Heavy resonances at energy frontier colliders

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Based on arXiv:1902.11217 (accepted by EPJC)

and in FCC CDRs Vol1 **Eur.Phys.J. C79 (2019)** and Vol3 **Eur.Phys.J.ST 228 (2019)**

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

Expectation from hadron future collider

Guaranteed deliverables

- Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

Exploration potential (New machines are build to make discoveries!)

- Mass reach enhanced by factor $\sqrt{s}$/14TeV (5-7 at 100TeV)
  - Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large Q^2) and indirect precision probes

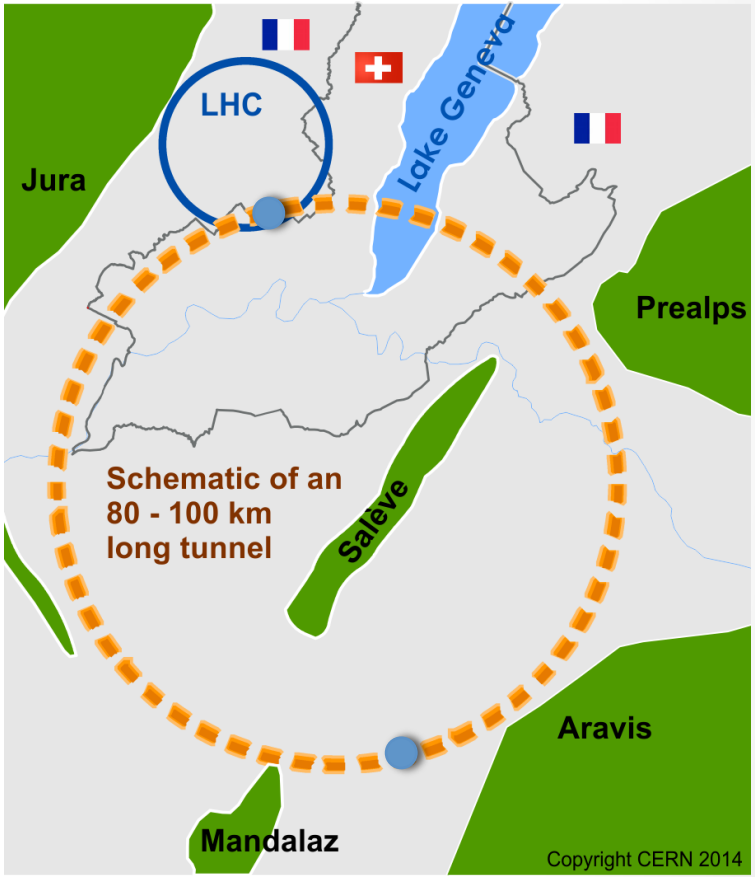
Could provide firm answers to questions like

- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is DM a thermal WIMPS?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

Circular hadron projects @CERN

FCC-hh

- Need a new 100km tunnel
- Need 16 Telsa magnet to reach 100TeV in 100km
- Baseline Luminosity (10y)
  - 5 10^{34} cm^{-2} s^{-1} (HL-LHC) <μ>200
- Ultimate luminosity (15y)
  - 30 10^{34} cm^{-2} s^{-1} <μ>1000
- 2.4MW sync rad/ring x300 HL-LHC
- Considering 30ab^{-1} for the study



Environment and detector requirements

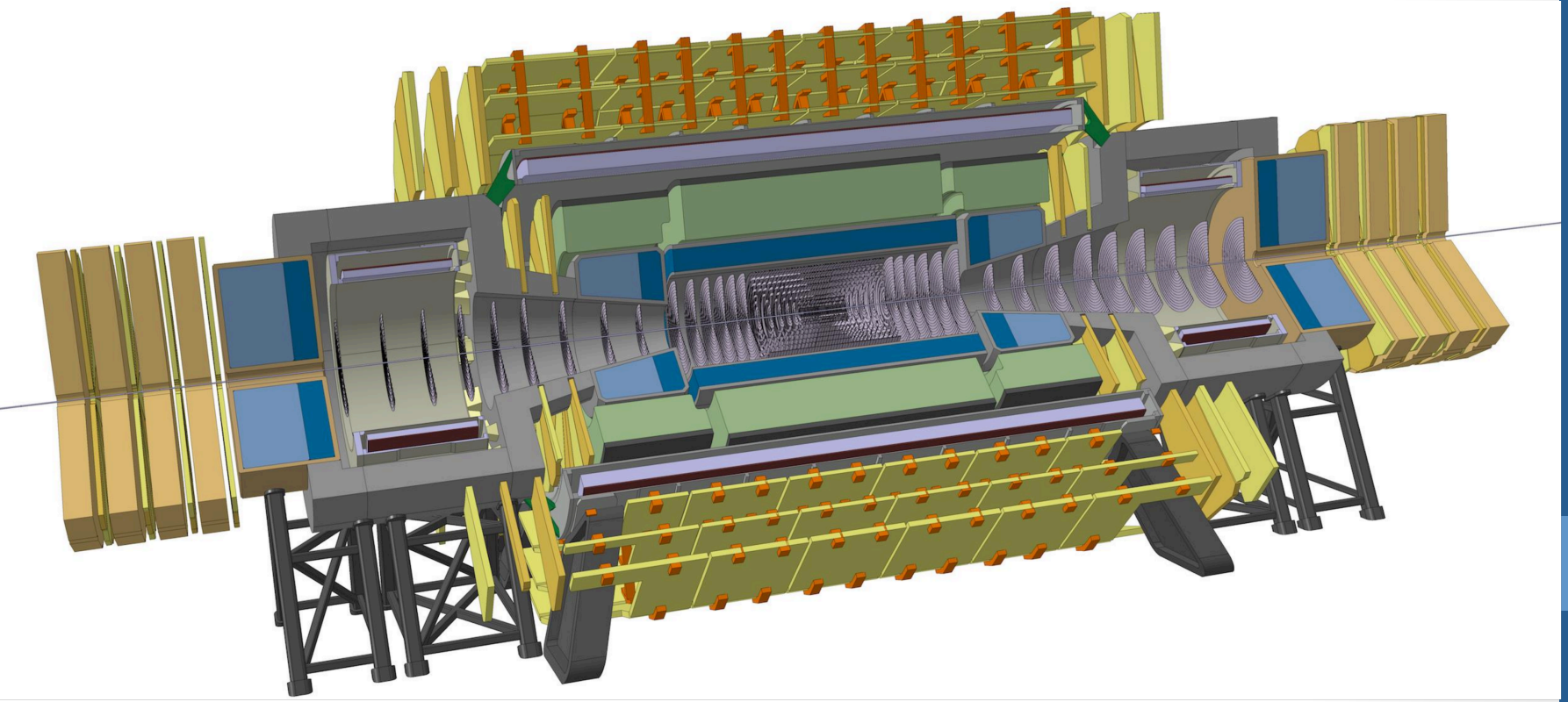
@100TeV FCC-hh

- The radiation level increase mostly driven by the jump in instantaneous luminosity
  - pp cross-section from 14 to 100TeV only grows by a factor 2
  - 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors

- More forward physics -> larger acceptance
  - Precision momentum spectroscopy and energy measurements up to $|\eta|<4$
  - Tracking and calorimetry up to $|\eta|<6$ (at 10cm of beam line at 18m of IP)

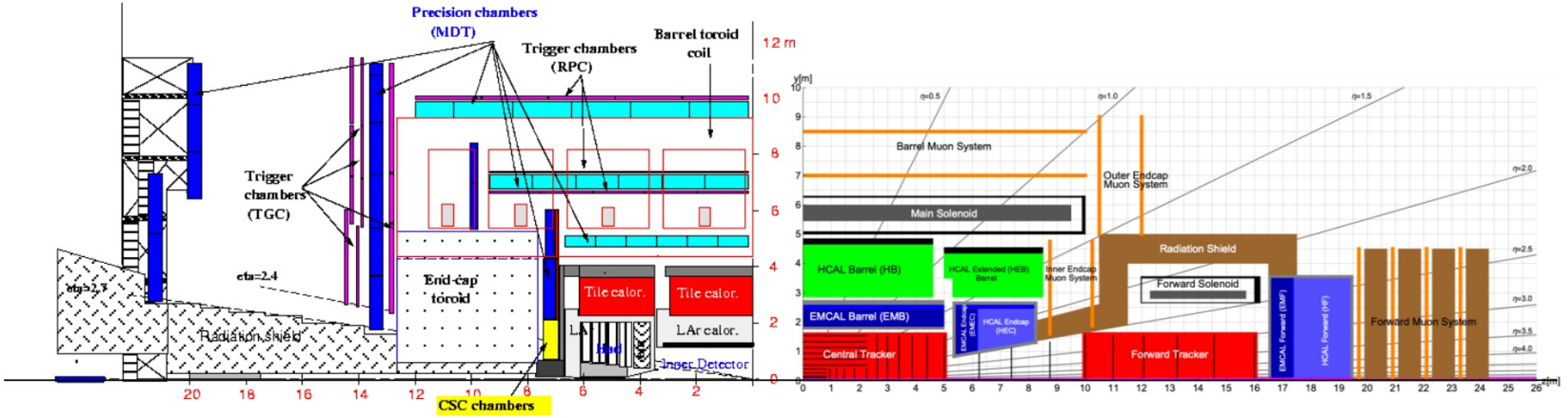
- More energetic particles
  - colored hadronic resonances up to 40TeV -> Full containment of jets up to 20TeV
  - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure

