Perspectives on Top Quark Physics

John Campbell
Fermilab, April 10
Top at Twenty

Thank you!

- …. to the organizers, for putting together a stimulating program of talks covering experiment and theory.
- …. to the speakers, for a thorough, informative and entertaining review of all things top.

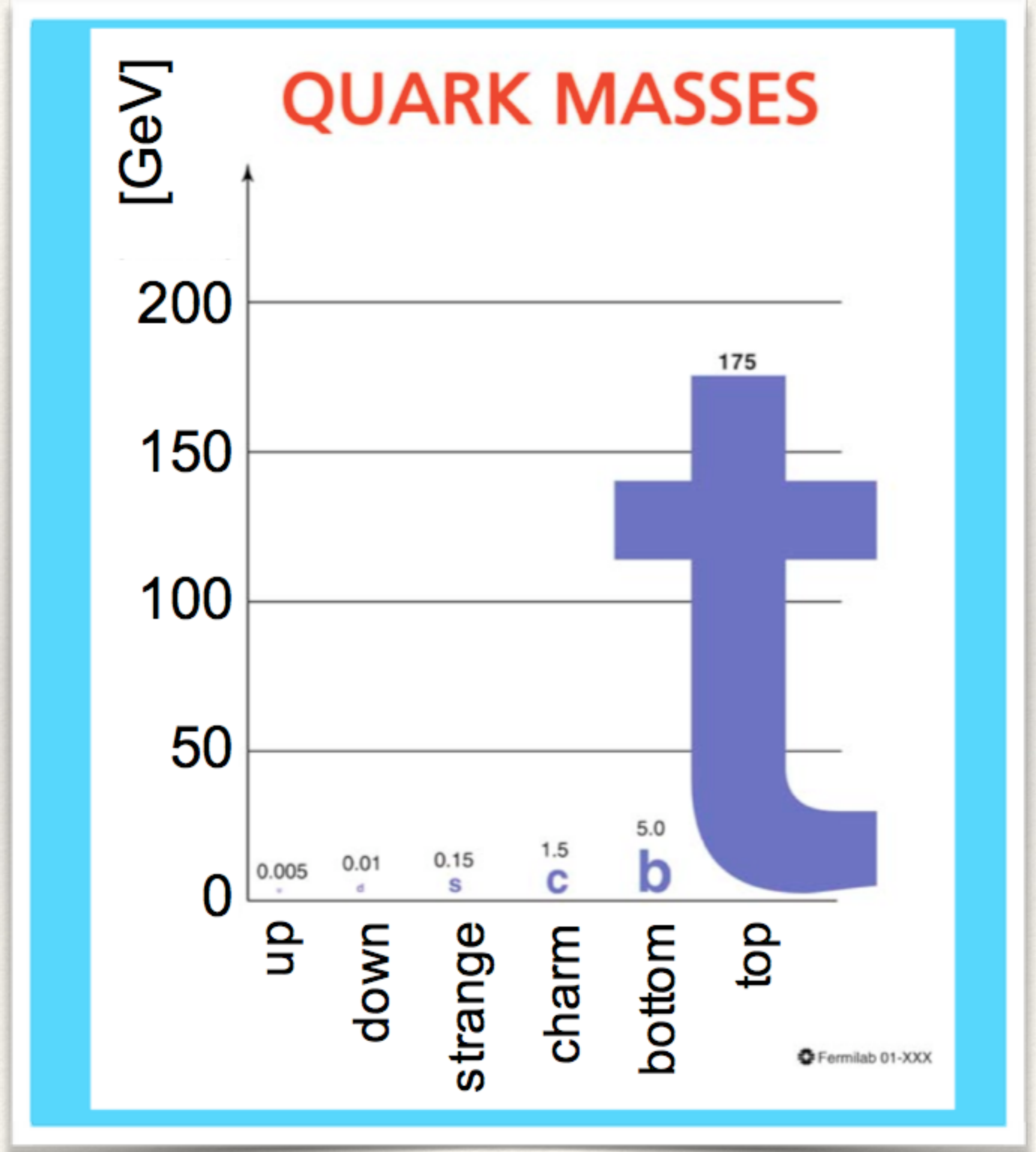
https://indico.fnal.gov/conferenceTimeTable.py?confId=8961

- Although this is not meant to be a typical summary, I will try to indicate the relevant talks for further details.

→ *like this*

Outline

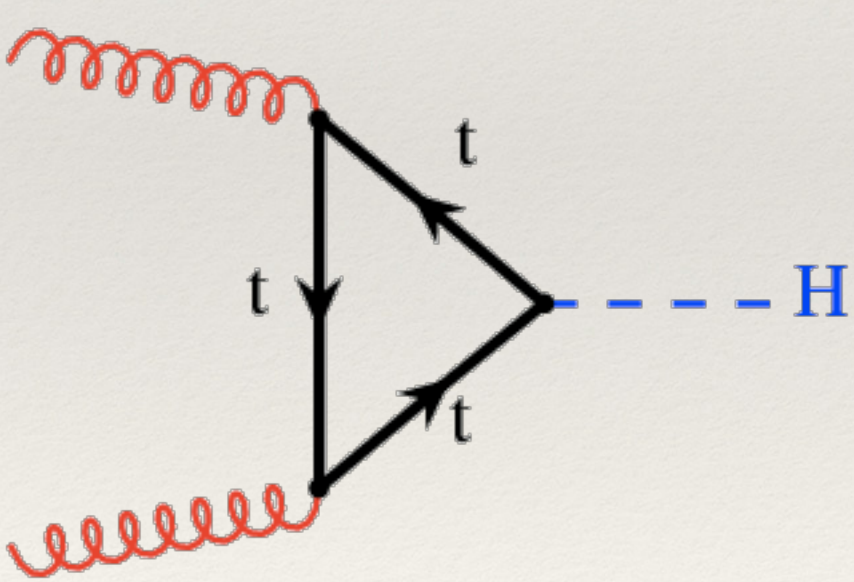
- What's so special about top?
- Theoretical tools for top quarks.
- Current status of top quark studies.
- Future prospects at the LHC.



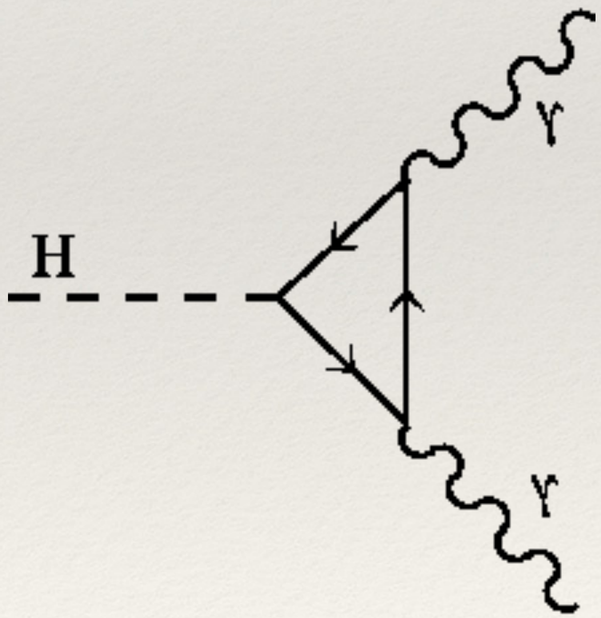
Why top is special

- Immediate consequence of mass is a substantial Yukawa coupling (special relationship with the Higgs boson)

$$y_t = \frac{\sqrt{2} m_t}{v} \approx 1$$



production

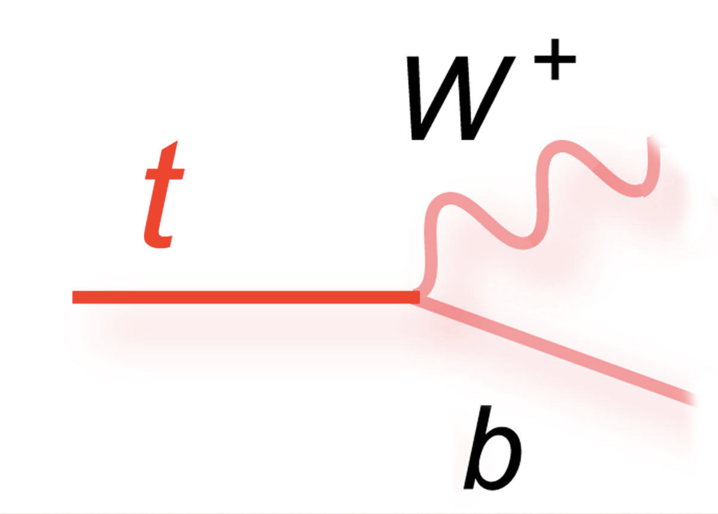


decay

Unlike the other quarks

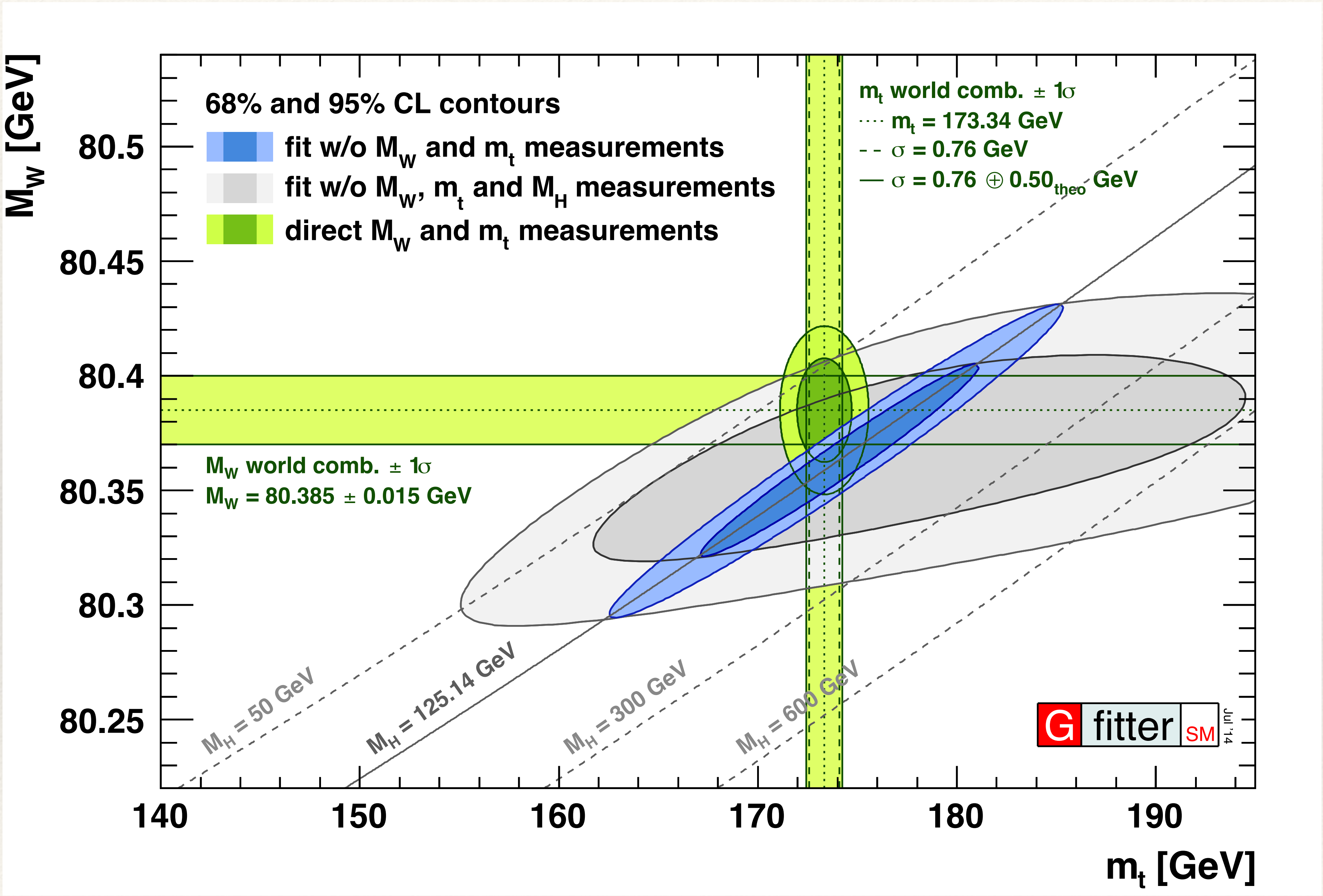
- Top quark is short-lived, decays almost exclusively to Wb:

$$\Gamma_t \approx \frac{\alpha_W}{16} \frac{m_t^3}{m_w^2} \approx 1.4 \text{ GeV}$$



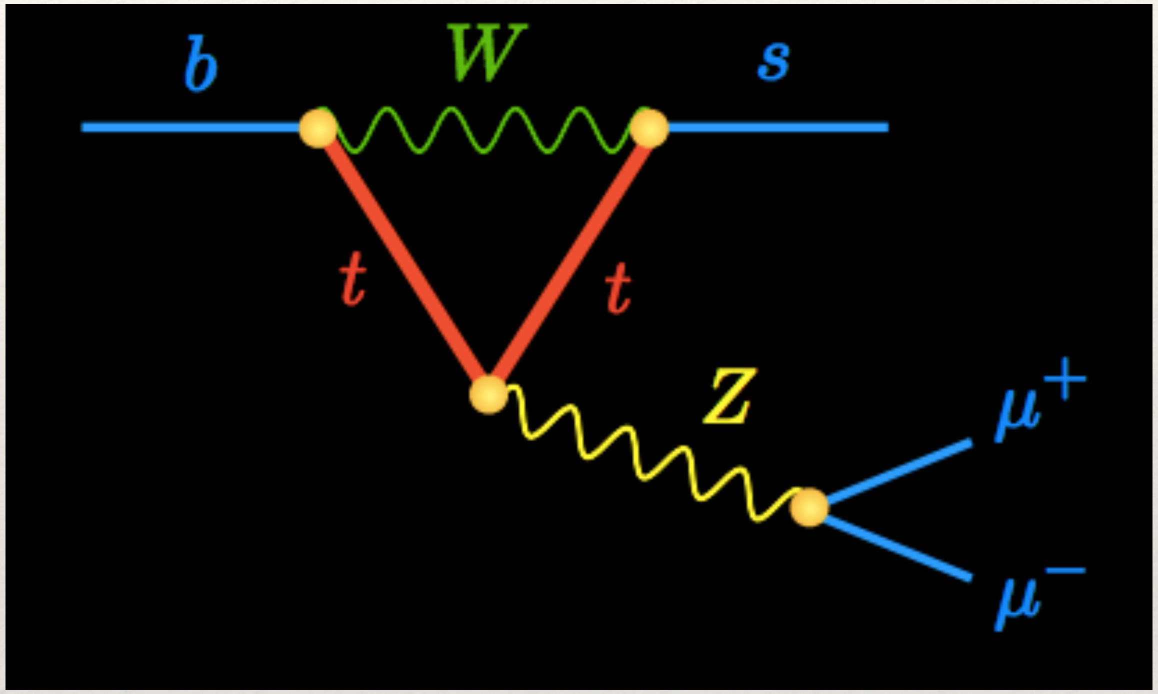
- Top quark decays before it hadronizes so:
  - direct handle on top properties from decay products.
  - no bound states of toponium etc.

Consistency check of the SM



Important role in flavor physics

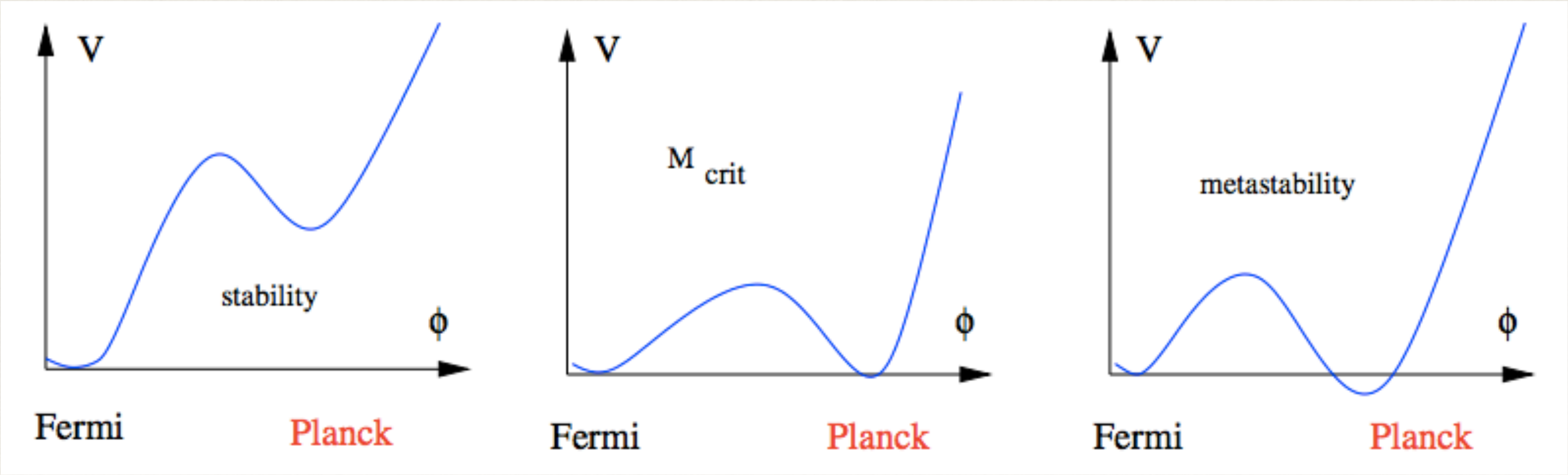
- Rare loop-induced processes very sensitive to top quark mass, e.g. $B_s \to \mu^+\mu^-$
  → ***Haisch***



$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\ \mathrm{GeV}}\right)^{3.06} (1 \pm 0.064) \times 10^{-9}$$

Stability of the vacuum

- The top quark and Higgs boson masses are essential for determining the stability of the Higgs effective potential ("fate of the universe").



- Quantum tunneling means lifetime of vacuum < age of Universe if $M_H < M_{crit}$. [Krasnikov, Hung, Politzer & Wolfram, late 70's]

Role of the top quark

- Most important parameters for computing M_{crit} are the top quark mass and strong coupling.

$$M_{\rm crit} = \left[126.3 + \frac{M_t - 171.2\ \mathrm{GeV}}{2.1\ \mathrm{GeV}} \times 4.1 - \frac{\alpha_s(M_Z) - 0.1176}{0.002} \times 1.5\right]\ \mathrm{GeV}$$

- If we demand that the SM and gravity are valid to arbitrary high scales, robust prediction that bound is saturated:

$$M_H = M_{\rm crit} = 126\ \mathrm{GeV}$$

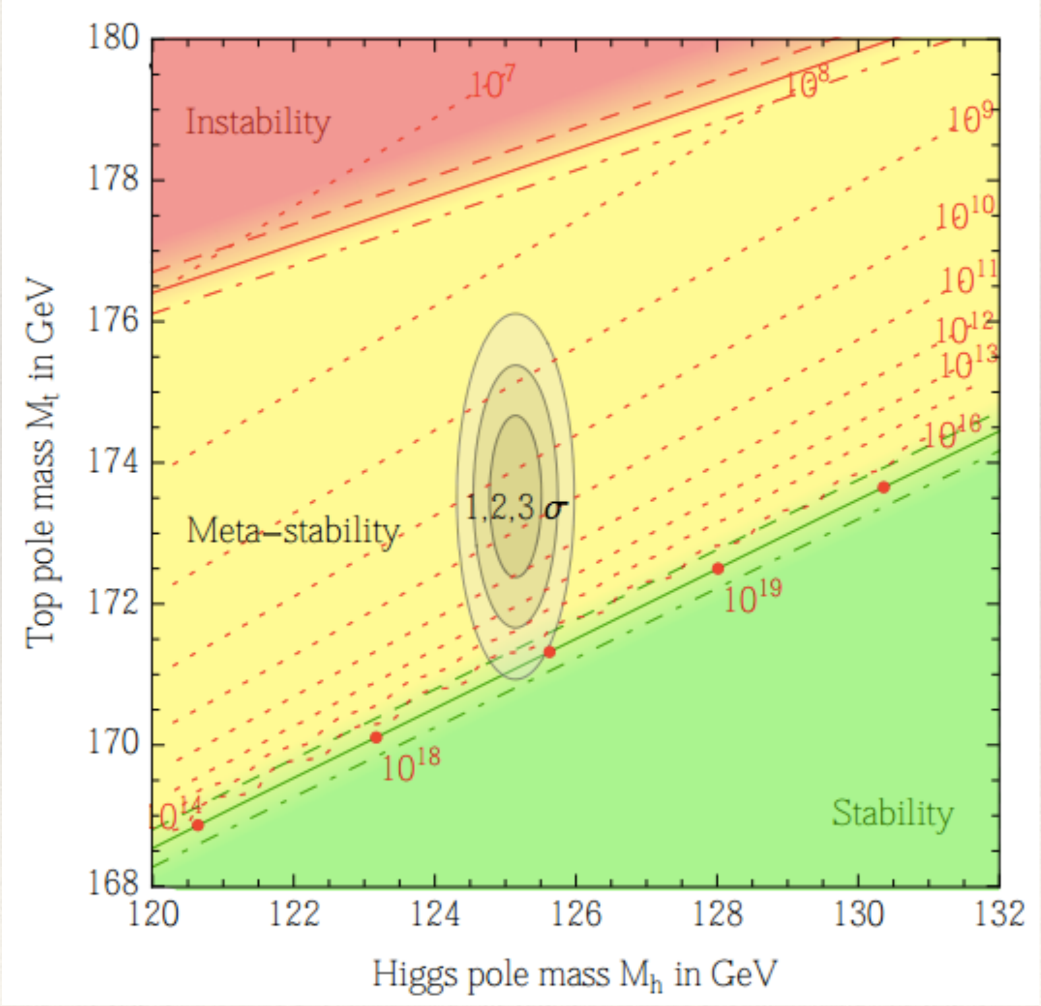
[Shaposhnikov, Wetterich 2010]

> Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hit for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

Three years on ...

$$M_{\text{crit}} = \left[128.95 + \frac{M_t - 172.9\ \text{GeV}}{1.1\ \text{GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.56\right]\ \text{GeV}$$

- Sensitivity to top quark mass is significant!
  - central value now higher
    → re-assess assumptions
  - can interpret as new physics entering at an intervening scale to restore stability (contour lines in figure).



[Buttazzo et al, 2013]

Hierarchy problem

- Loop corrections to the bare Higgs mass parameter involves loops of W, Z, top particles:

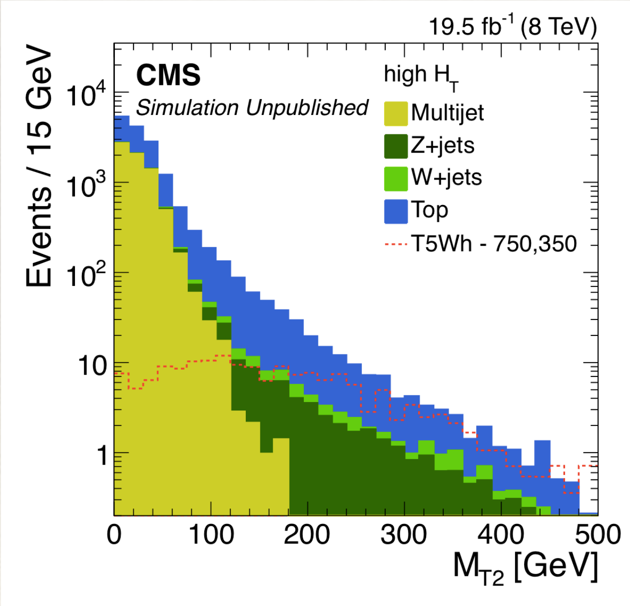
$$\frac{\delta m_h^2}{m_h^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right)\Lambda^2 = \left(\frac{\Lambda}{500\ \mathrm{GeV}}\right)^2$$

- Uncomfortable size of correction when momentum cutoff (Λ) becomes larger than about 500 GeV.
- Top loops are most important so might expect any solution to be connected to them, e.g. top partners, or decay to tops.

  → *Harnik*

My bottom (top?) line

- In addition to all the above …
  - we will study the top quark because it is still relatively new and untested, compared to many parts of the SM.
  - top quarks play an important role in virtually every LHC analysis.



