**Germán Rodrigo (IFIC Valencia)**
For the conveners and presenters of R&D3 Sessions

# Top / QCD/ Loopverein summary

LCWS12 International Workshop on
Future Linear Colliders
University of Texas at Arlington, USA
22–26 October 2012

Thanks to Laura Reina,
Roman Poeschl, Yuichiro Kiyo,
Takami Yoshioka and David Asner

# 17 presentations, one joint session with Higgs & EWSB

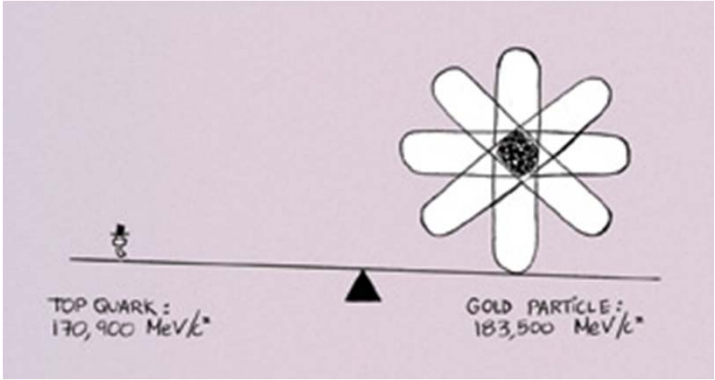
| | |
|---|---|
| Kenichi Hatakeyama | "Top and QCD at the Tevatron“ |
| Joey Huston | "Top and QCD at the LHC" |
| Markus Schulze | "QCD corrections to top production at hadron colliders“ |
| Michihisa Takeuchi | "Top tagging and jet substructure at the LHC" |
| Stefan Höche | "NLO QCD matrix elements and parton showers in e+e-→ had“ |
| Aleksander Kusina | "New method for QCD NLO to hard process in MC shower“ |
| Marcel Vos | “Top quark physics, from LHC to the LC“ |
| Jeremy Rouene | "Measurement of $t\bar{t}$ asymmetries with ILD at the ILC“ |
| Miguel Fiolhais | "Top effective operators at the ILC" |
| Frank Simon | “Top mass precision measurements at CLIC” |
| Vicent Mateu | “Theoretical progress on event shapes and fits $\alpha_S$“ |
| Fred Olness | "Heavy quarks at HO: ideas, issues and intricacies" |

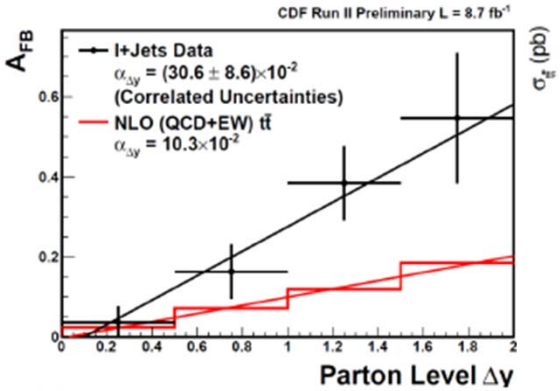
## Joint with Higgs & EWSB

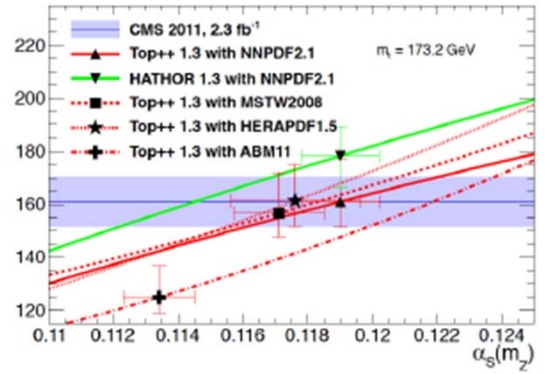
| | |
|---|---|
| Dirk Zerwas | “Sfitter” |
| Aurelio Juste | “$t\bar{t}H$ production a the LHC” |
| Tony Price | “Precision measurements of the top-Higgs Yukawa at the ILC” |
| Philipp Roloff | “Measurement of the top Yukawa at 1TeV using the SiD” |
| Shin-Ichi Kawada | “Higgs to $\tau\bar{\tau}$ study (ILD)” |

