TOP QUARK PHYSICS AT THE LHC

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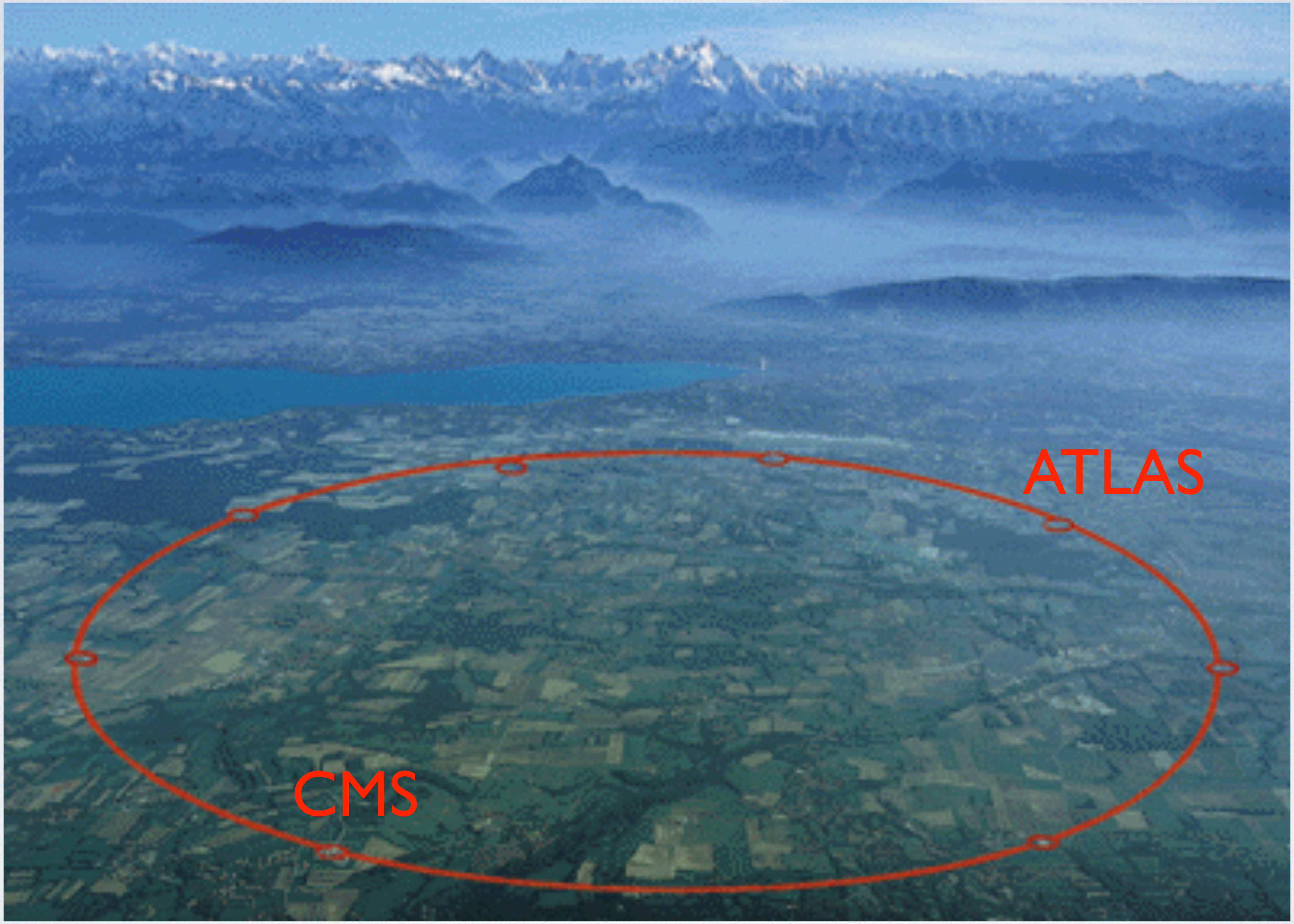
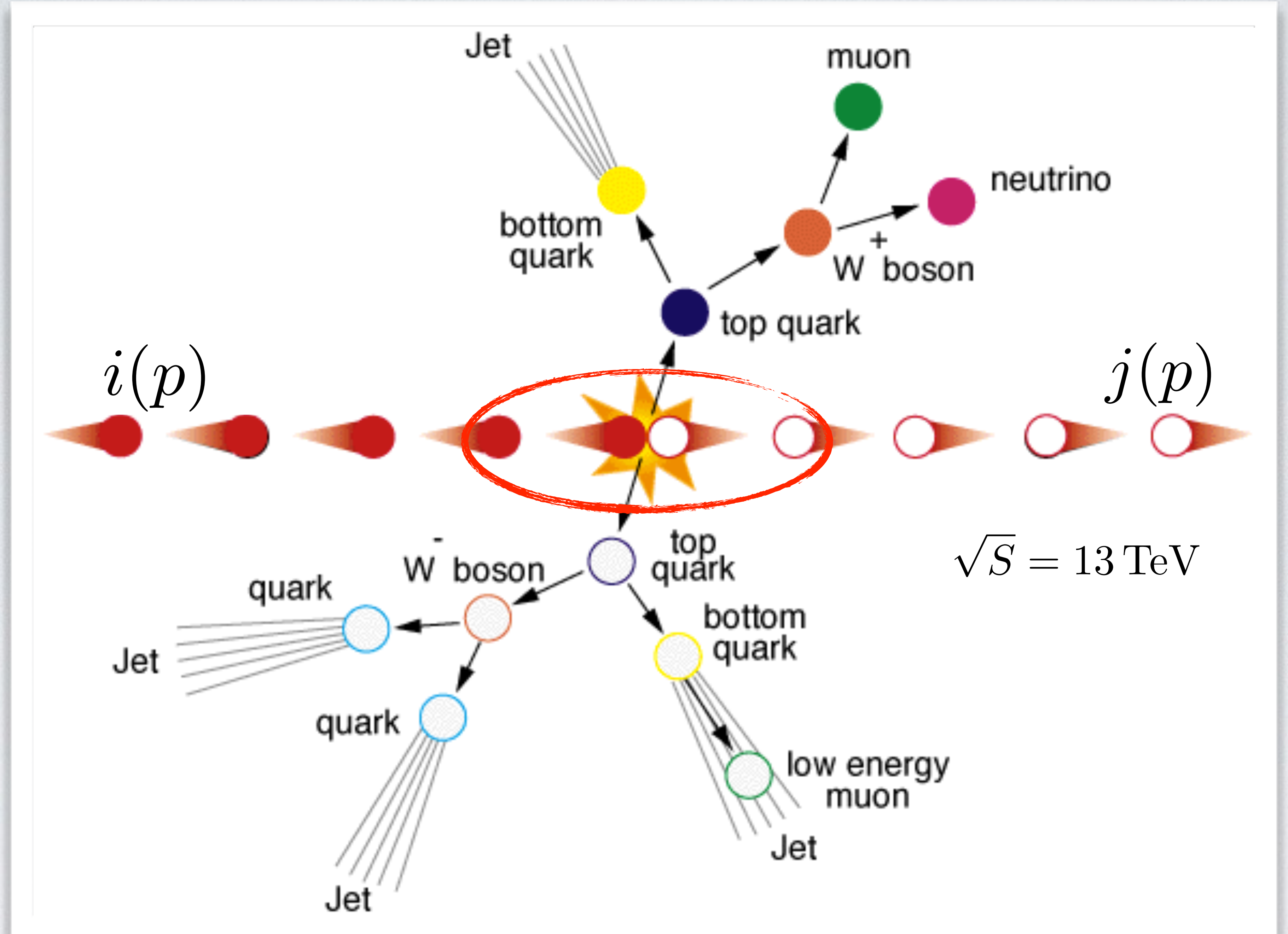
DELTA Workshop — April 28-30, 2016 — University of Heidelberg

A HALF-DAY TRIP FROM HEIDELBERG



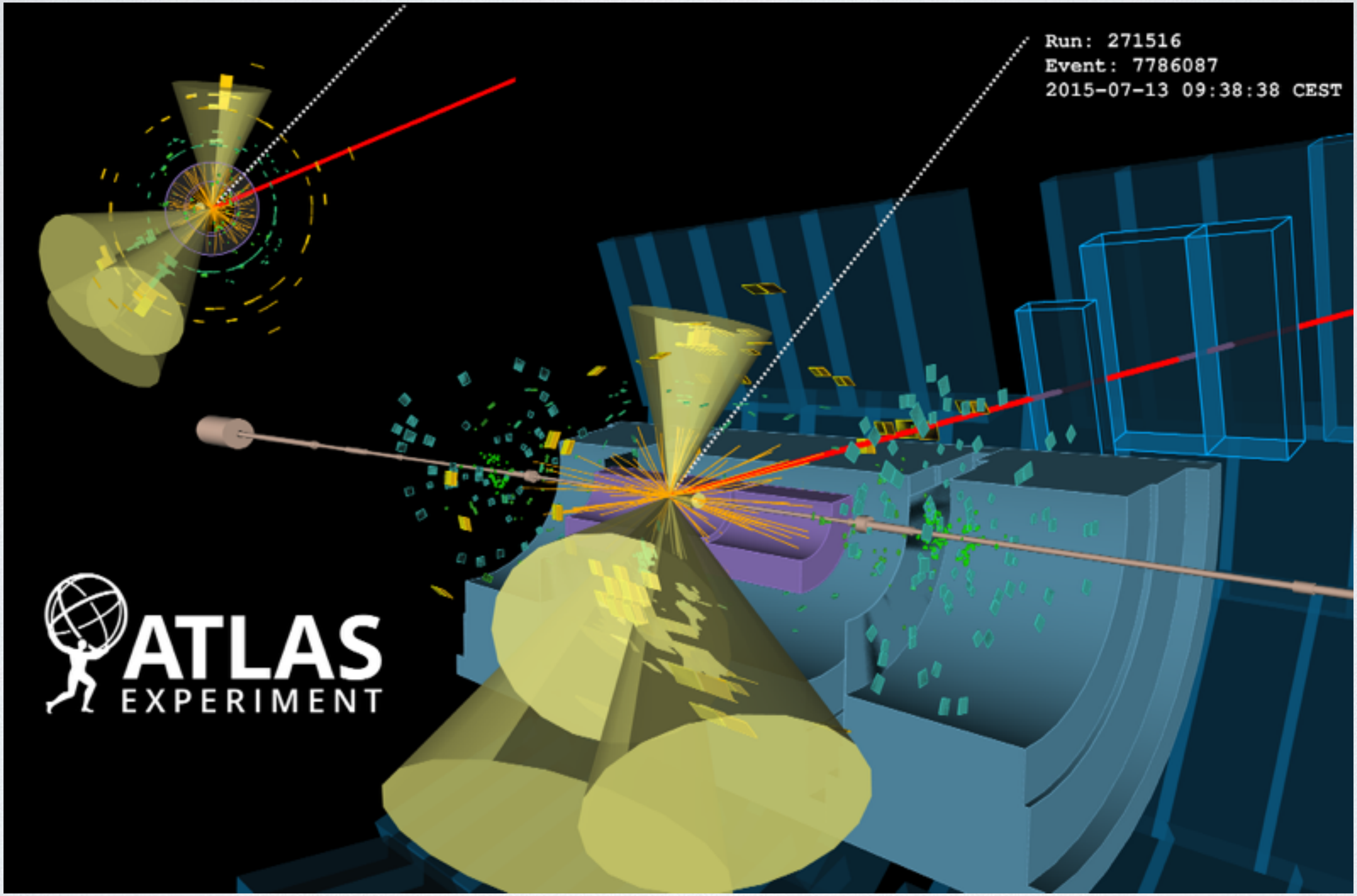
[picture credit: CERN]

IT ALL STARTS WITH QCD…



$$\sigma(S) = \sum_{i,j=q,\bar{q},g} \int d\tau\, \mathcal{L}_{ij}(\tau,\mu)\hat{\sigma}_{ij}(\tau S,\mu)$$

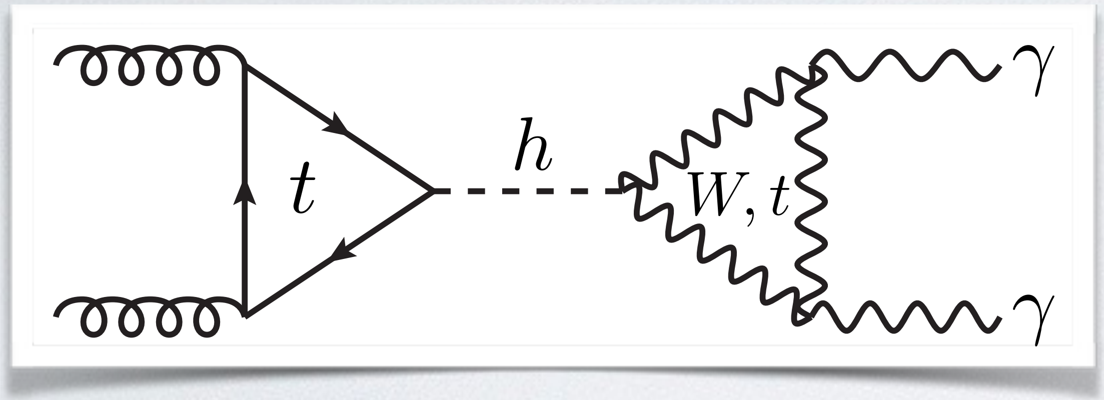
…AND OUT COMES A ~~BIG MESS~~ top-antitop pair



