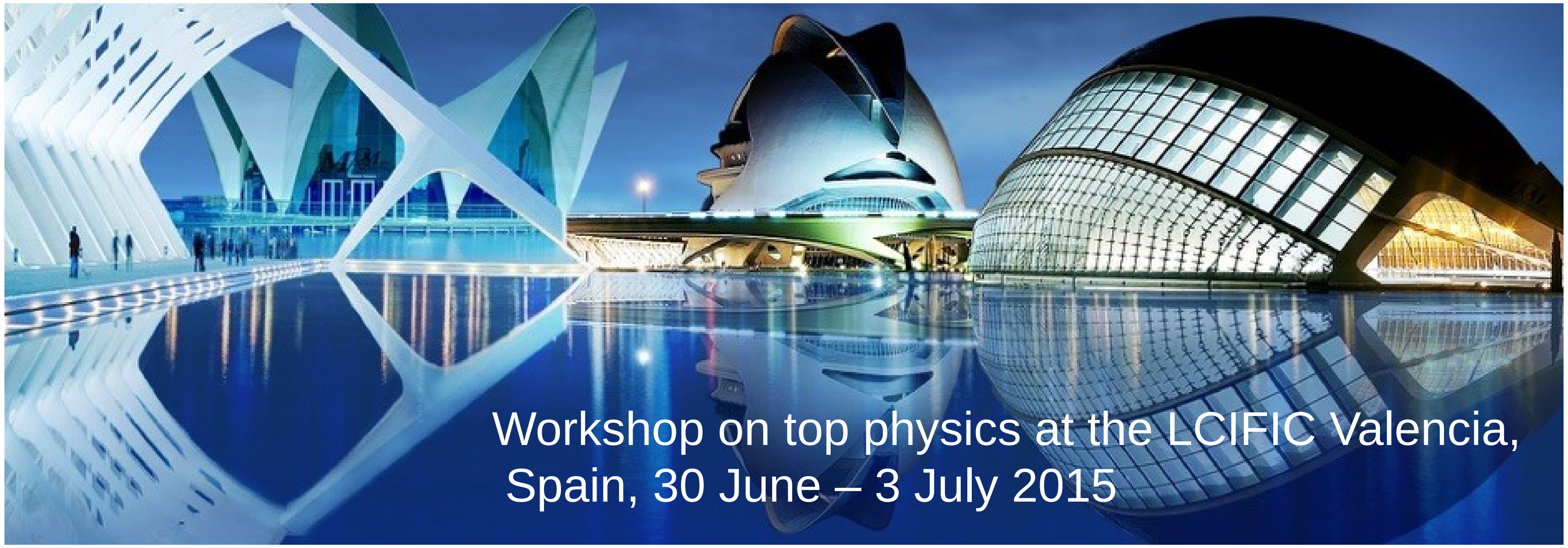
Summary of the Valencia top physics workshop



Contributions: theory

G. Abbas (IFIC, t → cH),

M. Beneke (TUM, threshold NNNLO),

S. de Curtis (Firenze, couplings 4DCHM)

A. Hoang (Vienna, top mass),

Y. Kiyo (Juntendo, threshold)

P. Marquardt (KIT, mass conversions)

M. Nebot (Lisbon, t → cH)

N. Quach (KEK, EW corrections),

J. Reuter (DESY, generators)

G. Rodrigo (IFIC, charge asymmetry)

Contributions: experiment

Projects: CLIC - L. Linssen (CERN), ILC - R. Poeschl (LAL)

Summary & outlook - F. Richard (LAL)

Top mass: P. Gomís (IFIC, continuum), A. Ishikawa (Tohoku, threshold), M. Perelló (IFIC, mass and α_s), F. Simon (MPI, threshold)

Reconstruction:

J. List (DESY, overview), J. Tian (KEK, jets), M. Kurata (Tsukuba, flavour tagging), S. Bilokin (LAL, jet charge)

Couplings: R. Poschl (LAL, overview), F. Zarnecki (Warsaw, $t \rightarrow cH$)

ttH: Philipp Roloff

Top quark physics

One of (at least) two particles to escape (direct) scrutiny at lepton colliders

It is **important** to know its properties: contributions through loops

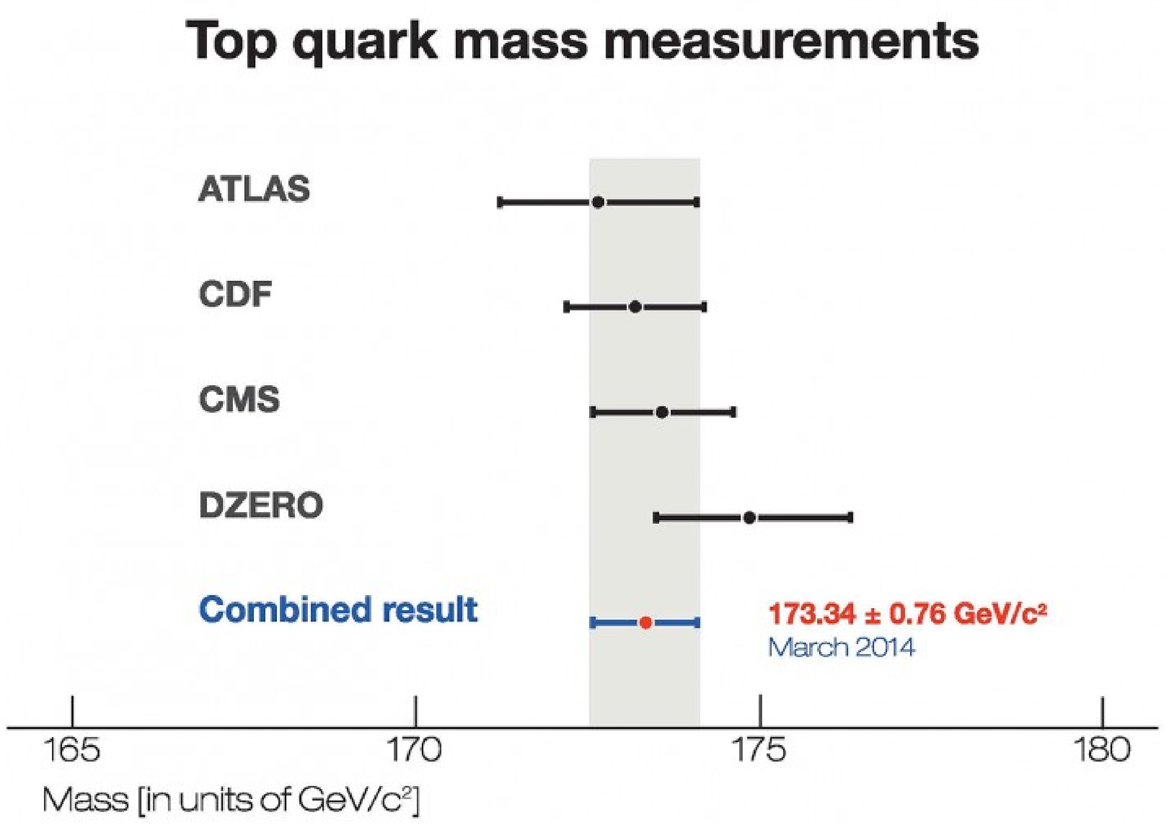
It is a quark we **can** characterize well: top-anti-top tagging, polarization

Precise measurements of properties and interactions provide sensitivity to new physics

- top quark mass
- couplings to photon/Z-boson

See Michael Peskin's talk in Monday plenary

Top quark mass today

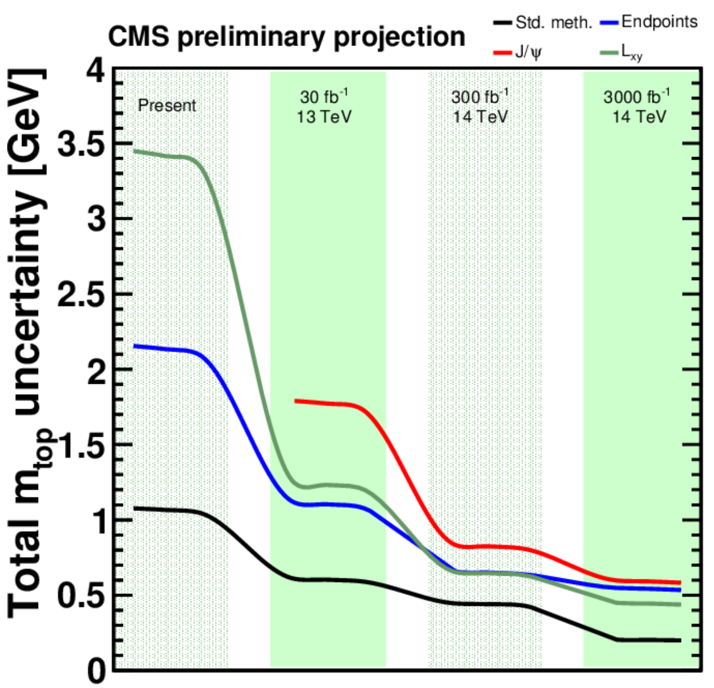


Measurements & prospects

Consistent set of measurements from 4 experiments

Combined precision well below 1 GeV

New results from CMS and D0 even more precise
0.5 GeV per measurement
some tension between most precise measurement



LHC already exceeding prospects, and much more to come
CMS: 200 MeV after 3/ab (conventional method, *CMS-FTR-13-017-PAS)*
based on "assumptions [that] are optimistic but not unrealistic."