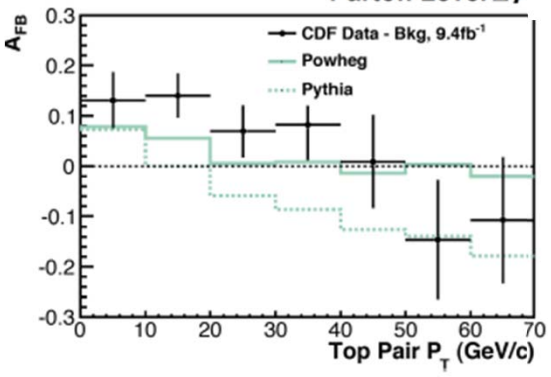
# the top quark: the gold(en) particle

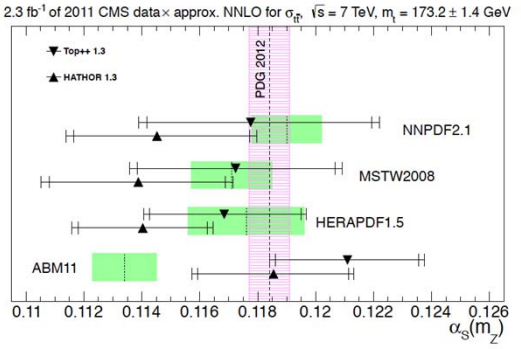
- The heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t = \mathcal{O}(1)$: bridge to EWSB
- Special role in many BSM: a window to new physics that couples preferentially to top quarks
- Tevatron anomalies (FB / charge asymmetries, single top) [Hatakeyama]
- LHC as a top factory for precision physics: mass, cross-section, properties, spin correlations
- Close to use cross-section for determination of PDFs and/or αs [Huston]



