# Top-quark physics at $e^+e^-$ colliders (with focus on FCCee)

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# Introduction

- The top-quark has been observed and studied so far only at hadron colliders (Fermilab, LHC).
- At the LHC, high energy and the large luminosity => large statistics of $t\bar{t}$ events.

- Precisions at hadronic colliders can be limited by pile-up, background contaminations or $\boldsymbol{t\bar{t}}$ **modelling** (hadronization, colour reconnection, extra jets etc…).

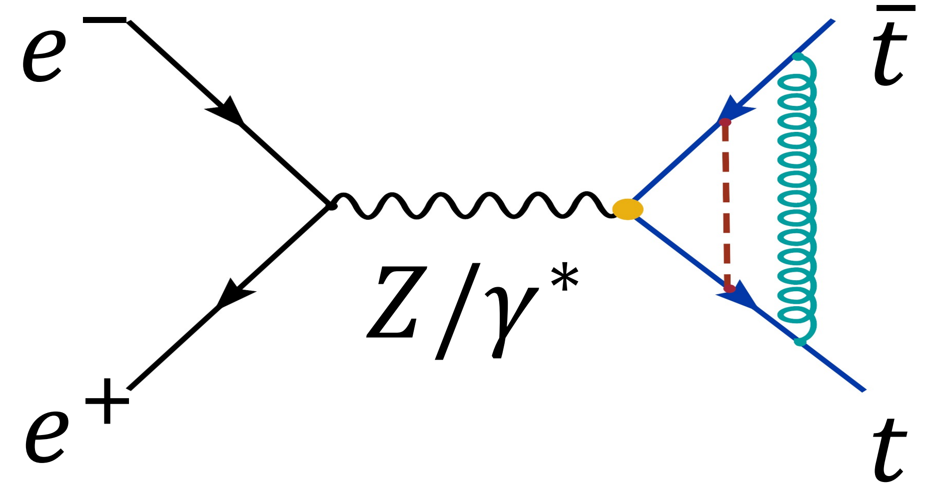
- The scientific relevance of lepton colliders for top quark physics has been studied, in the context of linear (ILC, CLIC) and circular (FCCee, CEPC) colliders.

- $e^+e^-$ colliders are expected to provide extremely precise measurements. Some examples are discussed here, with a focus on FCCee.

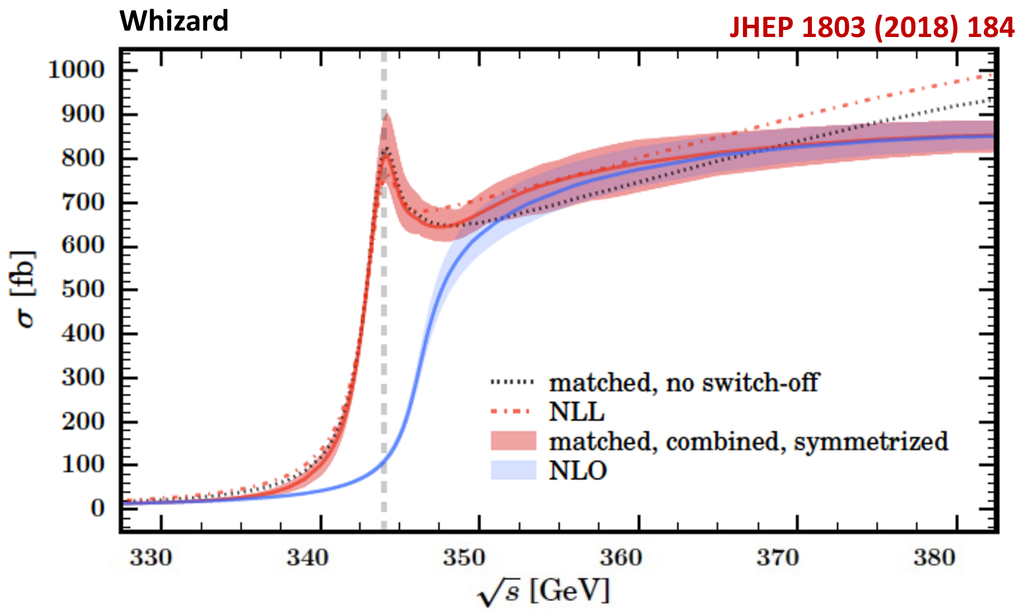
- Outline:
  - Top quark physics at (FCC)ee colliders,
  - Beam backgrounds and beam effects,
  - $t\bar{t}$ cross section and top quark mass,
  - Indirect searches for new physics from top-quark EWK couplings.

# Top quark physic at $e^+e^-$ colliers

- Physics program at lepton colliders <=> precision !
  - Low backgrounds,
  - Knowledge of the initial state,
  - Detectors with very high resolutions.



- **Above $t\bar{t}$ threshold** (differential) cross sections sensitive to :
  - **top quark mass $m_t$**, top quark width $\Gamma_t$,
  - Couplings $t\bar{t}Z$ and $t\bar{t}\gamma$ , but also couplings to Higgs ($t\bar{t}H$), $y_t$
  - $\alpha$ and $\alpha_s$.

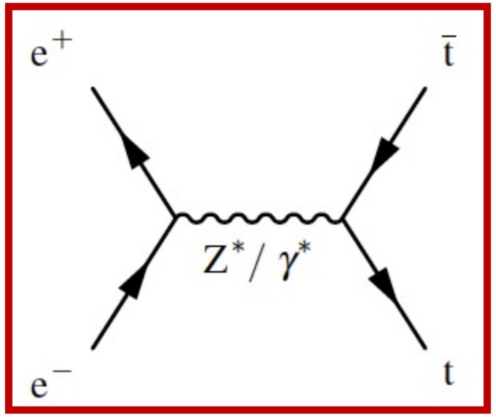


- **At $t\bar{t}$ threshold** : non relativist effects and cross section enhancement.

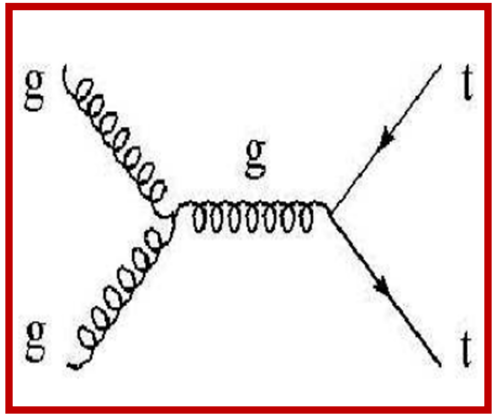
# $t\bar{t}$ decay channels : pp vs ee

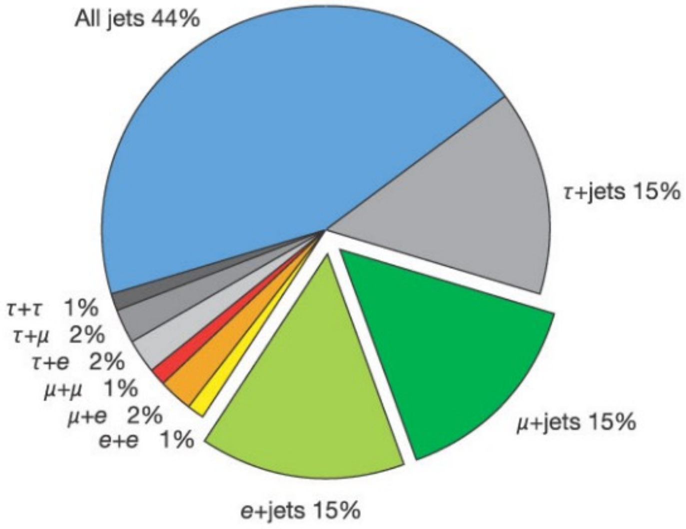
- Heaviest particle known so far.
- Decays before hadronises => top quark can be reconstructed precisely from decay products.
- Decays almost entirely into a $W$ boson and a $b$-quark.

LO $e^+e^-$



LO pp

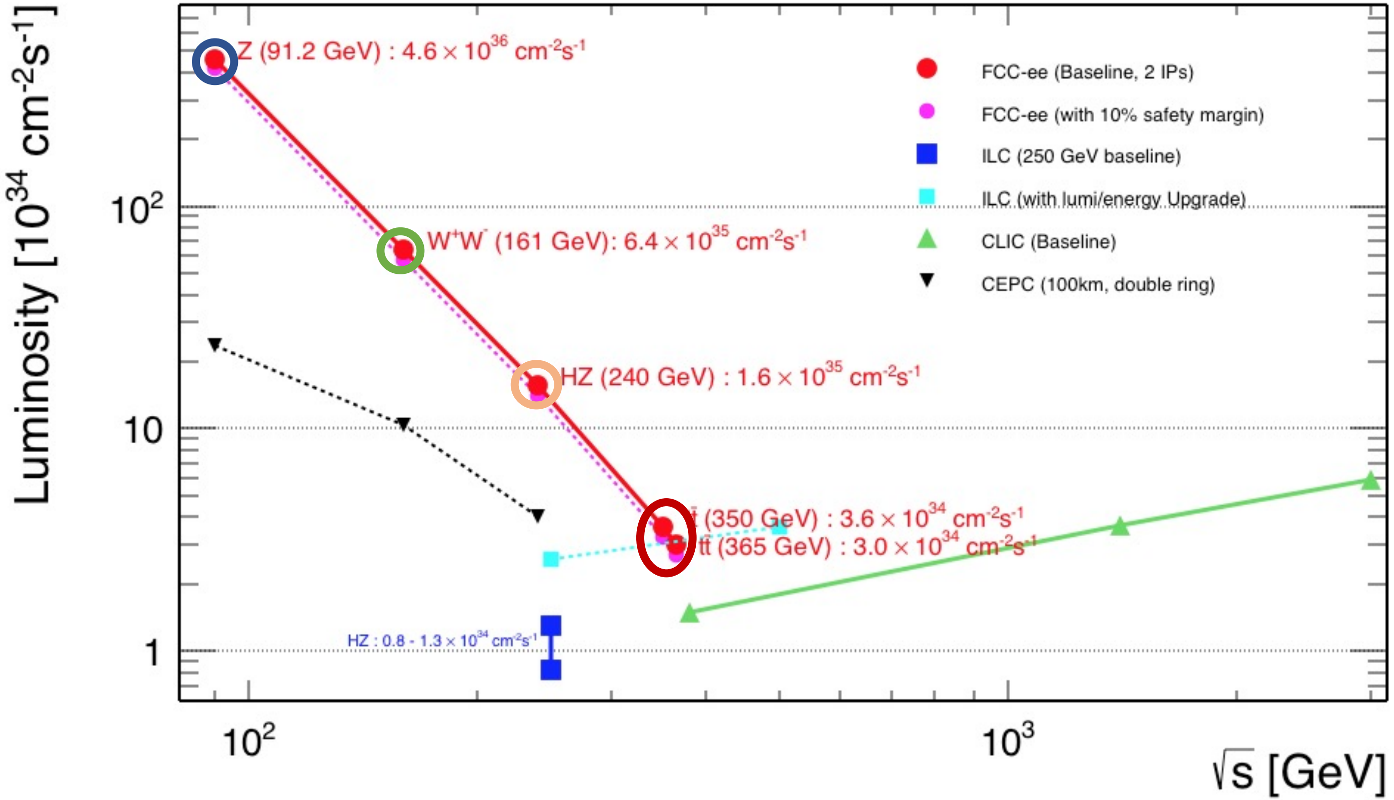


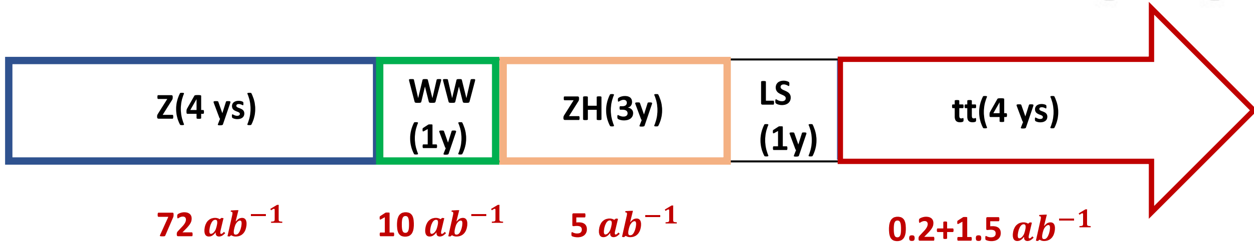


- At the LHC :
  - Dileptonic channels are clean, precise inclusive xs => low backgrounds contamination and large luminosity compensate the lower Br, event reconstruction difficult,
  - Full hadronic challenging because of the large QCD- multijet background,
  - Semi-leptonic channel shows a good compromise.
- At lepton colliders :
  - small backgrounds for all channels, mainly from WW,
  - higher selection efficiency,
  - precise knowledge of the initial state = more precise events reconstruction.

