Top Precision and Searches for New Physics – Part II

Christian Schwanenberger

DESY

SFB 676 Lectures

Particles, Strings, and the Early Universe

9 December, 2016

HELMHOLTZ | ASSOCIATION

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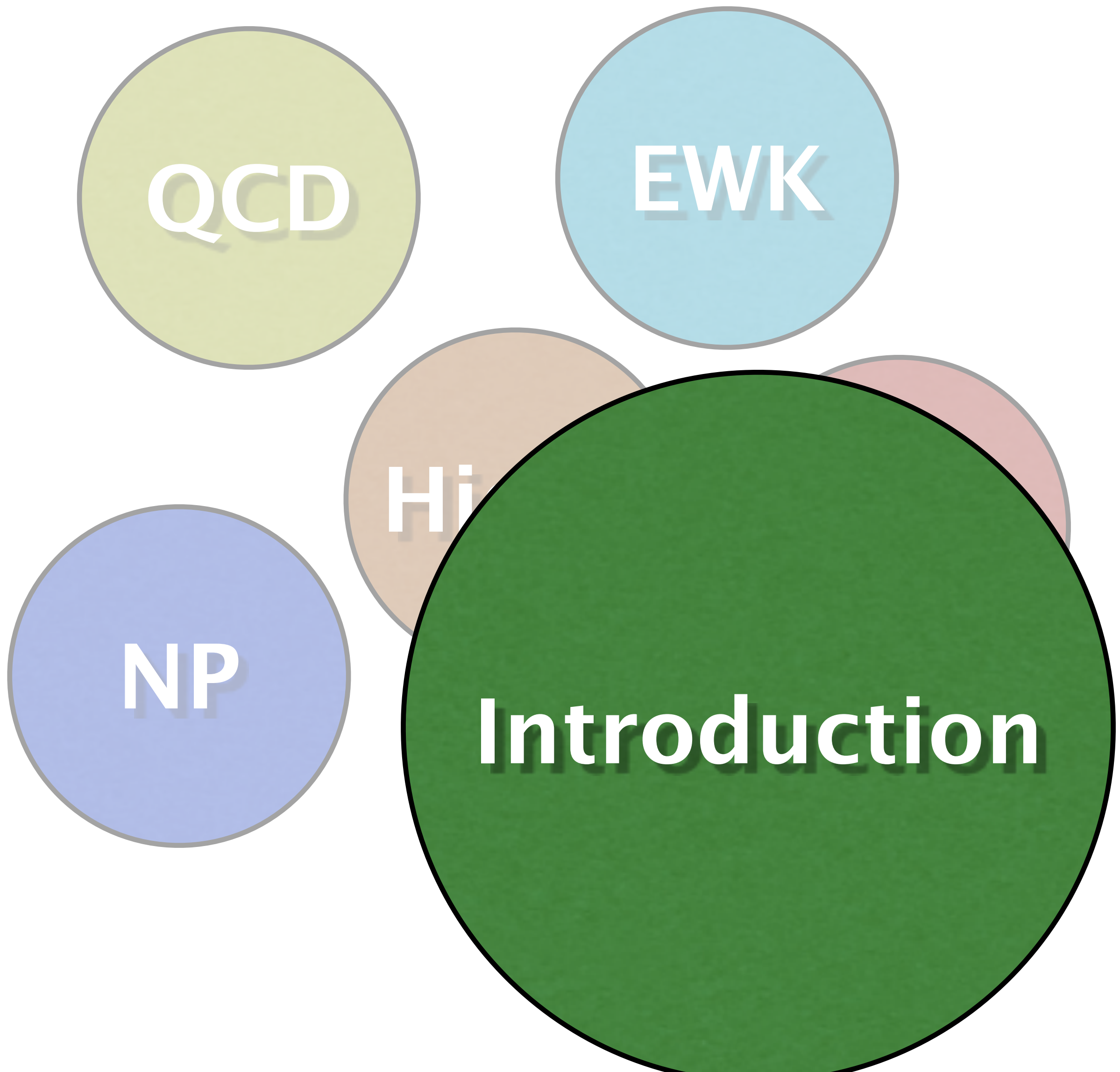
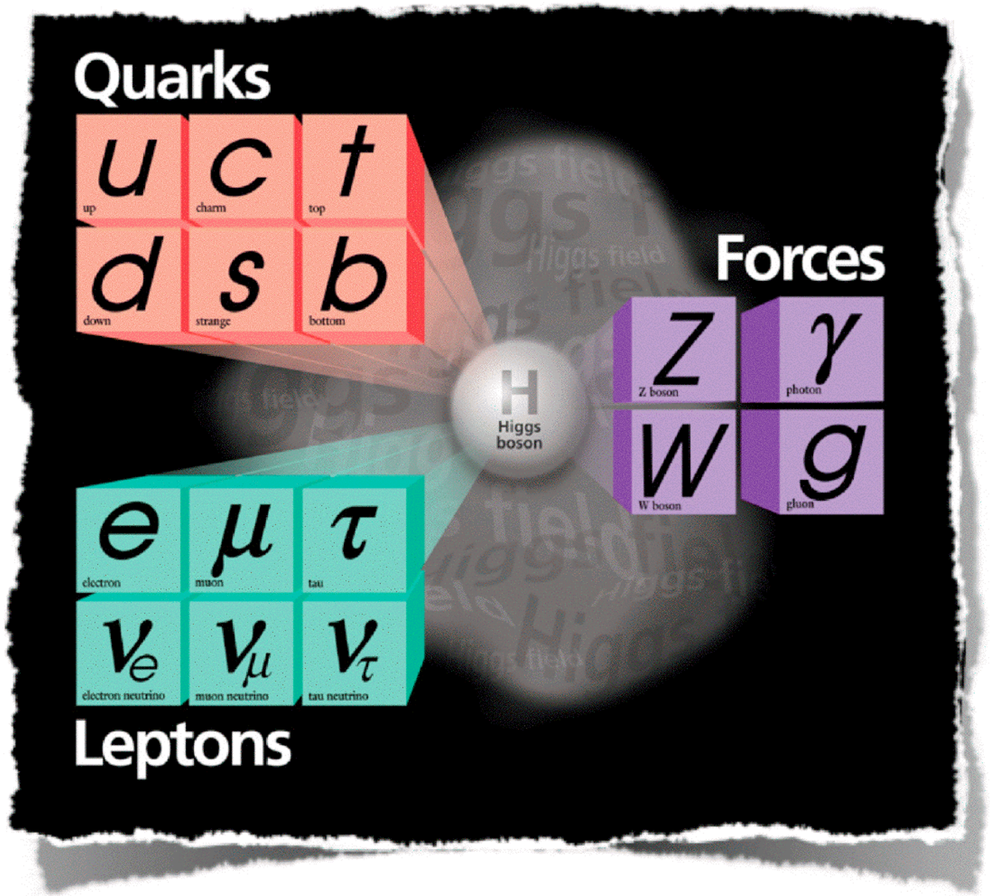
Top Quark Physics Topics

→ top physics collaboration

Top Quark Physics Topics

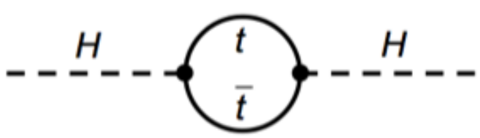


The Top Quark in the SM

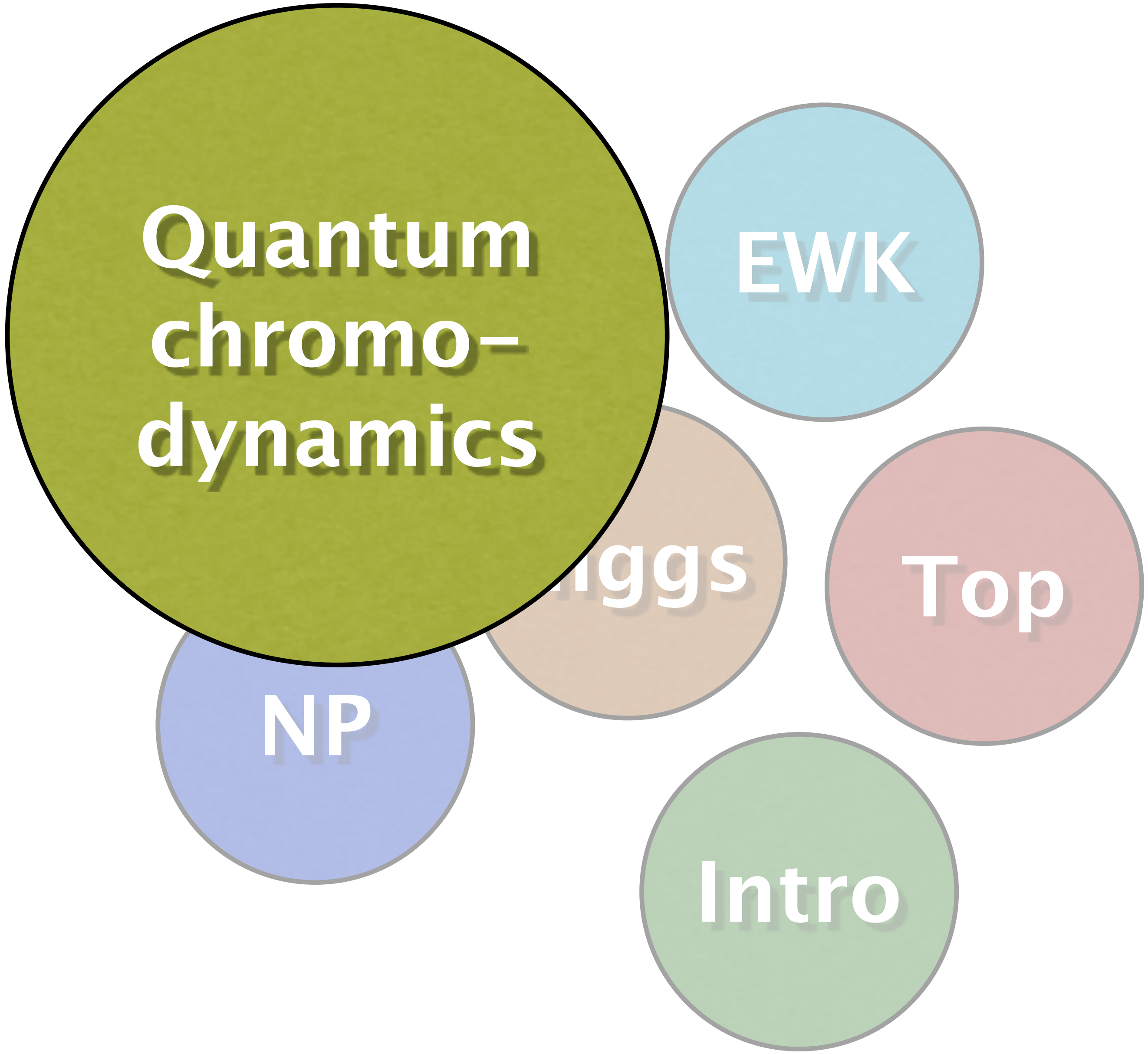


→ the top quark could play the decisive role in finding physics beyond the SM!

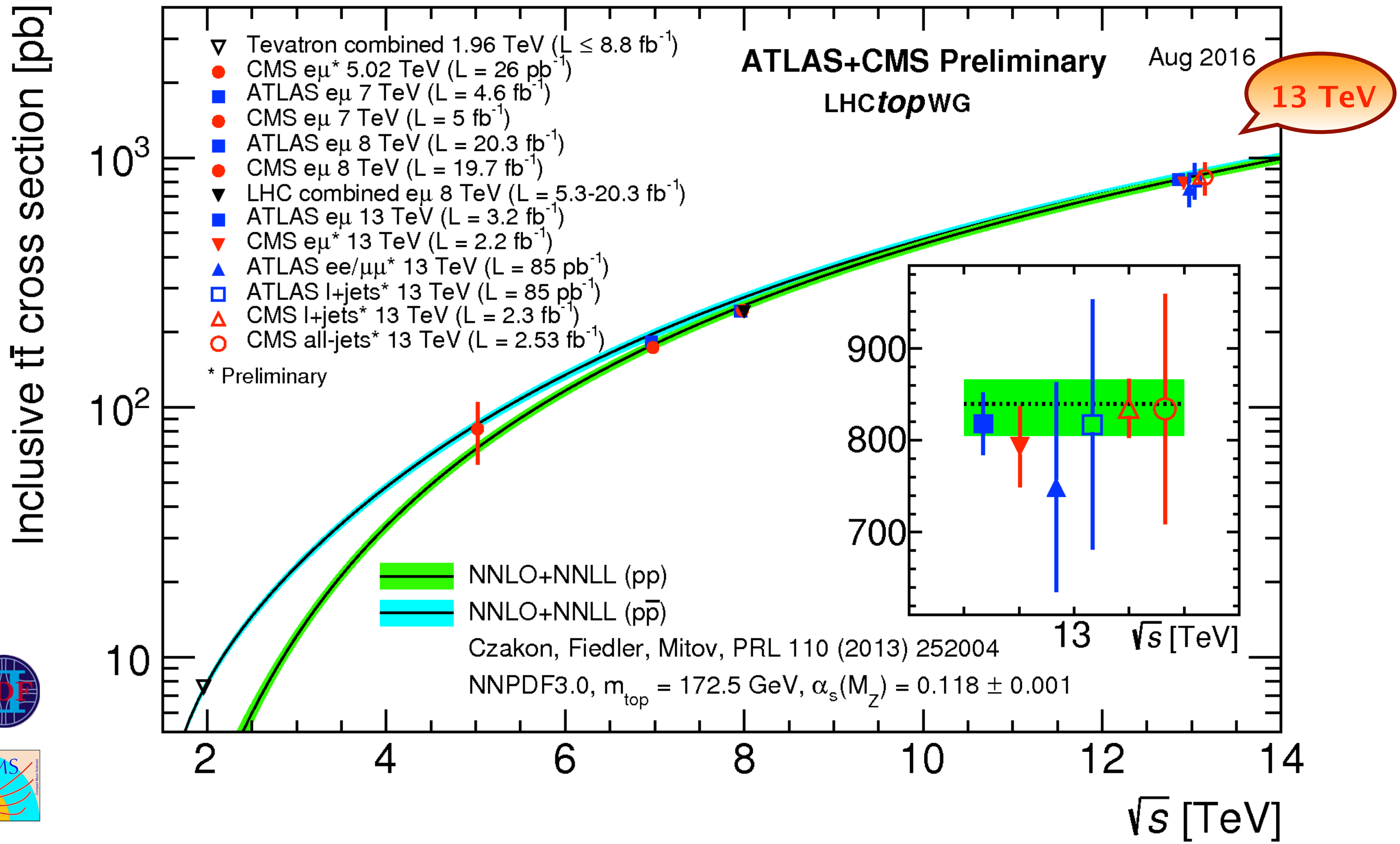
- top quark is needed as the isospin partner of the bottom quark
- Indeed, in 1995, it was discovered with a mass of the order of a gold nucleus (consisting of 79 protons and 118 neutrons). This is a very strange property for an elementary particle that is assumed to be point-like with no substructure.
- The top quark has a large Yukawa coupling to the Higgs boson of ~1, so it might play an important and exotic role in electroweak symmetry breaking
- largest quantum correction to Higgs mass involves a top quark loop, it is natural to suppose that BSM mechanisms involve top quarks



Top Quark Physics Topics



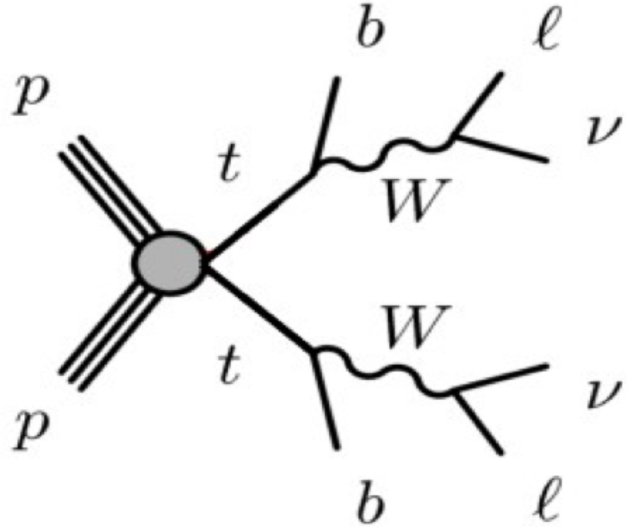
Top pair production at 13 TeV



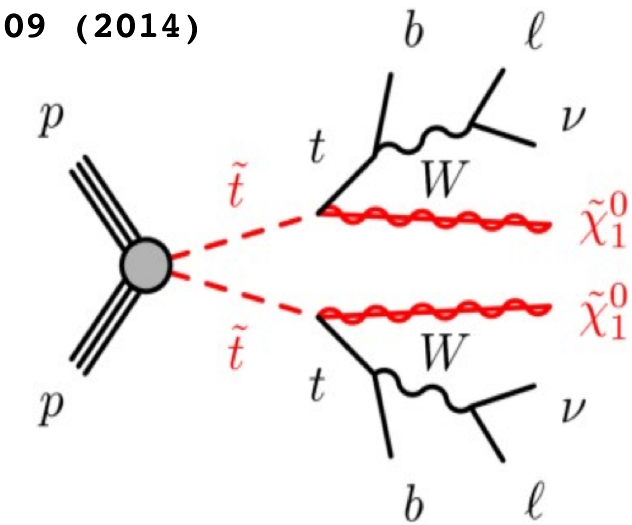
→ **agreement with SM prediction**

Stop Quark Pair Production

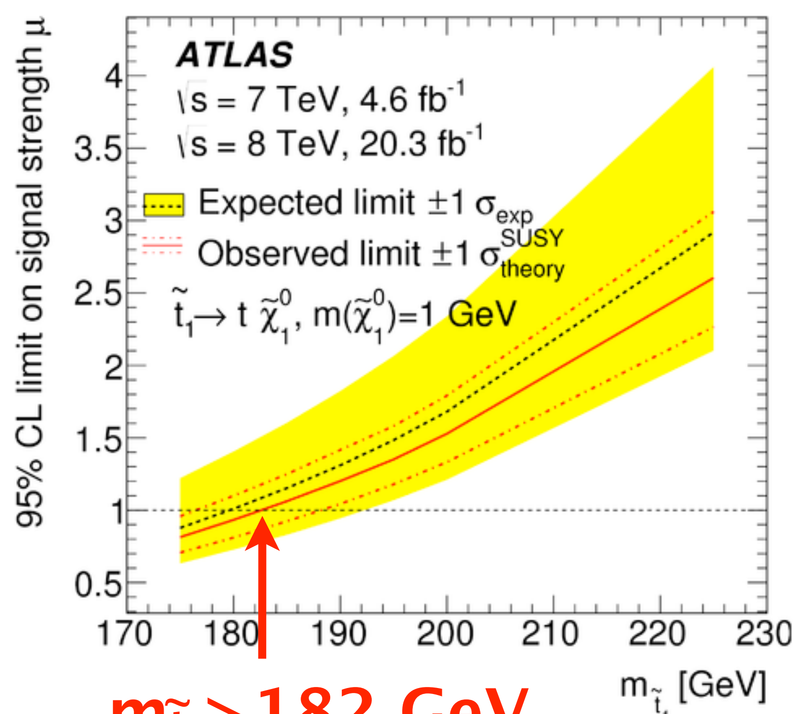
Eur. Phys. J. C74 3109 (2014)



do we see left or right?



$$\frac{\sigma_{\text{limit}}}{\sigma_{\text{SUSY}}}$$

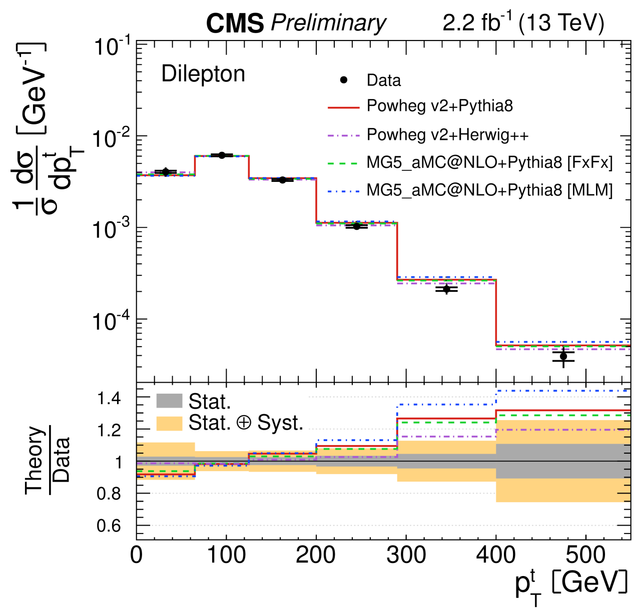


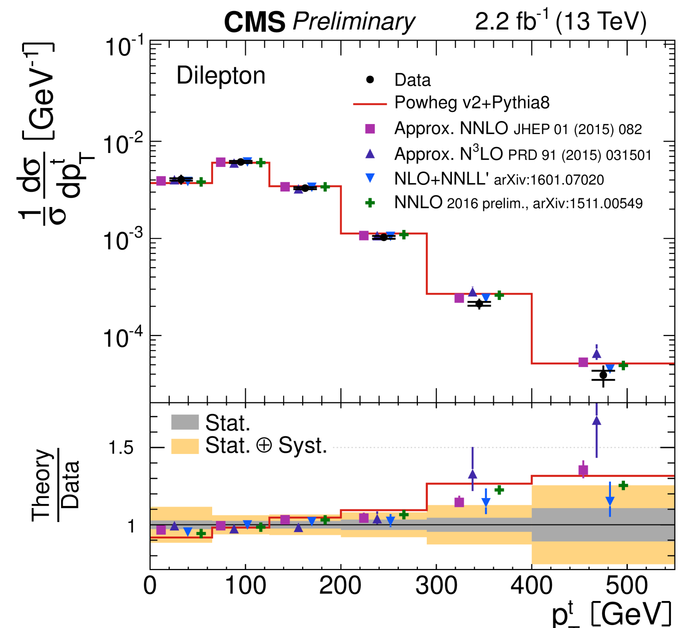
$m_{\tilde{t}} > 182$ GeV

"stealth" scenario:
- small neutralino mass
- stop mass close to top mass

Differential, unfolded: $m_{t\bar{t}}$ & $t\bar{t}\ p_T$

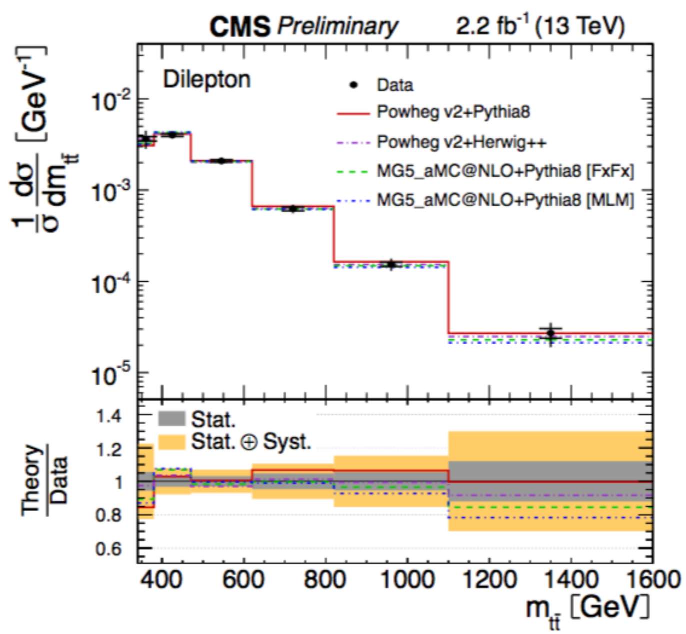
NLO+PS simulations

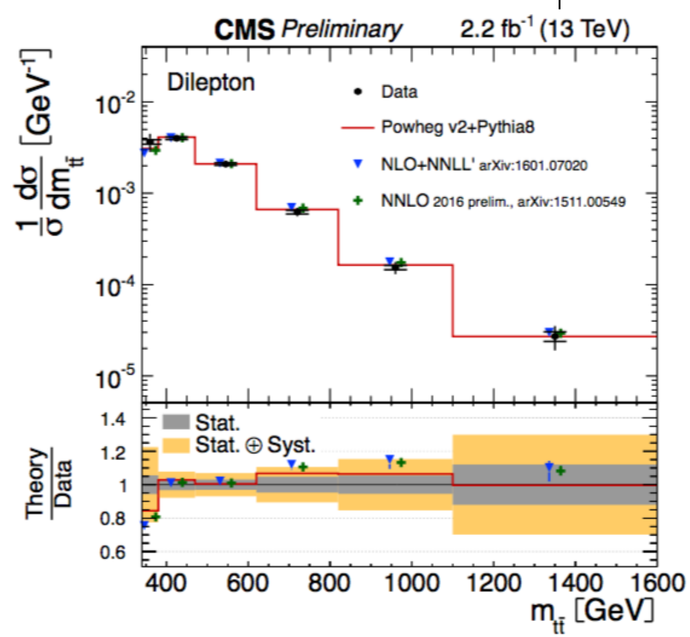


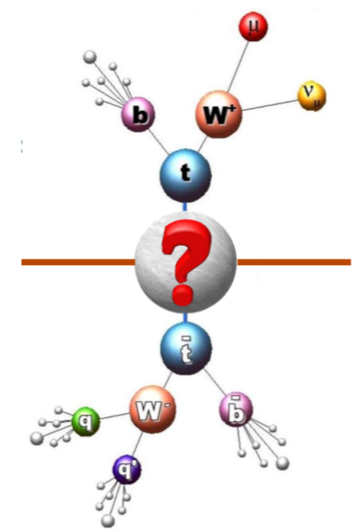


NNLO

13 TeV

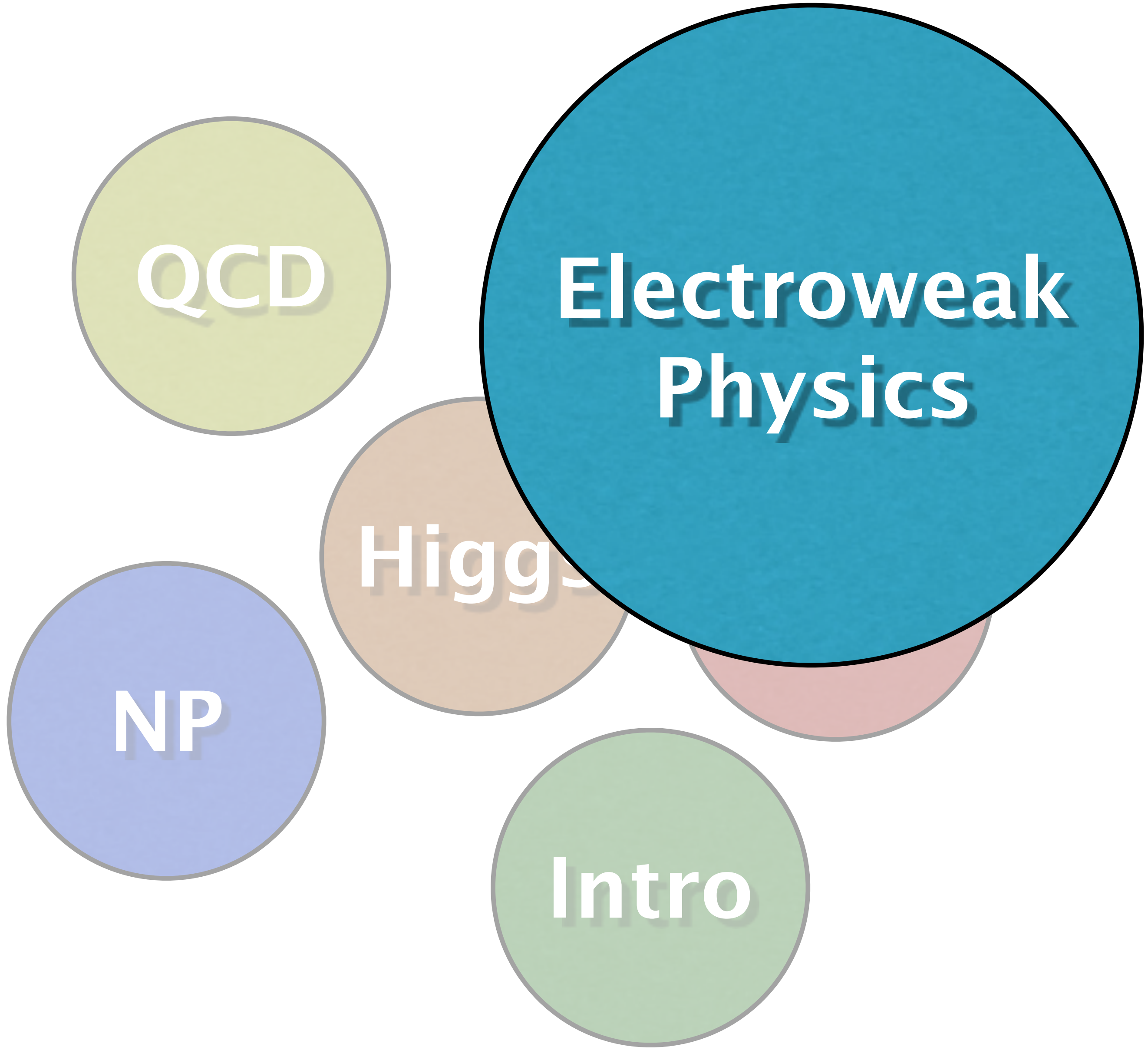




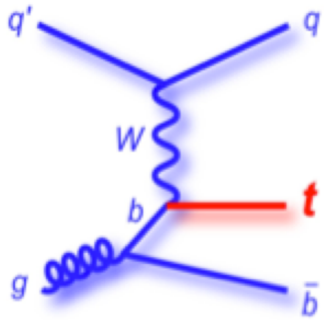


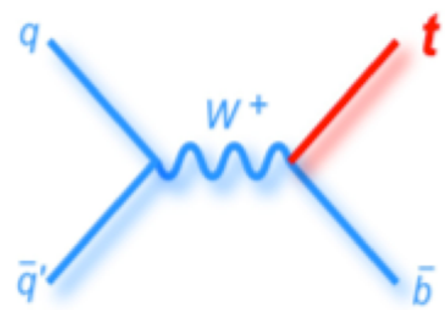
⇒ no new resonances

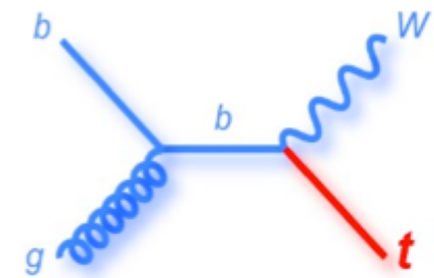
Top Quark Physics Topics

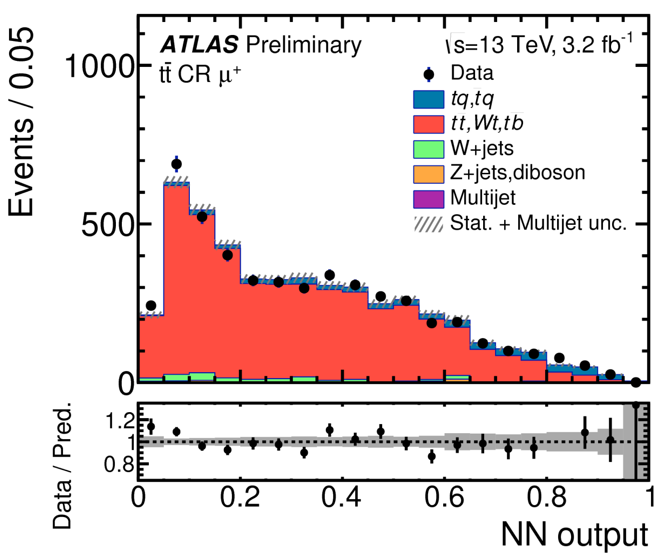


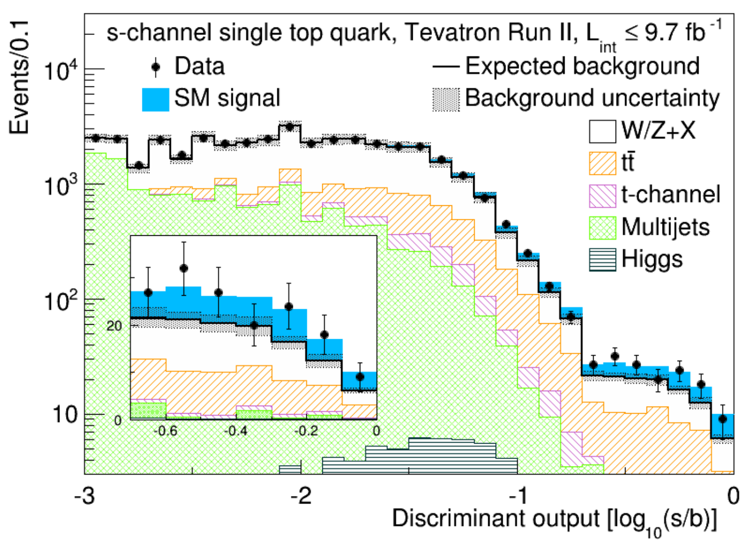
Search for single top production

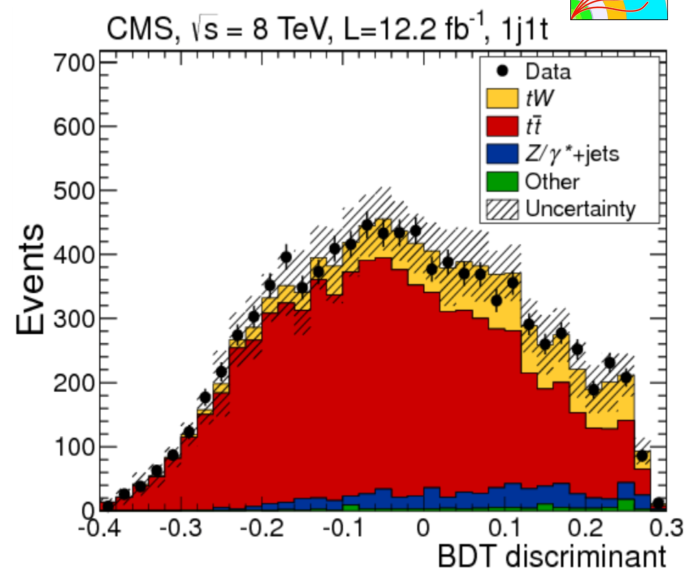






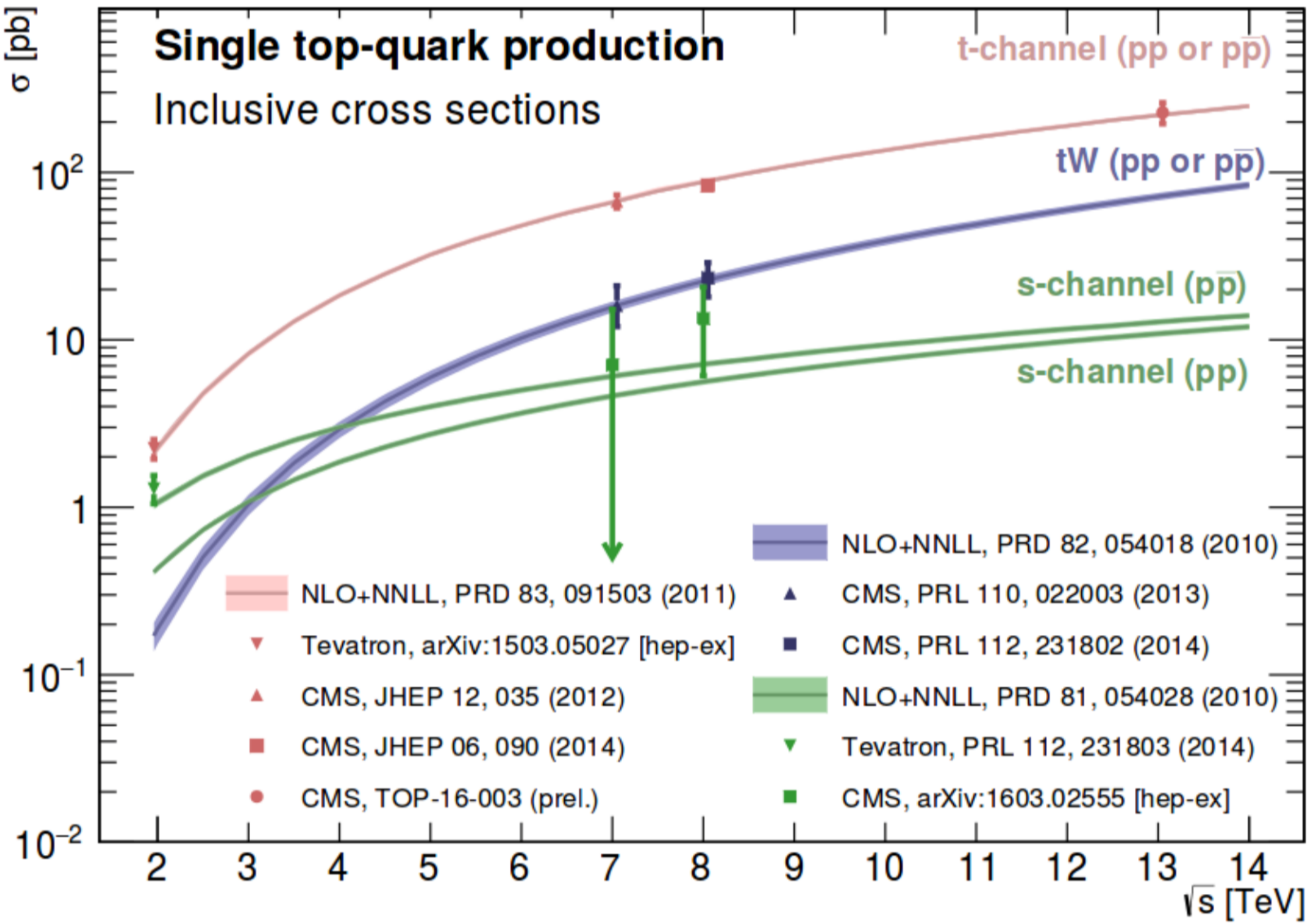


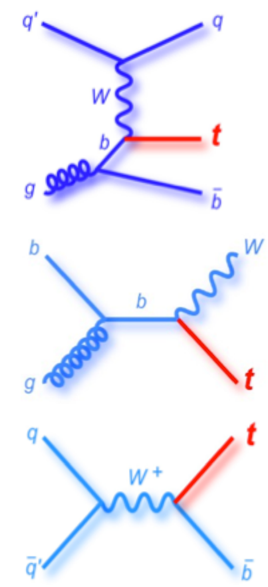




→ all production modes observed!

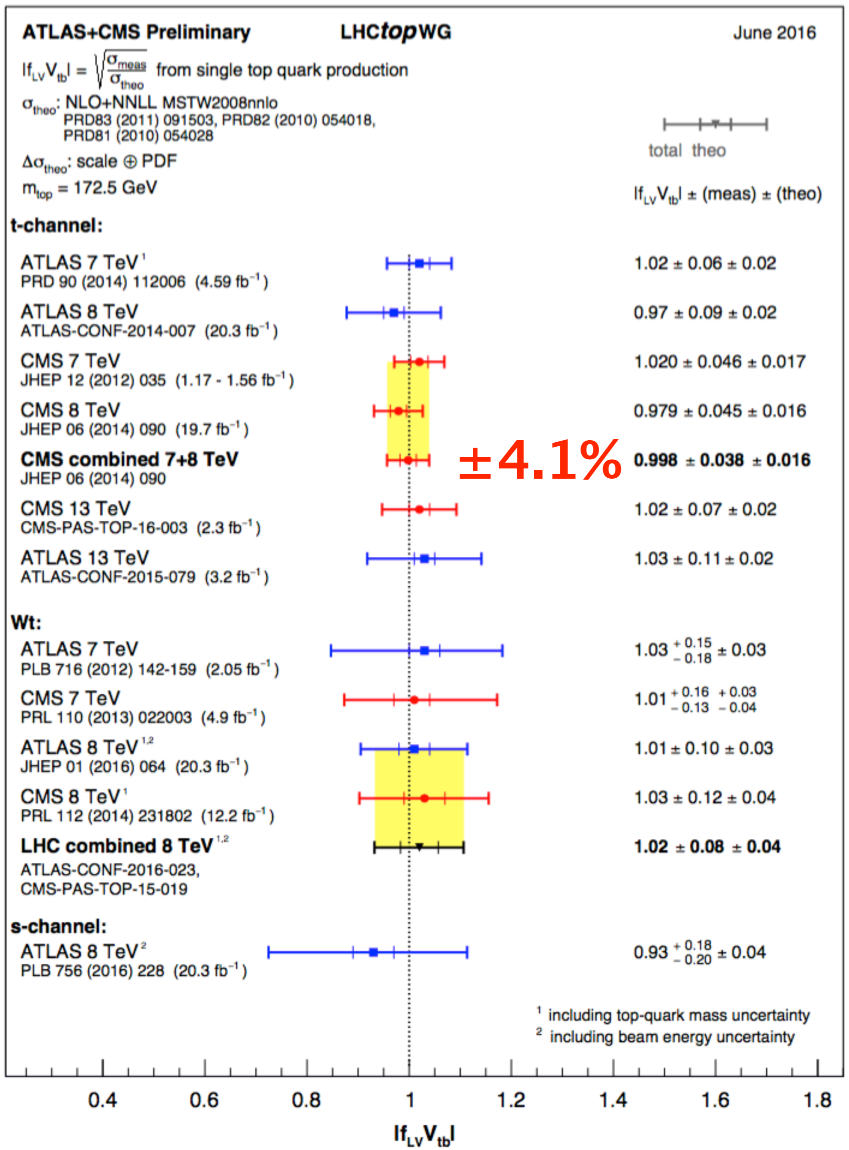
Single channel cross sections



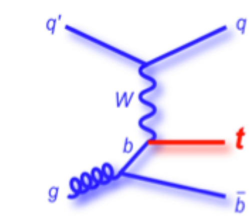


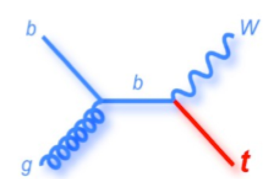
→ in agreement with SM prediction!

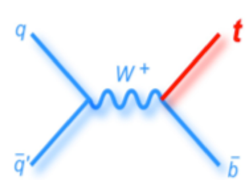
Direct measurement of $|V_{tb}|$



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

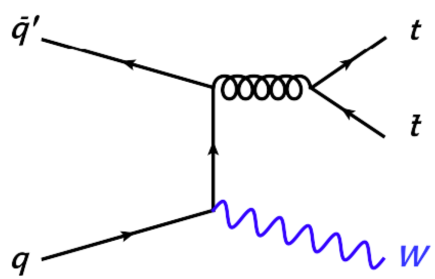




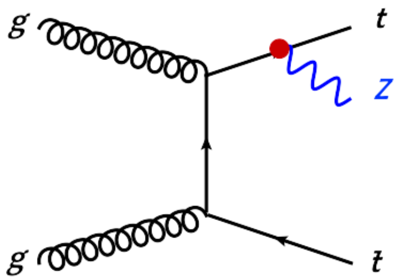


→ no hint for anomalous contribution

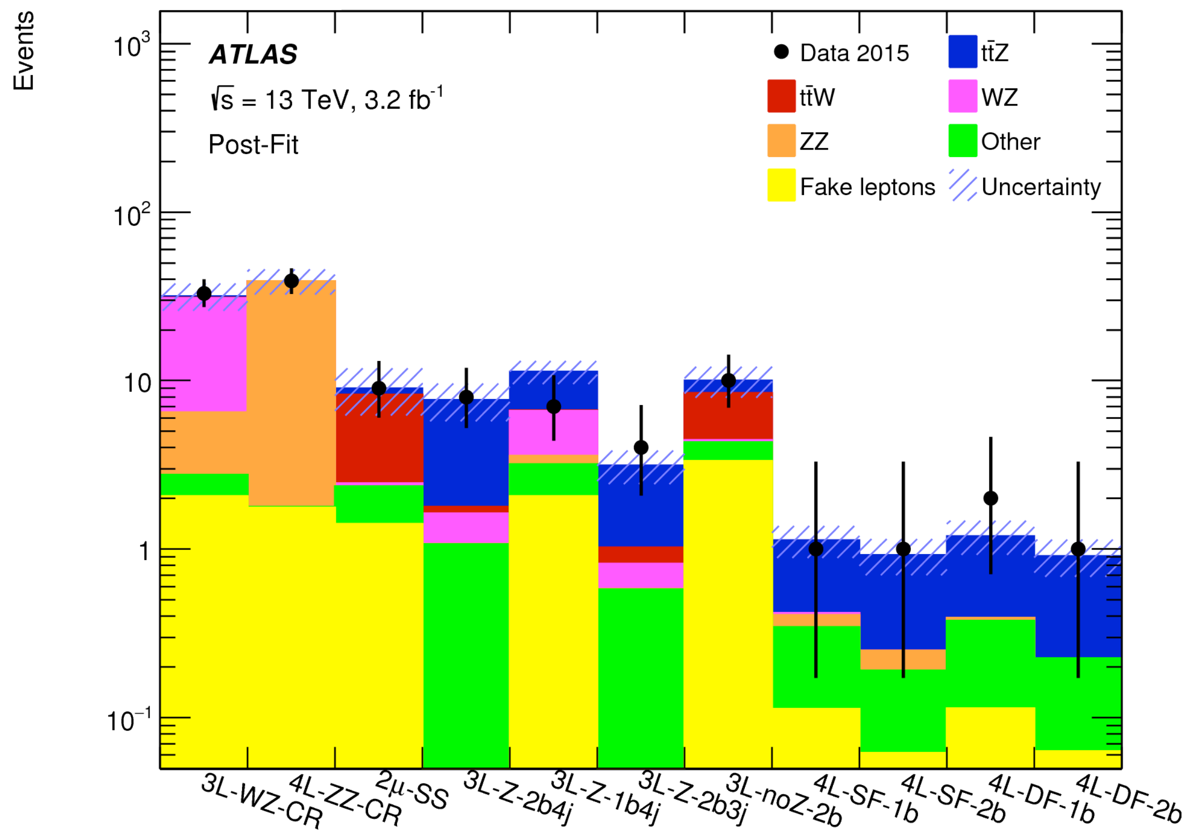
Search for $t\bar{t}Z$ and $t\bar{t}W$



ISR



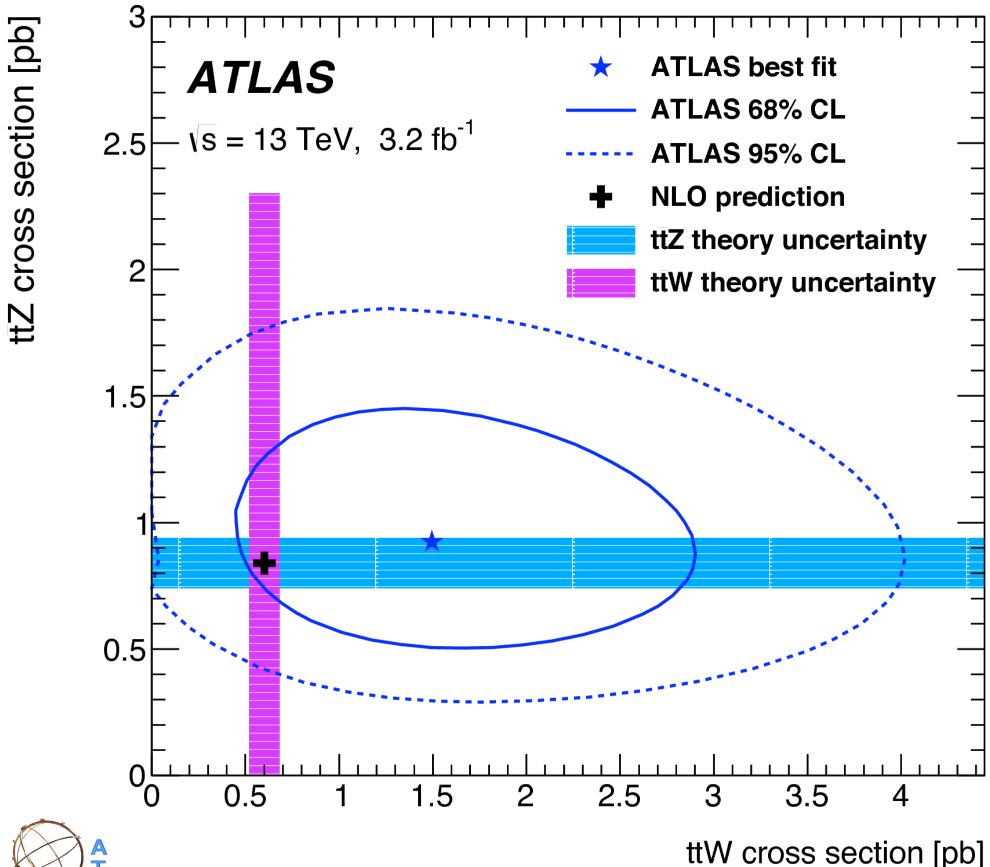
FSR



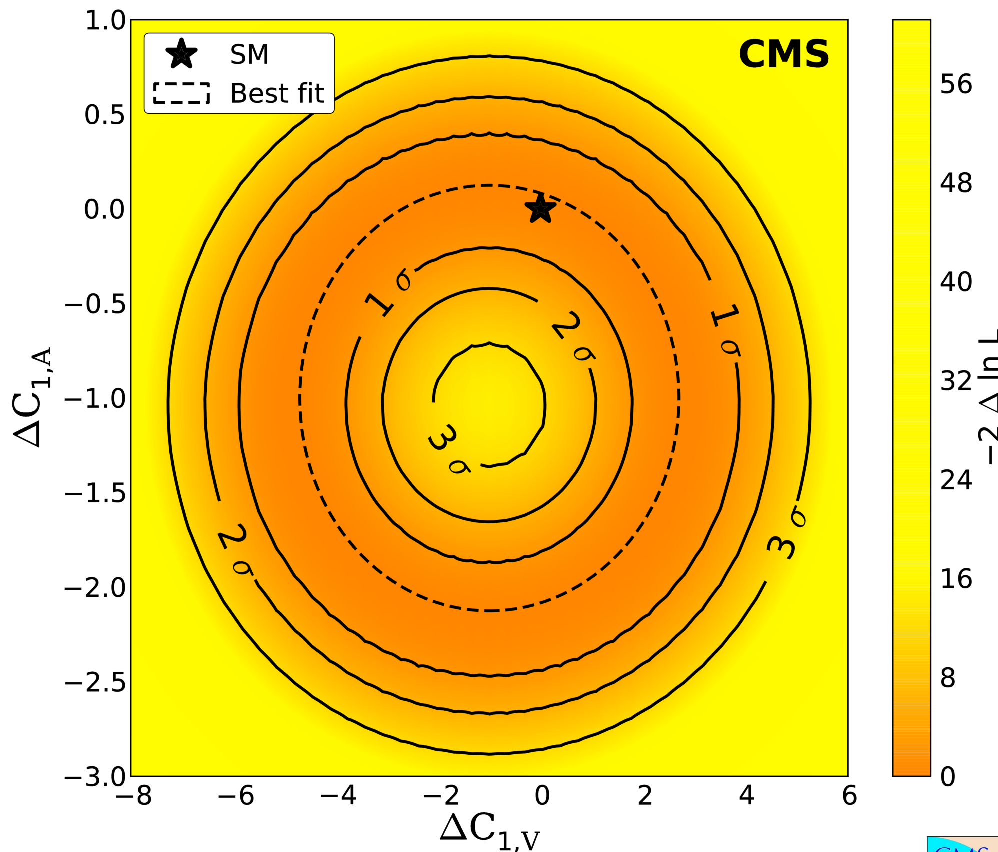
$t\bar{t}W$ ← → **$t\bar{t}Z$**

Observation of $t\bar{t}V$ production

ttZ vs. ttW cross sections:



anomalous V or A ttZ couplings:

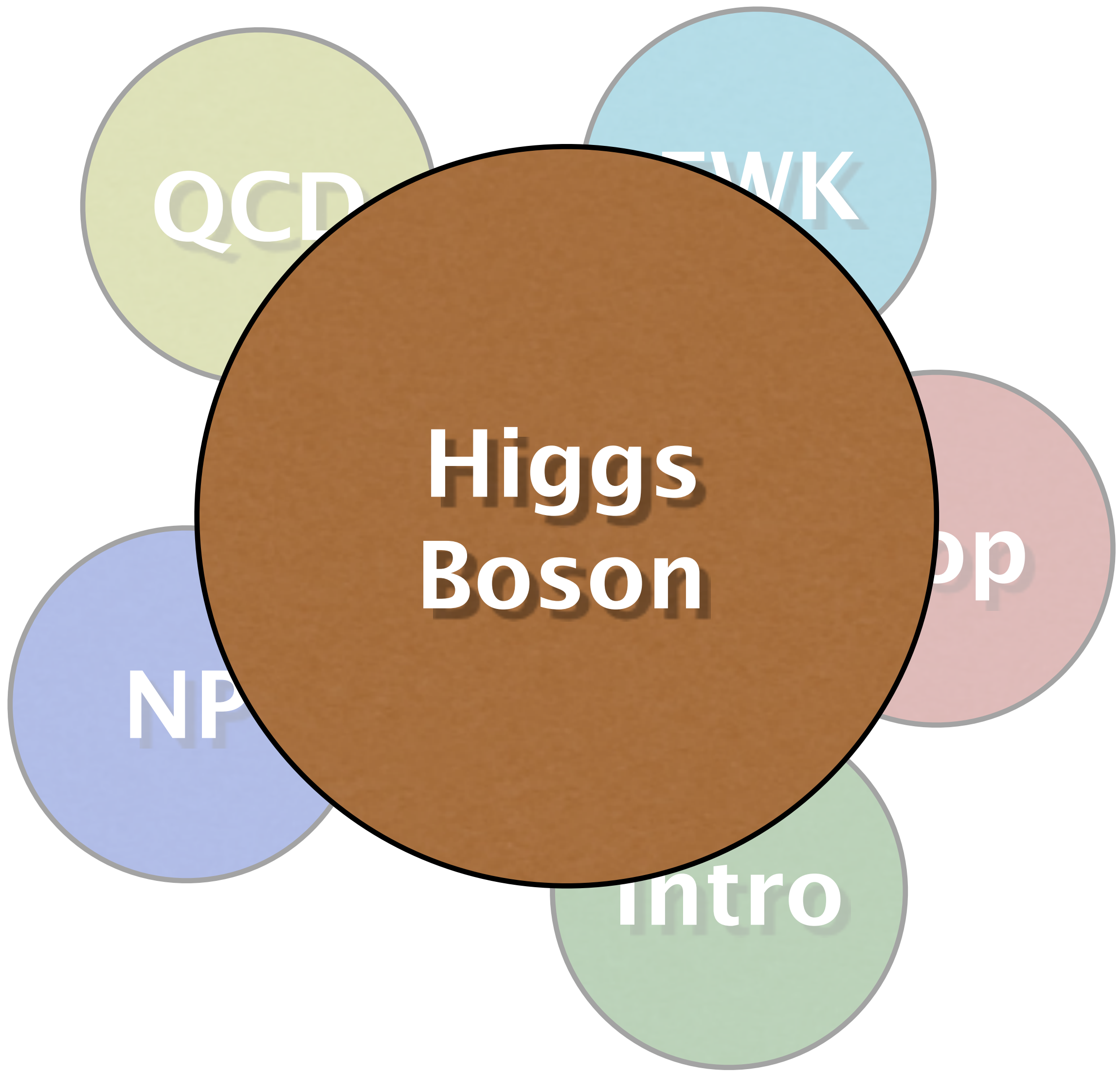


→ **in agreement with the SM prediction**

→ **no hint for anomalous contribution**

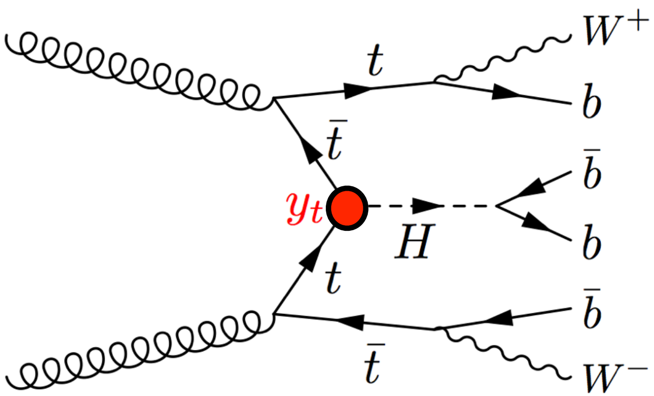
(ttγ also in agreement with SM prediction)

Top Quark Physics Topics

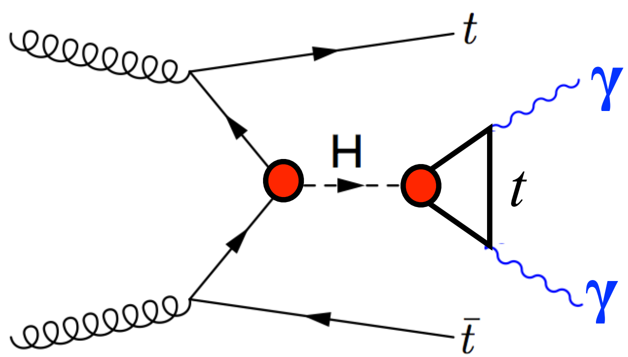


Search for $t\bar{t}H$ production

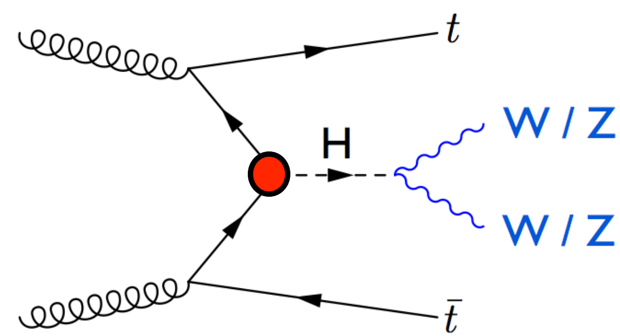
H→bb



H→γγ



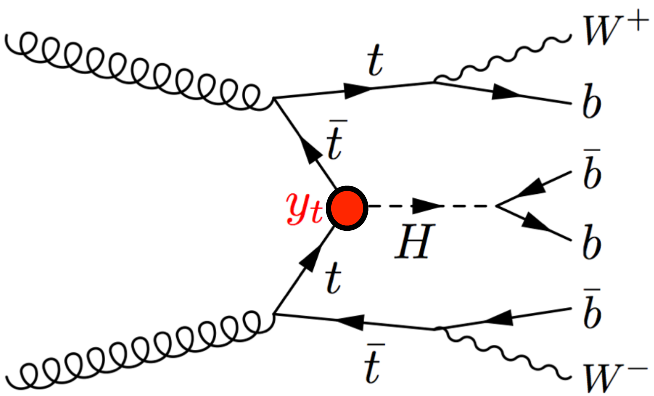
H→WW, ZZ

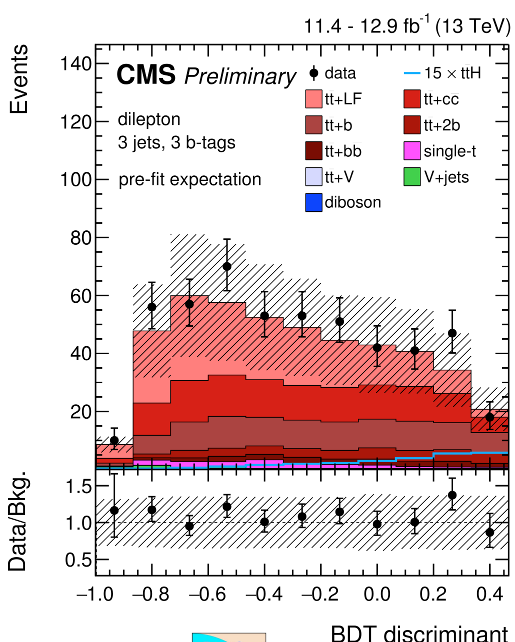


multi-leptons

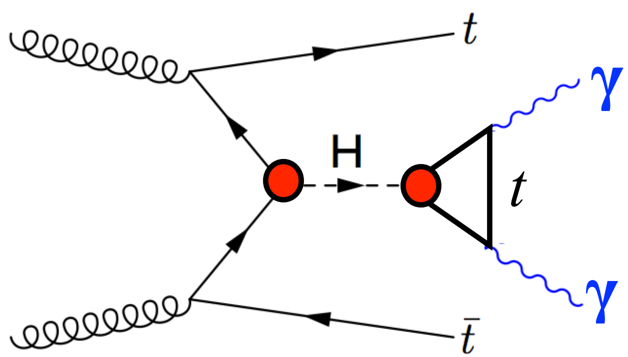
Search for $t\bar{t}H$ production

H→bb

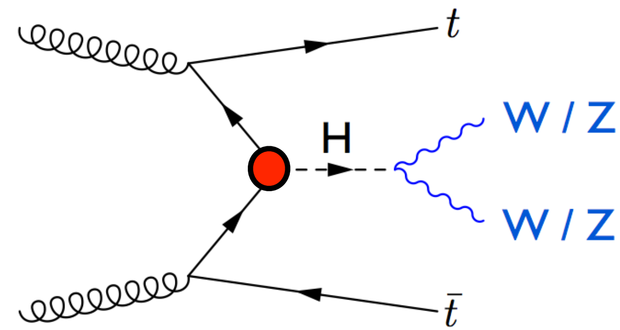




H→γγ



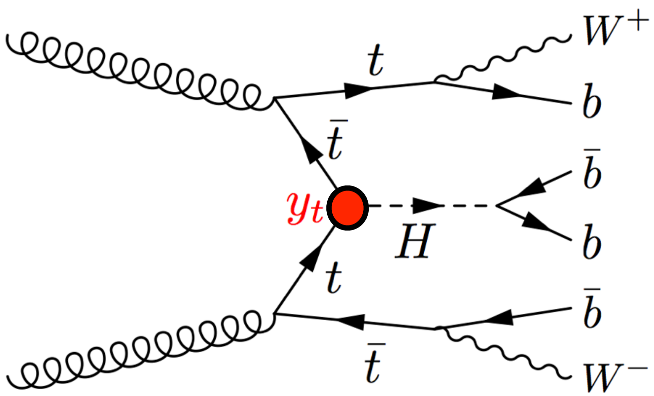
H→WW, ZZ

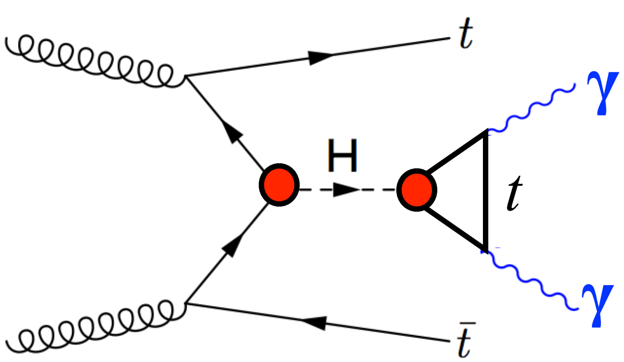


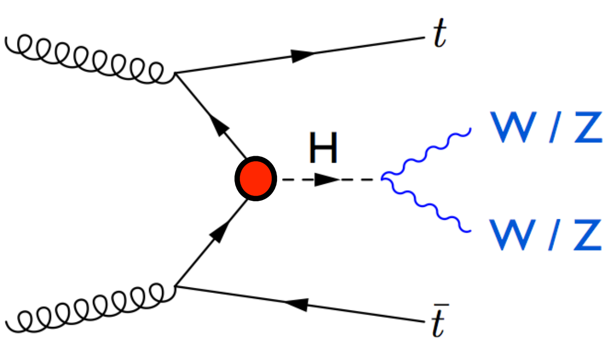
multi-leptons

Search for $t\bar{t}H$ production

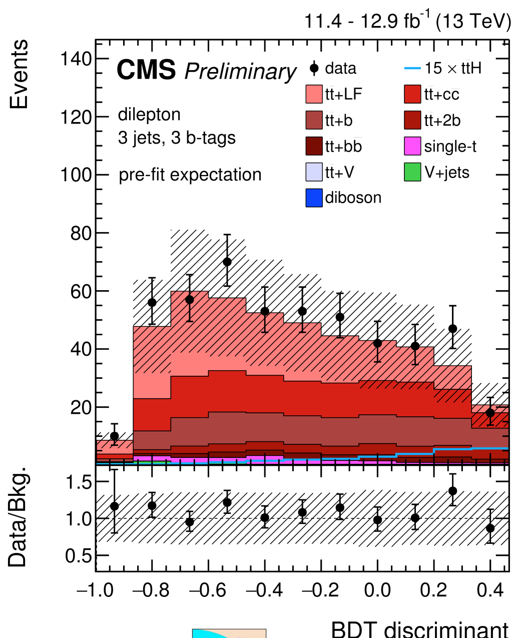
$H\to bb$ | **$H\to\gamma\gamma$** | **$H\to WW, ZZ$**

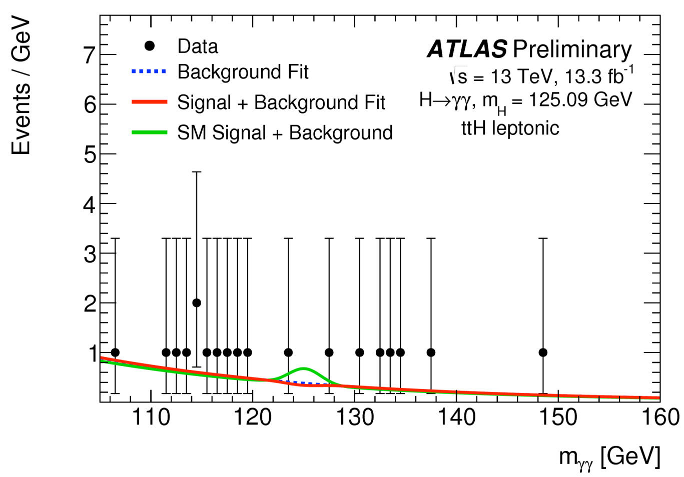






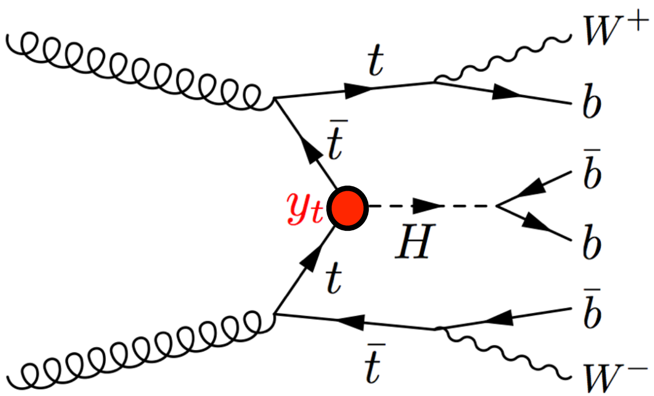
multi-leptons

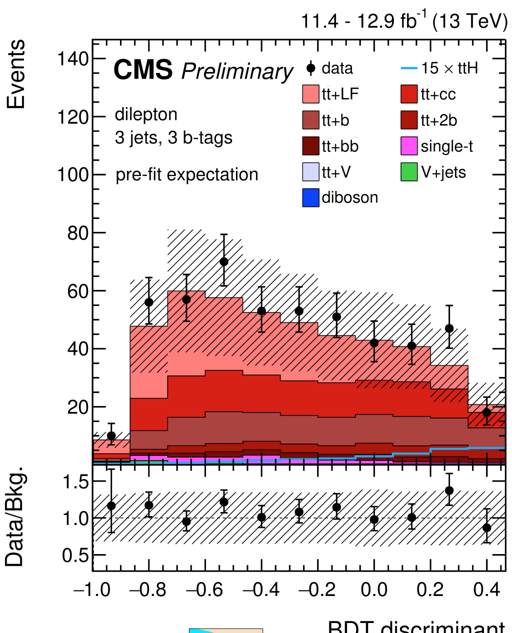




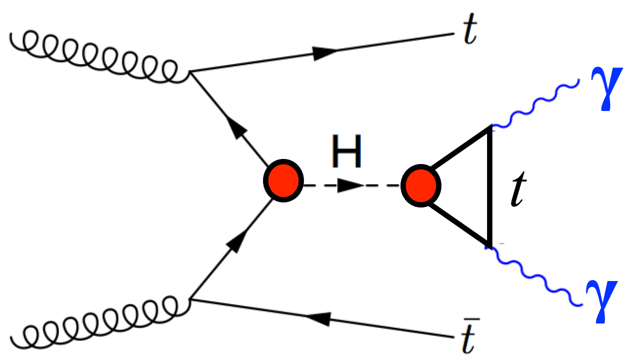
Search for $t\bar{t}H$ production

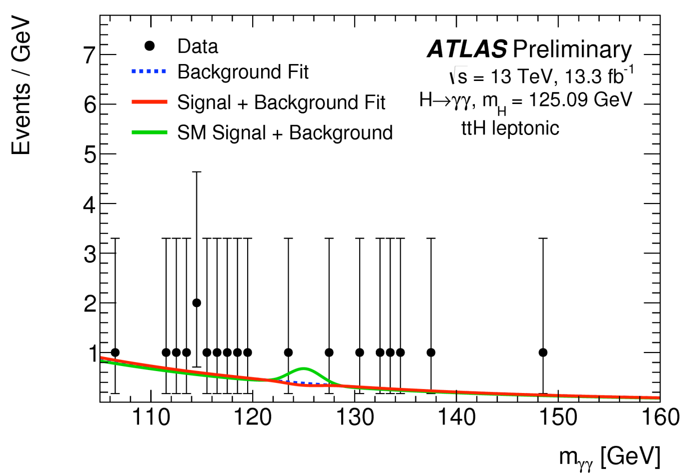
H→bb



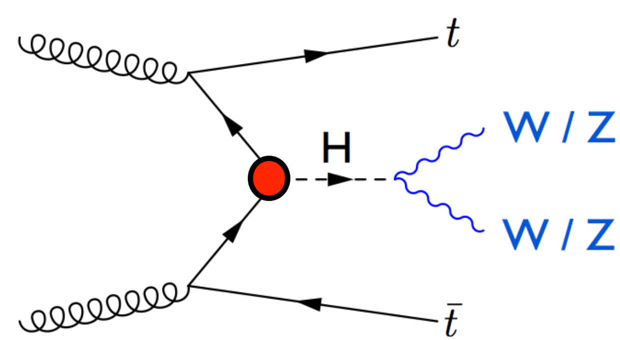


H→γγ

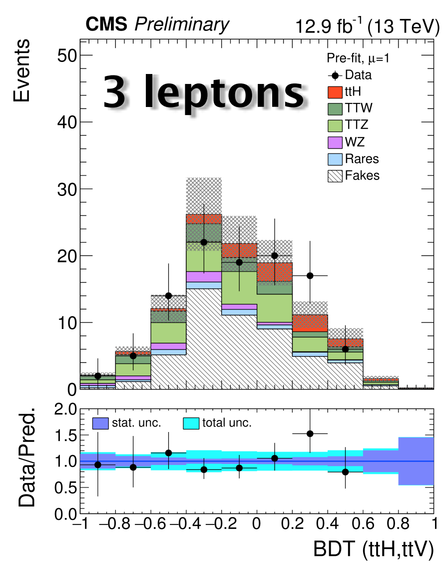


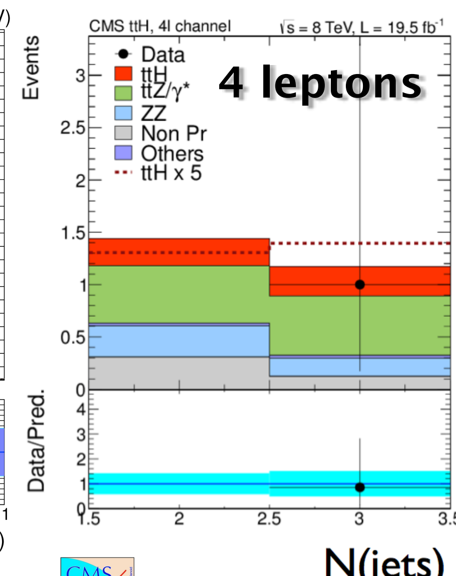


H→WW, ZZ



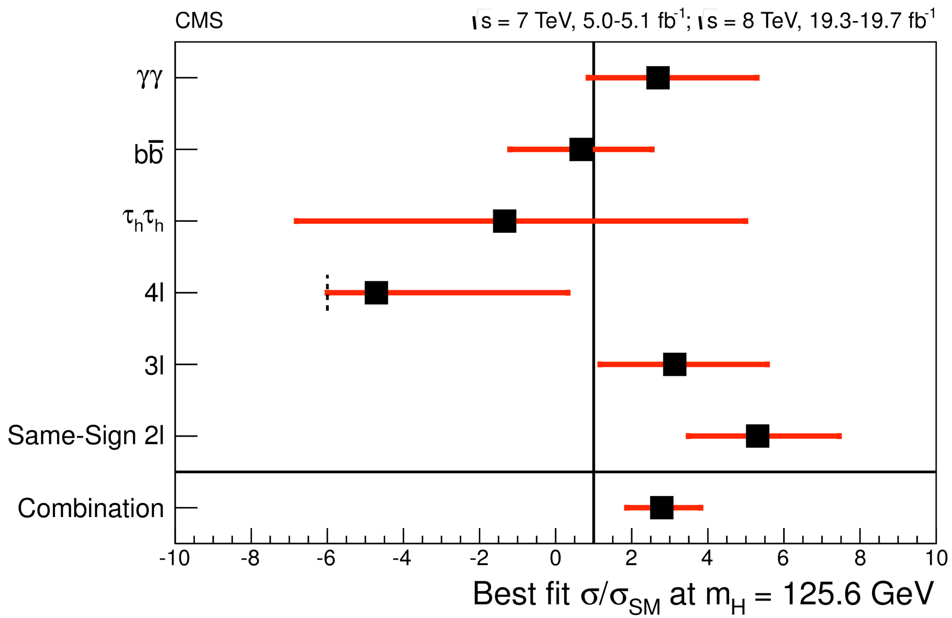
multi-leptons



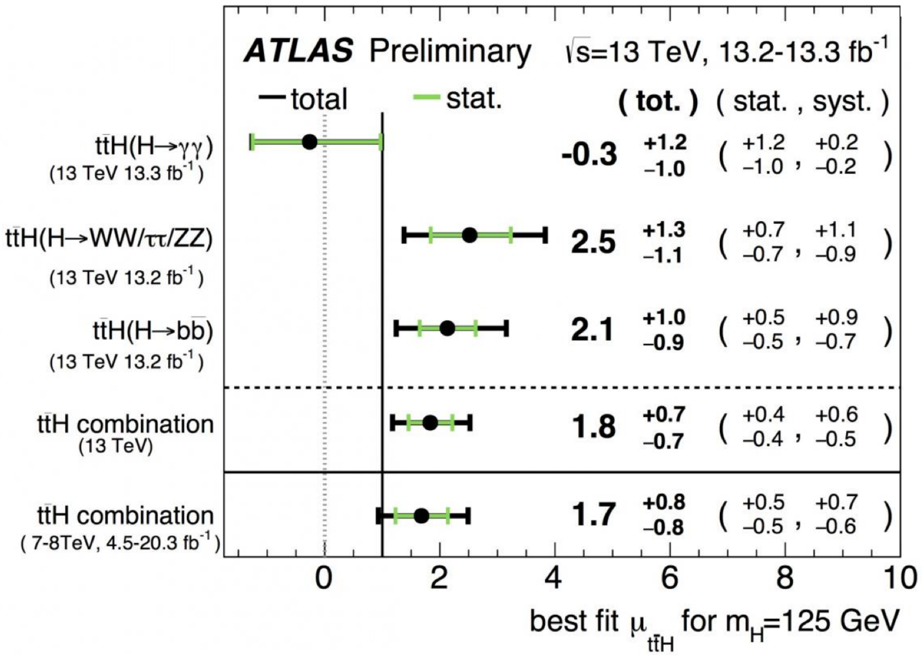


Results in $t\bar{t}H$

7 and 8 TeV



13 TeV



σ/σ_{SM} | **σ/σ_{SM}**

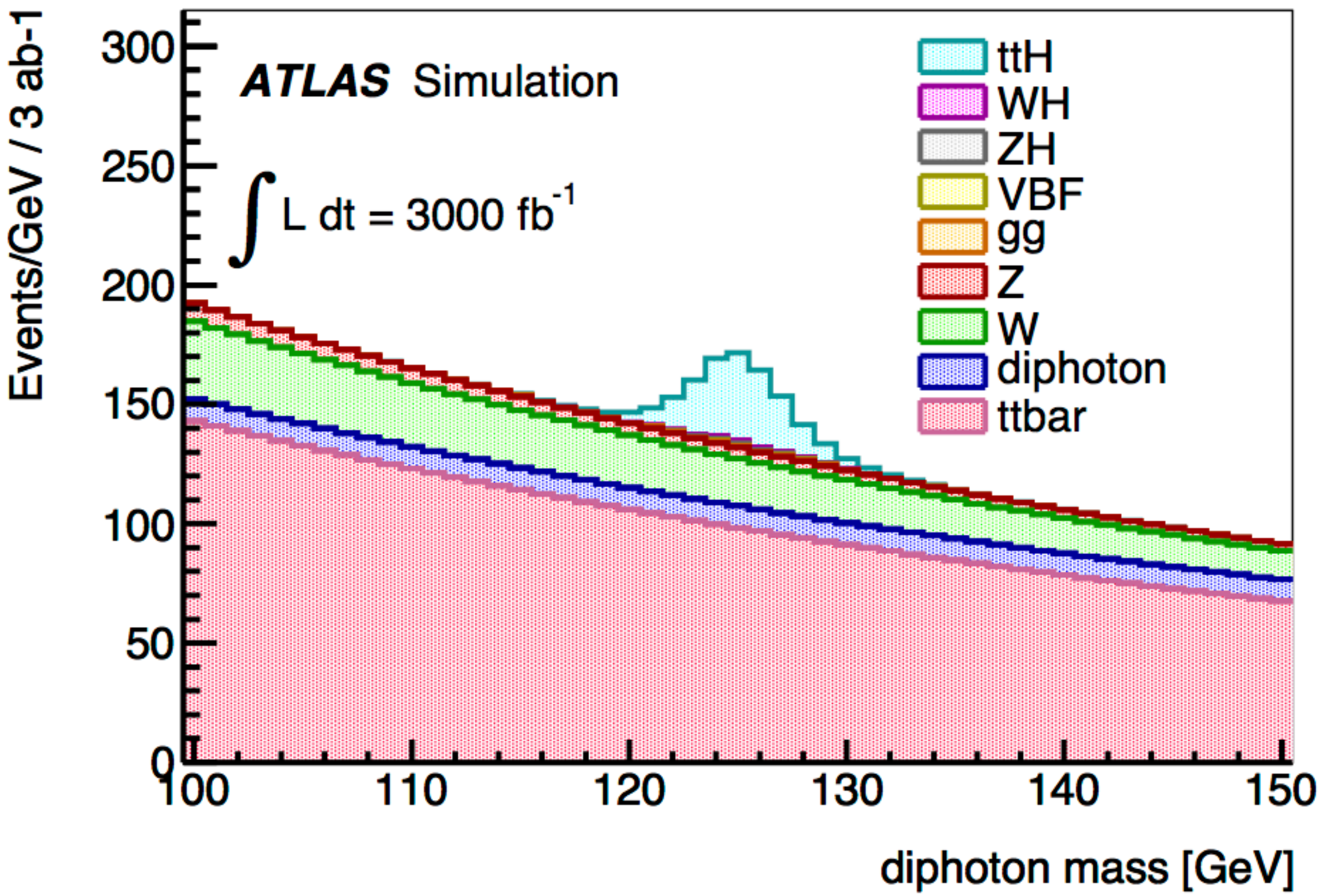
4.5σ (1.7σ exp) | **2.8σ (1.8σ exp)**

→ **observation in Run-II**

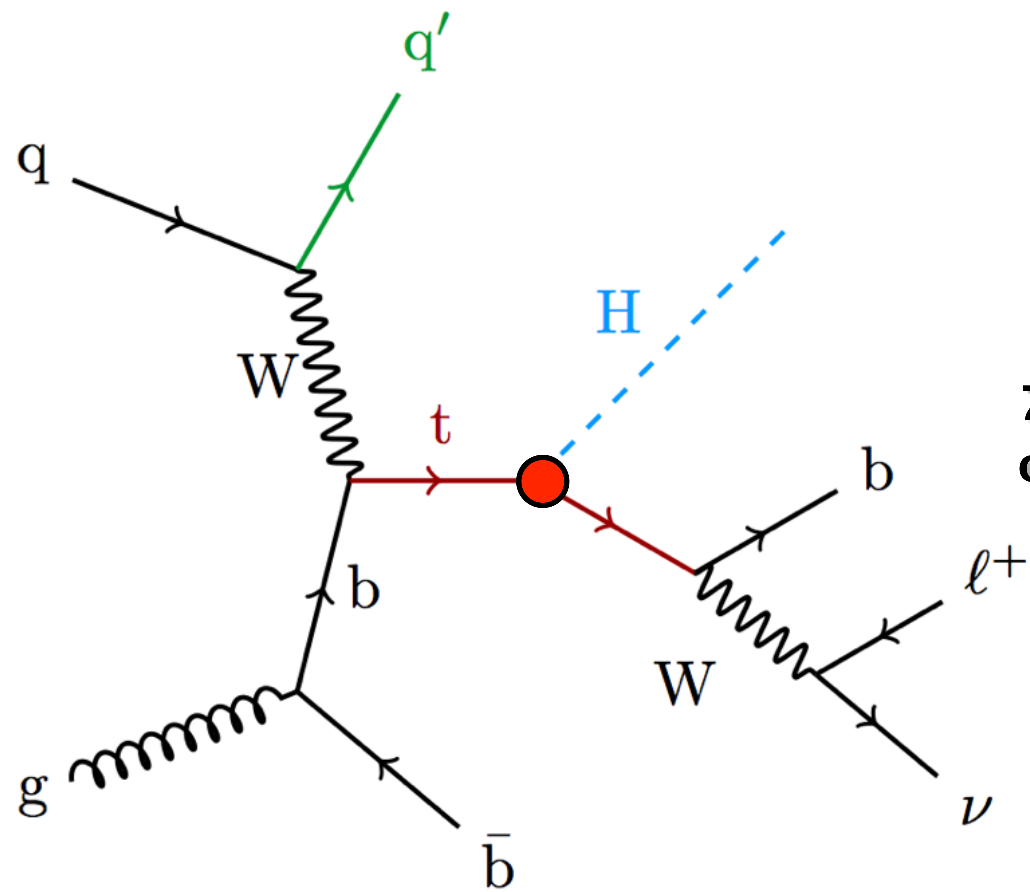
→ **measurement of top-Yukawa coupling**

High Lumi LHC

arXiv:1307.7292



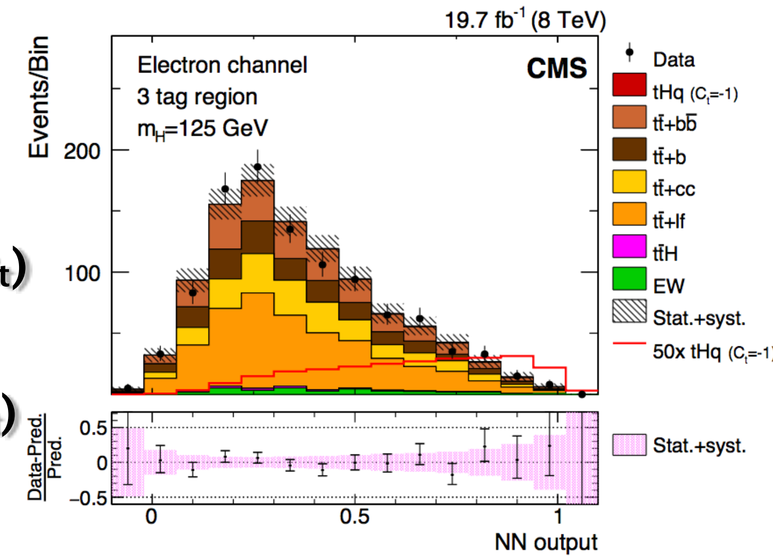
Search for tHq production



H→bb

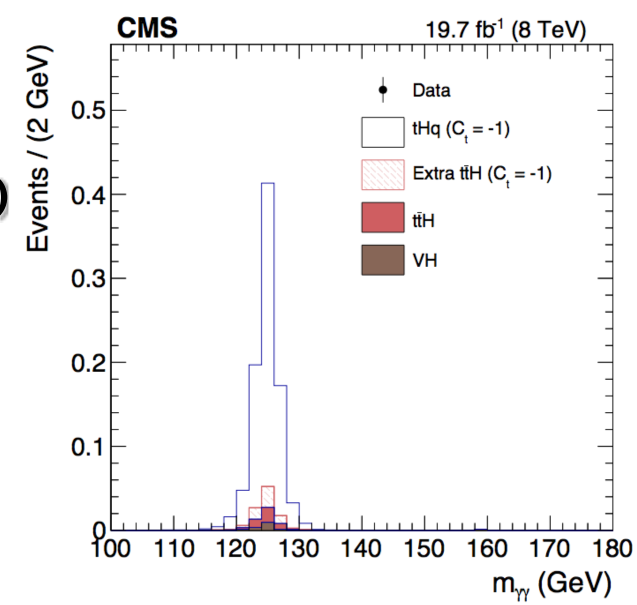
5.4×σ/σ(κ$_t$) expected

7.6×σ/σ(κ$_t$) observed



H→γγ

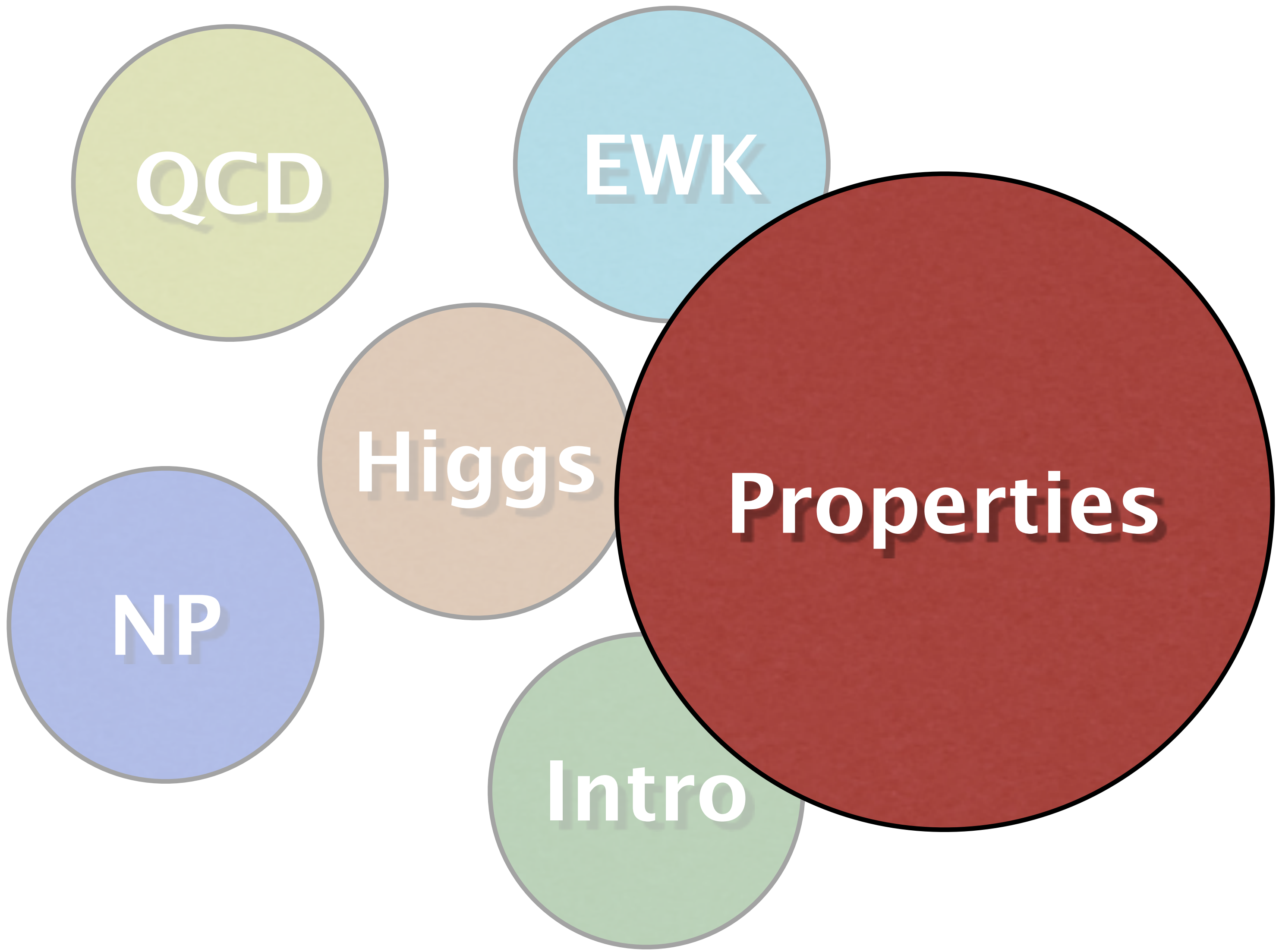
4.1×σ/σ(κ$_t$) expected and observed



in case top Yukawa coupling $\kappa_t = y_t / y_t^{SM} = -1$ coupling: cross section can be enhanced by factor 13

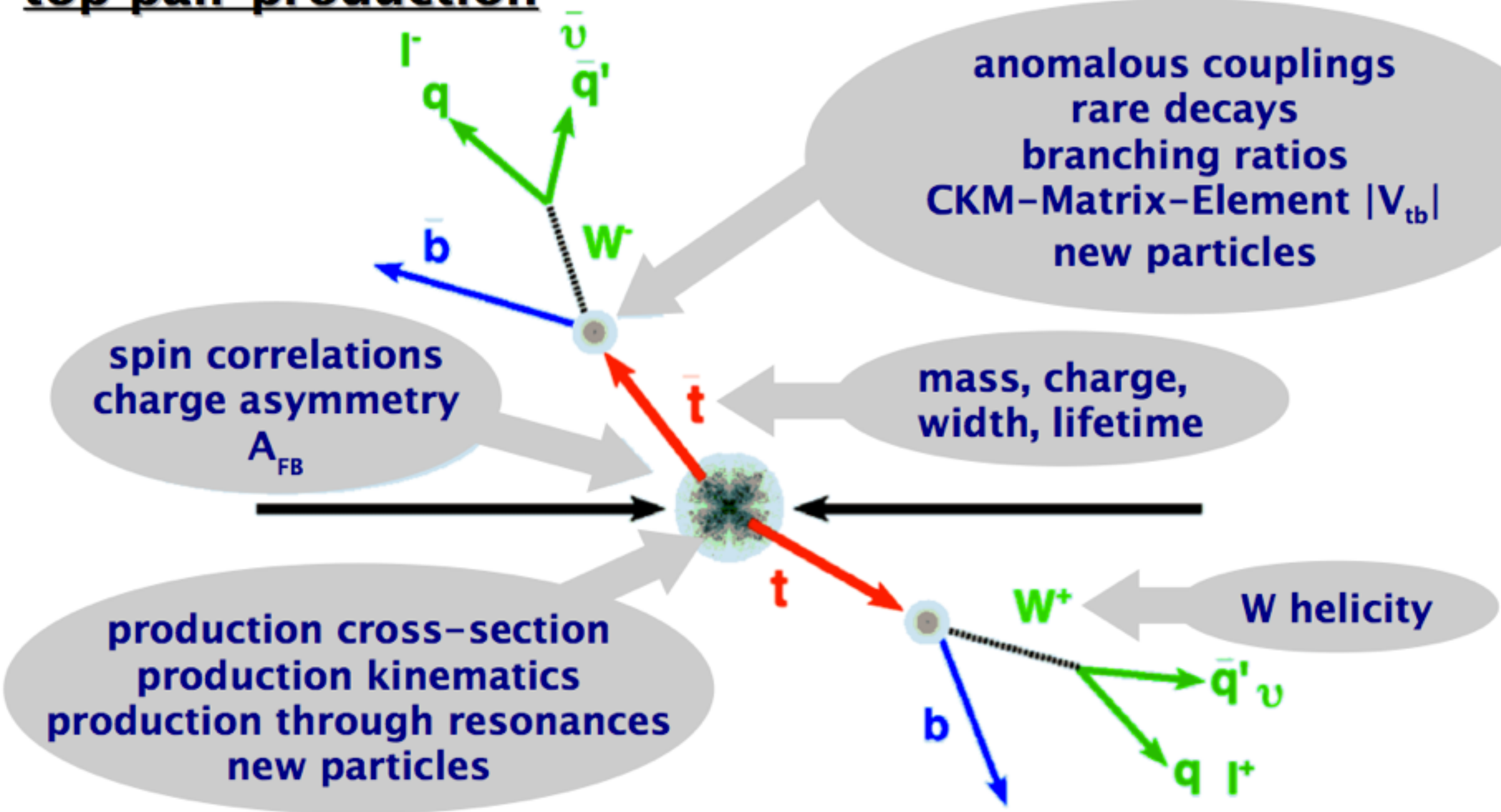
→ fun in Run-II

Top Quark Physics Topics



Top Quark Analyses

top pair production

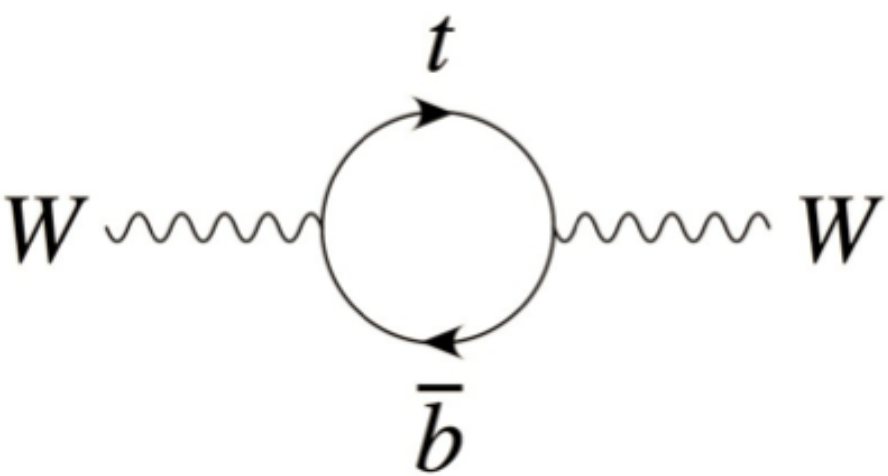


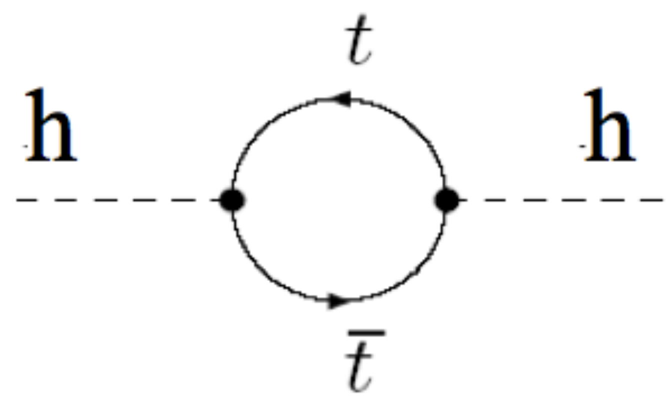
single top production cross sections, CKM matrix element $|V_{tb}|$, polarisation, SM and anomalous couplings, searches, …

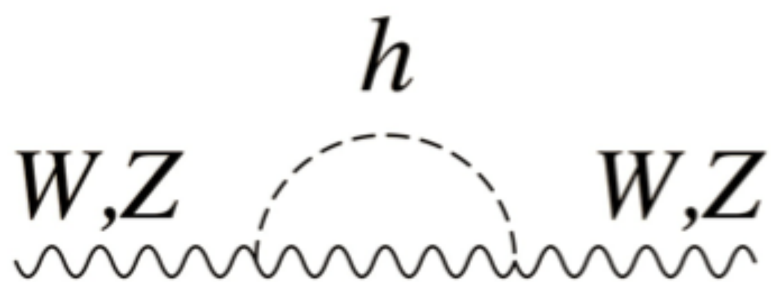
other production modes tt+jets, ttbb, ttZ, ttW, ttH and their couplings

The Top Quark Mass

- free parameter in the Standard Model
- check the **self-consistency of the Standard Model** in combination with W mass and **Higgs mass**

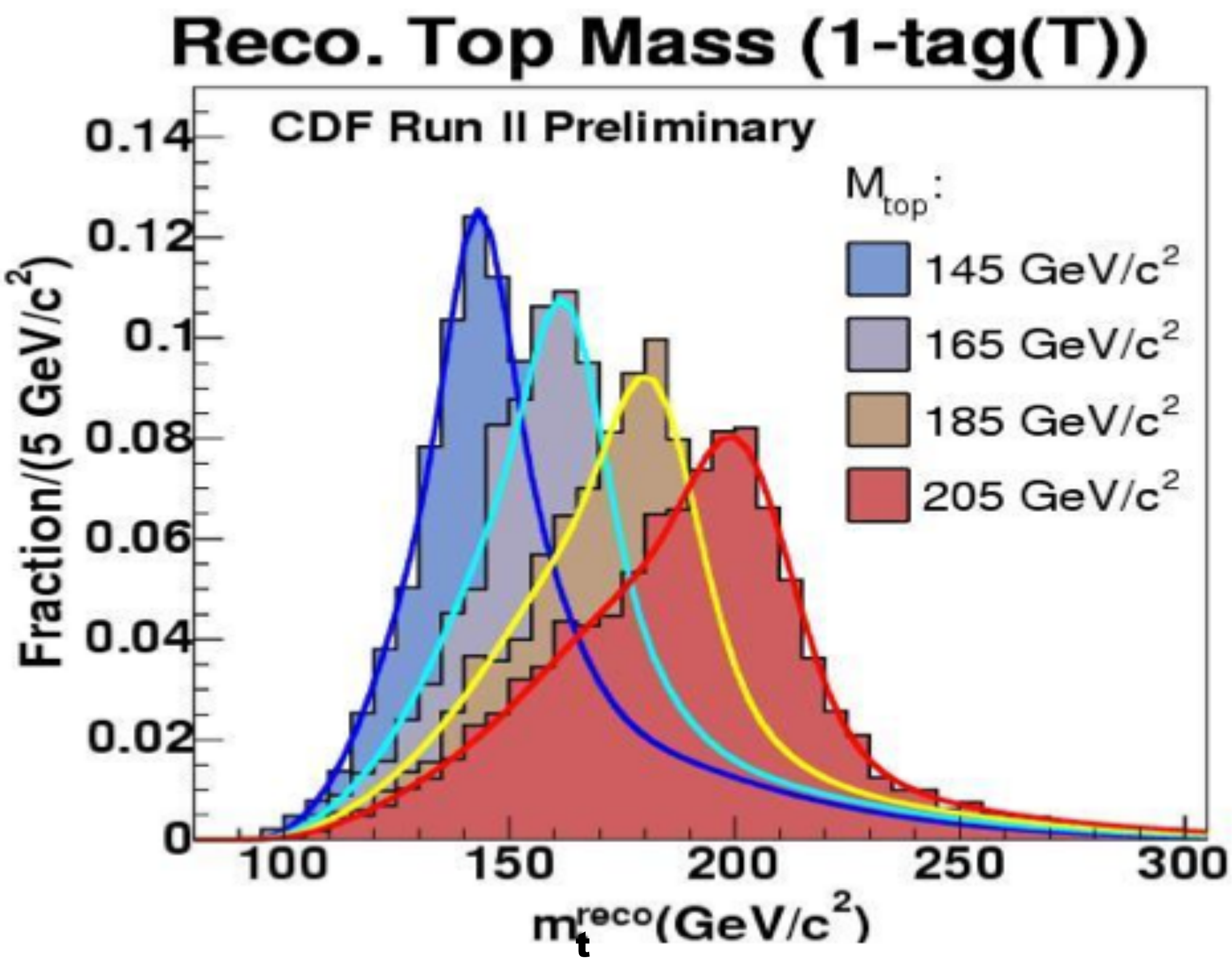






Extraction Techniques: Templates

- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses



Extraction Techniques: Templates

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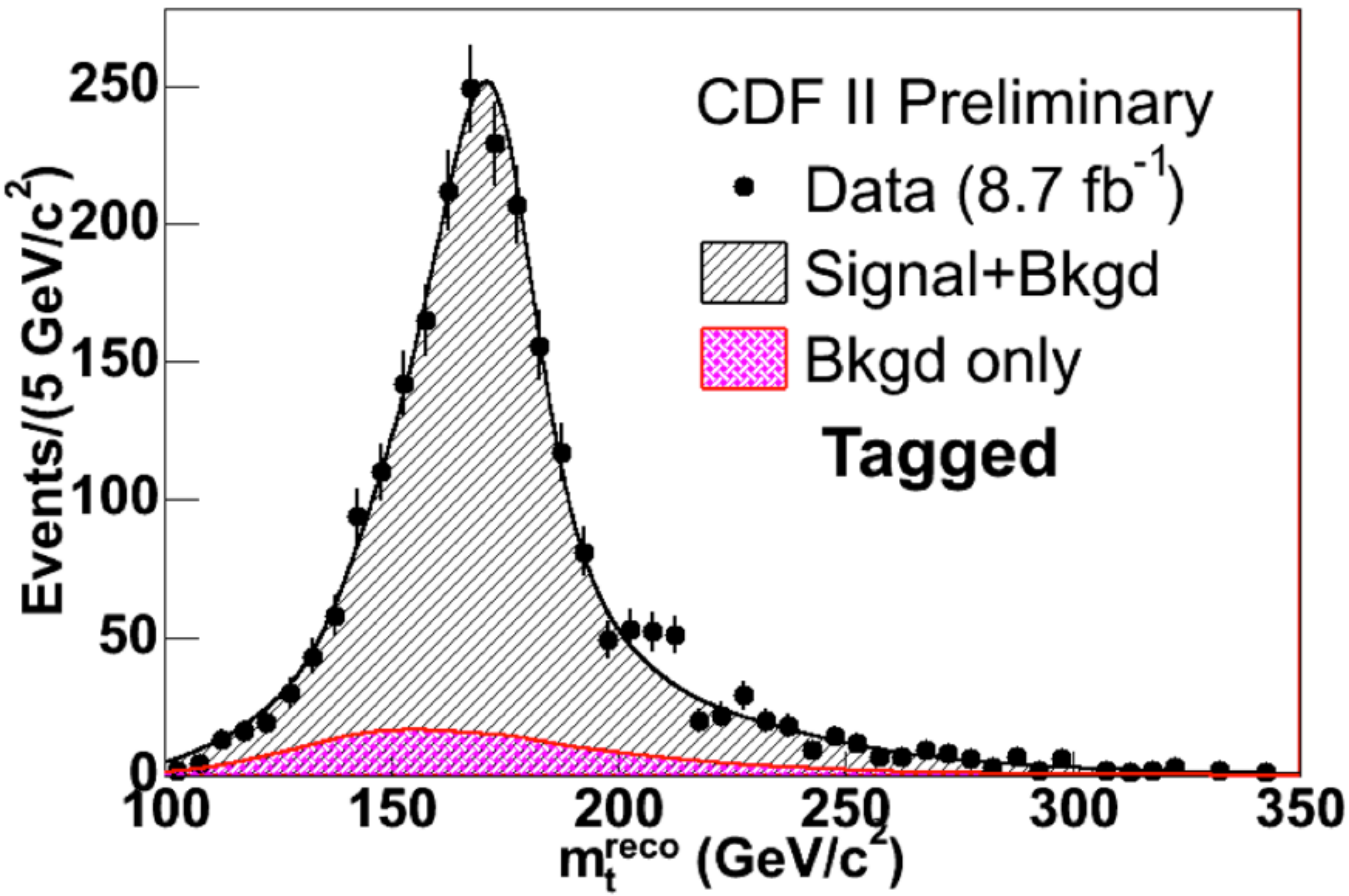

Extraction Techniques: Templates

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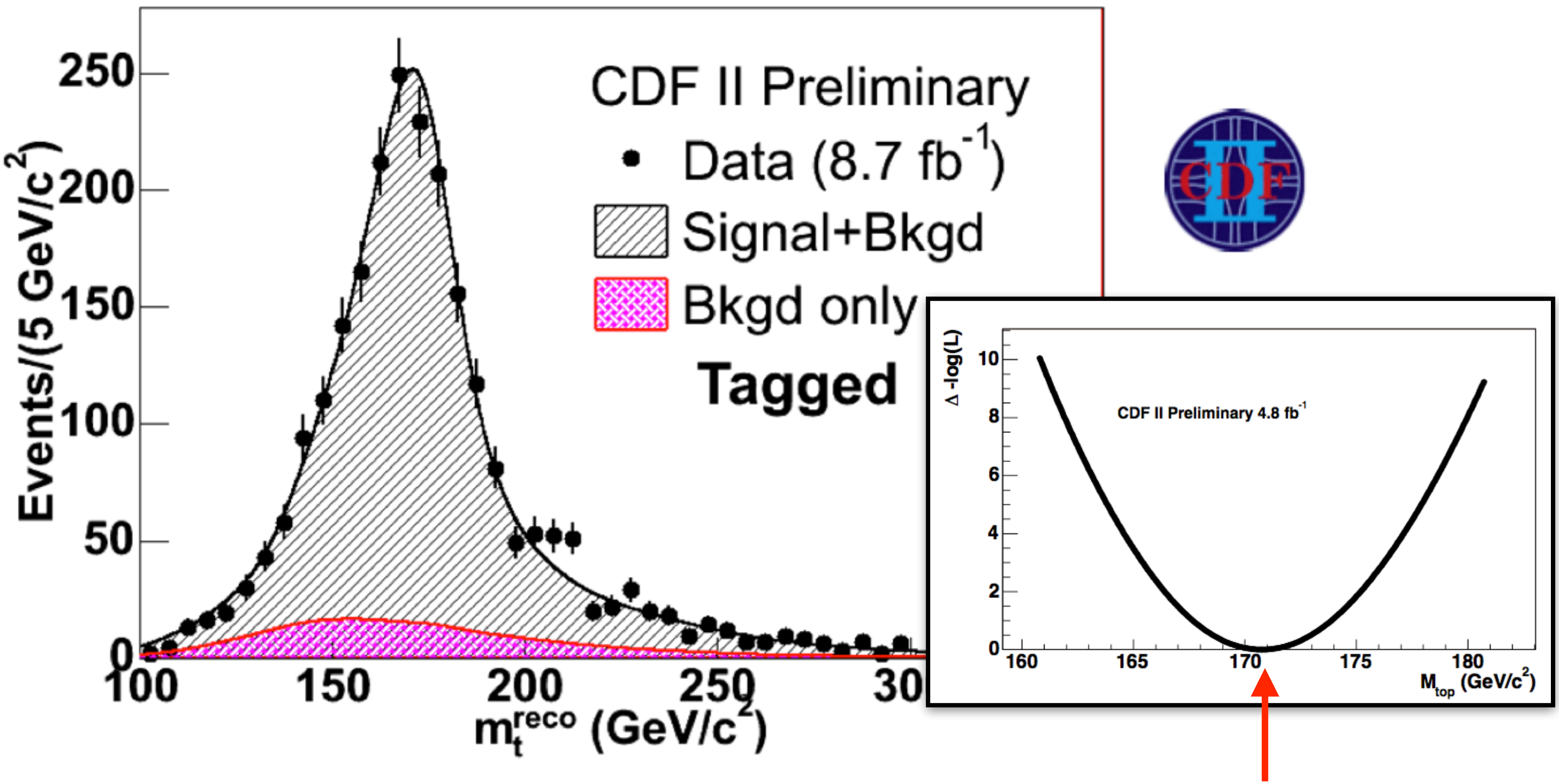
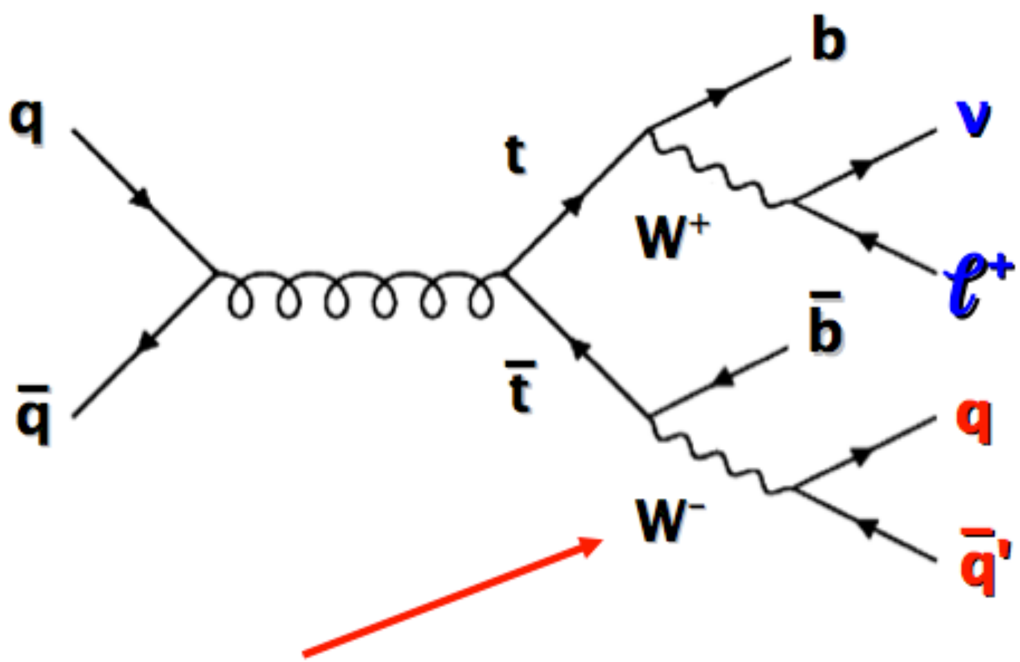