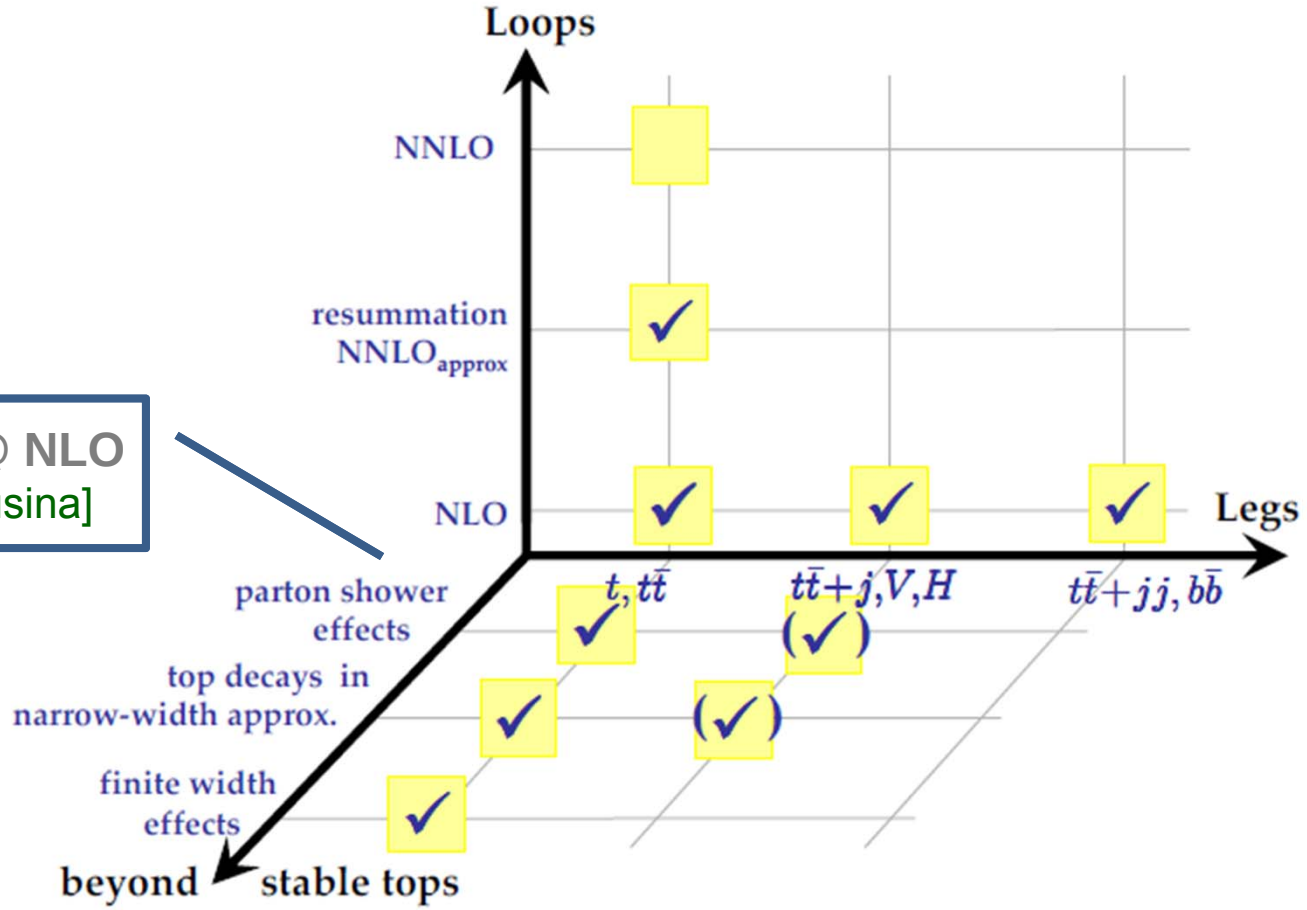



# driving directions to loopverein

**Higher Precision**




**ME + PS @ NLO**
[Höche, Kusina]

**Higher Energy**

[diagram by Schulze]

# the NLO revolution

[Schulze]

- 10 years ago 2→3 processes were at the border line
- With the development of **on-shell methods** based on analyticity/unitarity, which are a much more efficient than Feynman diagrams, today 2→4 (and even 2→5) have become state-of-the art
- Many contributors, and many new results ready for LHC phenomenology
- **Automated theoretical tools** @ NLO: BlackHat+Sherpa, aMC@NLO (CutTools, MadLoop, HELAC-NLO), Rocket, SAMURAI, NGluon
- Give also new insight into **structure and properties** of scattering amplitudes, not only in QCD

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- **NLO revolution driven by LHC:** higher order corrections in QCD at hadron colliders is not only a question of improving systematically the precision of theoretical predictions, but

**NLO** is the first reliable estimate of **central value**

# the upcoming NNLO revolution

- **NNLO** at hadron colliders **(**+ **EW** corrections at NLO) is the first serious estimate of the theoretical error
- A very few NNLO results: e.g. $e^+e^-$ →3jets (determination of $\alpha_S$), $pp \to \gamma\gamma$ (main background to Higgs [Catani et al.]), $q\bar{q} \to t\bar{t}$ [Baernreuther, Czazon, Mitov]
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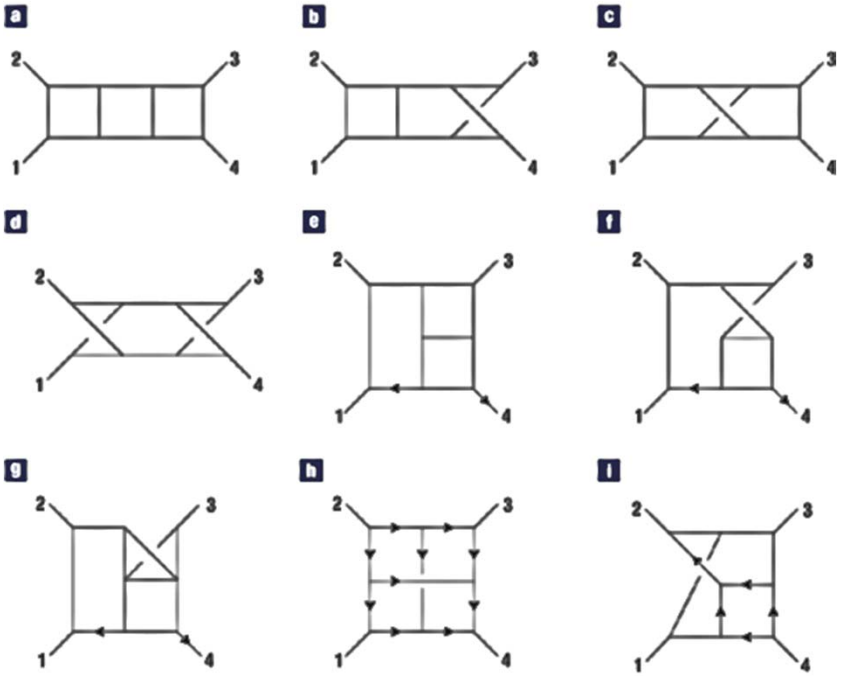
Teenager when