Past ---→ Future

Signal | Background | Precision, tool

“Dicebat Bernardus Carnotensis nos esse quasi nanos, gigantium humeris insidentes, ut possimus plura eis et remotiora videre, non utique proprii visus acumine, aut eminentia corporis, sed quia in altum subvenimur et extollimur magnitudine gigantea"

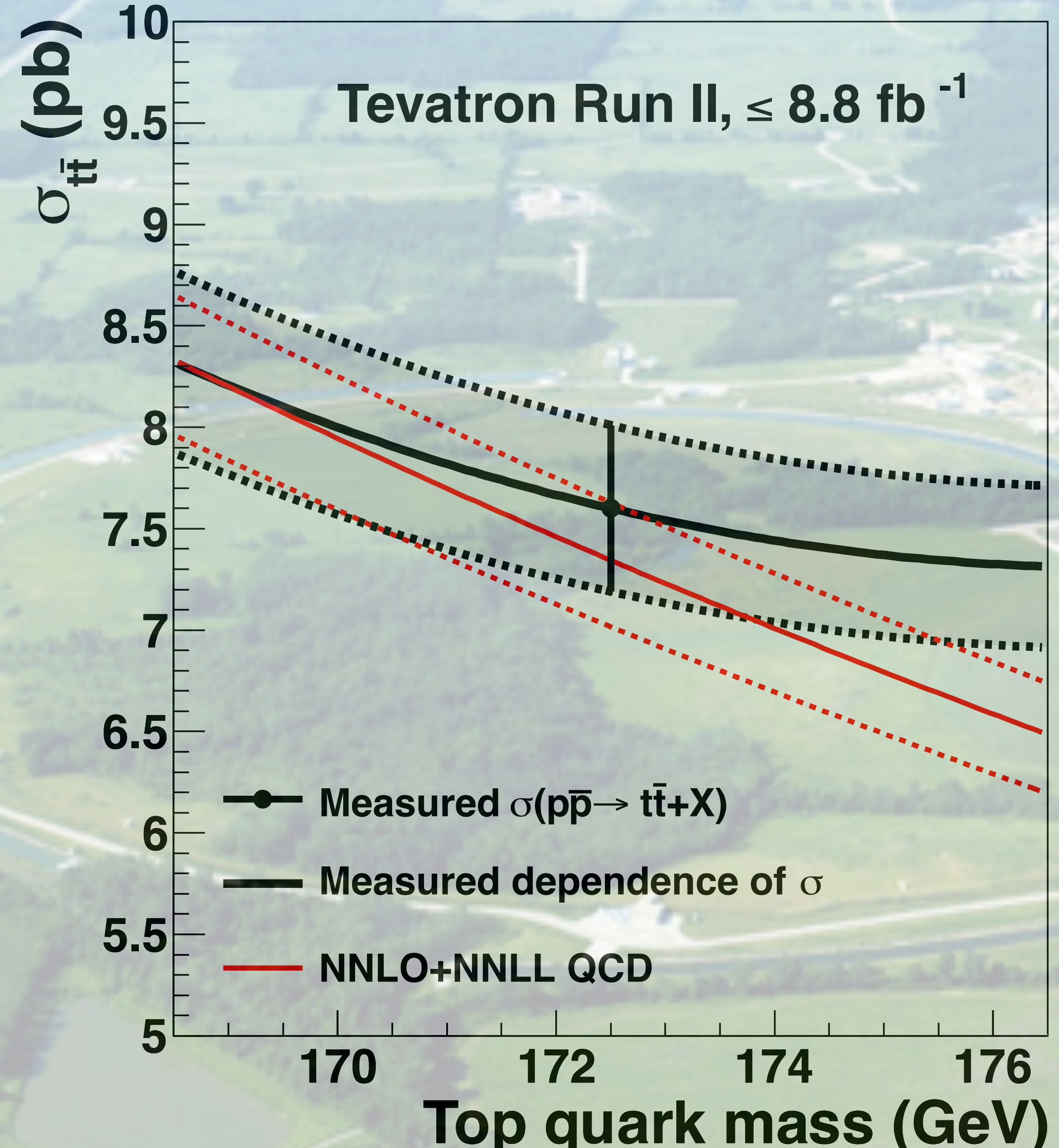
– John of Salisbury, 1159

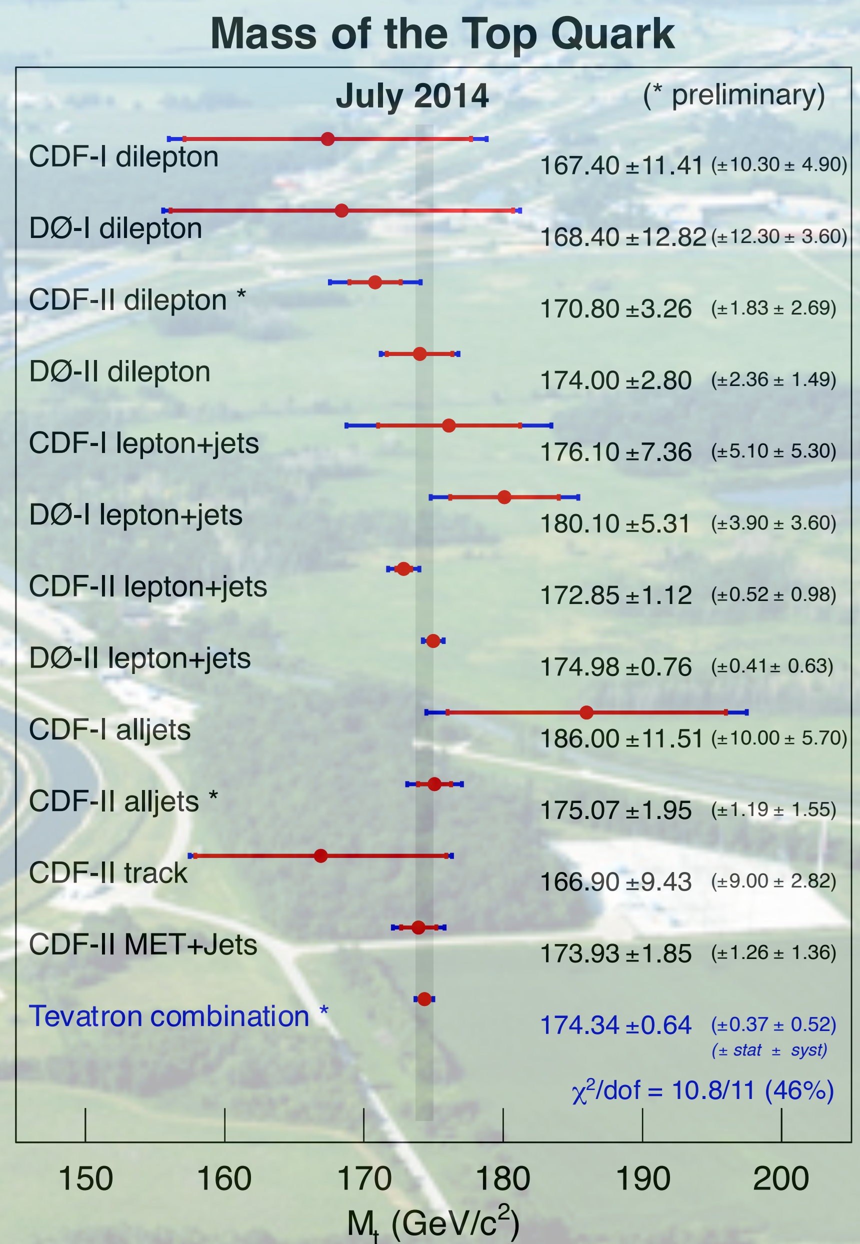
“Bernard of Chartres used to compare us to [puny] dwarfs perched on the shoulders of giants. He pointed out that we see more and farther than our predecessors, not because we have keener vision or greater height, but because we are lifted up and borne aloft on their gigantic stature”

– John of Salisbury, 1159
(+paraphrased by Newton, 1676)

On the shoulders of giants

[arXiv:1309.7570]



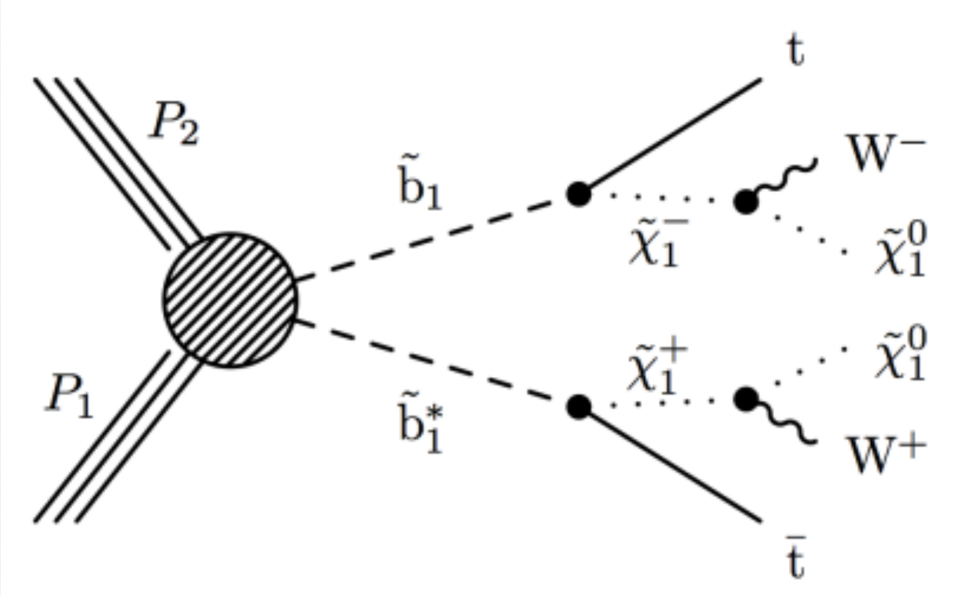


[arXiv:1407.2682]

→ *Canelli, Galloni, Hong, Jung, Schwienhorst, Thomson*

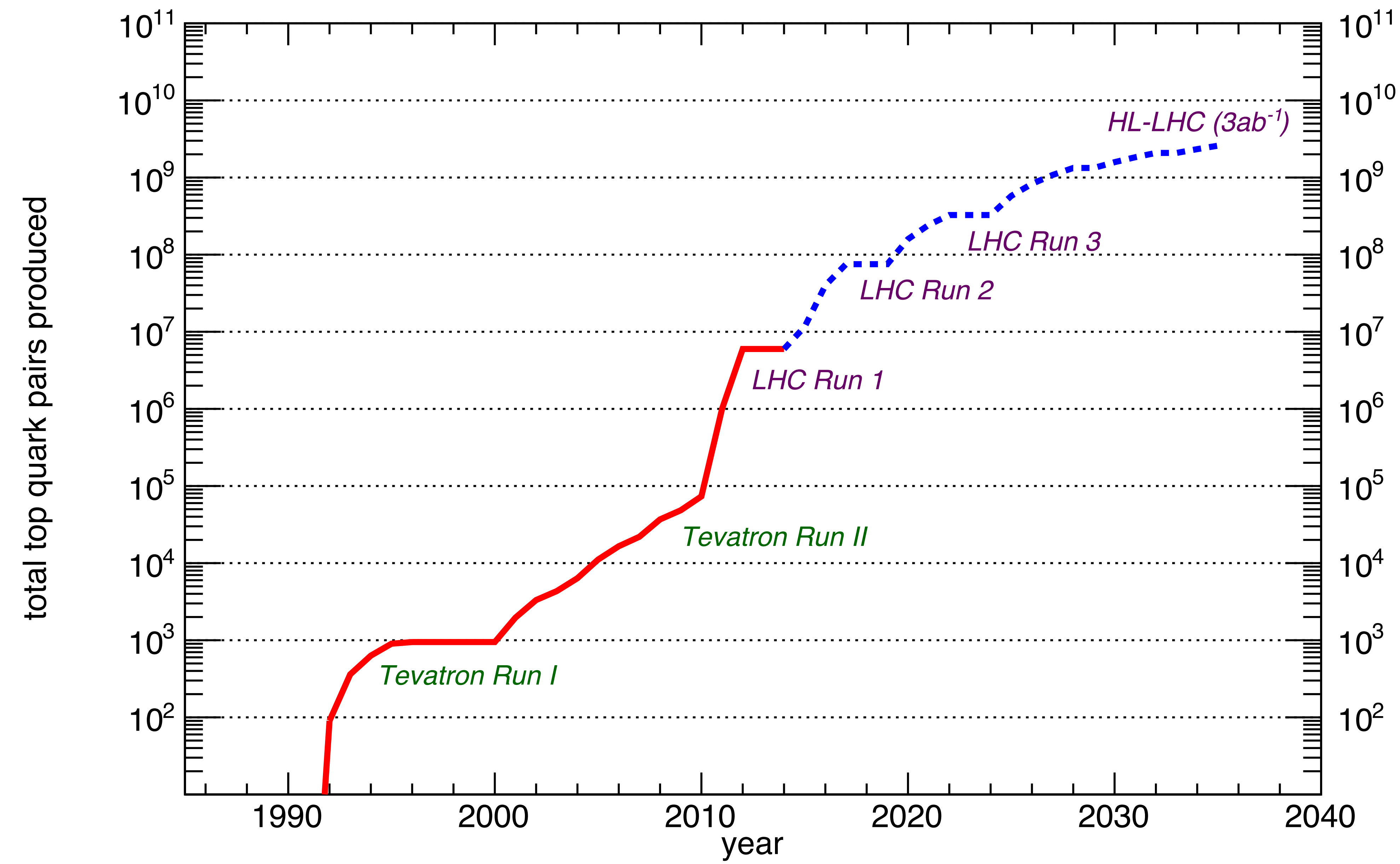
LHC to-do list

- Determine the top quark mass as precisely as possible.
- Verify couplings to other particles, including (especially) the top quark Yukawa coupling.
- Check if any room for New Physics:
  - precision tests of properties, rare decays, new top quark production modes.



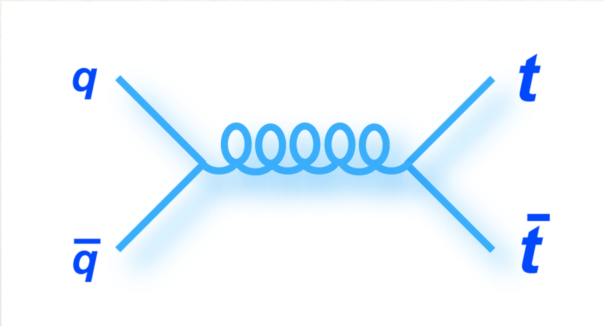
- Requires: lots of data, sophisticated analyses, precision theory.

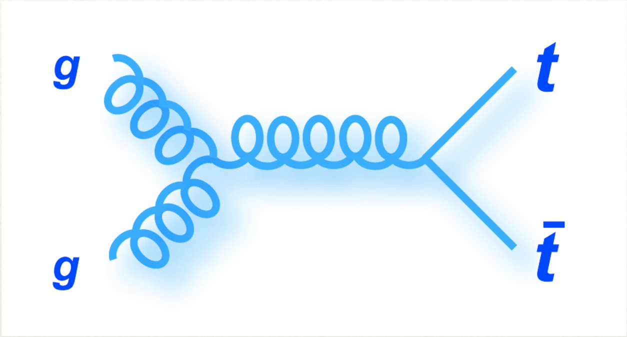
Top quark availability



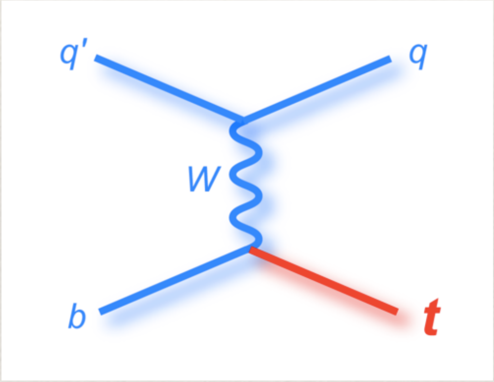
Top quark production modes

strong pair production

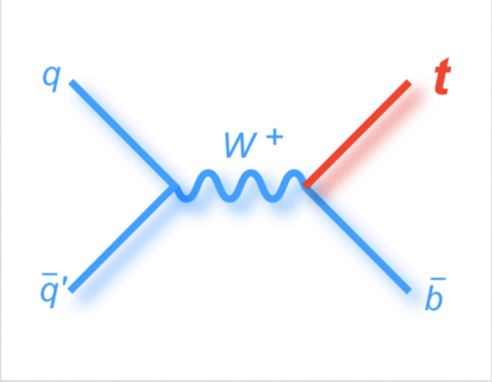




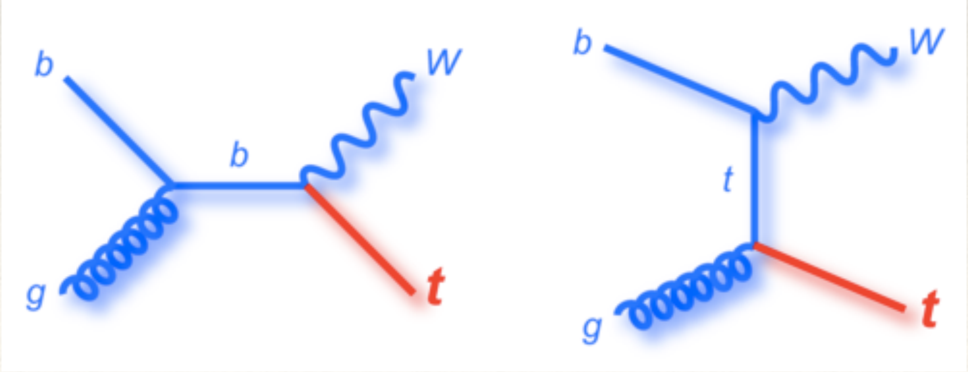
EW t-channel

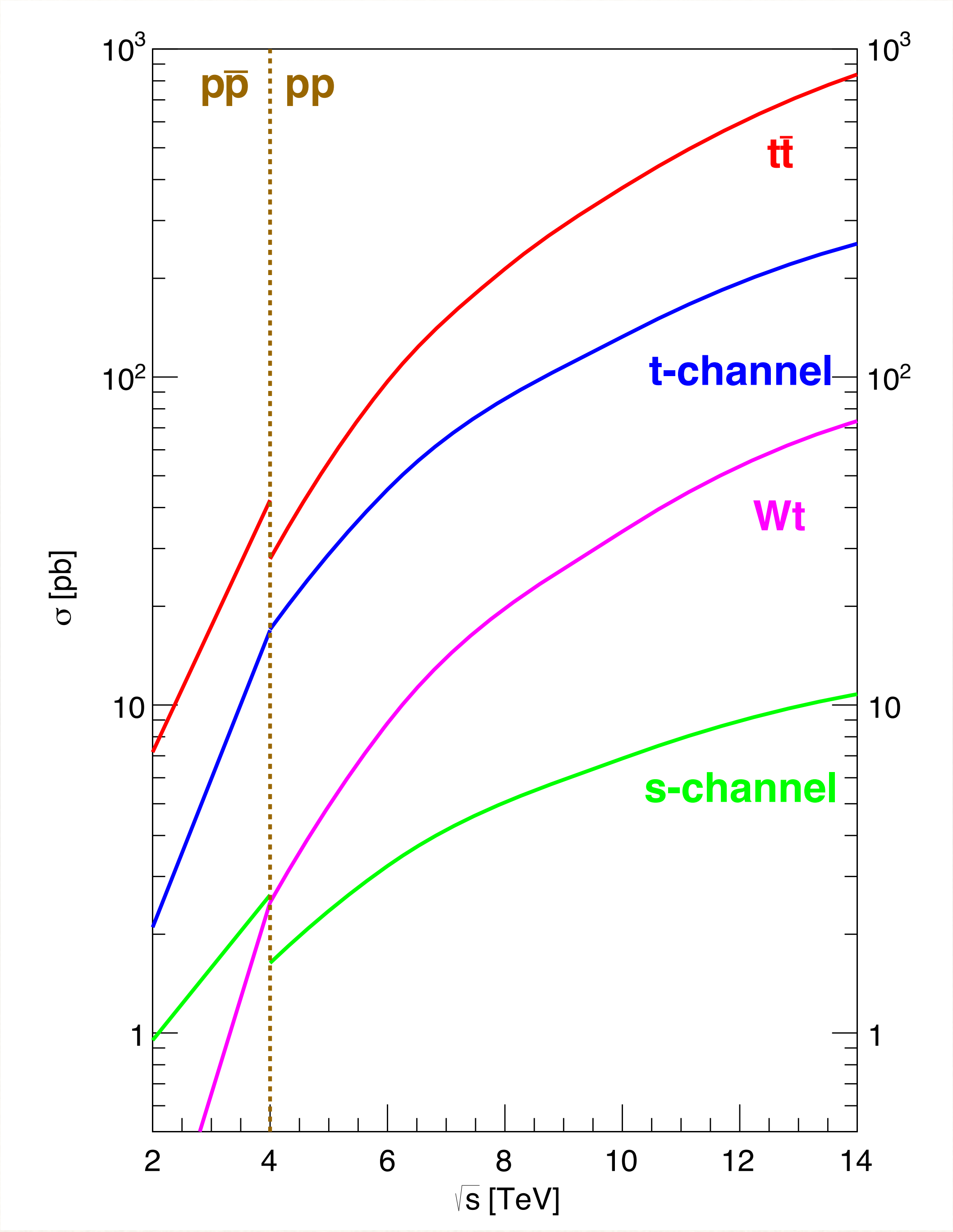


EW s-channel



EW Wt





Status of theoretical predictions

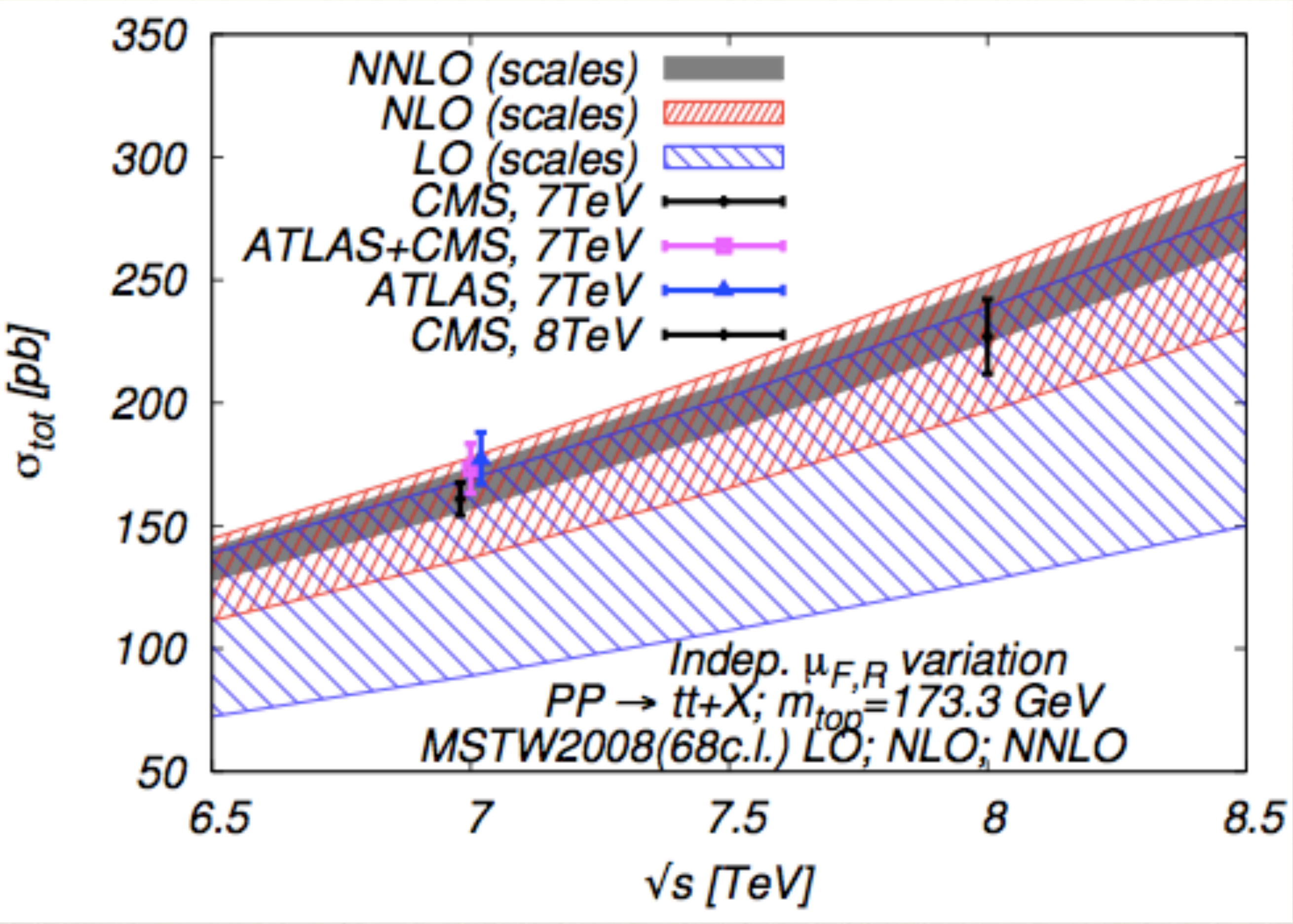
Theory requirements

- Require precise predictions for
  - top quark cross-section.
  - essential kinematic quantities, e.g. p_T, rapidity.
  - observed final state, i.e. including top quark decays.
  - (many!) events that contain additional jets.
- Many recent advances in both fixed-order QCD and Monte Carlo simulations. → *Mitov*

> We always want better theory and top pair production is the best playground since it offers all complications (i.e. toys) a theorist may wish for:

Pair production: precision

- Recent NNLO calculation of cross-section in the strong production mode.
- Much-reduced theoretical uncertainty.



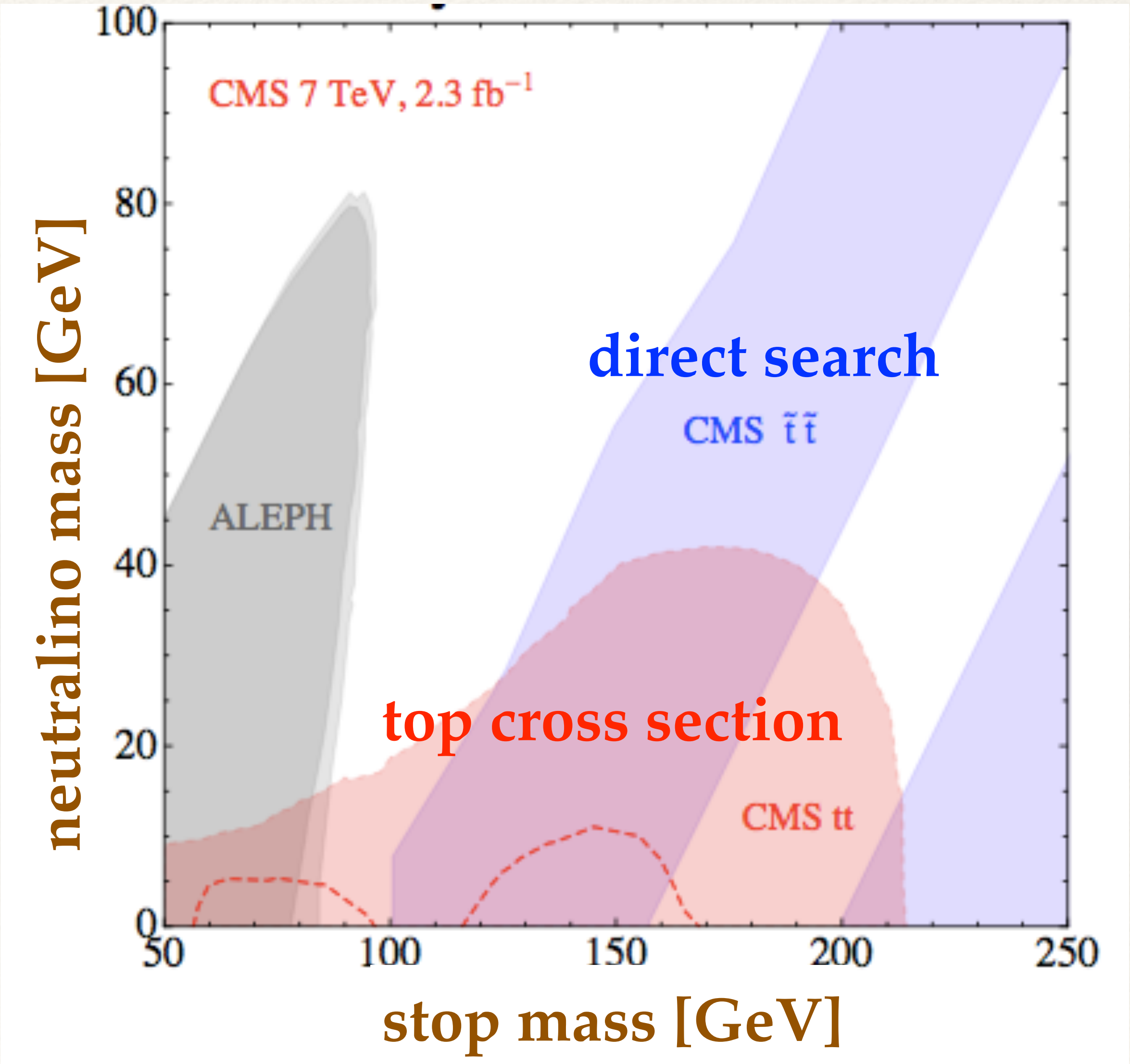
[Czakon, Fiedler, Mitov 2013]

- Enables high-precision test of SM.
  → *Yu*
- Better understanding of backgrounds to BSM searches.

