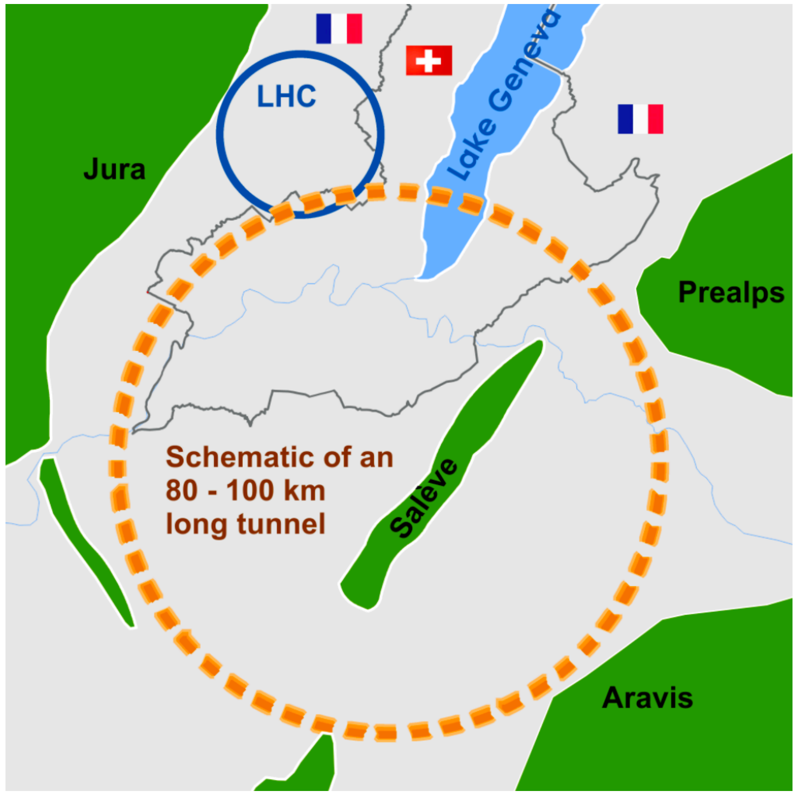
Physics requirements and performance of the FCC-hh Calorimeter

Michele Selvaggi (CERN)
on behalf of the FCC-hh calo group

Eugene (Oregon) - CALOR 2018 - 21/05/2018

FCC-hh - Scope

- FCC-hh Target:
  - E_{CM} =100 TeV
  - needs 16T magnets
  - 100 km long
- Direct Search for New Physics:
  - direct production of heavy resonances up to m ≈ 40 TeV
  - stops up to m ≈ 10 TeV
- Precision SM physics (complementary to e^+e^-):
  - Higgs potential, self-coupling (Δλ/λ ≈ 5%)
  - Higgs rare decays,
  - EWK, Top physics in new extreme dynamical regimes



Key parameters

- Luminosity:
  - baseline: 5e34 $cm^{-2} s^{-1}$ (200 PU)
  - ultimate: 30e34 $cm^{-2} s^{-1}$ (1000 PU)

→ O(20 ab^{-1}) over 25 years of operations

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 $\times 10^{16}$		2.6	25	90	324
flux of charged particles at $r = 2.5$ cm	GHz/cm^2	0.2	0.8	4.6	7.9
1 MeV-neq fluence $\times 10^{15}$ at r=2.5 cm	cm^{-2}	1	10	80	100
total ionizing dose at r=2.5 cm	MGy	1.45	14.6	59.3	253.5
$dE/d\eta\|_{\eta=0}$	GeV	.	.	.	13.6
$dE/d\eta\|_{\eta=5}$	GeV	.	.	.	670
$dP/d\eta\|_{\eta=5}$	kW	.	.	.	3.4

- Radiation levels:
  - pp cross-section from 14 TeV → 100 TeV only grows by factor 2
  - radiation level increase mostly driven by increase in inst. luminosity

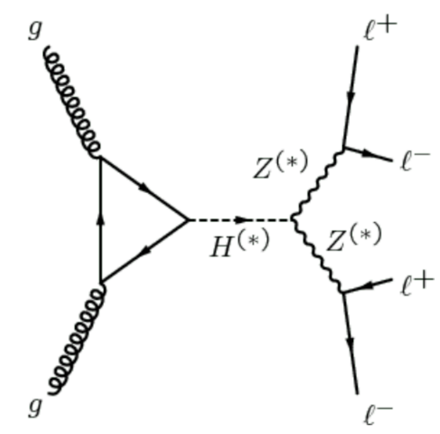
→ x10 more fluence compared to HL-LHC (x100 wrt to LHC)

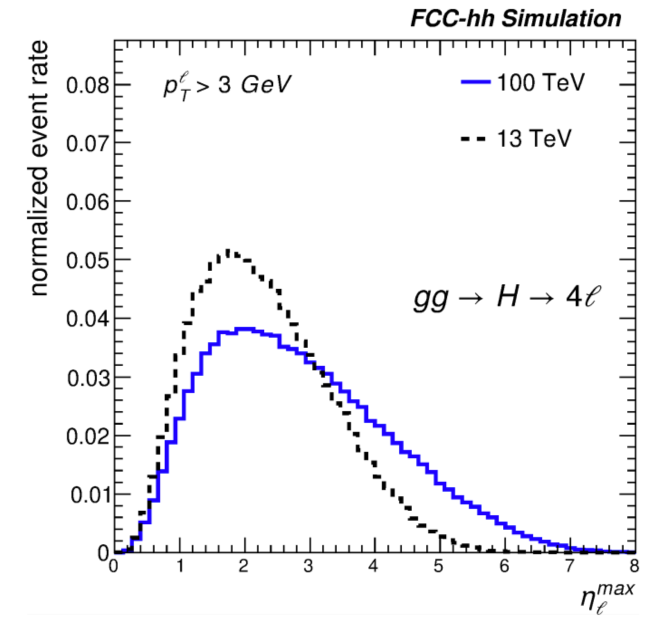
- Ex: calorimetry
  - 1 MeV-neq fluence ≈ 4e15(14) cm^{-2} in the Barrel for ECAL (HCAL)
  - 1 MeV-neq fluence ≈ 2e16 cm^{-2} in the EndCaps

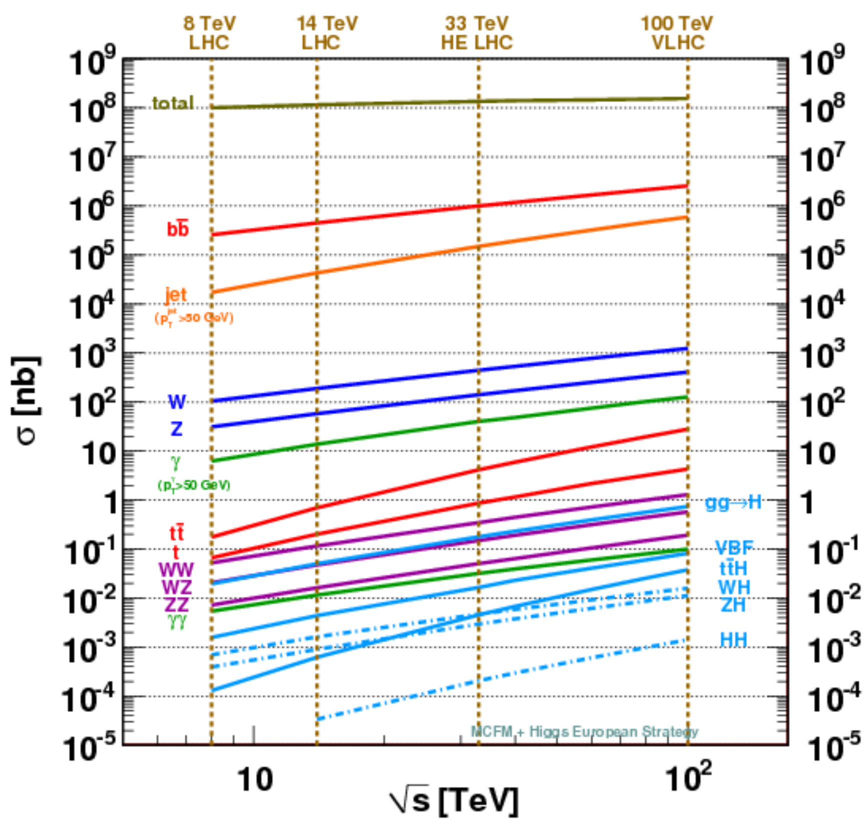
→ Radiation hardness needed (especially forward!)

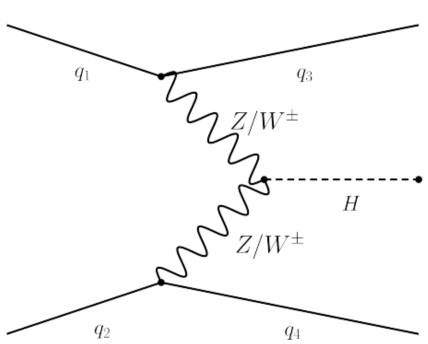
Physics requirements for calorimetry (low p_T)

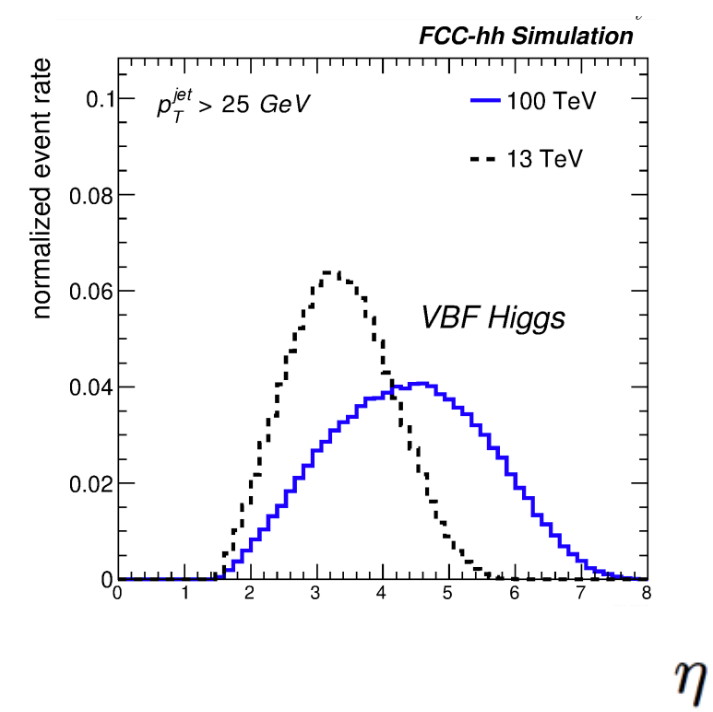
- Low p_T physics produced at threshold (EWK, Higgs, top) is more forward:
    - need larger η coverage (up to |η| = 6) compared to LHC
    - and radiation hard detectors (important especially FWD)