LC will be running



# boosted tops / boosted W/Z/H

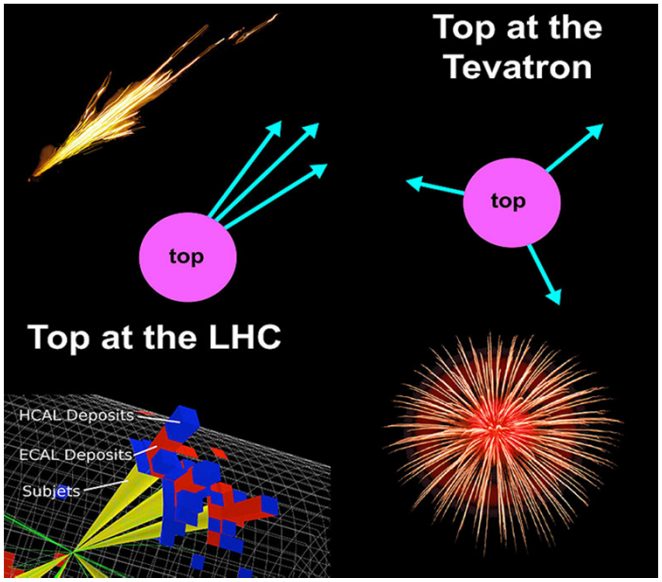



Image from Fermilab Today

- Boosted tops / objects fake QCD jets
- Look into substructure of fat jets
- Boosted Higgs to kill background in $b\bar{b}$ decay channel [Butterworth et al. 2008]
- Several boost taggers focus on $p_T > 500$ GeV, but moderately boosted tops $p_T > 200$ GeV also interesting [Takeuchi]

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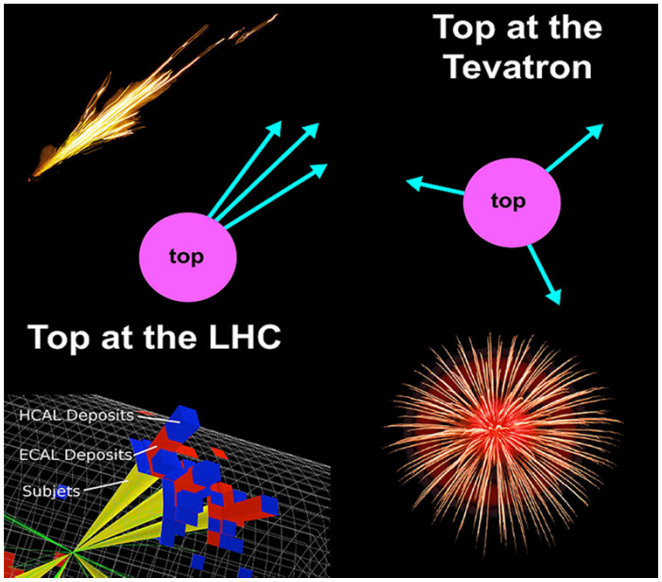


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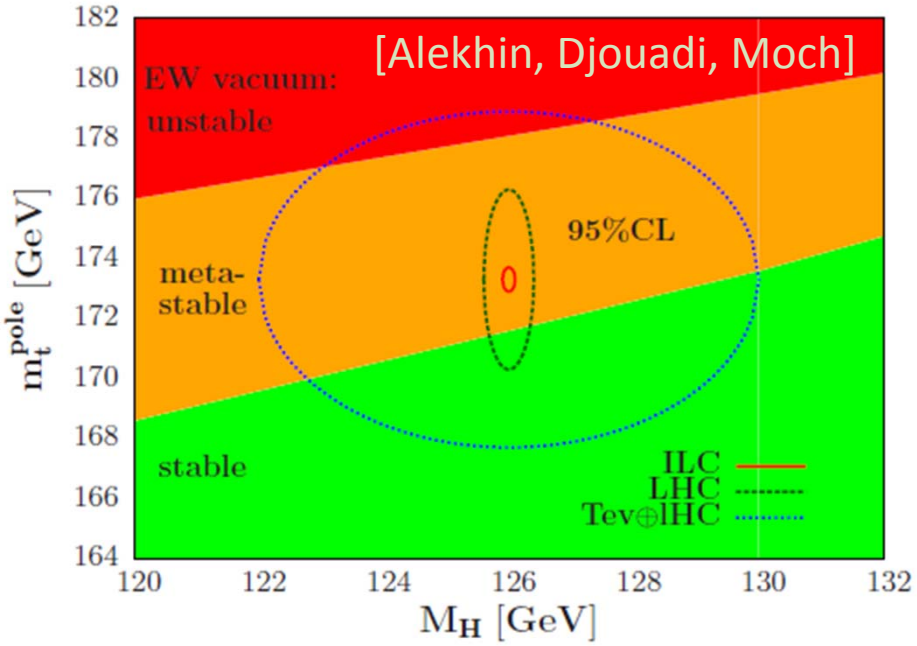
- Not enough boosted tops ($p_T > 150$ GeV) at a low energy LC
- But substructure methods for W/Z/H would be still possible [Takeuchi]

