Heavy resonances at 100TeV

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FCC week 2019, Brussels
Based on arXiv:1902.11217 (accepted by EPJC) and in FCC CDRs

Motivation

- Goal of the study
  - Discovery reach for heavy objects
  - Find ways to discriminate QCD, top and boson jets
  - Being validated with calorimeter and tracker performances in full simulation
- No pileup assumed
  - For such heavy object the effect is hopefully not large
  - Effect on jet reconstruction and performance being studied in full simulation
- In this talk
  - Not discussing yet the physic models
  - Neither designing fully state of the art analyses
  - But rather study the performance of the FCC-hh detector

Outline

- Leptonic resonances
  - ee, μμ, ττ
- Hadronic resonances
  - Ttbar, WW, jj
- Summary

$Z' \to l^+l^-$

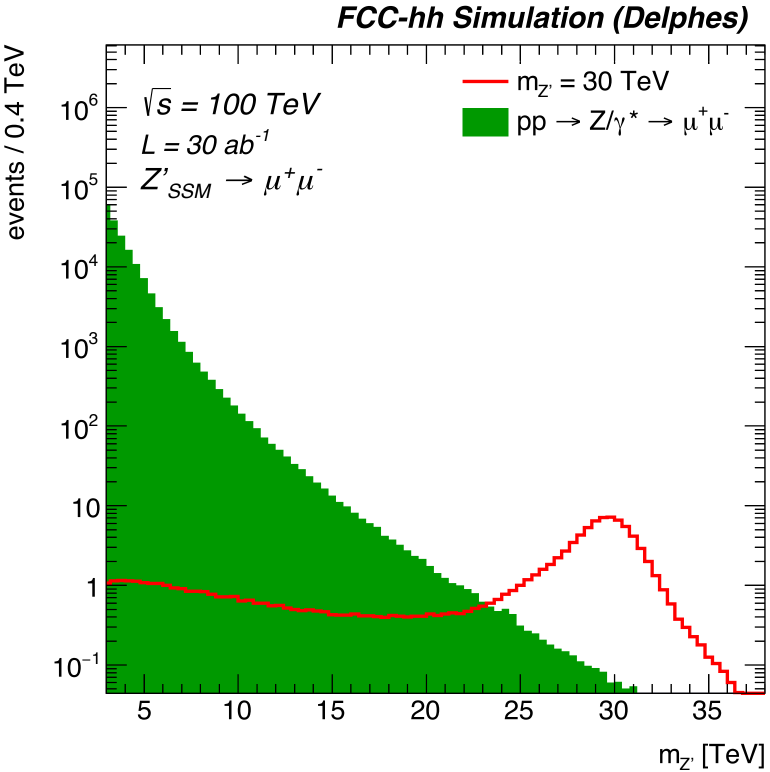
$Z' \to \mu^+\mu^- / e^+e^-$

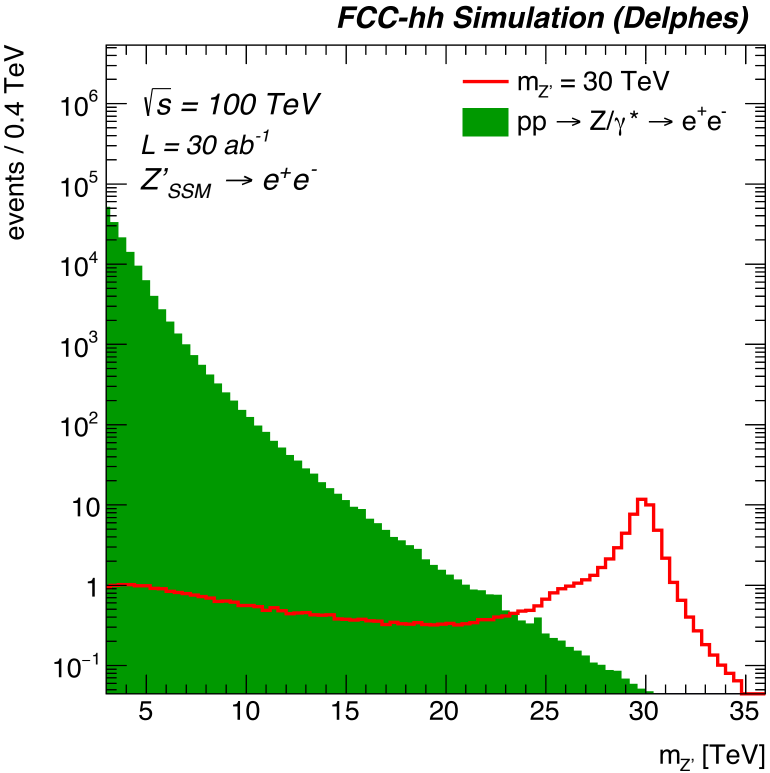
- Z' model
  - From Pythia8, no k-factor
  - Simple benchmarks used to check detector performance
  - Helped to tune the muon resolution initially of 10%@10TeV given the reach of such heavy objects

- Analysis selection
  - $p_T(\text{lepton}_1)$ and $p_T(\text{lepton}_2) > 1\text{TeV}$
  - $|\eta_{lepton1}|$ and $|\eta_{lepton2}| < 4$
  - M_{ll}>2.5 TeV (to bridge with HL-LHC reach of 6 TeV, start signal at 5 TeV)

- Uncertainties
  - 50% uncertainty on the Drell-Yan normalization

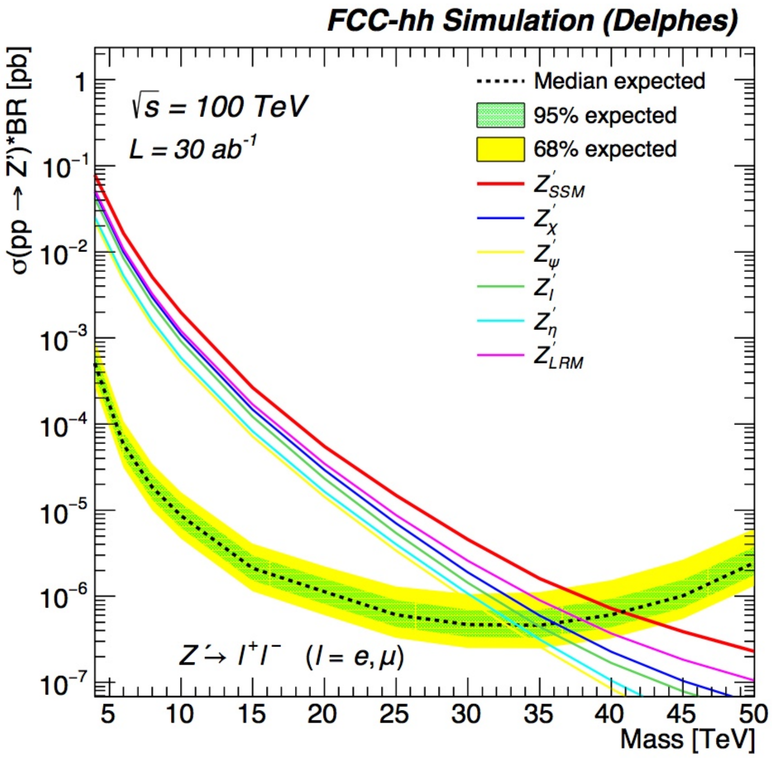
Z'->μ⁺μ⁻/e⁺e⁻ (30TeV)



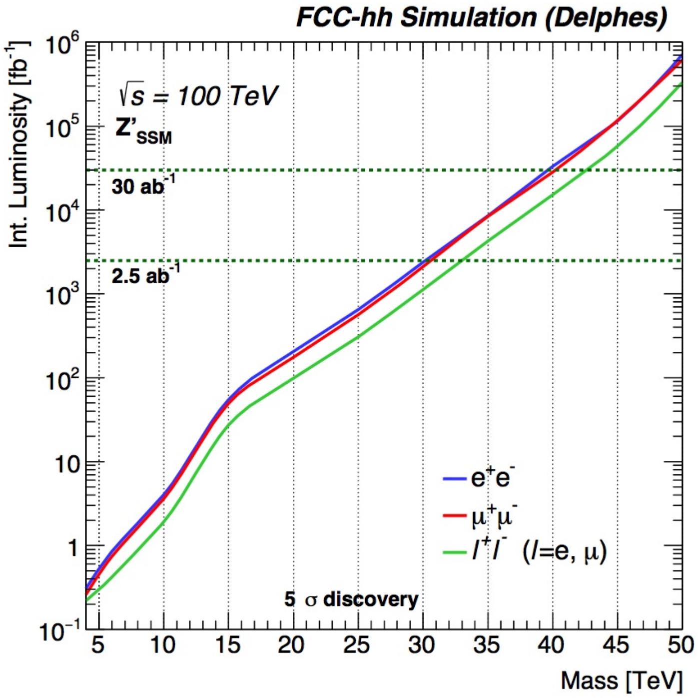


As expected better mass resolution for electrons

Limits and discovery



Reach up to 40TeV this very simple case!