[boosted top-pair production at 13 TeV; leptonic+hadronic top decay]

HIGHLIGHT FROM RUN I: THE HIGGS DISCOVERY

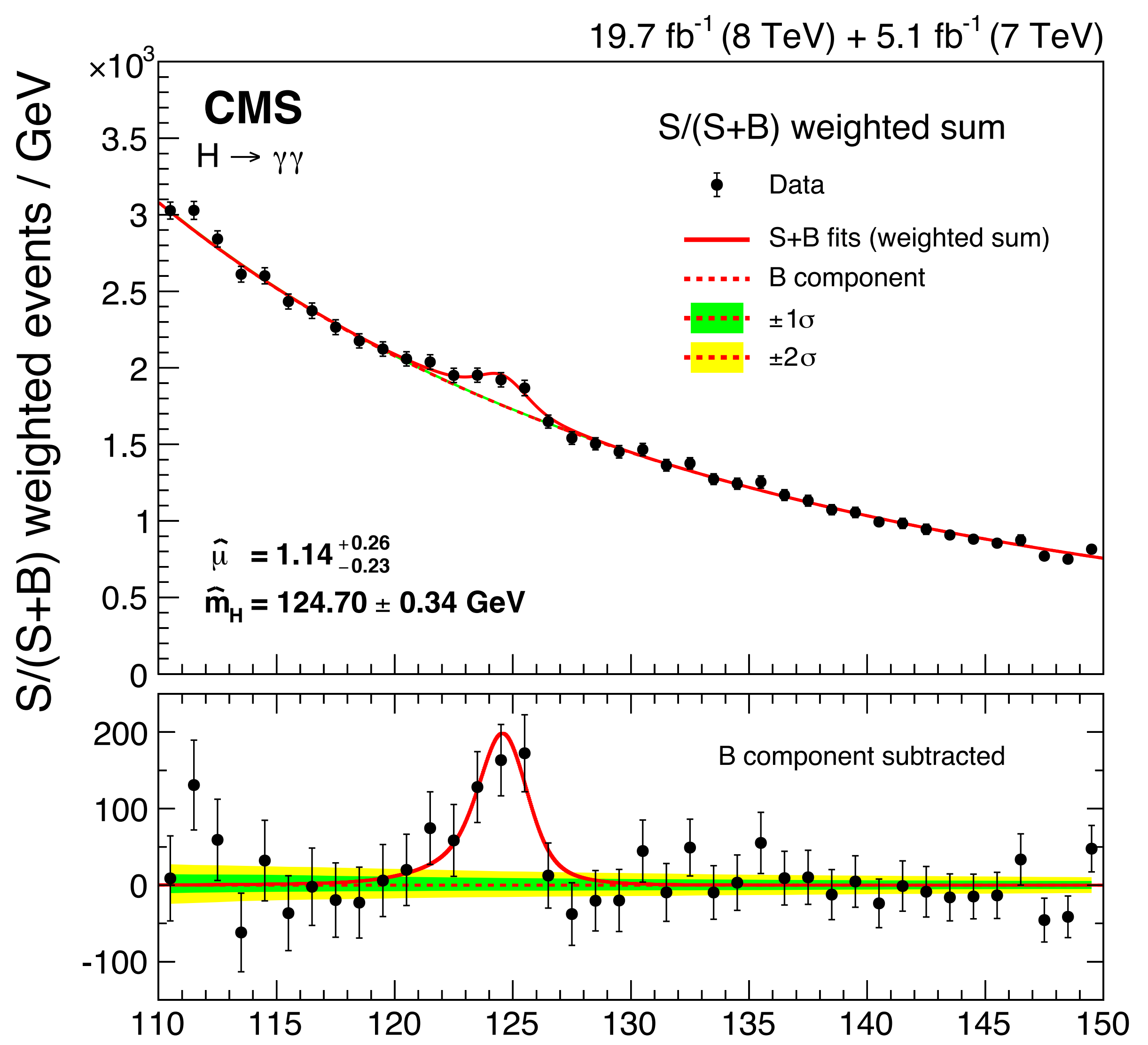
A very rare process with a very clean signature:



$$\sqrt{S} = 8\,\mathrm{TeV}:$$

$$\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma) \approx$$

$$\approx 20\,\mathrm{pb} \times 10^{-3} \approx 20\,\mathrm{fb}$$

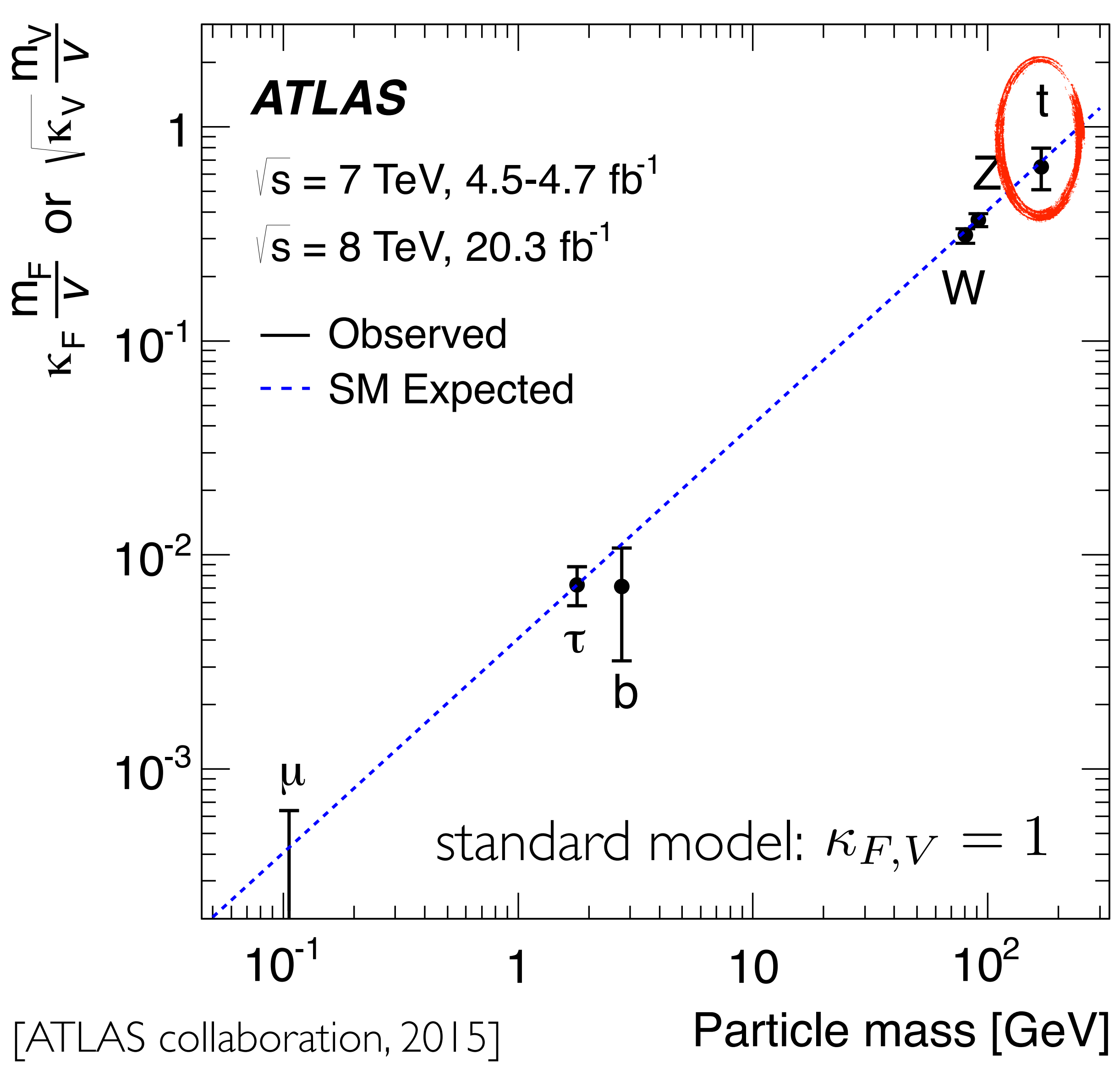


[CMS collaboration, arXiv:1407.0558]

Evidence for interactions with gauge bosons and fermions.

PROBING THE ORIGIN OF MASS

$$\mathcal{L}_{\text{SM}} \supset \frac{g^2 v}{2} h W^{\mu +} W^{-}_{\mu} - \frac{y_f}{\sqrt{2}} h(\bar{f}_R f_L + h.c.)$$



[ATLAS collaboration, 2015]

Higgs mechanism:

$$m_W = gv/2$$

$$m_f = y_f v/\sqrt{2}$$

Fermion mass hierarchies:

$$y_t \approx 1 \qquad m_b \ll m_t$$

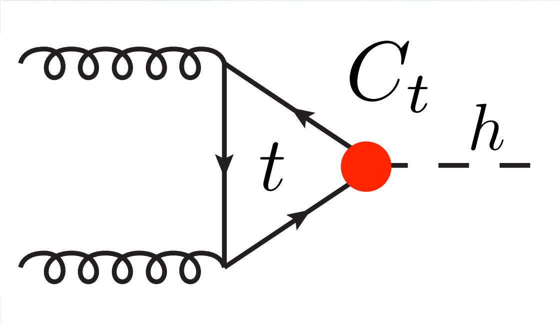
$$m_\mu \ll m_\tau$$

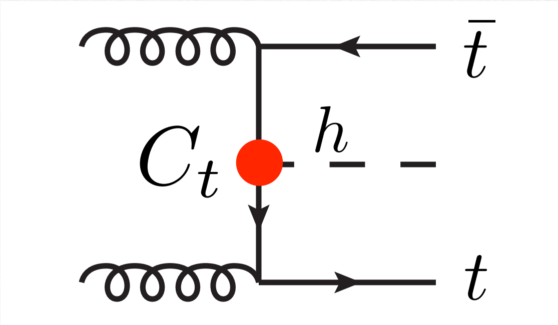
HIGGS EFFECTIVE THEORY

Low-energy effects of new physics at a high scale $\Lambda \gg v$:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \mathcal{O}(C_i^4/\Lambda^4)$$

Example: anomalous top-quark interaction



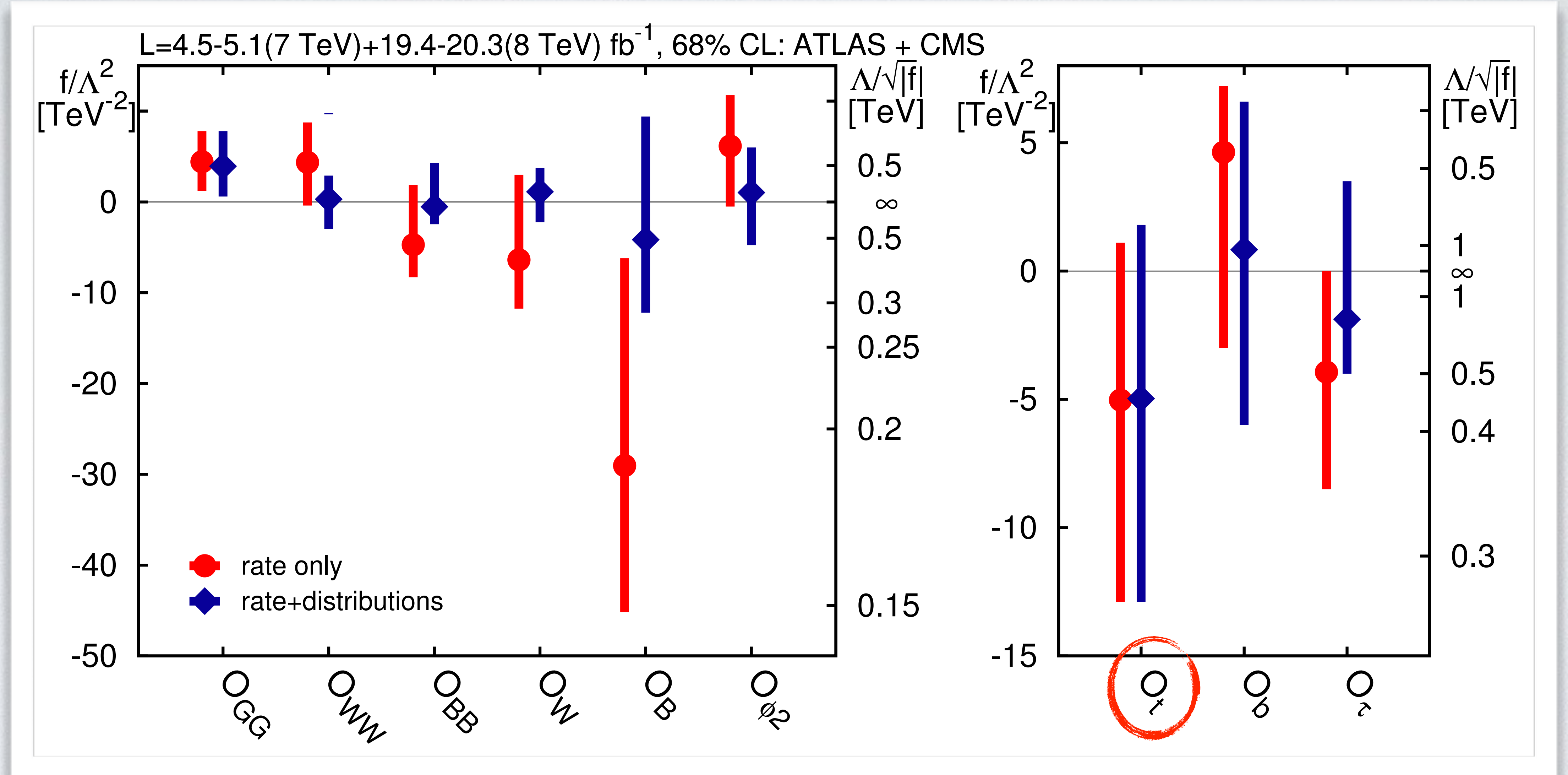


$$O_t \equiv (\varphi^\dagger \varphi)(\overline{Q_L}\, \widetilde{\varphi}\, t_R)$$

$$\varphi \to \langle \varphi \rangle = v/\sqrt{2}: \qquad \mathcal{L}_{ht\bar{t}} = -\frac{m_t}{v}\Big(1 - \frac{v^2}{\sqrt{2}}\frac{C_t}{\Lambda^2}\Big) h\, \overline{t_L} t_R + h.c.$$

ANOMALOUS HIGGS INTERACTIONS

Global fit of Higgs production and decay to Run I data:



[Corbett, Eboli, Goncalves, Gonzalez-Fraile. Plehn, Rauch, arXiv:1505.05516]

Starting to test new physics in the multi-GeV range.