# stability of the EW vacuum

[see also Bezkurov at Higgs&EWSB]

- Could one extrapolate the SM to higher scales while keeping the minimum of the scalar potential ? quartic Higgs coupling $\lambda_H(M_P) \geq 0$



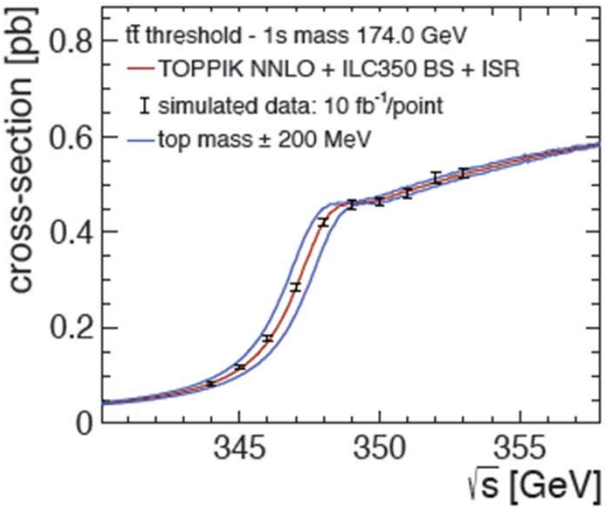

Critically depends on:

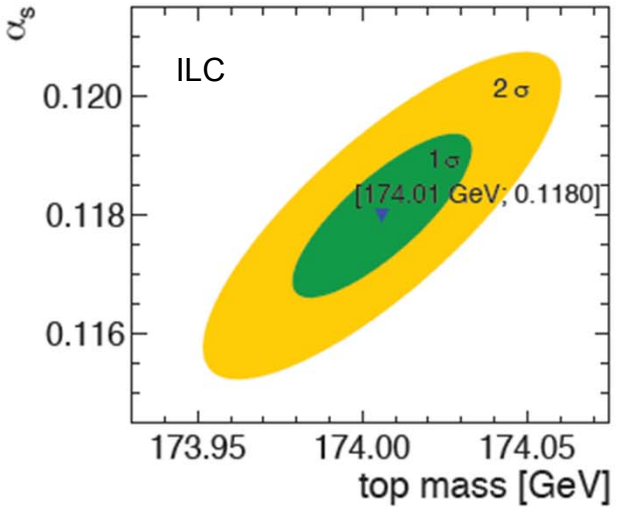
- The **Higgs boson mass**
- The **strong coupling** [Mateu, from event shapes]
- The **mass of the top quark**: value, MonteCarlo/pole/running mass, higher order QCD corrections [Schulze, Simon]

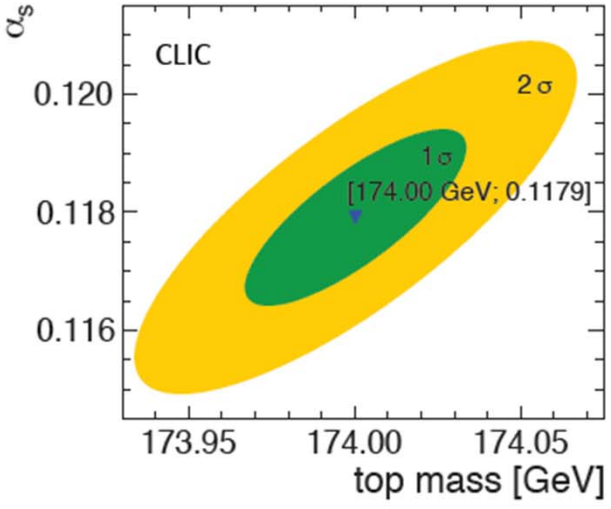
- Current values cover all possibilities within 2σ
- A precise assessment can only be made at the LC if $\Delta m_t{}^{pole} \approx 200$MeV (by threshold scan), and order of magnitude better than LHC - Tevatron

