Top-quark physics at FCCee

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Introduction

- The top-quark physics program at lepton colliders (here FCCee) is vast :
  - $t\bar{t}$ threshold (mass, width, yukawa, α_s) and anomalous couplings, (single-) top quark FCNC etc…

- Top-quark physics at FCCee, Snowmass opportunities :
  - Implement mature analyses, improve analysis techniques, expand the list of possible measurements, innovate,
  - Particular effort on the impact of beam related effects and detector optimisation,
  - Room for collaborations !

- Outline:
  - $t\bar{t}$ runs at FCCee,
  - Calculations and MC generator studies (whizard and aMC@NLO),
  - $t\bar{t}$ cross section and top-quark mass measurement from $\sqrt{s}$ scan,
  - Search for new physics : probing $t\bar{t}$ couplings and top-quark FCNC,
  - Plans for coming $t\bar{t}$ studies.

Snowmass LoI

Snowmass2021 - Letter of Interest

Top quark physics at FCC-ee

Thematic Areas:

- ■ (EF03) EW Physics: Heavy flavor and top quark physics
- ■ (EF04) EW Physics: EW Precision Physics and constraining new physics

Link to the LoI

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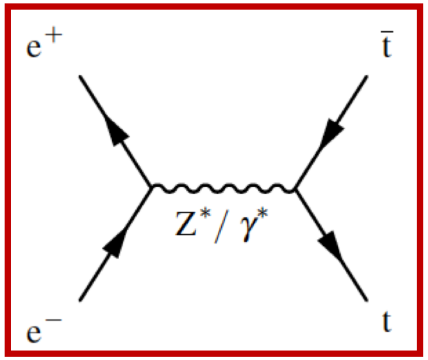
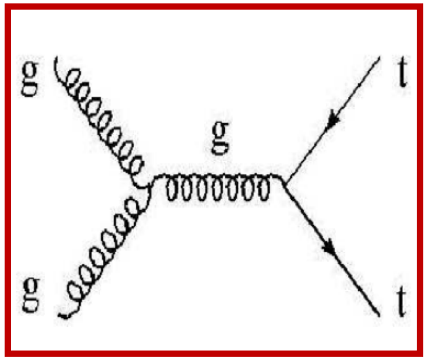
$t\bar{t}$ events properties : reminder

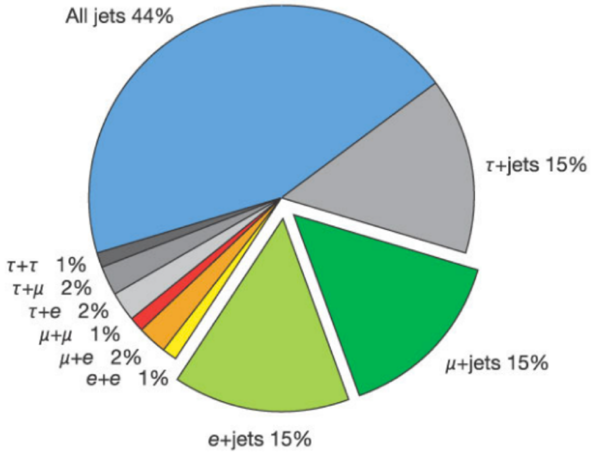
- Heaviest particle known so far, discovered at the Tevatron.
- Decays before hadronises => top quark can be reconstructed precisely from decay products.
- Decays almost entirely into a W boson and a b-quark (although it is interesting to measure a ratio to $|V_{tb}| + |V_{td}| + |V_{ts}|$).

LO e^+e^-



LO pp





- At the LHC :
  - Dileptonic channels are very precise => low backgrounds contamination and large lumi compensate the lower Br,
  - Full hadronic challenging because of the large QCD- multijet background,
  - Semi-leptonic channel shows a good compromise.

- At lepton colliders, the situation is different. Small backgrounds for all channels, mainly from WW,
  - Easier to exploit all events,
  - Precise knowledge of initial states = more precise events reconstruction.

$t\bar{t}$ decays contained all objects ! Very relevant for determining detector requirements.

$t\bar{t}$ runs at FCCee

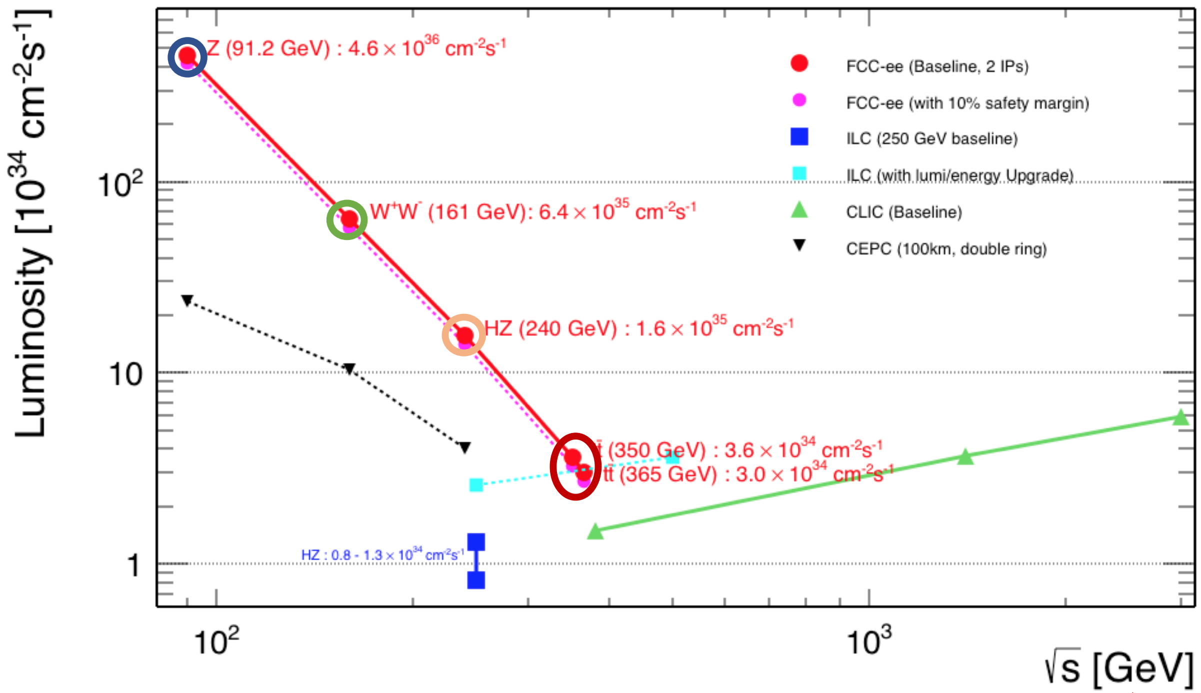
- FCCee schedule : runs at different collision energies.

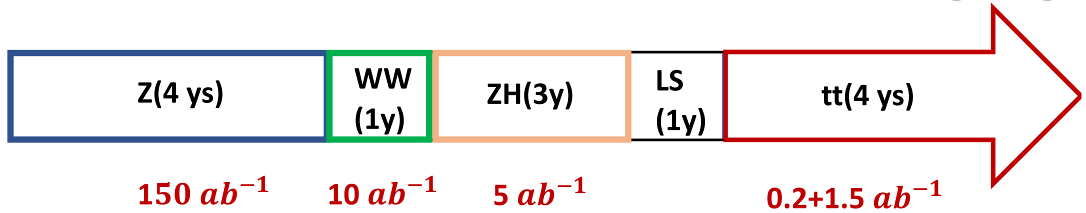
- Top quark physics program in two steps :
  - Scan energies from ~340 to ~350 GeV, 0.2 ab^{-1} in total,
  - Large statistic run at 365 GeV, 1.5 ab^{-1}.

- Cross section at 365 GeV ~1000 fb => ~2 Mevts in total.

- 1-2 order of magnitude lower during the scan.

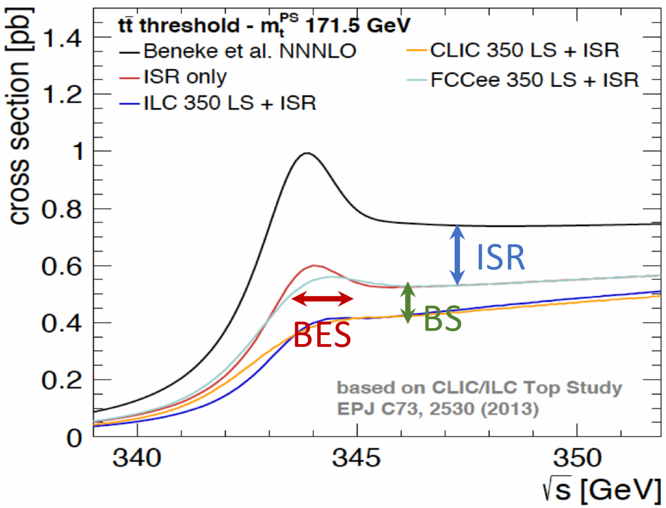
- Work on dominant systematics (detector design, theory, run plans) to achieve stat. dominated measurements.