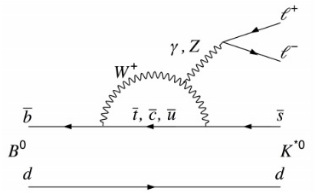
Considering 2.2fb^{-1} per day for baseline

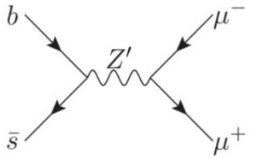
5σ discovery for:

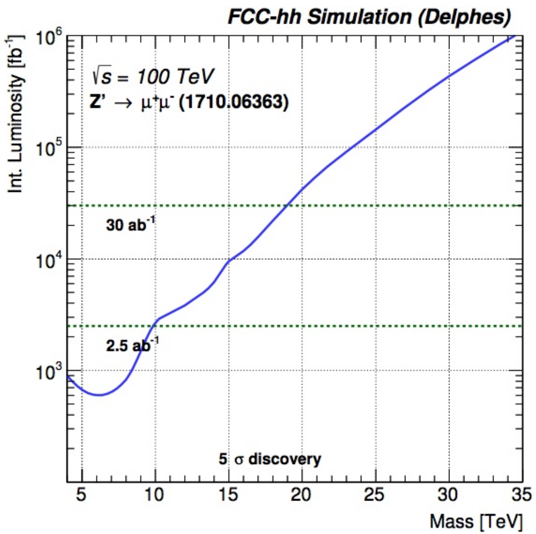
- 20TeV after ~50 days (first year?)
- 33TeV after 10 years @ baseline
- 42TeV after full operation 25 years

Z’ flavour anomaly

Quick interpretation of Z’->μμ

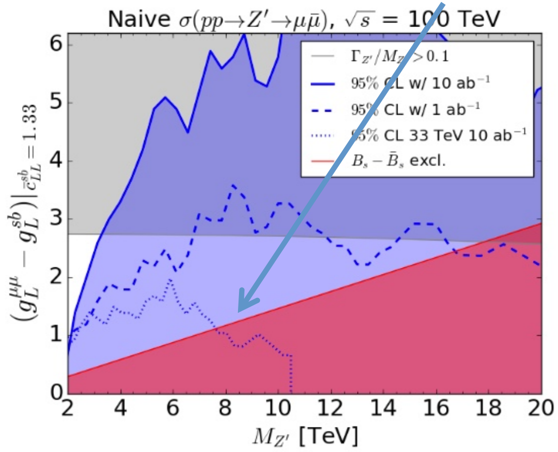


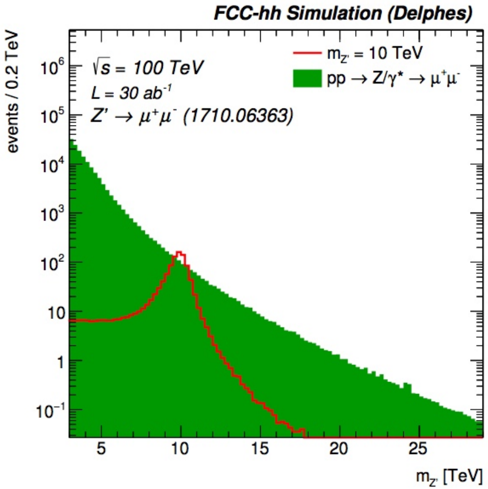


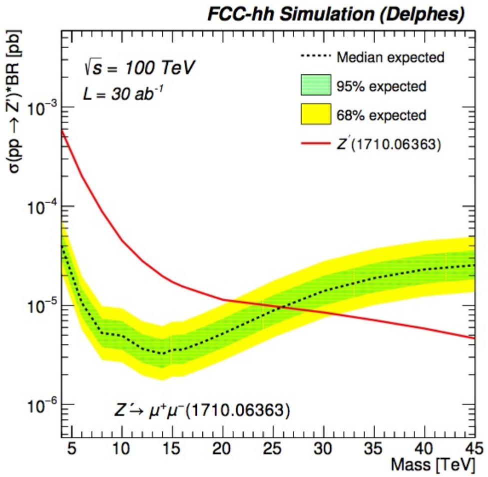


Arxiv:1710.06363

We test this line





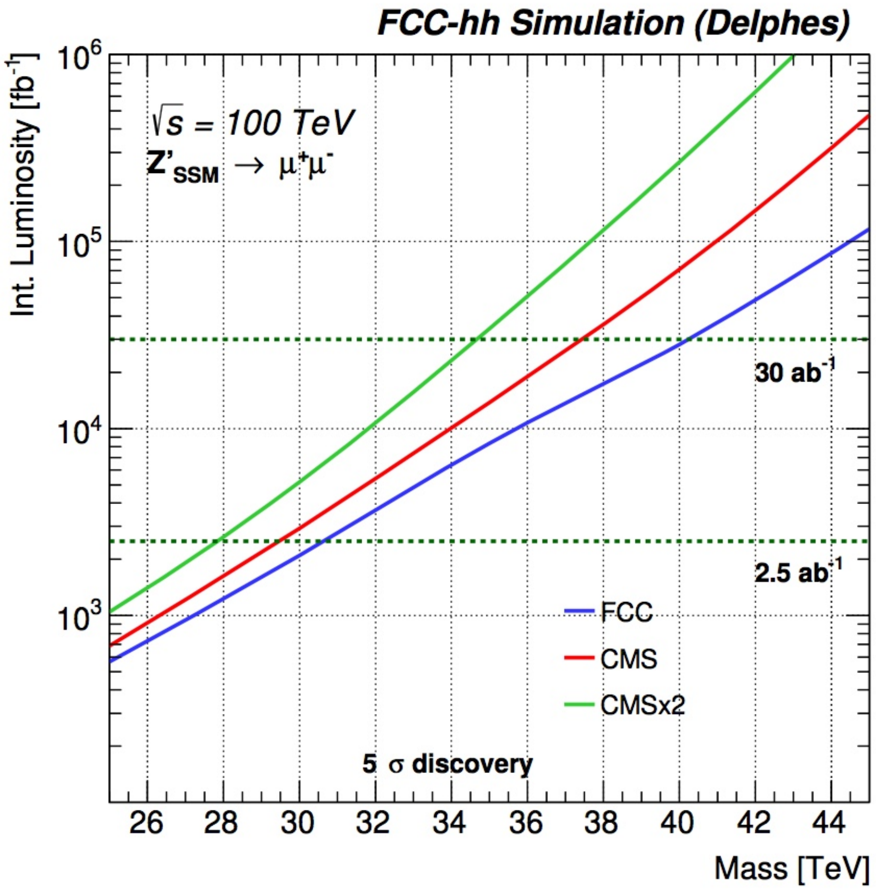


Discovery μμ degraded

Best sensitivity achieved with an assumed σ_p/p ≈ 5% at p_T = 20 TeV corresponding to our target for the FCC-hh detector

Worse results for projected CMS resolution of $\sigma_p/p \approx 40\%$.

Accurate reconstruction and momentum measurements of p_T = 20 TeV
-> require large lever arm, excellent spatial resolution and precise alignment of the tracking plus muon systems.

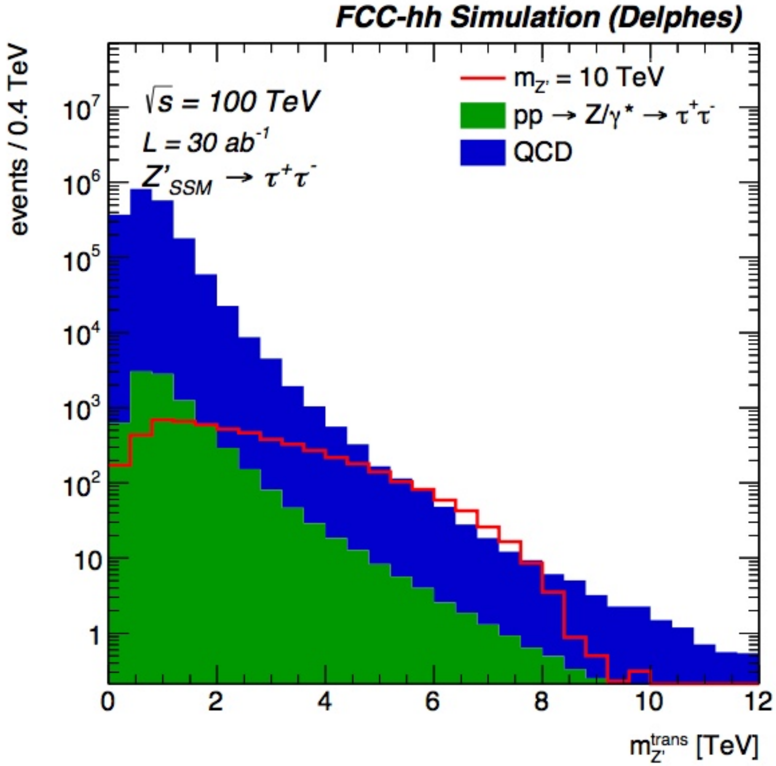


Z’->ττ

- Analysis selection (hadronic taus only as most sensitive)
  - p_T(j1/2) >1TeV, |η(j1/2)| <2.5
  - At least 2 tau tags

Z' mass [TeV]	$\Delta\phi(\tau_1,\tau_2)$	$\Delta R(\tau_1,\tau_2)$	E_T^{miss}
$4-8$	>2.4	>2.5 and <3.5	>400 GeV
10	>2.4	>2.7 and <4	>300 GeV
$12-14$	>2.6	>2.7 and <4	>300 GeV
$16-18$	>2.7	>2.7 and <4	>300 GeV
>18	>2.8	>3 and <4	>300 GeV

- Uncertainties
  - 50% uncertainty on the Drell-Yann normalization
  - 50% uncertainty on the Di-jet normalization