# top quark mass and $\alpha_S$ from energy scan and invariant mass

[Simon]



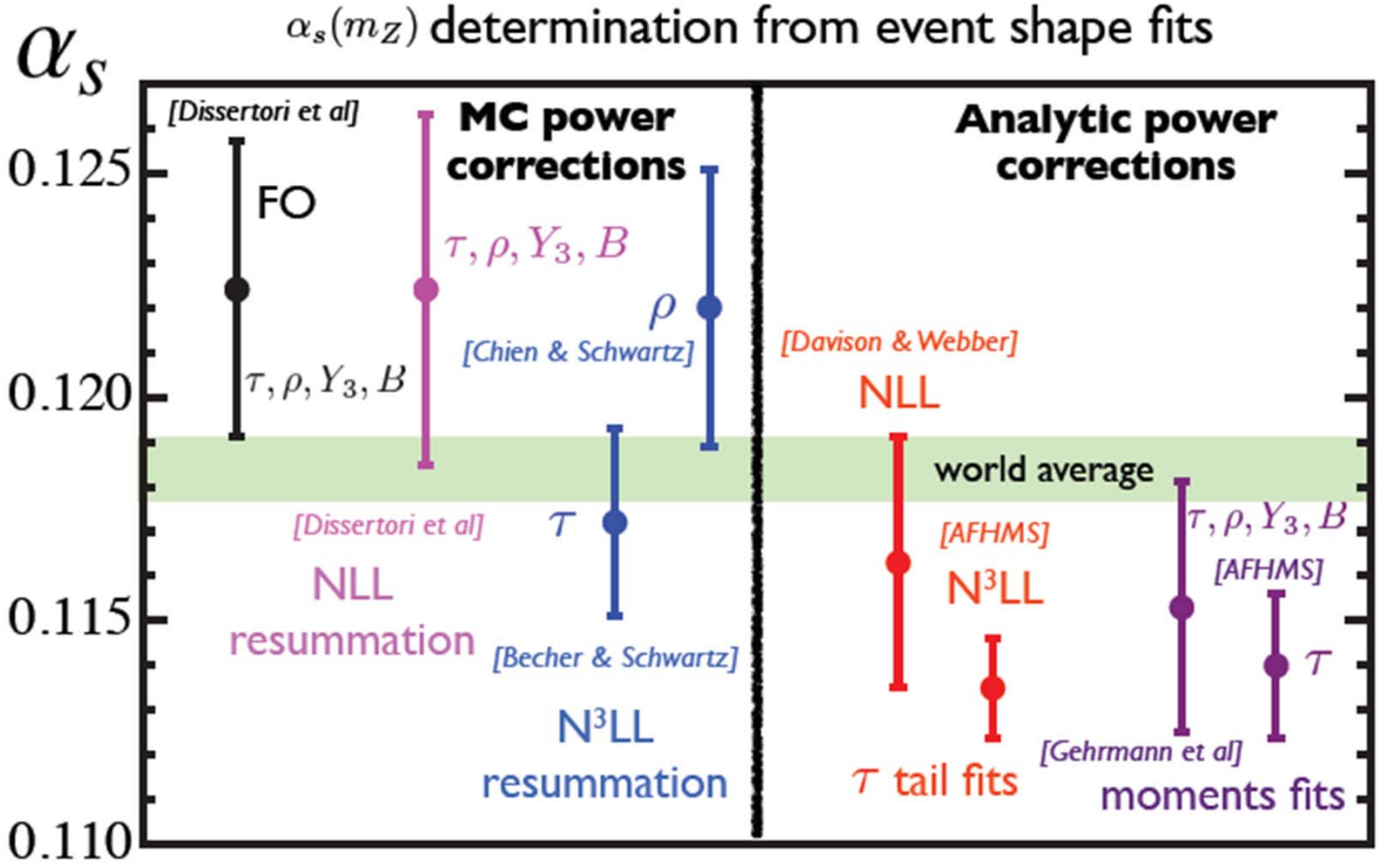




- CLIC above threshold (500 GeV) by reconstructing the **invariant mass**: **80 MeV** statistical precision with 100 fb$^{-1}$
- **Threshold scan** around 350 GeV at CLIC by fitting the 1S mass and αs: **34 MeV** statistical precision of the mass, **0.0009** statistical precision of αs with 100 fb$^{-1}$ split across 10 equally spaced scan points
- 15% better at ILC due to different luminosity spectrum (threshold scan, invariant mass) and higher background (invariant mass)