Beam characteristics and impact on $t\bar{t}$ at FCCee

F.Simon, PoS (ICHEP 2016) 872

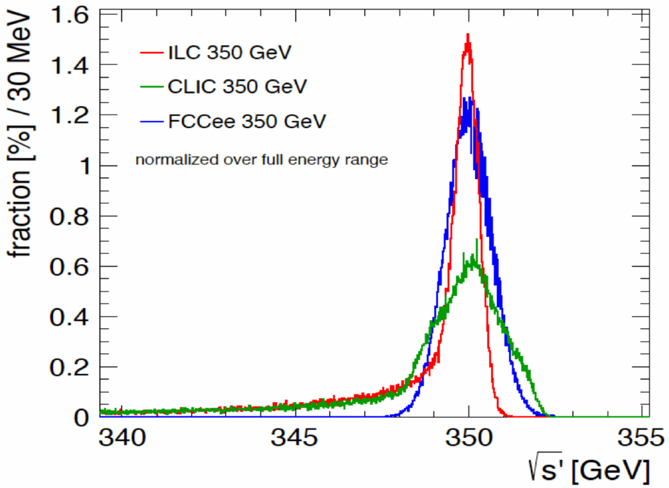


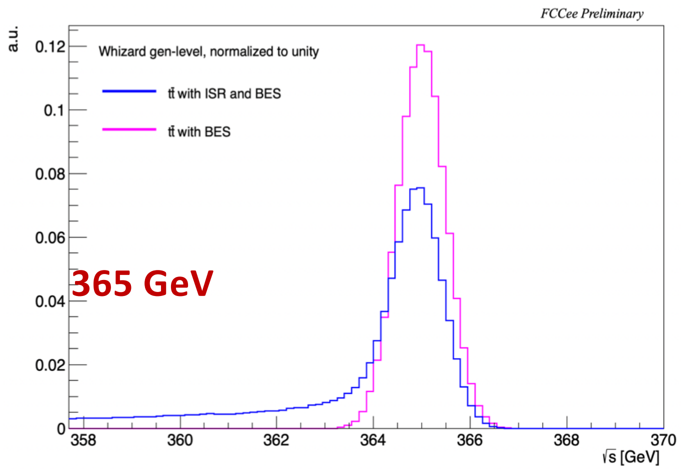
- Due to the energies involved and beam optimisation, there is some beam energy spread at $t\bar{t}$ threshold.

- ISR, Beam Energy Spread (BES) and Beamstrahlung (BS) affect the precision.

- At FCCee : narrow and small tails toward lower energies
  - Beamstrahlung effects on beam profile small, energy loss recovered by RF.

- Impact of beam effects:
  - lower effective cross sections (fraction of the lumi below the threshold),
  - broader "turn-on" ,
  - FCCee in a favourable position.





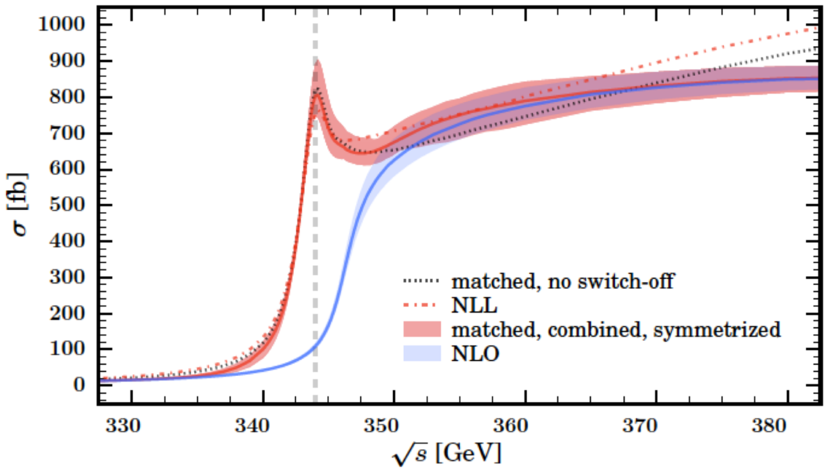
Generators : aMC@NLO and Whizard

- Having "state-of-the-art" generators is a key element for precisions
  - Maximum possible accuracy : NLO QCD+QED,
  - NLL+NLO matching : differential cross sections at threshold, effects of $\sqrt{s}$ on kinematics,
  - Account for the beam effects discussed above,
  - We need at least 2 generators to perform comparisons,
  - Two generators under investigations : Whizard and aMC@NLO.

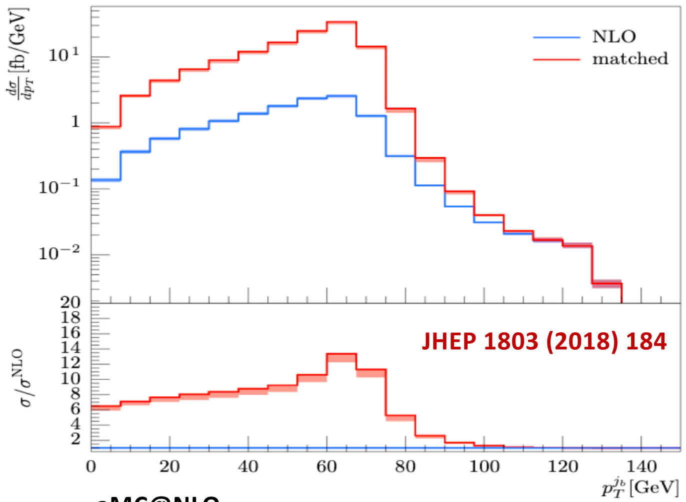
- Both generators contains most of the the key elements (in a not-yet public release for aMC@NLO link) :
  - NLO accuracy, **Whizard** : QCD+QED, **MadGraph** :QCD (QED under developments for e+e-),
  - Initial State (QED) Radiation, **both,**
  - Beamstrahlung : **Whizard** : interface with GuineaPig/CIRCE. **MadGraph** : parametrization fitted to GuineaPig++.
  - Beam Energy Spread : **Whizard** : Gaussian smearing in case of FCCee, **Madgraph** : not available yet.

Whizard

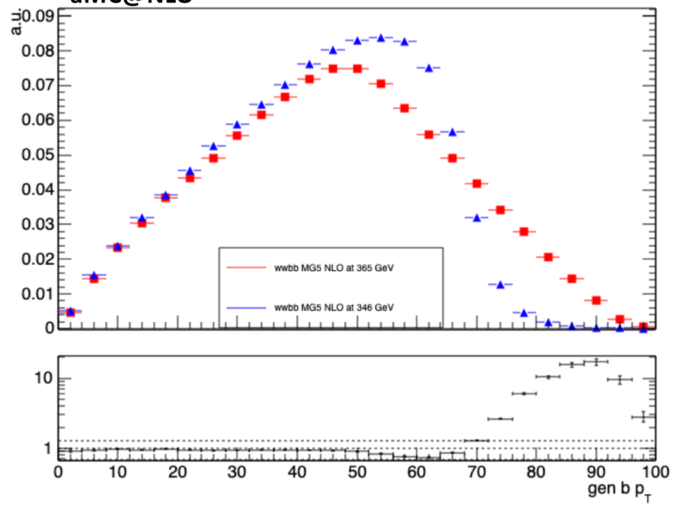
JHEP 1803 (2018) 184



Whizard



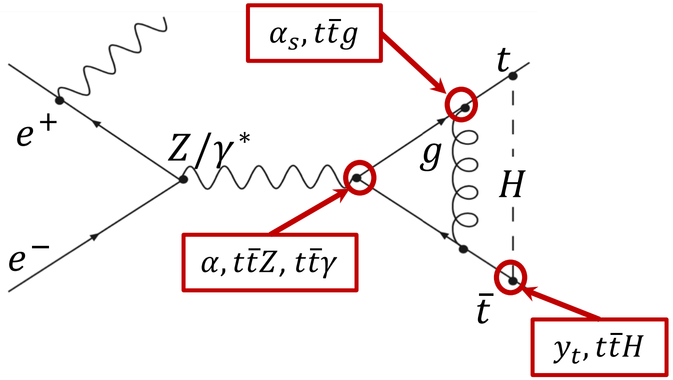
aMC@NLO



Precision of $t\bar{t}$ cross section measurements

- Inclusive and differential => probe of $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings (EFT related).

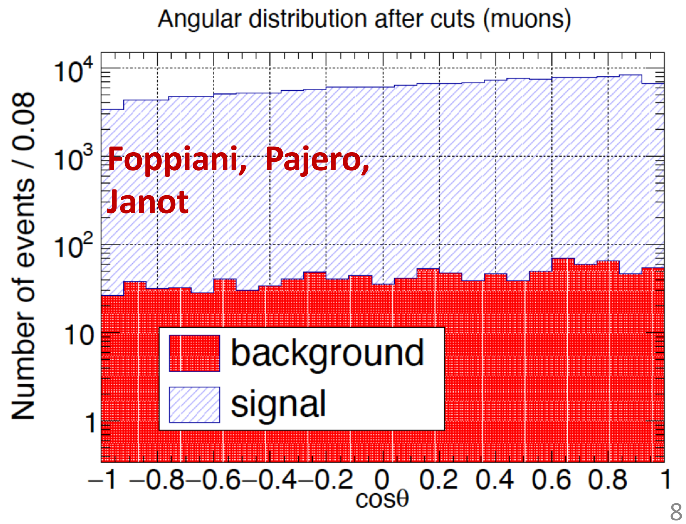
- Dominant backgrounds (lepton+jets):
  - WW(dominant)/ZZ => b-tagging !
  - WWZ, ZH => more difficult to reject, but much lower cross section (/20).