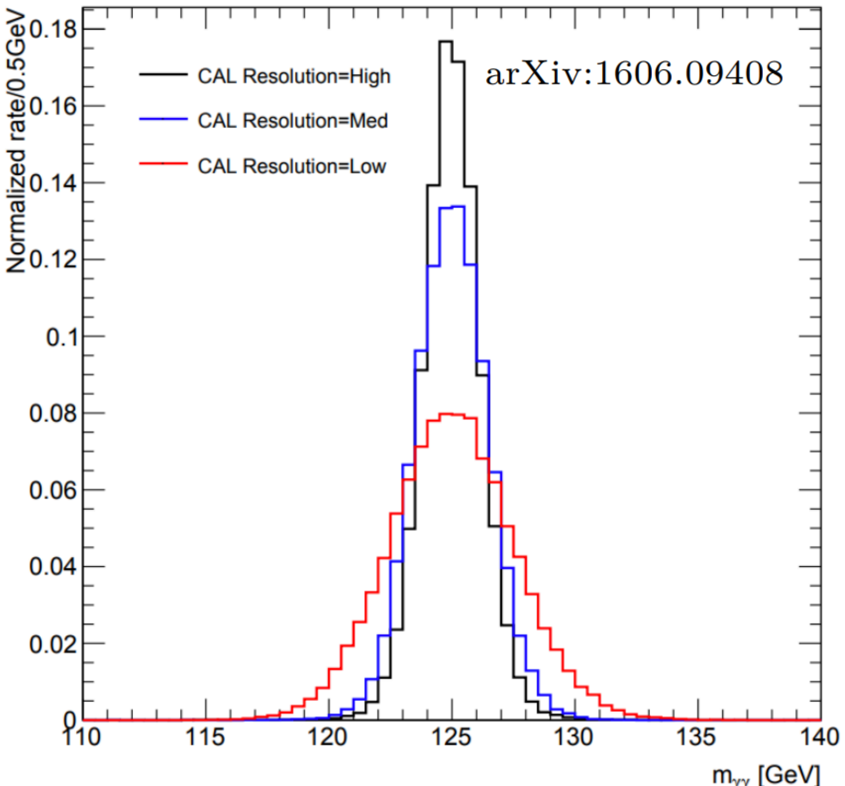


Physics requirements for calorimetry (low p_T)

- Low p_T physics produced at threshold (EWK, Higgs, top) is more forward:
  - need larger η coverage (up to |η| = 6) compared to LHC
  - and radiation hard detectors (important especially FWD)

- Need excellent energy and angular resolution at low energy for precision physics (ex: HH → γγ bb):
  - small noise and stochastic terms
  - robustness vs pile-up (noise)
  - π^0 rejection capabilities

$m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\Delta\alpha)$



$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus c$$

a=6%, c=0.7%

a=10%, c=1%

a=20%, c=2%

Physics requirements for calorimetry (low p_T)

- Low p_T physics produced at threshold (EWK, Higgs, top) is more forward:
  - need larger η coverage (up to $|\eta| = 6$) compared to LHC
  - and radiation hard detectors (important especially FWD)

- Need excellent energy and angular resolution at low energy for precision physics (ex: $HH \to \gamma\gamma\, bb$):
  - small noise and stochastic terms
  - robustness vs pile-up (noise)
  - π^0 rejection capabilities

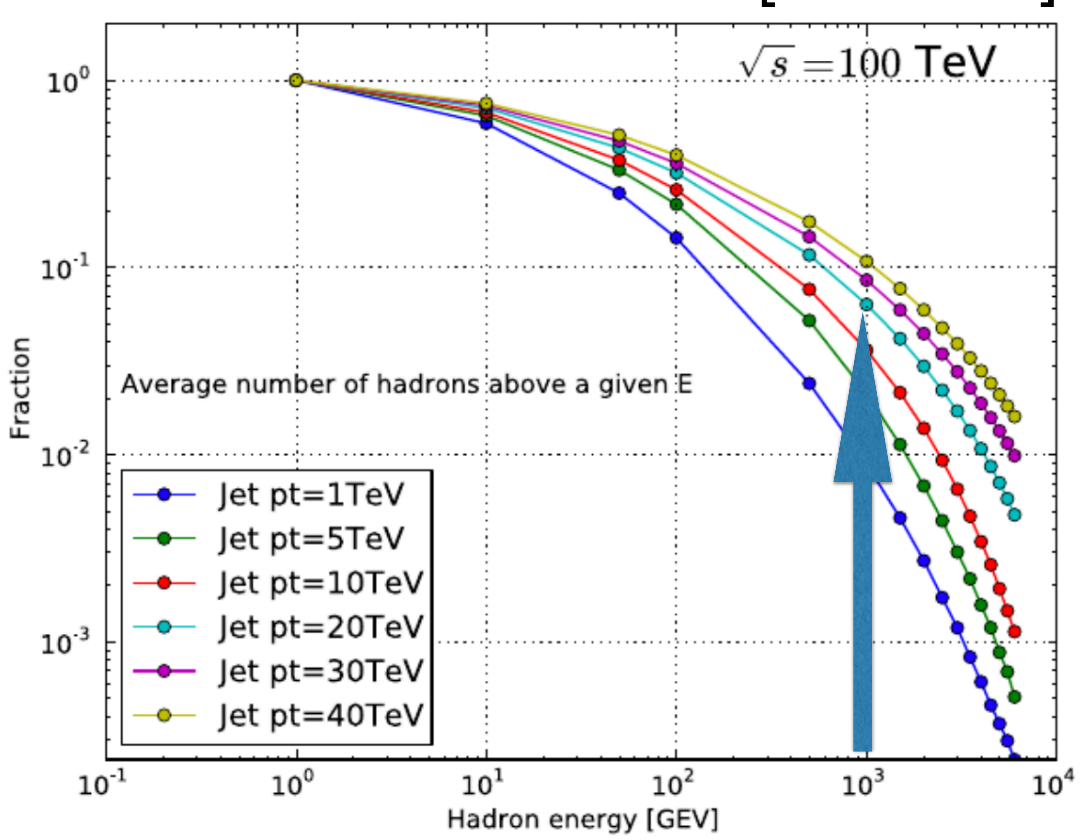
- Need excellent lateral and longitudinal granularity
  - make particle-flow algorithms more effective
  - pointing capabilities (needed to trigger on $HH \to \gamma\gamma\, bb$)
  - helps with photon Id and PU rejection (PU jet Id)

Physics requirements for calorimetry (high p_T)

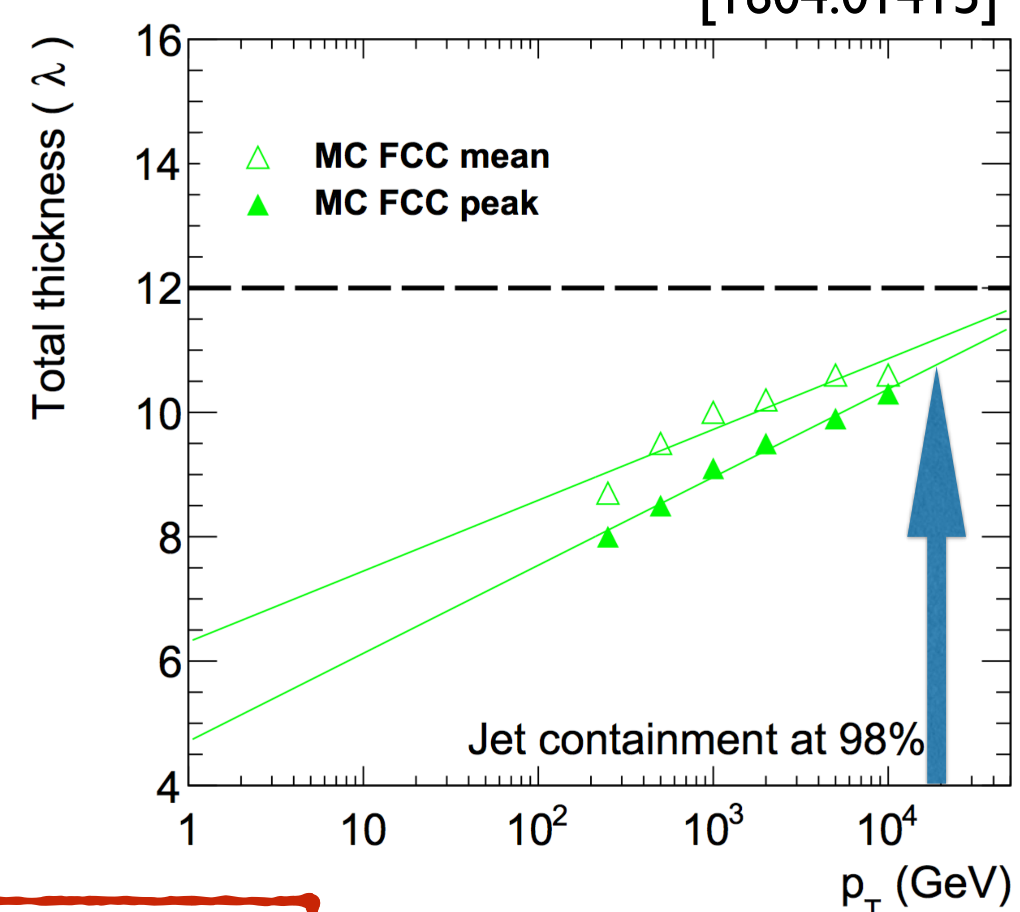
The FCC-hh has sensitivity for (colored) hadronic resonances up to m=40 TeV, hence require:

- full containment for jets with p_T = 20 TeV → small constant term

[1604.01415]



[1604.01415]



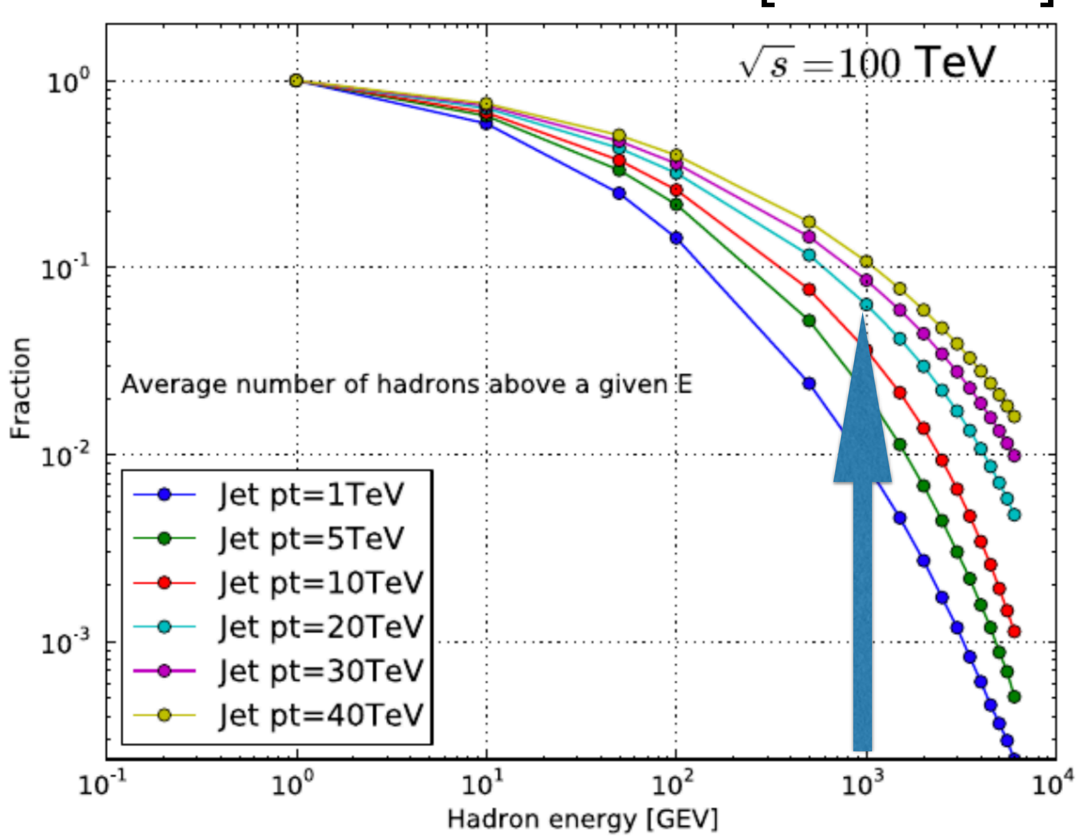
≳11 λ_I for Em + Had

Physics requirements for calorimetry (high p_T)

