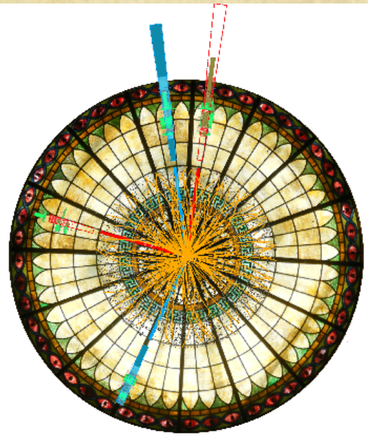
DIS 2015

XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects

Dallas, Texas

April 27 – May 1, 2015



Heavy Flavours

Alexander Mitov

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UNIVERSITY OF CAMBRIDGE

Heavy Flavors: topic as diverse as it gets!

✓ Charm, bottom and top physics

✓ Dominant physics is: perturbative (top) and non-perturbative (b,c)

✓ Different energy regimes are probed:

- Top physics probes both QCD and bSM searches at high scales
- Charm/bottom test:
    - QCD from low energy to moderately high energy
    - bSM physics up to very high scales

✓ Collider description of top/b,c is very different:

- Tops decay perturbatively and are studied only indirectly. Currently huge demand on MC's to describe this transition accurately
- b&c: at high energy (i.e. the QCD aspect) they are modeled like jets
- At low energy we need to model meson production and decay (FONLL for example)

✓ But there are many similarities and interplays:

- The top/bottom A_{FB} connection
- Role in PDF's

B-physics from hadron colliders

Some general comments about b/charm production

- ✓ Open b- and charm production is described generally OK.
- ✓ Jet rates are in NLO QCD. Theory precision is lagging behind measurements. Fiducial cross-section measurements are more precise than theory predictions.
- ✓ Identified meson production is generally described with FONLL (i.e. NLO+NLL) and it shows agreement with data. In some cases theory is harder than data
- ✓ One day, theory at NNLO will make a difference
- ✓ Heavy flavor production in heavy ion collisions, and its interplay with pp collisions, will be discussed in a number of talks

Further details in the talks by

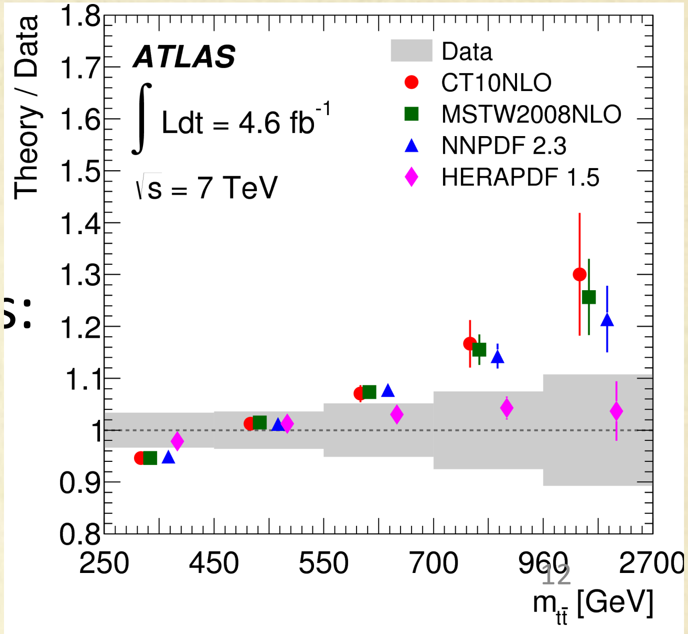
(Tue) Justas ZALIECKAS
(Wed) Matthew WING
(Wed) Paolo GUNNELLINI

Heavy flavour and PDF's

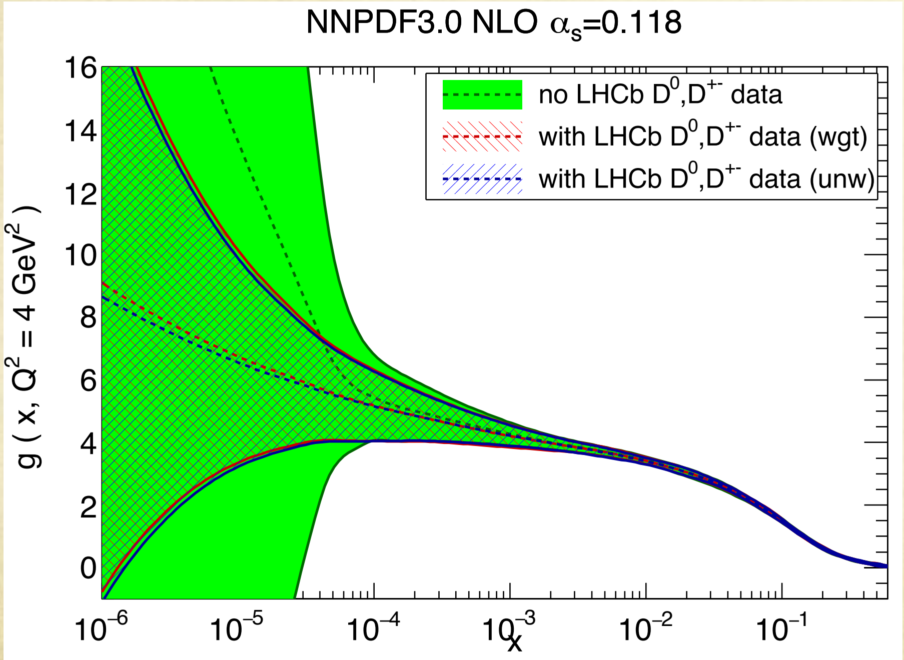
- ✓ Top data gives a handle on the gluon pdf at large x.
  - Studied at the the inclusive level at NNLO

Czakon, Mangano, Mitov, Rojo '13

- ✓ Top quark differential distributions give added access to the gluon PDF →



- ✓ But charm/ bottom LHC data can help, too:



Gauld, Rojo, Rottoli, Sarkar, Talbert, in preparation

For more on HF and pdf's
see the talk by
Alberto ACCARDI
Amanda COOPER-SARKAR

and the talks on Tue and Thu

Known discrepancies at LHC

Further details in the Tue talk by Marcin CHRZASZCZ

✓ For example: $\boldsymbol{B^+ \to K^+\ell^+\ell^-}$ shows 2.6σ deviation from SM

LHCb 1406.6482

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

$$R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst}).$$

For: $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

Compare to $R_K \approx 1$ in SM.

✓ Deviation suggest lepton non-universality. Major bSM discussions:

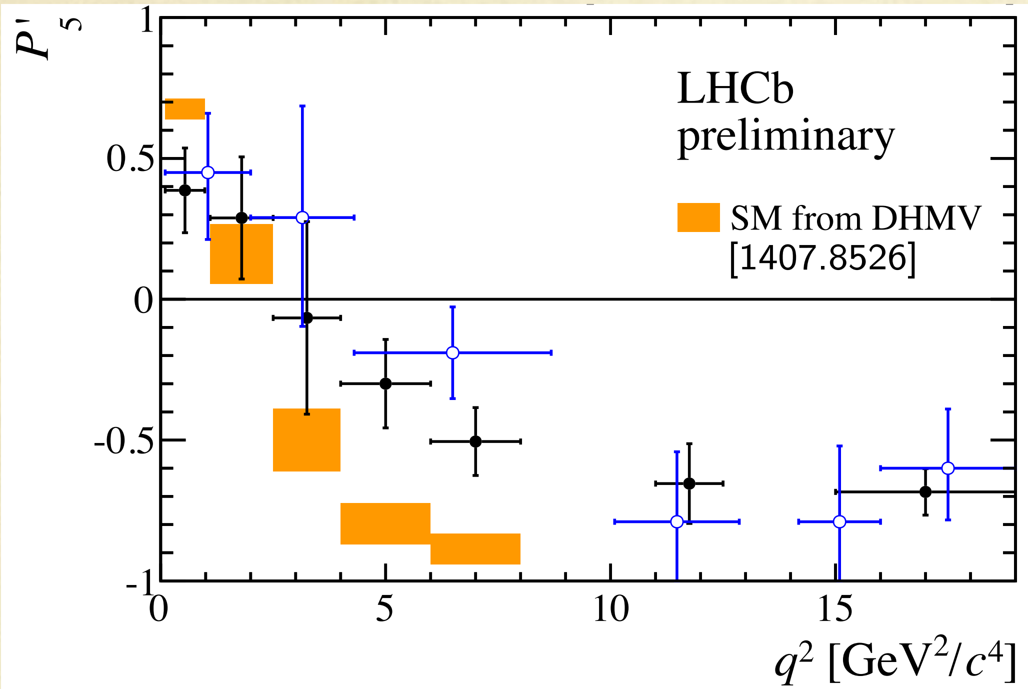
Ghosh, Nardecchia, Renner '14
Gripaios, Nardecchia, Renner '14
Hiller, Schmaltz '14
Niehoff, Stangl, Straub '15

✓ Another observable that generated a lot of interest: angular analysis of the decay

$$B^0 \to K^{*0}\mu^+\mu^-$$

LHCb CONF-2015-002

✓ New data (full data set) has the deviation, albeit closer to SM:



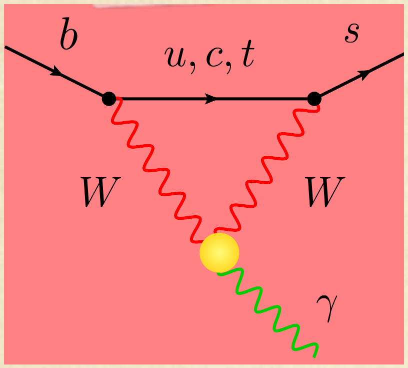
- (Blue) 2013 LHCb data 1 fb^{-1}
- (Black) 2015 data 3 fm^{-1}

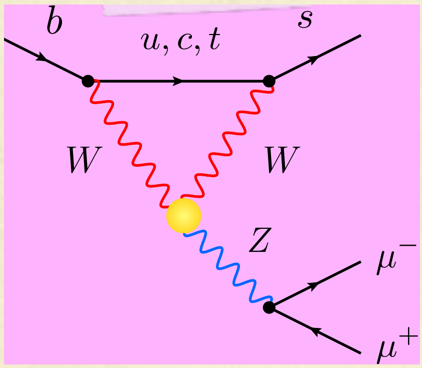
✓ The total deviation in the two bins [4-6,6-8] is 3.7σ (2.9σ in each bin)