! Caution with interpretation as effective interactions. !

[Brehmer, Freitas, Lopez-Val. Plehn, arXiv:1510.03443]

HIGHLIGHT FROM RUN II: 13 TEV WORKS!

High energies - apply brute force and enjoy

observe the standard model under new conditions
test the hypothesis of new heavy particles

Lots of data - challenge your patience

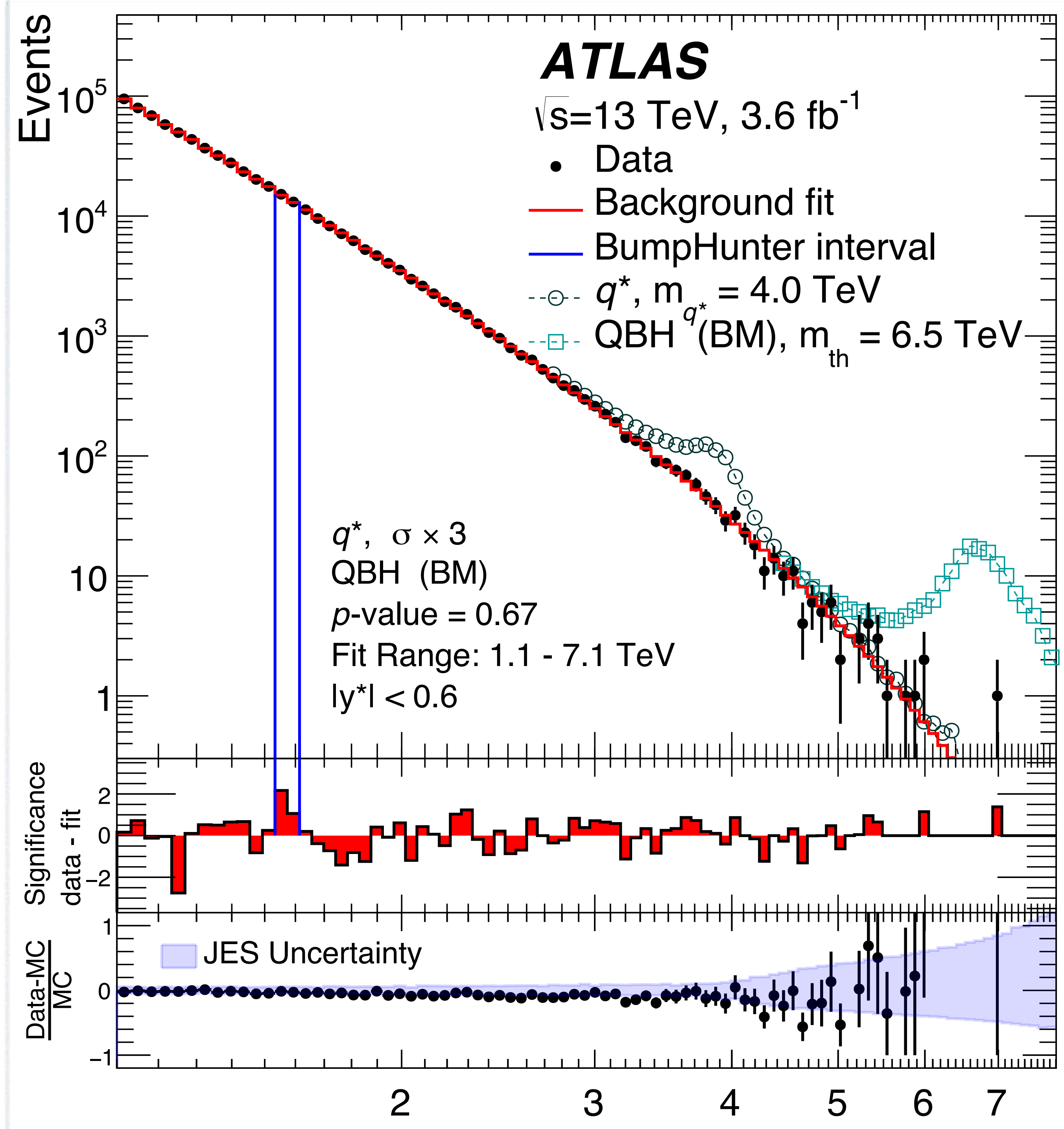
probe abundant processes with high precision
search for rare or hidden processes

Excellent tools - be up-to-date and use them

perform global analyses and investigate correlated signals
work at the intersection of theory and experiment

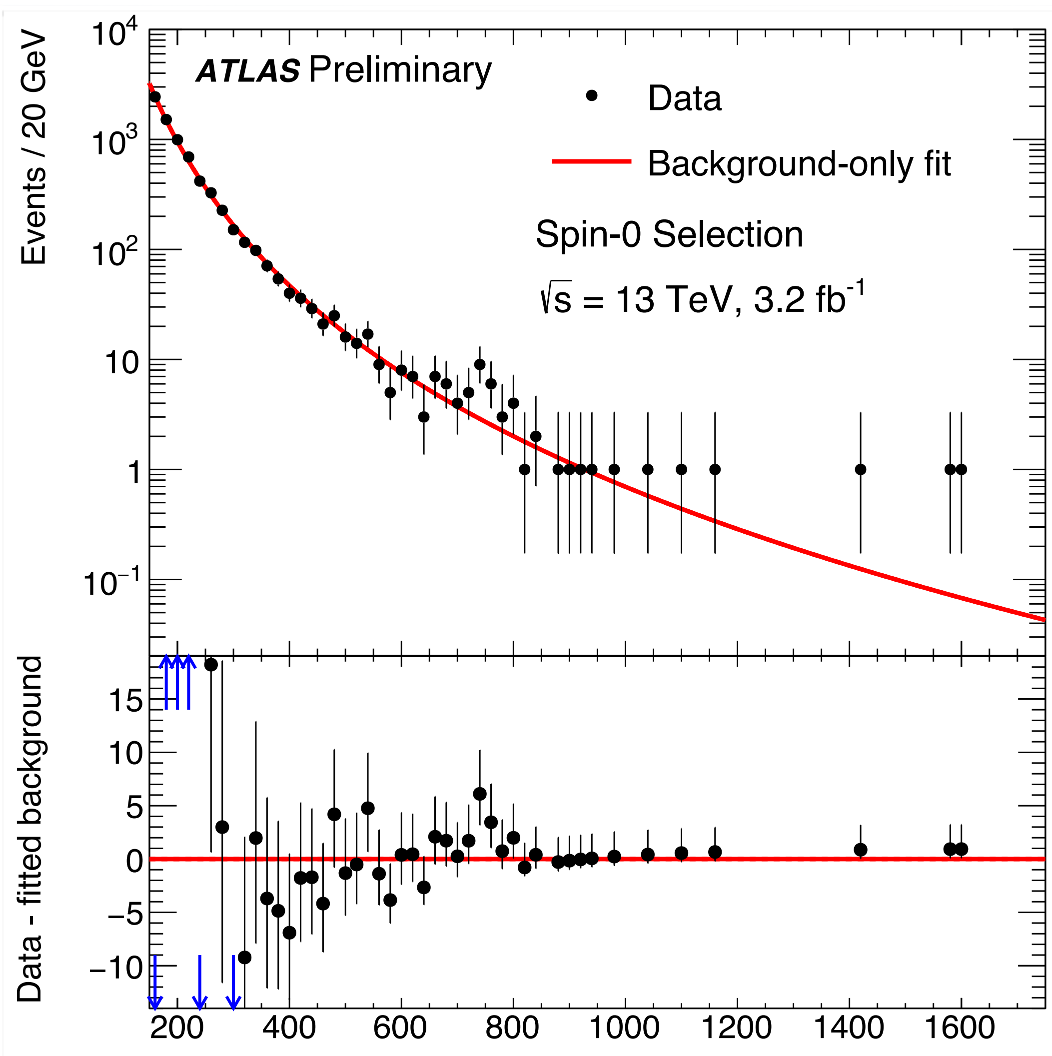
A FIRST LOOK AT 13-TEV DATA: RE-DISCOVERY OF QCD

Search for new resonances in dijet production

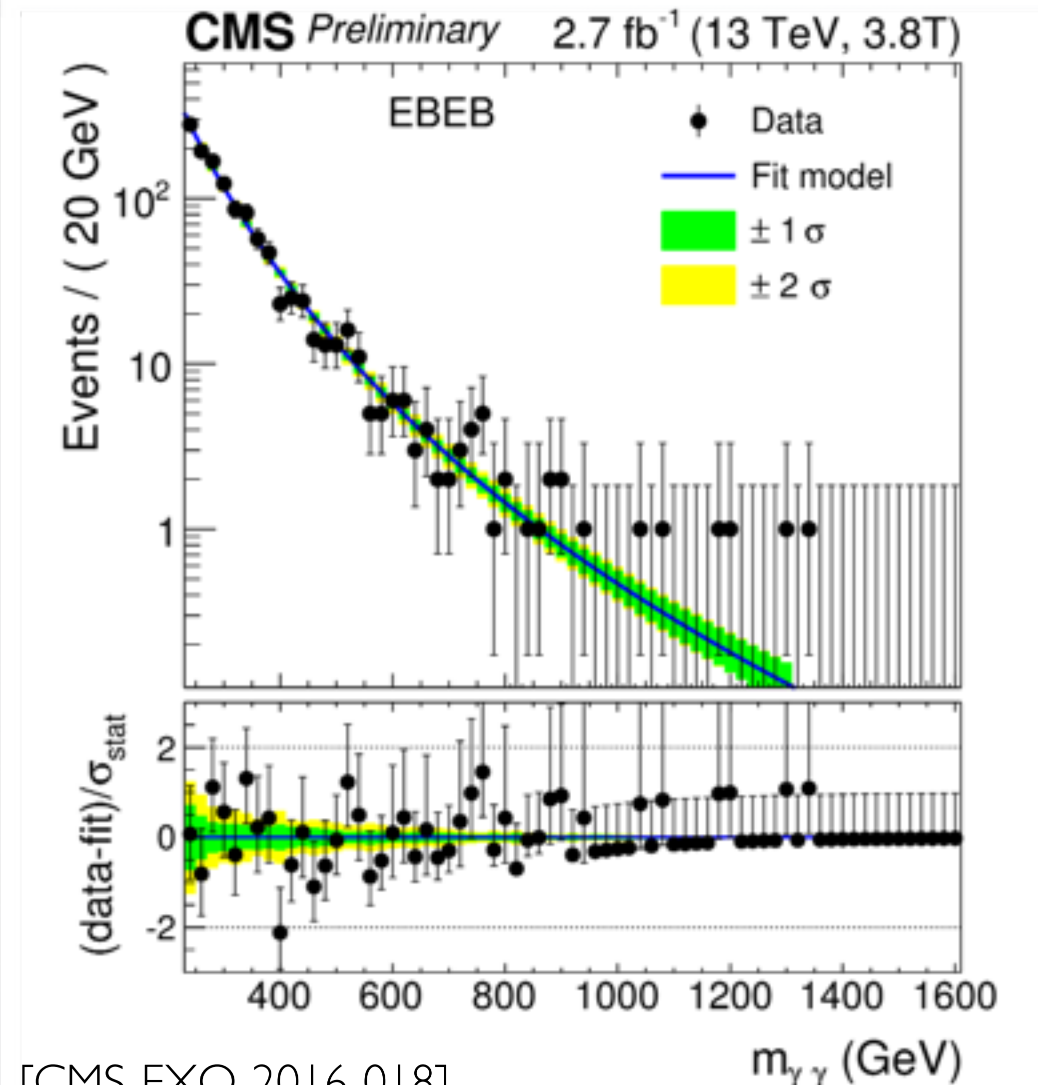


[ATLAS collaboration, arXiv:1512.01530]

SECOND LOOK: ANOTHER DIPHOTON RESONANCE?