- Events selection :
  - one (relatively loose) isolated lepton with E>10 GeV, 80-90% efficiency,
  - ≥4 jets reconstructed using an exclusive algorithm,
  - b-tagging requirements,
  - jets and lepton association to top-quark, with a kin-fit (W and top mass).

- Overall efficiency ~60% can be achieved (JHEP 11 (2019) 003), very high purity (>90%).

- Target **systematics ~few %** (even below ?)
  - physics background should not be a problem,
  - highest possible selection efficiency : flavour tagging (!) but lepton sel/jet reco not negligible => impact also acceptance and modelling uncertainties !
  - Excellent control of selection efficiencies (from data).



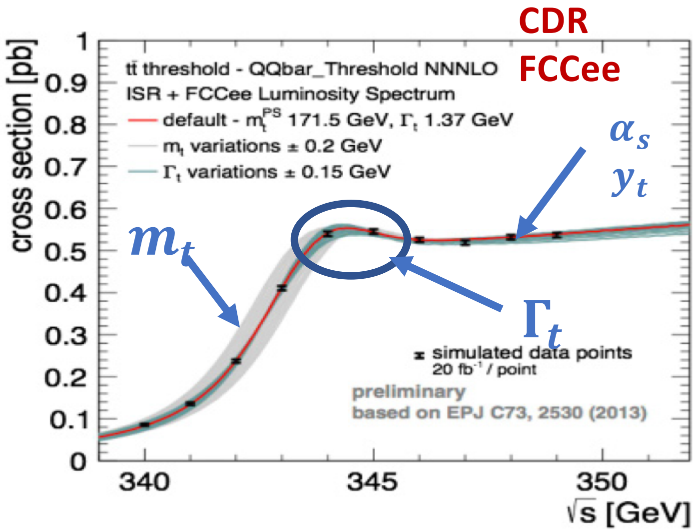
Top mass measurement

- Top mass measurement from cross sections => resolving top mass "ambiguities" : MC mass vs mass in various renorm. scheme. Also important to study vacuum stability.

- Typical mass difference in the various renorm. schemes ~200 MeV.

- Mass extracted from various cross section measurements while scanning $\sqrt{s}$, and then compared to theoretical predictions.

- Cross section measurement precision : 1-2% to reach <200 MeV.



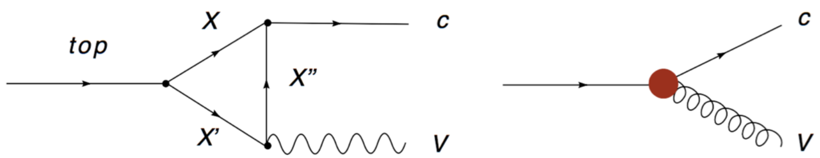
- Expected precisions (CLIC analysis revisited for FCCee):
  - Stat uncertainty at ~15 MeV,
  - Beam energy, reconstruction efficiency and background contamination ~50 MeV ,
  - And luminosity … ~10 MeV,
  - **Total uncertainty below 100 MeV**, previous measurements of α_s => **reduction to < 50 MeV could be achievable**!

- Experimental uncertainties (close to be) dominated by statistics is possible at the FCCee !

- Direct top-quark mass measurements below 200 MeV also possible.

Search of new physics through EFT

New vertices arise from the contributions of new particles (new physics) living at the loop level.



If the new particles are heavy enough => modelling of the loop by a new interaction vertex.

Wilson coefficients (complex number)

Higher order are neglected

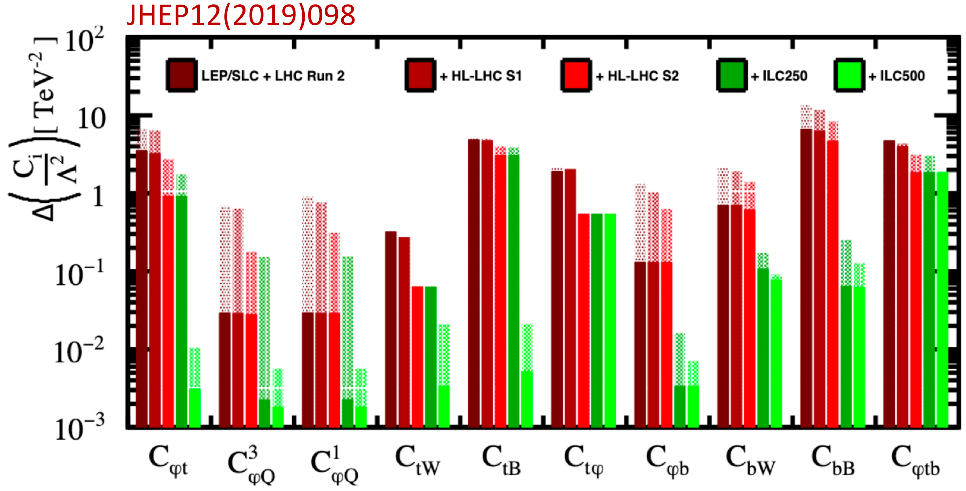
$$\mathcal{L}_{\text{eff}} = \sum \frac{C_x}{\Lambda^2}\mathcal{O}_{6,x} + \sum \frac{C_x}{\Lambda^4}\mathcal{O}_{8,x} + \sum \frac{C_x}{\Lambda^6}\mathcal{O}_{10,x} + \ldots$$

Energy scale of new physics

Dimension-6 gauge invariant operators

- Search for new physics through EFT.
- Thanks to high precision, lepton colliders are able to very significantly improve the sensitivity.

JHEP12(2019)098



Top-quark EFT : polarization vs statistics

- At linear colliders, to constrains EFT operators
  - beams polarization give an extra handle,
  - High energies can help to improve the sensitivity on some couplings, especially in multi-parameter fits,
  - Statistics (always?) help to improve the sensitivity.

- Investigating EFT at FCCee (no polarisation, 365 GeV) :
  - Low beam backgrounds and less ISR at lower energies,
  - Lower backgrounds at 365 GeV,
  - Larger statistics (for instance ~factor of 2 compared to the 500 fb^{-1} ILC scenario).

- Sensitivity can be further:
  - Differential measurements and combinations : benefit the most of the large statistics,
  - New observables and combinations to be investigated,
  - Collaborations with theorists required.

- Sensitivity on (anomalous) $t\bar{t}$ EWK couplings at FCCee. Based on lepton energy and polar angle :
  - very low expected experimental uncertainties,
  - dominated by stat. uncertainties (and theory).
  - ➔ high constrains without the need for polarisation, higher energies doesn't always help for all couplings at FCCee.

- Reproduce such analysis within the EFT framework. Include more information : b-jets, top reconstruction (asymmetries), all channes etc…

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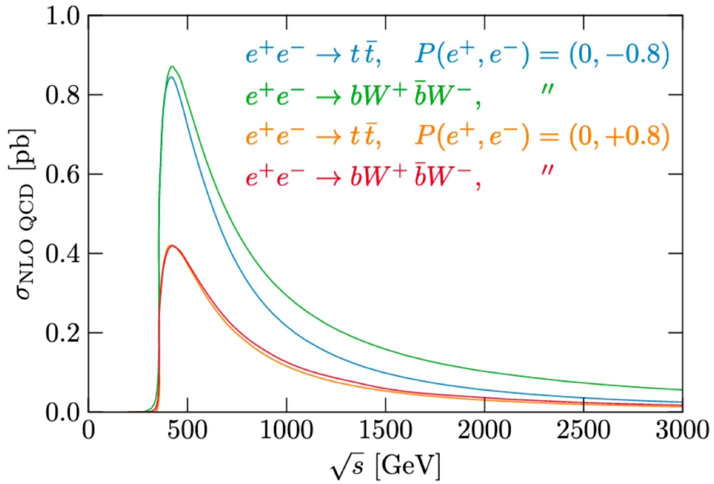