✓ The new data goes towards the SM prediction, albeit with smaller errors

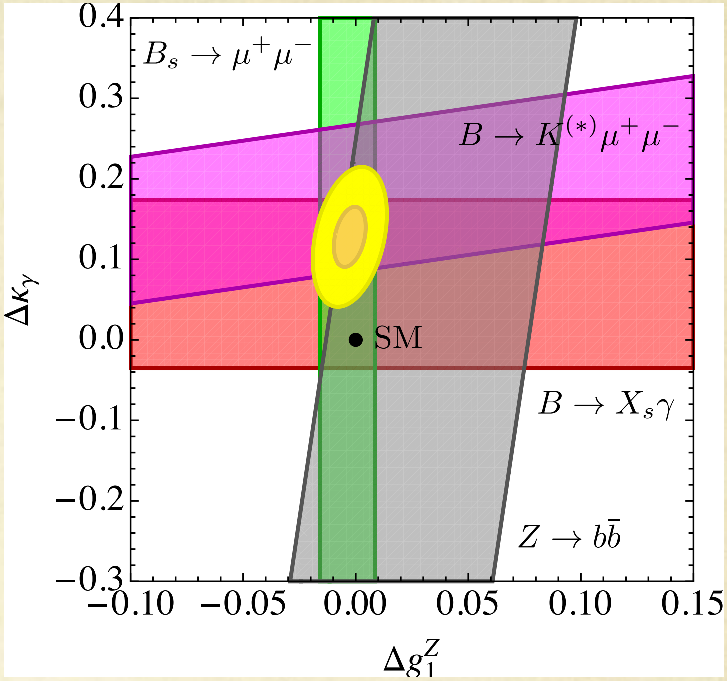
✓ The deviation has strong implications on limits of anomalous triple gauge boson couplings:

Bobeth, Haisch '15





- Deviation from SM in this fit driven by this observable →



✓ More on bSM alternatives

Altmannshofer, Gori, Pospelov, Yavin '14

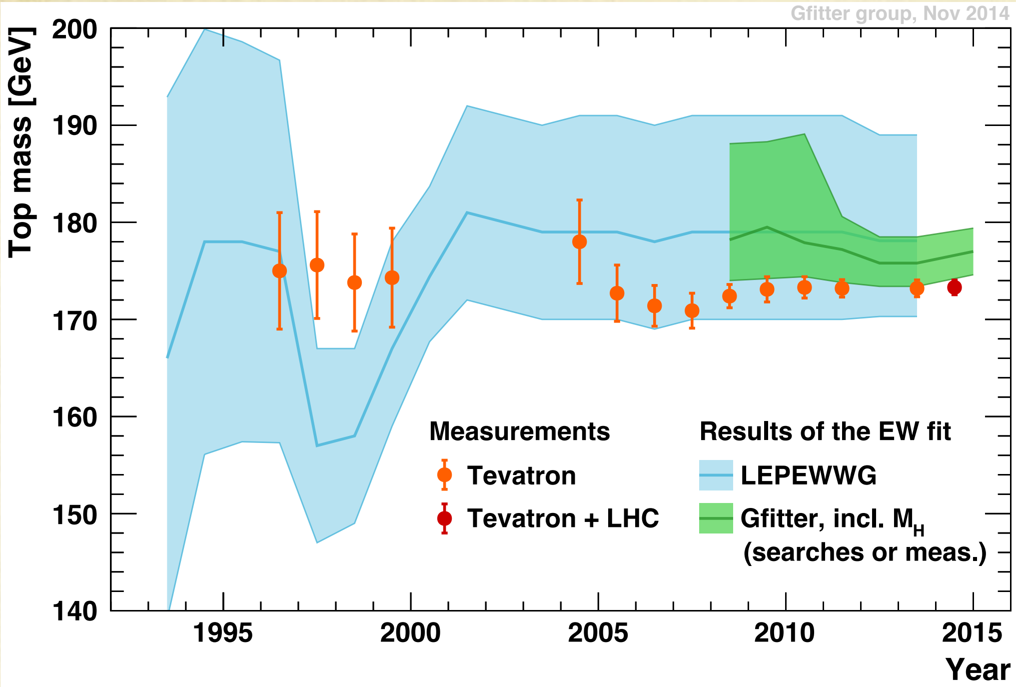
✓ Interesting, large charm contribution, is also a possible contender

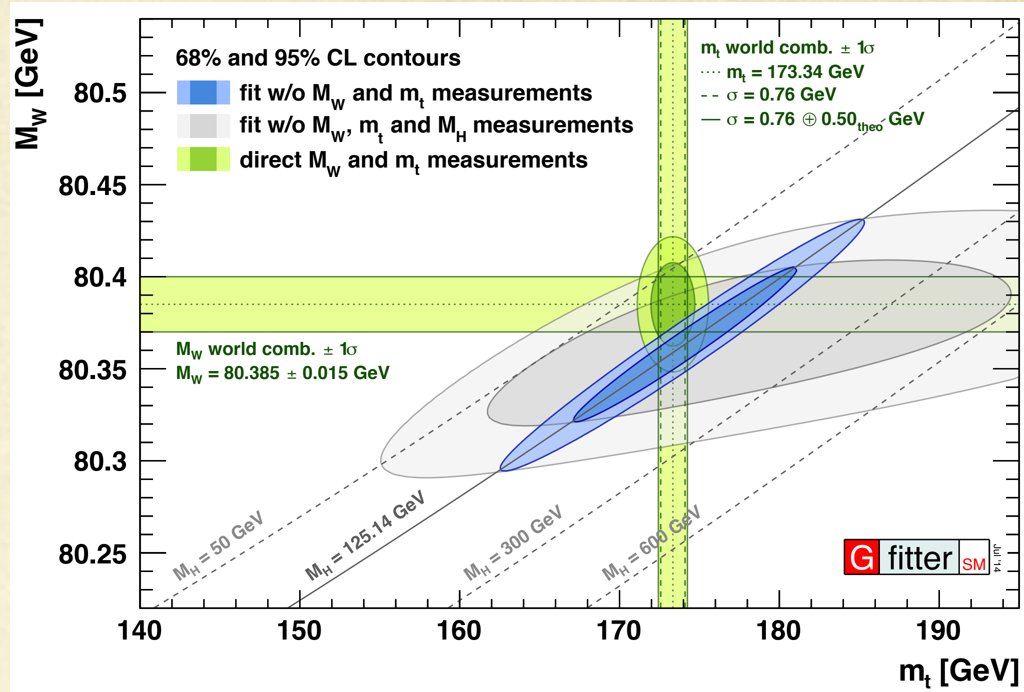
Talk by David Straub, Moriond EW '15

Top and Flavour

Indirect constraints on, and extraction of, the top quark mass

✓ EW precision fits:

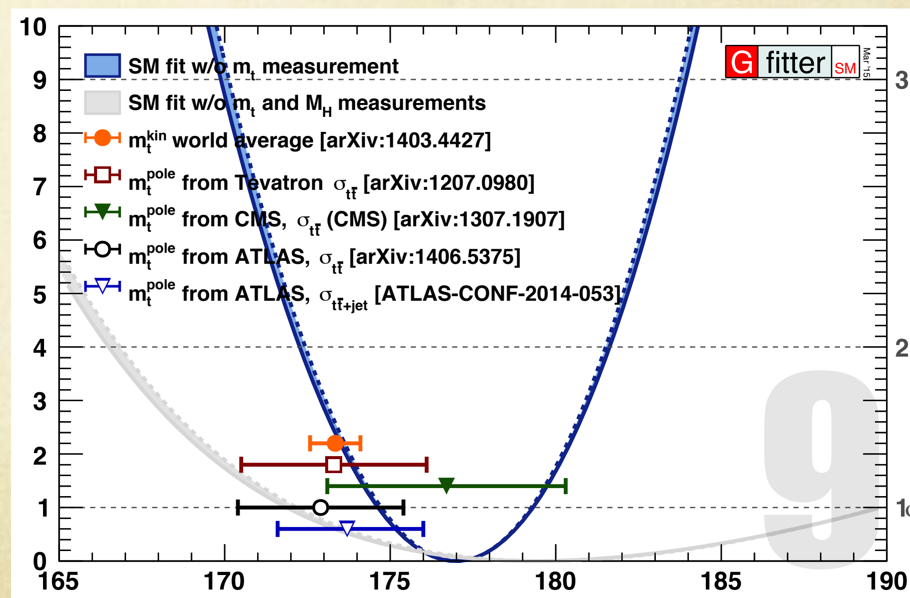




✓ A systematic picture of consistency, both before and after the Higgs discovery!

✓ Remarkably, assuming SM Higgs, M_{top} can be extracted with precision similar to direct extraction from total cross-section!

$$M_{top} = 177 \pm 2.5 \text{ GeV}$$



Indirect constraints on, and extraction of, the top quark mass

✓ Rare B decays ($B_s \to \mu^+\mu^-$)

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser '13
Talk by Uli Haisch SM@LHC '15

Current status →

$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\,\mathrm{GeV}}\right)^{3.06} (1 \pm 6.4\%) \cdot 10^{-9}$$

$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = 2.8 \left(1^{+25\%}_{-21\%}\right) \cdot 10^{-9}$$ [CMS & LHCb, 1411.4413]

$$\Downarrow$$

$$m_t^{\mathrm{pole}} = (158 \pm 13)\ \mathrm{GeV}$$

Ultimate LHC expectation →

$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\,\mathrm{GeV}}\right)^{3.06} (1 \pm 3\%) \cdot 10^{-9}$$

$$\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = 3.65\,(1 \pm 4\%) \cdot 10^{-9}$$ [LHCb, 1208.3355]

$$\Downarrow$$

$$m_t^{\mathrm{pole}} = (173.0 \pm 2.8)\ \mathrm{GeV}$$

Comparable to direct extraction from total cross-section!

