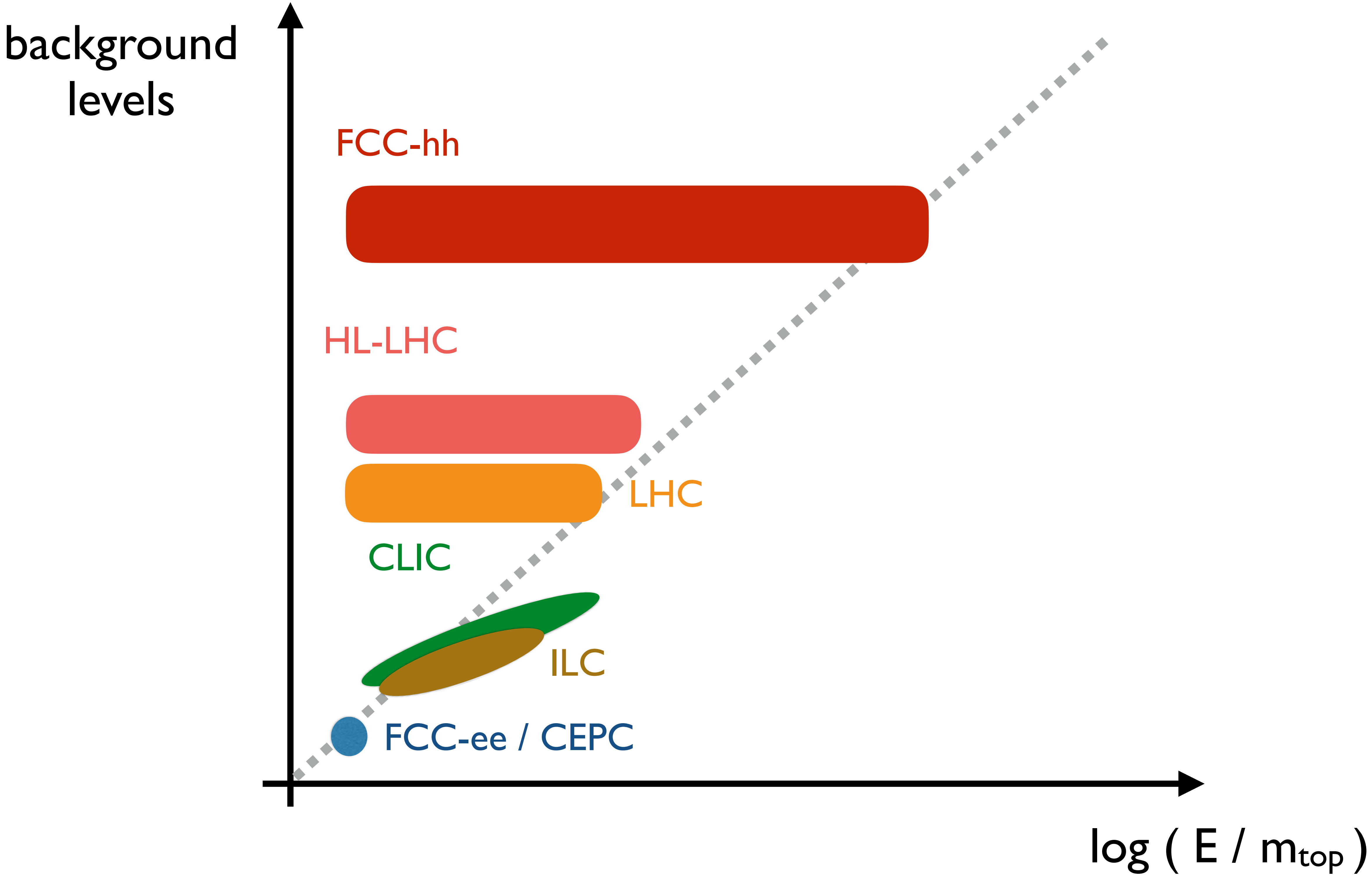
→ x6 HL-LHC

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

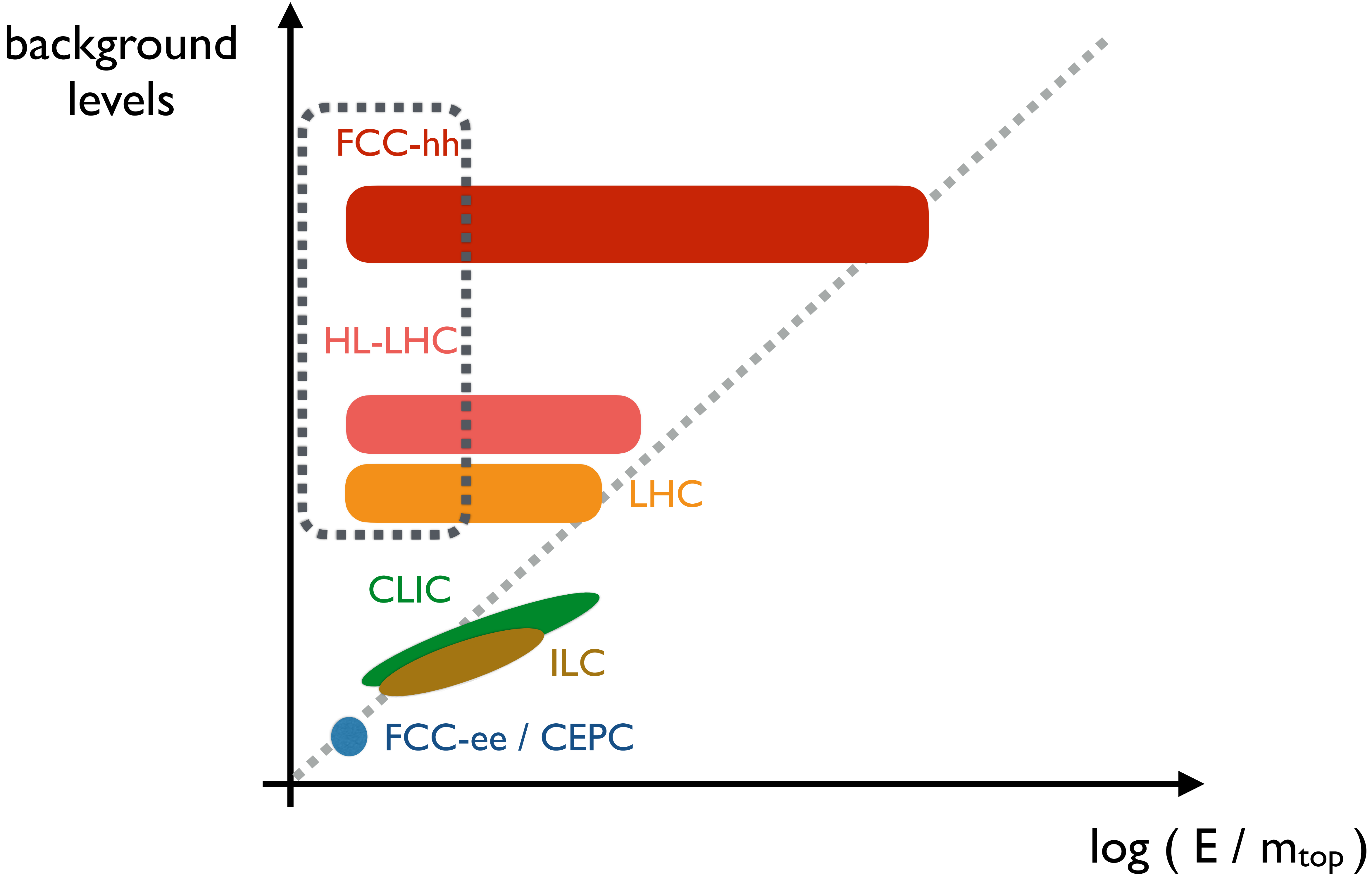
but also x10 integrated luminosity w.r.t to HL-LHC

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

Tops at hadron colliders



Tops at threshold hadron colliders

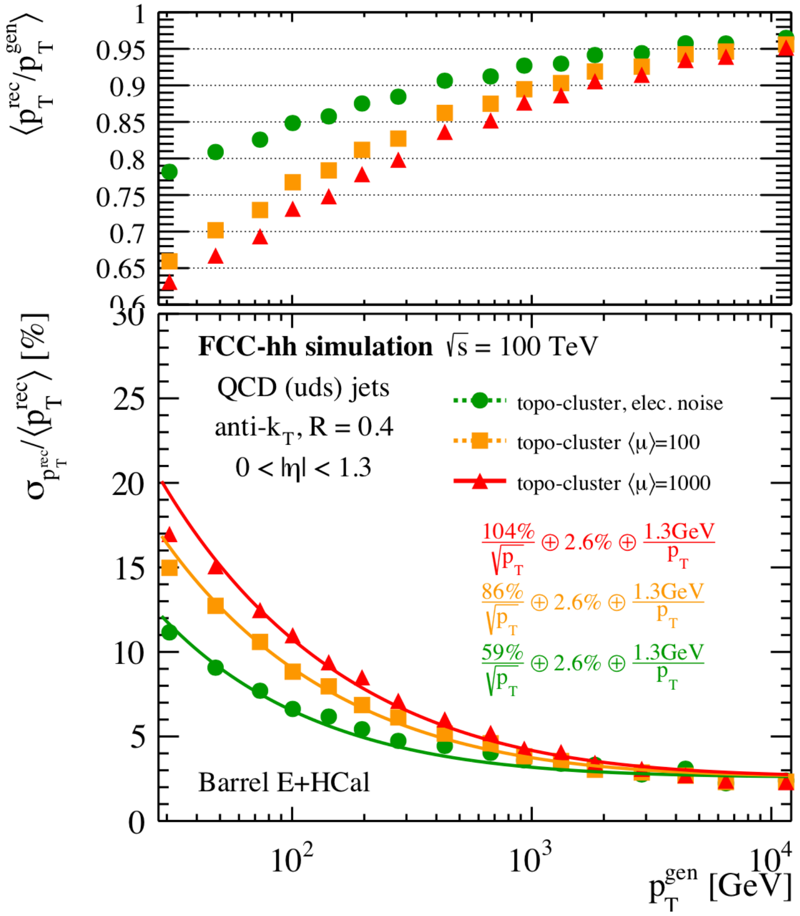


Experimental challenges: pile-up

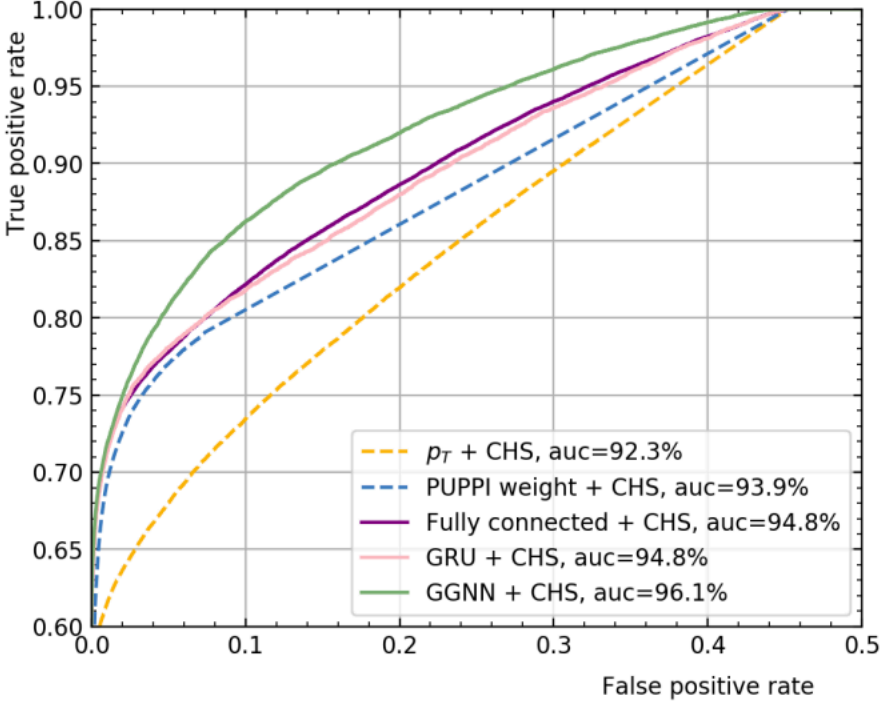
- relative impact of PU is large
  - jet energy resolution and scale
  - HF-tagging capabilities

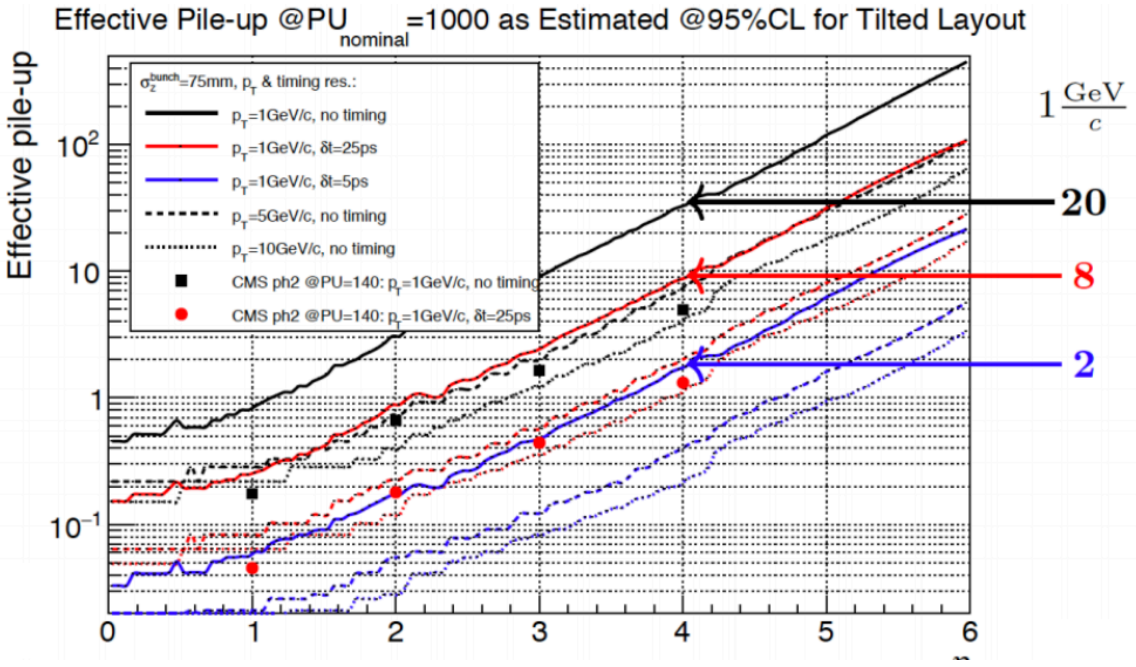
- PU subtraction techniques
  - charged hadron subtraction
  - timing information (5-10 ps resolution)
  - residual:
    - area-subtraction
    - PUPPI reconstruction
    - advanced graph based-ML

1912.09962

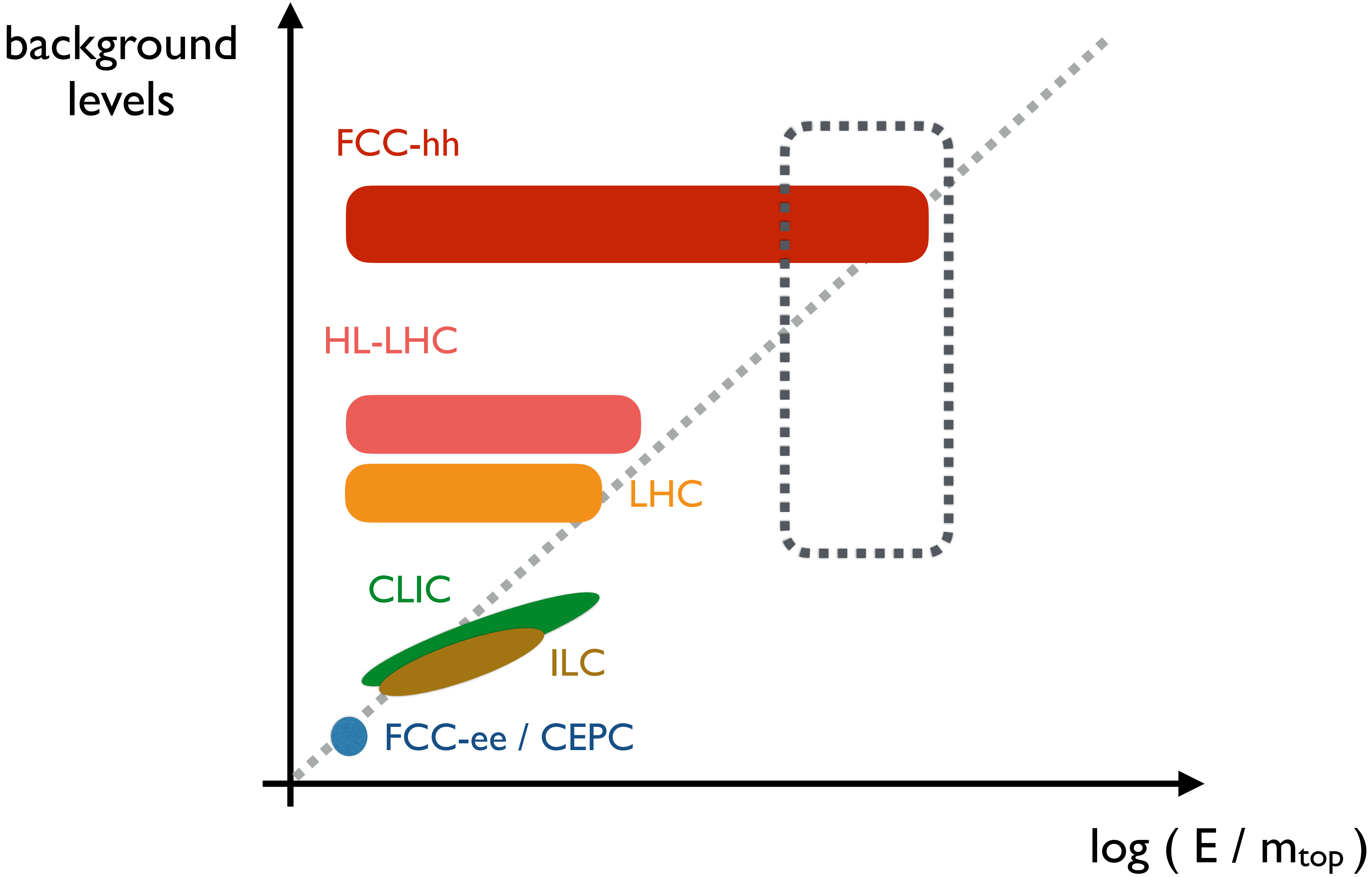


1810.07988





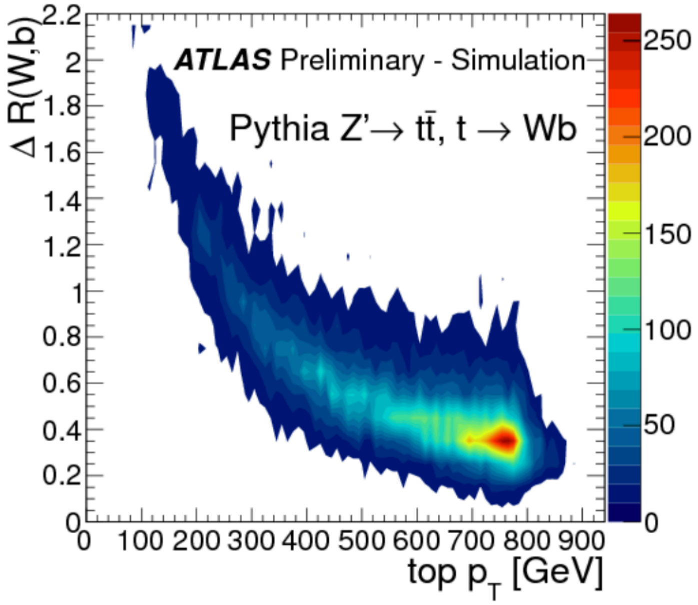
Tops in the boosted regime

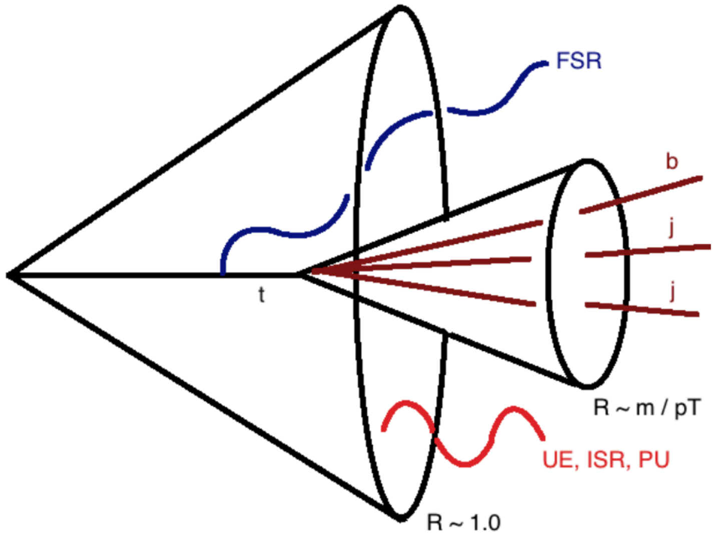


Boosted tops

min. distance to resolve two partons

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





- Top "jets" can be identified by means of
  - jet mass
  - Substructure
- Trade-off between large-R and small-R
  - small-R → suppress PU/FSR contribution
  - large-R → contain top decay product

ex for top:

p_T = 200 GeV → R ~ 2

p_T = 1 TeV → R ~ 0.4

p_T = 10 TeV → R ~ 0.05

in CMS:

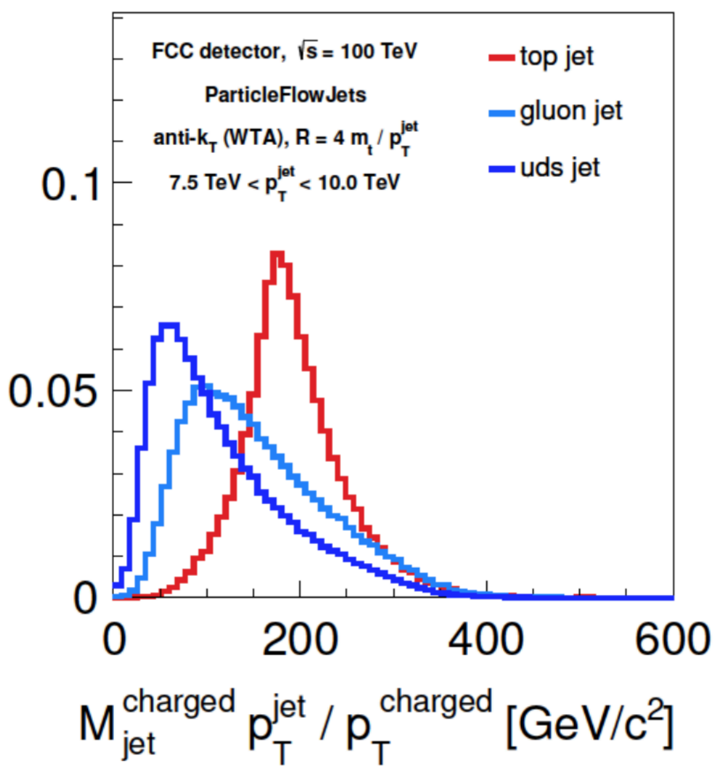
Tracking → ΔR ~ 0.002

ECAL → ΔR ~ 0.02

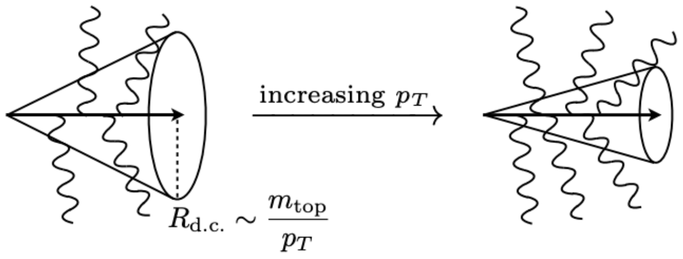
HCAL → ΔR ~ 0.1

Boosted tops (tracking)

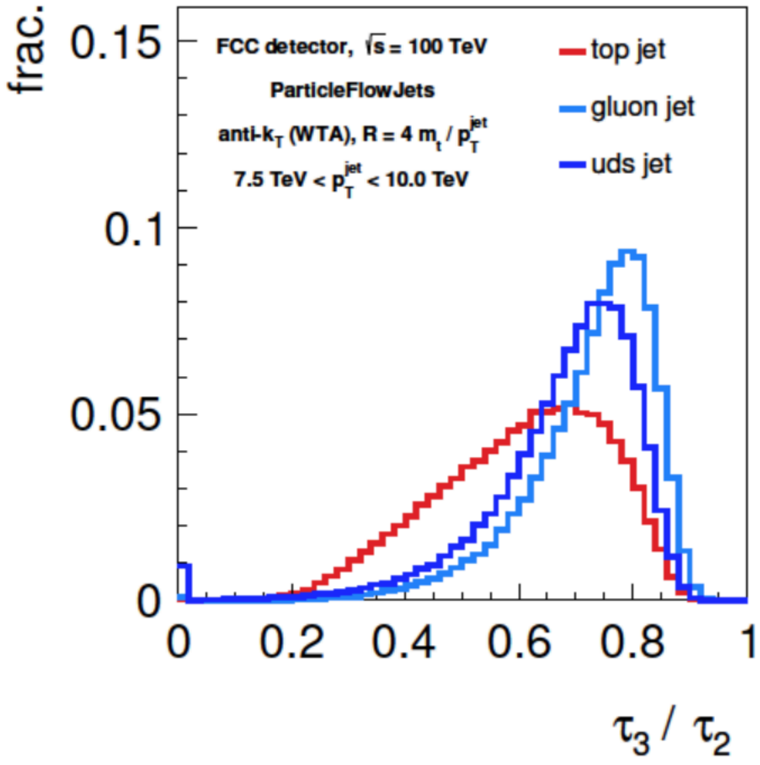
Track- based jet Mass

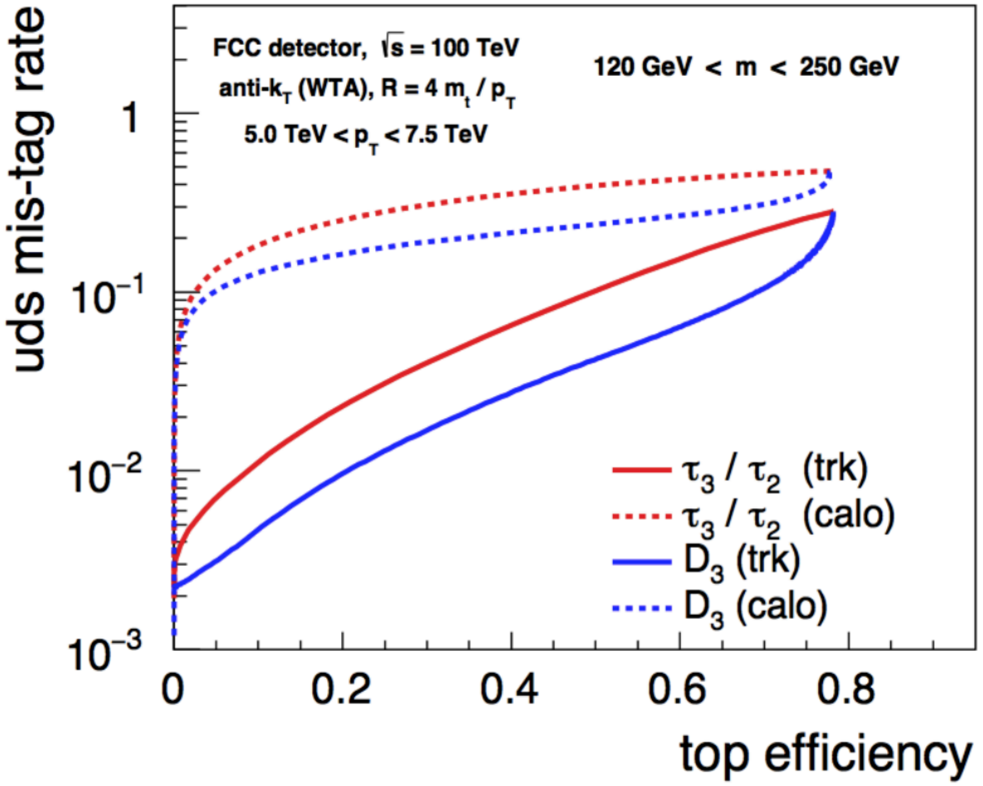


Larkoski, Maltoni, MS [1503.03347]



Track based



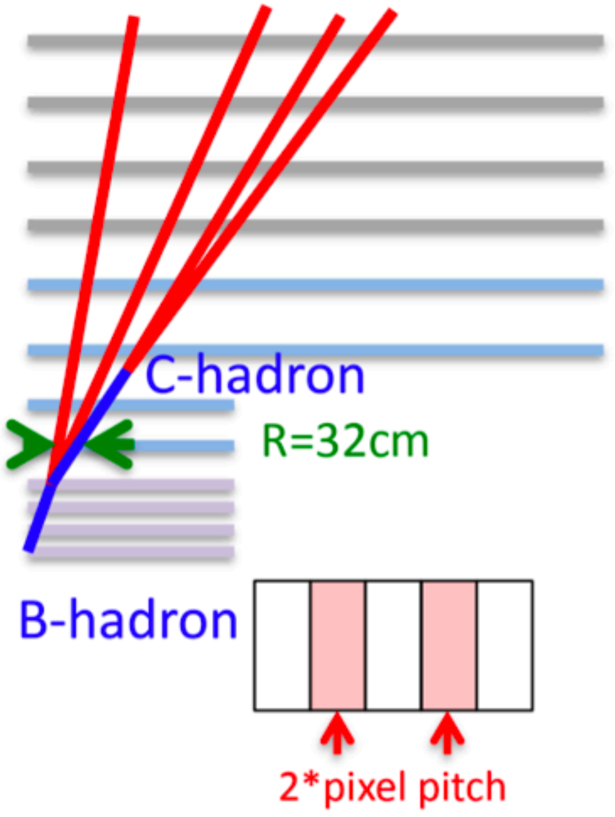


- Hadronic Top-tagging can be performed up to multi-TeV energies with:
  - tracking information
  - Variable (shrinking) cone
- should be regarded as minimal performance

High p_T b-tagging

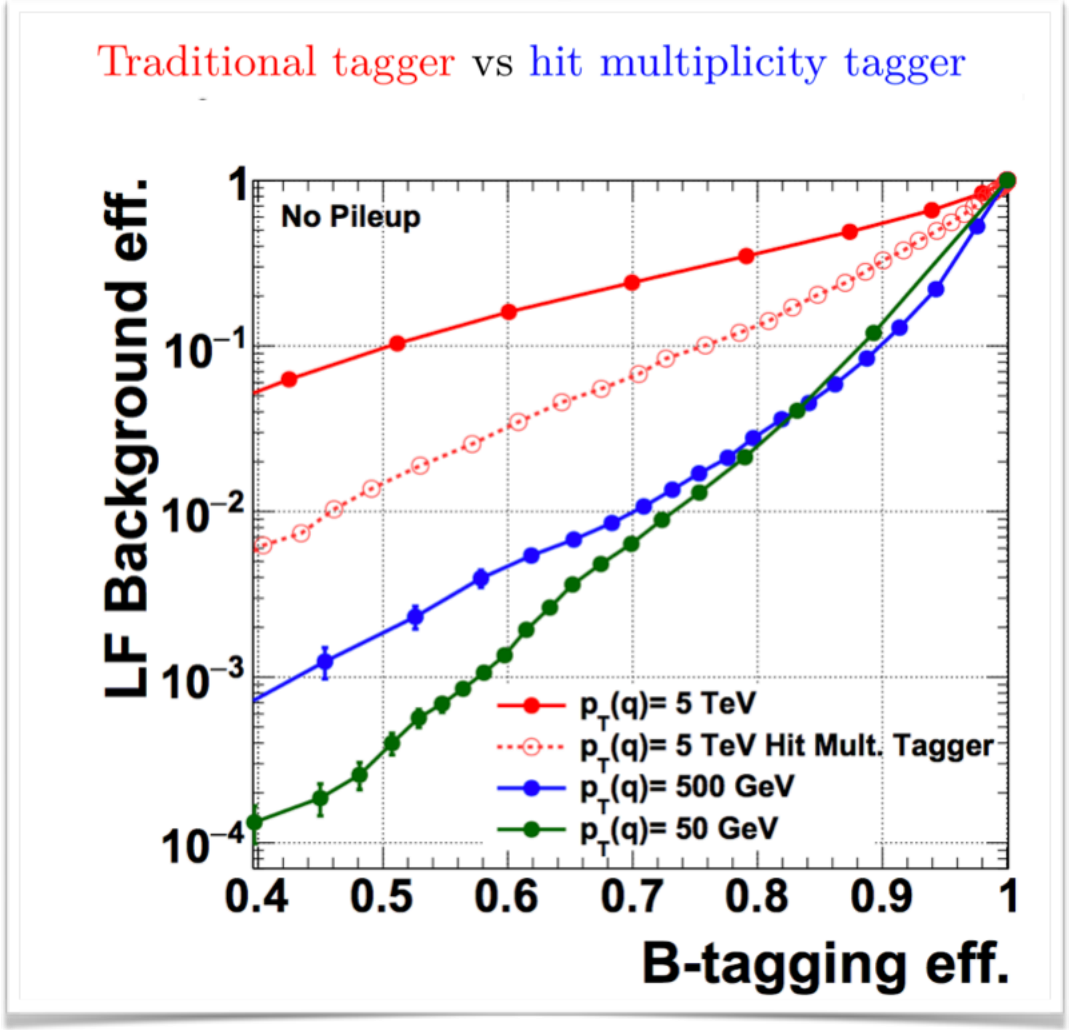
- Change in paradigm: heavy flavour tagging
- multi-TeV b-Hadrons decay outside the pixel volume ($p_T(b)$ = 2 TeV → $\gamma c\tau$ = 50 cm)
- Need to adapt identification algorithms for identifying multi-TeV tops

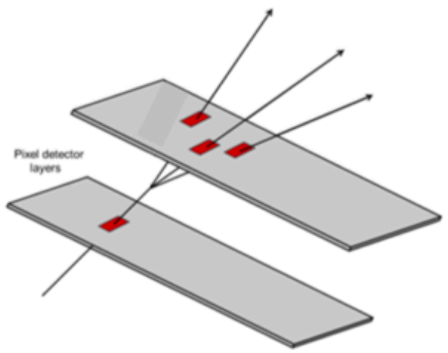
Perez Codina, Roloff [CERN-ACC-2018-0023]



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

- displaced vertices





arXiv:1701:06832

To be verified in high pile-up environment.

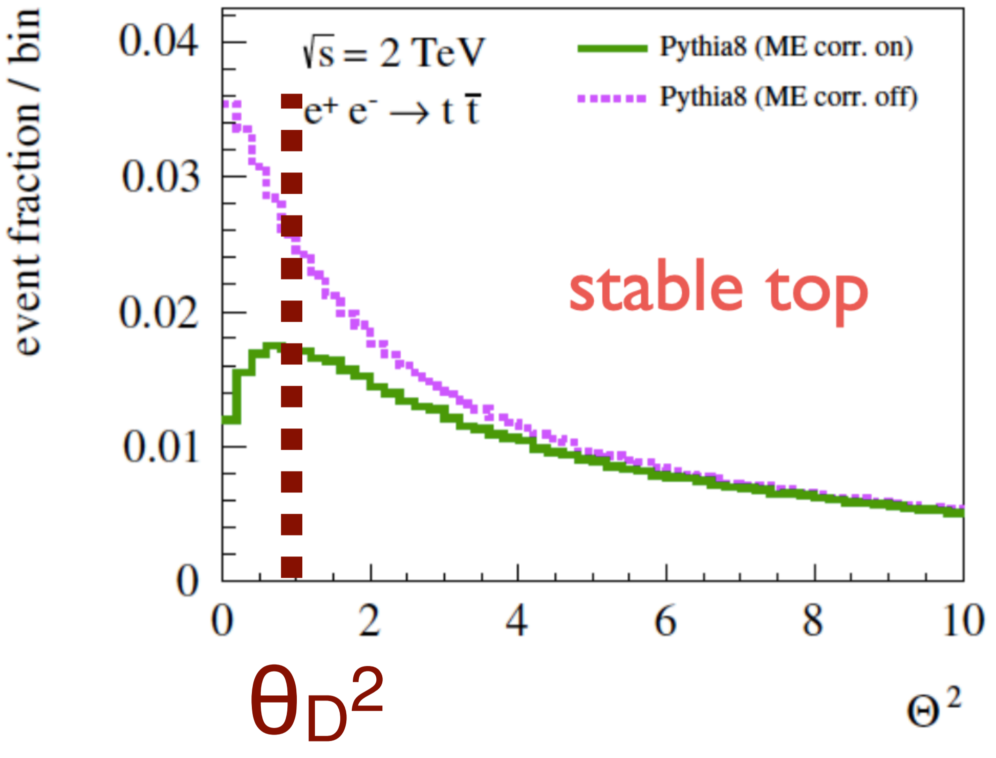
Boosted tops (dead-cone)

FSR in **soft** and **collinear** limit :

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

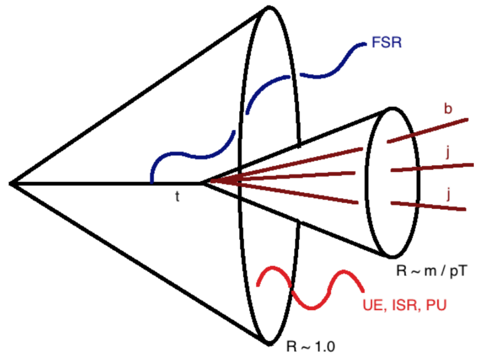
- Can the FS radiation pattern be exploited for top-tagging?
  - the effect is **small and difficult to disentangle**
    - operates at similar angular scales **R ~ m/p$_T$** as top decay products
    - **top decay products** produce their own FSR (much larger than top, because **m$_q$ ~ 0** !!)
    - **Can possibly be observed at HL-LHC, but** log-enhanced at high energies relevant for FCC)

Maltoni, MS, Thaler [1606.03449]

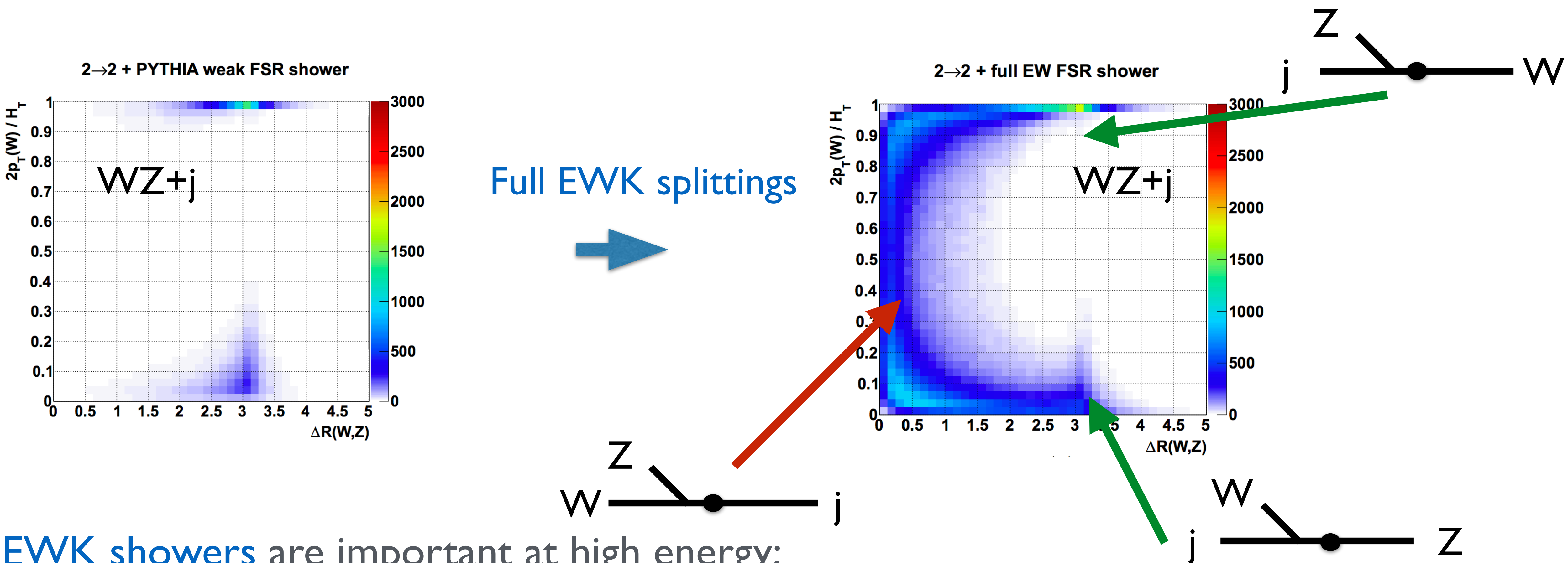


$$\boxed{\theta_D \equiv \frac{m_q}{E_q}}$$

for the top can be pretty large angle

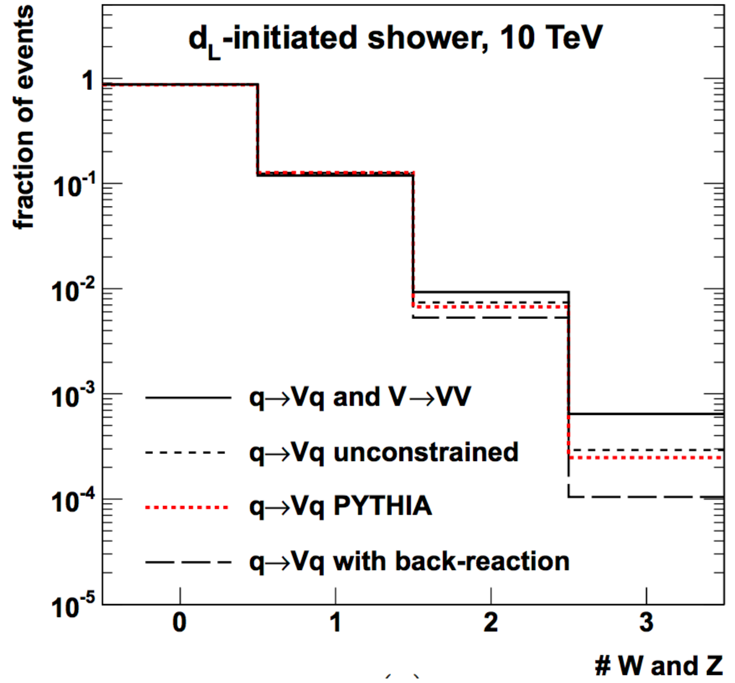


EWK high energy showers

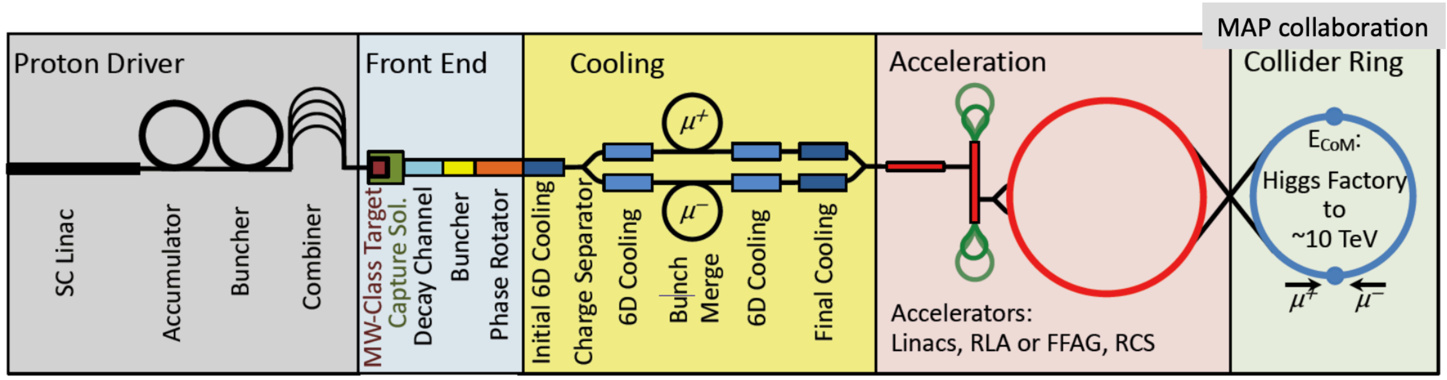


- EWK showers are important at high energy:
  - Tops can produce EWK showers (unlike gluon-jets)
  - j → jW can easily fake a top jet (~up to 10%)
- Gauge bosons and scalar can also radiate (not included in Pythia8):
  - can affect boosted top, bottom (yukawa) and vector identification performance (tH > bH > jH)
- Unlike QCD showers, EWK showers are directly observable