A benefit of precision

[Czakon et al, 2014]

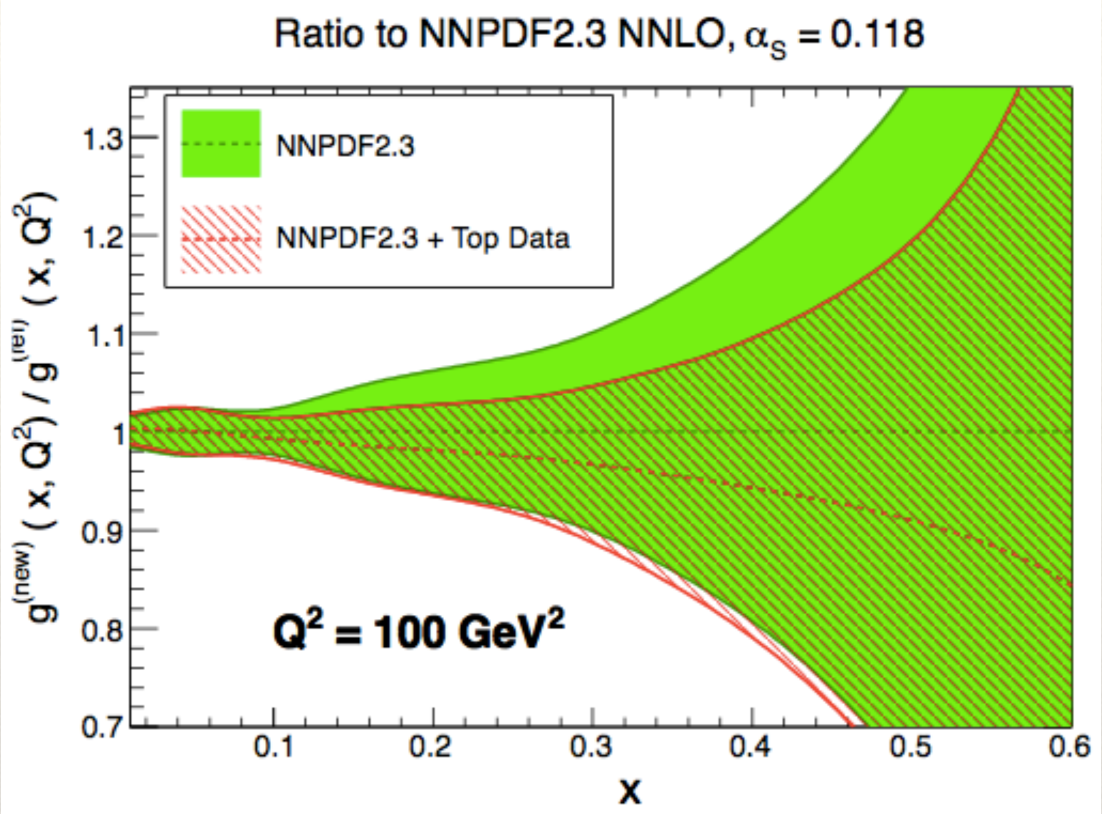
- Exploit the fact that stop quarks with mass close to m_t could look very similar to top quarks.
- Obtain a constraint from the measured cross-section.



Impact on LHC program

- Top pairs now sufficiently well-understood to be used as input in global PDF fits.
- Already some impact with existing data.

[Czakon et al, 2013]

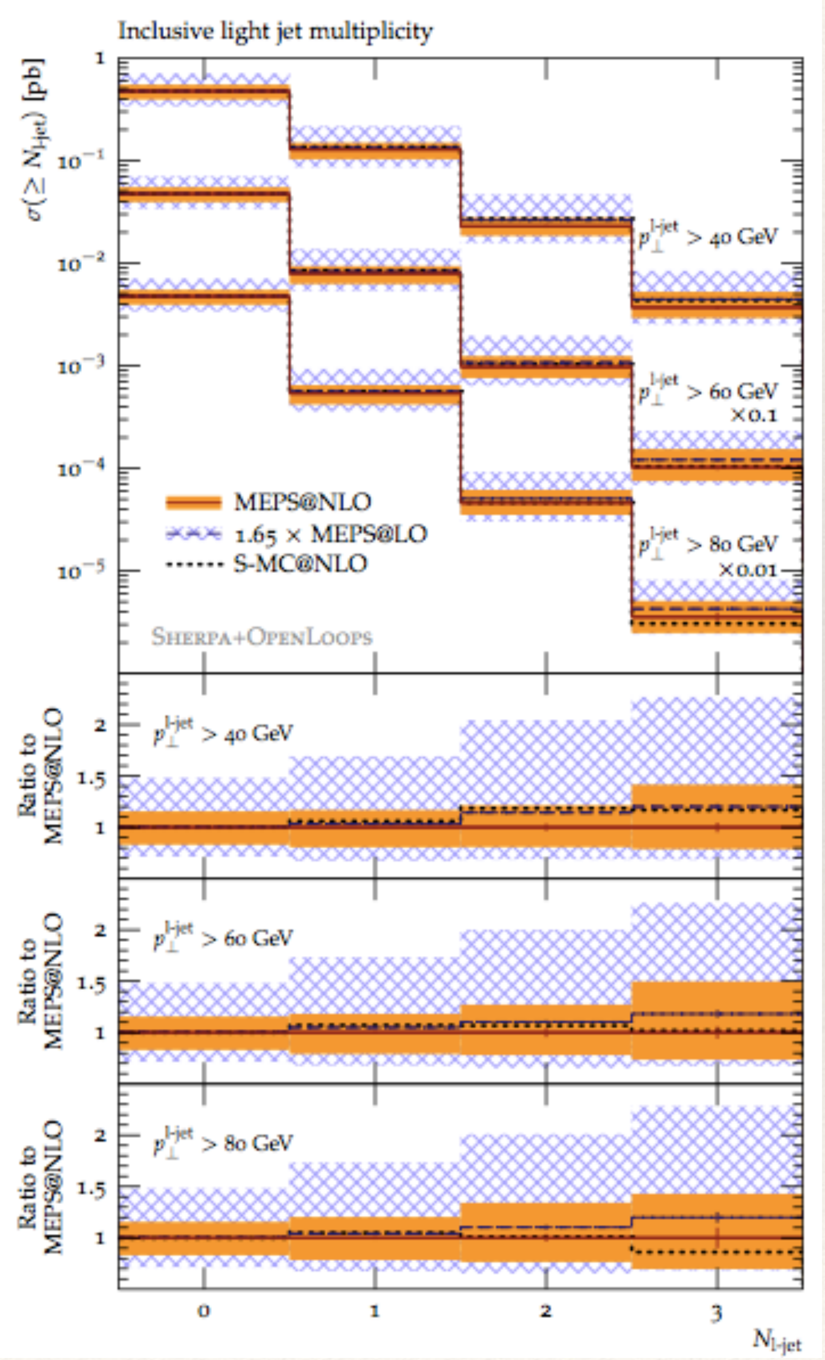


- Will only be more useful with more data: smaller uncertainties overall, ability to explore other kinematics.
- Improved control of gluon-dominated backgrounds.

Pair production with jets

- Substantial rate for producing top pair with extra jets.
- Important background for Higgs studies (H→WW and ttH), NP searches.
- Now able to simulate full MC events with up to 2 jets (SHERPA) and NLO accuracy (OPENLOOPS).
- Important validation of different MC generators through multiple kinematic distributions with high statistics.

  → *Brinkerhoff*

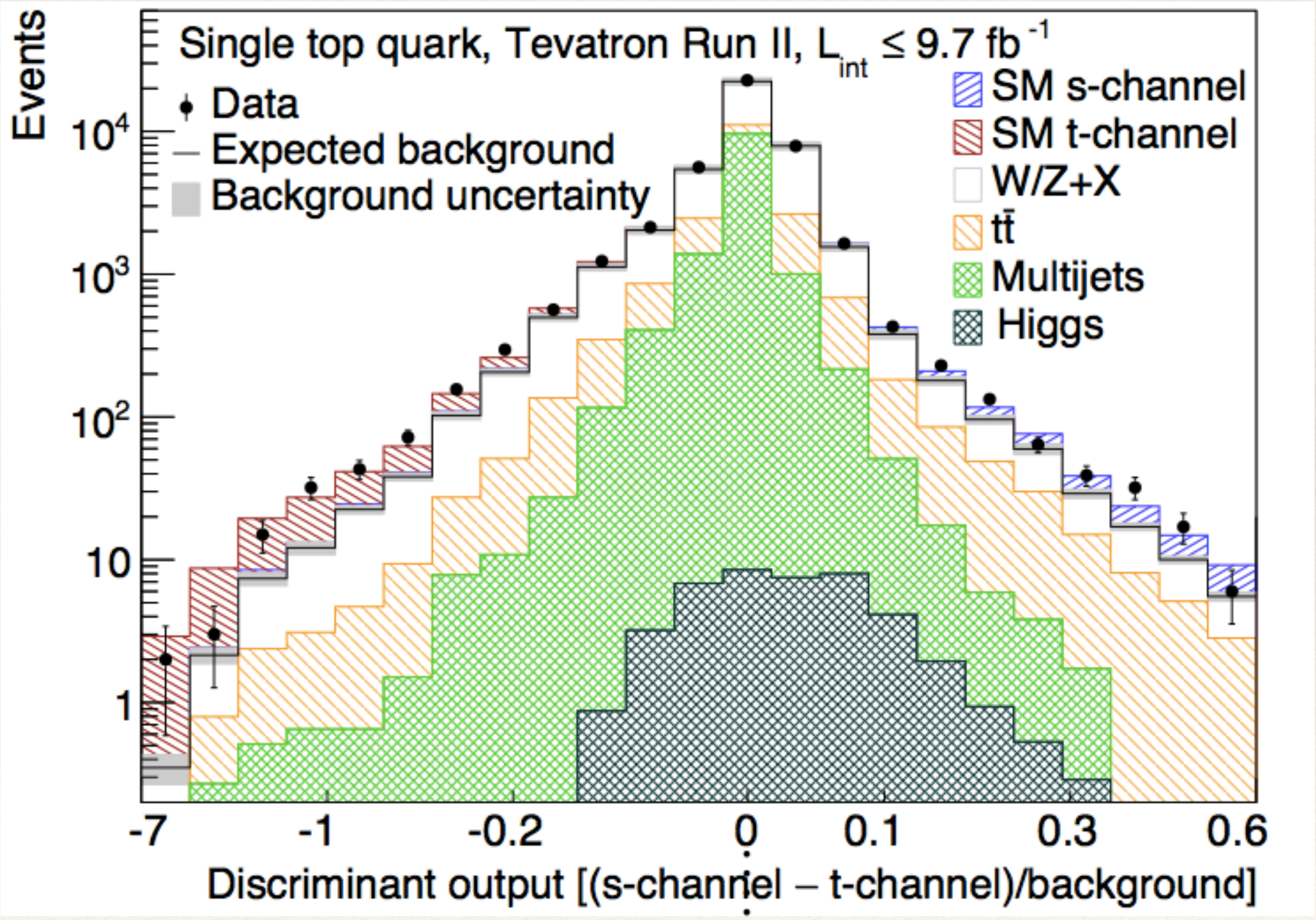


[Höche et al, 2014]

Single top

- Conclusive observation of single top production at the Tevatron in 2009.
- Impressive coming-together of experimental analysis techniques (e.g. MVA) and theory to overcome formidable backgrounds.

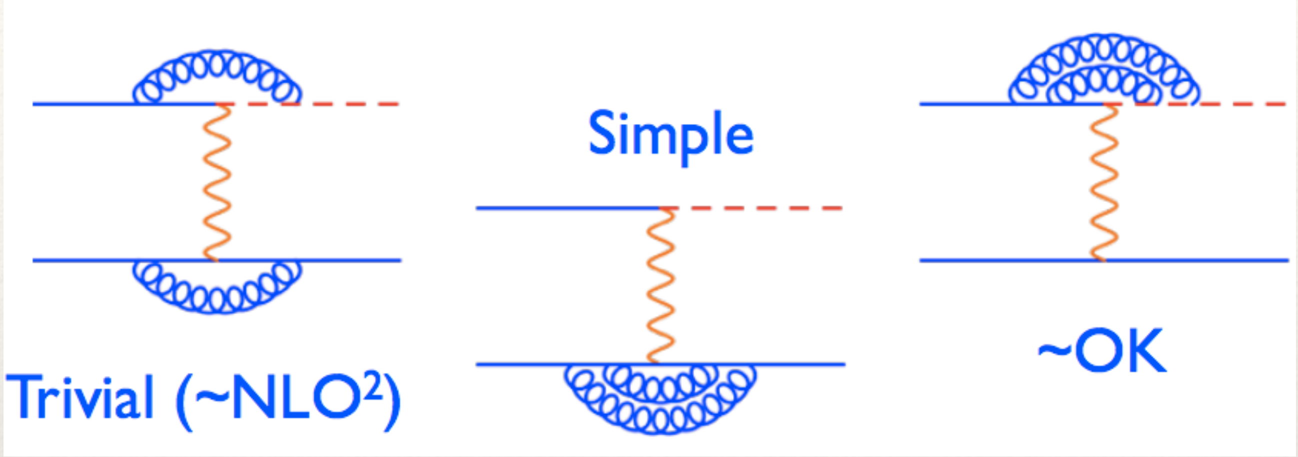
→ *Schwienhorst, Sullivan*



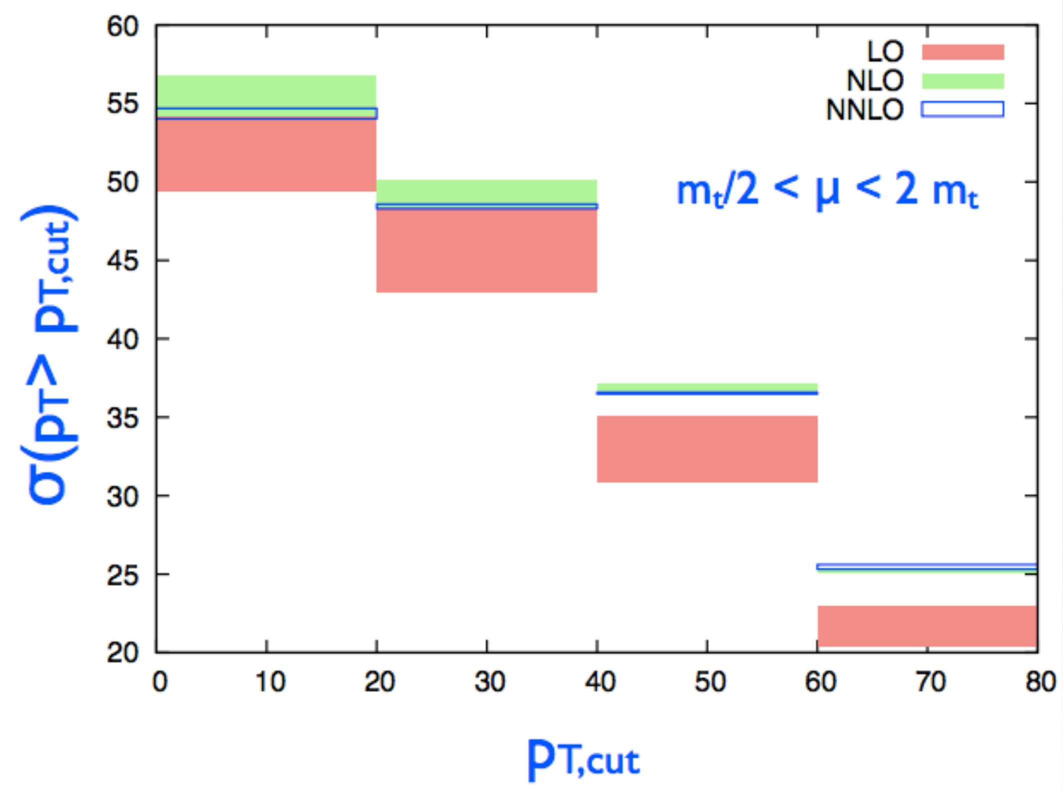
[Tevatron combination, 1503.05027]

Single top: precision

- Leading single-top mode at LHC now known to NNLO.
  - important for extraction of CKM matrix element V_{tb}.



Brucherseifer, Caola, Melnikov (2014)



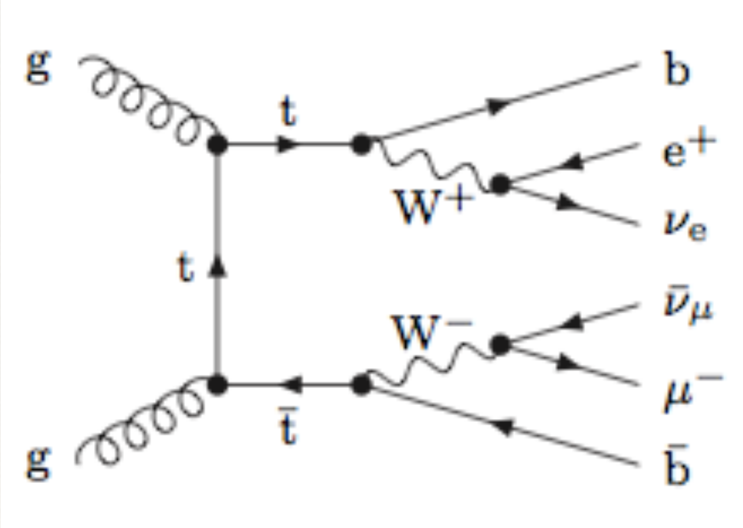
- Differential quantities also predicted at NNLO, e.g. as a function of top p_T.
- NNLO corrections small, but much-reduced uncertainty.

Top quark decays

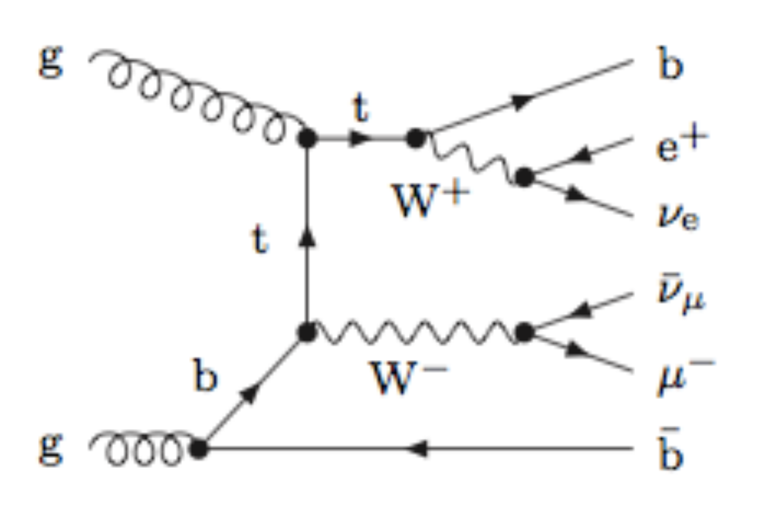
- It is much easier to provide theoretical predictions for stable top quarks.
- Decays can be added later in a factorized approach.
- This is only an approximation since it is impossible to define an observable based on intermediate particles.
- Important to understand:
  - to what extent can approximation be removed?
  - if it cannot, how can it be improved? → ***Mitov***

Example

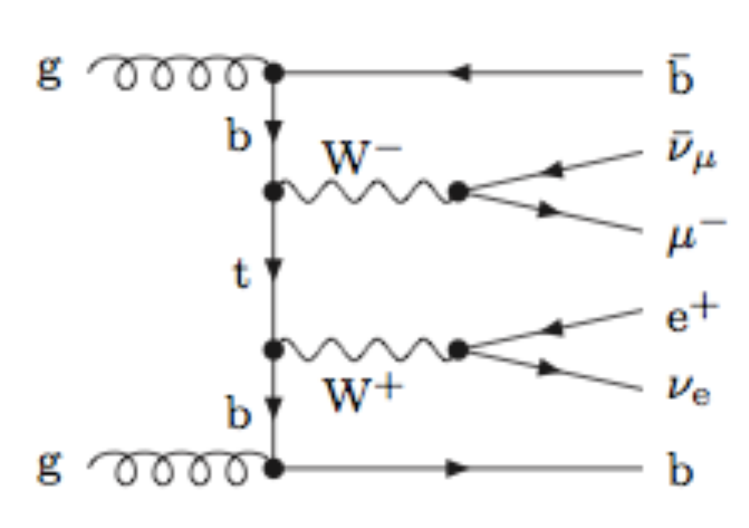
- Think of top pair production with both top quarks decaying leptonically: final state ($e,\nu_e,\mu,\nu_\mu,b,b\sim$).
- A full (gauge-invariant) set of diagrams must include more than just the "double resonant" top pair production contributions.



top pair-like



associated Wt-like



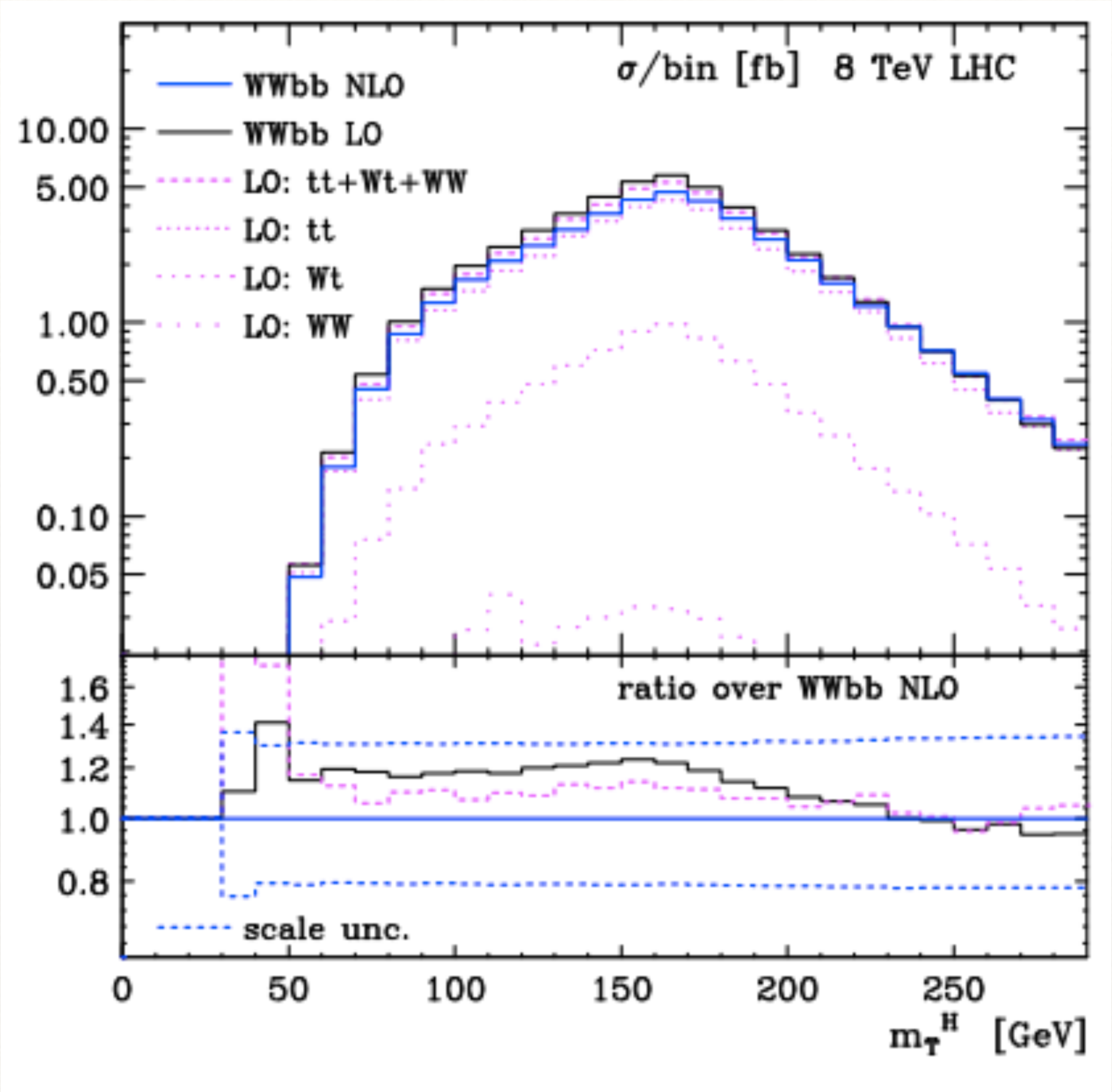
WWbb-like

- Multiple massive quarks, many particles in final state.

State of the art

- For this process, theory has caught up: full, flexible calculations now available at NLO.