Further details in the Wed talks by
Jon WILSON
Nikolaos KIDONAKIS

A_{FB}/A_C in the top and bottom sectors

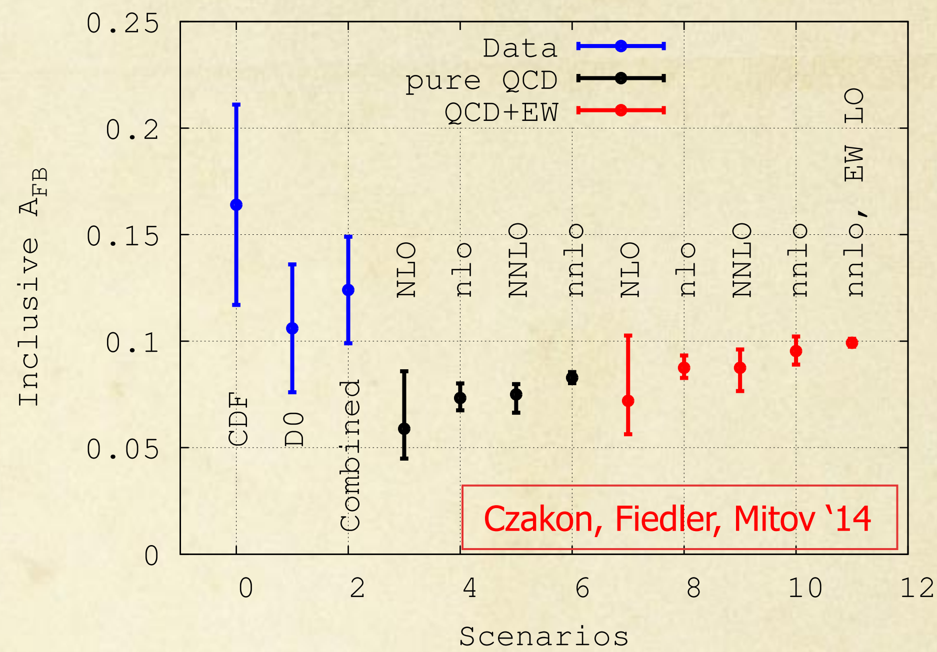
Top quark pair A_{FB}

✓ The observable that generate outsized interest due to discrepancy in the early days!

✓ Prompted dramatic improvements in
- SM
- bSM

$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}, \quad \text{where} \quad \sigma^\pm \equiv \int \theta(\pm\Delta y)\, d\sigma$$

◆ *NLO, NNLO* : exact numerator and denominator
◆ *nlo, nnlo* : expanded in powers of a_S

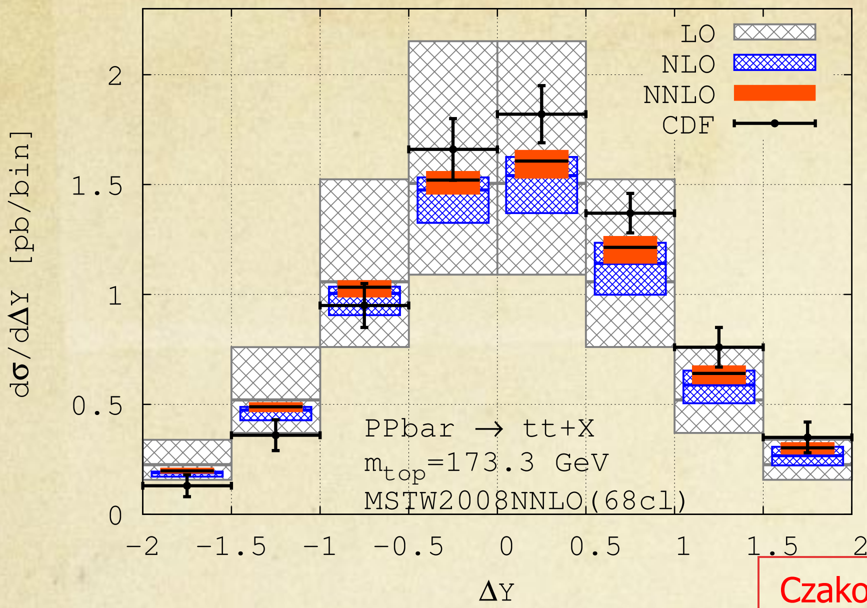


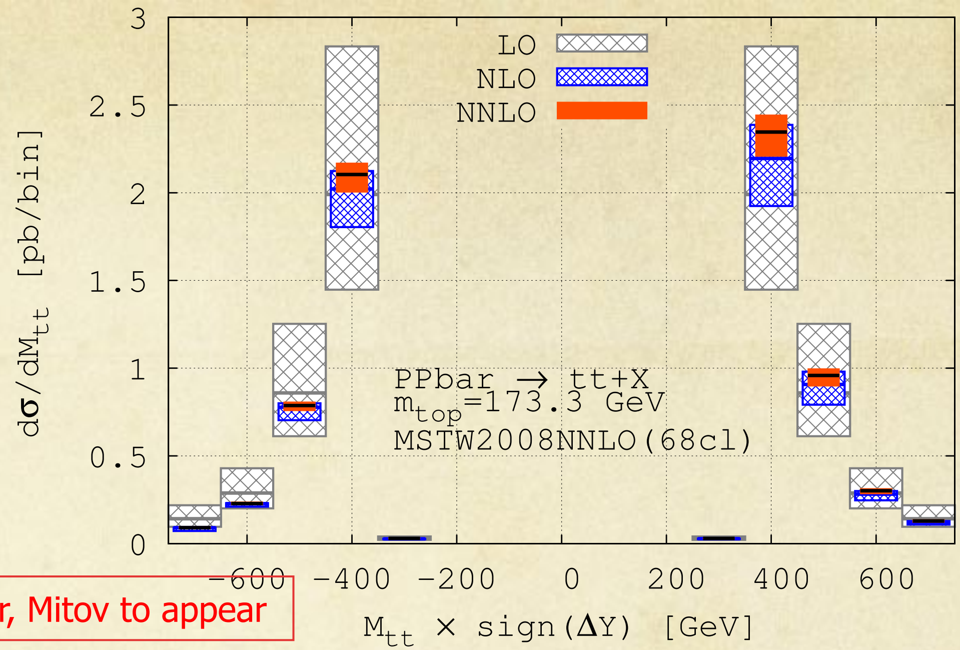
✓ Large QCD corrections: NNLO ~ 27% of NLO (recall EW is 25% of NLO)

✓ Adding all corrections A_{FB} ~ 10%

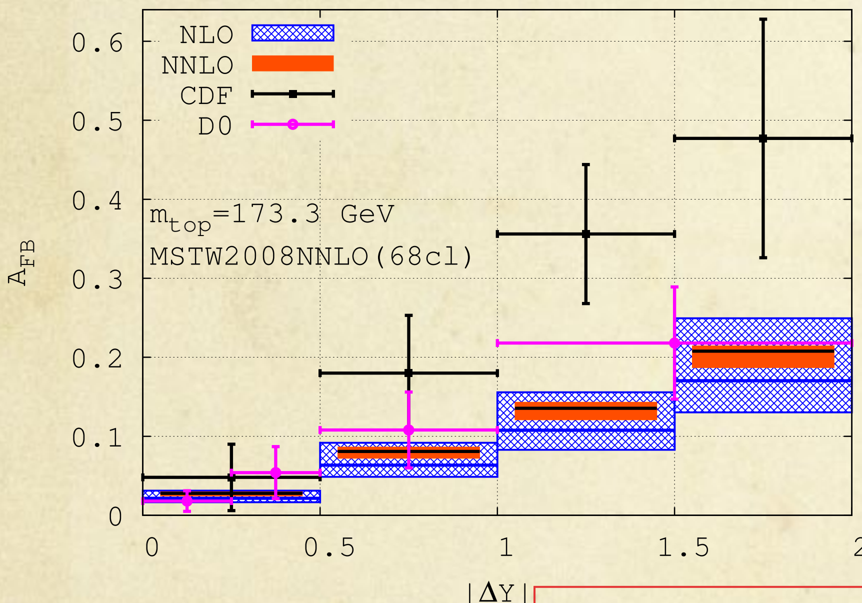
✓ Agrees with D0 and CDF/D0 naive combination
✓ Less than 1.5σ below CDF

✓ We observe good perturbative convergence (based on errors from scale variation)



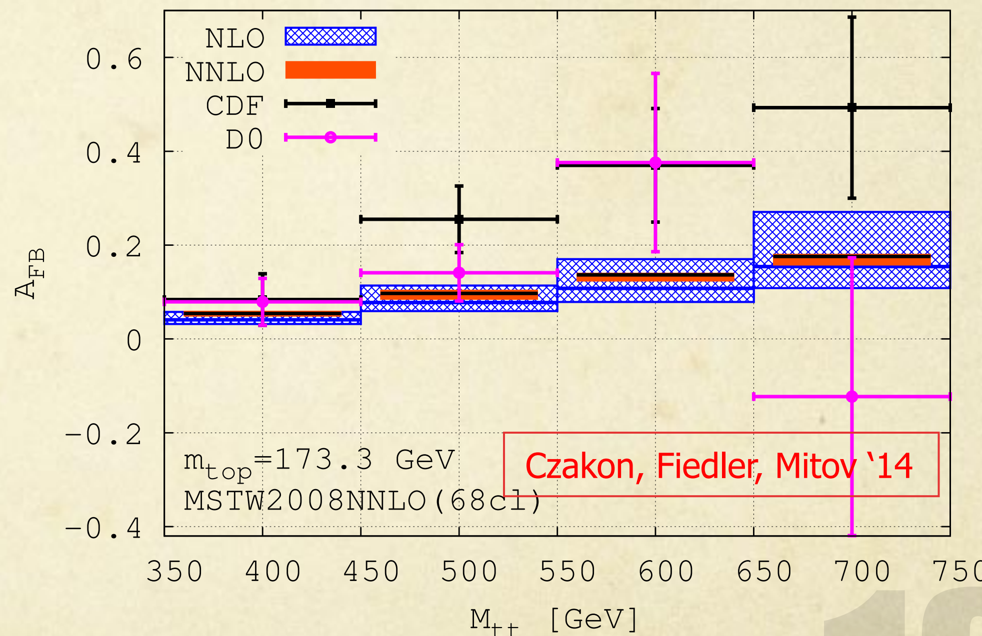


Czakon, Fiedler, Mitov to appear



Czakon, Fiedler, Mitov '14

FIG. 2: The $|\Delta y|$ differential distribution (top) and asymmetry (bottom) in pure QCD at LO (grey), NLO (blue) and NNLO (orange) versus CDF [2] and D0 [1] data. Error bands are from scale variation only. For improved readability some bins are plotted slightly narrower. The highest bins contain overflow events.