Chen, Han and Tweedie [1611.00788]



Muon collider: backgrounds



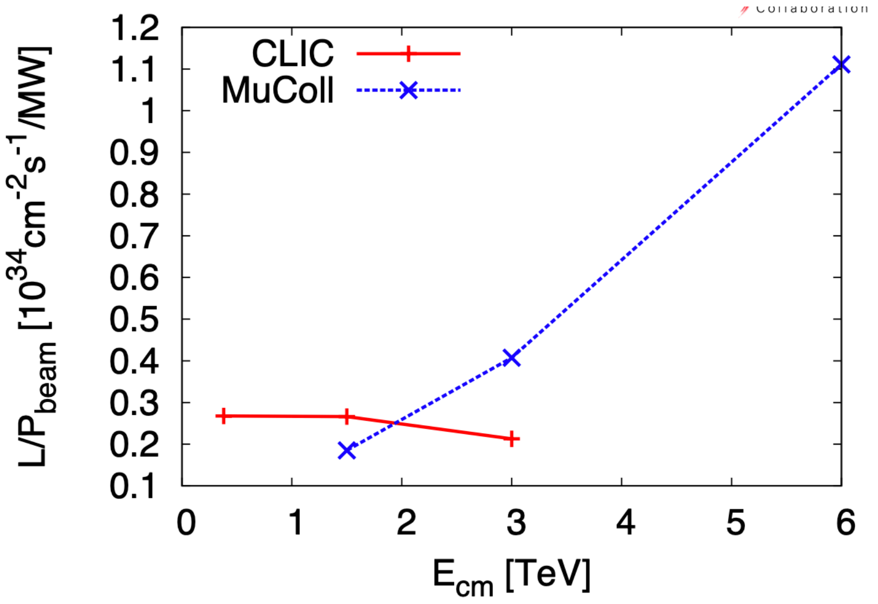
Short, intense proton bunches to produce hadronic showers

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

Acceleration to collision energy

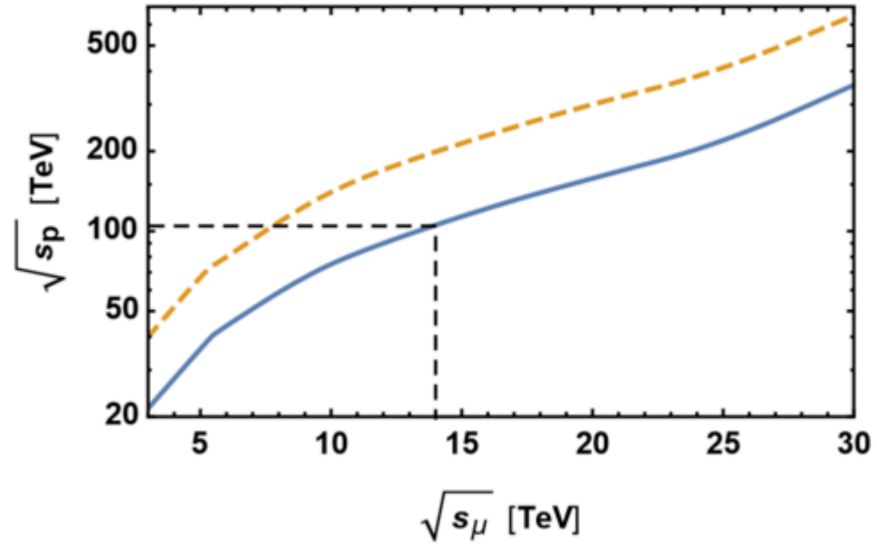
Collision

Pions decay into muons that can be captured

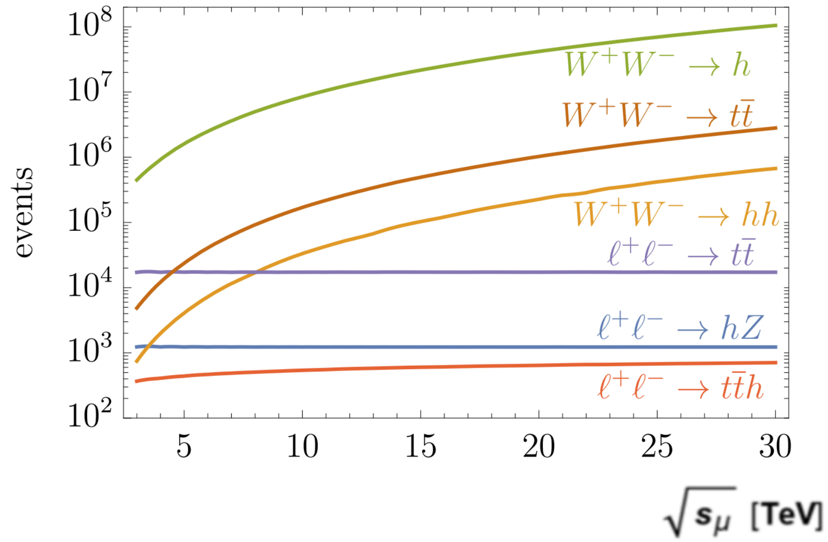


Direct top pair production:

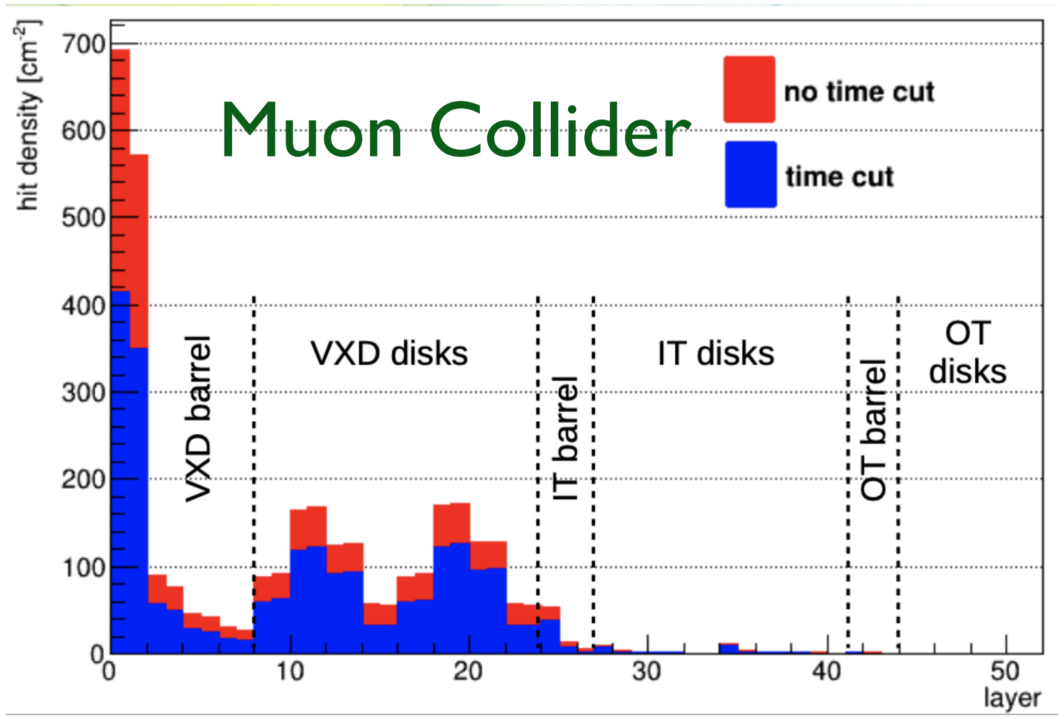
14 TeV mu collider will produce tops with similar boost as 100 TeV pp collider

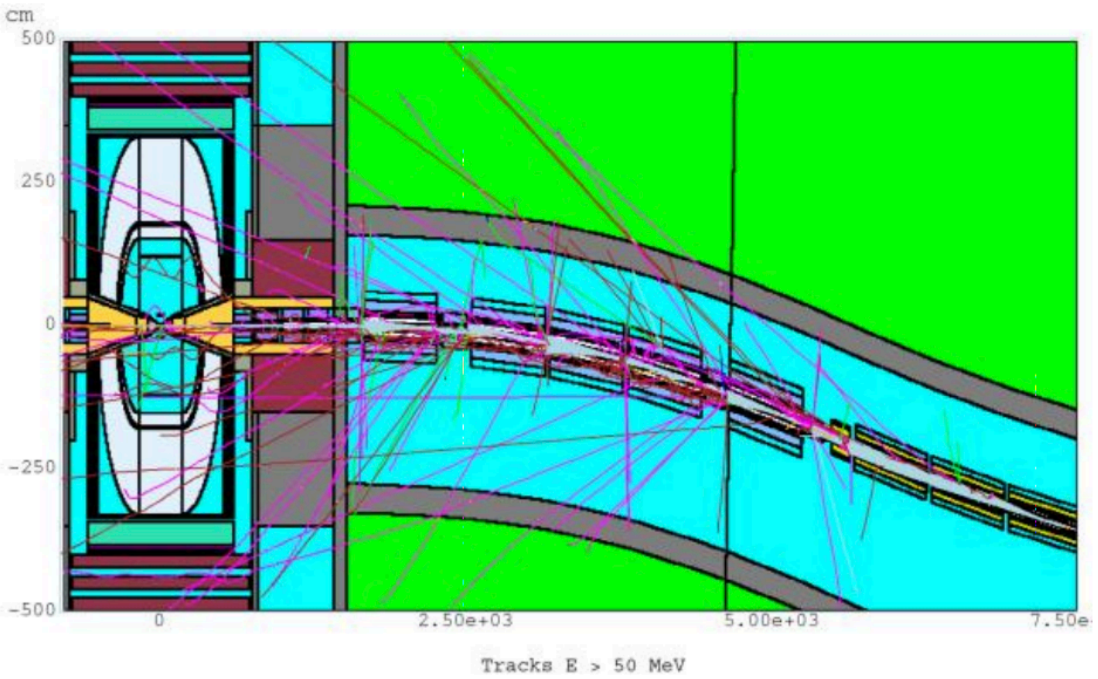


14 TeV mu collider will produce similar # tops with p_T ~ 5 TeV as the FCC-hh



Muon collider - challenges



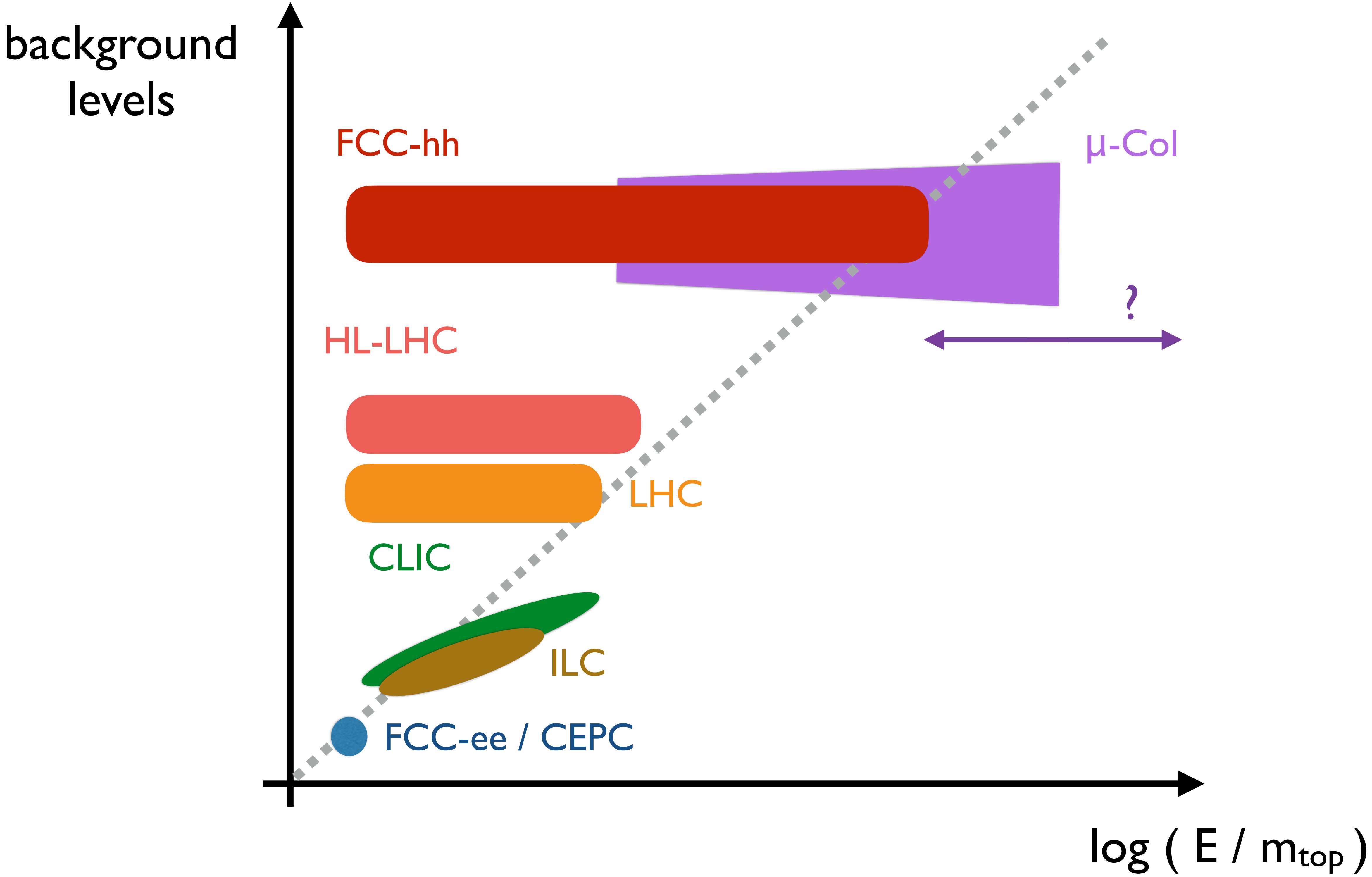


charged fluence: 400-700 (cm^{-2} / BX)

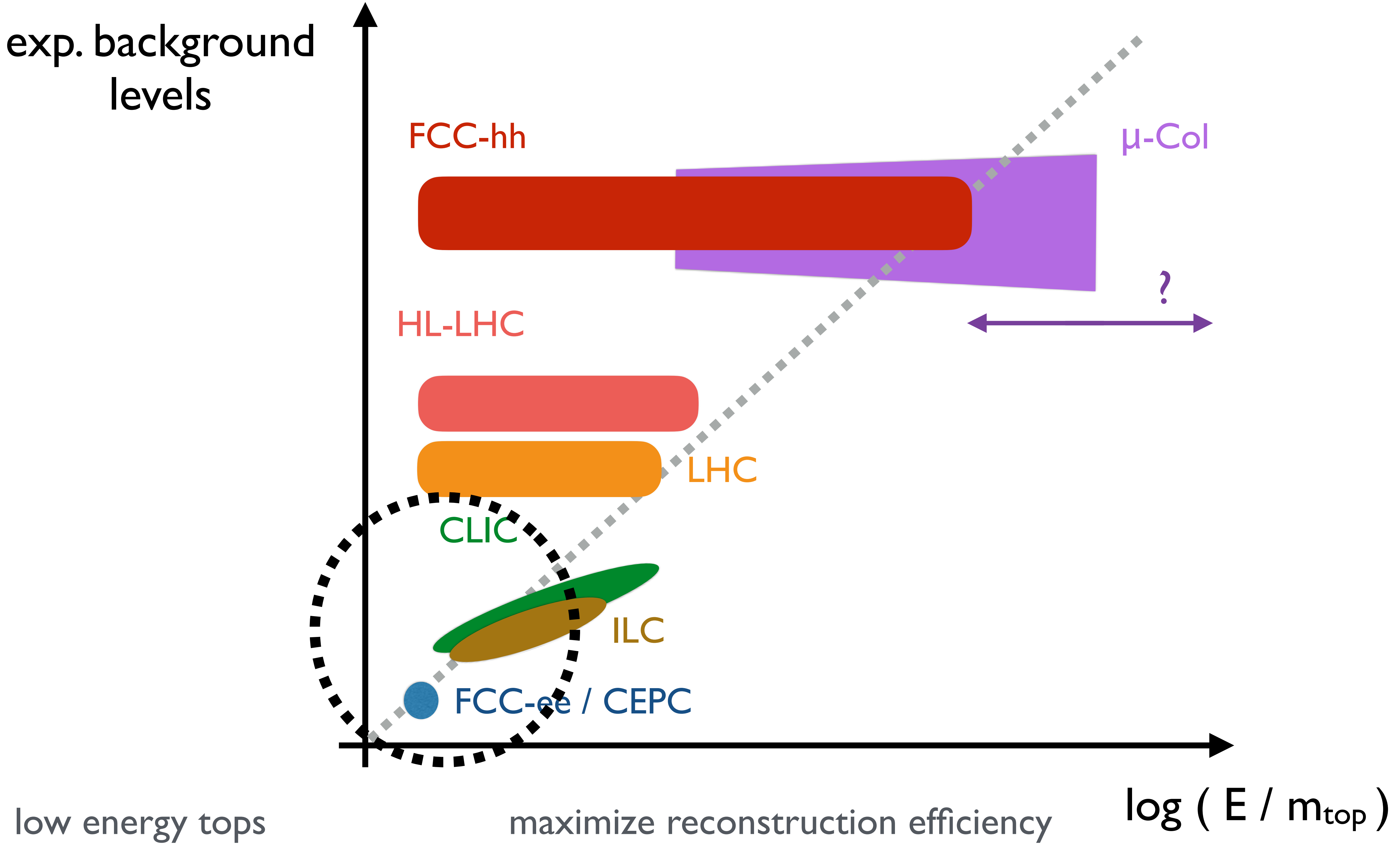
- At threshold (or low energy) top reconstruction will suffer from similar limitations as the FCC-hh (large PU → large Beam induced background)
  - Despite some conceptual differences (directionality, energy …)

- In the boosted regime most FCC-hh considerations apply as well:
  - If anything, cleaner events (no ISR, no UE, no colour connection between initial and final state)
  - much lower levels of physics backgrounds (QCD):
    - Top tagging will be required to perform optimally with less purity