# $t\bar{t}$ runs (at FCCee)

- Lepton colliders schedules : run 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 $ab^{-1}$.
- At 365 GeV, ~2 Mevts in total.
- 1-2 orders of magnitude lower during the scan.
- Important to identify dominating systematics ➔ improve detector design, analysis and run plan.




Z(4 ys) — 72 $ab^{-1}$

WW (1y) — 10 $ab^{-1}$

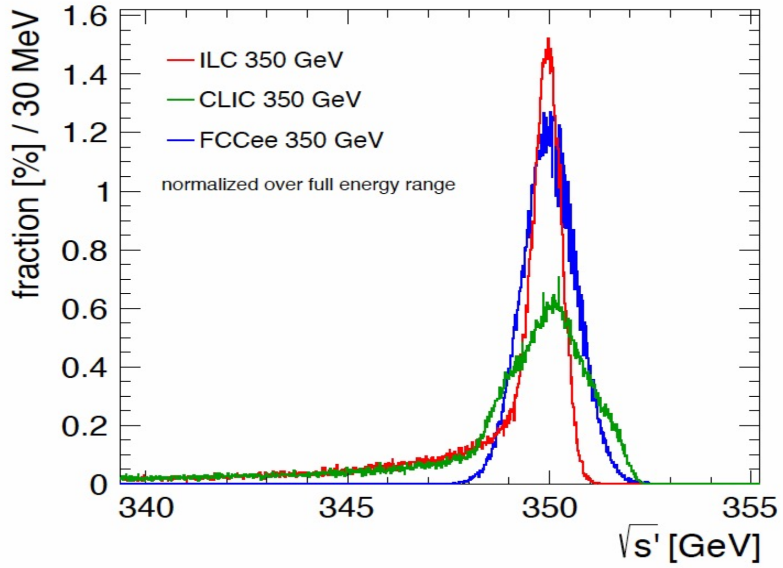
ZH(3y) — 5 $ab^{-1}$

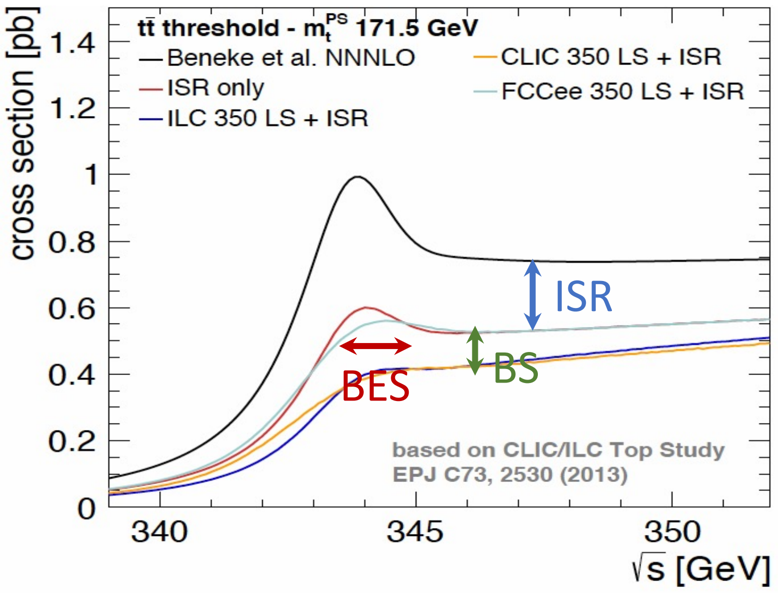
LS (1y)

tt(4 ys) — 0.2+1.5 $ab^{-1}$

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

F.Simon, PoS (ICHEP 2016) 872





based on CLIC/ILC Top Study
EPJ C73, 2530 (2013)

- There is some beam energy spread at $t\bar{t}$ thresholds.

- Beam energy spread (BES) systematics.
  - beam energy (spread) measured with dimuon-events at top energies to very precise values,
  - high muon resolution required.

- BES can be adjusted with machine optimisation.

- At FCCee : relatively narrow and no tails toward lower energies
  - Beamstrahlung effects on beam profile small, energy loss recovered by RF.

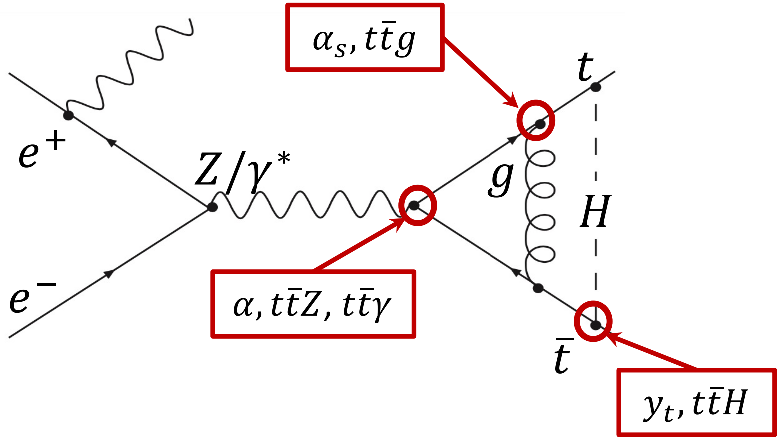
- Impacts of energy spread on the $t\bar{t}$ threshold scan : broader ”turn-on”

- Other beam dependent effects
  - ISR => lower effective cross sections,
  - FCCee in a favourable position regarding BS.

# $t\bar{t}$ cross section and top quark mass

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

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



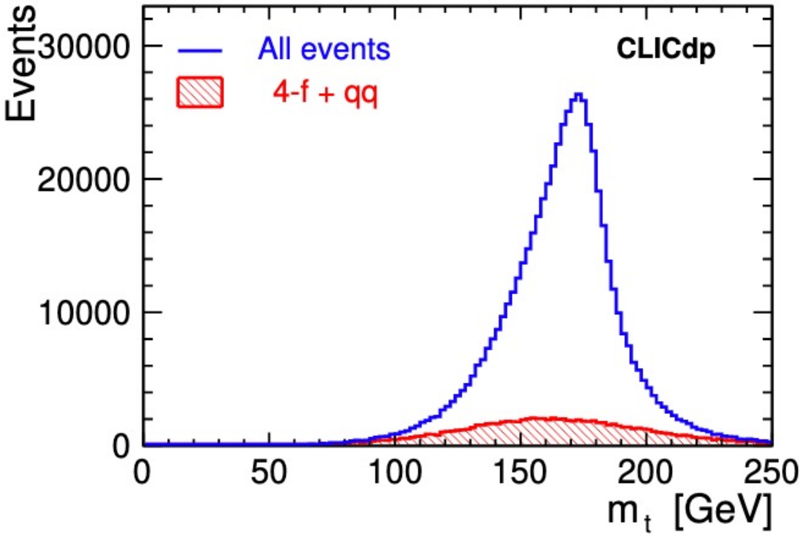
- Dominant backgrounds (lepton+jets):
  - WW(dominant)/ZZ
  - WWZ, ZH => more difficult to reject, but much lower cross section (/20).

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

- Overall efficiency >70% can be achieved (JHEP 11 (2019) 003), very high purity (>90%).

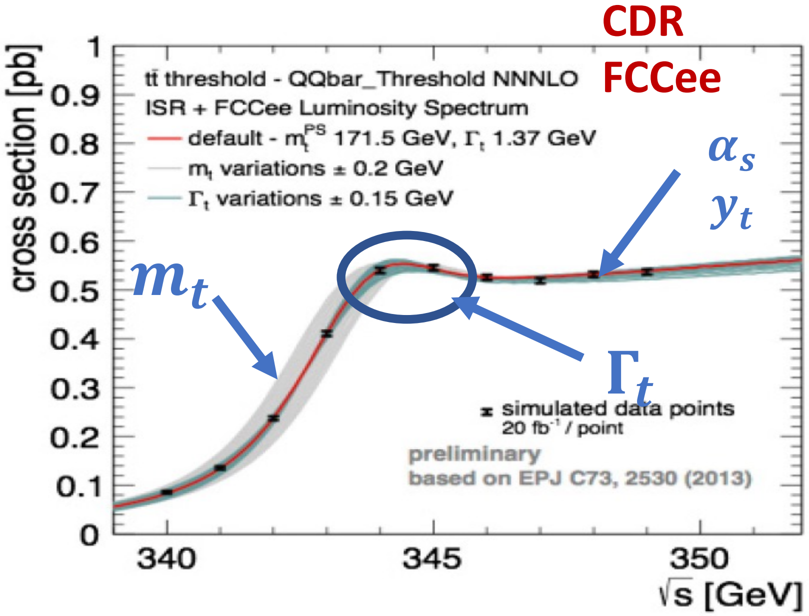
- Target **systematics ~few %** (even below ?)
  - physics backgrounds very small,
  - High selection efficiency : related to detector performance (lepton/jets selection, flavour tagging) => impact on acceptance and modelling uncertainties.
  - Excellent control of selection efficiencies (from data).