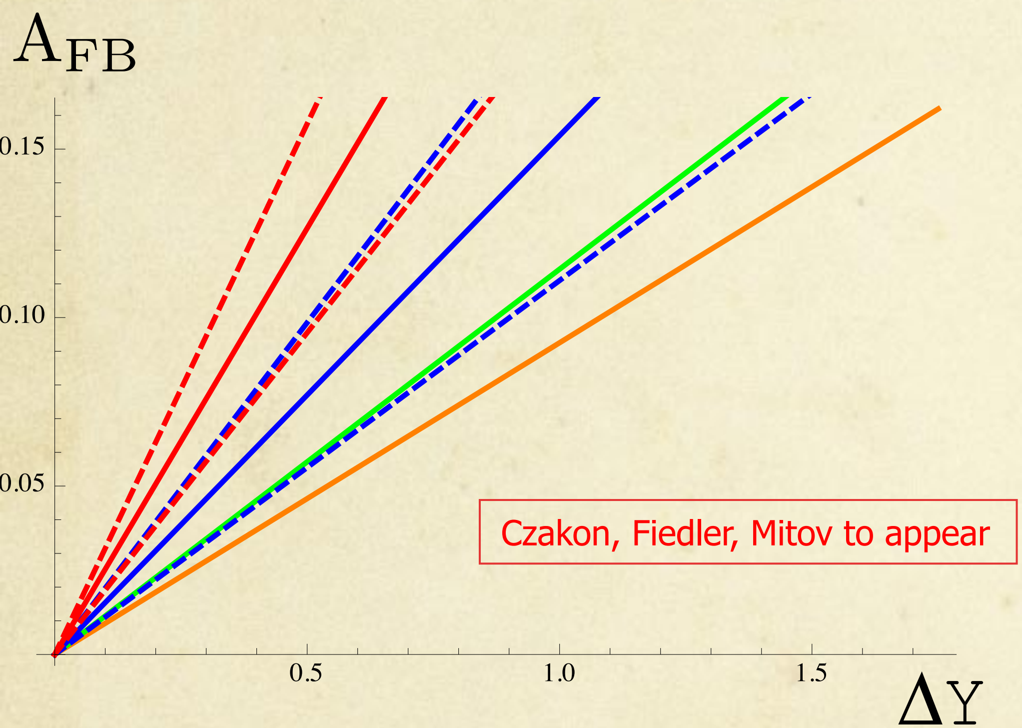


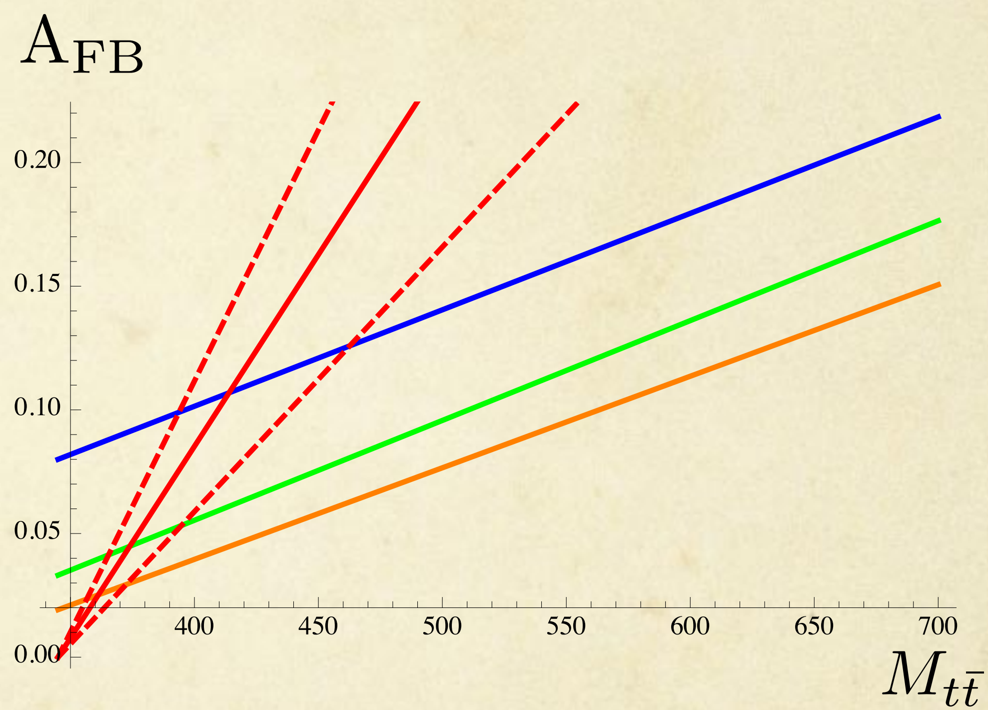
Czakon, Fiedler, Mitov '14

FIG. 3: As in fig. 2 but for the $M_{t\bar{t}}$ differential asymmetry. Both lowest and highest bins contain overflow events.

The slope of A_{FB}

- It was noted previously that the differential asymmetry is close to a straight line
- For the rapidity dependence it is clear it is actually slightly curved at both NLO and NNLO
- For M_{tt} at NNLO is very close to a straight line – unlike NLO



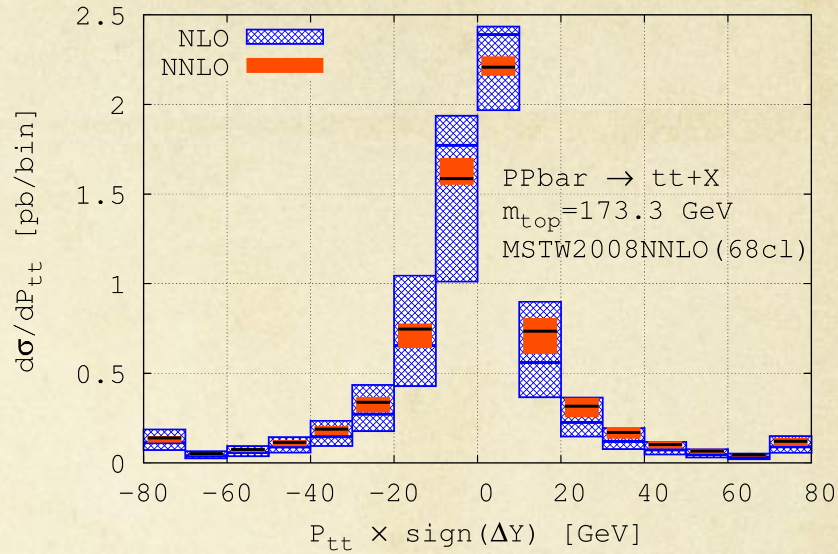


- CDF (dashes = errors)
- D0 (dashes = errors)
- NNLO QCD
- NLO QCD

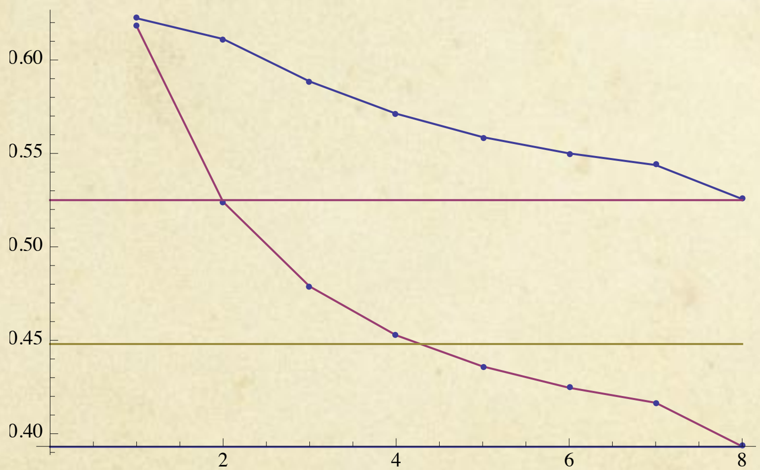
- Agreement with D0 within errors even without EW corrections (D0 error not shown)

The origin of the difference w/r to approximate NNLO

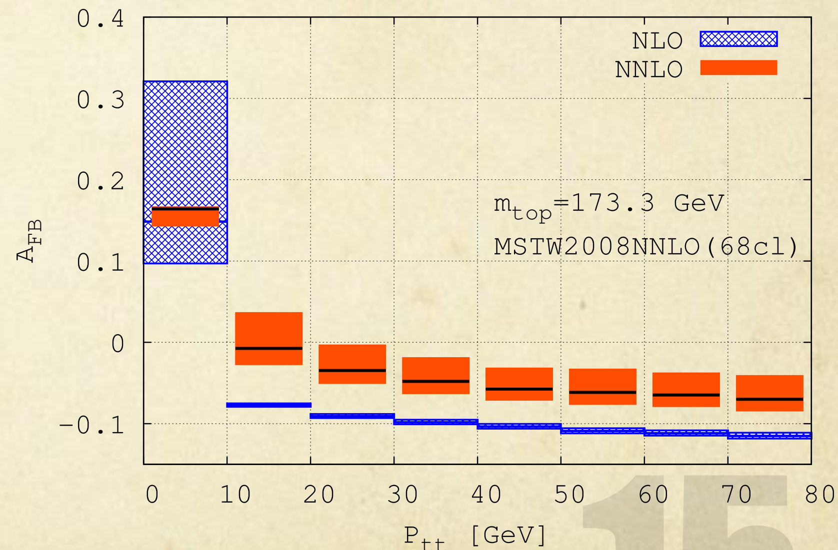
- It is better to look at the Cumulative differential asymmetry (i.e. the inclusive asymmetry with a cut on $P_{T,tt}$)
- Recall: the inclusive asymmetry is <u>not</u> an integral over the differential one …
- Soft gluon resummation "operates" near $P_{T,tt}=0$. The Cumulative asymmetry will illustrate how A_{FB} develops
- Cumulative $P_{T,tt}$ asymmetry:



NNLO and NLO numerators



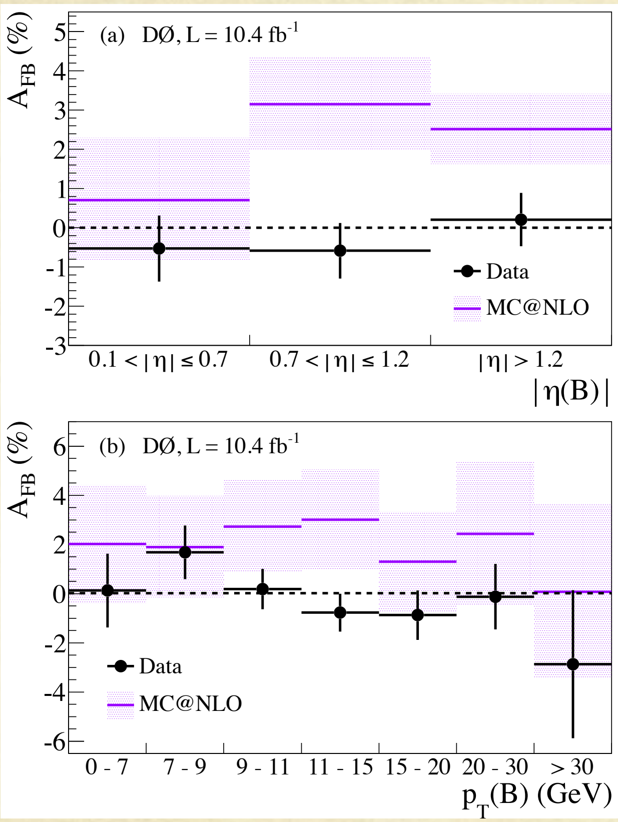
$P_{T,tt}$ bin



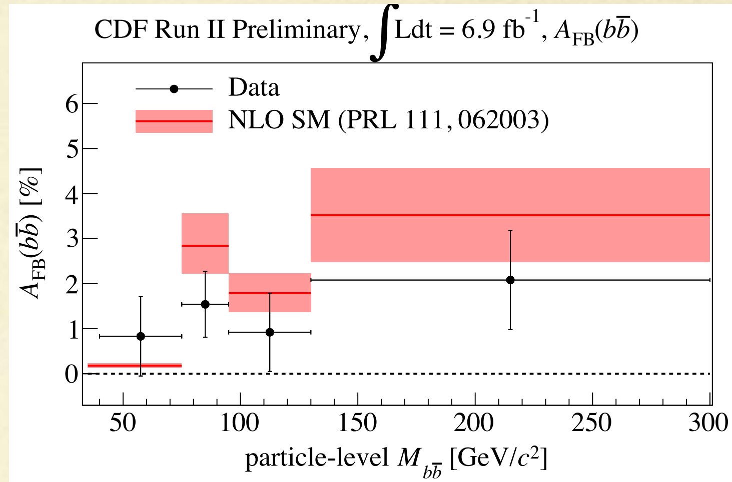
Czakon, Fiedler, Mitov to appear

A_{FB} in bb

- The related asymmetry in b-pair production has been suggested as a handle on the top puzzle
- There are some differences (Z->bb contributions, large gg component)
- Measurements now available from Tevatron and LHCb. Except for D0, they agree with SM



D0



CDF

$$A_C^{b\bar{b}}(40, 75) = 0.4 \pm 0.4\,(\text{stat}) \pm 0.3\,(\text{syst})\%,$$
$$A_C^{b\bar{b}}(75, 105) = 2.0 \pm 0.9\,(\text{stat}) \pm 0.6\,(\text{syst})\%,$$
$$A_C^{b\bar{b}}(> 105) = 1.6 \pm 1.7\,(\text{stat}) \pm 0.6\,(\text{syst})\%,$$

LHCb

The LHCb (2014) 3 bin measurement agrees with SM

Top-pair plus a boson production

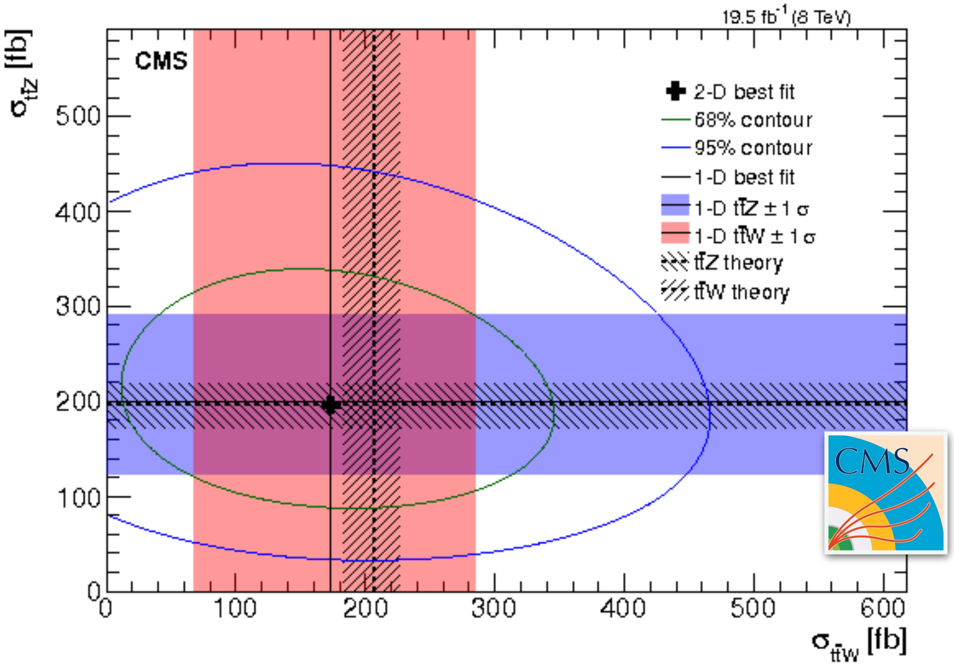
Top Physics: tt+W/Z

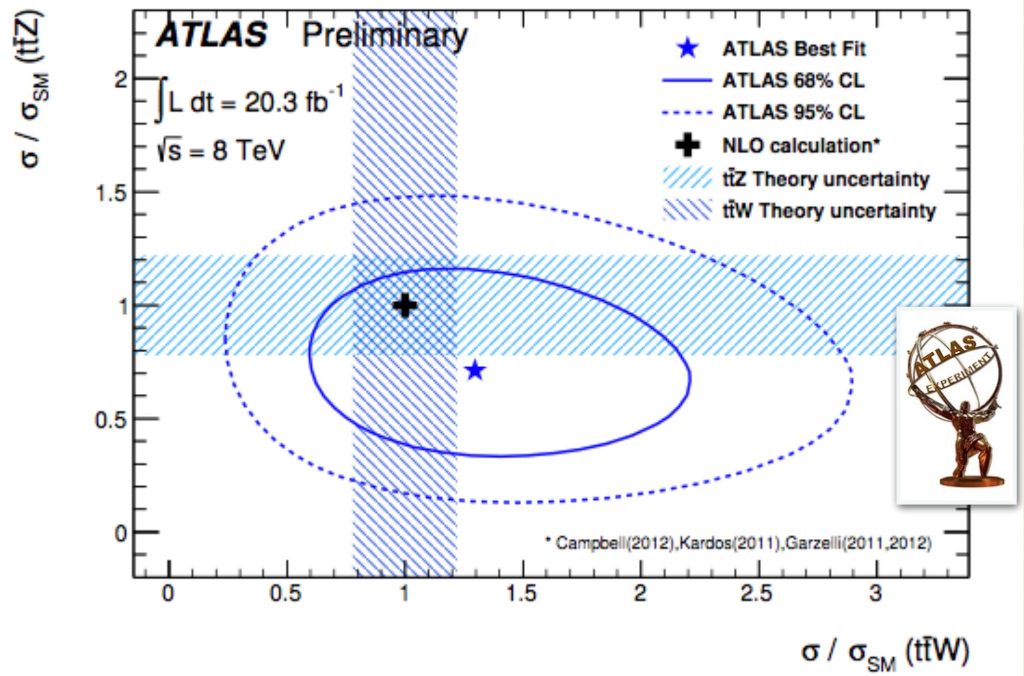
- ✓ Rare processes in SM
- ✓ Just been observed at ~ 3sigma
- ✓ ttZ probes directly the ttZ coupling; not so much for ttW

Evidence for **tt̄Z** (ATLAS, CMS) and **tt̄W** (ATLAS)!

8 TeV NLO cross sections: σ(tt̄Z) = 206 ± 45 fb, σ(tt̄W) = 232 ± 51 fb

Talk by Anne-Catherine Le Bihan SM@LHC '15





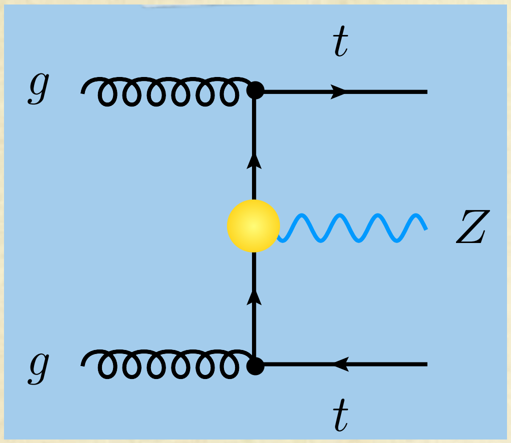
Channels used	Process	Cross section	Significance
2ℓ	tt̄W	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
3ℓ+4ℓ	tt̄Z	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ+3ℓ+4ℓ	tt̄W + tt̄Z	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

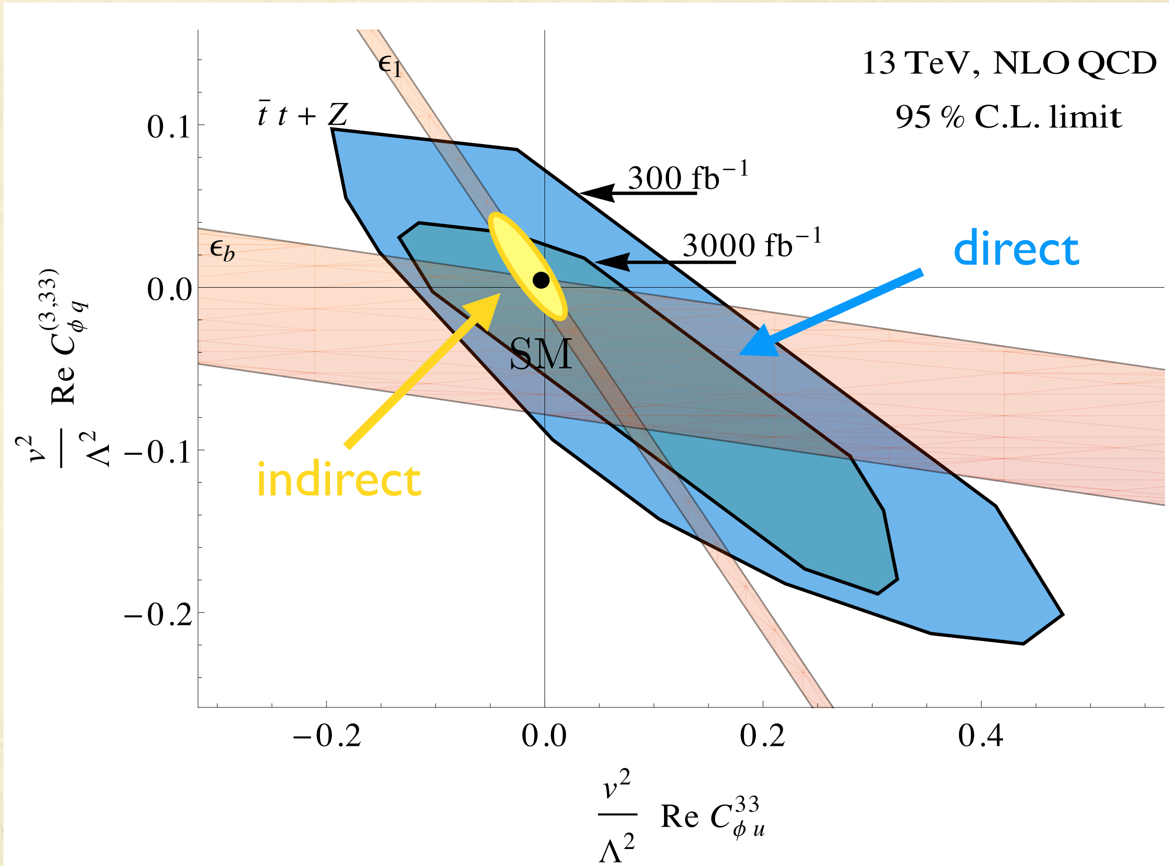
	Summary of combined simultaneous fit results		
Process	Measured cross-sections	Observed σ	Expected σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) ± 21(syst.) fb	3.1	3.7
$t\bar{t}W$	300^{+140}_{-110}(total) = 300^{+120}_{-100}(stat.)$^{+70}_{-40}$(syst.) fb	3.1	2.3