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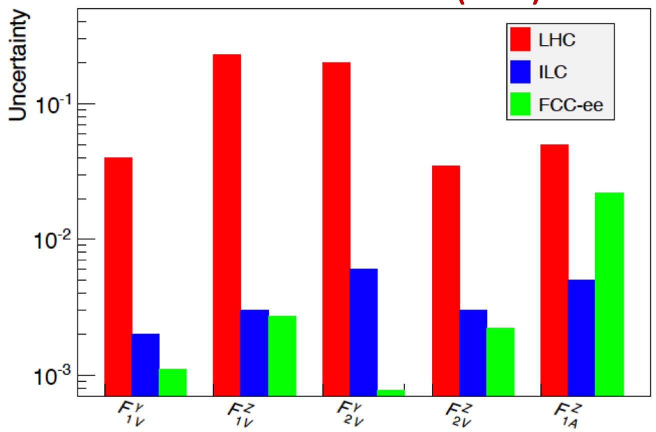
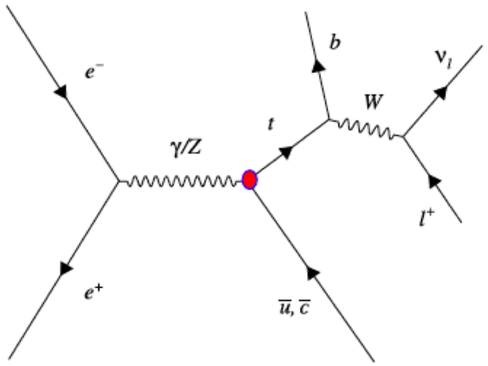
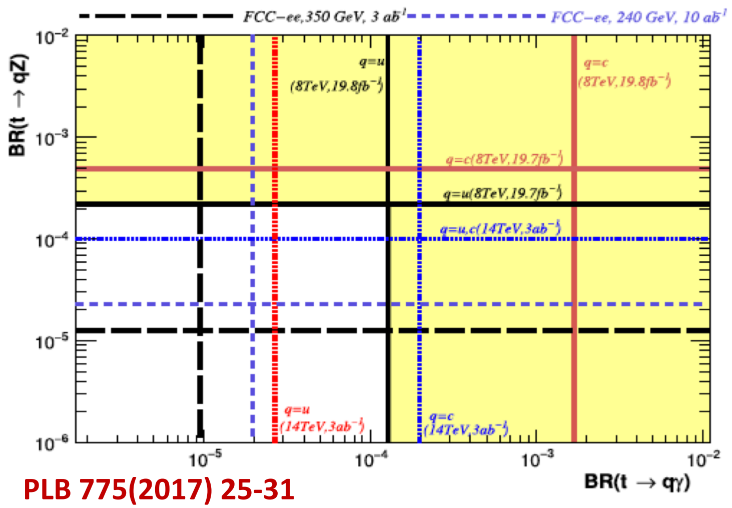


Top quark couplings to bosons





PLB 775(2017) 25-31

- Top-quark FCNC couplings to γ, Z, H usually probed in top quarks decays in $t\bar{t}$.
- Interesting channels at lepton colliders : single top production possible for $t\gamma$ and tZ-FCNC.
- Very promising channels : higher cross section, limited by statistics and background contamination (Wjj),
- Ultimately : combination of single top and $t\bar{t}$ channels ($t\bar{t}$ channels still useful to disentangle $t\gamma$ from tZ).
- Large impact of b and c-tagging.

“to-do” for $t\bar{t}$ at FCCee

- Preparation of analyses : getting the main ingredients :
  - Study/compare MC generators for signal (and backgrounds),
  - Within FCCSW, use Delphes Fast-Simulation and reconstruction, (tests other FastSim like SFS?),
  - Compare various object reconstruction algorithms,
  - Study backgrounds rejection,
  - Define baseline events selections for the different $t\bar{t}$ channels,

- Setting up the analysis :
  - Starts with a simple counting experiment, and implement stat and systematics uncertainties,
  - Study the possibility to use distributions to gain precision/sensitivity, also for the threshold scan,
  - Implement the best possible $t\bar{t}$ reconstruction : required for top properties measurements ! (and EFT!)

- Study detector performance impact on top events :
  - event selections or/and detector performances (modifying Delphes card, regenerate, determine the impact).

Conclusion

- The FCCee top-quark physics program is vast and should improve greatly the measurements precisions and sensitivity to new physics.

- FCCee will deliver a large luminosity, up to $2ab^{-1}$, with excellent beam conditions.

- The expected very low systematics should lead to statistically dominated measurements.

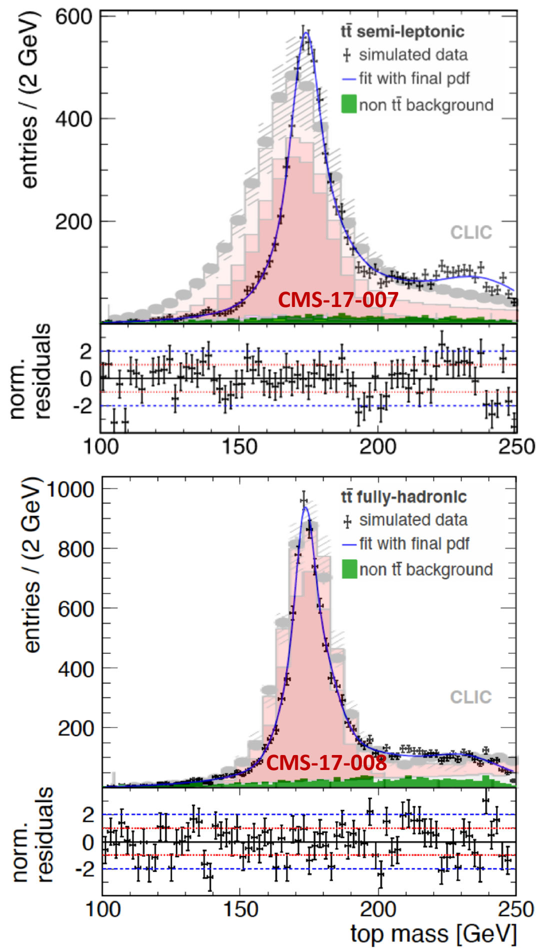
- Current efforts : facilitate work of new comers
  - Easy-to-use analysis framework in the FCC collaboration,
  - Setting-up and generating MC samples,
  - Implement top-quark related tools and baseline event selection.

- Now is an excellent moment to join ! We would be happy to collaborate with ILC/CLIC colleagues !

Backup

Direct measurement of top mass from decay products (above threshold)

CLIC, EPJC 73 (2013) 2530



- Direct mass measurement from top quark decay products (in a nutshell):
  - reconstruct and identify decay products,
  - reconstruct top quarks candidates using a kin fit (determine jets-lepton associations),
  - fit the reconstructed top mass with templates issued from MC generation. Simultaneous fit with JES reduces systematics,
  - requires "calibration" : input $m_t^{MC} \neq m_t^{reco}$.

- Comparisons with CMS top reconstruction at 13 TeV, 35.9 fb^{-1}.

- Estimations of the uncertainties (CLIC@380 GeV) :
  - stat: 30-40 MeV for $1ab^{-1}$,
  - moderate impact of JES : 2% variation of light and b jets = 200 and 350 MeV,
  - JES related uncertainties can be greatly reduced by including the perfect knowledge of the initial stat into the events reconstruction,
  - =>statistically dominated measurement?

- Direct top mass measurement can be competitive with the threshold scan measurement.

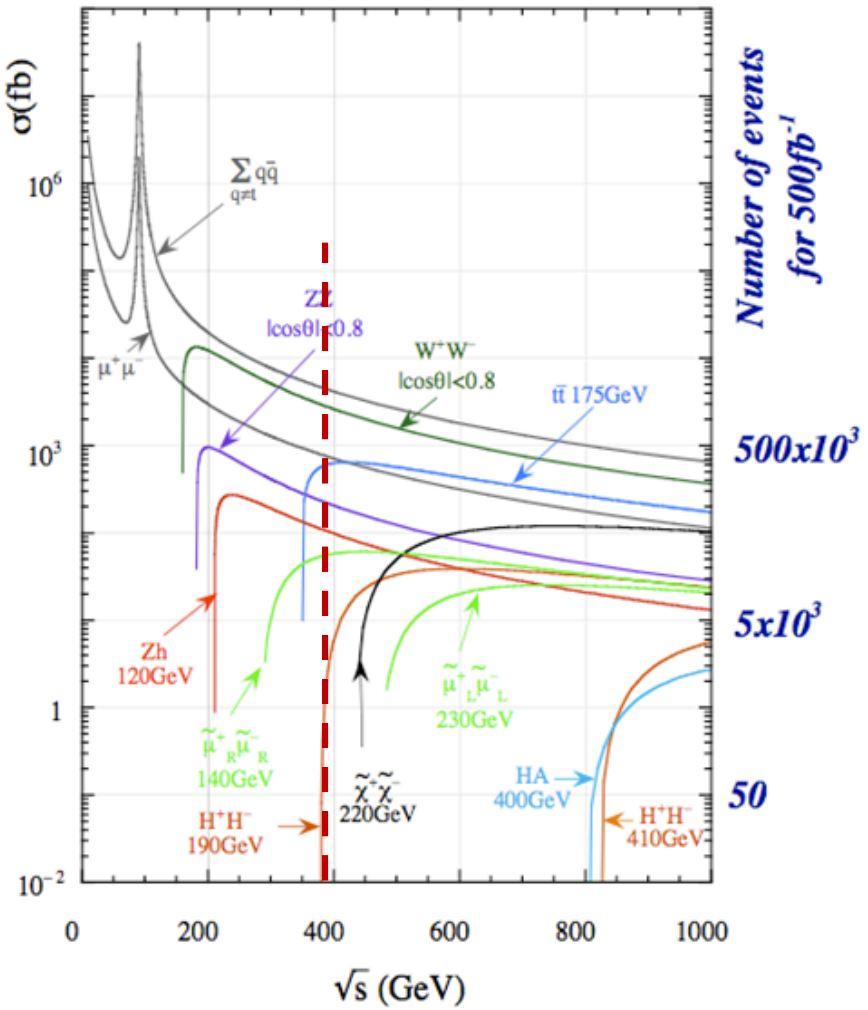
- Other "non" standard measurements can help (dilepton, J/ψ, endpoints, extra jet/γ) => combinations?