1.0 ab$^{-1}$ at 380 GeV (CLIC)



# Top mass measurement from threshold

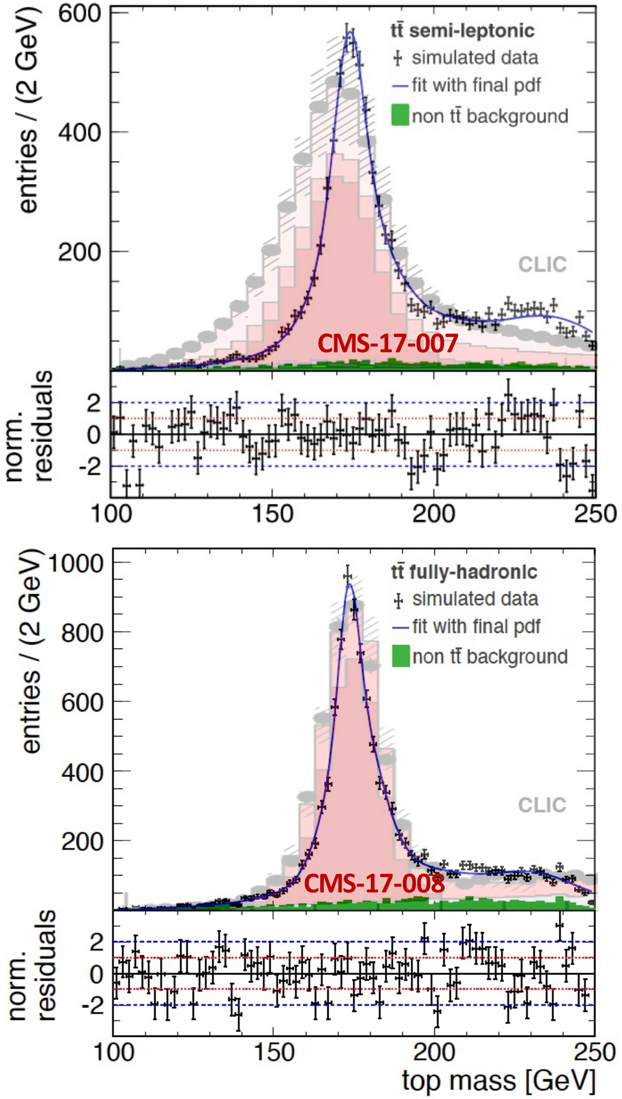
- Top mass measurement from cross sections => resolving top mass “ambiguities” : MC mass vs mass in various renorm. scheme.
- Typical mass difference in the various renorm. schemes ~200 MeV.
- Mass extracted from various cross section measurements while scanning $\sqrt{s}$ , and then compared to theoretical 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 ,
  - Luminosity … ~10 MeV,
  - Strong dependence on $\alpha_s$ in the interpretation,
  - **Total uncertainty below 100 MeV**, previous measurements of $\alpha_s$ => **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.

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

CLIC, EPJC 73 (2013) 2530



CMS-17-007

CMS-17-008

- 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 $fb^{-1}$.

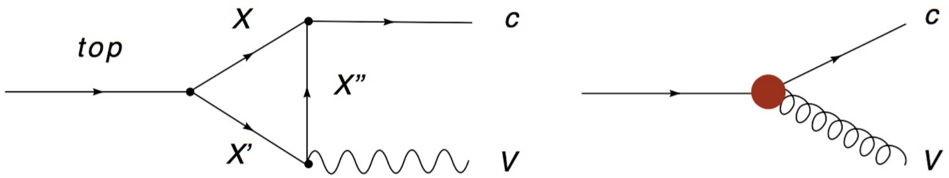
- Estimations of the uncertainties (CLIC@380 GeV) :
  - stat: 30-40 MeV for $1ab^{-1}$,
  - moderate impact of JES : 2% variation of light and b jets = 200 and 350 MeV,
  - JES related uncertainties can be greatly reduced by including the perfect knowledge of the initial state into the events reconstruction,

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

# EWK couplings in $t\bar{t}$ and search for new physics

# 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

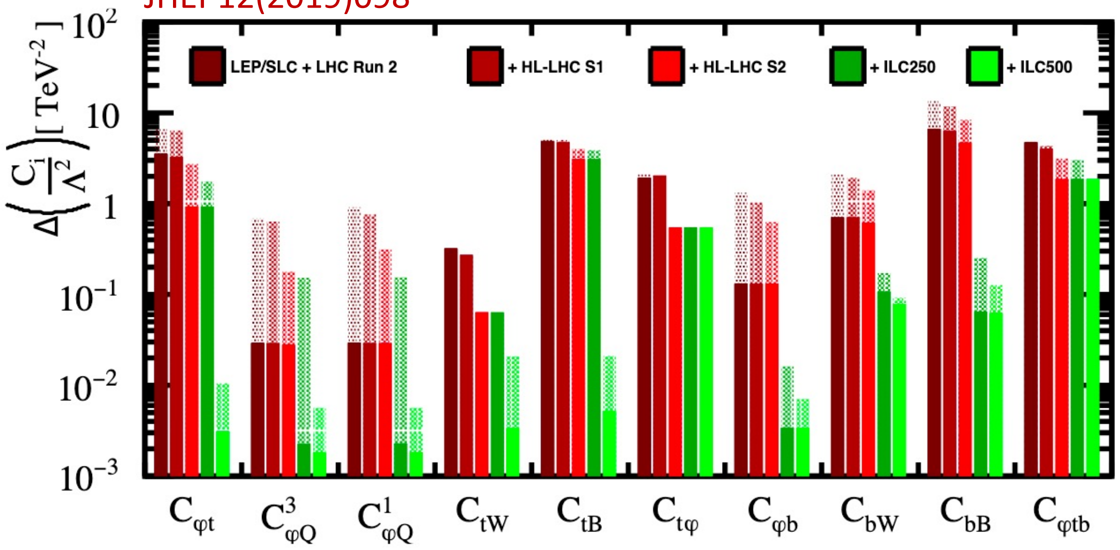
$$\mathcal{L}_{\text{eff}} = \sum \frac{C_x}{\Lambda^2}\mathcal{O}_{6,x} + \sum \frac{C_x}{\Lambda^4}\mathcal{O}_{8,x} + \sum \frac{C_x}{\Lambda^6}\mathcal{O}_{10,x} + \ldots$$

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 help to improve the sensitivity.

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

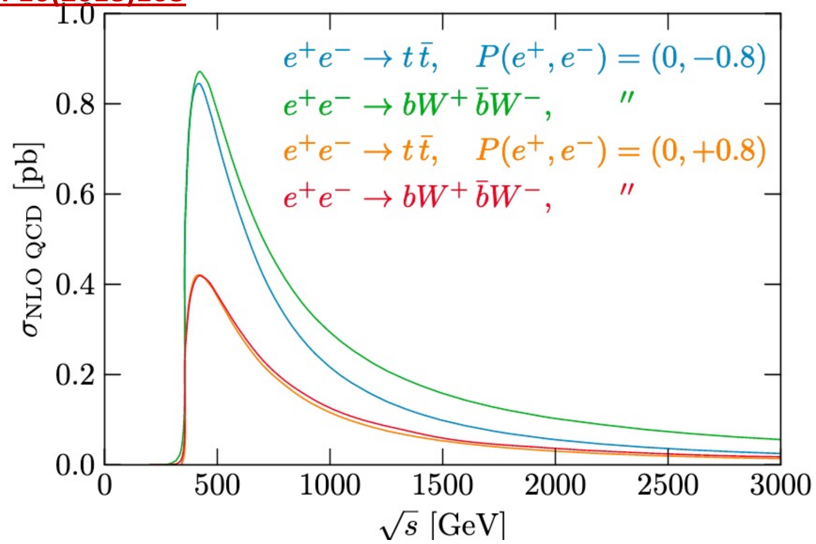
- Sensitivity on (anomalous) $t\bar{t}$ EWK couplings at FCCee. Based only lepton energy and polar angle :

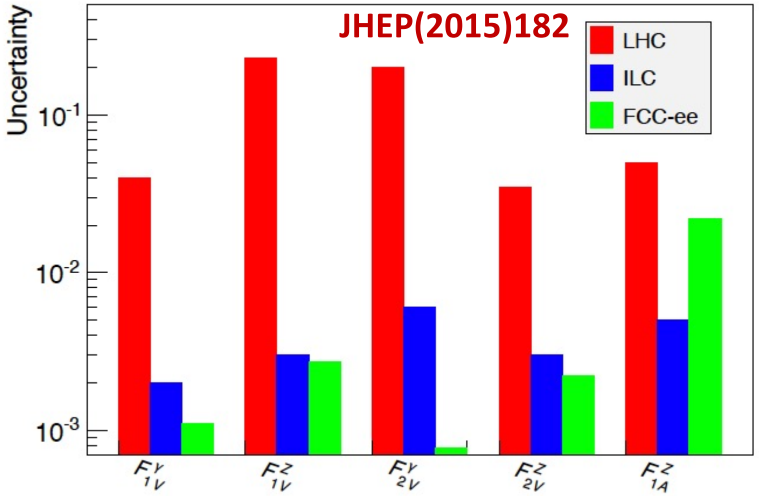
$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X+\gamma_5F_{1A}^X\right)+\frac{\sigma_{\mu\nu}}{2m_t}(p_t+p_{\bar{t}})^\nu\left(iF_{2V}^X+\gamma_5F_{2A}^X\right)\right\},$$

  - low expected experimental uncertainties,
  - dominated by stat. uncertainties.
  - ➔ high constrains even without polarisation.

- Unpolarized beam can still lead to strong constrains on top EWK couplings.

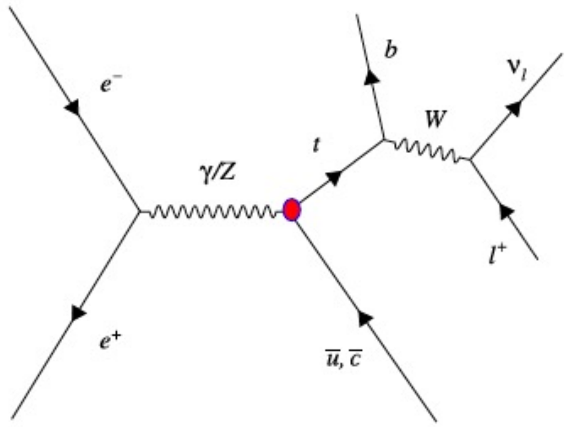
JHEP10(2018)168



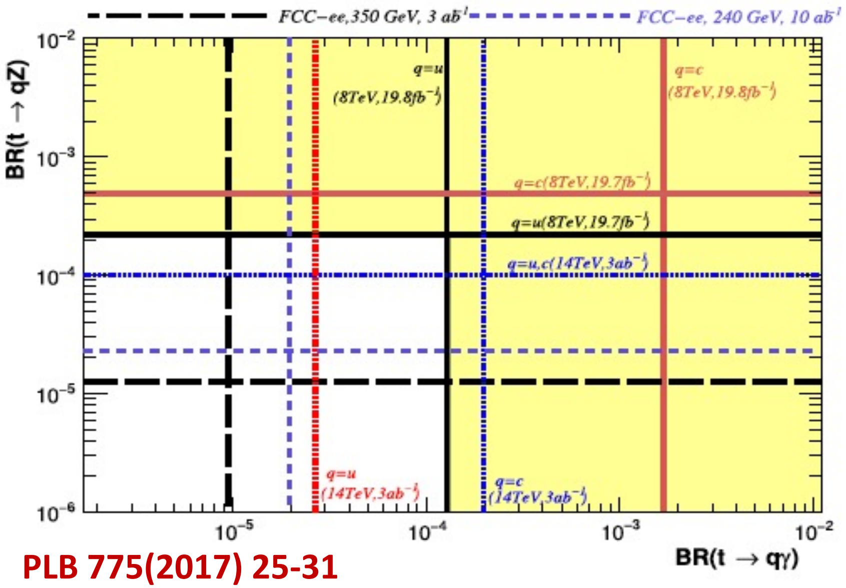

JHEP(2015)182

Sensitive to lumi projections !
Comparisons to be made with care.