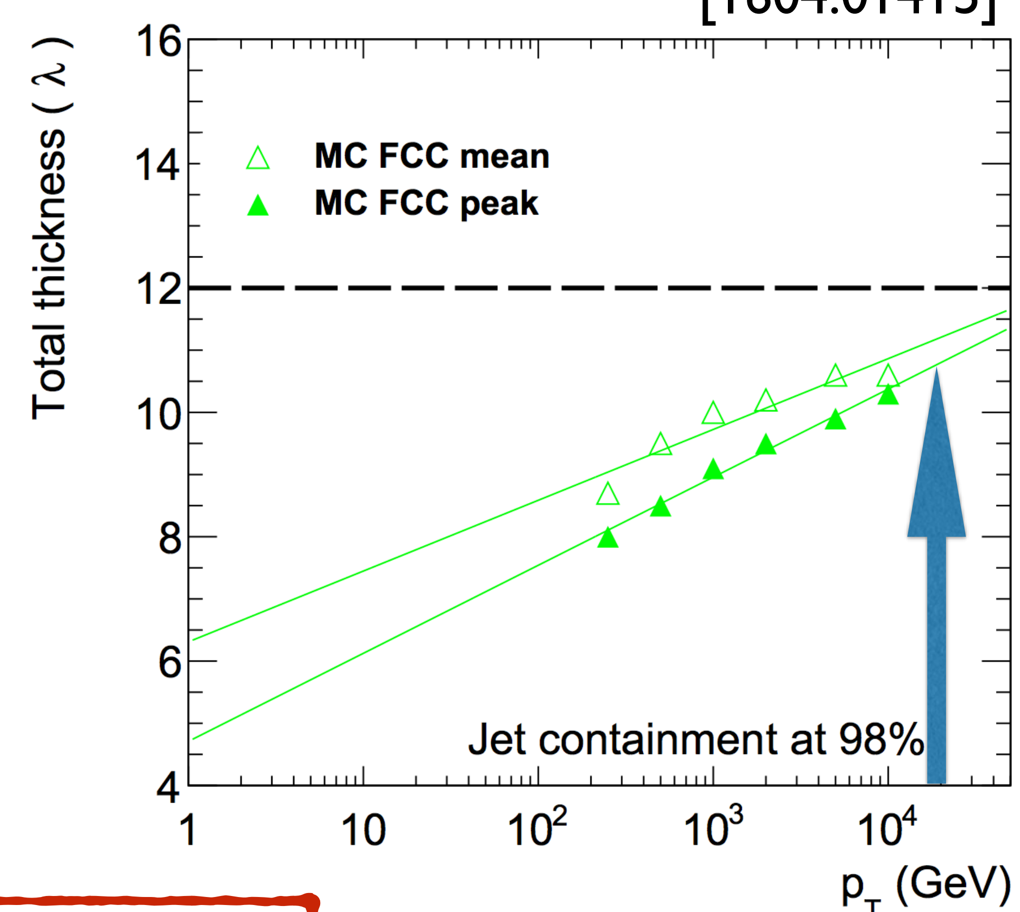
The FCC-hh has sensitivity for (colored) hadronic resonances up to m=40 TeV, hence require:

- full containment for jets with p_T = 20 TeV → small constant term
- limit punch throughs (and helps muon Id)
- assess requirements correctly drives detector size ⇒ magnet ⇒ cost

[1604.01415]



[1604.01415]

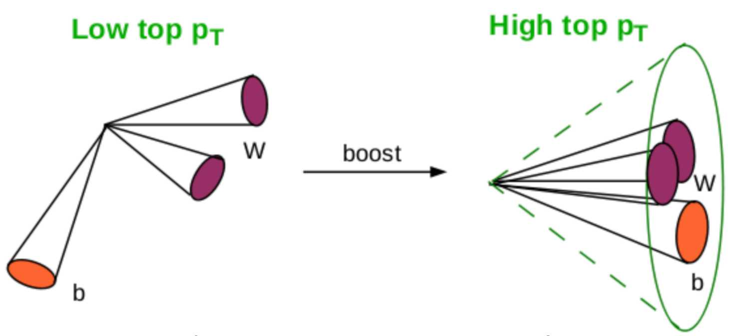


≳11 λ_I for Em + Had

Physics requirements (high p_T)

- The FCC-hh has sensitivity for (colored) hadronic resonances up to $m_R \approx 40$ TeV, hence require:

  $\Rightarrow$ full containment for jets with $p_T = 20$ TeV → small constant term



$\Delta R = 2m/p_T$

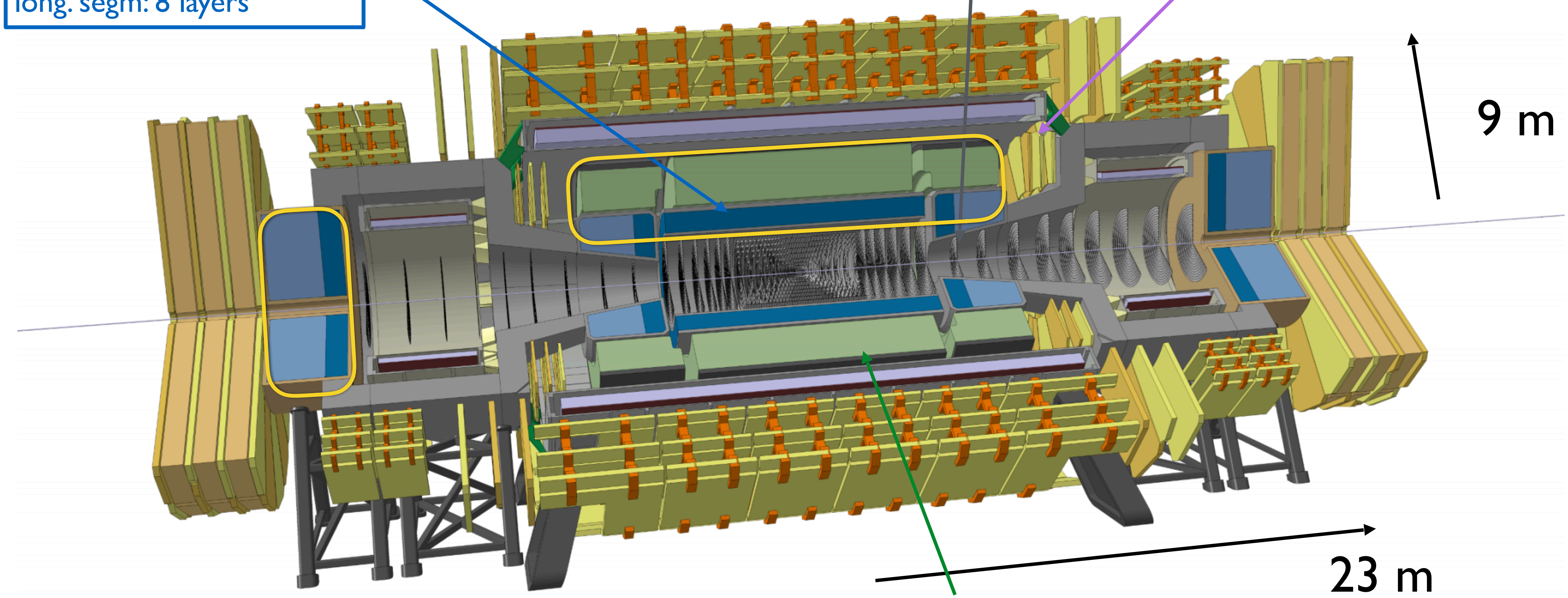
- The FCC-hh has sensitivity for boosted resonances (ex: Z' → tt or RSG → WW) up to $m_R \approx 20$ TeV
  - ex: W jet with p_T = 10 TeV → $\Delta R = 0.02$ (typical ECAL cell size at CMS/ATLAS)
  - need very high granularity to resolve such substructure (to discriminate against plain QCD).
    - tracking can achieve such separation
    - target: 4x better transverse granularity wrt ATLAS/CMS detectors
    - do calorimeters have the capability to resolve such objects? Does granularity translate it translate to actual separation power? Combine longitudinal/lateral information)