Explicitly excludes the ambiguity in the interpretation

Top quark mass interpretation

André Hoang:

→ Direct measurements determine “MC mass”, which cannot be used as direct input into NLO/NNLO calculations since it is not a field theoretic mass.

→ Currently: an additional error has to be accounted for when MC mass is used in pQCD.

Snowmass, Determination of the top quark mass circa 2013: methods, subtleties, perspective, arXiv:1310.0799
MITP, High precision fundamental constants at the TeV scale, arXiv:1405.4781
A. Hoang (TOP2014), The top mass: interpretation and theory uncertainties, arXiv:1412.3649

→ At least an approximate relation to field theory masses should exist for certain observables

→ Find the relation by fitting MC distributions for e+e- observables with SCET-based prediction

arXiv:1302.4743 (PRD 88, 034021 (2013))
arXiv:1309.6251 (PRD 89, 014035 (2013))
arXiv:1405.4860 (PRD 90 114001 (2014))

→ Preliminary results indicate 500 MeV theory uncertainty within reach

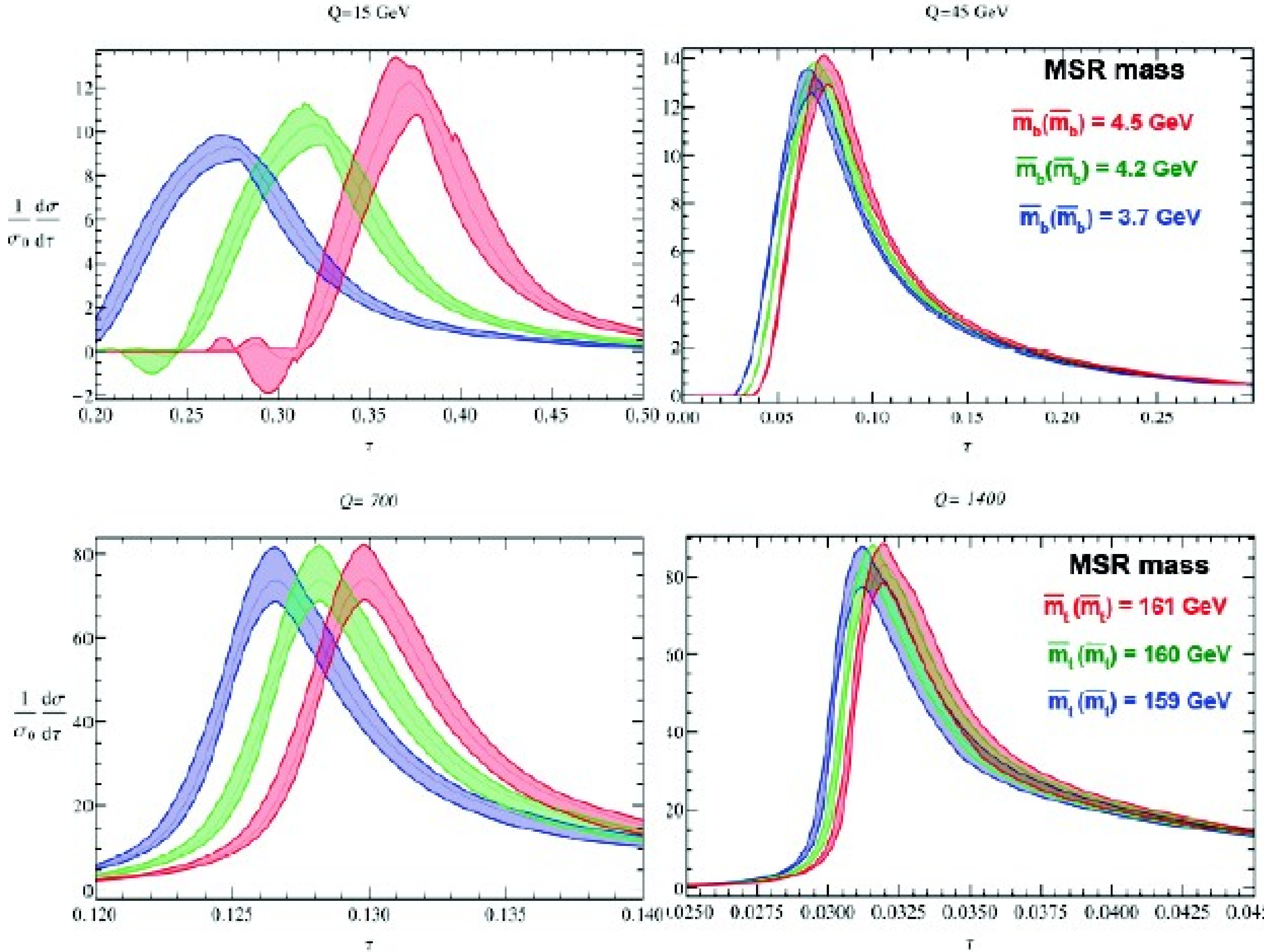
→ NNNLL seems mandatory

Thrust predicted in NLO+NNLL

Low energy | High energy

Bottom

Top

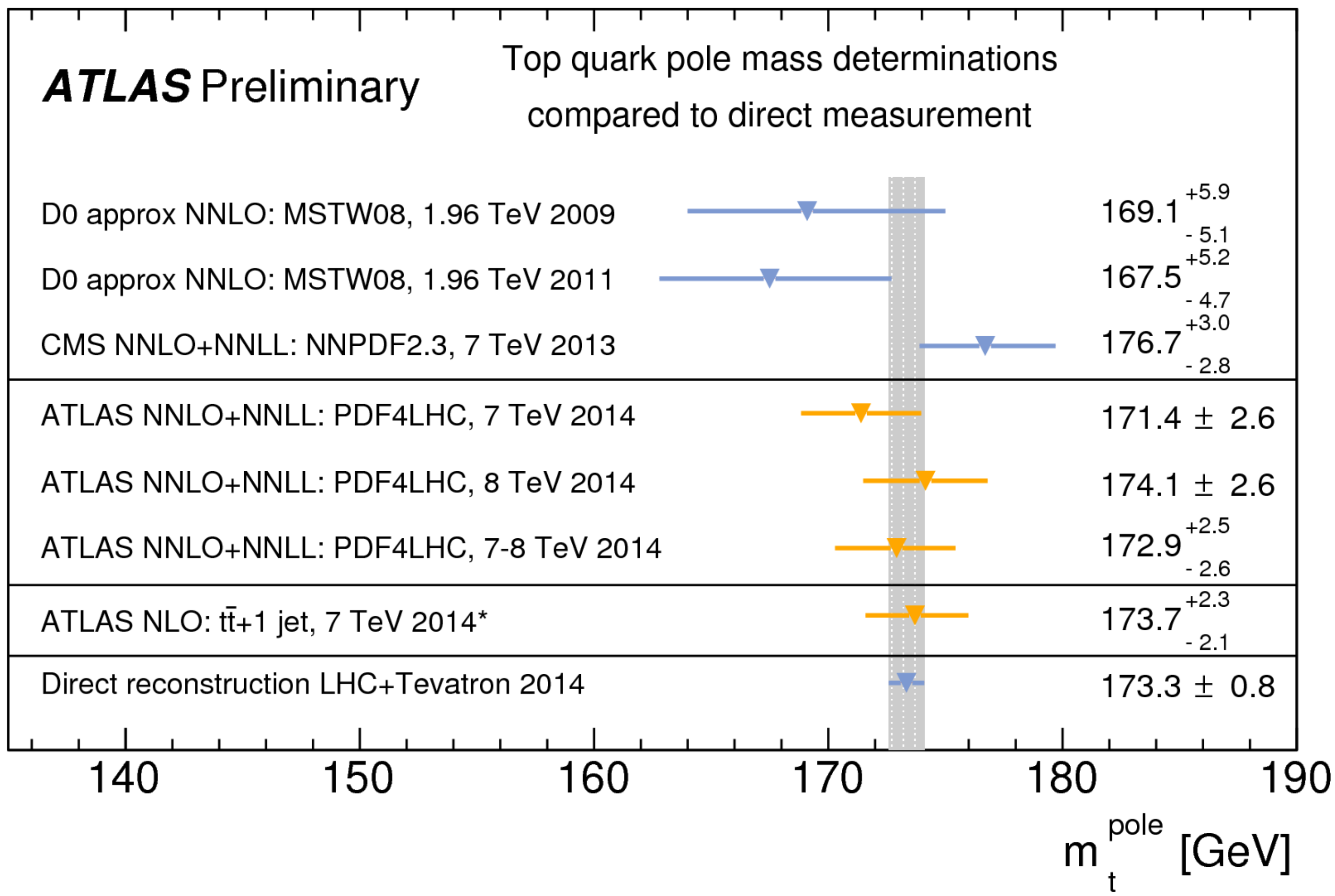


Pole mass from hadron collider

Adrian Irles: precise pole mass extraction is possible from differential cross-section in tt+hard jet production