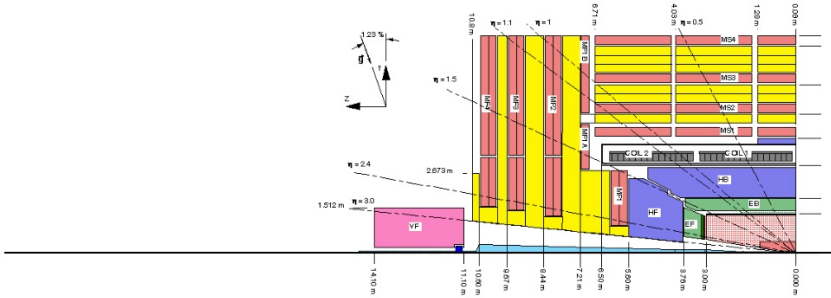
FCC-hh detector

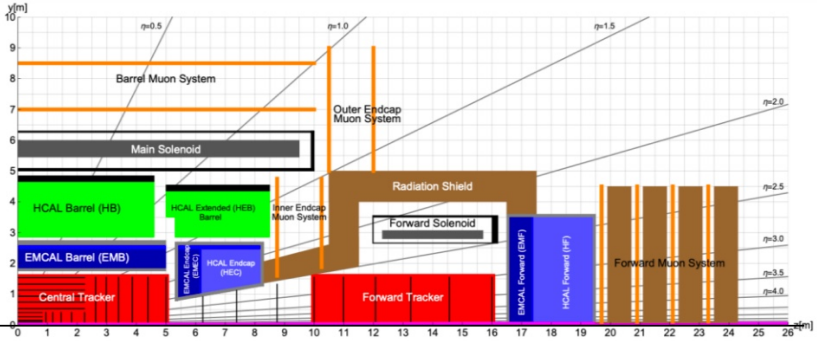


FCC-hh detector

Comparison to ATLAS & CMS

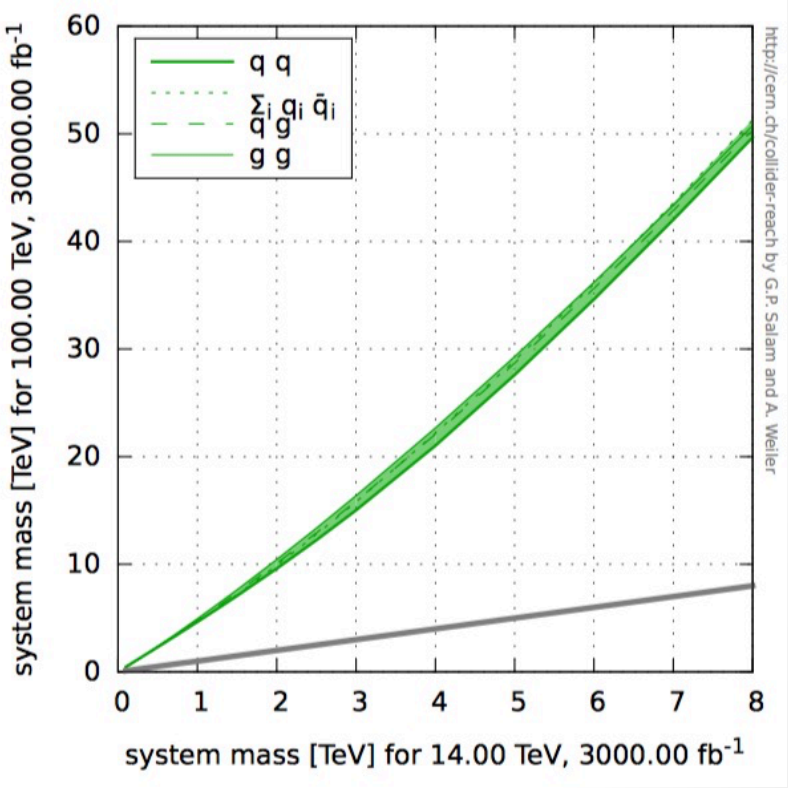






Direct discovery reach at 100TeV

- To first approximation
  - The discovery reach at the highest masses is driven by the energy increase wrt to LHC
  - For √s=100TeV we expect the reach to be extended by factors 5-7 wrt LHC for the same BSM parameters



Outline

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

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

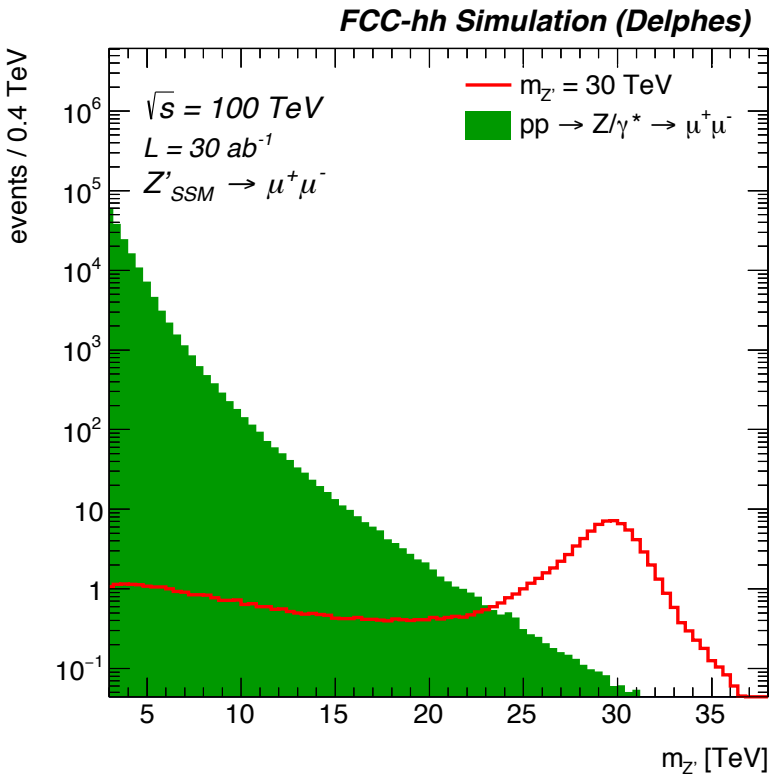
$Z' \to \mu^+\mu^-/e^+e^-$

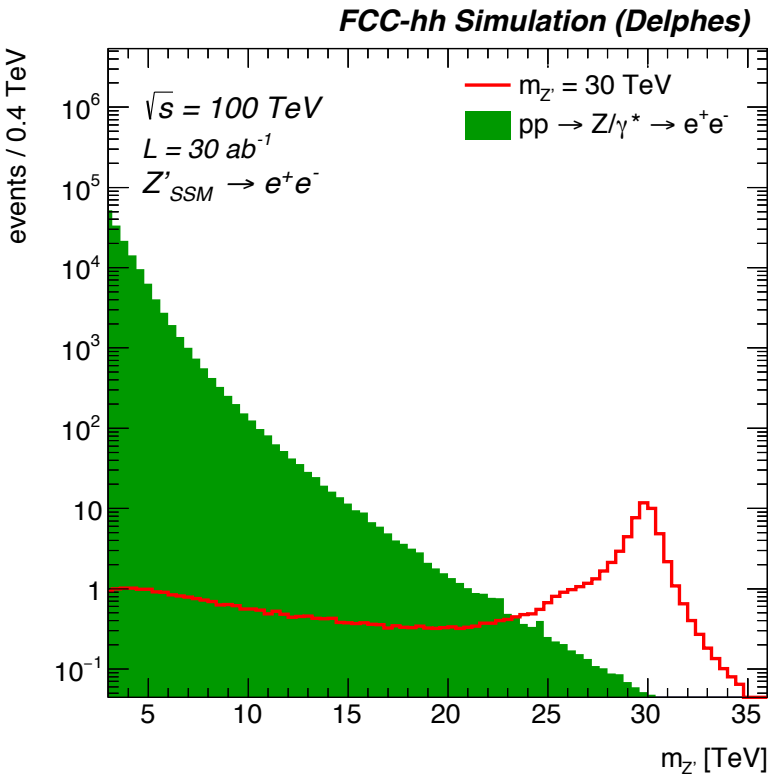
- Z' model
  - Simple benchmarks used to check detector performance
  - Helped to tune the muon resolution initially of 10%@10TeV given the reach of such heavy objects

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

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

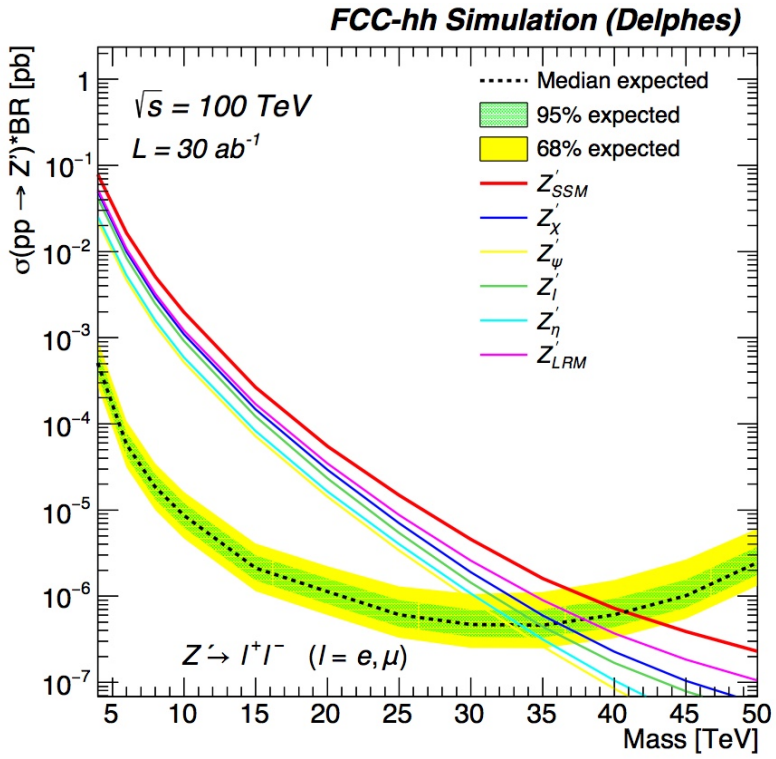
Z'->$\mu^+\mu^-/e^+e^-$ (30TeV)

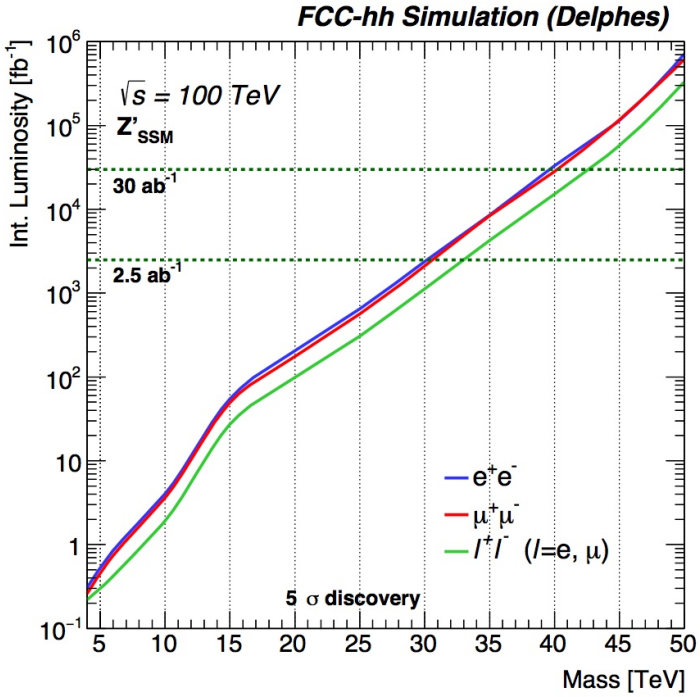




As expected better mass resolution for electrons

Limits and discovery





Reach up to 40TeV this very simple case!