Tops at future colliders



Key takeaways - low energy FCC-ee

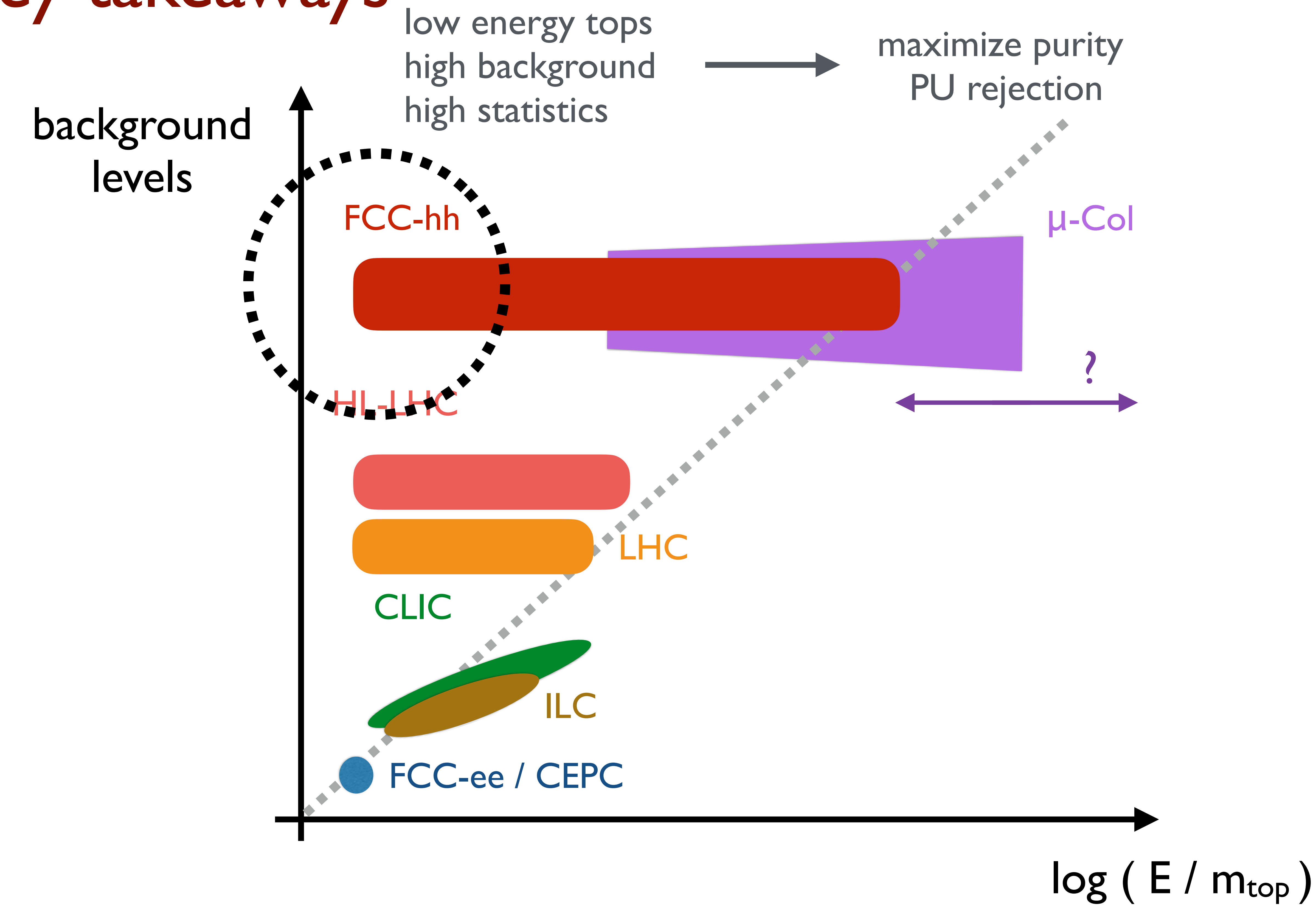


low energy tops
low background
low statistics

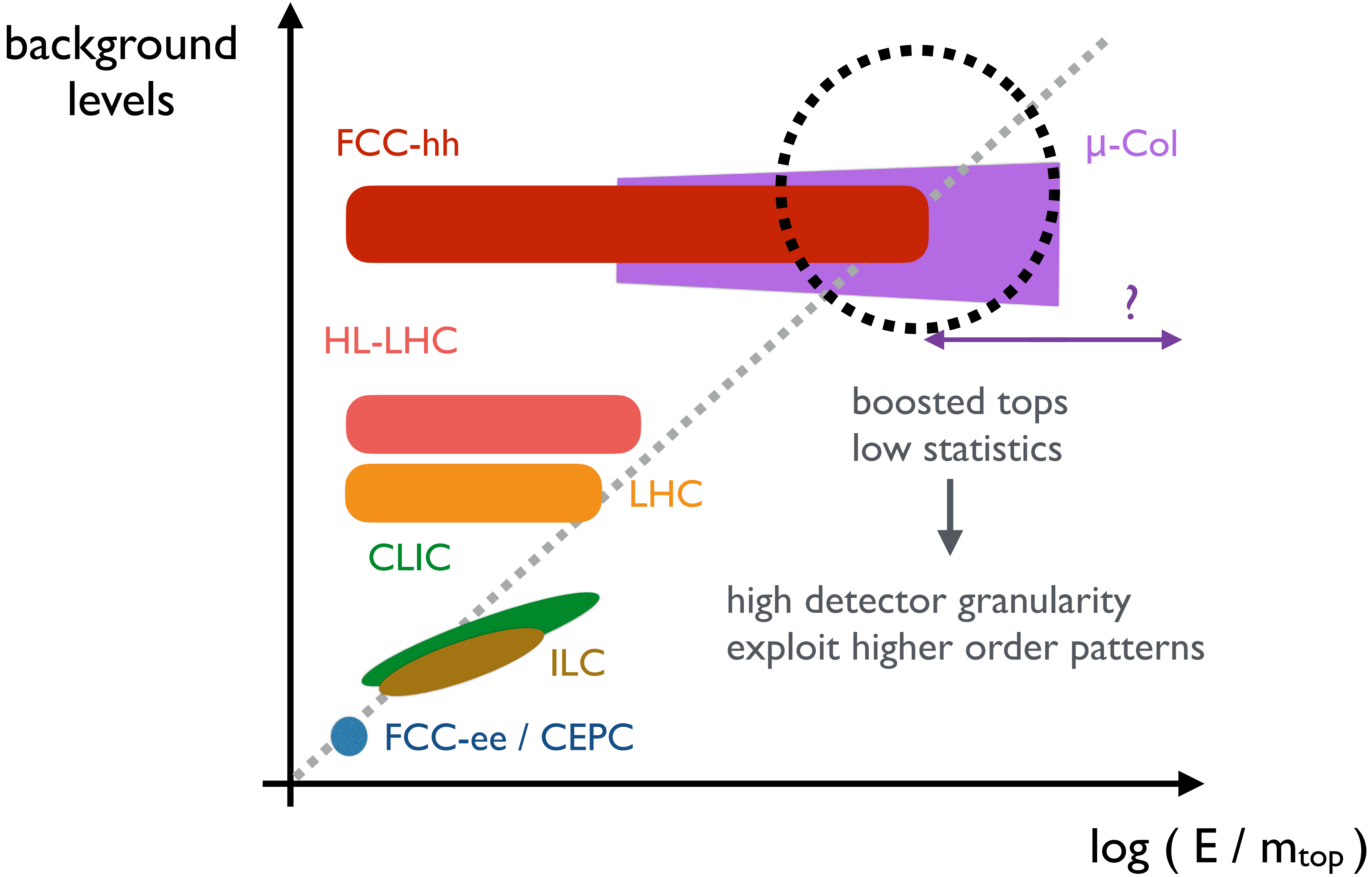
→

maximize reconstruction efficiency
of all possible decay modes
low mass detectors

Key takeaways



Tops at future colliders



boosted tops
low statistics

high detector granularity
exploit higher order patterns

Discussion

We should come up with software / detector specifications derived from the maximisation of the physics potential of key measurements (not always easy ..)

- Low energy / precision (FCC-ee / CEPC / ILC / CLIC)
    - Impact of flavour tagging on top related measurements
        - b-tagging
        - c-tagging for FCNCs
        - s-tagging for V_{ts}

- Experimental background rejection
    - Pile-up (FCC-hh), BIB (mu-Col)
    - requirements for detectors

- Are “NLO” (QCD/EWK) effects expected to be play a role in boosted top tagging ?

Backup

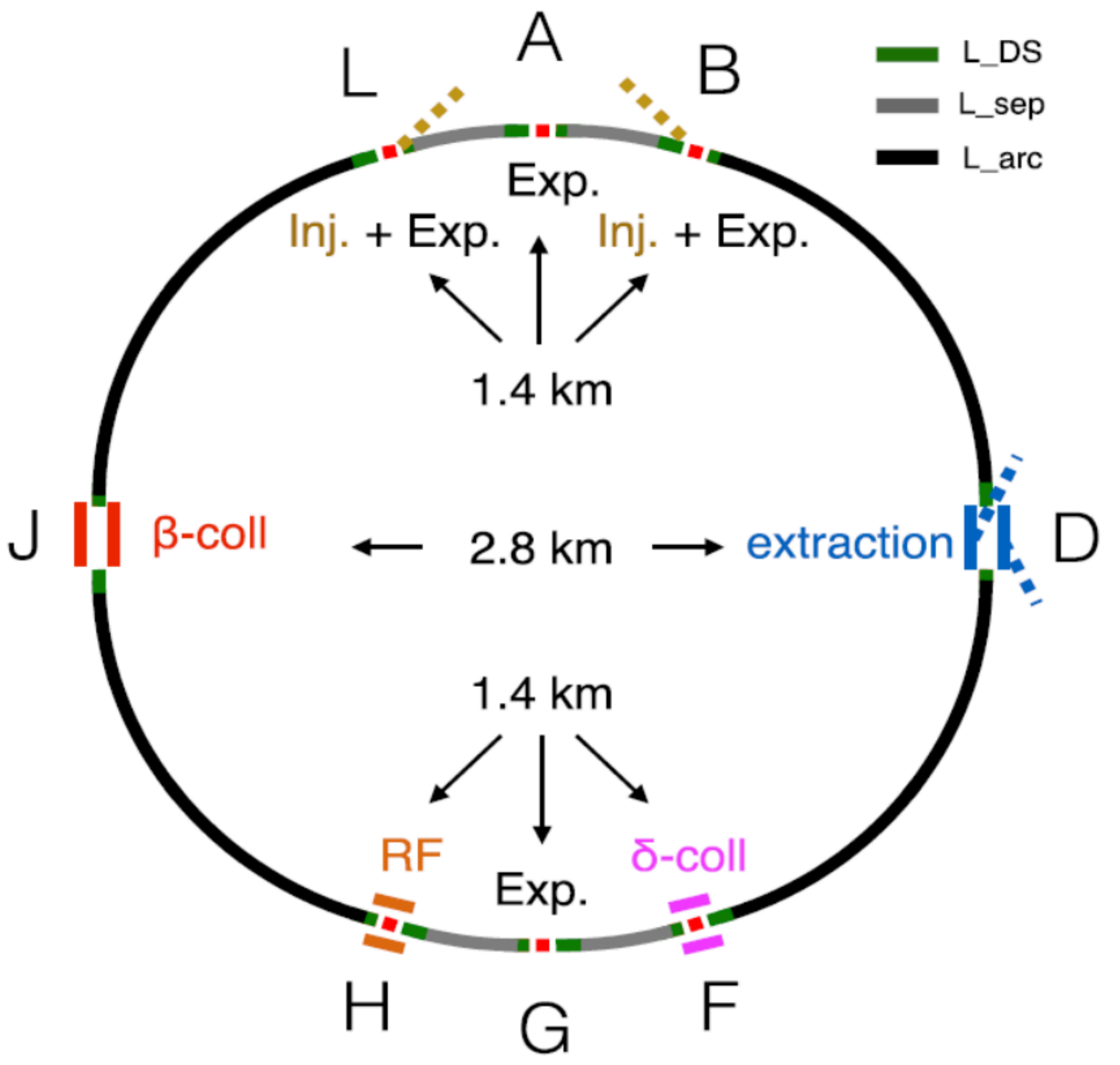
Possible future colliders: FCC-hh

- Circumference = 100 km
- Need dipoles that generate B = 16 T

$\sqrt{s}$ = 100 TeV

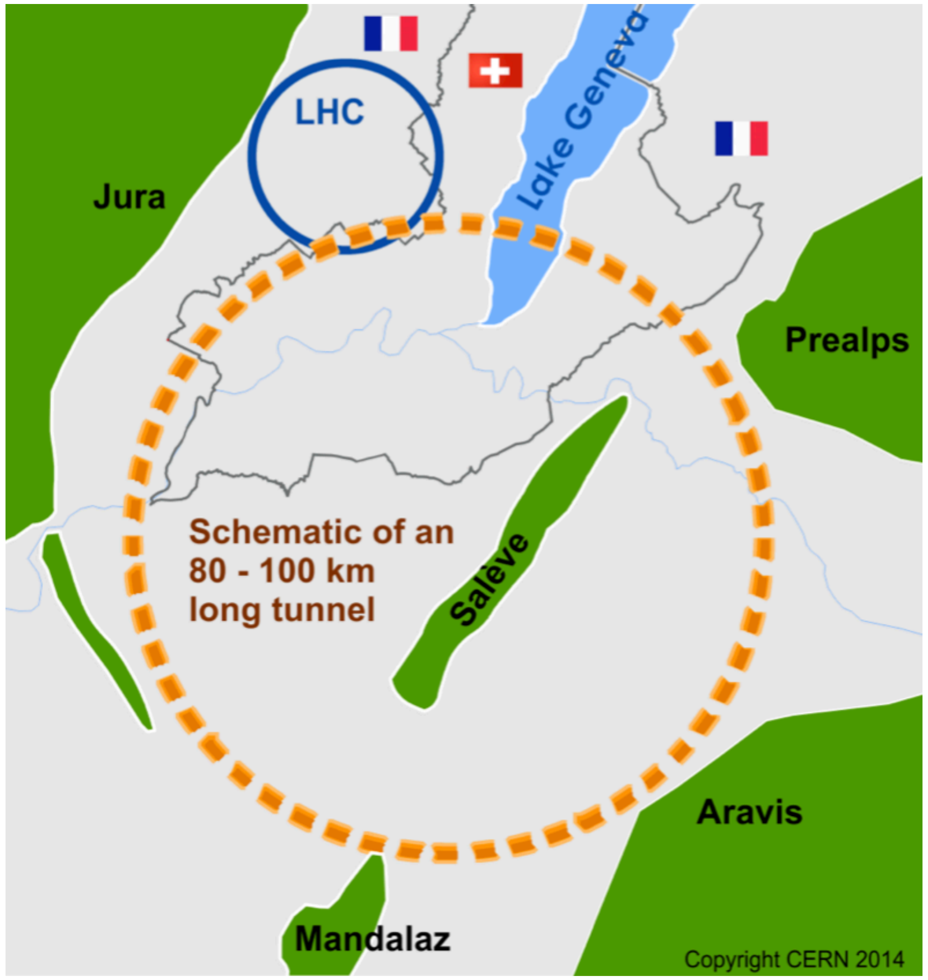
8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- O(20) times LHC

	FCC-hh Initial	FCC-hh Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4



In its high luminosity phase, FCC-hh produces **1000 PU interactions** per bunch crossing

Future hadron colliders



Within the FCC collaboration (CERN as host lab), 5 main accelerator facilities have been studied:

- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
- ee-collider (FCC-ee):
  - as a (potential) first step
- ep collider (FCC-eh)
- HE-LHC :
  - 27 TeV (16T magnets in LHC tunnel)
- Low E FCC-hh
  - 100 km - 6T - 37 TeV

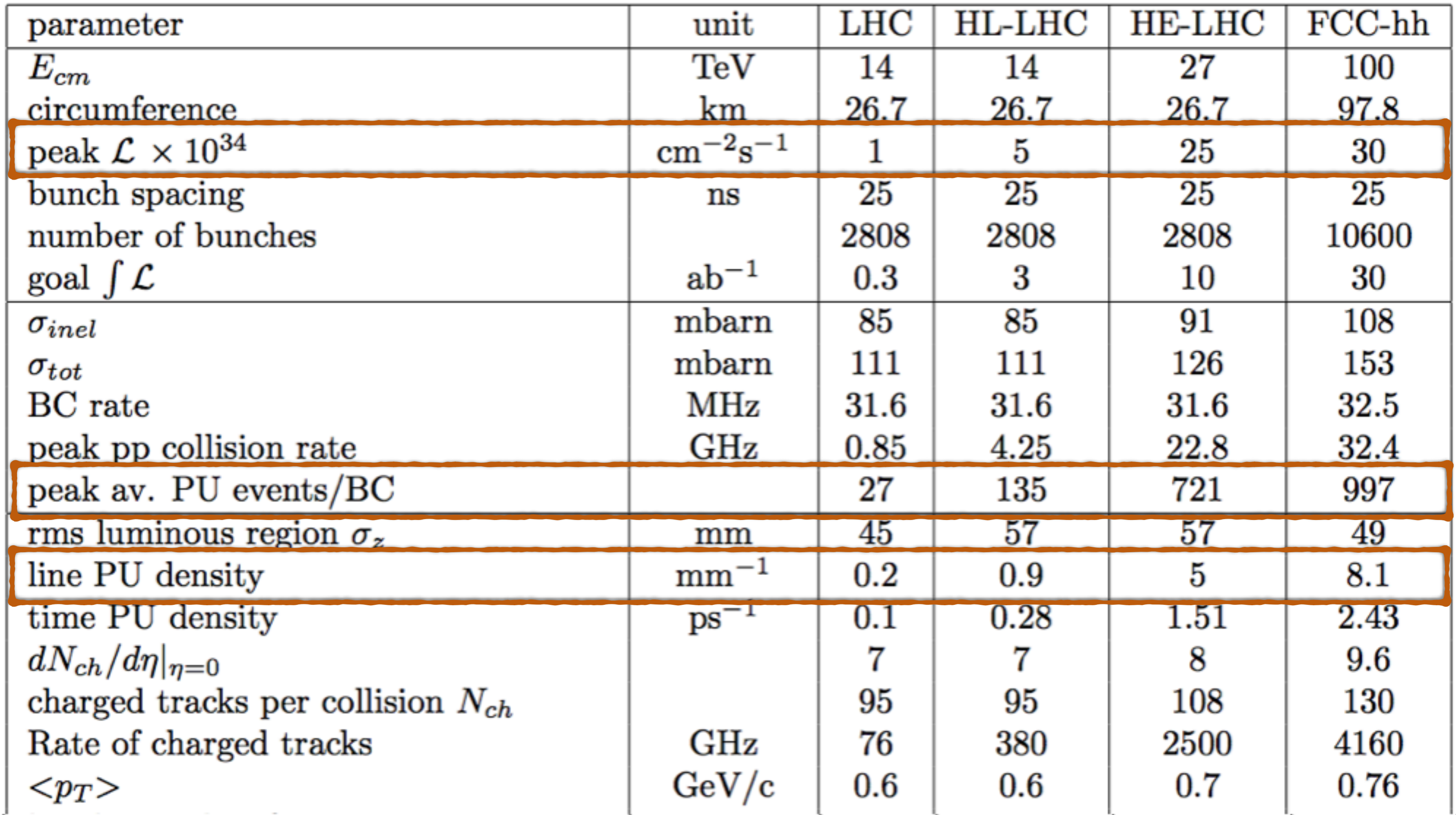
CERN-FCC-PHYS-2019-0001

CDRs and European Strategy documents have been made public in Jan. 2019

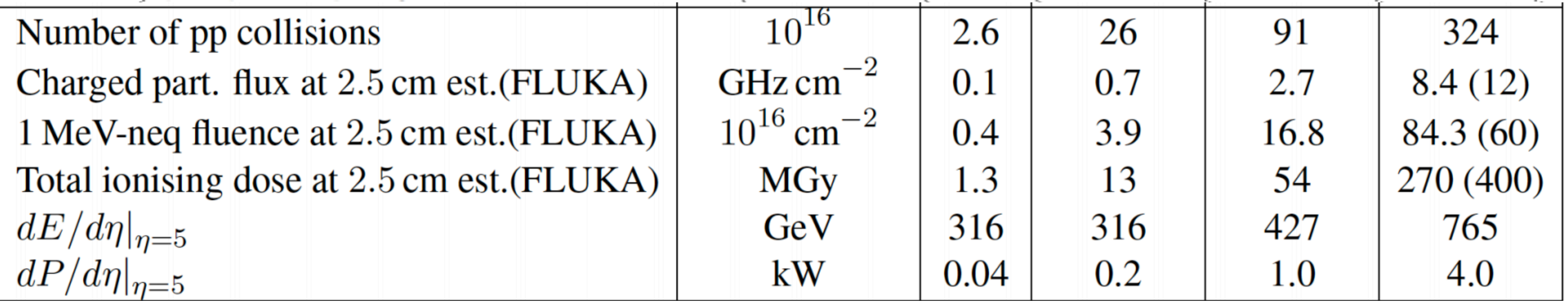
https://fcc-cdr.web.cern.ch/

Machine 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

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

Reach at high energies (I)