[ATLAS-CONF-2015-081]



[CMS-EXO-2016-018]

Assuming a scalar resonance, the largest excess occurs for:

$m_S = 750\,\mathrm{GeV}\quad \Gamma_S/m_S = 6\%$

Local significance: 3.9σ

Global significance: 2.0σ

$m_S = 750\,\mathrm{GeV}\quad \Gamma_S/m_S = 1.4\%$

Local sign.: 2.8σ

Global sign.: $< 1\sigma$

FACTS AND FICTION

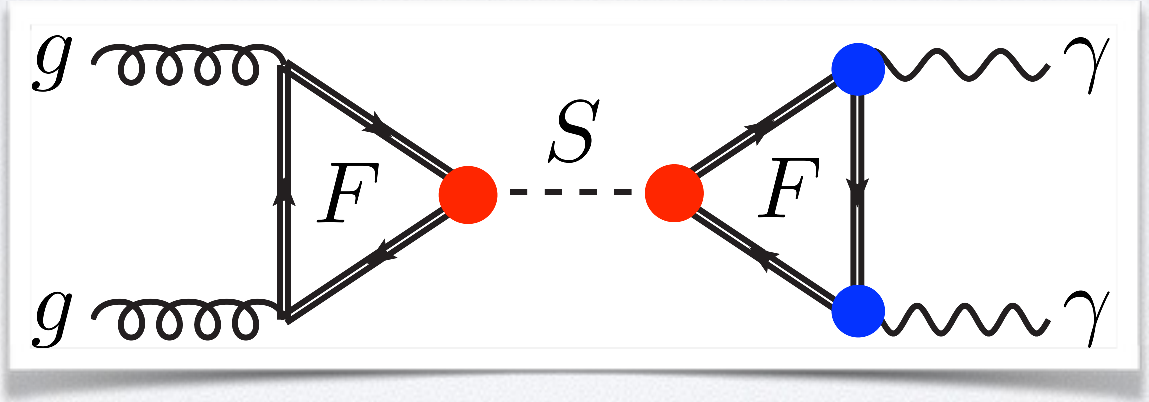
Landau-Yang theorem: resonance must have **spin 0 or 2**.

ATLAS+CMS, 8+13 TeV: $\sigma(pp \to S \to \gamma\gamma) \approx 5\,\mathrm{fb}$

[Buttazzo, Greljo, Marzocca, arXiv:1512.04929]

SM gauge invariance implies a **signal in diboson production**.

A minimal model:



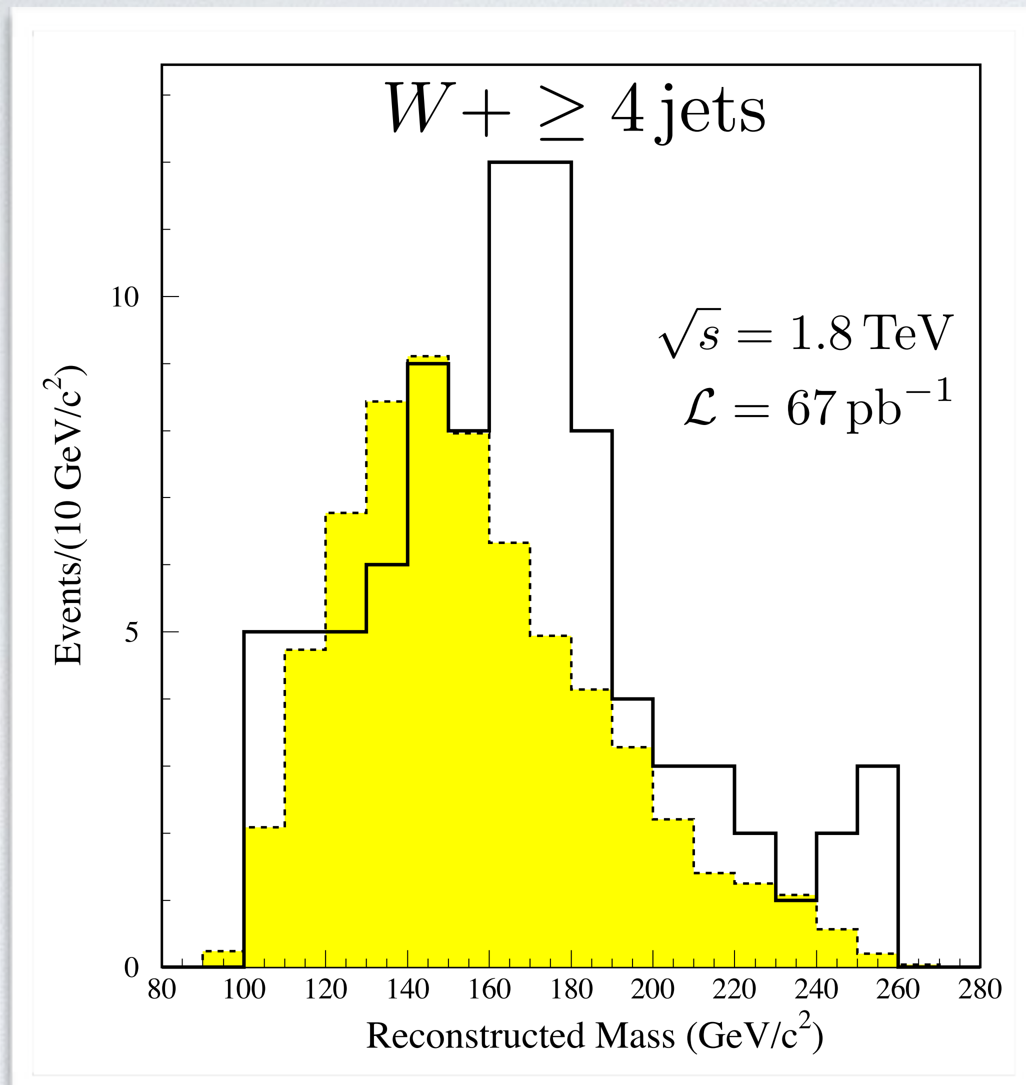
Need large couplings/electric charge/number of fermions.

For instance: new scalar in warped extra dimension, coupling to KK excitations of fermions.

[Bauer, Hoerner. Neubert, , arXiv:1603.05978]

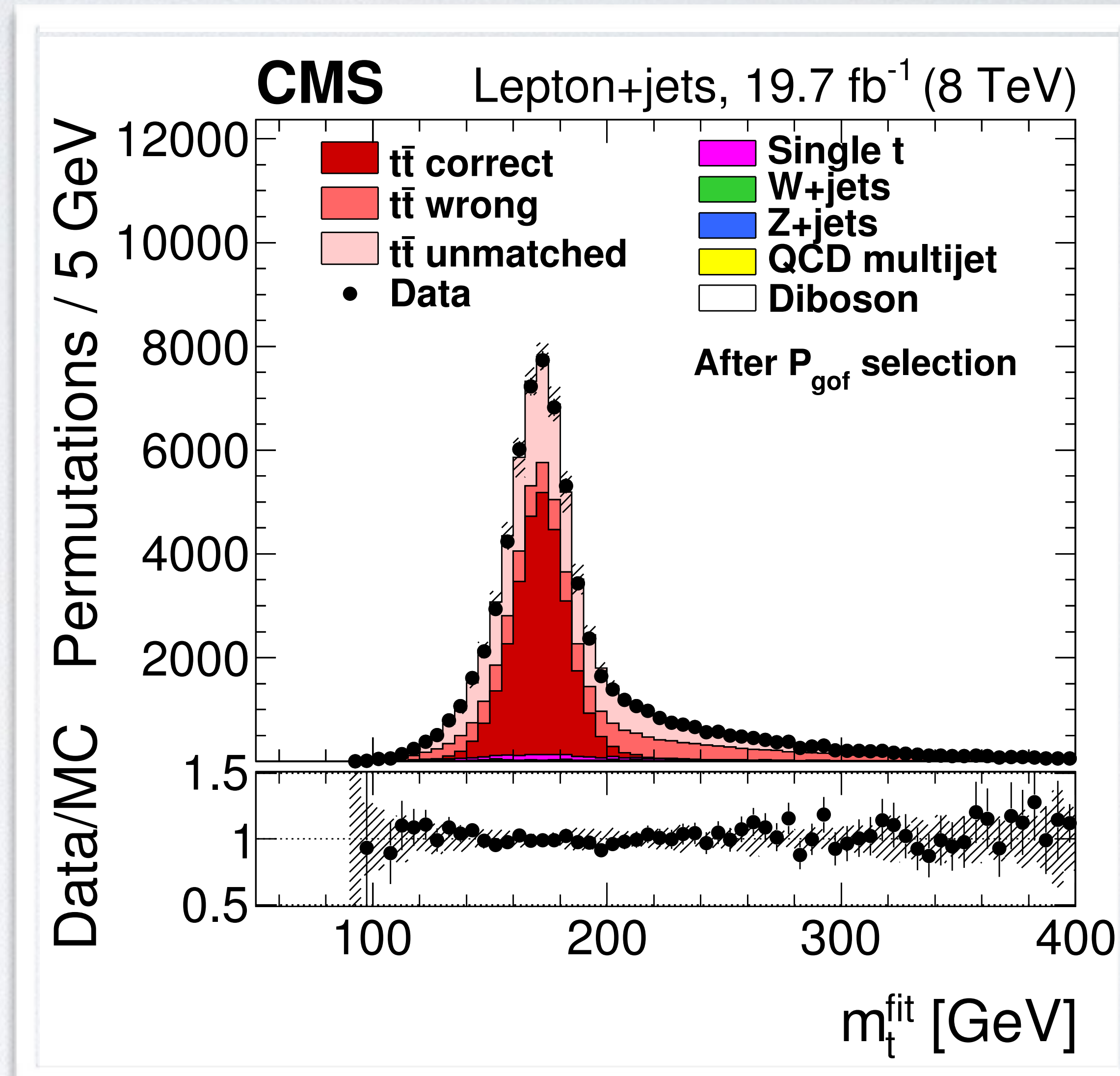
TOP-QUARK PHYSICS AT ITS PEAK

Tevatron 1995



[CDF collaboration, 1995]

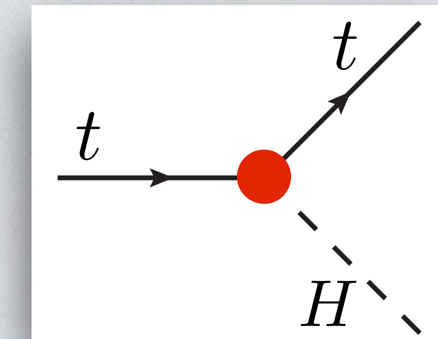
LHC 2016



[CMS collaboration, arXiv:1509.04044]

TOP AND HIGGS

Strong top Yukawa coupling to the Higgs boson



$$y_t = \frac{m_t}{v} \approx 1 \quad \longleftrightarrow \quad m_t = 173\,\mathrm{GeV}$$

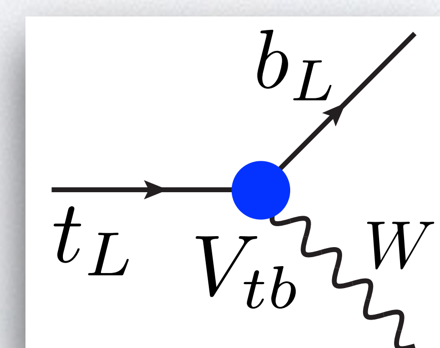
implies large decay rate into longitudinal W:

$$\Gamma(t \to bW) = \frac{G_F m_t^3}{8\sqrt{2}\pi}\left[1 + O(m_W^2/m_t^2)\right] = 1.5\,\mathrm{GeV}$$

Yukawa hierarchy breaks flavor symmetry of gauge interactions

$$\mathcal{L} \supset -y_{ii}\,\overline{u_L^i}\langle H\rangle u_R^i + \left(\frac{g}{\sqrt{2}}\,\overline{u_L^i}\gamma^\mu V_{ij} d_L^j W_\mu^+ + h.c.\right)$$

$y_t \gg y_u$:



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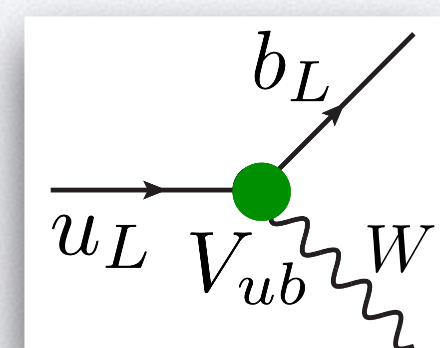