Discussions on backgrounds

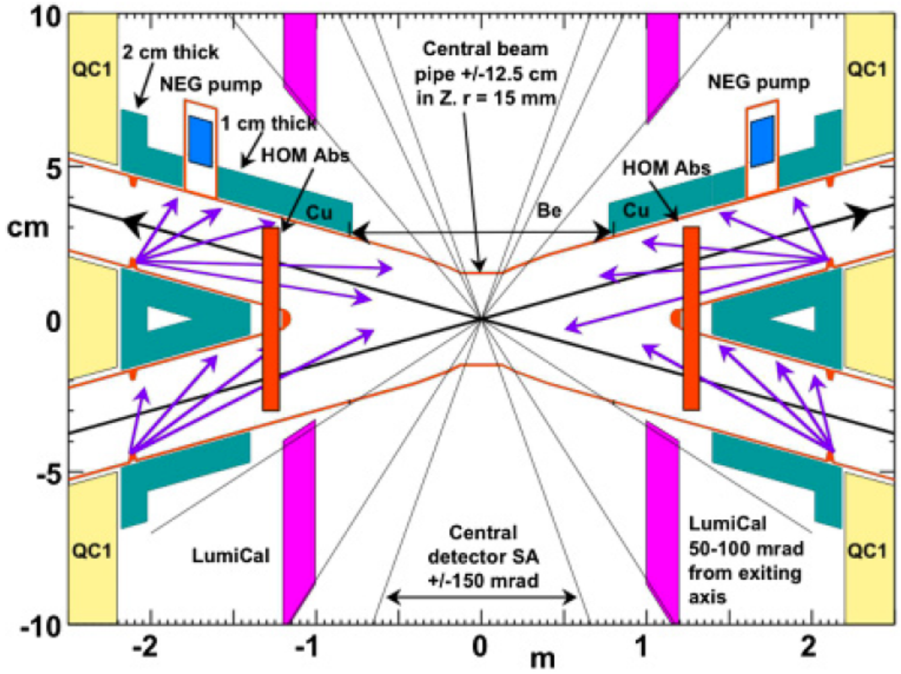
- List of the main background and cross sections.

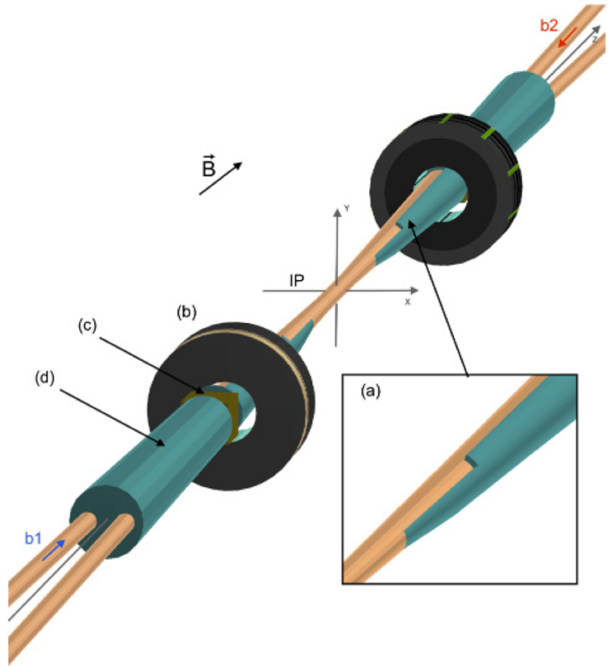
Beam backgrounds (large angle) M.Dam link

Energy	Process	Cross Section	Large angle $e^+e^- \to \gamma\gamma$	Large angle $e^+e^- \to e^+e^-$
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \to ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb	60 pb



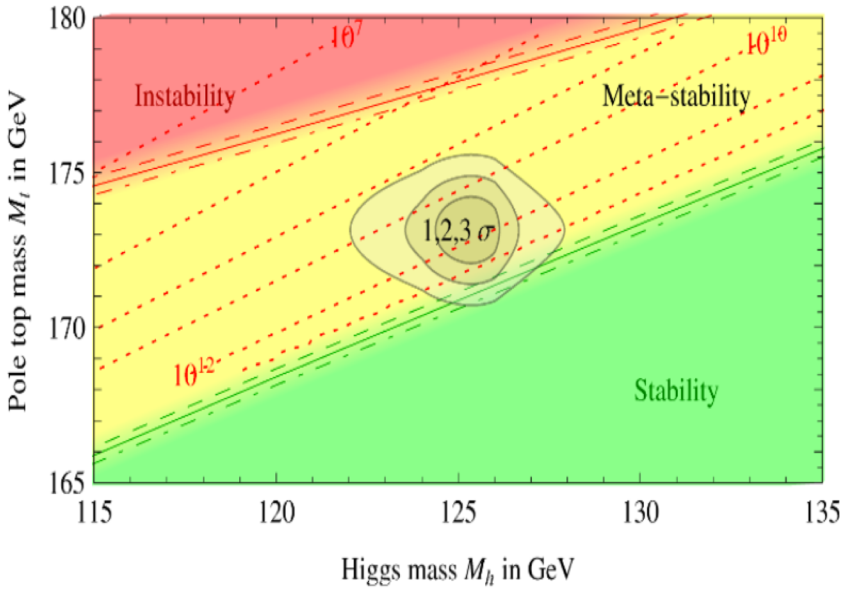
Interacting points





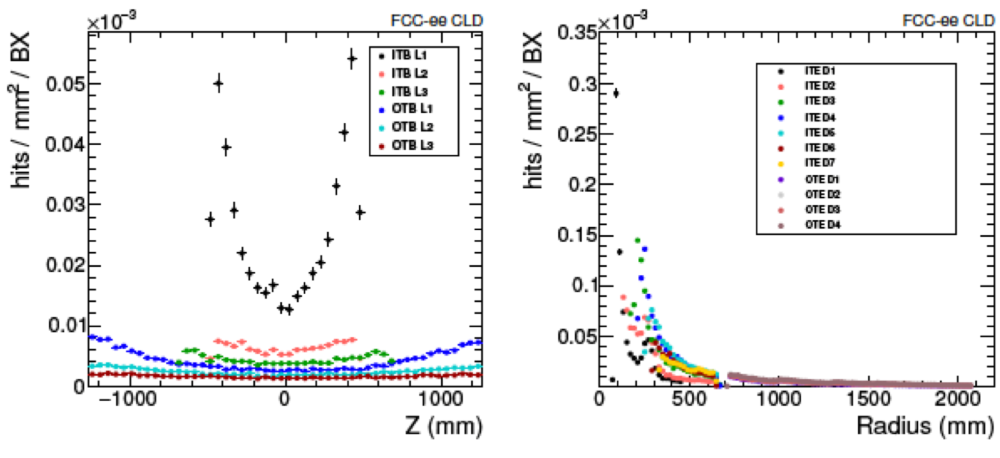
Top mass : target

JHEP08 98 (2012)



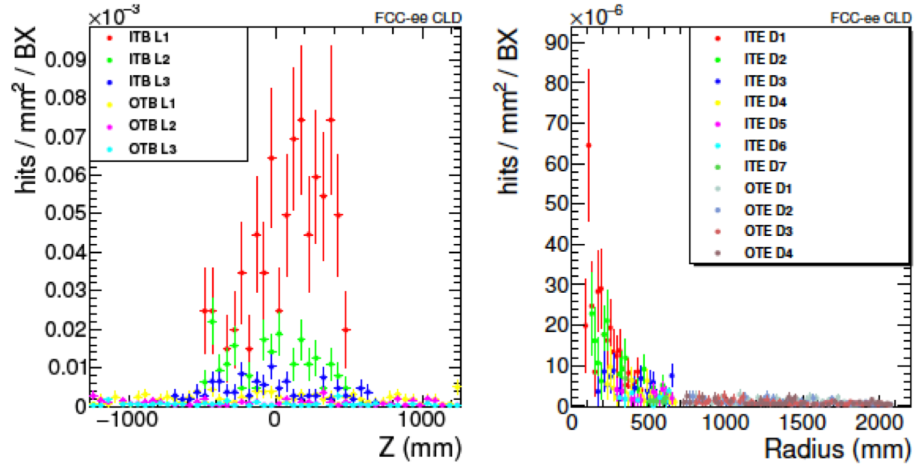
- Objectives of top mass measurement :
  - Test of the SM, yukawa couplings and top mass,
  - Confront pole mass to the “MC” mass (differences of a coupe f hundreds MeV),
  - Study of the stability of the vacuum, differentiations between stable and meta-stable universe.

Beam background



(a) (b)

Figure 17: Hit densities in the CLD tracking detector barrel layers (a) and discs (b) for particles originating from incoherent pairs, for operation at 365 GeV. Vertical error bars show the statistical uncertainty, horizontal bars indicate the bin size. Safety factors for the simulation uncertainties are not included.



(a) (b)

Figure 18: As Figure 17 but for hits related to synchrotron radiation photons.

