The top mass at the ttbar threshold with CEPC

2026 CEPC International Workshop

🇵🇹 Lisbon, Portugal

Leyan Li[1,2], Yuming Lin[1,2], Xiaohu Sun[1,2], Yajun Mao[1,2]

Zhan Li[3,4], Kaili Zhang[3,4,†], Shudong Wang[3,4], Gang Li[3,4], Hongbo Liao[3,4], Yaquan Fang[3,4,†]

[1] School of Physics and State Key Lab of Nuclear Physics and Technology, Peking University

[2] Center for High Energy Physics, Peking University

[3] Institute of High Energy Physics

[4] University of Chinese Academy of Sciences

[†] Deceased

April 8th 2026

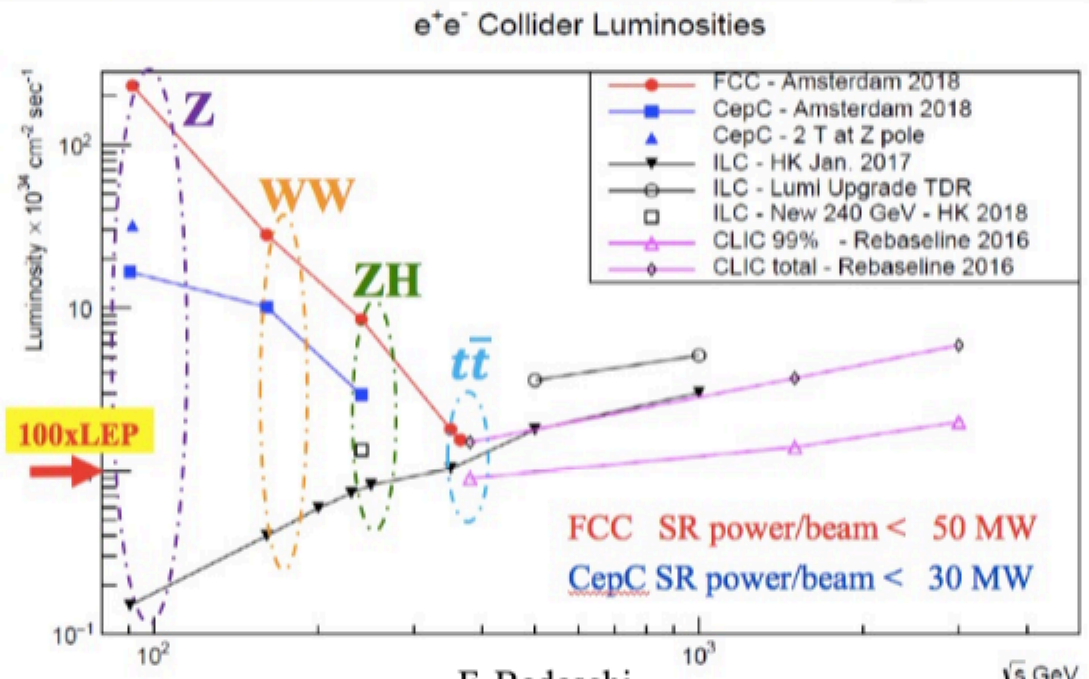
References: Eur. Phys. J. C (2023) 83:269 arXiv:2603.17454

Outline

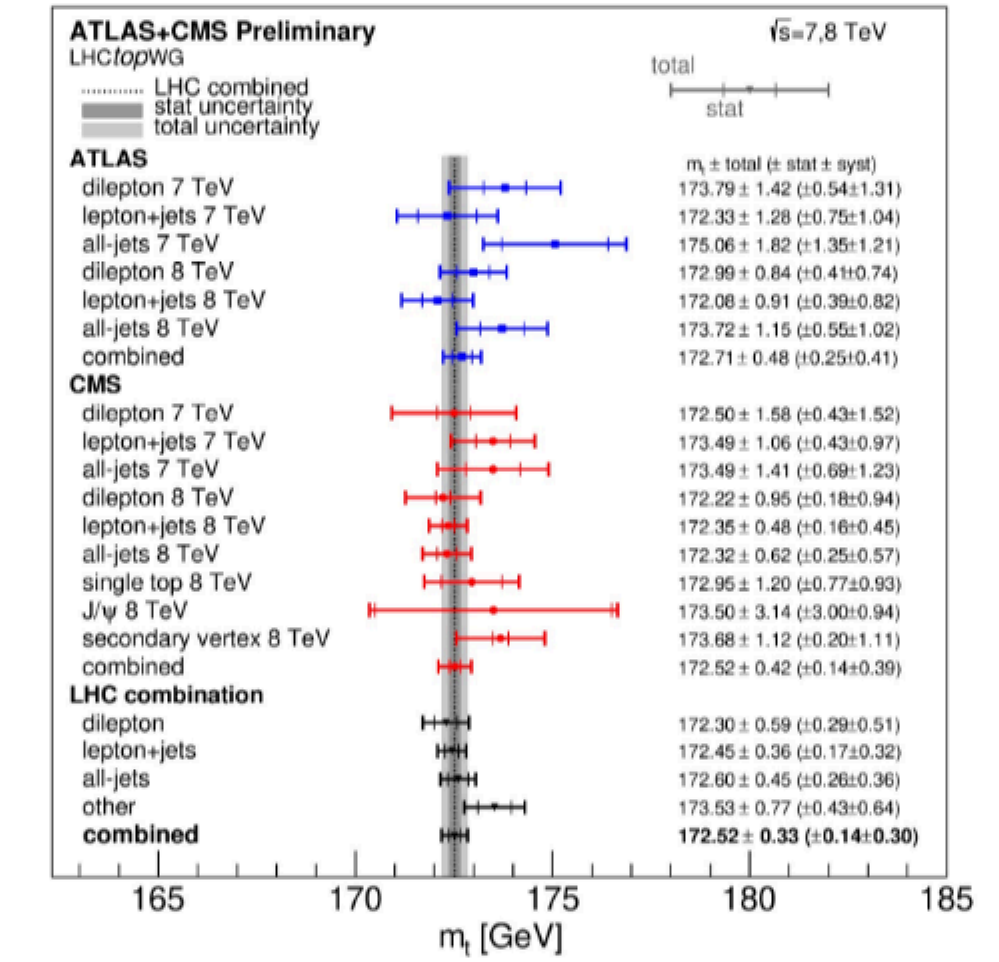
- Motivation
- Simulation & Event Selection
- Analysis & Uncertainties
- Results & Summary
- Comparison with CEPC TDR 2025
- Back Up

Motivation

- **CEPC: A Versatile Machine**
  - — Higgs factory @~240 GeV, Diboson factory @~160 GeV, Z factory @~90 GeV.
  - — @~360 GeV it acts as a playground for **Top quark precision measurements**.
- **Top quark mass measurements at LHC**
  - — The "pole" mass is measured using top reconstruction at hadron colliders.
  - — Heavily relies on the performance of missing transverse energy (MET) and **JER & JES**.
  - — ATLAS+CMS combined measurements reached uncertainties of **330 MeV**.
  - — HL-LHC projection anticipates a precision of **200 MeV**.
  - — Fundamentally limited by systematic uncertainties (e.g., Λ_{QCD} ambiguity).



F. Bedeschi



ATLAS-CONF-2023-066, CMS-PAS-TOP-22-001 for Run1
New results such as CMS Eur. Phys. J. C 83 (2023) 963 with 370 MeV using Run2

- **The Threshold Scan Approach at e^+e^- colliders:**
  - e^+e^- colliders uniquely enable both continuum top reconstruction and precise resonant $t\bar{t}$ threshold scans.
  - The cross-section line shape near the threshold is **highly sensitive to m_t**, serving as the direct observable against center-of-mass energy ($\sqrt{s}$).
  - Measurement extracts a well-defined short-distance mass (e.g., Potential-Subtracted scheme), completely avoiding the $\Lambda_{\mathrm{QCD}} \sim 200$ MeV theory ambiguity.

Our Goal:

Explore the $t\bar{t}$ threshold scan at CEPC using the latest reference detector simulation to **simultaneously extract**:

- Top quark mass m_t
- Top quark width Γ_t
- Strong coupling constant α_s
- Yukawa coupling modifier y_t

- **1. Baseline cross-section:**
  Calculated at **N^{3}LO** precision using `QQbar_threshold` `(v2.2.0)`.

- **2. Nominal Reference Setting:**

$$m_t^{\mathrm{PS}} = 171.5\ \mathrm{GeV}, \qquad \alpha_s(m_Z) = 0.1184$$
$$\Gamma_t = 1.33\ \mathrm{GeV}, \qquad y_t = 1.0$$

- **3. Initial-State Radiation (ISR):**
  ISR photons carry away beam energy, reducing the effective cross-section. (Included at Leading Logarithmic precision).