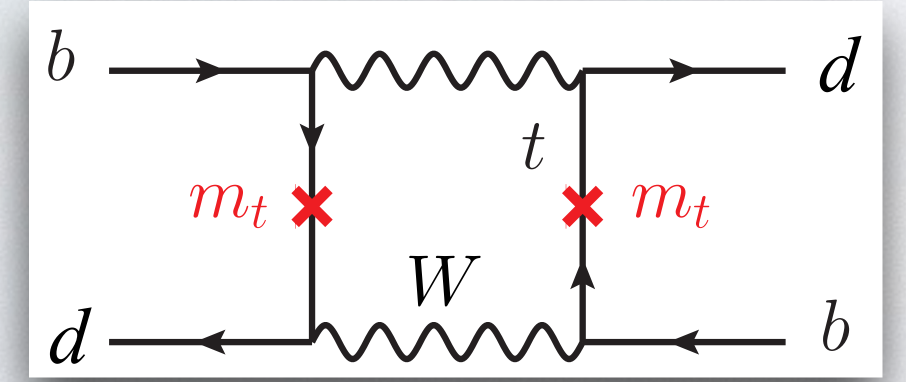
flavor-changing charged currents

TOP AND FLAVOR

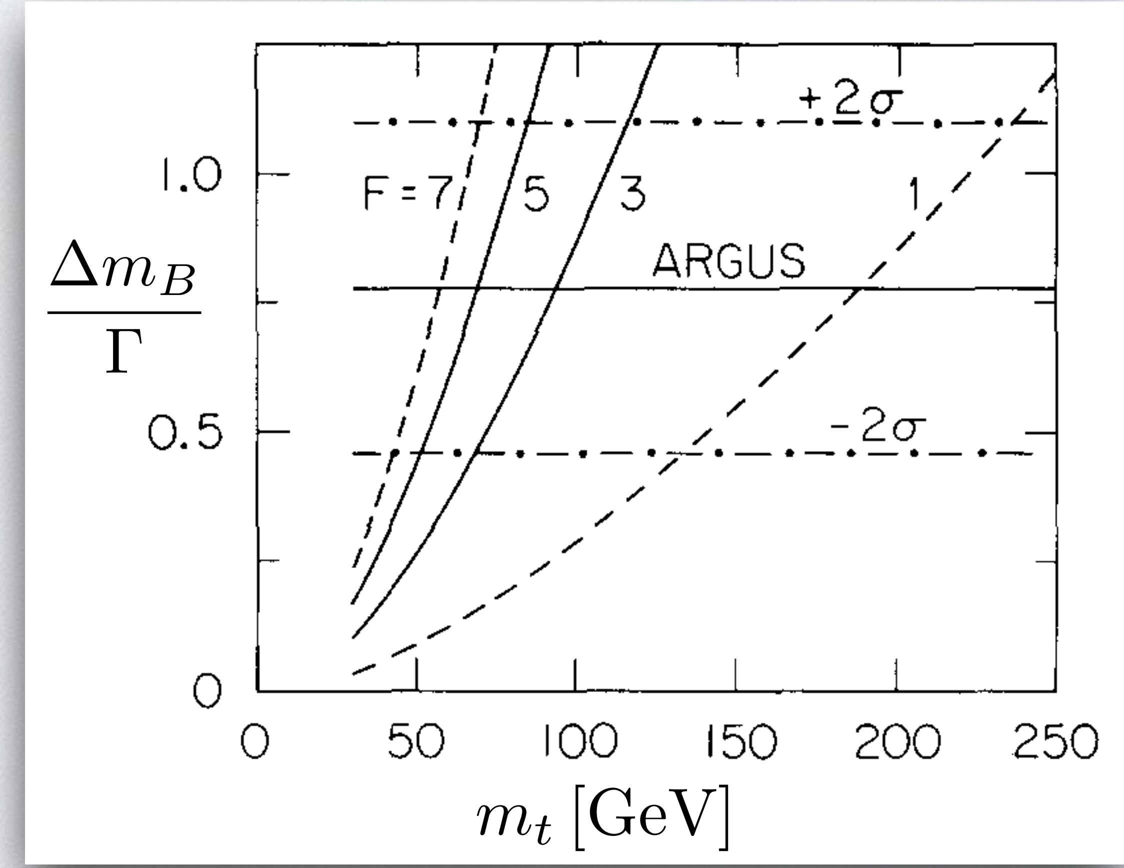
Gauge symmetry of weak interactions: $Q_L = (t, b)_L$

⟶ Top-quark induces **virtual effects in B physics**.

Example: $B_d - \overline{B}_d$ meson mixing



[Bigi, Sanda, 1987]

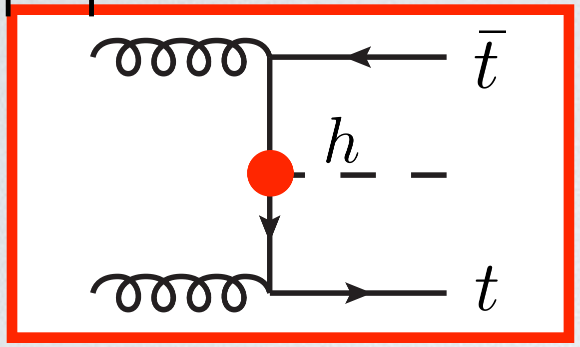


Indirect bound on top mass before discovery:

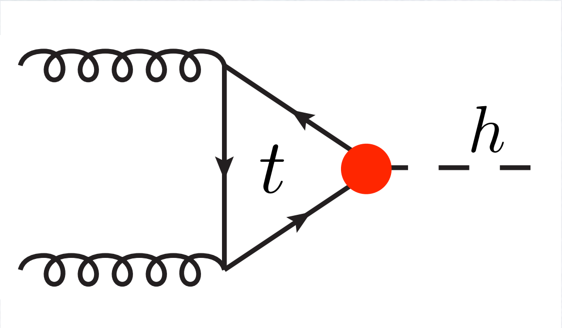
$$m_t > 50 - 70\,\mathrm{GeV}$$

PROBING THE TOP YUKAWA COUPLING

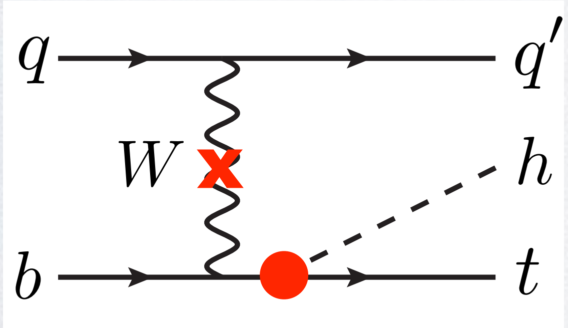
top-pair associated

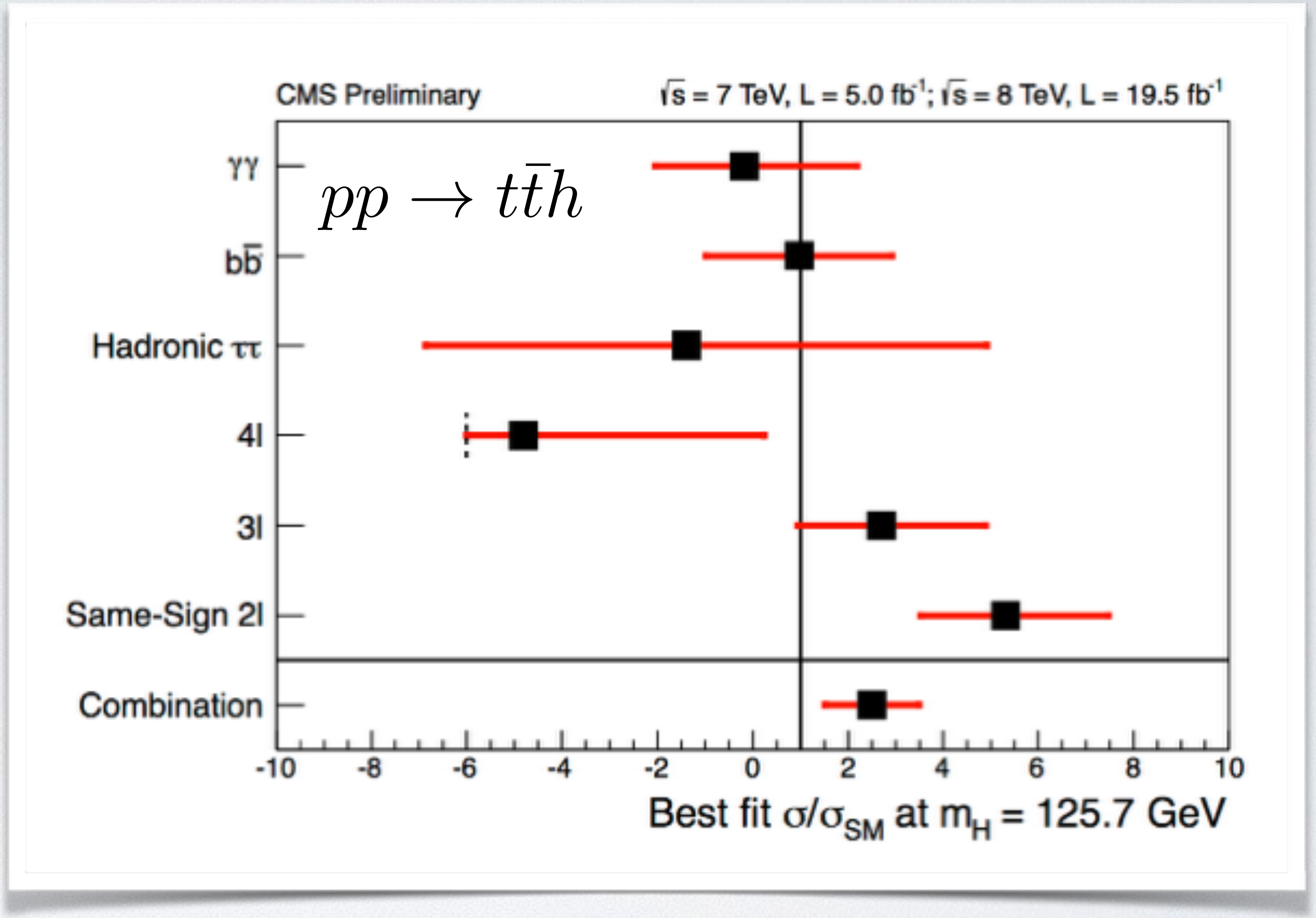


inclusive



electroweak





HL-LHC at 13 TeV: expect $\delta y_t / y_t \approx 10\%$

nNLO QCD: $\sigma(pp \to t\bar{t}h) \approx (470 \pm 20_{\rm scale})$ fb

[Broggio, Ferroglia, Pecjak, Signer, Yang. arXiv:1510.01914]

100-TeV collider: expect $\delta y_t / y_t \approx 1\%$ trick: use $\sigma(t\bar{t}h)/\sigma(t\bar{t}Z)$

[Mangano, Plehn, Reimitz, Schell, Shao, arXiv:1507.08169]

TOP-QUARK PAIR PRODUCTION

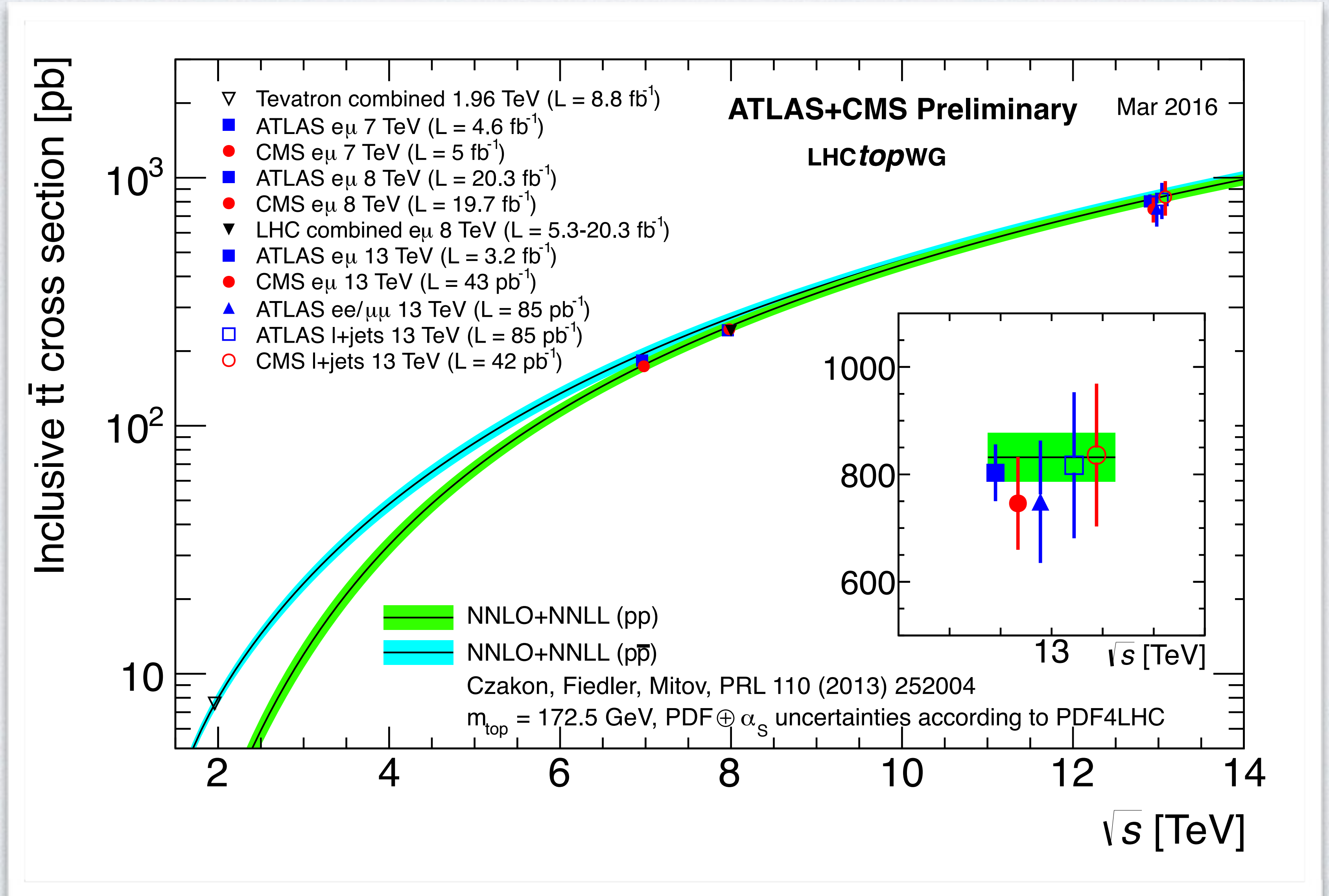
Precise predictions: Cross section at NNLO+NNLL QCD

$$\sqrt{S} = 8\,\mathrm{TeV} : \ \sigma_{t\bar{t}} = 245.8\,^{+6.2}_{-8.4}[\mathrm{scales}]\,^{+6.2}_{-6.4}[\mathrm{pdf}]\ \mathrm{pb}$$ [Czakon, Fiedler, Mitov, 2013; and many more]