  [Frederix 2013, Cascioli et al 2013]



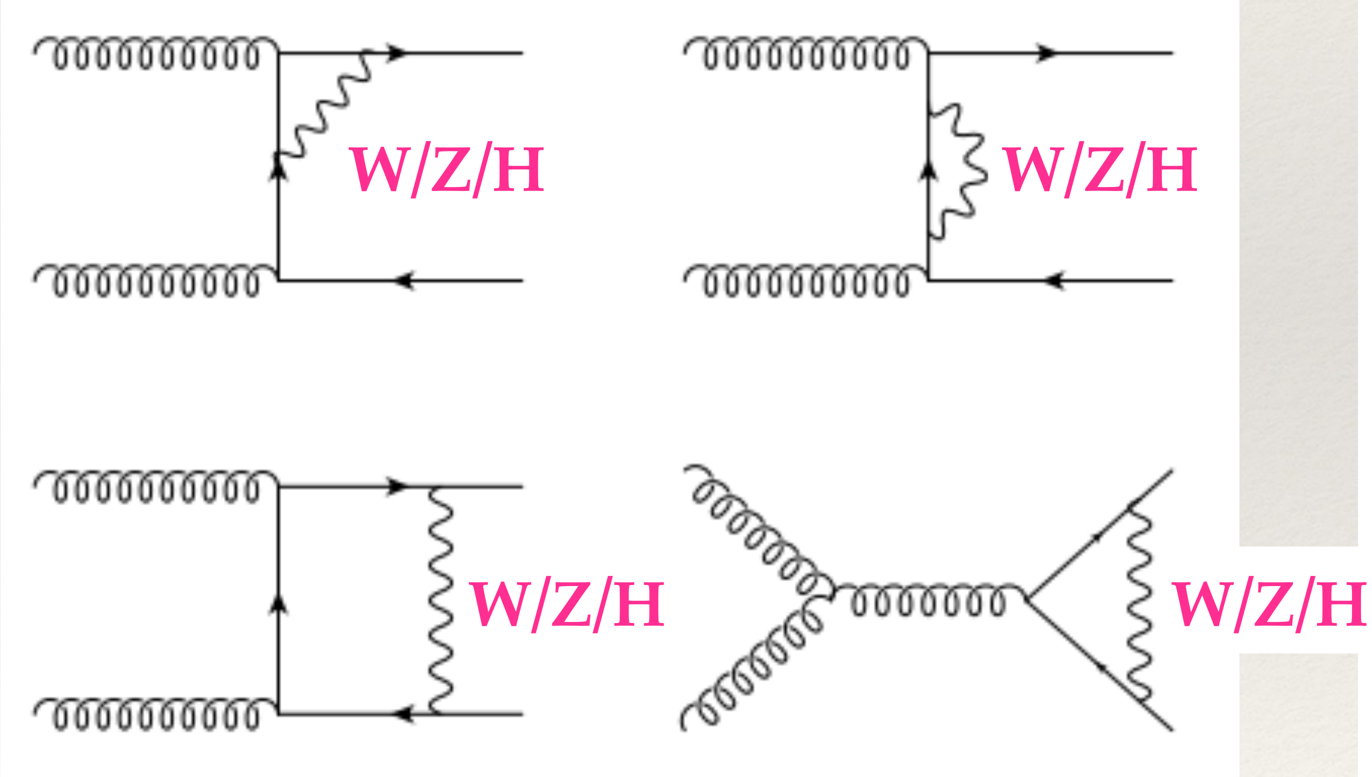
[Frederix 2014]

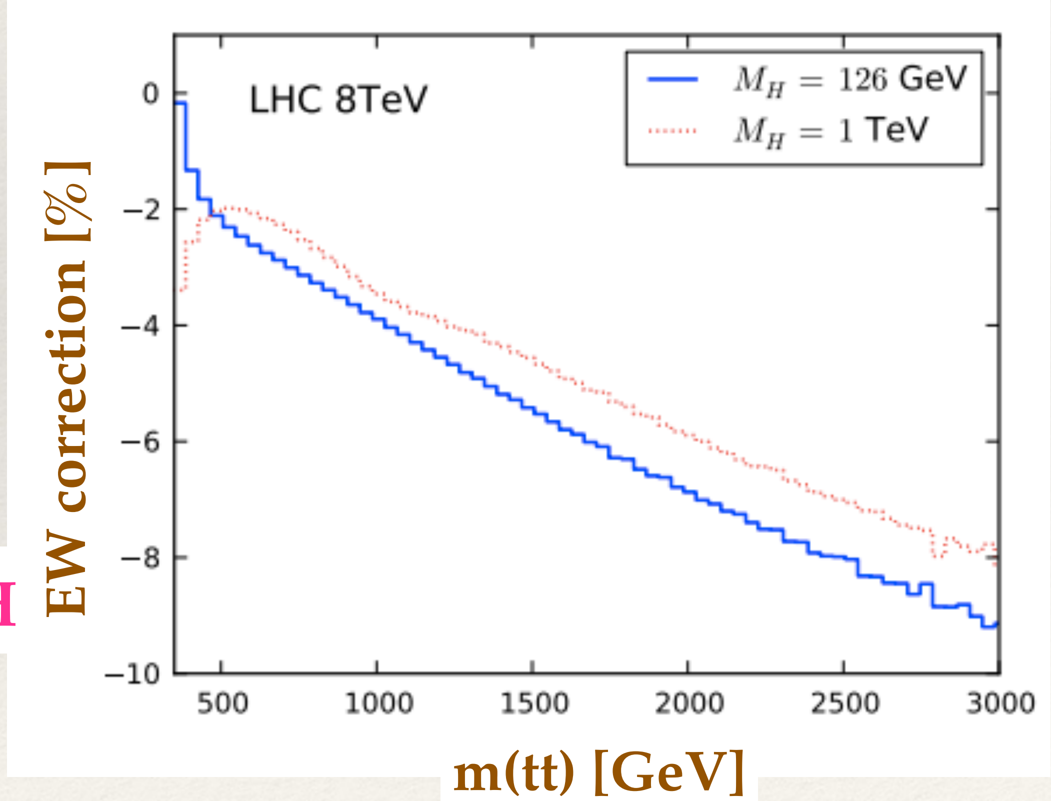
- Instructive to compare with factorized approach.

- Armed with full calculation, can separate channels with kinematic cuts.

Electroweak corrections

- Naively, might expect NLO EW corrections to be important once NNLO QCD under control.
- In fact, worse: log enhancement at high momentum transfer.





[Kuhn et al, 2014]

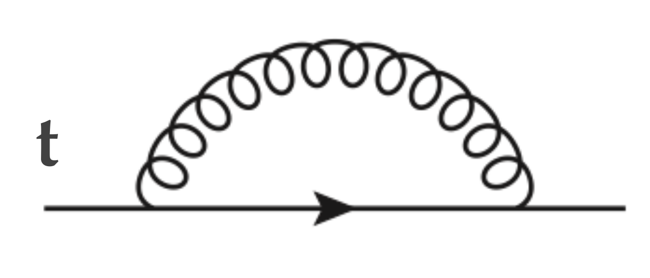
Important for BSM backgrounds!

The top quark mass

What is the top mass?

$\rightarrow$ ***Weinzierl***

- Parameter of the QCD Lagrangian that must be renormalized order-by-order.



$$m_t^0 = m_t^{\text{scheme}}\left(1 - \frac{\alpha_s}{\pi}\frac{1}{\varepsilon} + \ldots\right) + \text{ finite(scheme)}$$

- The top mass is not a physical observable (no asymptotic free top state) but is scheme-dependent, e.g. on-shell scheme $\rightarrow$ pole mass.
  - non-pert. (renormalon) effects mean pole mass ambiguity $O(\Lambda_{QCD})$.
- Should relate data to calculation in well-defined scheme.
- Can translate between schemes, e.g. pole and $\overline{\text{MS}}$ mass relationship is known at 4-loops. [Marquard et al, 2015]

What about Monte Carlos?

- Main method for determining top quark mass so far: fits of data compared to parton shower MCs (template, ideogram, matrix element method, ….).
- MC has perturbative QCD down to 1 GeV, then hadronization model takes over. No accounting for self-energy contributions:

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \mathcal{O}(\mathrm{GeV})$$

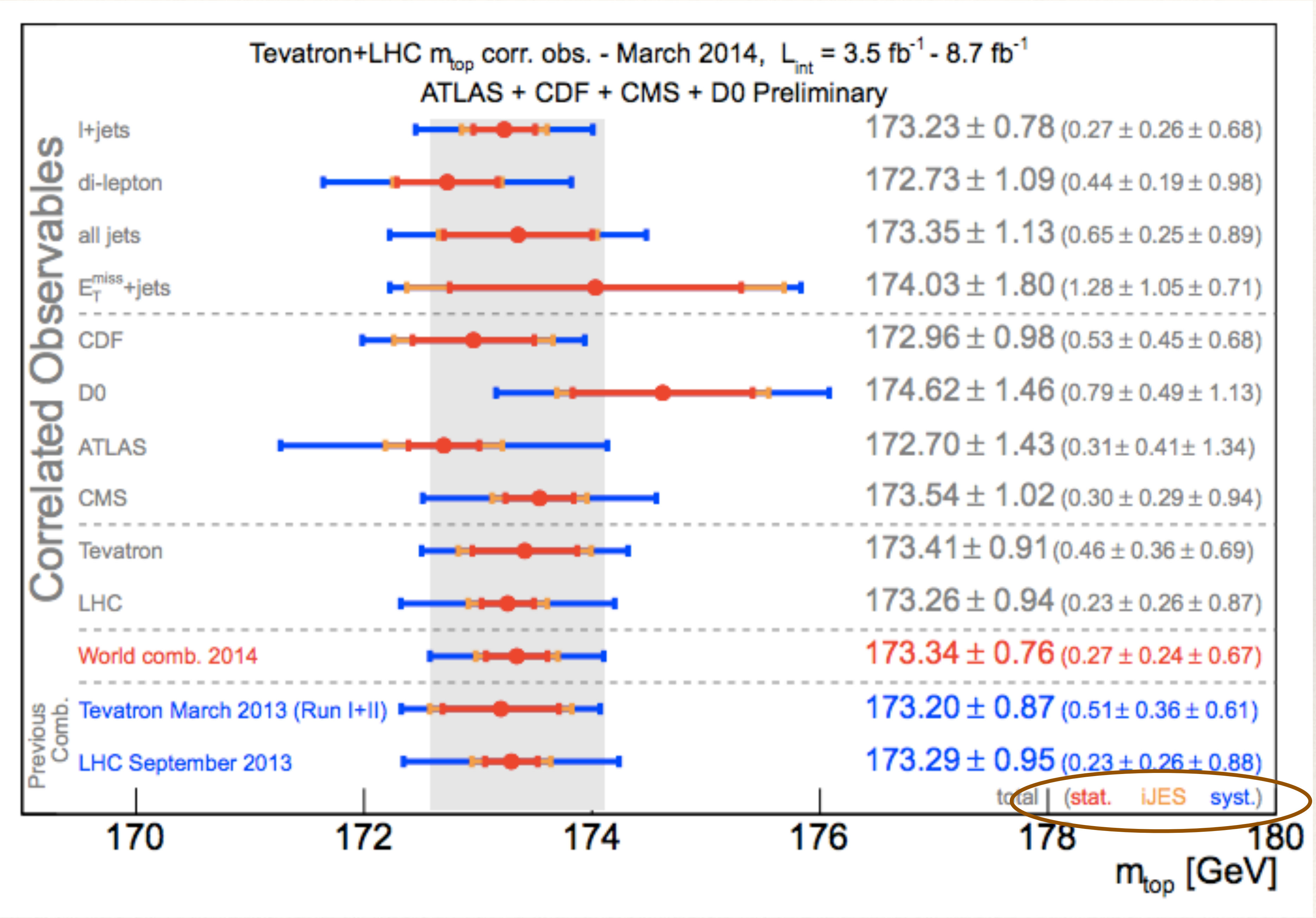
- In principle, top mass extracted using different MC generators do not have to agree.
- Ongoing work to understand relationship between MC mass and well-defined theory counterpart (no renormalon ambiguity).

[Hoang et al 2008, Hoang 2014]

Top mass measurements

→ Jung, Narain

[arXiv: 1403.4427]



→ Brandt

“Snowmass” projection

	Ref.[70]	Projections				
CM Energy	7 TeV	14 TeV				
Cross Section	167 pb	951 pb				
Luminosity	$5 fb^{-1}$	$100 fb^{-1}$		$300 fb^{-1}$		$3000 fb^{-1}$
Pileup	9.3	19	30	19	30	95
Syst. (GeV)	0.95	0.7	0.7	0.6	0.6	0.6
Stat. (GeV)	0.43	0.04	0.04	0.03	0.03	0.01
Total	**1.04**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**
Total (%)	0.6	0.4	0.4	0.3	0.3	0.3

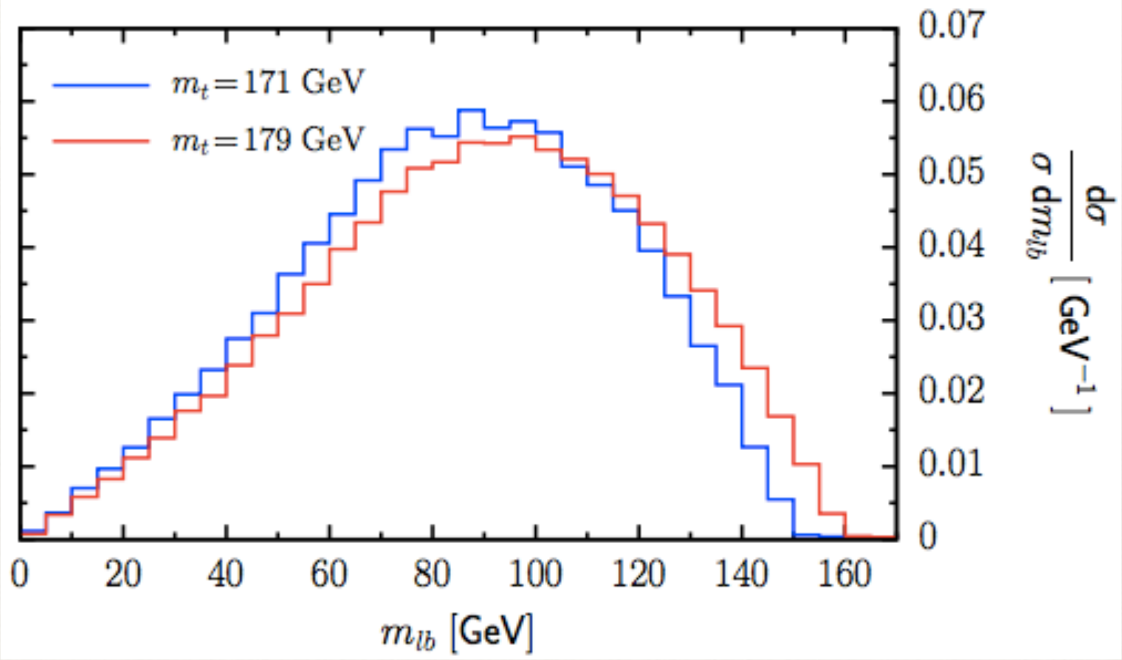
[Juste et al, 2013]

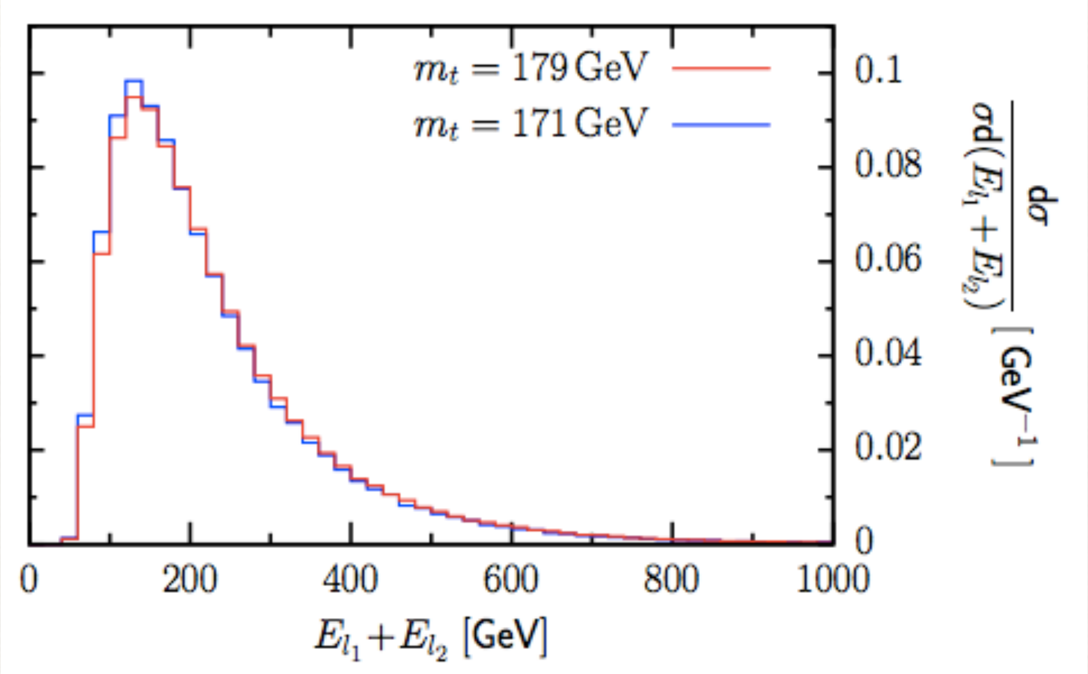
(a) Exploit improvements by tightening interpretation.

(b) Explore alternative determinations.

Leptonic observables

- Exploit observables that can be reliably predicted and measured cleanly → lepton+jets, dilepton decays.

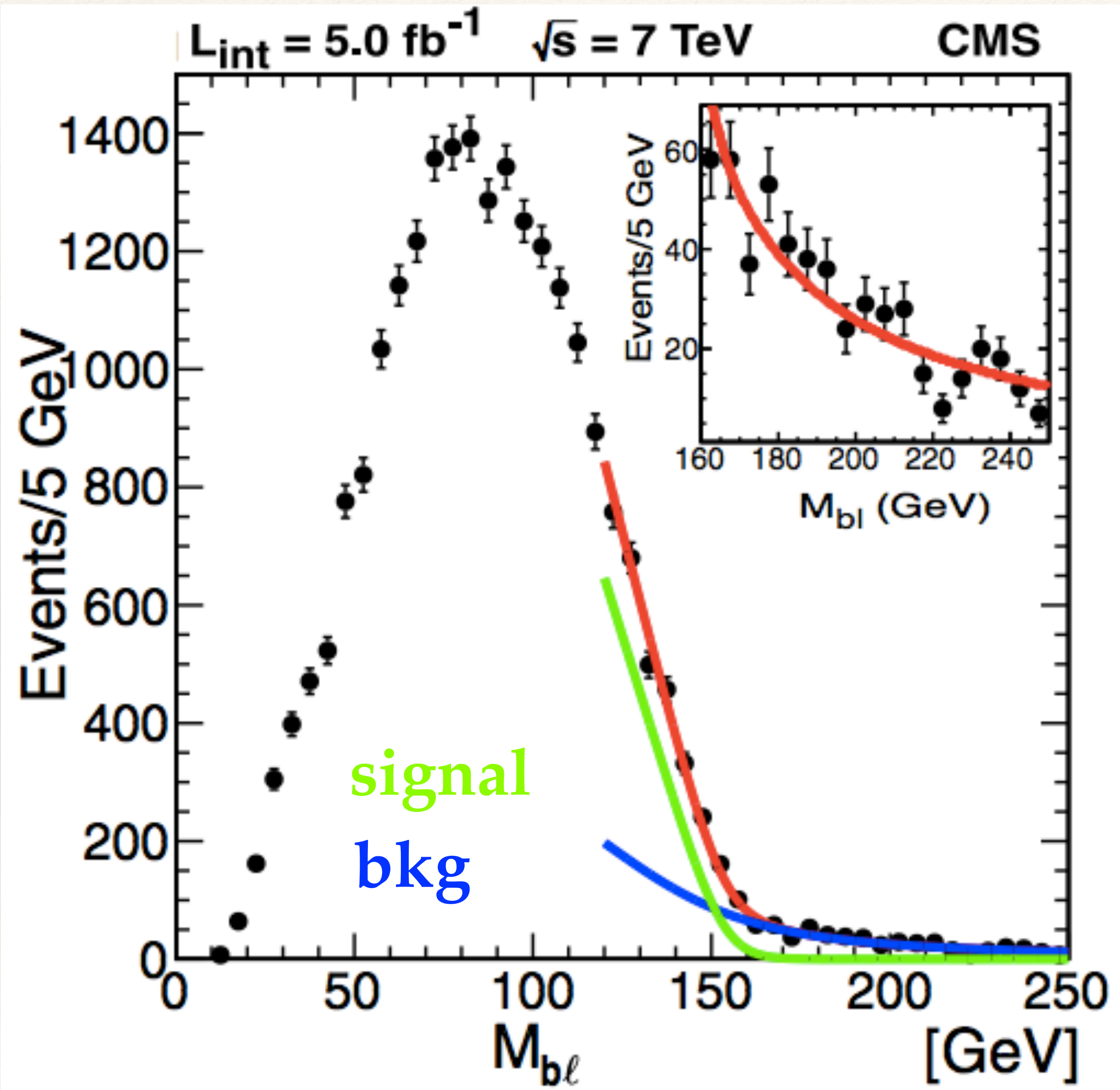




[Biswas et al, 2010]

- Utilize moments of multiple distributions to maximize information → theory uncert. 0.8 GeV. [Frixione, Mitov, 2014]

CMS endpoint determination



[arXiv: 1304.5783]

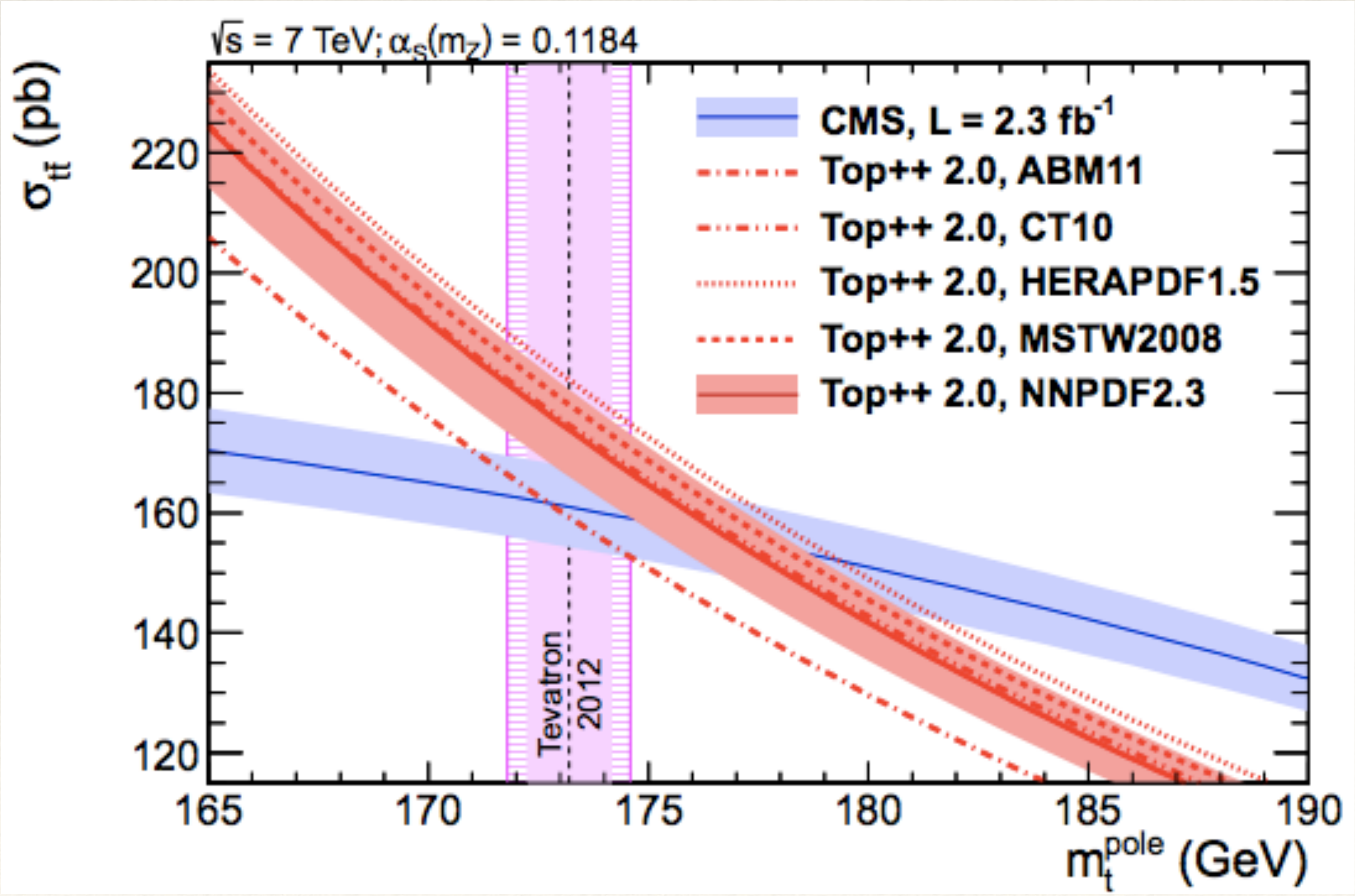
Source	δM_t (GeV)
Jet Energy Scale	$^{+1.3}_{-1.8}$
Jet Energy Resolution	± 0.5
Lepton Energy Scale	$^{+0.3}_{-0.4}$
Fit Range	± 0.6
Background Shape	± 0.5
Jet and Lepton Efficiencies	$^{+0.1}_{-0.2}$
Pileup	<0.1
QCD effects	± 0.6
Total	$^{+1.7}_{-2.1}$

(beware theory uncertainty in modeling of endpoint region)

Determination from cross-section

- Well-defined mass, only small theoretical uncertainties.
- Sensitivity relatively weak, can always be masked by compensating change in strong coupling, PDFs.

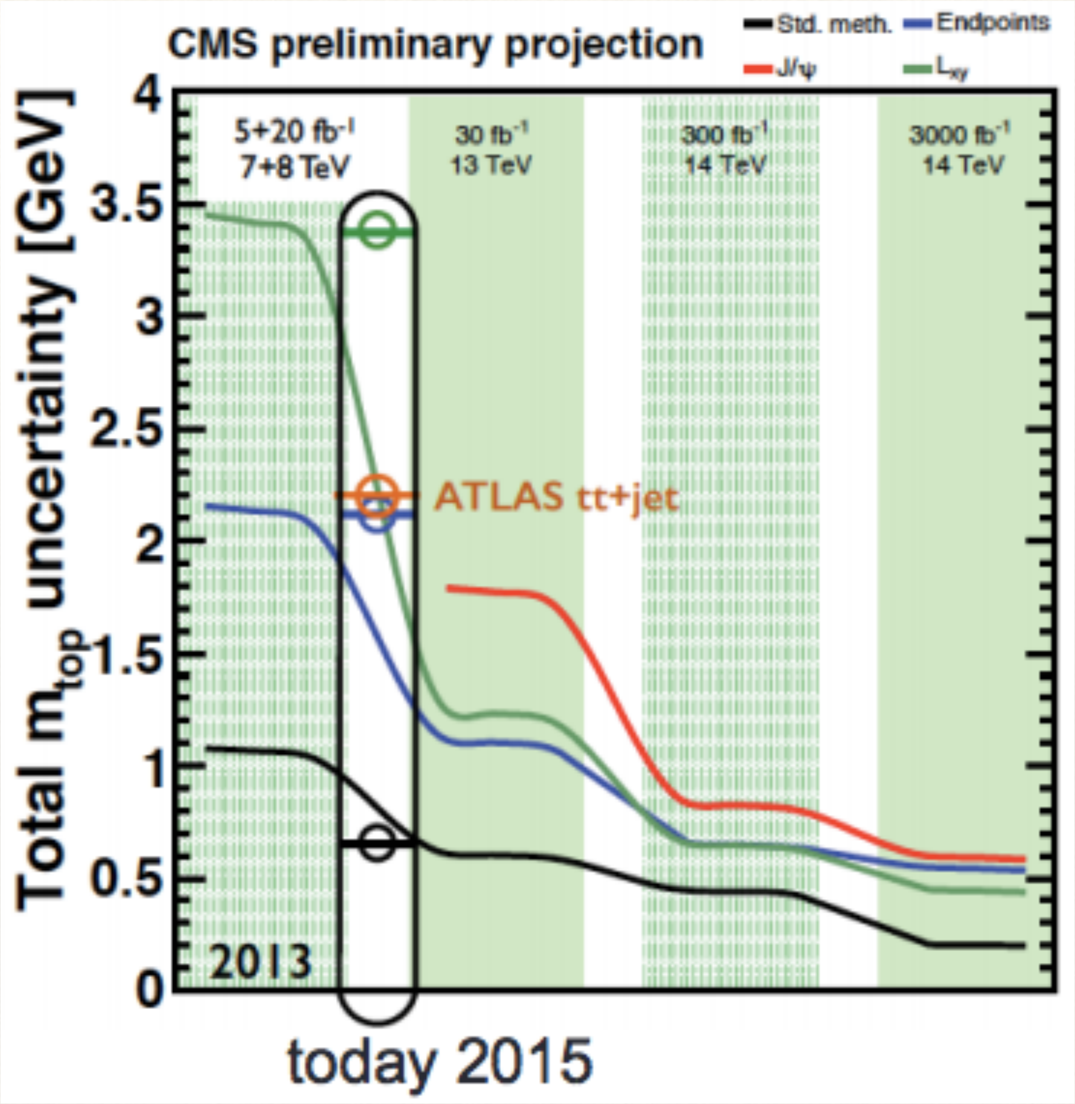
current
uncertainty
~ 2 GeV



[arXiv: 1307.1907]

Top mass prospects

- Ultimate LHC sensitivity ($3ab^{-1}$) ~ few hundred MeV
  - a variety of extractions will provide confidence in interpretations and uncertainties.