[Mateu]

# $\alpha_s$ determination: compendium

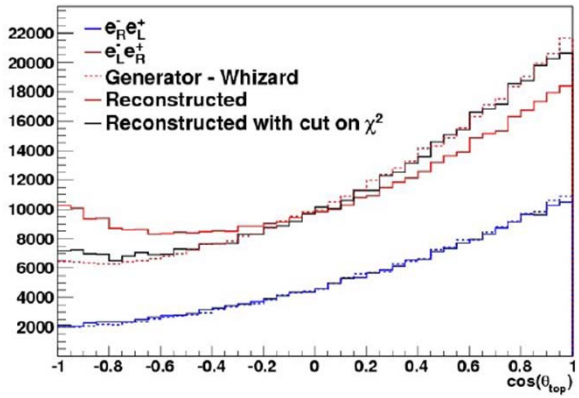
## Only consider analysis with 3-loop input

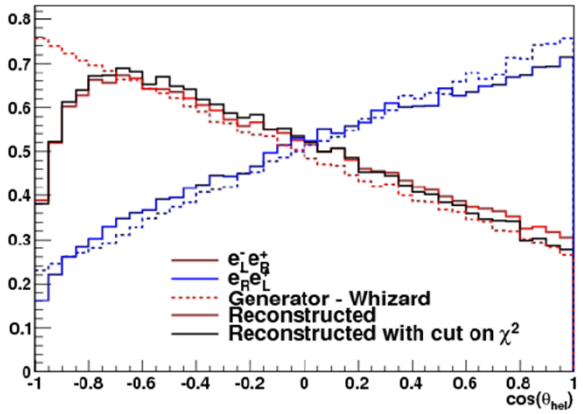


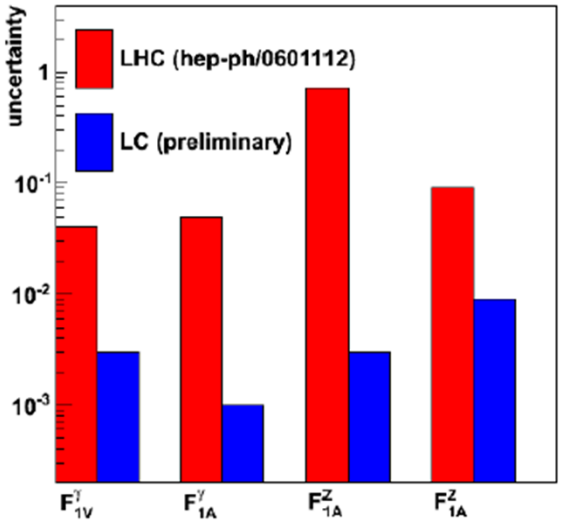

Negligible power corrections at ILC-CLIC energies

# $t\bar{t}Z$ and $t\bar{t}\gamma$ anomalous couplings

[Vos, Rouëné]



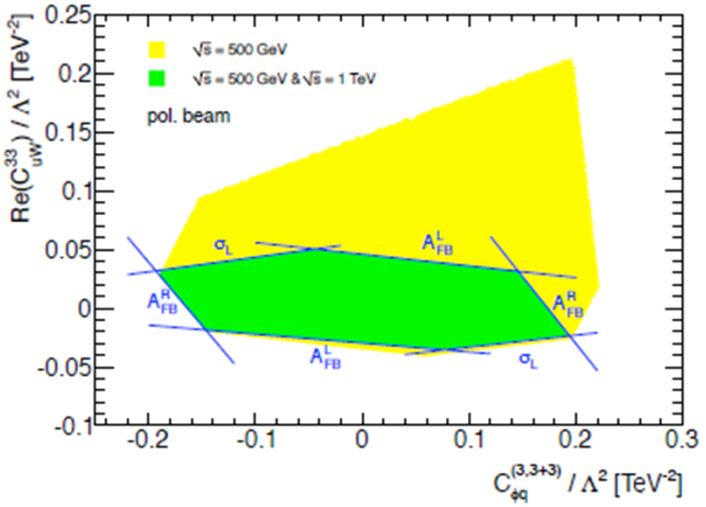




- Three observables (x 2 polarizations) to disentangle $t\bar{t}Z$ from $t\bar{t}\gamma$ couplings: cross-section, $A_{FB}$ and helicity angle