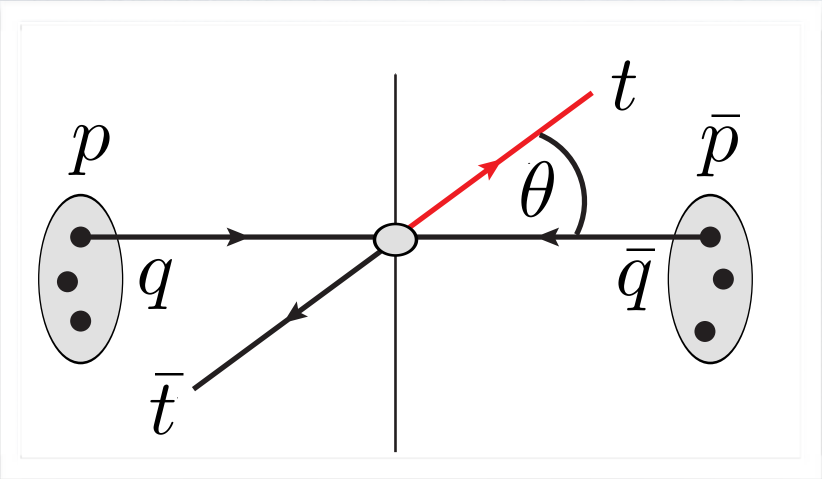
Powerful tools: event generators, top taggers, boosted top techniques

[e.g., MadGraph: Alwall et al., HEP Top Tagger: Plehn et al.]

Precise measurements:



TOP-ANTITOP CHARGE ASYMMETRY

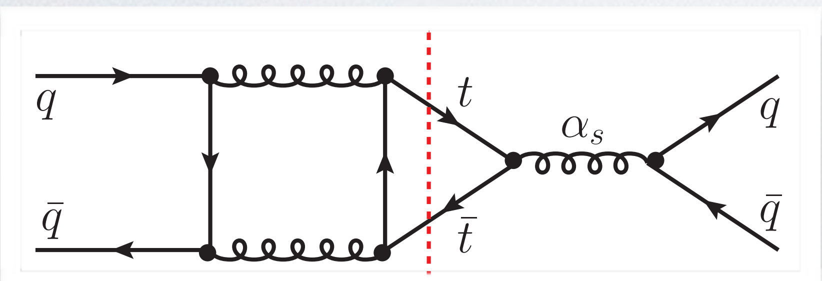


angular asymmetry $A_C = \sigma_a/\sigma_s$

$$\sigma_{s,a} = \int_0^1 d\cos\theta \left\{ \frac{d\sigma(p\bar{p} \to t\bar{t})}{d\cos\theta} \pm \frac{d\sigma(p\bar{p} \to \bar{t}t)}{d\cos\theta} \right\}$$

Small QCD asymmetry:

$$\sigma_a \sim \alpha_s^3/(4\pi)^2$$



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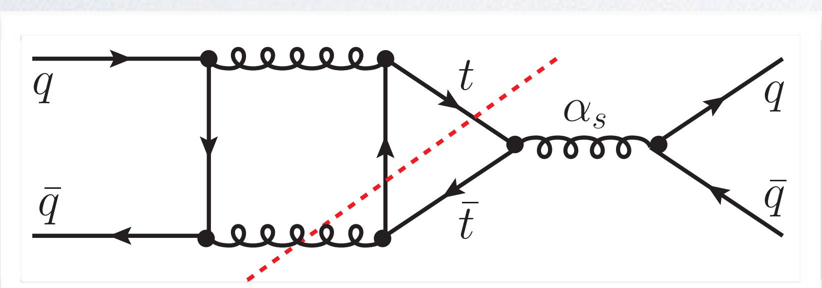
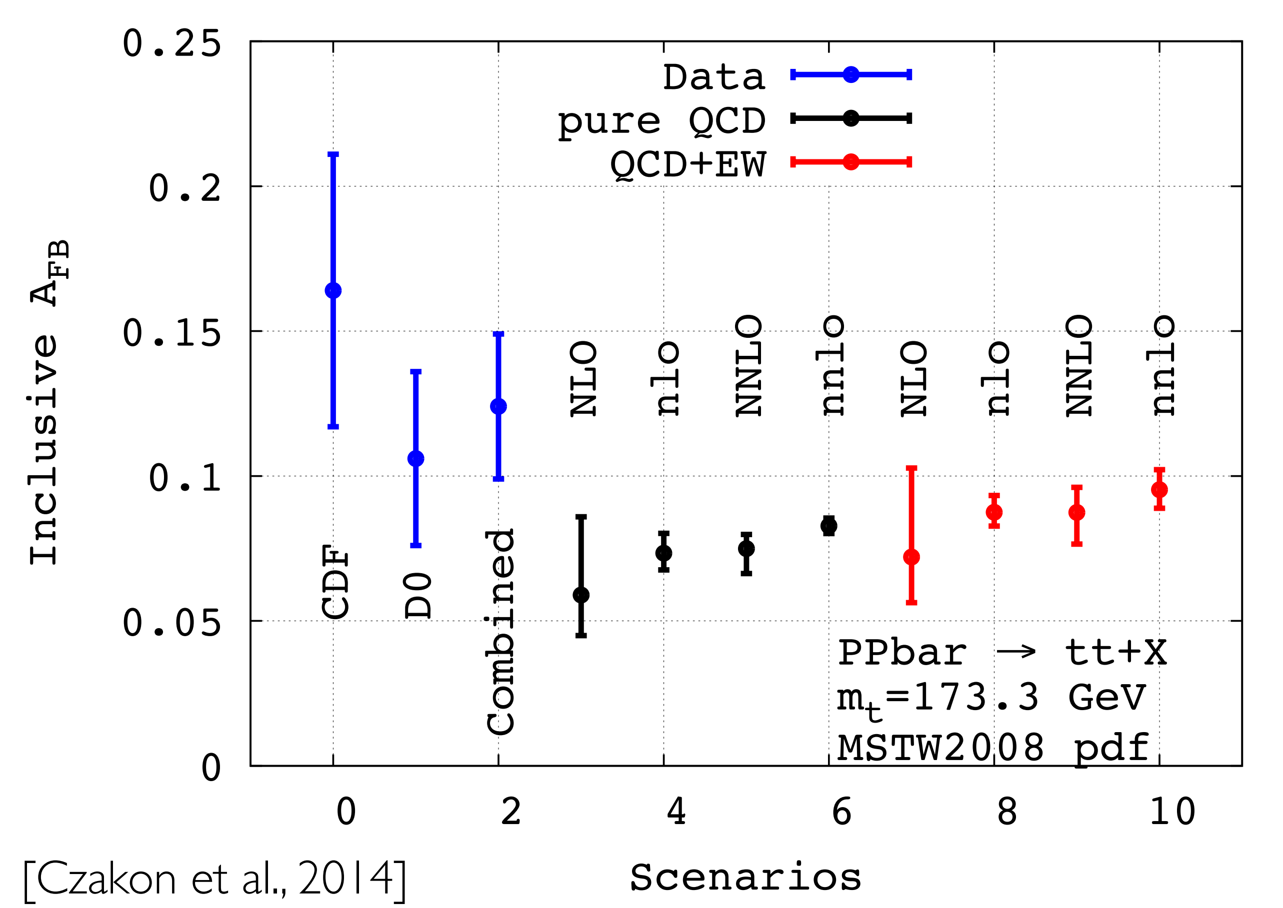


[QCD NLO: Kuehn, Rodrigo, 1999]
[EW: Hollik, Pagani, 2011]

A success of precision physics:

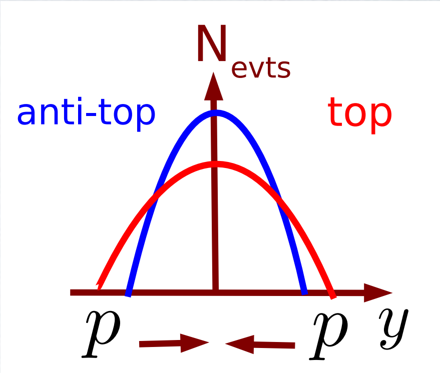


[Czakon et al., 2014]

CHARGE ASYMMETRY AT THE LHC

Up to now: measure **absolute rapidity difference**

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



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

Small asymmetry in standard model:

$A_{|y|} = 1.23 \pm 0.05\%$ [Bernreuther, Si, 2012: QCD NLO+EW]

suppressed by large gluon background

parton distributions

$\sigma_{t\bar{t}}(\sqrt{s} = 8\,\mathrm{TeV})$

$q\bar{q} : 7.7\%$

$qg + \bar{q}g : 26.7\%$

$gg : 65.6\%$

From 8-TeV pp collisions during Run I:

$A_{|y|}^{\exp} = 0.5 \pm 0.7 \pm 0.6\%$ [ATLAS+CMS comb., 2014]

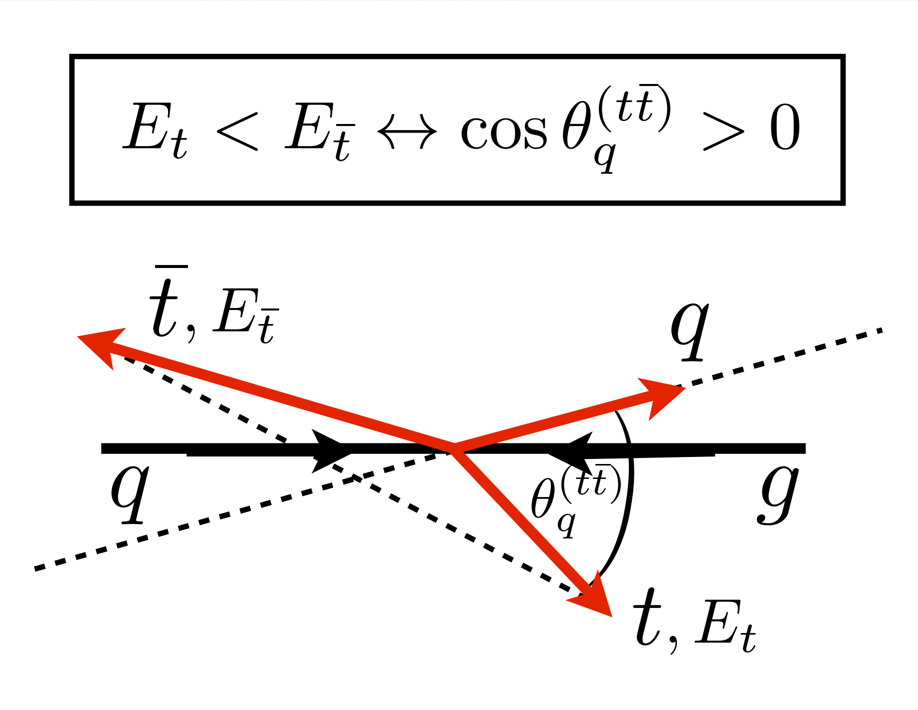
Difficult to achieve better significance during Run II.