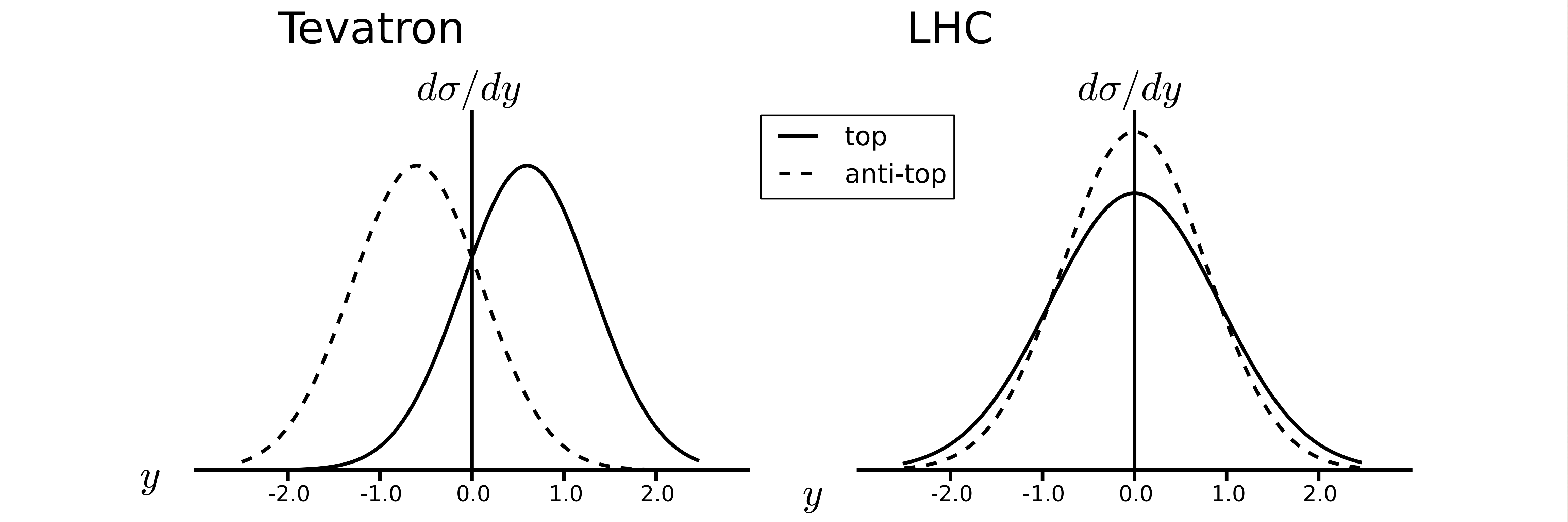
→ *Narain*

- Further input from lepton collider:
  - similar uncertainty from direct reconstruction of mass in top-pair events (systematics limited).
  - even better with dedicated threshold running: uncert. ~ 0.1 GeV

Properties and parameters

Top quark asymmetry

- Top and anti-top quarks are not produced identically.

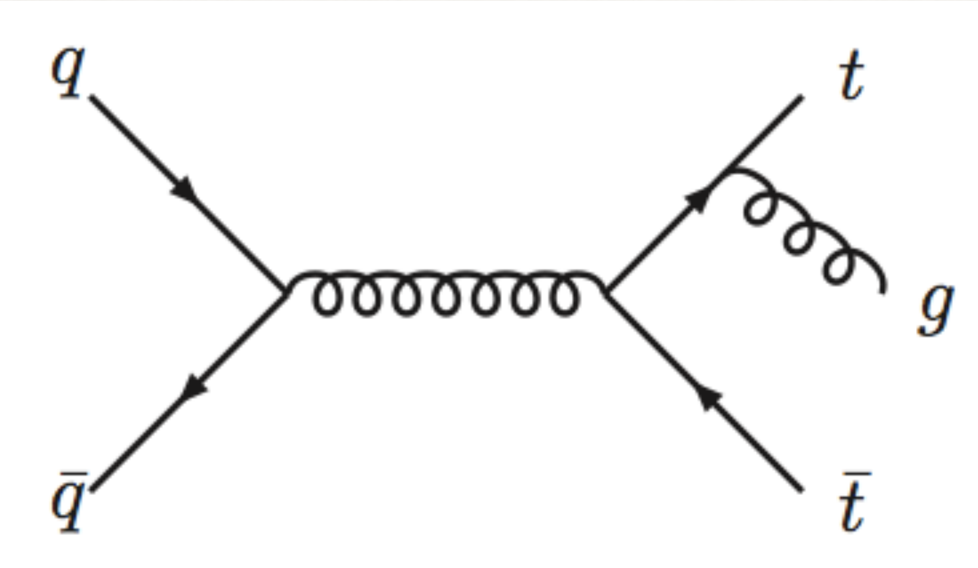


more top quarks with positive rapidity

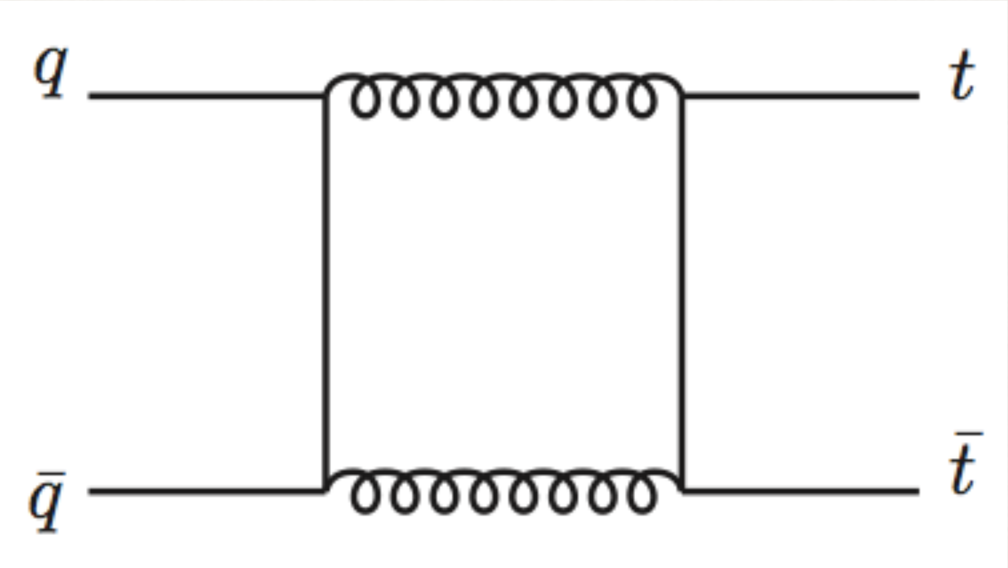
anti-top quarks more central

Theory prediction for asymmetry

- Tevatron lab-frame asymmetry: $A^{t\bar{t}}_{\text{lab}} = \dfrac{\sigma(y_t > 0) - \sigma(y_t < 0)}{\sigma(y_t > 0) + \sigma(y_t < 0)}$
- In pQCD, non-zero asymmetry arises only at NLO



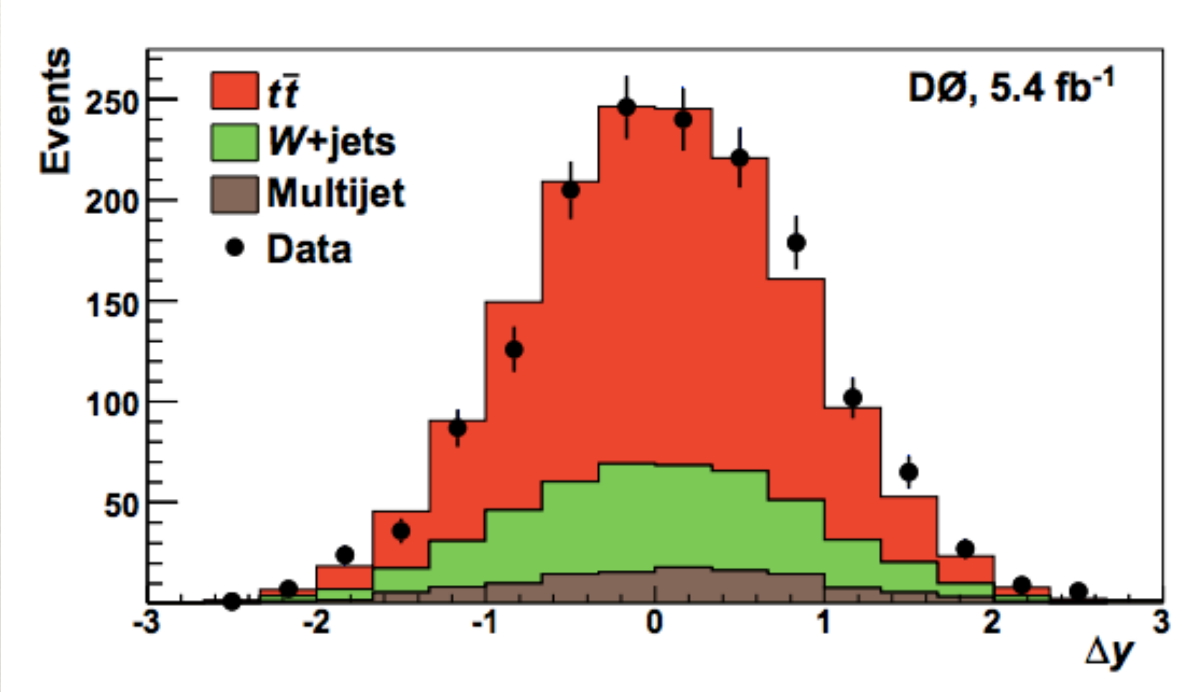
negative contribution to asymmetry, size grows with p_T



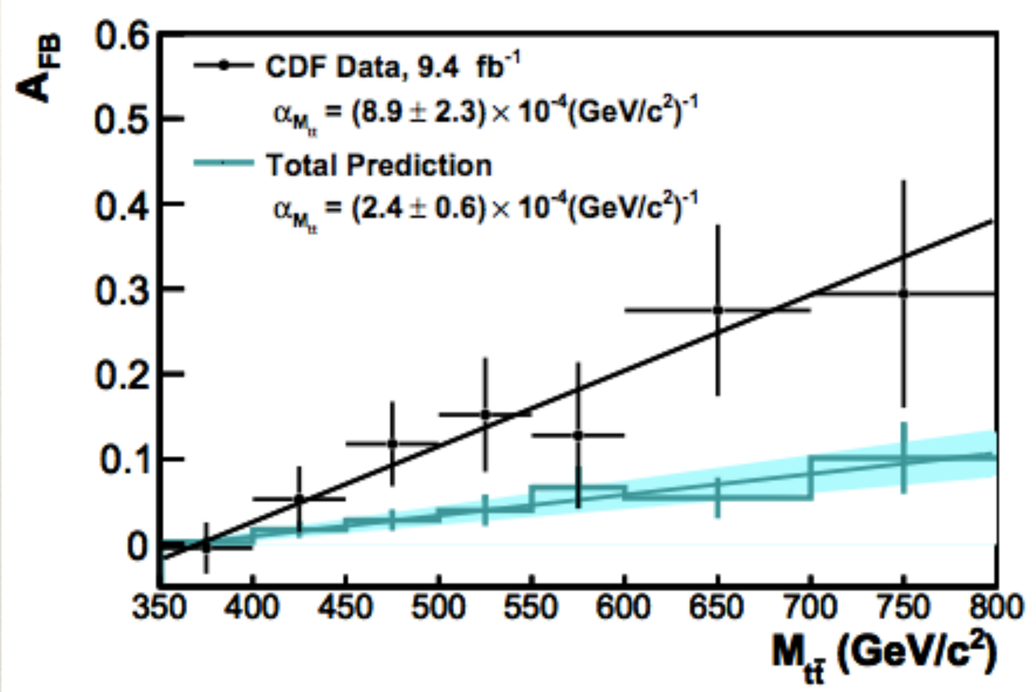
positive asymmetry at low p_T

Asymmetry in data

[arXiv: 1107.4995]



[arXiv: 1211.1003]



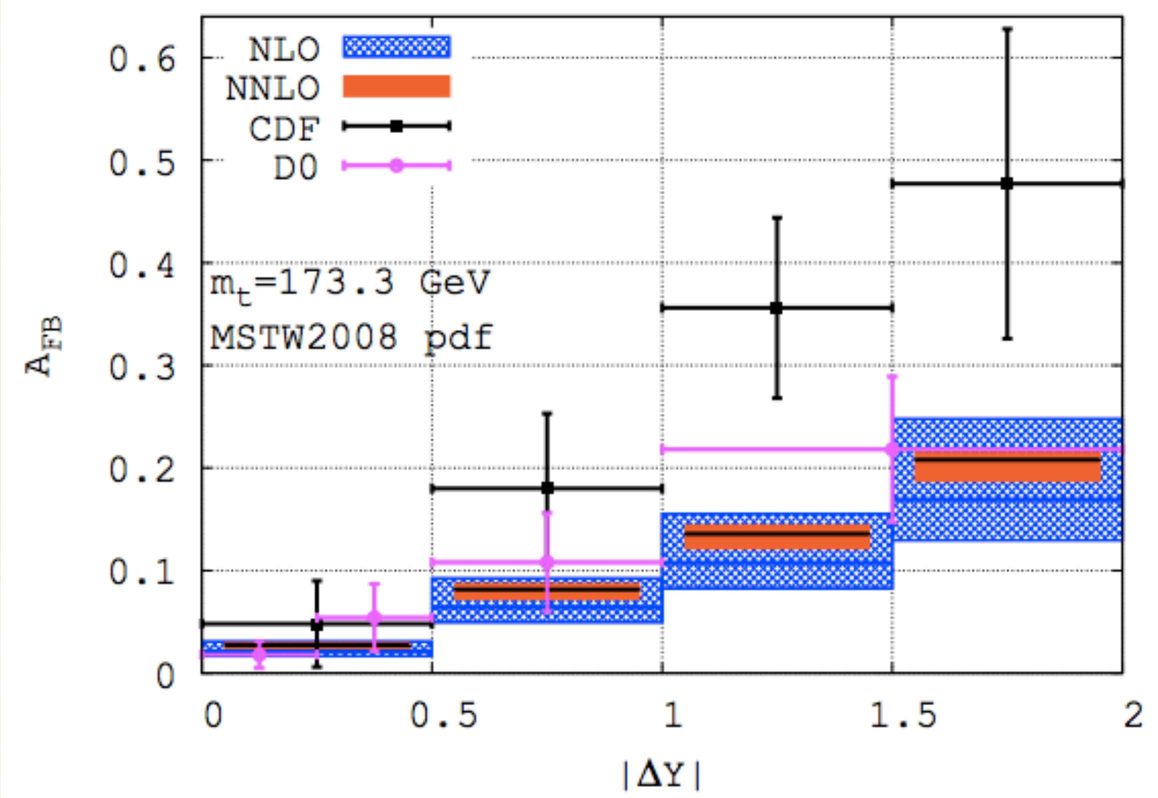
CDF+D0: asymmetry larger than SM prediction

CDF: anomalous growth in asymmetry with m(tt) and Δy(tt)

→ ***Hong***

Current status

- Experimental work: different analysis techniques, different observables (lepton vs. reconstructed top) …
- Theory: effect of MC showers on asymmetry, EW loops, QCD NNLO (~27% correction), wealth of BSM models.
- Resolution: pot-pourri of effects, including most of the above (but sadly, no NP).



[Czakon et al, 2014]

LHC asymmetry

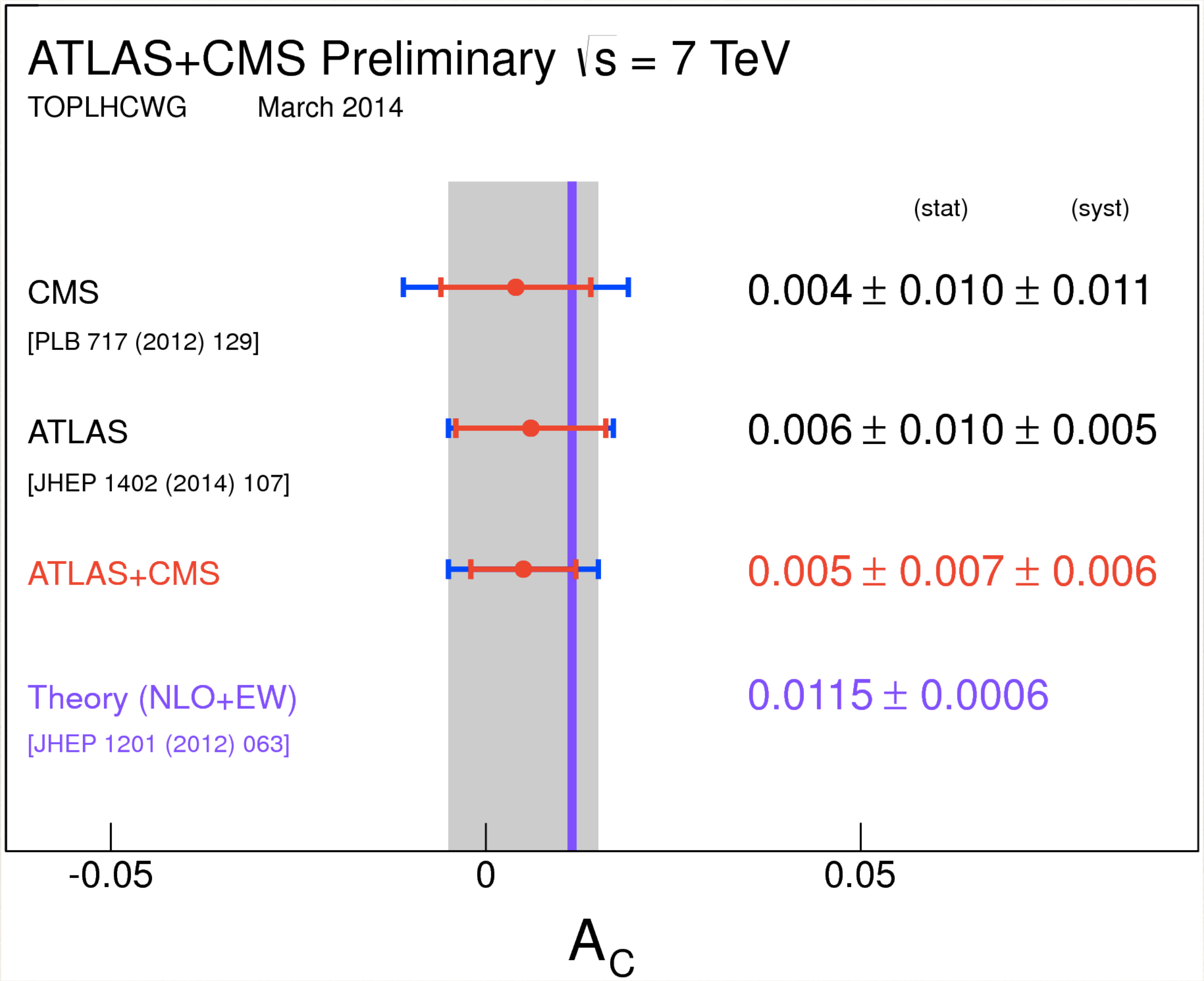
- Theory prediction for charge asymmetry very small.

$$A_c^t = \frac{N(\Delta_\eta^t > 0) - N(\Delta_\eta^t < 0)}{N(\Delta_\eta^t > 0) + N(\Delta_\eta^t < 0)}$$

$$\Delta_\eta^t = |\eta_t| - |\eta_{\bar{t}}|$$

- Measurements so far consistent with SM, but >100% uncertainty.

→ *Pinamonti*

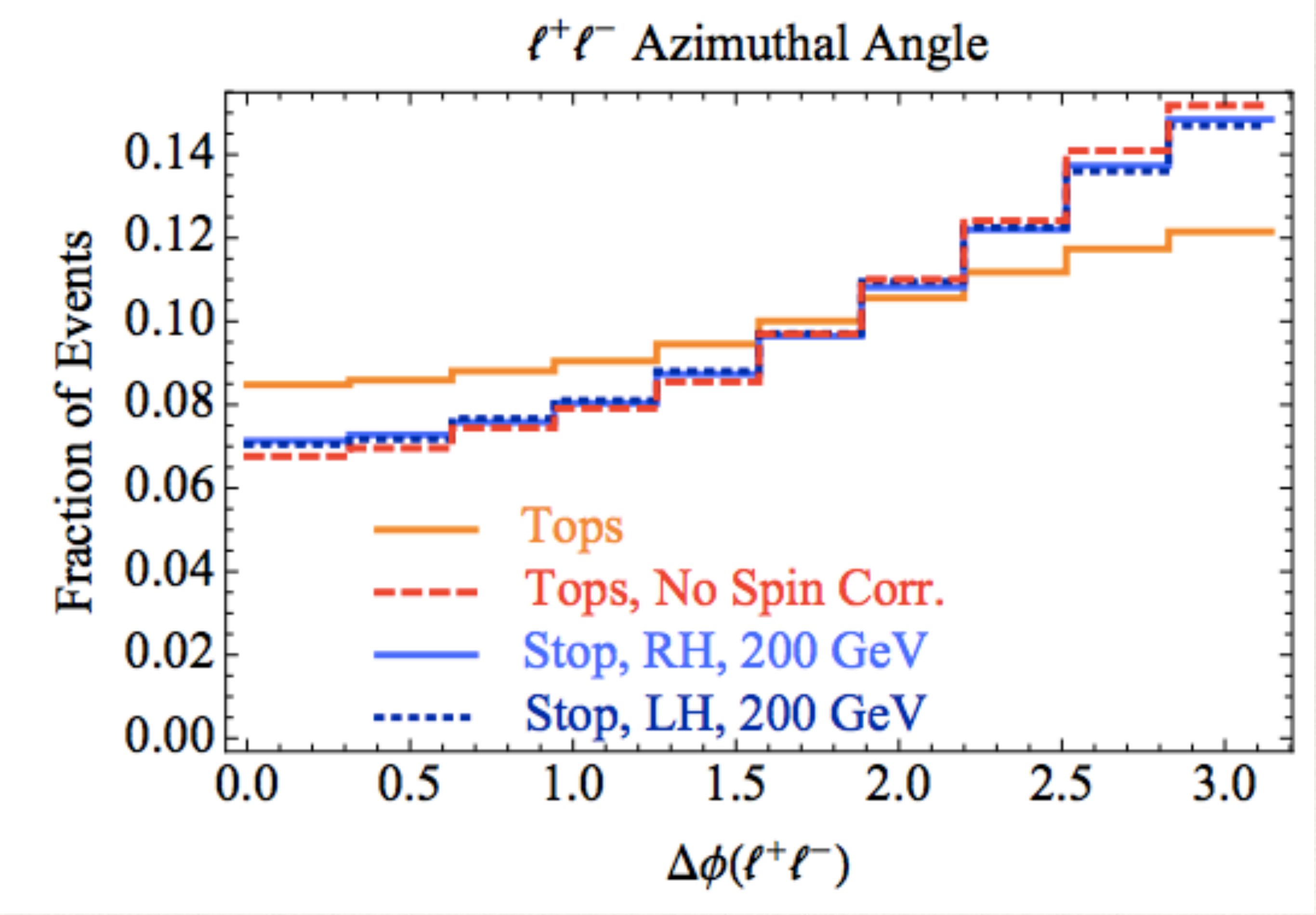


[ATLAS-CONF-2014-012, CMS-PAS-TOP-14-006]

Spin correlations

- Correlations between top and anti-top quark spins provide interesting test of SM. → ***Deliot***
    - one analyzer is the angle between the two leptons in dileptonic decays.
- Also, sensitive to BSM effects, e.g. can be used to search for nearly-degenerate stop quarks.

[Z. Han et al, 2012]

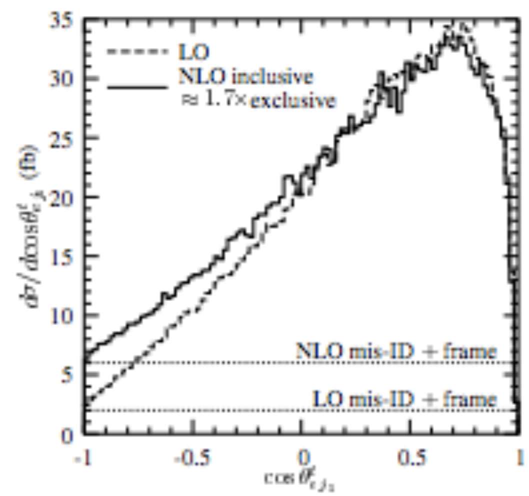


Angular correlations in single top

- A role in discovery and continuing searches for new physics.

Angle between e and lead jet

Mahlon, Parke ph/9611367;
ZS ph/0510224



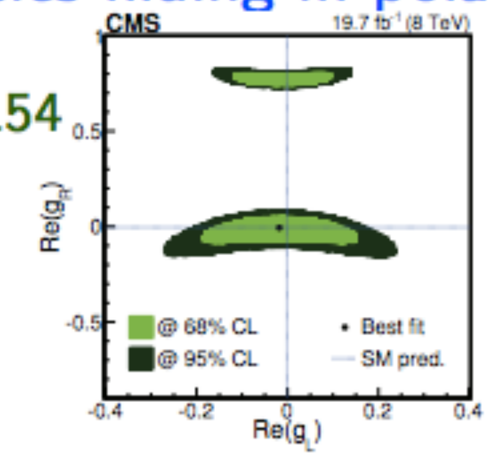
These angular correlations were critical to discovery

What if couplings were not pure $V - A$?