- **4. Luminosity Spectrum (LS) at CEPC:**
  Integrated via a Gaussian function reflecting CEPC expected beam energy spread:

$$\sigma_{\mathrm{LS}} \approx 0.51\ \mathrm{GeV} \times (\sqrt{s}/360\ \mathrm{GeV})^2$$

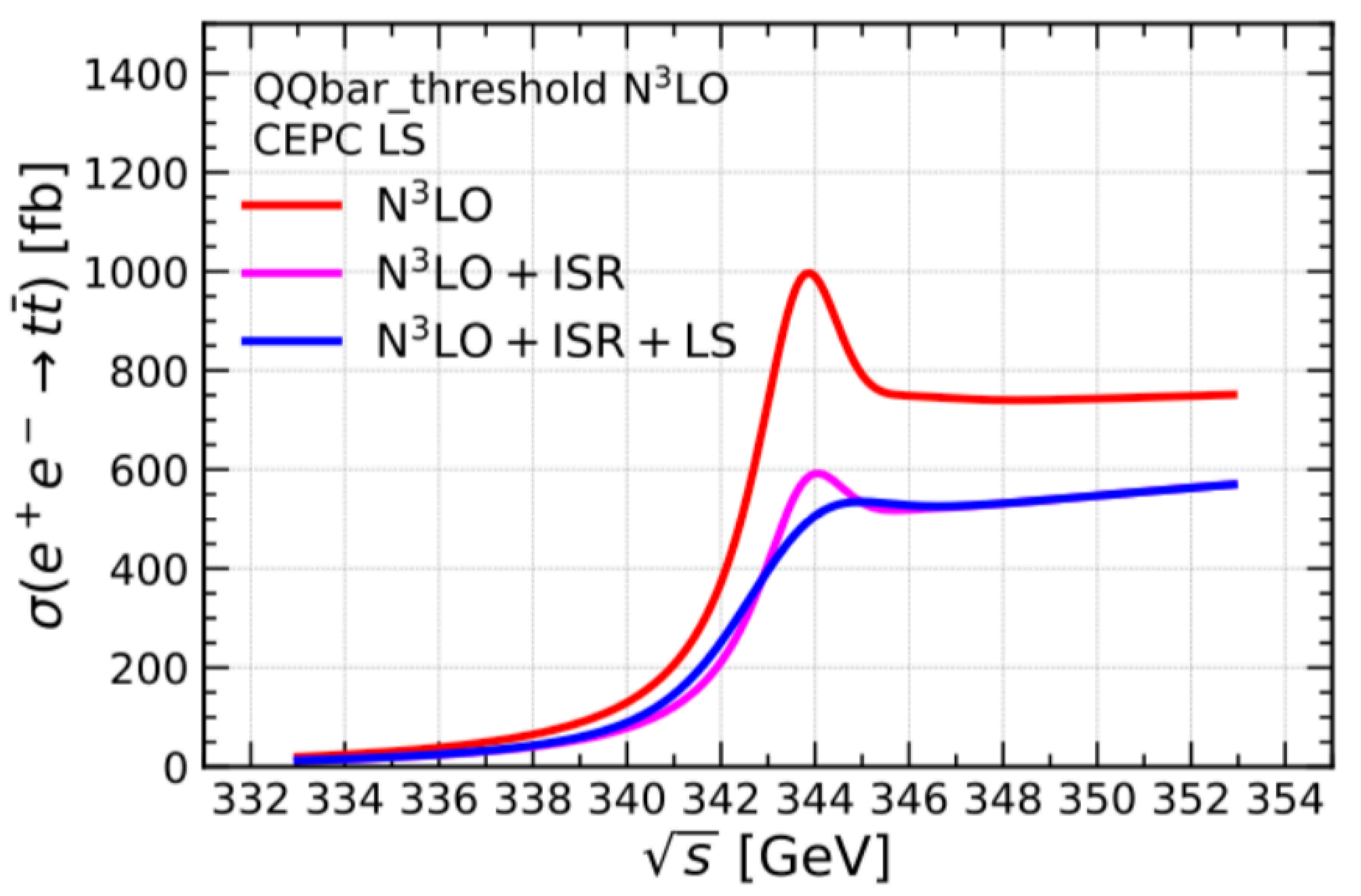


Fig 1. The $t\bar{t}$ cross-section at N^{3}LO with ISR and LS effects.

- **1. Fisher Information Definition:**
  - **Objective:** Quantify sensitivity to physical parameters $\theta \in \{m_t, \Gamma_t, \alpha_s, y_t\}$.
  - **Statistical Model:** Observed count n follows a Gaussian $G(n \mid n_0, \sqrt{n_0})$.
  - **Expected Yield:** $n_0 = \mathcal{L}\sigma_0$ ($\mathcal{L}$: luminosity, σ_0: theoretical cross-section).

$$I(\sqrt{s}) = \int \left(\frac{\partial \log G(n \mid n_0, \sqrt{n_0})}{\partial \theta} \right)^2 \times G(n \mid n_0, \sqrt{n_0})\, dn$$

- **2. Sensitivity Peaks → Scan Points (Fig 2):**
  - The **threshold region** maximizes sensitivity to m_t.
  - The **cross-section peak** is most sensitive to Γ_t (broadens the resonance), α_s and y_t (govern overall rate).
  - To capture **all** information peaks → 5-point scan:

$$\sqrt{s} = \{342.0,\ \underbrace{342.5}_{m_t},\ 343.0,\ \underbrace{343.5}_{\alpha_s,\, y_t},\ \underbrace{344.0}_{\Gamma_t}\}\ \text{GeV}$$

- **3. Luminosity Scenarios:**
  - **BASE:** 56 fb^{-1} / point (Total 280 fb^{-1}, 1 yr × 2 IPs)
  - **EXT:** 84 fb^{-1} / point (Total 420 fb^{-1}, 50% upgrade)

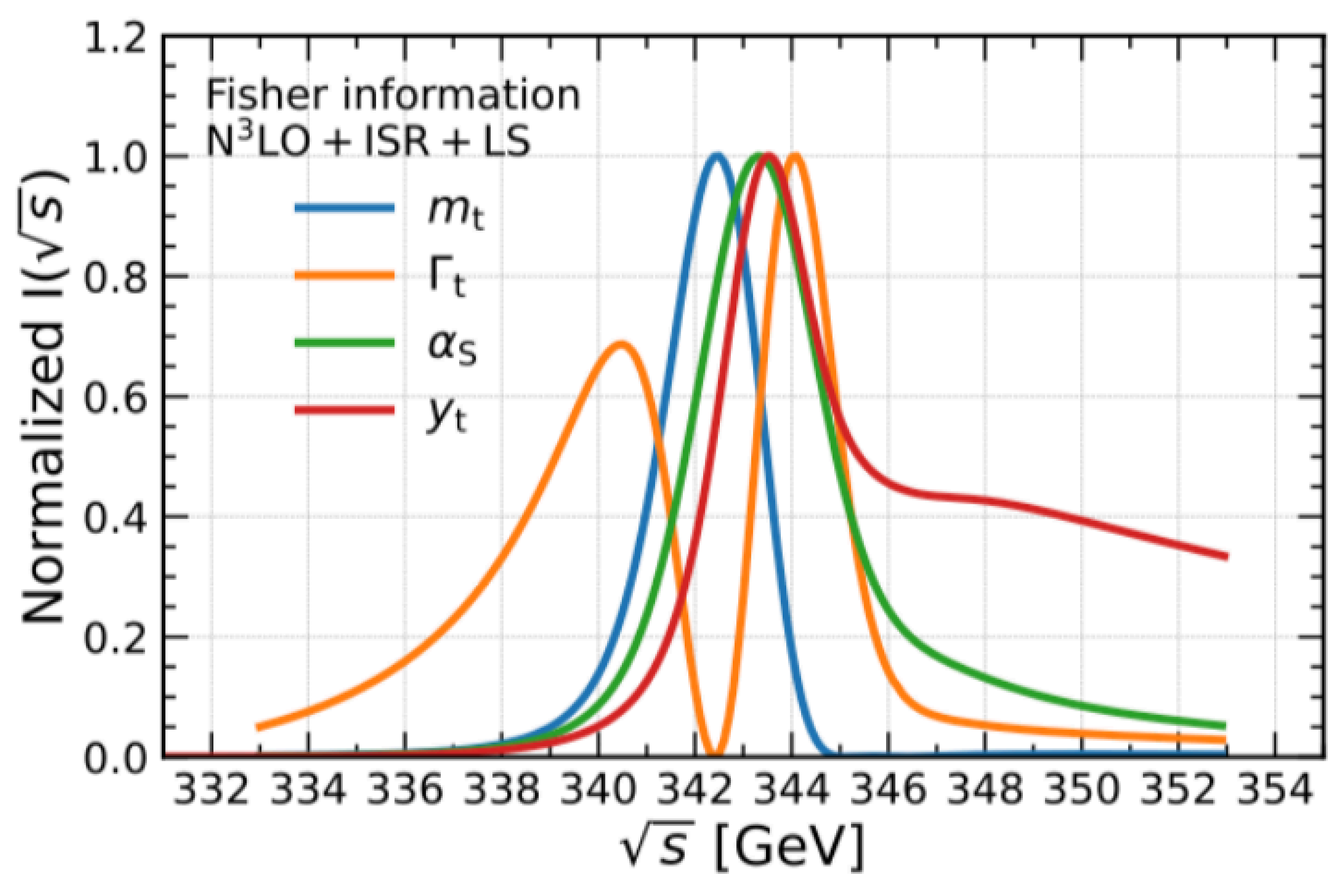


Fig 2. Normalized Fisher information for the four parameters.