- Effective operator framework allows to relate anomalous couplings in charge currents at LHC with $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings at LC: from polazired observables

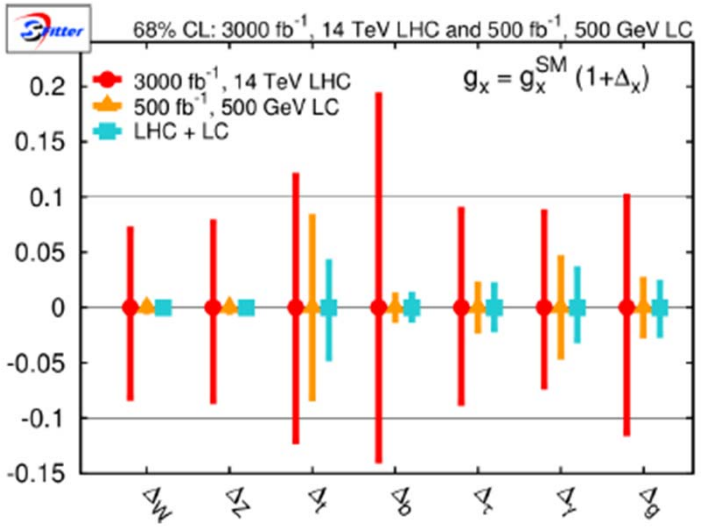
[Fiolhais]

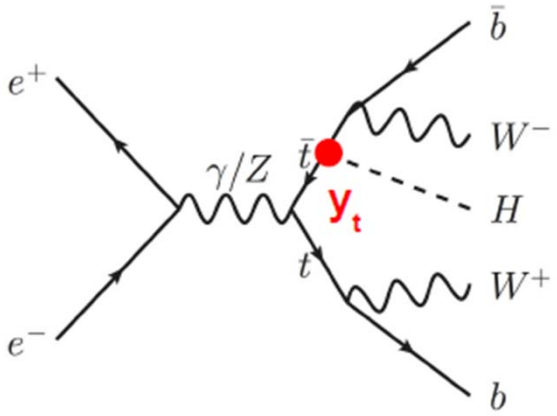


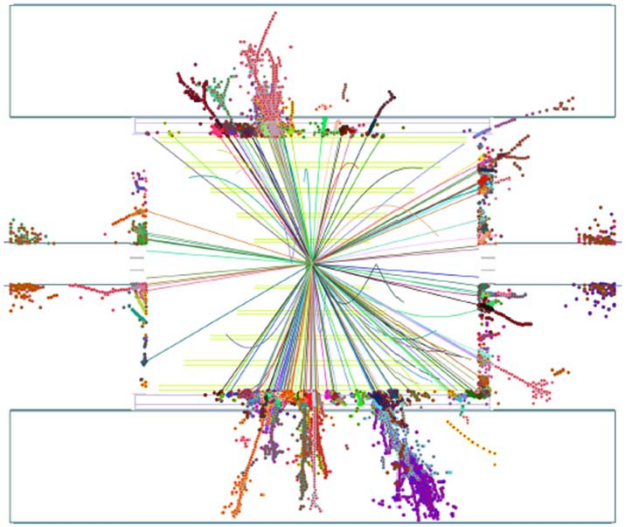
# $t\bar{t}H$

[Zerwas, Juste (LHC+LC), Price (ILD), Roloff (SiD)]

- Yukawa coupling to Higgs boson $y_t = \mathcal{O}(1)$
- Indirect constraints from $gg \to H$ and $H \to \gamma\gamma$ assuming no new particles in the loop
- Direct measurement from Higgs-strahlung from top quarks



# Summary

- The **Tevatron**, where the top was discovered, provided many precision measurements of top quark and QCD (some anomalies persist, FB/charge asymmetries, single top)
- The **LHC** brings top quark and QCD physics to a new level of precision, rapidly improving many Tevatron results
- Higher precision on the strong coupling, cross-sections, top mass (~100MeV) and properties, anomalous couplings (<1%) and top Yukawa coupling (~5%) reachable at a future **Linear Collider**
- Theoretical tools and experimental techniques developed for LHC will benefit analysis at the LC … the NNLO revolution is coming