→ *Sullivan*

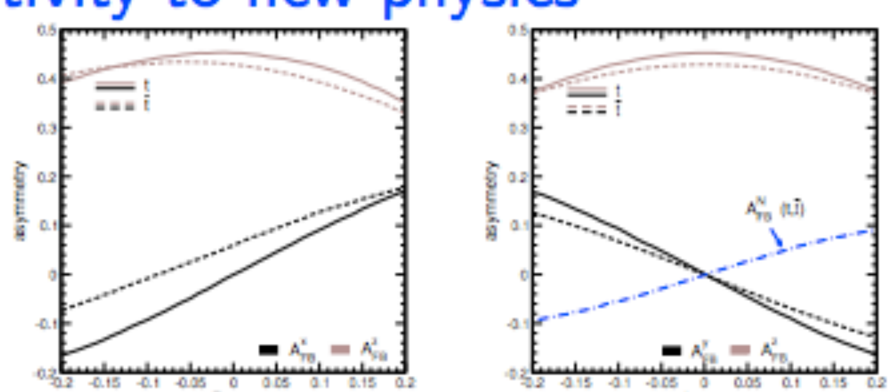
Is new physics hiding in polarization?

CMS 1410.1154



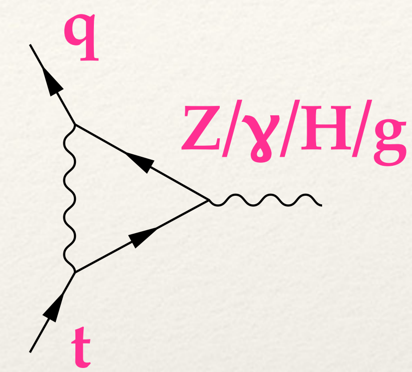
Boudreau, Escobar, Mueller, Sapp, Su 1304.5639
Aguilar-Saavedra, Amor dos Santos 1404.1585

Alternate spin axes may enhance sensitivity to new physics



Rare FCNC decays

- … are really rare in the SM due to GIM mechanism.
- On the bright side, would be beacons of BSM effects.



Process	SM BR	BSM BR (range)	current limit	3ab
t	10	10	10	10
t	10	10	10	10
t	10	10	10	10
t	10	10	10	10
t	10	10	10	10
t	10	10	10	10
t	10	10	10	10
t	10	10	10	10

[Snowmass report, arXiv: 1311.2028]

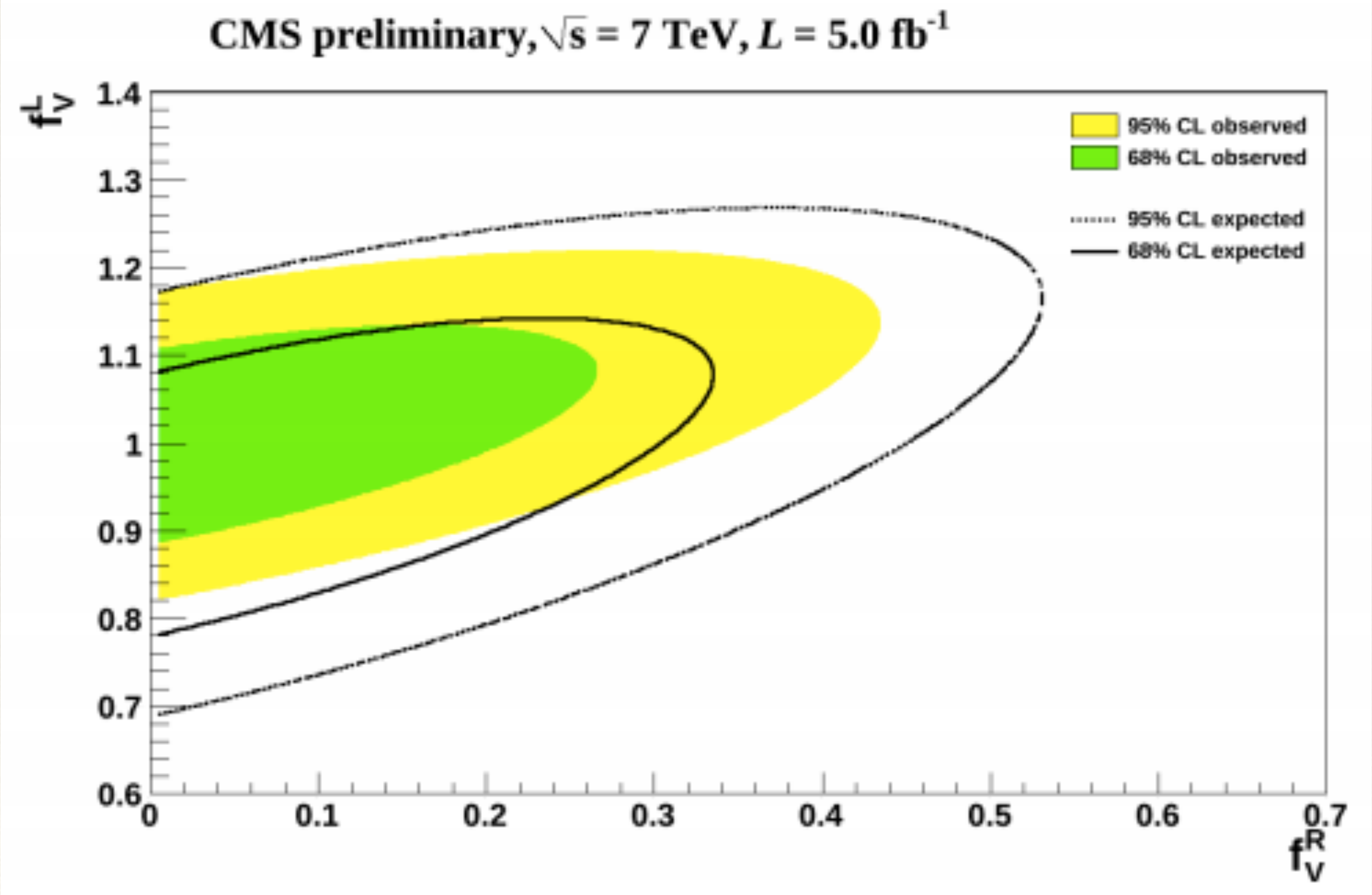
* 2HDM (FV/FC), MSSM (+RPV), RS

→ *Popov*

Single top measurements

- Directly sensitive to nature of weak coupling to W.

$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) tW_{\mu}^{-}$$



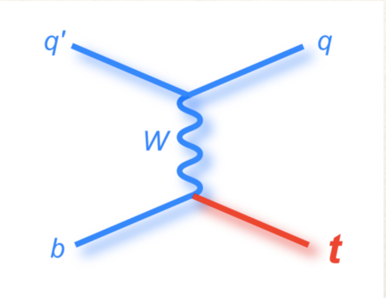
[CMS-PAS-TOP-14-007]

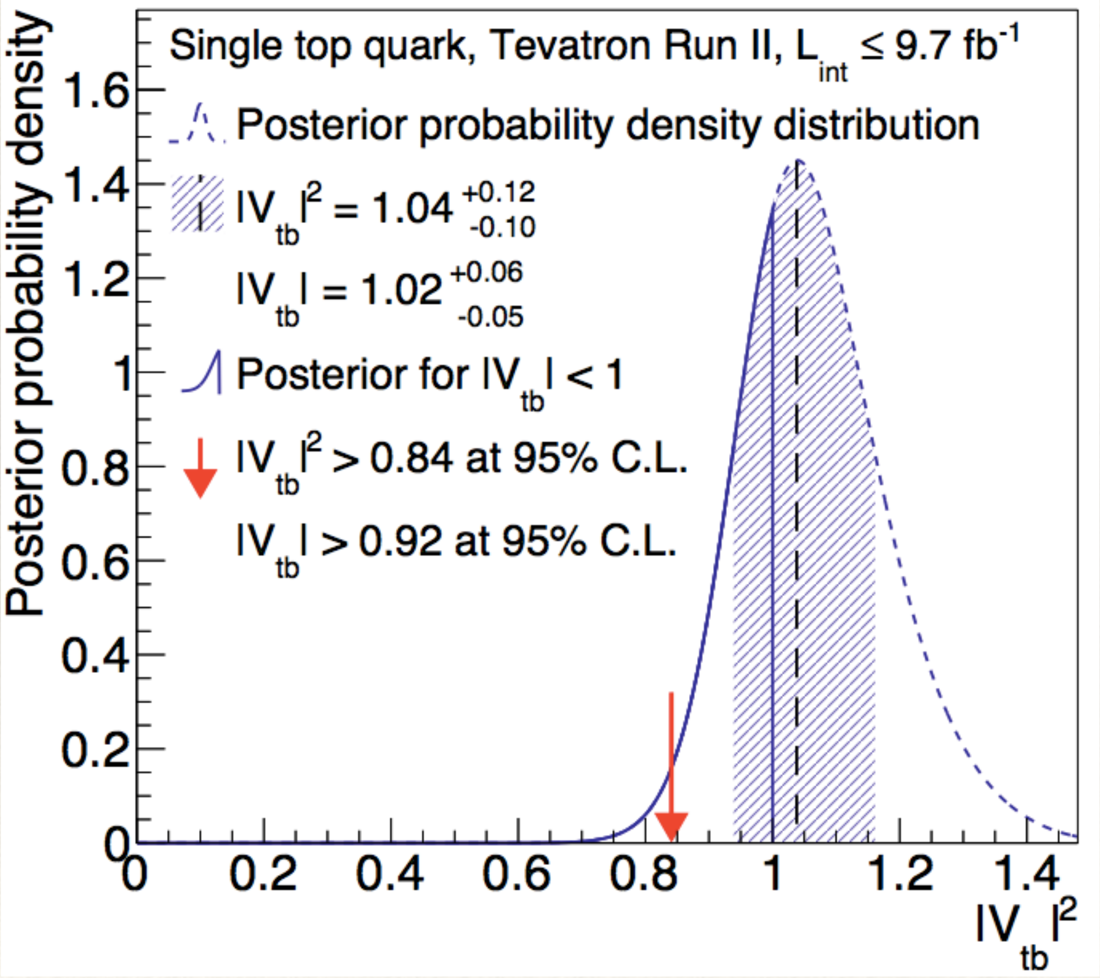
→ *Galloni, Howarth*

3ab^{-1}: probe
$f_V^R \sim 0.01$

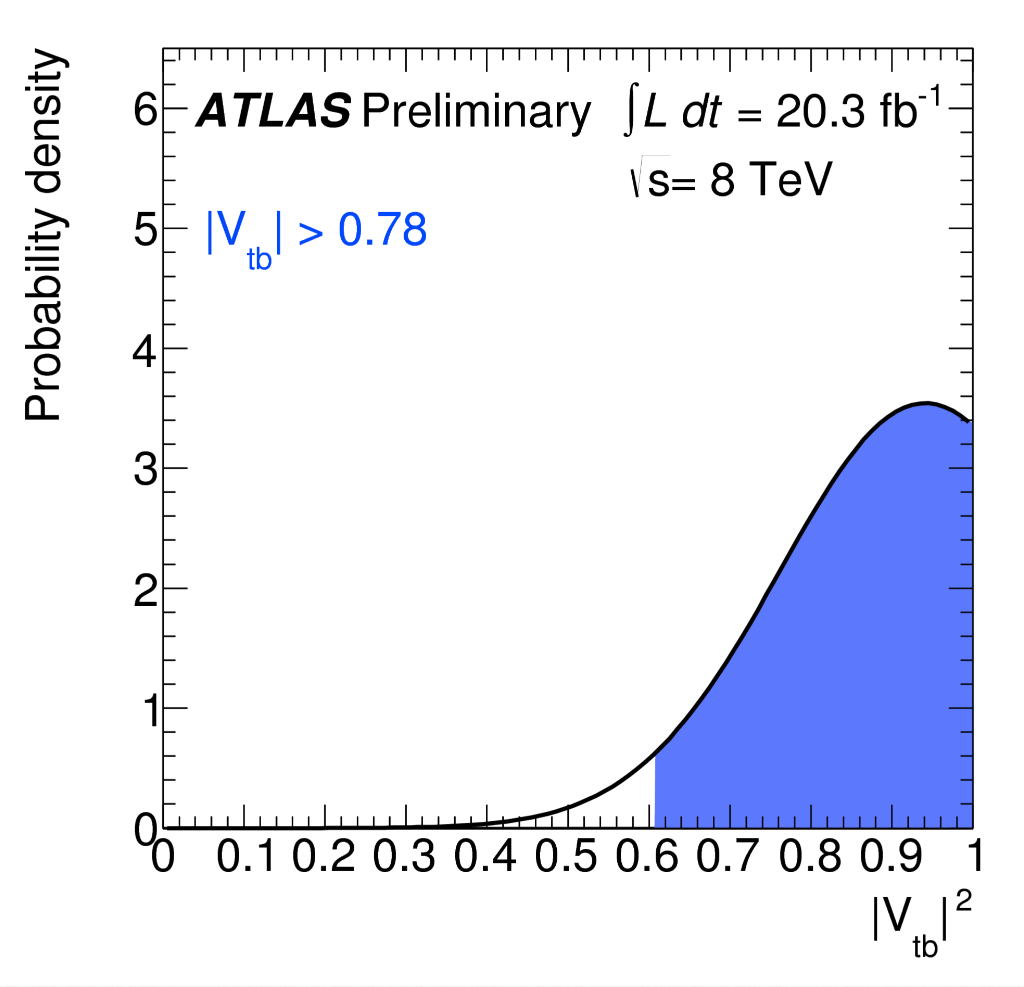
Single top measurements

- Production cross section proportional to $|V_{tb}|^2$, can constrain without appealing to unitarity.
  → ***Komm***





[Tevatron combination, 1503.05027]



[ATLAS-CONF-2014-007]

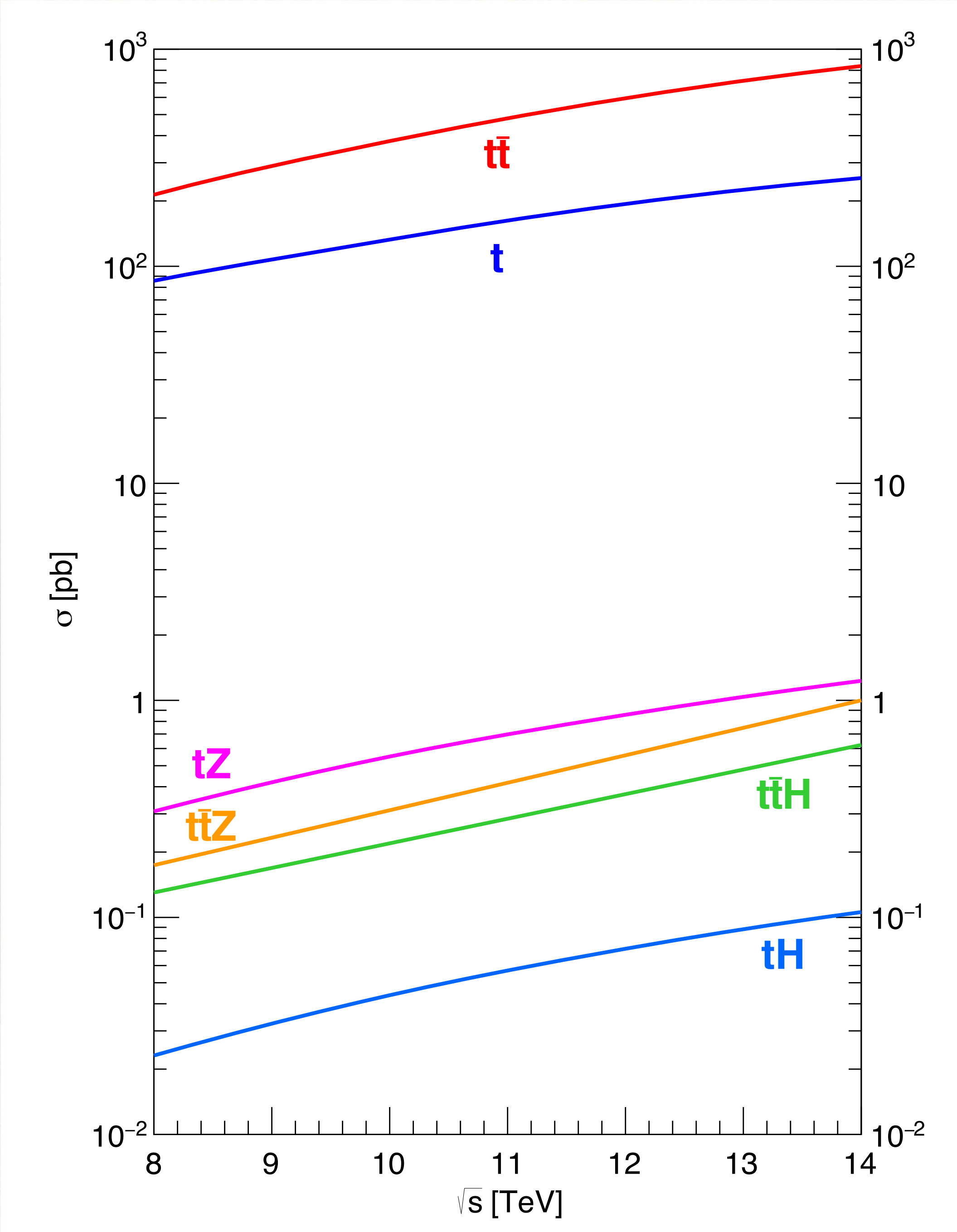
LHC 3ab^{-1}: V_{tb} precision ~ 2%

Rarer production modes

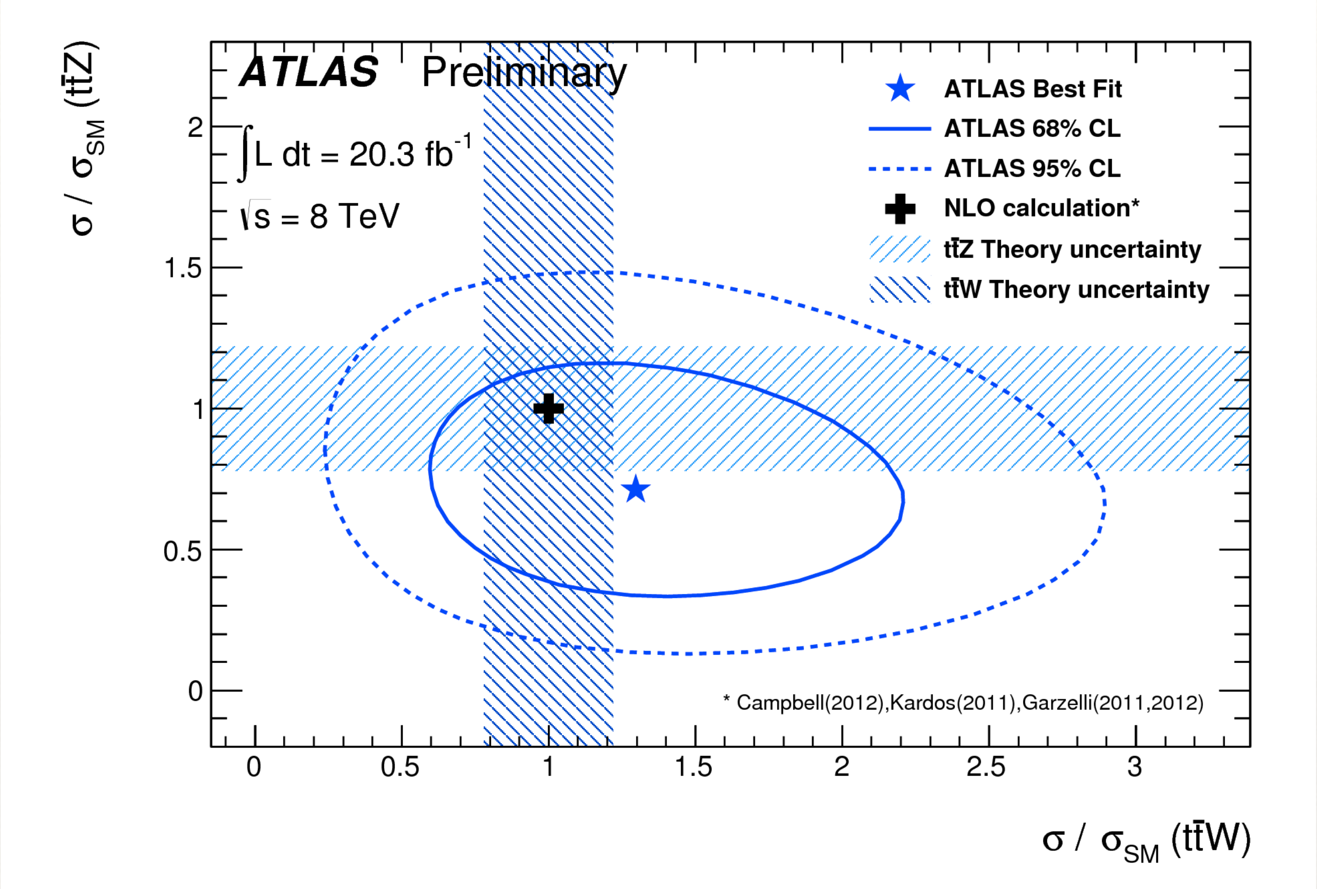
Top quarks+vector bosons

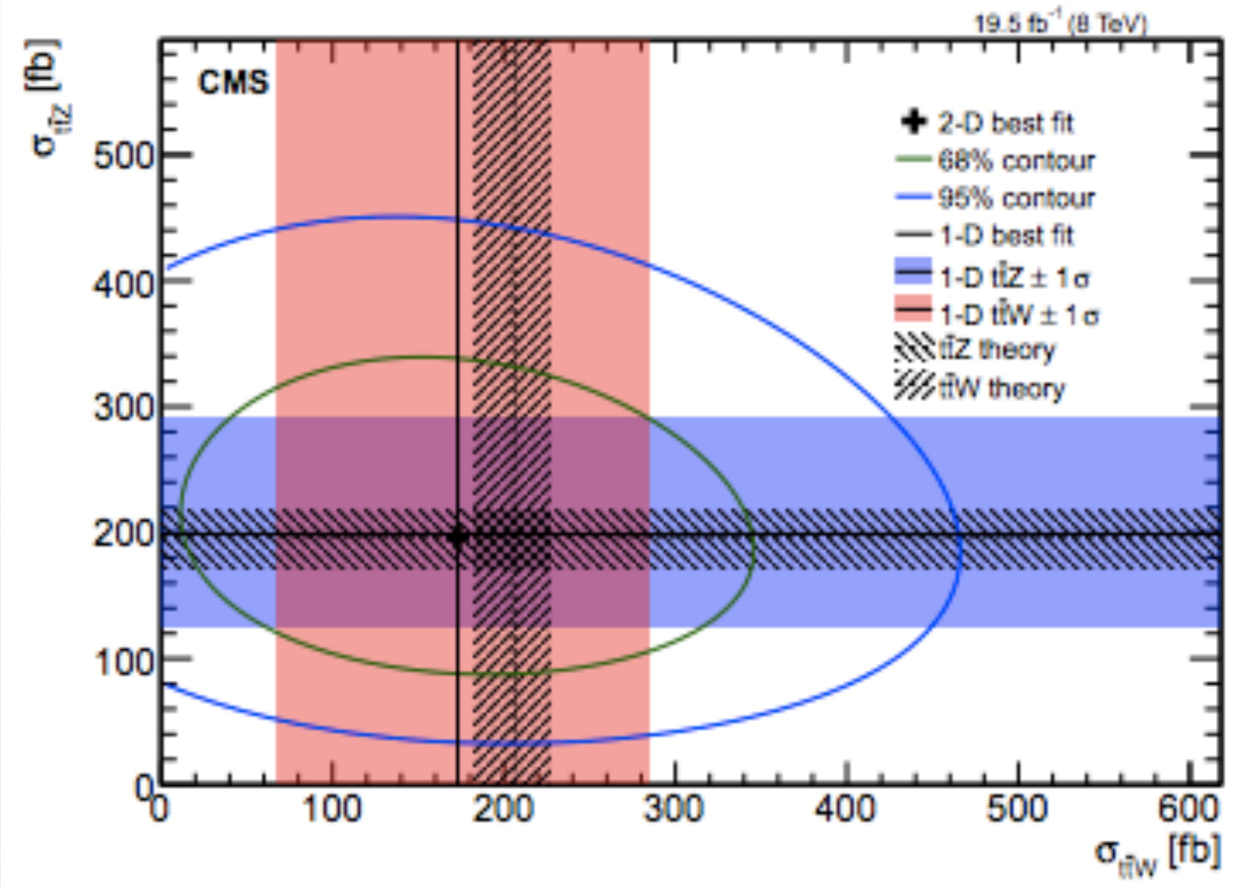
→ *Brinkerhoff*

- Associated production of top with vector bosons one of the next big challenges.
- Top + Z the biggest target; can directly probe (t,Z) coupling.
- Top + Higgs obviously high interest, slightly smaller x-sec.
- Top + W: does not yield as much information on top since W couples to light quarks, but important multilepton background, e.g. SUSY.



ttW, ttZ just within reach





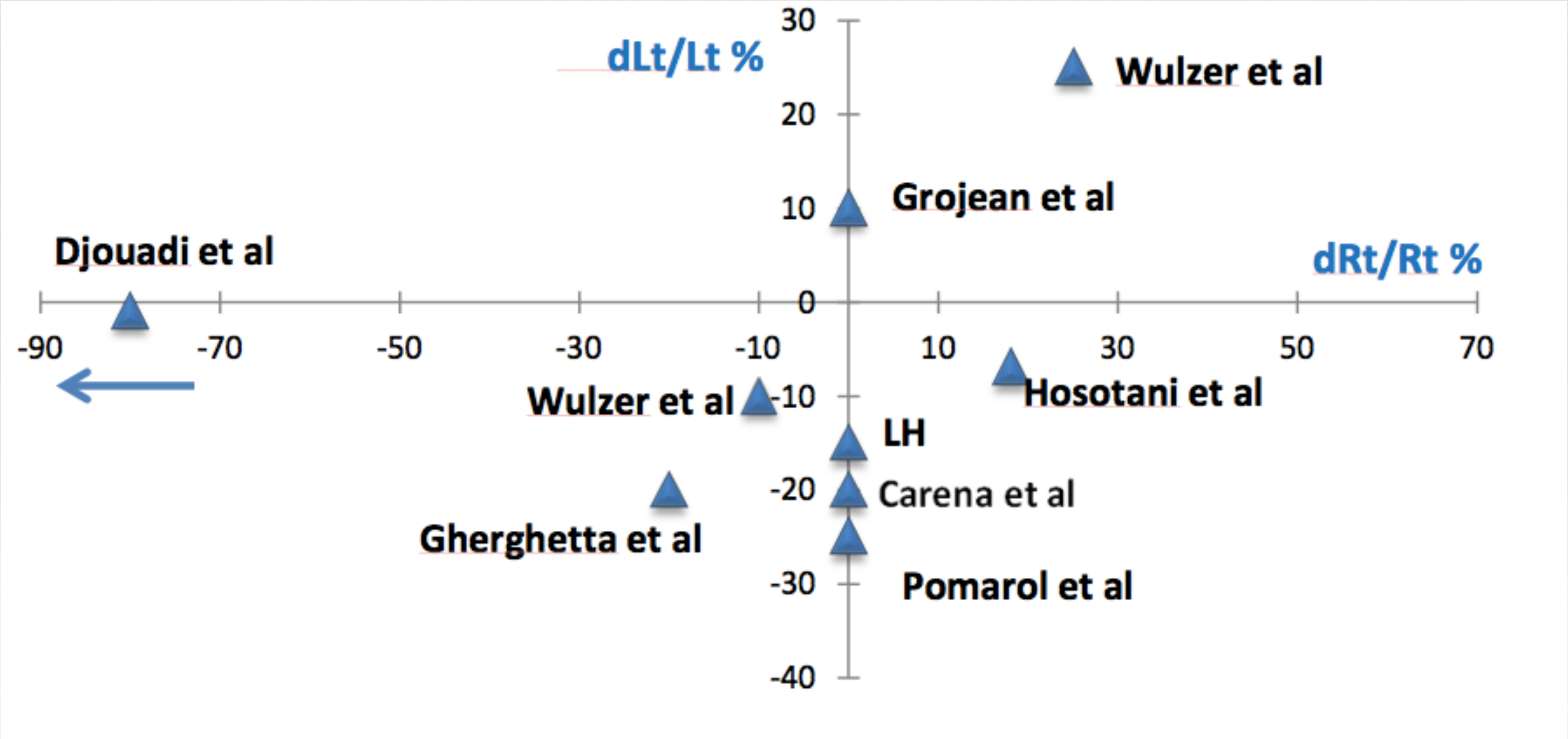
[prelim, ATLAS-CONF-2014-038] [CMS, arXiv:1406.7830]

- Same-sign dilepton, multi-lepton channels → BSM backgrounds.