For more details see L. Wang lectures at IAS ‘17

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

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

dimensional analysis

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

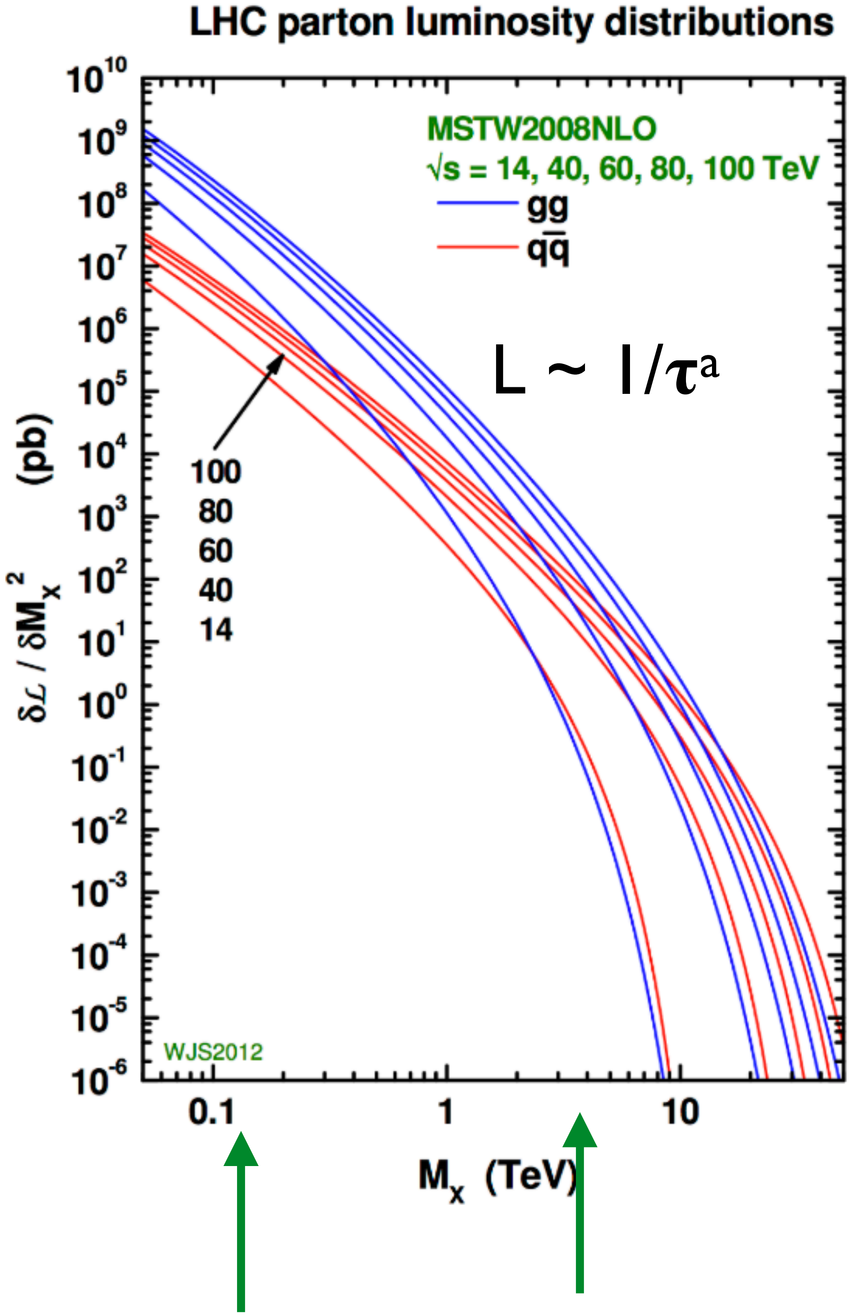
$$1/\tau^{a} \qquad\qquad 1/M^2$$

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

assumes mostly produce at threshold

$\mathscr{L}$: integrated luminosity

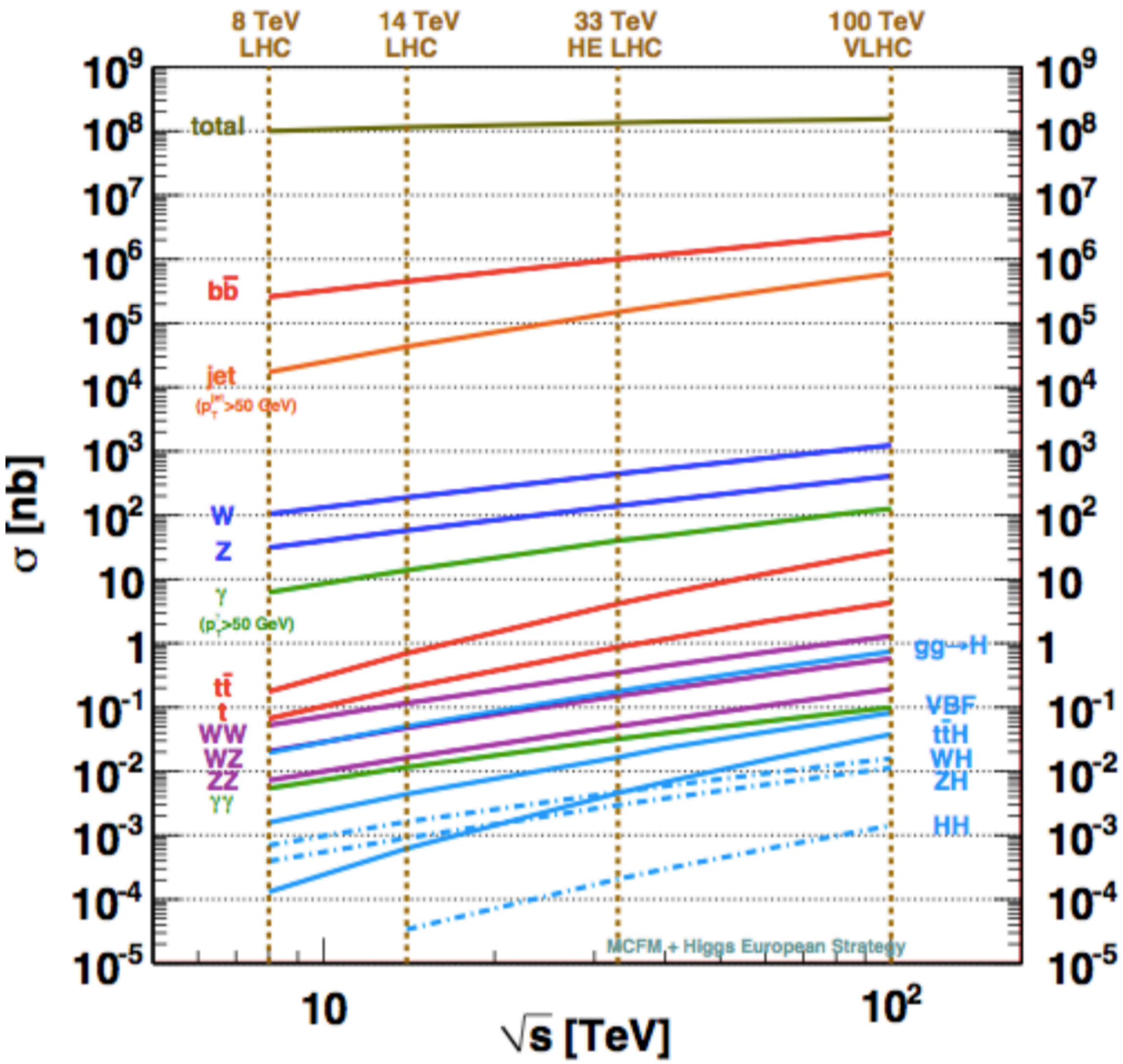
L_{parton} : parton luminosity



$L \sim 1/\tau^{a}$

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

(SM) Physics processes @high energy



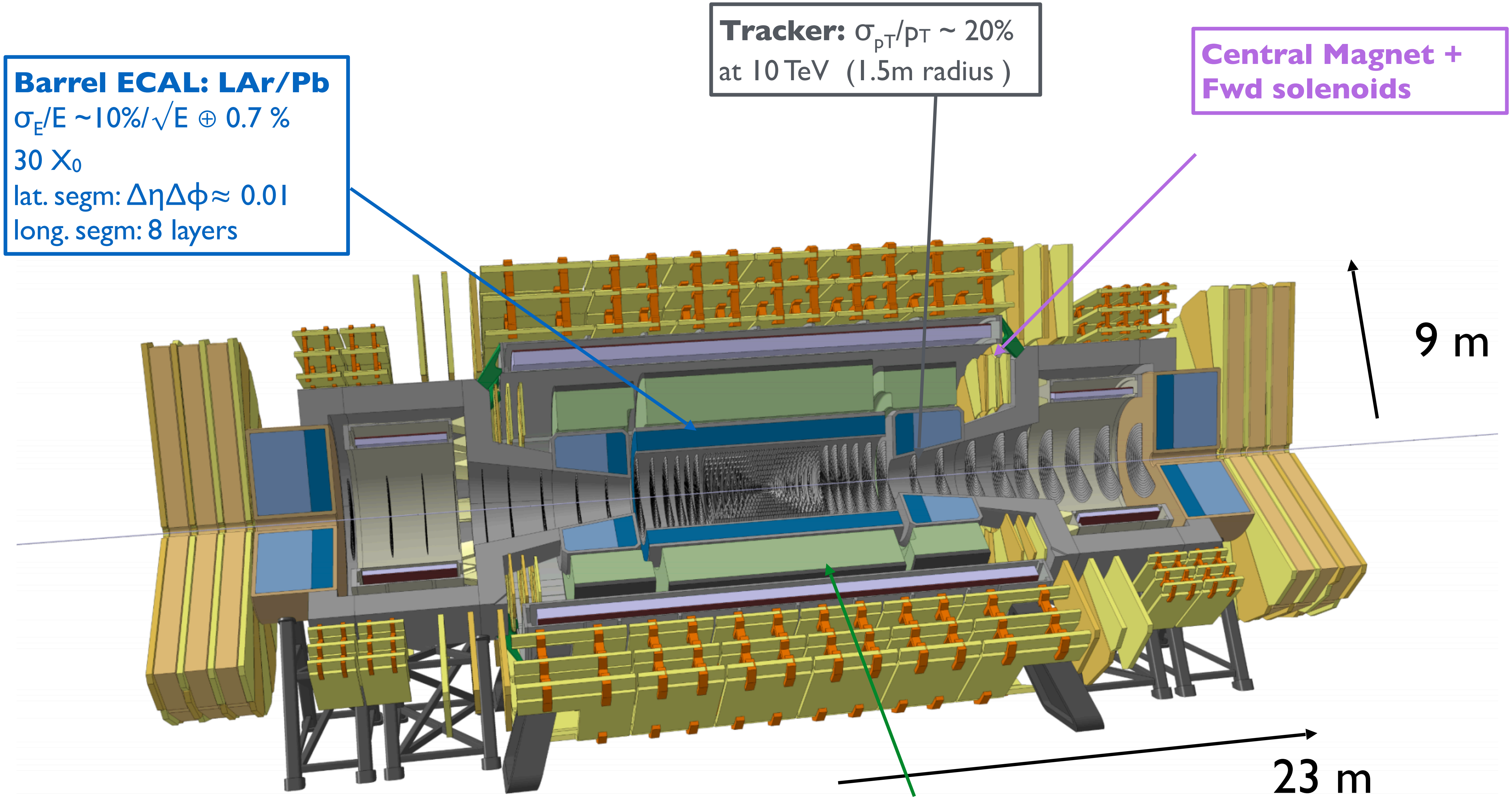
- Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

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

- *Inclusive cross-section* for relevant processes (single and HH) show a significant increase.
  - x 20-50 increase

→ interesting physics sticks out more !

The FCC-hh detector



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 λ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

100 TeV machine parameters

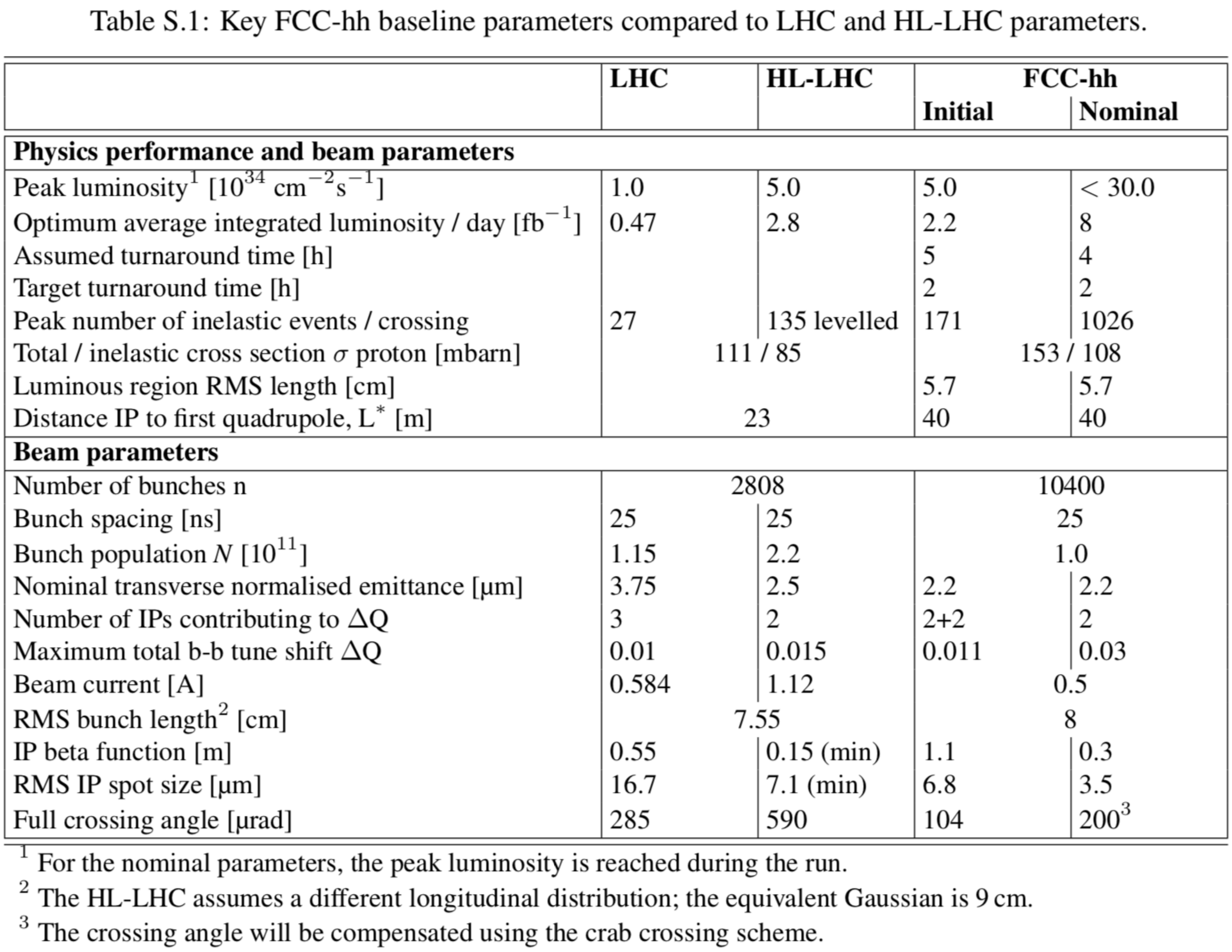


Table S.1: Key FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

	LHC	**HL-LHC**	**FCC-hh**	
			Initial	**Nominal**
Physics performance and beam parameters				
Peak luminosity[1] $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.0	5.0	5.0	< 30.0
Optimum average integrated luminosity / day $[\mathrm{fb}^{-1}]$	0.47	2.8	2.2	8
Assumed turnaround time [h]			5	4
Target turnaround time [h]			2	2
Peak number of inelastic events / crossing	27	135 levelled	171	1026
Total / inelastic cross section σ proton [mbarn]	111 / 85		153 / 108	
Luminous region RMS length [cm]			5.7	5.7
Distance IP to first quadrupole, L^* [m]	23		40	40
Beam parameters				
Number of bunches n	2808		10400	
Bunch spacing [ns]	25	25	25	
Bunch population N $[10^{11}]$	1.15	2.2	1.0	
Nominal transverse normalised emittance [μm]	3.75	2.5	2.2	2.2
Number of IPs contributing to ΔQ	3	2	2+2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.011	0.03
Beam current [A]	0.584	1.12	0.5	
RMS bunch length[2] [cm]	7.55		8	
IP beta function [m]	0.55	0.15 (min)	1.1	0.3
RMS IP spot size [μm]	16.7	7.1 (min)	6.8	3.5
Full crossing angle [μrad]	285	590	104	200[3]

[1] For the nominal parameters, the peak luminosity is reached during the run.

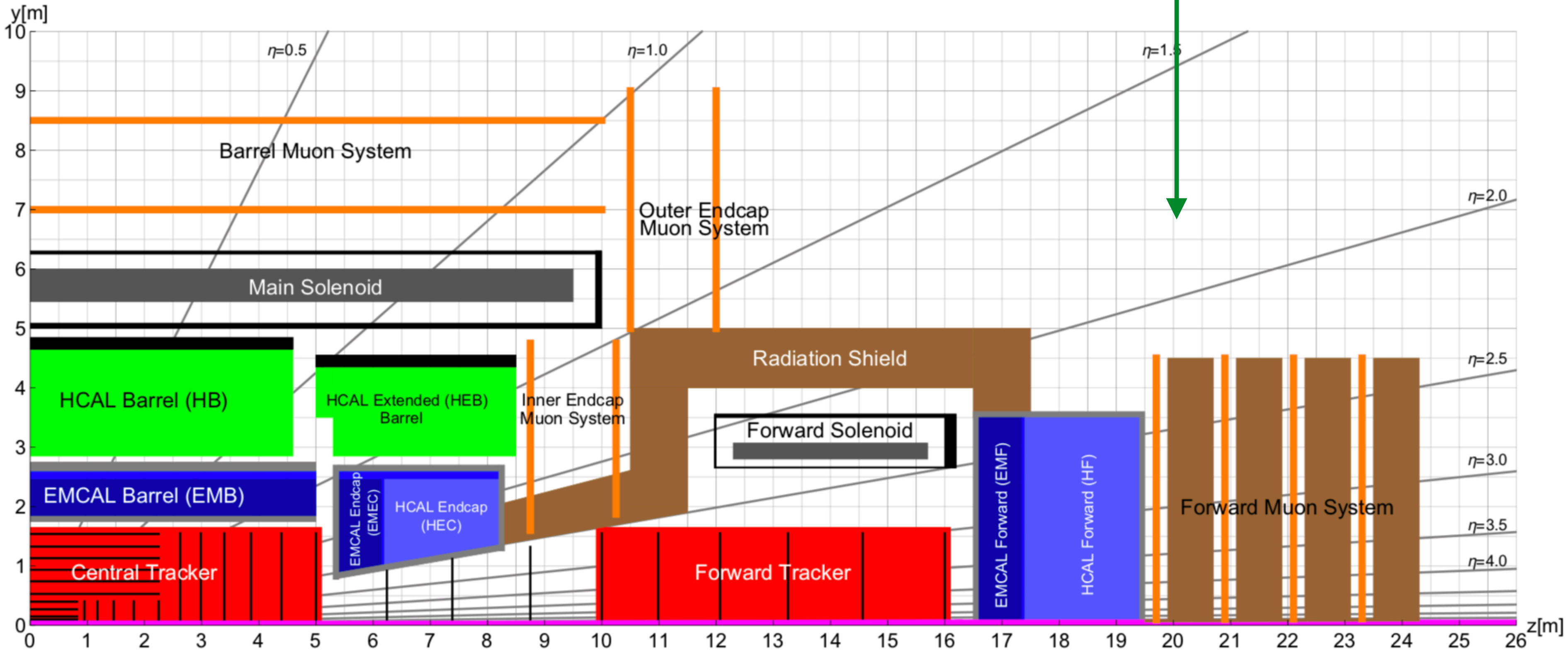
[2] The HL-LHC assumes a different longitudinal distribution; the equivalent Gaussian is 9 cm.

[3] The crossing angle will be compensated using the crab crossing scheme.

An FCC-hh detector

- Must be able to cope with:
  - very large dynamic range of signatures (E = 20 GeV -20 TeV)
  - hostile environment (1k pile-up and up to 10^{18} cm^{-2} MeV neq fluence)

- Characteristics:
  - large acceptance (for low p_T physics)
  - extreme granularity (for high p_T and pile-up rejection)
  - timing capabilities
  - radiation hardness



Towards defining the FCChh detector

Physics constraints

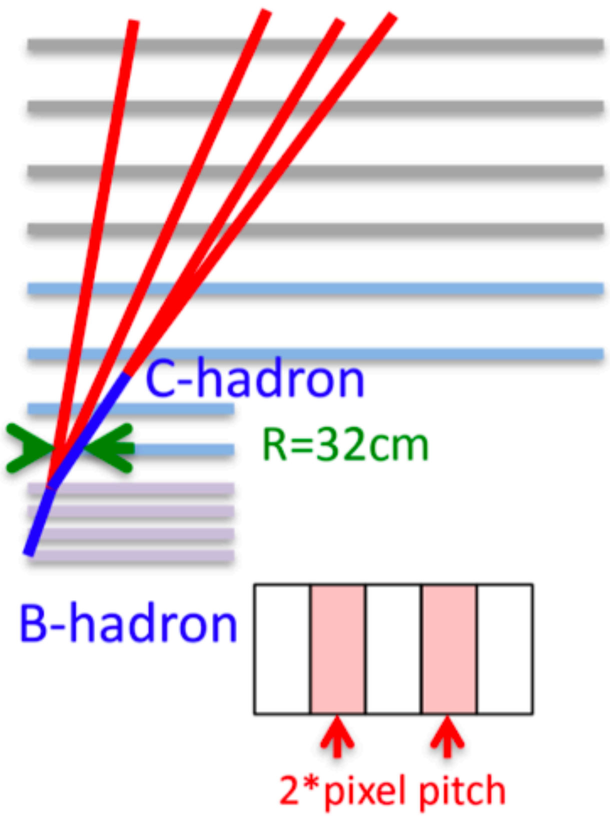
- The boosted regime:
  → measure b-jets, taus from multi-TeV resonances

- 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

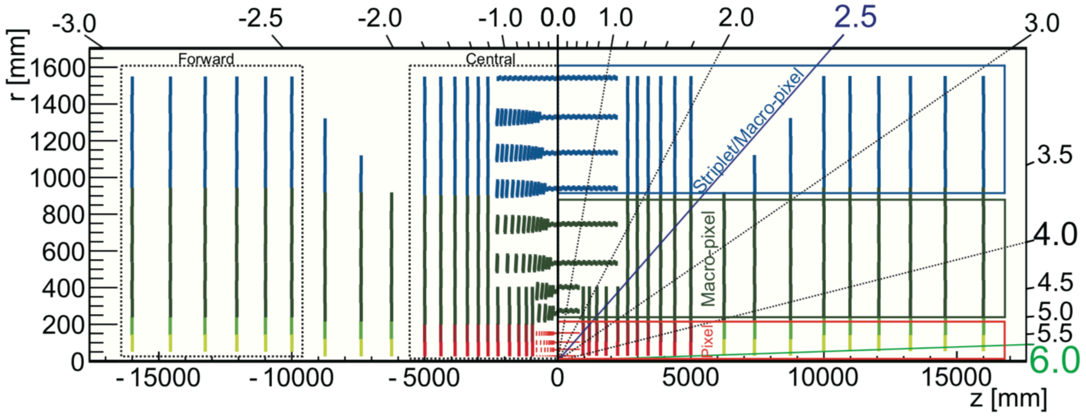
→ re-think reconstruction algorithms:
  - hard to reconstruct displaced vertices
  - **exploit hit multiplicity discontinuity**