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

Central Magnet + Fwd solenoids

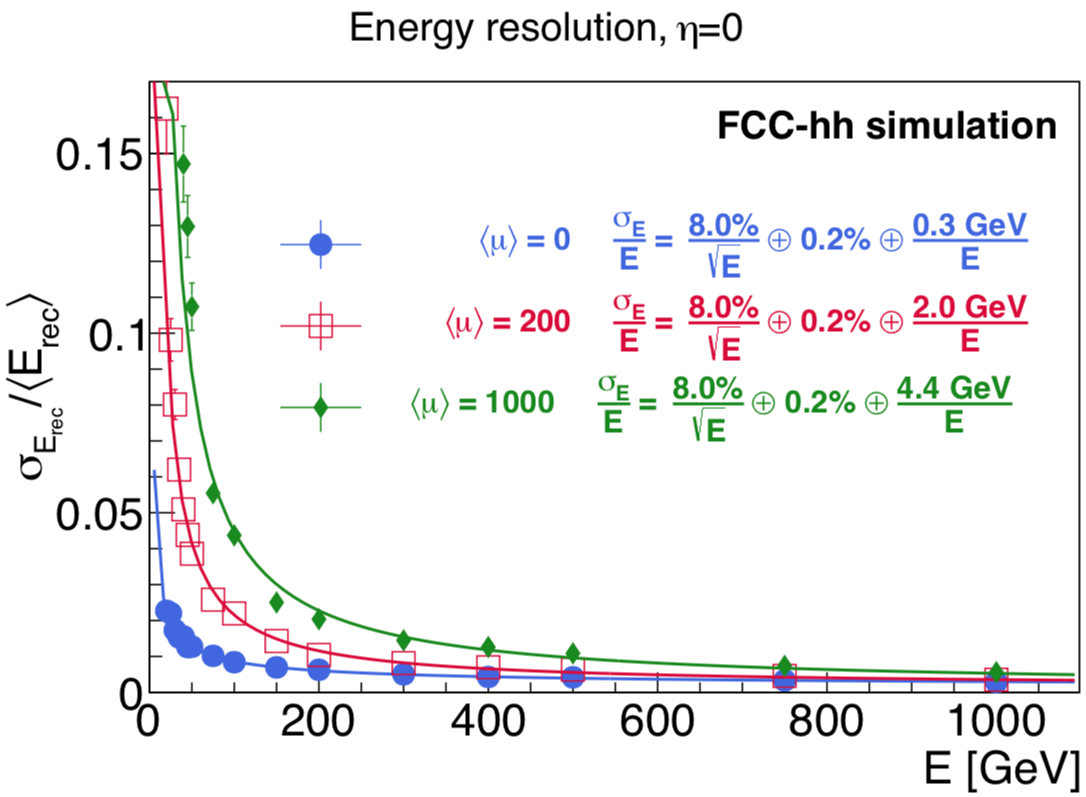


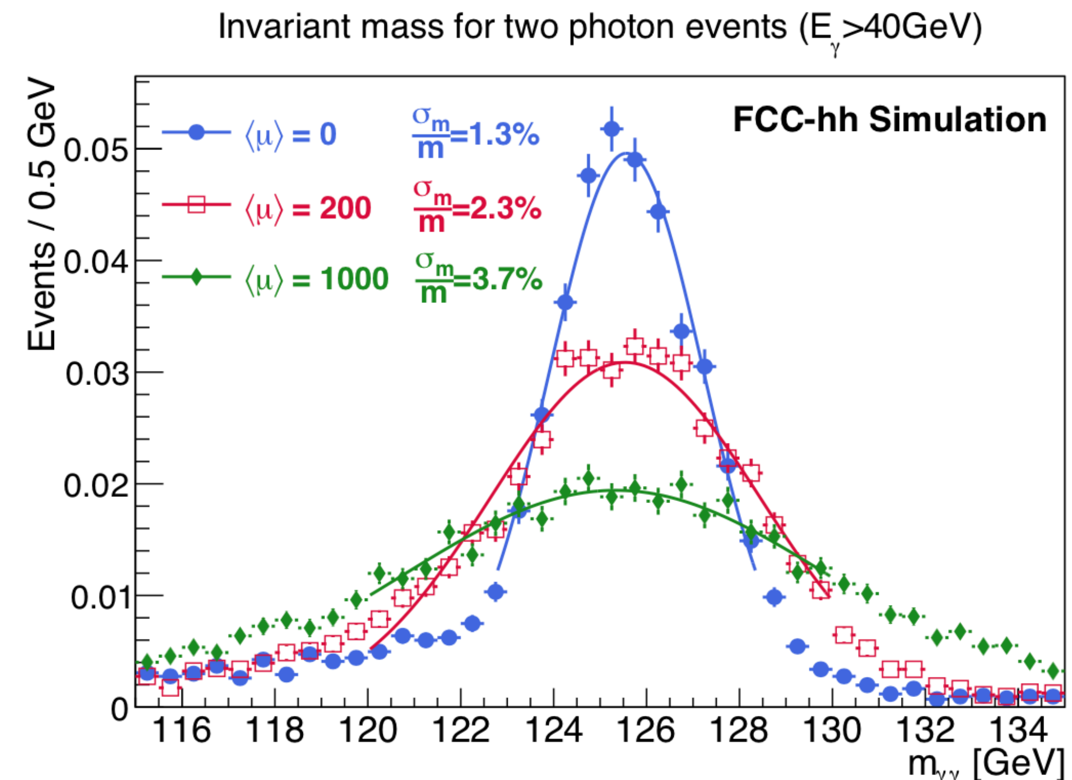
Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

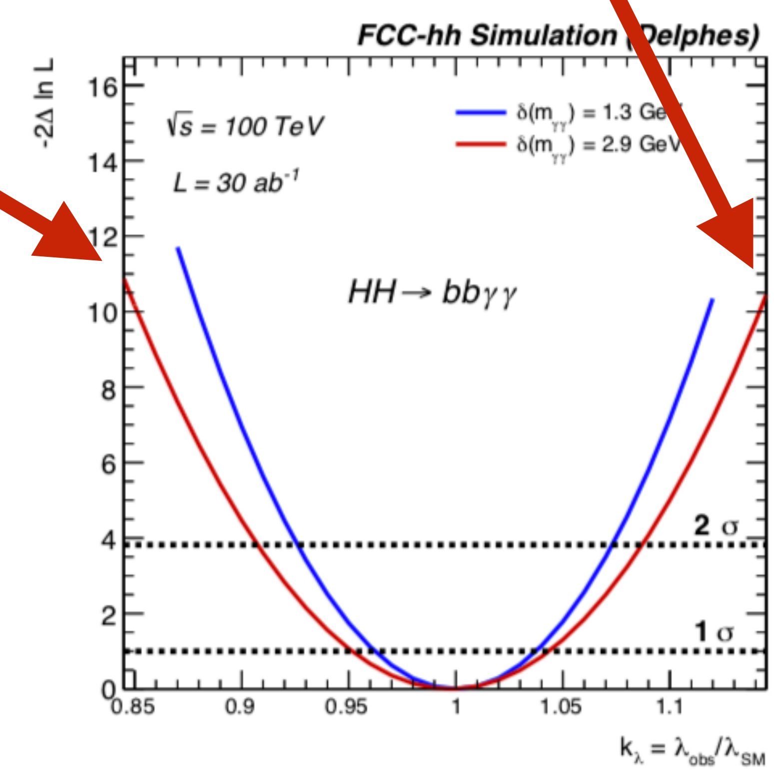
Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

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

Photon resolution with PU







m(γγ) resolution

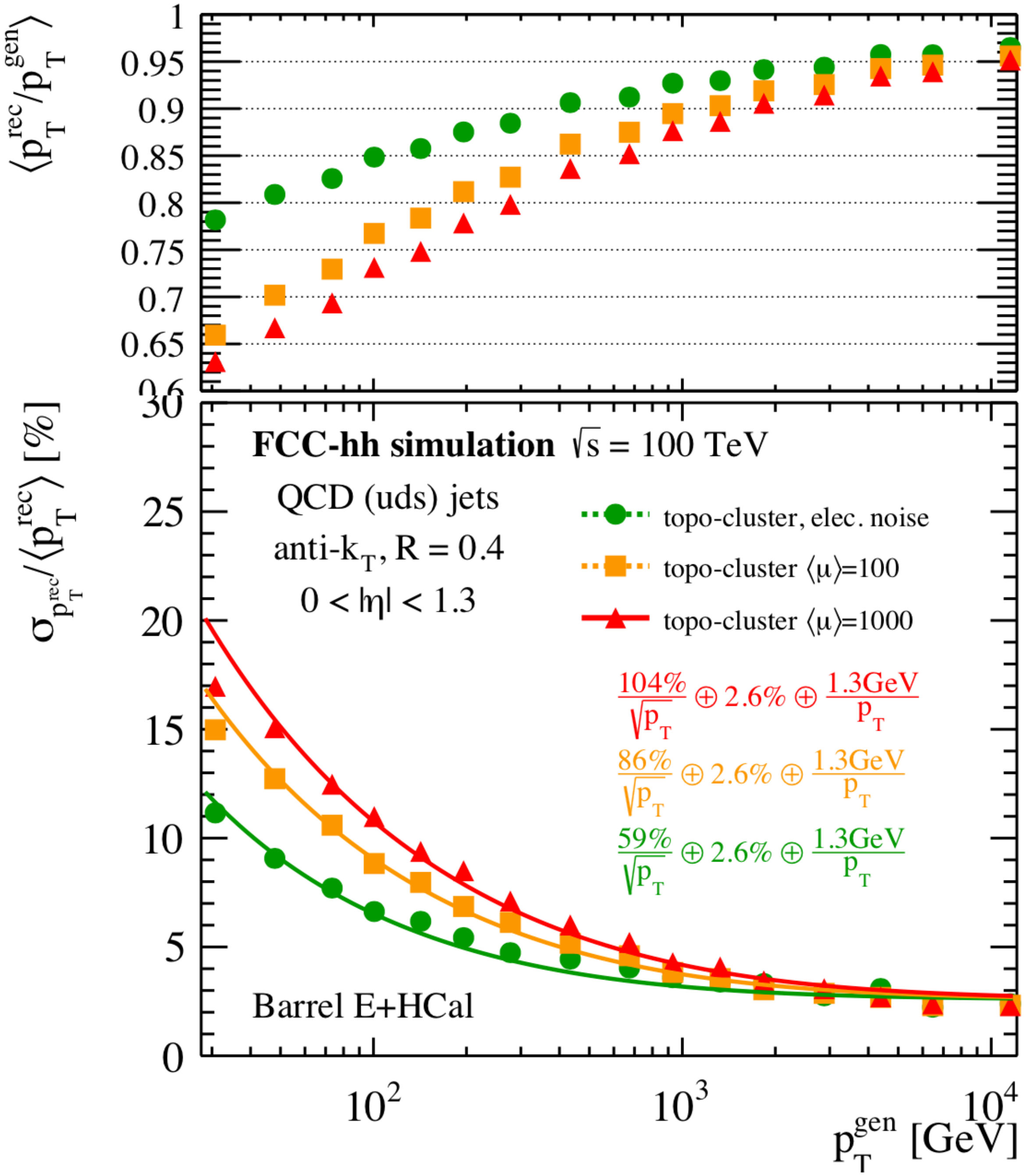
Large impact of in time PU on the noise term (out of the box with no improvements)!!

- severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)
- impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
- some thought needed (tracking, timing information can help?)

Jet Performance with Full sim

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

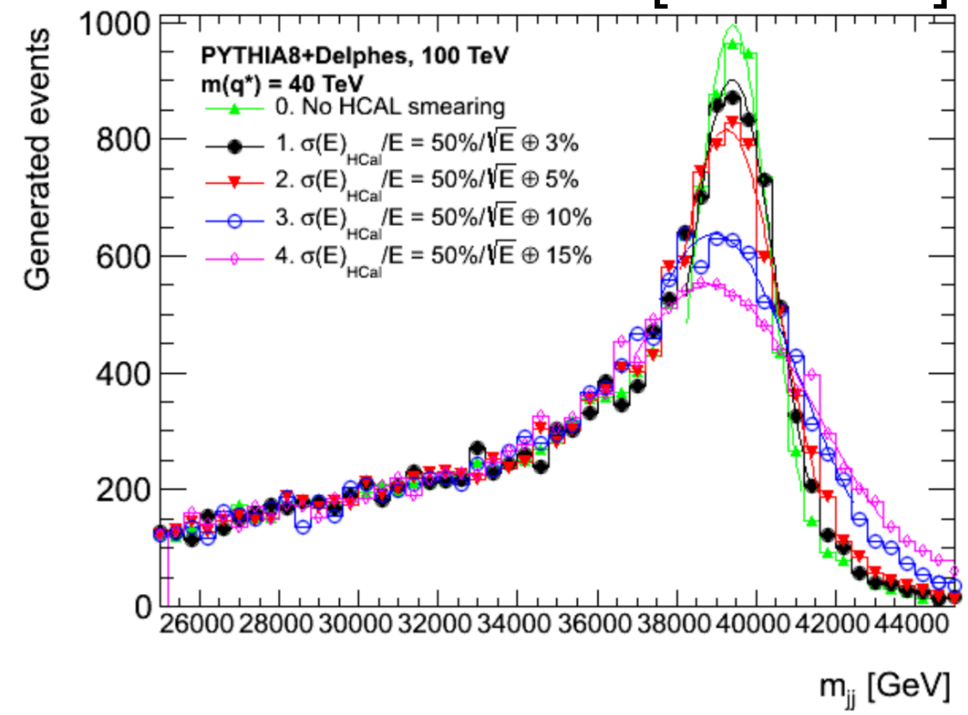
    → since charged PU contribution can be easily subtracted (Charged Hadron Subtraction)



