Top/QCD at LCWS 2015
- Summary -

Frank Simon
Max-Planck-Institute for Physics

Material taken from the speakers of the Top/QCD sessions:
Iurii Ilchenko, Laura Reina, Jan Strube, Yuji Sudo, Jürgen Reuter, Nadia Pastrone, Marcel Vos, Roman Pöschl, Francois Le Diberder, Peter Marquard, Andreas Maier, FS, Andre Hoang - and Michael Peskin

LCWS 2015
November 2015
Whistler, BC, Canada

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Introduction

"In discussion of the physics case for future e+e- colliders, the top quark is often unappreciated "

- M. Peskin, on Monday

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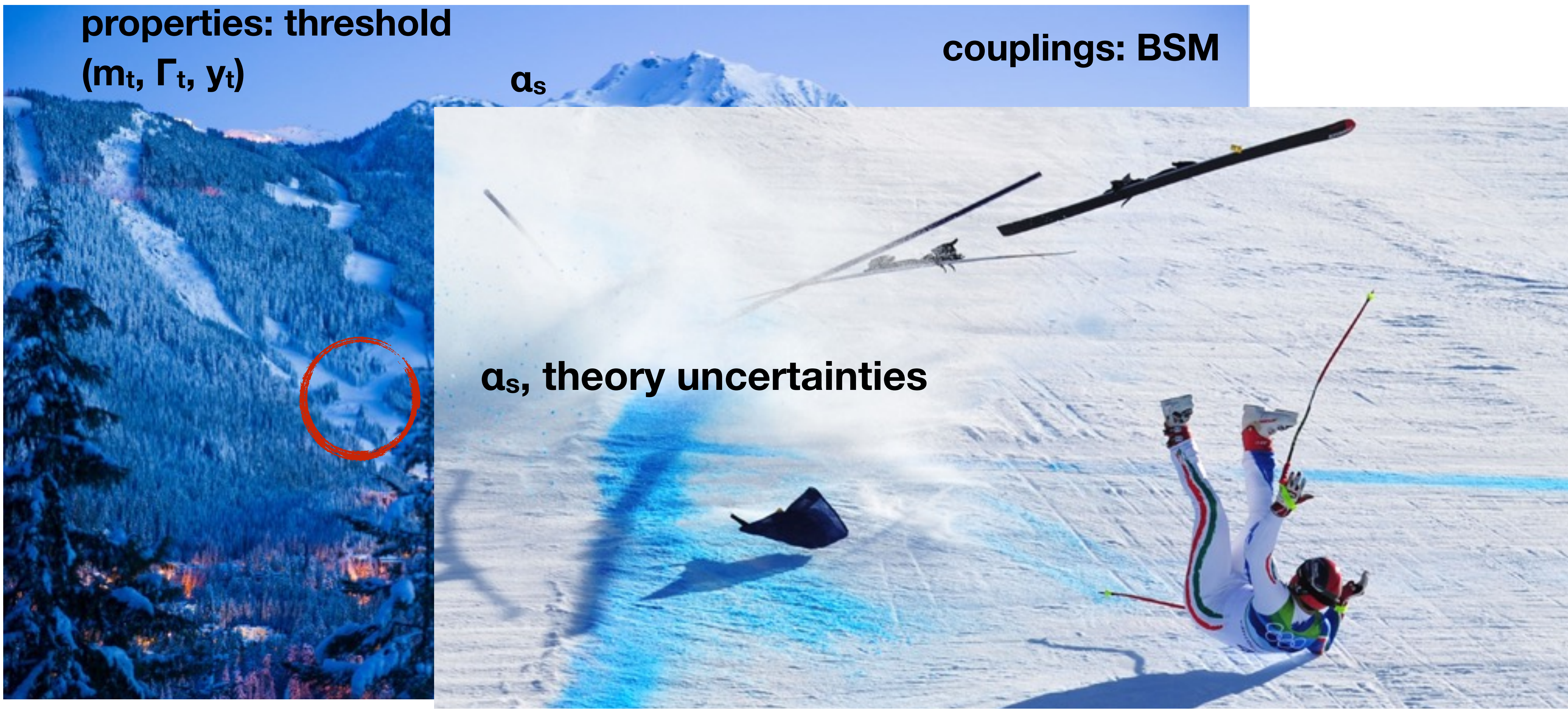
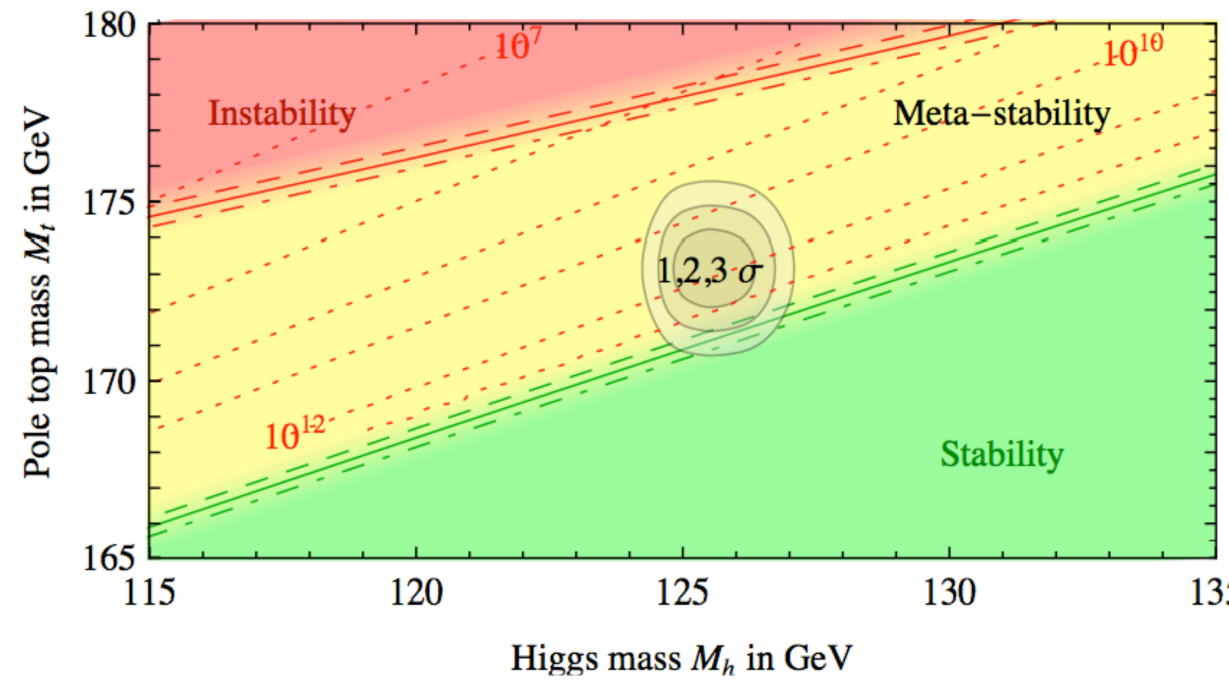


Top Questions

- The top physics program at LCs is broadly divided into two main directions:



- Properties of the top quark:
  - Mass
  - Width
  - Yukawa coupling

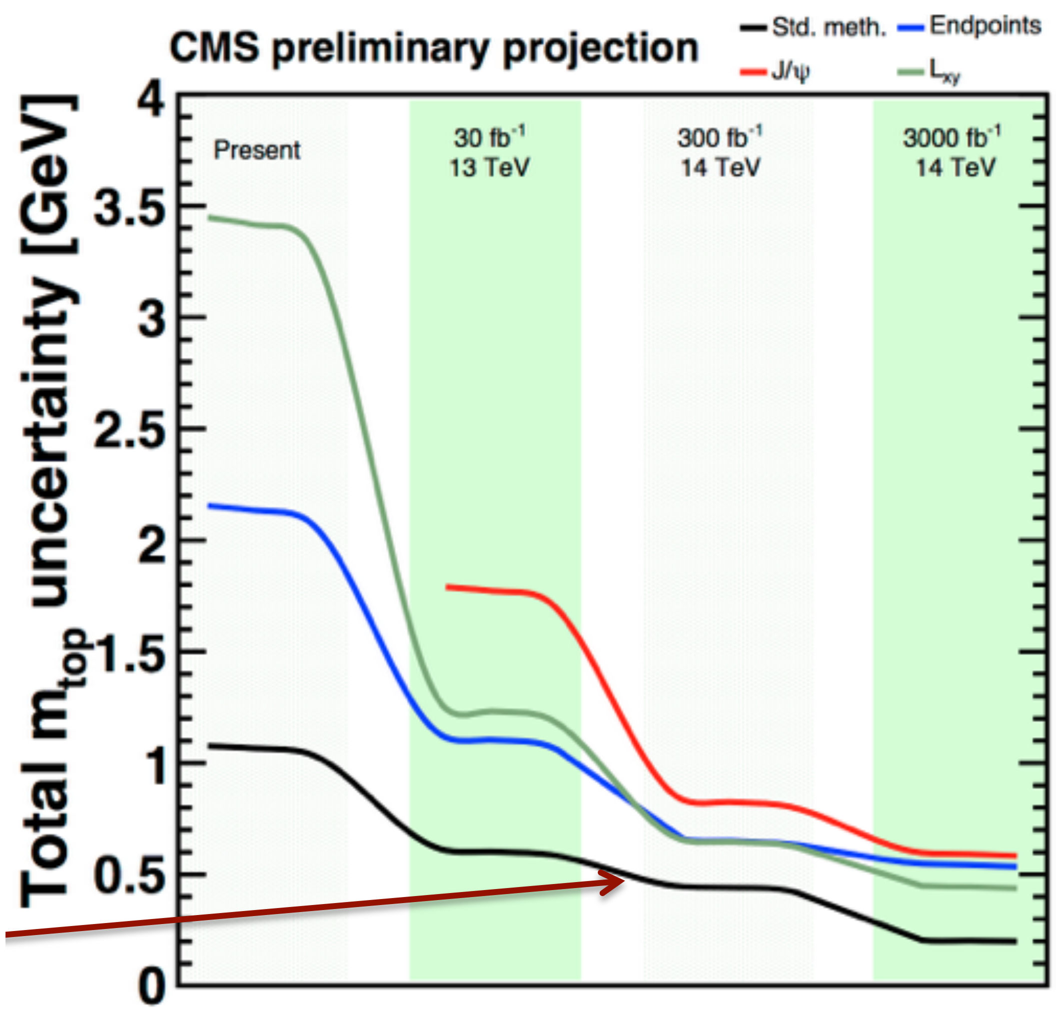
- Sensitivity to BSM physics
  - Electroweak couplings
  - What is the nature of the top quark?

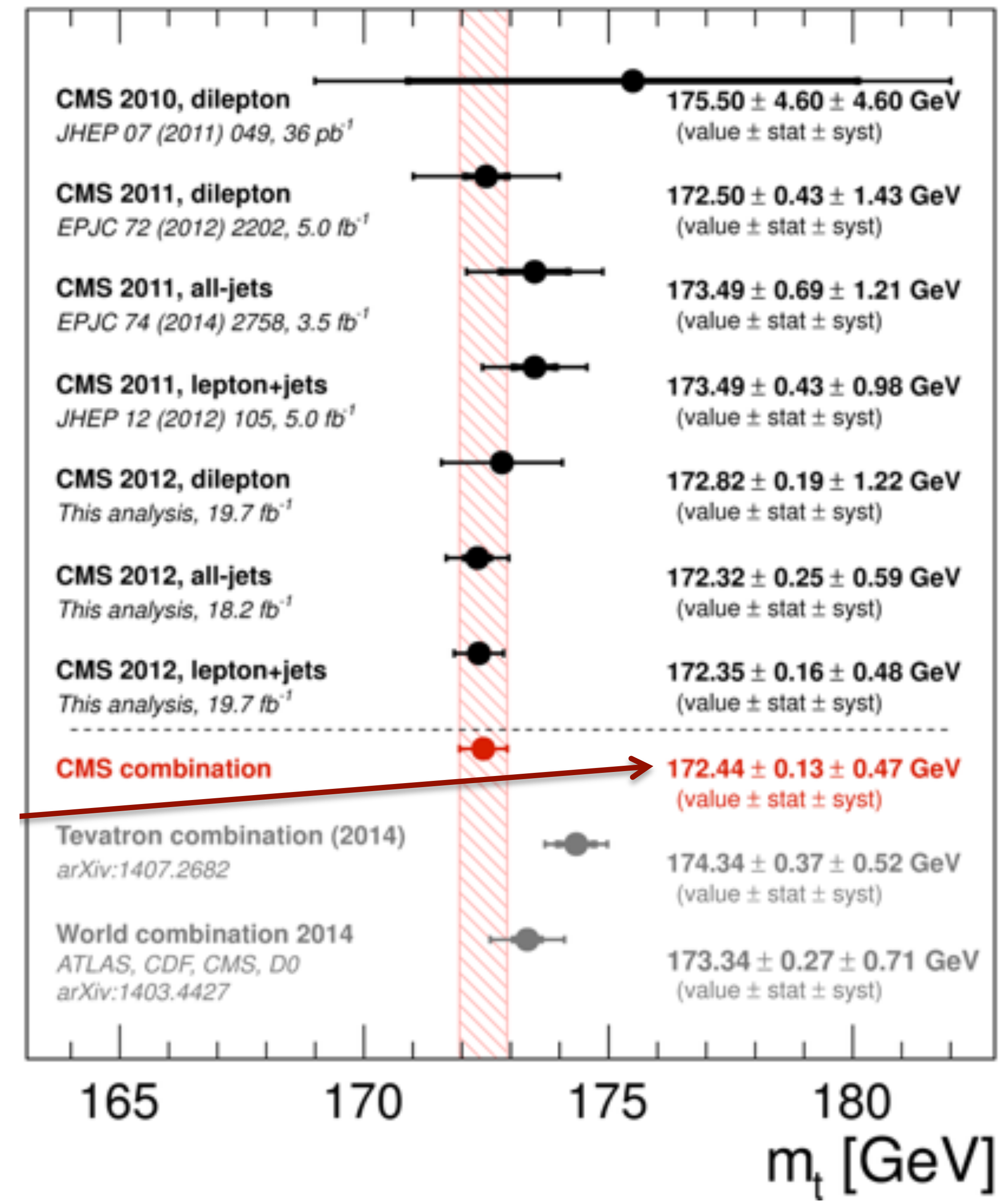
M. Peskin: Is the top quark a *normal* quark or a *heavy* quark?

LHC - Defining the Top Today

- LHC as a top quark factory: 1 top pair per second!
- The mass is now known with
  ~ 0.5 GeV uncertainty

  outperforming expectations / projections for Snowmass!