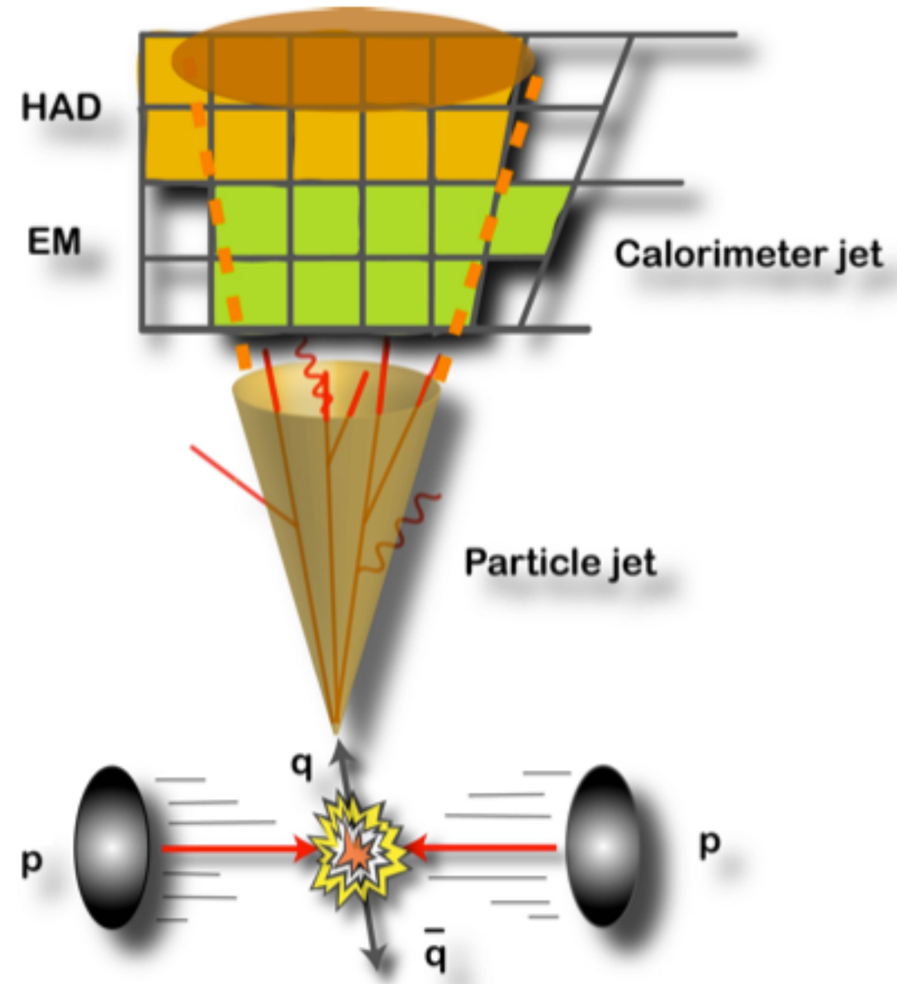
JES calibration



W mass constrains jet energy scale

jet energy scale:

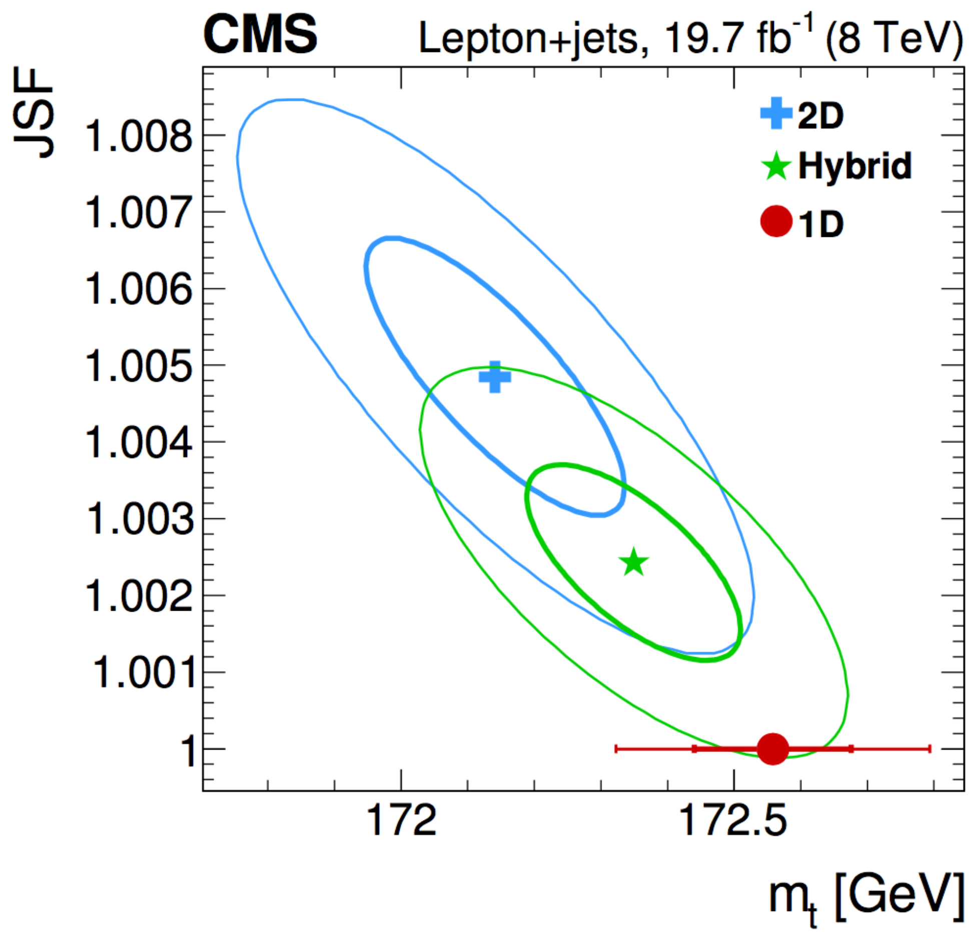
translate jet into parton energy



Result in l+jets Channel

jet energy scale:

translate jet into parton energy



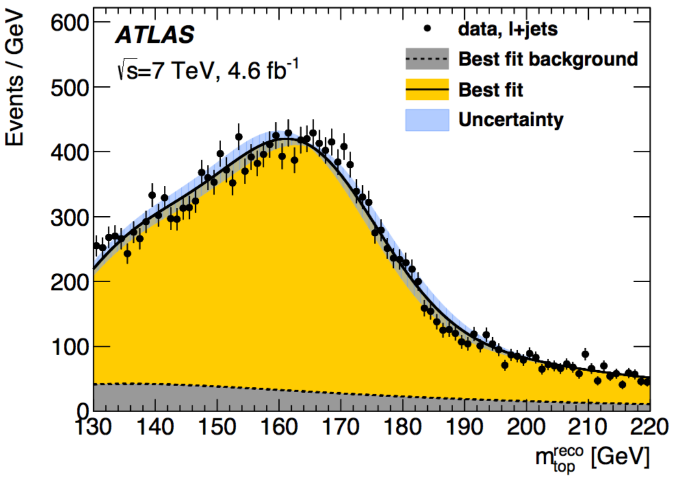
maximum likelihood fit to data

$$m_t^{\text{hyb}} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\ \text{GeV}$$

±0.29%

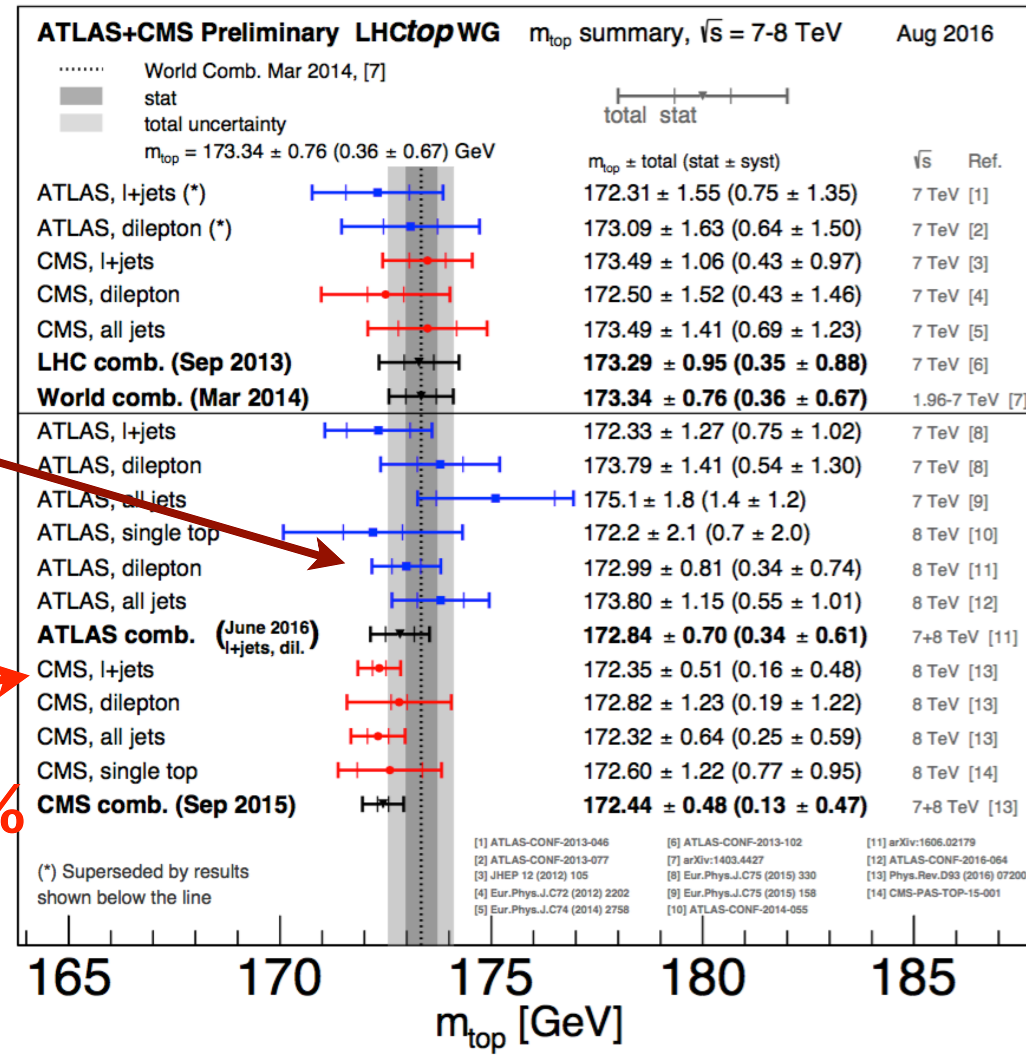
most precise single measurement

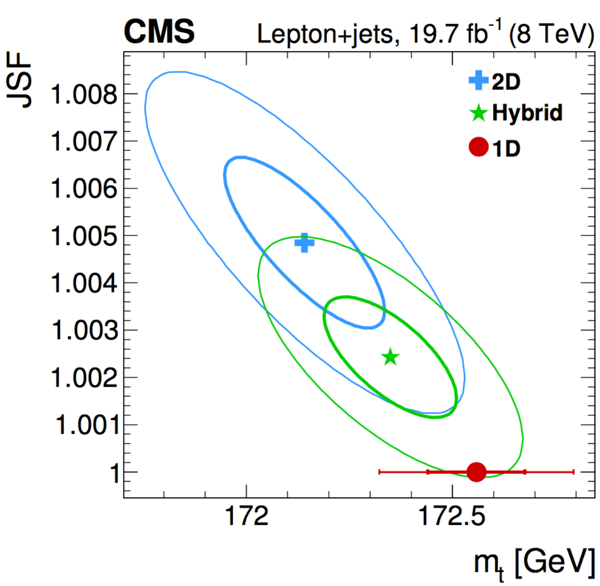
Top mass at the LHC



dilepton
±0.49%

$$m_{top} = 172.99 \pm 0.41\,(\text{stat}) \pm 0.74\,(\text{syst})\ \text{GeV}$$





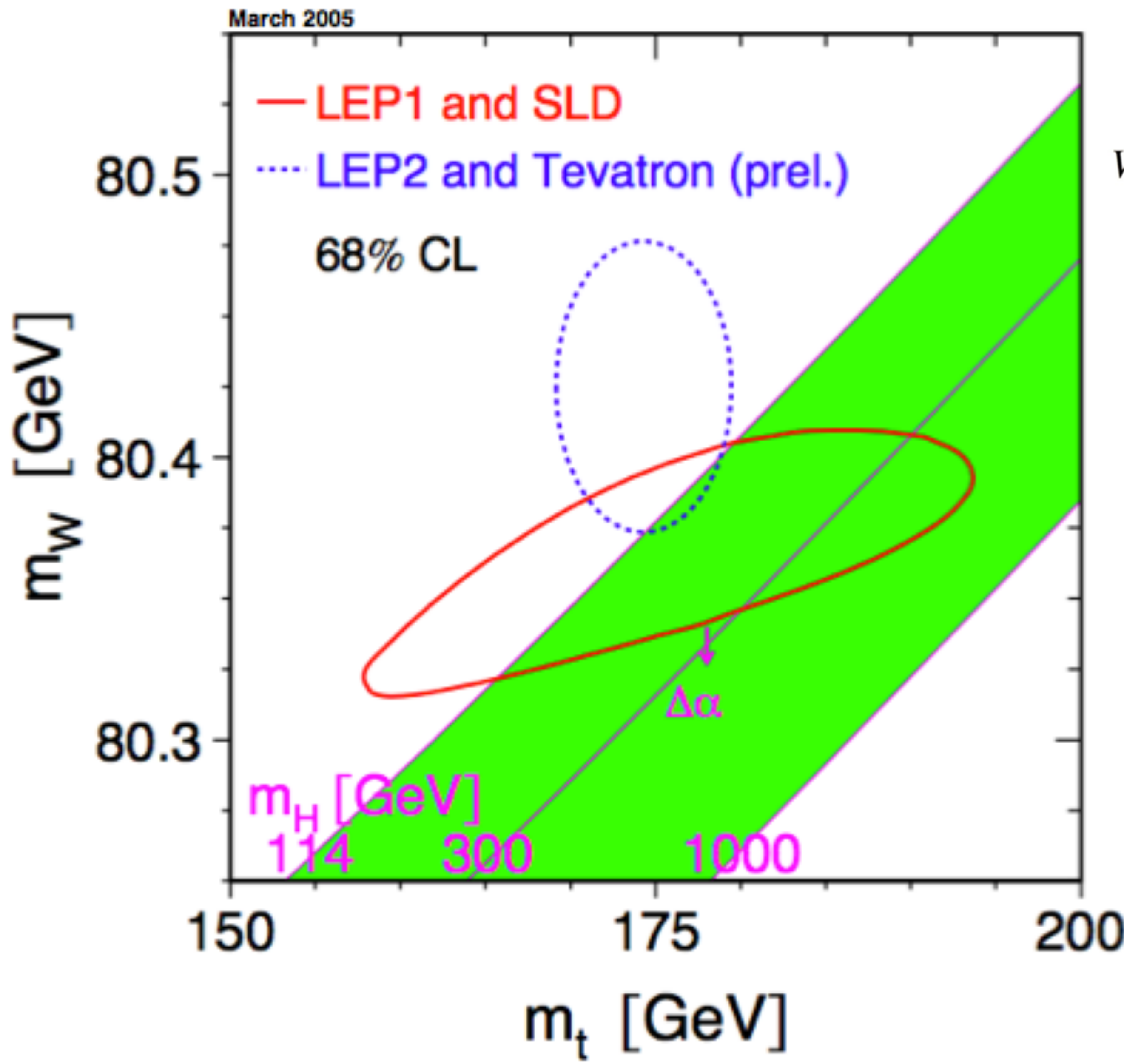
±0.28%

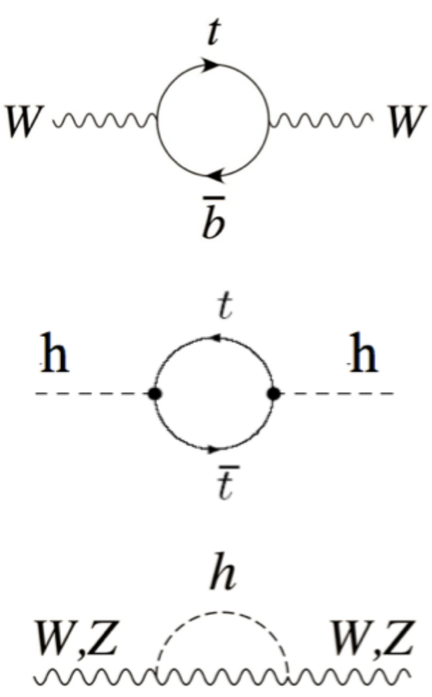
l+jets
±0.29%

$$m_t^{\text{hyb}} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\ \text{GeV}$$

→ jet energy scale is crucial

History m_{top} vs. M_W





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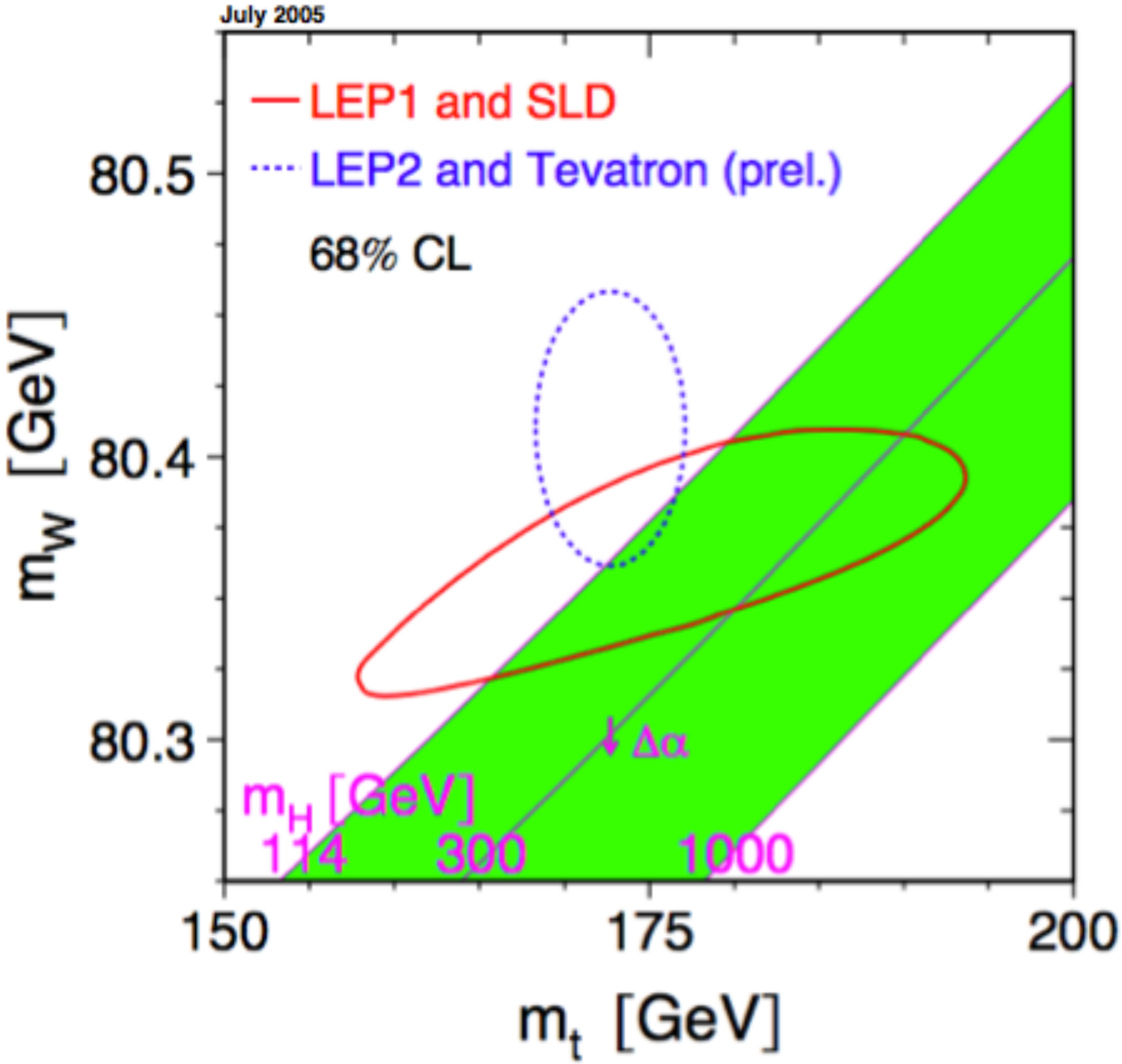

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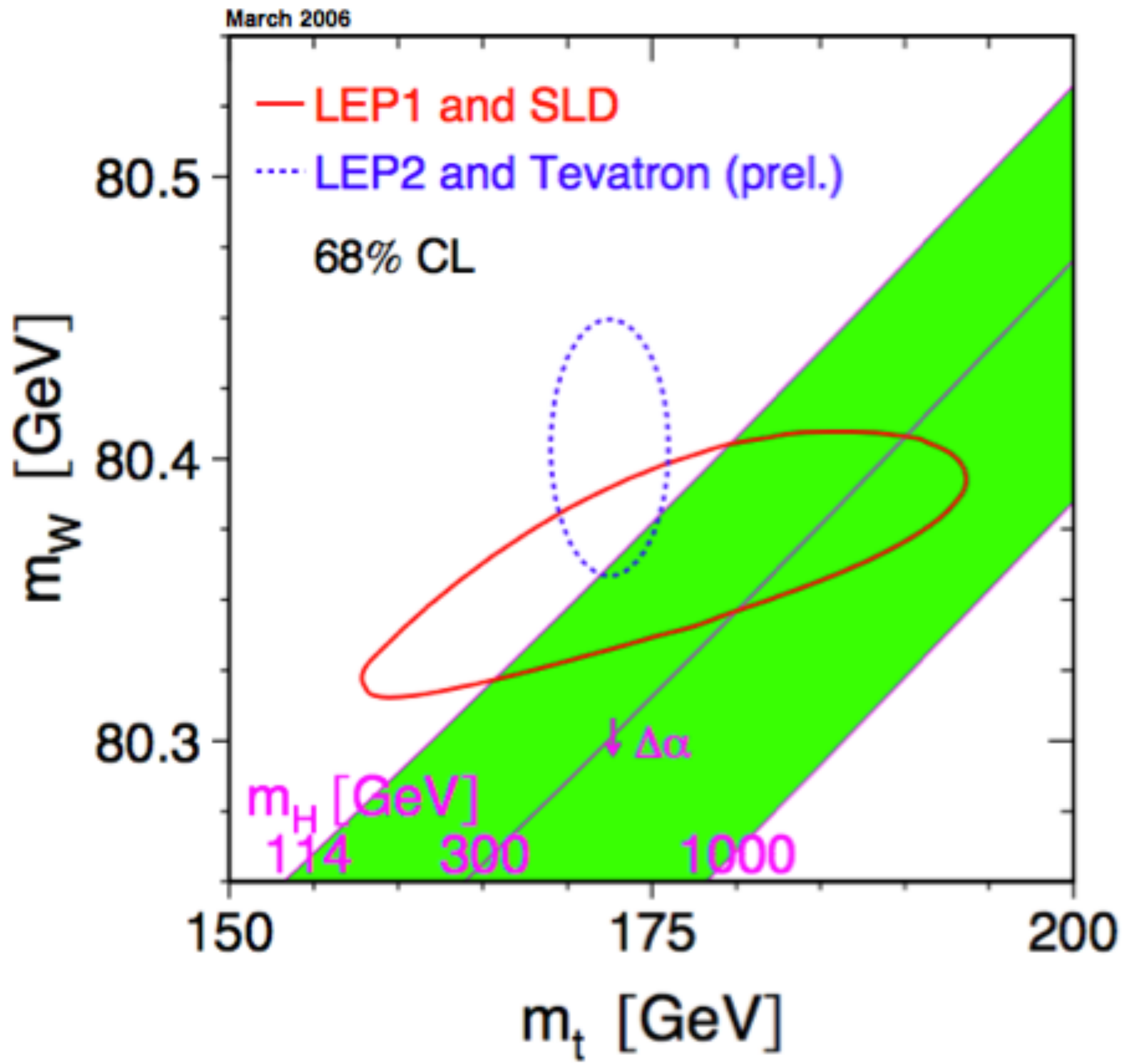

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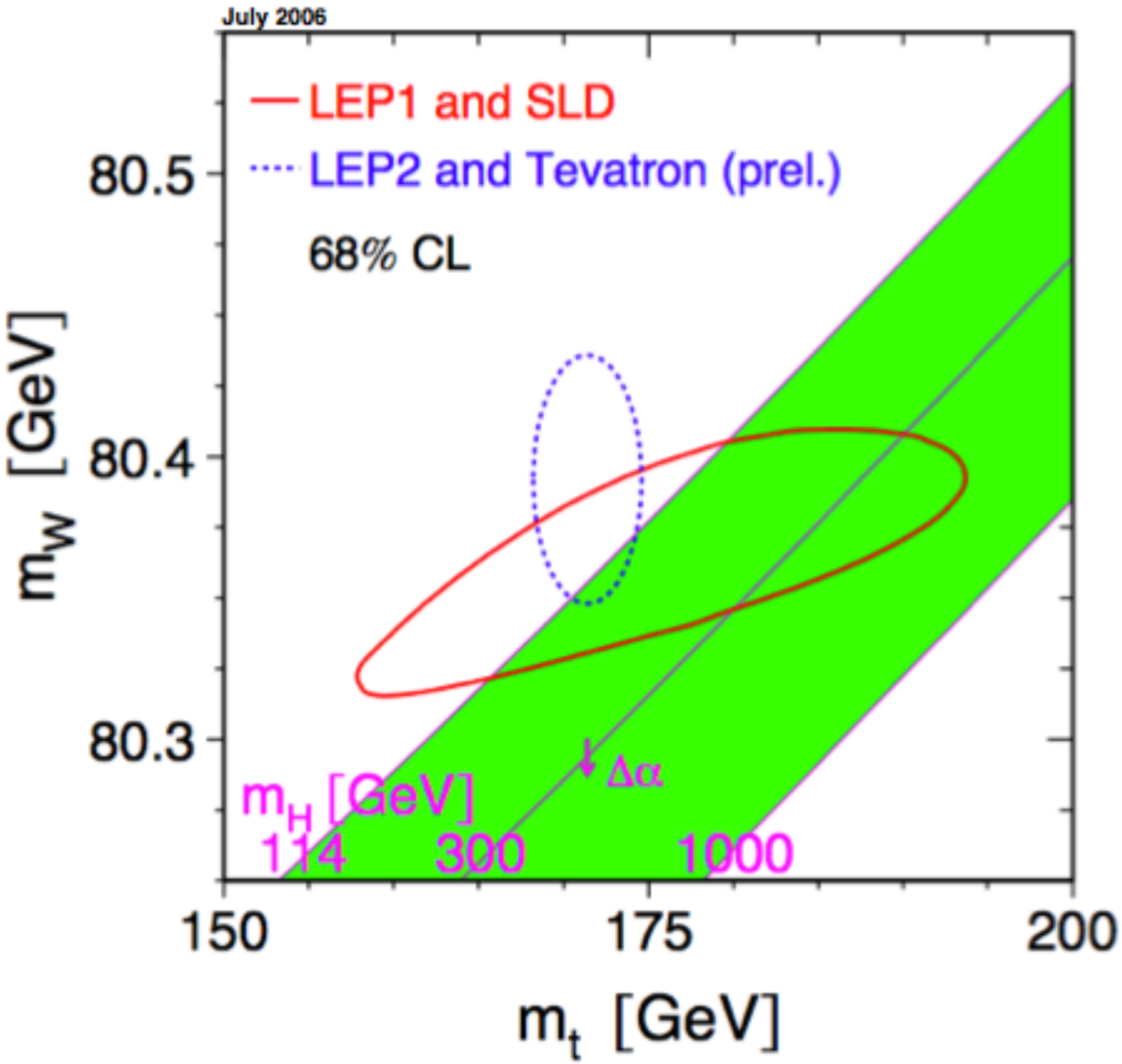

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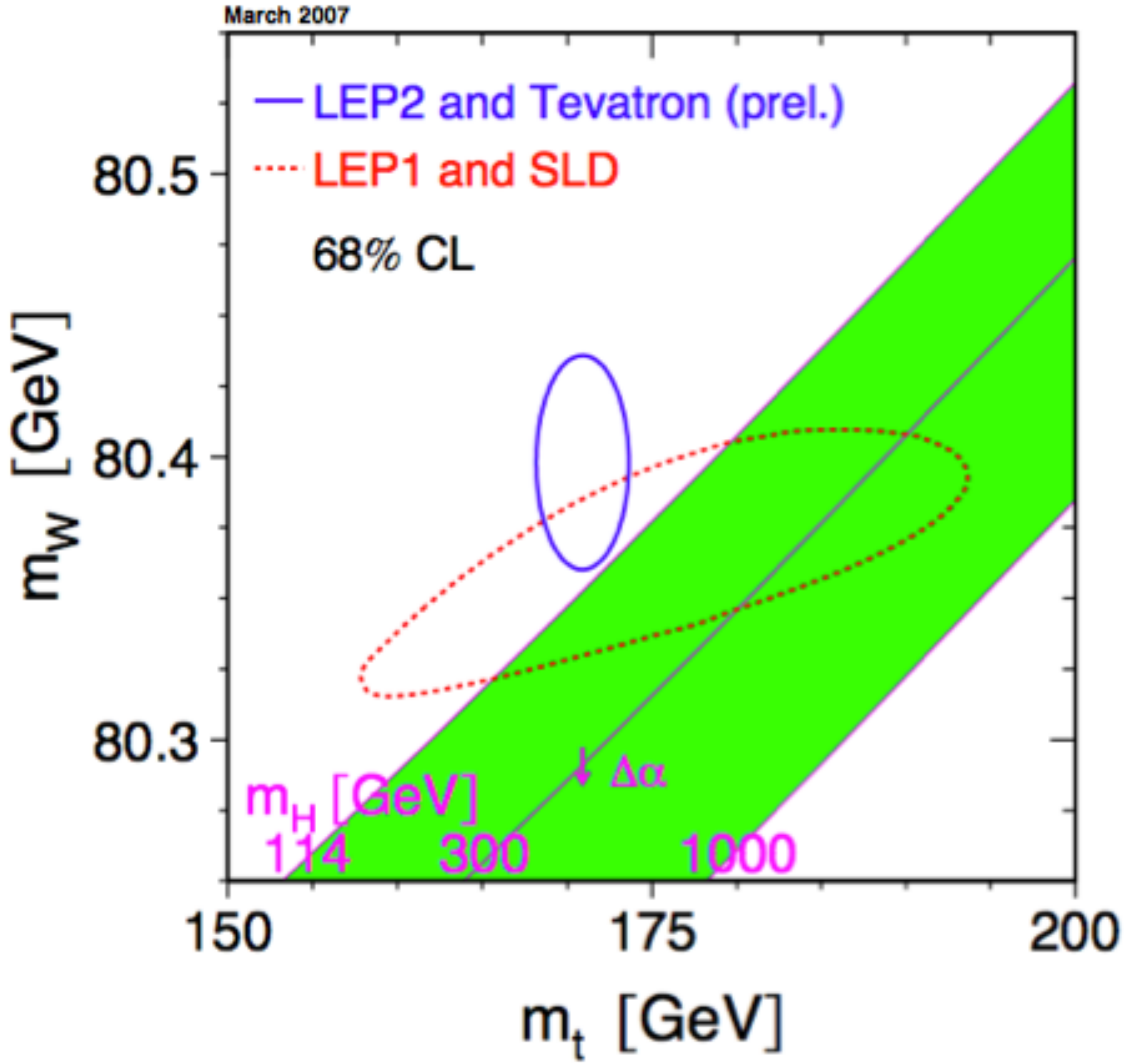
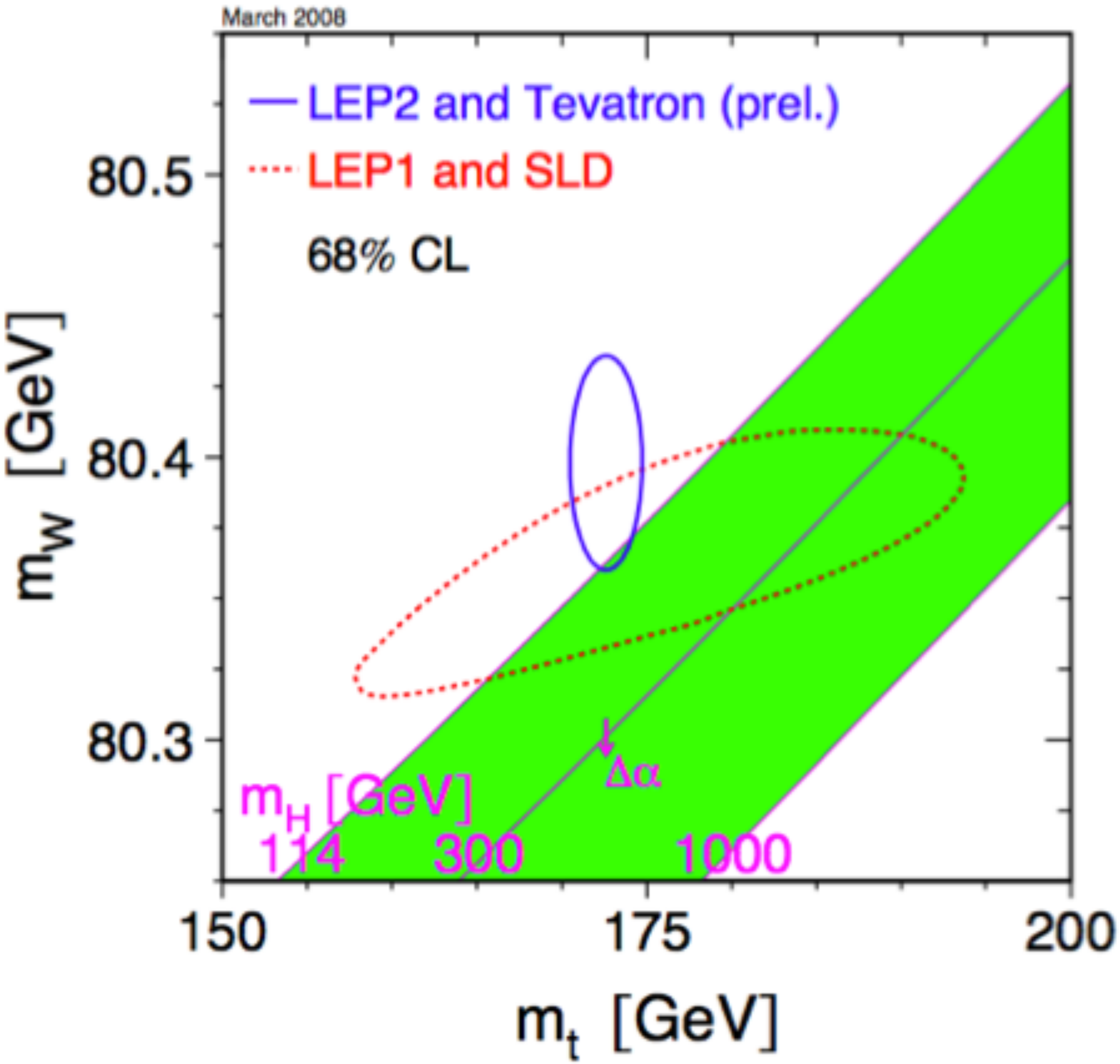
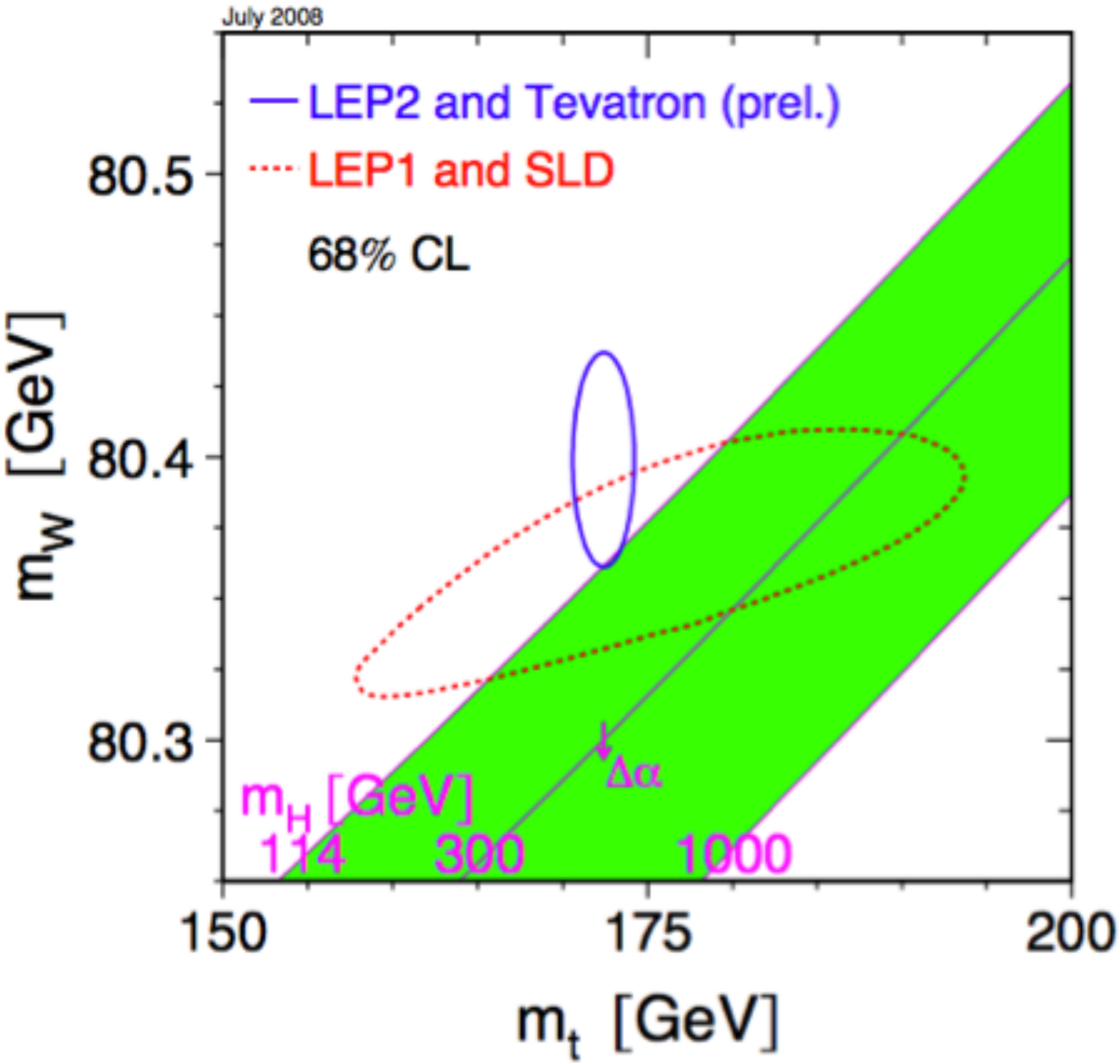


History m_{top} vs. M_W



History m_{top} vs. M_W



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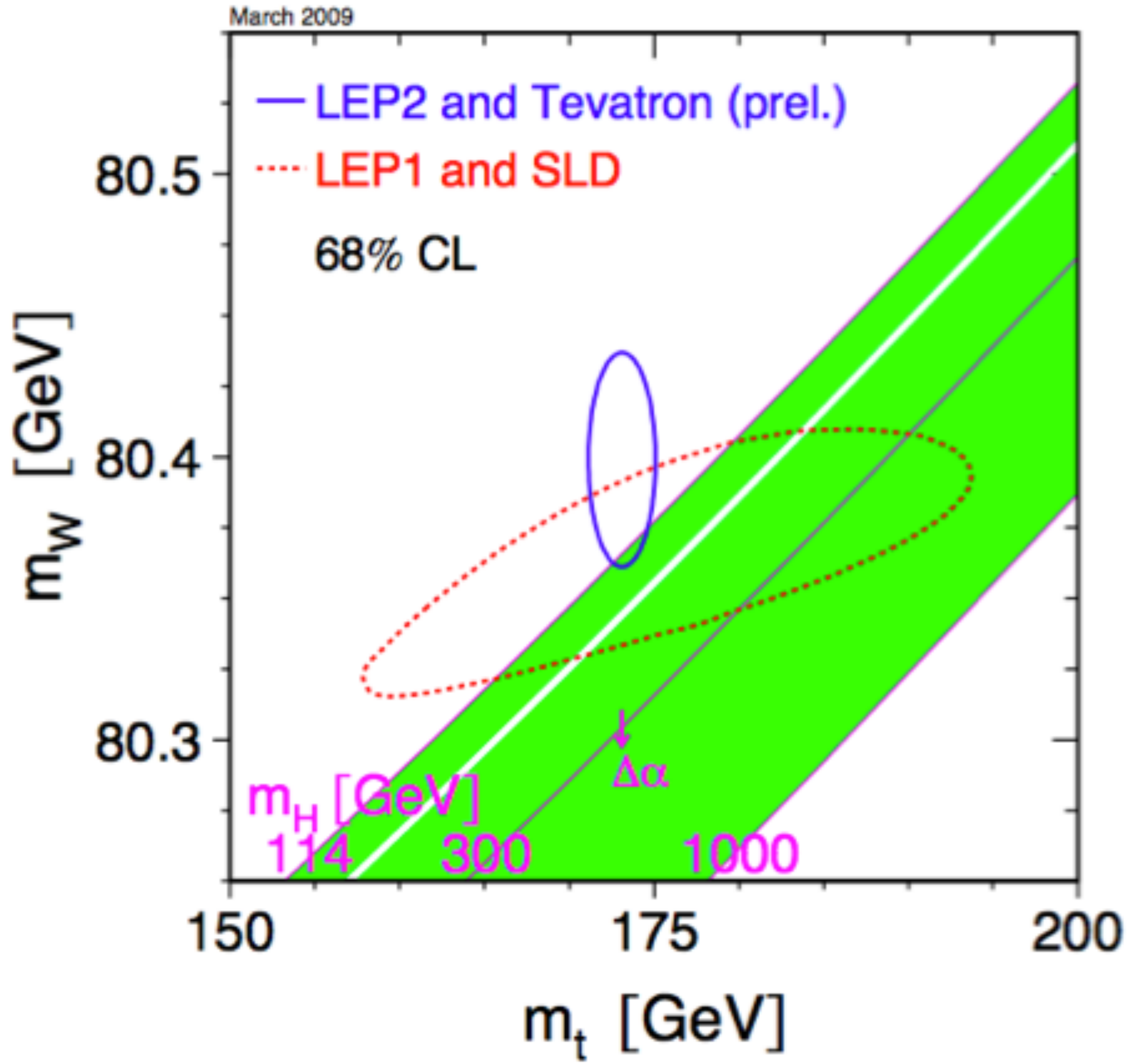
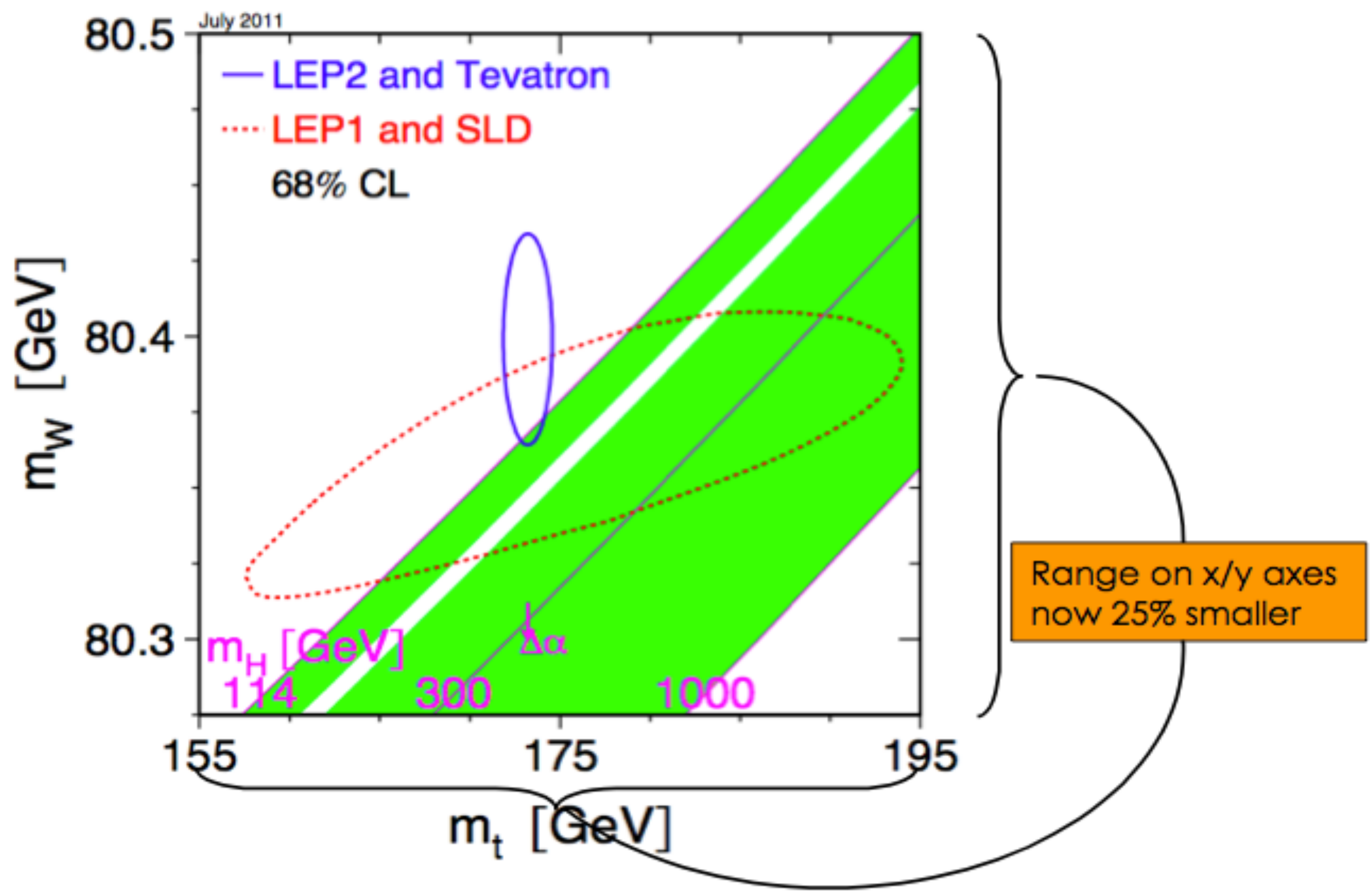


History m_{top} vs. M_W



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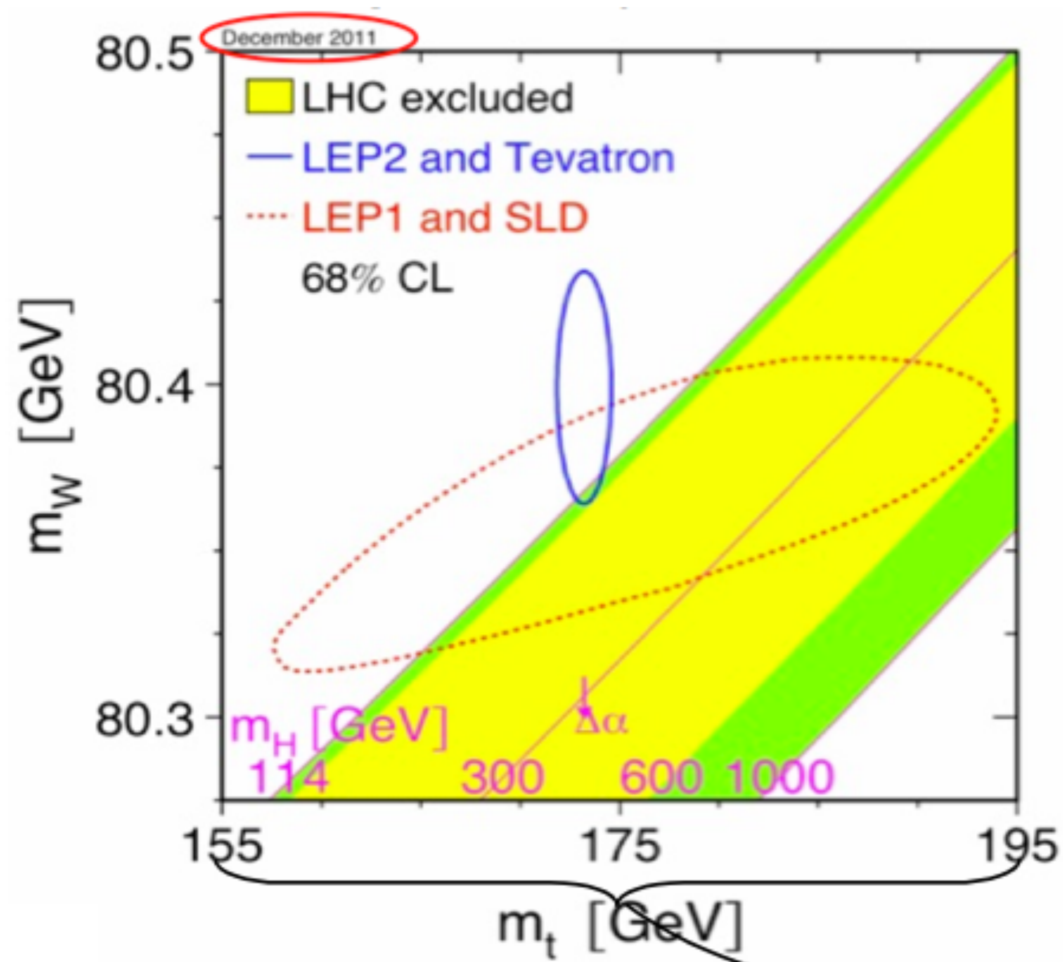
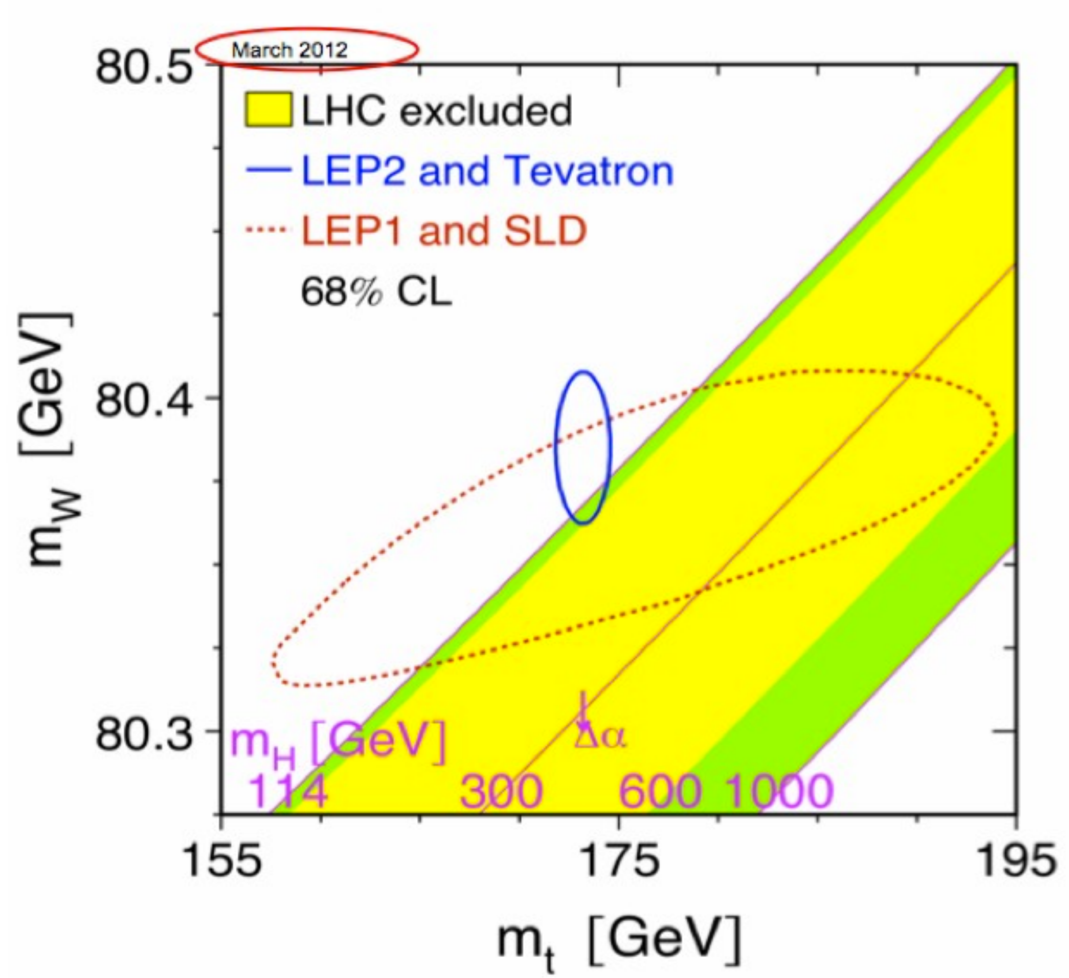