Today: mt = 173.7 ± 2.2 GeV

ATLAS 7 TeV, arXiv:1507.01769



Top mass from an LC threshold scan

Threshold shape depends strongly on mass & width.
Normalization sensitive to α_s and top Yukawa coupling

Kuhn, Acta Phys.Polon. B12 (1981) 347

Statistical precision for 1S/PS mass (10 x 10/fb):
16 – 30 MeV

Martinez, Miquel, EPJ C27, 49 (2003)

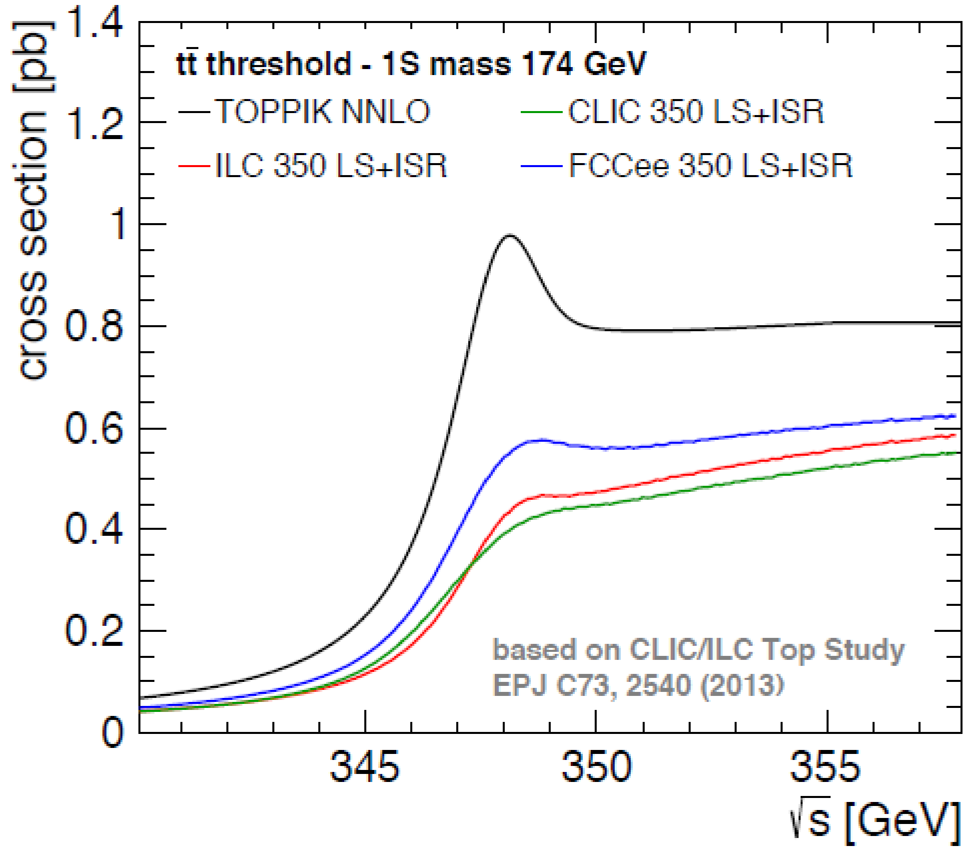
Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

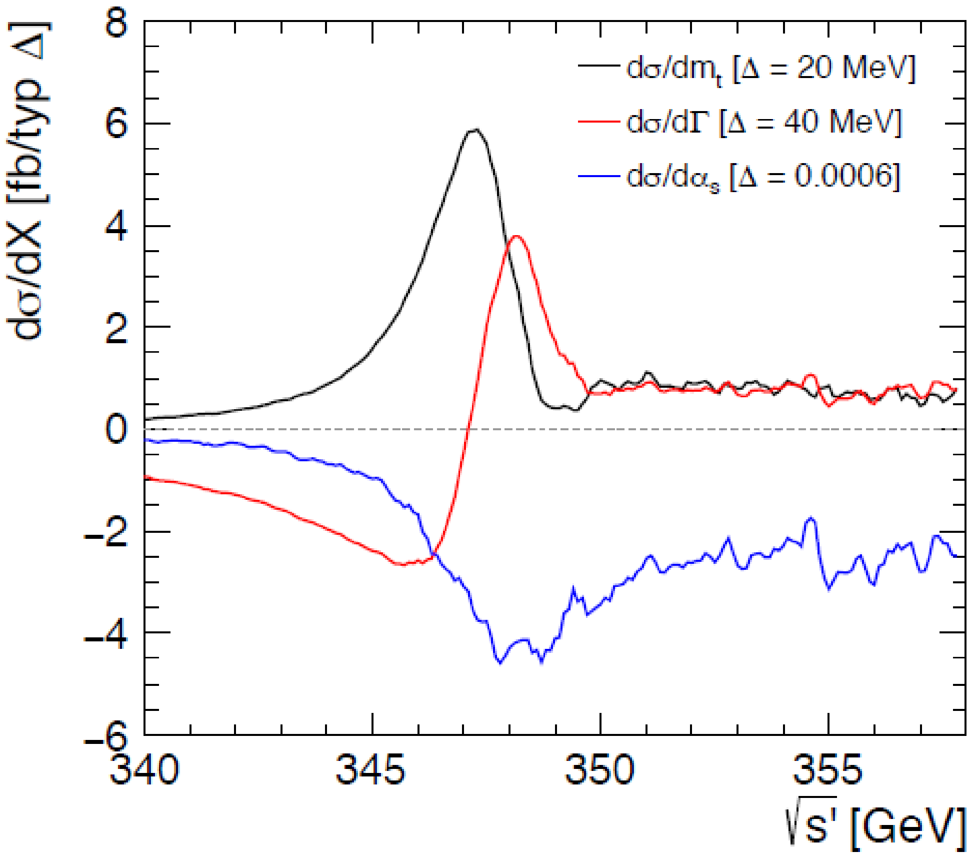
Horiguchi et al., arXiv:1310.0563

Simon: minor differences due to beam energy spectra of ILC, CLIC and FCC-ee

Simon: choice of scan range and points based on less precise LHC measurement

Ishikawa: add other observables to fit (A_{FB}, p), extract Yukawa coupling (potential: 6%, but what about theory & α_s?)