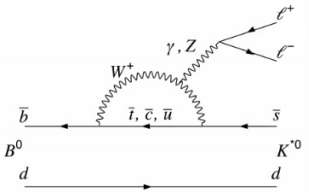
Considering 2.2fb^{-1} per day for baseline

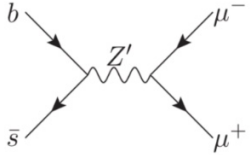
5σ discovery for:

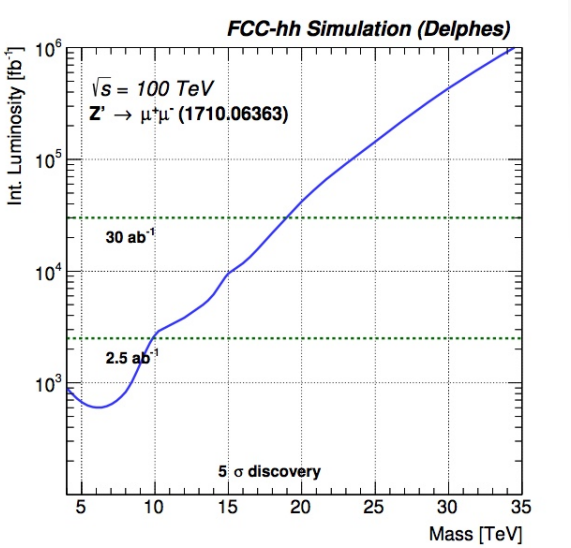
- 20TeV after ~50 days (first year?)
- 33TeV after 10 years @ baseline
- 42TeV after full operation 25 years

Z' flavour anomaly

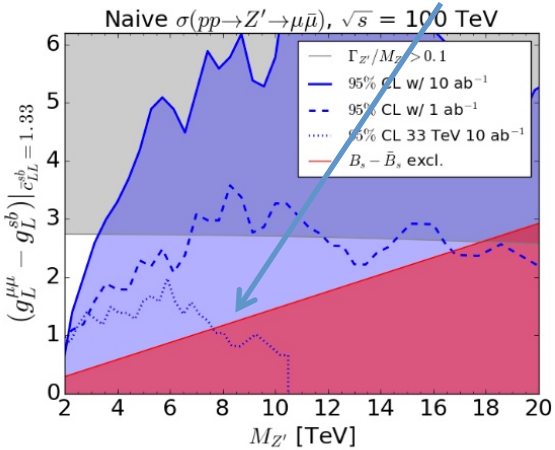
Quick interpretation of Z'->μμ

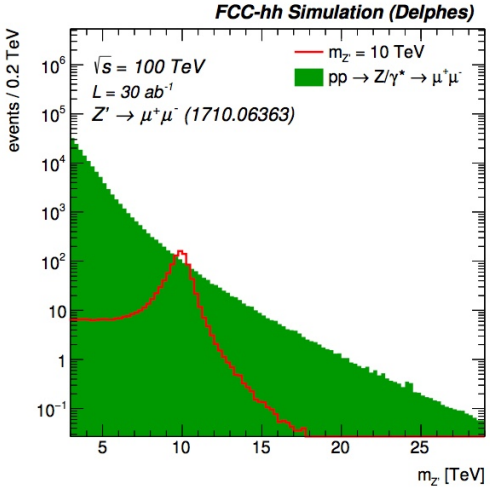


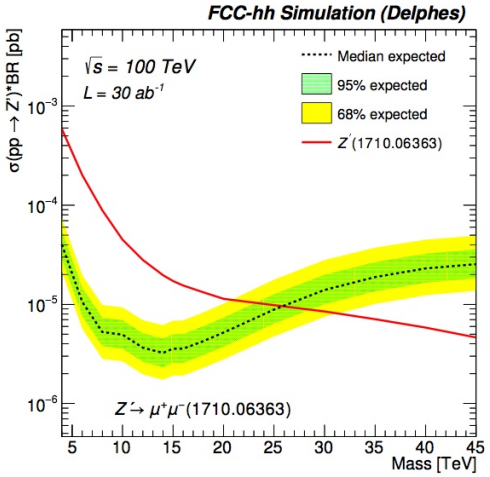




Arxiv:1710.06363 We test this line





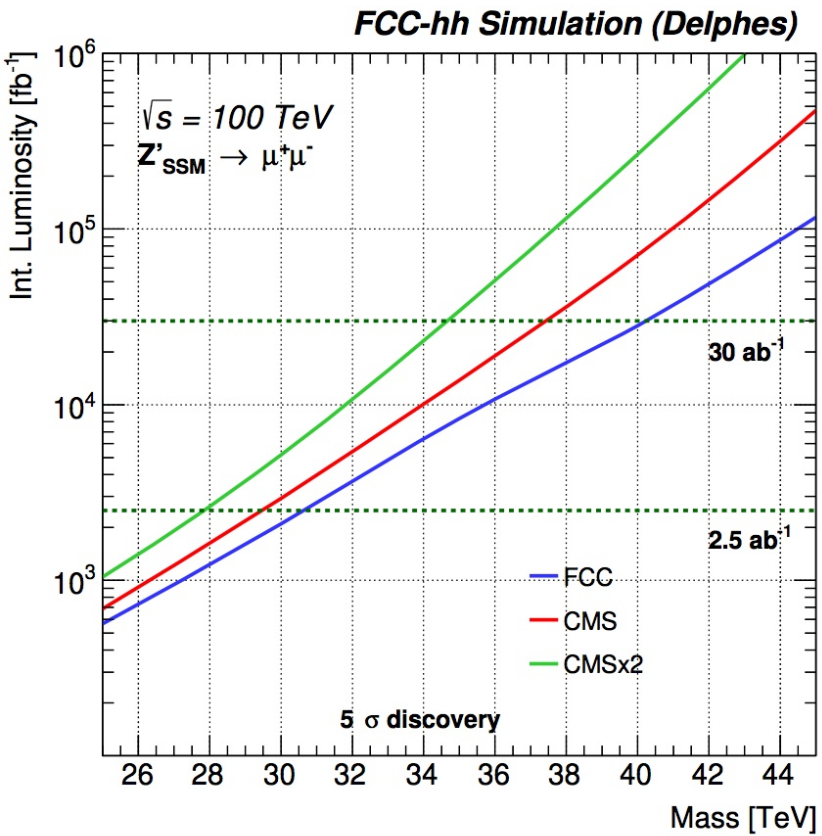


Discovery μμ degraded

Best sensitivity achieved with an assumed $\sigma_p/p \approx 5\%$ 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.

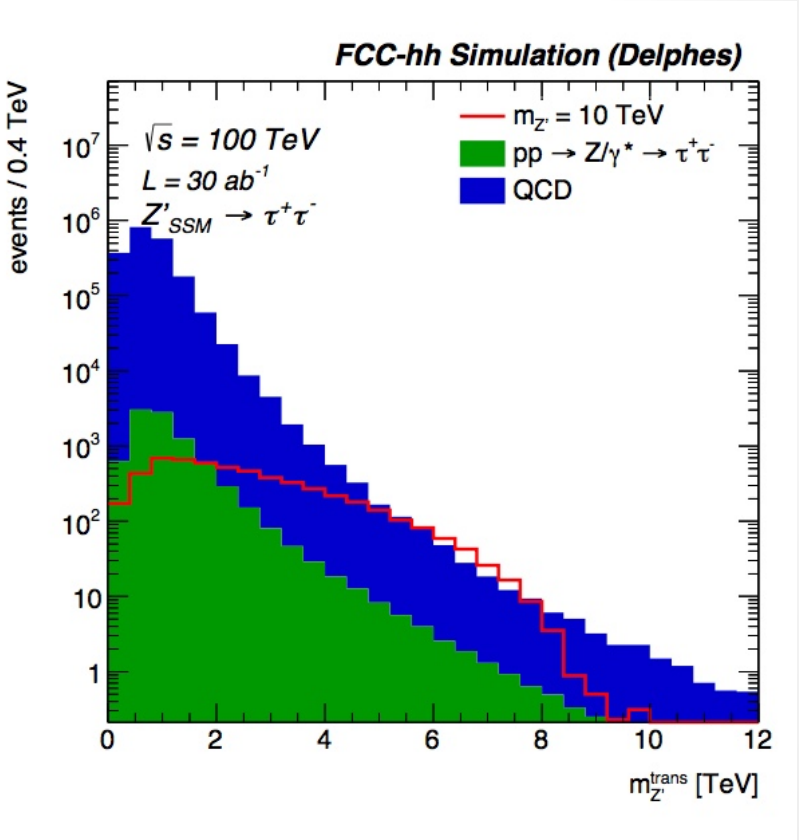


Z'->ττ

- Analysis selection (hadronic taus only as most sensitive)
  - $p_T(j1/2) > 1$TeV, $|\eta(j1/2)| < 2.5$
  - 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

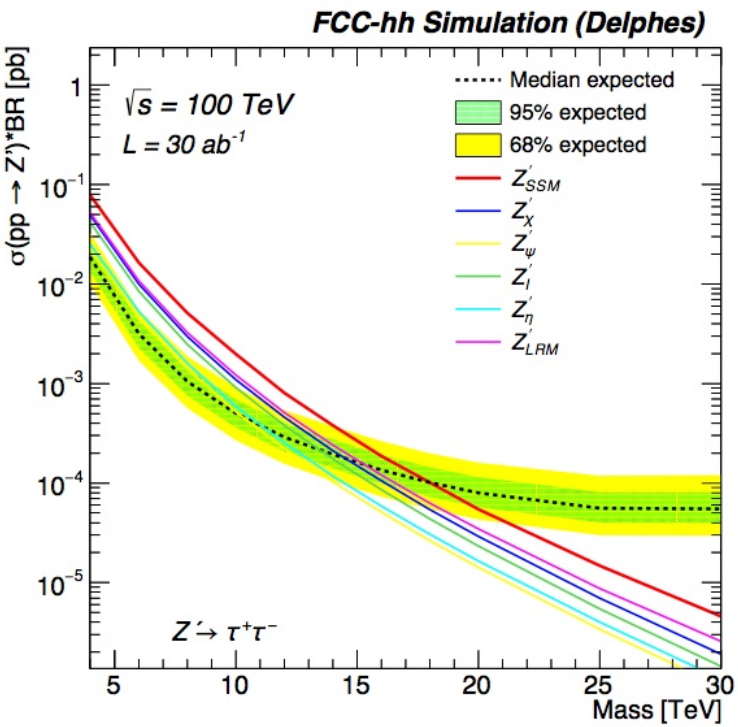


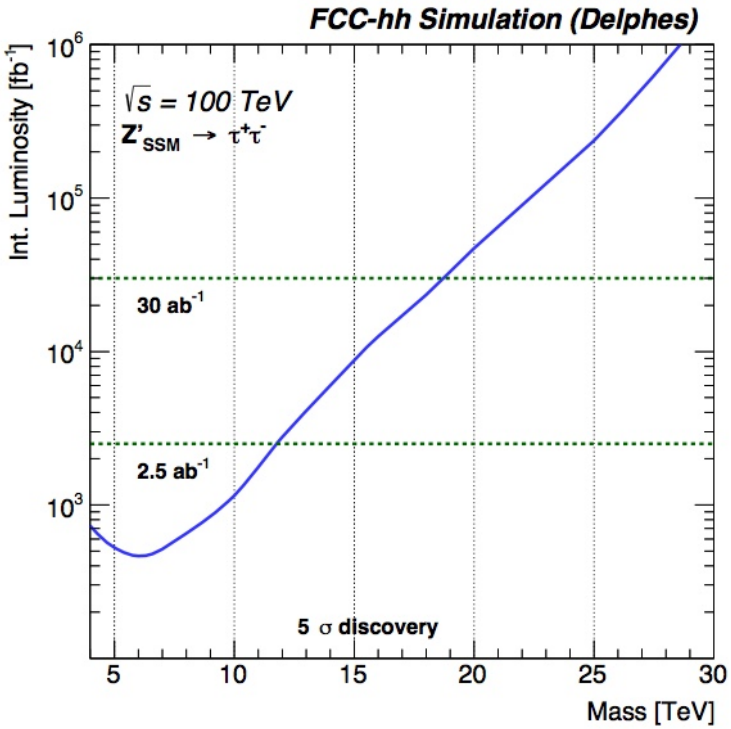
Limit/significance

5σ discovery for:

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

Challenges: better tau tagging at high p_T

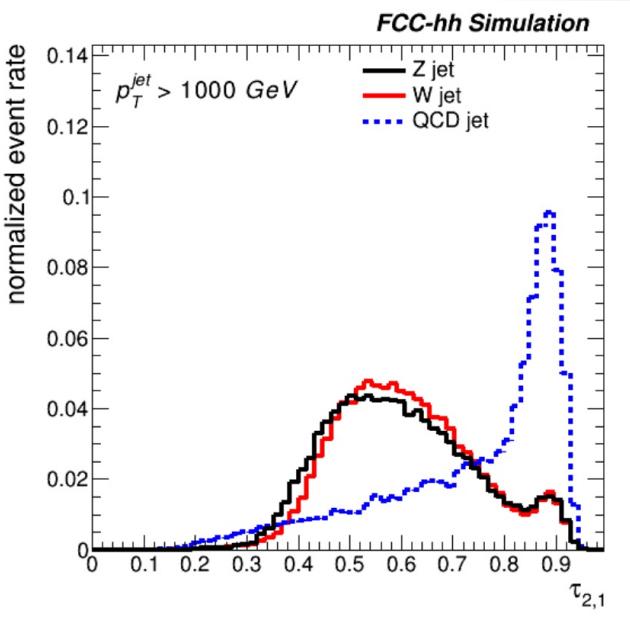




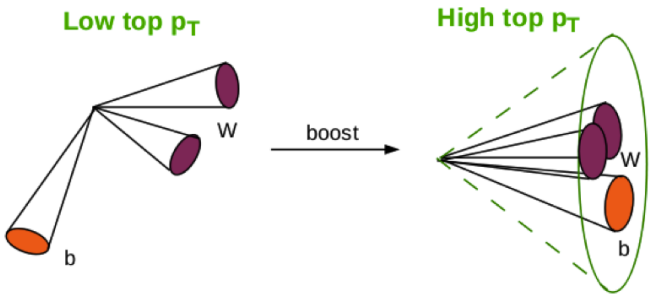
Z’->tt

Z'->ttbar

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



$\Delta R \cong 2m/p_T$



Top-quark

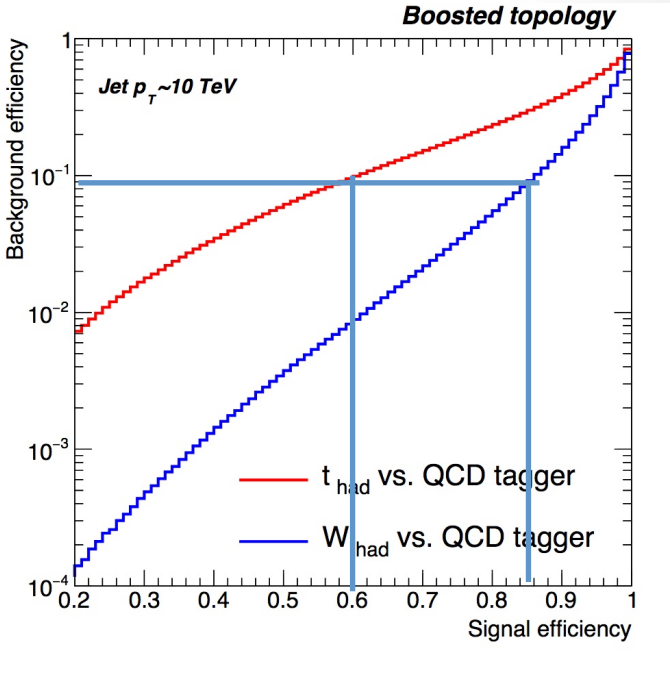
LHC: $p_T \sim 1$TeV $\rightarrow \Delta R = 0.5$

FCC: $p_T \sim 10$ TeV $\rightarrow \Delta R = 0.05$

Multivariate discriminant

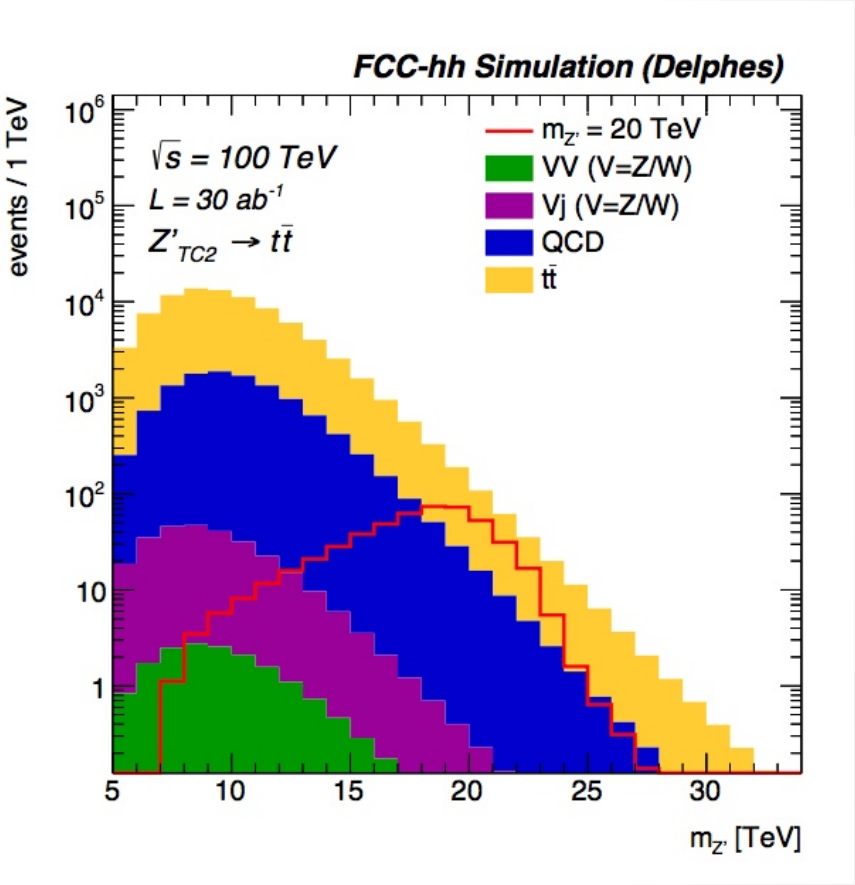
- Developed MVA discriminant to disentangle overwhelming QCD jets from boosted W/tops

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
  - Important benchmark model for detector performance
    on sub-structure
- Analysis 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:

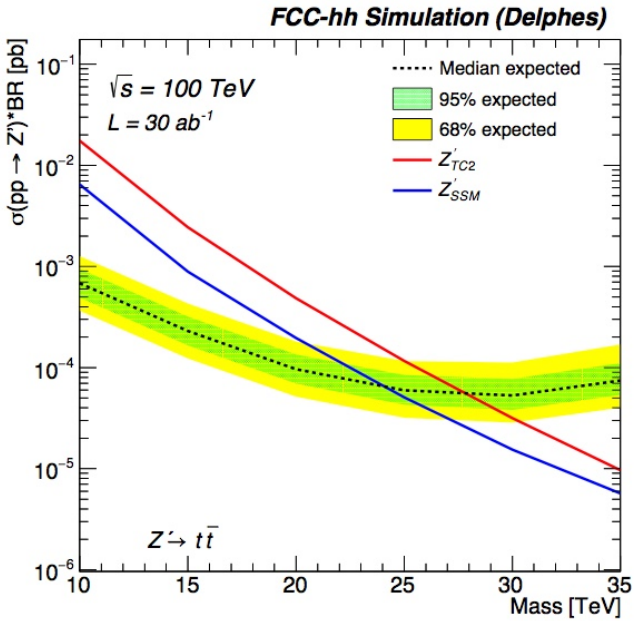
- 17TeV after 10 years @ baseline
- 23TeV after full operation (25y)

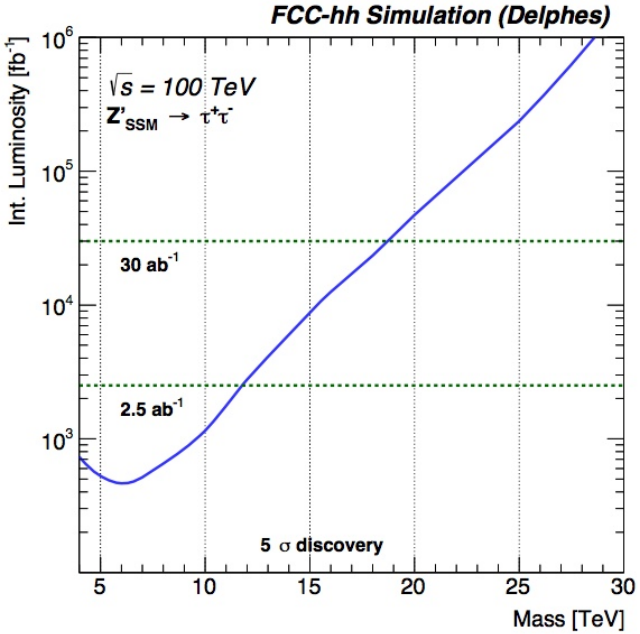
5σ discovery for SSM:

- 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





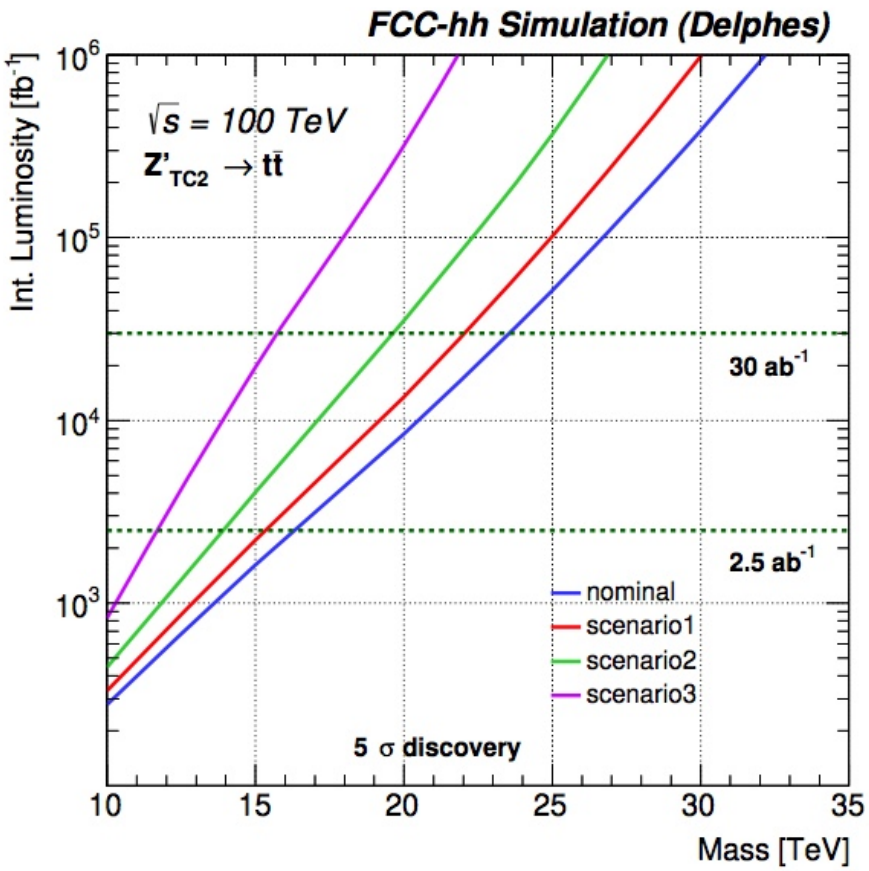
Discovery tt degraded

High efficiencies (ε_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.