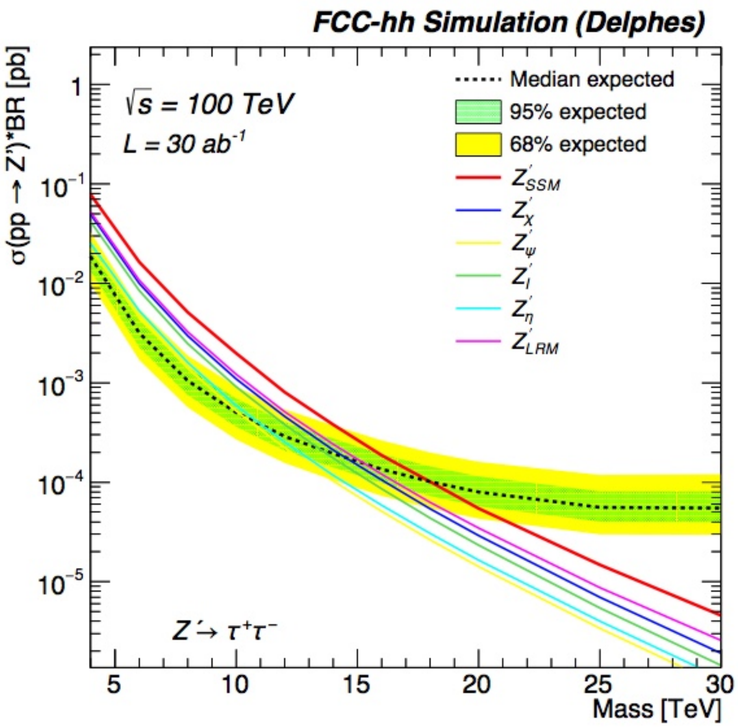


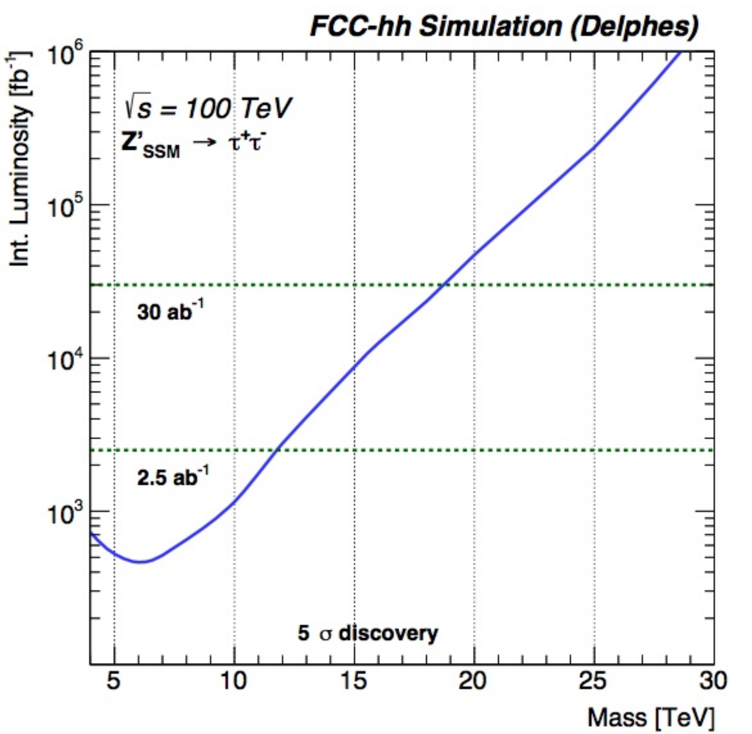
Limit/significance

5σ discovery for:

- 12TeV after 10 years @ baseline
- 19TeV after full operation 25 years

Challenges: better tau tagging at high p_T

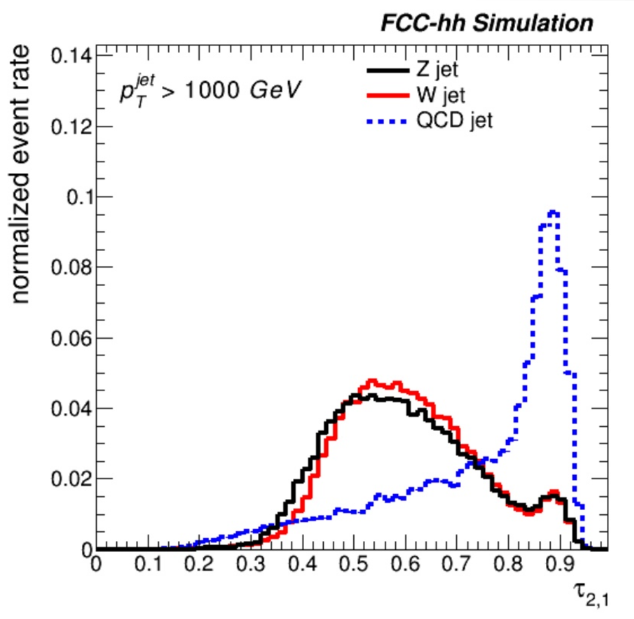




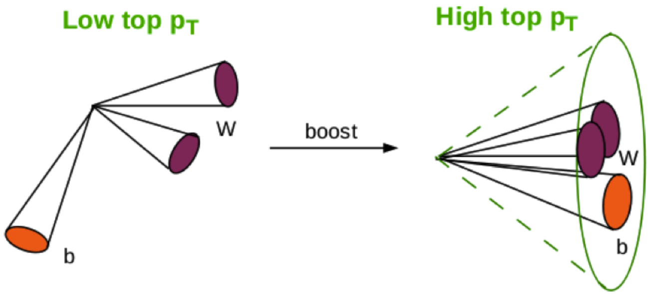
Z'->tt

Z'->ttbar

- Z' model
  - Signal with Pythia8
  - Important benchmark model for detector performance on sub-structure



$\Delta R \cong 2m/p_T$



Top-quark

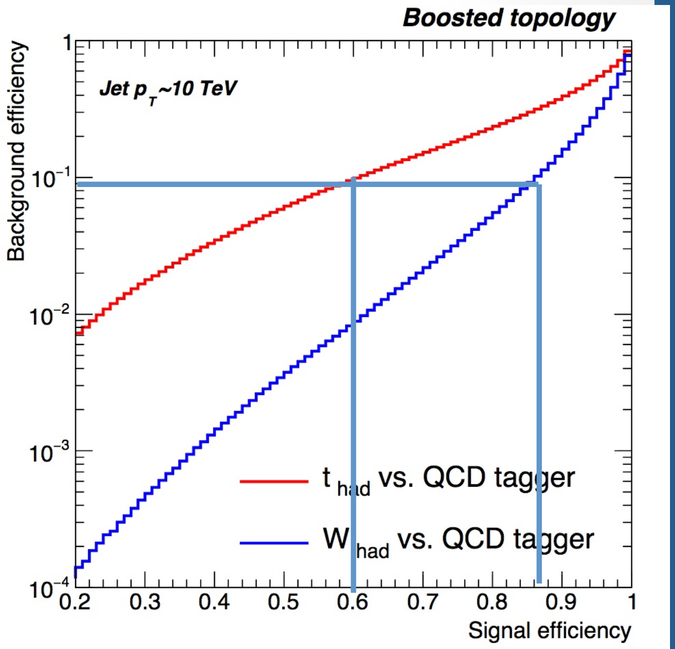
LHC: p_T ~ 1TeV →ΔR=0.5

FCC: p_T ~ 10 TeV → ΔR = 0.05

Multivariate discriminant

- Developed MVA discriminant to disentangle overwhelming QCD jets from boosted W/tops

W tagger		top tagger	
variable	weight	variable	weight
τ_3 (track jet, R=0.2)	0.12	τ_1 (track jet, R=0.2)	0.21
m_{SD} (track jet, R=0.2)	0.11	m_{SD} (track jet, R=0.2)	0.17
τ_{31} (track jet, R=0.2)	0.10	τ_{31} (track jet, R=0.2)	0.11
$E_F(n=5, \alpha=0.05)$	0.09	τ_2 (track jet, R=0.2)	0.10
$E_F(n=4, \alpha=0.05)$	0.09	τ_3 (track jet, R=0.2)	0.09
$E_F(n=1, \alpha=0.05)$	0.08	m_{SD} (track jet, R=0.8)	0.09
$E_F(n=2, \alpha=0.05)$	0.07	m_{SD} (track jet, R=0.4)	0.09
$E_F(n=3, \alpha=0.05)$	0.06	τ_{32} (track jet, R=0.2)	0.08
τ_{21} (track jet, R=0.2)	0.06	τ_{21} (track jet, R=0.2)	0.06
m_{SD} (track jet, R=0.8)	0.06		
m_{SD} (track jet, R=0.4)	0.06		
τ_1 (track jet, R=0.2)	0.05		
τ_2 (track jet, R=0.2)	0.04		
τ_{32} (track jet, R=0.2)	0.02		

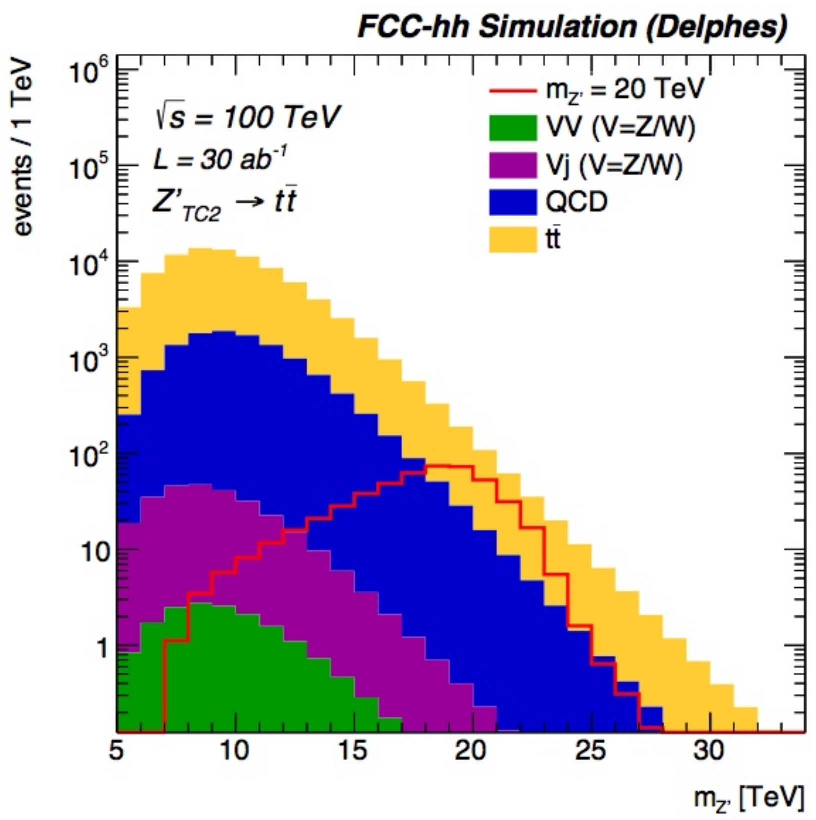


Z'->ttbar

- Z' model
  - Signal with Pythia8
  - Important benchmark model for detector performance
    on sub-structure

- Analysis pre-selection
  - $p_T(j_{1/2})$ >3TeV, $|\eta(j_{1/2})|$ <3
  - Jet1,2 Soft Dropped mass>100GeV
  - Jet1,2 τ_{21}, τ_{32}>0
  - $|\eta_{jet1} - \eta_{jet2}|$<2.4
  - 2 b-tag jets, 2 top jets from MVA discriminant
  - Do not explicitly select leptons,
    but "correct" di-top mass for MET

- Uncertainties
  - 20% uncertainty on the ttbar normalization
    50% on di-jet 40% on Vj and 20% on VV