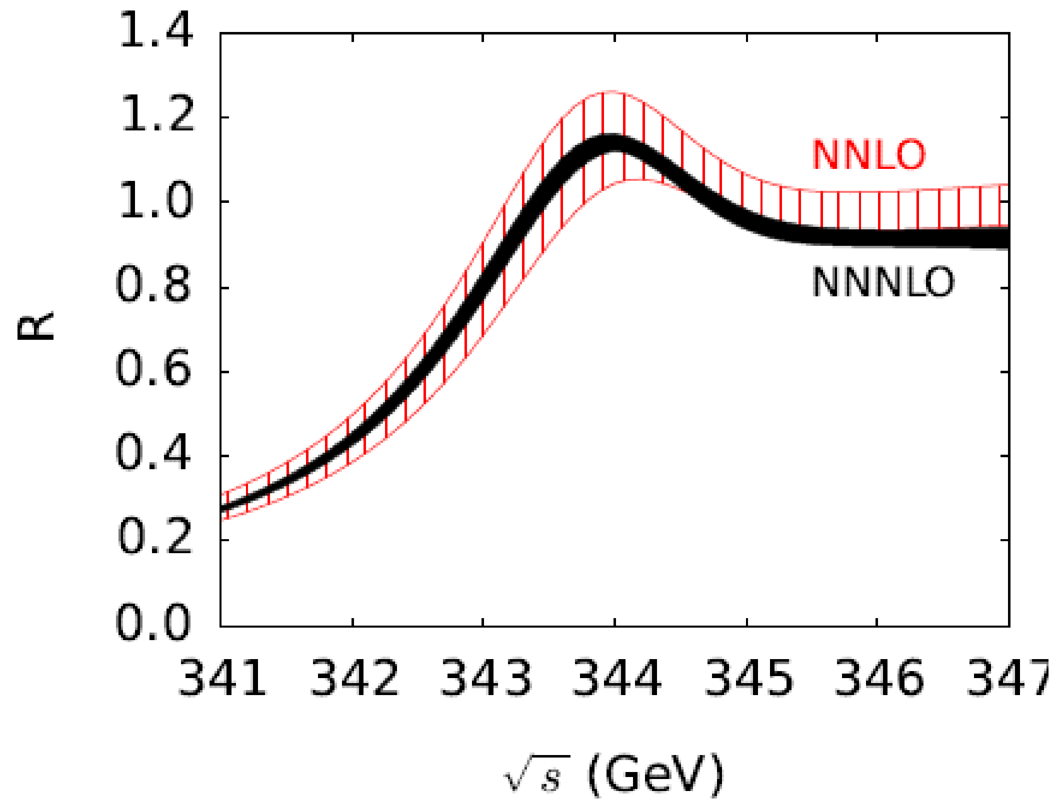


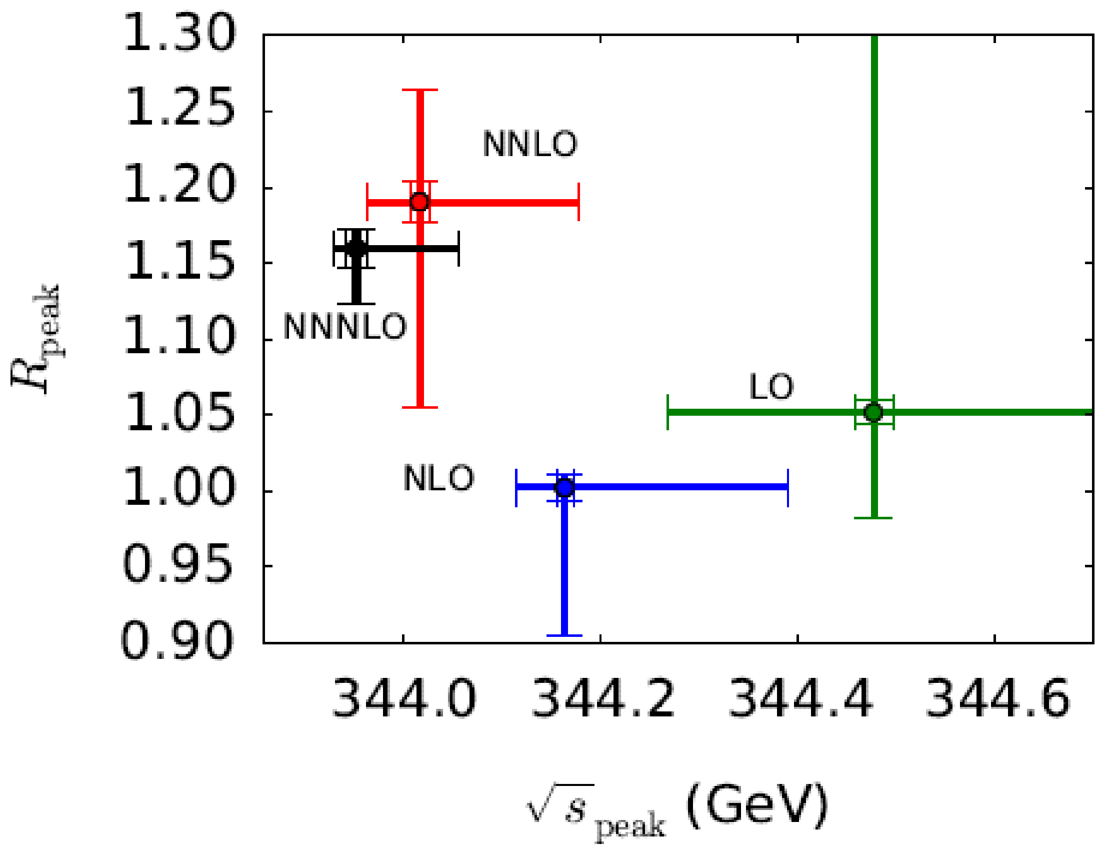


Threshold theory

Beneke/Kiyo: N[3]LO description of $t\bar{t}$ production at threshold

Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864 [hep-ph]





Position shift for PS mass: 310 MeV (LO to NLO) 150 MeV (to NNLO) 64 MeV (to NNNLO)
Improvement of factor 3 in uncertainty in peak height.

Alternative approach proposed by Kiyo/Mishima/Sumino: perform calcullation directly in terms of the $\overline{\text{MS}}$ mass (corrections LO → NLO are large, but rapid convergence, final scale uncertainty seems smaller, arXiv:1506.06542)

Threshold theory uncertainties

Need today's best theory uncertainty estimate

See F. Simon, this workshop

Adding all pieces together:

QED/EW/ISR

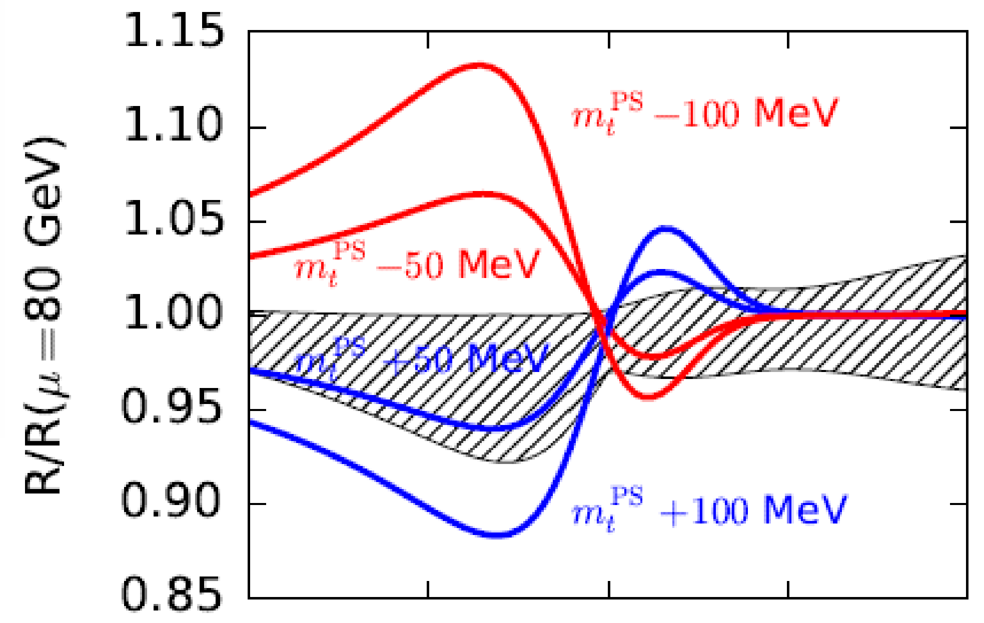
Higgs exchange

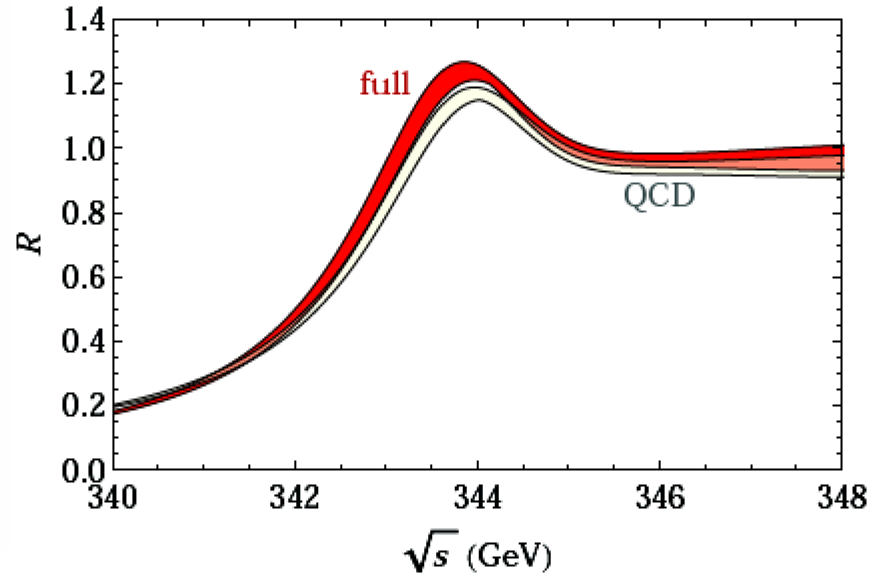
Axial-vector Z coupling

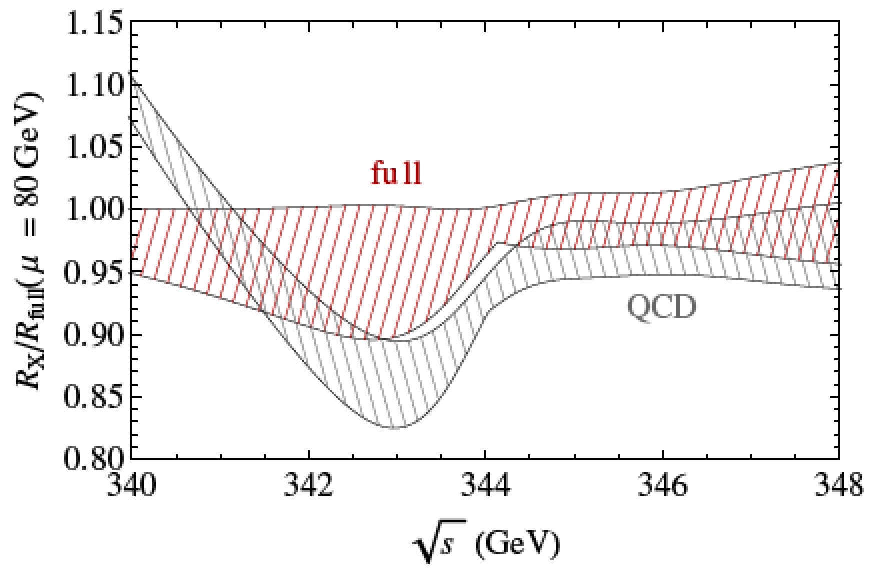
Non-resonant effects

($e^+e^- \rightarrow$ WbWb, NLO)

[MB, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864]