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

- displaced vertices

An FCC-hh detector that can do the job

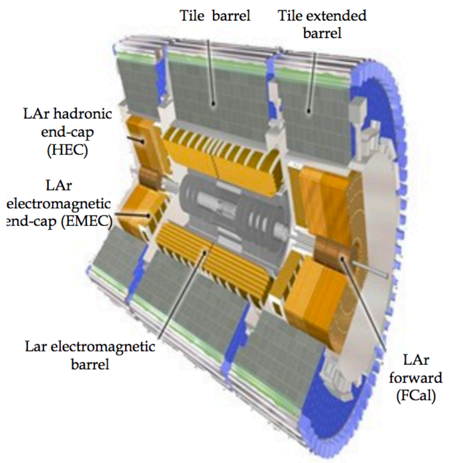


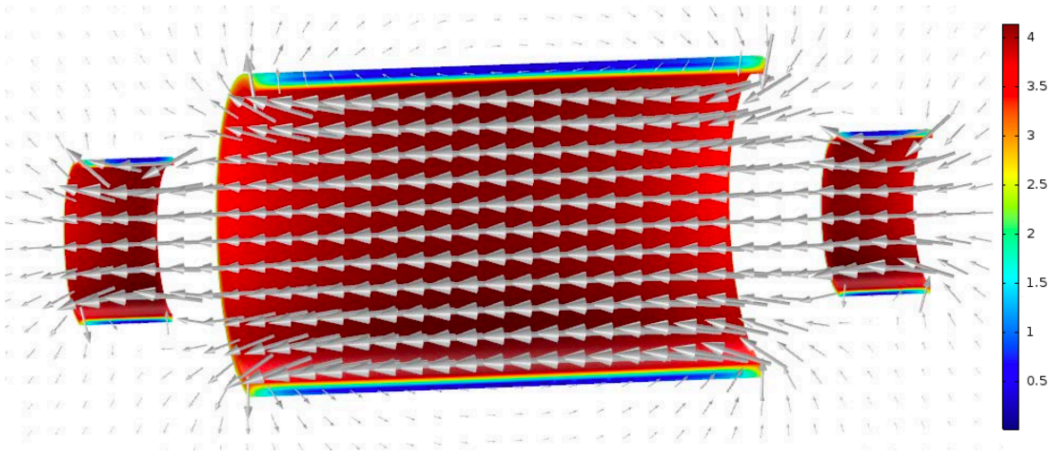
Tracker

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

Calorimeters

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



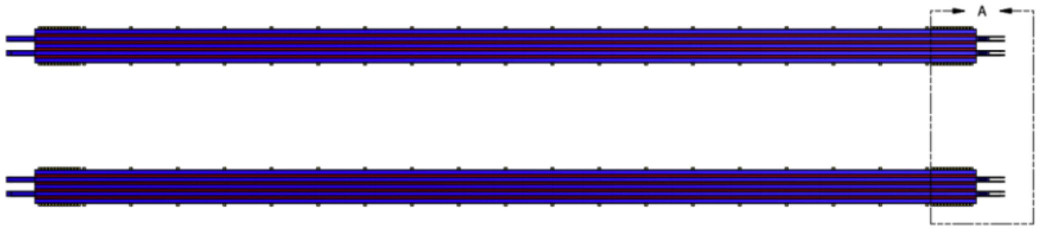


Magnet

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

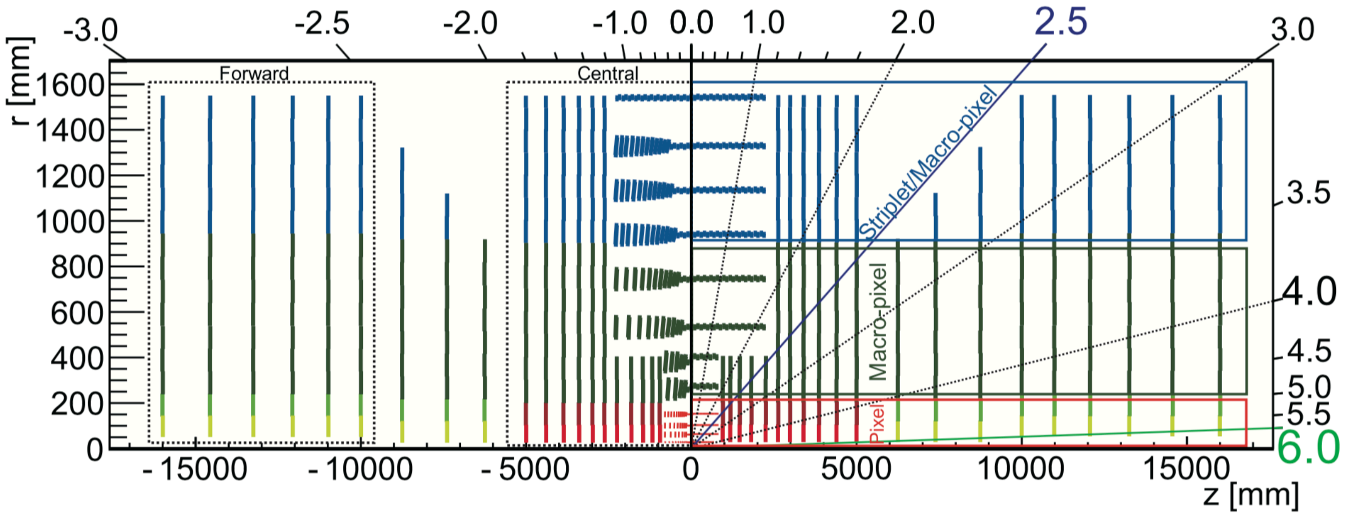
Muon spectrometer

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



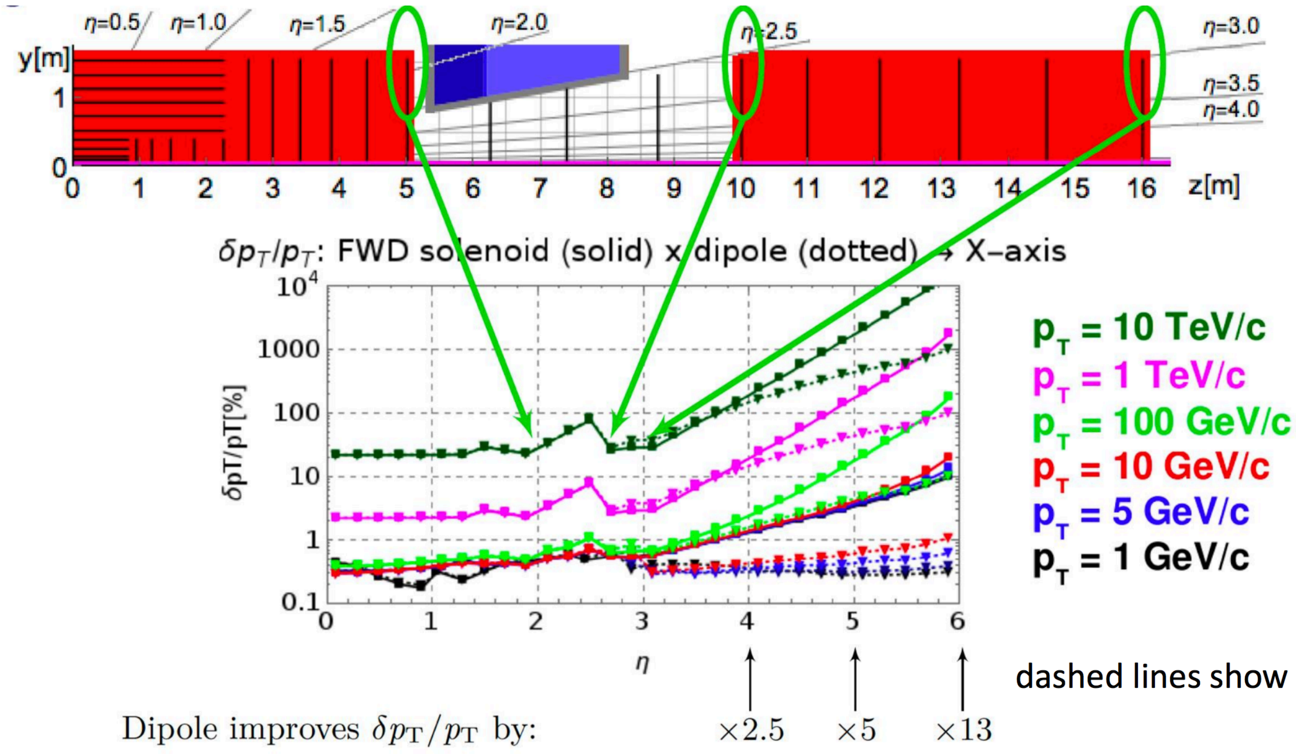
Tracker

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



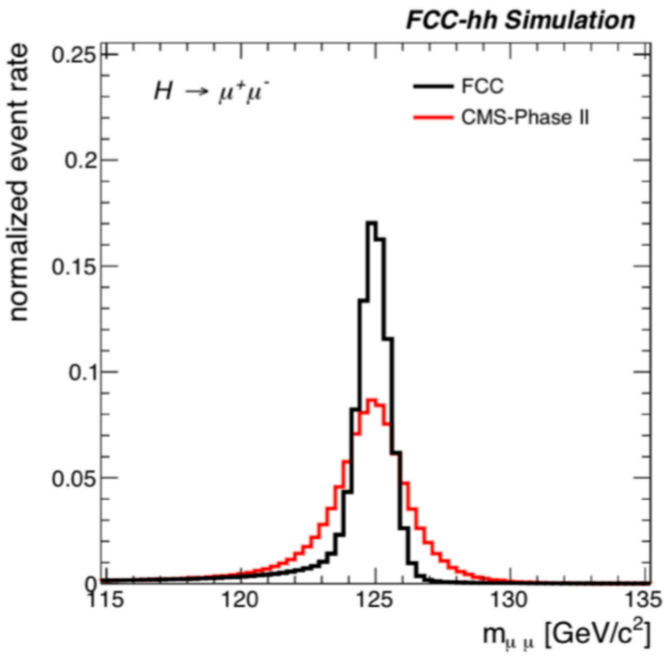
- Tilted geometry with inclined modules:
  - minimize effect of Multiple scattering (low material)
  - helps with pattern recognition

tkLayout



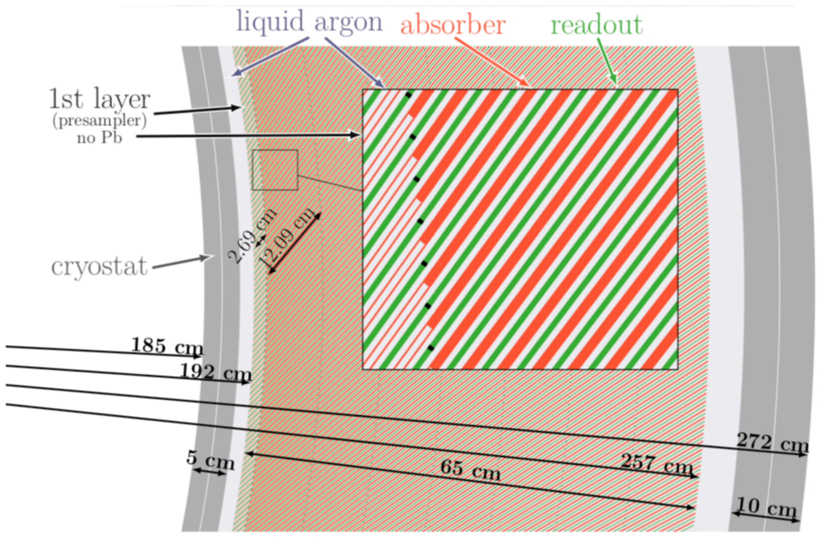
dashed lines show the

Delphes

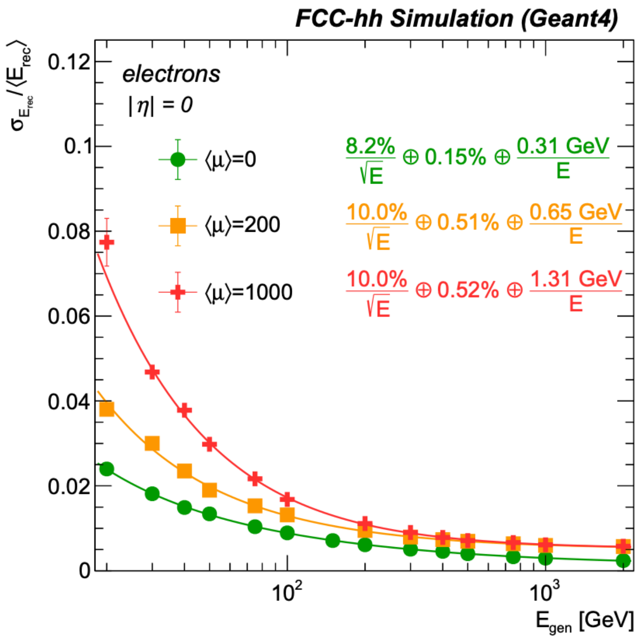


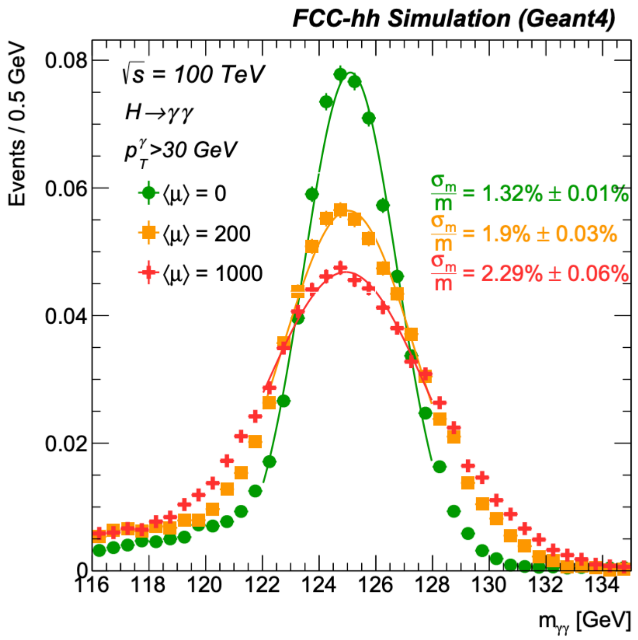
low p_T muons → resolution dominated by MS

Calorimeters



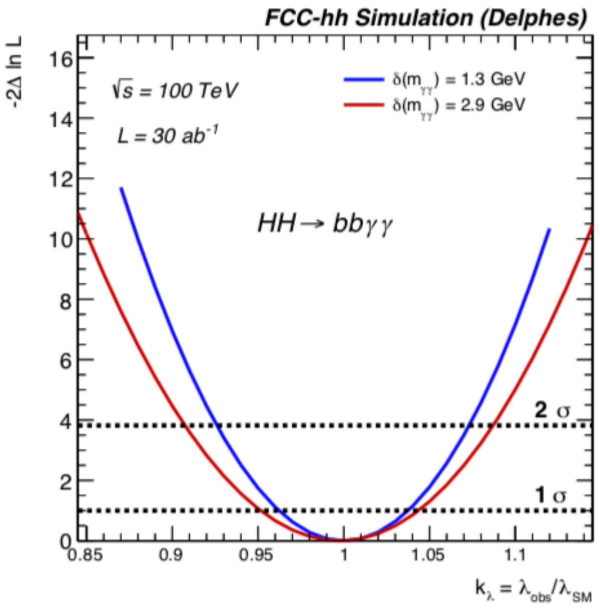
Full Sim





Delphes

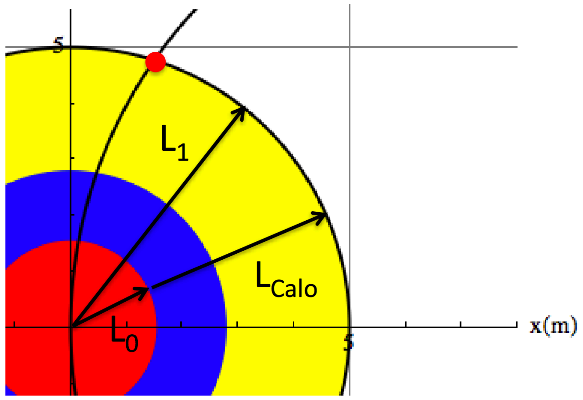
- ECAL: LAr + Pb technology driven by radiation hardness
- HCAL:
  - Organic scintillator + Steel, R/O with WLS fiber + SiPM
  - LAr in the forward (Dose > 10 MGy)



m(γγ) resolution

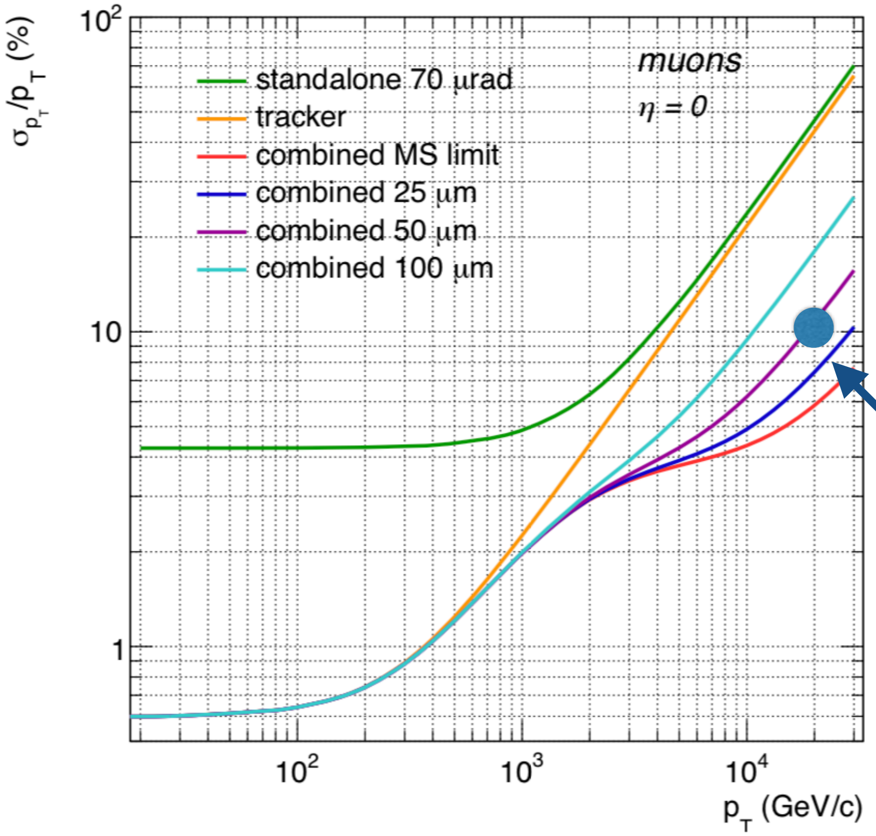
- Design goals:
  - High longitudinal (7+10 layers) + transverse segmentation (x4 CMS and ATLAS)
  - Particle-flow compliant
  - standalone PU rejection

Muons



pen & paper

W. Riegler formulae

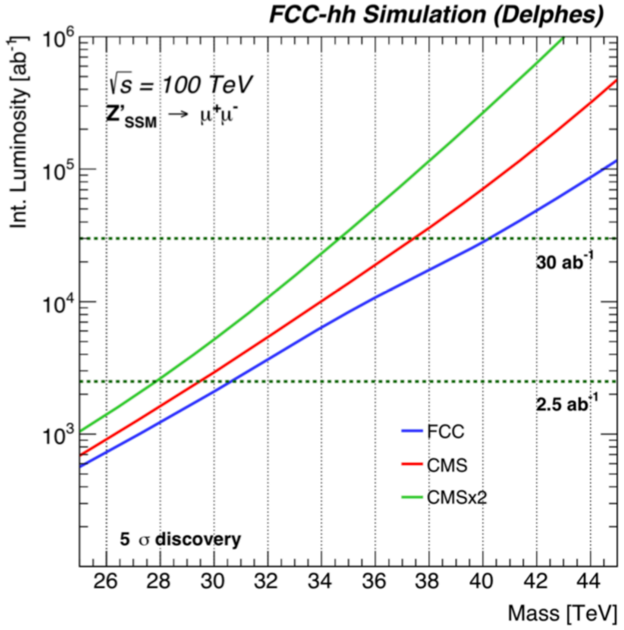


σ_p/p = 10%
@20 TeV

Delphes

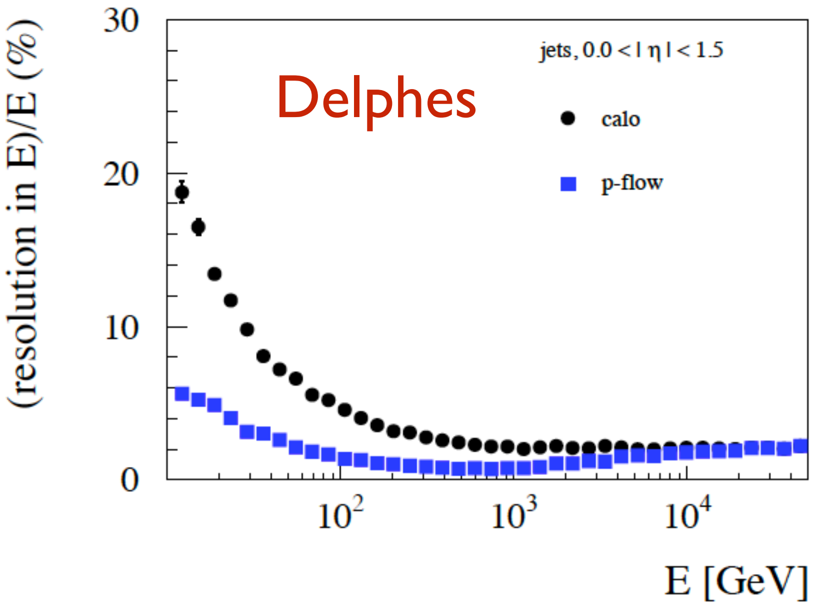
- pT = 4 GeV muons enter the muon system
- pT = 5.5 GeV leave coil at 45 degrees