ENERGY ASYMMETRY

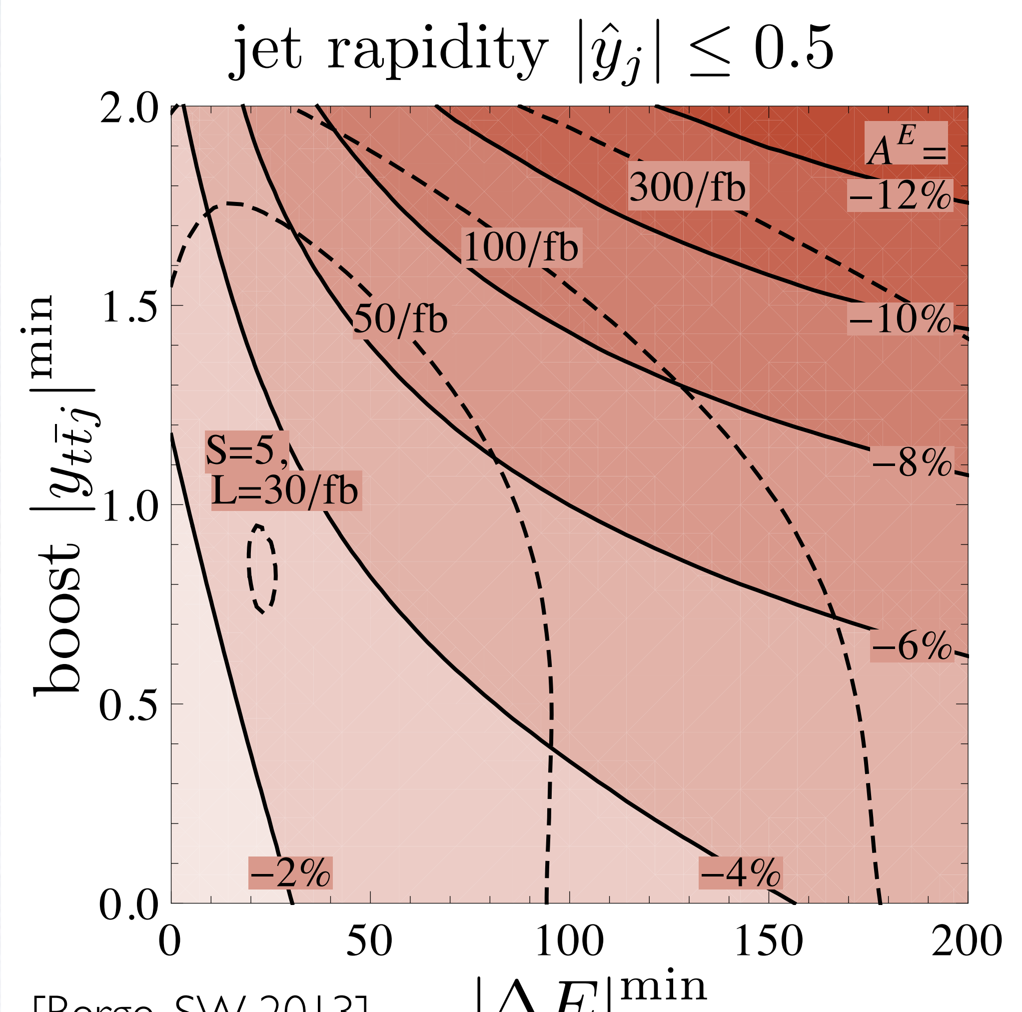
Measure **energy difference**

$$\Delta E = E_t - E_{\bar{t}}$$

$$A^E = \frac{\sigma_a^E}{\sigma_s} = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma(\Delta E > 0) + \sigma(\Delta E < 0)}$$



Significance for 14-TeV LHC



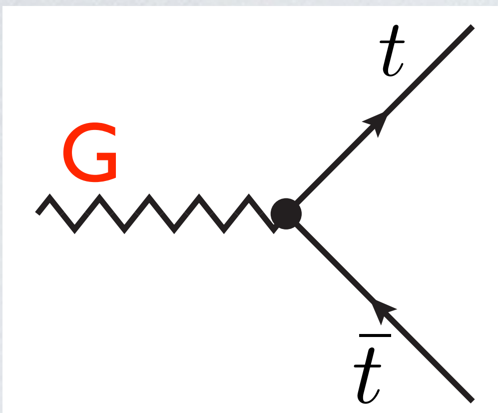
[Berge, SW, 2013]

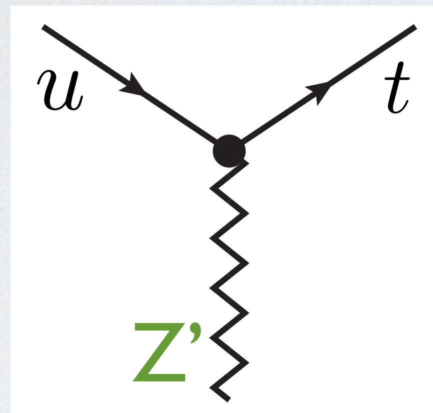
energy asymmetry in qg frame
=
angular asymmetry in $t\bar{t}$ frame

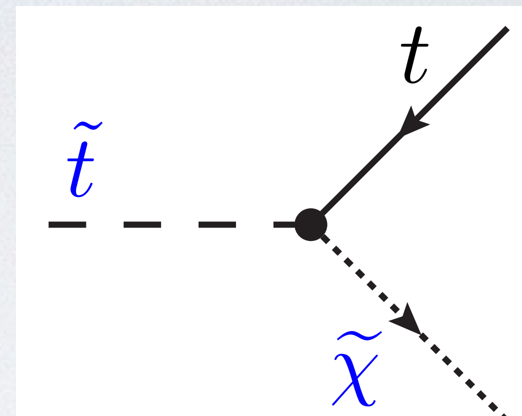
Good significance achievable at LHC during Run II.

NEW PHYSICS WITH TOPS AT THE LHC

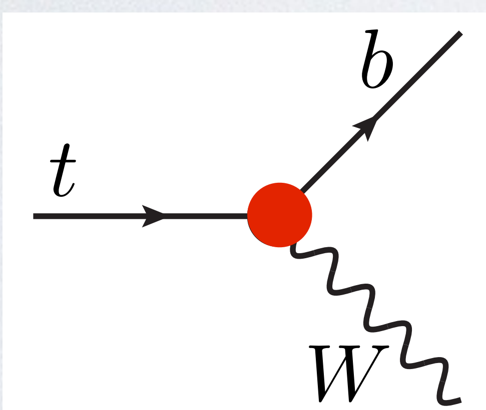
Direct interactions with top-quarks

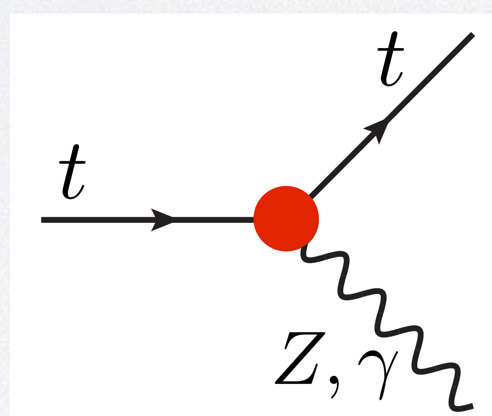


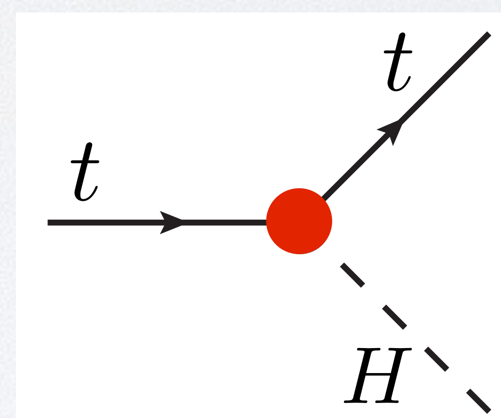




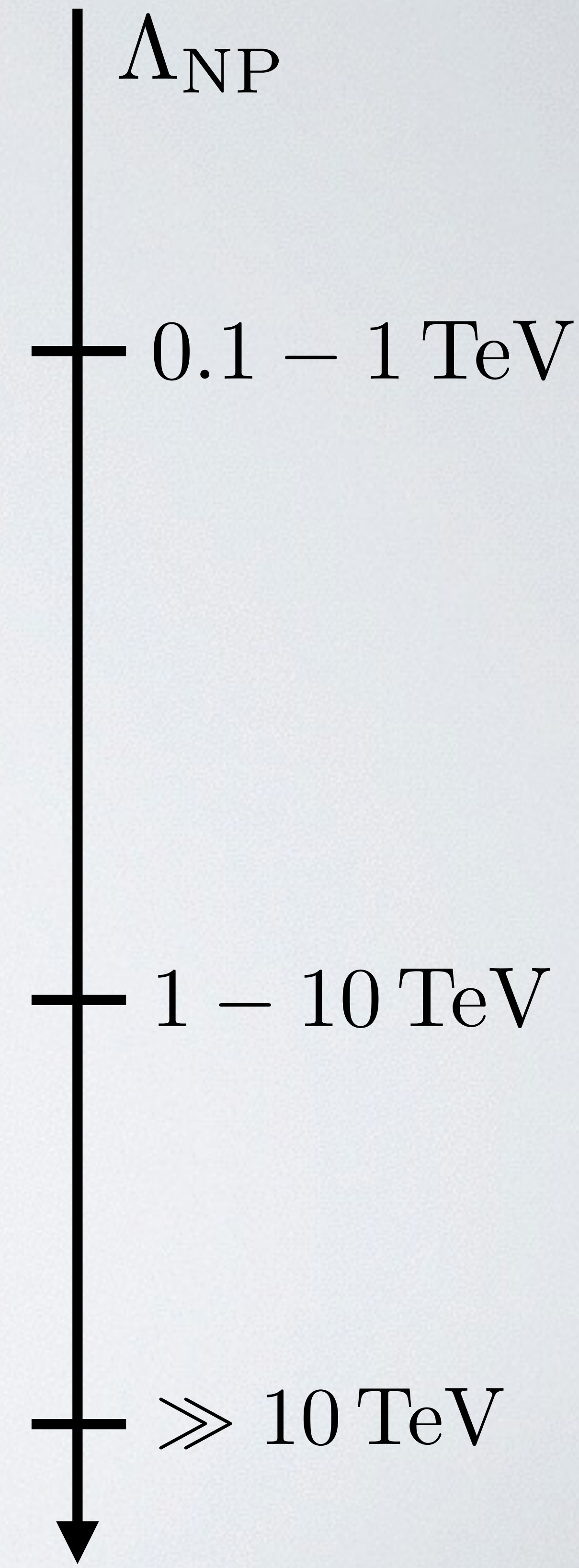
Virtual corrections to top-quark interactions

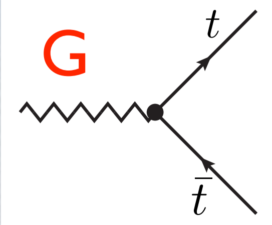






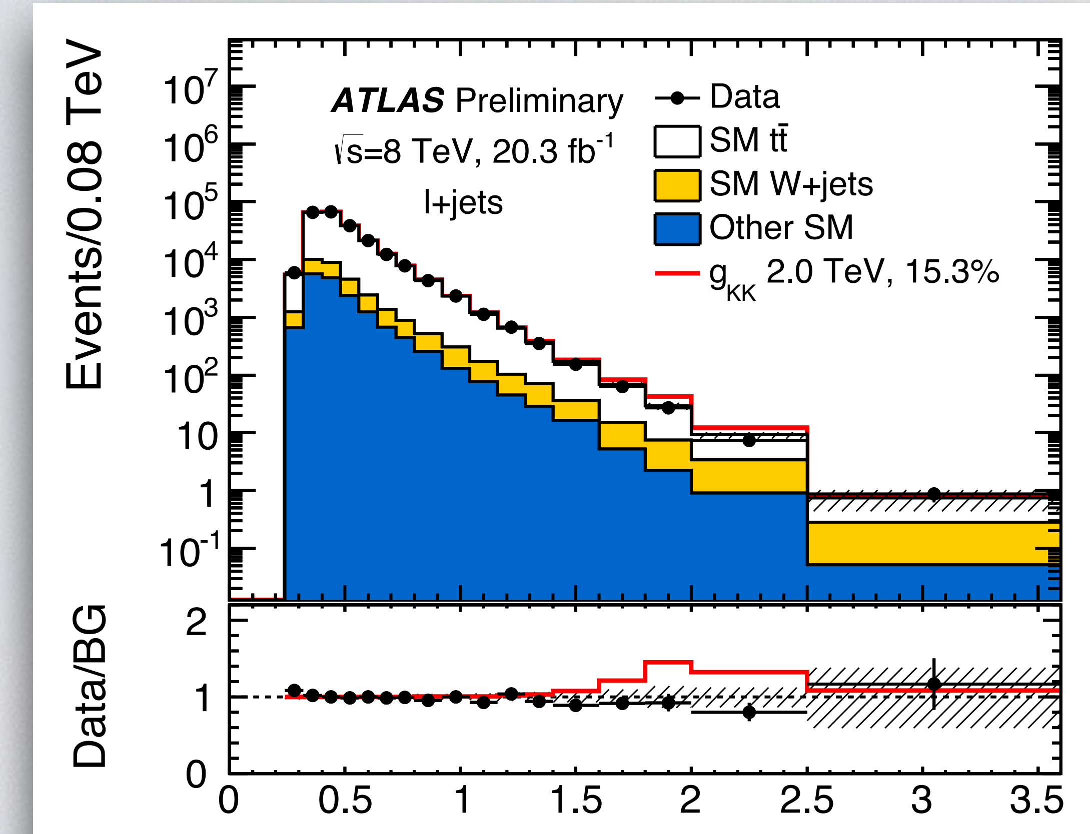
Related virtual effects in b-quark interactions