# Top quark couplings to bosons



- Top-quark Flavour Changing Neutral current => clear sign of new physics.
- Top-quark FCNC couplings can probed in $t\bar{t}$ with $t \rightarrow Xq$ $(X = \gamma, Z, H$ and $q = u, c)$, but also in single top signatures.
- Single top production possible for $t\gamma -$ and $tZ$-FCNC, already accessible at $\sqrt{s} = 240\ GeV$.
- Very promising channels : higher cross section than $t\bar{t}$ , 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.

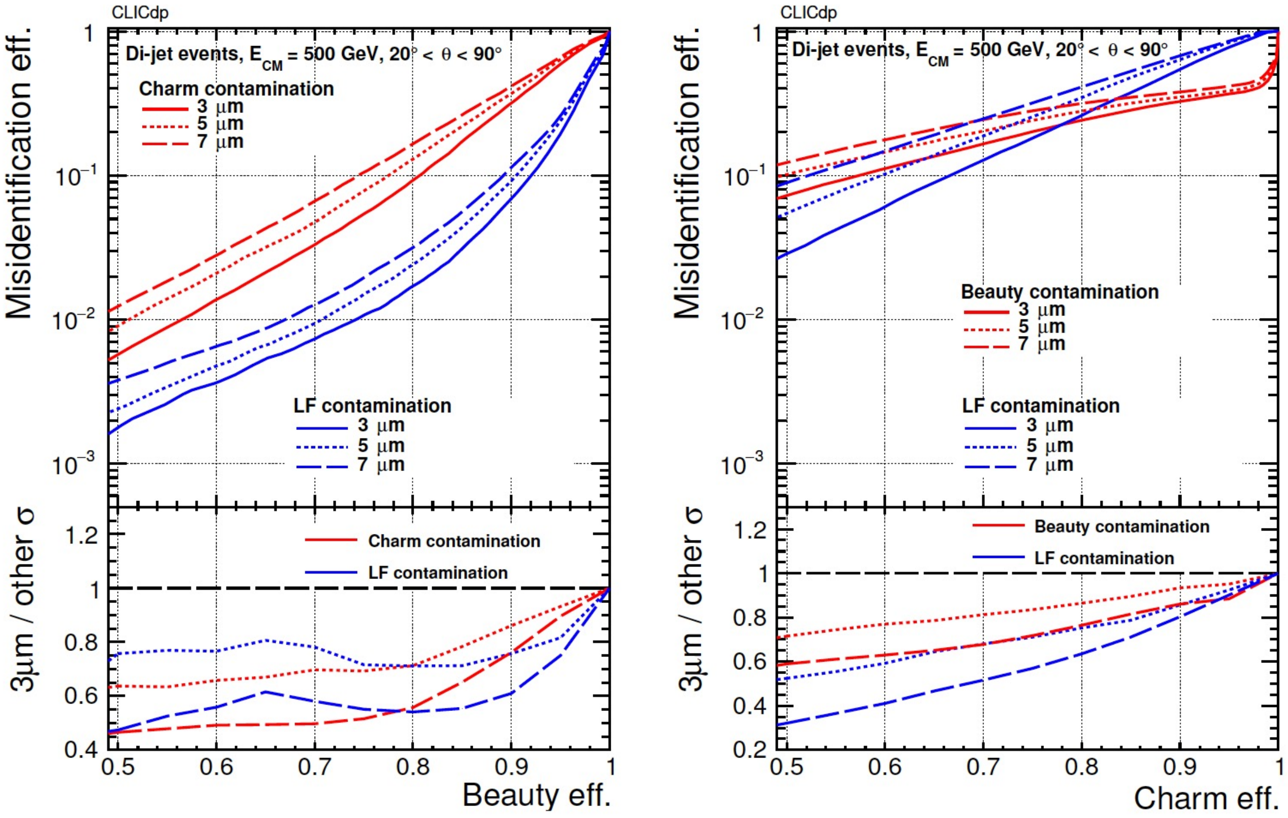


PLB 775(2017) 25-31

**New results coming !**

# 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 , $t \rightarrow cH(b\bar{b})$, $\varepsilon_{tHc} \propto \varepsilon_b^2 \varepsilon_c$.
- B-tagging and c-tagging performances for various single point resolutions.
- From $7\mu$ to $3\mu$:
  - $\varepsilon_b$: $\sim 8\%$(abs.) improvement at $\varepsilon_l \approx 1\%$,
  - $\varepsilon_c$: $\sim 18\%$(abs) improvement at $\varepsilon_l \approx 10\%$.
- Physics performance ⇔ detector designs.

# Conclusion

- The top-quark physics program at lepton colliders is rich.
- Large improvements of precisions measurements and sensitivity to new physics.
- FCCee will deliver a large luminosity, with excellent beam conditions and low background contaminations, but **top quark physics is very relevant at any $e^+e^-$ colliders !**
  - Linear collider (not so much discussed here) also very relevant !
  - Strong benefit from polarisation, but can be compensated by statistic.
- A significant effort should be invested in increasing the maturity of FCCee analyses, with a strong interplay with detector performance related studies.
- Collaborations between ILC, CLIC, CEPC and FCCee very beneficial and important !


YOU CAN NEVER HAVE
TOO MANY BACKUP SLIDES
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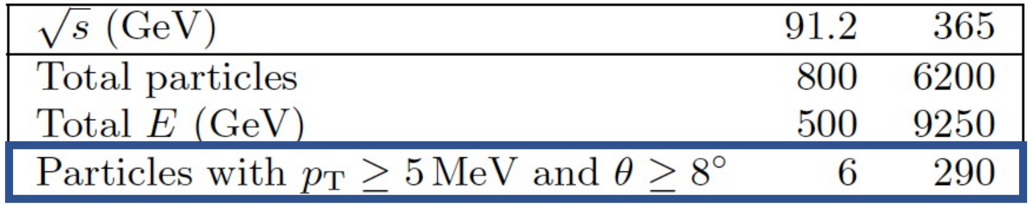
# Beam backgrounds at $t\bar{t}$ threshold

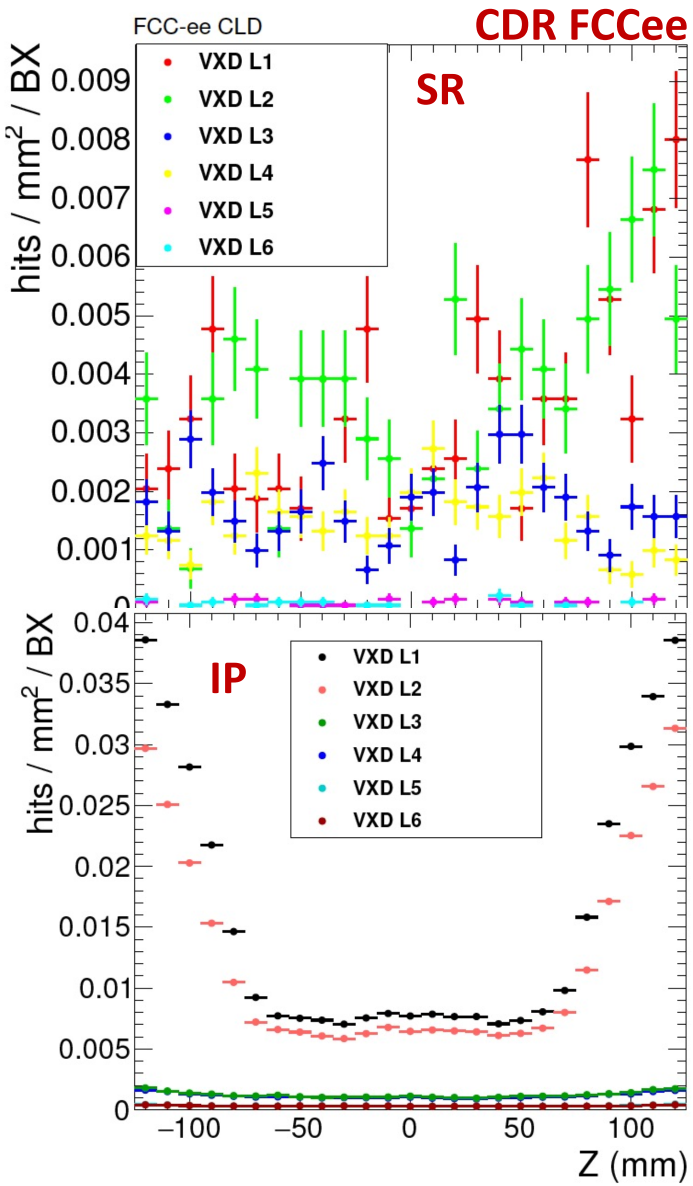
- Beam Backgrounds :
  - $\gamma\gamma \rightarrow hadrons$ found to be negligible,
  - Synchrotron Radiation (SR) from last bending magnet,
  - Incoherent Pair Creation (IPC, $e^+e^-$ pair via interaction with beamstrahlung).

- 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.



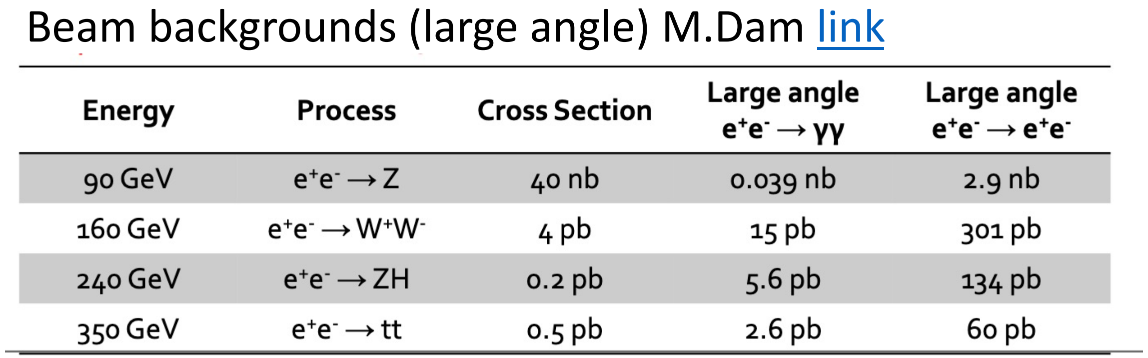
| $\sqrt{s}$ (GeV) | 91.2 | 365 |
|---|---|---|
| Total particles | 800 | 6200 |
| Total $E$ (GeV) | 500 | 9250 |
| Particles with $p_T \geq 5\,\text{MeV}$ and $\theta \geq 8°$ | 6 | 290 |