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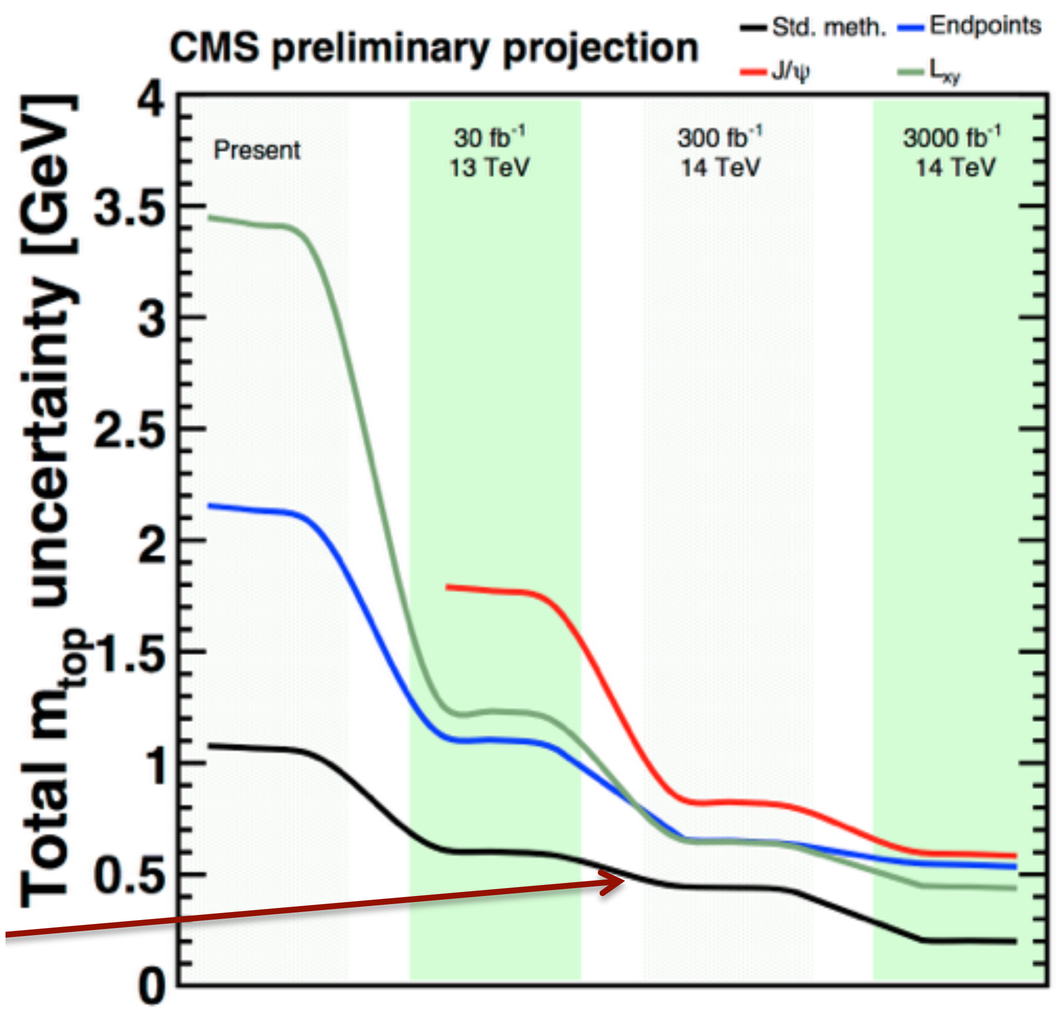
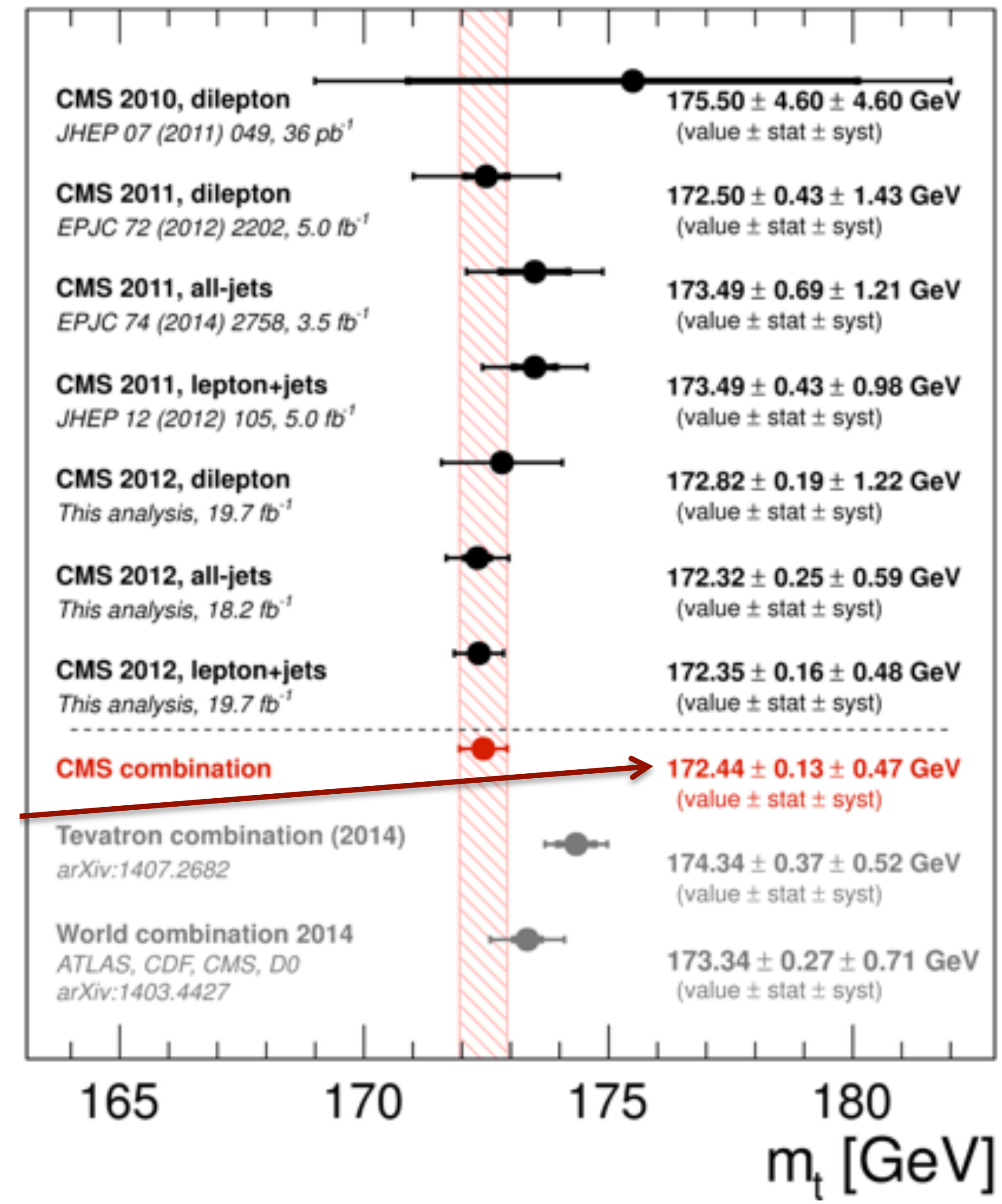
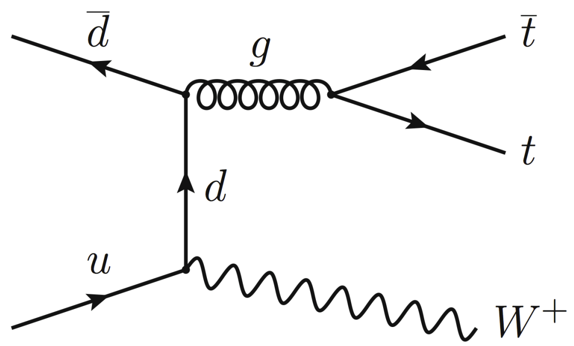


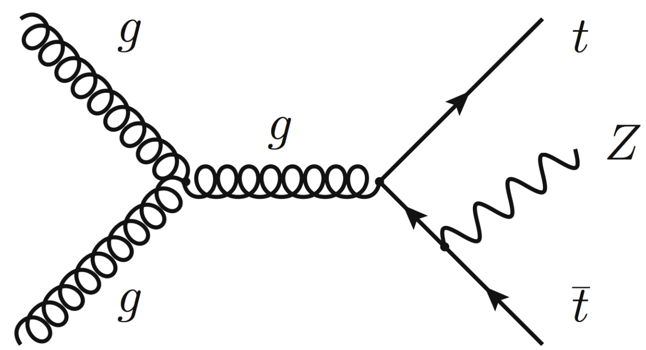


N.B.: Uncertainties of connecting measured mass to msbar mass not included!

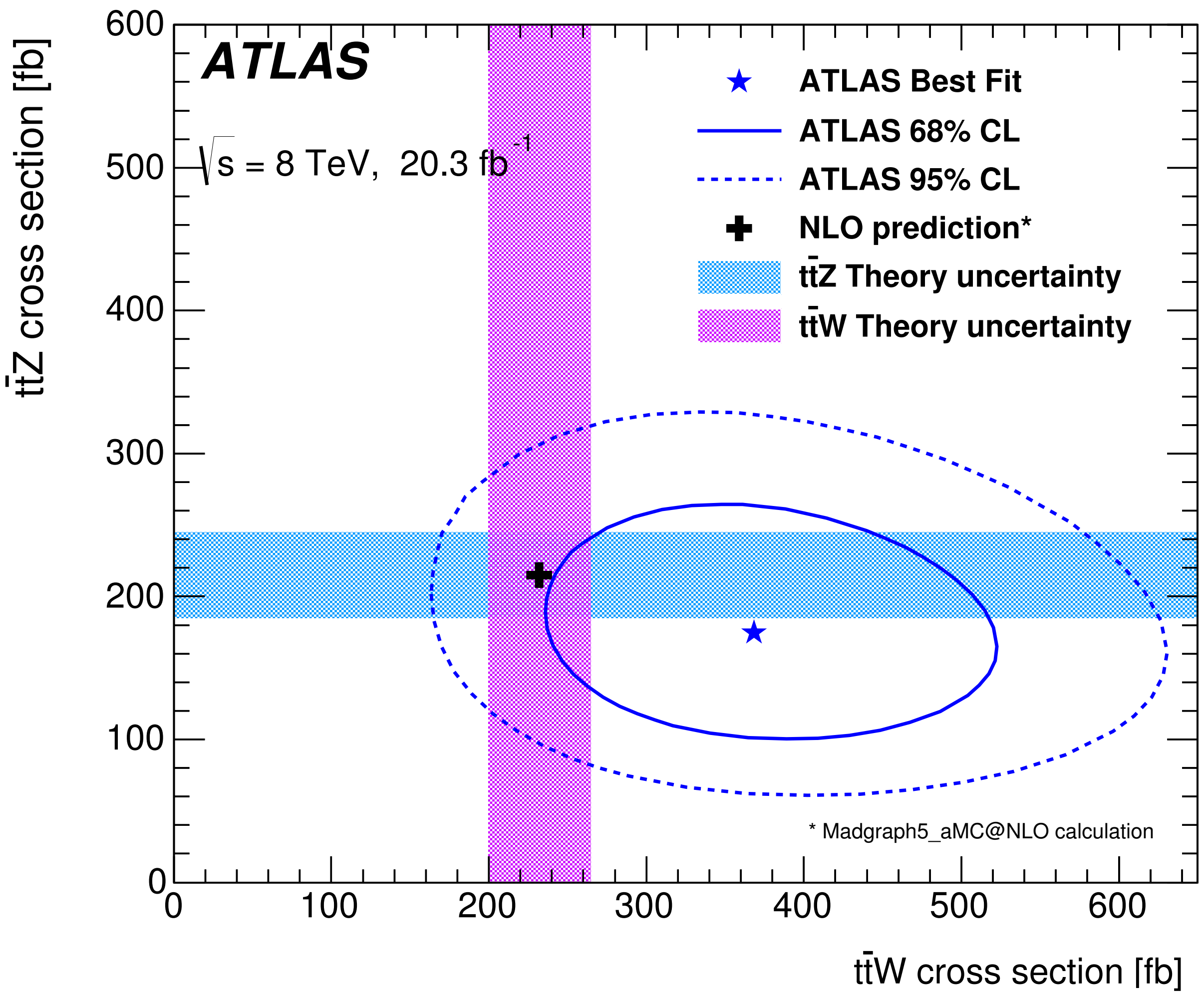
LHC - Defining the Top Today

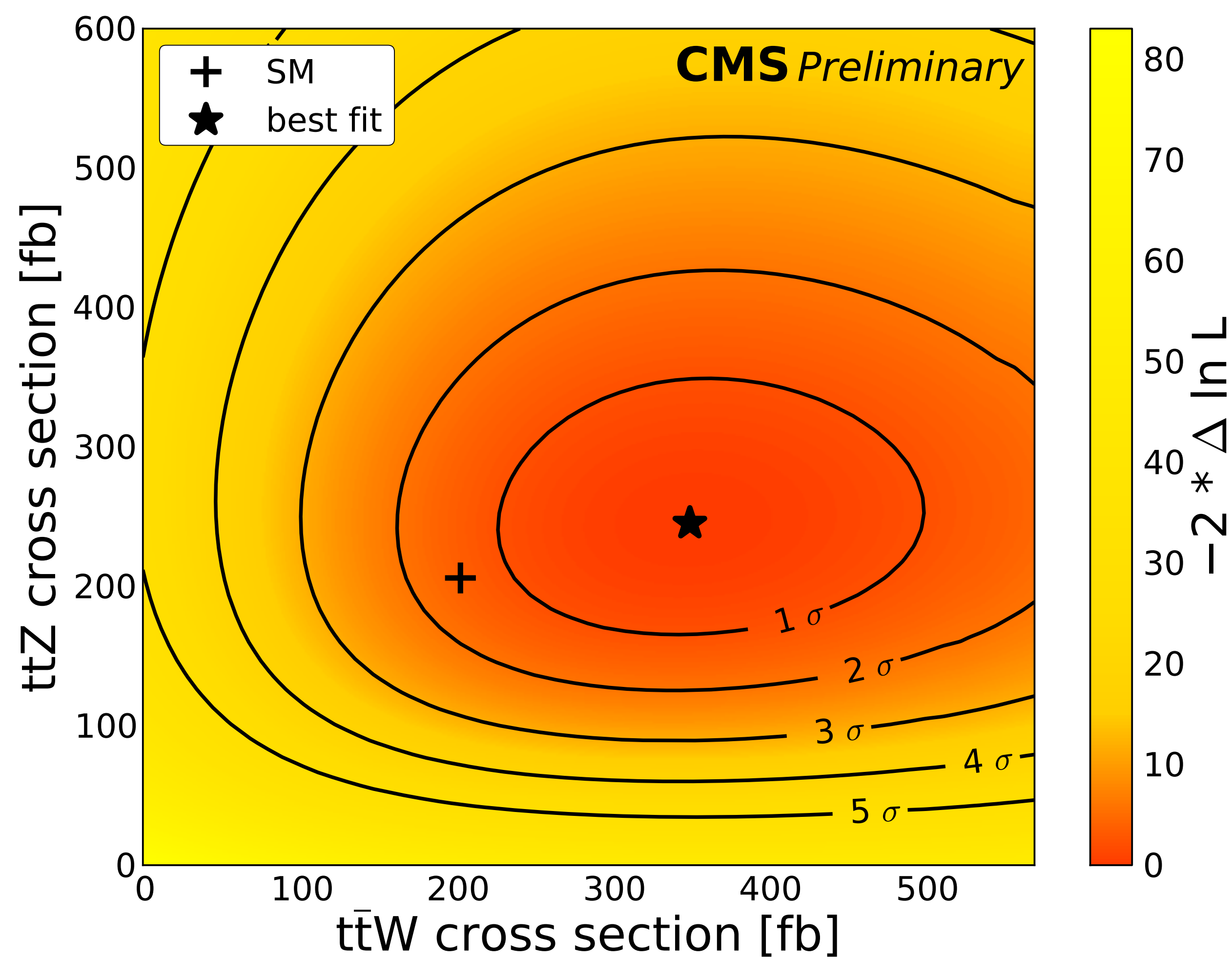
- First observations of ttV (V= Z, W) production





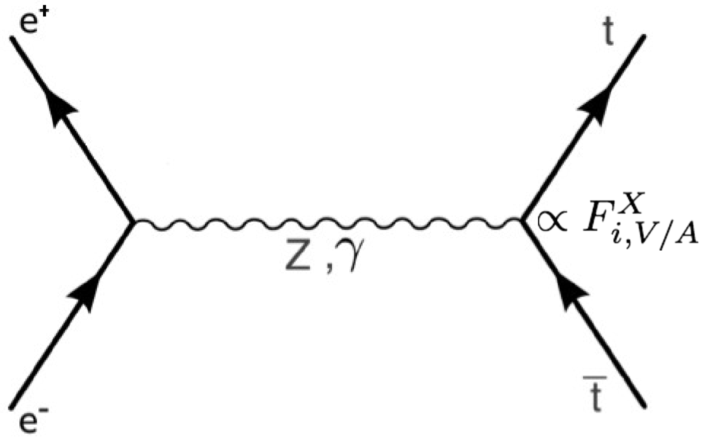
provides access to top-Z coupling at LHC