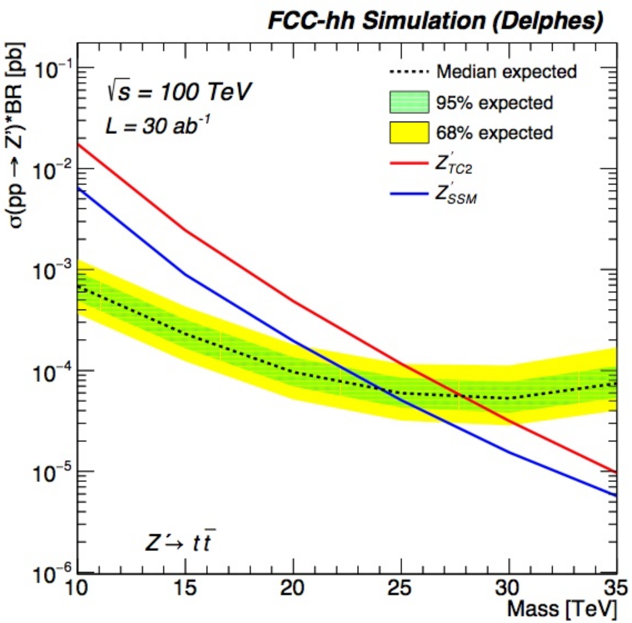
Z'->ttbar

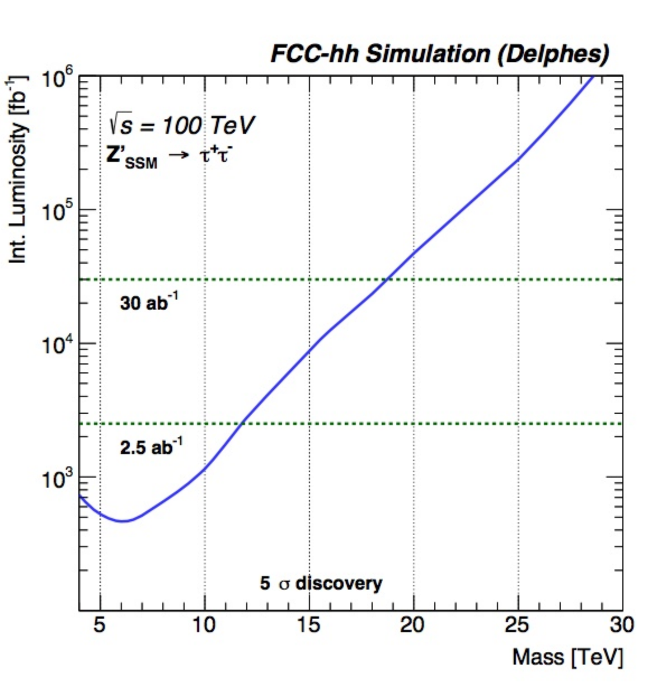
5σ discovery for TC2:
- 17TeV after 10 years @ baseline
- 23TeV after full operation (25y)

5σ discovery for SSM:
- 11TeV after 10 years @ baseline
- 16TeV after full operation (25y)

Challenges: better top tagging from sub-structure, and improve m_{tt} mass resolution

SSM is obviously a benchmark for leptonic decays





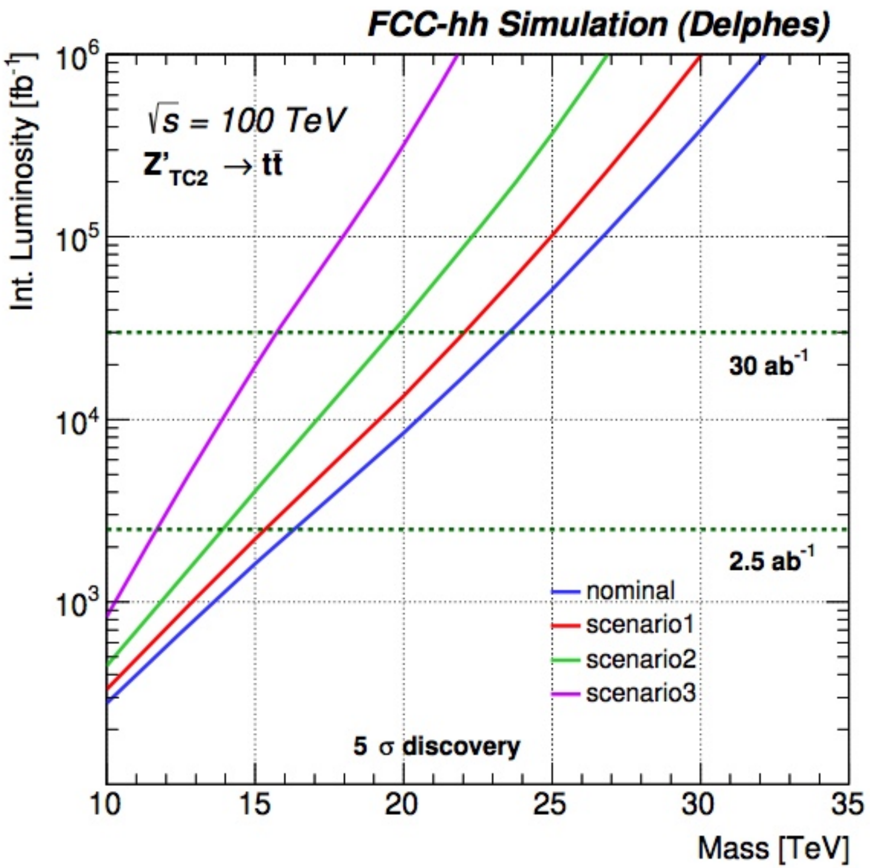
Discovery tt degraded

High efficiencies ($\varepsilon_b > 60\%$) for corresponding low mis-identification probability ($\varepsilon_{u,d,s} < 1\%$) from light jets have to be achieved up to p_T = 5 TeV.

For example, searches for heavy resonances decaying to hadronic tt pairs heavily rely on efficient b-tagging performance at such energies.

The discovery reach for a specific Z′ model assuming several scenarios for b-jet identification at very large p_T are considered
-> Nominal efficiency $(1-p_T/15)*85\%$
-> scenarios 1,2, 3 correspond to reduction of the slope by a factor 25%, 33% and 50%.

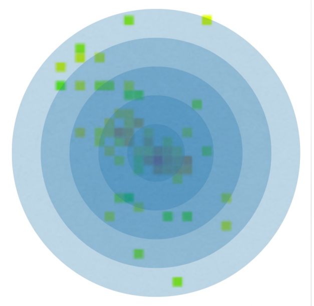
As expected the discovery reach strongly depends on the b-tagging performances.



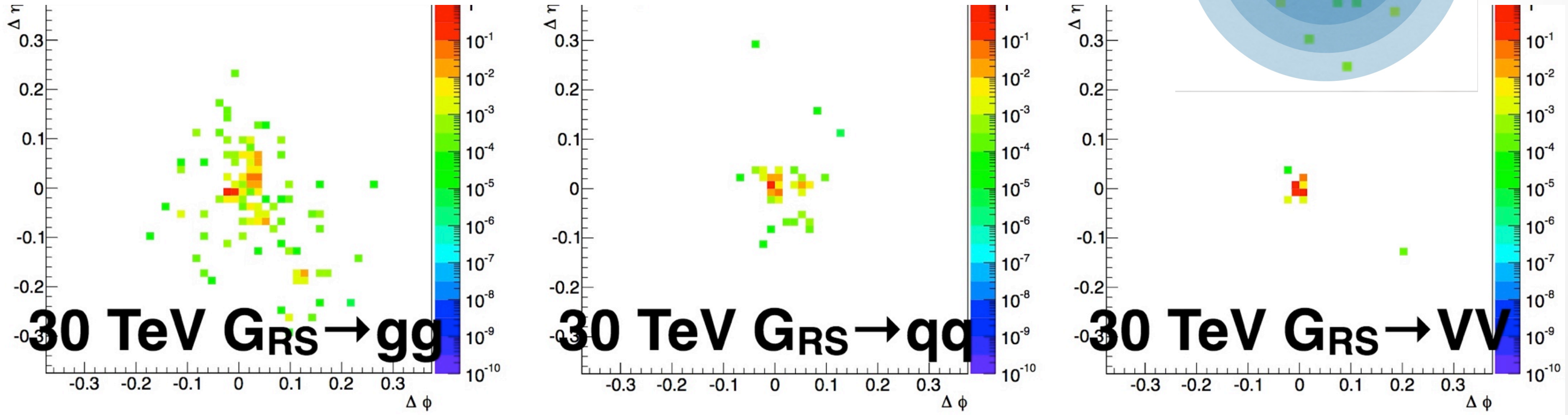
RSG->WW
W->jj

Di-boson resonance (only hadronic)

- Randall-Sundrum Graviton
  - Signal with pythia8
  - Important benchmark model for detector performance on sub-structure
- W/Z bosons
  - LHC: p_T ~ 1TeV →ΔR=0.25
  - FCC: p_T ~ 10 TeV → ΔR = 0.025

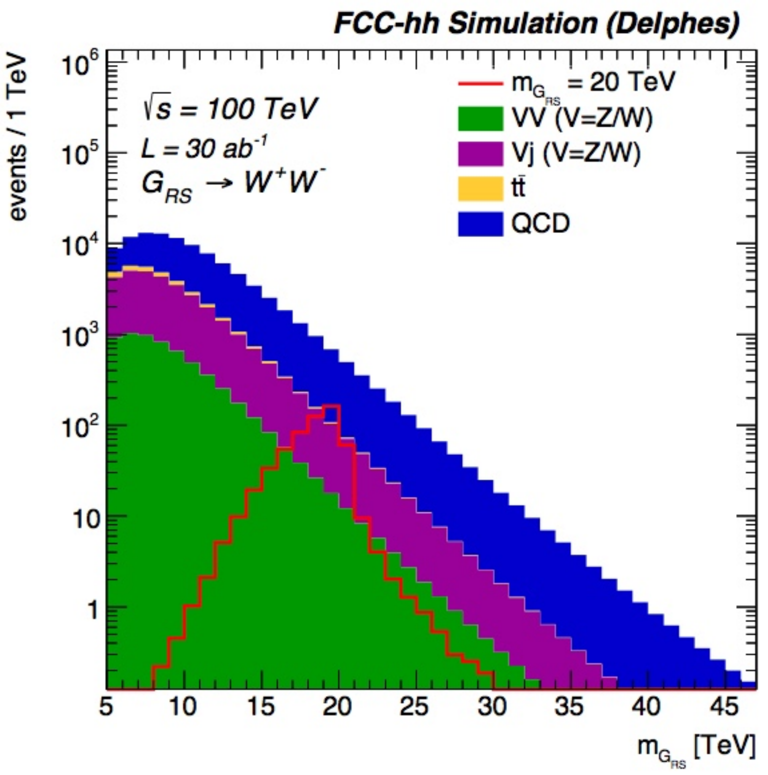


$$\frac{n-1}{5}R \leq \Delta R(k, \text{jet}) < \frac{n}{5}R, \quad \text{Flow}_{n,5} = \sum_k \frac{|p_T^k|}{|p_T^{\text{jet}}|}$$