Simulation & Event Selection

- **Target Signal Topologies:**
  - **Full-hadronic:** $t\bar{t} \to bq\bar{q}'\bar{b}q''\bar{q}'''$ (BR = 44.2%)
  - **Semi-leptonic:** $t\bar{t} \to bq\bar{q}'\bar{b}l\nu$, $l \in \{e, \mu\}$ (BR = 29.9%)
  - Excluding $W \to \tau\nu$ channels, as the multiple neutrinos from τ decays severely degrade the kinematic fit resolution.
- **MC Generation Chain:**
  - **Signal XS Calculation:** N^{3}LO precision using `QQbar_threshold 2.2.0`.
  - **Event Generation (Sig & Bkg):** `MG5_aMC@NLO 3.6.3` with ISR effects enabled.
  - **Shower & Hadronization:** `PYTHIA 8.3`.
  - **Note:** The $q\bar{q}$ background represents $q = u, d, s, c$.

Process	Order	Cross section [fb] at $\sqrt{s}$ [GeV]		
		342.0	343.0	344.0
$t\bar{t}$ (full-had)	N^{3}LO	98.58	181.52	248.03
$t\bar{t}$ (semi-lep)	N^{3}LO	66.75	122.89	167.93
Single top	LO	6.01	6.40	6.80
WW	LO	11,632	11,594	11,552
ZWW	LO	11.05	11.27	11.47
ZZ	LO	705.0	701.9	699.2
ZZZ	LO	0.608	0.605	0.603
$b\bar{b}$	LO	4,678	4,646	4,621
$q\bar{q}$	LO	18,486	18,381	18,258

Tab 1. Cross-sections of signal and background processes.

- **Detector Simulation:**
  - Employs **DELPHES** with the latest CEPC Reference TDR detector card [K. Zhang, iHEP GitLab (2025)].
  - Provides parameterized tracking, calorimetry, and PID responses.
- **Lepton Reconstruction:**
  - Tracking efficiency ~99.7% for $p_T > 0.5$ GeV within $|\eta| < 3.0$.
  - ECAL resolution: $\sigma_E/E \approx 1\% \oplus 3\%/\sqrt{E}$.
  - Isolation requirement: $\sum p_T^{\Delta R<0.5} < 12\% p_T^l$.
- **Jet Reconstruction & Flavor Tagging:**
  - $e^+e^- k_T$ (Durham) algorithm in exclusive mode (6 jets for FH, 4 jets for SL).
  - Parametric b-tagging: **95%** efficiency and 1% mis-tag rate for both c- and light-flavor jets.

CEPC Reference Detector

Features high-precision tracking (with 30 ps time resolution) and excellent electromagnetic calorimetry, enabling robust physics object reconstruction essential for precision top-quark mass extraction.

- **Pre-selection Requirements:**
  - **Semi-leptonic:** **1 isolated lepton** ($E > 12$ GeV, IPS < 3.3) + **4 jets** (≥ 2 b-tags).
  - **Full-hadronic:** **Lepton veto** + **6 jets** (≥ 2 b-tags).
- **Event shape variables cuts:**
  - Jet clustering bounds (y_{ij}) and global shapes (S, T) strongly suppress backgrounds with **fewer or softer jets** (e.g. $b\bar{b}$, $q\bar{q}$, multi-bosons).
  - After these 8 criteria, total remaining backgrounds (excluding single-top) are heavily reduced to $\lesssim$ **1 fb** in both channels.

Variable / Cut	Semi-leptonic	Full-hadronic
$\log y_{34}$	> -3.0	> -2.0
$\log y_{45}$	> -4.3	> -2.5
$\log y_{56}$	-	> -3.0
Total PFOs (N_{PFO})	≥ 40	≥ 50
Charged PFOs ($N_{\text{PFO}}^{\text{charged}}$)	≥ 14	≥ 28
Max momentum [GeV]	< 86	< 65
Visible energy E_{vis} [GeV]	$[212, 318]$	$[262, 359]$
Sphericity (S)	> 0.34	> 0.42
Thrust (T)	< 0.87	< 0.82

Kinematic Fit

- **Combinatorial Challenge:** Resolving correct jet-parton pairing to reconstruct top quarks.
- The χ^2 comprises three groups of constraints:
  - **4-momentum conservation** — total energy and 3-momentum must equal E_{com}.
  - **Mass constraints** — reconstructed W and top masses match their nominal values.
  - **Energy calibration** (sf) — unity scale factors $(sf_k - 1)^2$ penalize deviations of the rescaled jet/lepton energies from their measured values, preventing unphysical energy shifts during the fit.
- **χ^2-Constrained Kinematic Fit Components:**

4-Momentum Conservation

SL (4 terms):

$$\left(\frac{E_{b_H b_L jjl\nu} - E_{com}}{\sigma_E}\right)^2 + \sum_{P=x,y,z}\left(\frac{\Sigma_{b_H b_L jjl\nu} P_i}{\sigma_P}\right)^2$$

FH (4 terms):

$$\left(\frac{\sum_{i\in 6j} E_i - E_{com}}{\sigma_E}\right)^2 + \sum_{P=x,y,z}\left(\frac{\sum_{i\in 6j} P_i}{\sigma_P}\right)^2$$

Mass Constraints

SL (4 terms):

$$\left(\frac{M_{b_H jj} - M_{t_H}}{\sigma_{M_{t_H}}}\right)^2 + \left(\frac{M_{b_L l\nu} - M_{t_L}}{\sigma_{M_{t_L}}}\right)^2 + \left(\frac{M_{jj} - M_{W_H}}{\sigma_{M_{W_H}}}\right)^2 + \left(\frac{M_{l\nu} - M_{W_L}}{\sigma_{M_{W_L}}}\right)^2$$

FH (4 terms):

$$\left(\frac{M_{(bjj)_1} - M_{t_1}}{\sigma_{M_{t_1}}}\right)^2 + \left(\frac{M_{(bjj)_2} - M_{t_2}}{\sigma_{M_{t_2}}}\right)^2 + \left(\frac{M_{(jj)_1} - M_{W_1}}{\sigma_{M_{W_1}}}\right)^2 + \left(\frac{M_{(jj)_2} - M_{W_2}}{\sigma_{M_{W_2}}}\right)^2$$

Energy Calibration

SL (4 terms):

$$\sum_{k\in\{b_{H,L},jj,l\}} (sf_k - 1)^2$$

FH (6 terms):

$$\sum_{k=1}^{6} (sf_{\text{jet}_k} - 1)^2$$

- **Optimization Thresholds:** Semi-leptonic (12 terms): $\chi^2 < 10.0$ | Full-hadronic (14 terms): $\chi^2 < 9.0$. Strict χ^2 cuts deeply suppress irreducible **single-top backgrounds**.
- **Final Signal Efficiency** ($\sqrt{s}$ = 342–344 GeV): sl **~50%**, hh **~60%**.

Analysis & Uncertainties

- **Profiled Likelihood Scan:**
  - Multi-dimensional scan on $\mathcal{L}$ over $m_t, \Gamma_t, \alpha_S, y_t$; all systematics **except** theoretical $t\bar{t}$ cross-section uncertainty are **profiled**.
  - Combines $N = 5$ energy points $\sqrt{s} = \{342.0,\ 342.5,\ 343.0,\ 343.5,\ 344.0\}$ GeV; observed count D follows Poisson distribution P at each energy.

Likelihood Function (Eq. 2):

$$\mathcal{L} = \prod_{i=1}^{N} P\Big(D \;\Big|\; \big(\sigma_i^{t\bar{t}}(m_t, \Gamma_t, \alpha_S, y_t, \sqrt{s}_i, \xi) \cdot \epsilon_i^s(\xi) + \sigma_i^{\text{bkg}}(\sqrt{s}_i, \xi) \cdot \epsilon_i^b(\xi)\big) \times L_i\Big) \;\times\; \mathcal{N}(\xi \,|\, 0, 1)$$

$\sigma_i^{t\bar{t}}$: signal XS from QQbar_threshold; $\epsilon_i^{s,b}$: selection efficiencies; σ_i^{bkg}: background XS; L_i: integrated luminosity; ξ: nuisance parameters constrained by Gaussian priors $\mathcal{N}(\xi|0,1)$.

- **Profiled Systematic Uncertainties** — impacts on m_t / Γ_t:
  - **Physics parameters** — the **leading** systematic sources:
    — y_t (3% precision by HL-LHC era): → **4.2 / 5.9 MeV**
    — α_S (projected 0.0001 from Z-pole): → **2.4 / 3.1 MeV**
  - These are constrained by **Gaussian priors** from external measurements and profiled in the likelihood fit.

Uncertainties	m_t [MeV]		Γ_t [MeV]	
	BASE	EXT	BASE	EXT
Statistics	±5.6	±4.6	±18.0	±14.6
α_S ★	**±2.4**		**±3.1**	
y_t ★	**±4.2**		**±5.9**	
Luminosity	±0.1		±0.1	
BE	±1.3		±0.0	
LS	±0.2		±2.8	
b-tagging	±1.0		±1.7	
Total	**±7.5**	**±6.7**	**±19.4**	**±16.2**
Theory	$^{+1.3}_{-32.9}$		$^{+0.0}_{-79.9}$	

Tab. 3. Uncertainty budget. ★ = highlighted on this slide.

- **Machine & Detector** — sub-dominant sources:
  - Luminosity spectrum (1%): 0.2 / **2.8** MeV — largest detector effect on Γ_t.
  - Beam energy (1.8 MeV/beam): **1.3** / 0.0 MeV.
  - b-tagging efficiency (1%): 1.0 / 1.7 MeV.
  - Luminosity measurement (0.01%): 0.1 / 0.1 MeV — negligible.