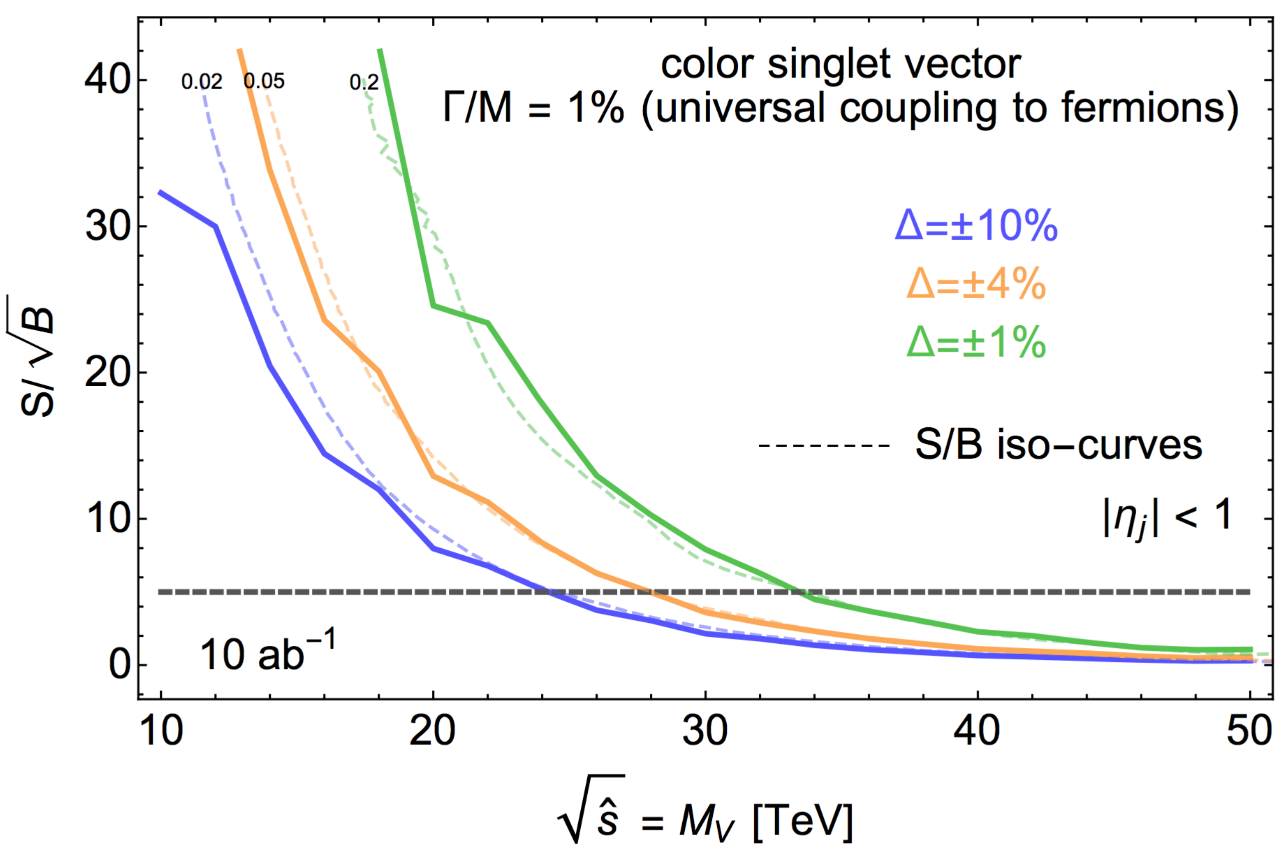
High Mass resonances

- Constant term drives jet energy resolution at high p_T
- Directly impacts sensitivity for excluding discovering narrow resonance high mass resonances $Z' \to j\,j$
- Small impact on strongly coupled (wide) resonances

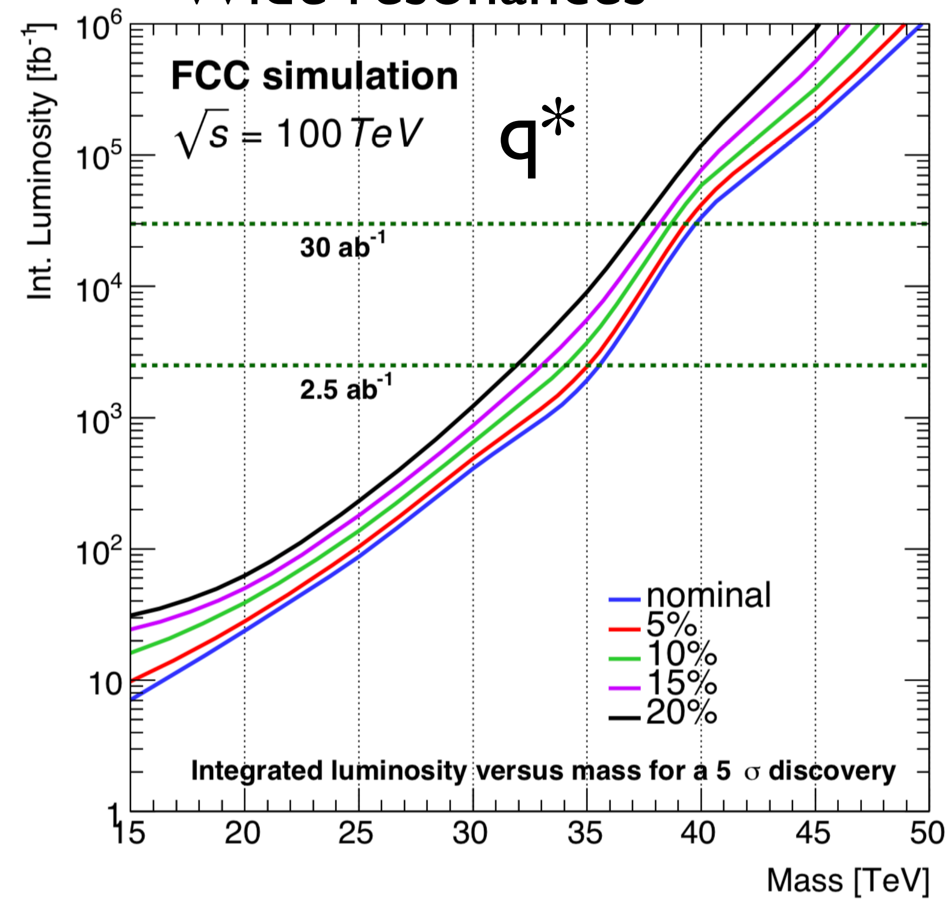
[1606.00947]



Narrow resonances



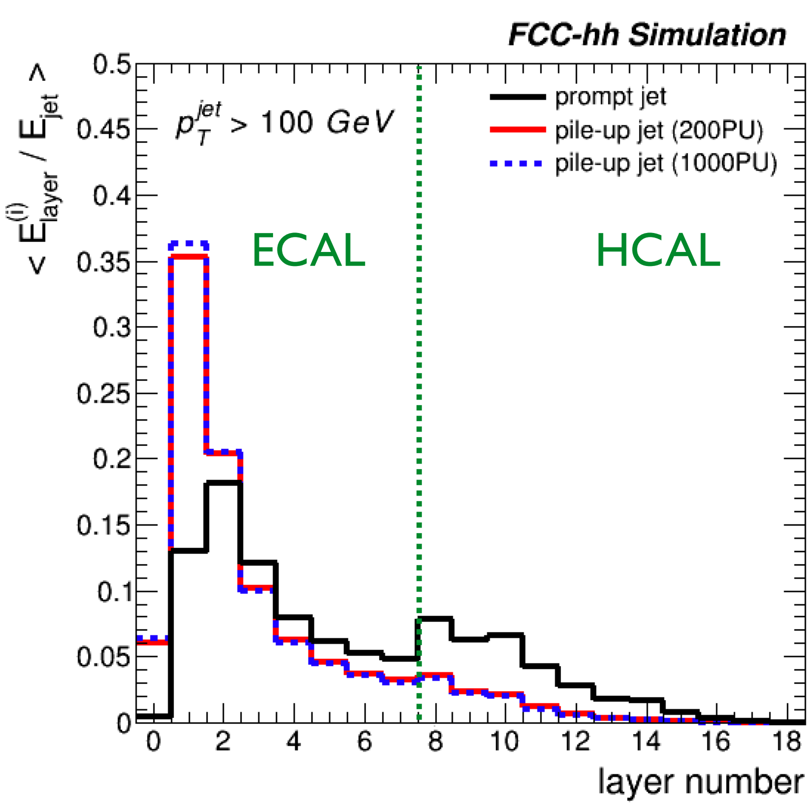
Wide resonances



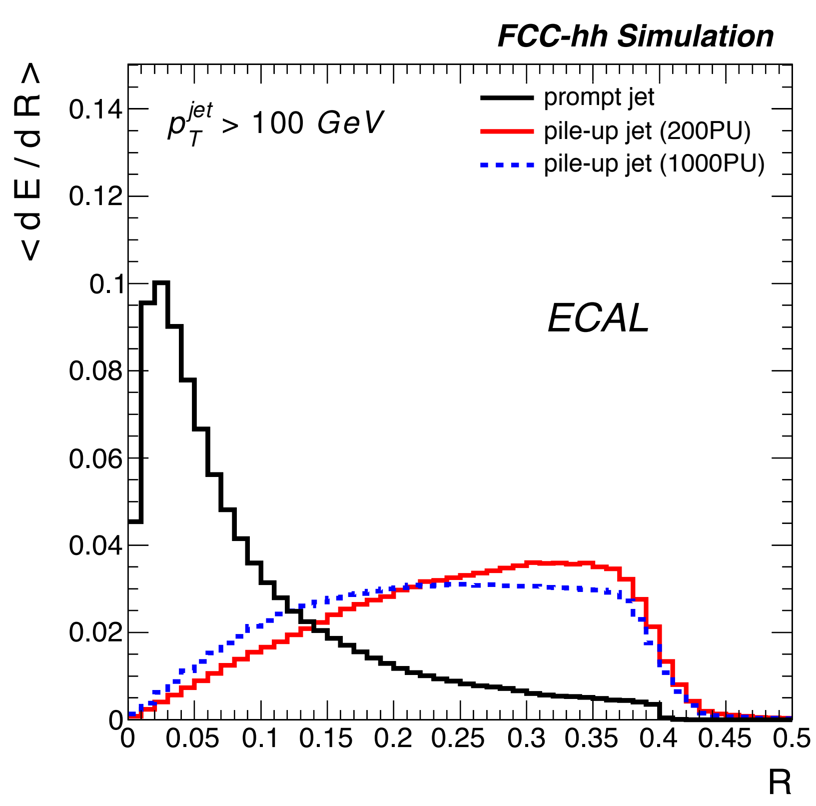
Jet Pile-Up identification

- 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)