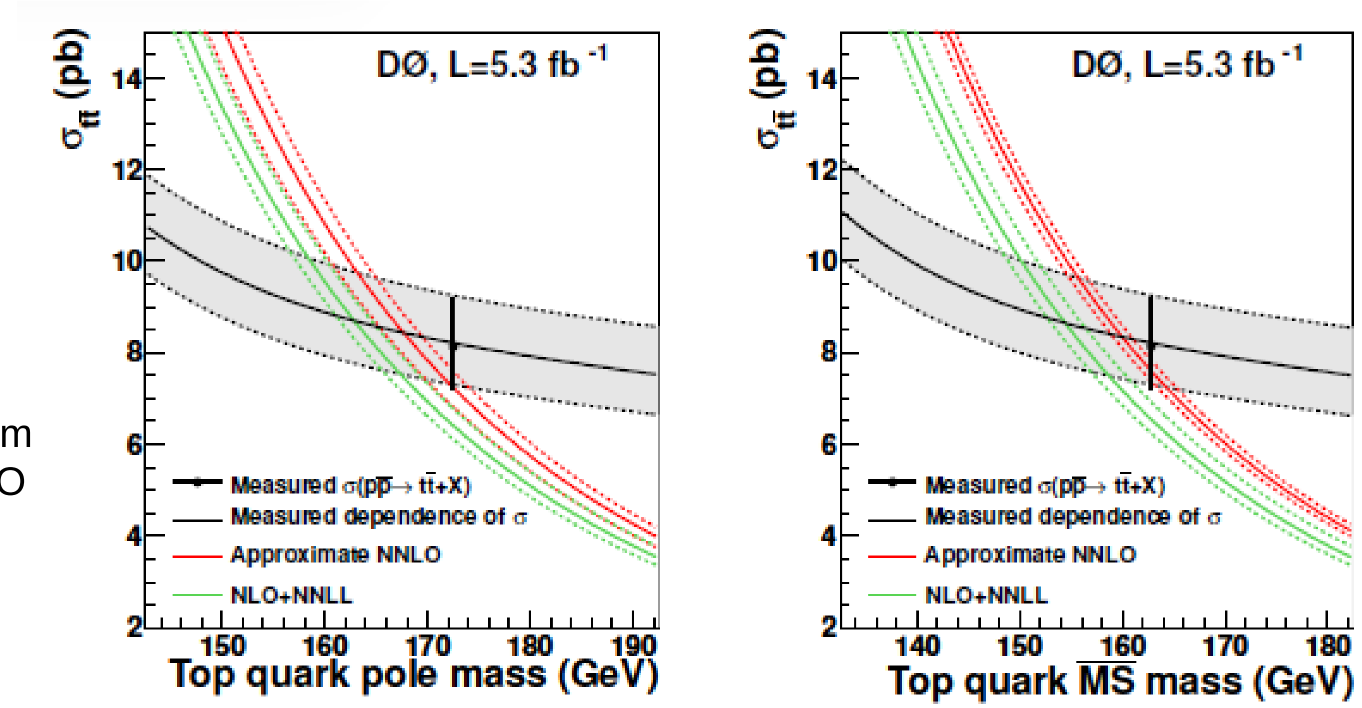
Merge in resummed calculation?

Match with continuum calculation?

Top quark mass schemes

The scheme makes a difference:
The pole mass and the $\overline{\mathrm{MS}}$ mass
at the top mass differ by order 10 GeV

D0, extraction of the the pole and running mass from the inclusive cross section using approximate NNLO calculation, PLB 703 , 422 (2011)



$m_t^{pole} = 167.5^{+5.2}_{-4.7}$ GeV $\qquad m_t^{\overline{MS}} = 160.0^{+4.8}_{-4.2}$ GeV

Peter Marquardt:
Theory uncertainty in conversion from 1S to $\overline{\mathrm{MS}}$ scheme:

3-loop calculation → ~100 MeV
4-loop calculation → <10 MeV
(P. Marquard et al., arXiv:1502.01030, PRL114 (2015)

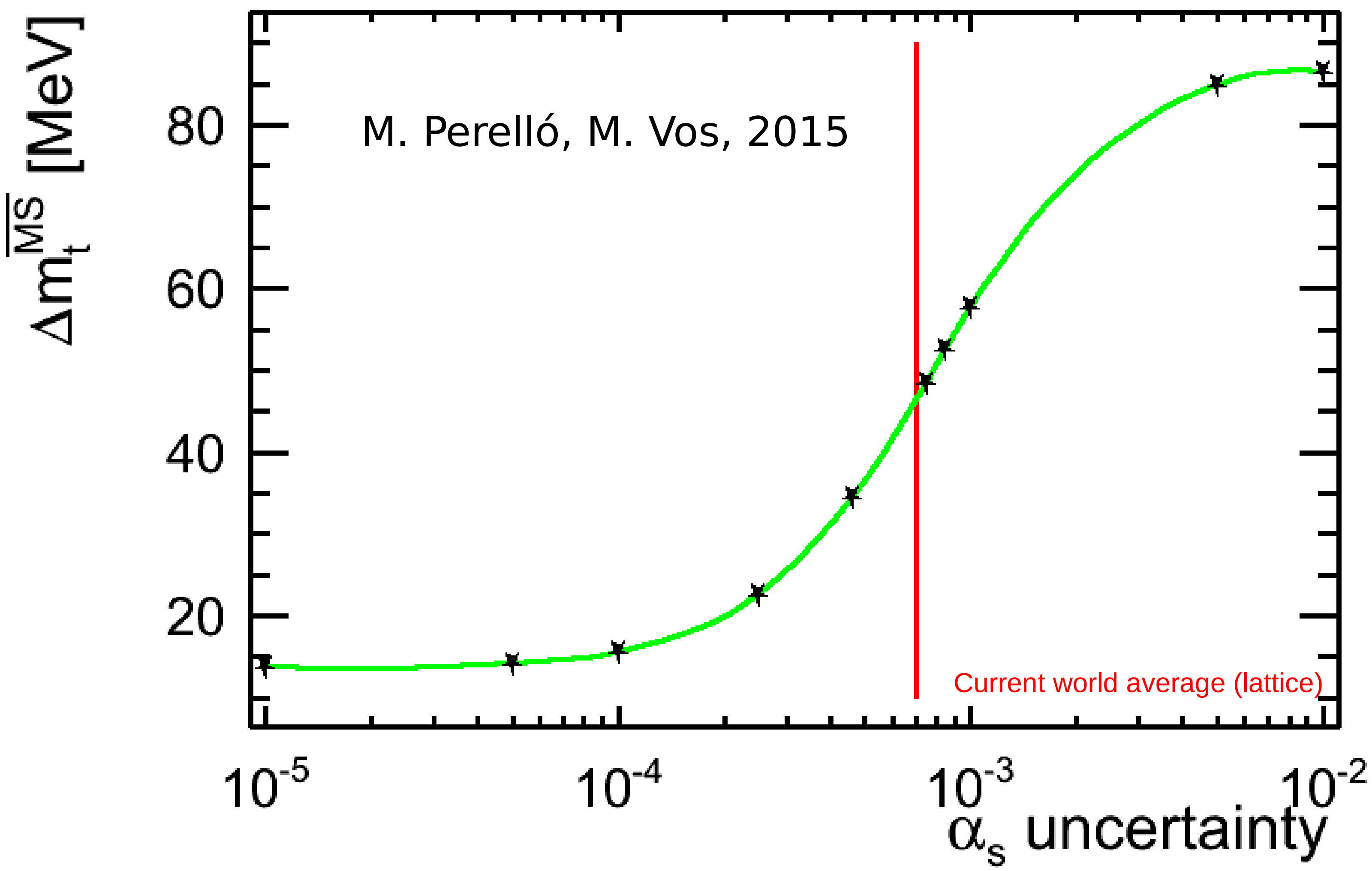
Dominant uncertainty in determination of the $\overline{\mathrm{MS}}$ mass from the threshold scan reduced by factor 10!
However, to take advantage of this fully we need to reduce parametric uncertainty due to α_s

Top quark mass & α_s

M. Perelló

Uncertainty on strong coupling constant strikes twice:

- as a degree of freedom in the fit to extract 1S mass (δM^{1S} goes from 12 MeV → 42 MeV)
- as a parametric uncertainty in the 1S → $\overline{MS}$ conversion



Top quark mass precision vs. prior knowledge of strong coupling strength

$t\bar{t}g$ x-section at $\sqrt{s}$ = 500 GeV has similar sensitivity to α_s as threshold production, but very small top mass dependence. With large luminosity a competitive α_s can be obtained, provided theory & exp. systematics can be controlled to ~0.5%.