Top Couplings at the ILC

- In e^+e^- collisions: production via γ/Z: strong sensitivity, also to new particles, asymmetries *O*(1)



Extraction of different γ and Z couplings / form factors rely on polarized beams

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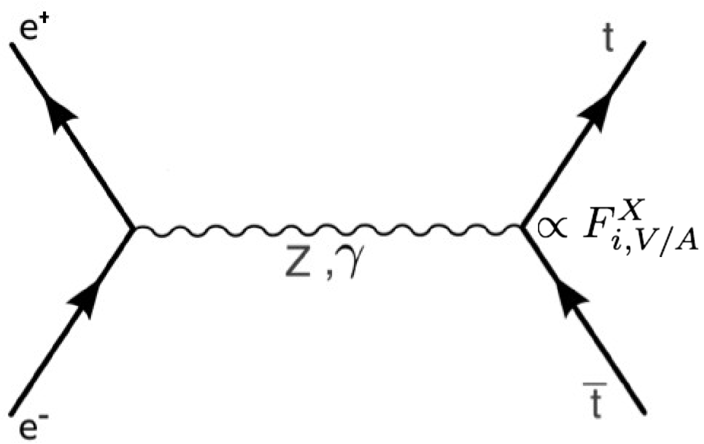
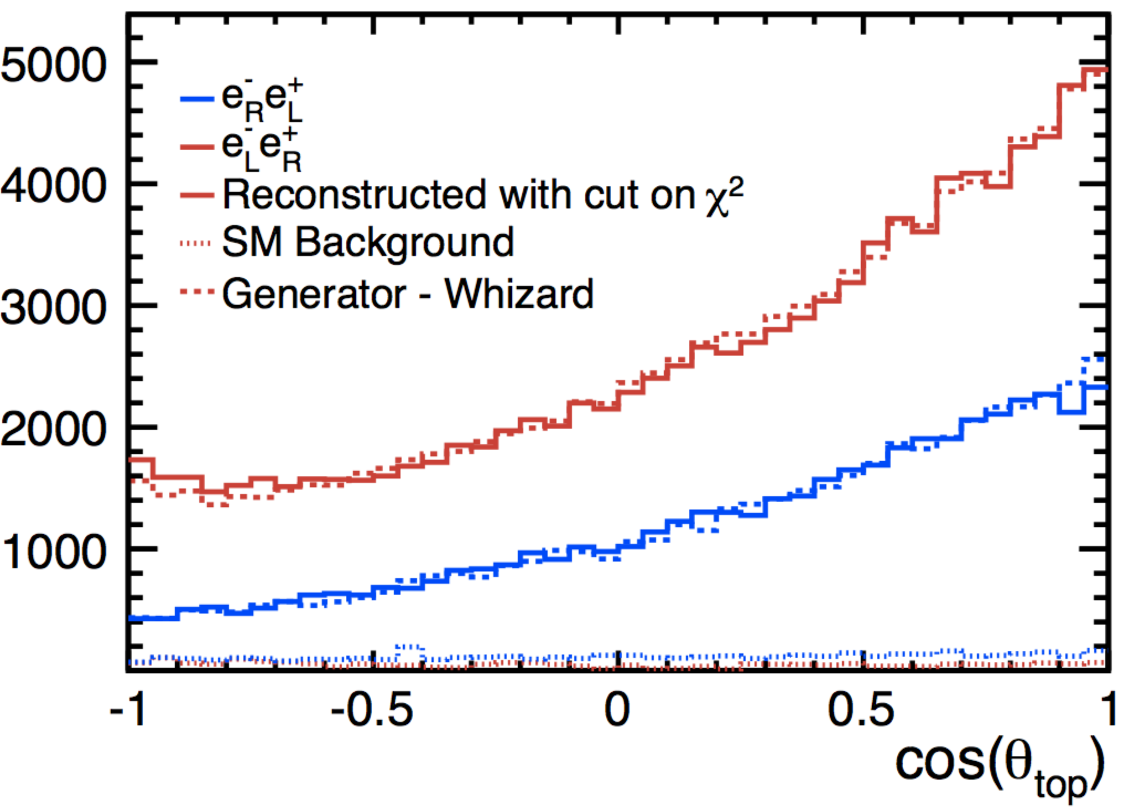


Extraction of different γ and Z couplings / form factors rely on polarized beams

top angle to measure A_{FB}



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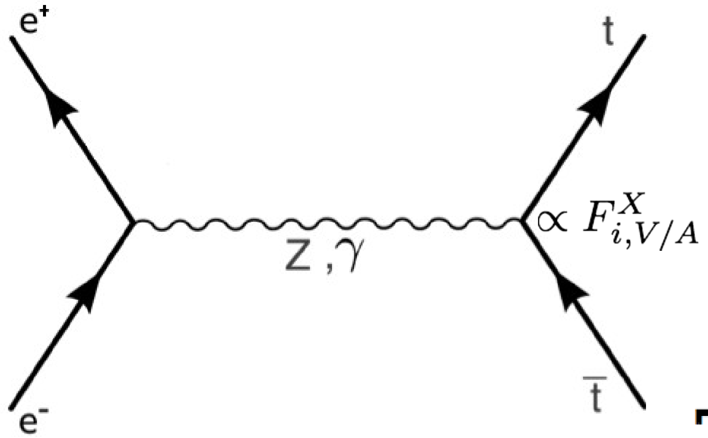

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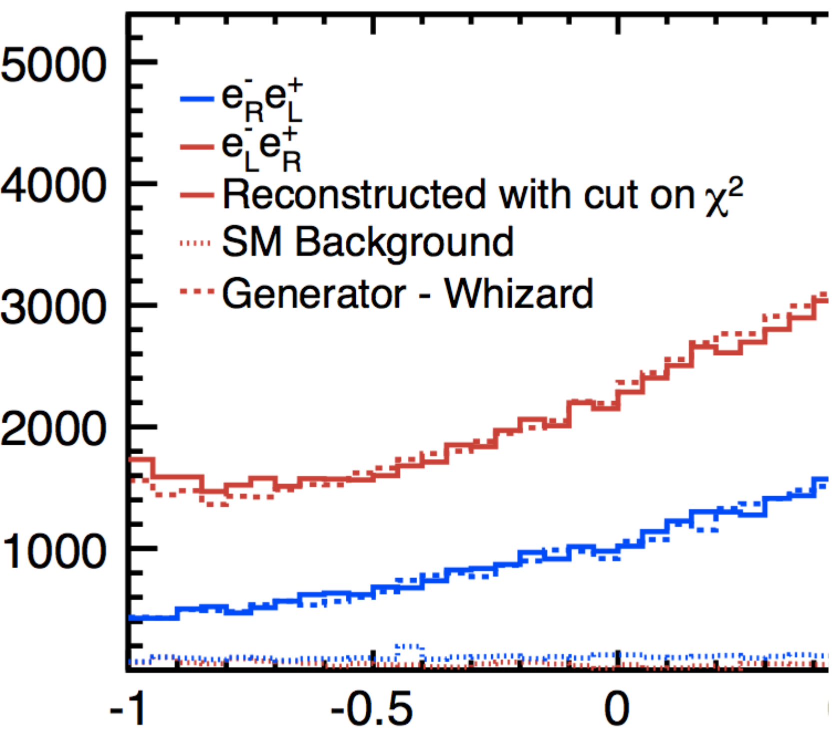
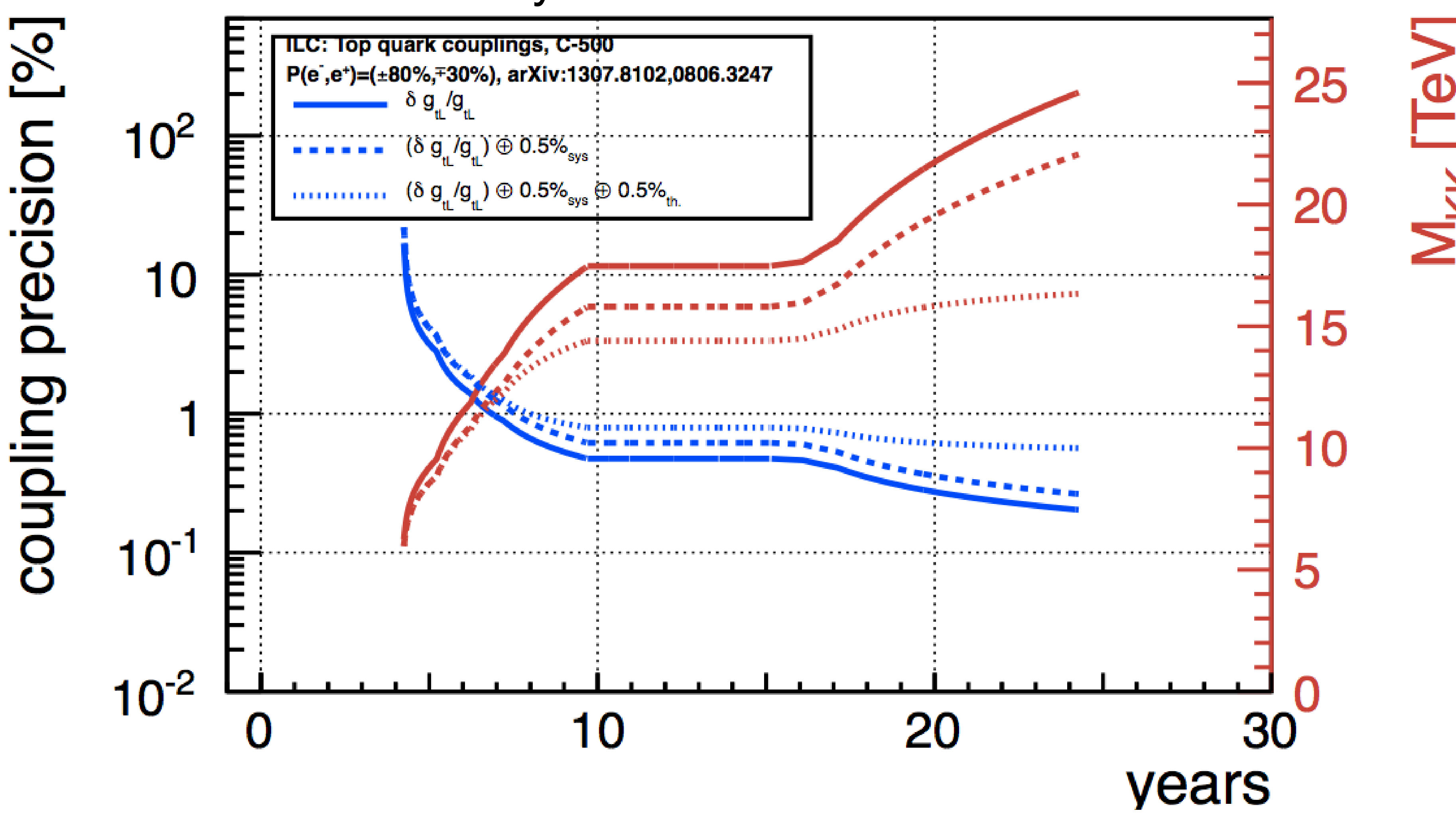
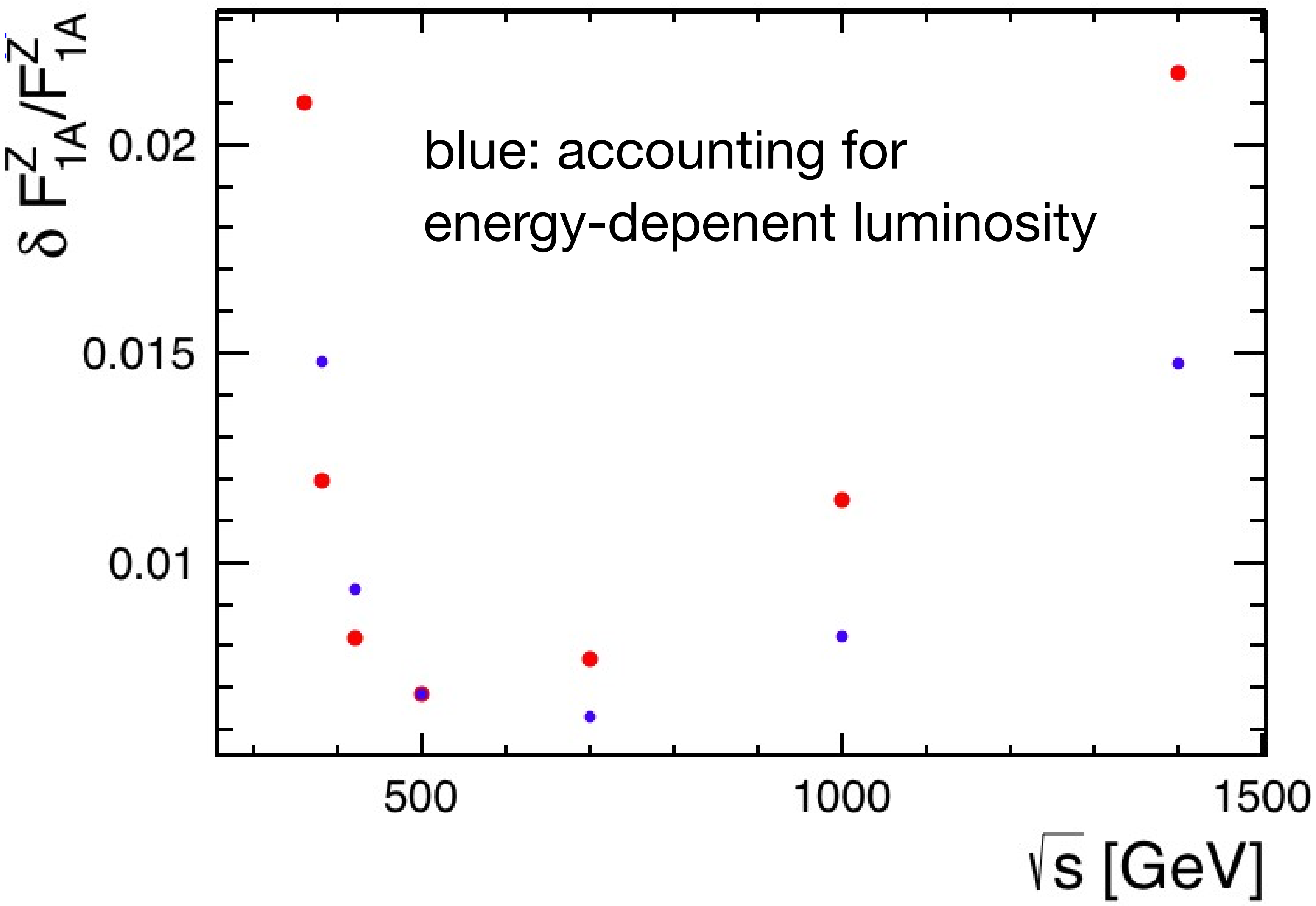


ILC sensitivity to extra-dimensional models



Top Coupling: Which Energy to Choose?