Uncertainties	m_t [MeV]		Γ_t [MeV]	
	BASE	EXT	BASE	EXT
Statistics	±5.6	±4.6	±18.0	±14.6
α_S	±2.4		±3.1	
y_t	±4.2		±5.9	
Luminosity ★	**±0.1**		**±0.1**	
BE ★	**±1.3**		**±0.0**	
LS ★	**±0.2**		**±2.8**	
b-tagging ★	**±1.0**		**±1.7**	
Total	**±7.5**	**±6.7**	**±19.4**	**±16.2**
Theory	$^{+1.3}_{-32.9}$		$^{+0.0}_{-79.9}$	

Tab. 3. Uncertainty budget. ★ = highlighted on this slide.

Uncertainty Budget & Extraction

- **Non-profiled Theoretical Uncertainty**:
  - **Renormalization scale variation** (×0.5, ×2.0), envelope convention:
  - Highly asymmetric: marginal upward, significant downward shift up to -5%.
  - $\Delta m_t = ^{+1.3}_{-32.9}$ **MeV**, $\Delta\Gamma_t = ^{+0.0}_{-79.9}$ **MeV — currently the limiting factor.**
- α_S **and** y_t **extraction:**
  - $\delta\alpha_S = 0.00143\ (0.00116)$
  - $\delta y_t = 0.197\ (0.160)$
  - With m_t, Γ_t profiled as free parameters.

Uncertainties	m_t [MeV]		Γ_t [MeV]	
	BASE	EXT	BASE	EXT
Statistics	±5.6	±4.6	±18.0	±14.6
α_S	±2.4		±3.1	
y_t	±4.2		±5.9	
Luminosity	±0.1		±0.1	
BE	±1.3		±0.0	
LS	±0.2		±2.8	
b-tagging	±1.0		±1.7	
Total ★	**±7.5**	**±6.7**	**±19.4**	**±16.2**
Theory ★	$^{+1.3}_{-32.9}$		$^{+0.0}_{-79.9}$	

Tab. 3. Uncertainty budget. ★ = highlighted on this slide.

Results & Summary

- **Two-dimensional Likelihood Scans:**
  - Full systematic uncertainties **except** theoretical $t\bar{t}$ XS are profiled.
  - BASE scenario: 56 fb^{-1}/pt (total 280 fb^{-1}).
- **Precision (BASE):**

Δm_t: stat. = **±5.6** MeV, total = **±7.5** MeV
$\Delta\Gamma_t$: stat. = ±18.0 MeV, total = ±19.4 MeV
$\delta\alpha_S = 0.00143, \;\; \delta y_t = 0.197$

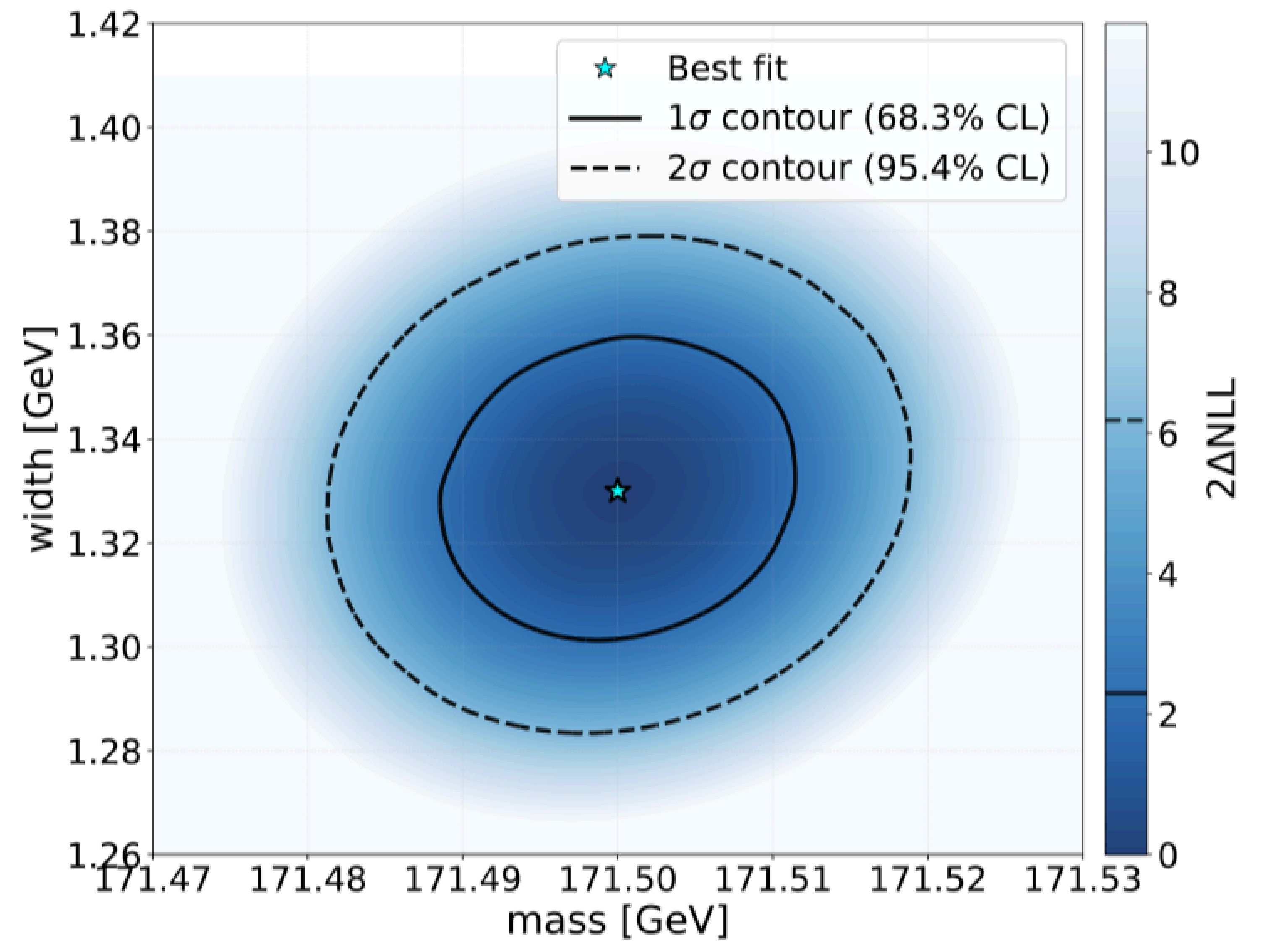


Fig 3. 2D likelihood scan over m_t and Γ_t, BASE scenario (56 fb^{-1}/pt).

- **Two-dimensional Likelihood Scans:**
  - Full systematic uncertainties **except** theoretical $t\bar{t}$ XS are profiled.
  - EXT scenario: 84 fb^{-1}/pt (420 fb^{-1} total), 50% lumi upgrade.
- **Precision (EXT):**