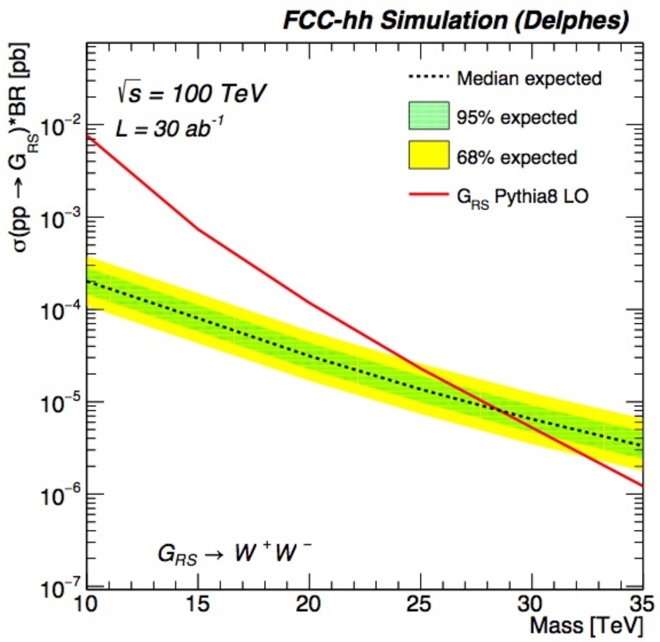
Di-boson resonance (only hadronic)

- Randall-Sundrum Graviton
  - Signal with pythia8
  - Important benchmark model for detector performance on sub-structure
- Analysis pre-selection (Fully hadronic)
  - Jet1/2 p_T>3TeV, jet1/2 $|\eta|$ <3
  - J1,2 τ_{21}, τ_{32}>0
  - $|\eta_{jet1} - \eta_{jet2}|$<2.4
  - 2 W jets from MVA discriminant
- Norm uncertainties
  - ttbar 20% QCD 50%, VV 20%, VJ 40%



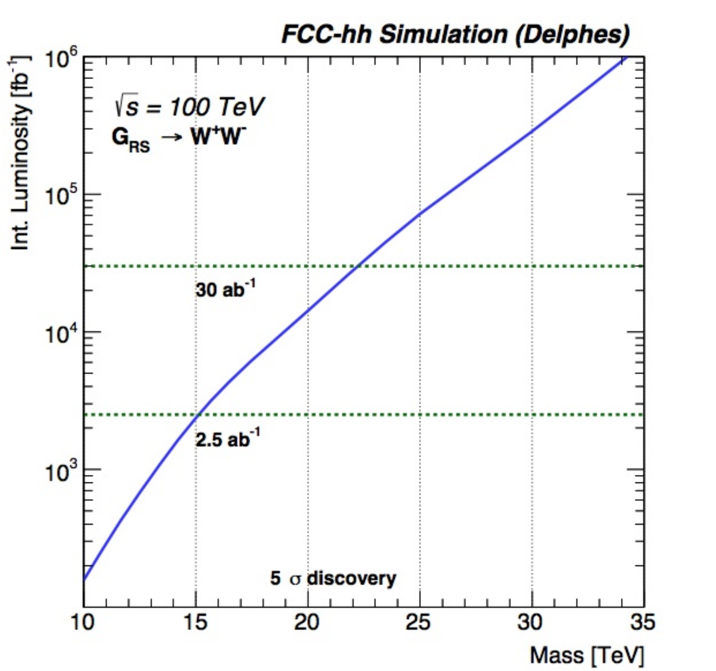
RSG->WW

Challenges: better W tagging from sub-structure, and improve m_{WW} mass resolution



5σ discovery for RSG:

- 10TeV after 1 years (~100fb^{-1})
- 15TeV after 10 years @ baseline
- 22TeV after full operation 25 years



Q*->jj

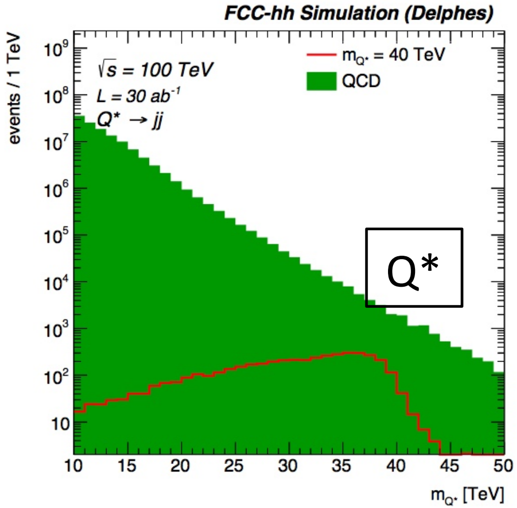
Q*/Z'->jj

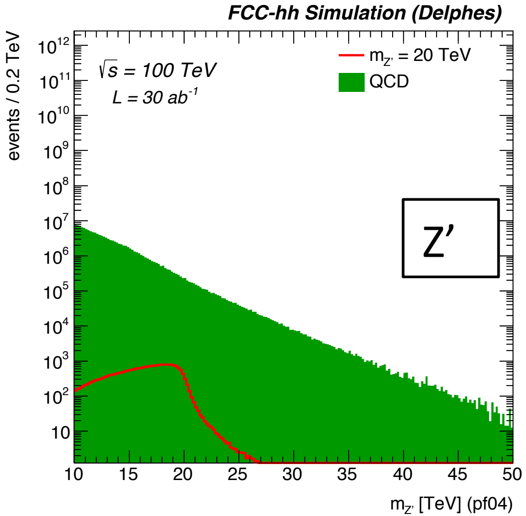
- Q* model
  - Strongly coupled
  - Wide, large cross section

- Z' model
  - Same benchmark as Z' -> leptons
  - Narrow, small cross section

- Analysis selection
  - $p_T(j1)$ and $p_T(j2)$>3TeV
  - Y*=|yjet1-yjet2|/2 < 1.5

- Uncertainties
  - 50% uncertainty on the Di-jet normalization

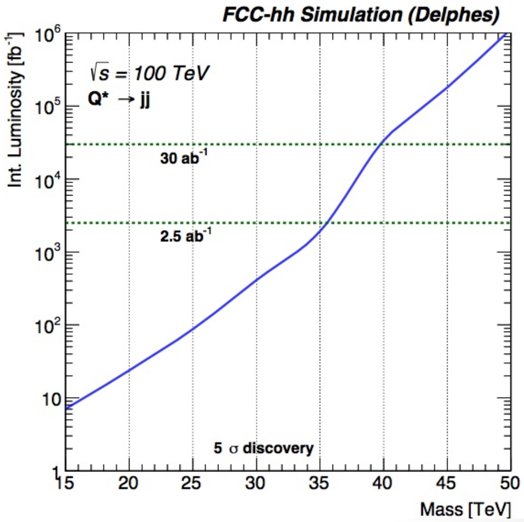




5σ discovery for Q* (wide and strongly coupled):

- 15TeV after 1 day (1fb^{-1})
- 36TeV after 10 years @ baseline
- 40TeV after full operation 25 years

Q*

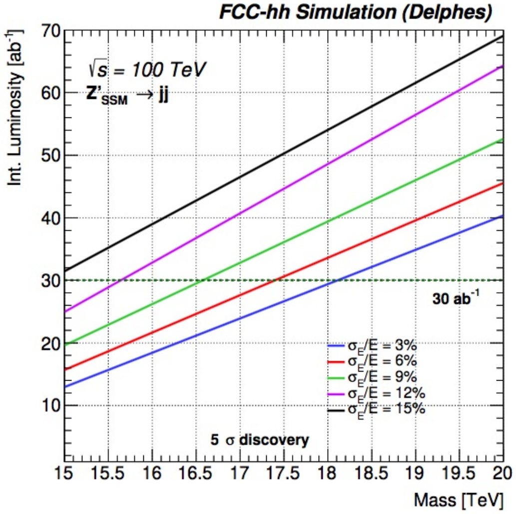


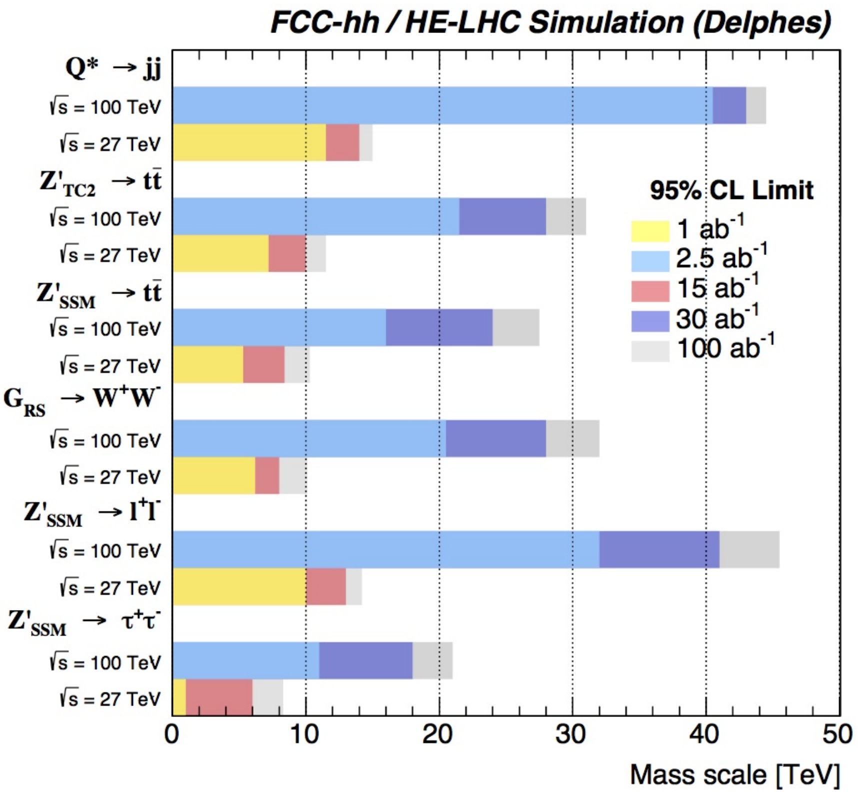
5σ discovery for Z' (narrow and weakly coupled):