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- For ILC: Importance of > 500 GeV running for top couplings

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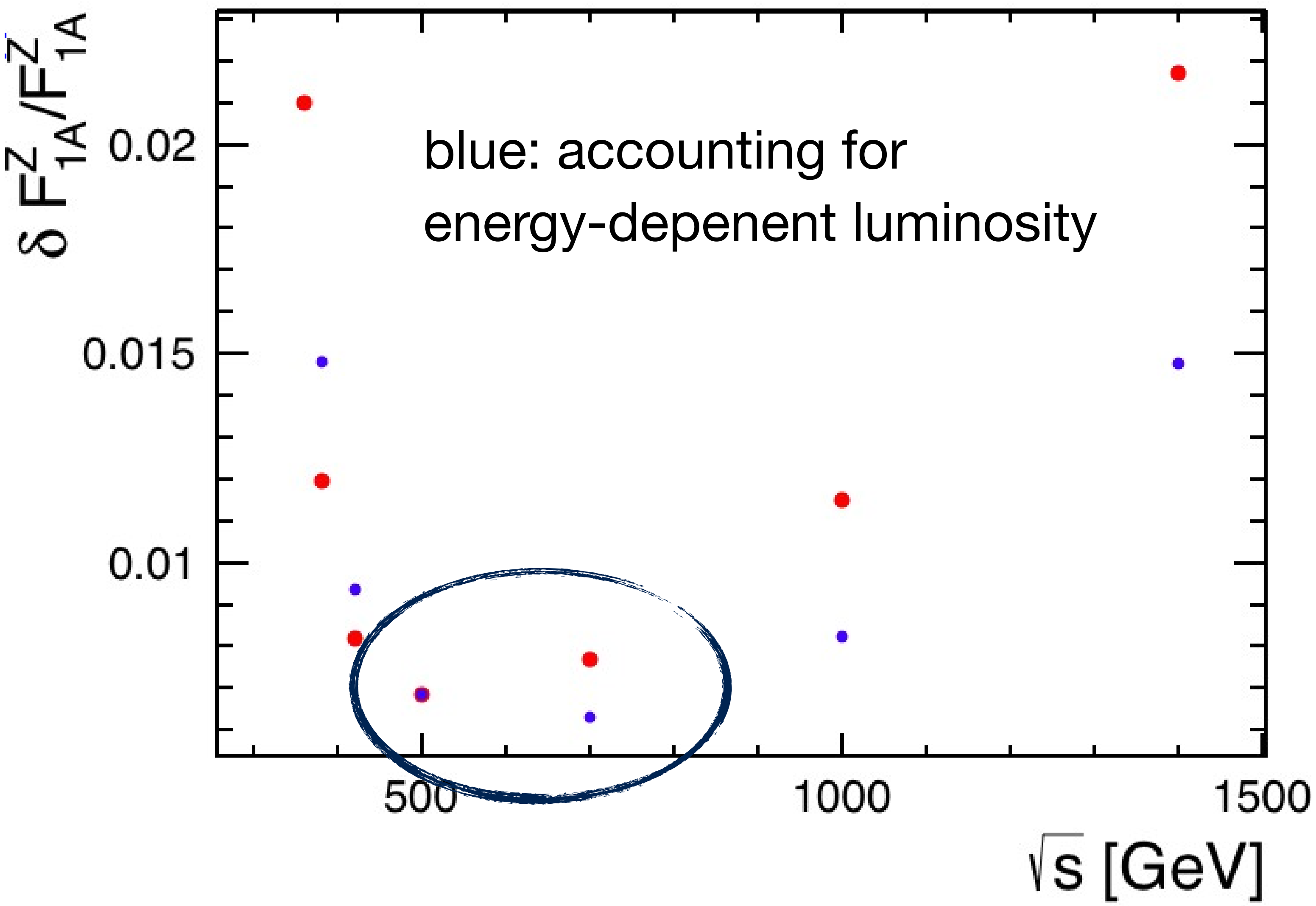

sweet spot around 500 - 700 GeV

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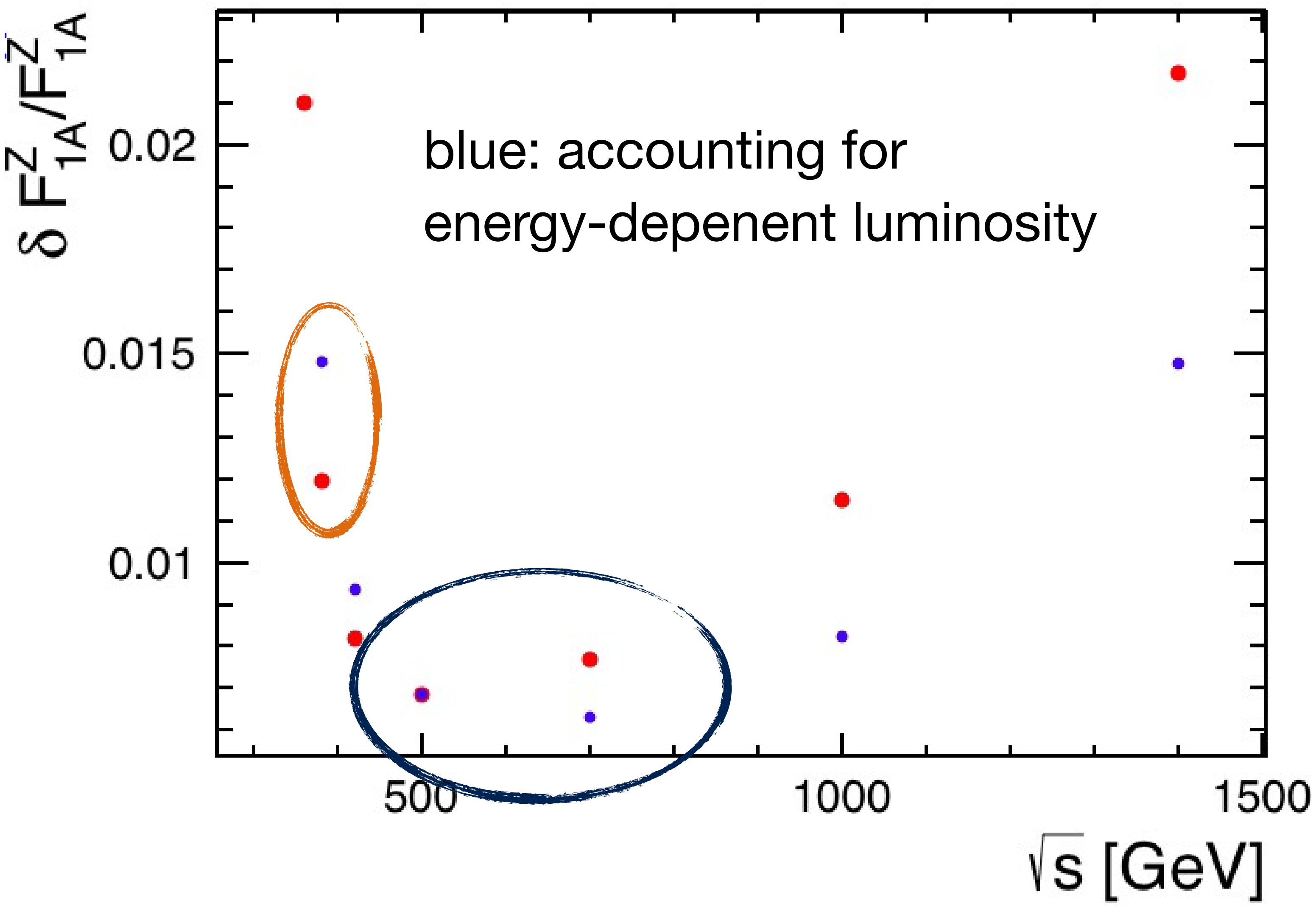

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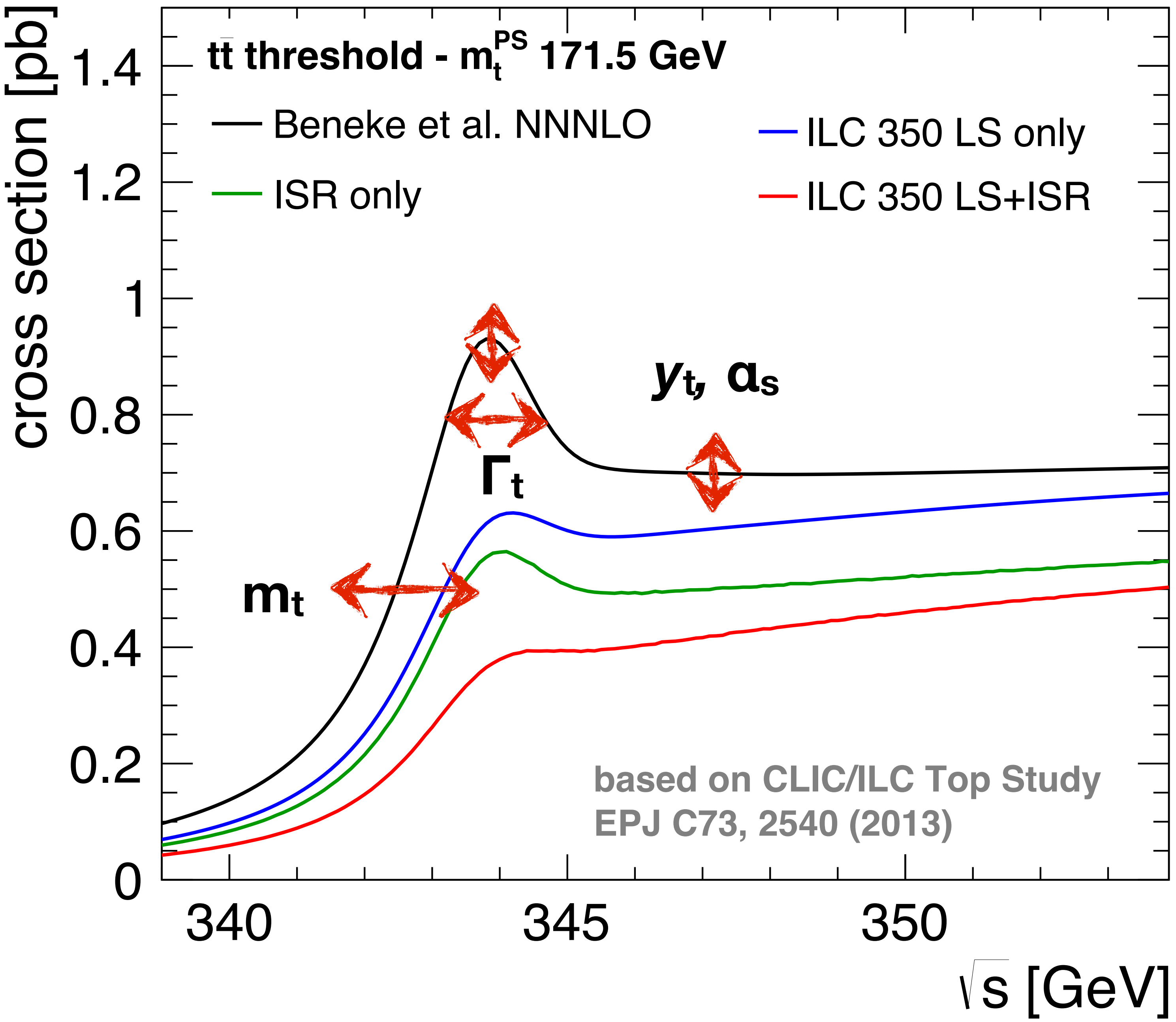
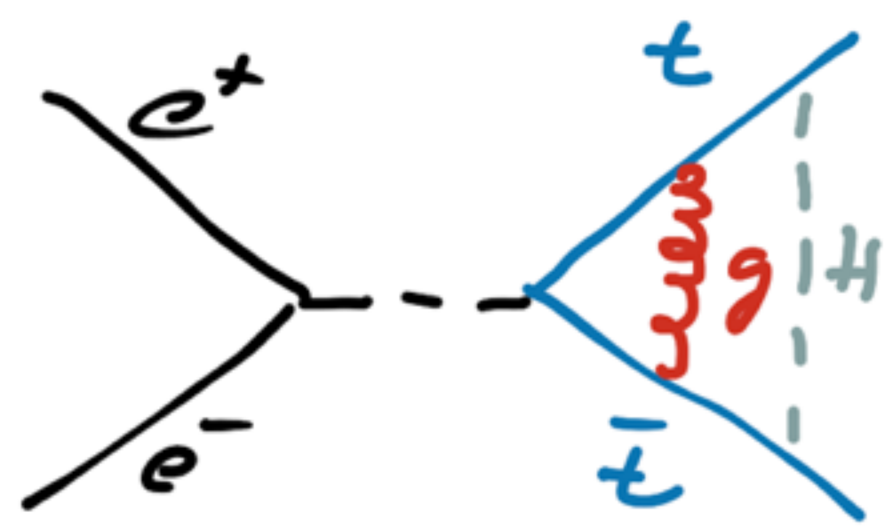
for CLIC stage 1: 380 GeV best compromise between Higgs and Top physics

The Top Pair Threshold



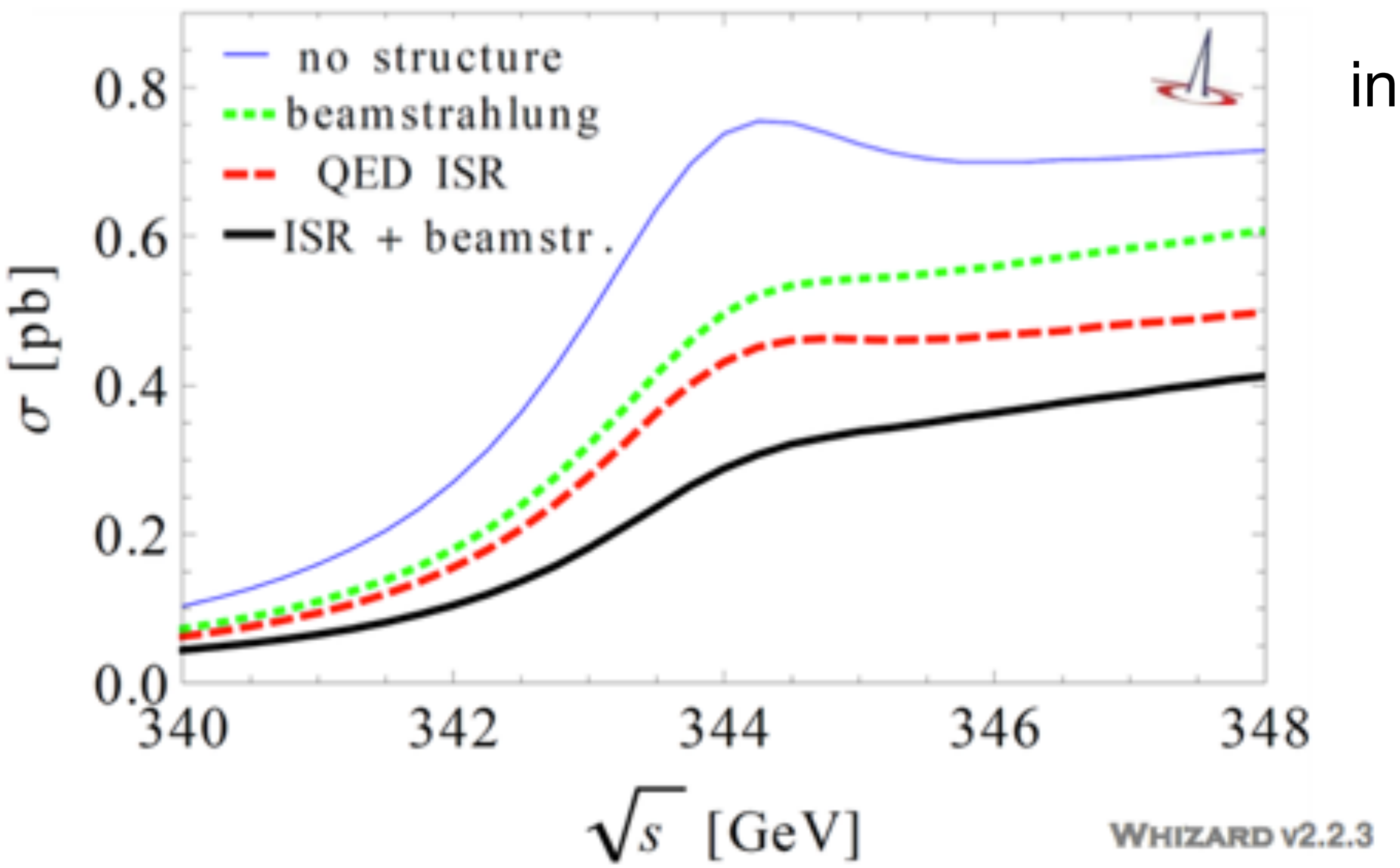
- The cross-section around the threshold is affected by several properties of the top quark and by QCD
  - Top mass, width, Yukawa coupling
  - Strong coupling constant



- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak - precise external α_s helps

The Threshold in MC

- Now available: NLO simulation of the ttbar threshold in WHIZARD
    - Opens up the possibility for more sophisticated experimental studies at threshold beyond total cross section: Asymmetries, momentum distribution



incorporation of ISR and luminosity spectrum

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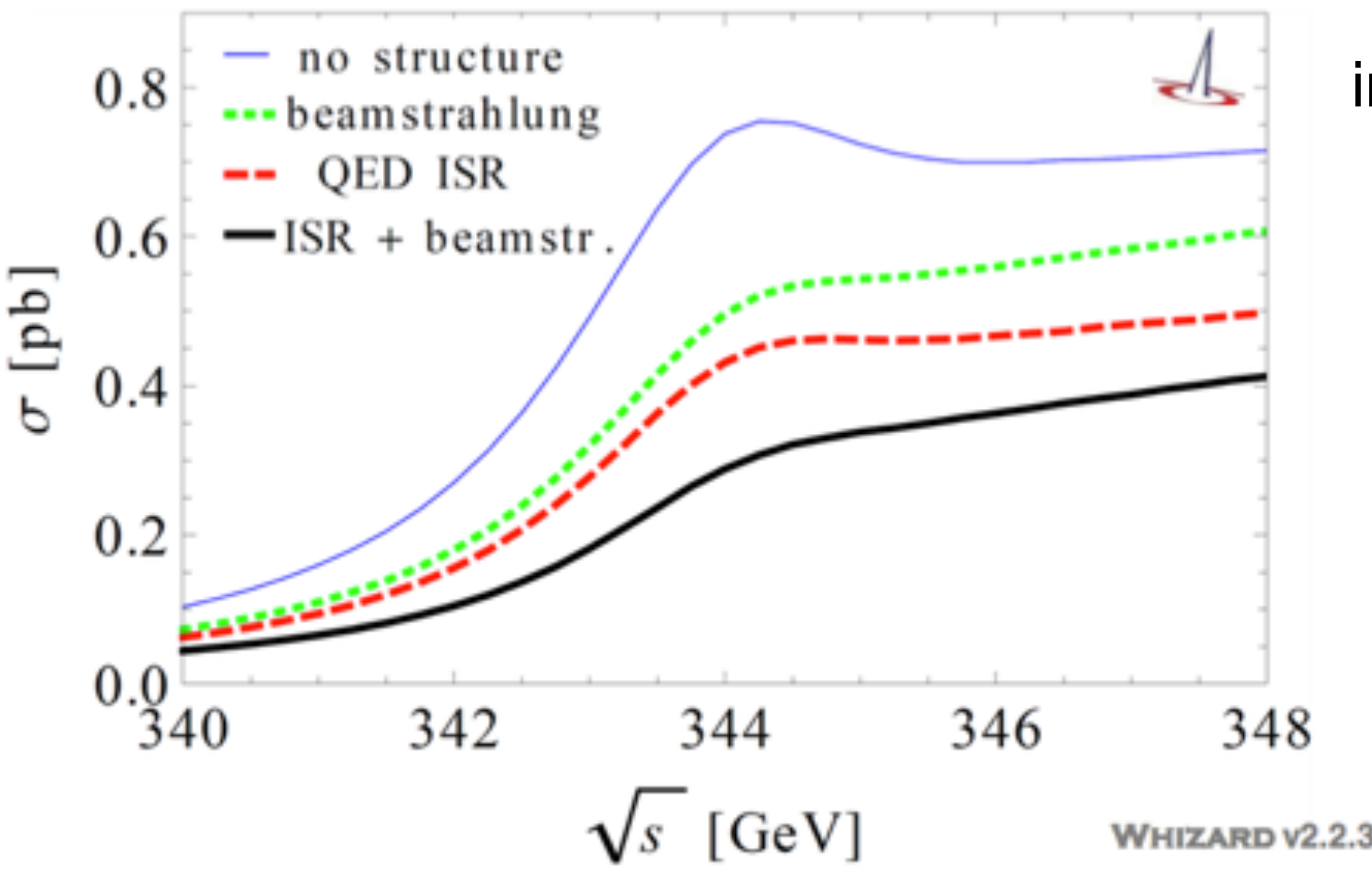

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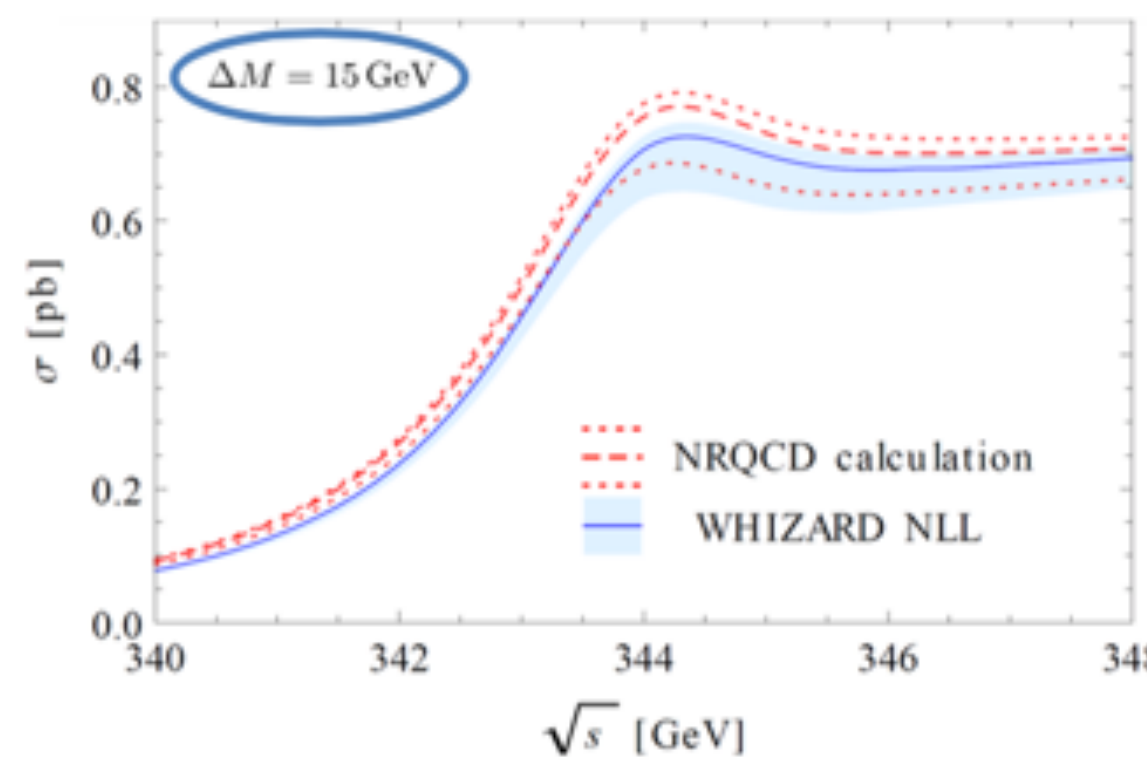
successful sanity check with theory calculations:



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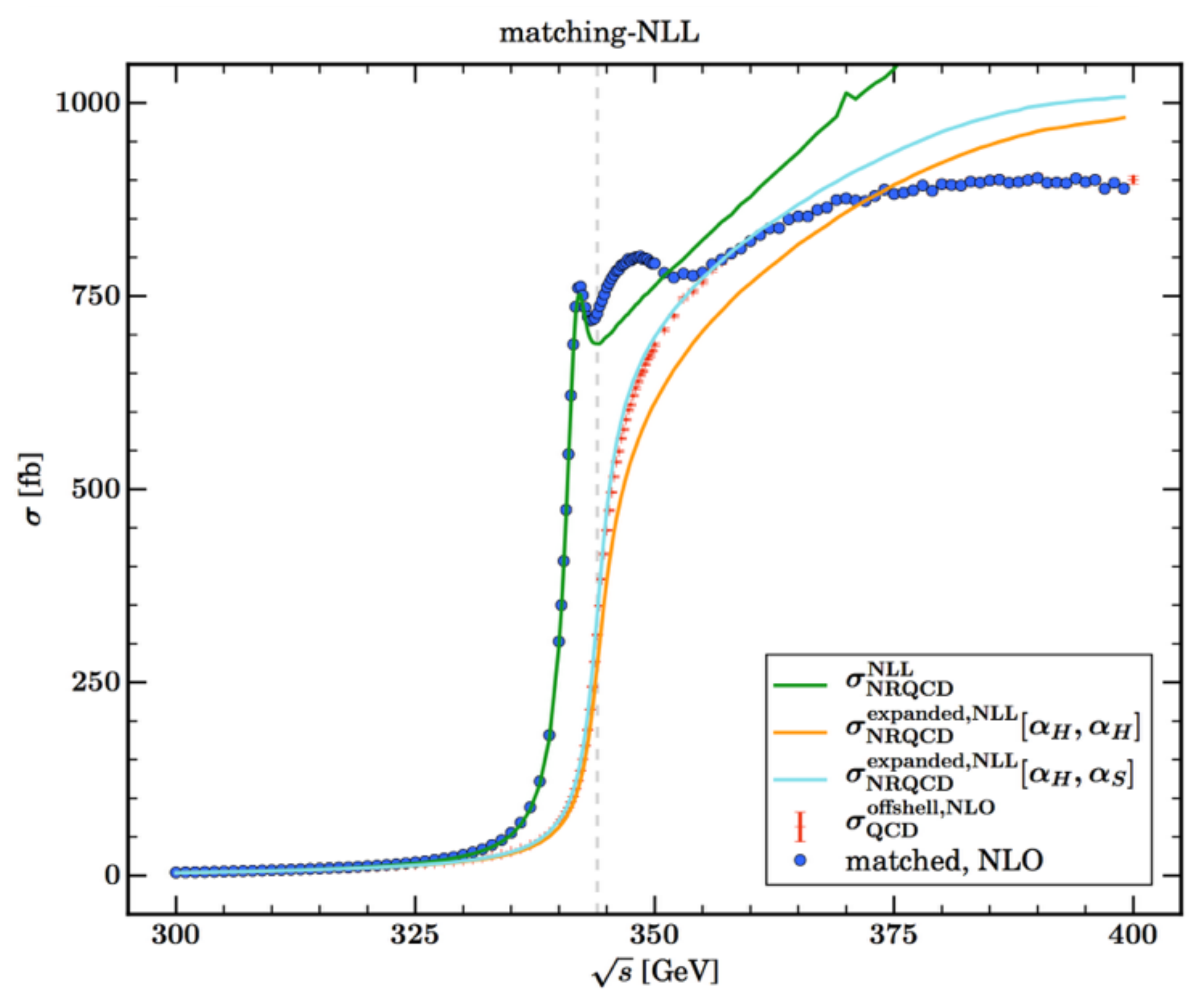

matching to continuum to consistently describe full energy range

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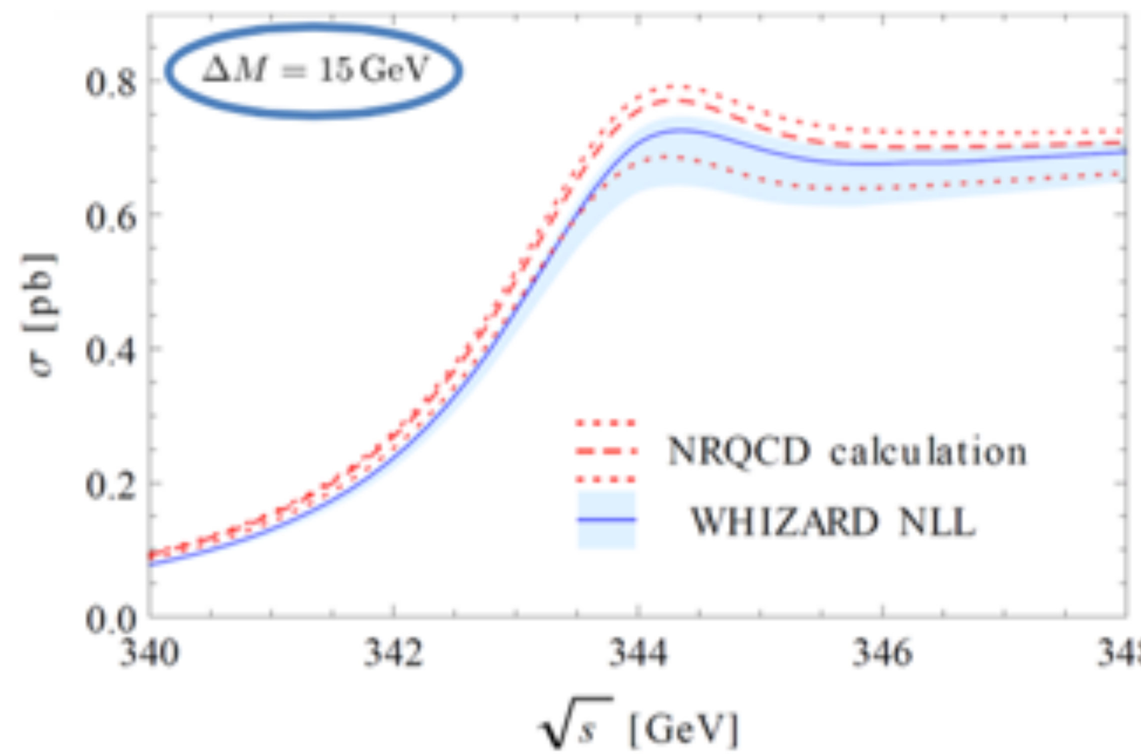

Higher Order Calculations

- Two key steps forward this year:
  - Conversion of pole / 1S / PS mass to msbar mass at NNNNLO QCD

$\overline{\mathrm{MS}} \rightarrow$ on-shell

$$\begin{aligned} M_t &= m_t \Big(1 + 0.4244\,\alpha_s + 0.8345\,\alpha_s^2 + 2.375\,\alpha_s^3 \\ &\quad + (8.49 \pm 0.25)\,\alpha_s^4\Big) \\ &= 163.643 + 7.557 + 1.617 + 0.501 + 0.195 \pm 0.005 \text{ GeV} \end{aligned}$$

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2	163.943	163.861	163.853	1-2 GeV
3	163.687	163.651	163.663	$\lesssim$ 250 MeV
4	163.643	163.643	163.643	$\lesssim$ 40 MeV
4 ($\times$1.03)	163.637	163.637	163.637	6 MeV

$$\left.\begin{array}{l} \text{half the 4-loop contribution } \{22, 4, 10\} \\ \text{3\% uncertainty } \equiv 6 \text{ MeV} \end{array}\right\} \Rightarrow \{23, 7, 11\}\text{MeV error}$$

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+ uncertainty induced by α_s uncertainty