Range on x/y axes now 25% smaller

History m_{top} vs. M_W



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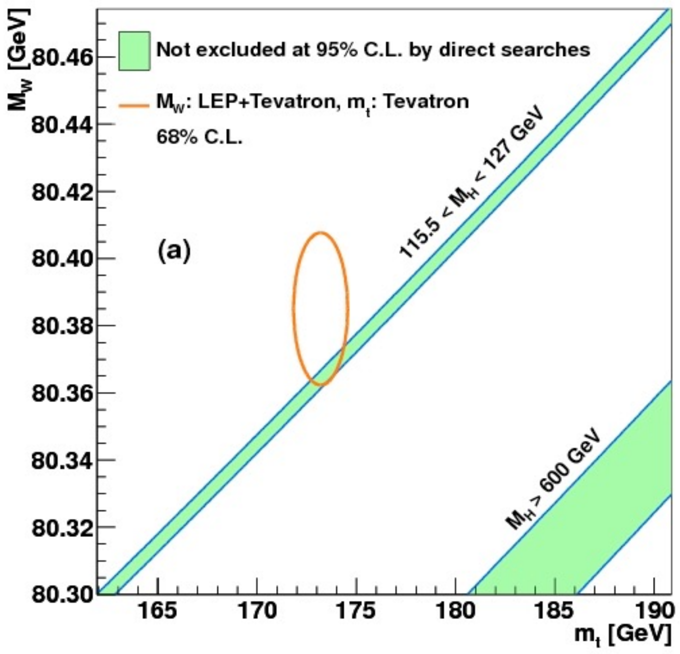
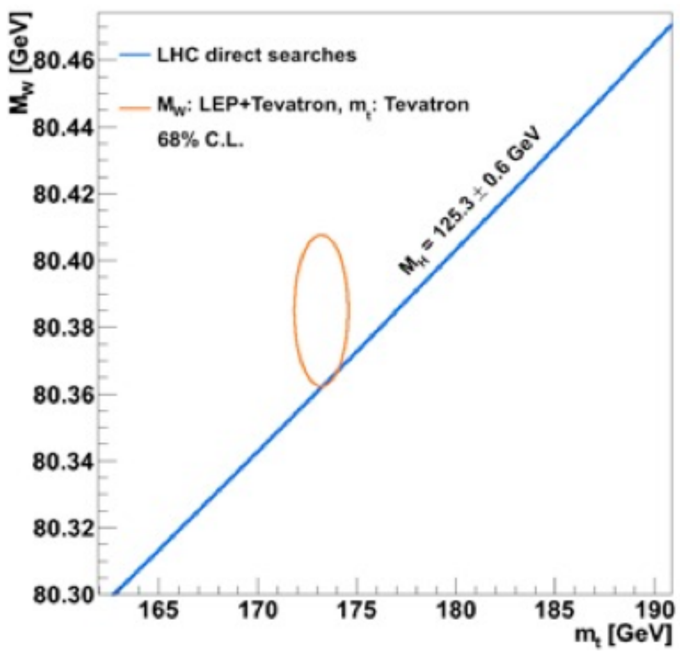


History m_{top} vs. M_W

July 2012

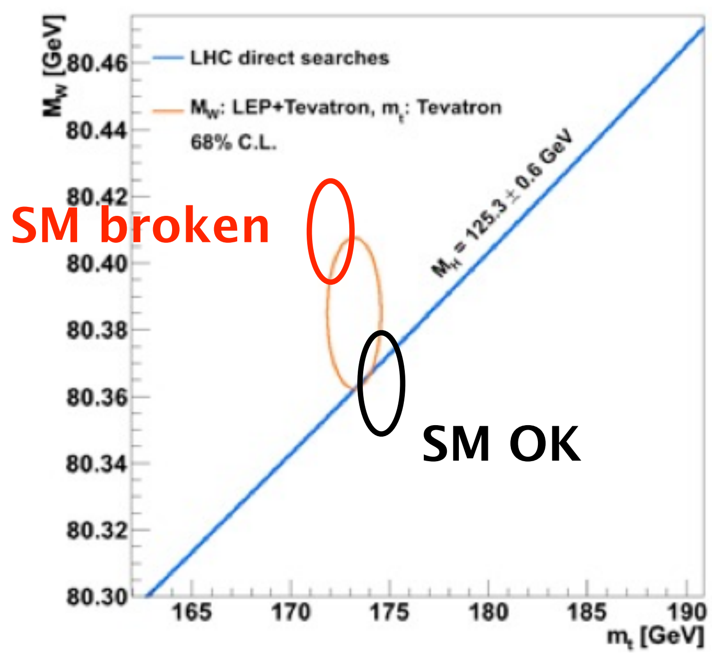


→ Standard Model is self-consistent

History m_{top} vs. M_W

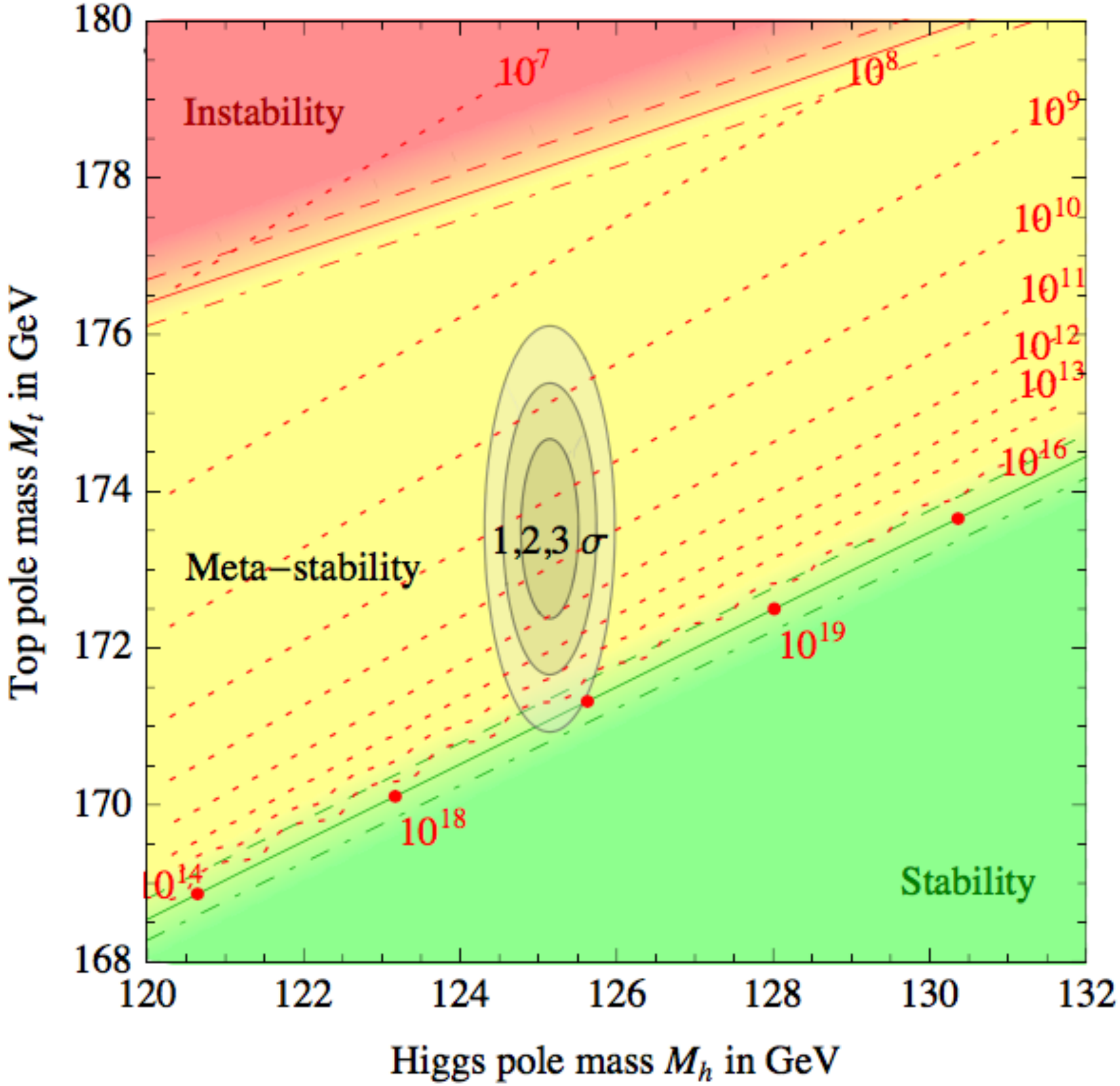
future:
$\Delta(m_W)$=6 MeV

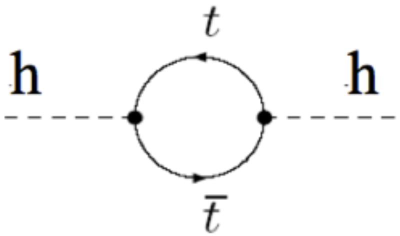
July 2012



improved W mass measurement is critical

m_{top} vs. M_H





check the "fate of the Universe"

What mass do we measure?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

m_{top}

- **LO QCD: free parameter**
- **NLO QCD: dependent on the renormalisation scale M**

"Bare" parameters of QCD:

$$g_s,\ m_u,\ m_d,\ m_s,\ m_c,\ m_b,\ m_t$$

Renormalised parameters of QCD:

$$g_s(M),\ m_u(M),\ m_d(M),\ m_s(M),\ m_c(M),\ m_b(M),\ m_t(M)$$

the concept of quark mass is convention-dependent!

Different Top Mass Definitions

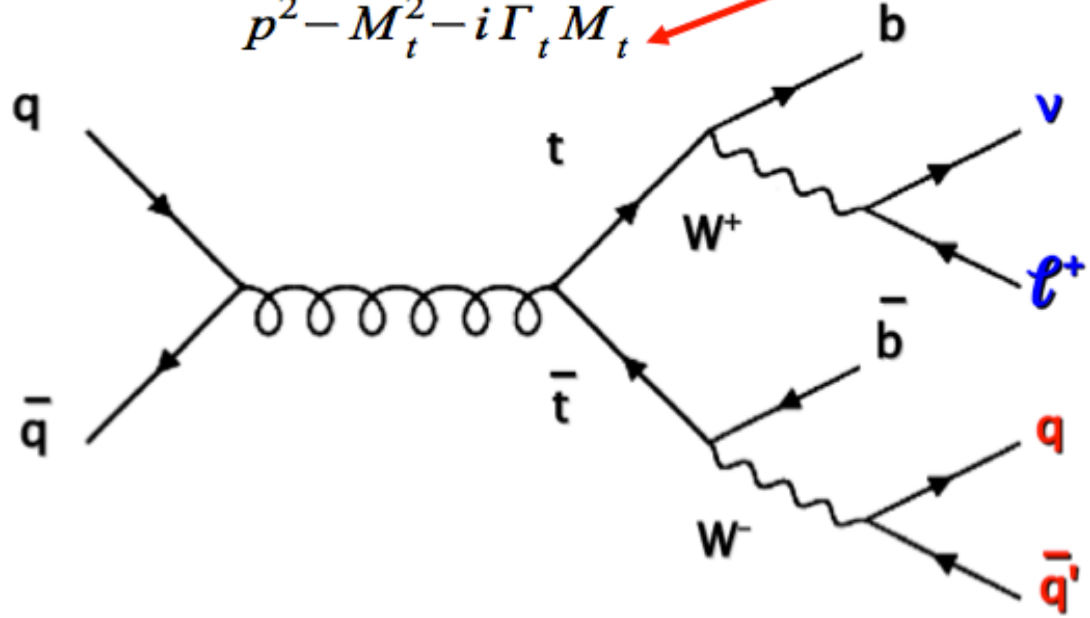
hep-ph/0001002

$$\overline{m}_t \equiv m_t^{\overline{\rm MS}}\ (m_t) = \frac{M_t}{1+\frac{4}{3\pi}\alpha_s(M_t)}$$

pole mass

$\overline{\rm MS}$ scheme

$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$



→ difference between $\overline{\rm MS}$ and pole mass is ≈10 GeV...

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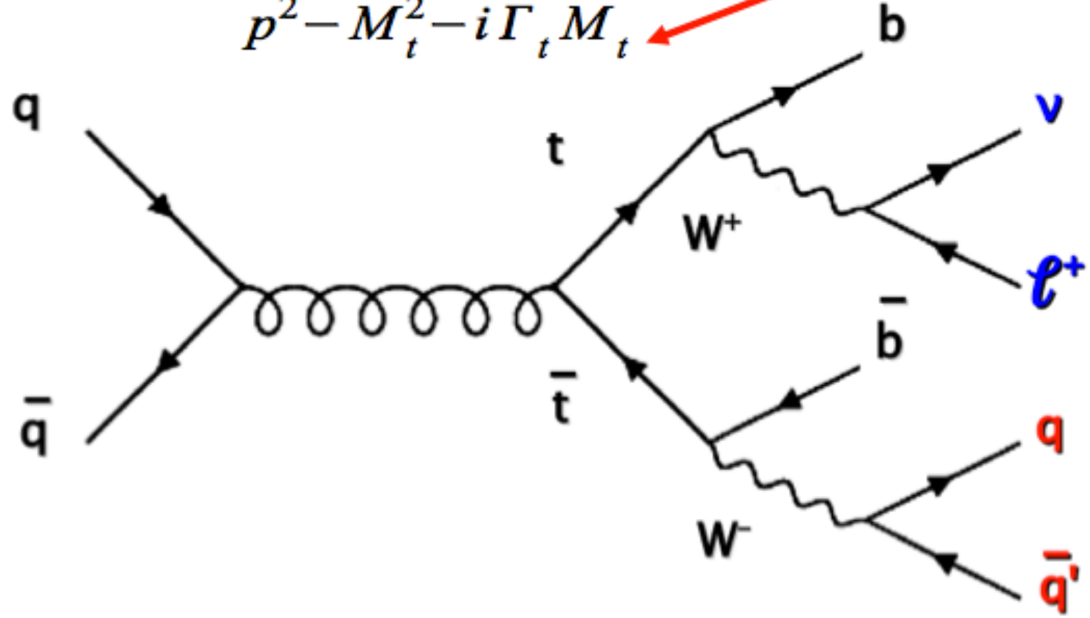
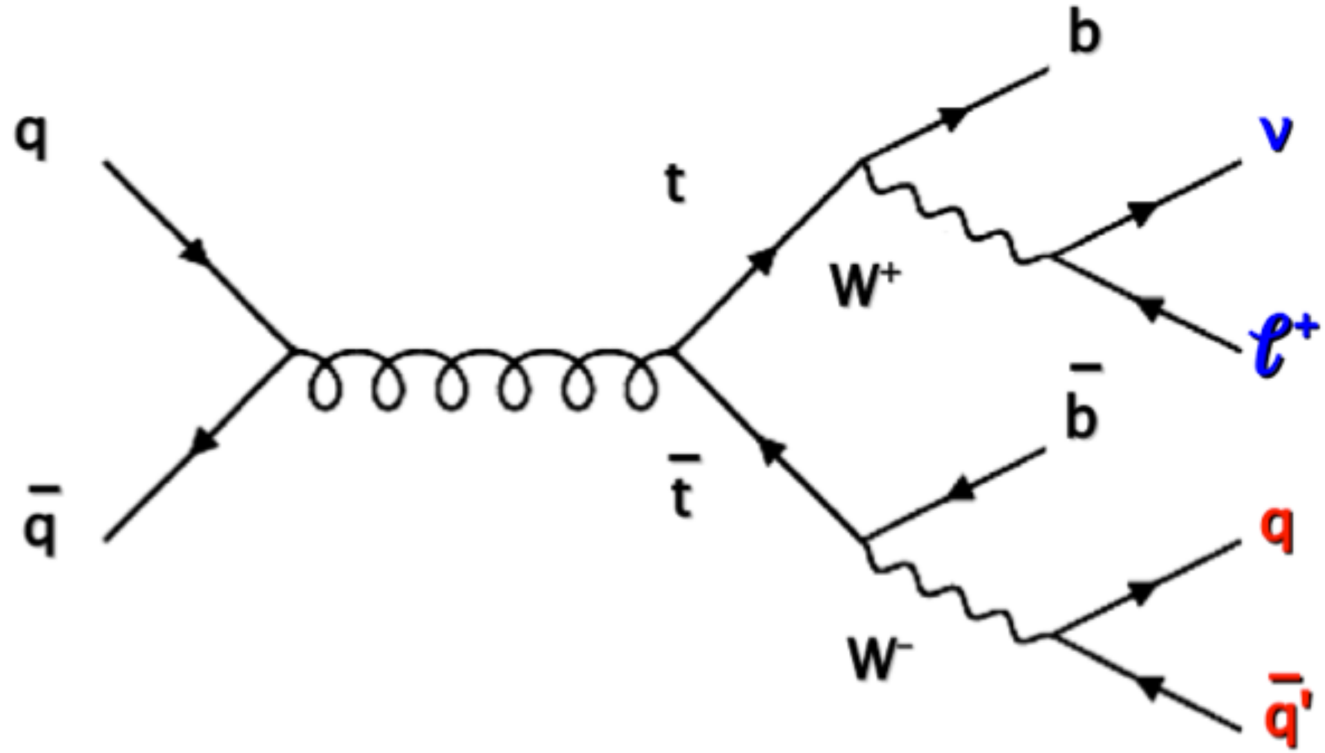


→ difference between $\overline{\mathrm{MS}}$ and pole mass is ≈10 GeV...

- measurement reconstructing decay products: depends on MC mass details
- how does MC mass relate to pole mass or running mass scheme?

Which Top Mass Does a LO MC Contain?

- matrix element in LO QCD



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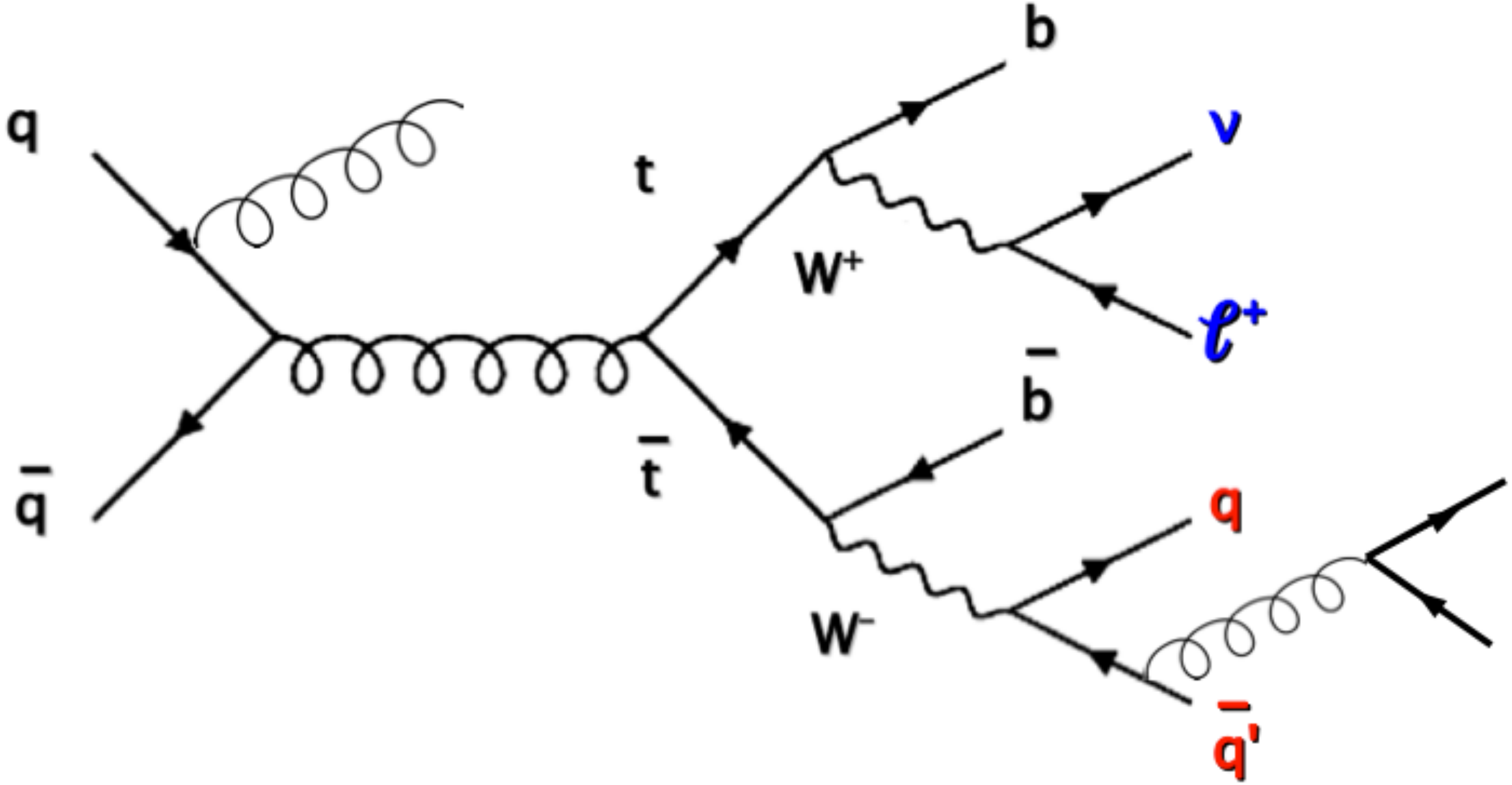

- parton showers simulate higher orders,

Which Top Mass Does a LO MC Contain?

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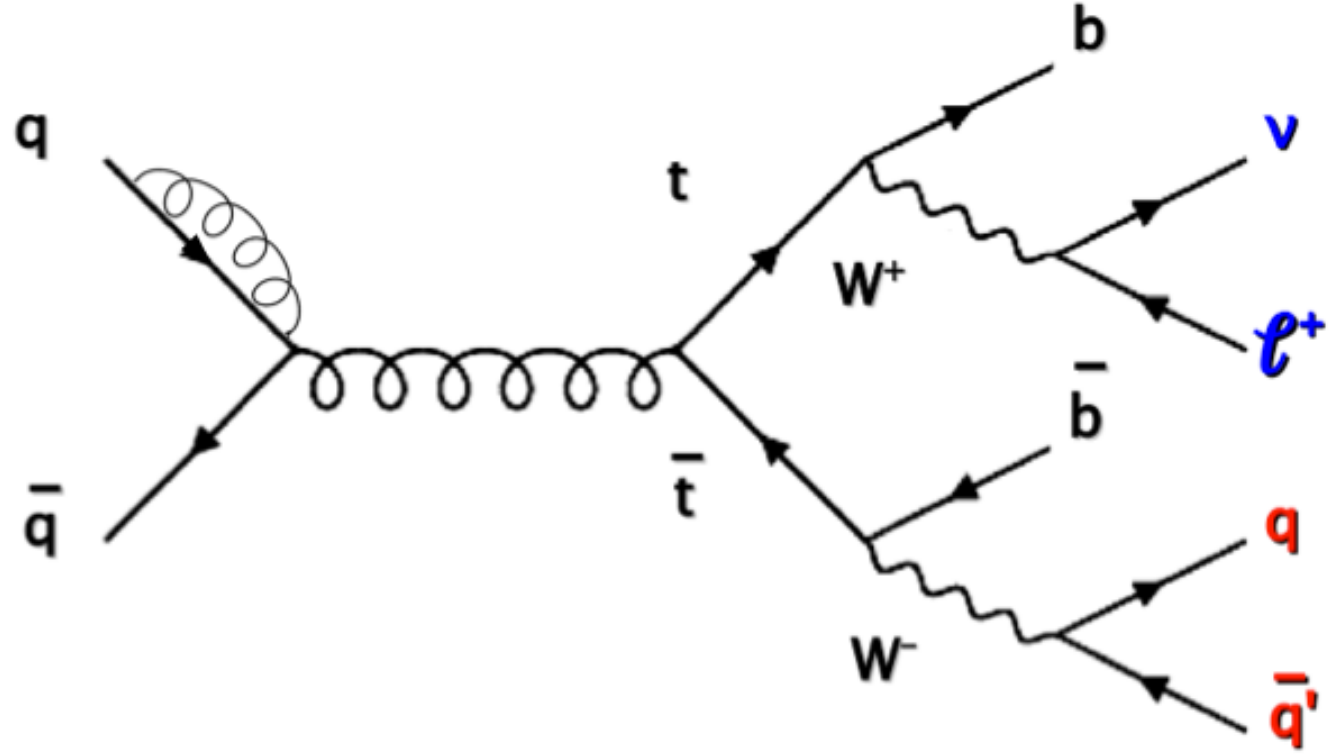

- parton showers simulate higher orders, i.e. not only radiating additional gluons!

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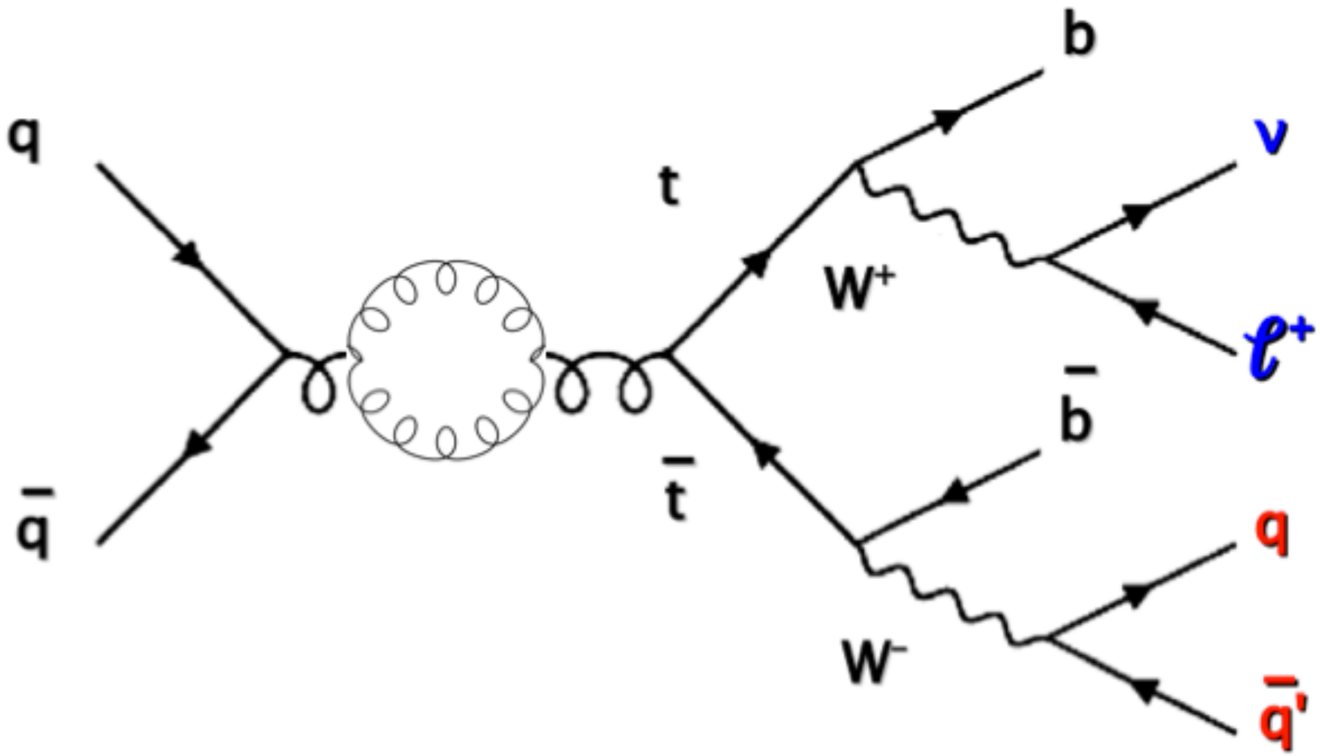

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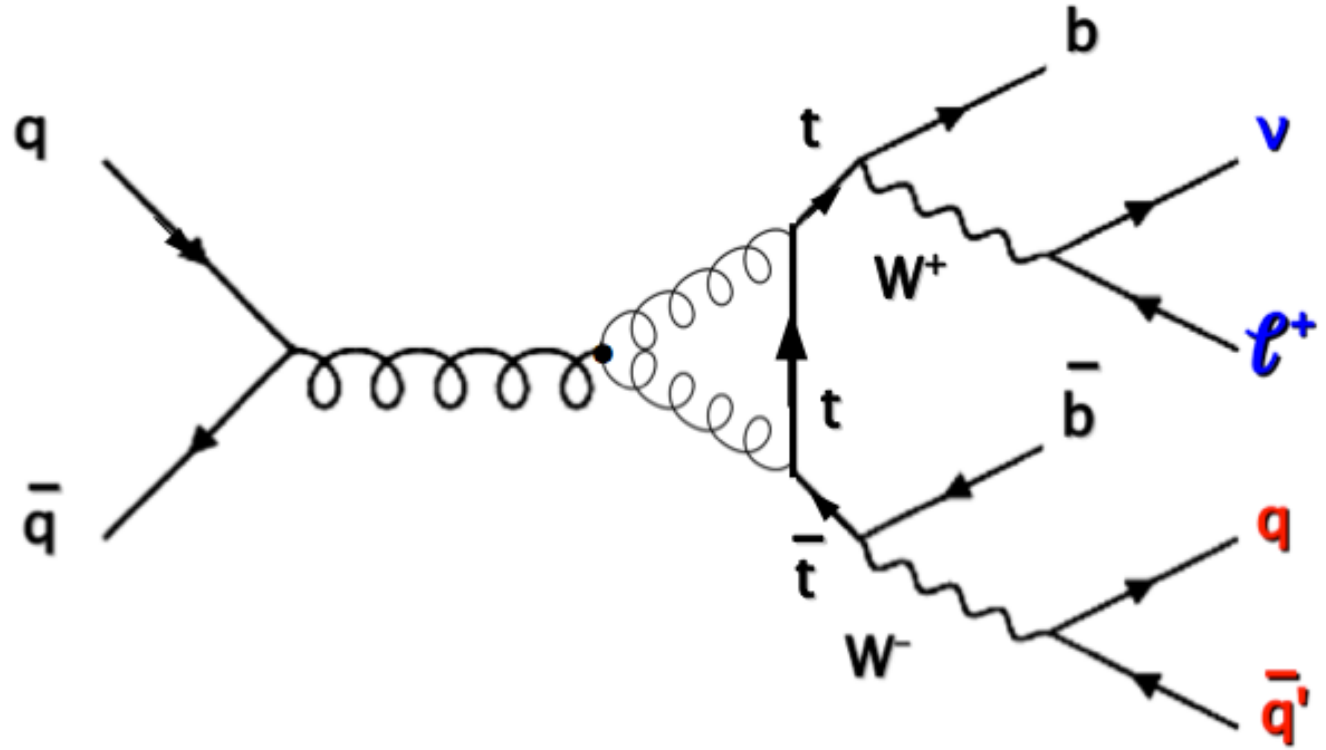

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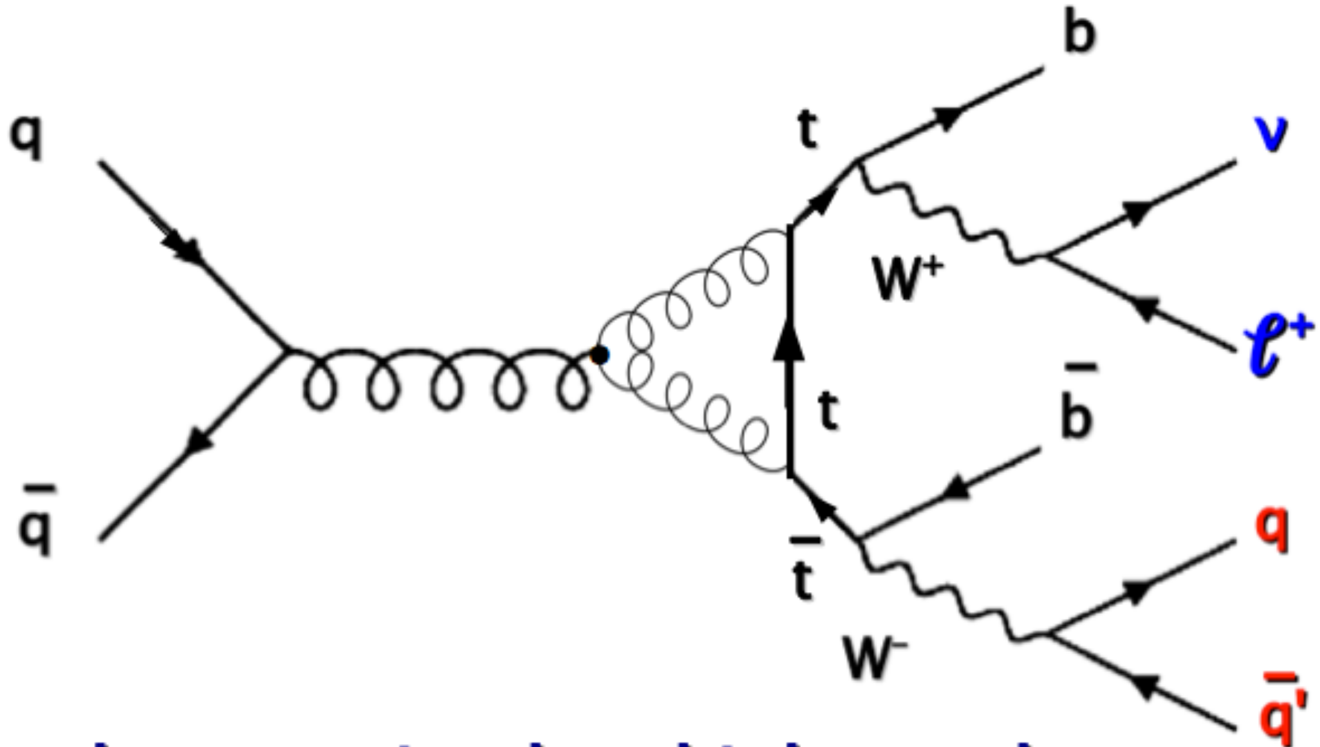
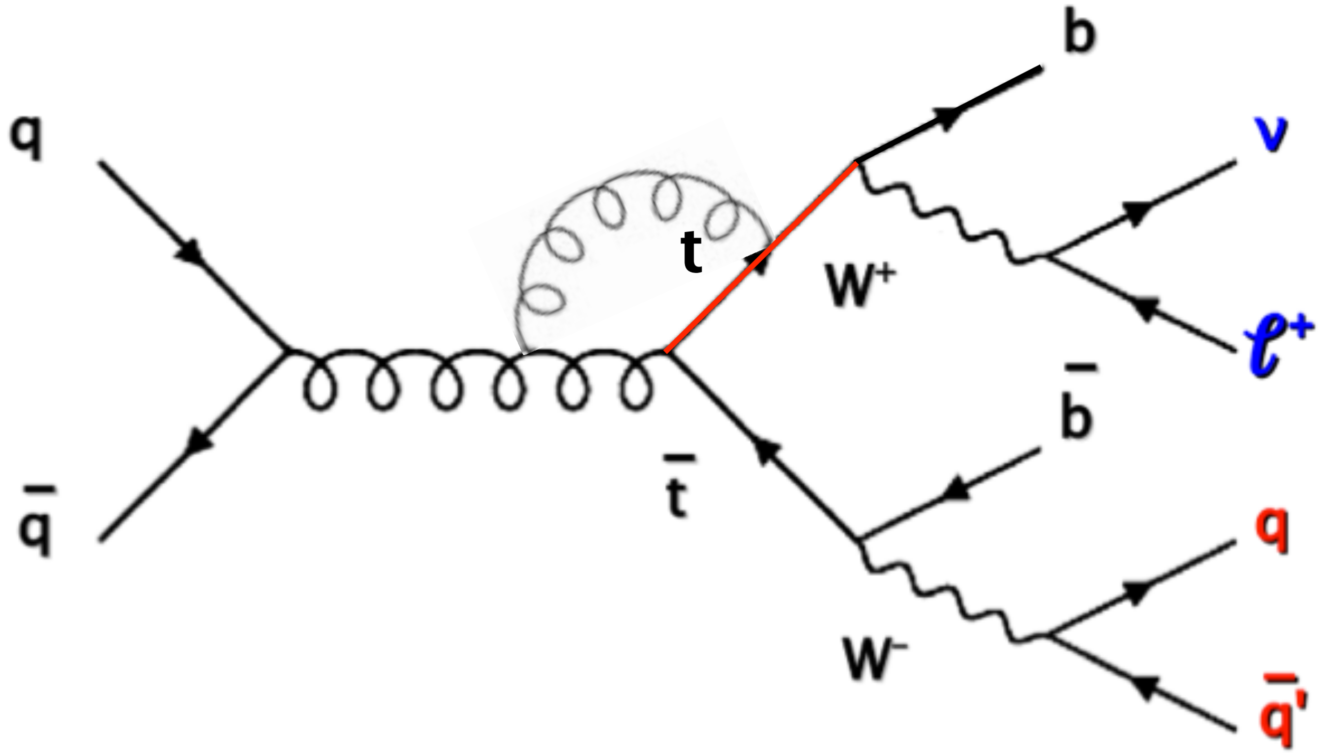


- parton showers simulate higher orders, i.e. not only radiating additional gluons!

$\Rightarrow$ VERY DIFFICULT TO SAY...

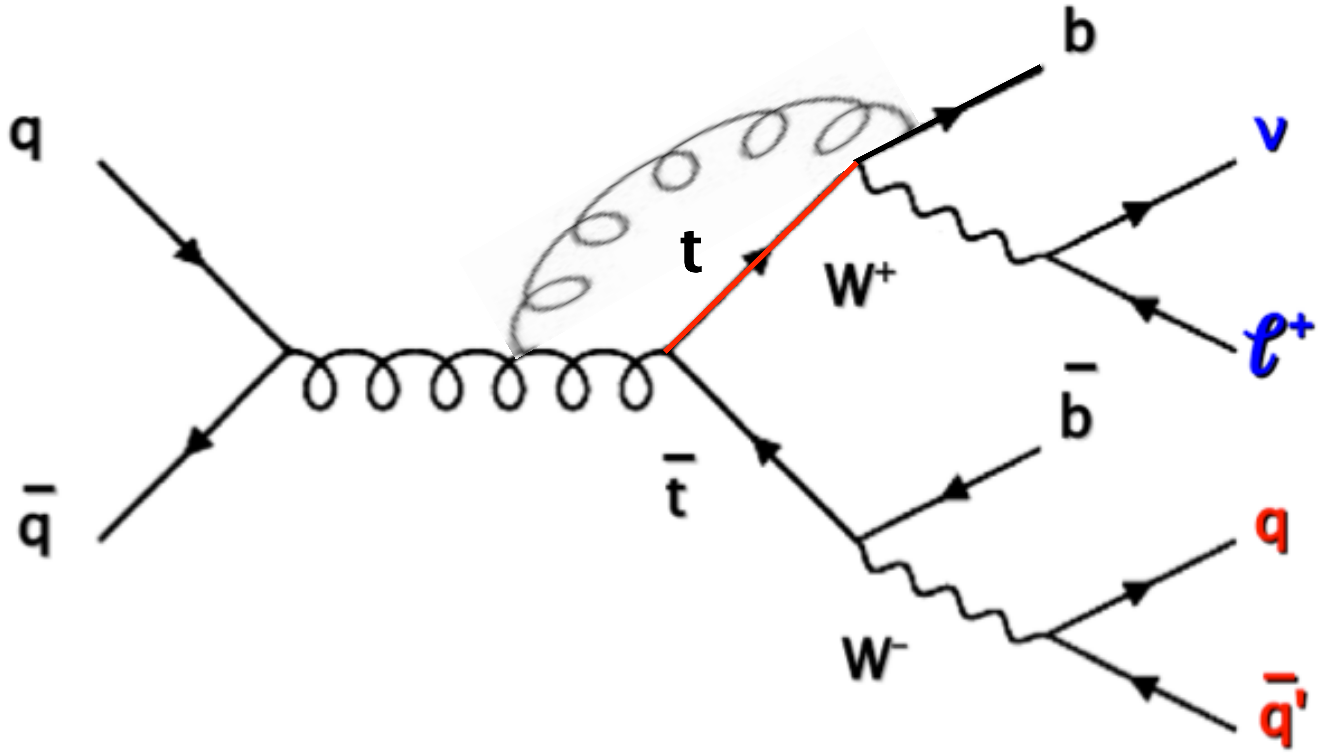
- arguments that it should be close to pole mass

Do NLO MCs Contain Mass information?



- Powheg, MC@NLO have contributions like this, but then the on-shell top quark decay is simulated by a Breit-Wigner function

Do NLO MCs Contain Mass information?

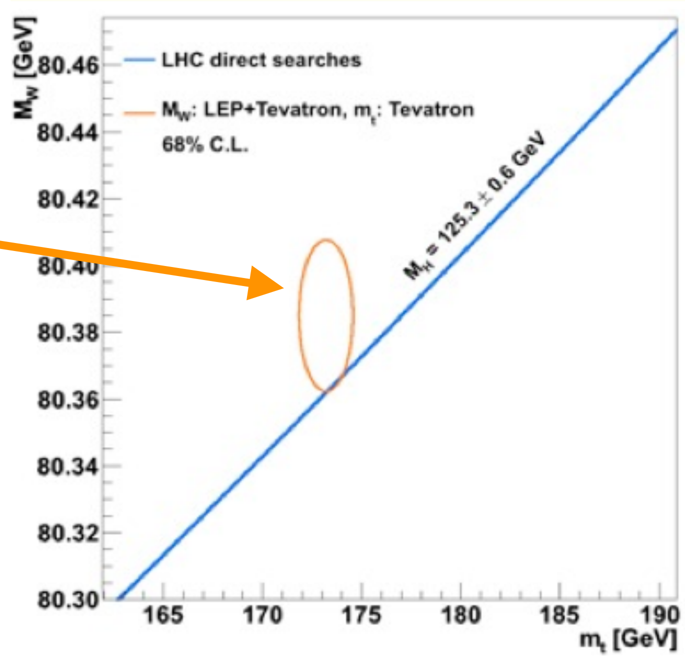


- only if they have contributions like this, since top quark propagator needs to be renormalized
- contributions can be of order $\sim\Gamma_t$=1.35 GeV (at world average top mass)
  → it matters!
- has become available recently (only for dilepton final states...)

Important to Know...

July 2012

pole mass

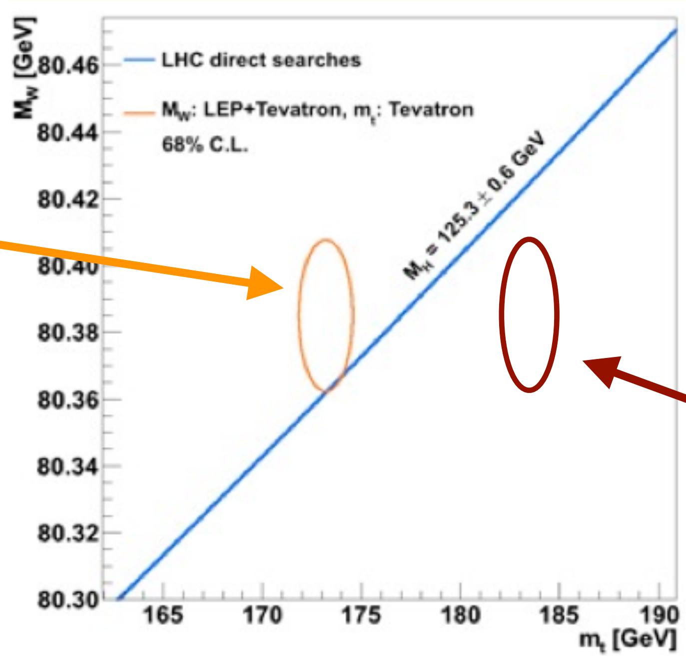


→ Standard Model is self-consistent

Important to Know...

July 2012

pole mass



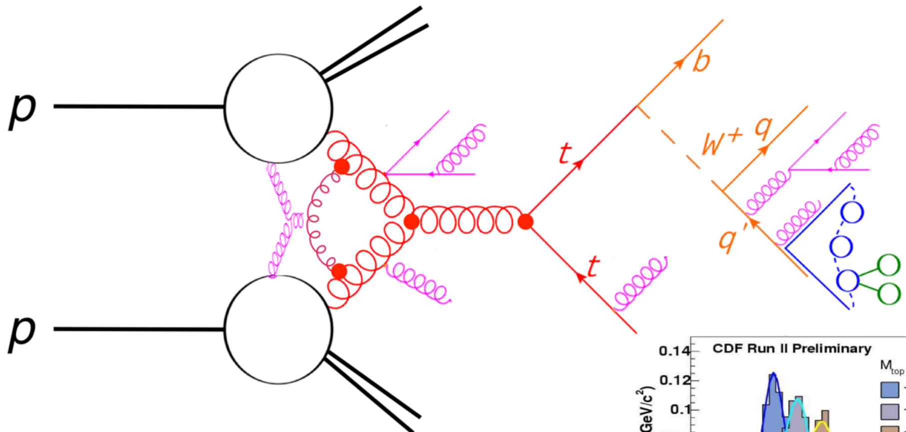
world average interpreted as $\overline{\text{MS}}$ mass

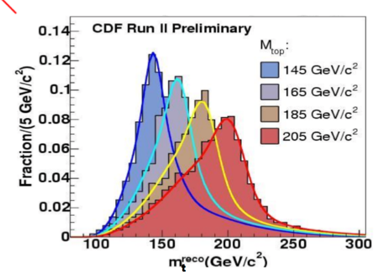
~10 GeV (3-loop)

→ Standard Model is self-consistent??

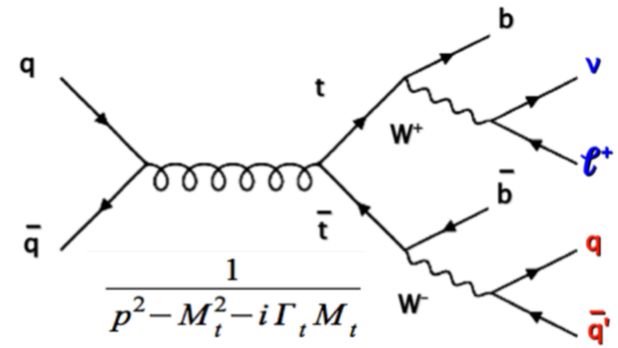
What mass do we need?

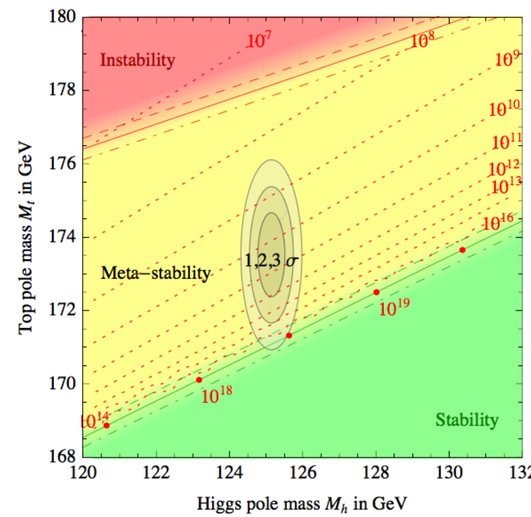
- we measure the MC mass





- we need the pole mass





- we need to calculate:

Scheme-dependent

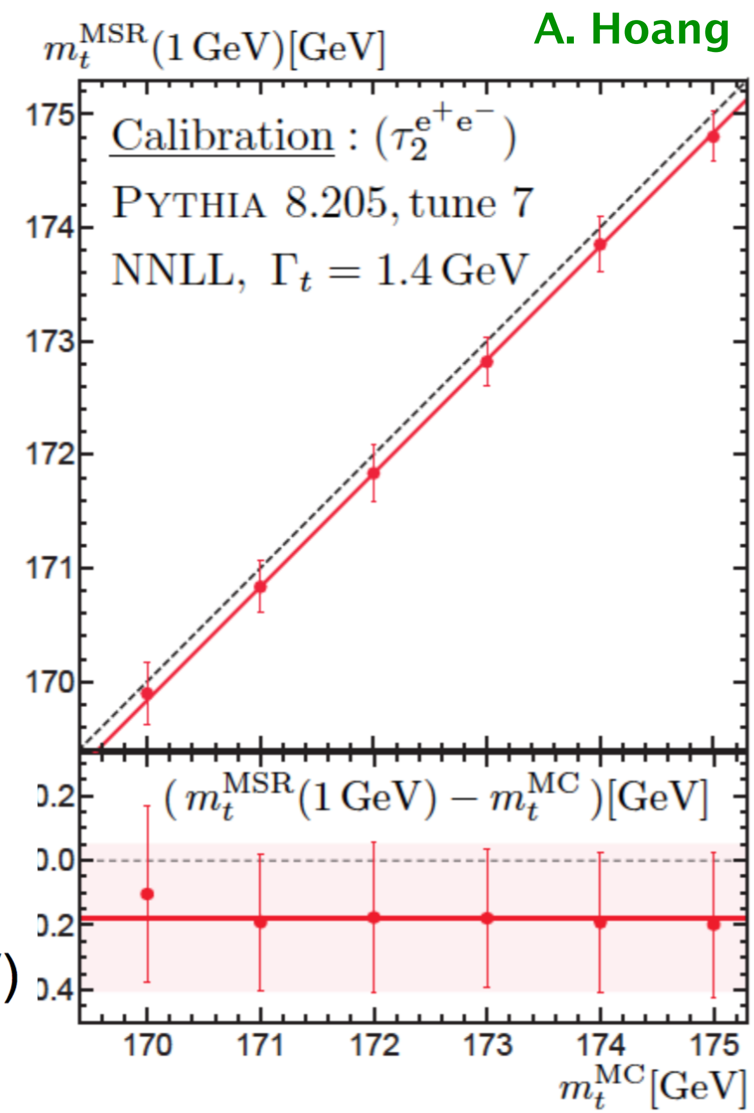
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{quark}} + \Delta$$

~ O(1 GeV)

e.g. pole mass

- every MC generator mass can can correspond to a different pole mass

Top mass interpretation



Scheme-dependent

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{quark}} + \Delta$$

~ O(1 GeV)

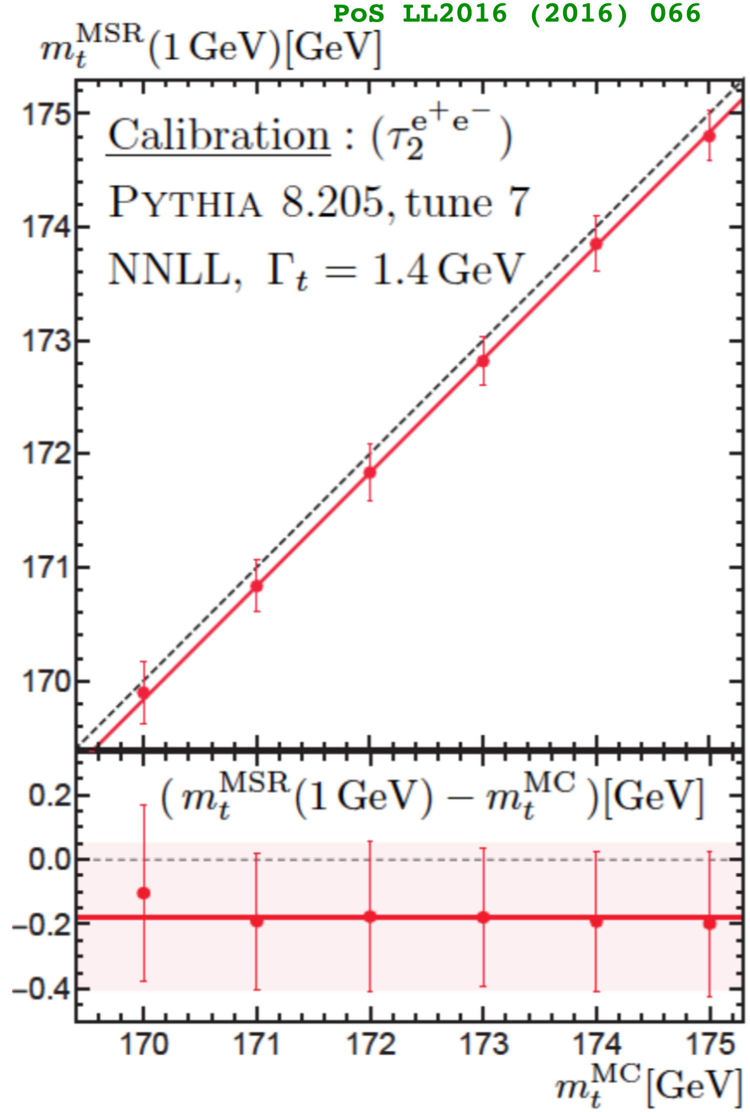
e.g. MSR mass

Top mass interpretation

Open questions:

Butenschoen, Dehnadi, Hoang, Mateu, Preissner, Stewart, PoS LL2016 (2016) 066

- does calibration also work for pp? How related to pole mass? Renormalon?
- when is off-shell pp → W⁺W⁻bb+X MC available with parton showers (also for hadronic W decays) that contains proper top pole mass?
- what about non-perturbative effects on top mass interpretation?