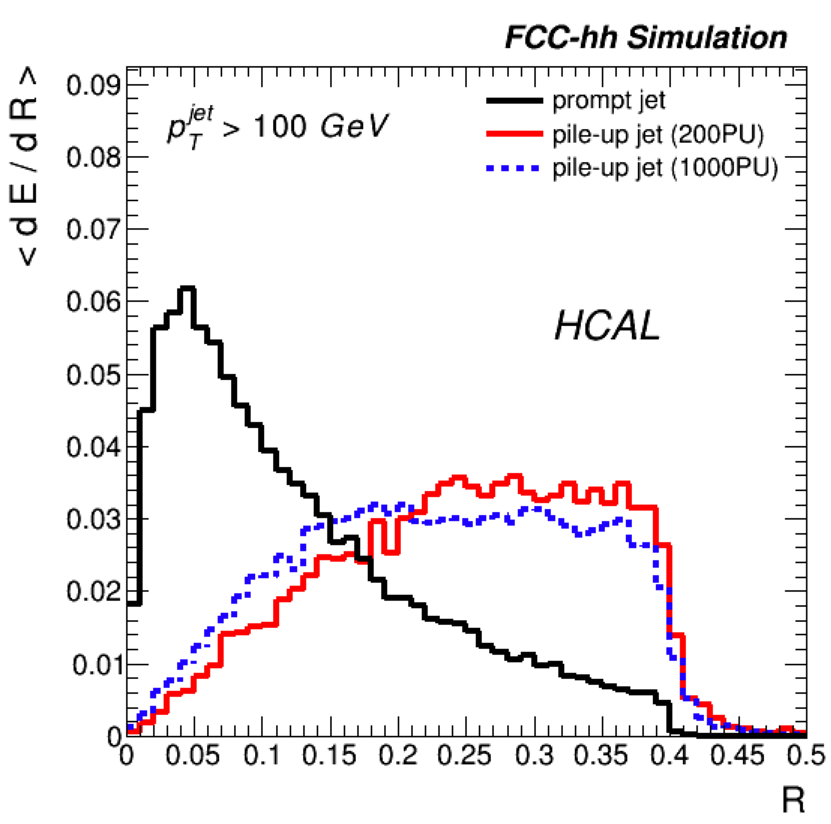
longitudinal



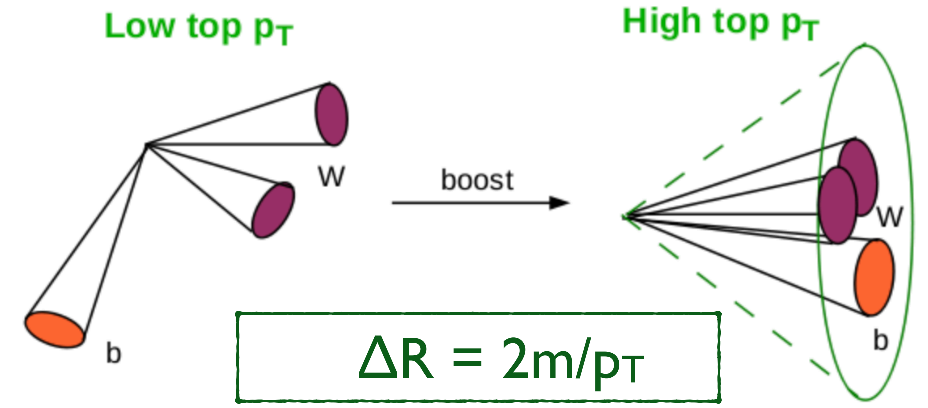
lateral (ECAL)

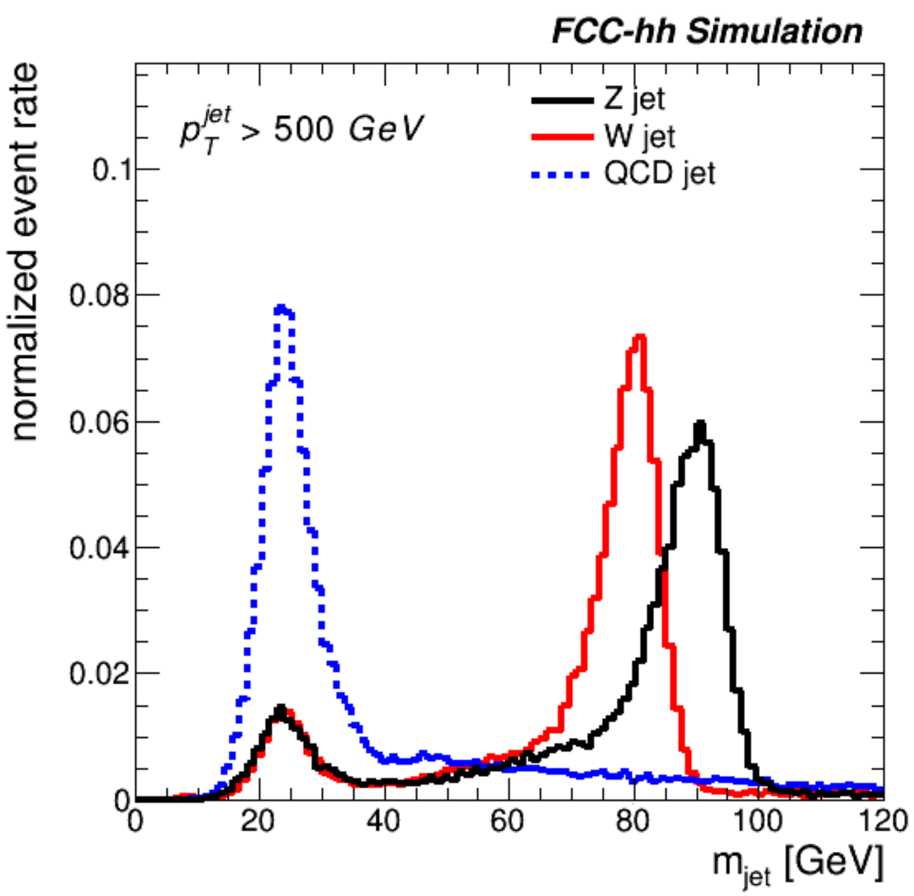


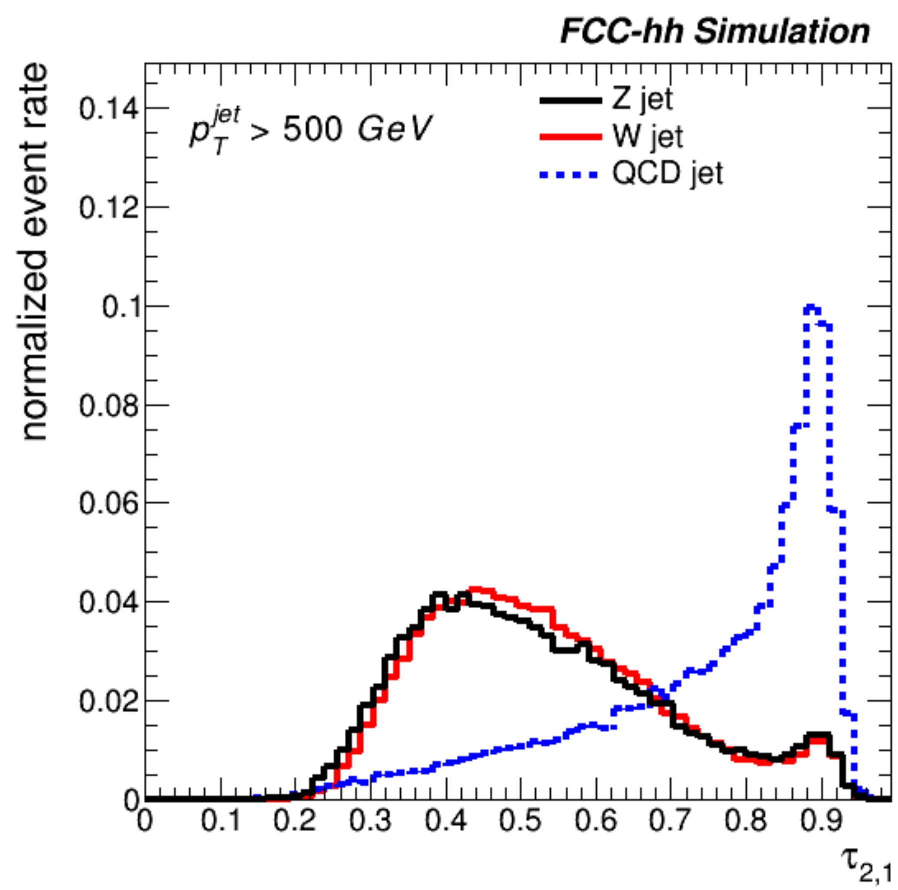
lateral (HCAL)