Higher Order Calculations

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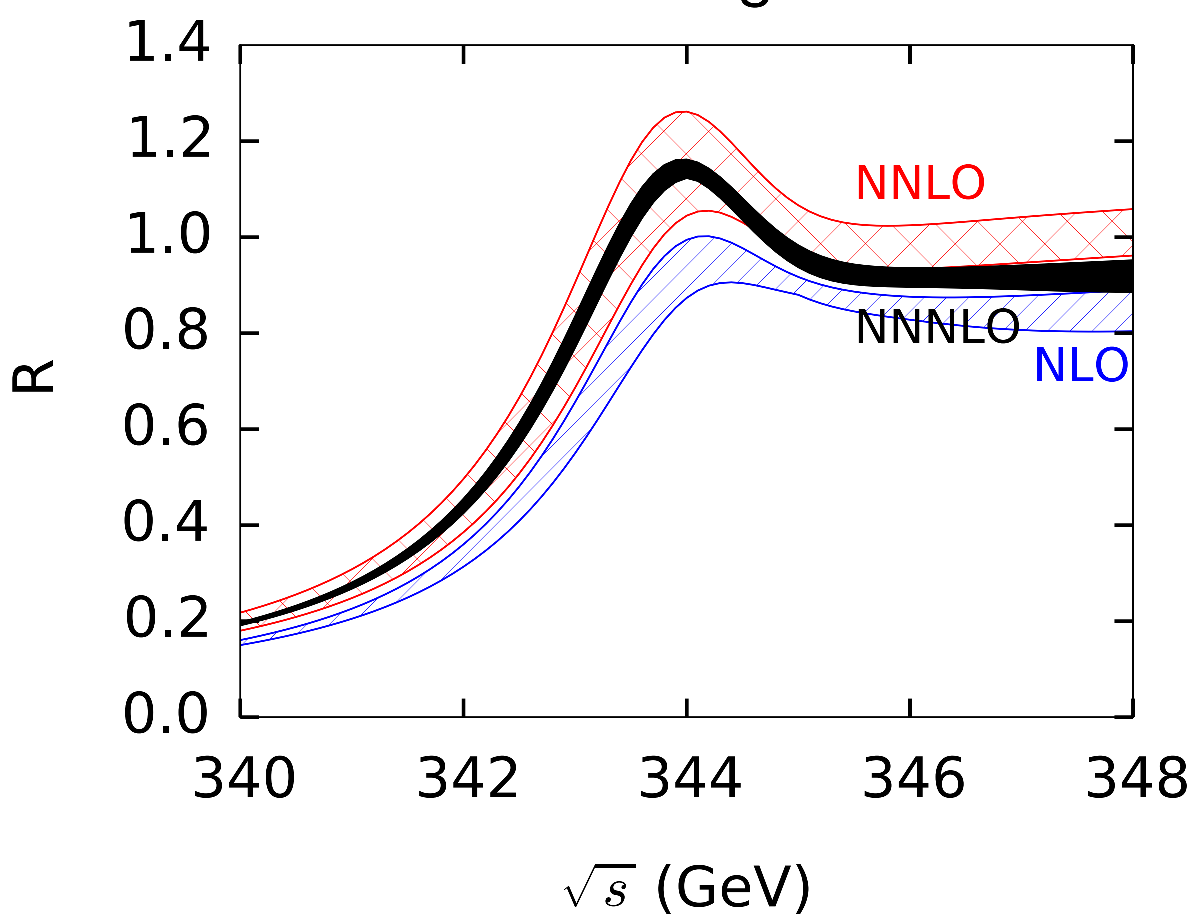
  - NNNLO QCD calculations of threshold

A decade of work to get the 3rd order:



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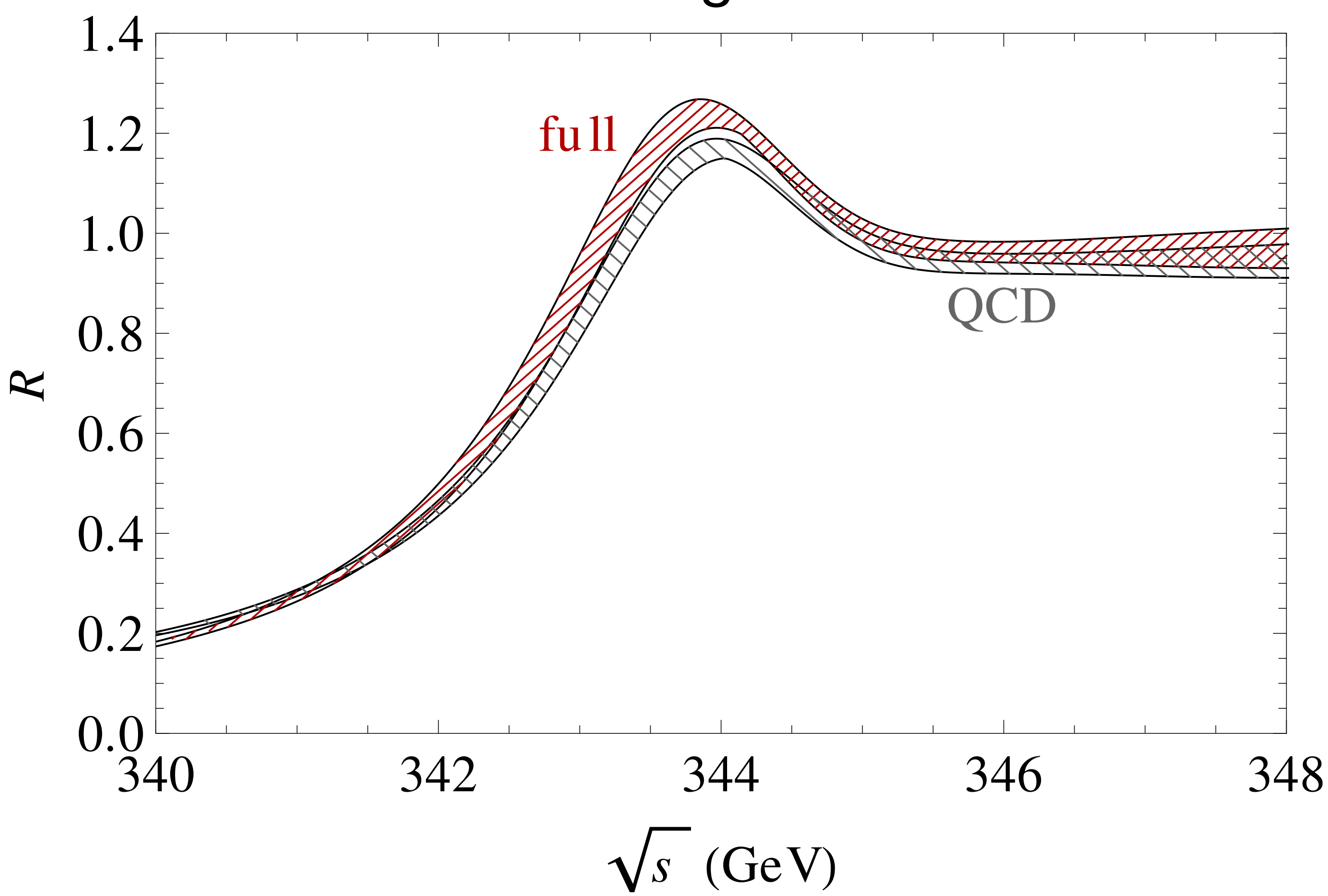

QCD uncertainties under control: $\sim 3\%$

Further corrections $(v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha)$:

- Higgs corrections
- QED Coulomb potential
- Nonresonant production
- P-wave production
- Further NNLO electroweak corrections

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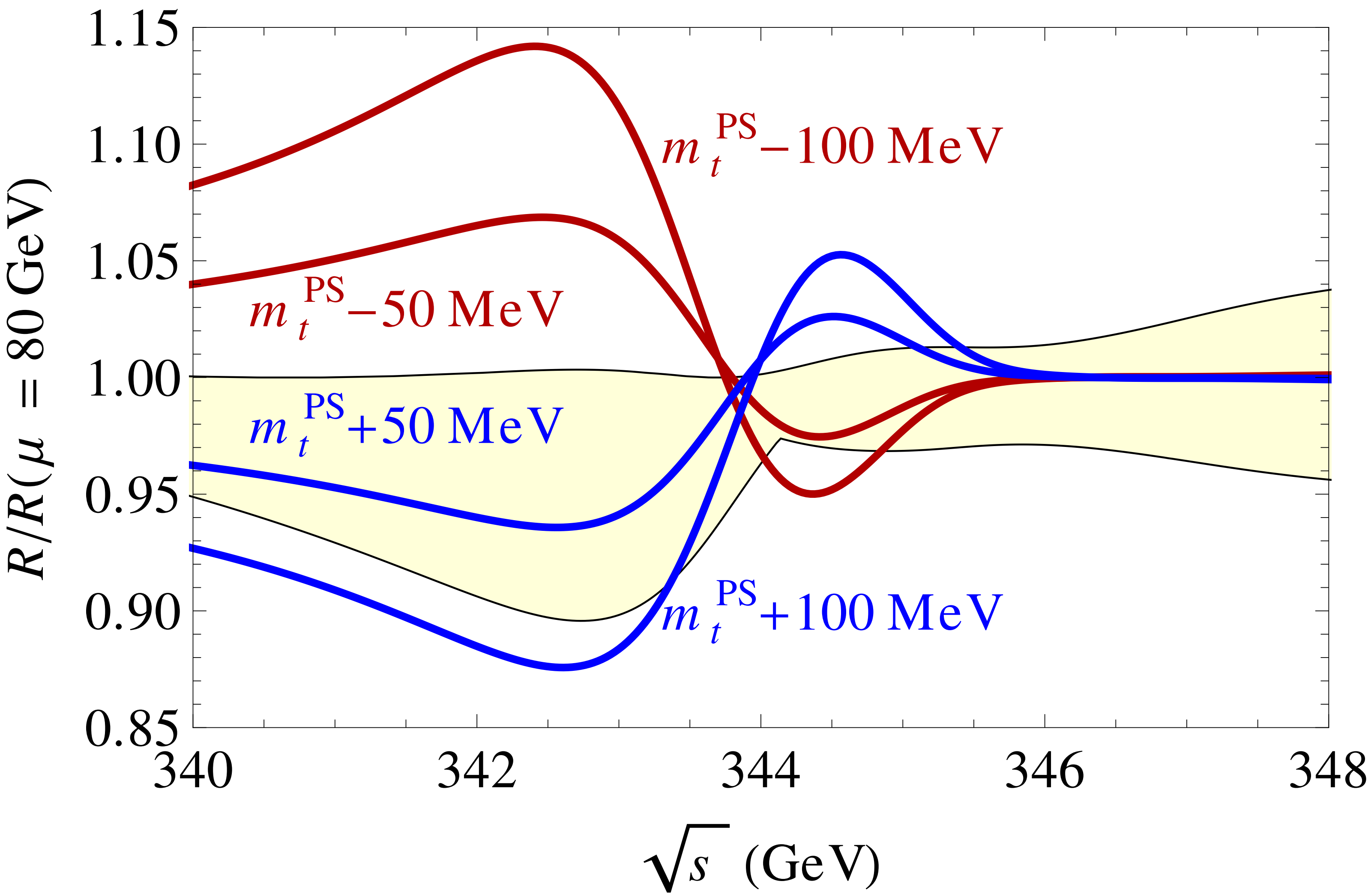

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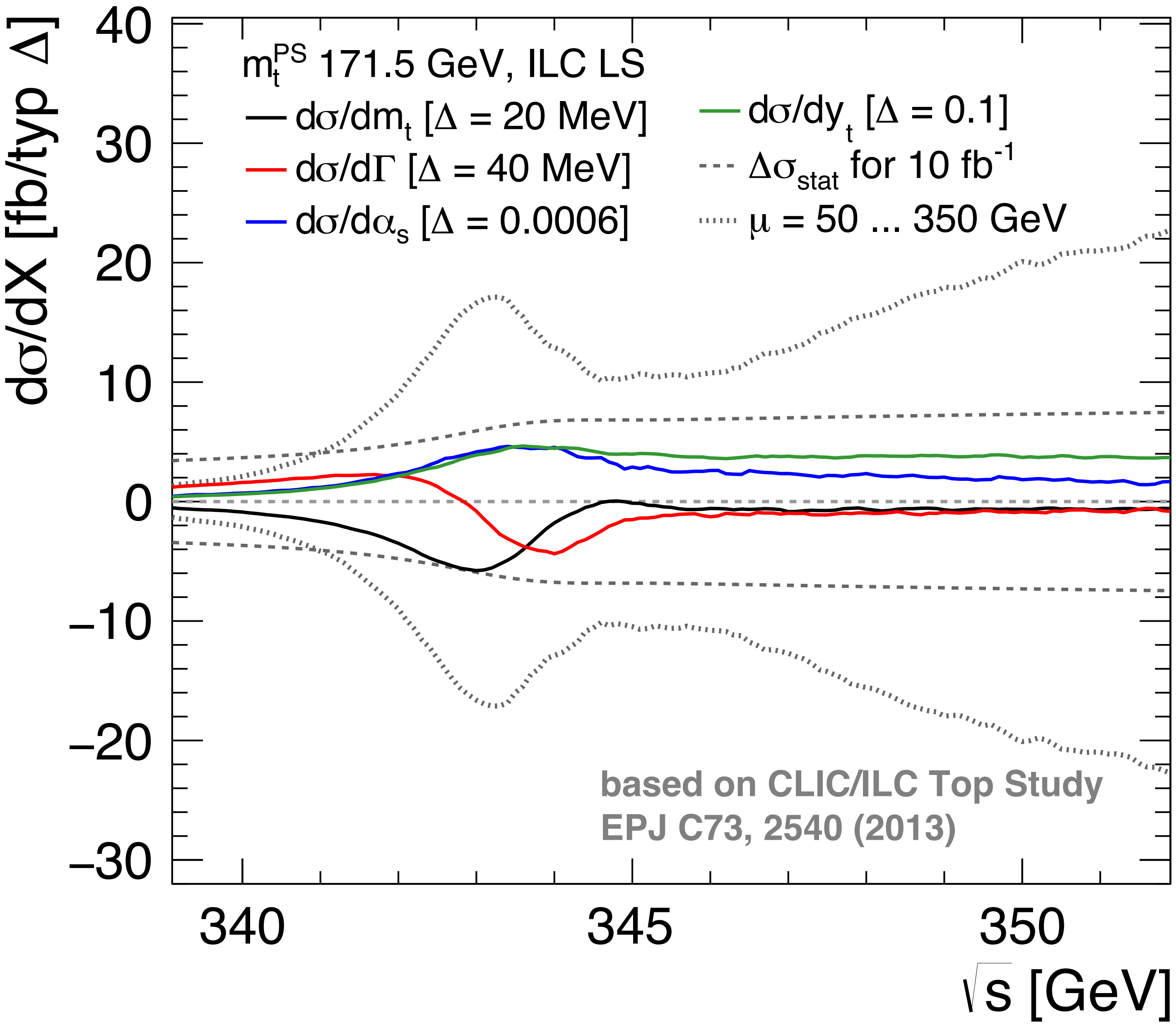
➩ suggests uncertainties on the 50 MeV level