Δm_t: stat. = **±4.6** MeV, total = **±6.7** MeV

$\Delta\Gamma_t$: stat. = ±14.6 MeV, total = ±16.2 MeV

$\delta\alpha_S = 0.00116,\ \ \delta y_t = 0.160$

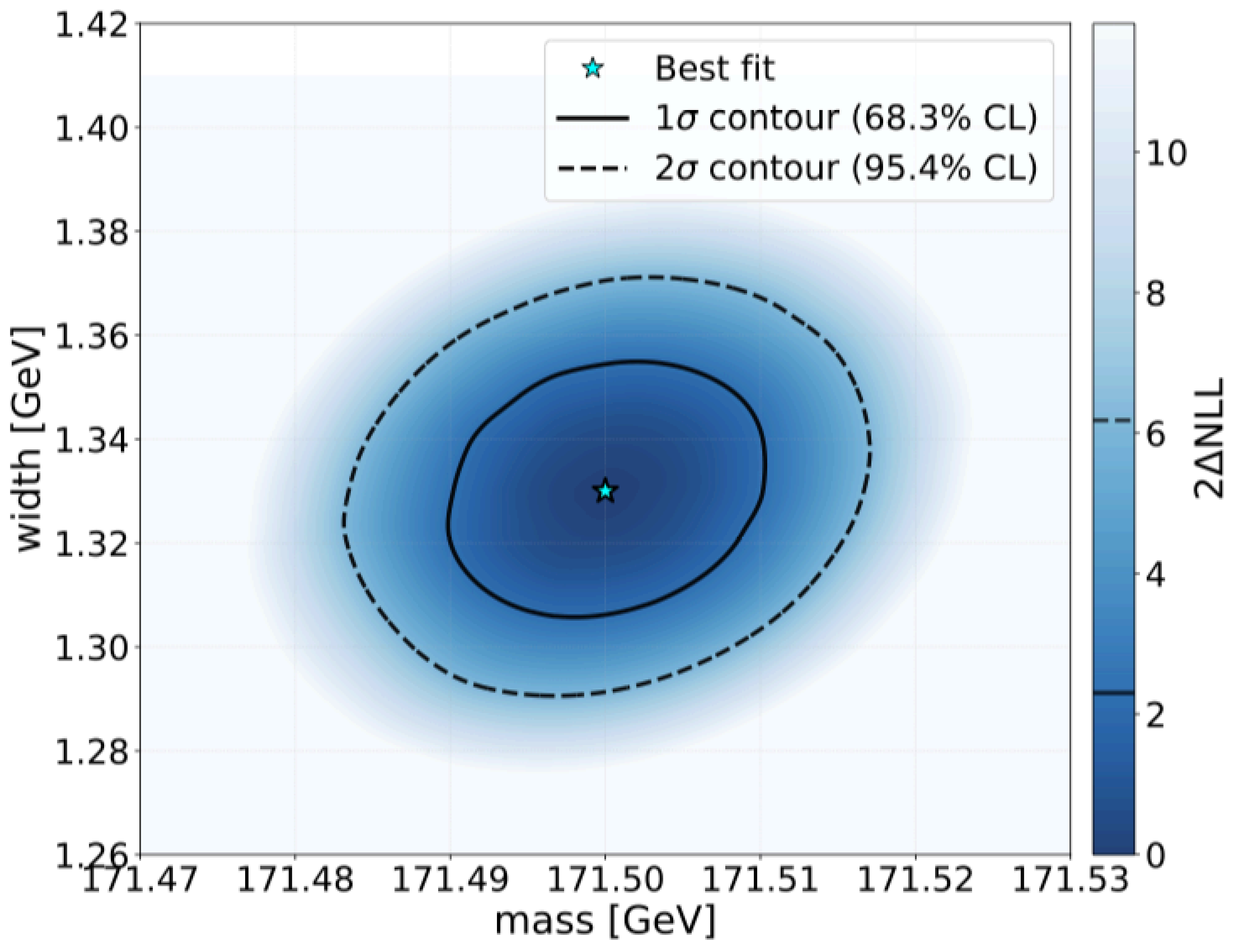


Fig 4. 2D likelihood scan over m_t and Γ_t, EXT scenario (84 fb^{-1}/pt).

- **Milestone: First comprehensive study with the CEPC reference detector**
  - Simultaneous extraction of $m_t, \Gamma_t, \alpha_S, y_t$ via optimized 5-point scan.
  - Dedicated kinematic selections newly optimized at the $t\bar{t}$ threshold.
- **Key Projected Precision (excl. theoretical XS uncertainty):**
  - $\Delta\Gamma_t = 19.4$ (16.2) MeV — one order of magnitude improvement.
  - $\delta\alpha_S = 0.00143\ (0.00116),\ \ \delta y_t = 0.197\ (0.160)$.
  - **FCC-ee context:** EXT luminosity yields mass precision highly consistent with FCC-ee.

Top-Mass Precision (BASE / EXT):

7.5 (6.7) MeV

Nearly 2 orders of mag. beyond HL-LHC

Critical Outlook:

Precision is currently **dominated by theoretical $t\bar{t}$ XS uncertainty** (N^{3}LO scale variation): $\Delta m_t = ^{+1.3}_{-32.9}$ MeV, $\Delta\Gamma_t = ^{+0.0}_{-79.9}$ MeV. If improved to the scale of experimental statistical uncertainty, m_t precision can reach **a few MeV**.

Comparison with CEPC TDR 2025

Setup Comparison: TDR 2025 vs. This Work

- **Key Differences:**
  - — **Fit dimension:** 1D (m_t only) → **2D** (m_t, Γ_t), with α_S and y_t **profiled** (Gaussian priors).
  - — **Luminosity:** 100 fb^{-1} (1 point) → 280 / 420 fb^{-1} (5 points).
- **Prior Assumptions Tightened:**
  - — Beam energy: 2.6 → **1.8** MeV/beam.
  - — LS uncertainty: 10–20% → **1%**.
  - — α_S: external 0.0007/0.0001 → **profiled** (prior 0.0001).
  - — y_t: not considered → **profiled** (prior 3%).
- **Theory treatment:**
  - — TDR: assumed flat 1% / 3%.
  - — This work: explicit **scale variation** (×0.5, ×2.0), non-profiled.

Parameter	TDR 2025		This Work	
	Optim.	Conserv.	BASE	EXT
Fit dimension	1D (m_t)		**2D (m_t, Γ_t) + profiled α_S, y_t**	
$\mathcal{L}_{\text{total}}$	100 fb^{-1}		**280**	**420** fb^{-1}
Scan points	1 (optimal for 1D)		**5 (Fisher-optimized)**	
Beam energy unc.	2.6 MeV/beam [Boogert et al., ILC, 0904.0122]		**1.8 MeV/beam** [Tang et al., RSI 91 (2020) 033109]	
LS prior	10%	20%	**1%** [FCC-ee 2025 result, 2503.18713]	
α_S **prior**	0.0001	0.0007	**0.0001 (profiled)**	
y_t	—		**3% prior (profiled)** [Azzi et al., HL-LHC YR, 1902.04070]	
Theory XS unc.	Flat 1%	Flat 3%	**Renorm. scale var. ×0.5/×2, envelope (non-profiled)**	

Theory treatment: TDR 2025 assumed a flat 1%/3% cross-section uncertainty (Stahlhofen & Hoang, NNLL threshold, 1111.4486; Hoang & Stahlhofen, ILC QCD unc., 1309.6323). This Work follows the theorist-recommended method [Beneke & Kiyo, N³LO, arXiv:2409.05960] and is consistent with FCC-ee [2503.18713]: vary renormalization scale by ×0.5 and ×2, take the envelope as uncertainty. The result is **highly asymmetric** ($^{+1.3}_{-32.9}$ MeV) — downward variation dominates, reflecting genuine N³LO scale dependence, not an assumption.

Tab. Setup comparison between TDR 2025 (Ref: Li et al. EPJC 2023) and this work.

- **Side-by-side m_t uncertainty budget** — TDR 2025 (1D fit, 100 fb^{-1}) vs. this work (2D fit with α_S, y_t profiled, 280/420 fb^{-1}).

TDR 2025 — m_t only (1D)

Source	Optim.	Conserv.
Statistics	±7	±7
Theory	±8	±24
Quick scan	±2	±2
α_S	±3	±16
Top width	±5	±5
Exp. efficiency	±4	±9
Background	±1	±3
Beam energy	±2	±2
Lumi. spectrum	±3	±6
Total (excl. theory)	**±11**	**±21**
Total	**±14**	**±32**

All values in MeV.

This Work — 2D fit (m_t, Γ_t) + profiled α_S, y_t

Source	BASE	EXT
Statistics	**±5.6**	**±4.6**
α_S	±2.4	
y_t	±4.2	
Luminosity	±0.1	
Beam energy	±1.3	
Lumi. spectrum	±0.2	
b-tagging	±1.0	
Total (excl. theory)	**±7.5**	**±6.7**
Theory	$^{+1.3}_{-32.9}$	

All values in MeV.

TDR items no longer separate in this work:
- **Top width** — now a POI in the 2D fit, not an external prior.
- **Quick scan** — replaced by fixed 5-point Fisher-optimized strategy.
- **Exp. efficiency** — decomposed into explicit b-tagging evaluation.
- **Background** — absorbed into the profiled likelihood (σ_i^{bkg}, ϵ_i^b).

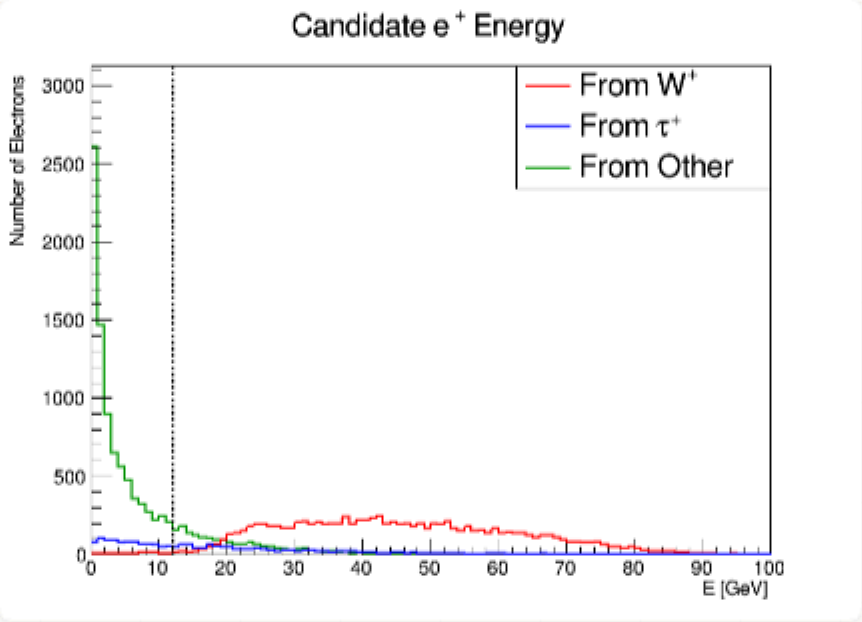
New systematics in this work:
- y_t (±4.2 MeV) — top Yukawa coupling, profiled with 3% prior (HL-LHC projection).
- **b-tagging** (±1.0 MeV) — explicitly evaluated at 1% uncertainty level.
- **Luminosity meas.** (±0.1 MeV) — from Z-pole calibration (0.01%).

Key Improvements: Statistics: ±7 → **±5.6 (±4.6)** MeV | Total (excl. theory): ±11 → **±7.5 (±6.7)** MeV | Now extracting **m_t and Γ_t simultaneously**, with α_S and y_t profiled as constrained nuisances.