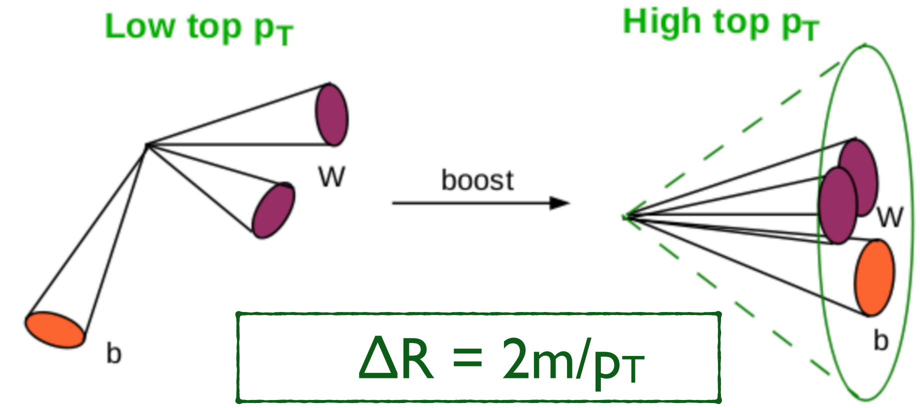
Jet substructure

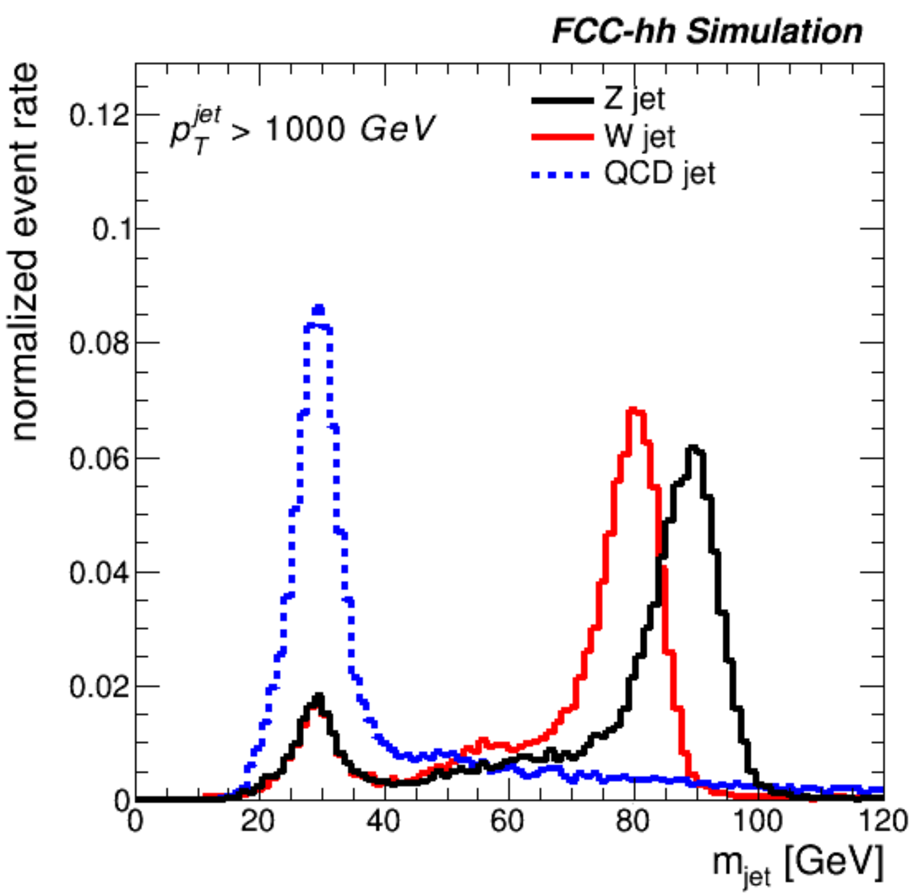


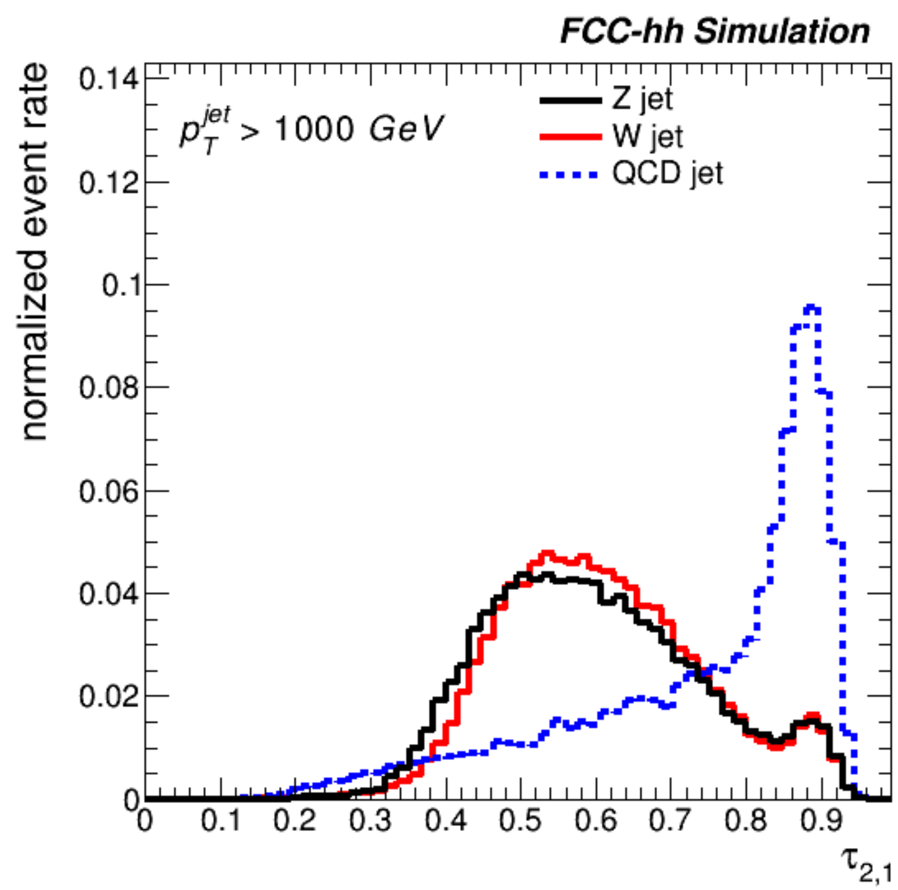




Jet substructure







- 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)

Conclusion

Several Challenges for Calorimeters at the FCC-hh:

- L = 30e34 $cm^{-2}s^{-1}$ imposes high radiation levels and high PU

  → radiation hardness is needed (especially in fwd region)

- 1000 PU is a hostile environment, also for calorimetry (impacts energy resolution)

  → need help from tracking and timing
  → longitudinal/lateral segmentation is suitable for:

    - Photon Id, PU jet Identification
    - Particle-Flow algorithm

- Both precision physics (low p_T) and New Physics (high p_T) require excellent performance:
  - excellent angular and energy resolution
  - high segmentation, both longitudinally and laterally

- Next talk (A. Zaborowska) will discuss more specific aspects of technology and reconstruction. Stay tuned!

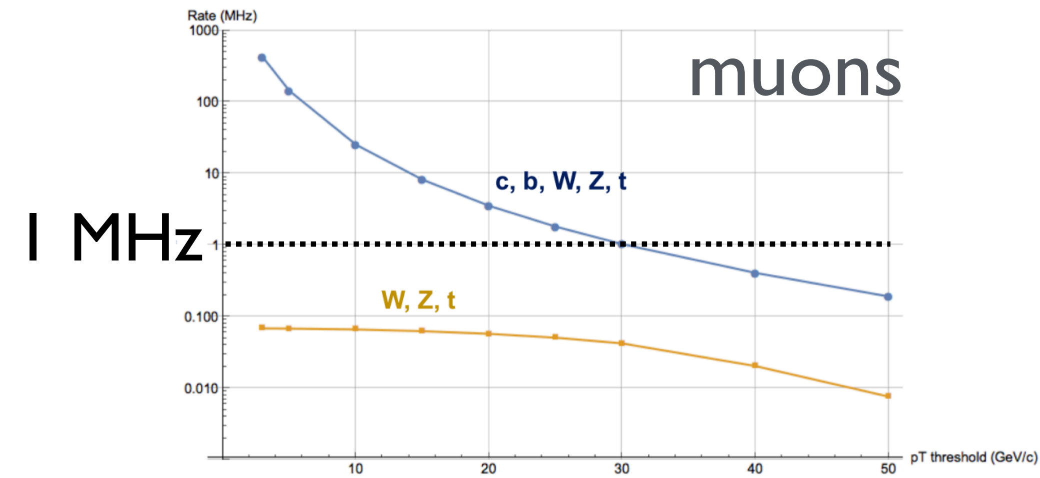
Trigger/data rates

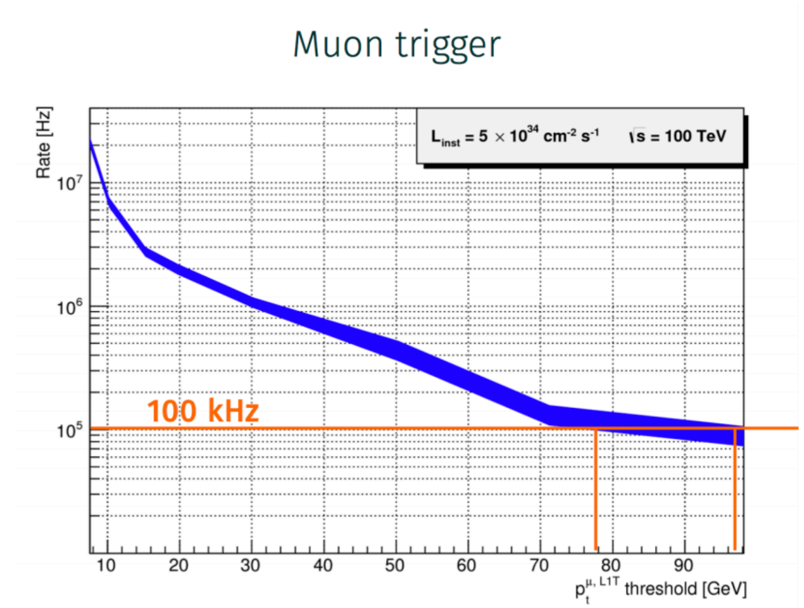
HL-LHC

- rates:
  - Calo + Muon : 20 Tb/s
  - Tracker : 80 Tb/s
- ATLAS approach:
  - read out full Calo+Muon @40MHz (L0) (better muon standalone trigger?)
  - read the tracker @1MHz
- CMS approach:
  - read Calo+Muon + part of tracker (stubs) @40MHz as input to L1 trigger

FCC:

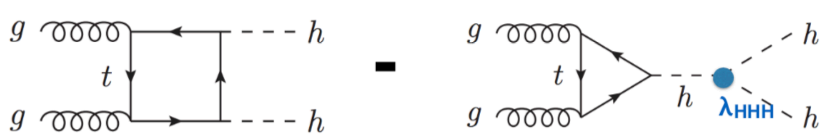
- rates:
  - Calo + Muon : 200-300 Tb/s
  - Tracker : 800 Tb/s
- Could be possible to read-out Calo+Muon @40MHz (200 Tb/s)
- Sounds hard to read full detector @ 40MHz (1Pb/s)
- Calo+Muon alone will not provide enough selectivity for reading @1MHz → need a track trigger



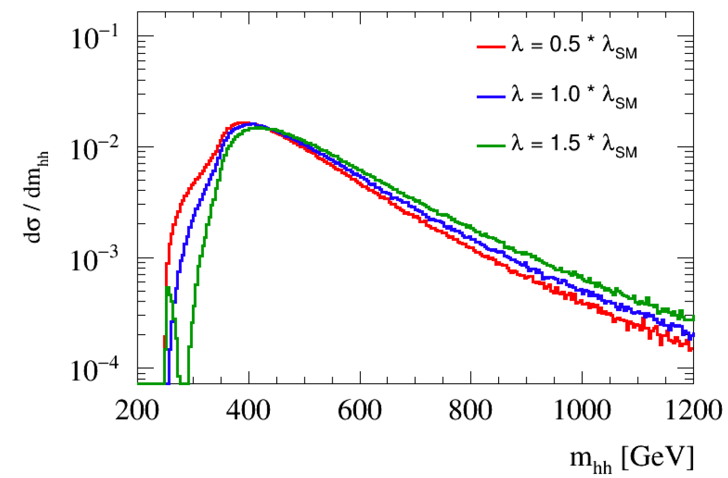


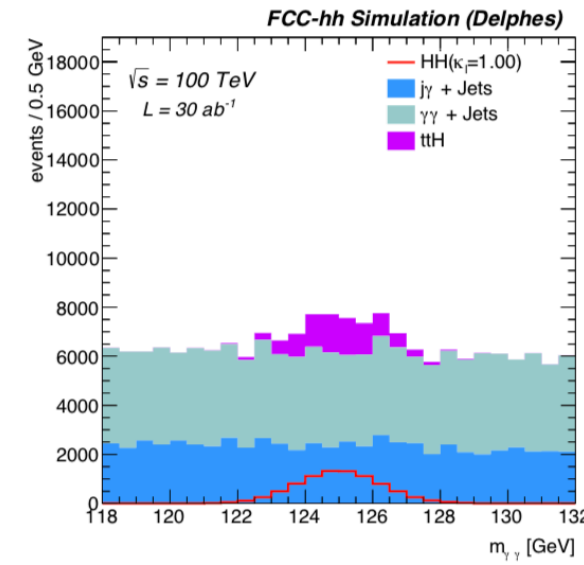
Di-Higgs - bbγγ

gluon fusion:

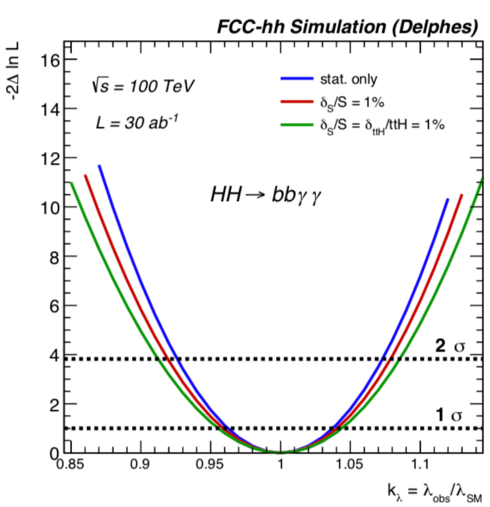


σ(100 TeV) / σ(14 TeV) ≈ 40



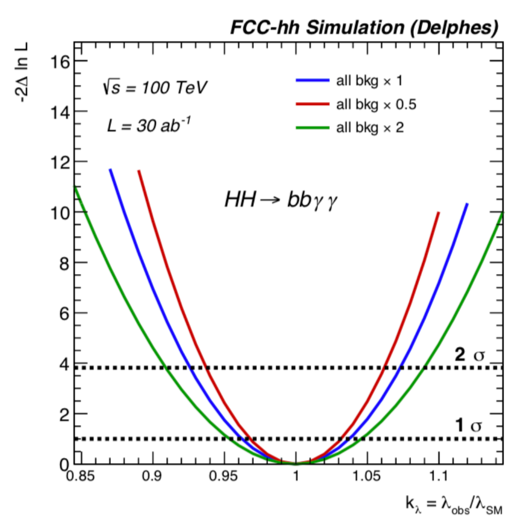


assuming QCD can be measured from sidebands



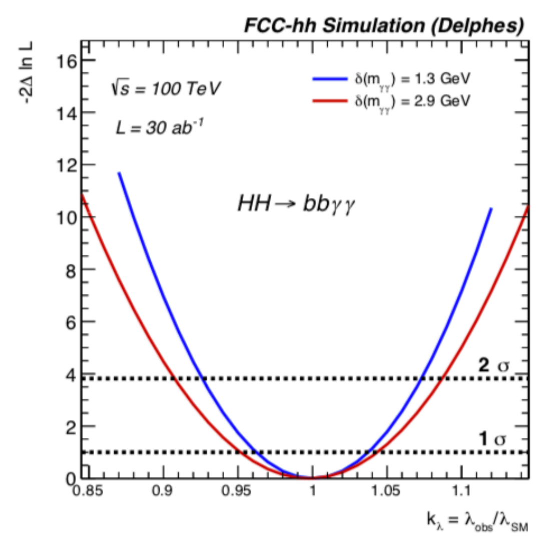
nominal background yields:

δκλ(stat) ≈ 3.5 %
δκλ(stat + syst) ≈ 4.5 %
δr(stat) ≈ 2.5 %
δr(stat + syst) ≈ 3 %



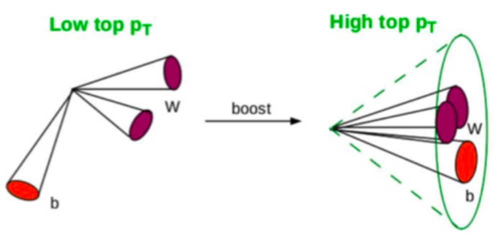
varying (0.5x-2x) background yields:

δκλ(stat) ≈ 3 - 5 %
δr(stat) ≈ 2 - 3%



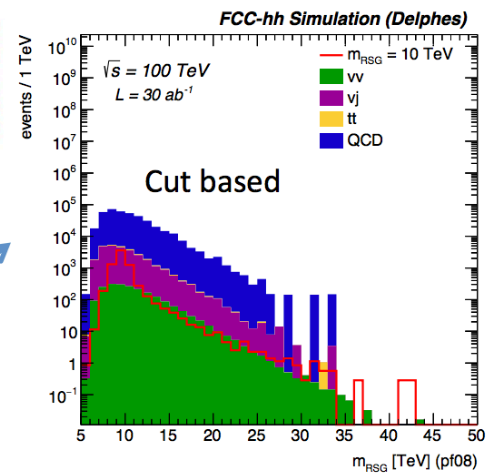
m(γγ) resolution

Heavy resonances (RSG →WW)

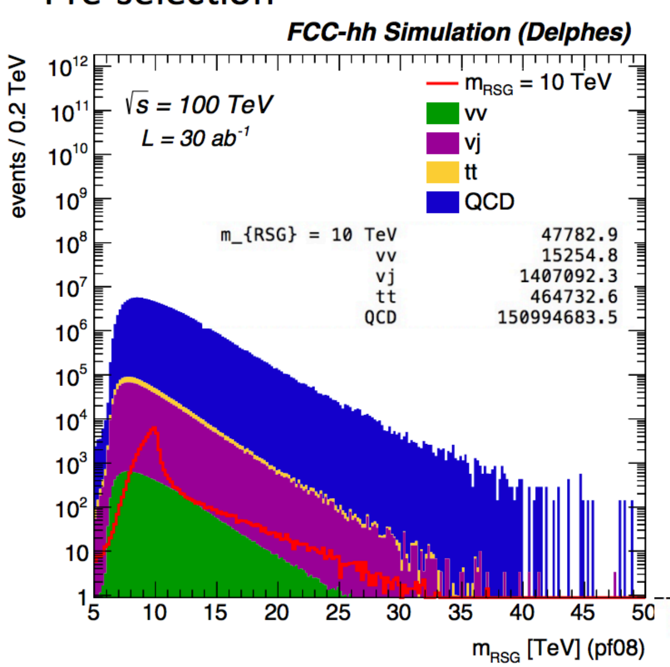


m_{RSG} = 10 TeV	7035.8
vv	2023.4
vj	25824.7
tt	1795.2
QCD	377427.6

Jet1/2 SD 100<m<50GeV
Jet1/2 τ_{21} < 0.6
Jet1/2 Flow45 < 0.07
Jet1/2 Flow55 < 0.07

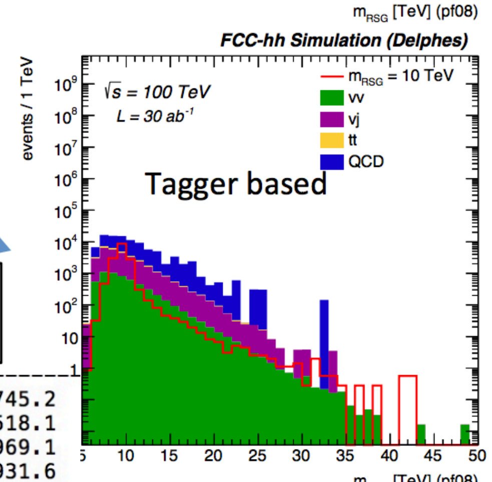


Pre-selection

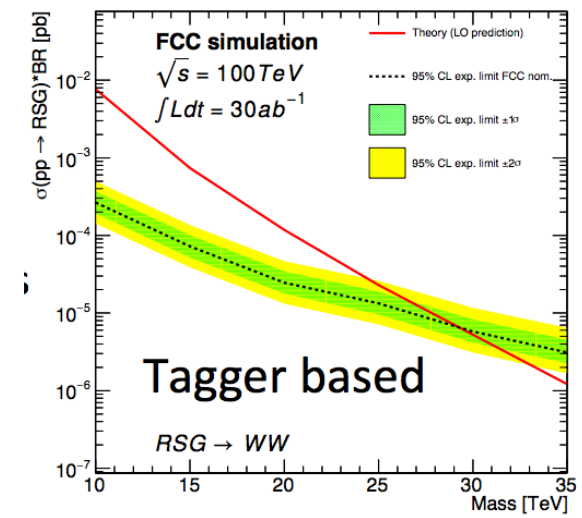


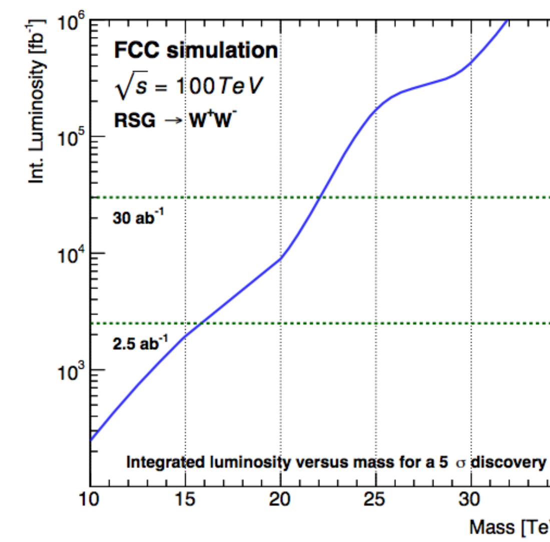
Need more di-jet 1k raw of 50M

Jet1/2 tagger>0.15
Jet1/2 SD mass > 40GeV



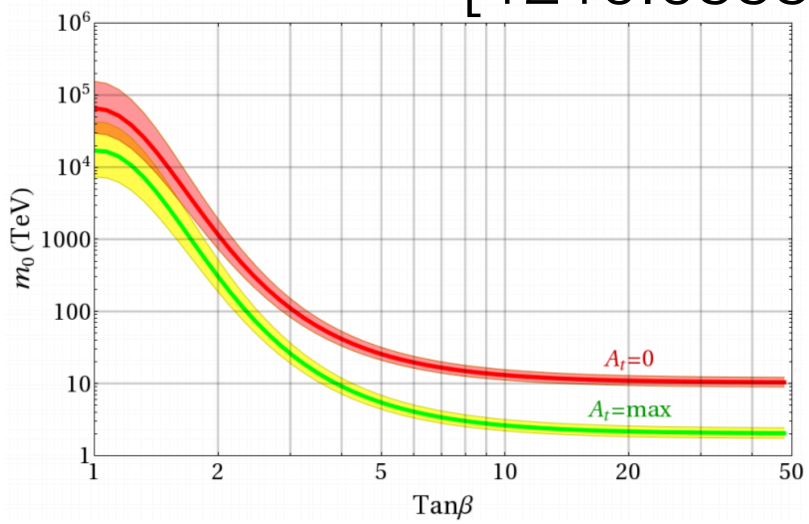
m_{RSG} = 10 TeV	15745.2
vv	5518.1
vj	24969.1
tt	2931.6
QCD	64910.7

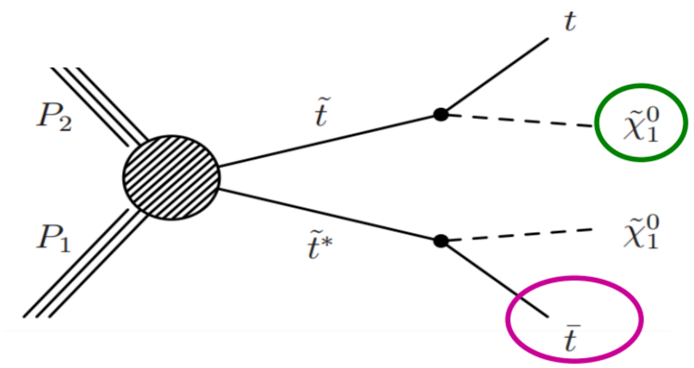




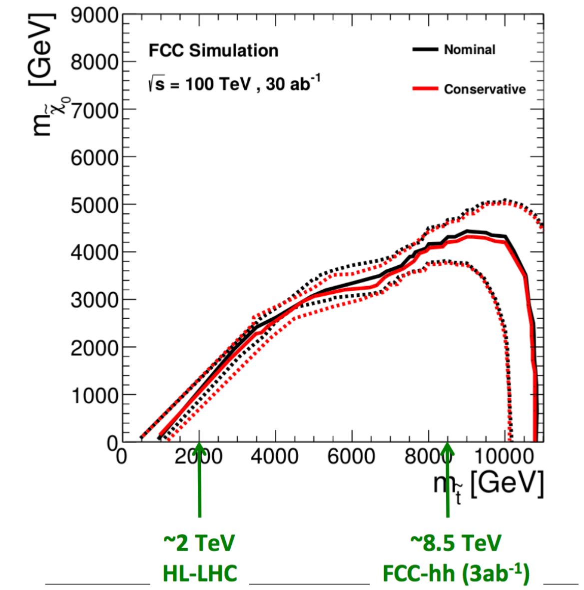
Supersymmetry (stop production)

[1210.0555]

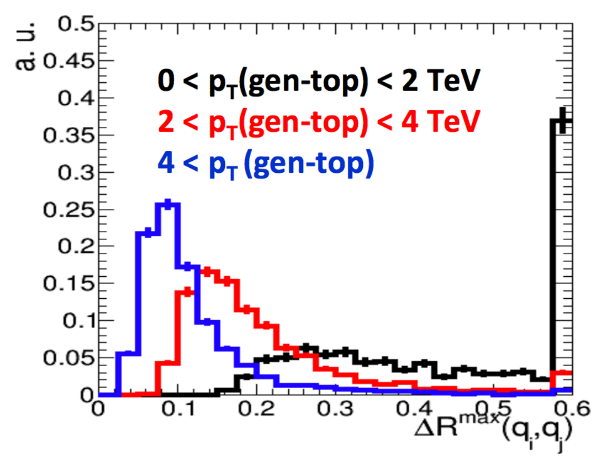




Expected limit @95% CL



- **Multiple jets**
- **2 b-jets**
- **On-shell top quarks**
- **Large ME_T [from the two LSPs]**



Discovery potential (5σ)