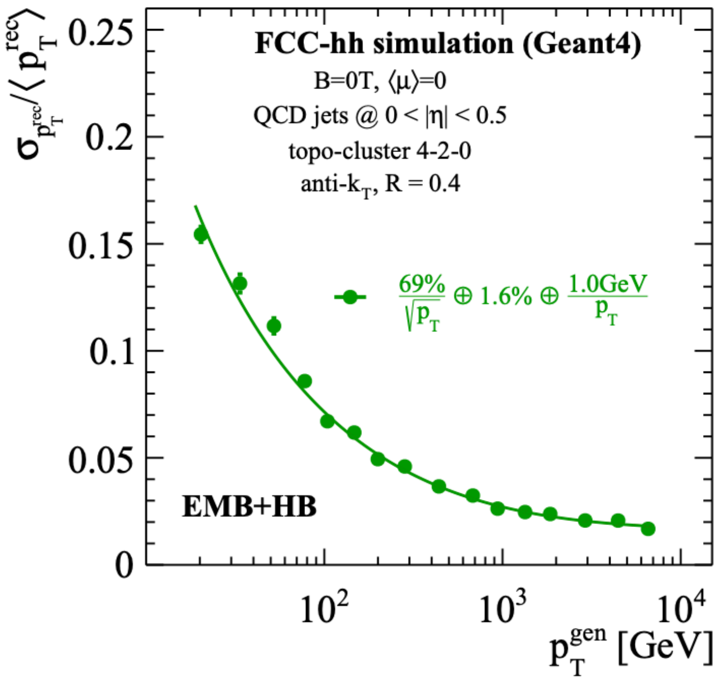
- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 μm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5

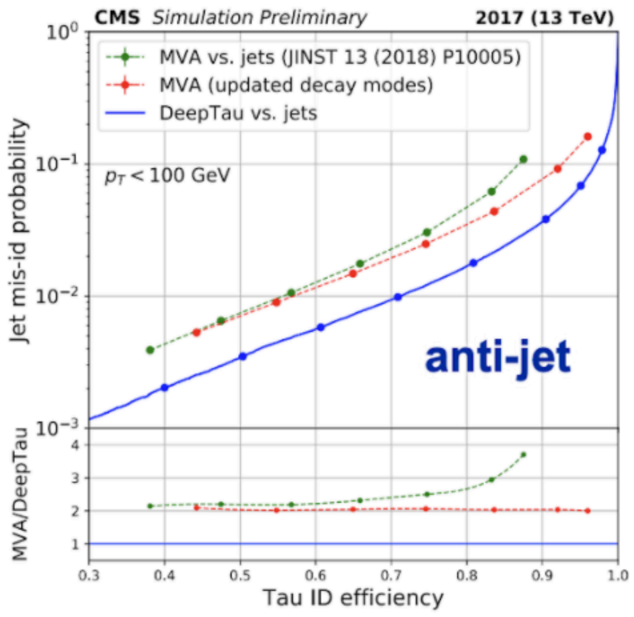


High level objects

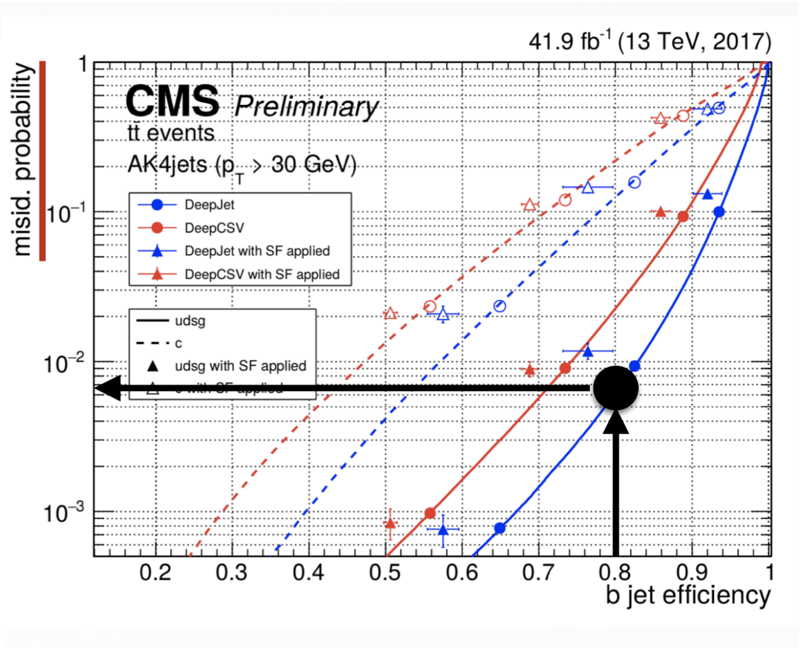
- Jets
  - hard to compare: no PFlow in full sim, but calo only OK (with simplistic clustering ECAL+HCAL clustering)







- Heavy flavour tagging:
  - no full-sim implementation
  - guided from LHC performance, but slightly improved motivated by more granular tracker and calorimeters



Material budget

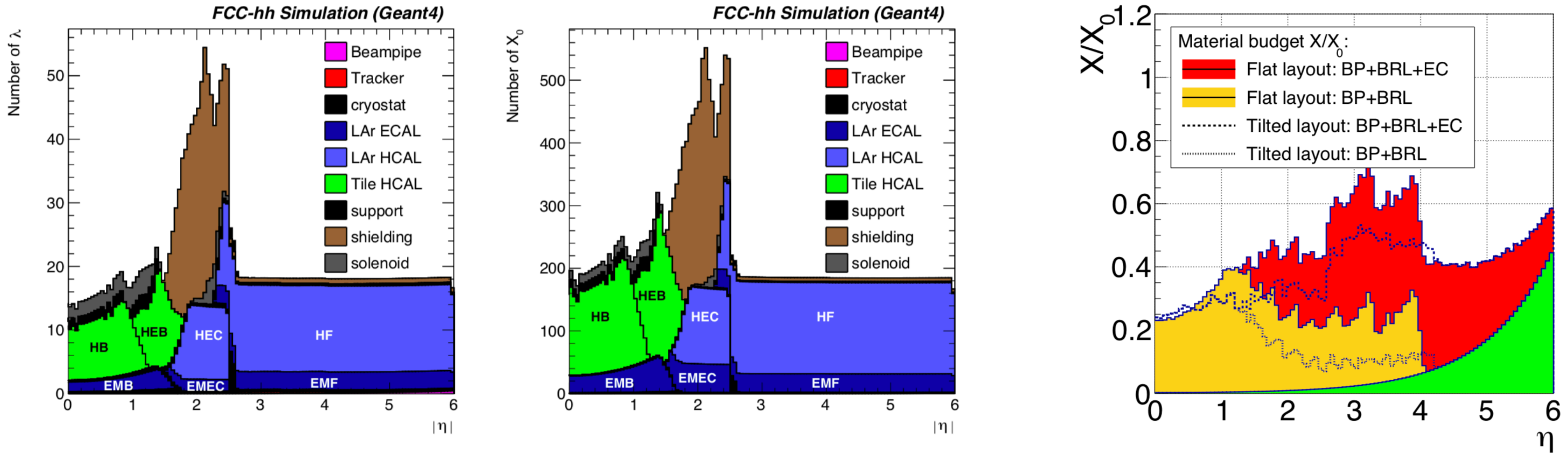
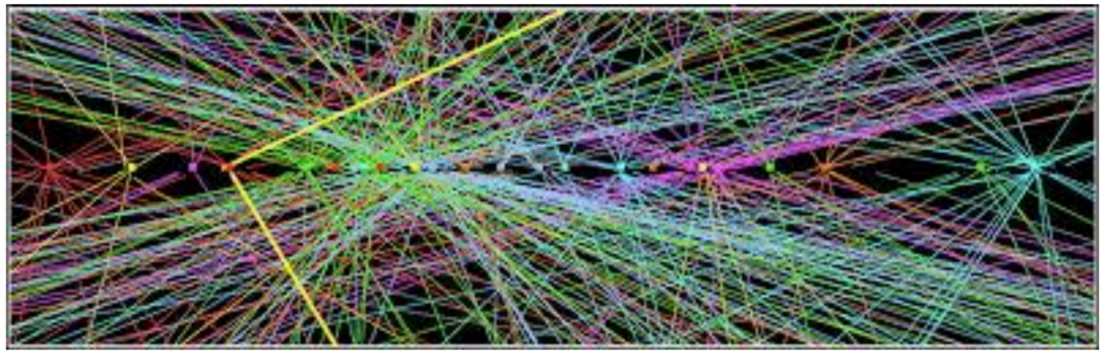


Figure 7.10: Material budget of the different sub-systems. The calorimetry provides $\geq 10.5\,\lambda$ nuclear interaction lengths to maximise shower containment and the total detector material represents between 180 and 280 X_0 radiation lengths.

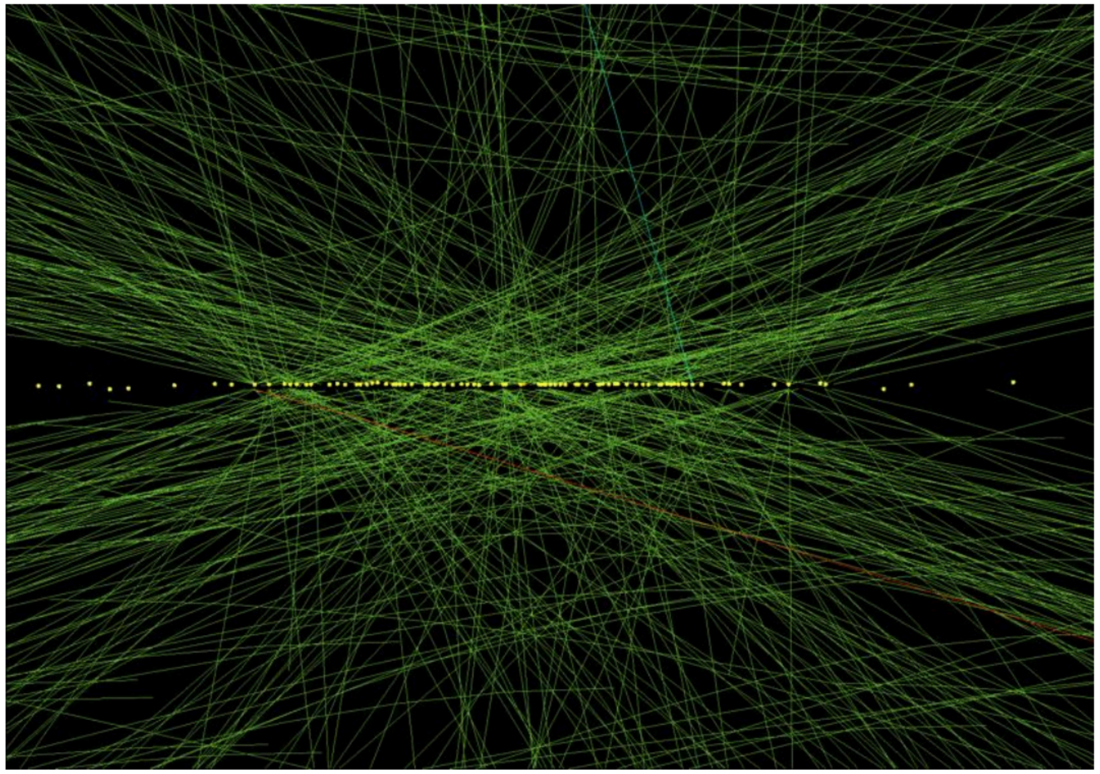
Machine and detector requirements

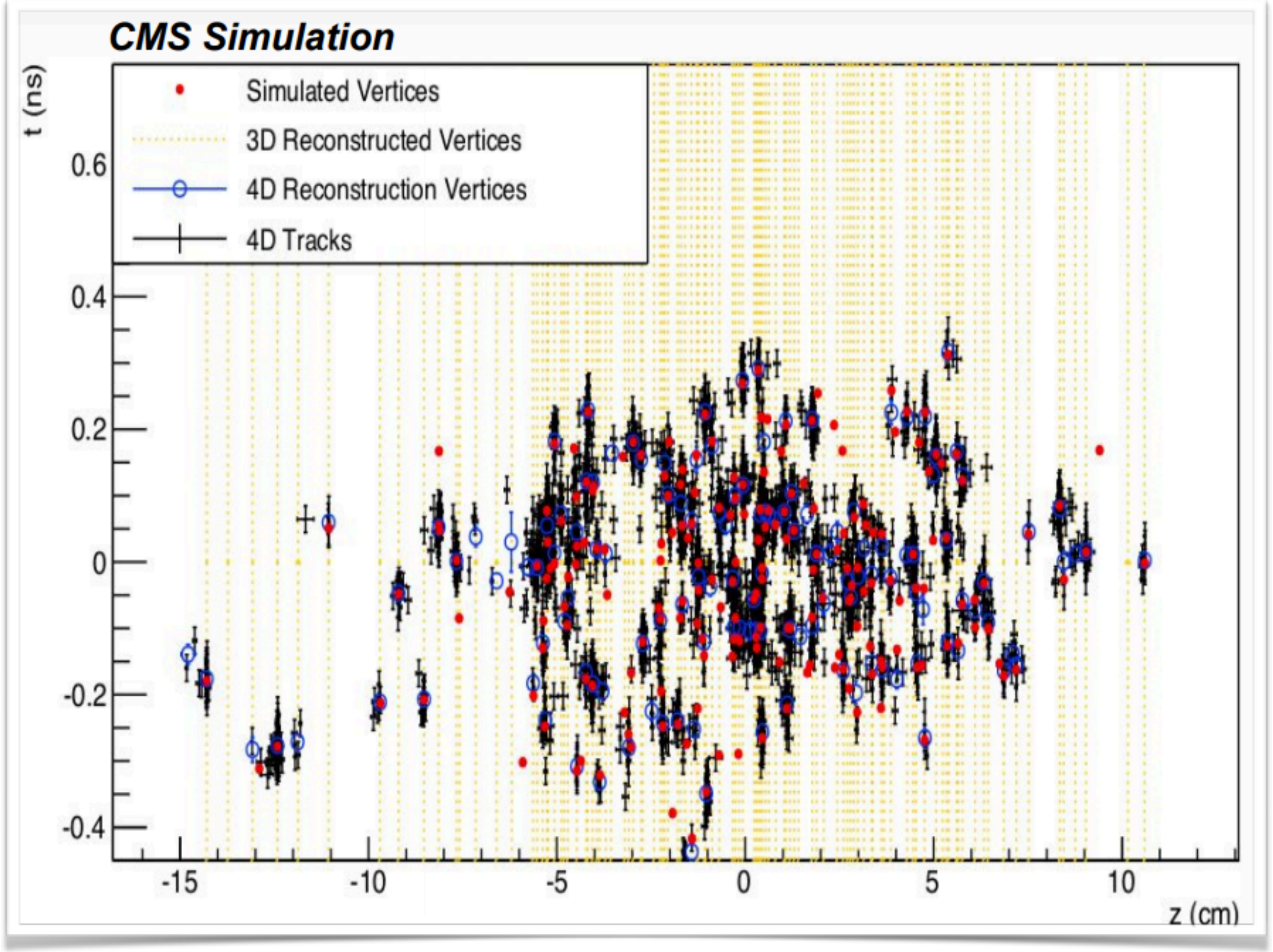
lumi & pile-up



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

Timing helps in identifying PU vertices

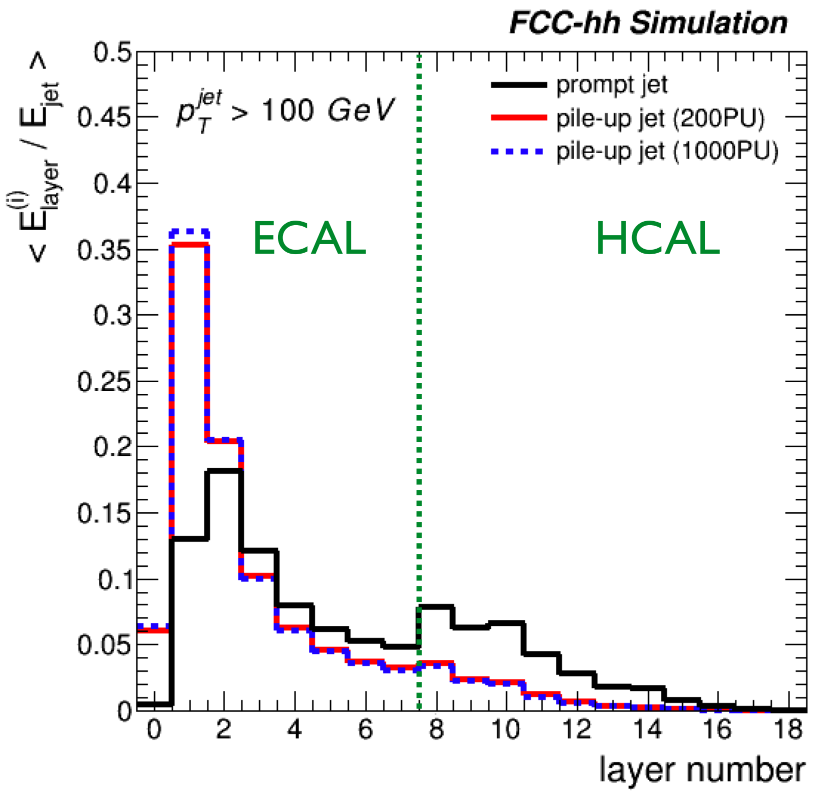




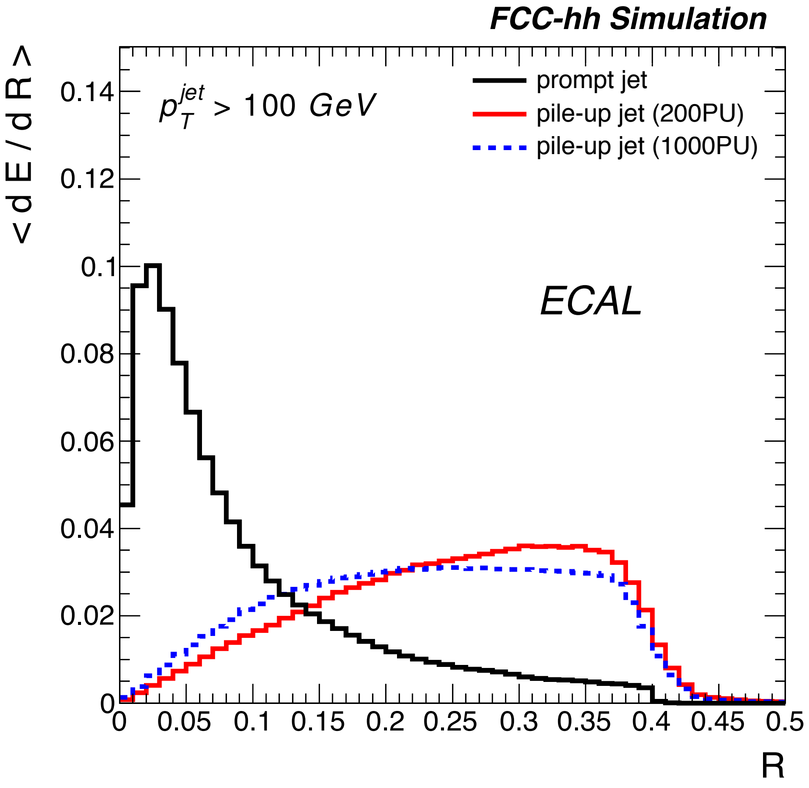
Jet Pile-Up identification

- With 200-1000PU, will get huge amount of fake-jets from PU combinatorics
- need both longitudinal/lateral segmentation for PU identification
- Simplistic observables show possible handles, pessimistic.. (in reality tracking will help a lot)

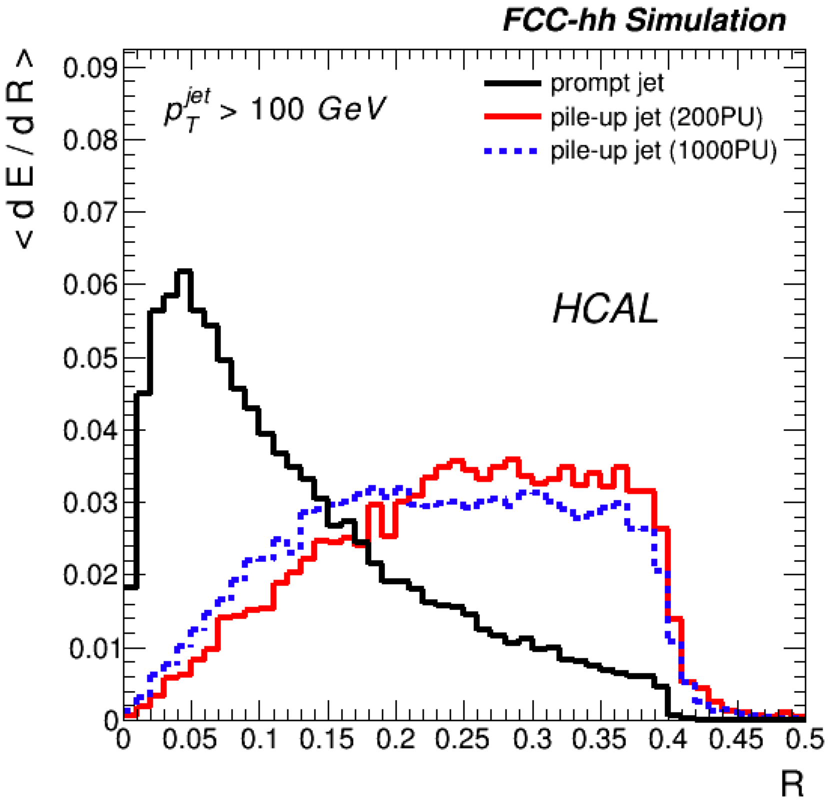
longitudinal



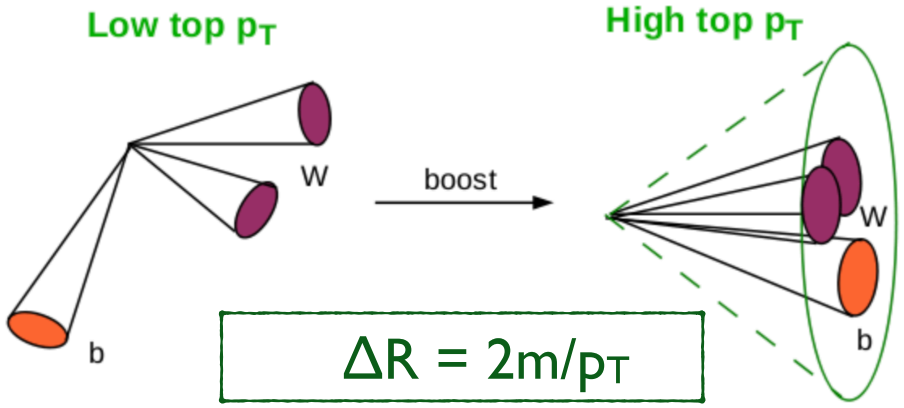
lateral (ECAL)