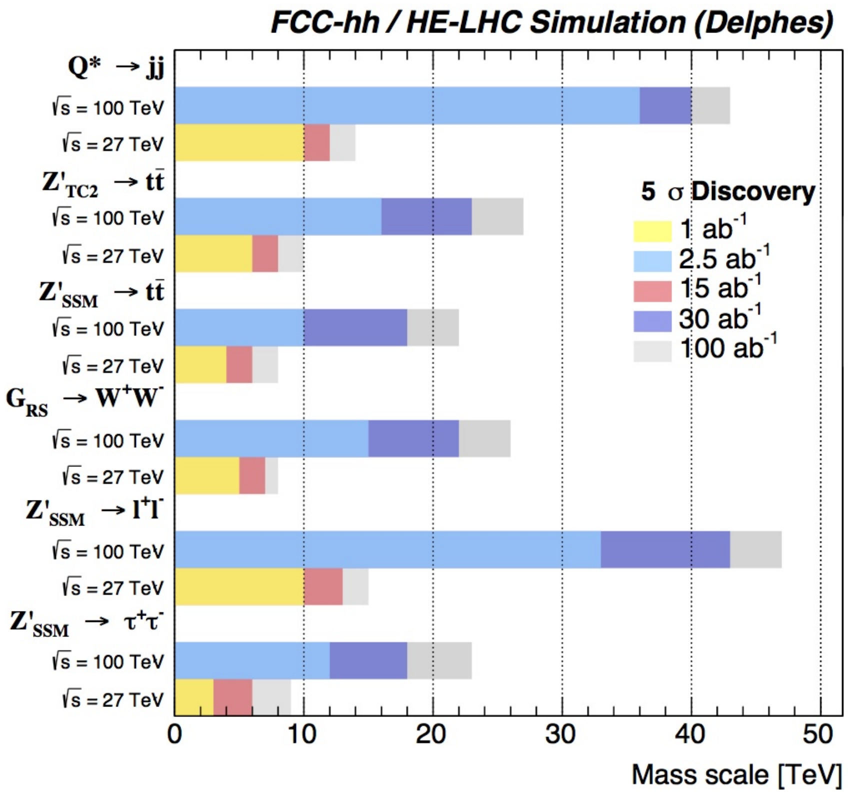
- <15TeV after 10 years @ baseline
- 19TeV after full operation 25 years

Smearing the mass (increasing the calorimeter constant term) has a large impact on the discovery potential

Z'




FCC-hh / HE-LHC Simulation (Delphes)
Q* → jj
√s = 100 TeV
√s = 27 TeV
Z'TC2 → tt̄
√s = 100 TeV
√s = 27 TeV
Z'SSM → tt̄
√s = 100 TeV
√s = 27 TeV
GRS → W+W-
√s = 100 TeV
√s = 27 TeV
Z'SSM → l+l-
√s = 100 TeV
√s = 27 TeV
Z'SSM → τ+τ-
√s = 100 TeV
√s = 27 TeV
95% CL Limit
1 ab-1
2.5 ab-1
15 ab-1
30 ab-1
100 ab-1
0
10
20
30
40
50
Mass scale [TeV]


FCC-hh / HE-LHC Simulation (Delphes)
Q* → jj
√s = 100 TeV
√s = 27 TeV
Z'TC2 → tt̄
√s = 100 TeV
√s = 27 TeV
Z'SSM → tt̄
√s = 100 TeV
√s = 27 TeV
GRS → W+W-
√s = 100 TeV
√s = 27 TeV
Z'SSM → l+l-
√s = 100 TeV
√s = 27 TeV
Z'SSM → τ+τ-
√s = 100 TeV
√s = 27 TeV
5 σ Discovery
1 ab-1
2.5 ab-1
15 ab-1
30 ab-1
100 ab-1
0
10
20
30
40
50
Mass scale [TeV]

Summary

- Di-lepton(ee/μμ)
  - Background free analysis
  - Discovery reach ~42TeV with full dataset for SSM model
- Z'->ττ (hadronic taus)
  - More complex final state
  - Discovery reach ~19TeV with full dataset
  - Need better high p_T tau tagging techniques
- Ttbar
  - Discovery reach up to 23TeV
  - better top tagging from sub-structure, and improve m_{tt} mass resolution
- Di-boson
  - Discovery reach up to 22TeV
  - better W tagging from sub-structure, and improve m_{WW} mass resolution
- Di-jet
  - Reach up to 40TeV
  - Calorimeter containment for best resolution

Bonus

Next steps

- Di-lepton(ee/μμ)
  - Interpretation with Lepto-Quarks
  - add other Z' signal XS to limit
  - Di-elec results basically RSG->γγ
- Z'->ττ (hadronic taus)
  - Not fully optimised for m<10TeV
  - Further checks to be done in full sim
- Ttbar
  - Sub-structure performance to be checked with full sim
  - Include other benchmarks
- Di-boson
  - Sub-structure performance to be checked with full sim
  - Could add leptonic channels
  - Add other benchmarks and ZZ/WZ
- Di-jet
  - Possibly add other benchmarks Contact interaction, etc…

Technicalities

- Signals:
  - Mainly produced with Pythia8
  - MG5 in some cases (interpretations)
  - No k-factor assumed
- Backgrounds :
  - with MG5 LO
  - k-factor of 2 assumed
- Software
  - Using FCC software with detector parameterization
  - When setting limits, use full shape and profile likelihood ratio

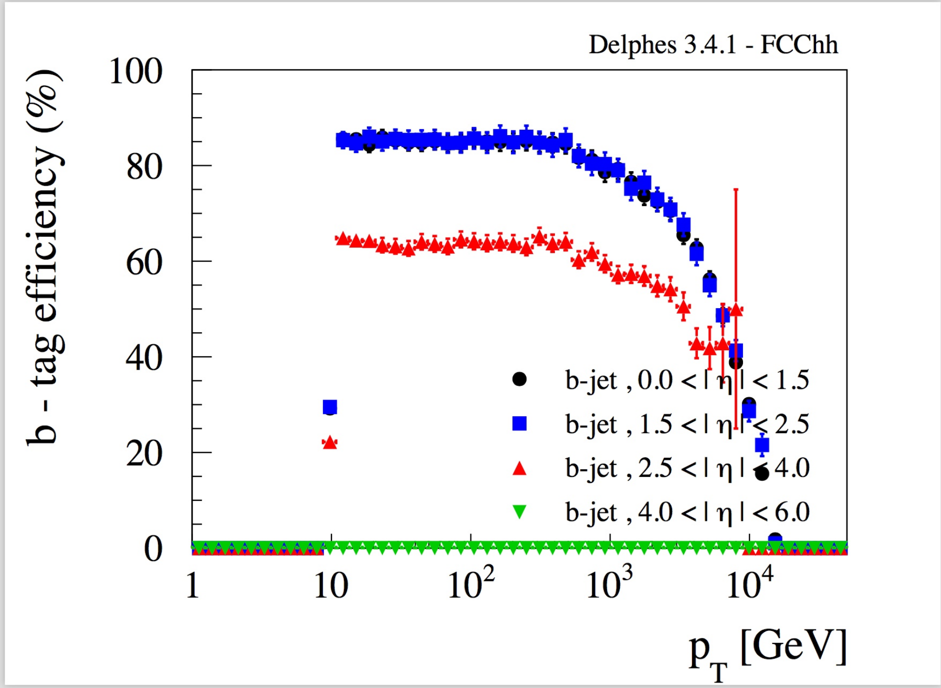
Sample	Cut (TeV)	Statistic (10^6)
Di-electron	$p_T(e)>5$	10
Di-muon	$p_T(\mu)>5$	10
Di-tau	$p_T(\tau)>2.5$	10
Di-tau	$2.5>p_T(\tau)>1$	5
Di-jet	$p_T(j)>2.5$	50
Di-jet	$2.5>p_T(j)>1$	30
Di-boson	$p_T(V)>2.5$	15
V+jets	$m_{vj}>5$	10
Top pair	$p_T(t)>2.5$	10

FCC-hh Analysis Framework

- GridPack producer
  - Makes MG5_aMC@NLO GridPacks
- LHE Producer
  - Produce LHE files on LSF/condor queues from GP or standalone MG5
  - About a 2 billion events produced
  - http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php
- FCCSW
  - Runs Pythia8 parton shower+hadronisation and Delphes with FCC detector
- Analysis preselection and high level variable definitions
  - Python framework produces flat ROOT trees
- Analysis Final selection and plots
  - Python framework for optimising analysis cut flows and producing
- Limit setting
  - Atlas inspired tool for limits and significance
- More info in my talk at the FCC software session Thursday afternoon

B-tagging

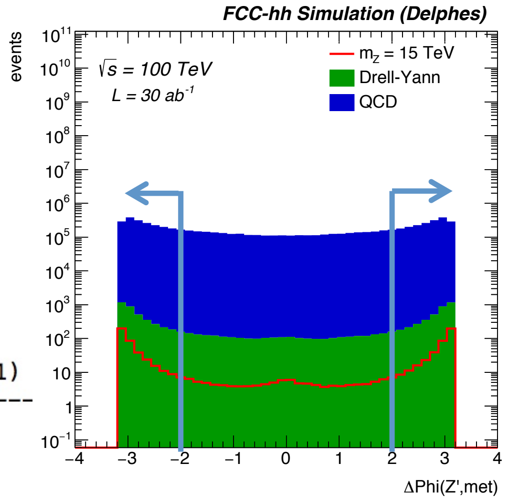
- High p_T b-tagging
  - Very displaced vertices
  - After the 1st 2nd or even 3rd layer of the pixel detector
  - Used for this top pair resonance search
- Estimate
  - Need a first realistic estimate of how b-tagging will perform
  - Using results from full simulation study without tracks (hit multiplicity jump)
  - See Estel Perez talk at detector session