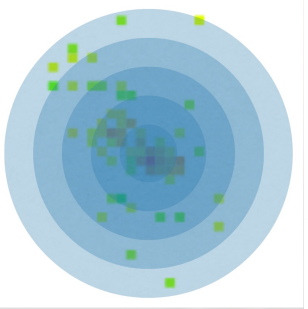


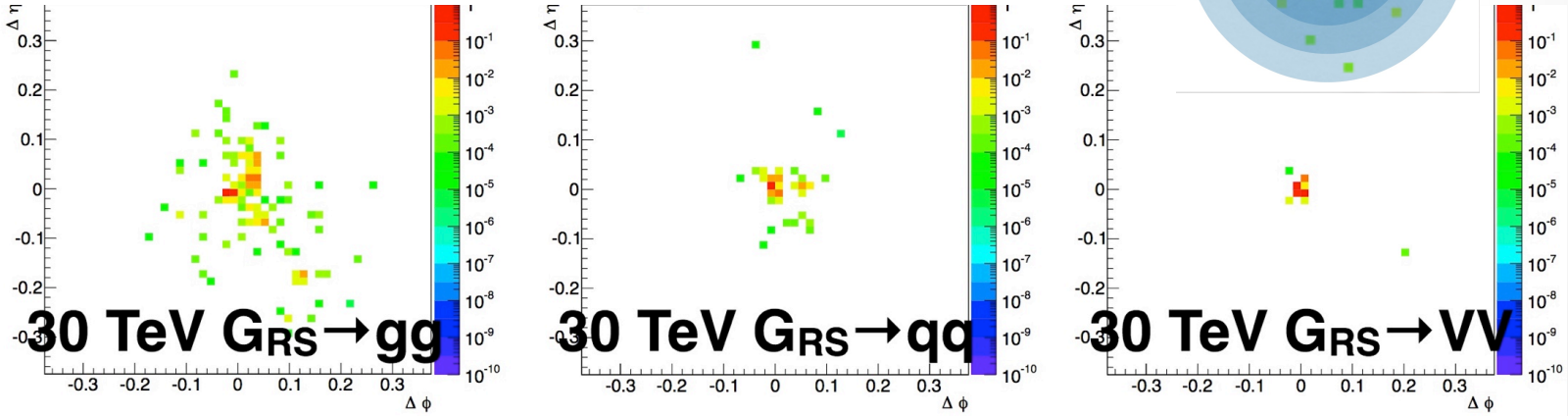
RSG->WW
W->jj

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

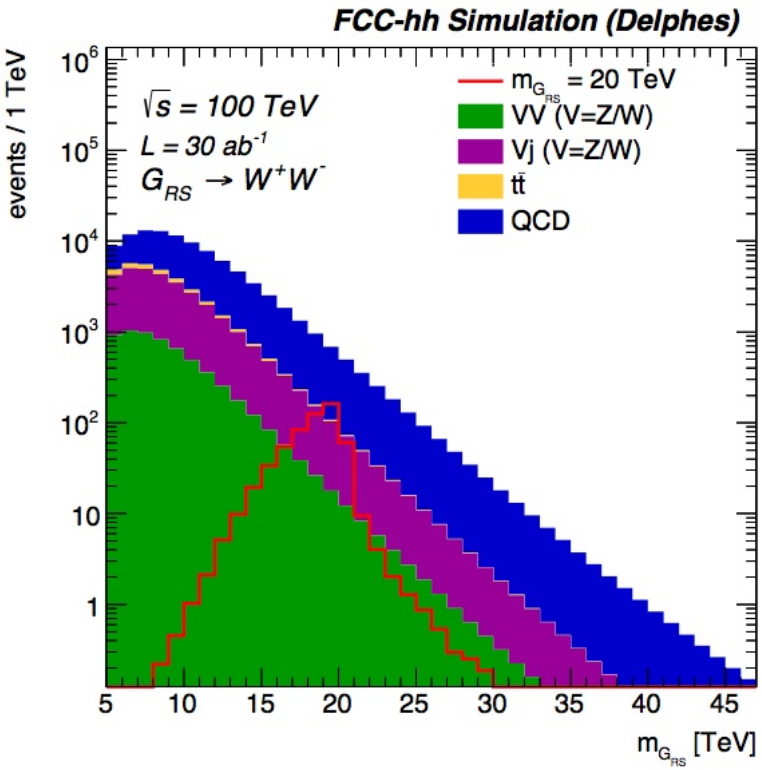
$$\frac{n-1}{5}R \leq \Delta R(k, \text{jet}) < \frac{n}{5}R, \quad \text{Flow}_{n,5} = \sum_k \frac{|p_T^k|}{|p_T^{\text{jet}}|}$$





Di-boson resonance (only hadronic)

- Randall-Sundrum Graviton
  - Important benchmark model for detector performance on sub-structure
- Analysis 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%

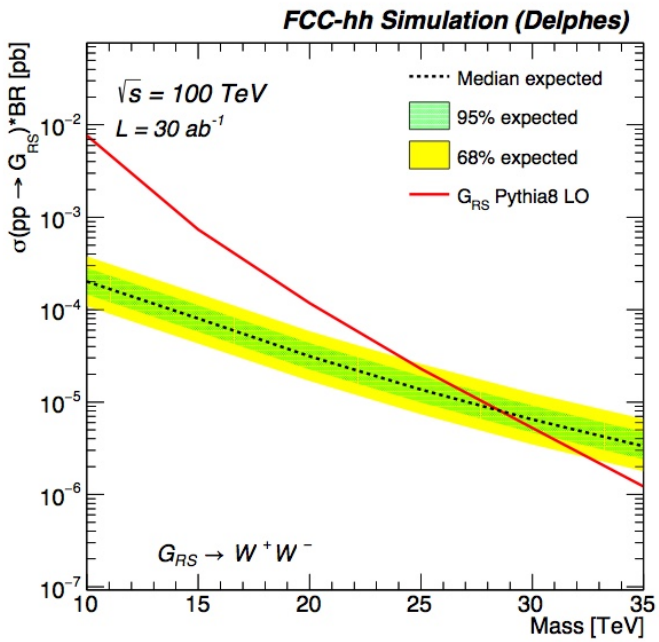


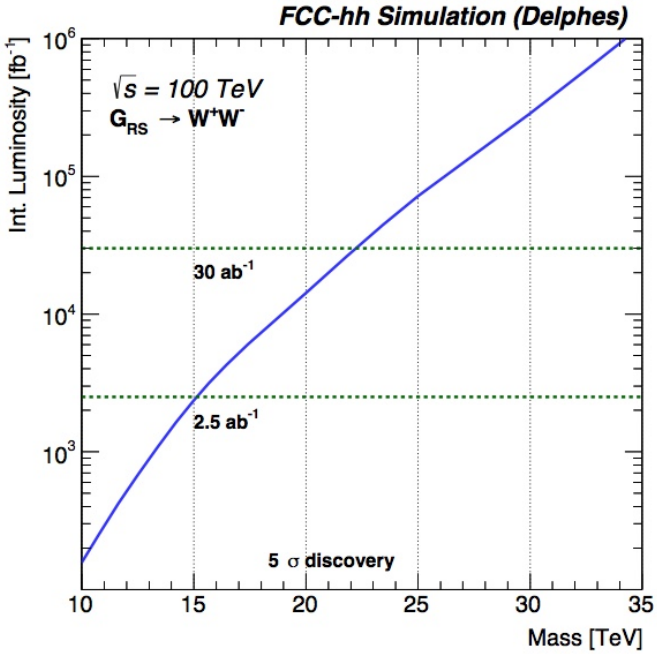
RSG->WW

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

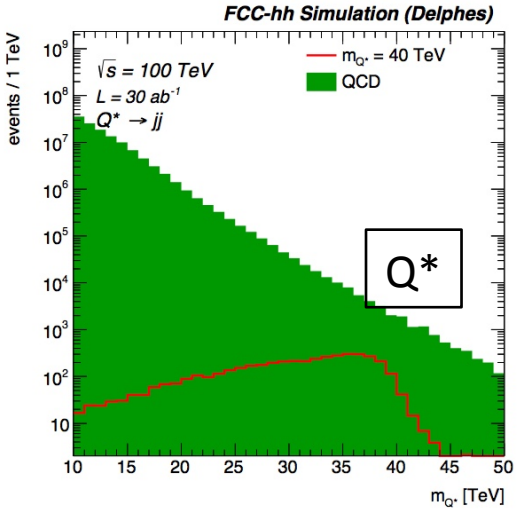


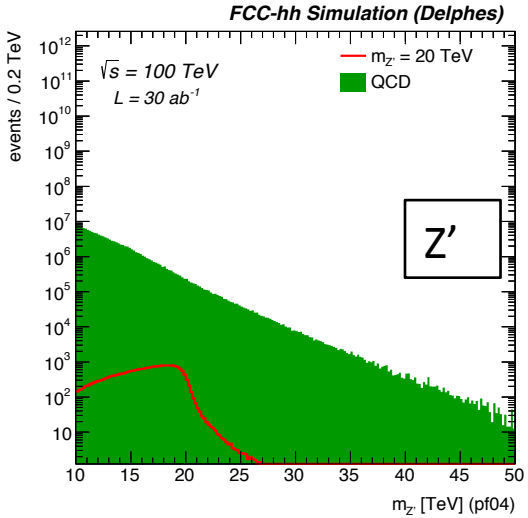


Q*->jj

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 $p_T(j2)>3$TeV
  - $Y^*=|yjet1-yjet2|/2 < 1.5$
- Uncertainties
  - 50% uncertainty on the Di-jet normalization

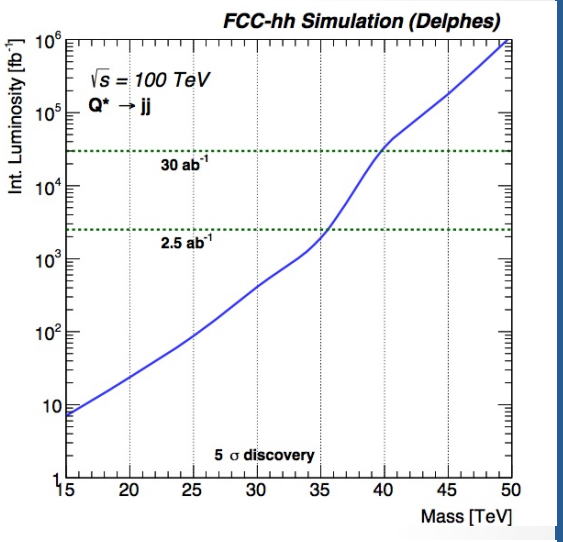




5σ discovery for Q* (wide and strongly coupled):

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

Q*

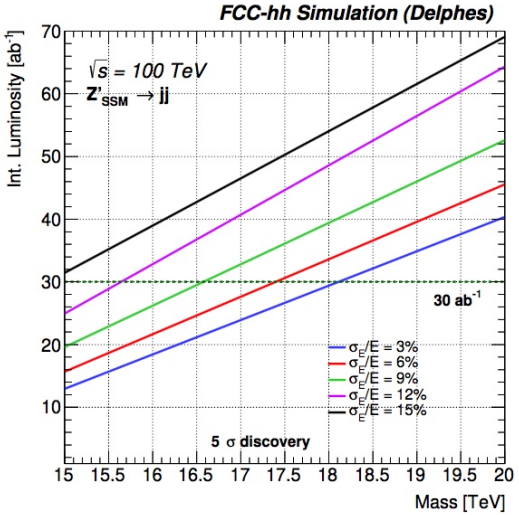


5σ discovery for Z' (narrow and weakly coupled):