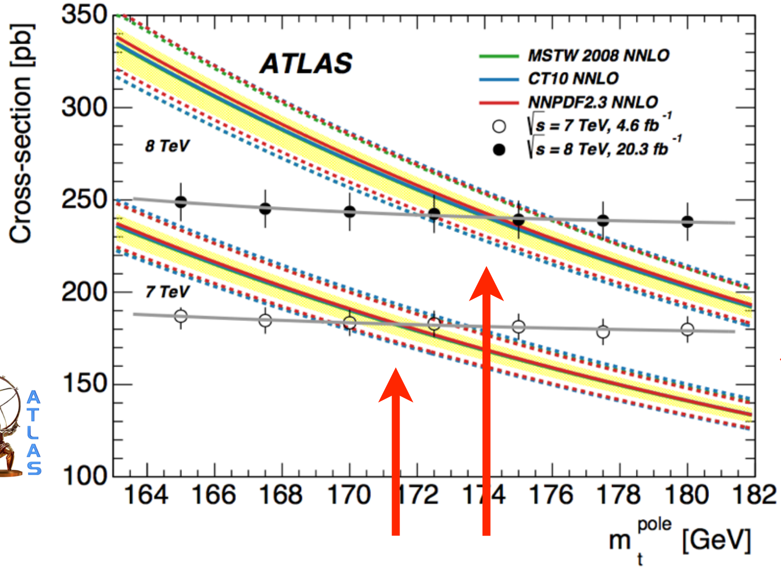
Scheme-dependent

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{quark}} + \Delta$$

~ O(1 GeV)

e.g. MSR mass → still many discussions in future

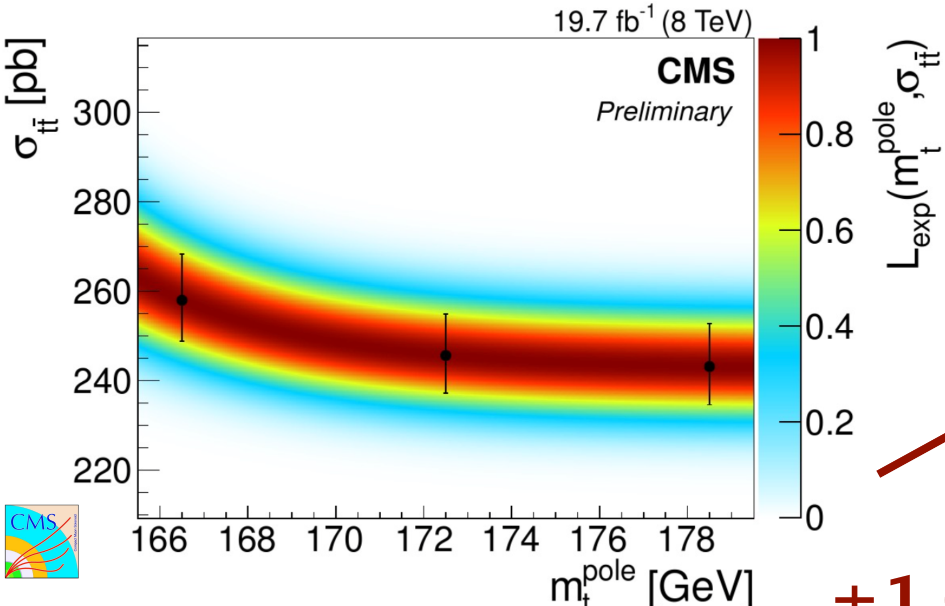
Top Quark Pole Mass

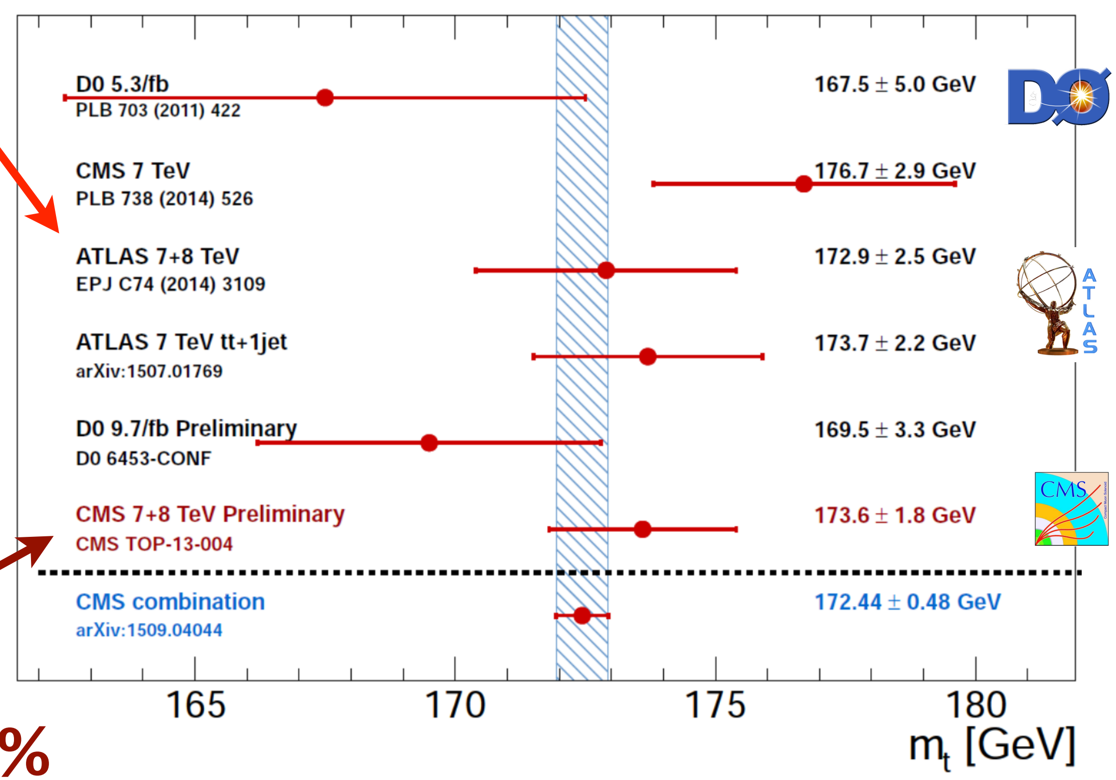


$$m_t^{\rm pole} = 172.9^{+2.5}_{-2.6}\,\mathrm{GeV}\ (\sqrt{s} = 7/8\,\mathrm{TeV})$$

→ pole mass unambiguously!

±1.4%

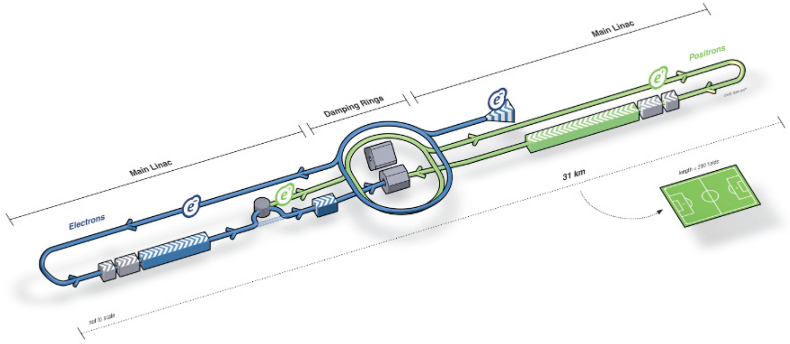


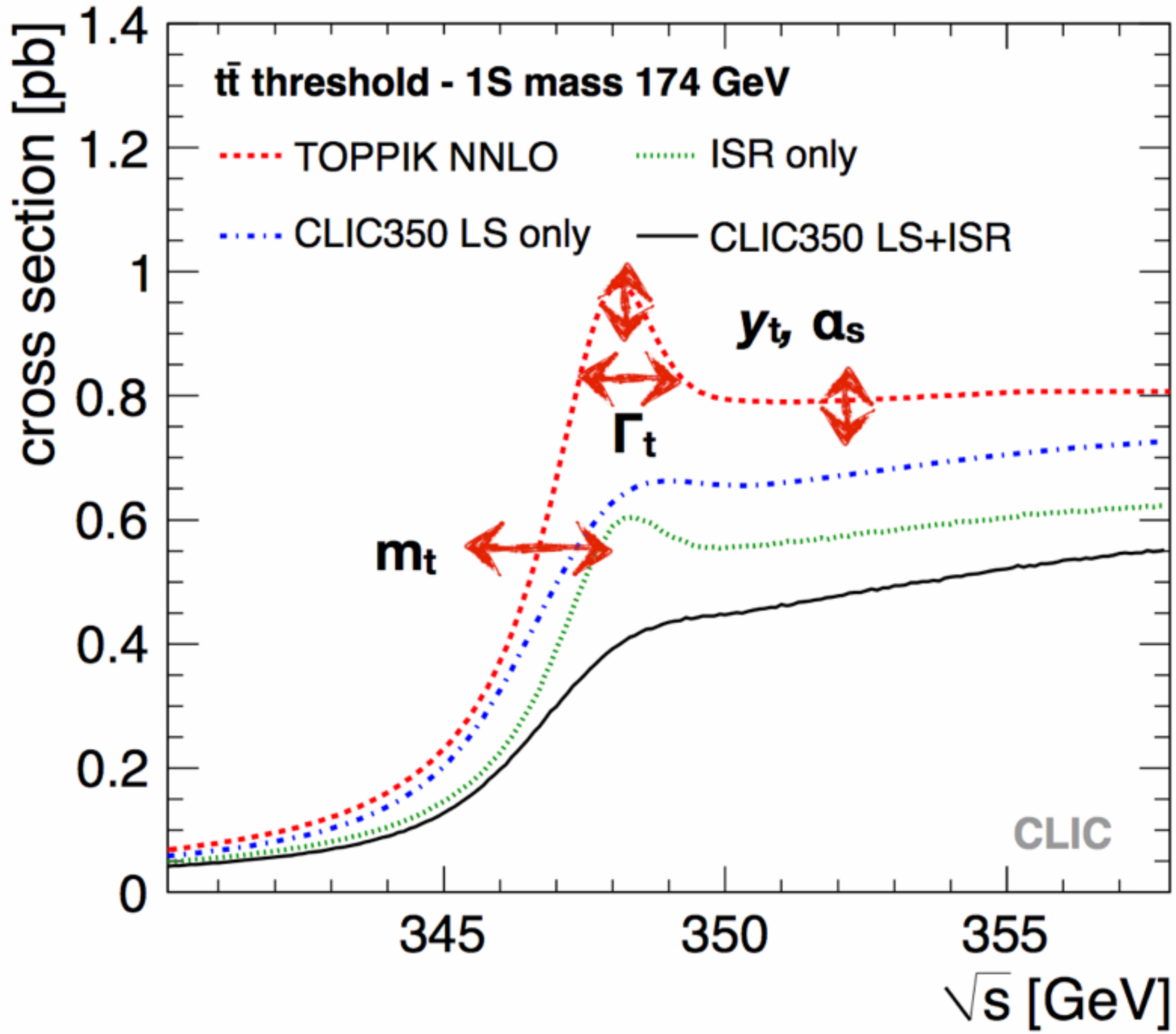


±1.0%

$M_t^{\rm pole}$=173.6 ± 1.8 GeV

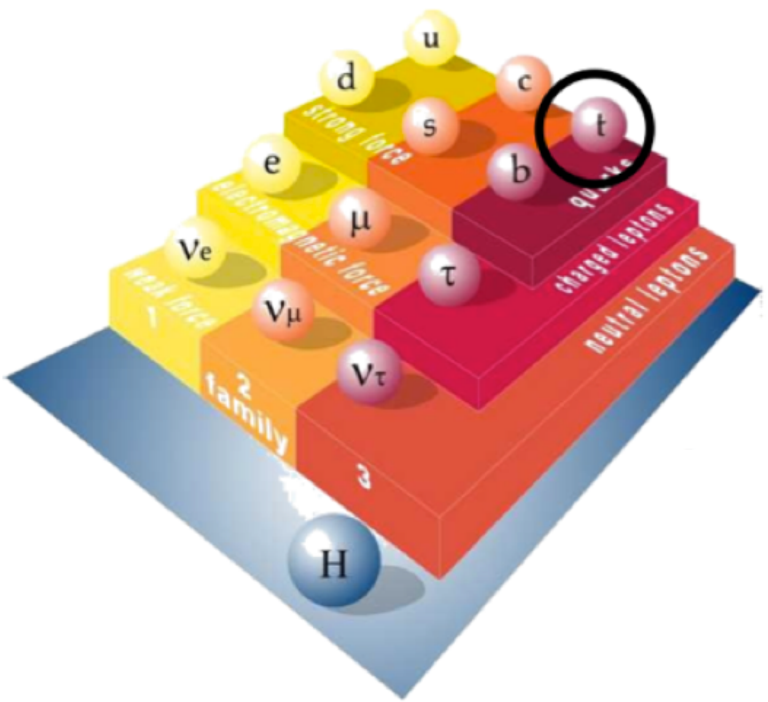
Top mass at ILC



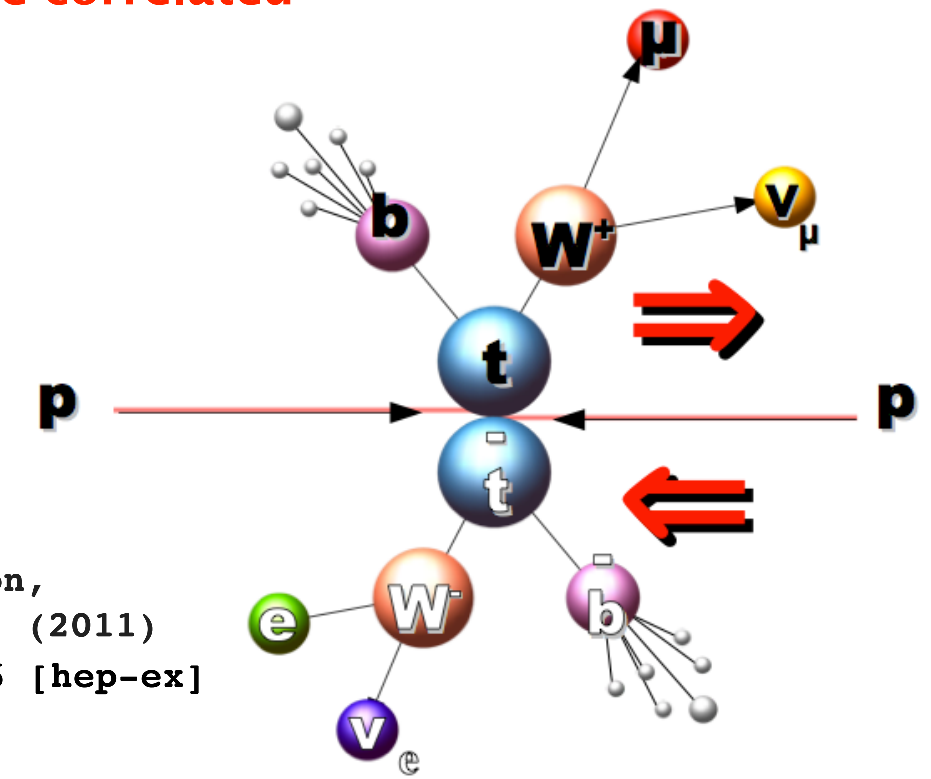


→ **well-defined top mass with ~O(100 MeV) uncertainty**

Top Pair Spin Correlation



- top quark: discovered in 1995 by CDF&DØ
- does the top quark have spin 1/2?
- top quark pair production: top quarks are not polarised, but spin of top and anti-top quarks are correlated



- top quarks have short lifetime:

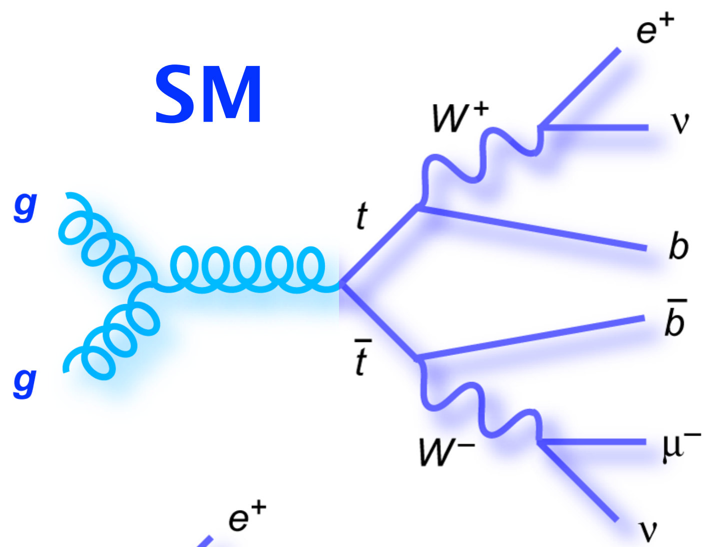
$$\boxed{\tau_t = (3.3^{+0.9}_{-0.6}) \times 10^{-25}\ \mathrm{s}}$$

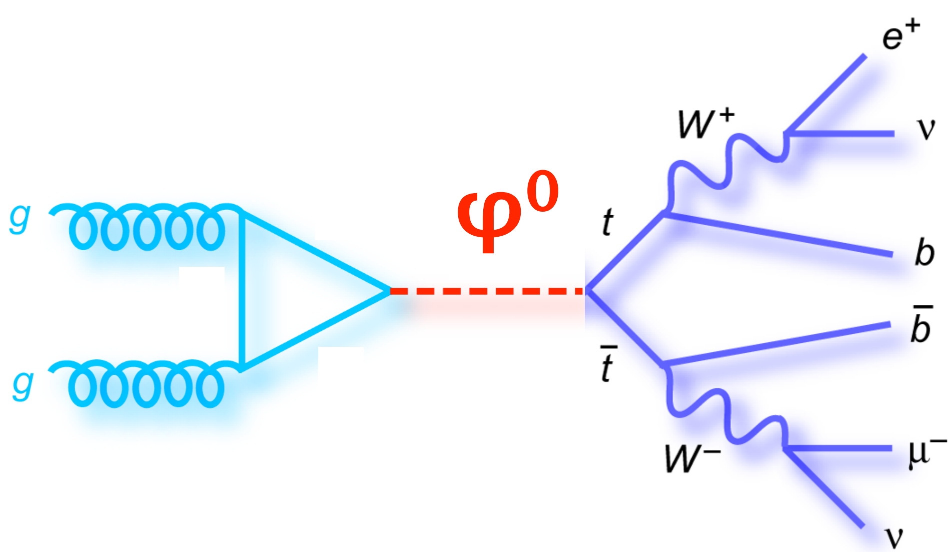
DØ Collaboration,
PRL 106, 022001 (2011)
arXiv:1201.4156 [hep-ex]

- decay before spins can flip
- spin information is contained in decay product
- measure $t\bar{t}$ spin correlation: consistent with SM prediction for a spin 1/2 particle?

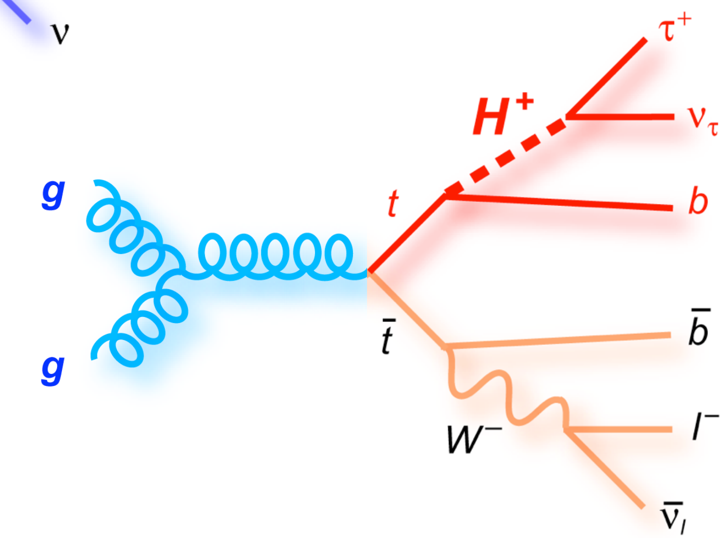
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay





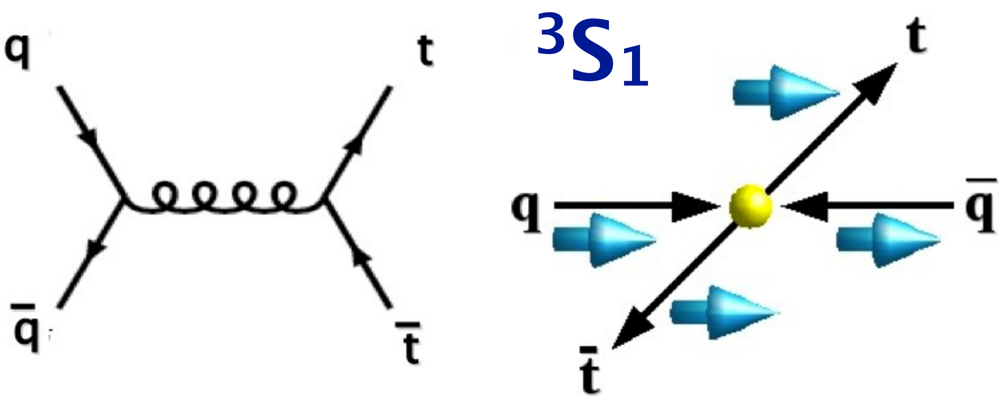
Higgs, KK gravitons, Z’, stop pairs, …



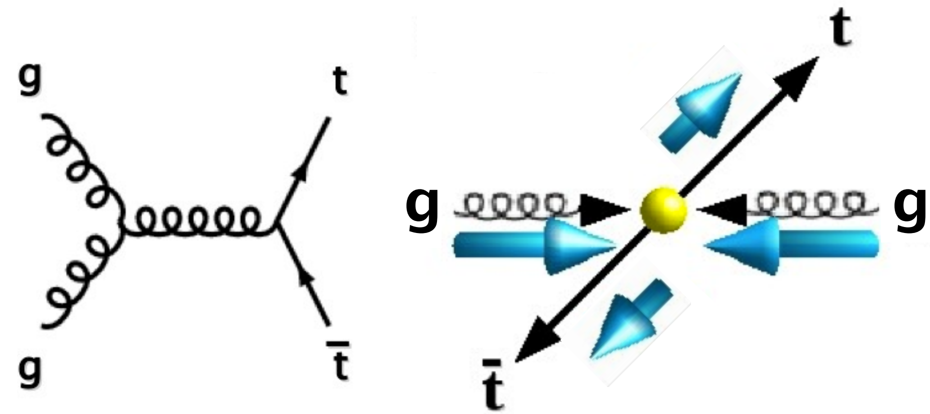
charged Higgs, b’, …

Spin correlation strength

$$\boxed{A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}}$$



Tevatron



LHC

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold
- beam axis as spin quantisation axis

  NLO QCD: A = 0.78

- dominated by gg fusion
- $t\bar{t}$ pairs far off the threshold
- helicity basis as spin quantisation axis

  NLO QCD: A = 0.32 (7 TeV)

`Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)`

- optimised “off-diagonal” basis
- maximal basis

complementary between Tevatron and LHC

Spin Correlation at the LHC

- first measurement of spin correlation between top and anti-top quark in dilepton final states at the LHC
- azimuthal angle between charged leptons in laboratory frame: sensitive and simple!

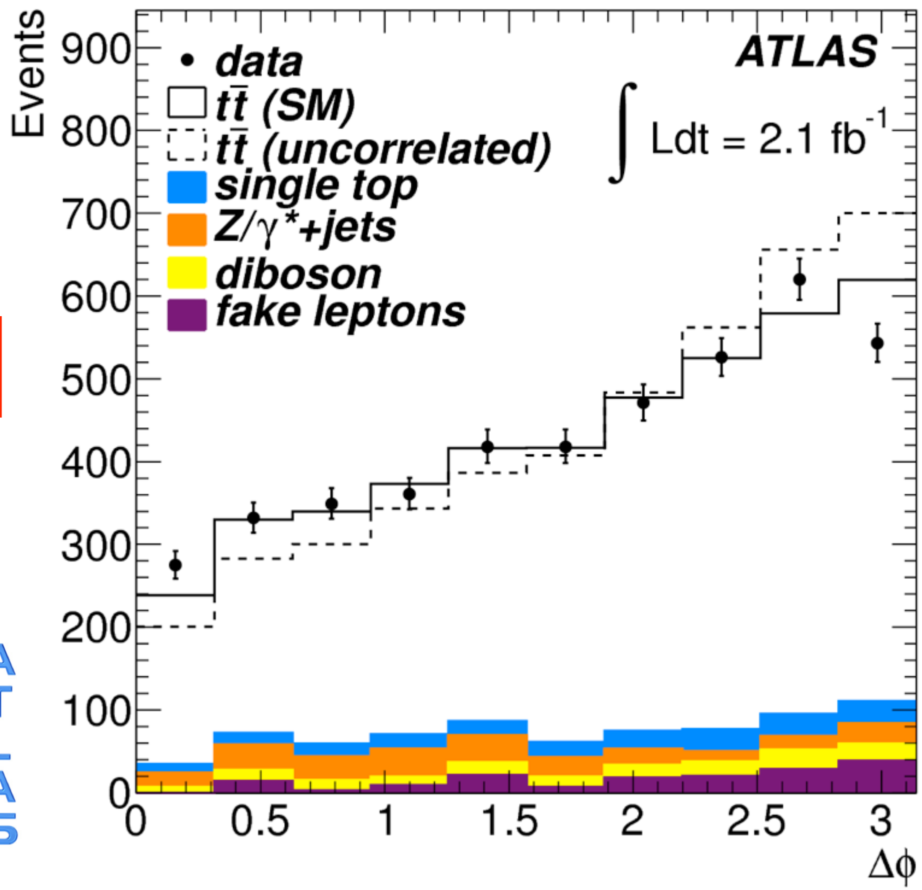
Phys. Rev. Lett. 108, 212001 (2012)

$$\boxed{f^{\mathrm{SM}} = 1.30 \pm 0.14\,(\mathrm{stat})\,^{+0.27}_{-0.22}\,(\mathrm{syst})}$$

(=1 in SM)

$$\boxed{C_{\mathrm{helicity}} = 0.40\,^{+0.09}_{-0.08}}$$

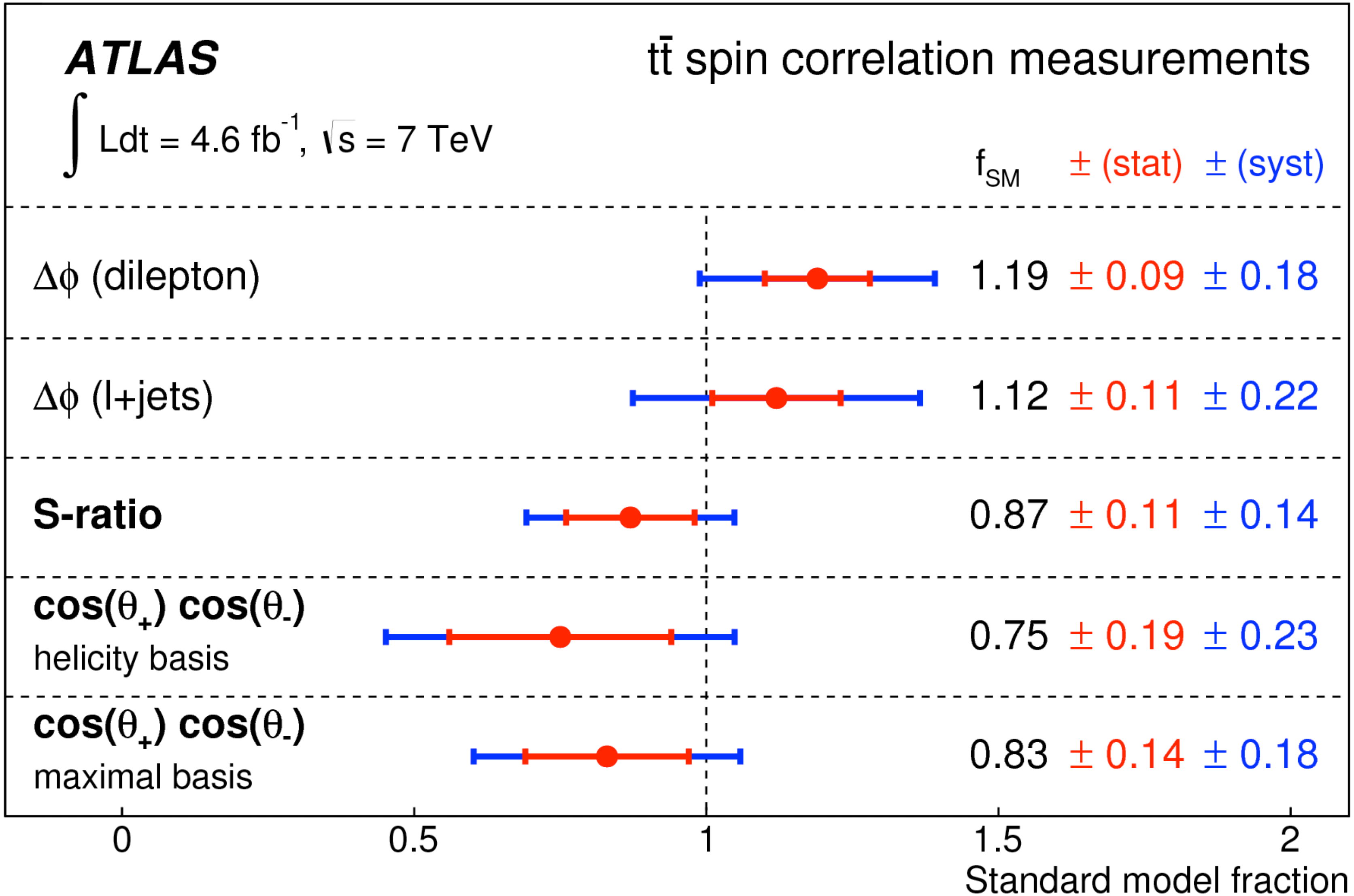
(=0.32 in NLO QCD)



→ **first observation of spin correlation with 5.1σ**

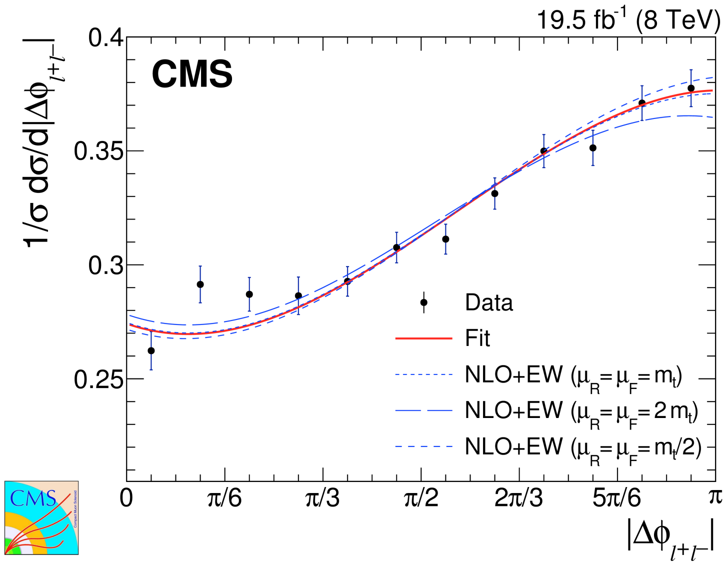
→ **correlation agrees with SM spin 1/2 hypothesis**

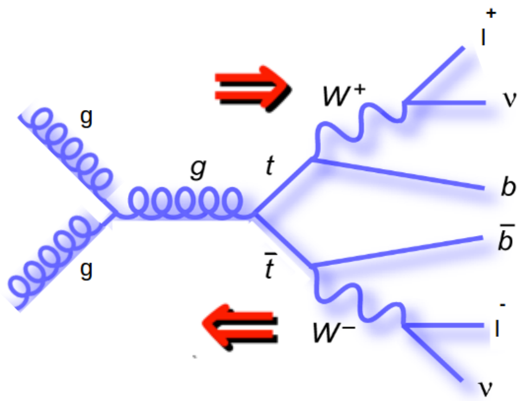
Spin Correlation at the LHC



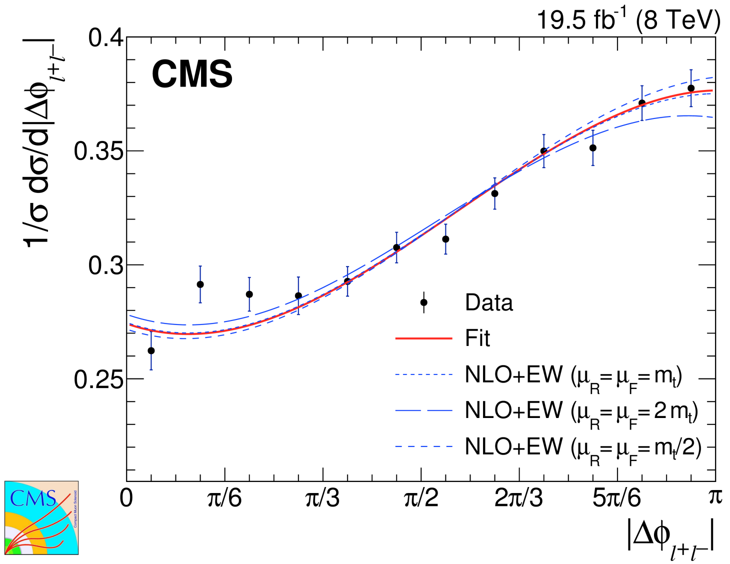
→ **correlation agrees with SM spin 1/2 hypothesis**

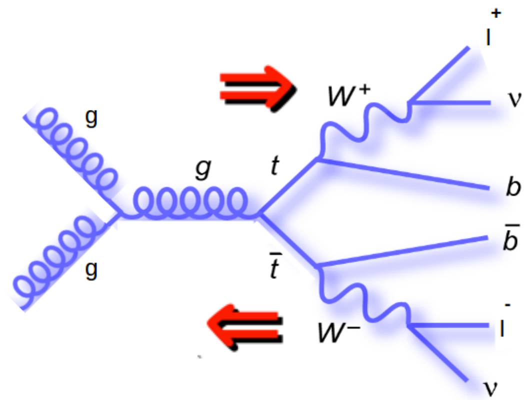
$t\bar{t}$ spin correlation at 8 TeV



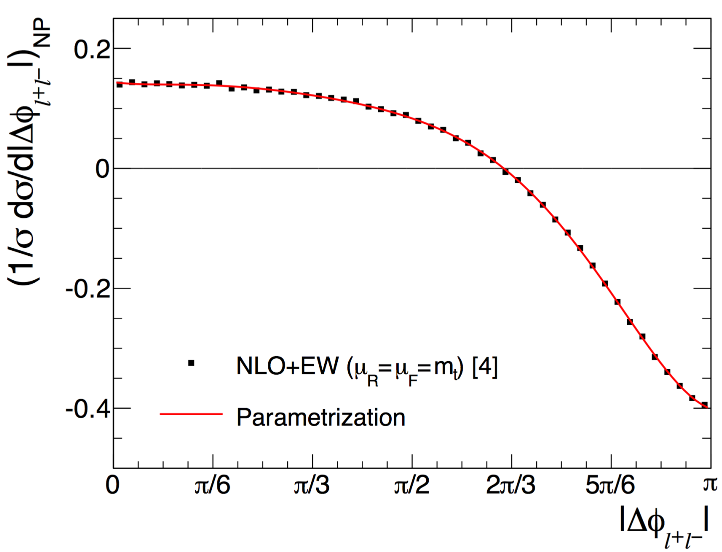


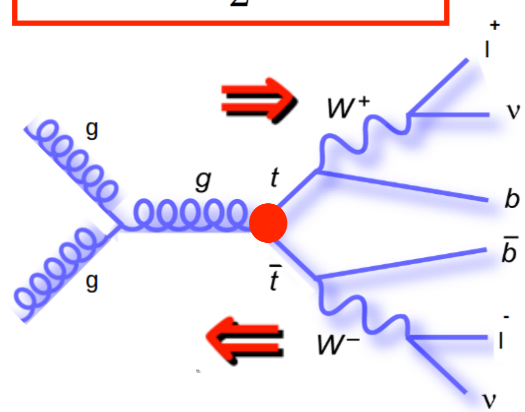
Search for anomalous couplings





$$\boxed{\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}G_{\mu\nu}t}$$

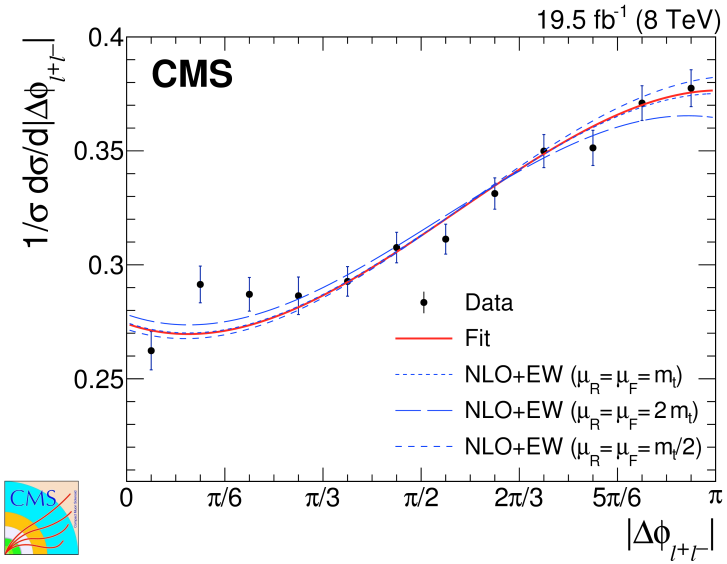


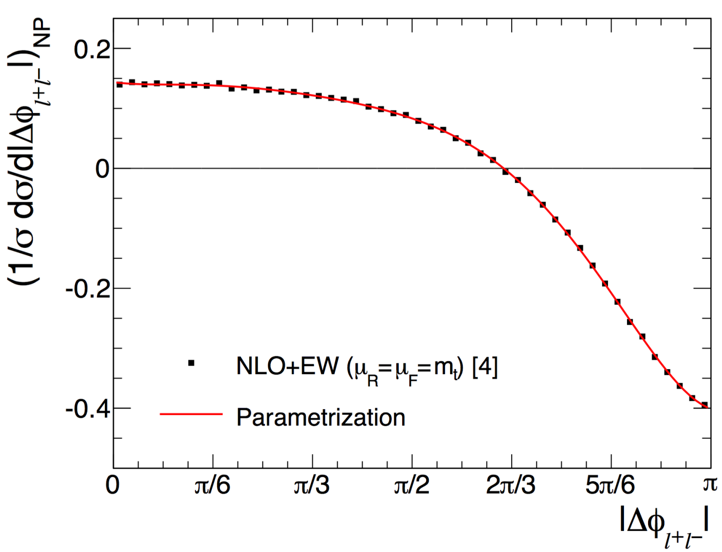


→ **no chromomagnetic dipole moments**

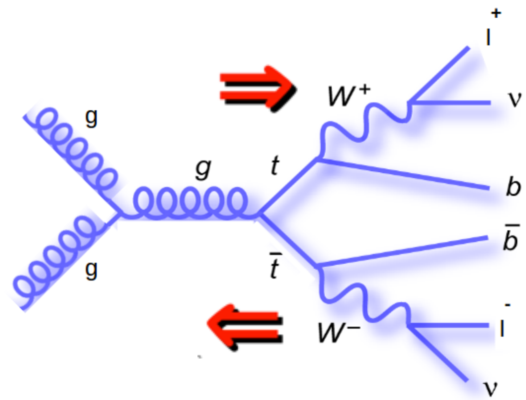
$$\boxed{\mathrm{Re}(\hat{\mu}_t) = -0.006 \pm 0.024}$$

Search for anomalous couplings





→ **no chromomagnetic dipole moments**



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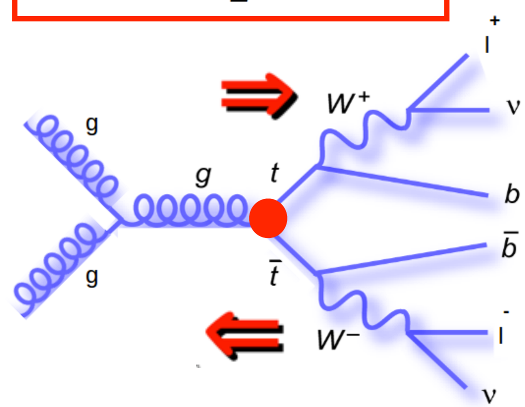
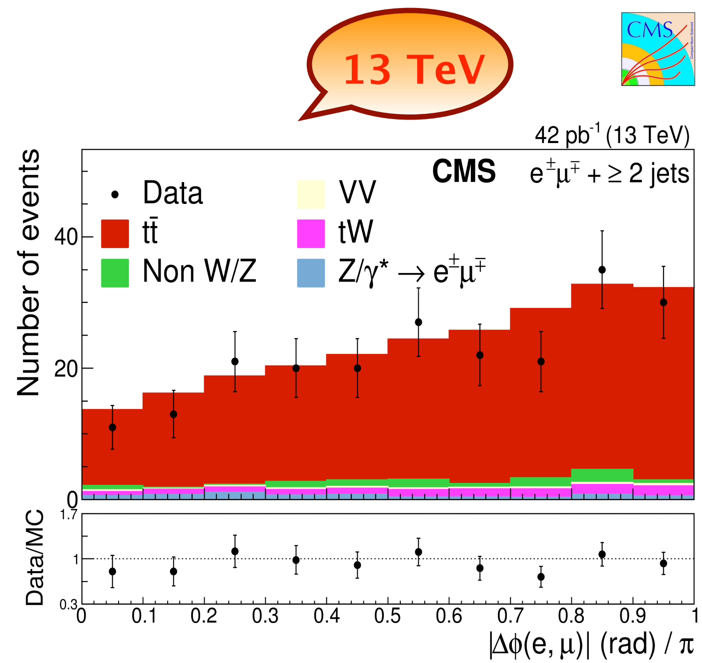


$$\boxed{\mathrm{Re}(\hat{\mu}_t) = -0.006 \pm 0.024}$$

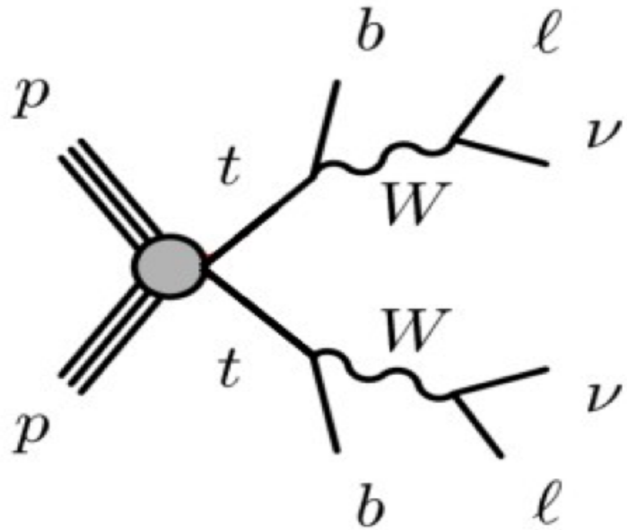


→ **only first look: similar to SM, but keep looking in Run-II**

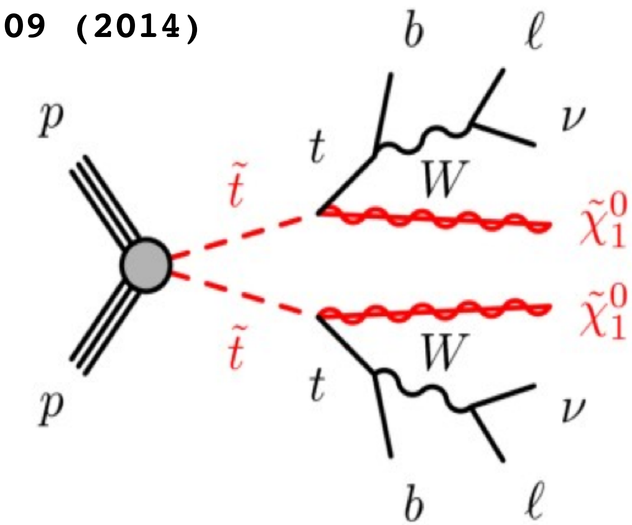
no hint for new physics so far

Stop Quark Pair Production

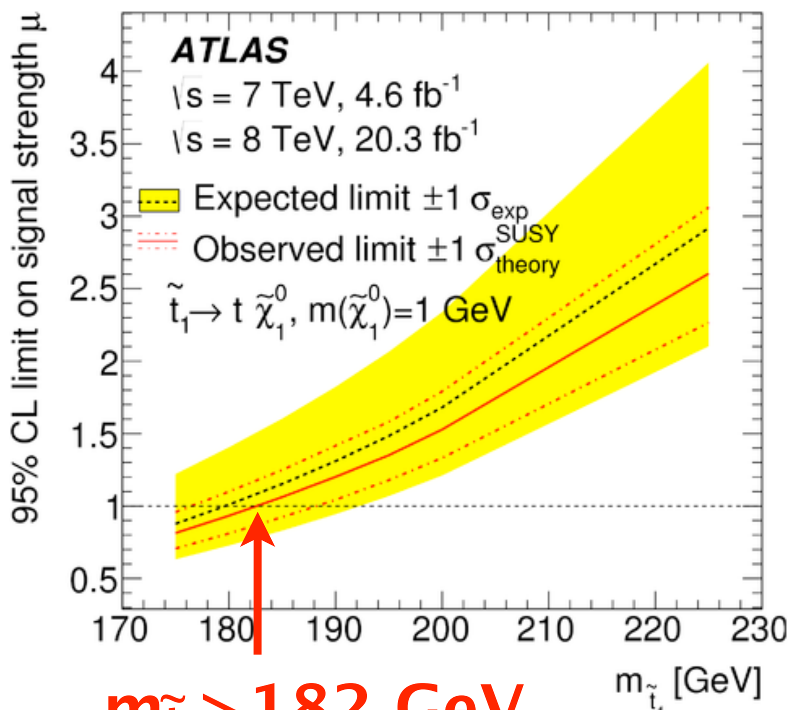
Eur. Phys. J. C74 3109 (2014)



do we see left or right?



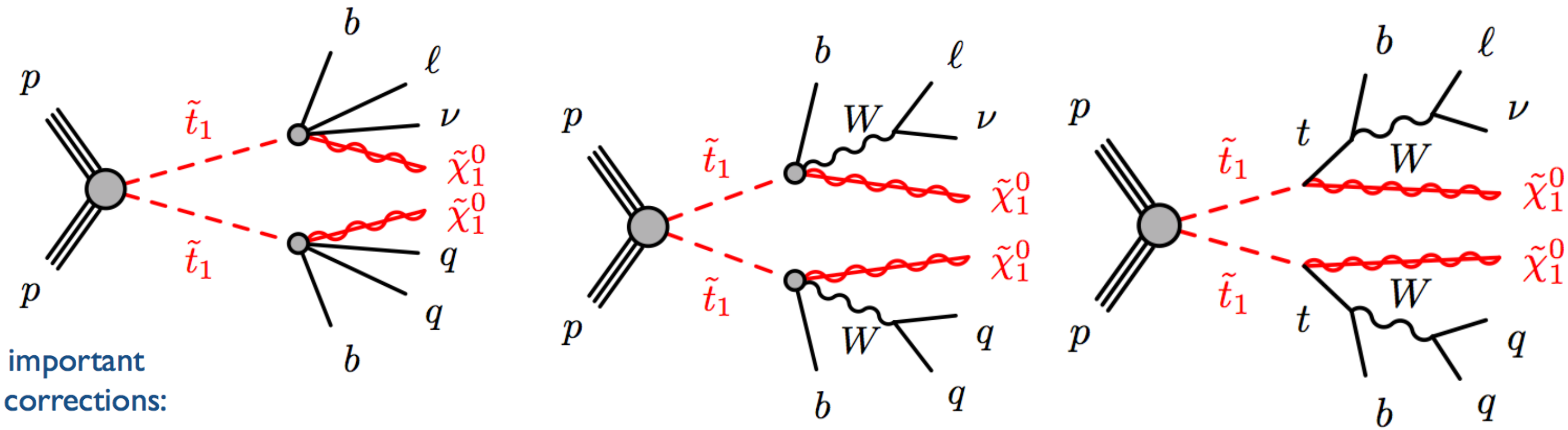
$\frac{\sigma_{limit}}{\sigma_{SUSY}}$



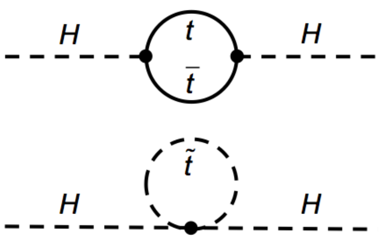
$m_{\tilde{t}} > 182$ GeV

"stealth" scenario:
- small sneutrino mass
- stop mass close to top mass

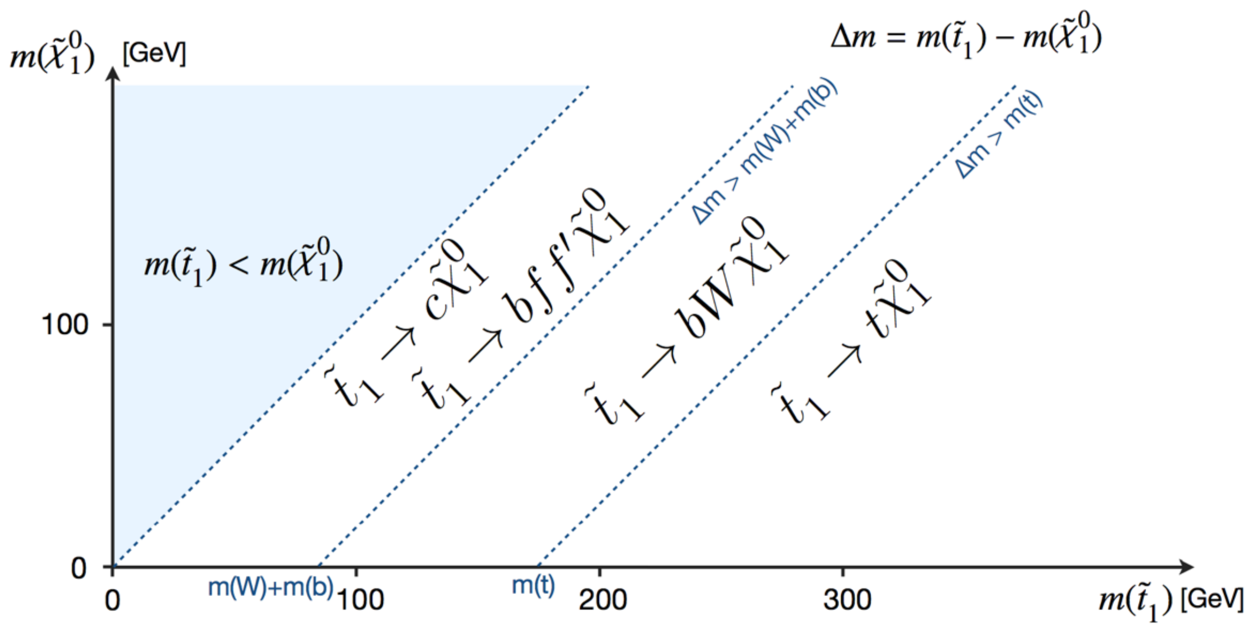
Direct searches for light stop



Recall: **Top loop** is the most important contribution in Higgs virtual corrections:

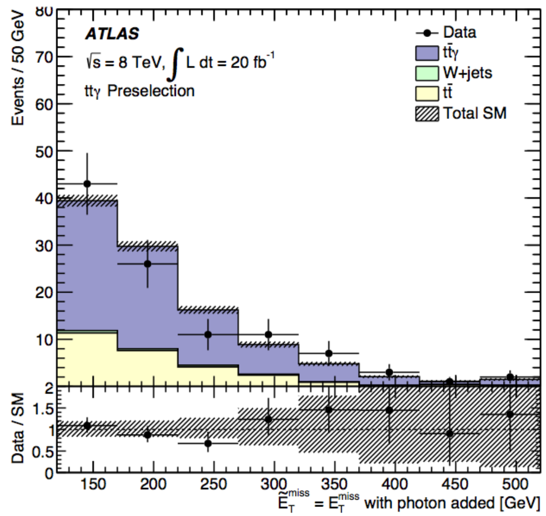


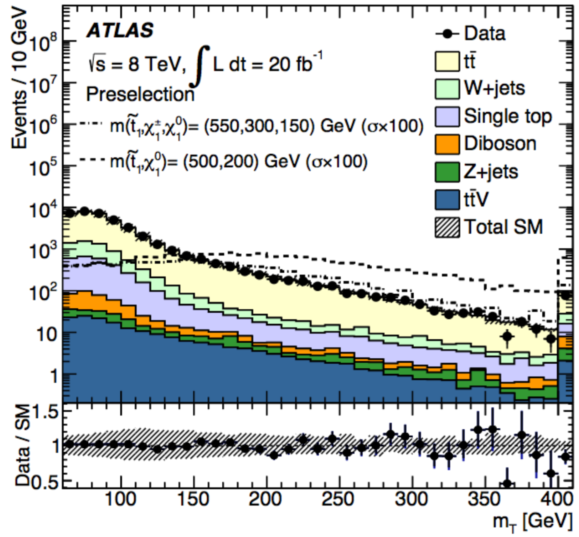
small stop mass is natural

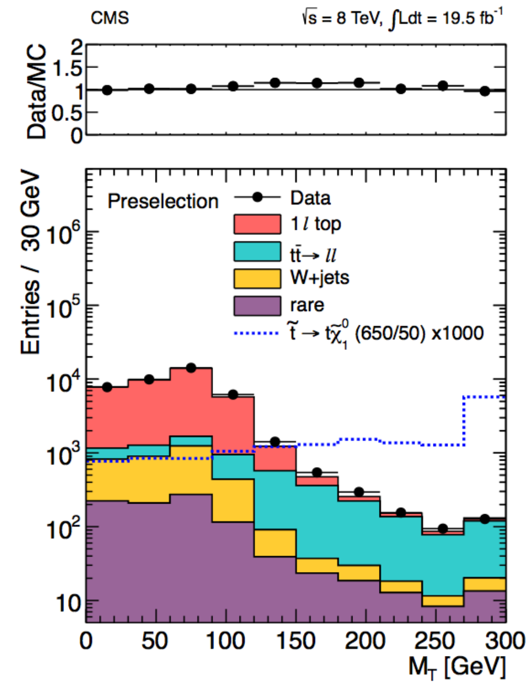


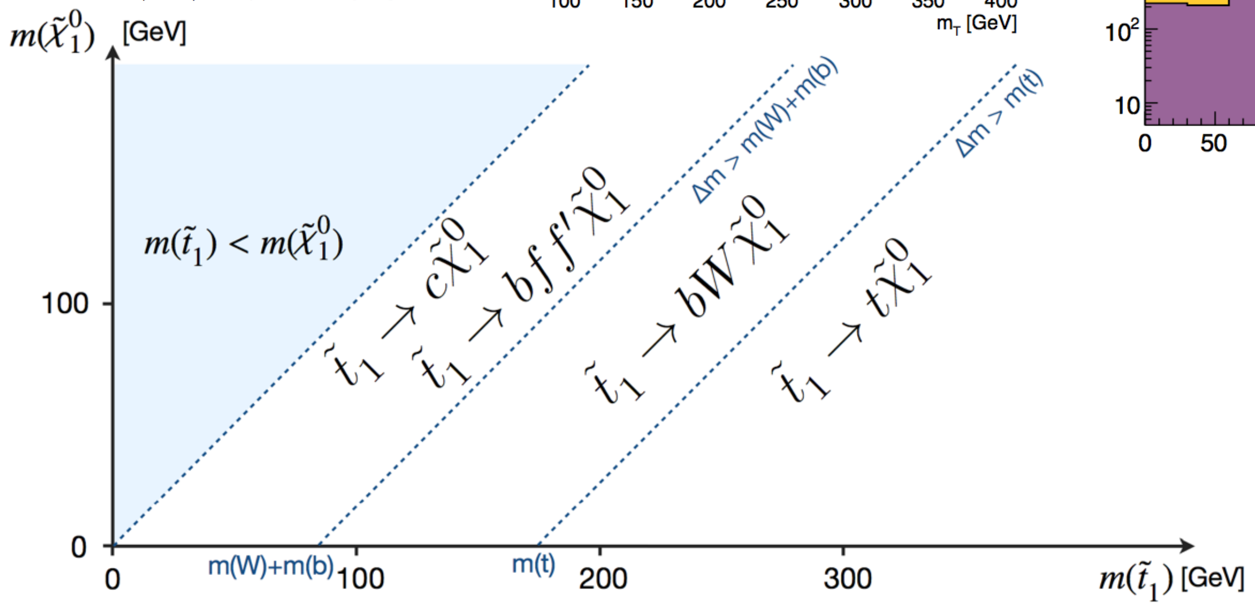
we check every little corner...