First CLD layer acceptance



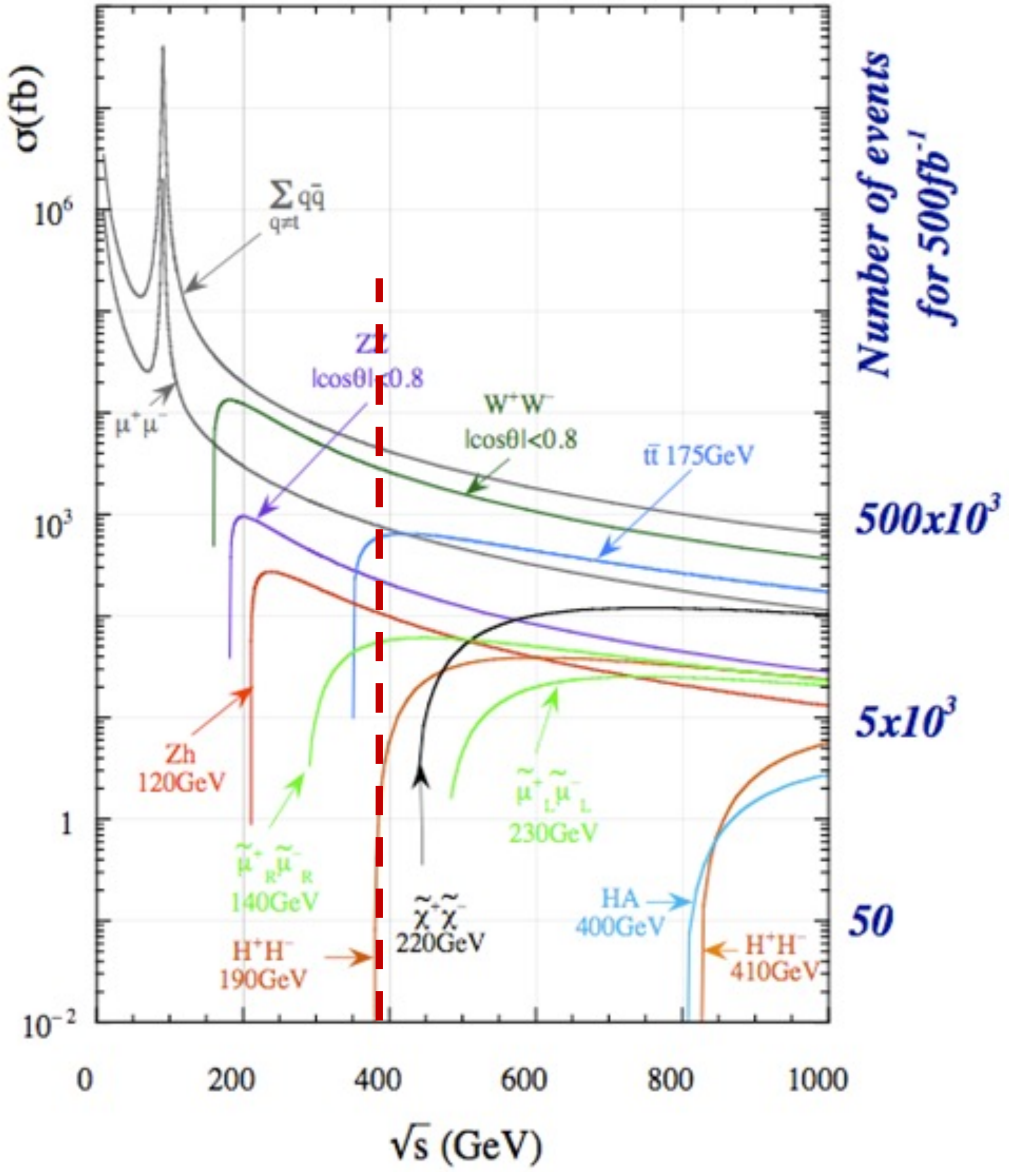
# Discussions on backgrounds

- List of the main background and cross sections.

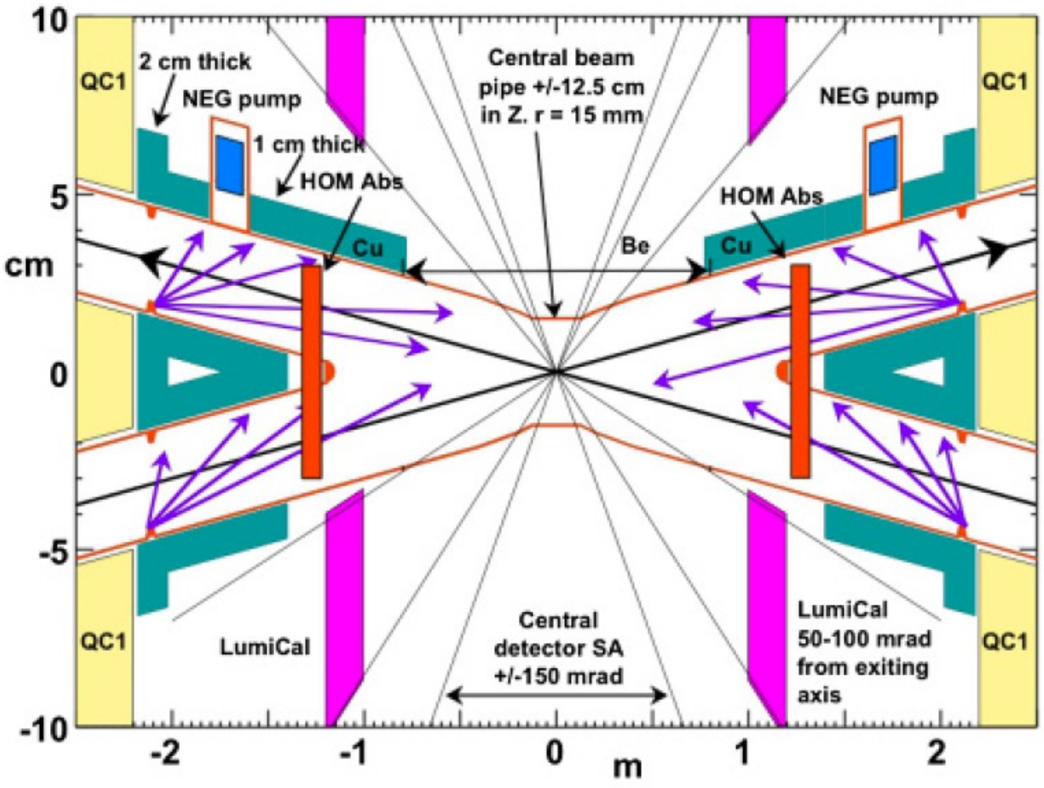


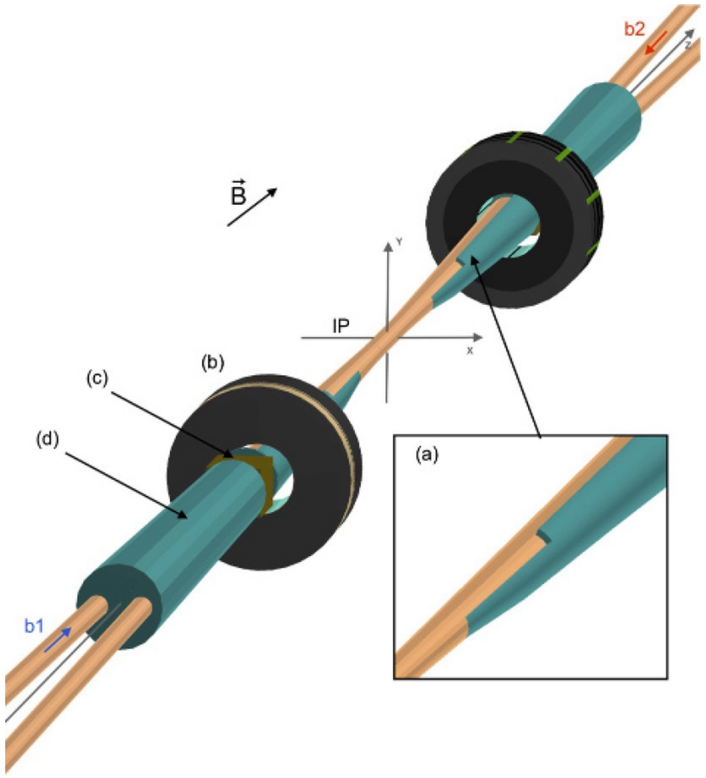
Beam backgrounds (large angle) M.Dam link

| 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 |



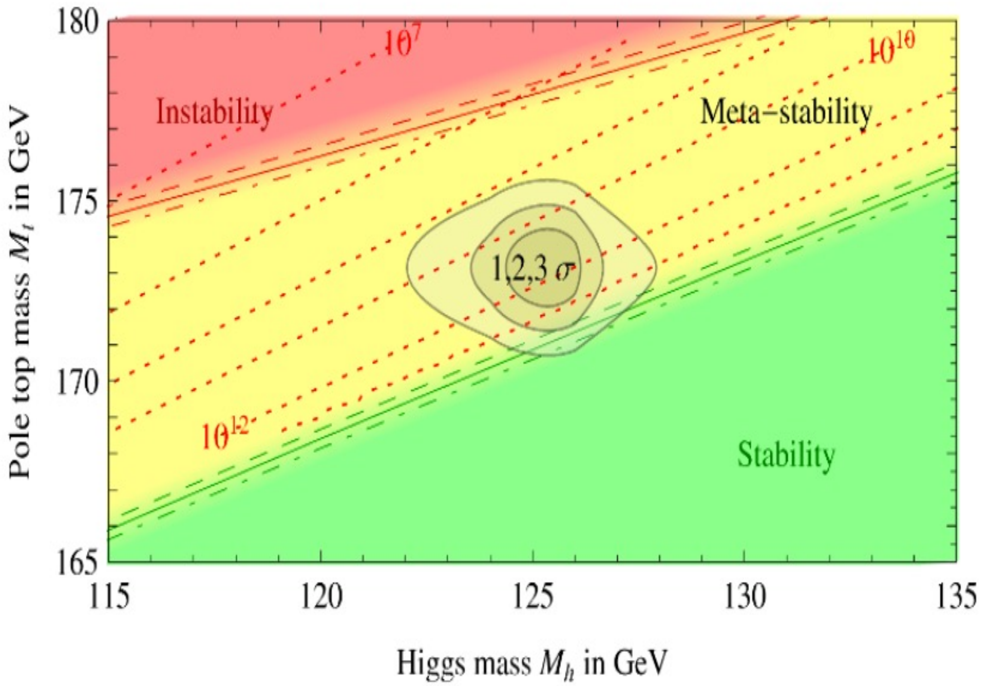
# Interacting points





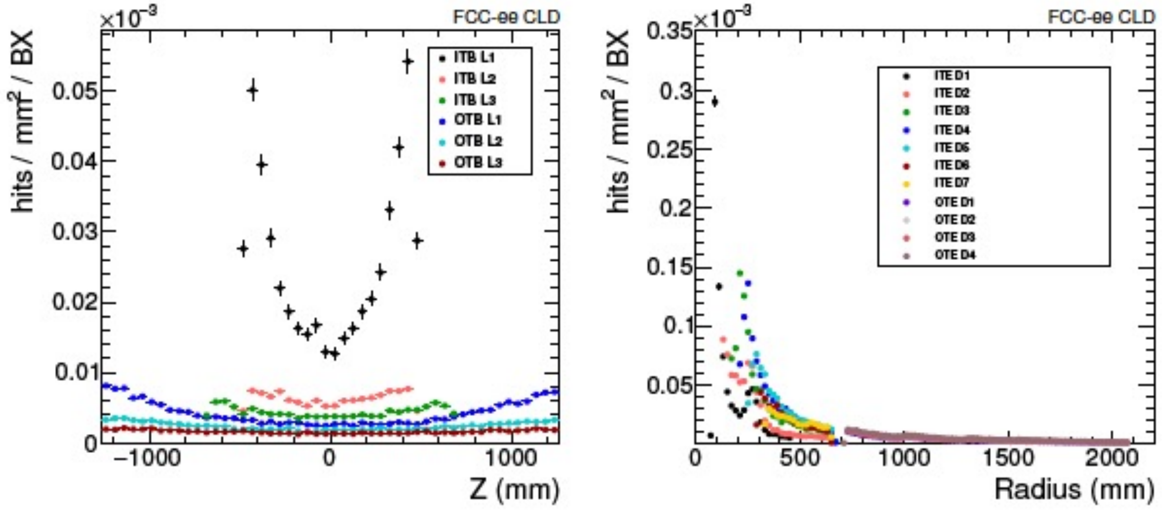
# Top mass : target

JHEP08 98 (2012)