Experimental Consequences for Mass Precision



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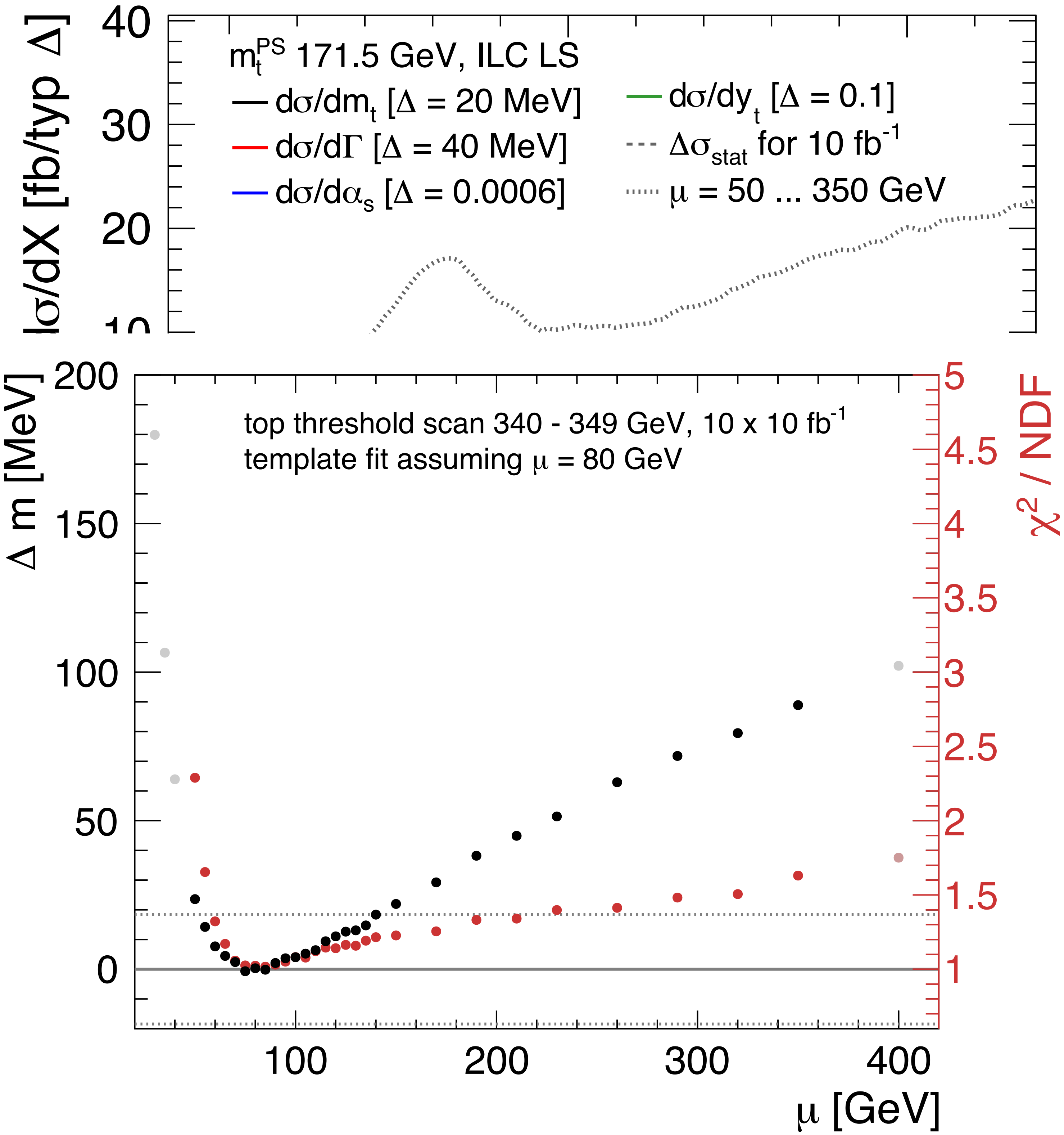
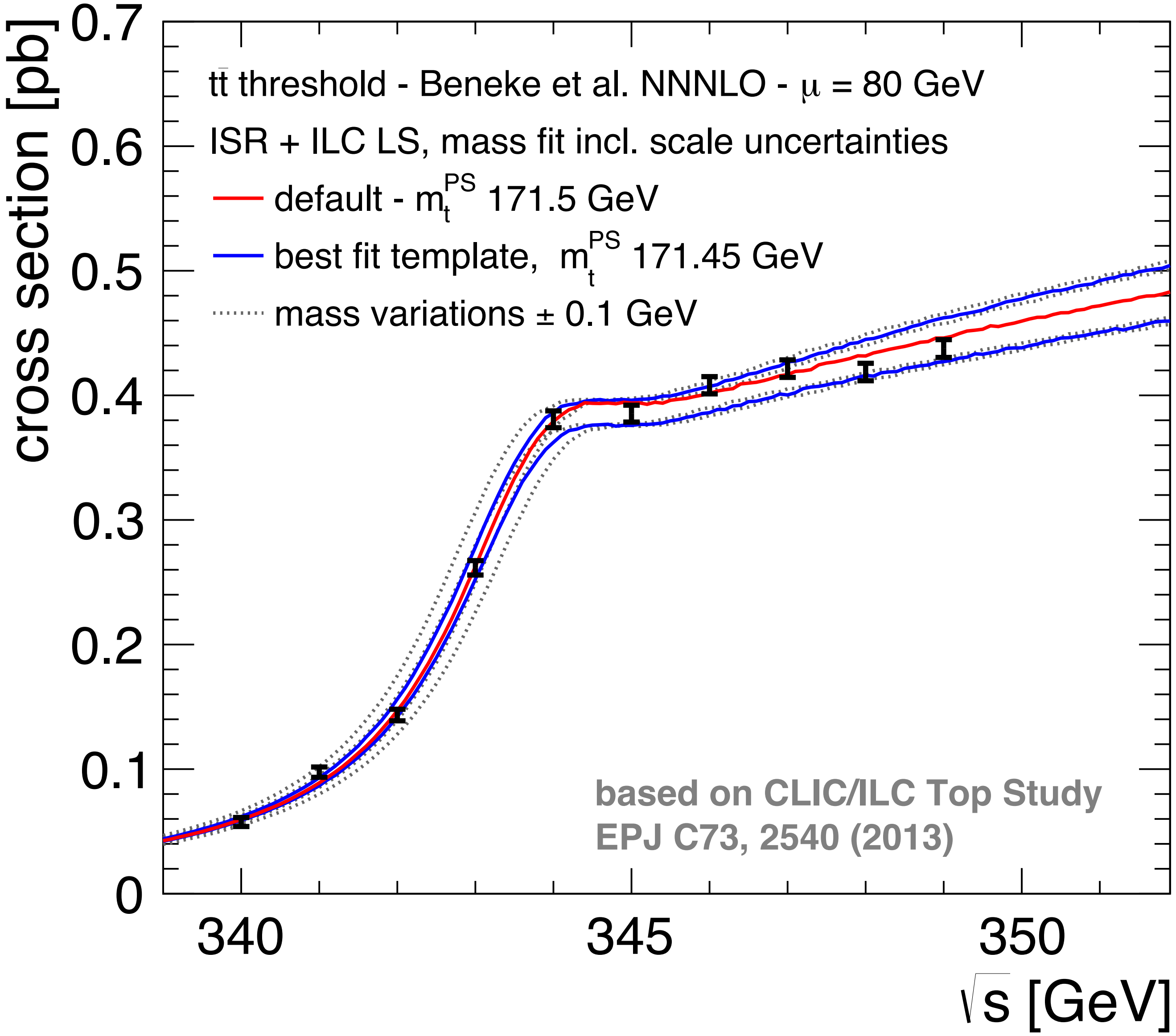


- NNNLO scale uncertainties have a substantial impact on the expected precision of threshold scans - comparable or larger than stat. uncertainty on σ
- In a “standard” 10 point scan & fit: mass value changes by 90 MeV for the considered scale variations:

± 45 MeV systematic on mass from NNNLO scale uncertainties (symmetrized)

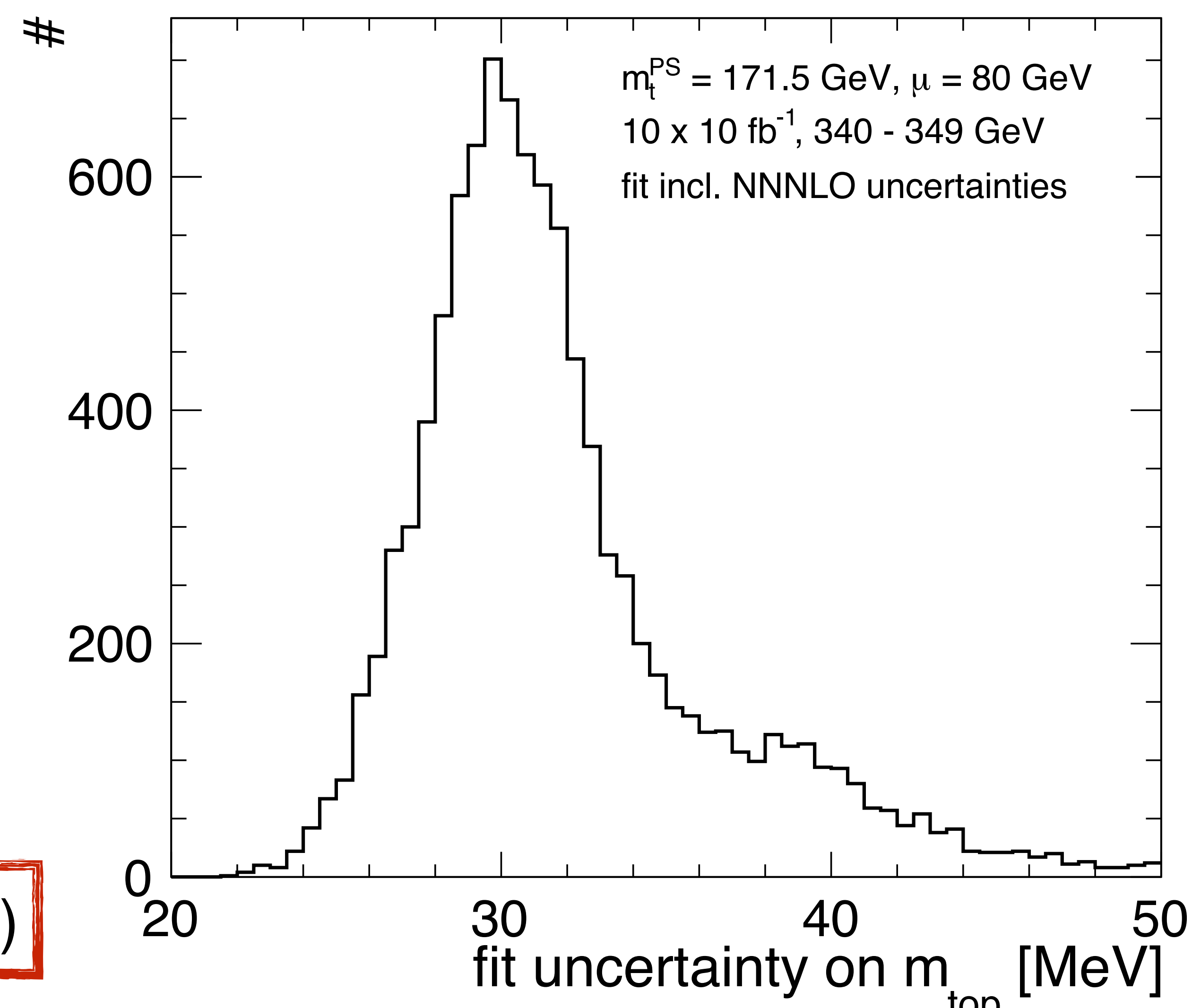
Experimental Consequences for Mass Precision



- For fully consistent treatment of scale uncertainties: Inclusion in template fit - bands instead of lines

- Consequence: Fit uncertainty not purely statistical - for 10 x 10 fb^{-1}

32 MeV fit uncertainty (including 19 MeV stat)

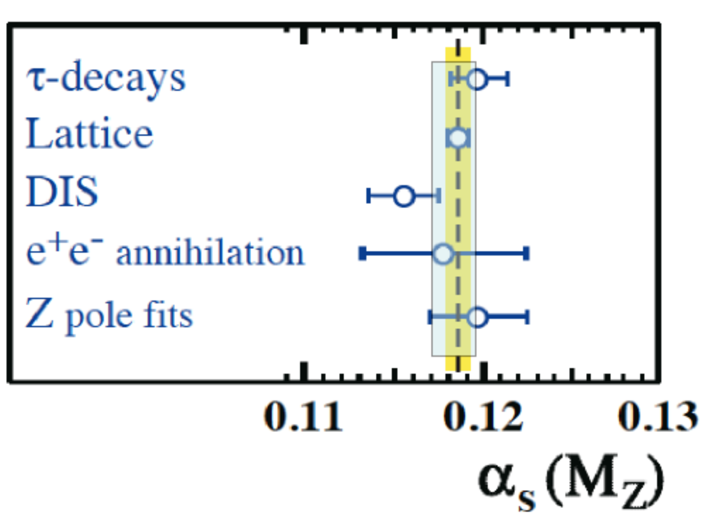


The Strong Coupling

- The strong coupling plays a central role in top (and other) physics:
  - Precise predictions for observables sensitive to QCD corrections.
  - Consistency of determinations from different observables reflects our understanding of QCD.

- For the preliminary 2015 world average, uncertainties (including theory) of input results have been re-examined

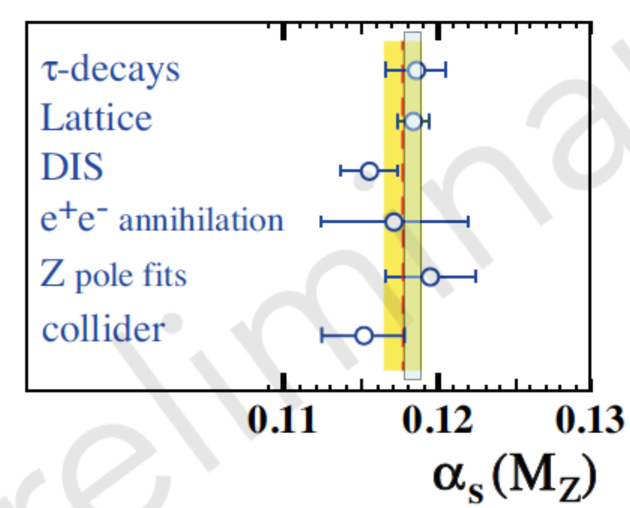
World Summary of α_s 2013:



$\alpha_s(M_Z) = 0.1185 \pm 0.0006$

without lattice: $\alpha_s(M_Z) = 0.1183 \pm 0.0012$

2015 summary of α_s



$\alpha_s(M_Z) = 0.1177 \pm 0.0013$

without lattice: $\alpha_s(M_Z) = 0.1170 \pm 0.0018$

preliminary

The Strong Coupling

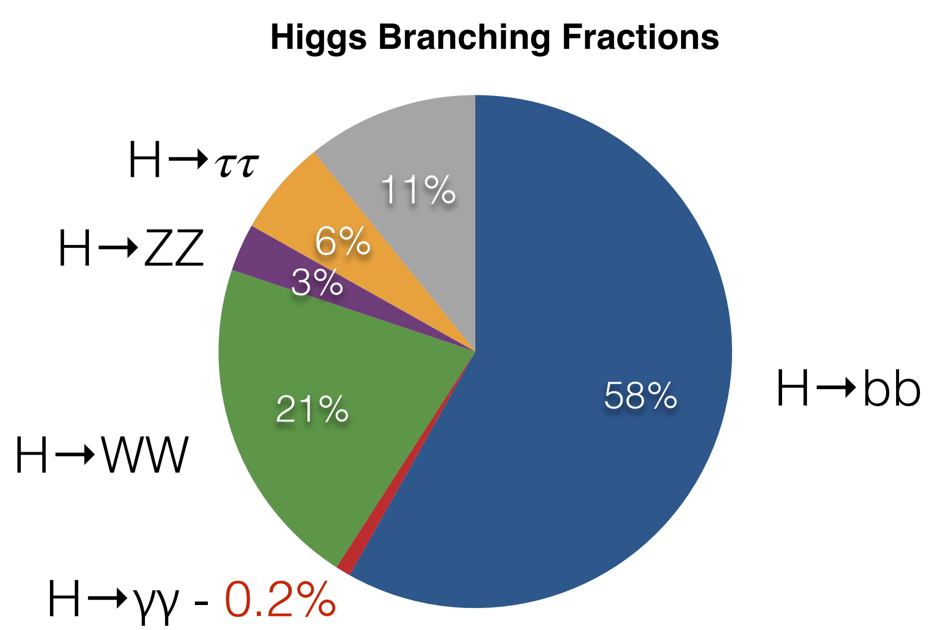
- new **preliminary** value of world $\alpha_s(M_Z)$: = 0.1177 ± 0.0013
- change from 2013 value ($\alpha_s(M_Z)$=0.1185 ± 0.0006) mainly due to:
  - decreased weight (increased error) of lattice results
  - decreased central value from τ-decays
  - result from new class (hadron collider, ttbar x-section), with only one published result, however known to be systematically low
- known but unresolved issues for almost all classes
- no convergence of issues in sight

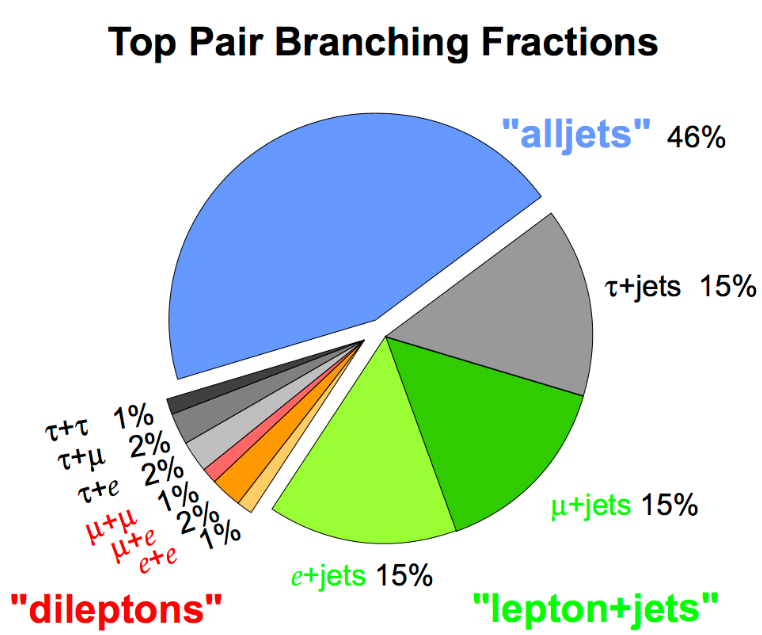
– however –

- even within conservative uncertainties, Asymptotic Freedom and in general, QCD is in excellent shape !

ttH: Direct Access to the Top Yukawa Coupling

- Very complex final state





Intense search at the LHC in various channels:

- Best fit signal strength
  - $\mu_{ttH} = 1.9^{+0.8}_{-0.7}$ - *ATLAS*
  - $\mu_{ttH} = 2.9^{+1.0}_{-0.9}$ - *CMS*
  - $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$ - *Combined*
    - significance - 4.4σ obs (2.0σ exp)
- Combined upper limits on σ/σ_{SM}
  - 3.2 obs (1.4 exp) - ATLAS
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➫ quickly rising sensitivity!