Anomalous top-Z couplings

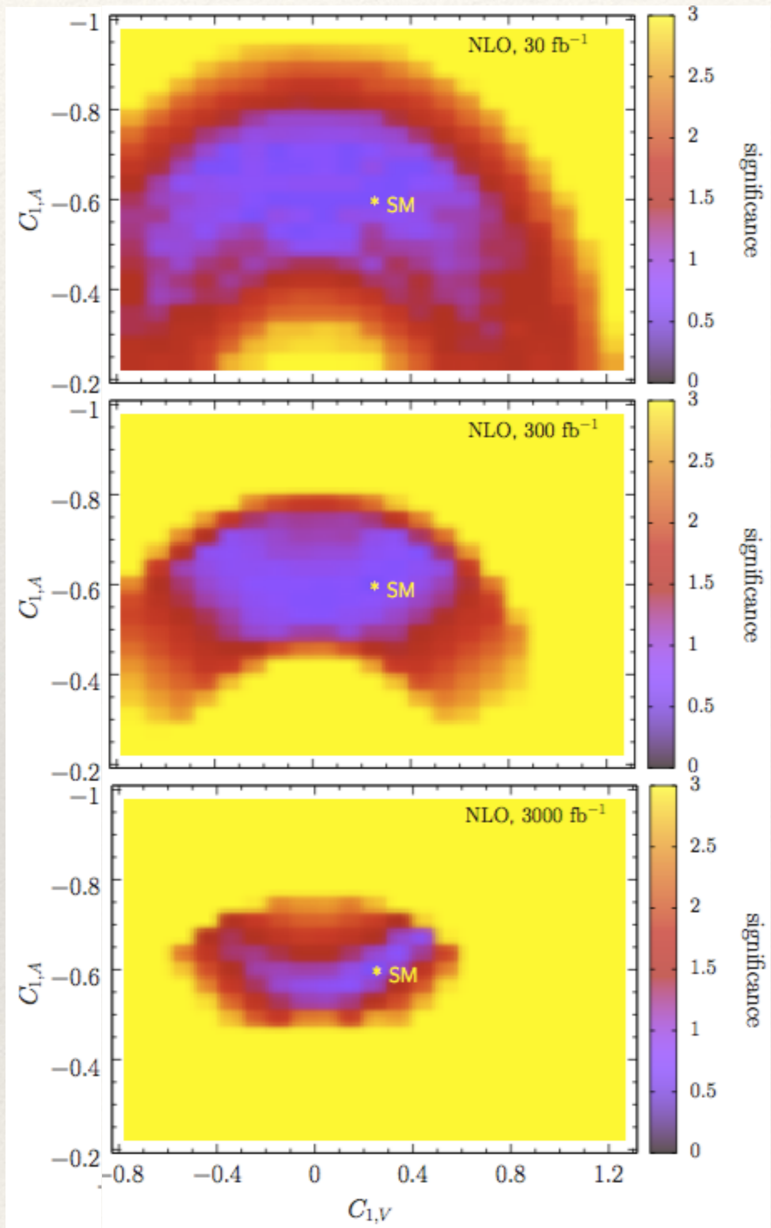
- The left- and right-handed top quark couplings to Z bosons can vary widely in, e.g. composite theories, Little Higgs models, …

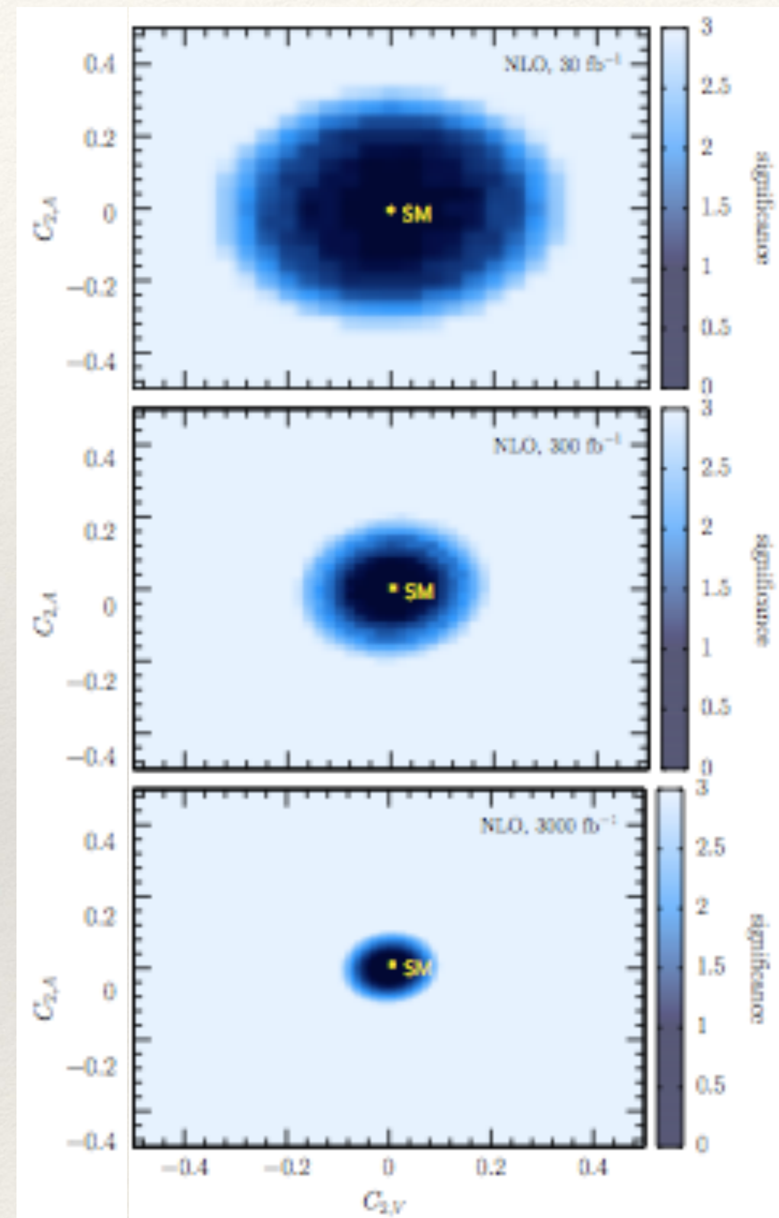
[Richard, 2014]



Direct LHC constraints

[Rontsch, Schulze, 2015]





Run 2

Run 3

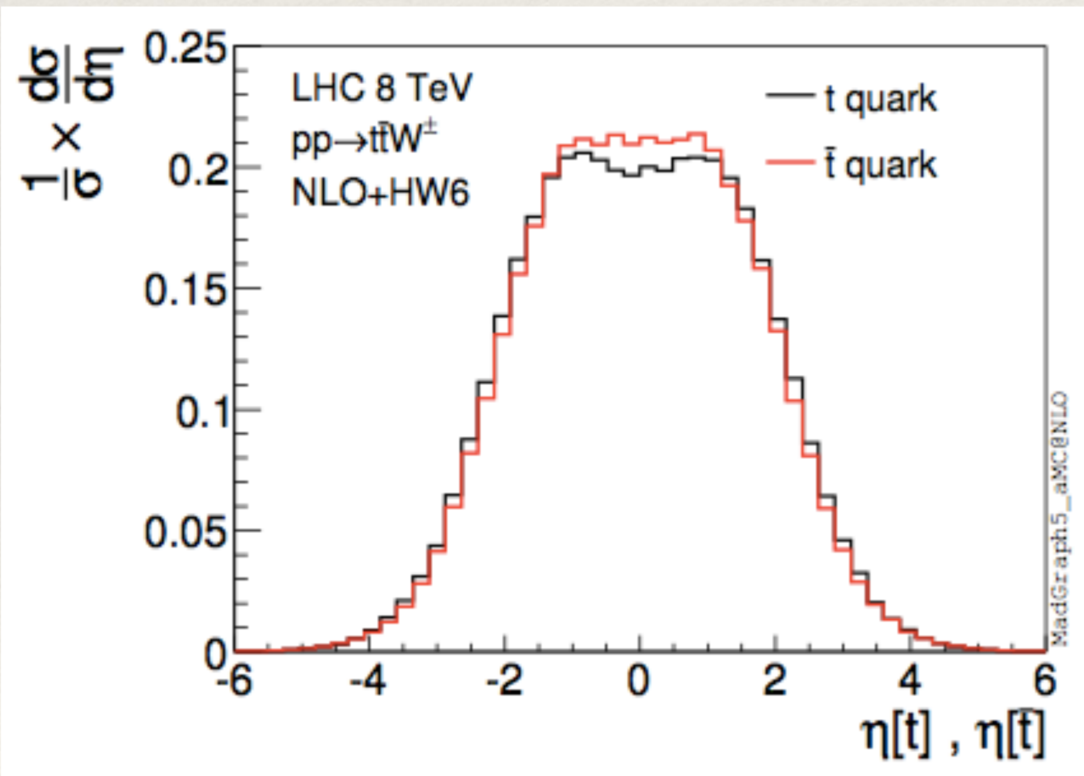
HL-LHC

$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V} + \gamma_5 C^Z_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C^Z_{2,V} + i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

weak dipole moments, tiny in SM

Top asymmetry in ttW

- Much smaller rate than top pairs, but occurs at LO through quark-antiquark reaction only; emission of W ensures production of polarized top quarks → much bigger effect.

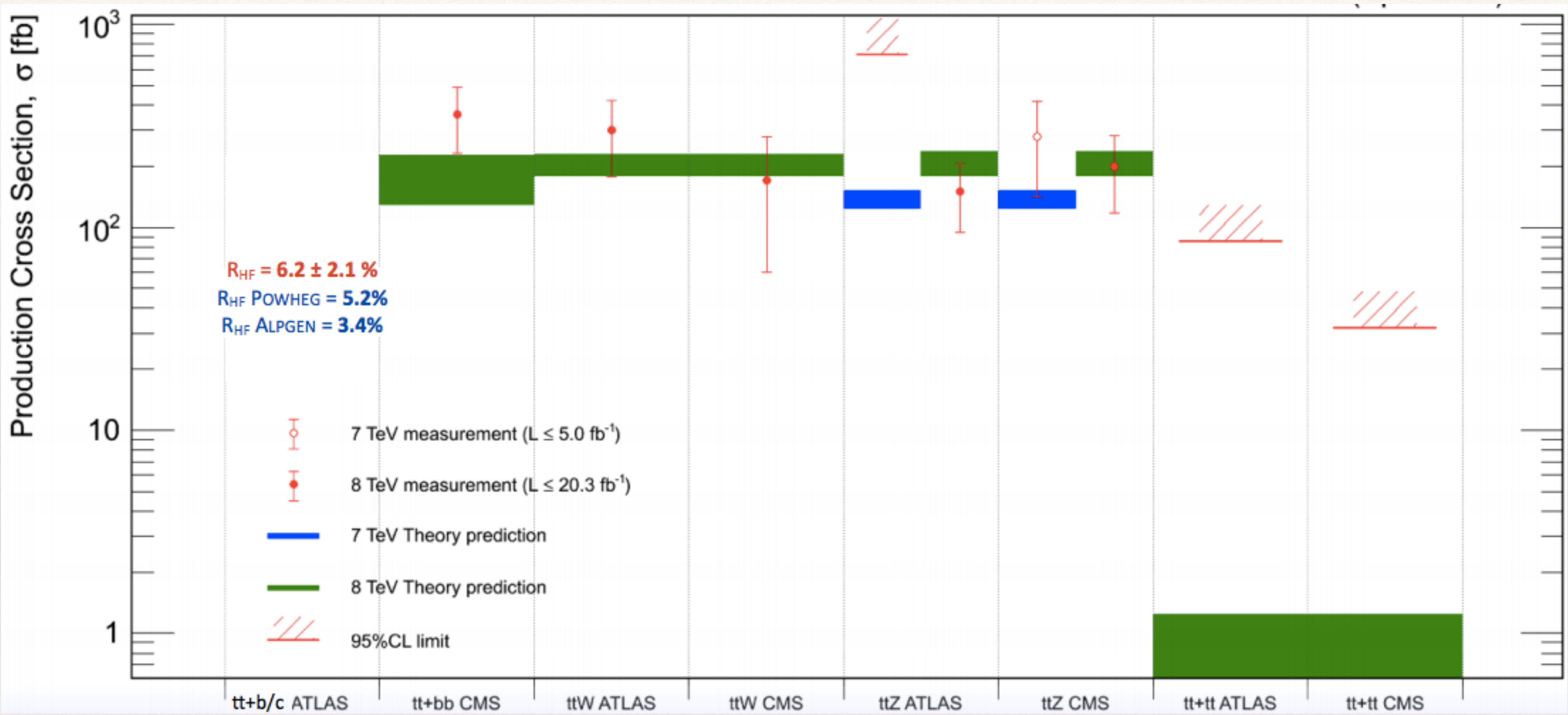


[Maltoni et al, 2014]

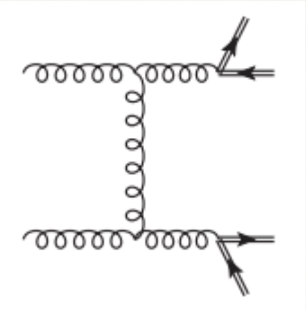
		8 TeV	13 TeV	14 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$
	$A_c^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$
	$A_c^\ell(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$

Complementary to top pair asymmetry in Run 2 and beyond

Current status



→ *Brinkerhoff*



four top quarks!

tt + photon

Results: ATLAS

$$\sigma^{\text{fid}}_{t\bar{t}+\gamma} \times \text{BR} = 63 \pm 8\ (stat.)^{+17}_{-13}\ (syst.) \pm 1\ (lumi.)\ \text{fb}$$

$$\sigma^{\text{fid theory}}_{t\bar{t}+\gamma} \times \text{BR} = 48 \pm 10\ \text{fb}$$

5.3 σ significance from the zero hypothesis

Dominated by jet modelling uncertainties (17%)

Results: CMS

$$\mathcal{R} = (1.07 \pm 0.07\ (stat.) \pm 0.27\ (syst.)) \times 10^{-2}$$

$$\sigma_{t\bar{t}+\gamma} = 2.4 \pm 0.2\ (stat.) \pm 0.6\ (syst.)\ \text{pb}$$

$$\sigma^{\text{theory}}_{t\bar{t}+\gamma} = 1.8 \pm 0.5\ \text{pb}$$

Dominated by background modelling uncertainties (23%)

- $t\bar{t}\gamma$ measurements can constrain composite top-quark models as well as excited top-quark models ($t^* \rightarrow t\gamma$).

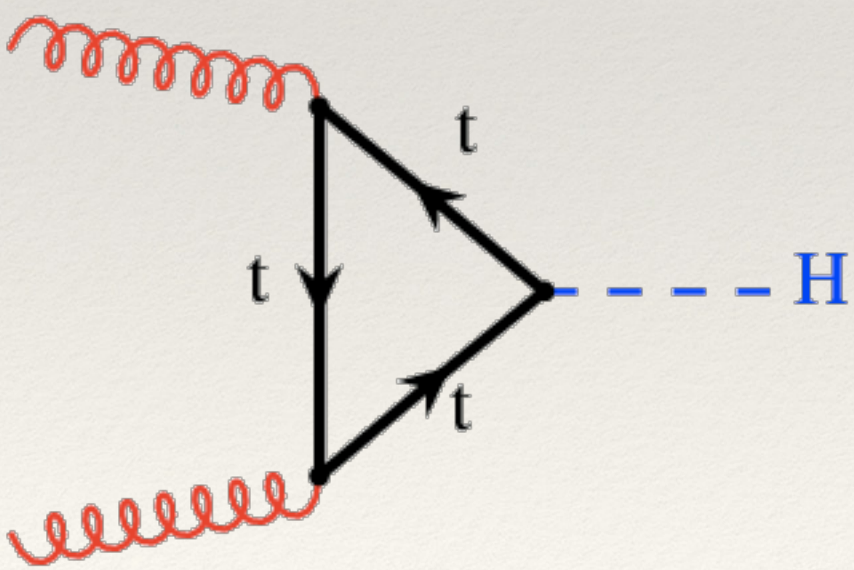
→ *Howarth*

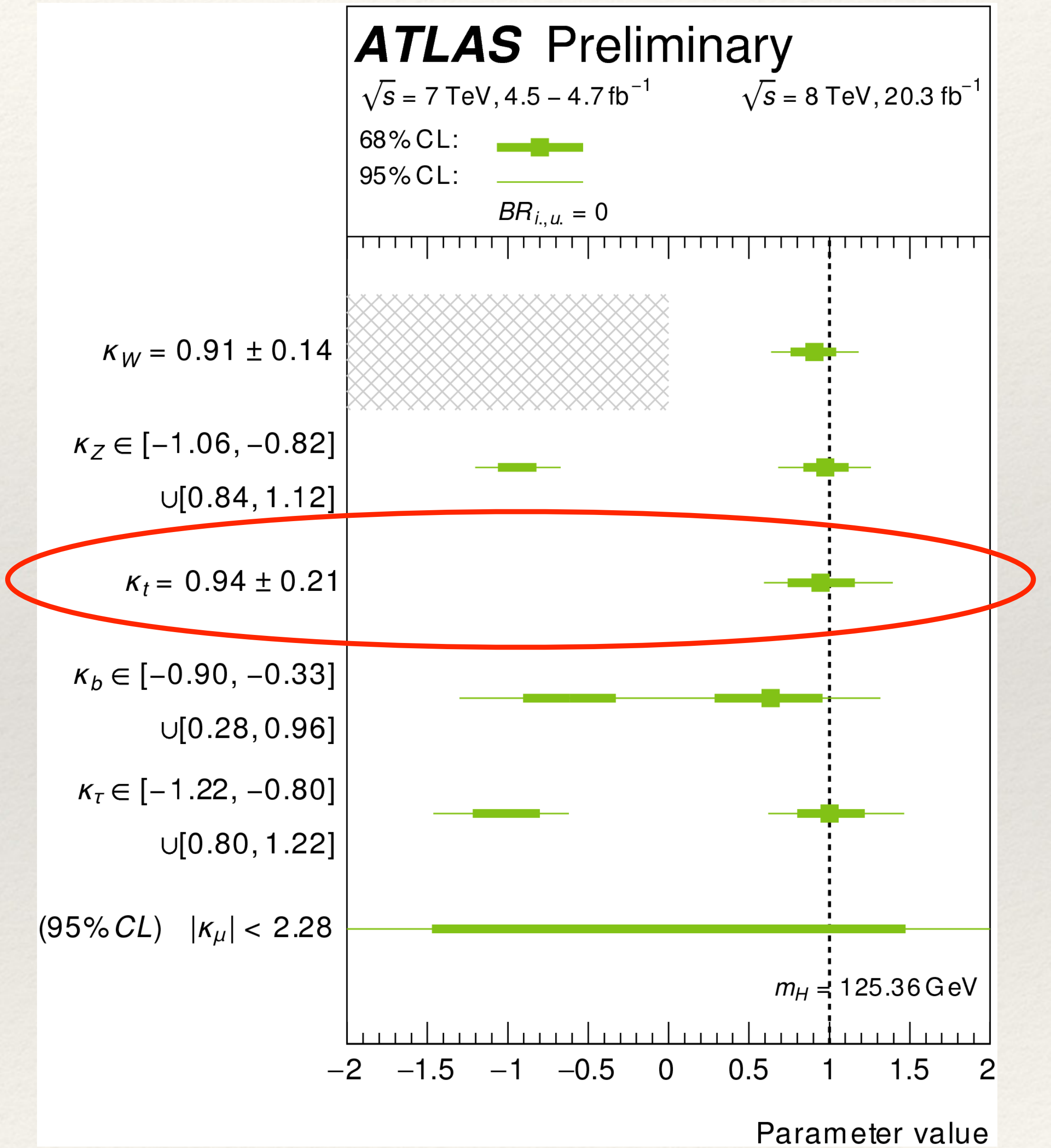
Top, Higgs and New Physics

Top quark Yukawa

- Studies of interactions between the top quark and Higgs boson needed to understand any "special relationship".
- Indirect information already available from the Higgs boson discovery.

[ATLAS-CONF-2015-007]

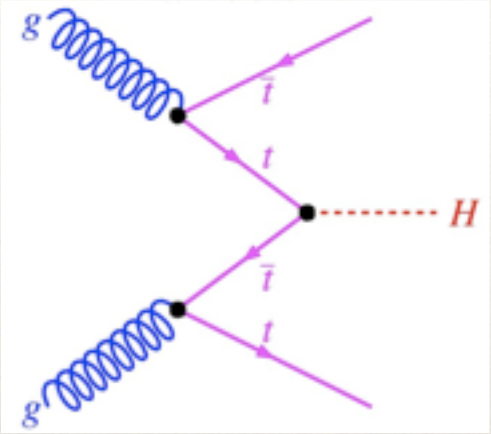




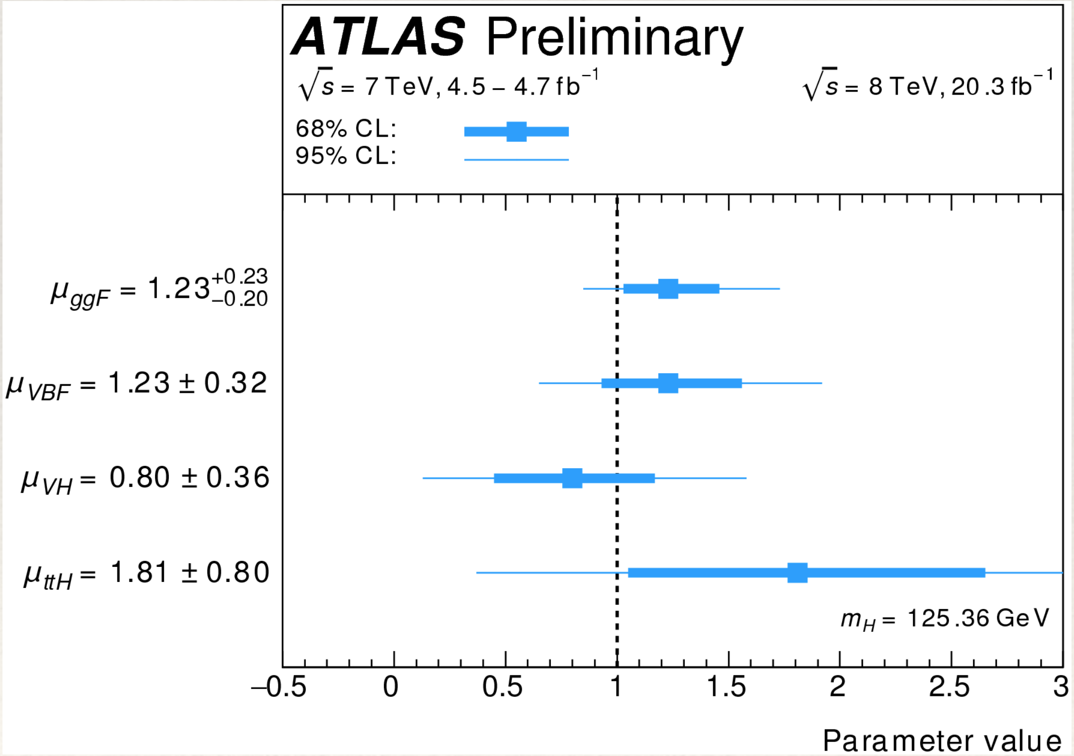
(assuming only SM particles in loops)

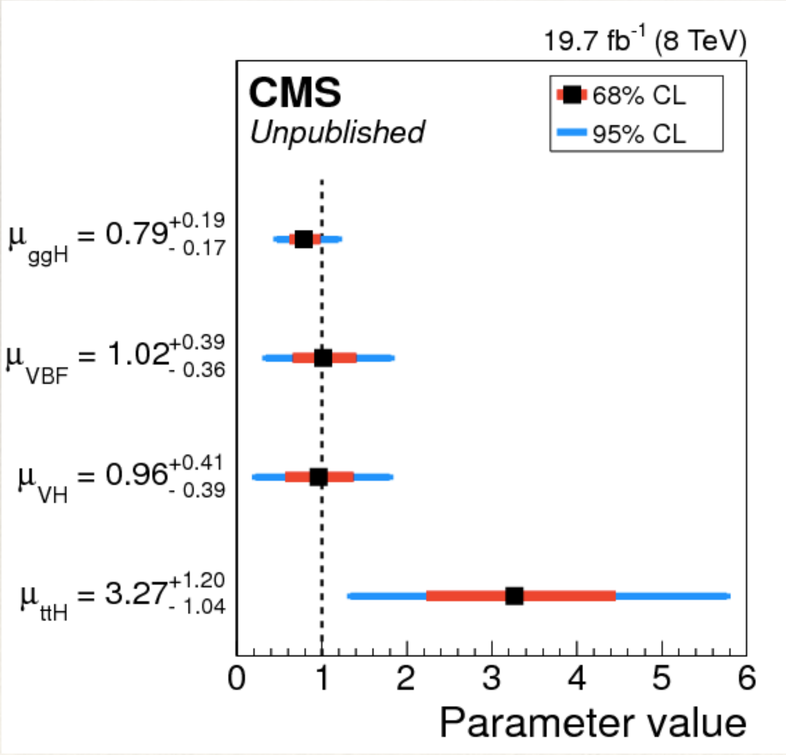
Tree-level coupling

- Gluon-fusion channel susceptible to contamination from BSM particles in loops → really want to observe tree-level coupling in ttH process.
- Difficult: H→bb (backgrounds), ɣɣ, multileptons (small).