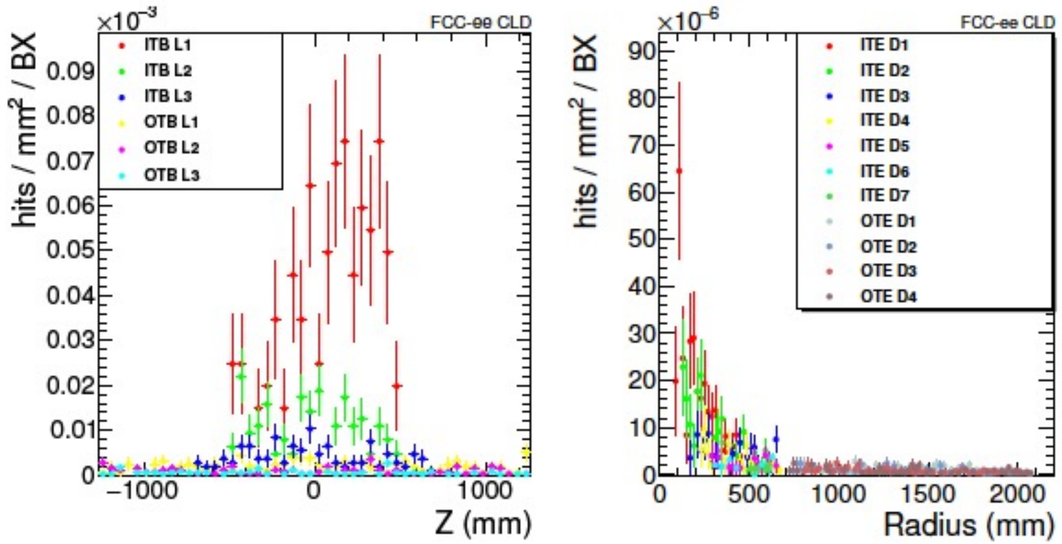
- Objectives of top mass measurement :
  - Test of the SM, yukawa couplings and top mass,
  - Confront pole mass to the “MC” mass (differences of a coupe f hundreds MeV),
  - Study of the stability of the vacuum, differentiations between stable and meta-stable universe.

# 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

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

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|---|---|---|
| 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

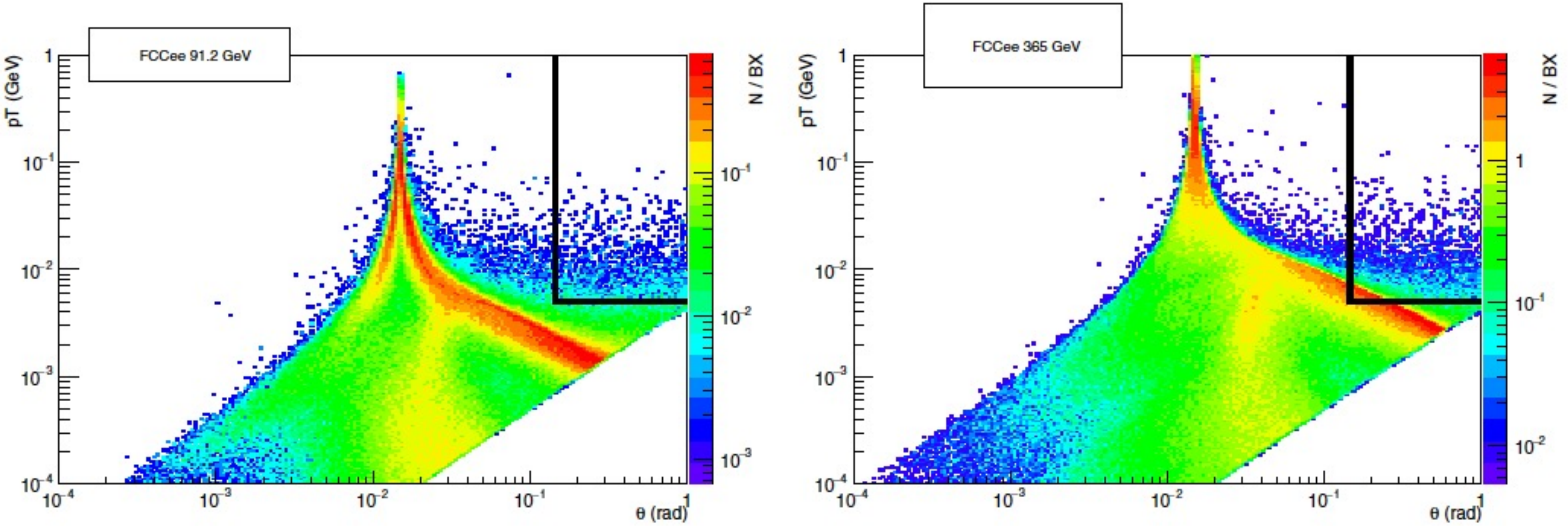


**Fig. 7.2.** Rates of $e^{\pm}$ from IPC in the $(p_{\mathrm{T}}, \theta)$ plane, in the detector frame, for $\sqrt{s} = 91.2\,\mathrm{GeV}$ (left) and 365 GeV (right). The black line in the upper-right corner delineates the CLD vertex detector acceptance within a field of 2 T.

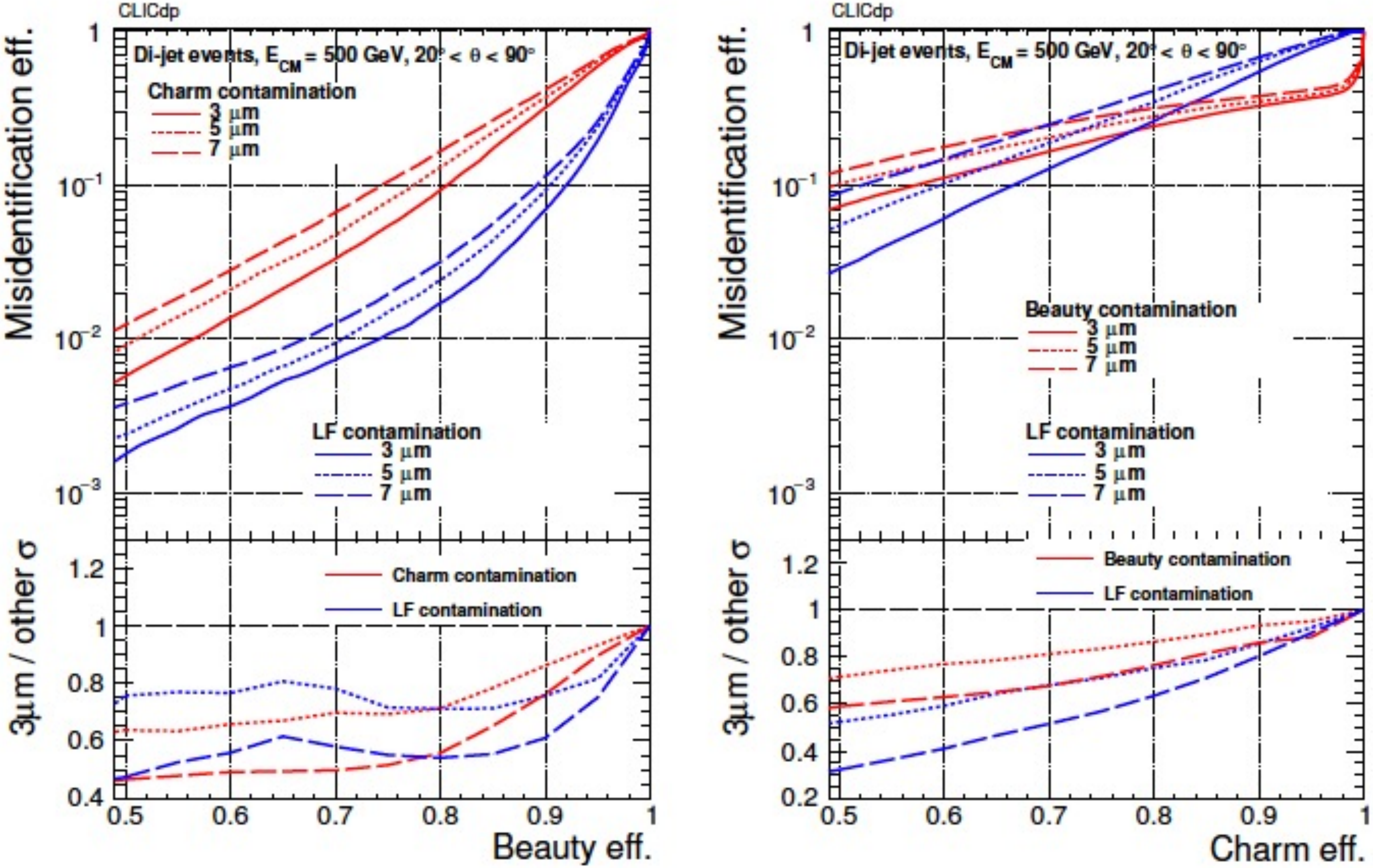
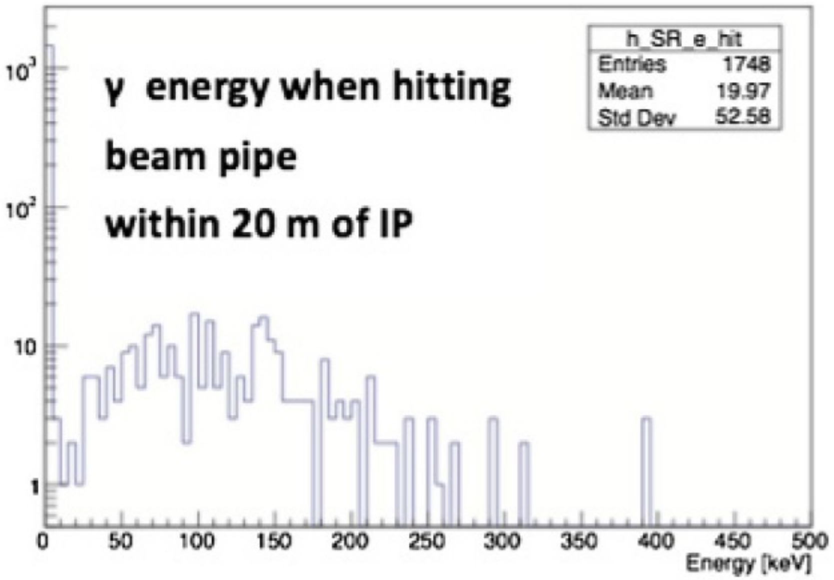


Figure 62: Global performance of beauty tagging (left) and charm tagging (right) for jets in di-jet events at $\sqrt{s} = 500\,\text{GeV}$ with a mixture of polar angles between 20° and 90°. A comparison of performance obtained with different single point resolutions in the vertex detector is presented. 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.