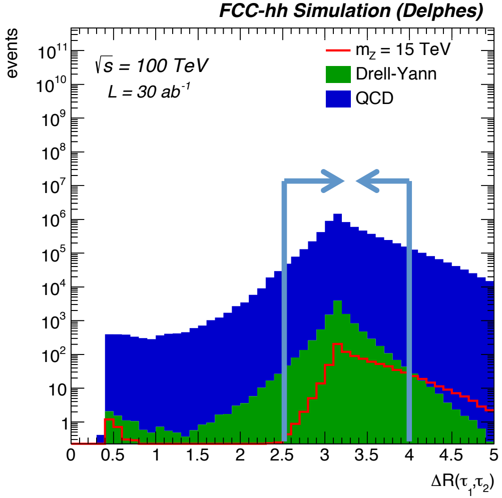


Z'->ττ

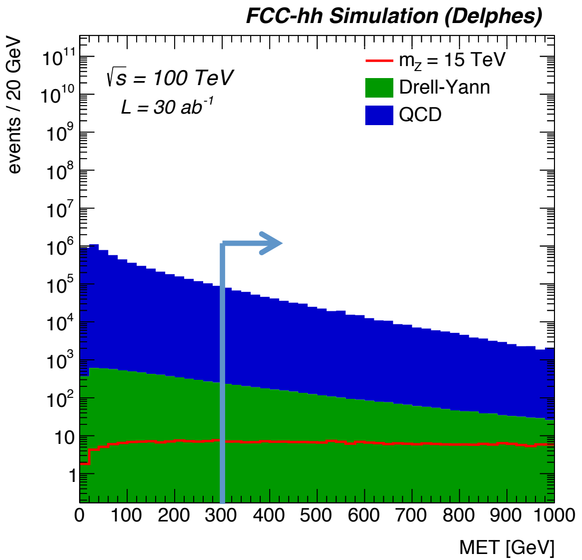
$p_T(j1/2) > 1\text{TeV}$, $|\eta(j1/2)| < 2.5$

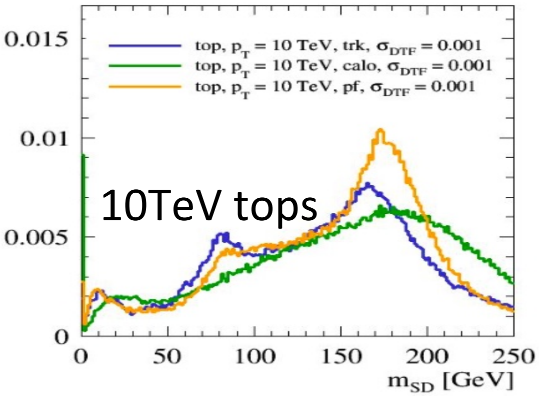
process	yield (30.0 ab-1)
m_{Z} = 15 TeV	888.9
Drell-Yann	10237.8
QCD	7116045.3

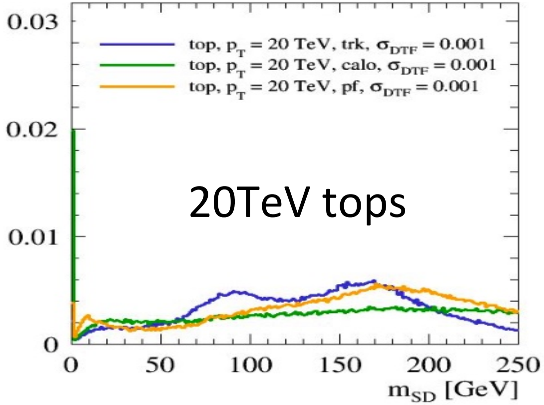


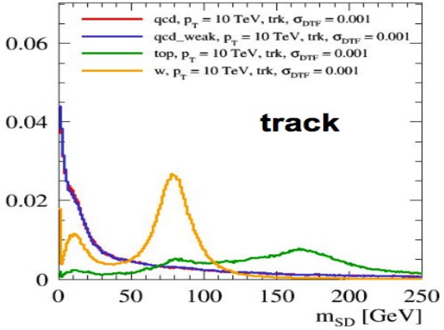


process	yield (30.0 ab-1)
m_{Z} = 15 TeV	781.0
Drell-Yann	10083.6
QCD	6426072.2

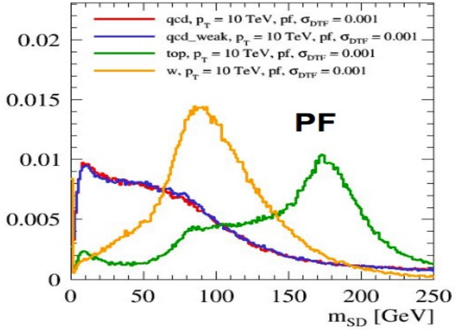








10TeV objects



- Track jets seems to be more robust and better understood at high p_T
- Use those at high p_T corrected by p-flow jet p_T when using substructure

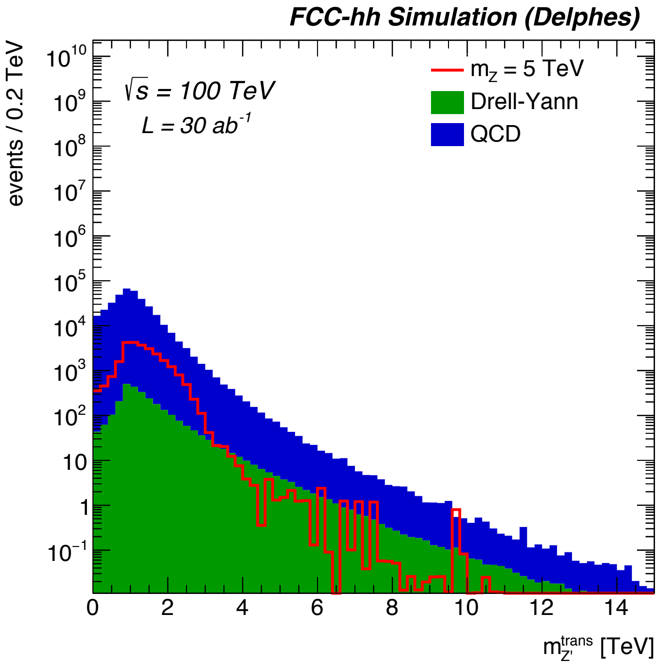
Z’->ττ

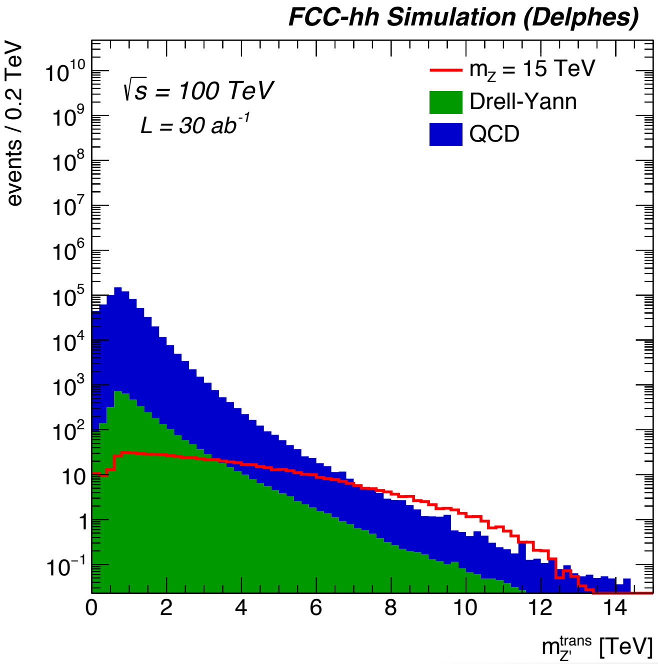
Z’ = τ1+τ2 (4 vectors)

m_T = sqrt(2*p_T(Z’)*MET*(1 – cos(Δϕ($\phi_{Z'}$ - ϕ_{MET}))))

process	yield (30.0 ab-1)
m_{Z} = 5 TeV	25345.8
Drell-Yann	2715.5
QCD	361221.2

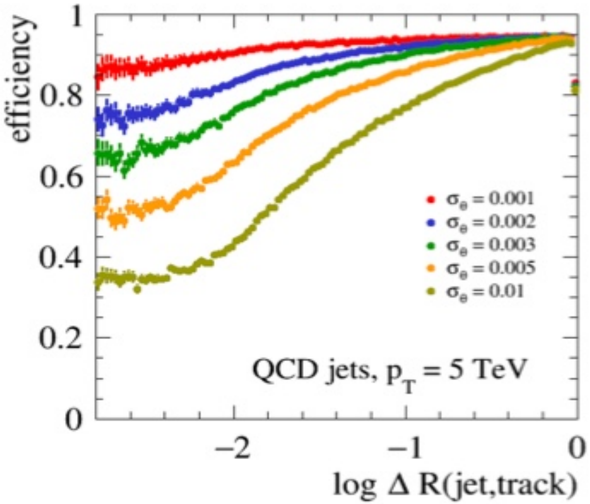
process	yield (30.0 ab-1)
m_{Z} = 15 TeV	686.2
Drell-Yann	3769.5
QCD	695272.8

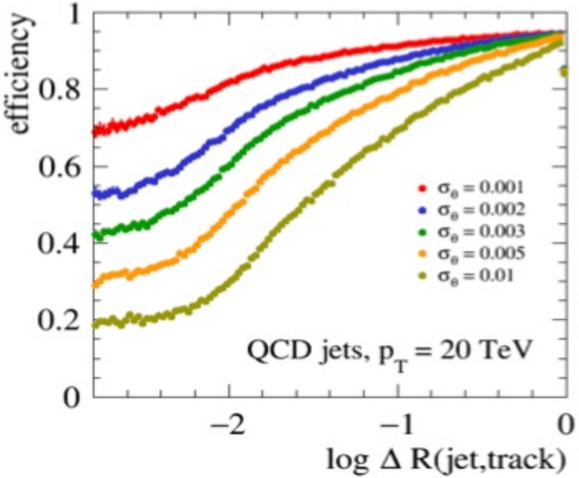




Tracking in dense env.