Direct stop searches



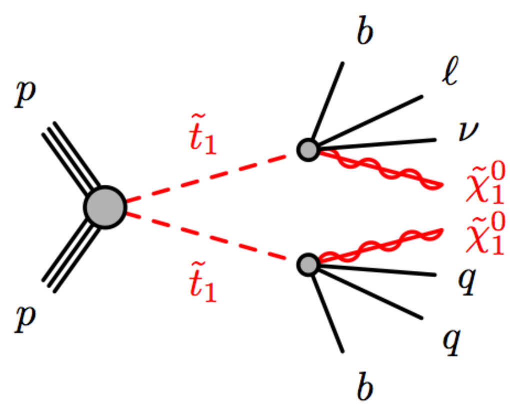


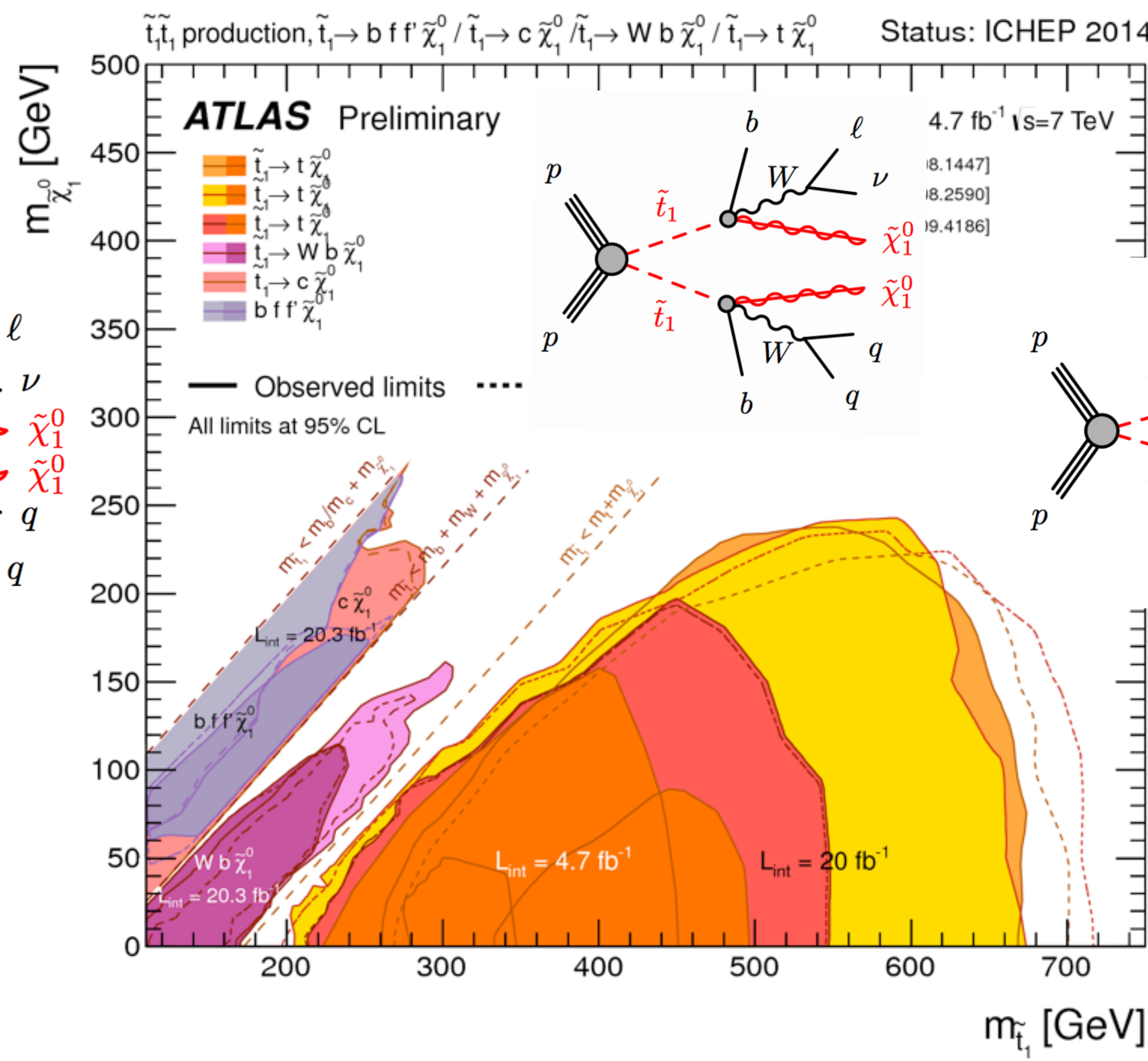


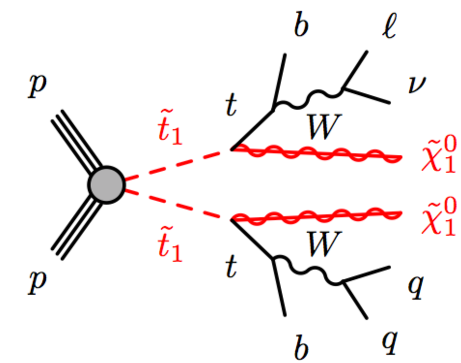


we check every little corner...

Direct stop searches

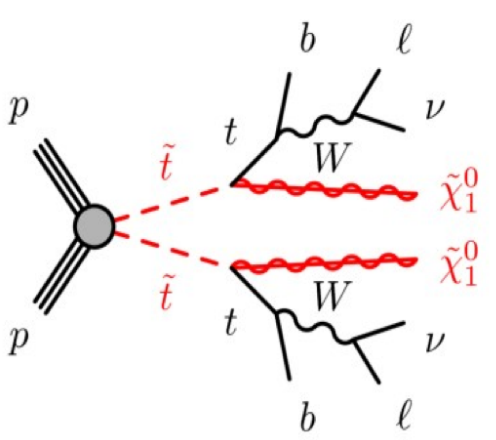


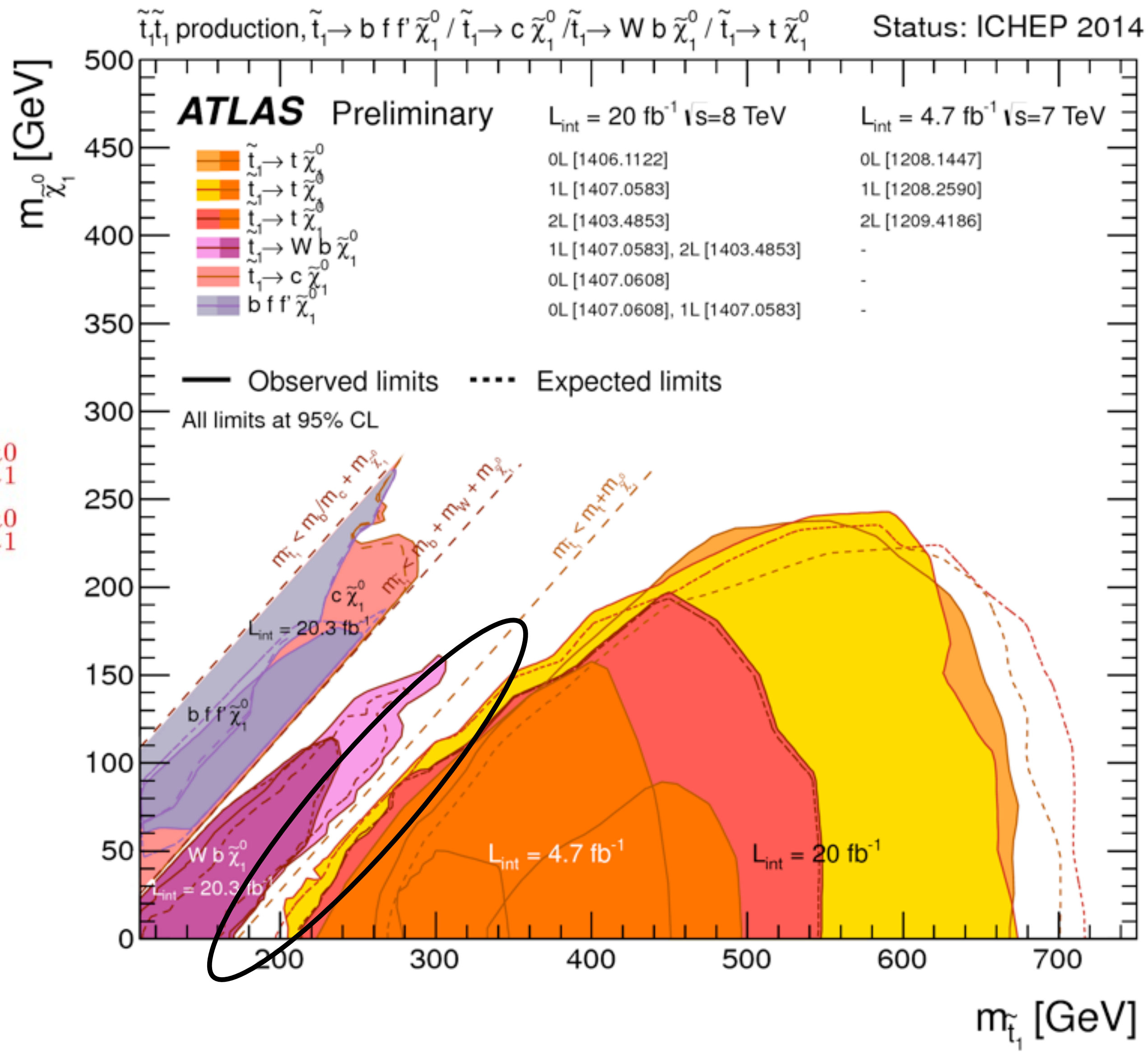




we check every little corner...

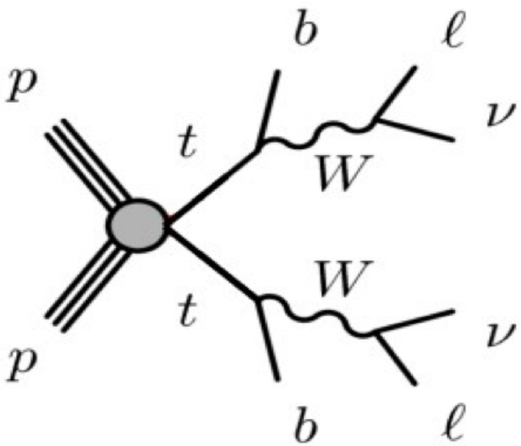
“Stealth” Stop Quarks

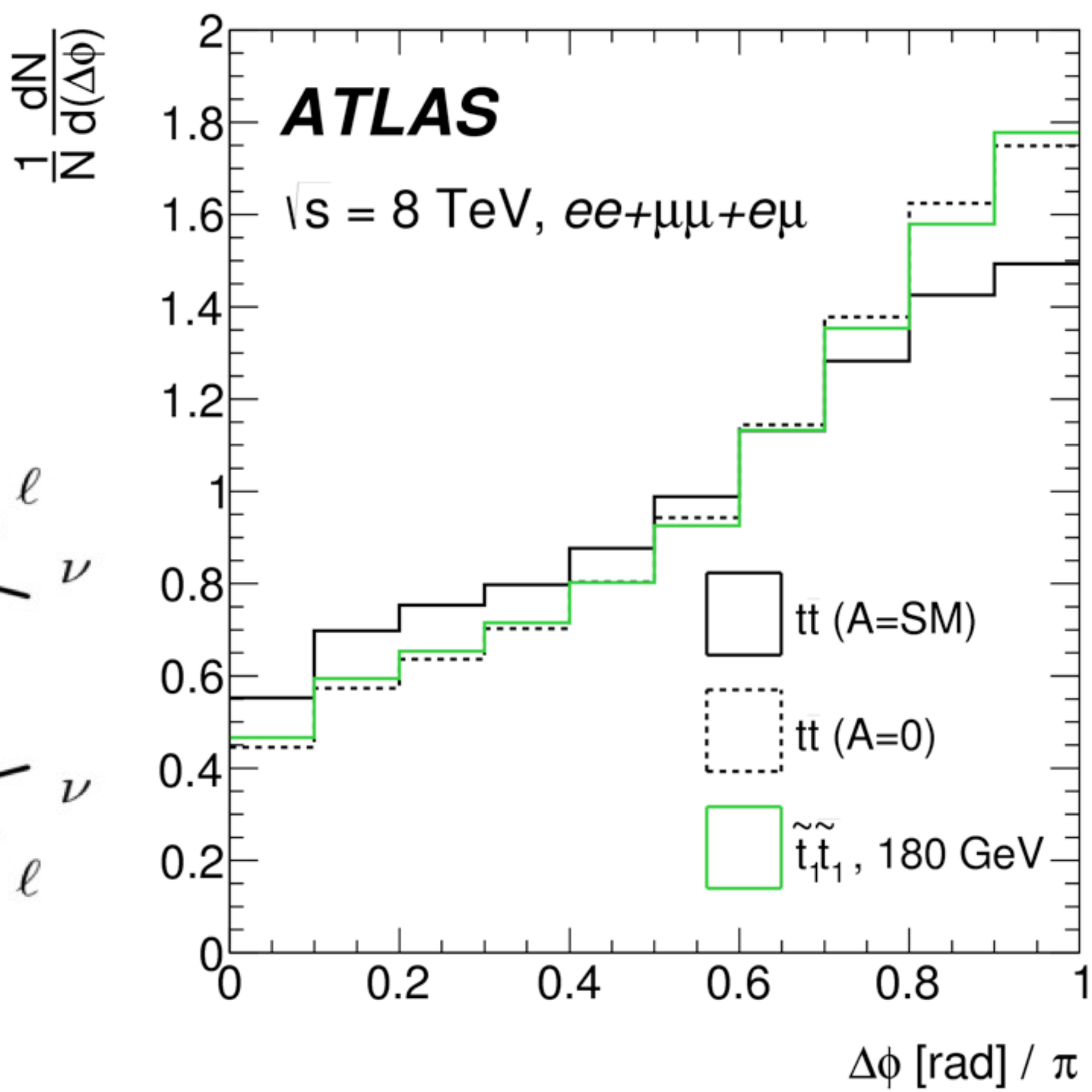


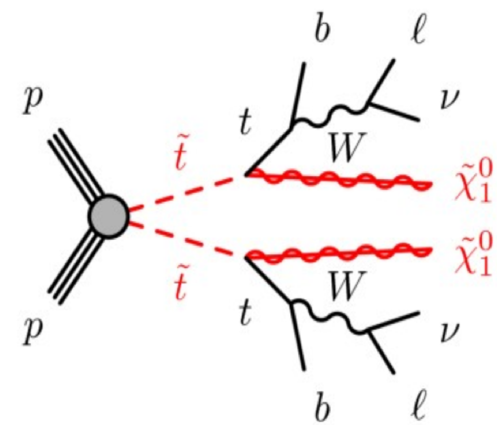


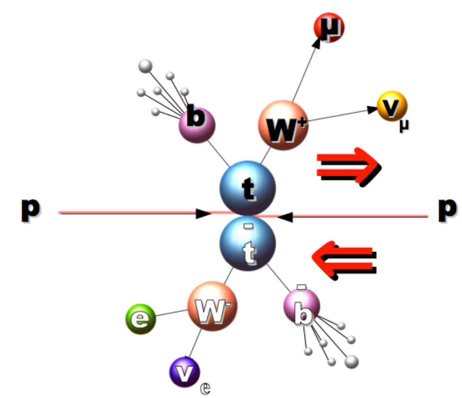
we check every little corner...

Spin correlations for "Stealth" Stop

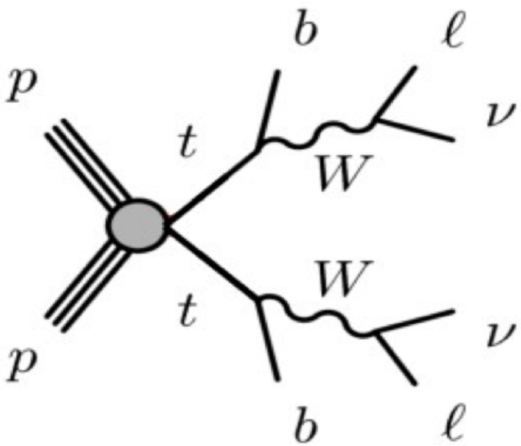


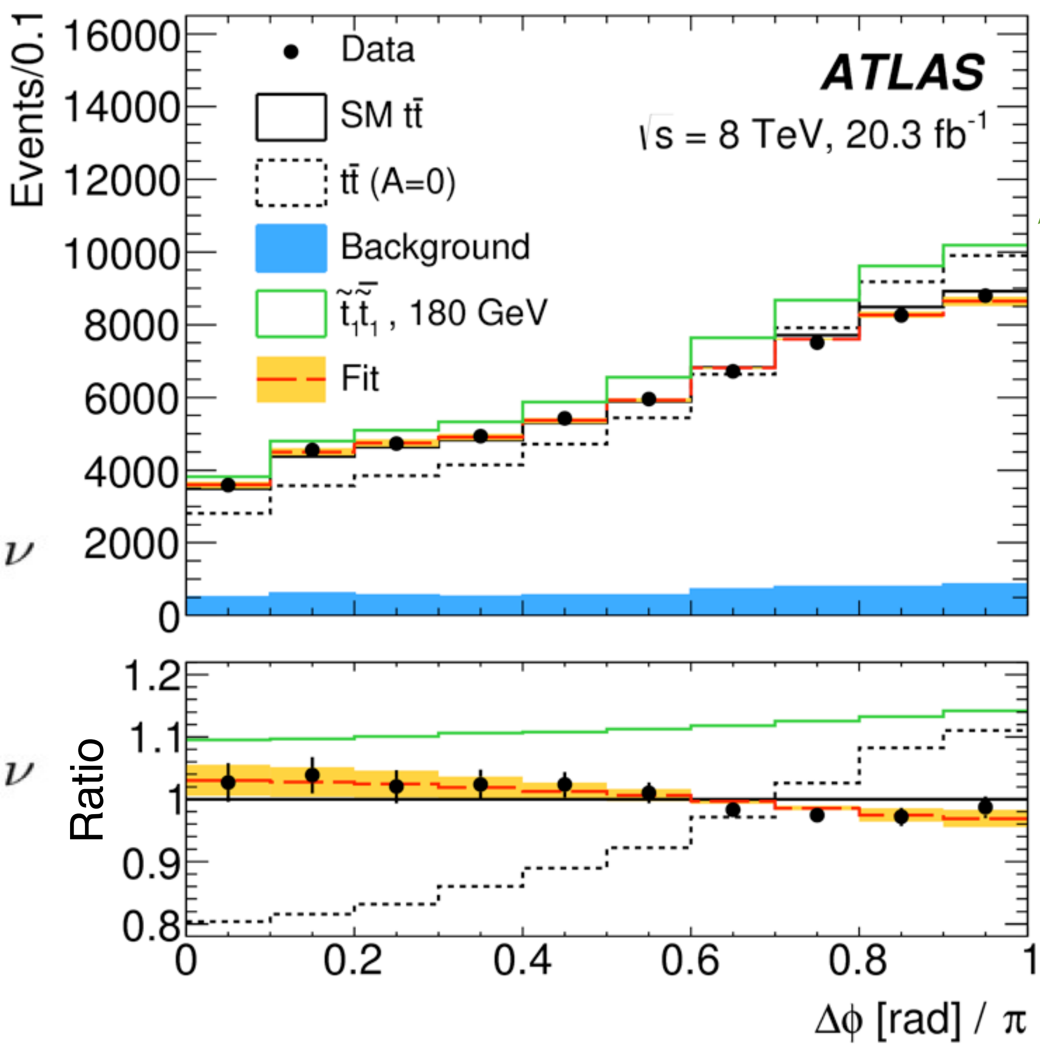


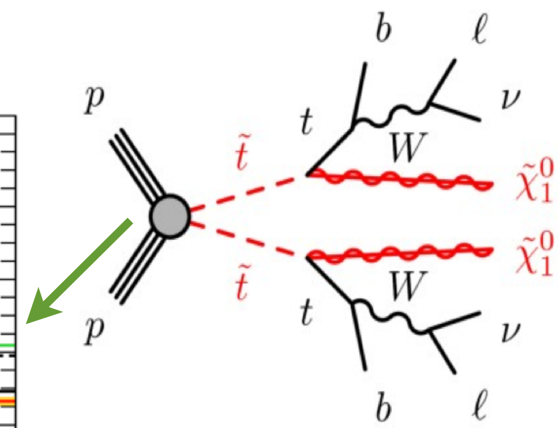


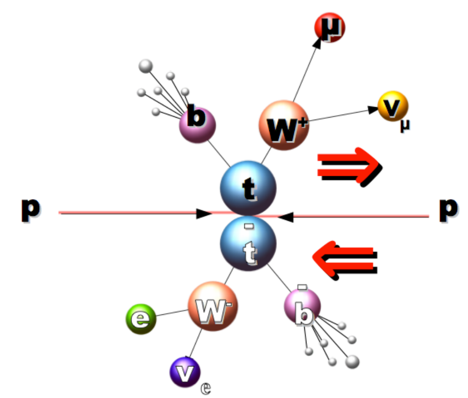


Spin correlations for “Stealth” Stop



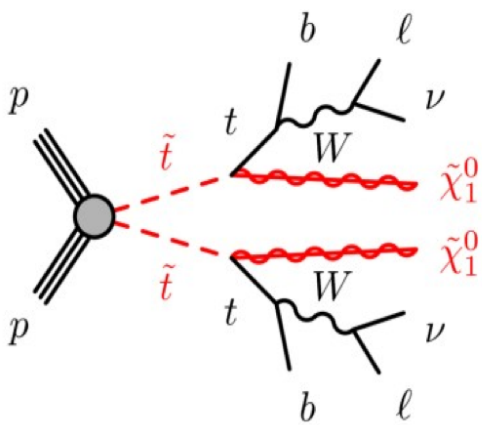


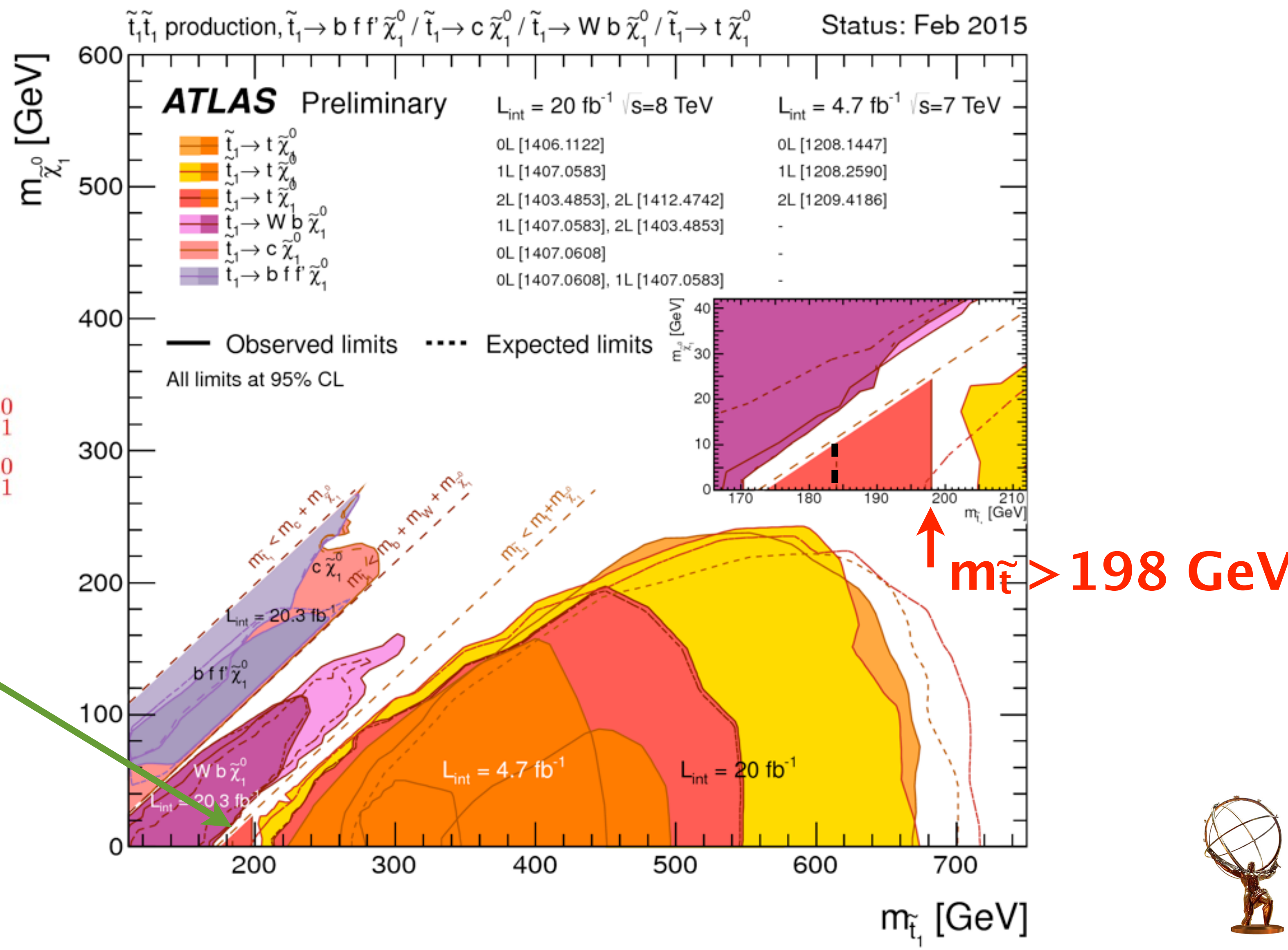




→ **no hint of stop quarks**

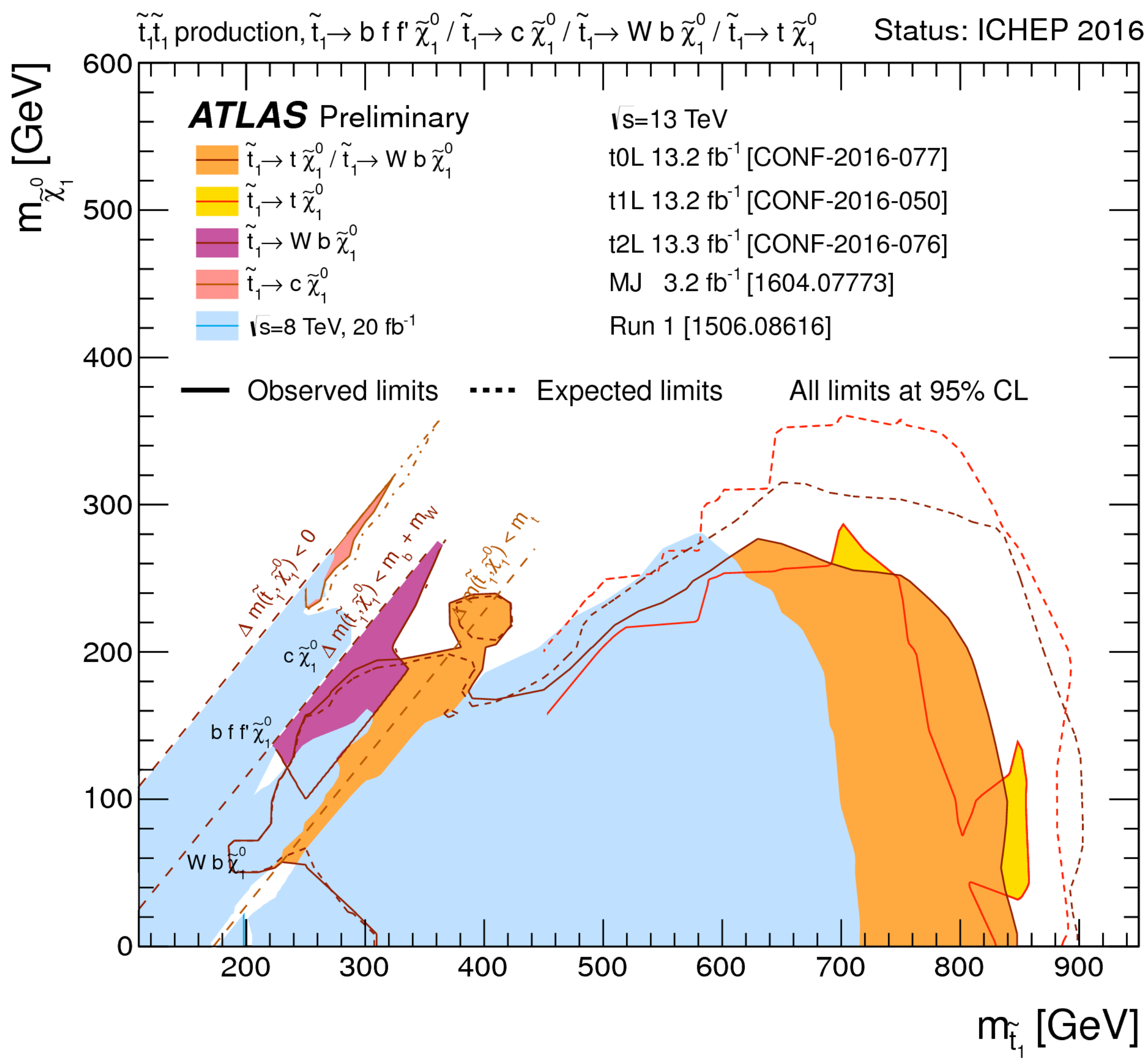
Direct stop searches





→ **using a "standard candle" for complementary exclusion**

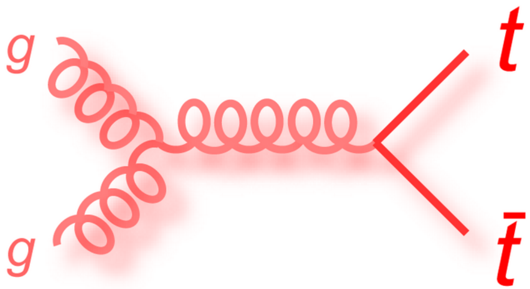
Stop searches in Run-II



→ **extended limits at 13 TeV**

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

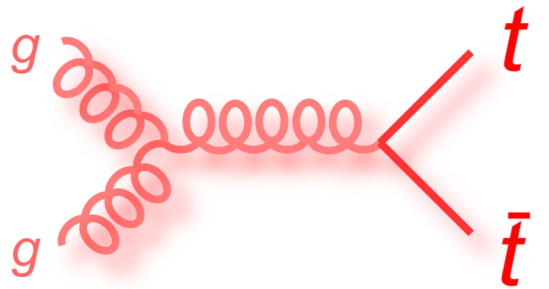


$$g(p_1) + g(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2)$$

Bernreuther, Heisler, Si, JHEP 1512, 026 (2015)

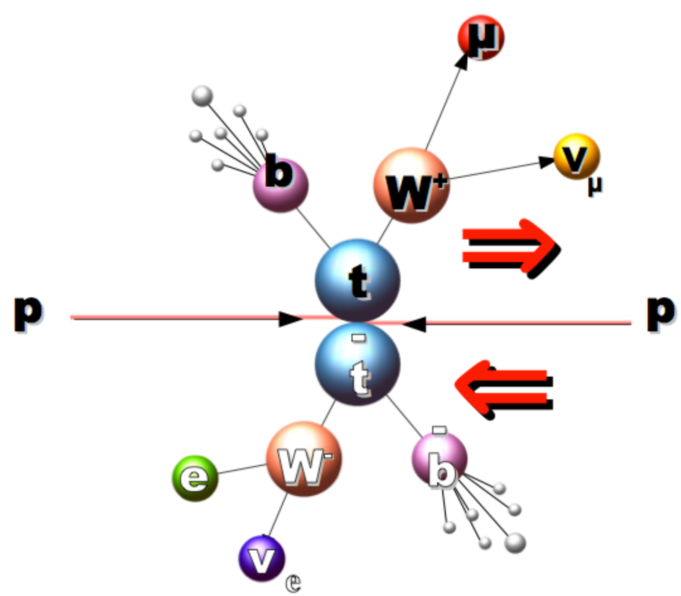
$t\bar{t}$ production density matrix

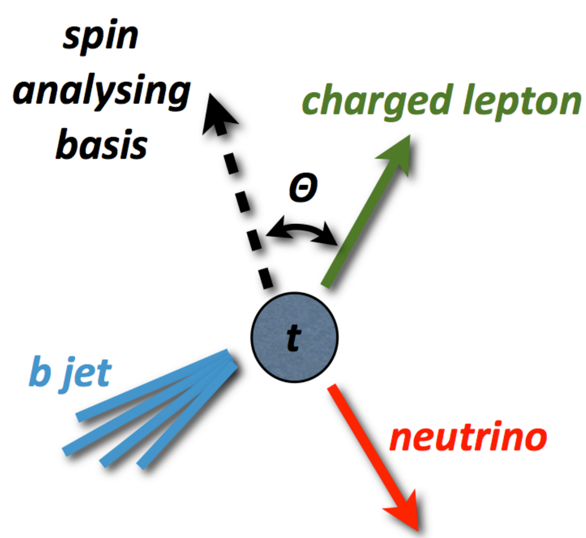
$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



$$g(p_1) + g(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2)$$

Bernreuther, Heisler, Si, JHEP 1512, 026 (2015)





in top quark rest frame

- almost 100% analysis power

- polarisation and spin information is contained in decay products

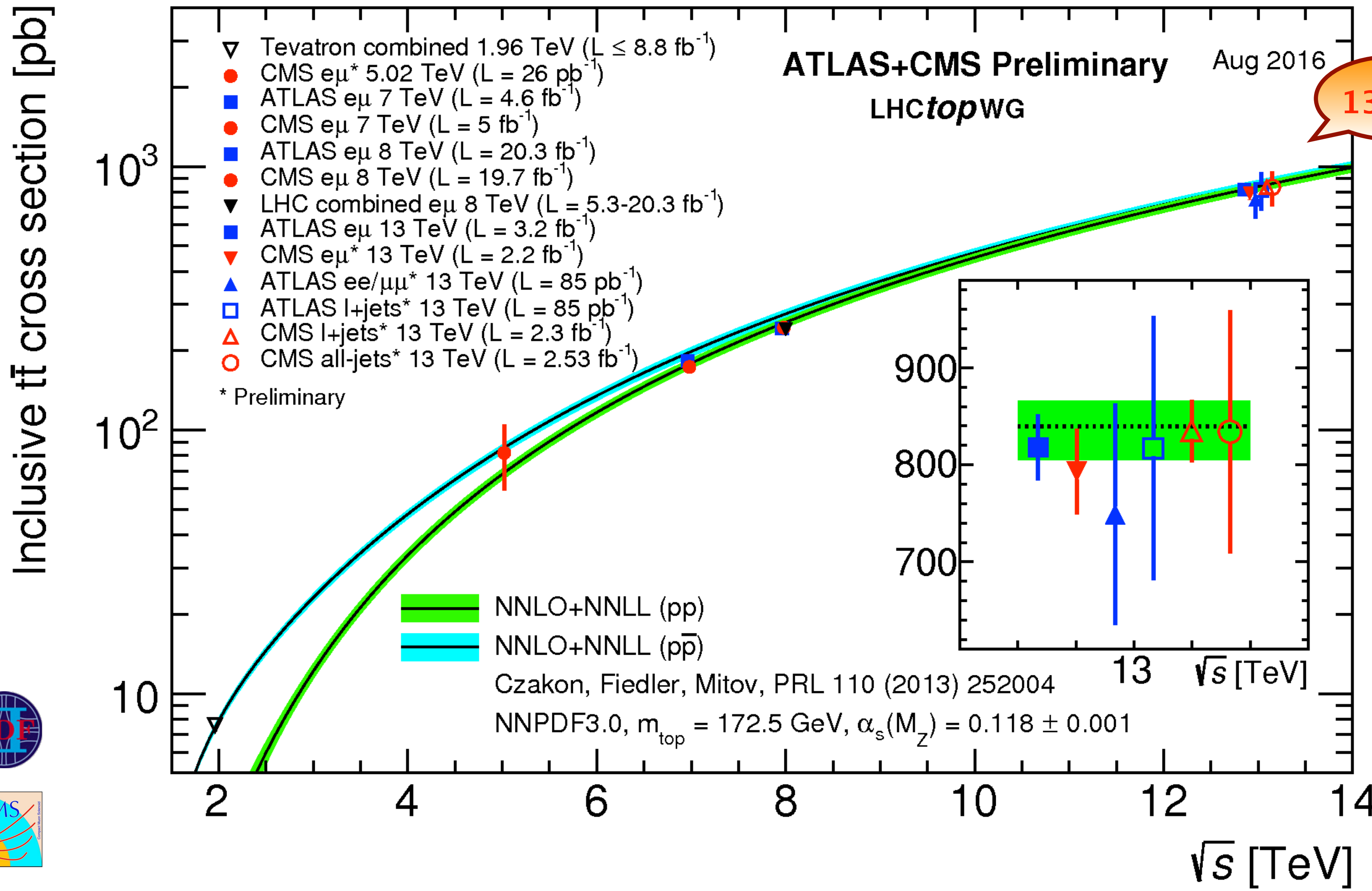
$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

determines cross section and distributions independent of top spin (e.g. p^t_T distribution etc.)

- **test of QCD predictions**
- **search for new physics**

Top pair production at 13 TeV



→ **agreement with SM prediction**

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

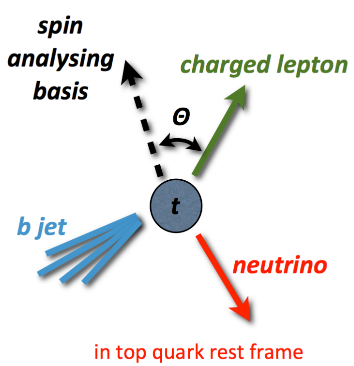
$$\tilde{B}_i^\pm = b_1^\pm \hat{p}_i + b_2^\pm \hat{k}_i + b_3^\pm n_i \quad \mathbf{n} = \hat{\mathbf{p}} \times \hat{\mathbf{k}}$$

longitudinal polarisation

transverse polarisation

$b_1^\pm$, $b_2^\pm \neq 0$: P-violation
(=0 in LO QCD)

$b_3^\pm \neq 0$: CP-violation,
($\neq$0 through absorptive parts)



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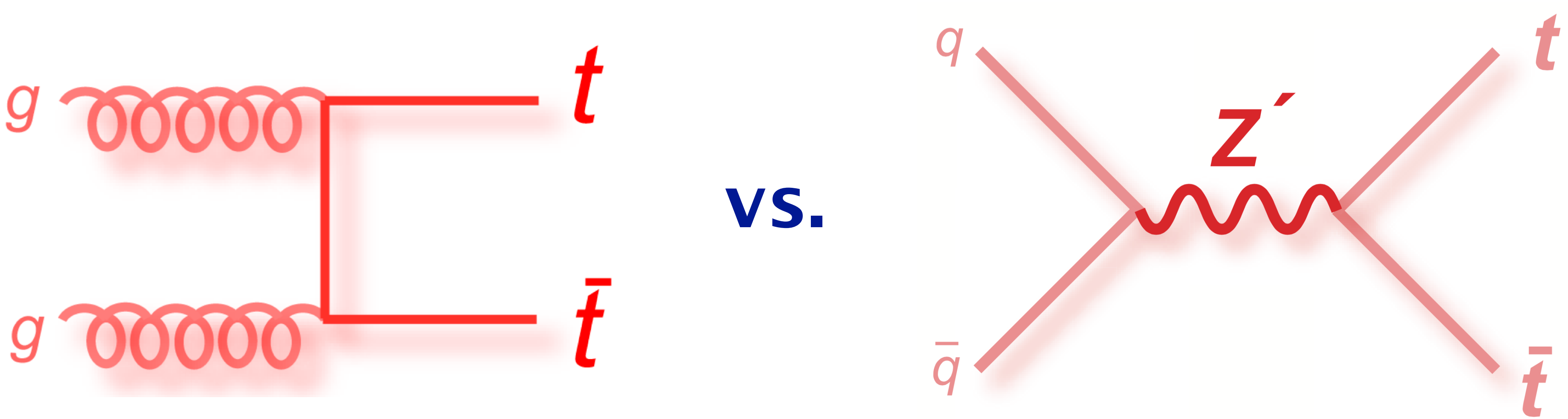
longitudinal polarisation   transverse polarisation



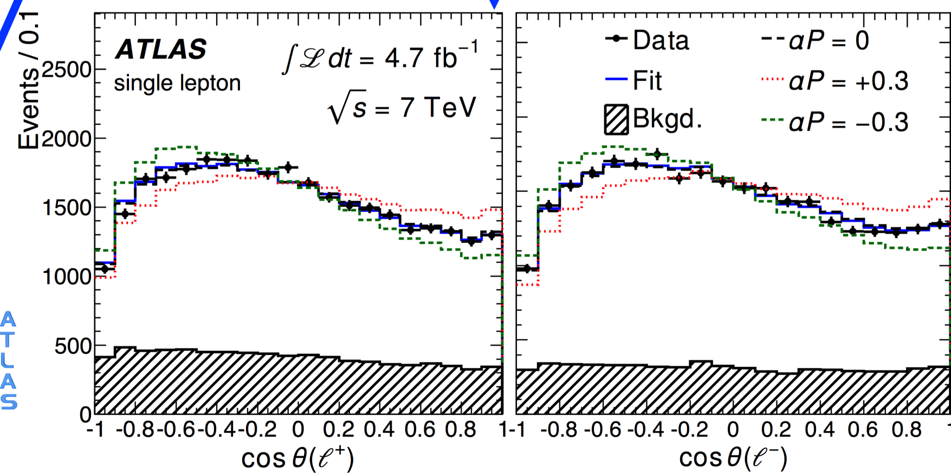
→ **would lead to different polarisation**

Longitudinal and transverse polarisation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

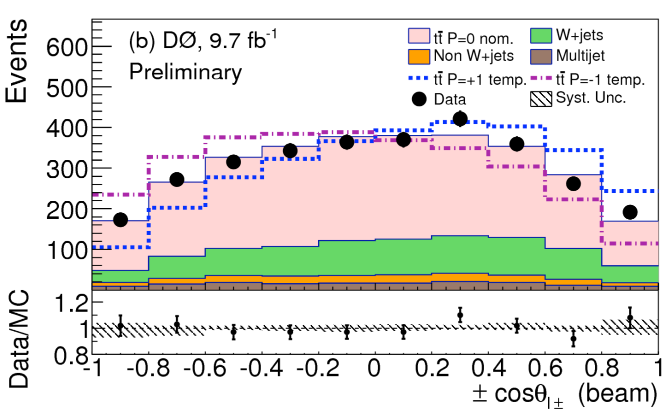
$$\tilde{B}_i^\pm = b_1^\pm \hat{p}_i + b_2^\pm \hat{k}_i + b_3^\pm n_i \qquad \mathbf{n} = \hat{\mathbf{p}} \times \hat{\mathbf{k}}$$

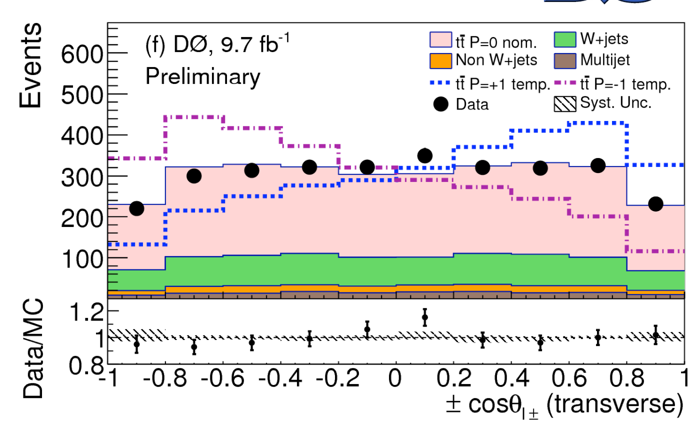
PRL 111, 232002 (2013)



PRD 93, 052007 (2016)

D0 Note 6471-CONF



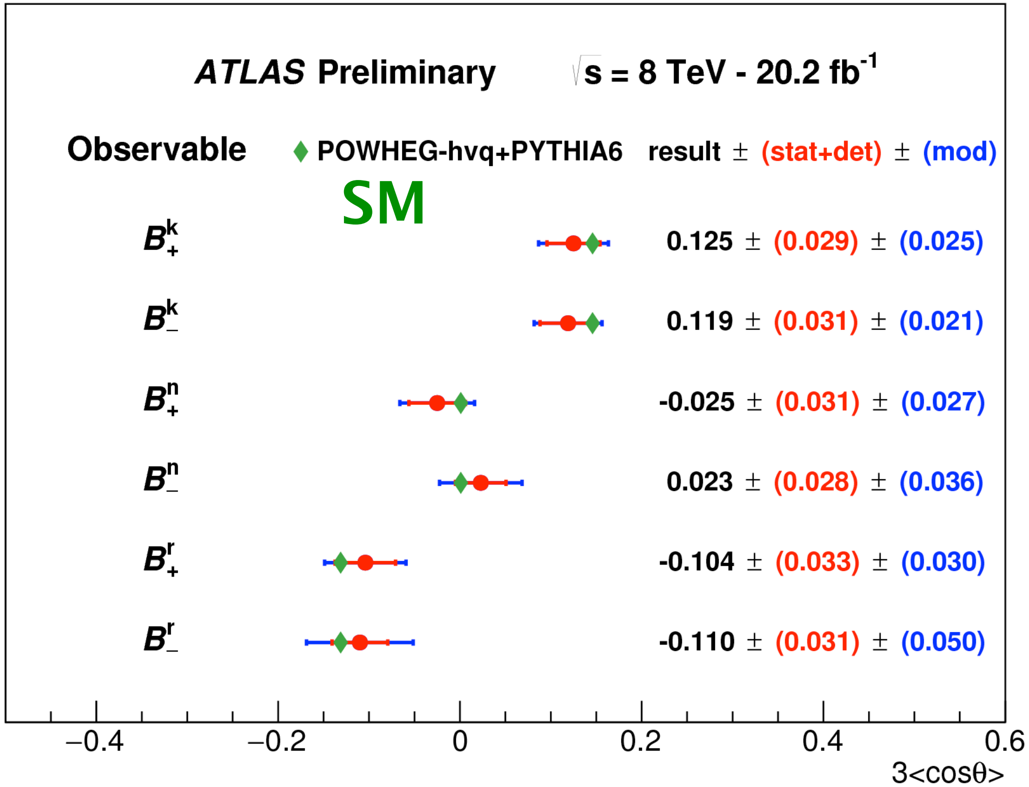


→ **in agreement with SM**

Longitudinal and transverse polarisation

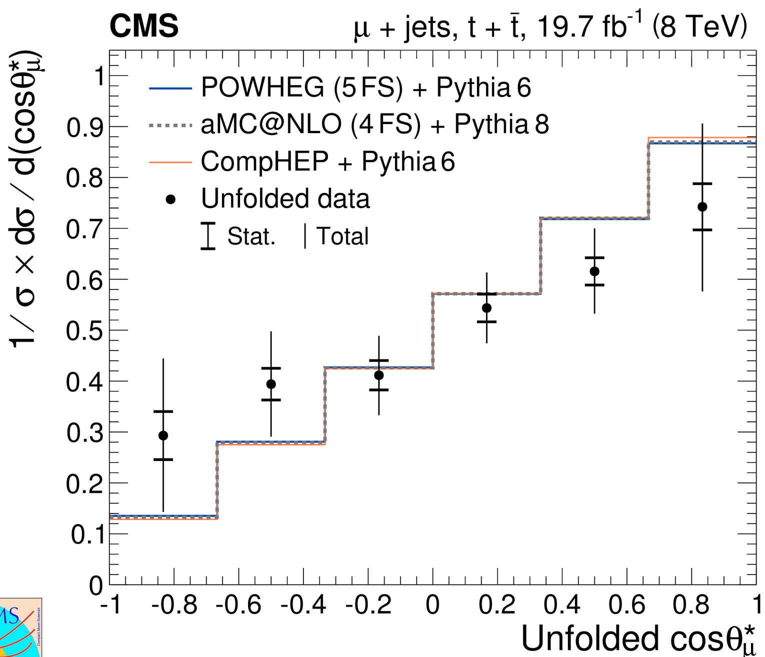
$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

$$\tilde{B}_i^{\pm} = b_1^{\pm} \hat{p}_i + b_2^{\pm} \hat{k}_i + b_3^{\pm} n_i \quad \mathbf{n} = \hat{\mathbf{p}} \times \hat{\mathbf{k}}$$