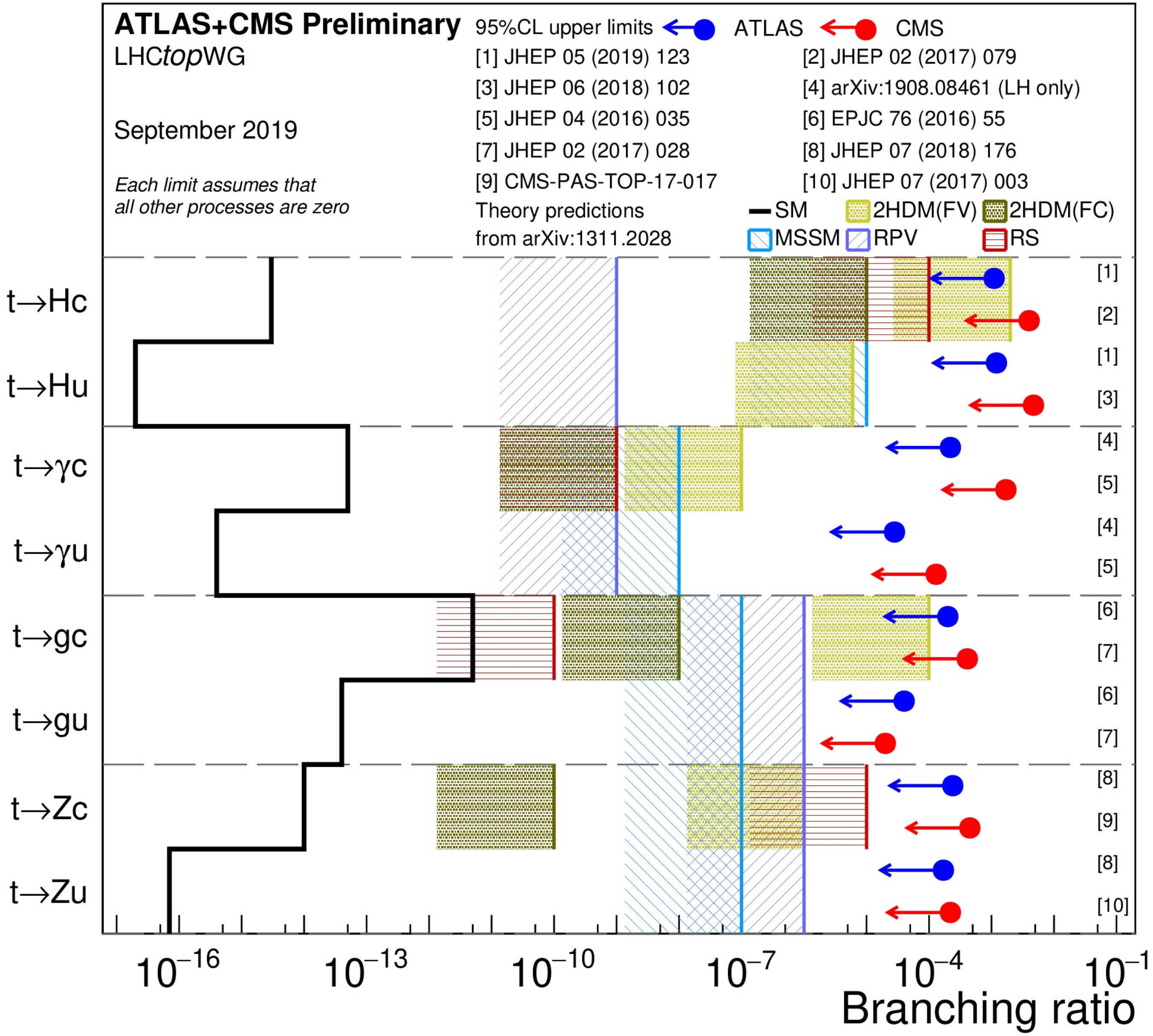


**Notes.** The second column refers to the number of photons incident at 500 $\mu$m from mask tip and with an energy >1 keV, the third and fourth columns give the incident number of photons in the central beam pipe per beam crossing and per second, respectively. Solenoid fields and collimators were not 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.

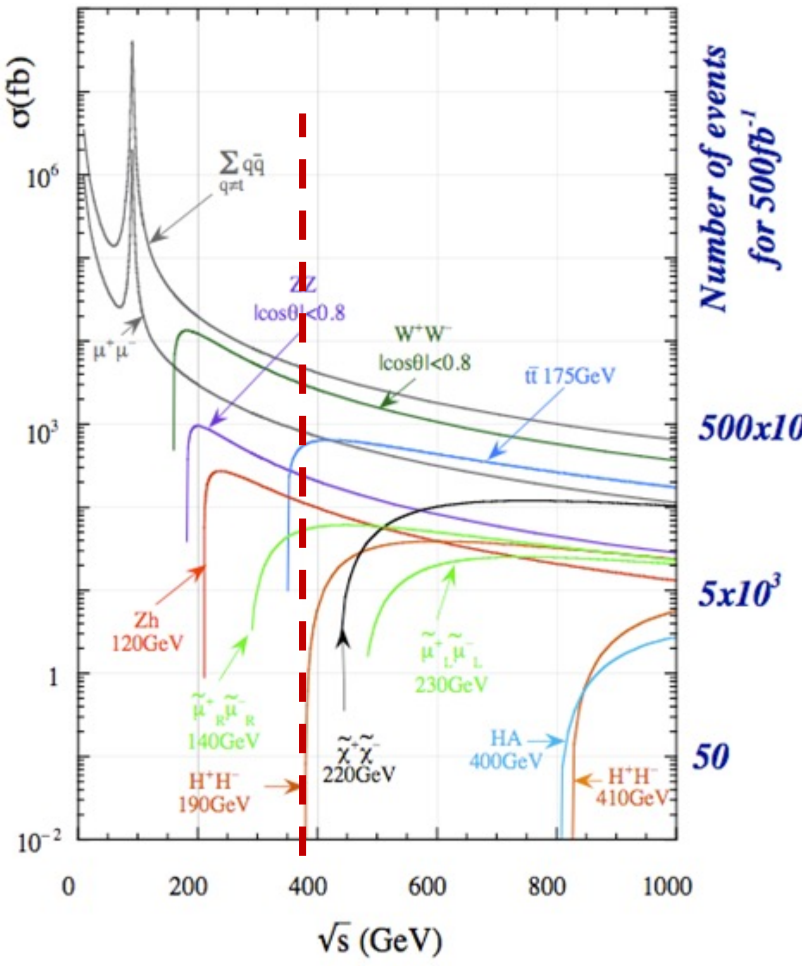
| $E_{\text{beam}}$ GeV | $E_{\text{critical}}$ keV | Incident $\gamma$/crossing (500 $\mu$m from tip) | Incoming on central pipe/crossing | $\gamma$ rate on central pipe (Hz) |
|---|---|---|---|---|
| 182.5 | 113.4. | $3.32 \times 10^9$ | 1195 | $1.18 \times 10^8$ |
| 175 | 100 | $3.06 \times 10^9$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

# Status top FCNC at LHC



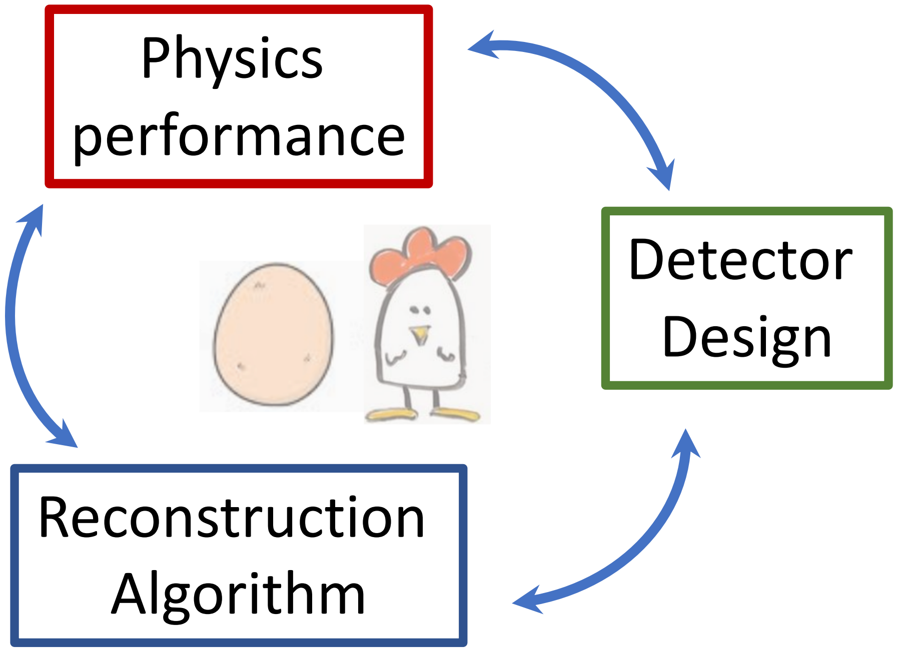
# Do we need a trigger at $t\bar{t}$ threshold ?