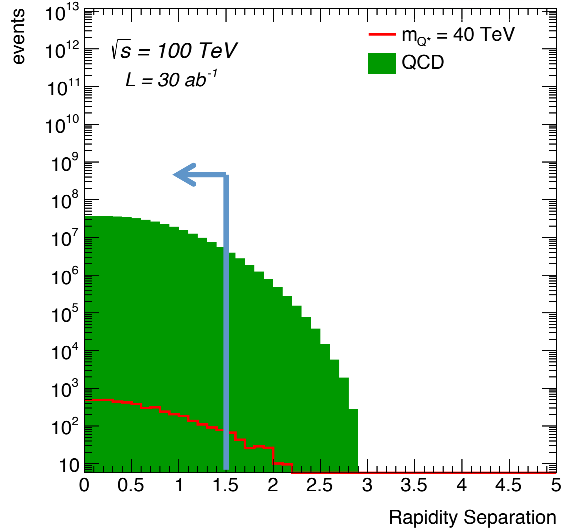
- Tracker granularity
  - Defined in (η x ϕ)
  - Worst case scenario
    - pitch size in the first pixel layer: reso = (2-3)*10um/(0.025) ~ 0.001
- Inefficiency
  - when two or more tracks hit same pixel
  - keep only highest p_T track
  - Arbitrary and probably conservative, considering that this is only first pixel layer
- Conservative value
  - 0.001 used for FCC studies

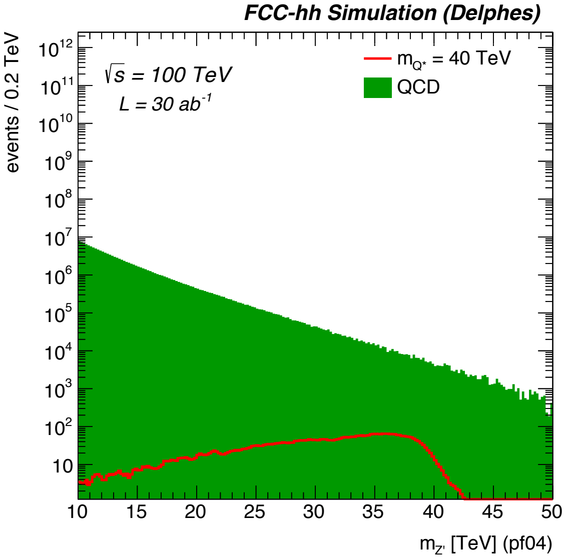


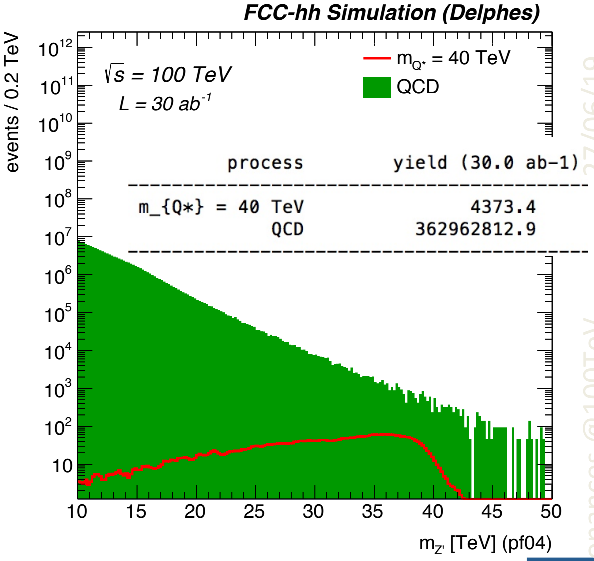


Q*->jj

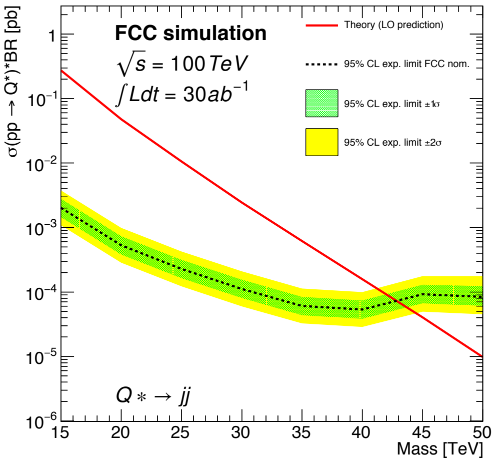
process	yield (30.0 ab-1)
m_{Q*} = 40 TeV	4588.9
QCD	374687859.9

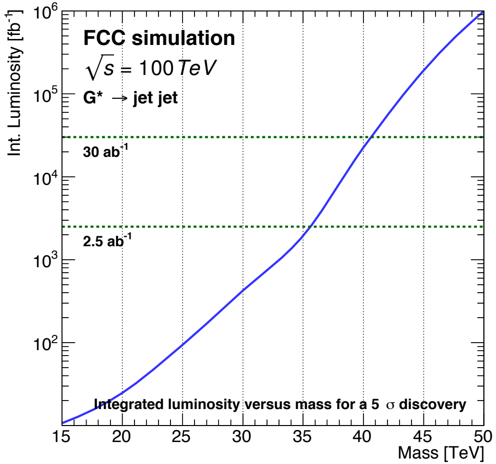






process	yield (30.0 ab-1)
m_{Q*} = 40 TeV	4373.4
QCD	362962812.9



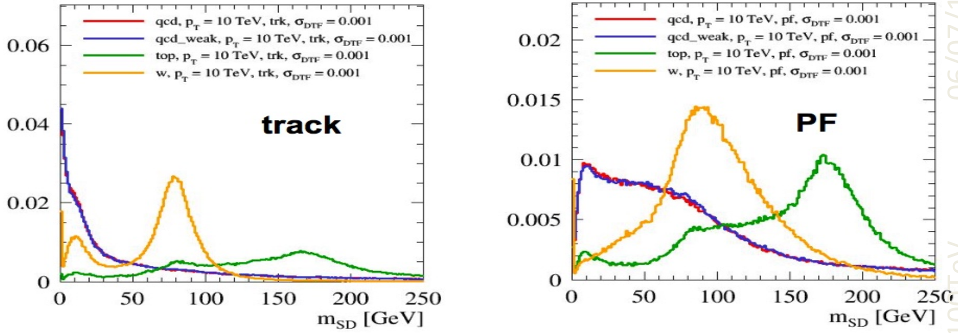


5σ discovery for Q*:

- 15TeV after 1 day (1fb^{-1})
- 36TeV after 10 years @ baseline
- 40TeV after full operation 25 years

Boosted objects

10TeV objects



- What is:
  - Optimal jet collection
  - Minimal track angular resolution?
- Assessed using :
  - QCD, QCD+weak shower, W and Top jets
  - GenJets, CaloJets, Particle Flow Jets, Track Jets with 2-5-10-20 TeV
- Outcome:
  - Use track jets for sub-structure corrected to pf jets
  - More information in this talk here
- Performance of reconstructing such boosted objects is being further investigated in full simulation for the report
- Track jets seems to be more robust and better understood at high p_T
- Use those at high p_T corrected by p-flow jet p_T when using substructure

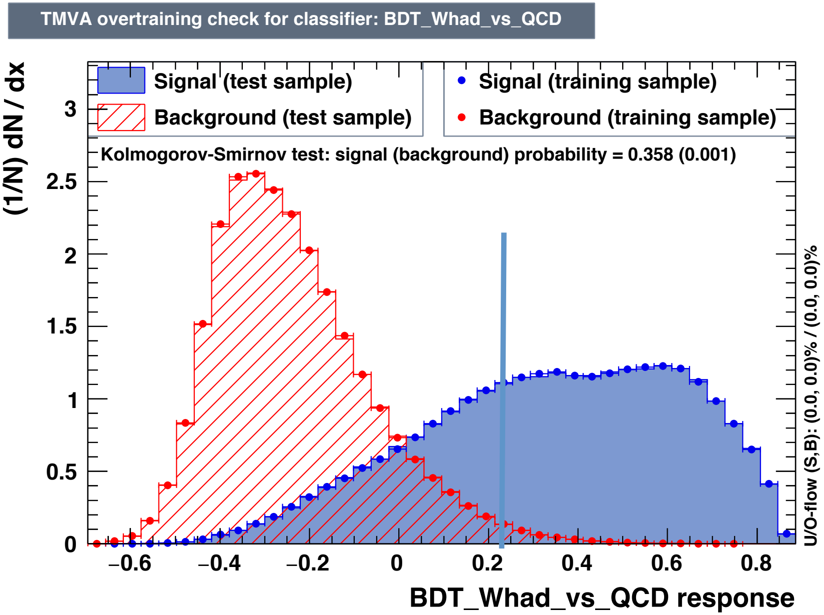
W versus QCD jet tagger

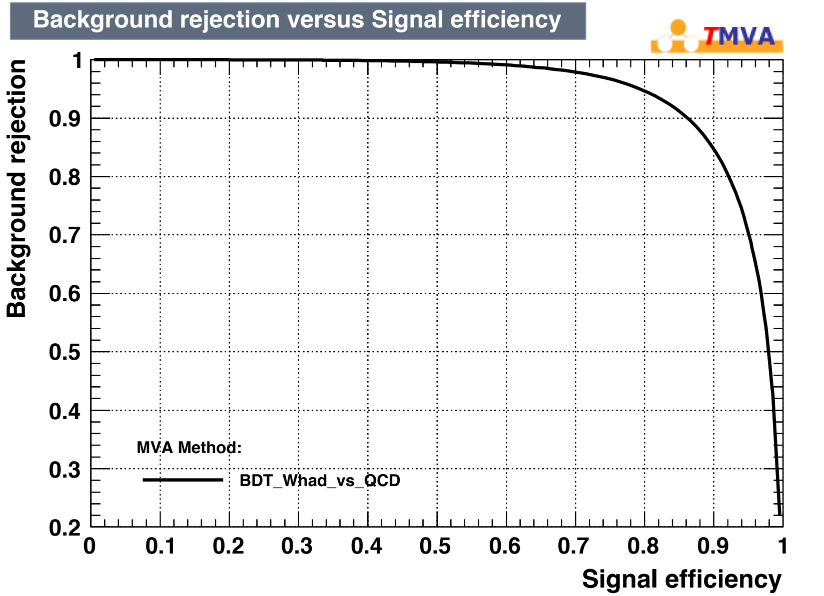
Variables used

Flow 1,2,3,4,5/5

Soft dropped mass

τ32, τ21, τ1/2/3





W versus QCD jet tagger

Variables used
Flow 1,2,3,4,5/5
Soft dropped mass
τ32, τ21, τ1/2/3