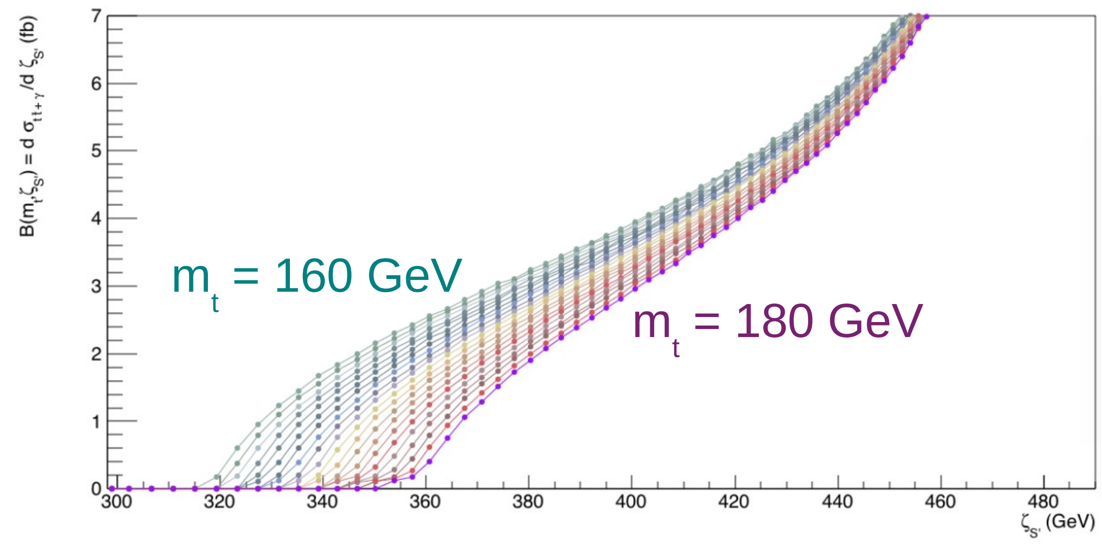
Alternative techniques

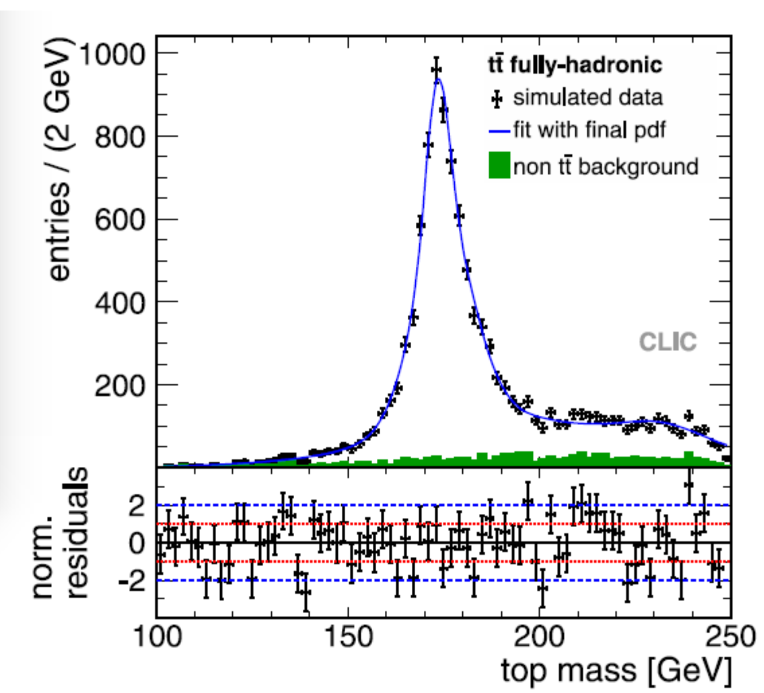
Scenarios start with 500 GeV. The first top quark mass measurement will be made there.
Special opportunities at 1 TeV? Below threshold? 250 GeV seems unlikely to add much after 500 GeV

Extraction of the top quark mass from the differential ttγ and ttg cross-section versus s'

Precision seems competitive for √s ~ 400 GeV

Boronat, Fuster, Gomis, in preparation
(cf. m(b) at m(Z) at LEP, EPJC73 (2013) 2438, ATLAS-CONF-2014-053)





Conventional measurement on top decay products

80 MeV stat. precision at 500 GeV

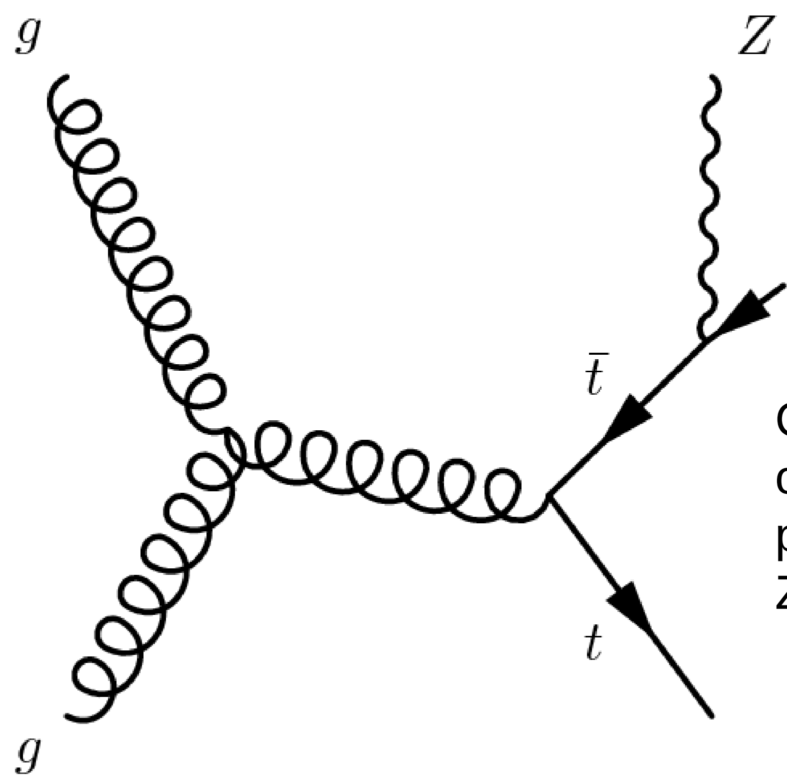
→ input to clarify MC mass interpretation

Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Boosted top quark jets at a 1 TeV e^+e^- collider

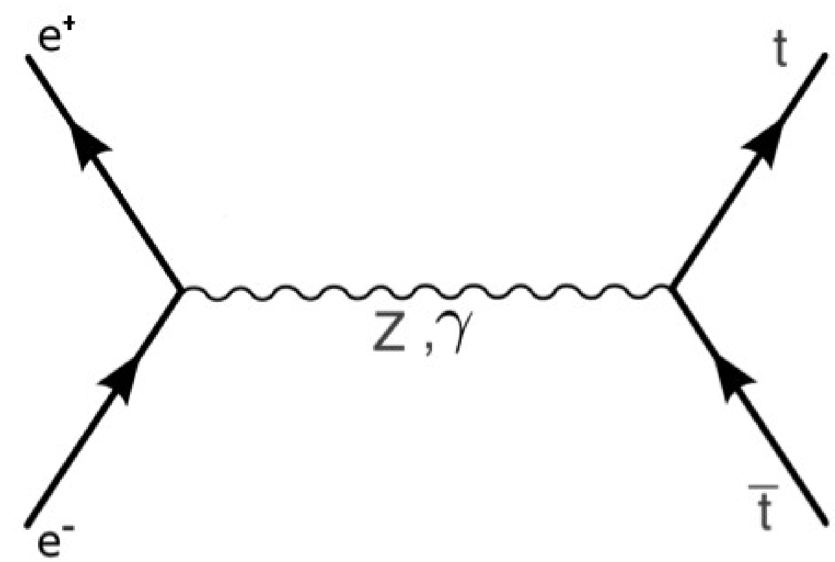
- Extraction from top jets (Hoang, Mantry et al., PRD77 (2008) 074010 & 114003)
  (rigorous SCET interpretation, can “compete” with threshold scan)
- Experimental studies largely lacking so far

BSM and top quark pair production



Costa: LHC observation of associated top quark pair production with W, Z and photon