- 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)!**



Physics performance

Detector Design

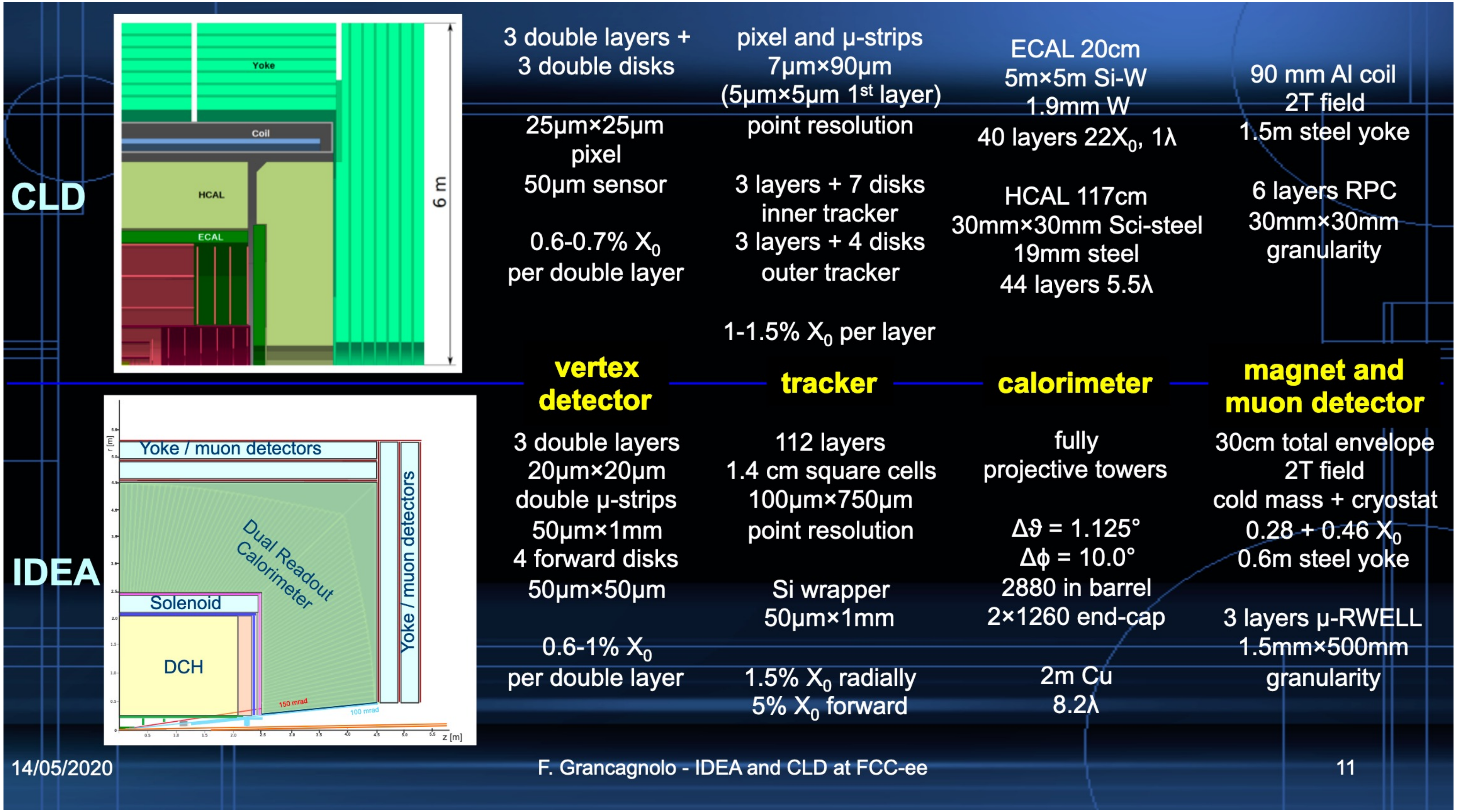
Reconstruction Algorithm

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

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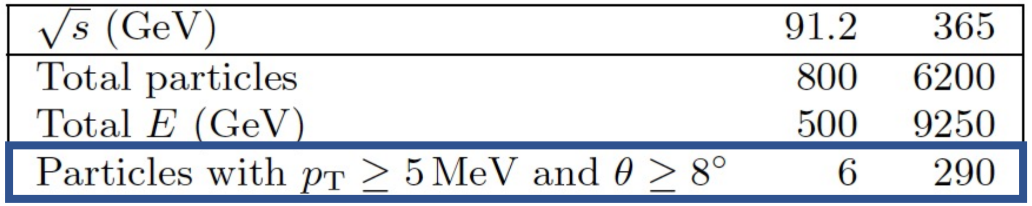
# Beam backgrounds at $t\bar{t}$ threshold

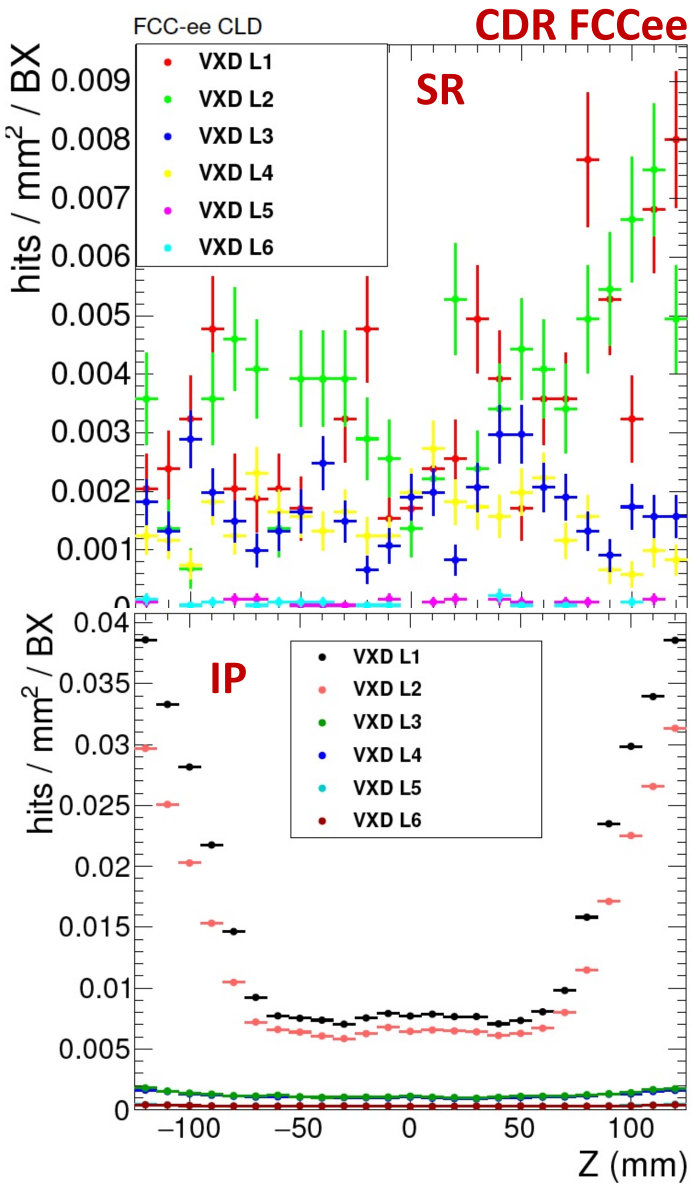
- Beam Backgrounds (CDR) :
  - $\gamma\gamma \rightarrow hadrons$ found to be negligible,
  - Synchrotron Radiation (SR) from last bending magnet,
  - Incoherent Pair Creation (IPC, $e^+e^-$ pair via interaction with beamstrahlung).

- 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 $p_T \geq 5\,\mathrm{MeV}$ and $\theta \geq 8°$ | 6 | 290 |

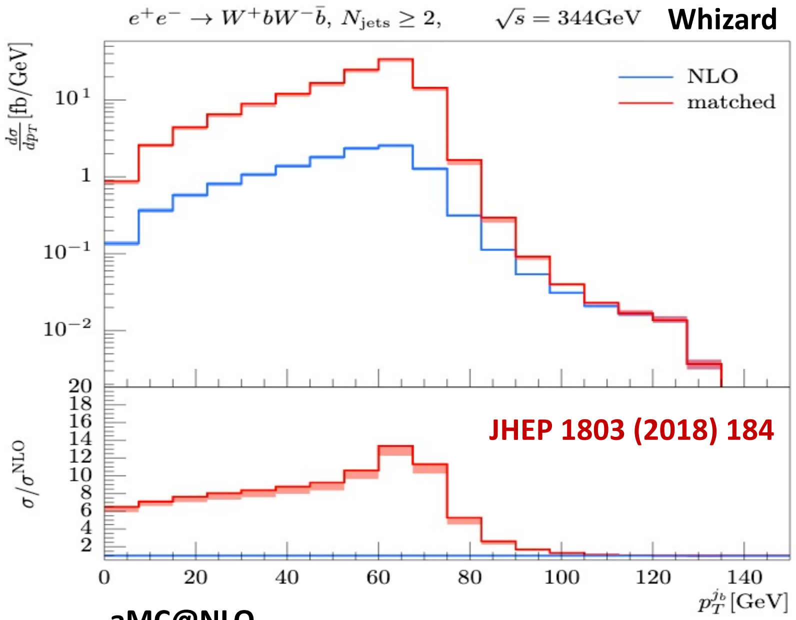
First CLD layer acceptance



# 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 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**

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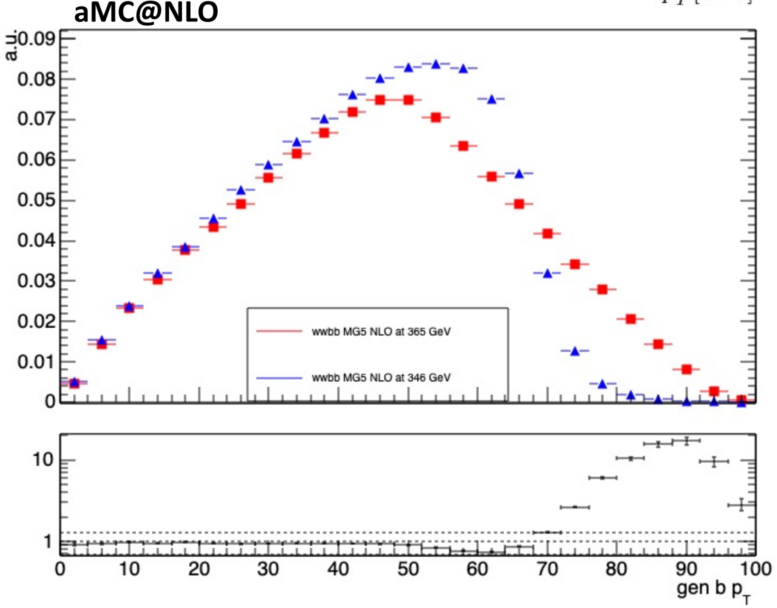
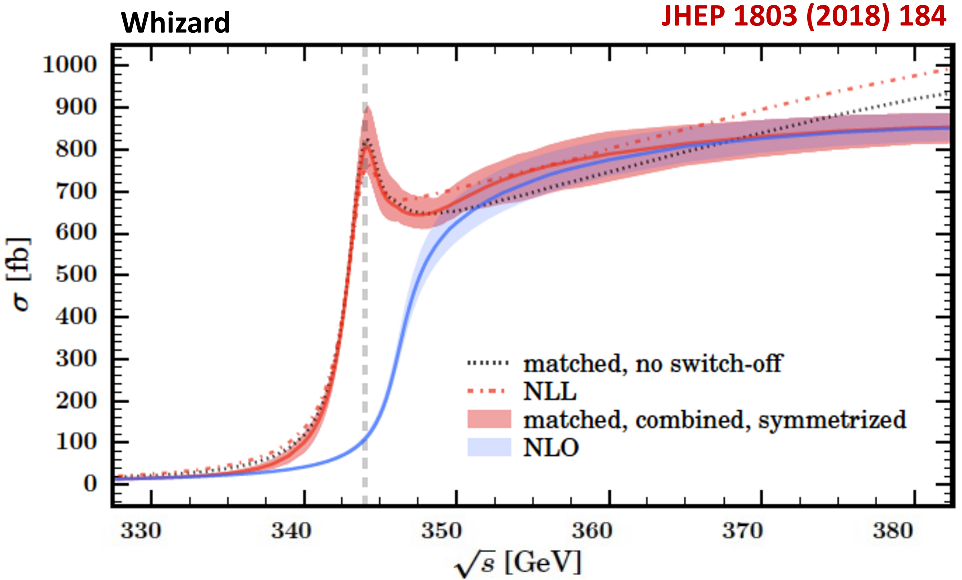

**aMC@NLO**


**Whizard**

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