✓ The top/flavour interplay can be quite dramatic here.

✓ Anomalous ttZ couplings from LHC & Flavour:

Röntsch, Schulze '14
Brod, Greljo, Stamou, Uttayarat '14
Talk by Uli Haisch SM@LHC '15



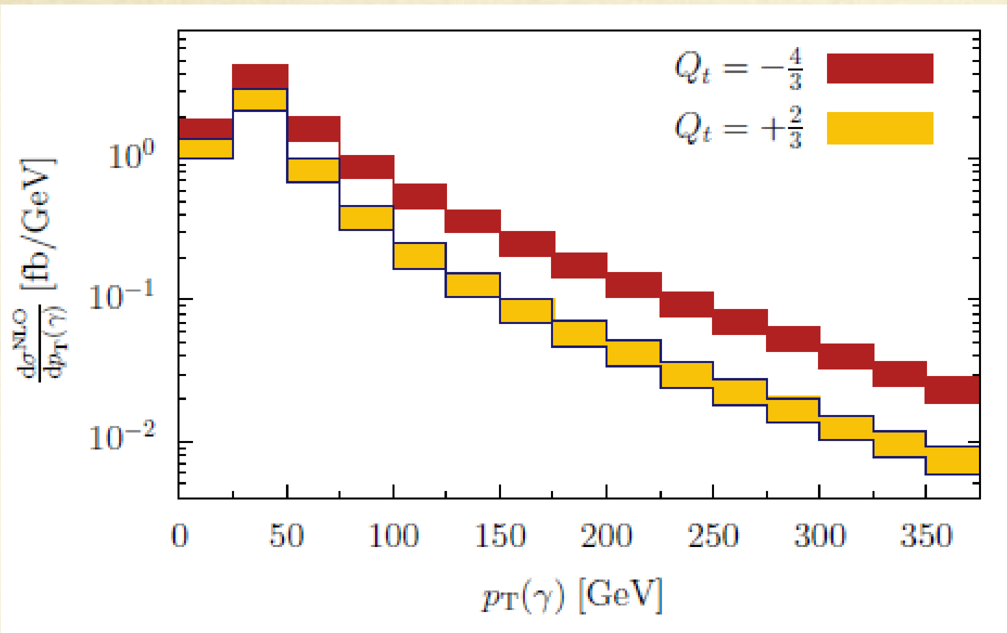


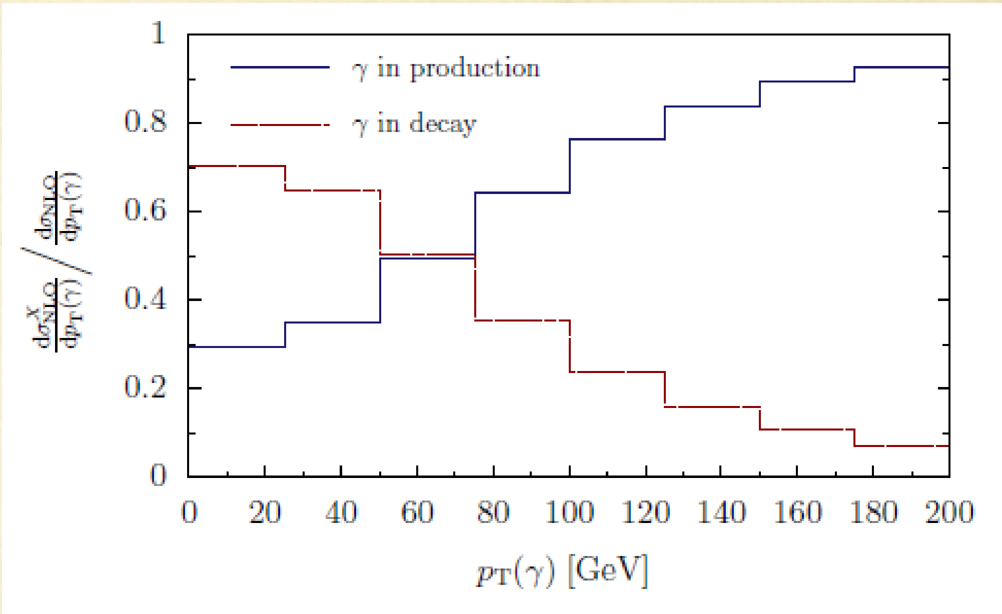
✓ Indirect bounds can be much stronger than direct one. Strong interplay between the two.

Top Physics: tt+gamma

- ✓ Solid brand new observation (ATLAS '15) of this associated production mode
  - ✓ 5.3 sigma
  - ✓ Fiducial measurements agrees with SM
- ✓ Handling top decay correctly is crucial for getting this observable right
- ✓ Opens interesting questions about how well MC's deal with this situation

Melnikov, Scharf, Schulze '11

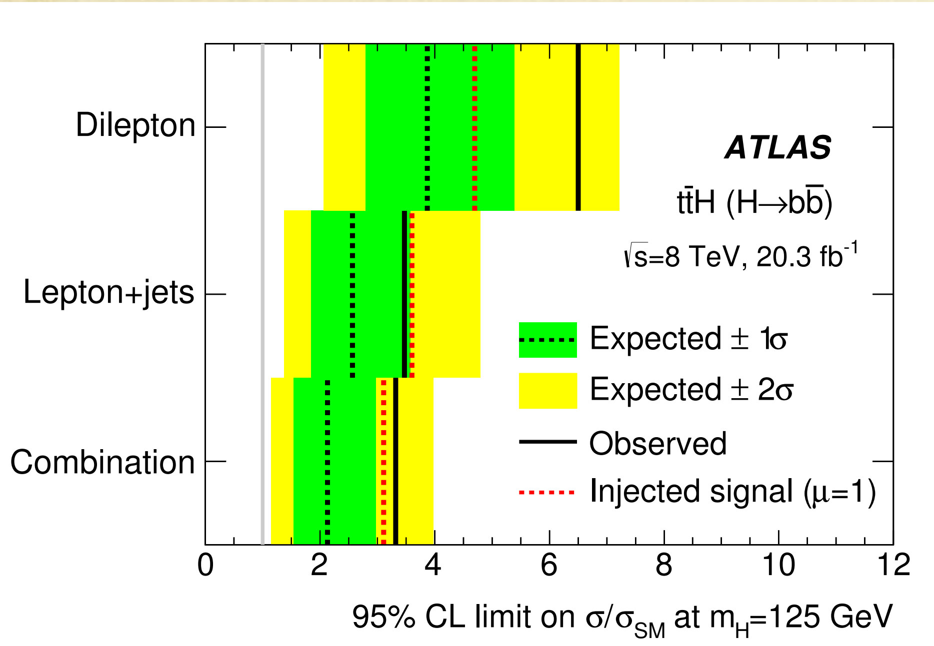


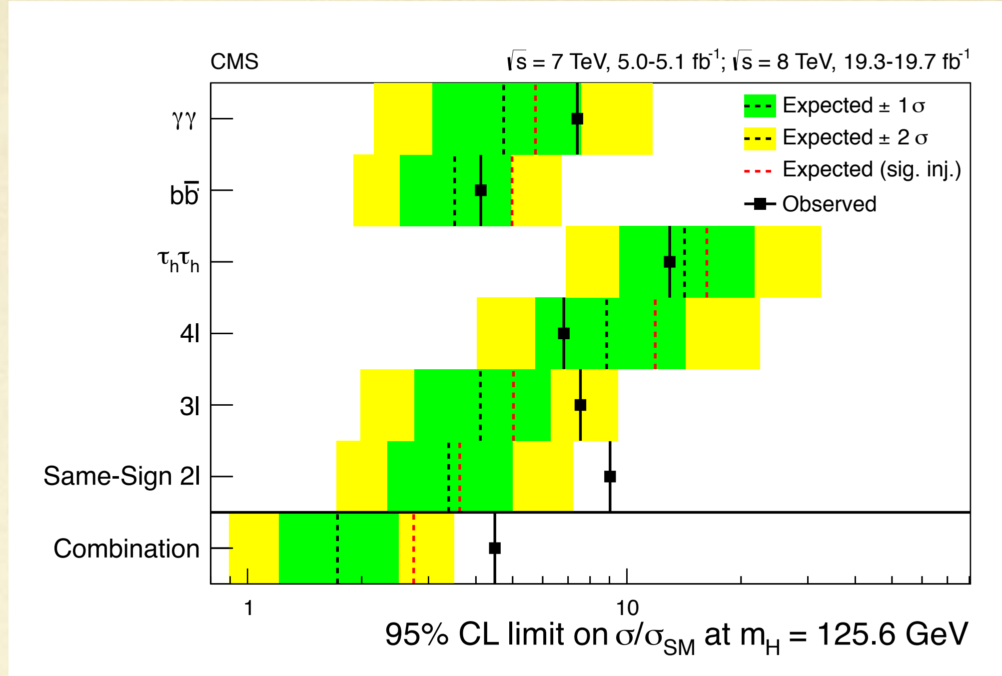


- Directly probe the top electric charge
- Radiation in top decay is dominant for P_T below 50 GeV or so.