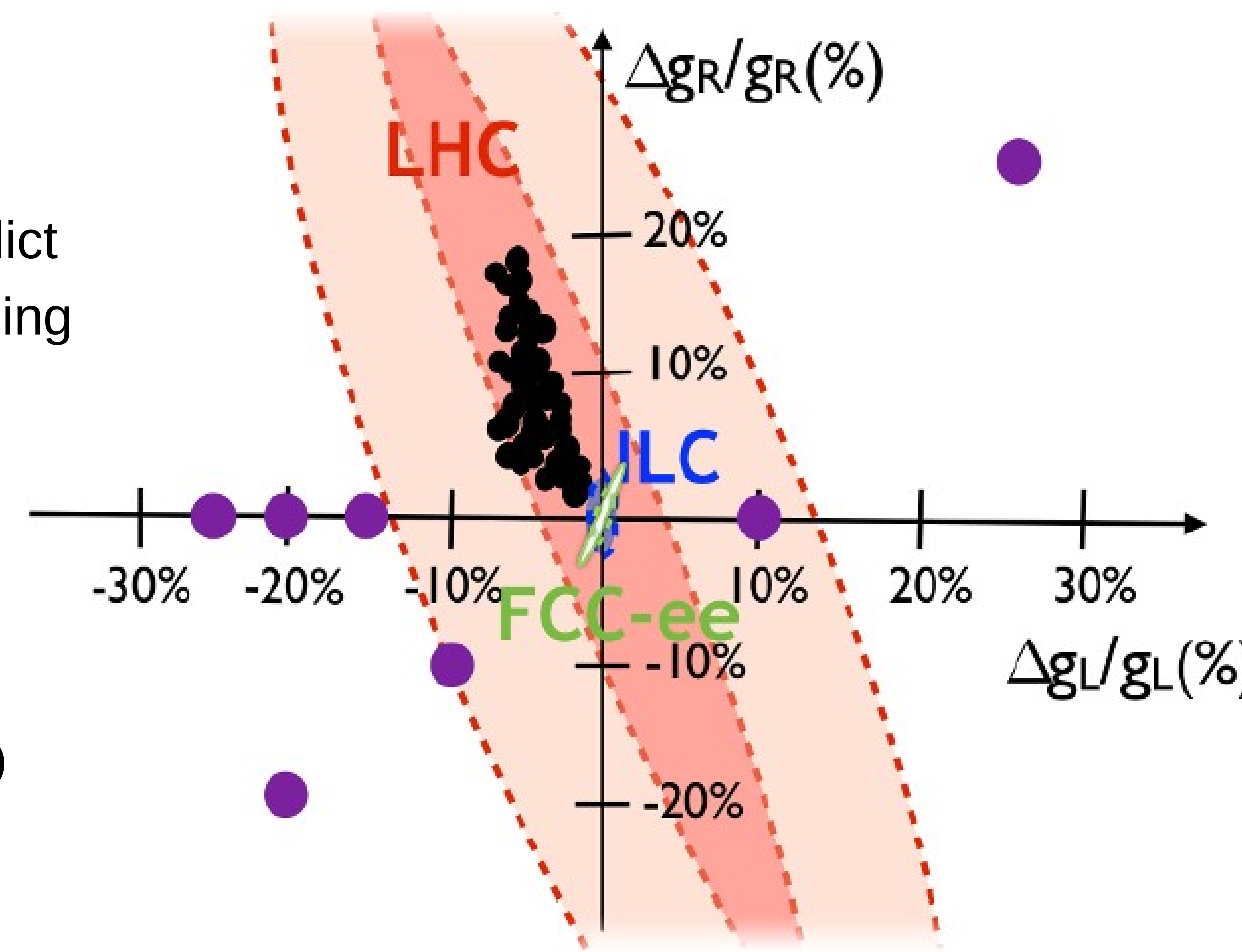
At a LC $e^+e^- \rightarrow t\bar{t}$ production is one of the most prominent 6f processes and readily isolated



Pöschl/deCurtis: Certain classes of SM extensions predict large deviations from the SM prediction for the $t\bar{t}Z$ coupling

Complete ILC programme is senstive to Λ = 10-20 TeV

- 5D models proposed by several authors
  Richard, arXiv:1403.2893
- 4D Composite Higgs Model
  Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)



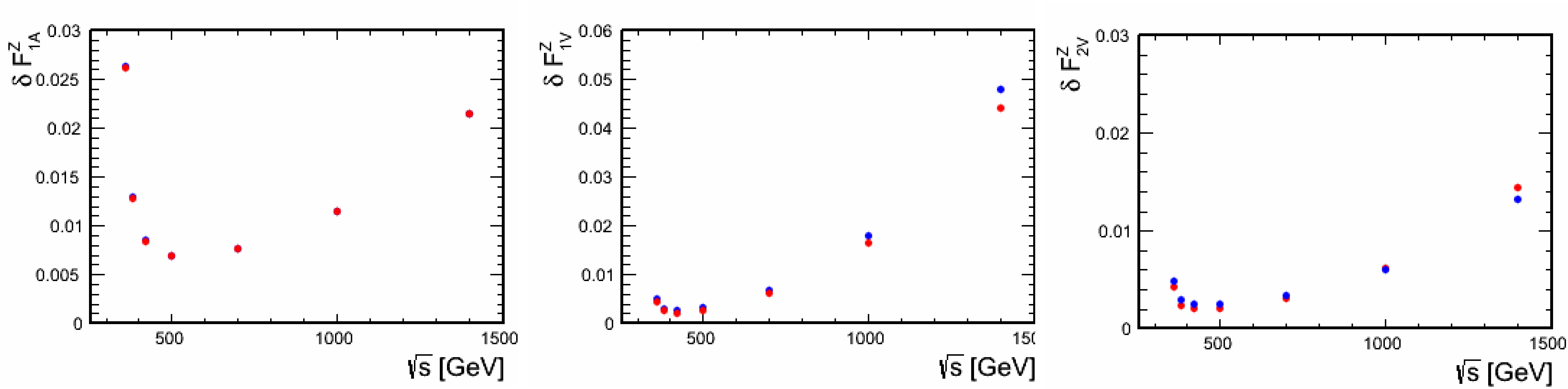
Top quark couplings: sensitivity vs. sqrt(s)

Simple evaluation of statistical uncertainty. A thorough full-simulation CLIC study started.

stat. dominated uncertainty:
$\delta\sigma/\sigma \sim 1/\sqrt{N}$ $\delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$
Integrated luminosity: 2 x 250/fb

Nominal beam polarization (e^- 80%, e^+ 30%)

Electron polarization only



F_{1V}: shallow minimum → *optimal around 400 GeV*

F_{1A}; A_{FB} degraded strongly close to threshold → *500 GeV*

F_{2V}; impact of new physics grows strongly with energy → 1-3 TeV

Truly optimal: comprehensive program at several energies

See next talk by R. Poeschl

Marcel Vos (marcel.vos@ific.uv.es)

sophisticated methods (parton level)

Khiem, Kou, Kurihara, le Diberder, Probing new phyiscs using top quark polarization in the e+e- → tt process at future Linear Colliders, arXiv:1503.04247 [hep-ph]

- show feasibility of kinematic reconstruction of the di-lepton final state: $e^+e^- \rightarrow t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b\bar{b}$
- extract all ten form factors – simultaneously – using ME method

See next-to-next talk by François le Diberder

P. Janot, arXiv:1503.01325, assesses potential of circular machine

- run right above threshold; study assumes 2.4 ab^{-1} at $\sqrt{s}$ = 365 GeV

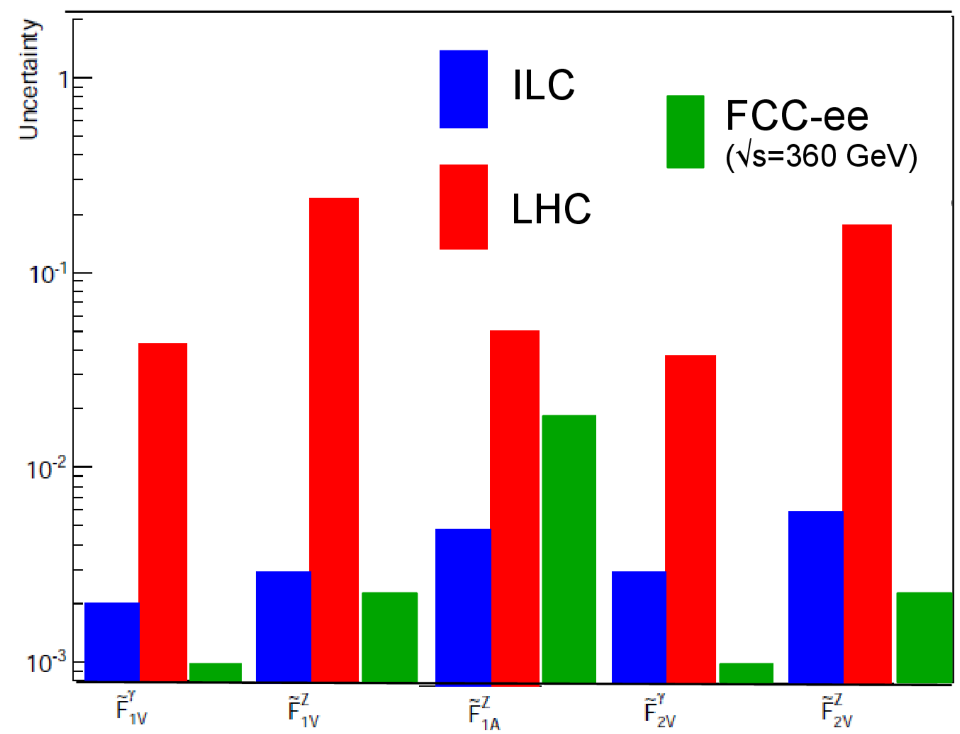
  (theory systematics close to threshold to be evaluated)

- no beam polarization, use final-state polarization instead

  (ILC beam polarization expected to be known to 10^{-3}, can one understand final state polarization to that level?)

Fast simulation analysis based on lepton energy and angle yields:

- similar precision for Z couplings, except F1AZ
- better than ILC for photon couplings



ttH

Roloff:
ttH overview at LC

Excellent detectors
Are our reconstruction tools ready for the high-multiplicity challenge?