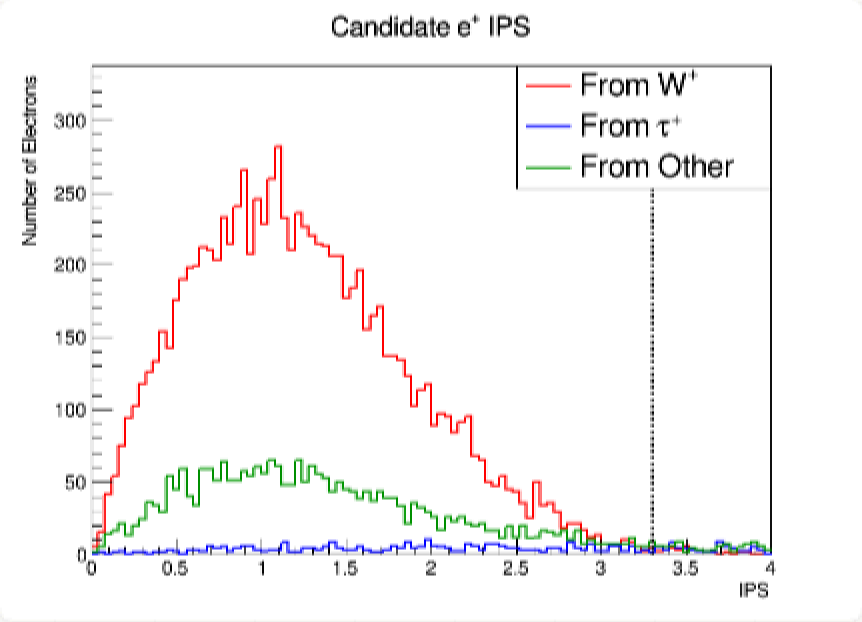
Back Up

- To distinguish between **semi-leptonic (sl)** and **fully hadronic (hh)** events, the number of **isolated leptons** in the event is a key discriminant.

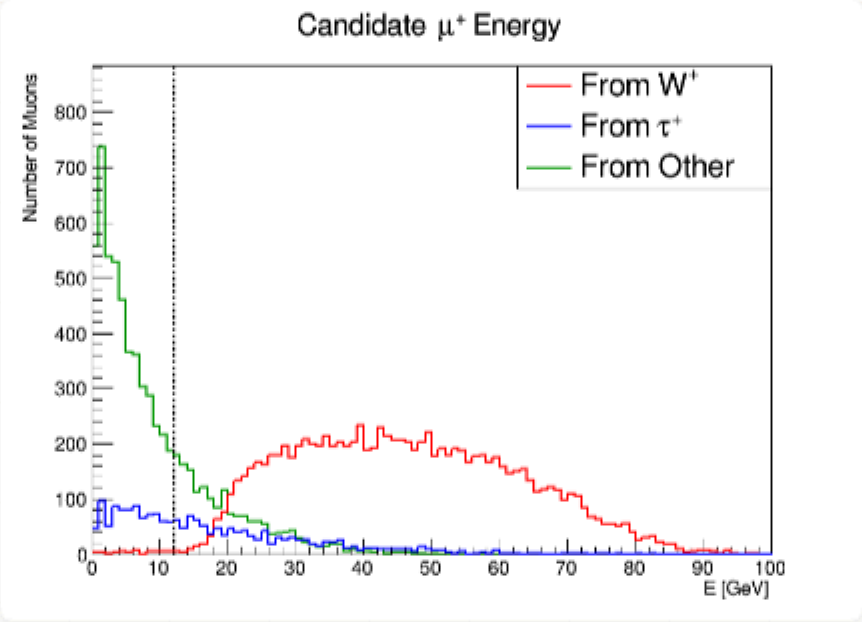
- Leptons with **E > 12 GeV** and **IPS < 3.3** are selected as isolated leptons.
  — The distributions shown below are based on W^+ decays as a representative example; W^- decays exhibit identical kinematic trends as expected from charge symmetry.