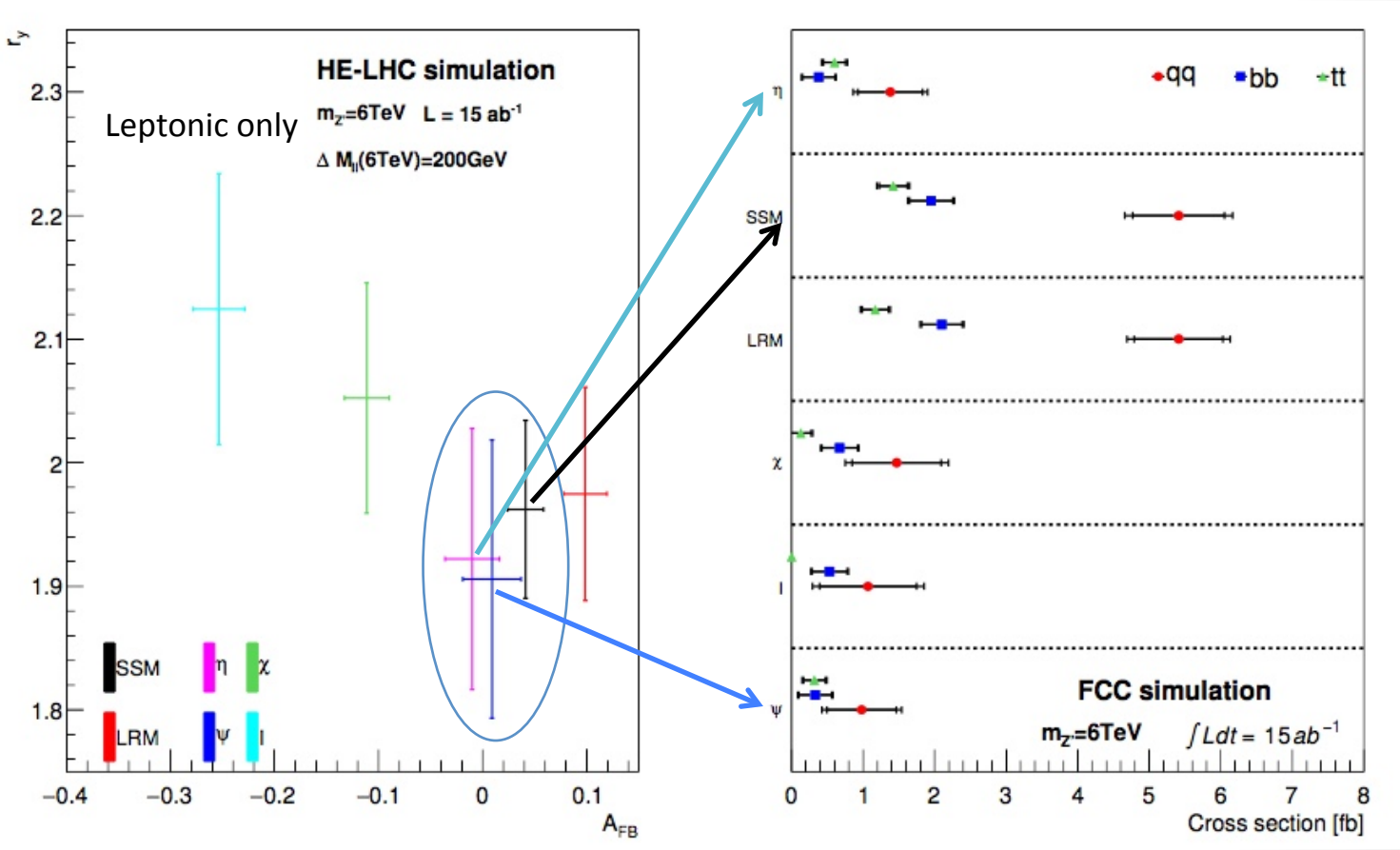
- <15TeV after 10 years @ baseline
- 19TeV after full operation 25 years

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

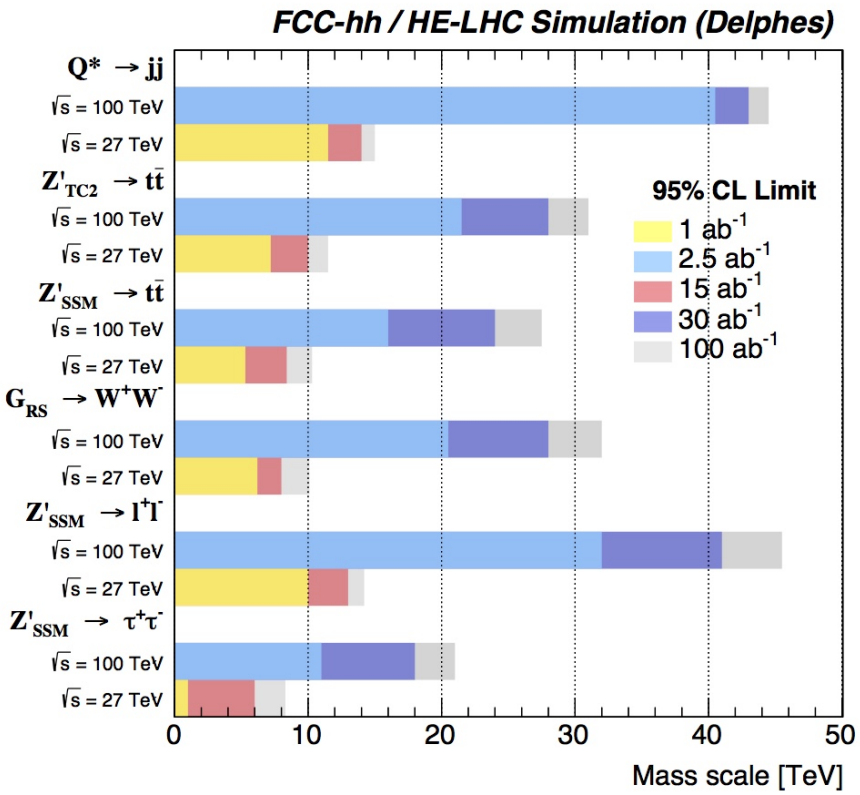
Z'

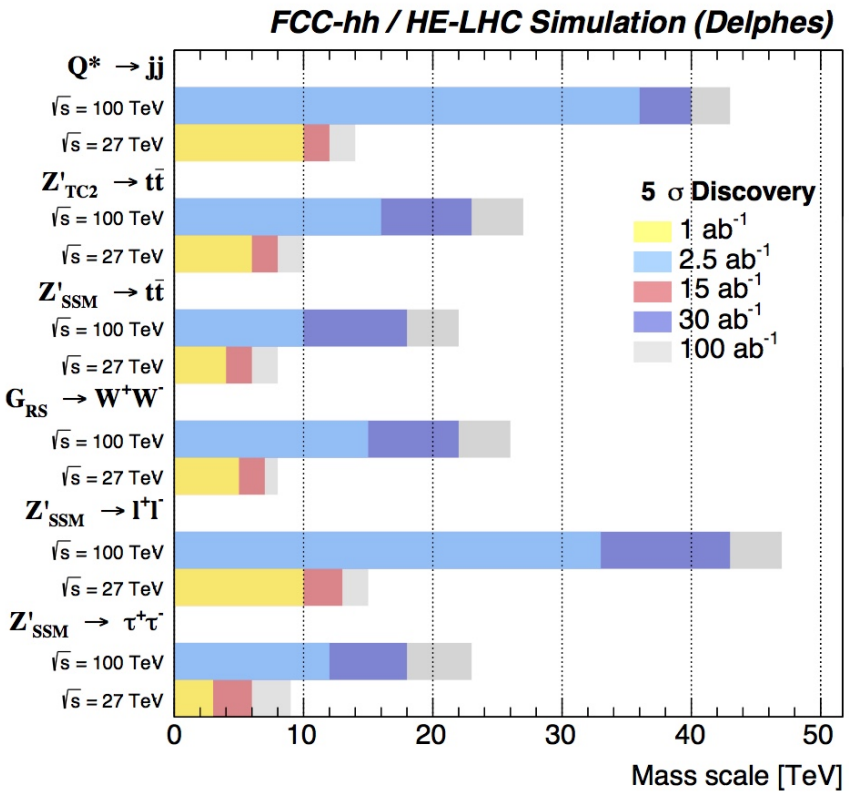


Discrimination of Z' models within LHC reach



Summary


FCC-hh / HE-LHC Simulation (Delphes)
Q* → jj
√s = 100 TeV
√s = 27 TeV
Z'TC2 → tt̄
Z'SSM → tt̄
GRS → W+W-
Z'SSM → l+l-
Z'SSM → τ+τ-
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]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Z'SSM → l+l-
Z'SSM → τ+τ-
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]

Bonus

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

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

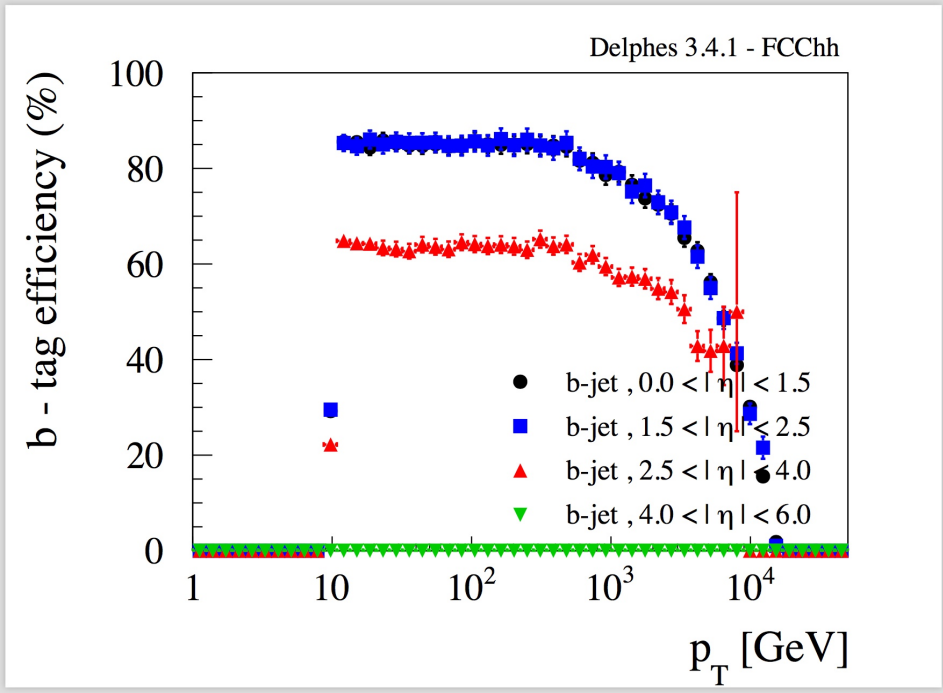
Sample	Cut (TeV)	Statistic (10^6)
Di-electron	$p_T(e)>5$	10
Di-muon	$p_T(\mu)>5$	10
Di-tau	$p_T(\tau)>2.5$	10
Di-tau	$2.5>p_T(\tau)>1$	5
Di-jet	$p_T(j)>2.5$	50
Di-jet	$2.5>p_T(j)>1$	30
Di-boson	$p_T(V)>2.5$	15
V+jets	$m_{vj}>5$	10
Top pair	$p_T(t)>2.5$	10