Top Physics: tt+H

✓ New results in this difficult channel





✓ Starting to test the SM cross-section predictions.

✓ High-requirements for the MC's to model the final state well

✓ It is important to understand top production well in order to model ttH properly. In particular the top P_T and tT P_T are important (presently reweighting to top P_T is used)

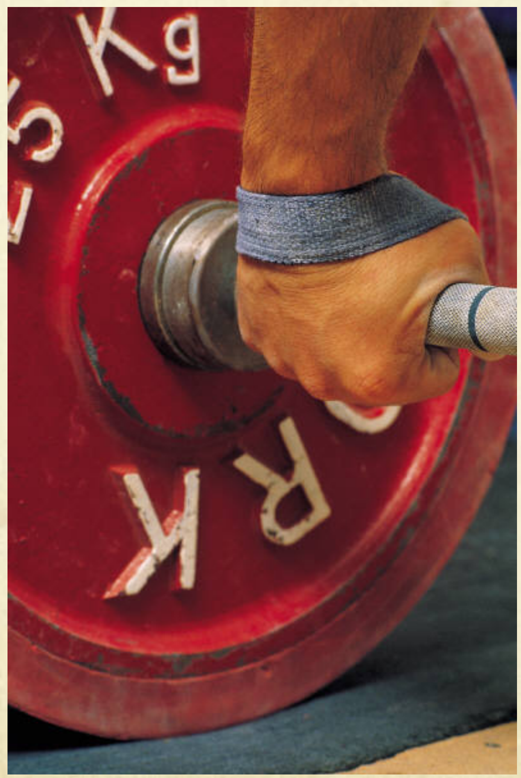
✓ Also important to control exp systematics in tT: for example, in the most sensitive channel (H-> bb), ATLAS has S/B ~6%

Further details in the Wed talks by

(exp) Serban PROTOPOPESCU
Christian SCHWANENBERGER
Jasone GARAY GARCIA

(th) Nikolaos KIDONAKIS

Top physics



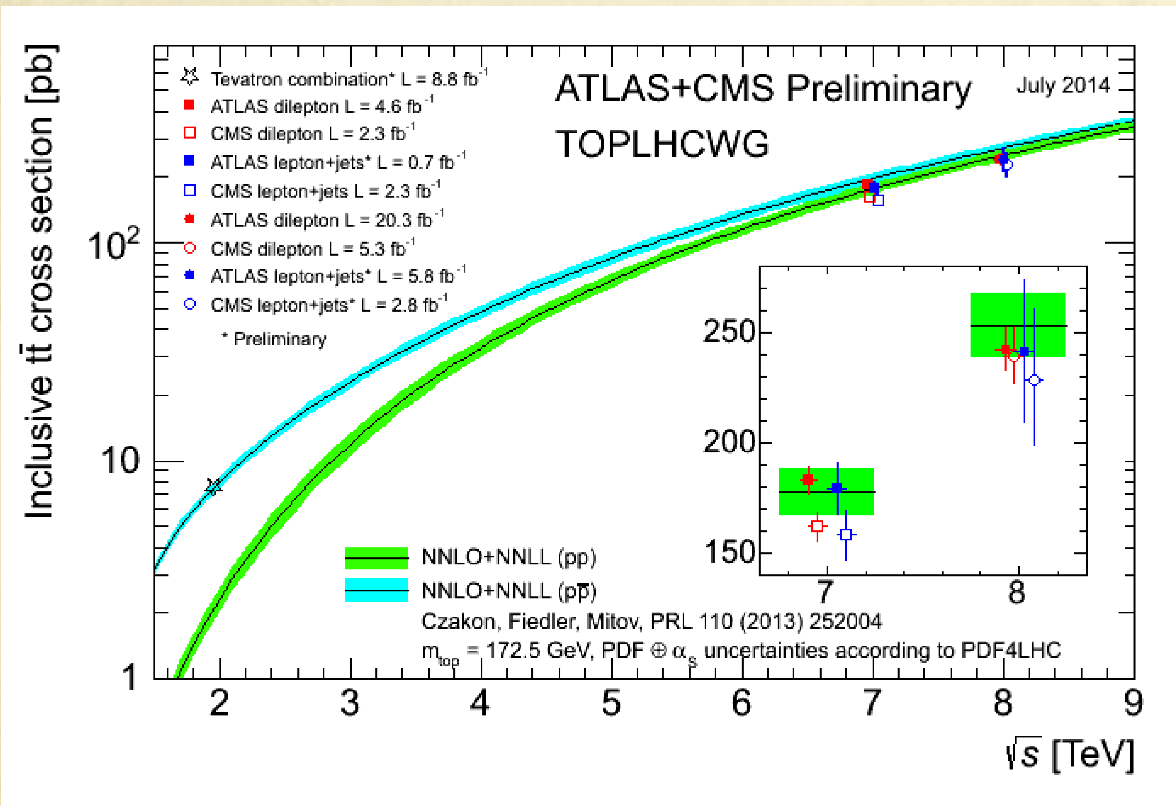
Calculational Status

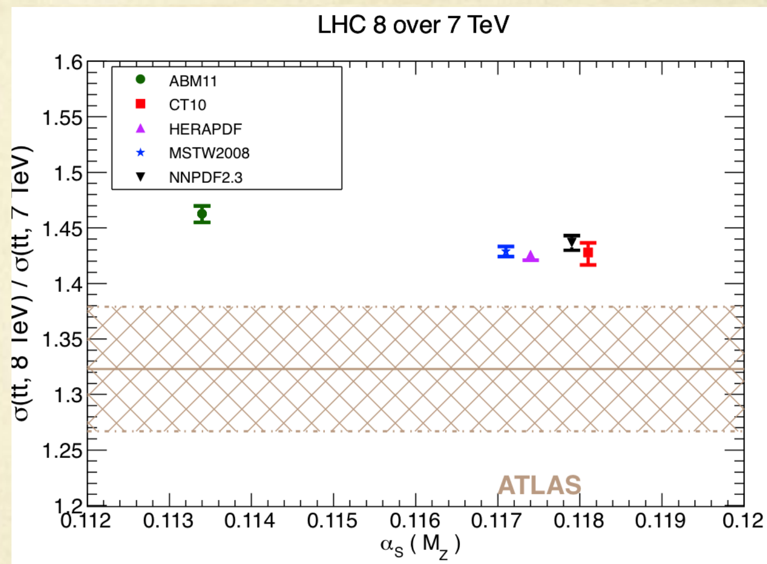
- ✓ Total inclusive cross-section known fully
  P. Bernreuther, Czakon, Fiedler, Mitov '12-'13
- ✓ First differential distributions have been computed for the Tevatron.
  Czakon, Fiedler, Mitov '14 and to appear
- ✓ Methods are based on the subtraction scheme STRIPPER
  Czakon '10
- ✓ Alternative approaches are possible
- ✓ Work in progress based on antennae subtractions.
  Abelof, Gehrmann-De Ridder, Maierhofer, Pozzorini '14
- As a proof of principle the calculation of qq->tt (NF parts done). Very encouraging result although not yet pheno-relevant.
  Abelof, Gehrmann-De Ridder '14
- ✓ Alternative approach based on top pair PT resummation
  Zhu, Li, Li, Shao, Yang '13
  Catani, Grazzini, Torre '14
- Currently at NNLL and NLO; the remaining tasks for NNLO are not that formidable.

Top Physics: top pair inclusive

- ✓ Inclusive top pair production is in a very good shape
- ✓ Theory & experimental errors are small – at few %.
- ✓ Agreement is very good (both 7 and 8 TeV).
- ✓ The 8 TeV measurement dominated by luminosity/beam energy uncertainties !!

- ✓ 8/7 TeV ratio is not as good
  - Is it modeling (i.e. the way we estimate theory errors in ratios – recall top A_{FB})?
  - Is it real (if this then it will become obvious at 13 TeV!).



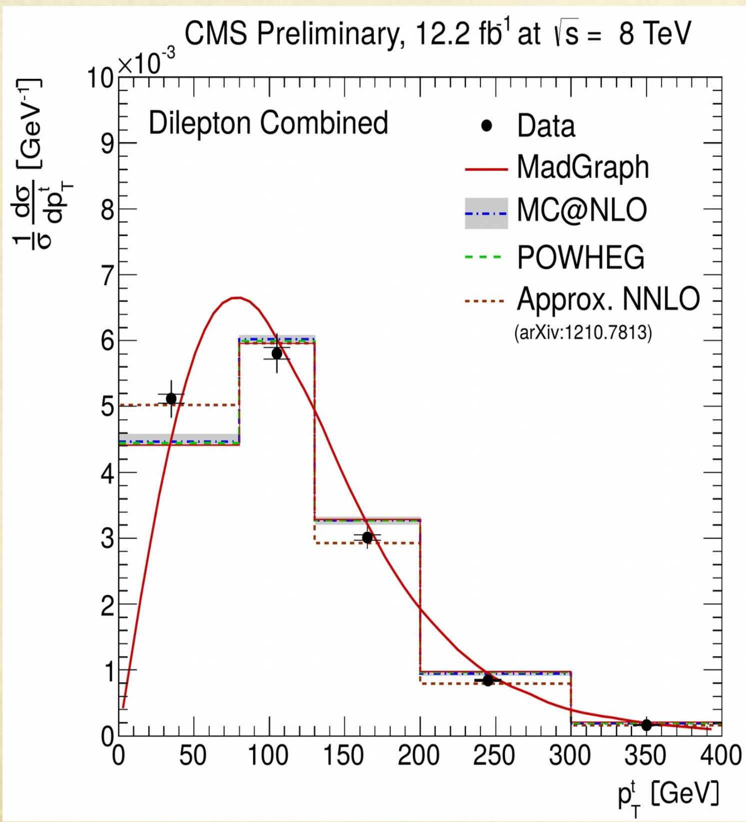


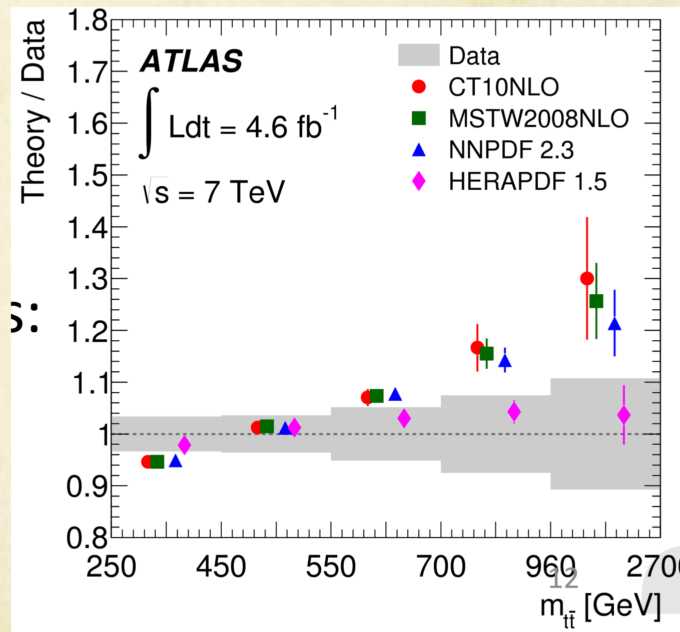
Top Physics: top pair inclusive differential