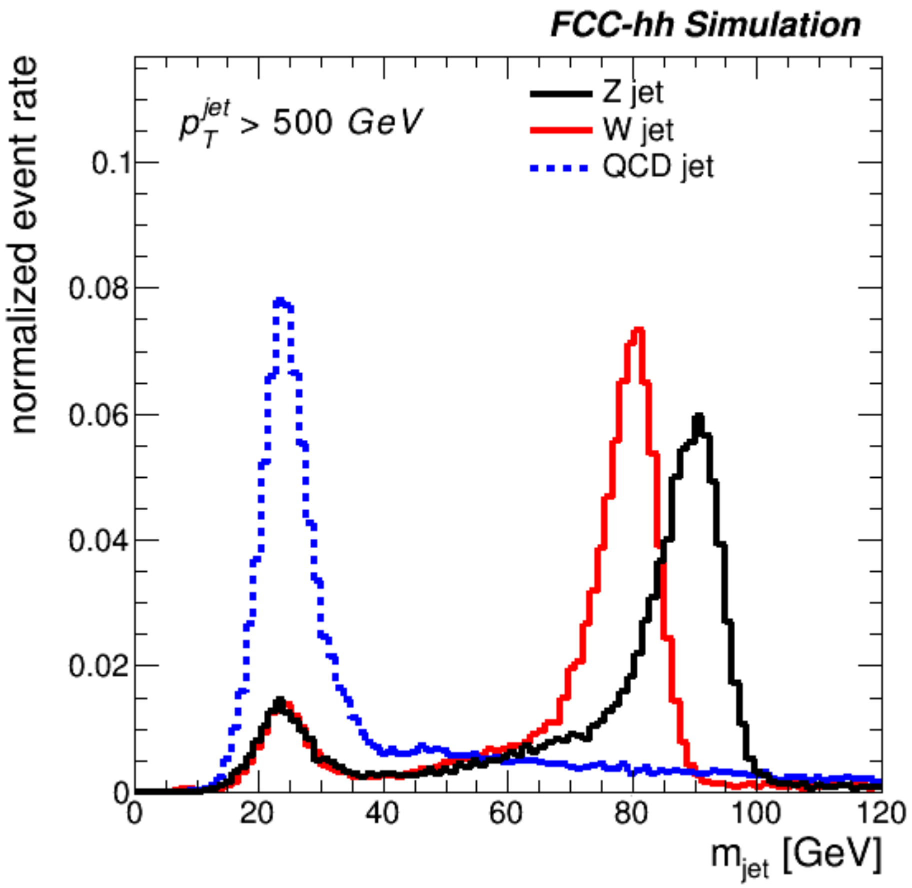
lateral (HCAL)

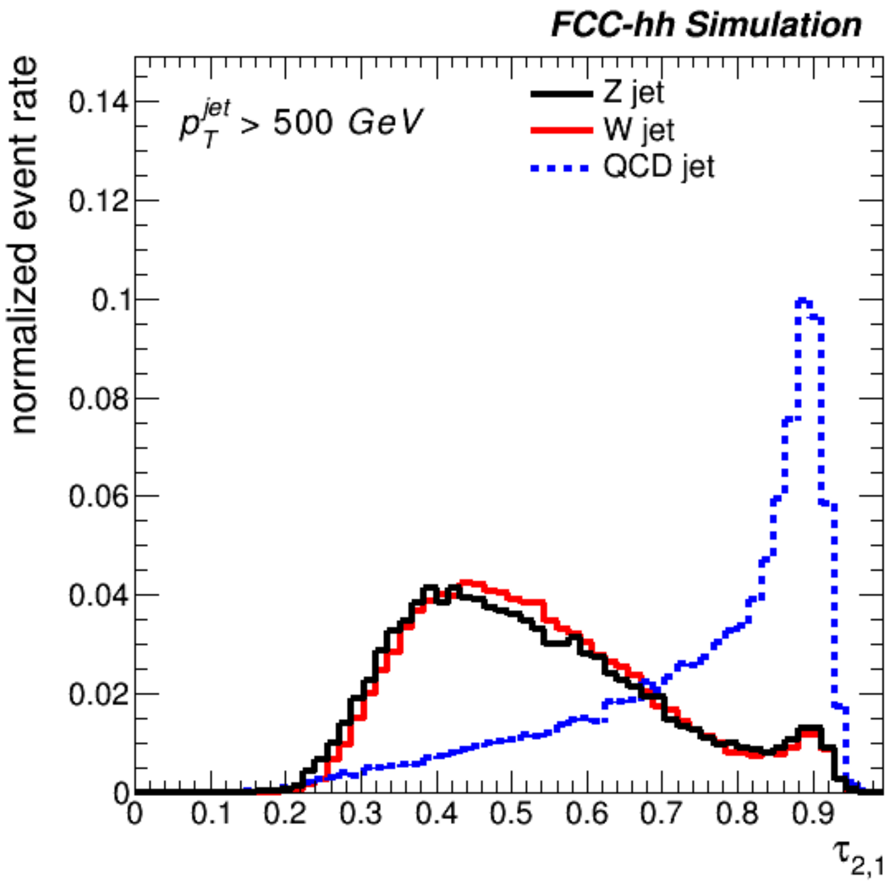


Jet substructure

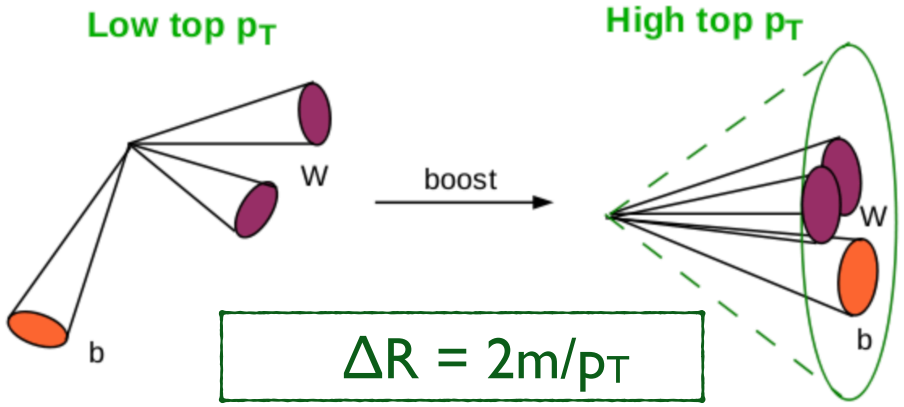


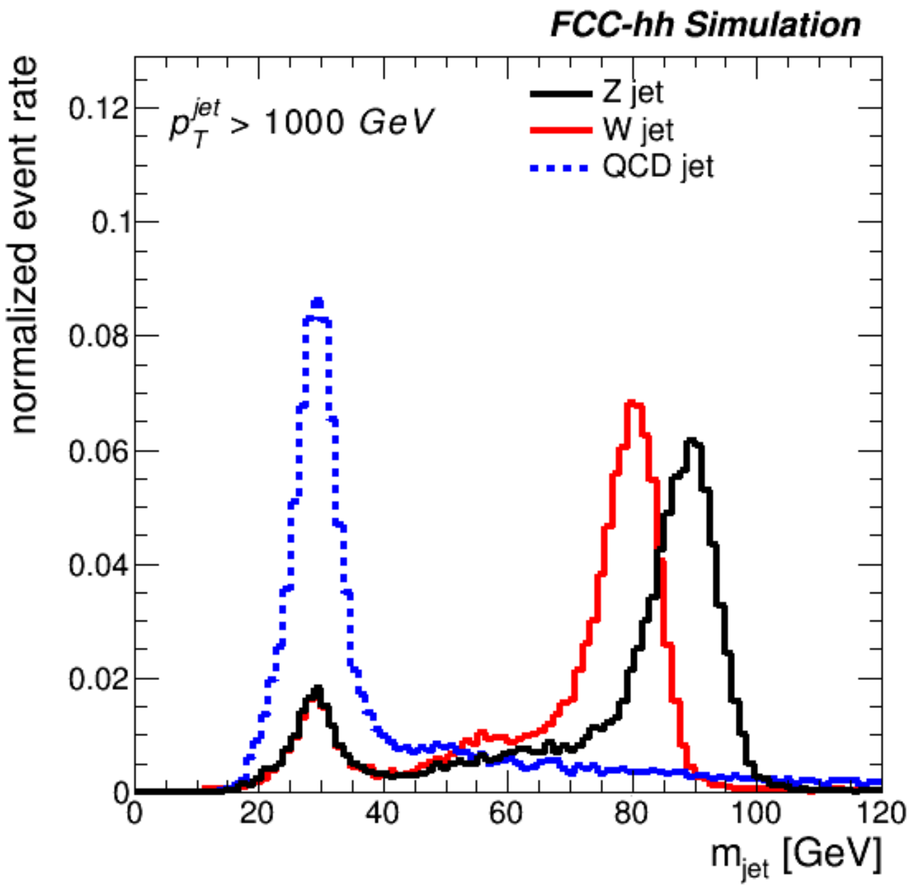
$\Delta R = 2m/p_T$

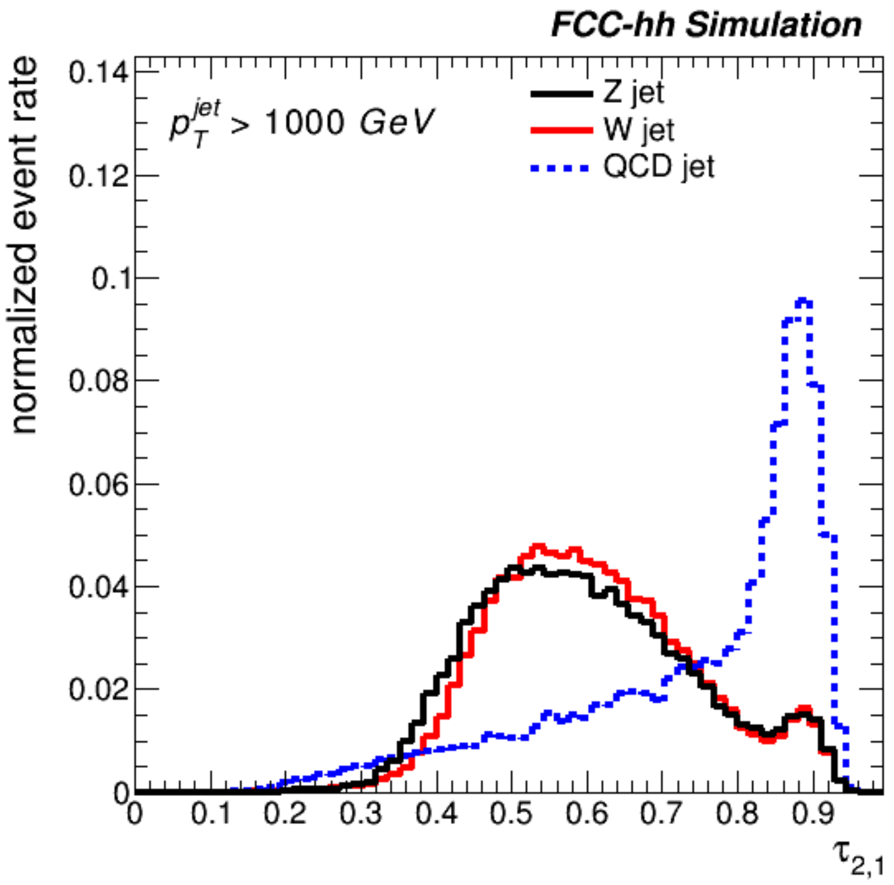




Jet substructure







- Performance good up to 1 TeV, with Calorimeter standalone, and without B field!
- Far from having explored everything possible:
  - Particle-Flow tracks and B field (decrease local occupancy) will improve
  - Machine Learning techniques will help a lot (train on 3D shower image)

Beam induced background

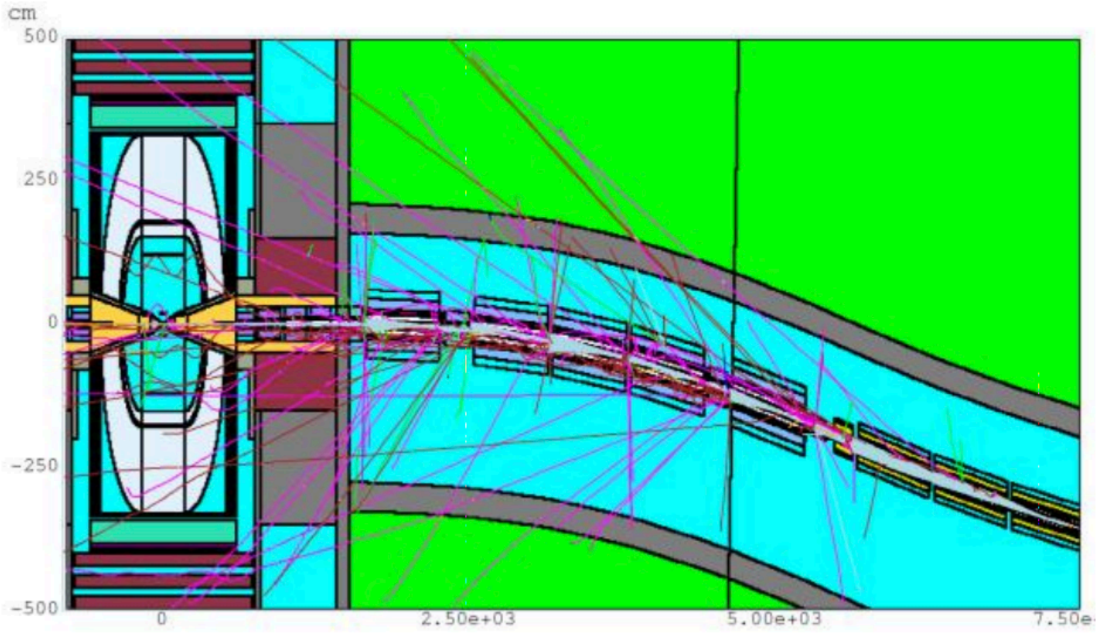
- High energy Muon collider specs are not known yet, can only extrapolate from low energy:

- Beam-induced background:

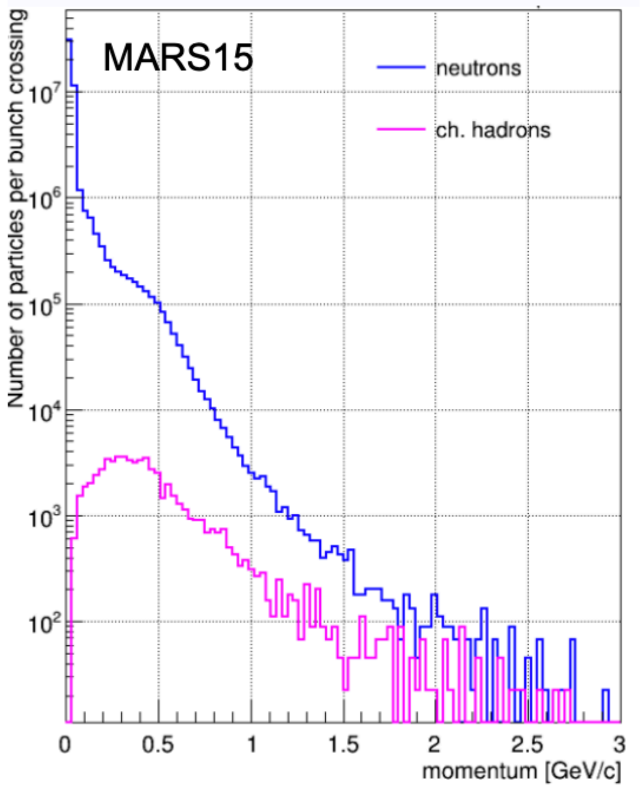
  - For 0.75 TeV beams, N = 2e12 muons/bunch → 4e5 muon decays/m
  - For 7.5 TeV beams → 4e4 muon decays/m
    - But x10 more energetic, more forward
  - Conservatively assume ~ similar energy deposited in detector (will be distributed differently however)

- vs. pile-up at hadron collider:

  - ~ diffuse low energy deposit in detector
  - ≠ not pointing towards beamspot, much wider time profile
    - more handles



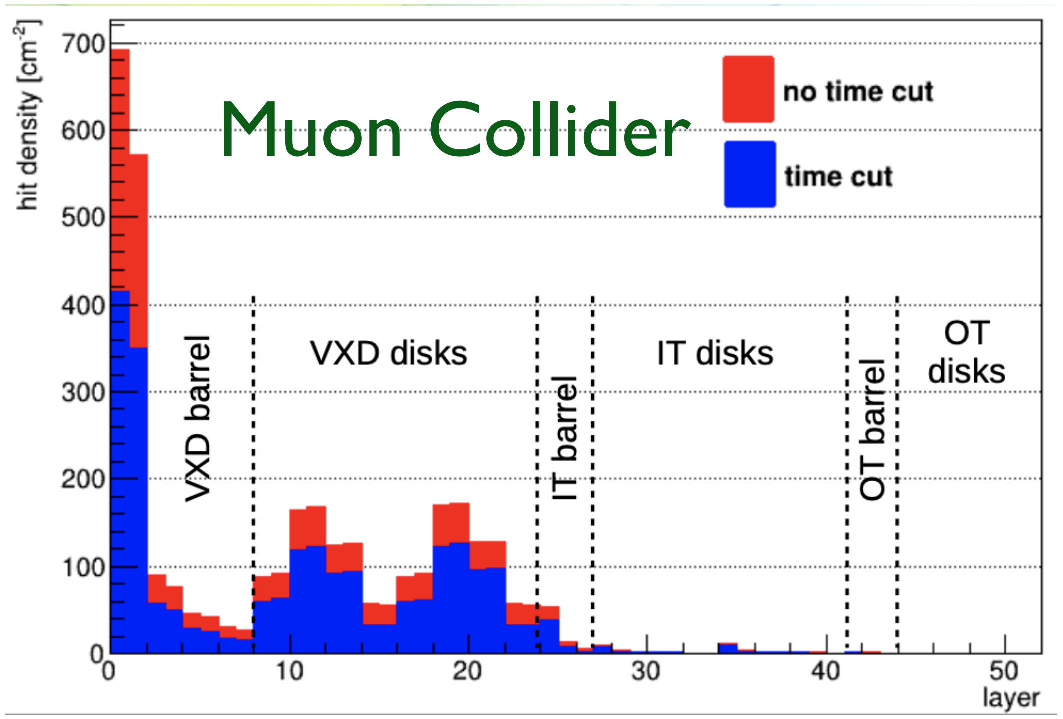
Tracks E > 50 MeV



Occupancy

@first pixel ~ 2 cm from beam-pipe

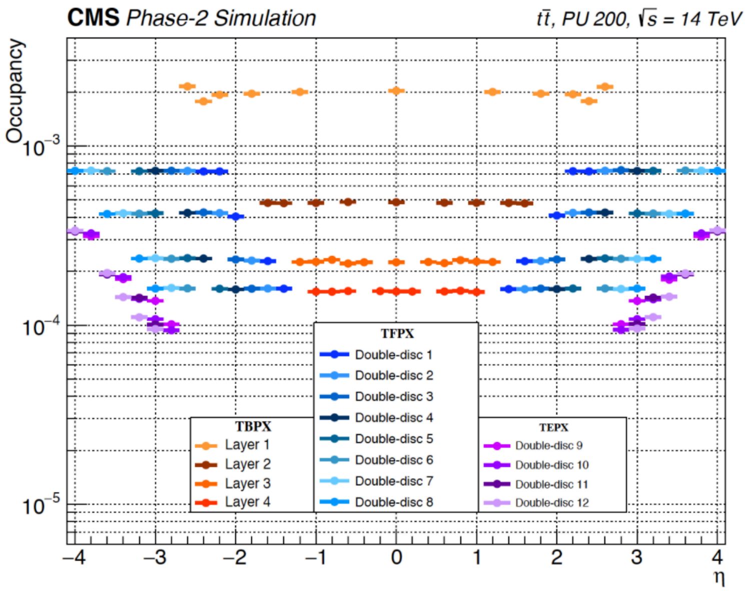
FCC-hh



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

Barrel layer:	1	2	3	4	5	6
Average radius [mm]	25	60	100	150	260	380
Maximum fluence [cm^{-2}]	328.1	79.7	35.1	16.9	6.8	3.3
Module occupancy [%]	1.63	0.39	0.18	0.10	0.28	0.15

charged fluence: 330 (cm^{-2} / BX)



At MuonCollider can afford **low power pixel** sensors thanks to **low BX rate** (70 kHz) e. g MAPs (30 μm x 30 μm):

→ occupancy: 0.6% (700 / (1cm^2 / 30 μm^2)) ~ **2x HL-LHC** or **0.5x FCC-hh**

Definitely challenging, but not impossible …

Data rates

- LHC Phase II :
  - Raw Event size ~ 5 Mb
  - ATLAS/CMS calorimeters/muons readout @40MHz and sent via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions (25 Tb/s)
  - Full detector readout at @1MHz ~ 5 Tb/s (@40MHz ~ 200 Tb/s)

- FCC-hh:
  - Raw Event size ~ 25 Mb
  - At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
  - However full detector would correspond to 1-2 Pb/s
    - Seems hardly feasible (30 yrs from now)

At MuonCollider, we collide at much lower rate ~ 10-20 μs bunch crossing (@ 50 kHz)

Assuming similar event size as FCC-hh → 1 Tb/s, we can probably read full detector without triggering