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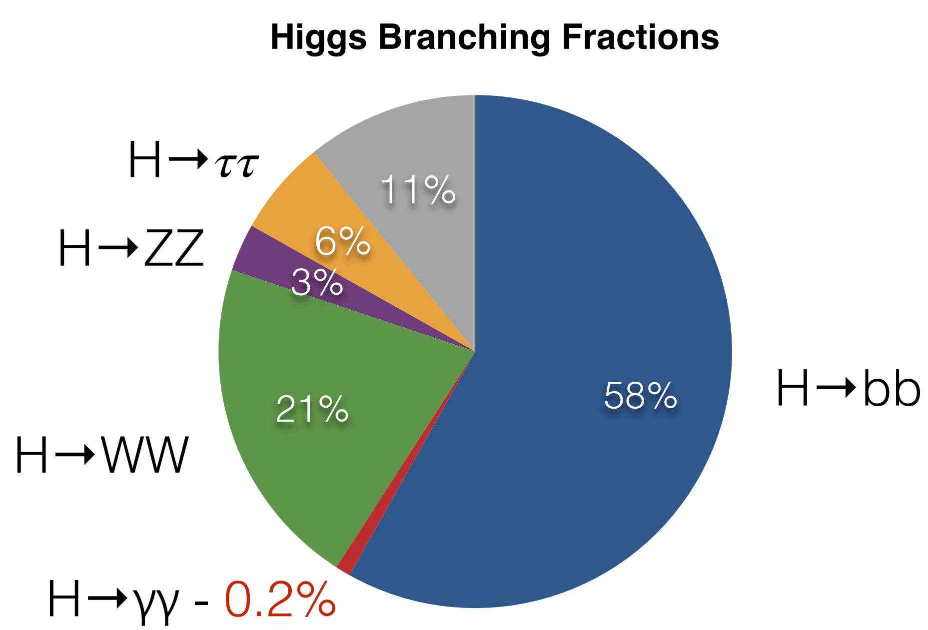

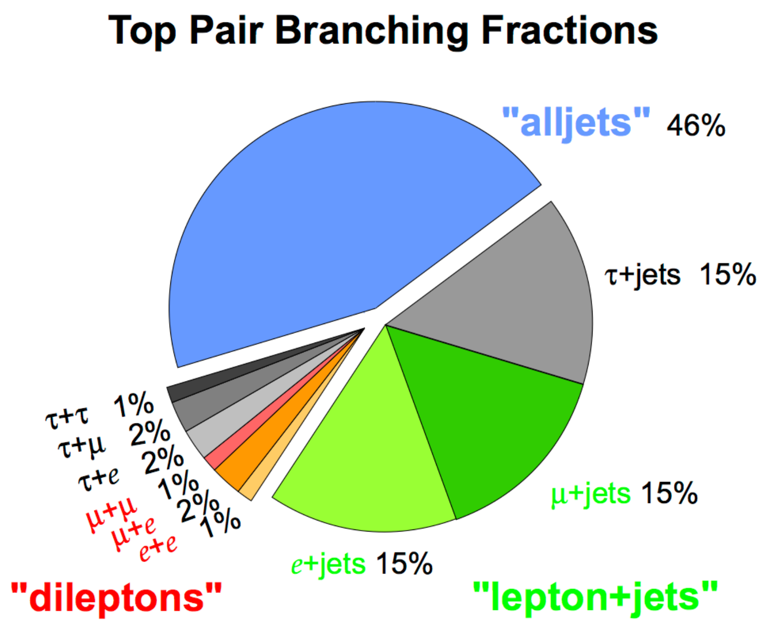

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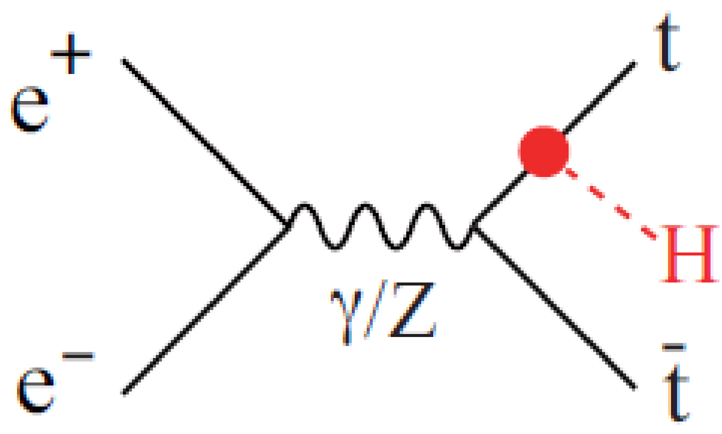
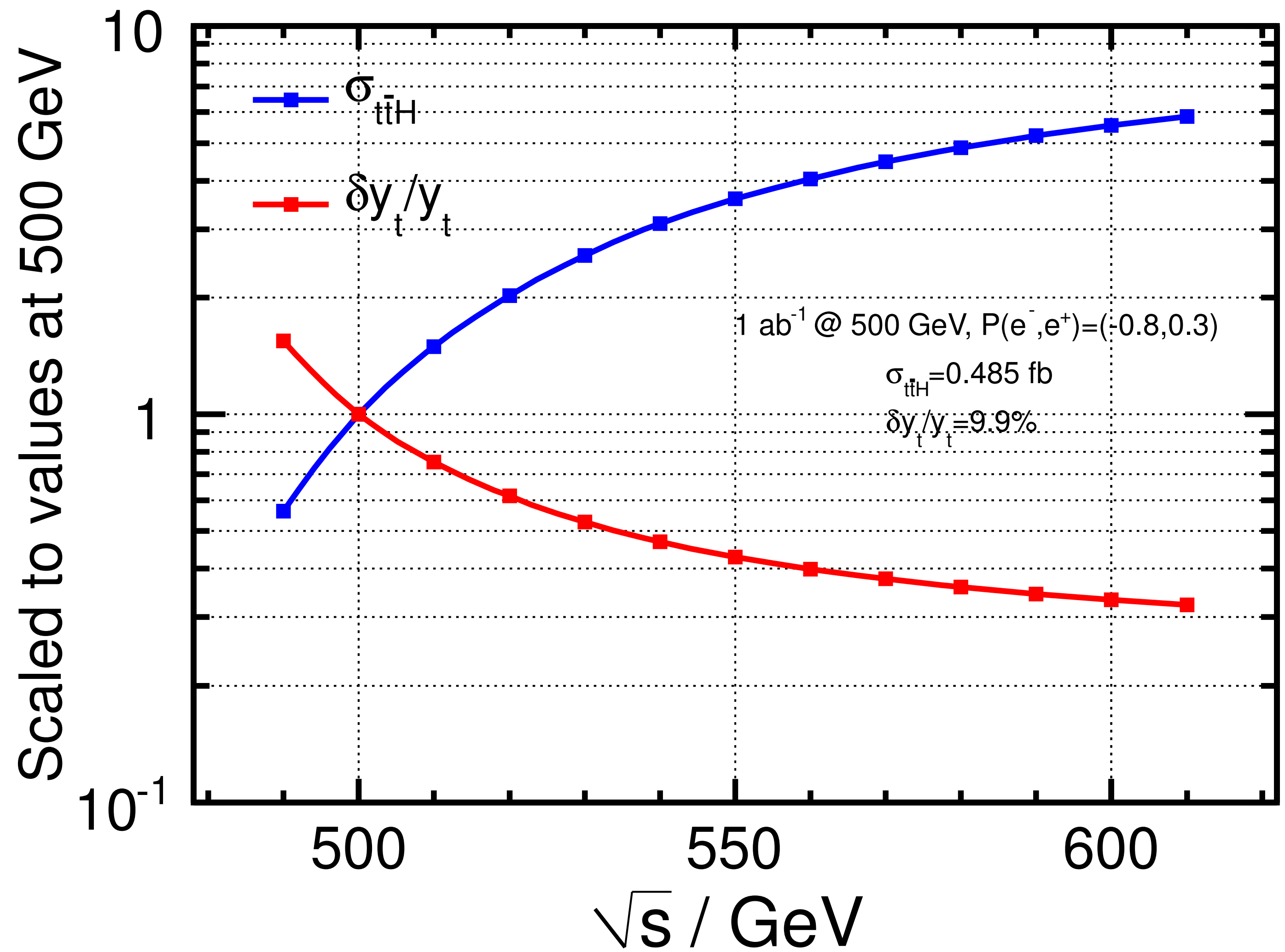
And: large progress on theory - both for signal (NLO QCD, matching to PS, off-shell effects, EW corrections, soft gluon resummation) and backgrounds (ttbb, ttV, ttVV)

ttH at ILC



- Threshold very close to 500 GeV



➯ every bit of extra energy helps: If extra 10% of ILC length can be used for higher energy (in a scenario where the design gradient achieved): 550 GeV

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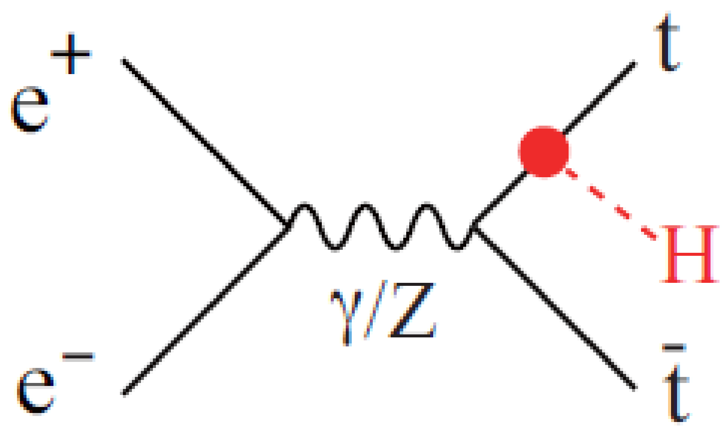

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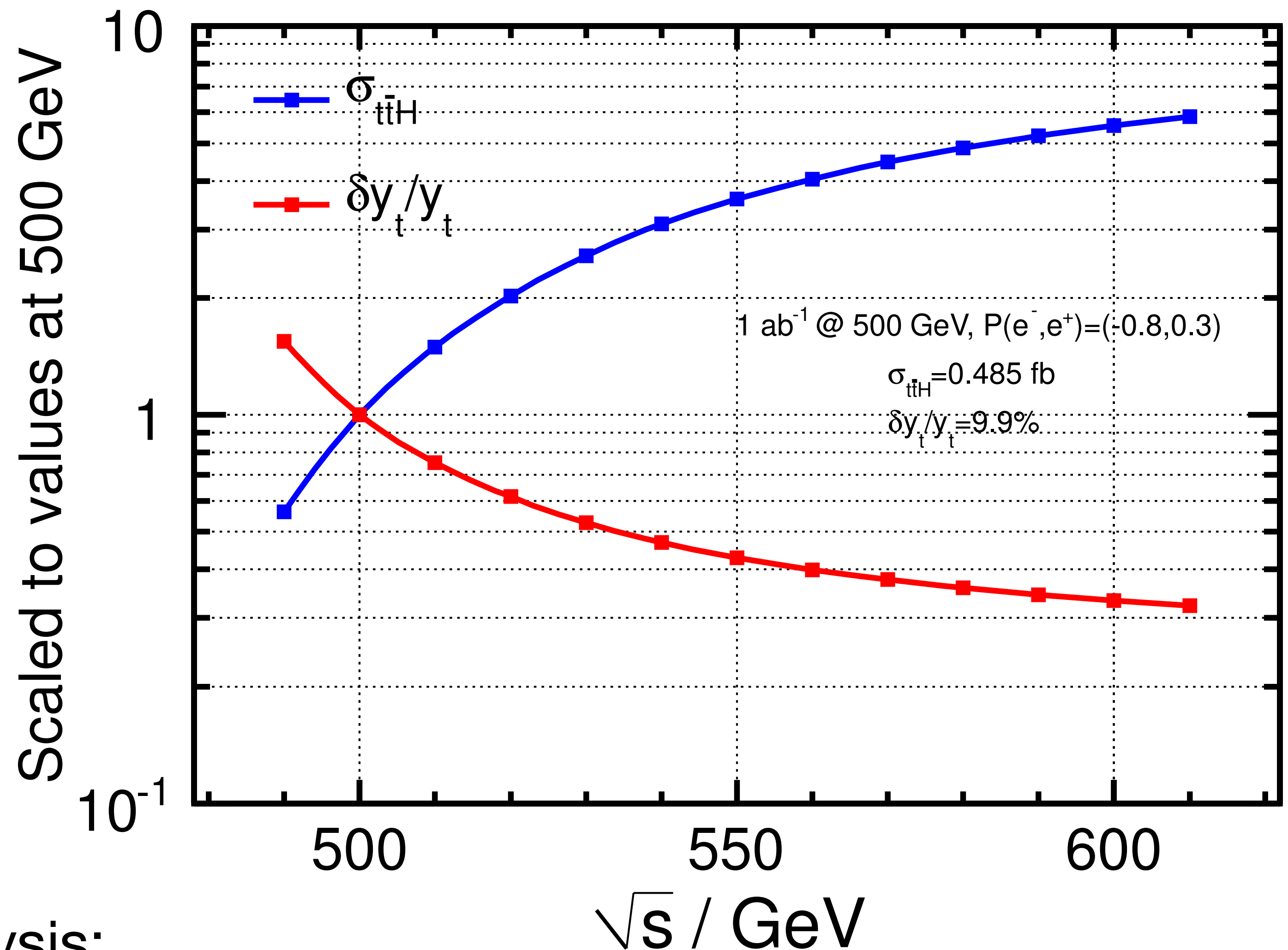

➯ every bit of extra energy helps: If extra 10% of ILC length can be used for higher energy (in a scenario where the design gradient achieved): 550 GeV

Big effort to constantly improve the analysis:
New this time: maximum-likelihood jet pairing at 500 GeV for H20 (200 + 1400 fb^{-1}):
$\Delta g_t/g_t$ = 7.85 % (*550 GeV: 3.3%*)

Final Words

- Top physics is a very lively field - both at the LHC with a constant stream of new results, and at Linear Colliders with steady improvement of the understanding of the physics capabilities
  - A major topic: Systematics - theory and experiment

- QCD is still good for “surprises”: For the first time, the WA uncertainty on α_s has increased by a factor of two - but in general, QCD is in excellent shape

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The top quark needs to be front and center in the physics case for Linear Colliders.