Breit-Wheeler

$$\gamma + \gamma \rightarrow e^- + e^+$$

Bethe-Heitler

$$\gamma + e^\pm \rightarrow e^\pm + e^- + e^+$$

Landau-Lifshitz

$$e + e \rightarrow e + e + e^- + e^+$$

Bremsstrahlung

$$e + e \rightarrow e + e + \gamma$$

$\sqrt{s}$ (GeV)	91.2	365
Total particles	800	6200
Total E (GeV)	500	9250
Particles with $p_T \geq 5\,\mathrm{MeV}$ and $\theta \geq 8^\circ$	6	290

Rates of electron pair backgruonds

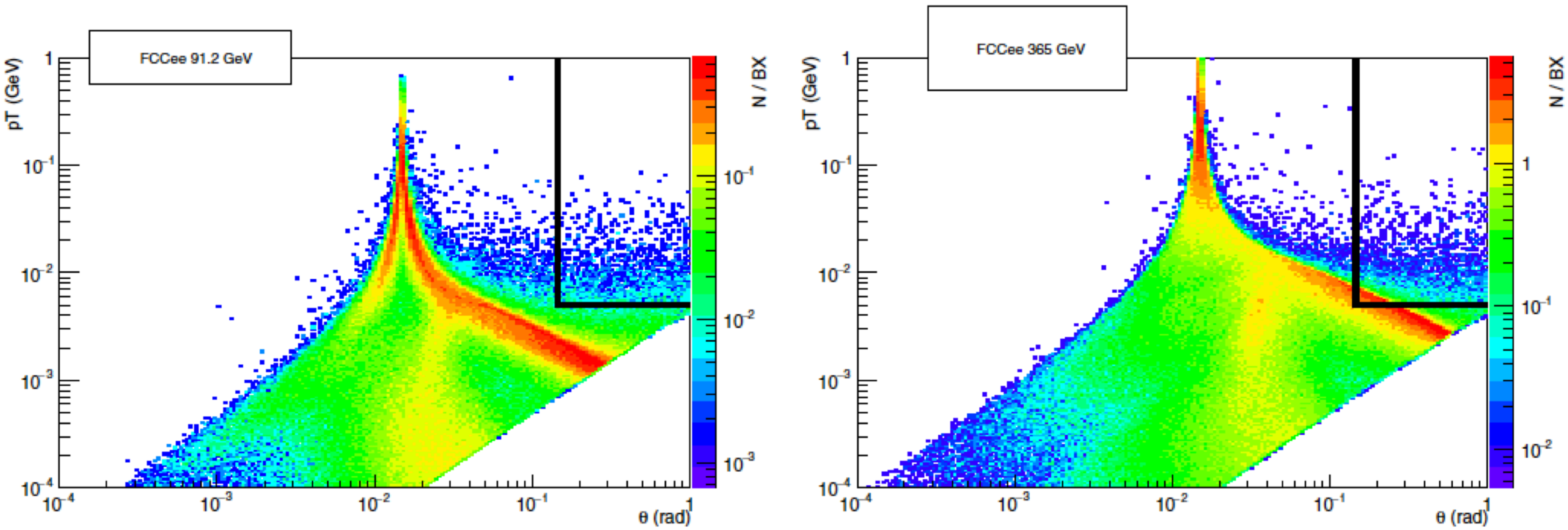


Fig. 7.2. Rates of $e^{\pm}$ from IPC in the (p_T, θ) plane, in the detector frame, for $\sqrt{s} = 91.2$ GeV (left) and 365 GeV (right). The black line in the upper-right corner delineates the CLD vertex detector acceptance within a field of 2 T.

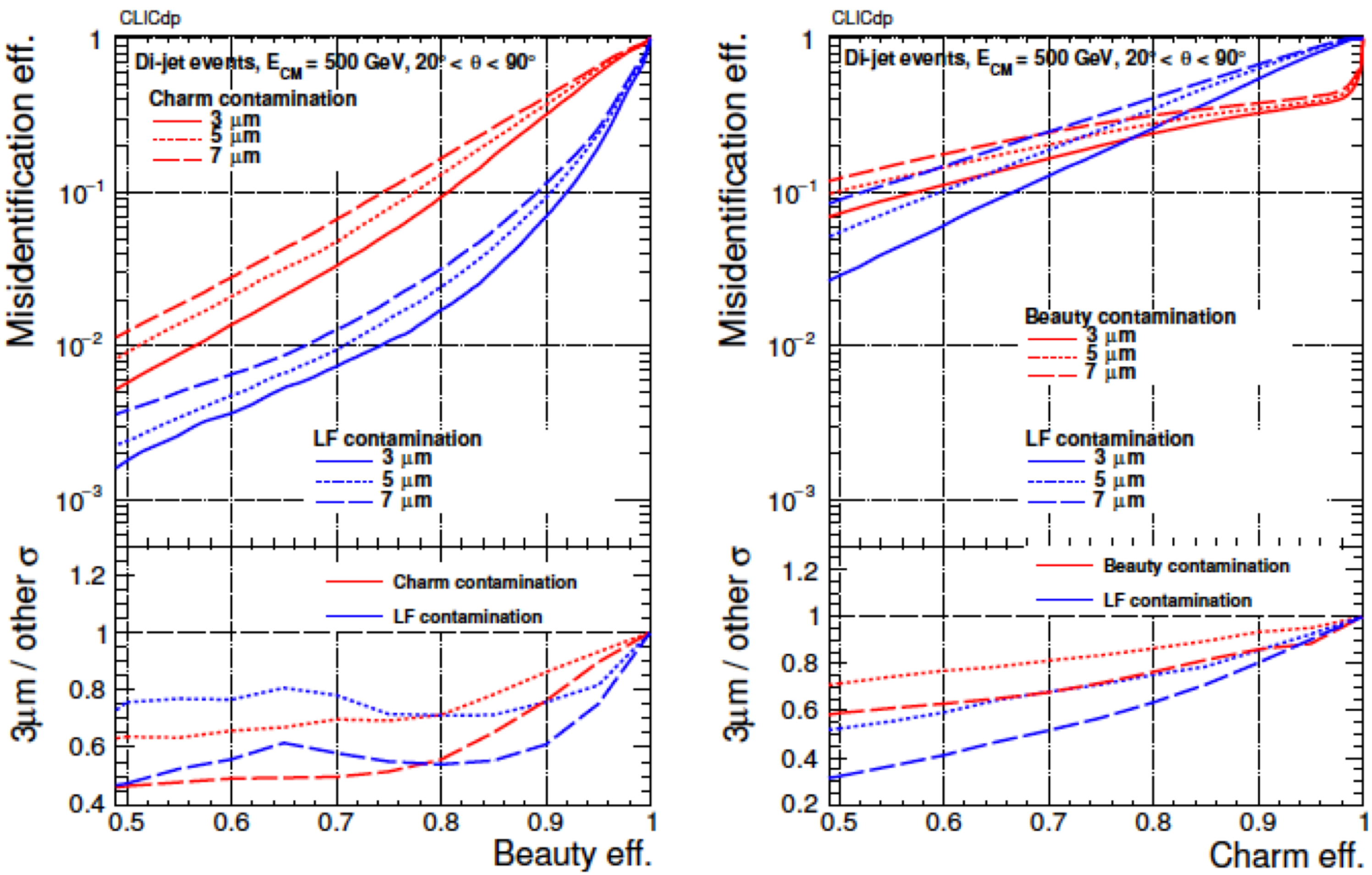
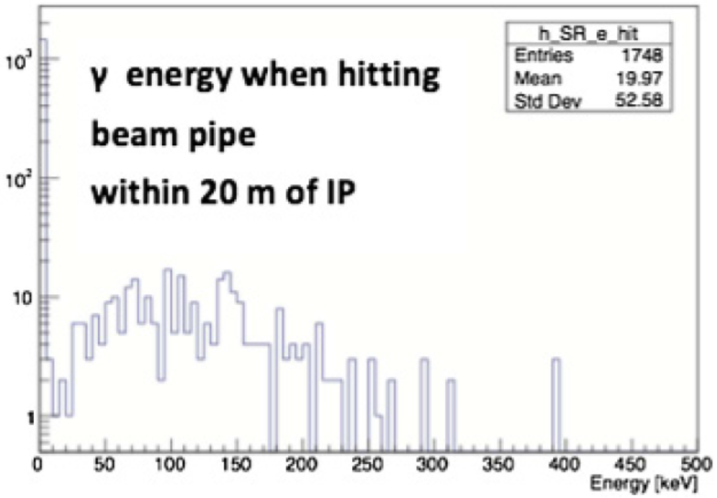


Figure 62: Global performance of beauty tagging (left) and charm tagging (right) for jets in di-jet events at $\sqrt{s} = 500\,\text{GeV}$ with a mixture of polar angles between 20° and 90°. A comparison of performance obtained with different single point resolutions in the vertex detector is presented. On the y-axis, the misidentification probability and the ratio of misidentification probabilities with respect to the nominal (3 µm) single point resolution are given.