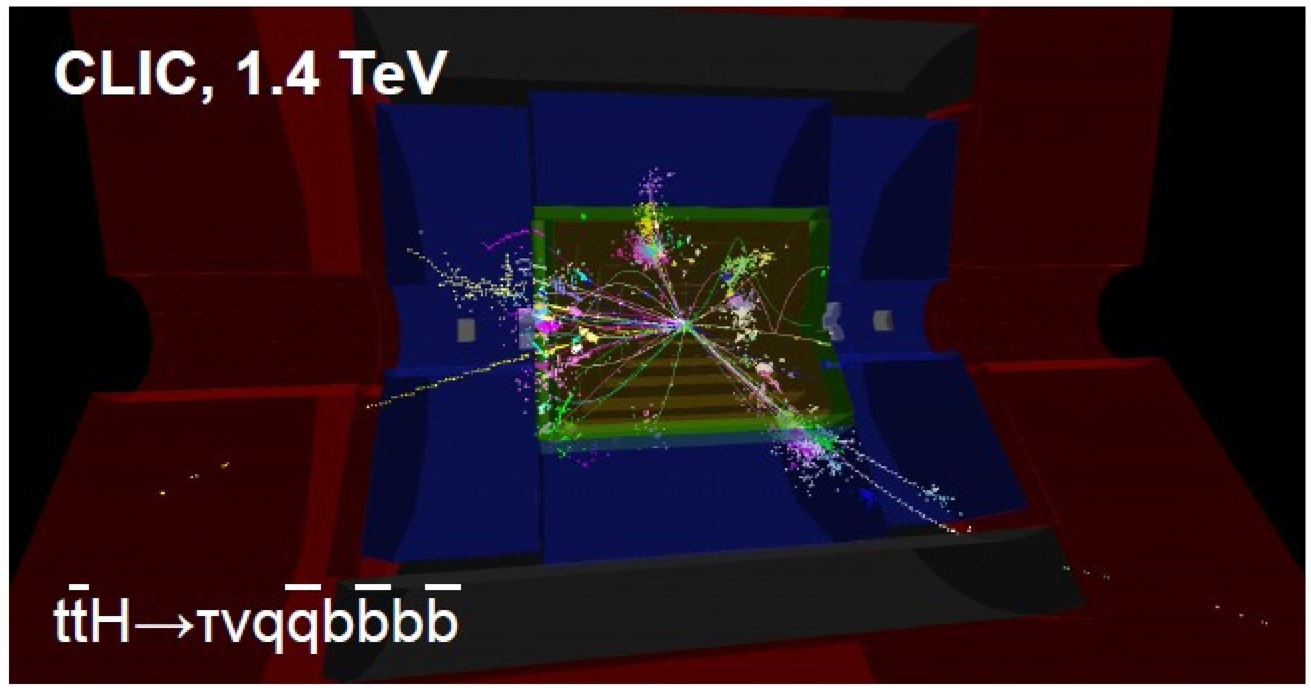
Vertex/jet charge?

Investigated final states:

"*8 jets*": $t(\to q\bar{q}b)\bar{t}(\to q\bar{q}\bar{b})H(\to b\bar{b})$

"*6 jets*": $t(\to q\bar{q}b)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$

["*4 jets*": $t(\to l\nu b)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$]



Crucial tests of various detector Performance and reconstruction aspects:

- Jet reconstruction in complex final states
- Flavour tagging
- Charged lepton identification
- Missing energy reconstruction

- About 4% precision on the top Yukawa coupling achievable with 1 ab^{-1} at 1 TeV at the ILC or 1.5 ab^{-1} at 1.4 TeV at CLIC

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1500
Top Yukawa coupling κ_t	$(14-15)\%$	$(7-10)\%$	10%	4%	4%

from arXiv:1311.2028

Differential distributions can be explored to study CP properties

550 GeV known to be much better than 500 GeV

top → charm Higgs

Standard Model: strongly (loop, GIM) suppressed flavour violation in Higgs sector: BR $(t \to cH) \sim 10^{-15}$

Nebot: sizeable deviations in 2HDM with tree-level FCNC
BR $(t \to cH)$ up to 10^{-2} arXiv:1508.05101

Abbas: aligned 2HDM escapes LHC detection
BR $(t \to cH)$ up to 10^{-8} arXiv:1503.06423

BR $(t \to cH) = 10^{-4}$ in Randall-Sundrum models

$t \to cH$ enhanced more than "traditional" $t \to c\gamma$, $t \to cg$, $t \to cZ$

LHC: CMS $H \to \tau\mu$ excess?
LHC using rare Higgs signatures ($H \to \gamma\gamma$, ZZ)
ATLAS $t \to qH$ search ($H \to \gamma\gamma$): BR < 0.79%, JHEP06 (2014)
CMS $t \to cH$ search: BR < 0.56%, CMS-PAS-HIG-13-34
LHC projections from Snowmass top working group:
BR$(t \to cH) < 5\ (2) \times 10^{-4}$ after 300 (3000) fb^{-1}

Linear Collider t → cH prospects

F. Zarnecki: Parton-level study in WHIZARD with 2HDM signal and major SM backgrounds

Basic event selection:

- 1 lepton + Etmiss + 4 jets, among which 3 b-jets
- 0 lepton, no Etmiss, 6 jets, among which 3 b-jets

Reconstruction:

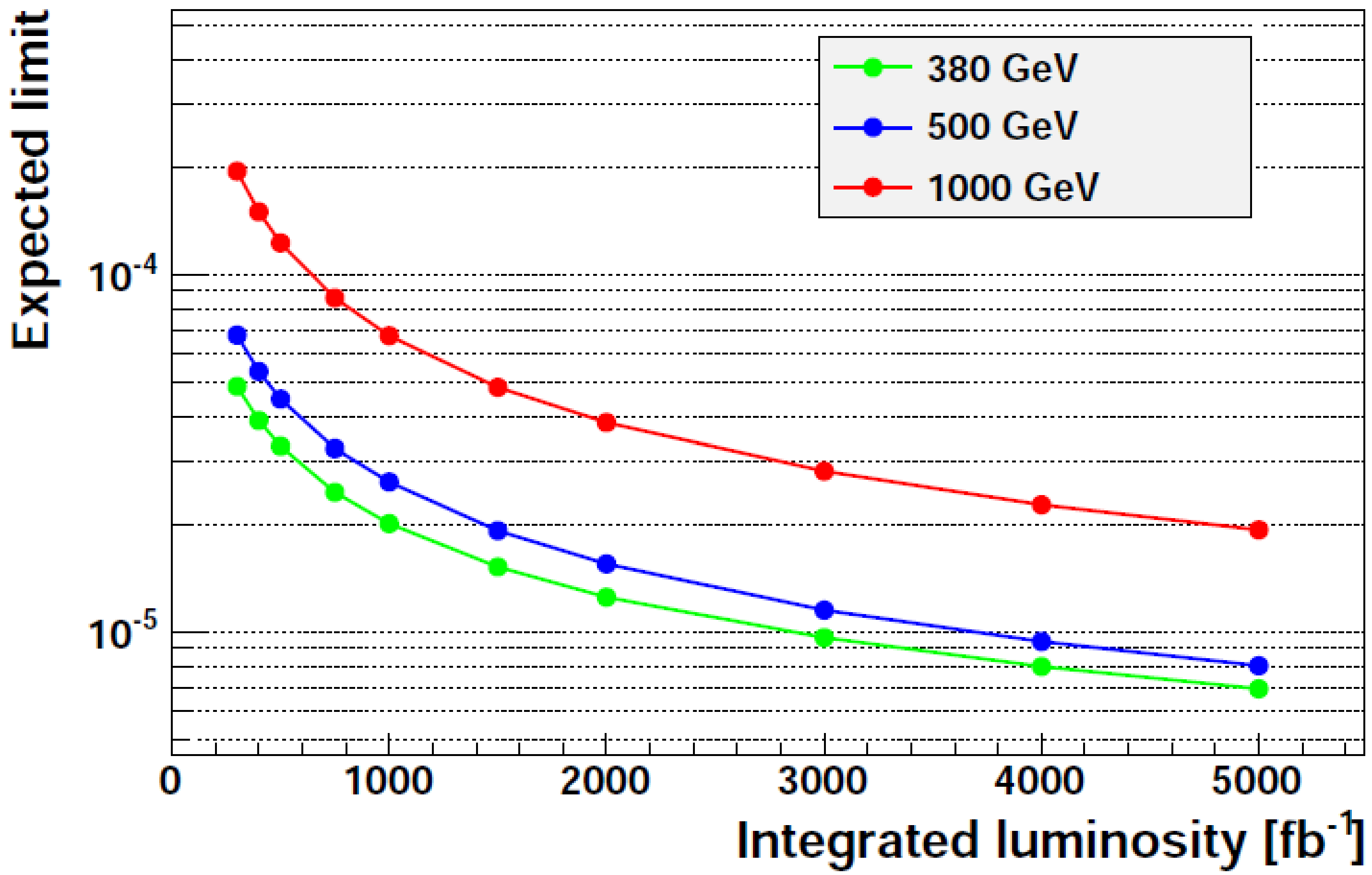
Create spectator top candidate (blν, or bqq) and signal top (bbq)

Higgs candidate is bb combination in signal top candidate

SM background can be controlled using b-tagging and kinematic constraints *even with imperfect b-tagging and finite jet energy resolution*

Limits improve proportional to # top pairs

Order of magnitude better sensitivity wrt LHC after complete ILC programme



Summary²

Workshop collects a wealth of evidence for the exquisite sensitivity of the Linear Collider top quark physics programme...

… classical claims ($\overline{\mathrm{MS}}$ mass < 50 MeV, ttZ coupling to 1%) are getting more solid

… top and Higgs → a golden couple

… top physics case extending (t → cH)

… challenging our reconstruction tools and our understanding of systematics

Progress in all these areas demonstrates top@LC is alive and kicking!

Full programme on INDICO:

http://ific.uv.es/~toplc15/index.html