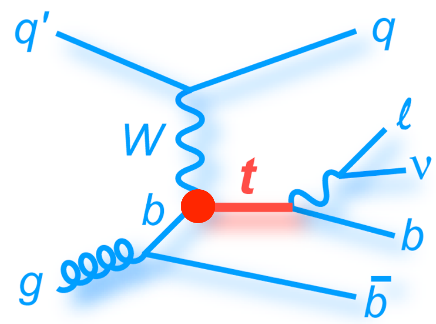


→ in agreement with SM

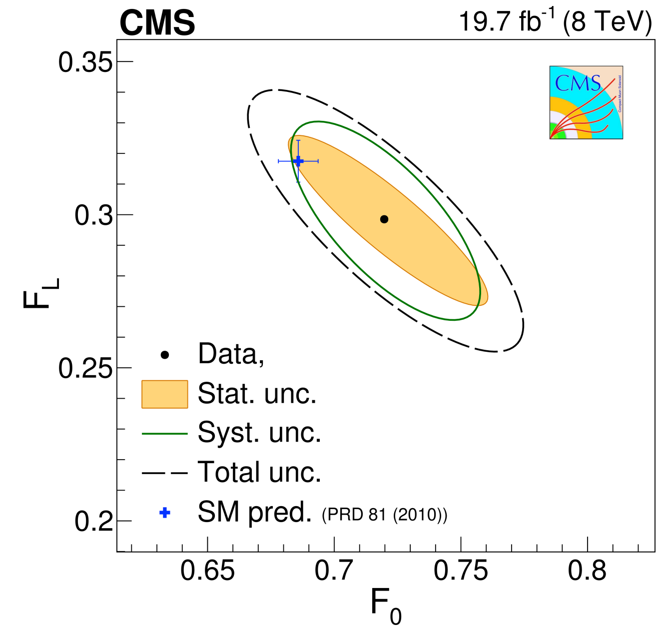
Polarisation and W boson helicity



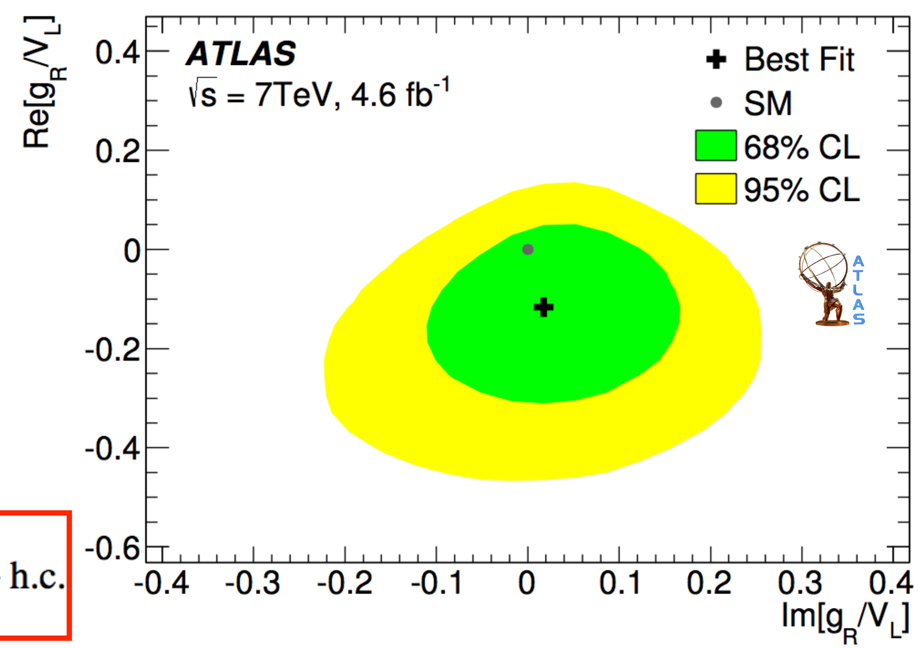
→ **top quarks polarised as in SM**



$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$

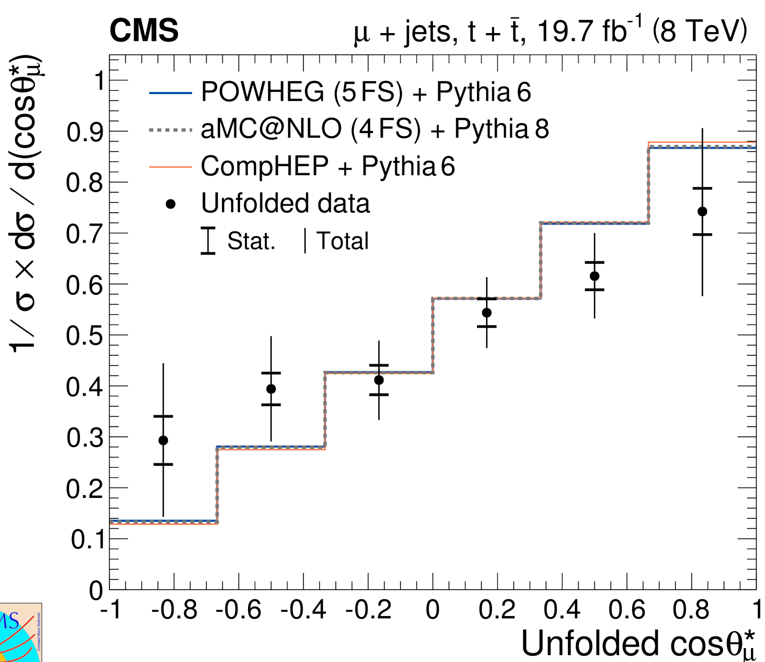


no new physics

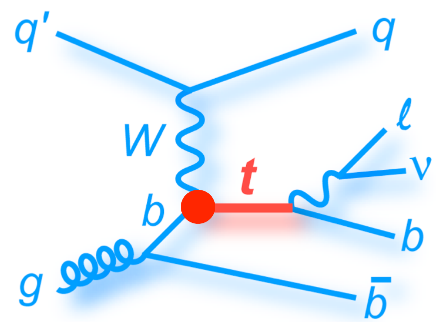


$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W^{-}_{\mu} + \text{h.c.}$$

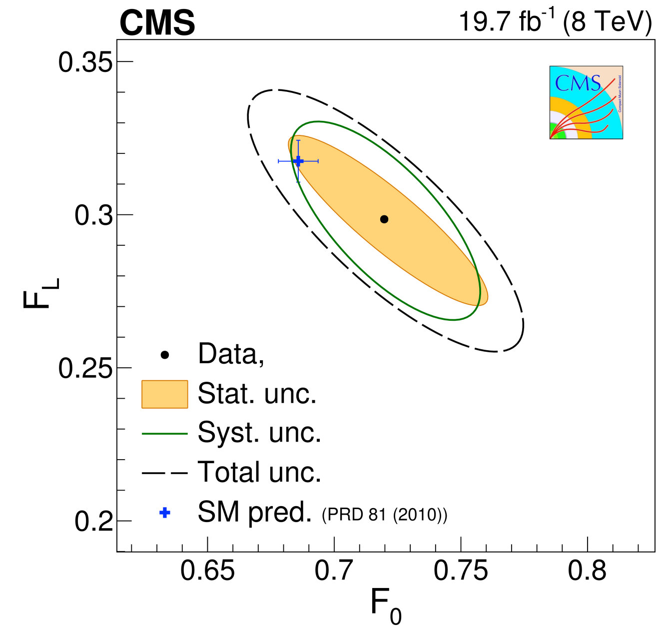
Polarisation and W boson helicity

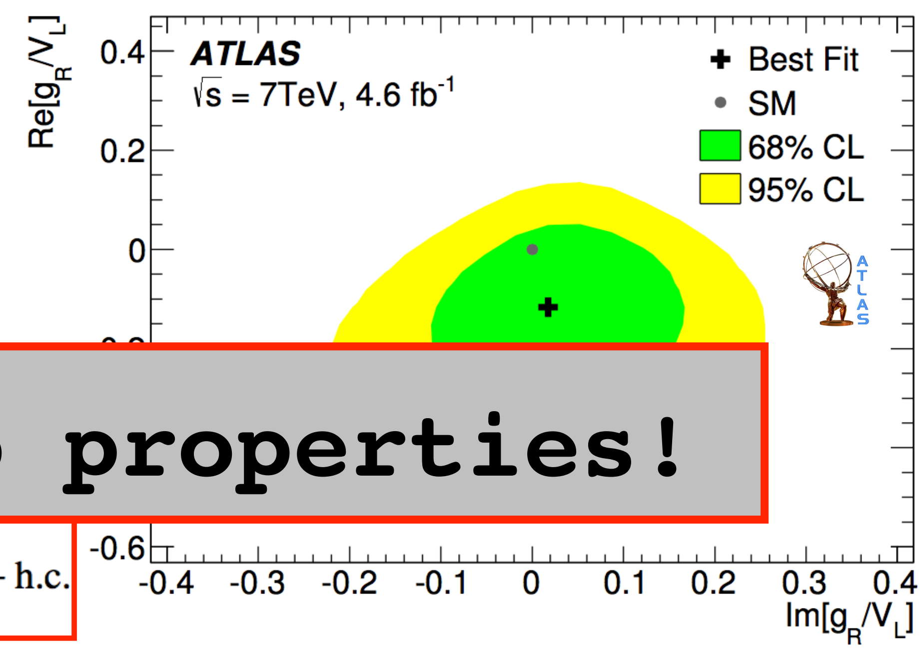


→ **top quarks polarised as in SM**



$$\frac{-ig}{2\sqrt{2}}\bar{t}\,\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$





no new

We ♥ single top properties!

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\rm L}P_{\rm L}+V_{\rm R}P_{\rm R}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{W}}\left(g_{\rm L}P_{\rm L}+g_{\rm R}P_{\rm R}\right)tW_{\mu}^{-} + \text{h.c.}$$

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

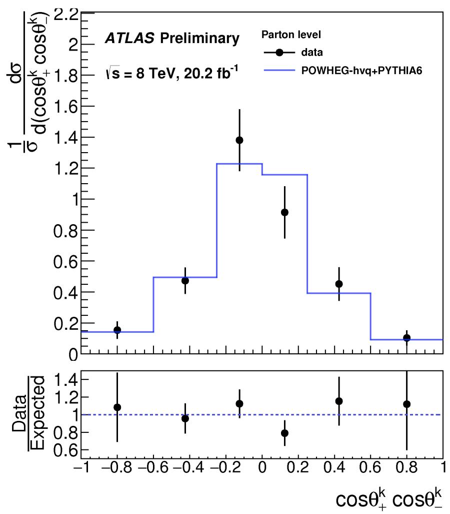
spin correlation

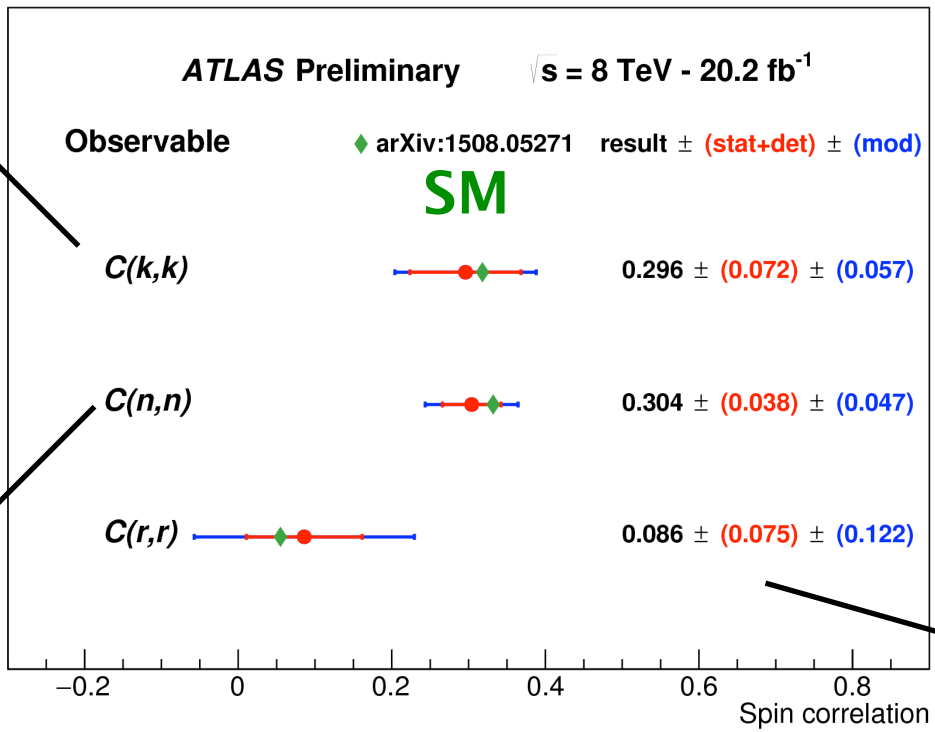
P-even, C-even, but also
CP-odd and P-odd ≠0
only in BSM

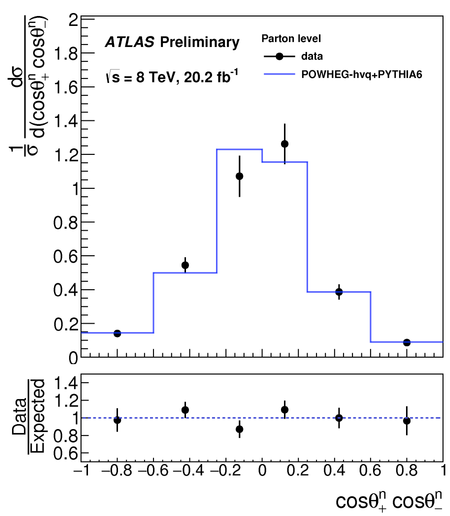
$t\bar{t}$ production density matrix

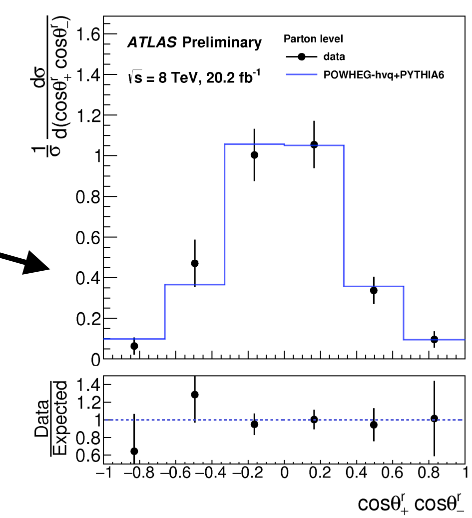
$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

spin correlation







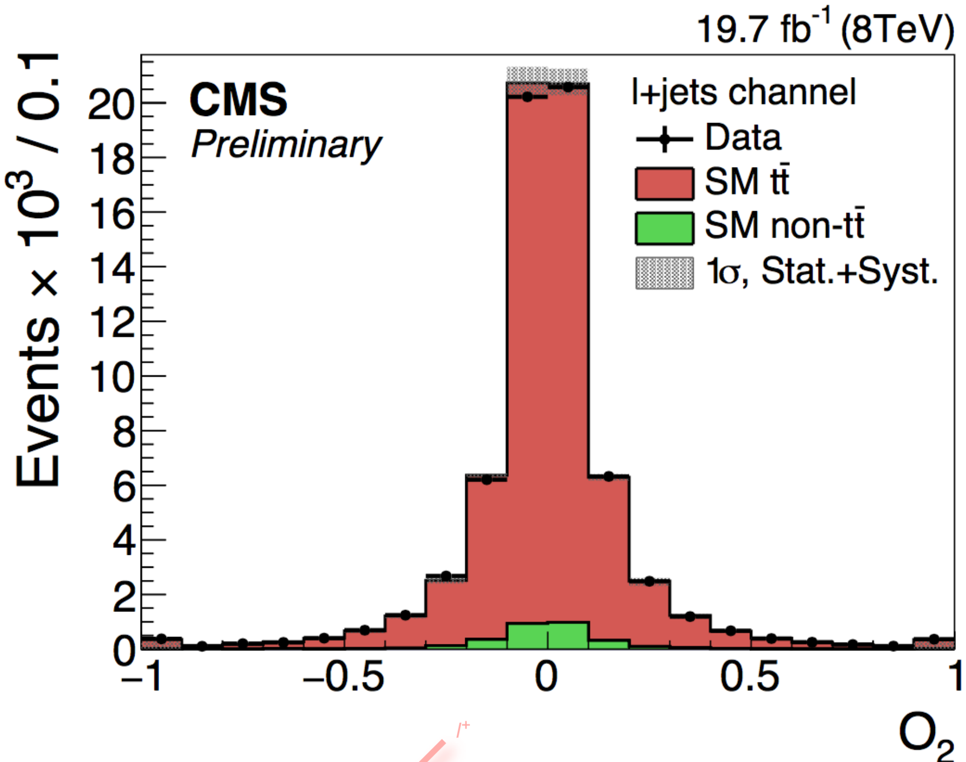


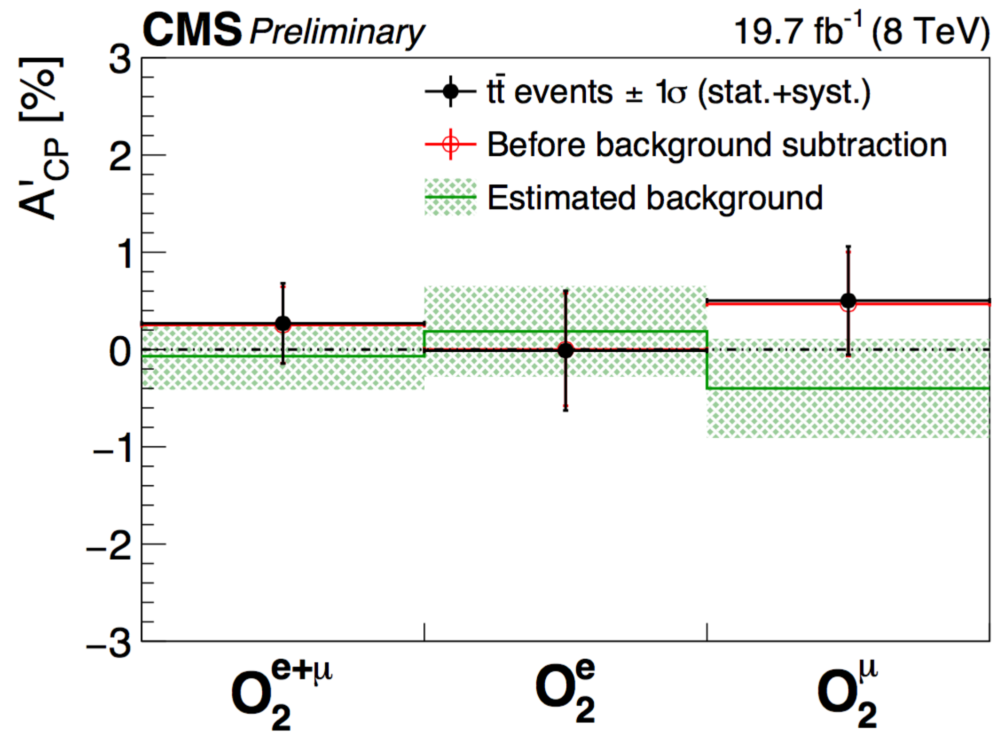
→ **in agreement with SM**

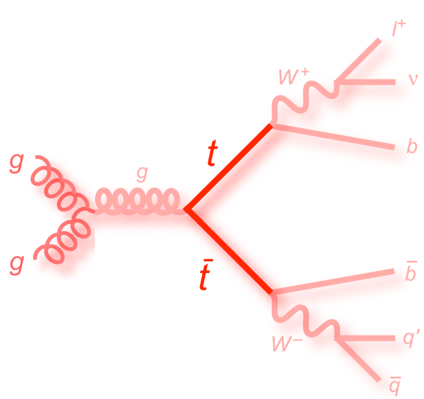
Search for CP-violation

$$O_2 = (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}$$

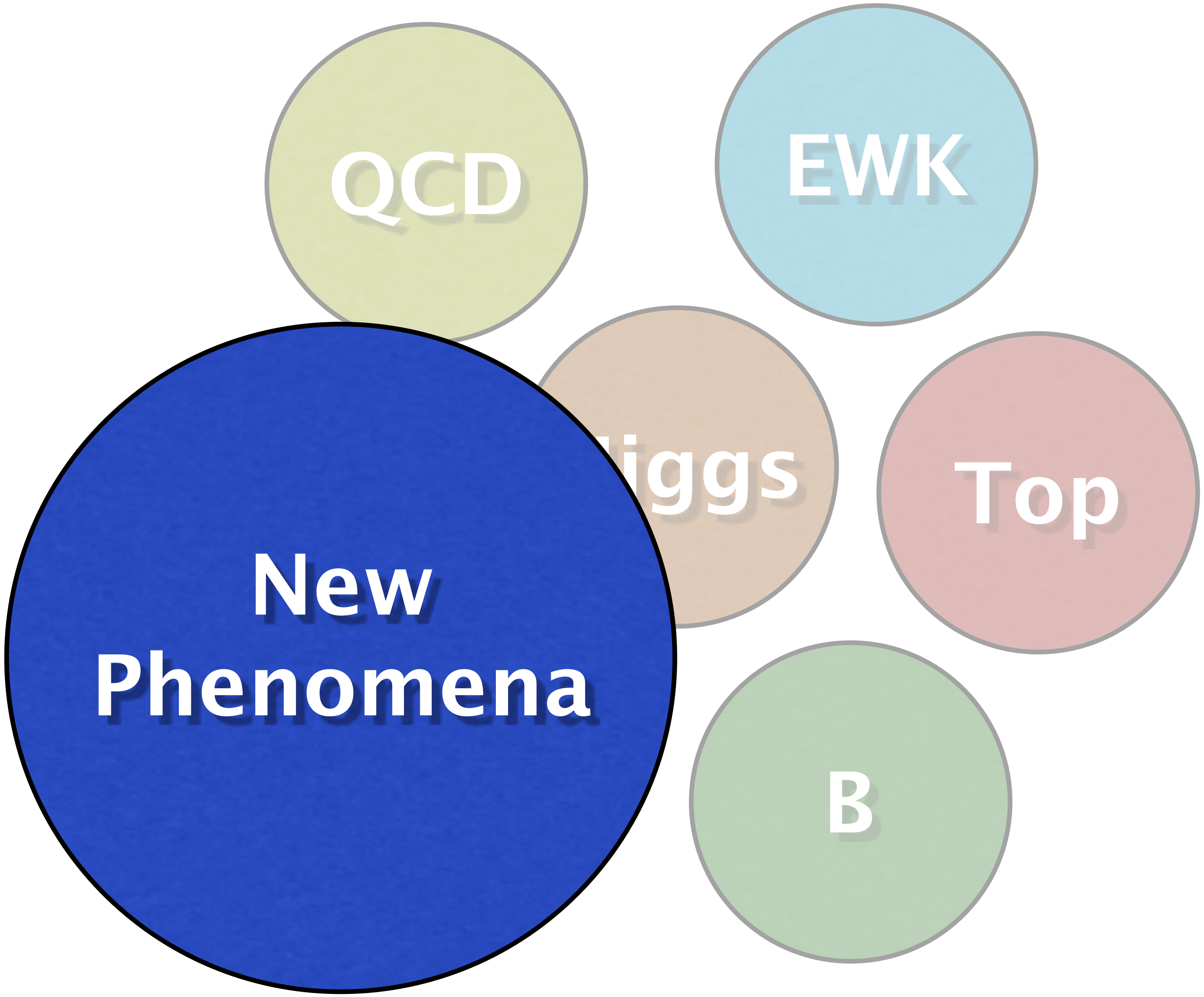




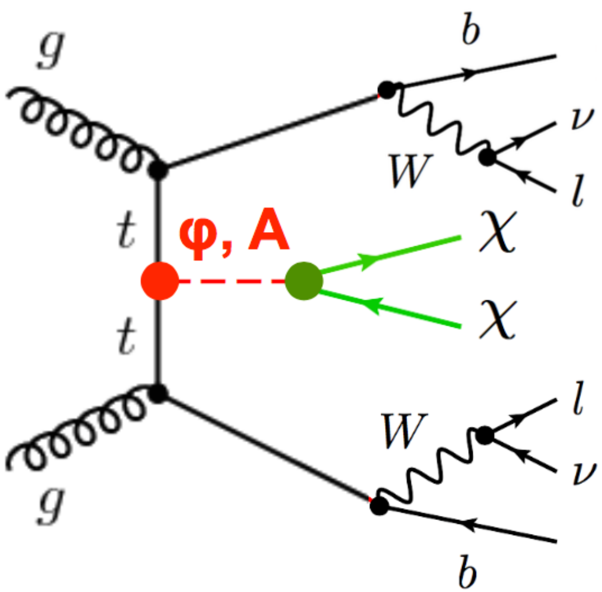


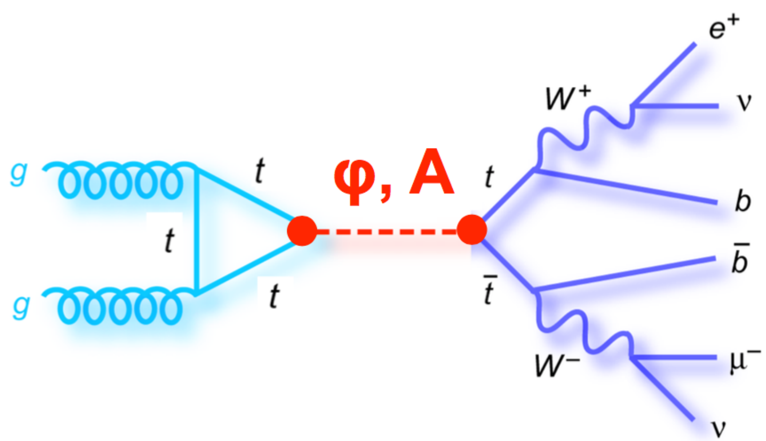
→ **no hint for CP-violation**

Top Quark Physics Topics



Search for top-philic Dark Matter

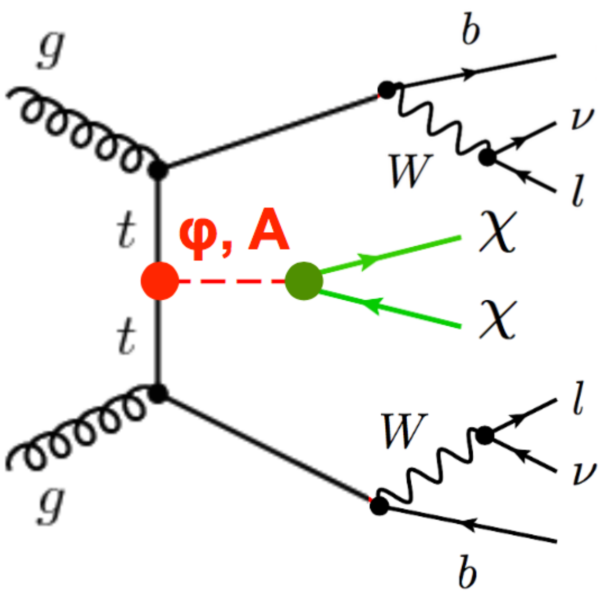


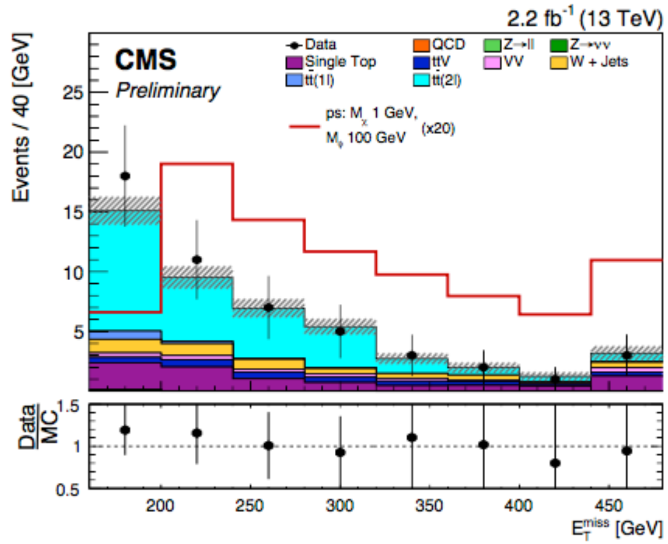


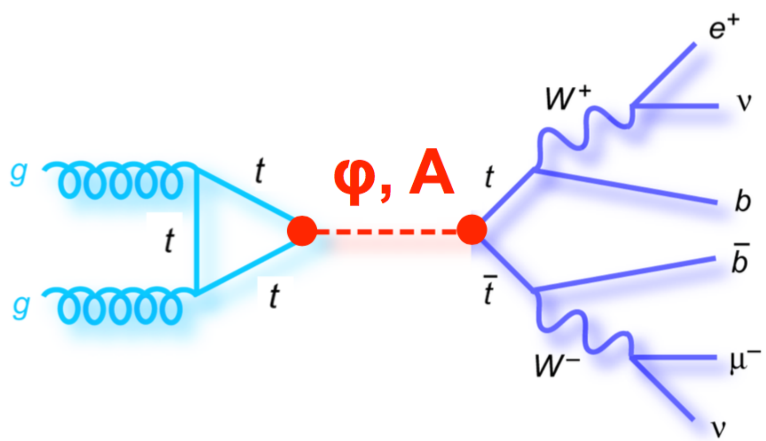
darth matter

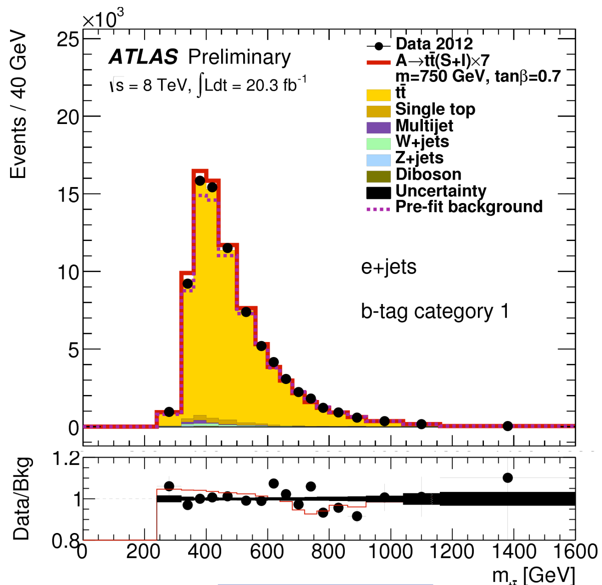
→ **particularly interesting for Yukawa-like couplings between DM mediator and SM particles, e.g. for scalar or pseudoscalar mediators**

Search for top-philic Dark Matter



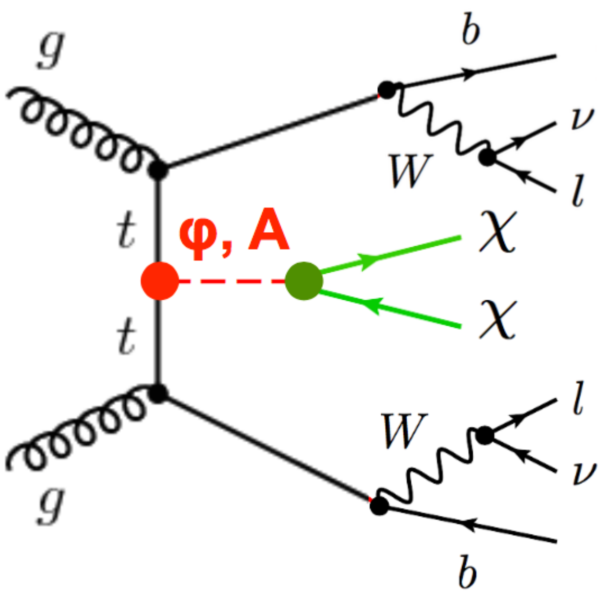


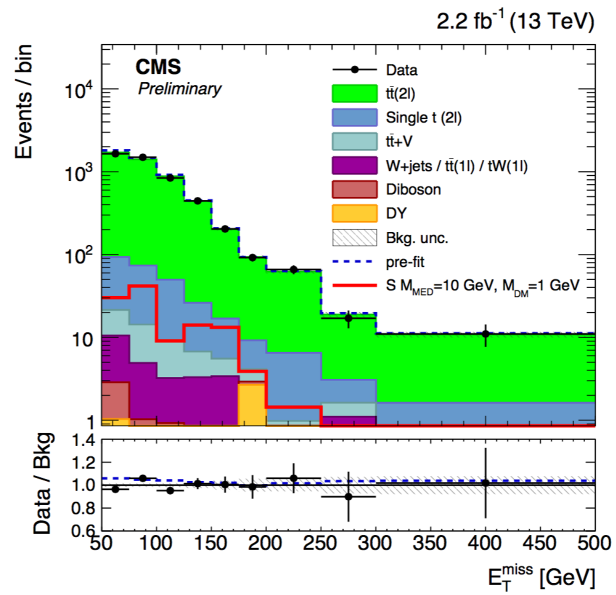


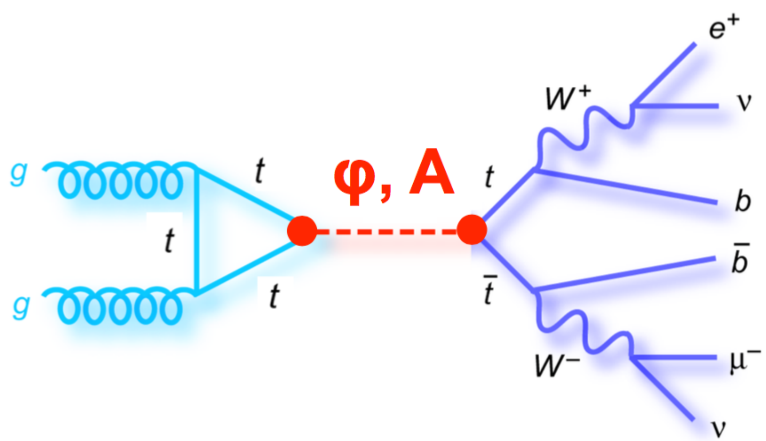


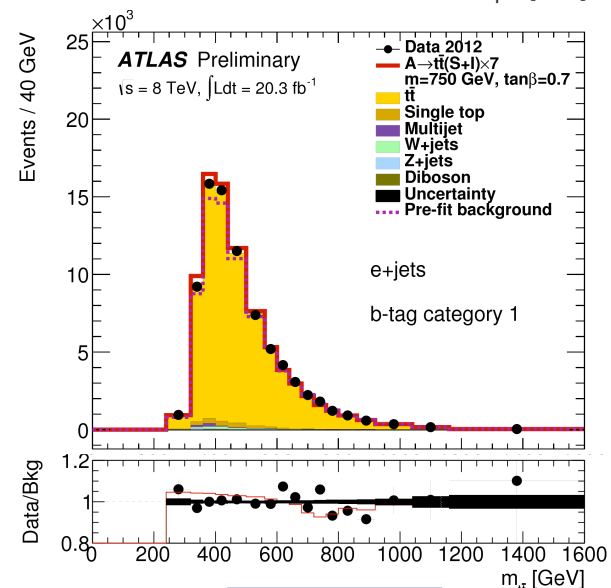
search

Search for top-philic Dark Matter



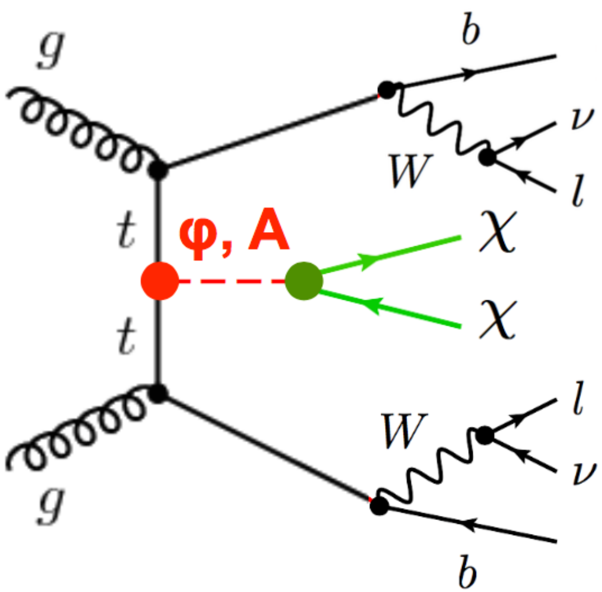


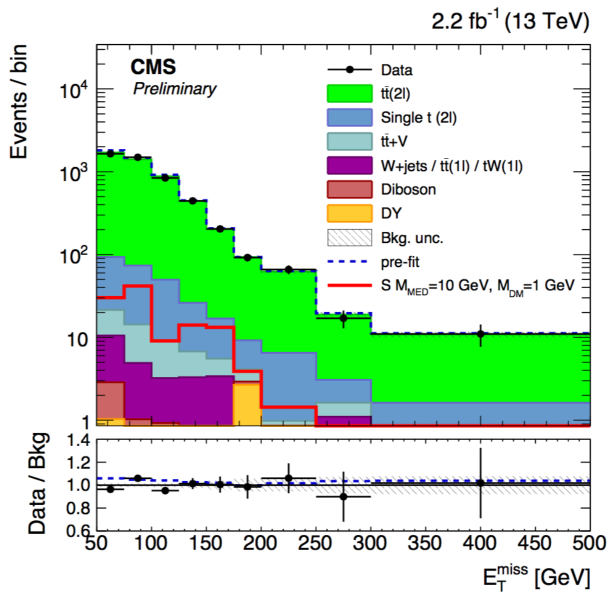


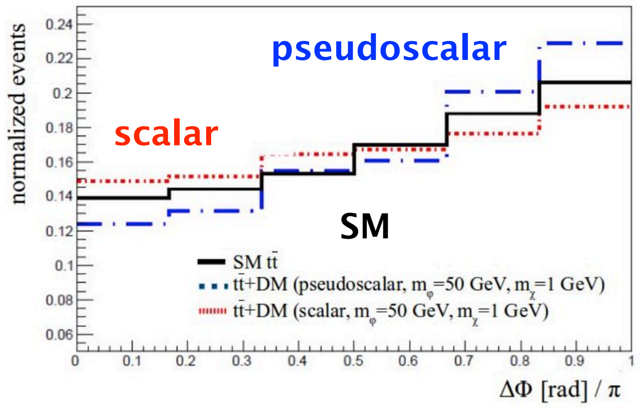


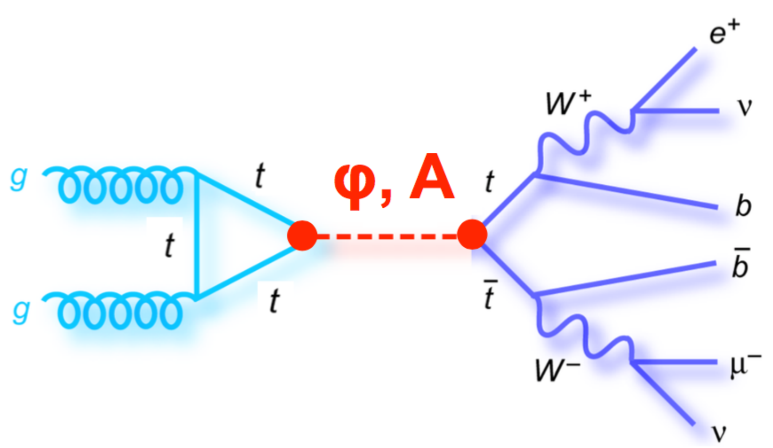
search

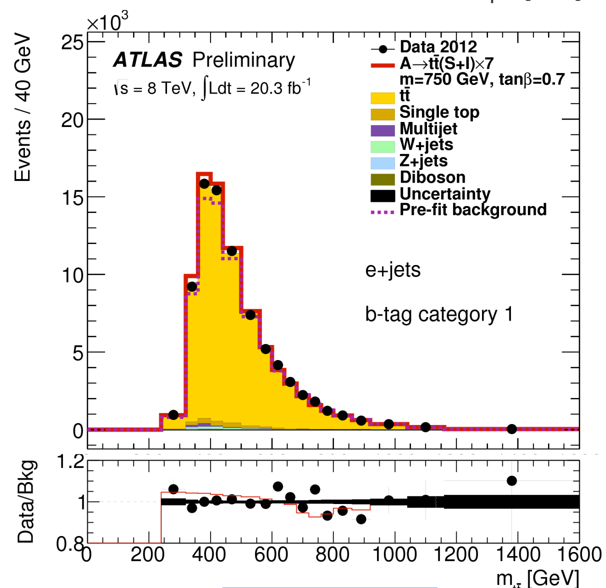
Search for top-philic Dark Matter

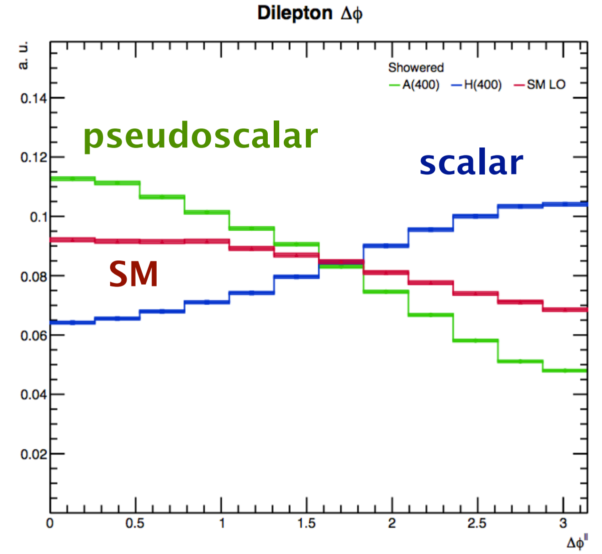








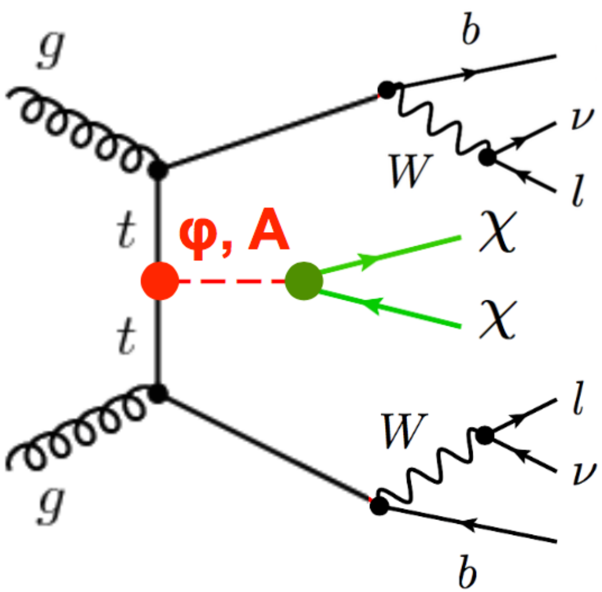


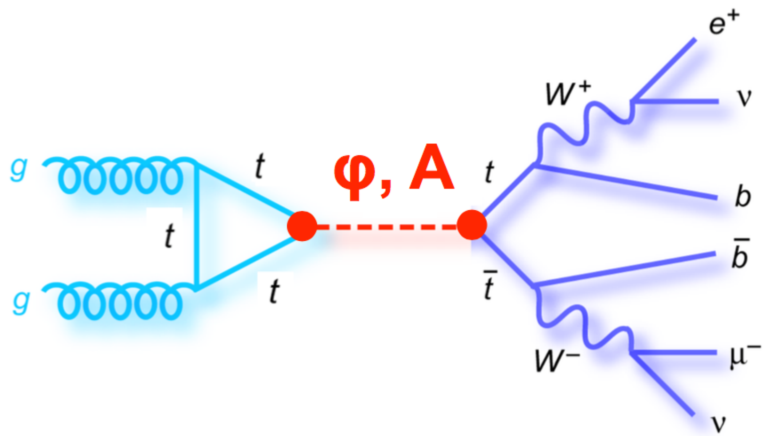


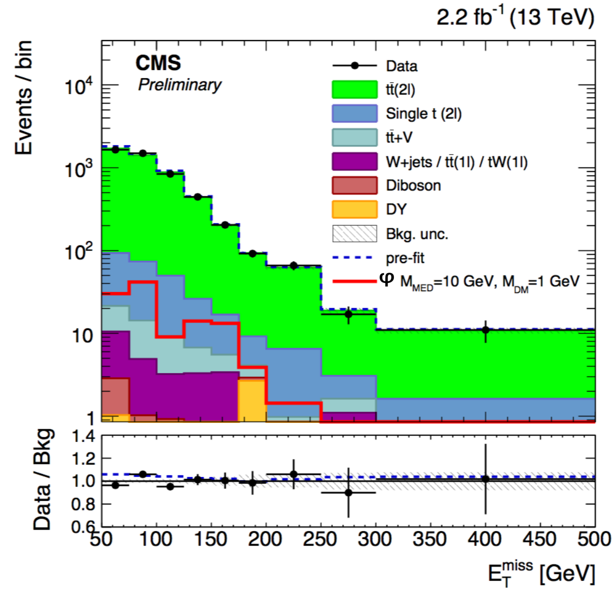
search

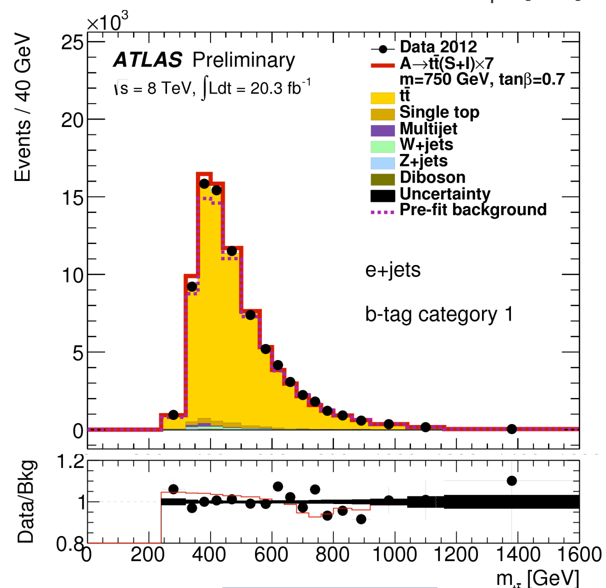
nature

Search for top-philic Dark Matter



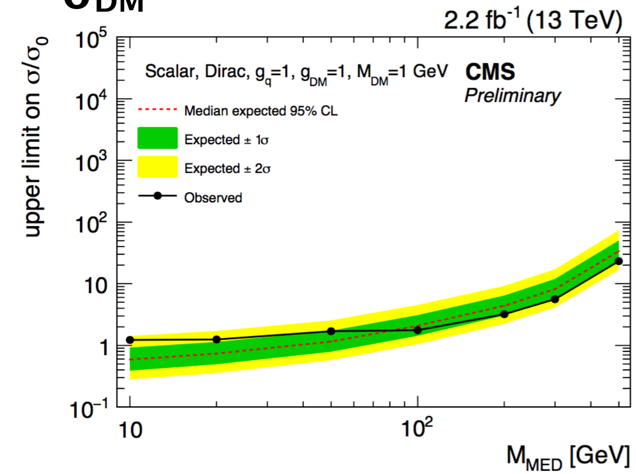






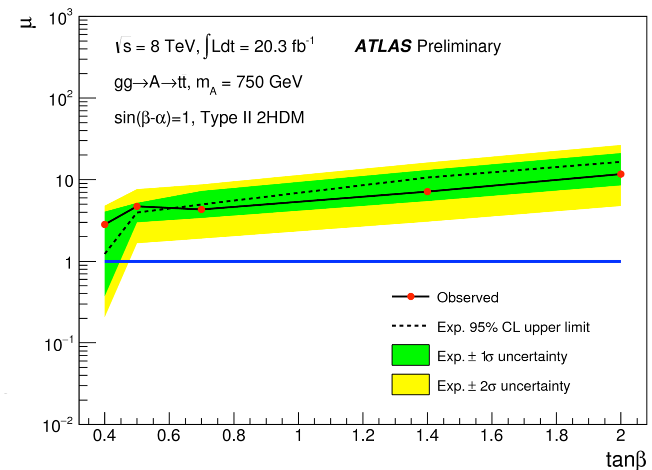
$\frac{\sigma_{limit}}{\sigma_{DM}}$

CMS-PAS-EXO-16-028



$\frac{\sigma_{limit}}{\sigma_{SUSY}}$

ATLAS-CONF-2016-073

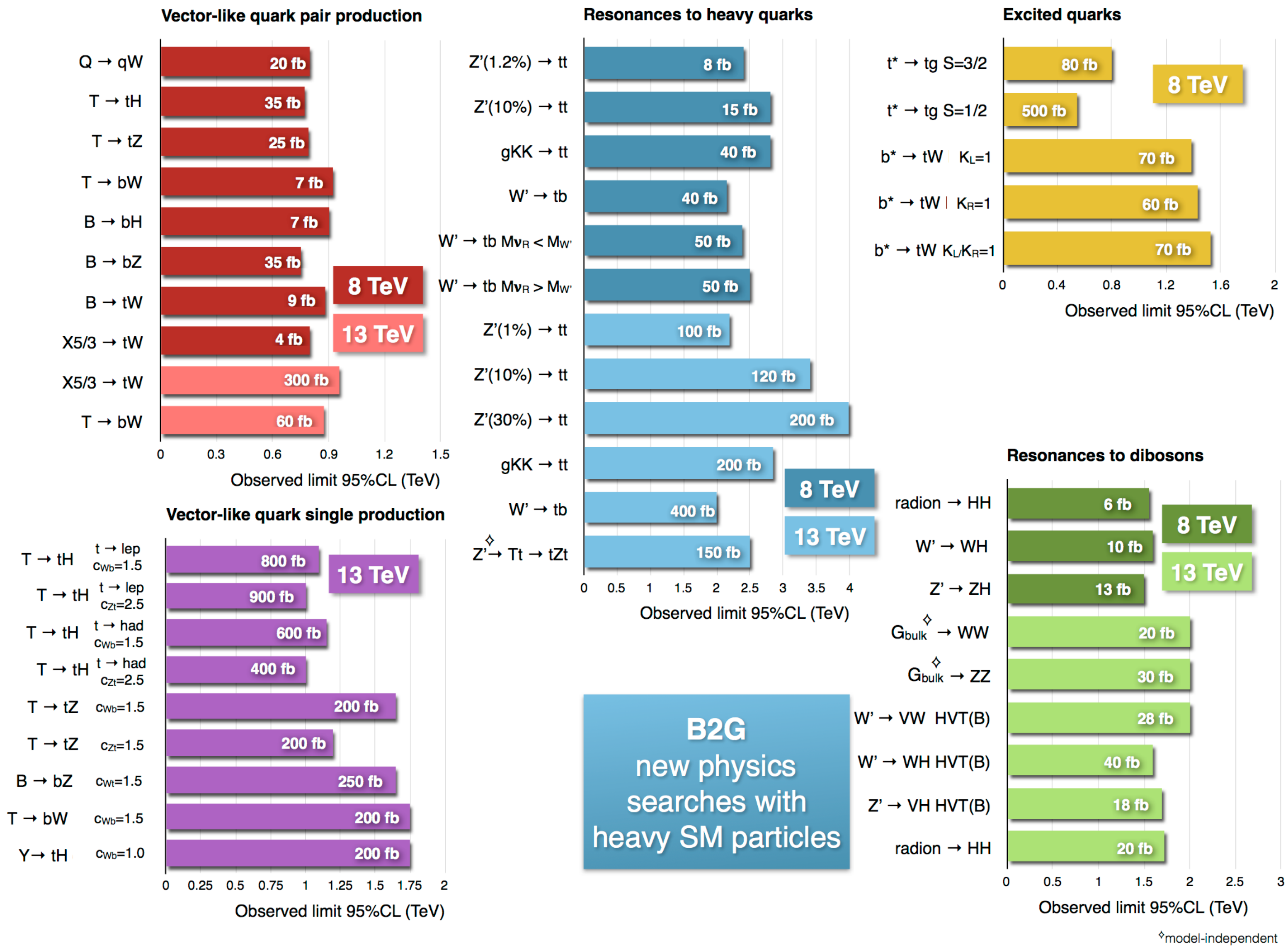


→ no hint for Dark Matter so far

search

exclusion

Pushing the TeV scale

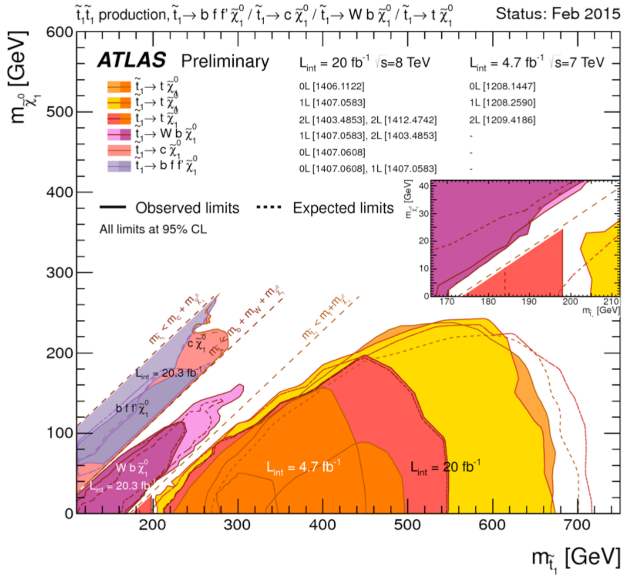


→ lots of opportunities for discovery in Run-II

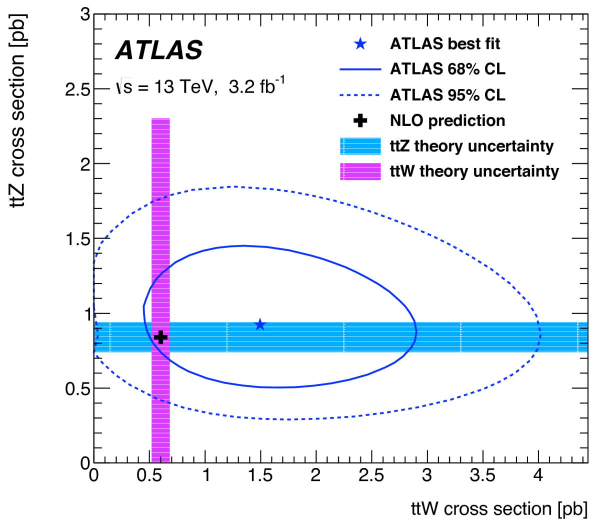
Summary

- the top quark is a very rich field of research
- very interesting candidate for new physics!
- measure properties with highest possible precision and perform direct searches

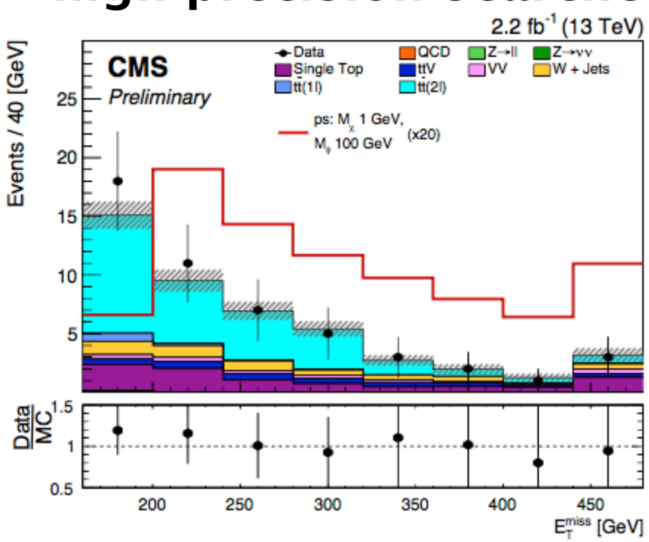
– high precision cross sections and properties



– rare processes



– high precision searches



→ observe more SM processes in Run-II, many high precision property/cross section measurements to come, discover new physics (in)directly…

Summary

let's smash the SM in Run-2!