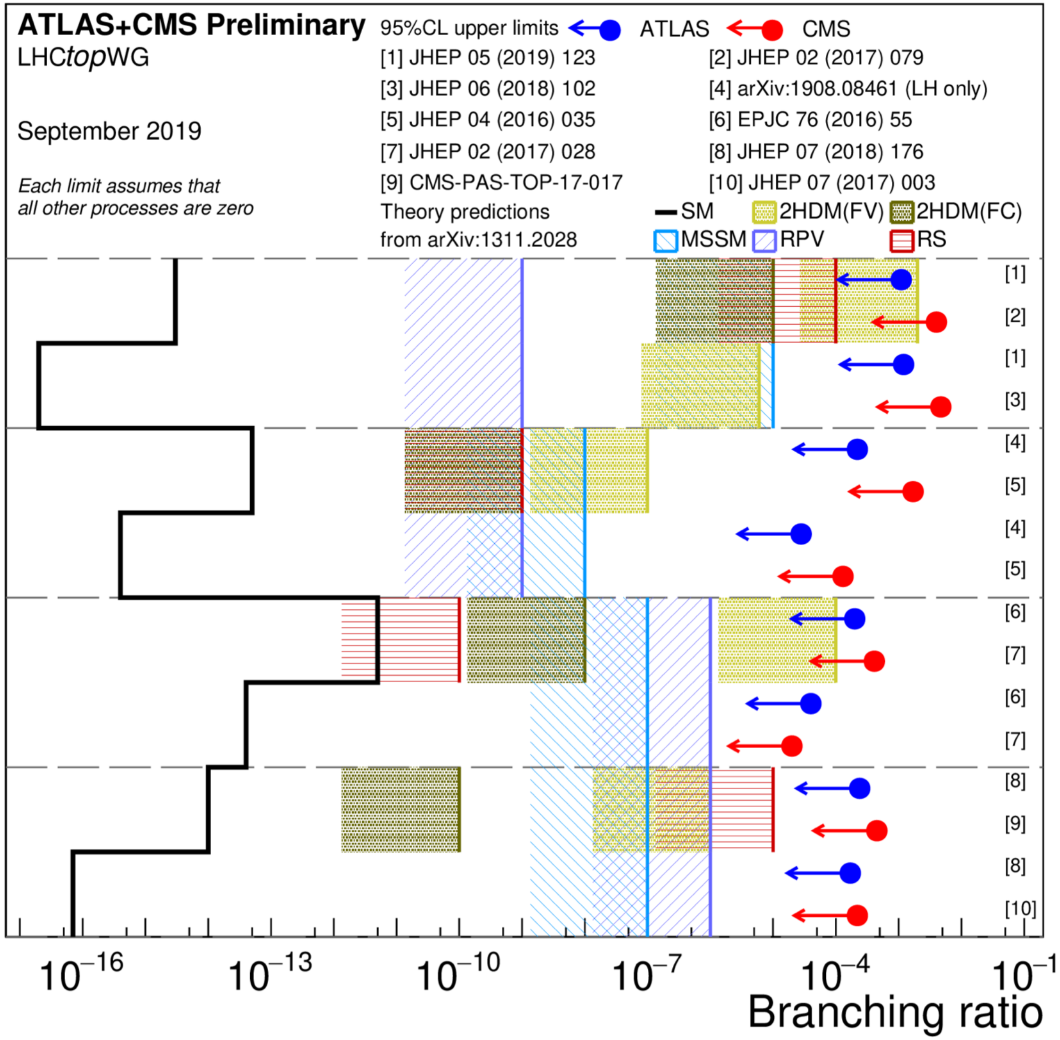


Notes. The second column refers to the number of photons incident at 500 μm from mask tip and with an energy >1 keV, the third and fourth columns give the incident number of photons in the central beam pipe per beam crossing and per second, respectively. Solenoid fields and collimators were not taken into account. Note that this table was calculated for an older version of the beam optics with a maximum beam energy of 175 GeV. For the more recent optics of Section 2.4 even at a beam energy of 182.5 GeV the critical photon energy is below 100 keV.

Table 2.7. Summary of the SR coming from the last soft bend upstream of the IP.

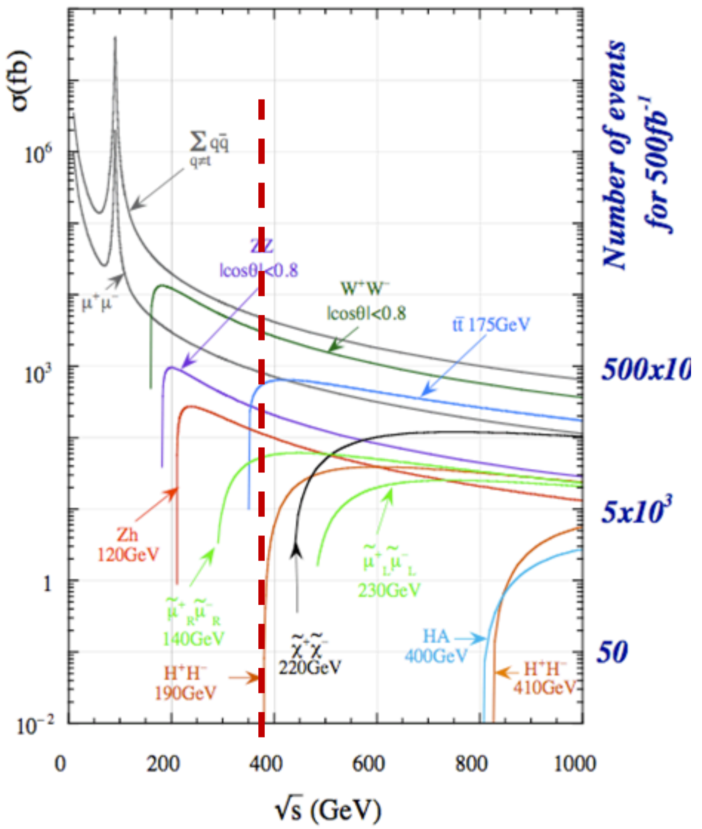
E_{beam} GeV	$E_{critical}$ keV	Incident γ/crossing (500 μm from tip)	Incoming on central pipe/crossing	γ rate on central pipe (Hz)
182.5	113.4.	3.32×10^9	1195	1.18×10^8
175	100	3.06×10^9	1040	1.25×10^8
125	36.4	1.05×10^9	10.3	1.01×10^7
80	9.56	6.11×10^8	0.18	7.02×10^5
45.6	1.77	9.62×10^7	1.92×10^{-4}	9.58×10^3

Status top FCNC at LHC



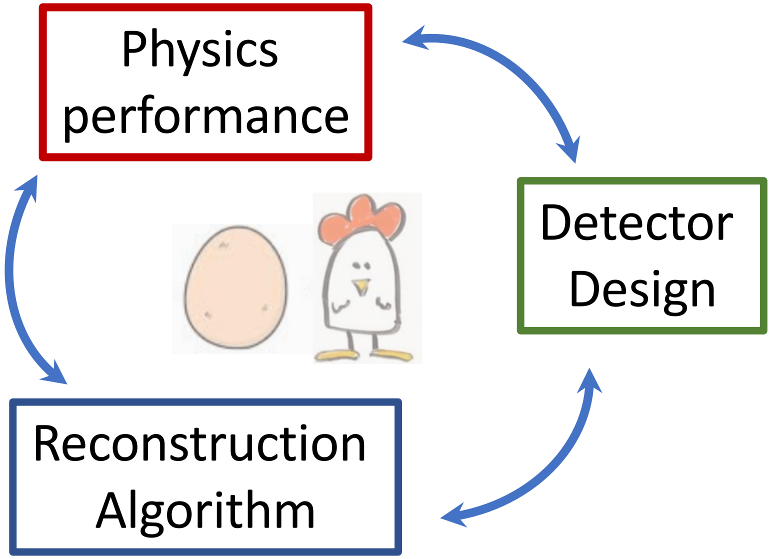
Do we need a trigger at $t\bar{t}$ threshold ?

- Trigger (at least software) might be foreseen for the Z run.
- Effects of trigger selection on analysis (my LHC bias) :
  - Could cause lower signal efficiencies ?
  - Systematics on the trigger efficiency ?
- At FCCee : mainly to reject beam-backgrounds, we want to keep all physic backgrounds (physics, alignment, calibrations and efficiencies measurements etc…).
- Rate of bunch crossing at $t\bar{t}$ (back of the envelop) : ~3000 ns of bunch spacing => ~300kHz, that is ~3 times the actual CMS/ATLAS L1 trigger rate, but half of the HL rates.
- Can/should we avoid L1 and/or HLT triggers ?
- (Naïve) questions to answer :
  - What is the rate of beam backgrounds ?
  - What is a typical size of an event ?
  - What is the needed readout speed and disk throughput ?
- At minima : low trigger requirements to detect a collision (a la LEP). Trigger systematics should be small !