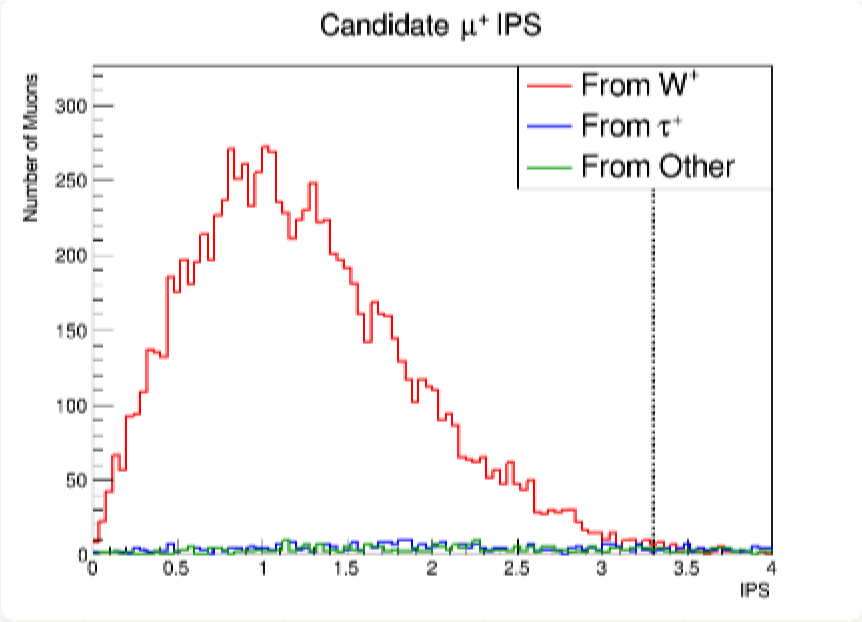
e^+ Energy



e^+ IPS



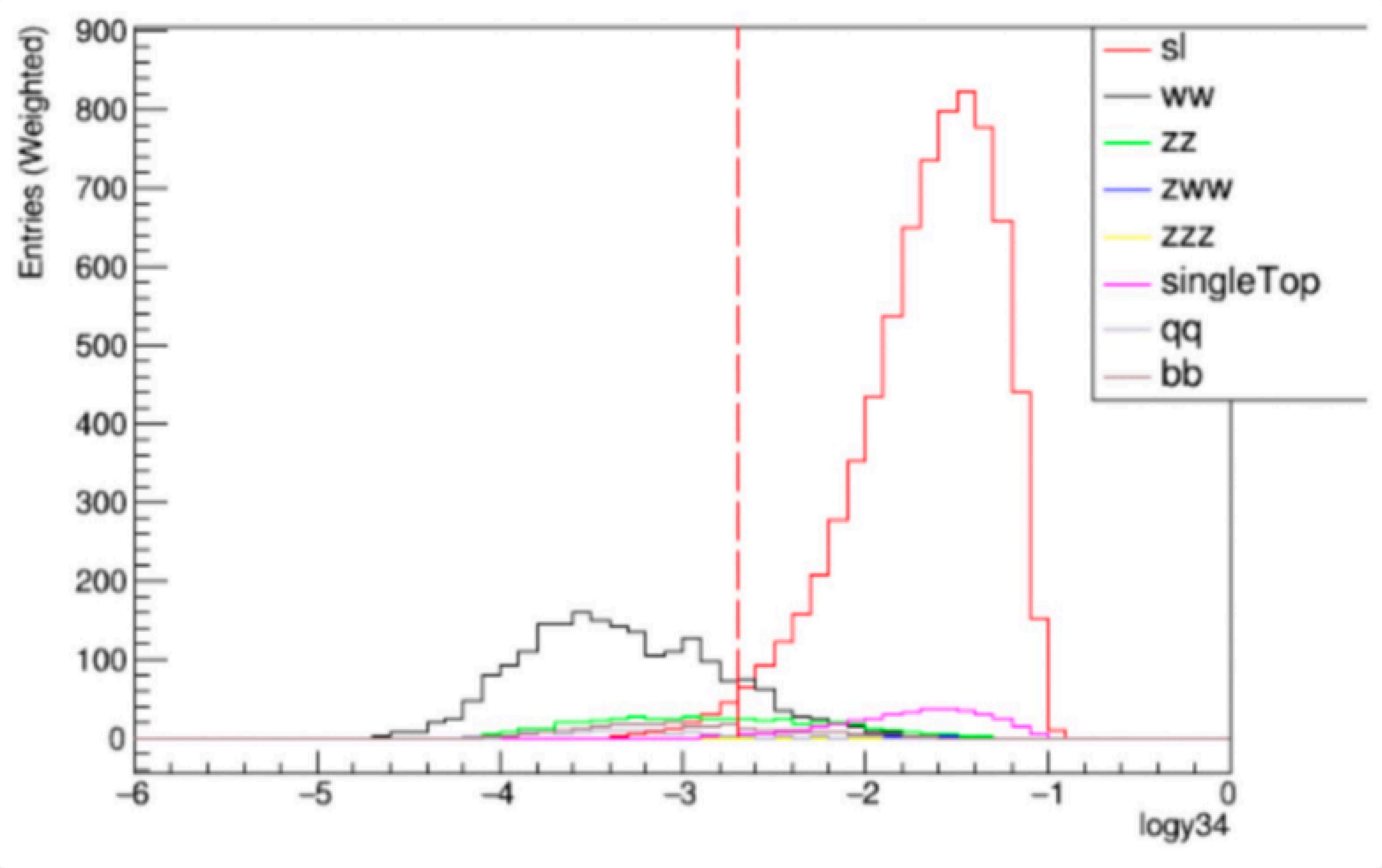
μ^+ Energy



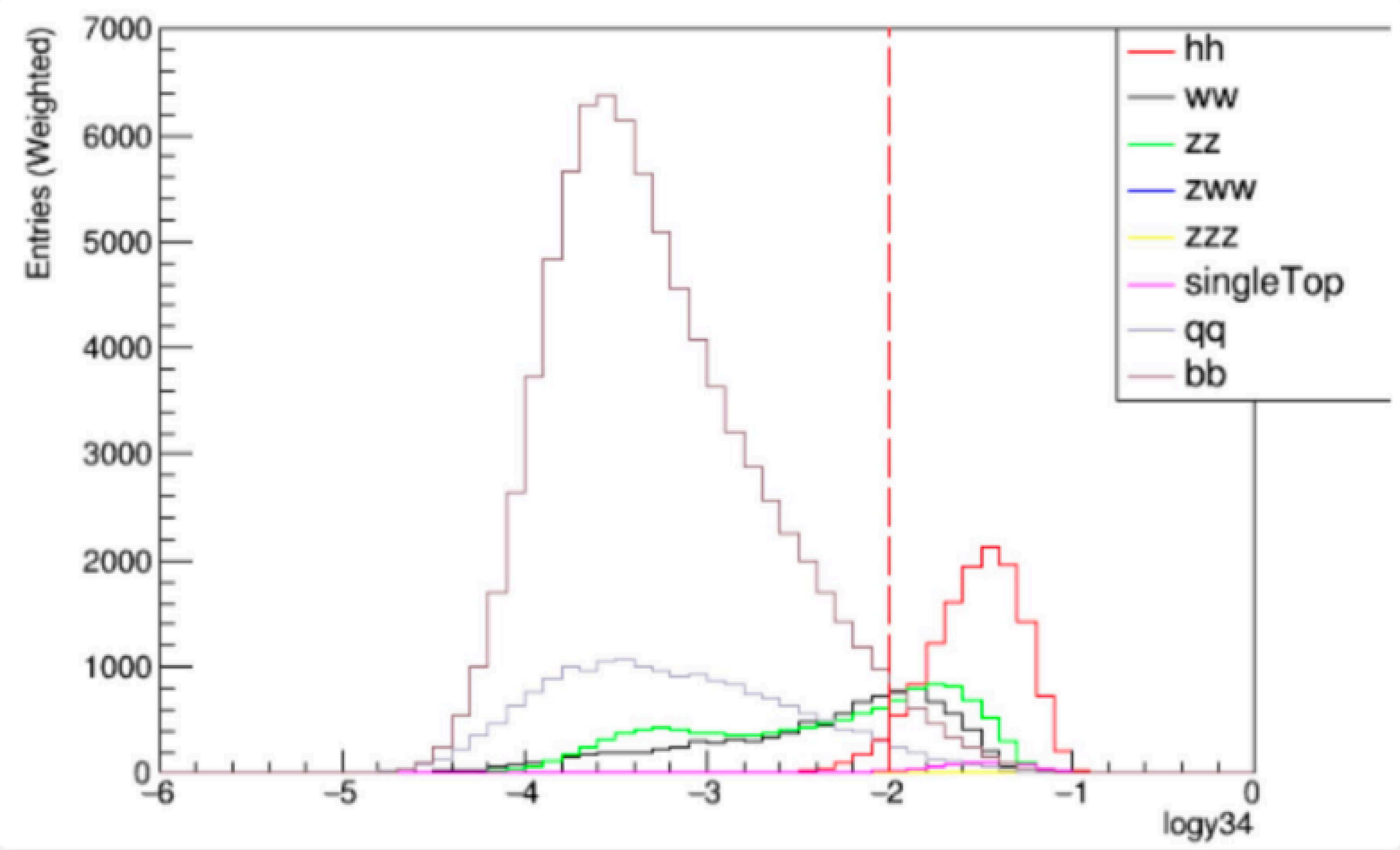
μ^+ IPS

- In the $e^+e^- k_T$ **algorithm**, the distance measure is defined as $d_{ij} = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$, and the dimensionless clustering cost is $y_{ij} = d_{ij}/s$.

- **Strong Discriminating Power:** Signal events ($t\bar{t}$) contain more Born-level partons and hard gluon emissions, incurring significantly higher clustering costs (e.g. y_{34}) when clustering to fewer jets. This allows for an effective separation of signal from multi-boson and $q\bar{q}$ backgrounds.