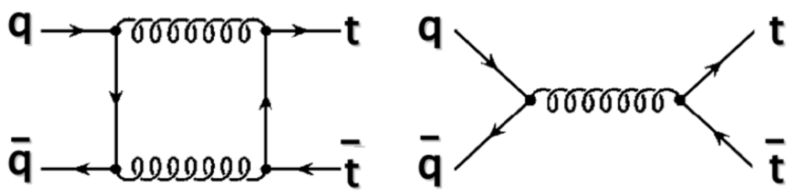
Backup

Charge Asymmetry

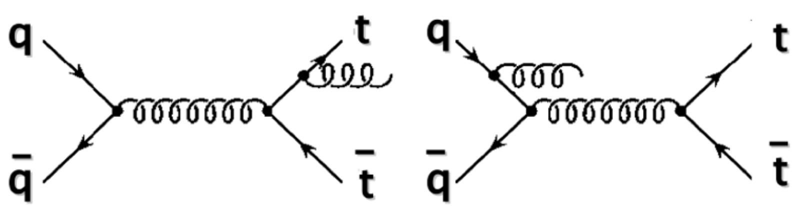
- asymmetry in $O(\alpha_s^3)$

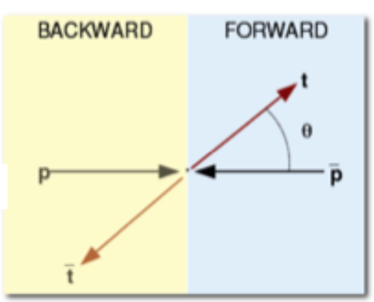
NLO QCD

interference between:



interference between:





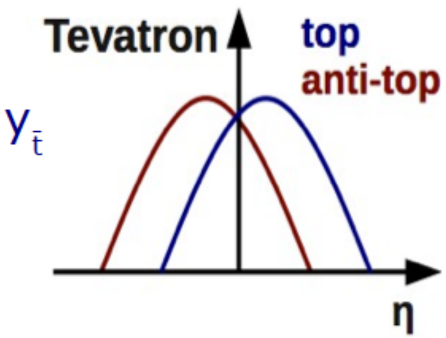
$$A_{fb} = \frac{F - B}{F + B}$$

- **complementary to the LHC**

Tevatron

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

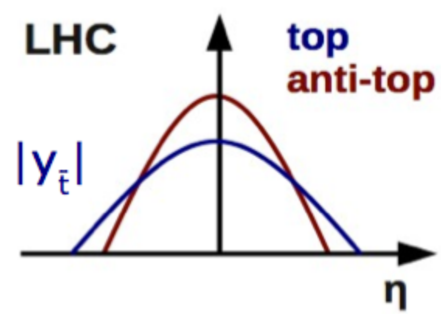
$\Delta y = y_t - y_{\bar{t}}$



LHC

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

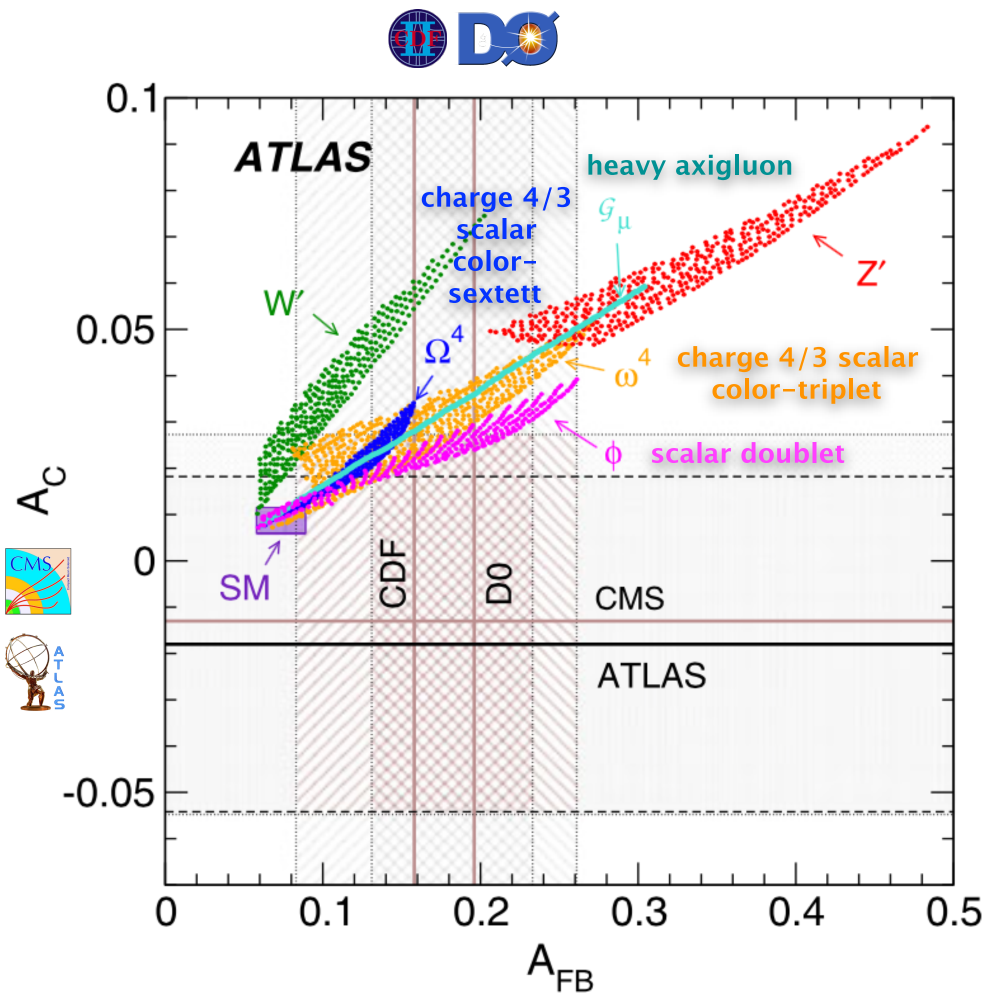
$\Delta|y| = |y_t| - |y_{\bar{t}}|$

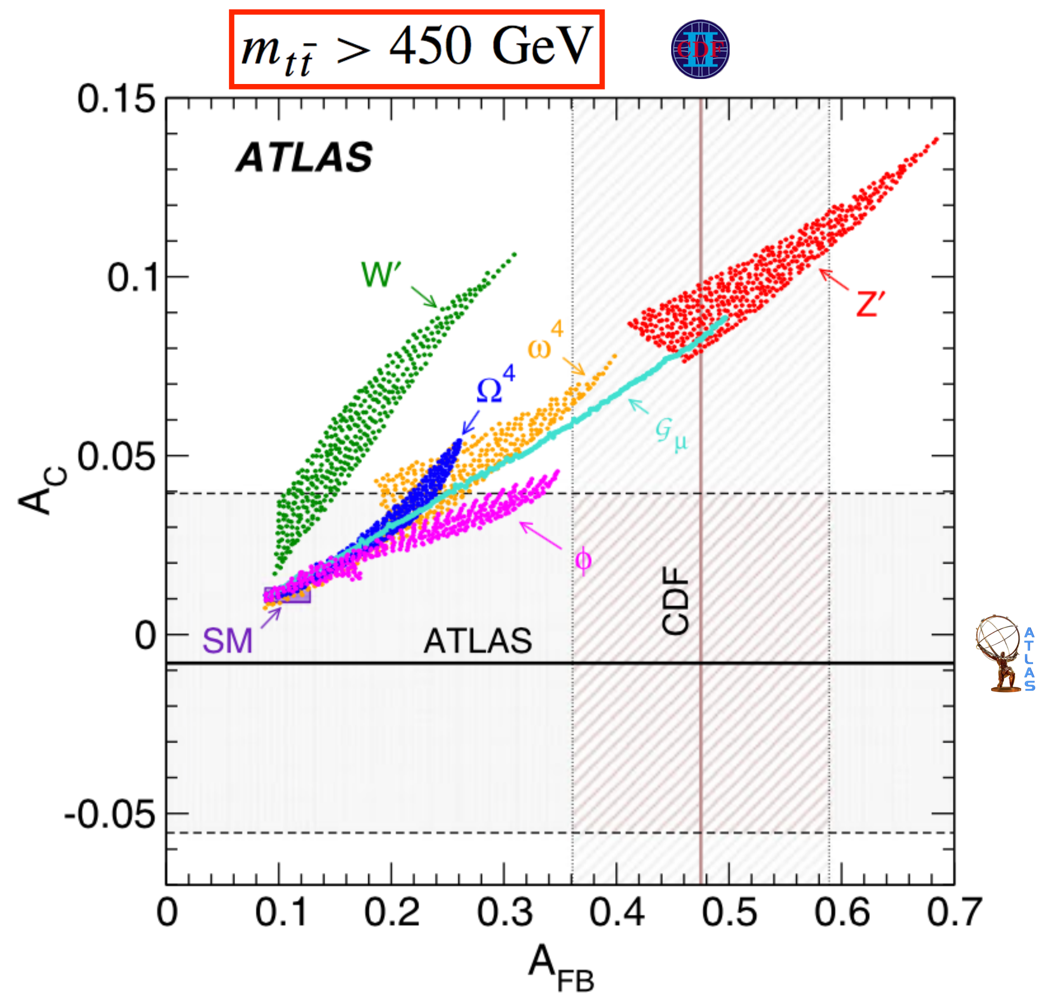


led to excitement at Tevatron

FB vs Charge Asymmetry

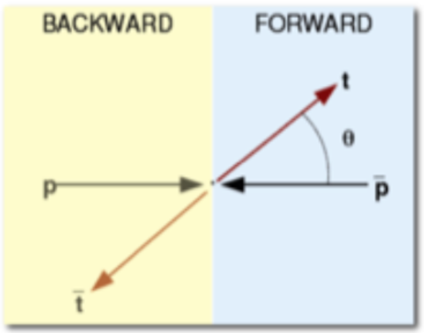
Eur.Phys.J. C72, 2039 (2012)



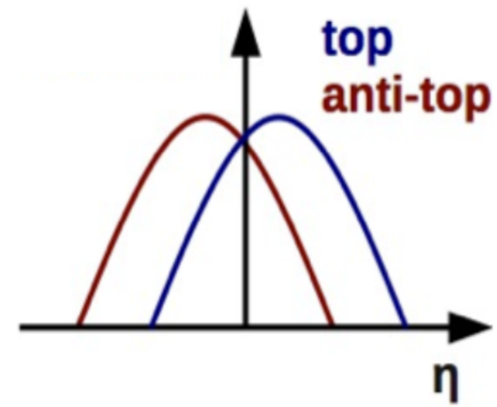


→ **Tevatron observed a slight excess (half of data set)**

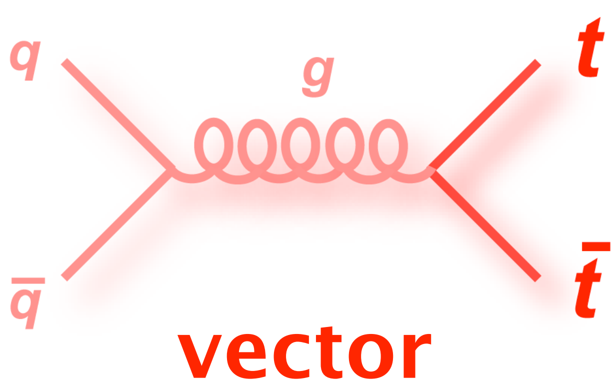
Forward–backward $t\bar{t}$ asymmetry



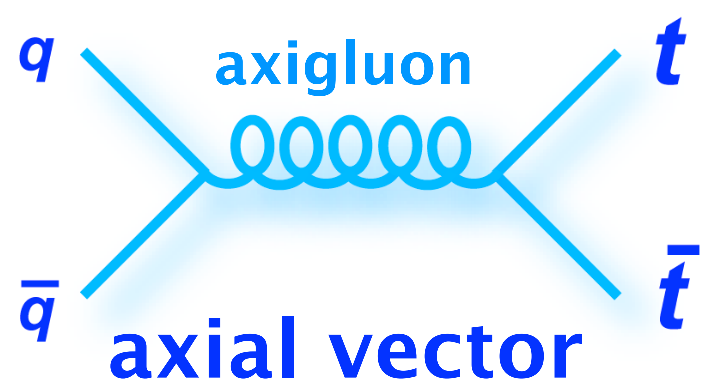
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



SM

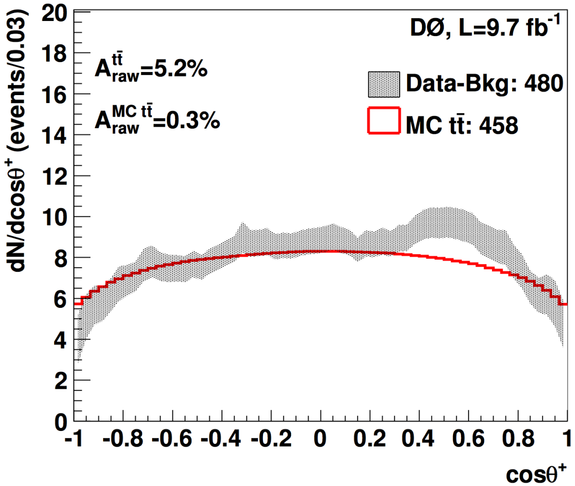


BSM



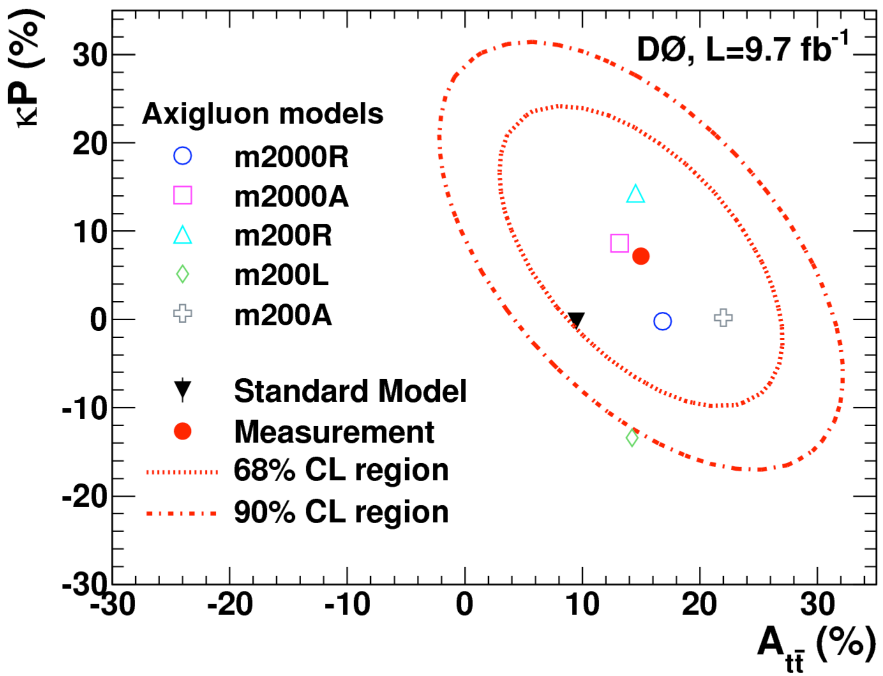
→ **would lead to asymmetry**

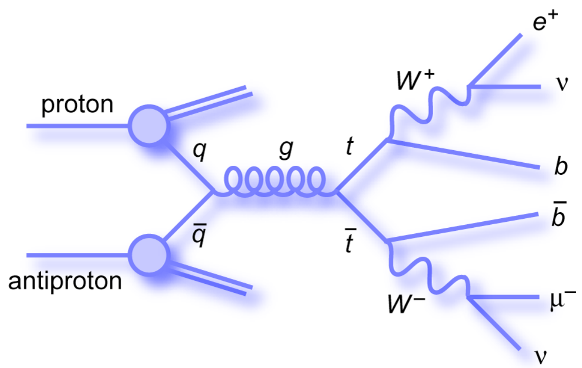
Asymmetry and polarisation



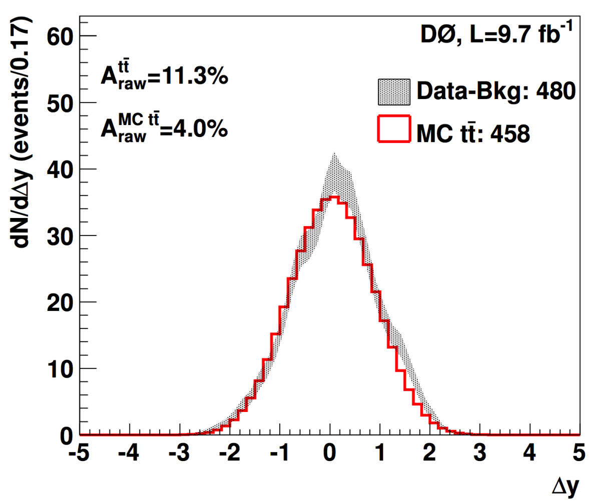
polarisation (helicity)

PRD 92, 052007 (2015)



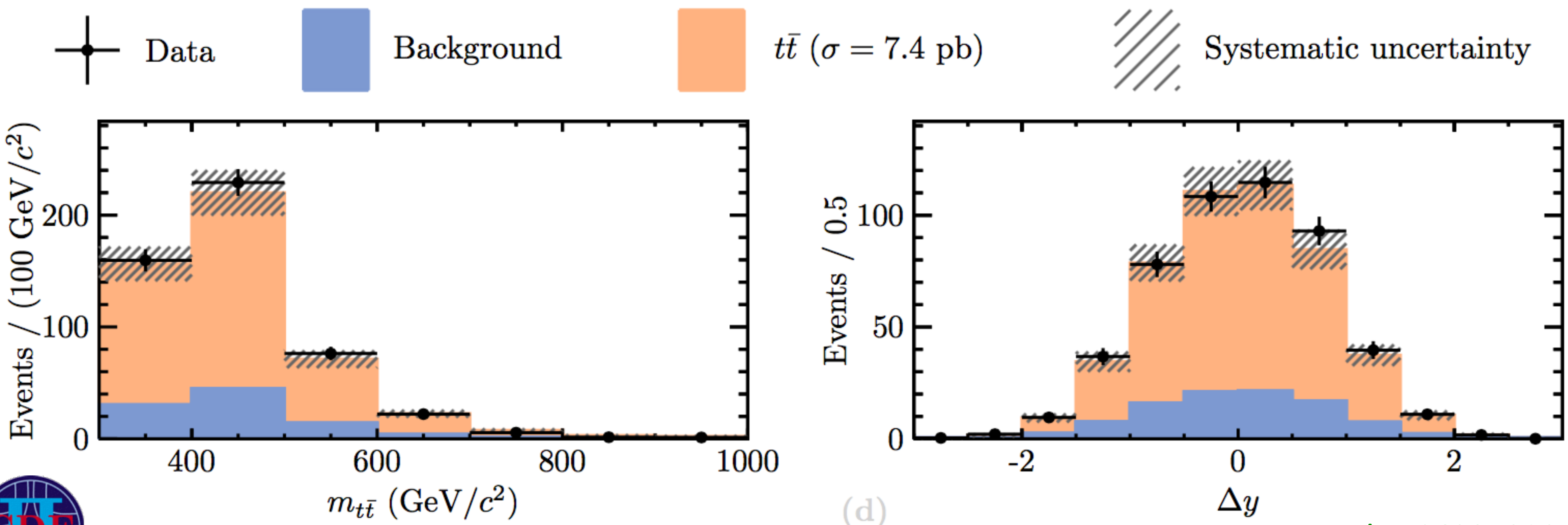


asymmetry

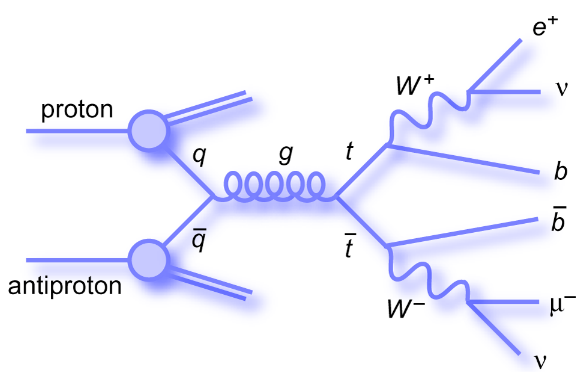


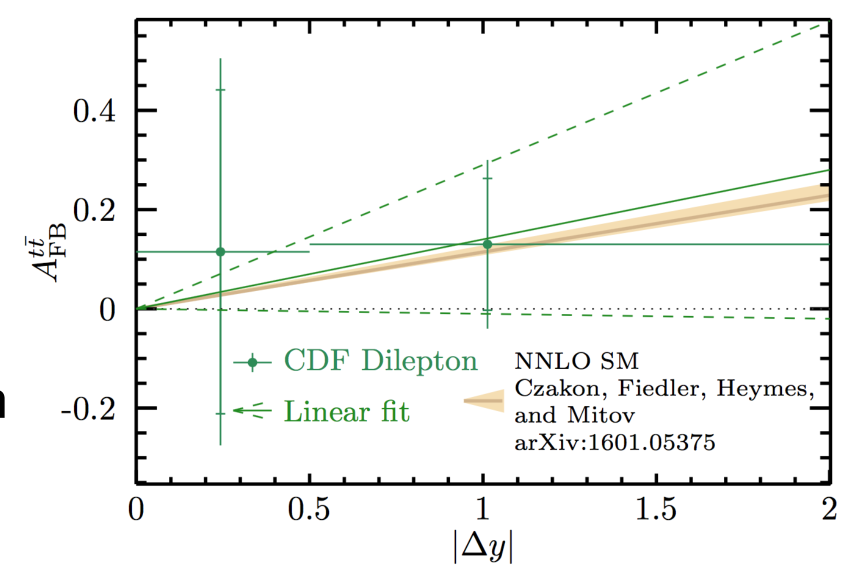
- ME integration method to reconstruct events
- background subtraction and calibration give true parton-level distributions

$t\bar{t}$ FB asymmetry



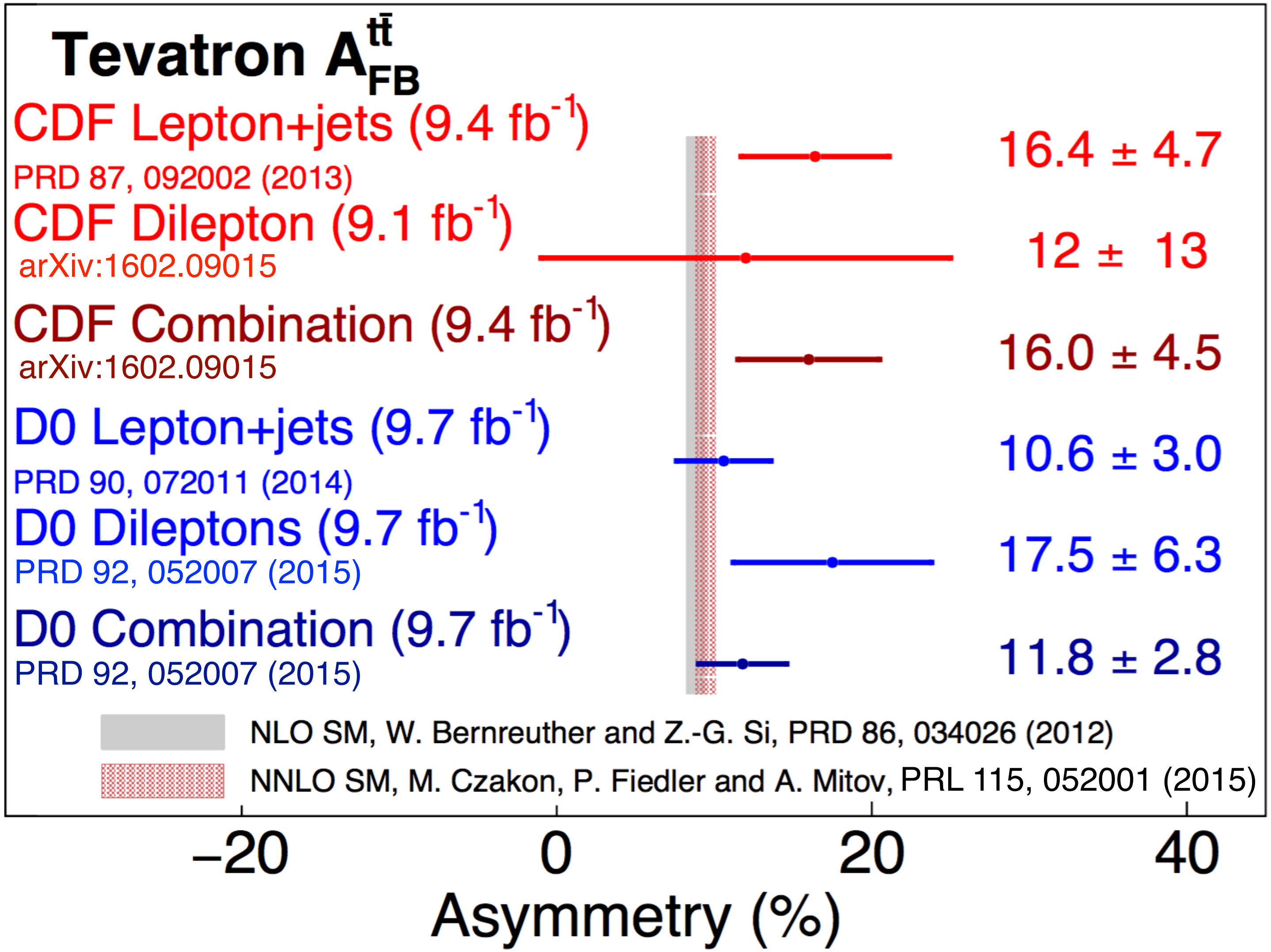
arXiv:1602.09015

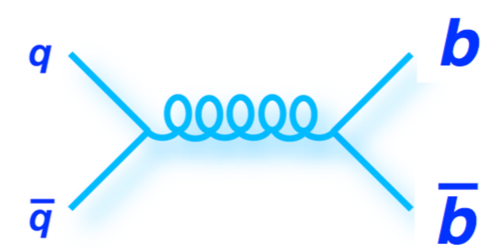




- **optimised kinematic top pair reconstruction**
- **Bayesian procedure to extract parton-level asymmetry**

Summary: $t\bar{t}$ FB asymmetry



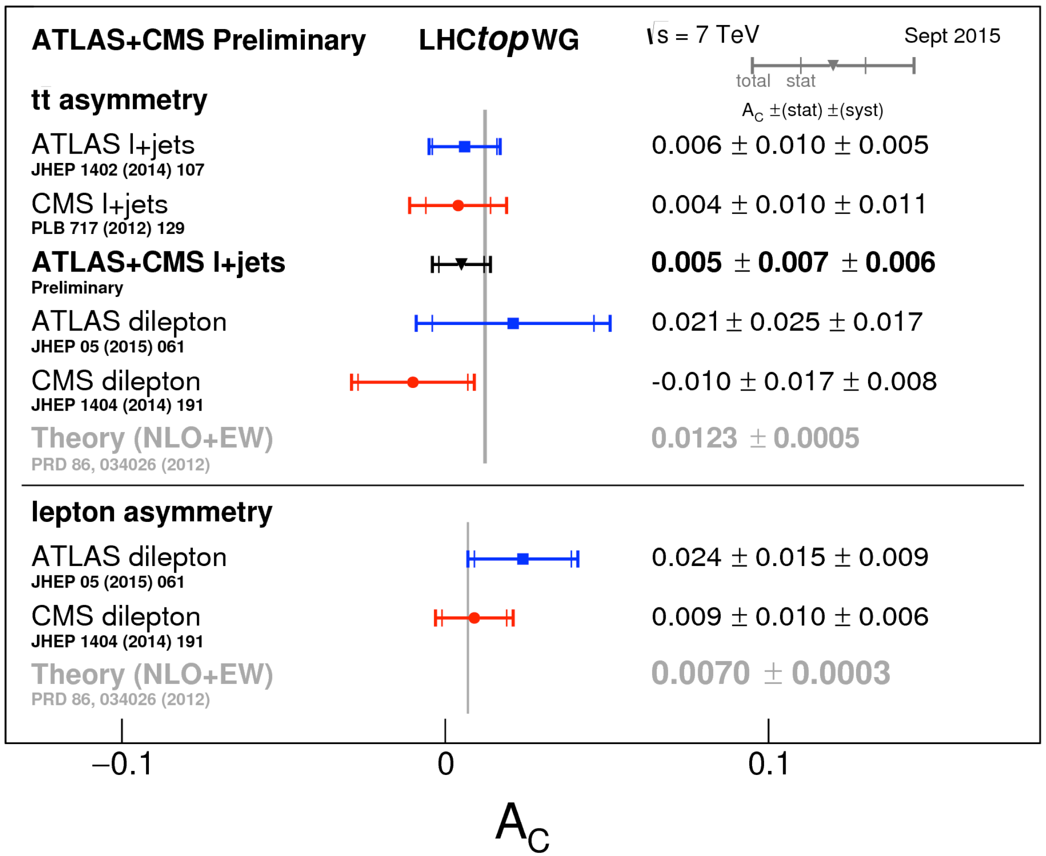


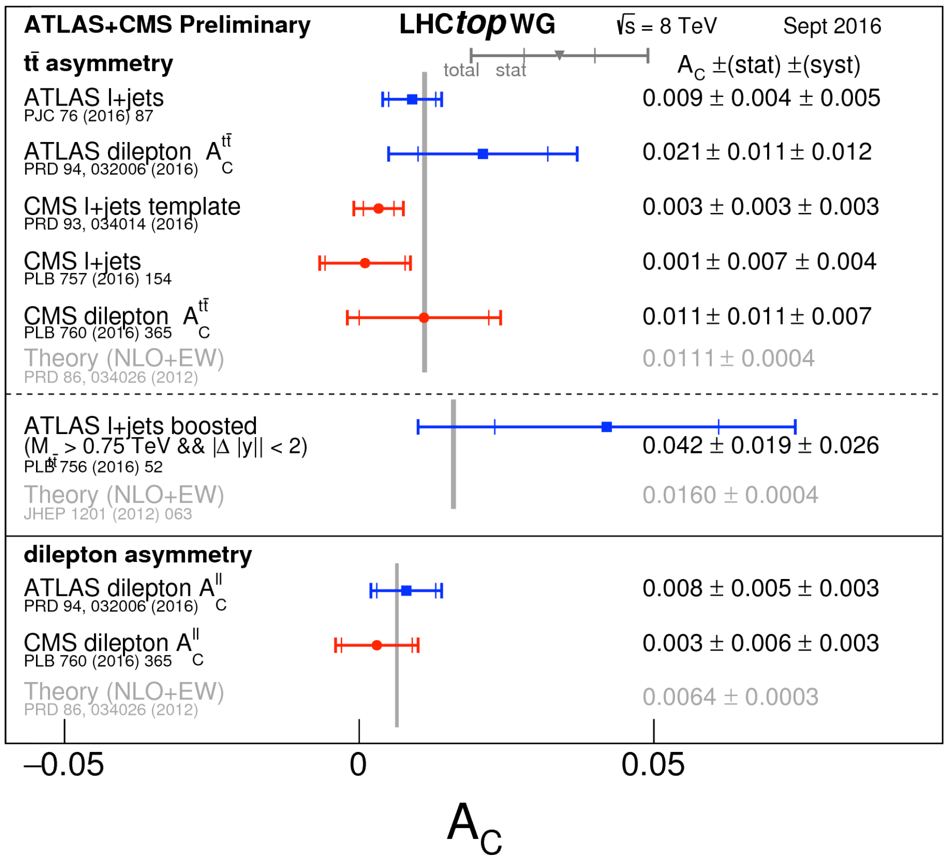
→ **in agreement with SM**

$A_{FB}^{b\bar{b}}$ in agreement with SM

arXiv:1601.06526
PRD 92, 032006 (2015)

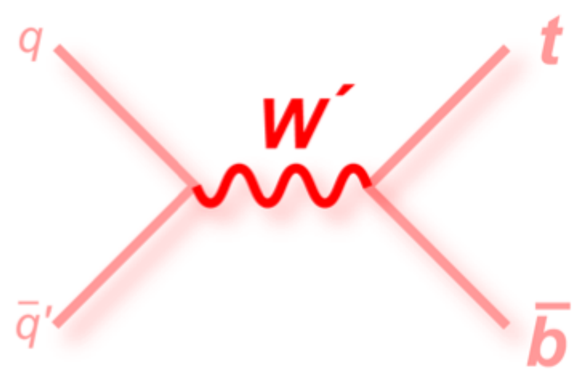
LHC: $t\bar{t}$ charge asymmetry



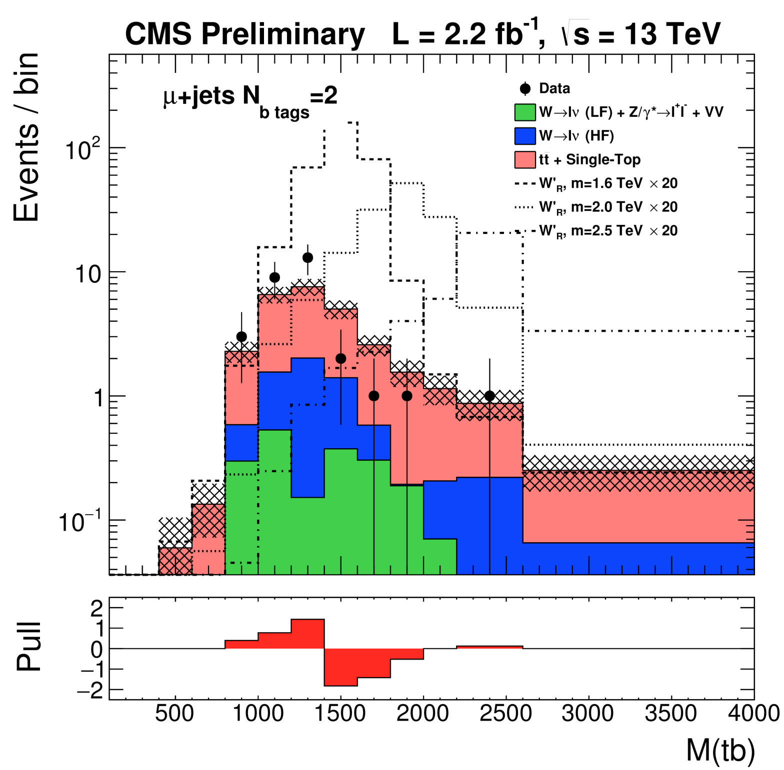


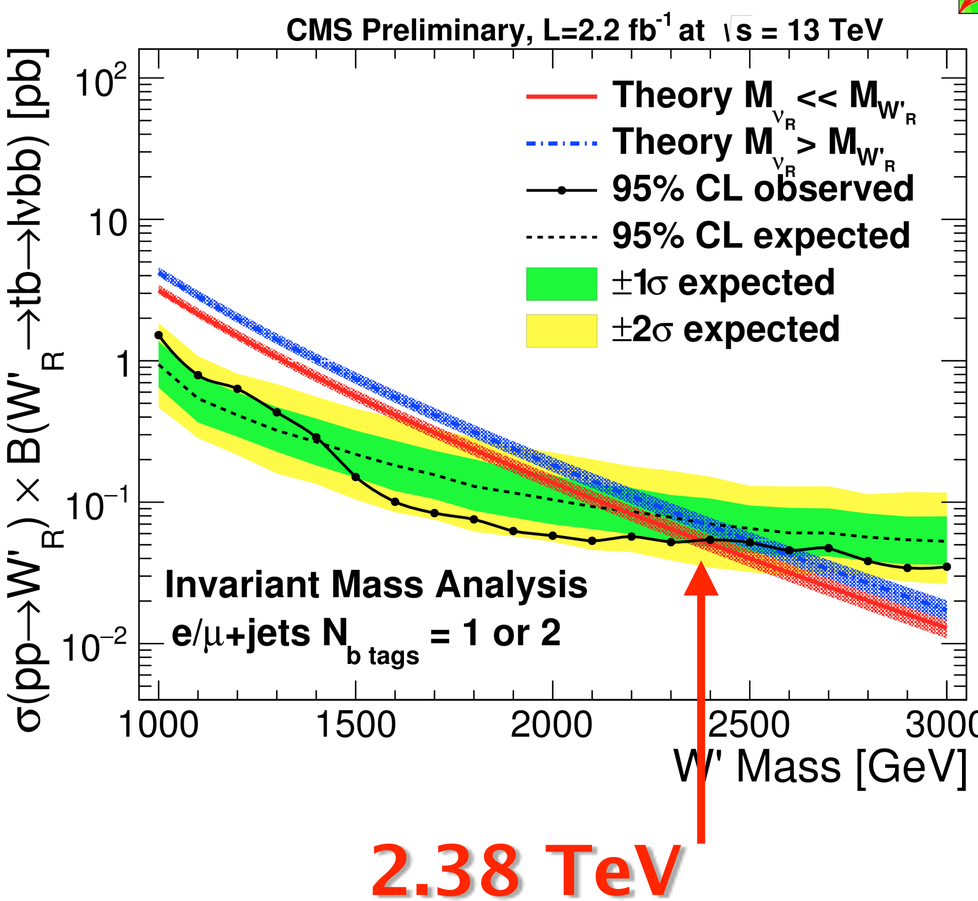
→ **in agreement with SM**

Search for W' production



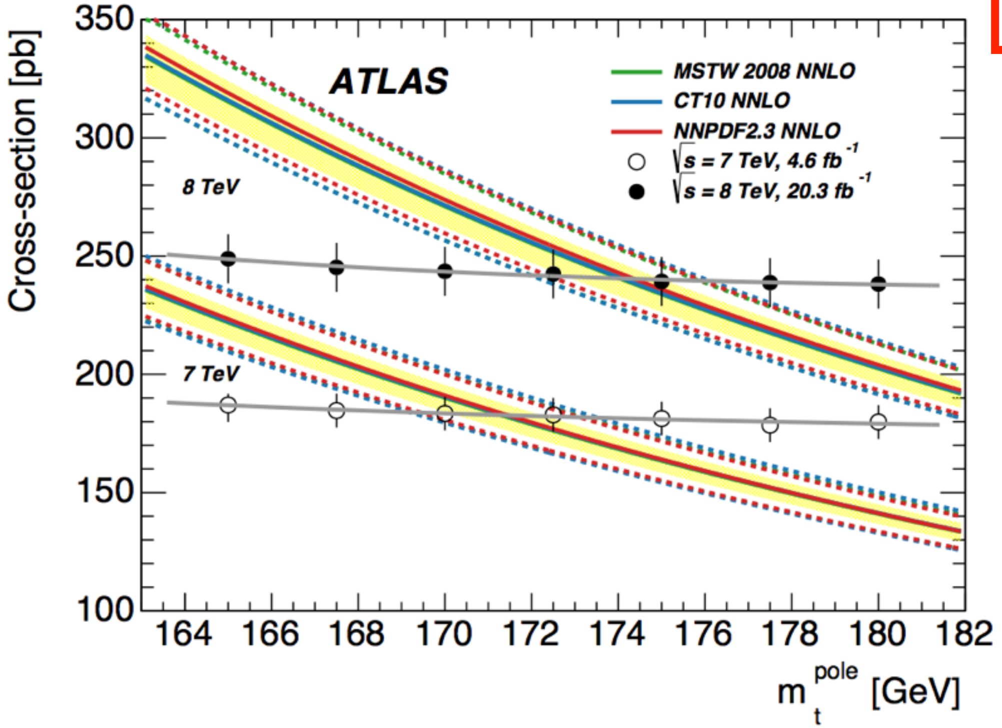
13 TeV





→ **no new physics**

Top Quark Pole Mass



many alternative measurements

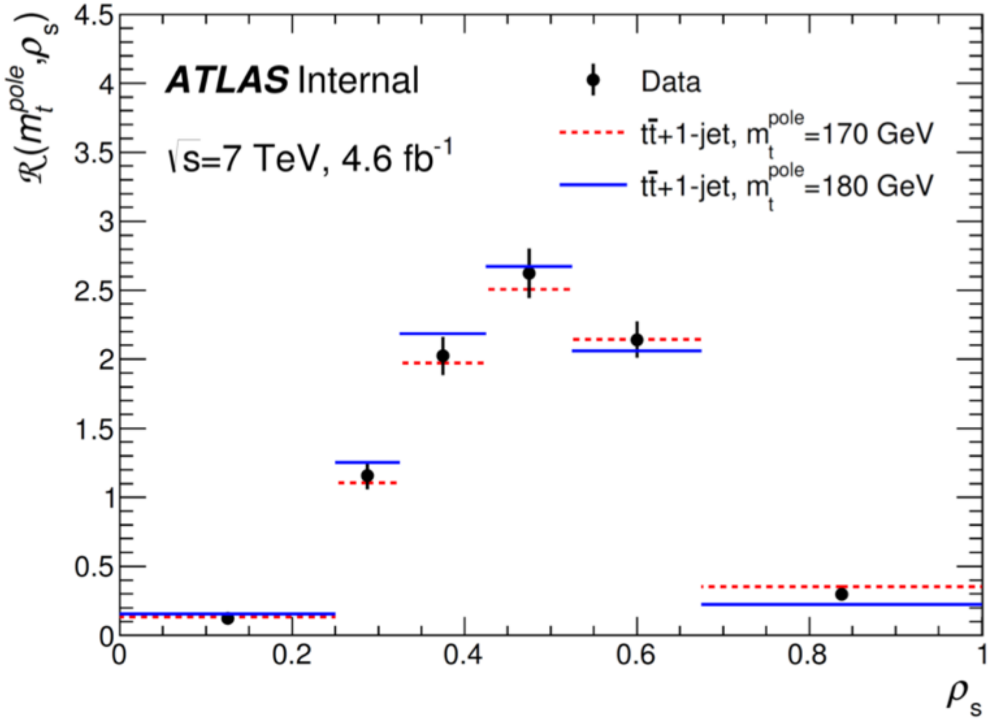
tt+1jet: differential cross section

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \frac{d\sigma_{t\bar{t}+1-\mathrm{jet}}}{\rho_s}(m_t^{pole}, \rho_s)$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \qquad m_0 = 170\ GeV$$

$$m_t^{\mathrm{pole}} = 172.9^{+2.5}_{-2.6}\,\mathrm{GeV}\ (\sqrt{s} = 7/8\,\mathrm{TeV})$$

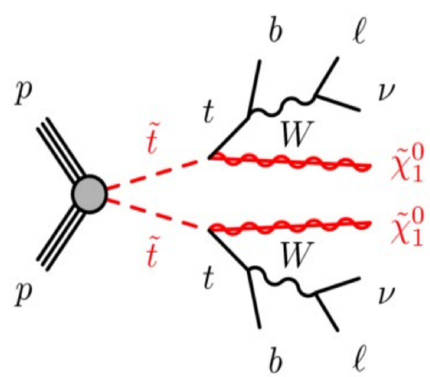
→ pole mass unambiguously!

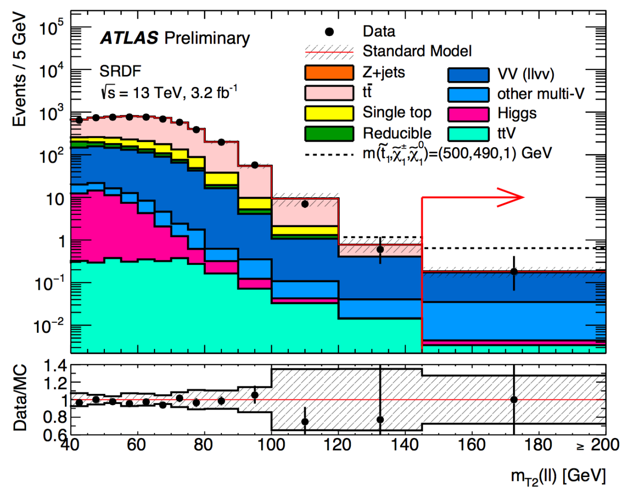


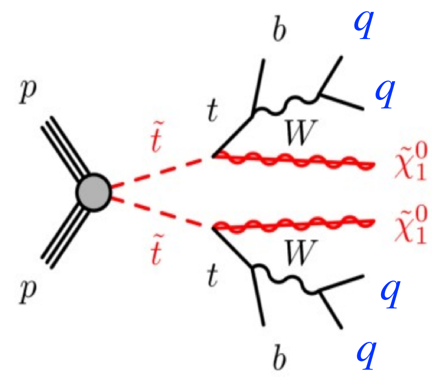
is it really the pole mass?

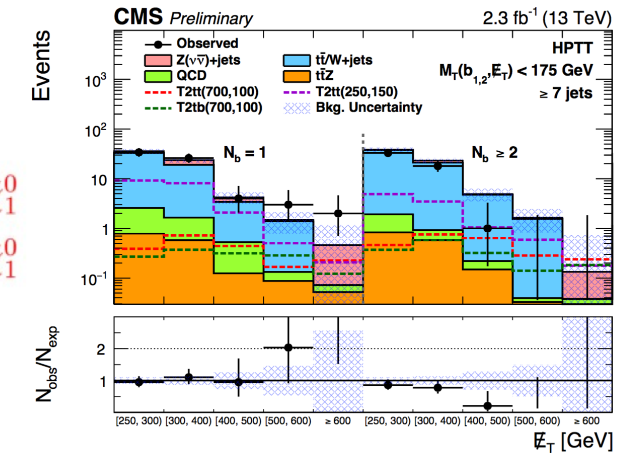
Direct Stop Searches

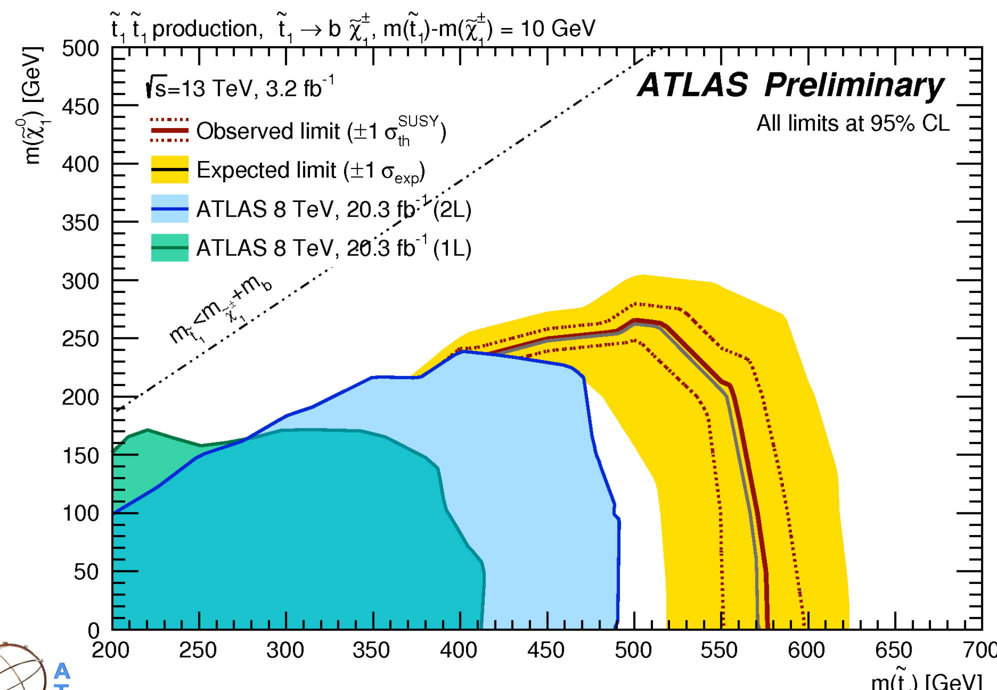
13 TeV



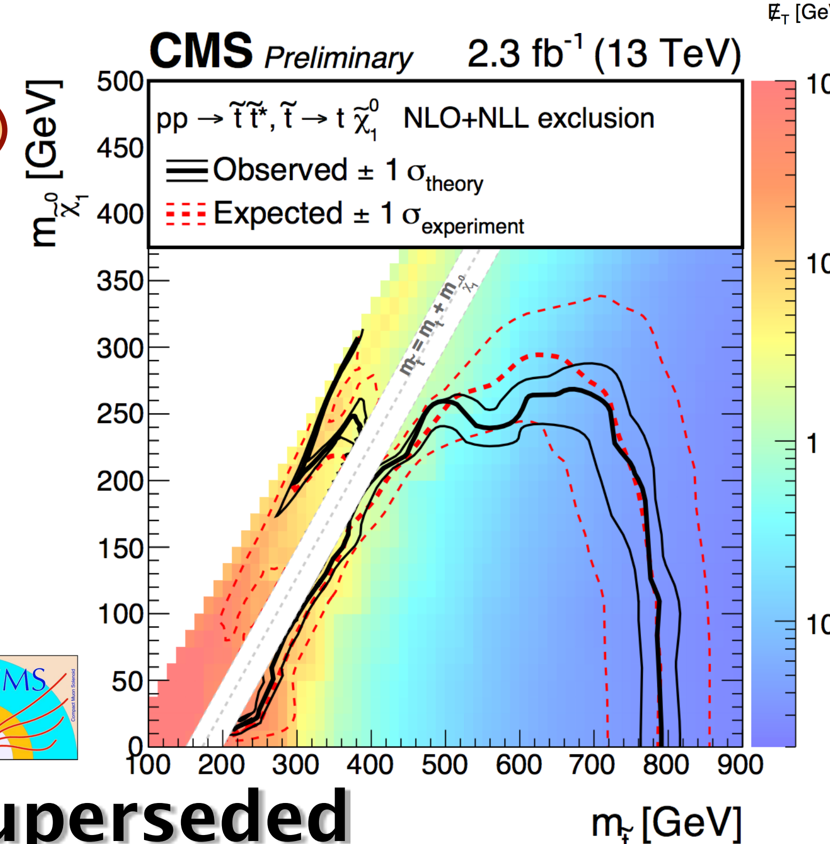








13 TeV



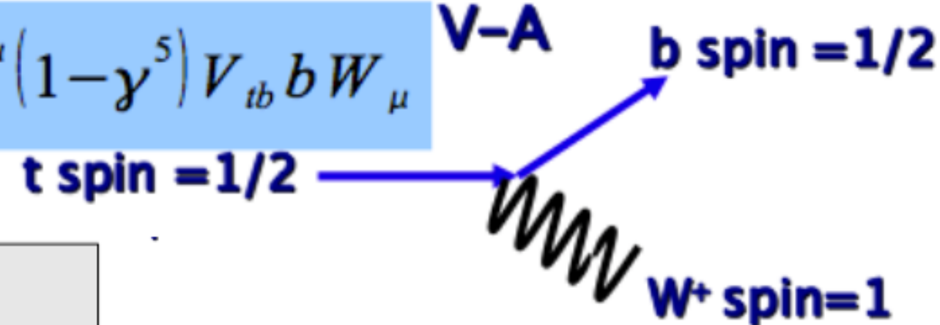
→ **8 TeV limits are superseded**

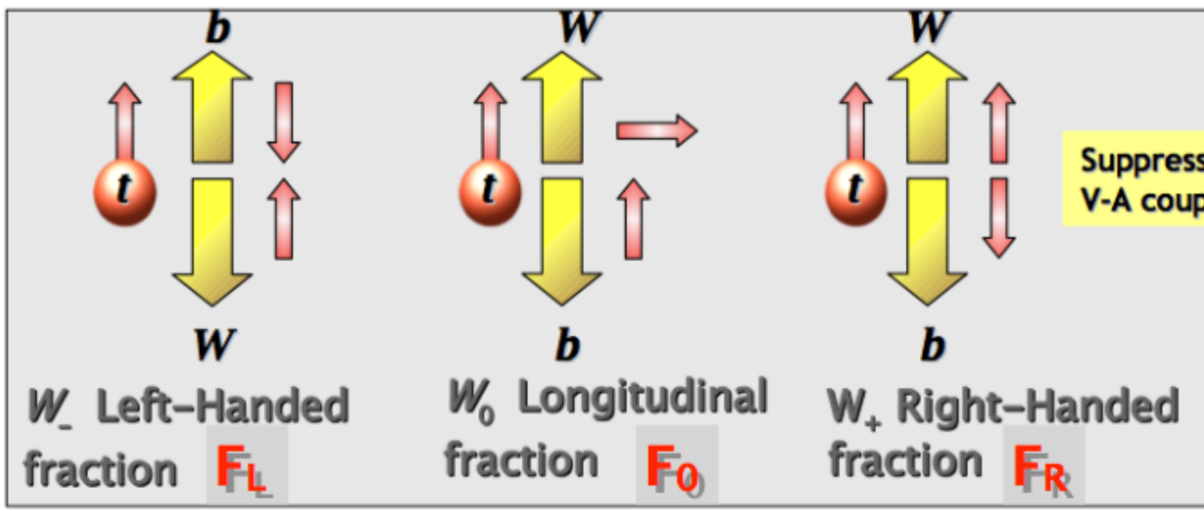
W Boson Helicity Fractions

Phys. Rev. D83, 032009 (2011)

$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$

V–A





Suppressed by the V-A coupling