General (naïve) comments on detector design "optimisation"

- Needs (resolutions, efficiencies etc…) for top quark physics are probably very similar to the Higgs physics, at first order.
- We need to verify this assumption at $t\bar{t}$ threshold **(different beam conditions and backgrounds)!**

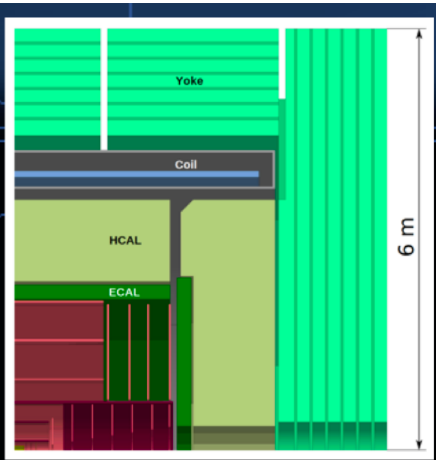


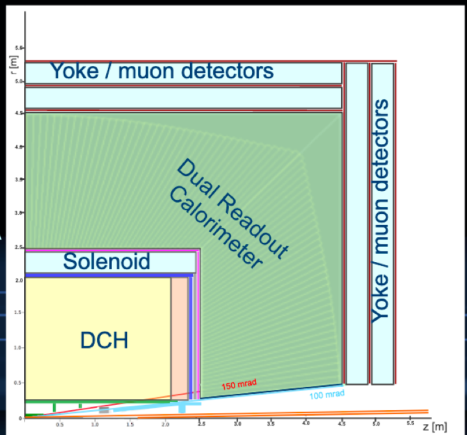
- Tools needed for Physics performance studies :
  - FastSim => interesting to test sensitivity on detector performance, but rapidly limited,
  - FullSim => ultimately needed, but takes time, need (flexible) reconstruction,
  - Intermediate approach with some modelling ? Partial fullsim (not entire detector) to feed fastsim?
- Developments need to proceed in parallel.
- Enough work on all topics to keep us busy for years.

- Some of this work already done for CLD/IDEA : do we want to join effort there, or create our own design? A lot to learn from ILC/CLIC here as well !

High involvement required !

Franco Grancagnolo, FCC-France link





	vertex detector	tracker	calorimeter	magnet and muon detector
CLD	3 double layers + 3 double disks 25μm×25μm pixel 50μm sensor 0.6-0.7% X_0 per double layer	pixel and μ-strips 7μm×90μm (5μm×5μm 1st layer) point resolution 3 layers + 7 disks inner tracker 3 layers + 4 disks outer tracker 1-1.5% X_0 per layer	ECAL 20cm 5m×5m Si-W 1.9mm W 40 layers 22X_0, 1λ HCAL 117cm 30mm×30mm Sci-steel 19mm steel 44 layers 5.5λ	90 mm Al coil 2T field 1.5m steel yoke 6 layers RPC 30mm×30mm granularity
IDEA	3 double layers 20μm×20μm double μ-strips 50μm×1mm 4 forward disks 50μm×50μm 0.6-1% X_0 per double layer	112 layers 1.4 cm square cells 100μm×750μm point resolution Si wrapper 50μm×1mm 1.5% X_0 radially 5% X_0 forward	fully projective towers $\Delta\vartheta$ = 1.125° $\Delta\phi$ = 10.0° 2880 in barrel 2×1260 end-cap 2m Cu 8.2λ	30cm total envelope 2T field cold mass + cryostat 0.28 + 0.46 X_0 0.6m steel yoke 3 layers μ-RWELL 1.5mm×500mm granularity

14/05/2020 F. Grancagnolo - IDEA and CLD at FCC-ee 11

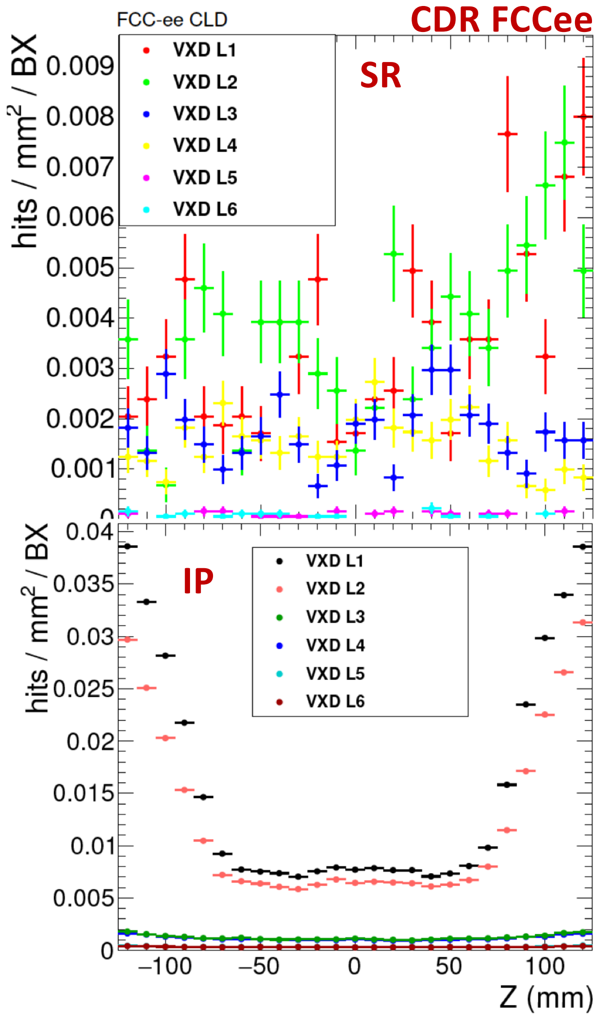
Beam backgrounds at $t\bar{t}$ threshold

- Beam Backgrounds (CDR) :
  - $\gamma\gamma \rightarrow hadrons$ found to be negligible,
  - Synchrotron Radiation (SR) from last bending magnet,
  - Incoherent Pair Creation (IPC, e^+e^- pair via interaction with beamstrahlung).

- Effects estimated from full simulation, impact on the CLD vertex detector shown.
  - SR largely reduced by shielding : #hits/BX reduced by 2 order of magnitude to achieved 700 hits/BX (<40 extra MeV per bunch crossing),
  - IPC contribution significant (especially in first layers), but moderate => acceptance choices.

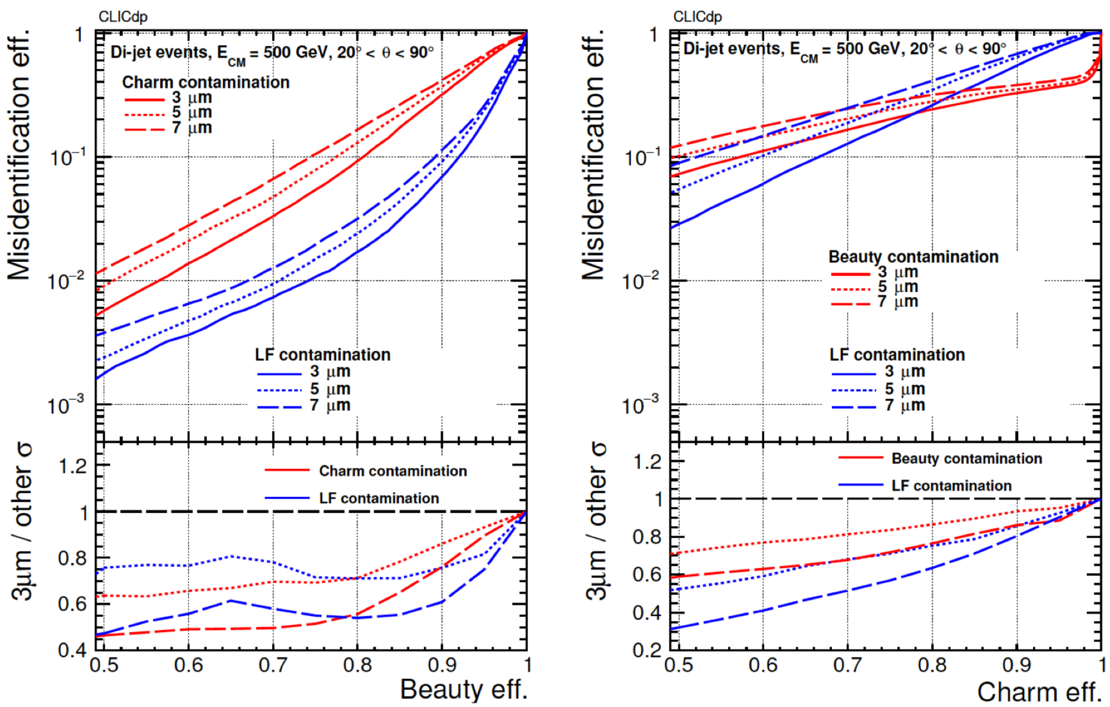
$\sqrt{s}$ (GeV)	91.2	365
Total particles	800	6200
Total E (GeV)	500	9250
Particles with $p_T \geq 5\,\text{MeV}$ and $\theta \geq 8^\circ$	6	290

First CLD layer acceptance



Detector impact on flavour tagging

CLICdp-Note-2018-005



- Flavour (b/c)-tagging is a key element for top quark physics.
  - $\varepsilon_{t\bar{t}} \propto \varepsilon_b^2$,
  - Top-FCNC , $t \to cH(b\bar{b})$, $\varepsilon_{tHc} \propto \varepsilon_b^2 \varepsilon_c$.
- B-tagging and c-tagging performances for various single point resolutions.
- From 7μ to 3μ:
  - ε_b: ~8%(abs.) improvement at $\varepsilon_l \approx 1\%$,
  - ε_c: ~18%(abs) improvement at $\varepsilon_l \approx 10\%$.
- ➔ increase of ~10% abs (**20% rel**) of $\varepsilon_{t\bar{t}}$ (for Medium P…) and ~15% abs (**75% rel**) of ε_{tHc}.
- Flavour tagging systematics ⬄ data driven estimations of efficiencies.