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

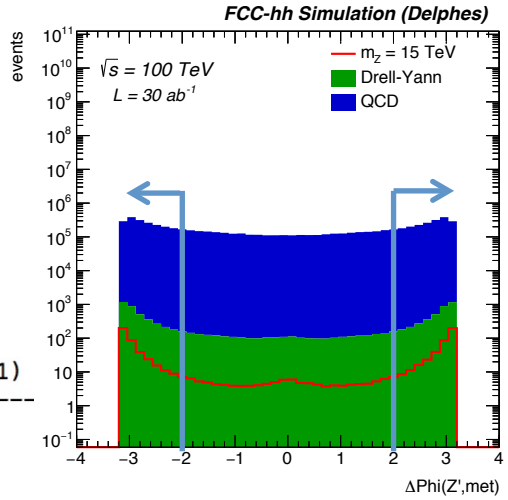
- High p_T b-tagging
  - Very displaced vertices
  - After the 1st 2nd or even 3rd layer of the pixel detector
  - Used for this top pair resonance search
- Estimate
  - Need a first realistic estimate of how b-tagging will perform
  - Using results from full simulation study without tracks (hit multiplicity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

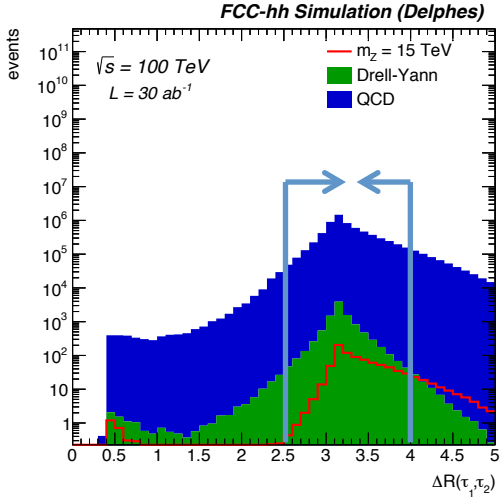


Z'->ττ

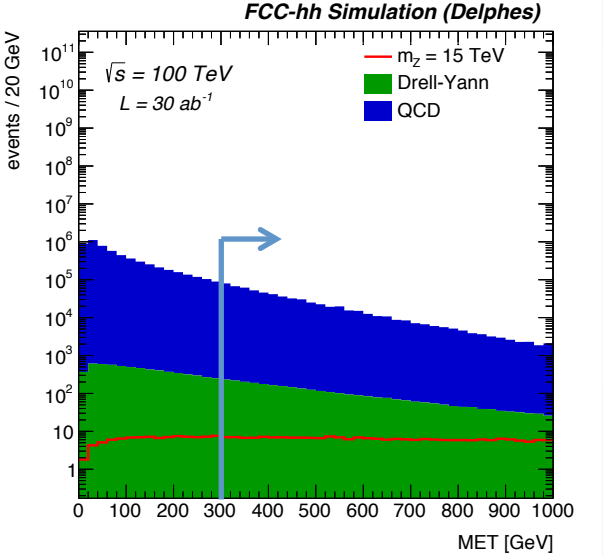
$p_T(j1/2) > 1TeV$, $|\eta(j1/2)| < 2.5$

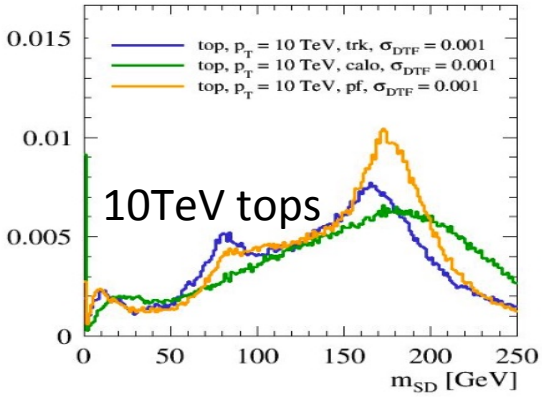
process	yield (30.0 ab-1)
m_{Z} = 15 TeV	888.9
Drell-Yann	10237.8
QCD	7116045.3

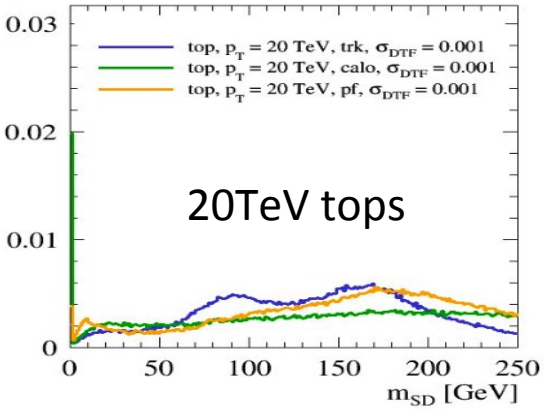


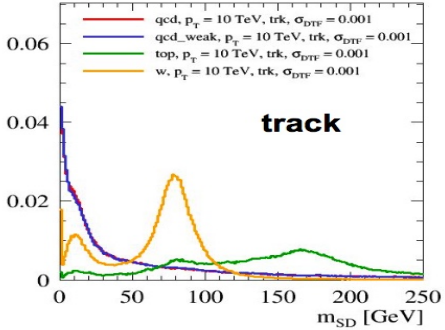


process	yield (30.0 ab-1)
m_{Z} = 15 TeV	781.0
Drell-Yann	10083.6
QCD	6426072.2

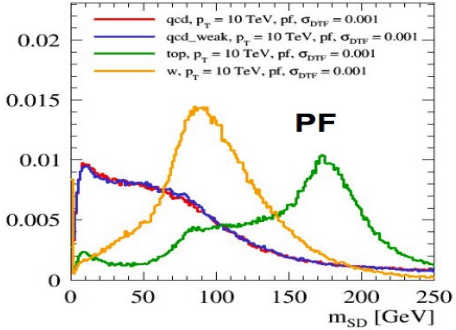








10TeV objects



- 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

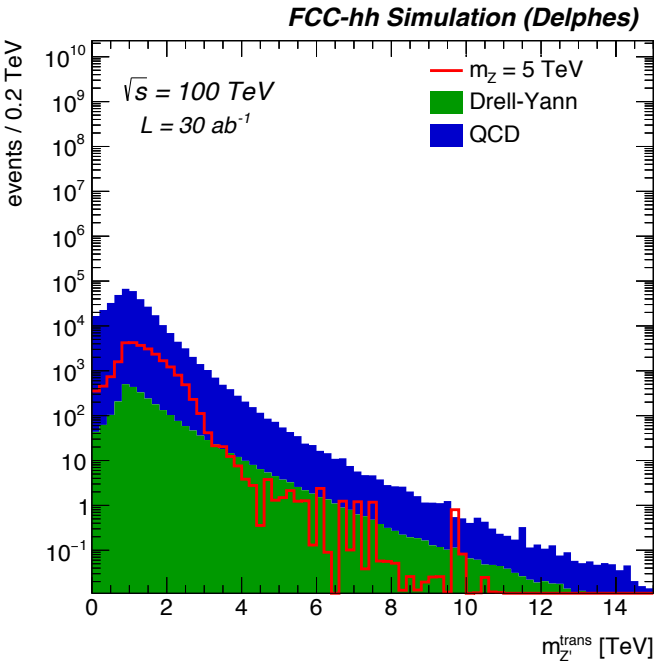
Z'->ττ

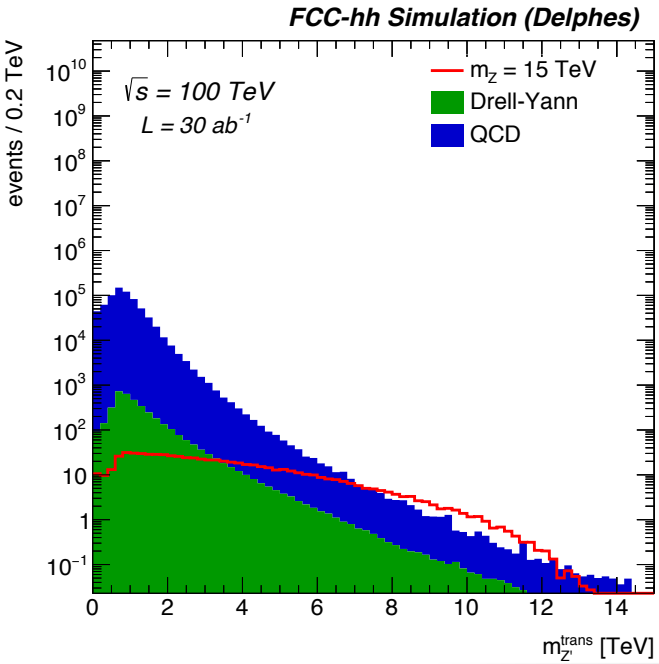
Z' = τ1+τ2 (4 vectors)

$m_T = \mathrm{sqrt}(2*p_T(Z')*MET*(1 - \cos(\Delta\phi(\phi_{Z'} - \phi_{MET}))))$

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

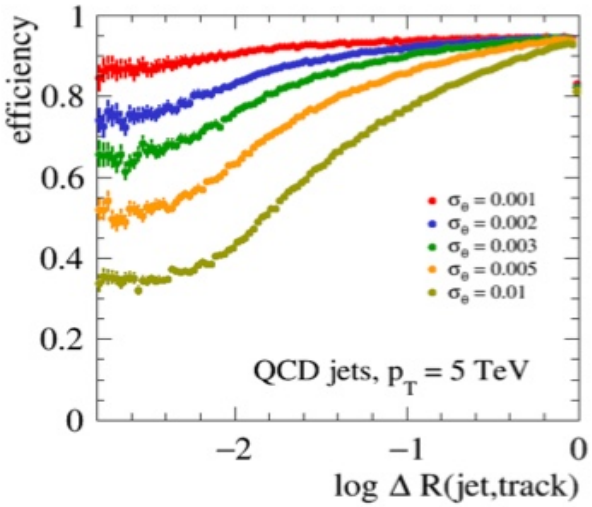
process	yield (30.0 ab-1)
m_{Z} = 15 TeV	686.2
Drell-Yann	3769.5
QCD	695272.8

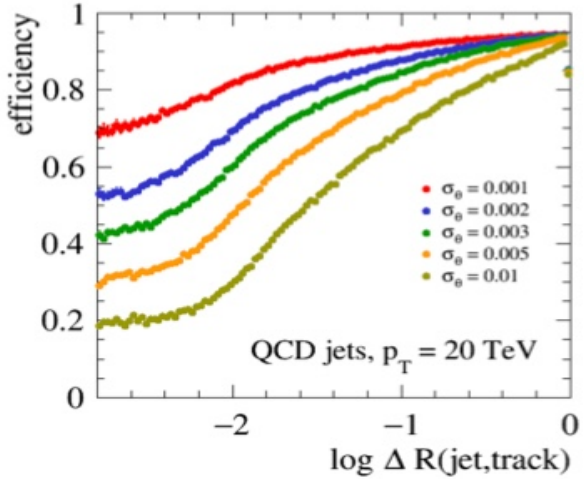




Tracking in dense env.