[ATLAS-CONF-2015-007]





[CMS-HIG-14-009]

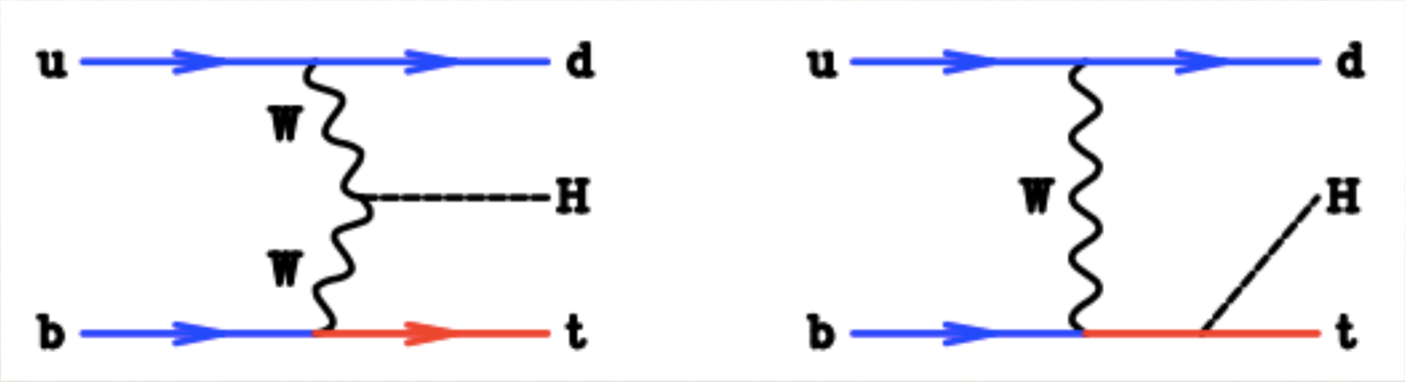
→ ***Popov***

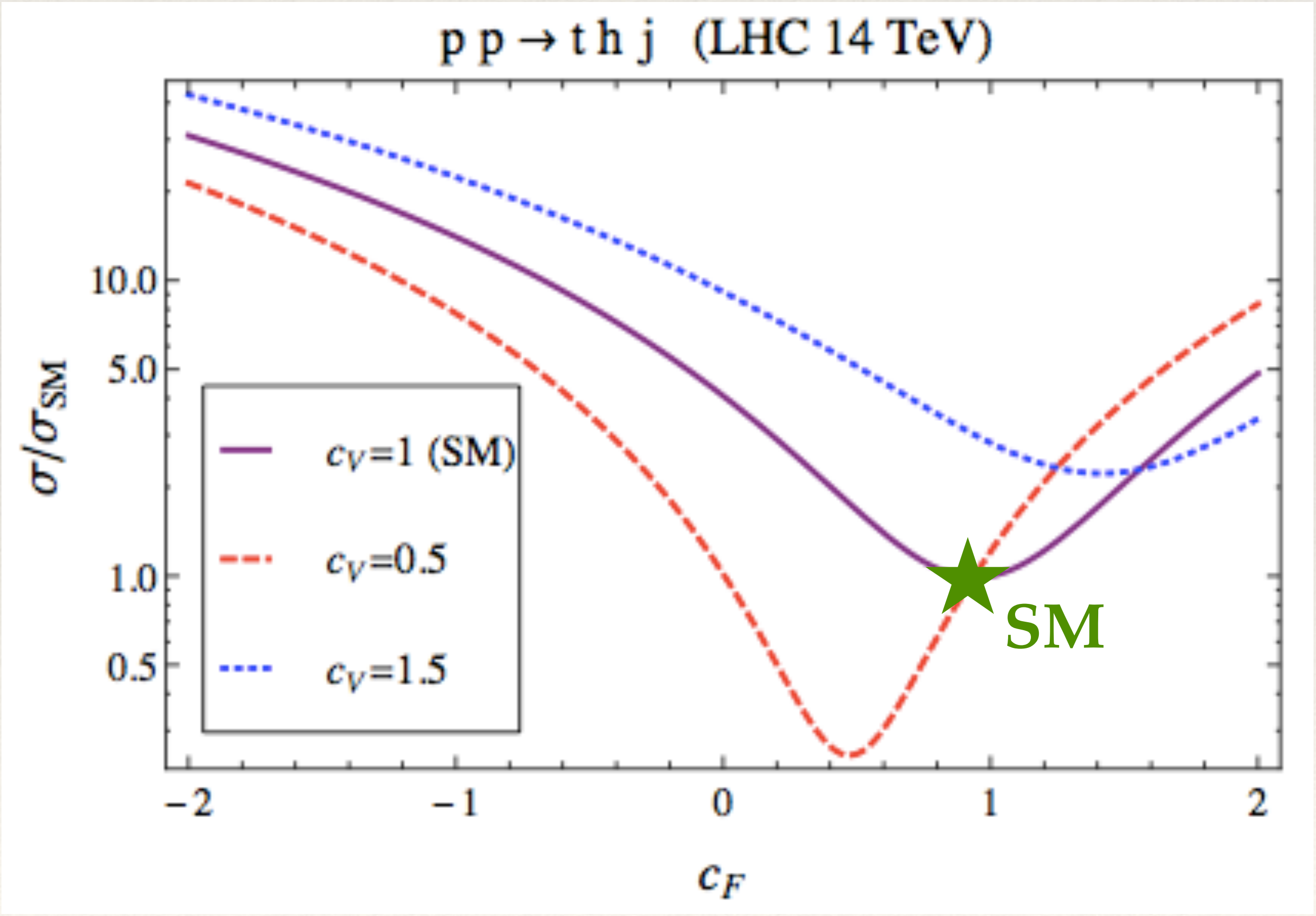
Current limit: $\sigma_{obs} < (3 - 4) \times \sigma_{SM}$

Single top + Higgs

- Cross-section is very small due to destructive interference between radiation from W and top.
- Opportunity for a sensitive probe of the top Yukawa, including:
  - the sign (due to interference).
  - possible CP-violating coupling.

[Demartin et al, 2015]



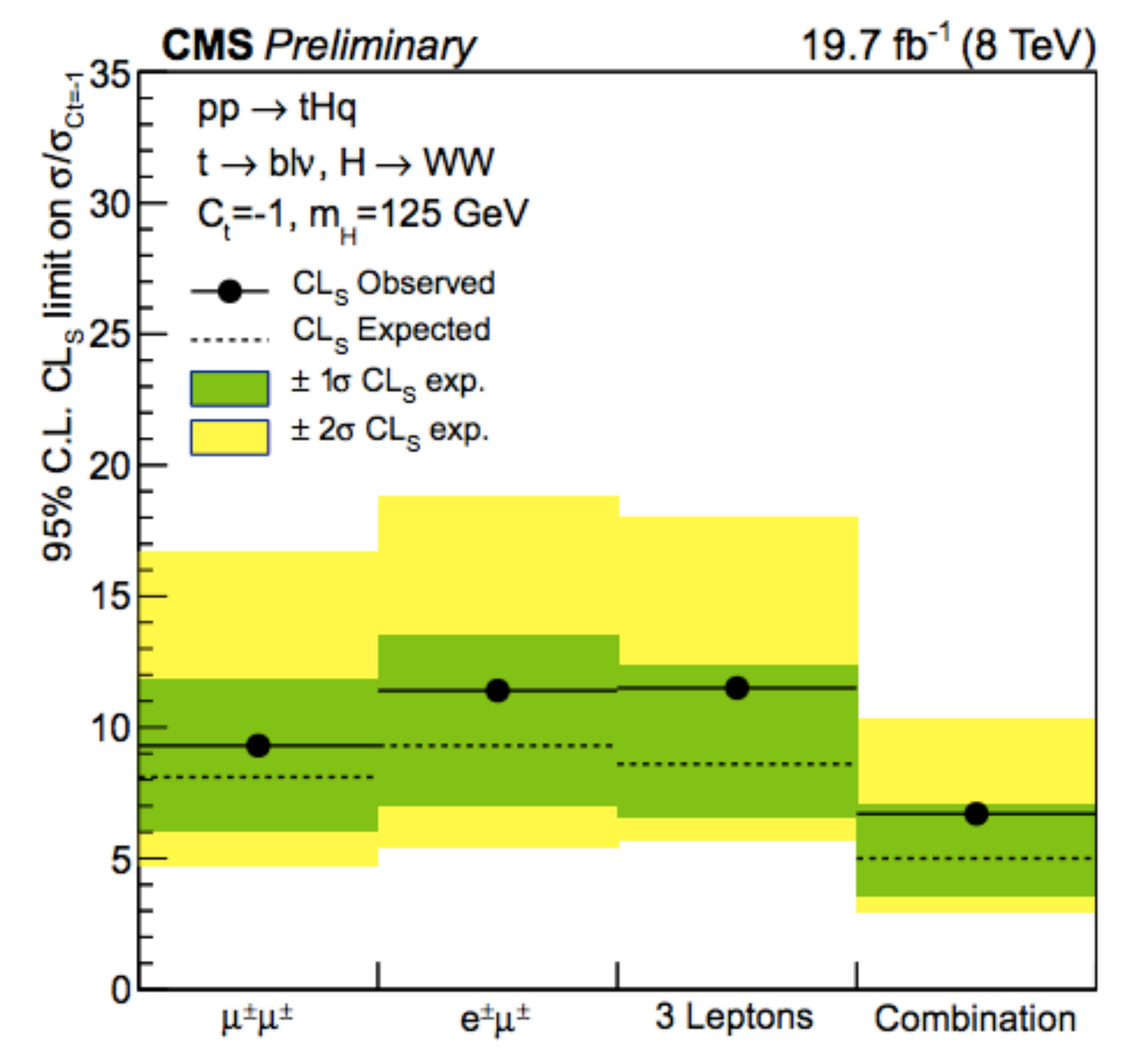


[Farina et al, 2012]

Out of reach for now …

- Can only place limit on cross-section in "opposite-sign SM":

$\sigma_{\text{obs}} < (5 - 10) \times \sigma_{\text{SM-neg. Yt}}$

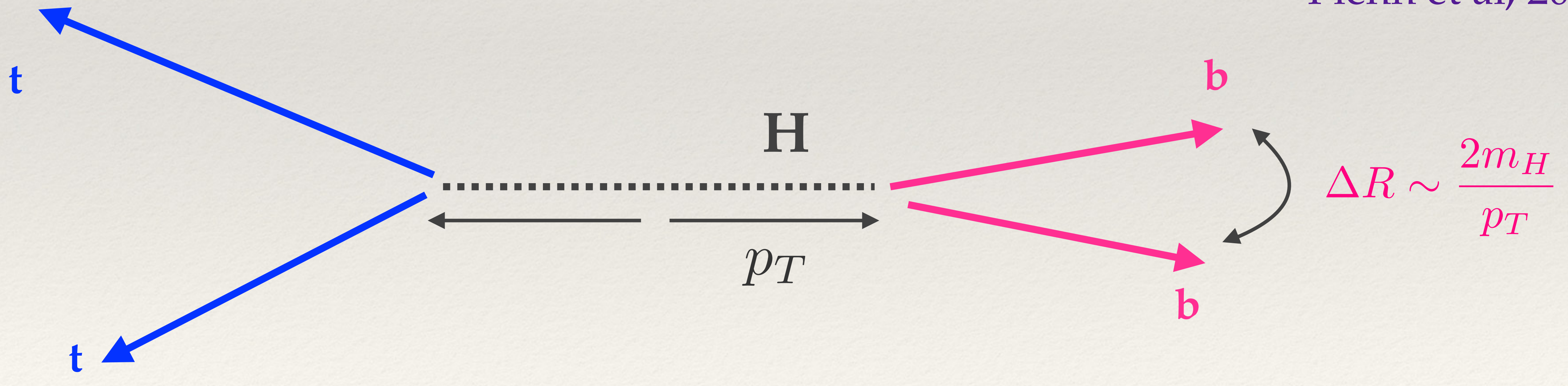


[CMS-PAS-HIG-14-026]

Boosted Higgs

- To maximize cross-section would like to use Higgs decay to bottom quarks, but must handle large BG.
- One idea is to utilize characteristic angular separation of bottom quarks when they are produced in a Higgs boson decay with large boost.

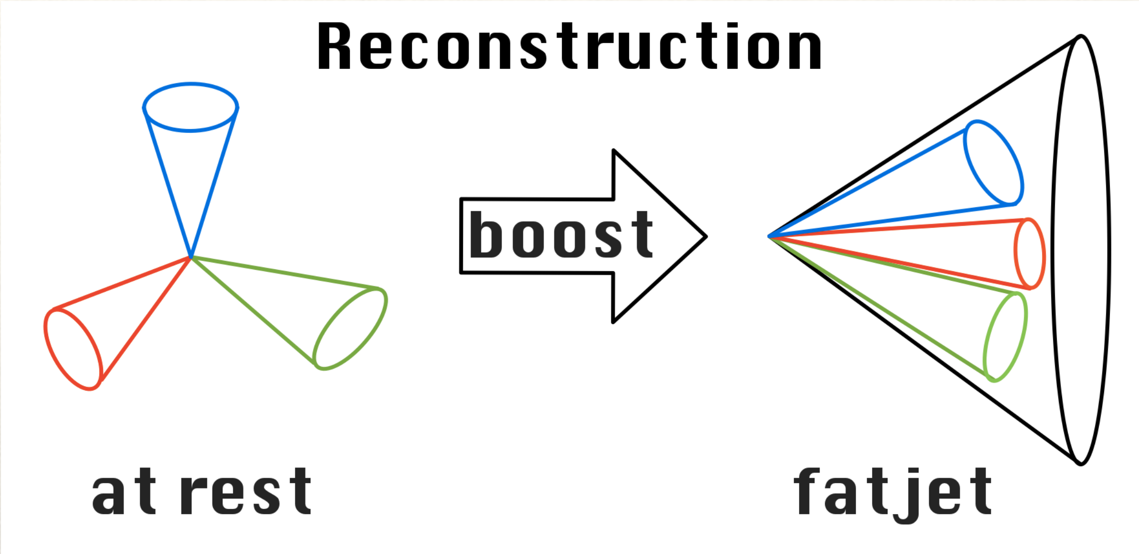
[Seymour 1994, Butterworth et al 2008, Plehn et al, 2009]



→ substructure a useful tool for tagging massive objects decaying to jets

Top taggers

- Same idea can be applied to hadronically decaying top quarks → "top tagger" successfully demonstrated in Run 1.



→ *Gerbaudo*

- Will be key to searches for boosted top quarks, e.g. in searches for new heavy particles decaying to tops.
- Will benefit greatly from higher energy and more statistics in Run 2+ (higher boosts available).
- Wealth of alternative top tagging techniques including multivariate taggers, template taggers, shower/event deconstruction.

09:00	**Top mass theory and connection with experiment**	*Stefan WEINZIERL*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	09:00 - 09:30
	Top mass at the Tevatron	*Andreas JUNG*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	09:30 - 10:00
10:00	**Top mass at the LHC**	*Meenakshi NARAIN*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	10:00 - 10:30
	Break		*Wilson Hall Atrium, Fermi National Accelerator Laboratory*	10:30 - 11:00
11:00	**Top properties (excluding mass) at the Tevatron**	*Camilla GALLONI*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	11:00 - 11:30
	Top properties (excluding mass) at the LHC	*James HOWARTH*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	11:30 - 12:00
12:00	**Top couplings at the Tevatron and LHC**	*Andrey POPOV*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	12:00 - 12:30
	Lunch		*Wilson Hall Atrium, Fermi National Accelerator Laboratory*	12:30 - 14:00
13:00				
14:00	**Models of testable new physics in the top sector**	*Roni HARNIK*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	14:00 - 14:30
	Searches for new physics in the top sector at the Tevatron	*Florencia CANELLI*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	14:30 - 15:00
15:00	**Searches for new physics in the top sector at the LHC**	*Davide GERBAUDO*	*Wilson Hall, One West, Fermi National Accelerator Laboratory*	15:00 - 15:30

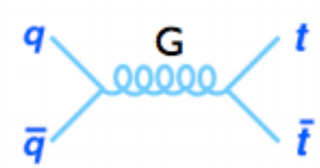
Measurements

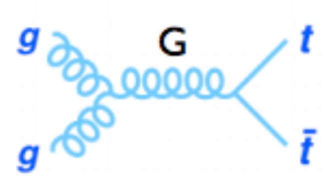
New Physics

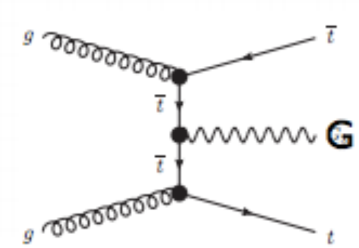
A few examples of BSM top

Top in Composite Higgs

- Fermionic top partners ($T \to tZ$, th, Wb,...)
- Both pair and single T production.
- rho-like resonances (KK gluons in RS-speak) that decay to tops.
    - t-tbar resonance.
    - Boosted tops (see e.g. Perez et al).
    - Multi-top final states (KC Kong et al).





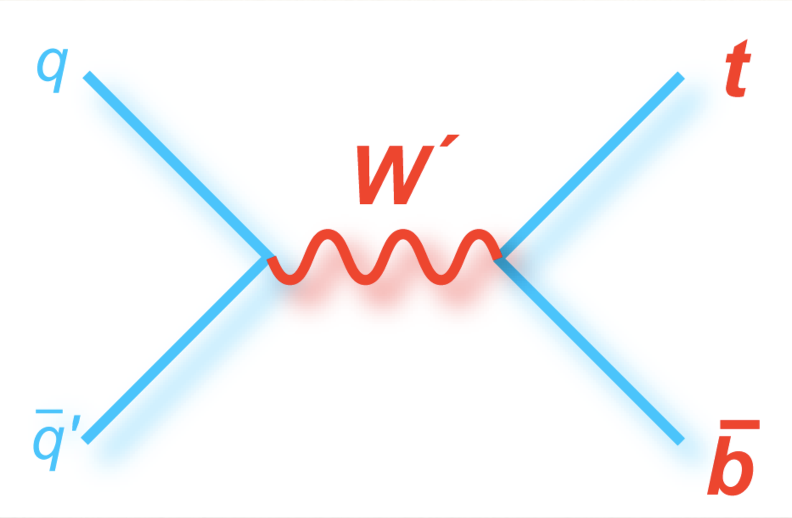


Composite Higgs
+ large top Yuk.
→ composite top,
top partners

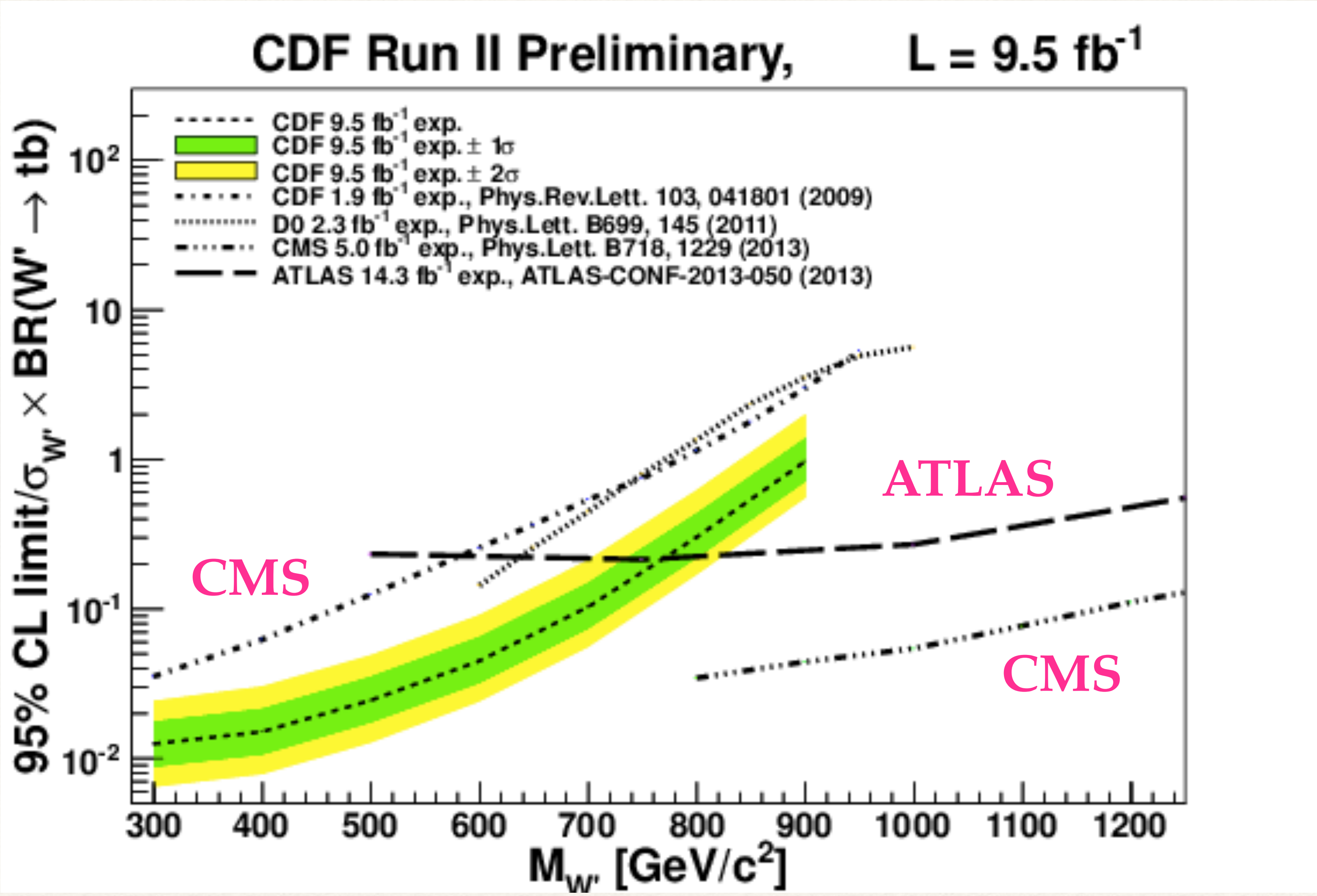
→ ***Harnik***

Still Tevatron results …

→ *Canelli*

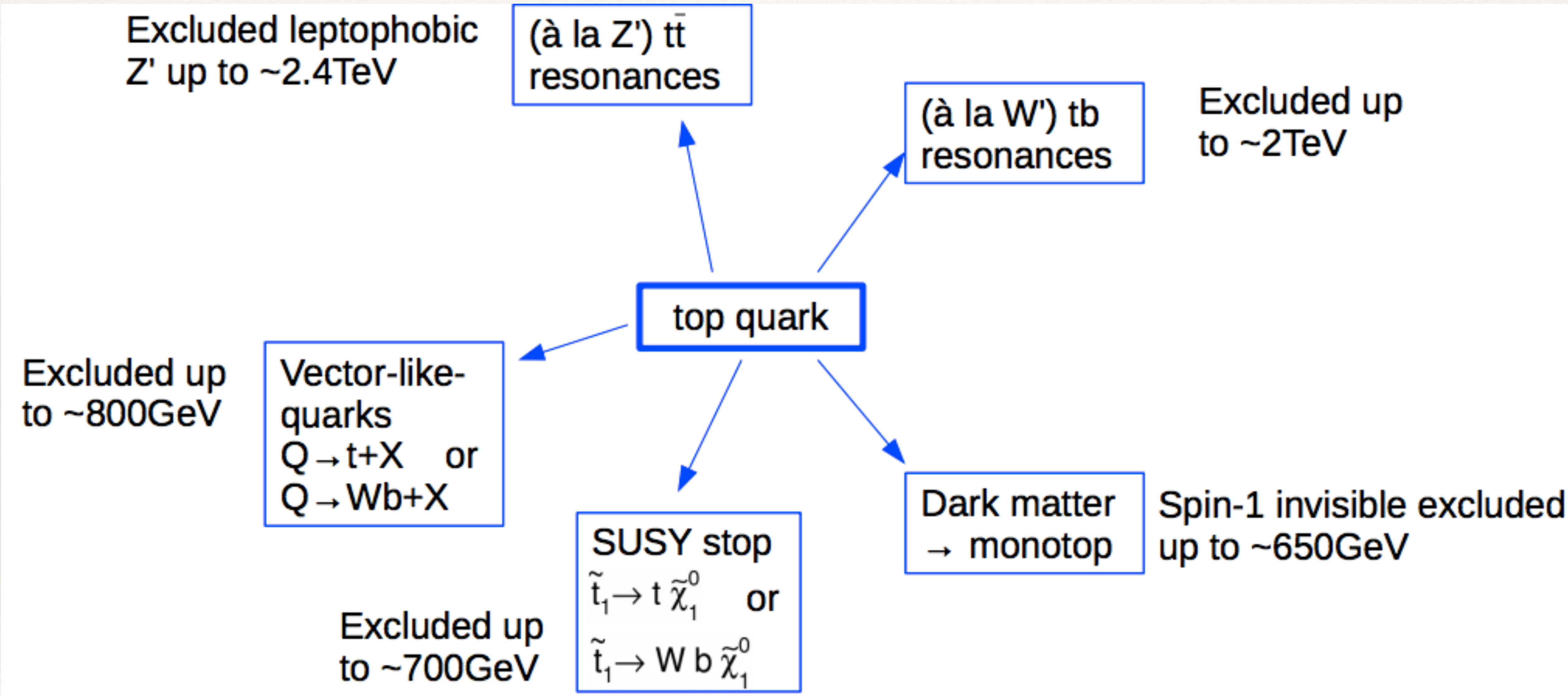


Proton-antiproton
means better S/B
at lower masses



[CDF/PHYS/EXOTIC/PUBLIC/11110]

… but much more now at LHC



→ *Gerbaudo*

Conclusion

- There is a lot of top quark physics!
- The 20 years since discovery have been incredibly productive: precision mass measurement, confirmation of production modes, couplings.

- Let's hope for a few surprises in the years ahead:
  - precision measurements of properties.
  - rare production modes (esp. with H,Z,W), rare decays.
  - production of top in new particle decays.