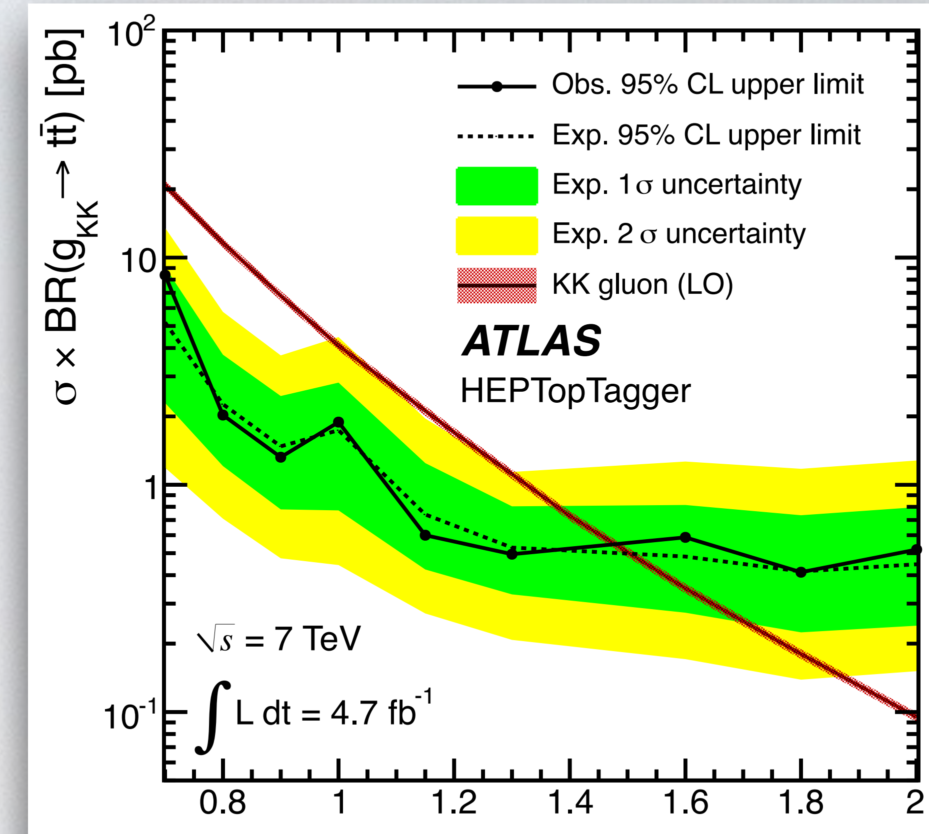
DIRECT: TOP-ANTITOP RESONANCES

leptonic+hadronic decay



[ATLAS-CONF-2015-009]

fully hadronic decays

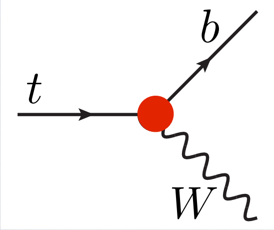


[ATLAS-HD: Schoening, 2013]

Benefit from precision:

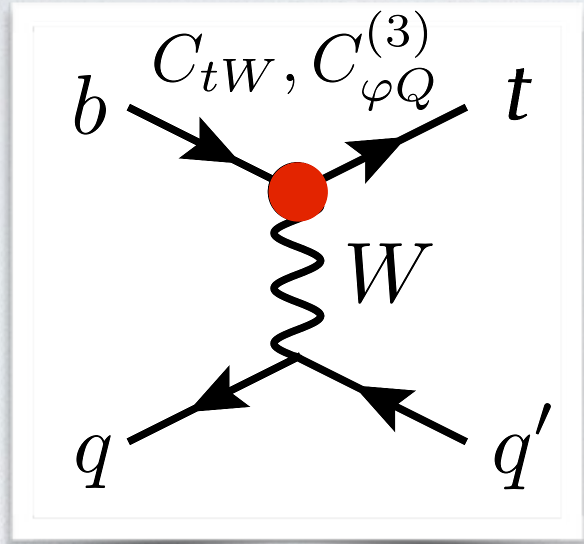
Prediction for tail of distribution improves by including information on PDFs from top-pair production cross section.

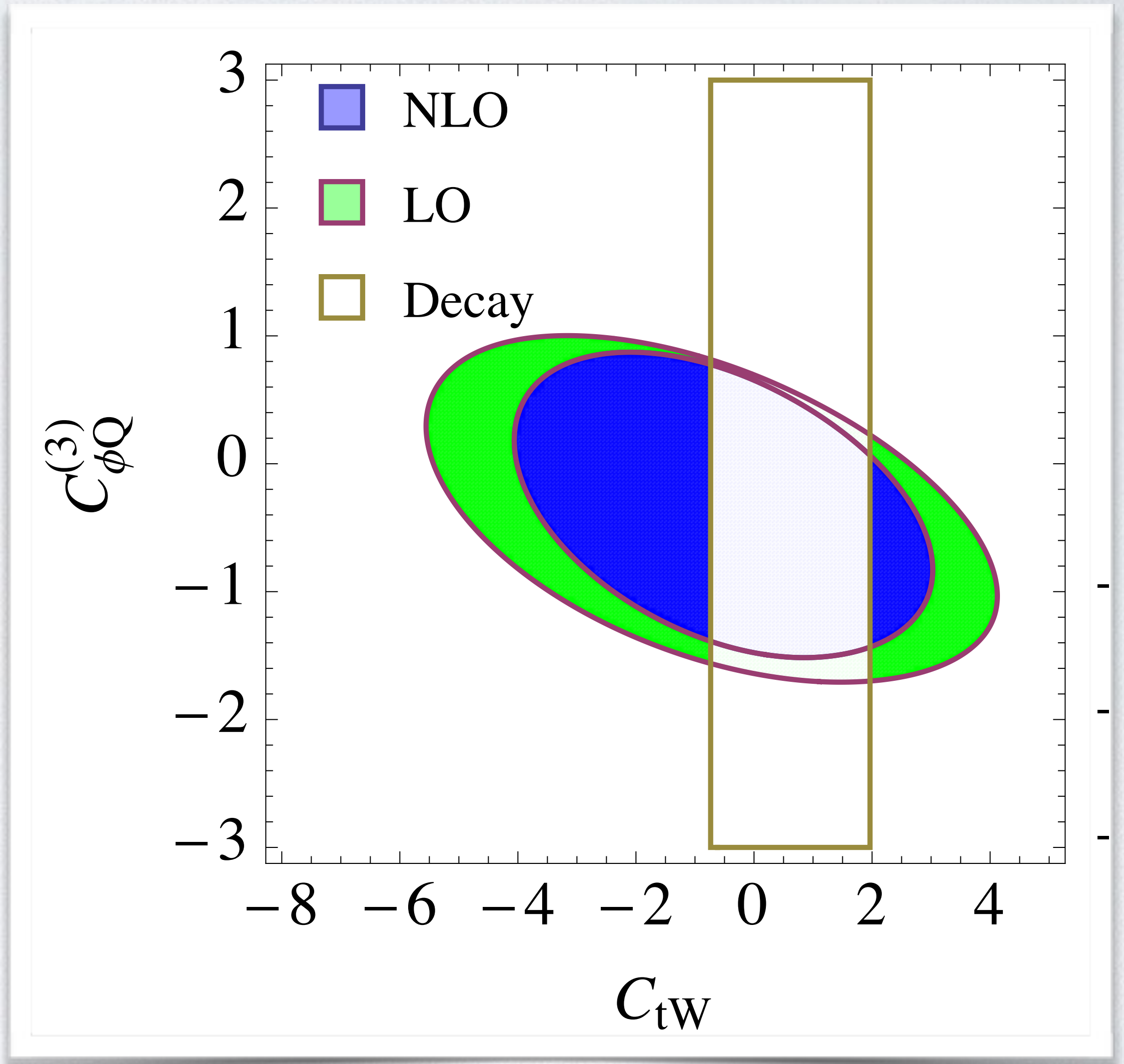
[Czakon, Mangano, Mitov, Rojo, arXiv:1303.7215]



INDIRECT: ANOMALOUS TOP INTERACTIONS

Example: electroweak production of a single top-quark





[C. Zhang, arXiv:1601.06163]

two contributing operators:

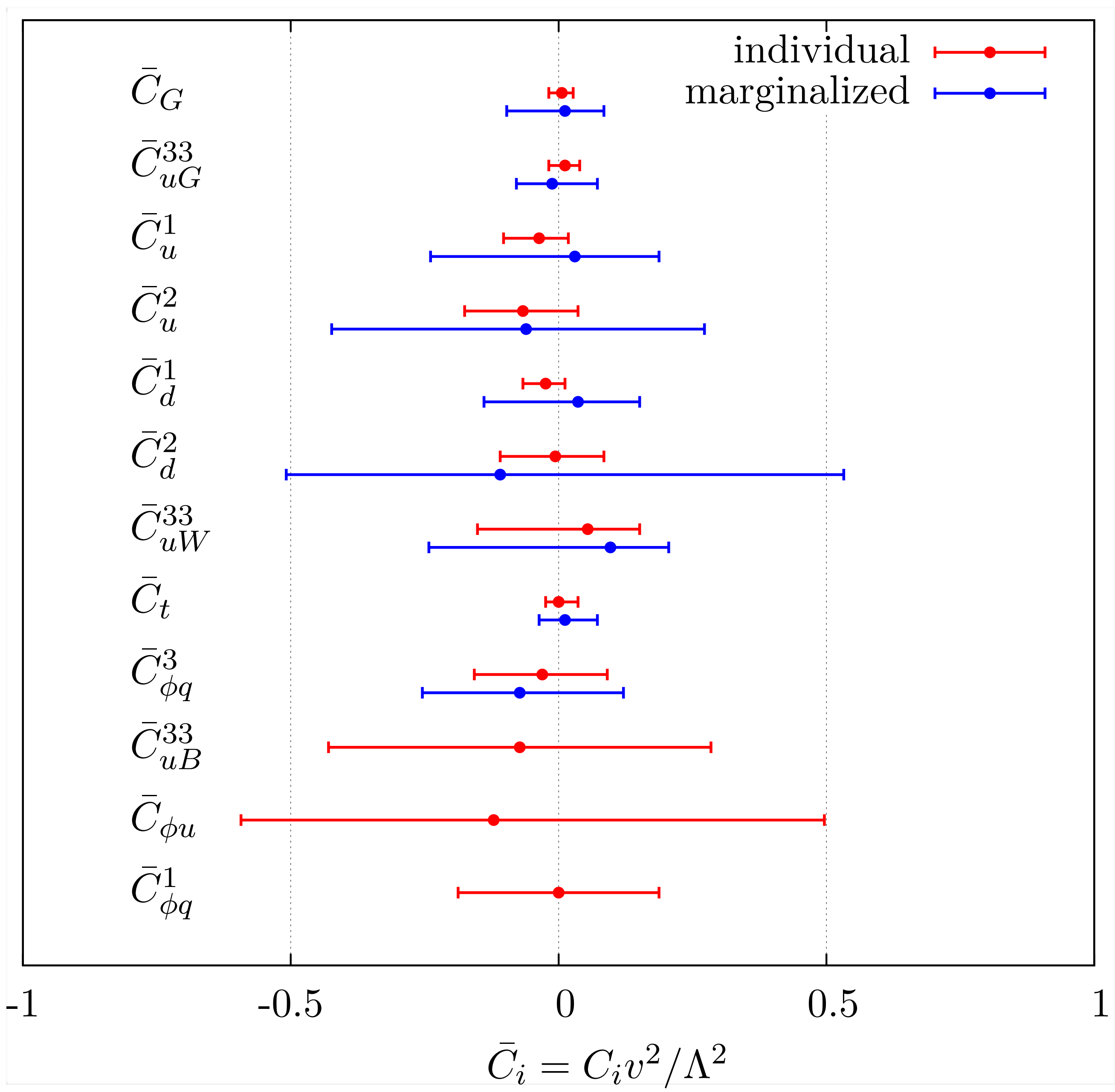
$$O_{tW} = y_t g(\bar{Q}\sigma^{\mu\nu}\tau^I t)\widetilde{\varphi} W^I_{\mu\nu}$$

$$O_{\varphi Q}^{(3)} = i\frac{y_t^2}{2}(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar{Q}\gamma^\mu\tau^I Q)$$

Precision matters, especially in differential distributions.

ANOMALOUS TOP INTERACTIONS

Global fit to top-quark data from Tevatron and Run I



[Buckley et al., arXiv:1512.03360]

Sensitive to new physics at the TeV scale in some interactions.

TAKE HOME

Maturity in theory and experiment shifts the LHC paradigm:

The LHC is a **discovery machine**. [Higgs physics]

and

The LHC is a **precision laboratory**. [Top physics]

Two opportunities to find new physics during Run II:

Direct evidence of new phenomena at **high energies**.

Indirect evidence of new physics in **precision observables**.