$\log y_{34}$ distribution in the **sl channel**

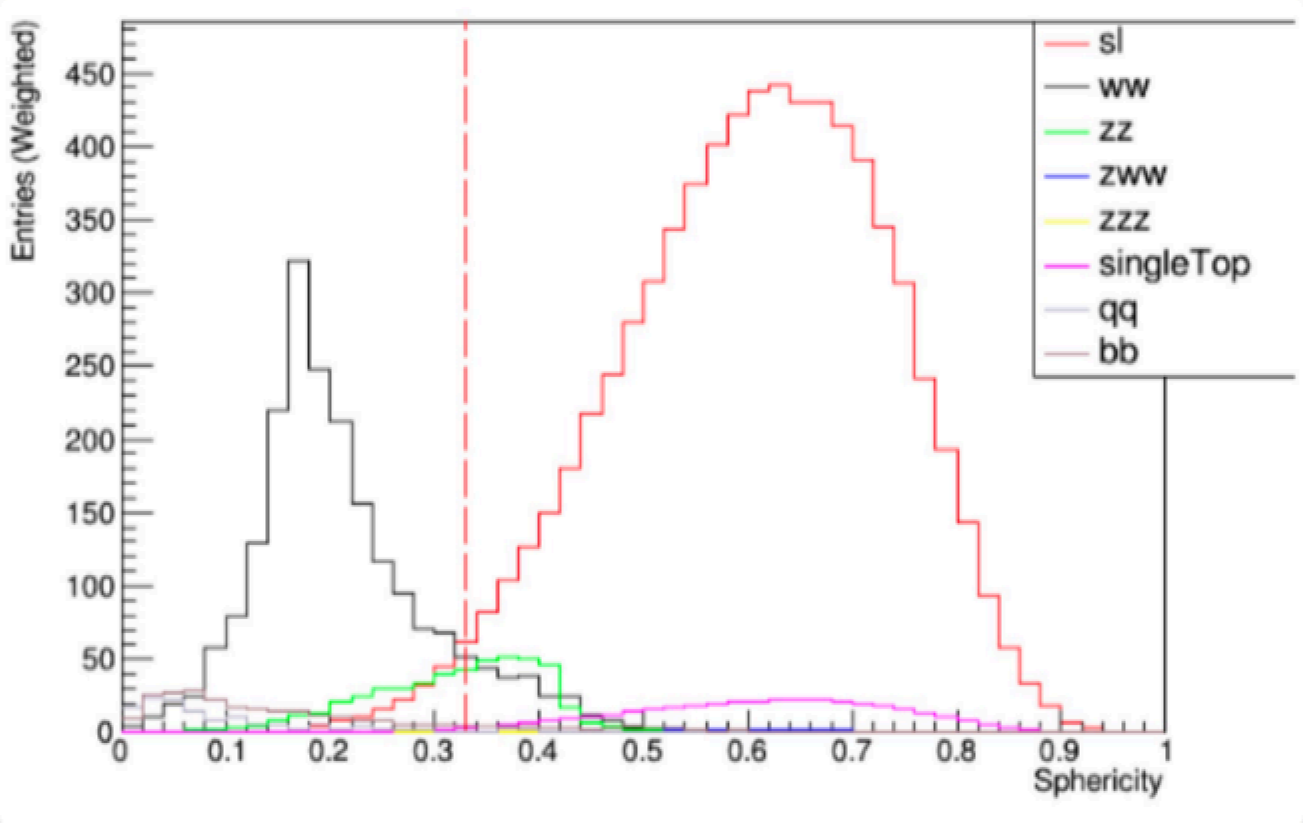


$\log y_{34}$ distribution in the **hh channel**

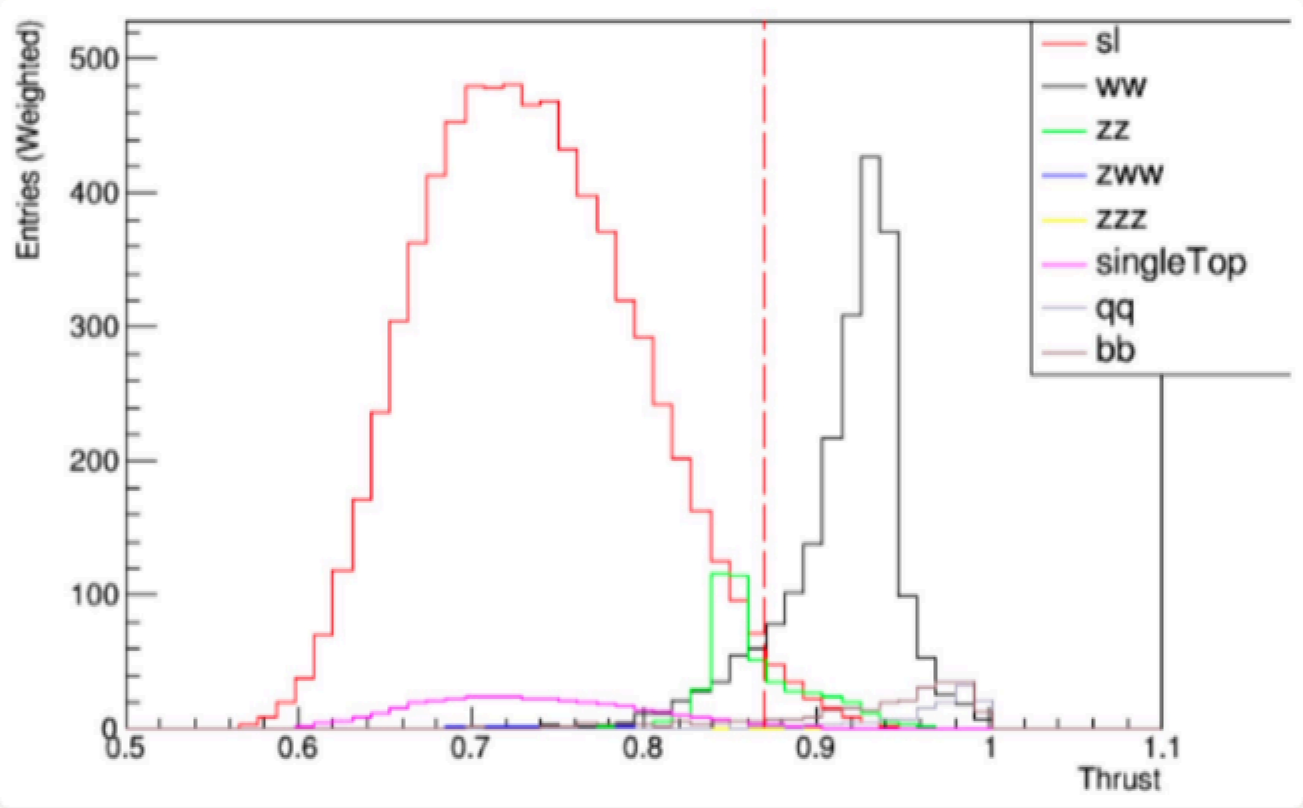
- **Sphericity (S):** Calculated from the sphericity tensor $S^{\alpha\beta} = \left(\sum_i p_i^\alpha p_i^\beta / |\mathbf{p}_i|\right) / \left(\sum_i |\mathbf{p}_i|\right)$ with eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$. Defined as $S = \frac{3}{2}(\lambda_2 + \lambda_3) \to 1$ for sphere-like events ($t\bar{t}$), distinguishing them from pencil-like topologies (dijet, diboson, $\to 0$).

- **Thrust (T):** Defined as $T = \max_{|\mathbf{n}|=1}[\sum_i |\mathbf{p}_i \cdot \mathbf{n}| / \sum_i |\mathbf{p}_i|]$, it ranges from 0.5 (isotropic events) to 1 (back-to-back topologies).

- (Both distributions shown below take the **sl channel** as a representative example.)

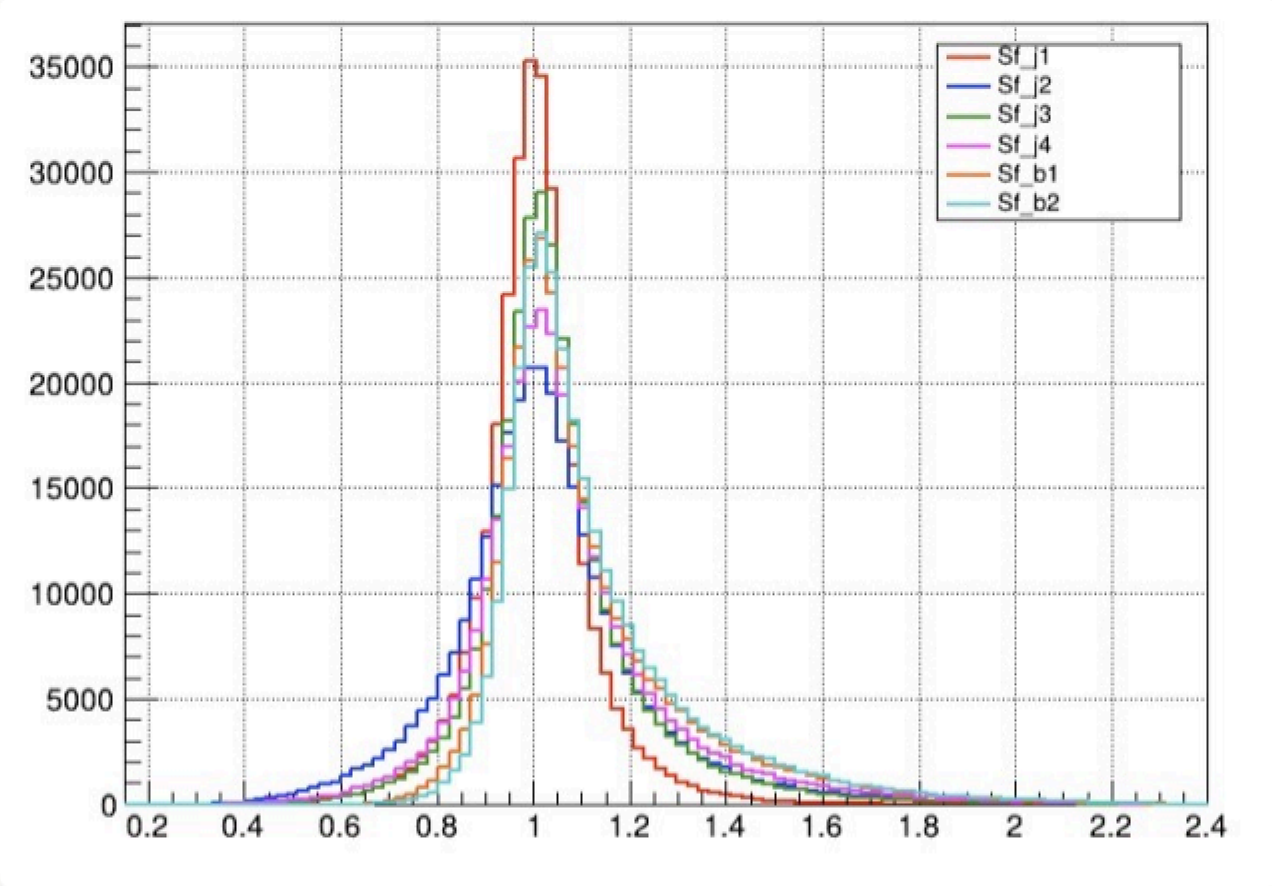


Sphericity (S)



Thrust (T)

- **Energy scale factor s_f in kinematic fit:**
  - The kinematic fit introduces an energy scale factor s_f for each jet to absorb detector resolution effects.
  - Taking the **fully hadronic (hh) channel** as an example, the fitted s_f distribution peaks sharply at $s_f \approx 1$, confirming that the detector energy response is well-calibrated.
  - A narrow spread around unity indicates that the kinematic constraints are functioning as designed, with minimal bias introduced by the fit.



Energy scale factor s_f distribution for fully hadronic $t\bar{t}$ events.

- **Comparison with FCC-ee latest result** (arXiv:2503.18713):
  - At comparable luminosity (EXT), the CEPC projected m_t **precision is highly consistent** with FCC-ee.
  - The Γ_t precision is **worse** than FCC-ee, mainly from **theory**:
    - — CEPC: $^{+0.0}_{-79.9}$ MeV vs. FCC-ee: ~−25 MeV.
    - — Γ_t is extracted from the **width of the threshold peak** — scale variation's downward shift compresses the peak shape, impacting Γ_t far more than m_t.
    - — This work takes a **conservative full envelope** (×0.5/×2), while FCC-ee applies a more refined scale decomposition → smaller envelope.

Source	Δm_t [MeV]		$\Delta\Gamma_t$ [MeV]	
	BASE	EXT	BASE	EXT
Statistics ★	**±5.6**	**±4.6**	**±18.0**	**±14.6**
α_S	±2.4		±3.1	
y_t	±4.2		±5.9	
Lumi / BE / LS / b-tag	sub-dom.		sub-dom.	
Total ★	**±7.5**	**±6.7**	**±19.4**	**±16.2**
Theory ★	$^{+1.3}_{-32.9}$		$^{+0.0}_{-79.9}$	

Tab. 3. CEPC uncertainty budget. ★ = comparison rows.

Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	Input values
Experimental (stat. ×1.2)	4.3	10.4	$L = 410\,\text{fb}^{-1}$ (FCC-ee)
Parametric y_t	4.2	3.6	$\delta y_t = 3\%$
Parametric α_S	2.2	1.7	$\delta\alpha_S(m_Z^2) = 10^{-4}$
Luminosity calibration (uncorr.)	0.5	1.0	$\delta L/L = 0.1\%$
Luminosity calibration (corr.)	0.4	0.4	$\delta L/L = 0.05\%$
Beam energy calibration (uncorr.)	1.2	1.8	$\delta\sqrt{s} = 5$ MeV [36, 37]
Beam energy calibration (corr.)	1.2	0.1	$\delta\sqrt{s} = 2.5$ MeV
Beam energy spread (uncorr.)	0.3	0.8	$\delta\Delta E = 1\%$ [36]
Beam energy spread (corr.)	0.1	1.1	$\delta\Delta E = 0.5\%$
Total profiled	6.8	11.5	
Theory, unprofiled (scale)	35	25	N^{3}LO NR-QCD [11]

Table 3. Impact of the various sources of systematic uncertainties to the total uncertainty in m_t and Γ_t. The impacts are estimated as the difference in quadrature between the total uncertainty