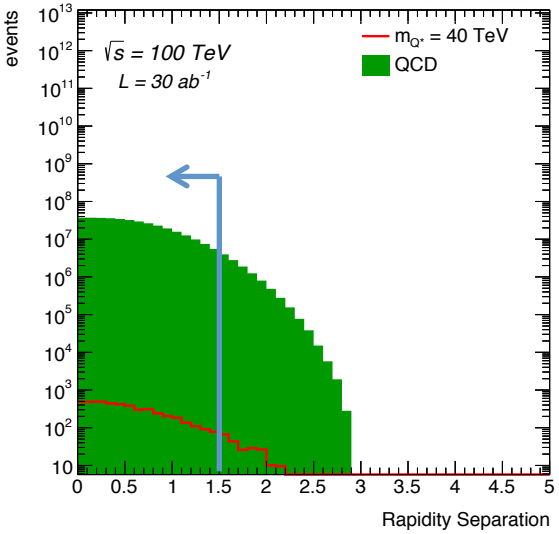
- Tracker granularity
  - Defined in (η x ϕ)
  - Worst case scenario
    - pitch size in the first pixel layer:
      reso = (2-3)*10um/(0.025) ~ 0.001
- Inefficiency
  - when two or more tracks hit same pixel
  - keep only highest p_T track
  - Arbitrary and probably conservative, considering that this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

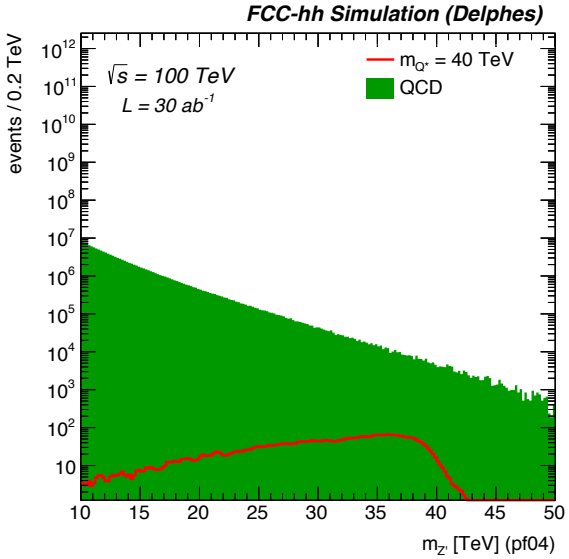


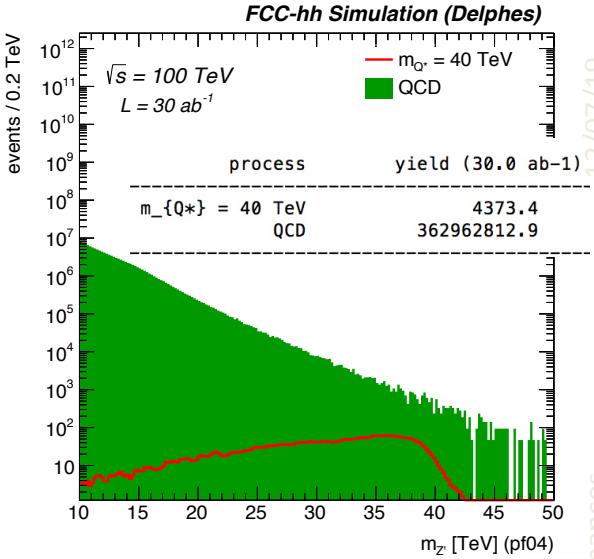


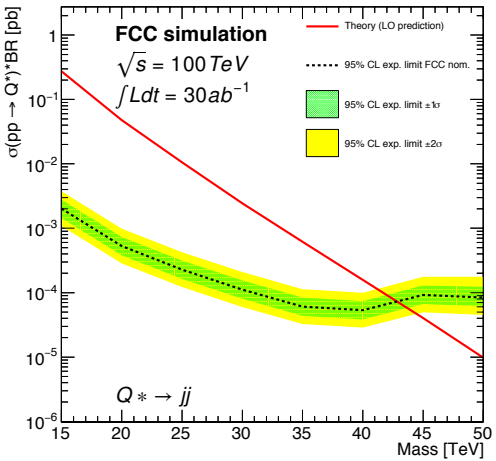
Q*->jj

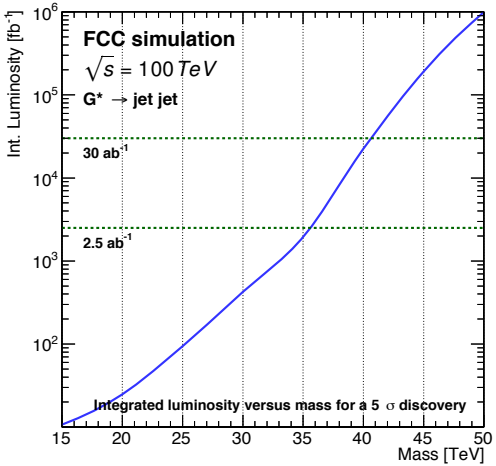
process	yield (30.0 ab-1)
m_{Q*} = 40 TeV	4588.9
QCD	374687859.9









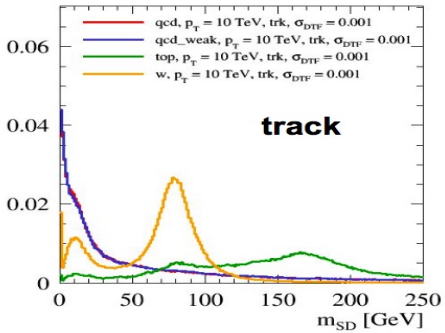


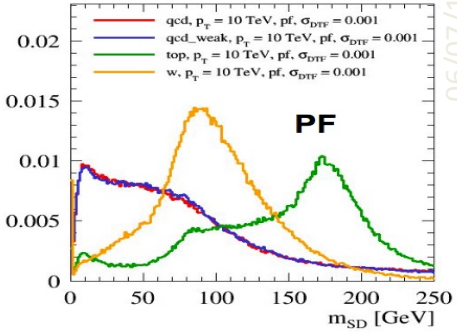
5σ discovery for Q*:

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

Boosted objects

10TeV objects

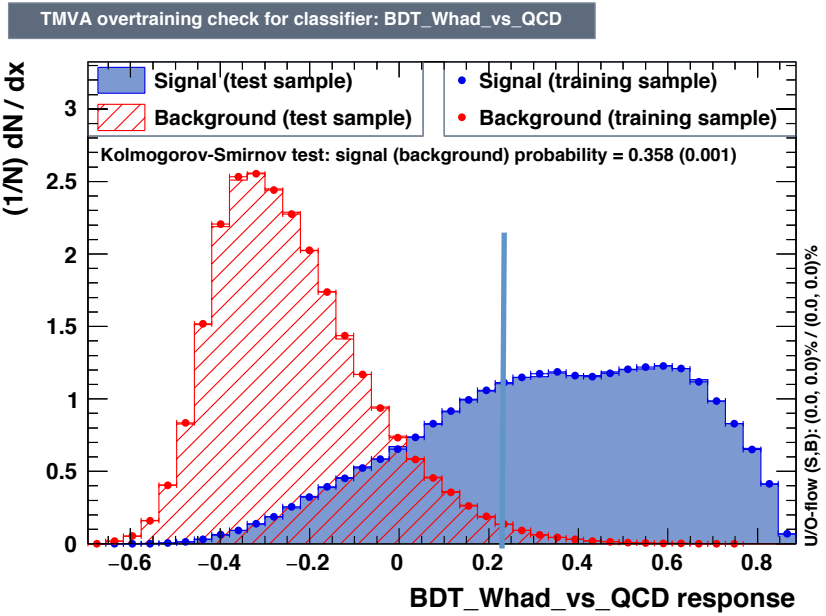


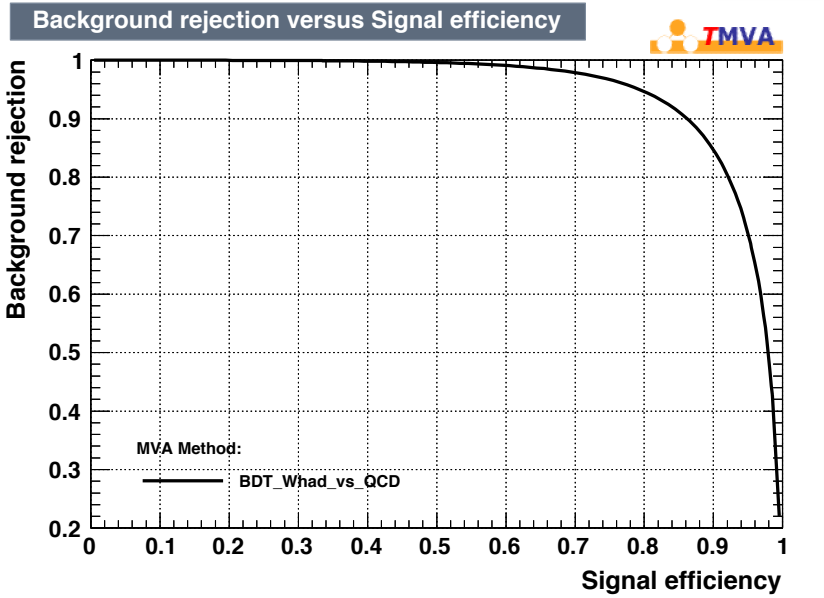


- What is:
  - Optimal jet collection
  - Minimal track angular resolution?
- Assessed using :
  - QCD, QCD+weak shower, W and Top jets
  - GenJets, CaloJets, Particle Flow Jets, Track Jets with 2-5-10-20 TeV
- Outcome:
  - Use track jets for sub-structure corrected to pf jets
  - More information in 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

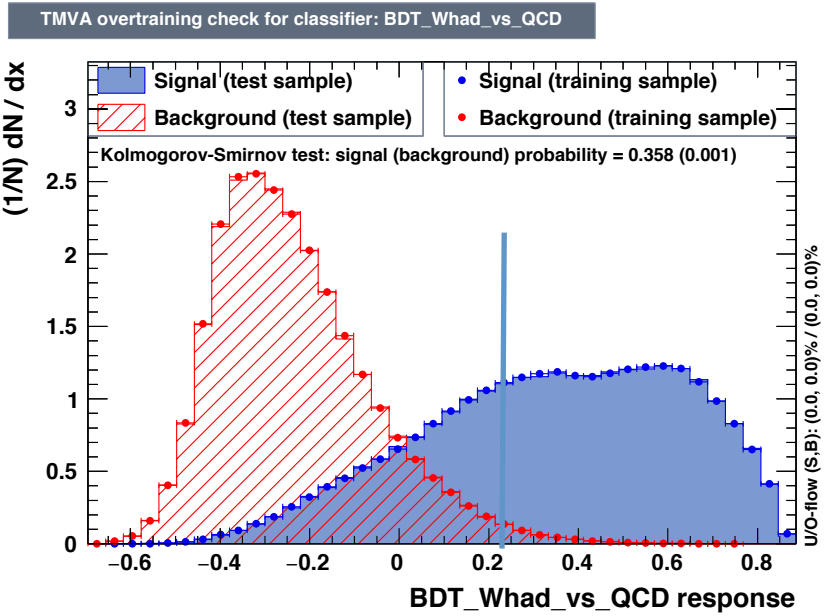
Variables used
Flow 1,2,3,4,5/5
Soft dropped mass
τ32, τ21, τ1/2/3





W versus QCD jet tagger

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



Top vs QCD
W versus QCD