- ✓ Inclusive differential top pair production
  - theory at NLO(+)
  - Discrepancies between theory predictions and exp for top P_T (plays a role in many places: searches, ttH)
  - Sensitive to PDF
  - NNLO QCD should help

- ✓ First NNLO differential results have appeared Czakon, Fiedler, Mitov '14

- ✓ Applied to top A_{FB}
  - Significant corrections
  - SM in agreement with Tevatron data

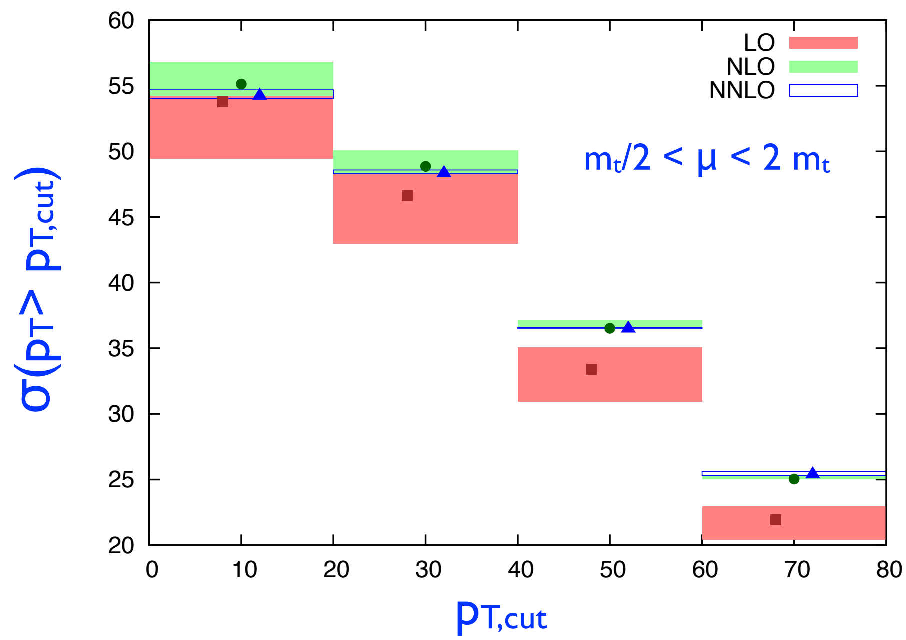




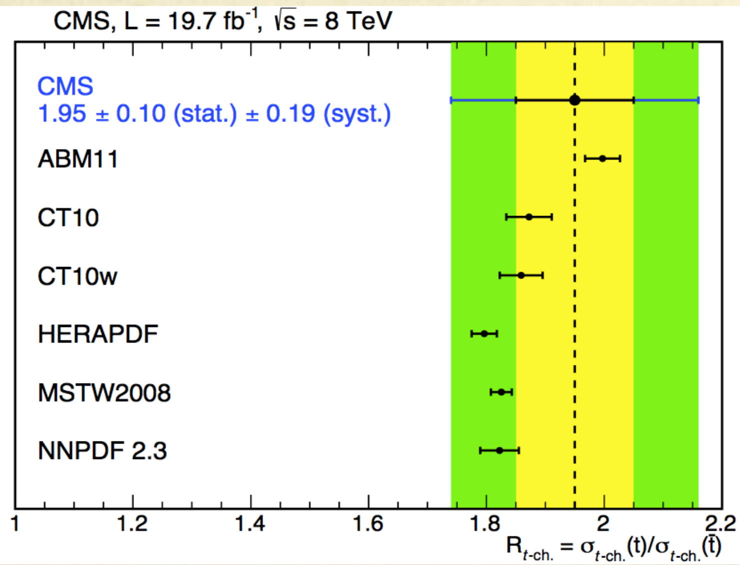
Top Physics: single top theory

✓ Dominant (t-ch) NNLO QCD known; theory in good shape
✓ Top decay will be added soon

Brucherseifer, Caola, Melnikov '14



- Contrary to NLO, results stable in the full spectrum
- Scale dependence typically improved
- K-factor is small but not constant



top/anti-top ratio very stable

$$\sigma_{t,\mathrm{LO}}/\sigma_{\bar{t},\mathrm{LO}} = 1.85$$

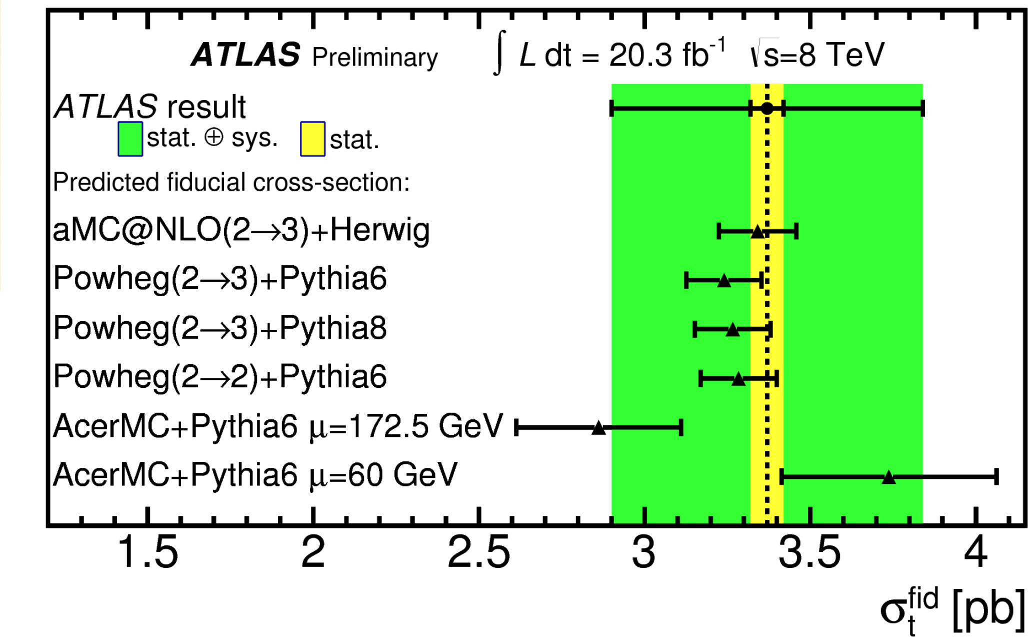
$$\sigma_{t,\mathrm{NLO}}/\sigma_{\bar{t},\mathrm{NLO}} = 1.83$$

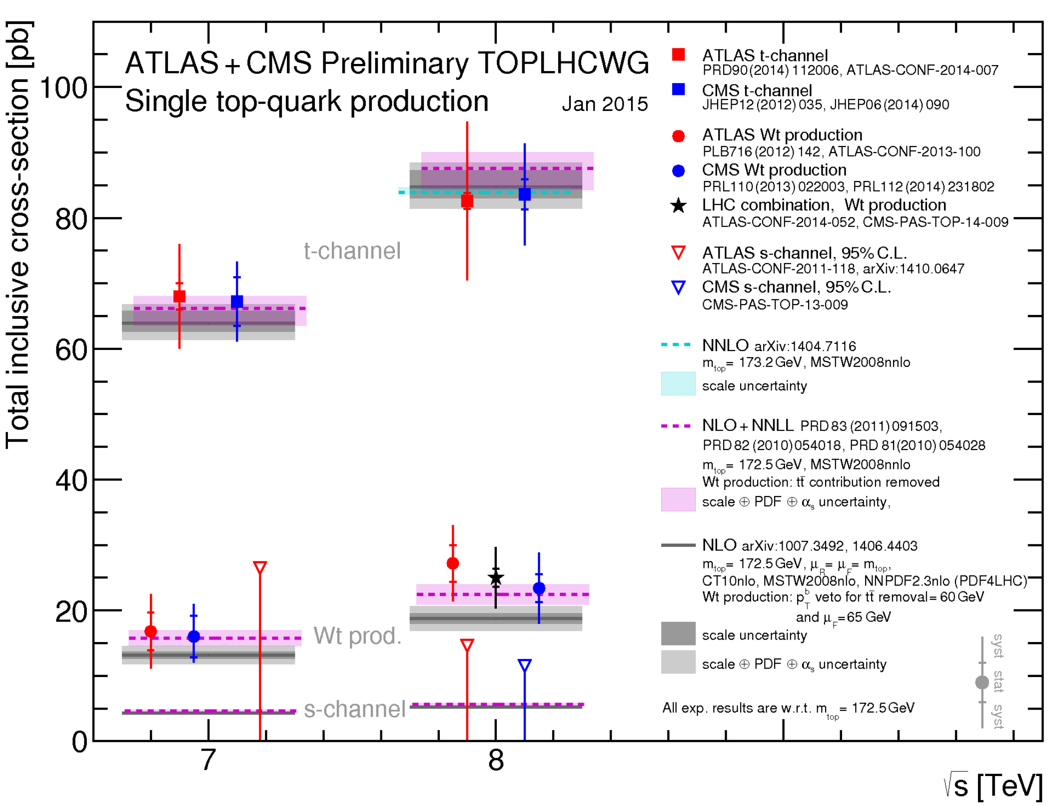
$$\sigma_{t,\mathrm{NNLO}}/\sigma_{\bar{t},\mathrm{NNLO}} = 1.83$$

Top Physics: single top exp

- ✓ Inclusive and fiducial measurements available
- ✓ All channels seen
- ✓ Precision currently at ~ 10%

ATLAS-CONF-2014-007





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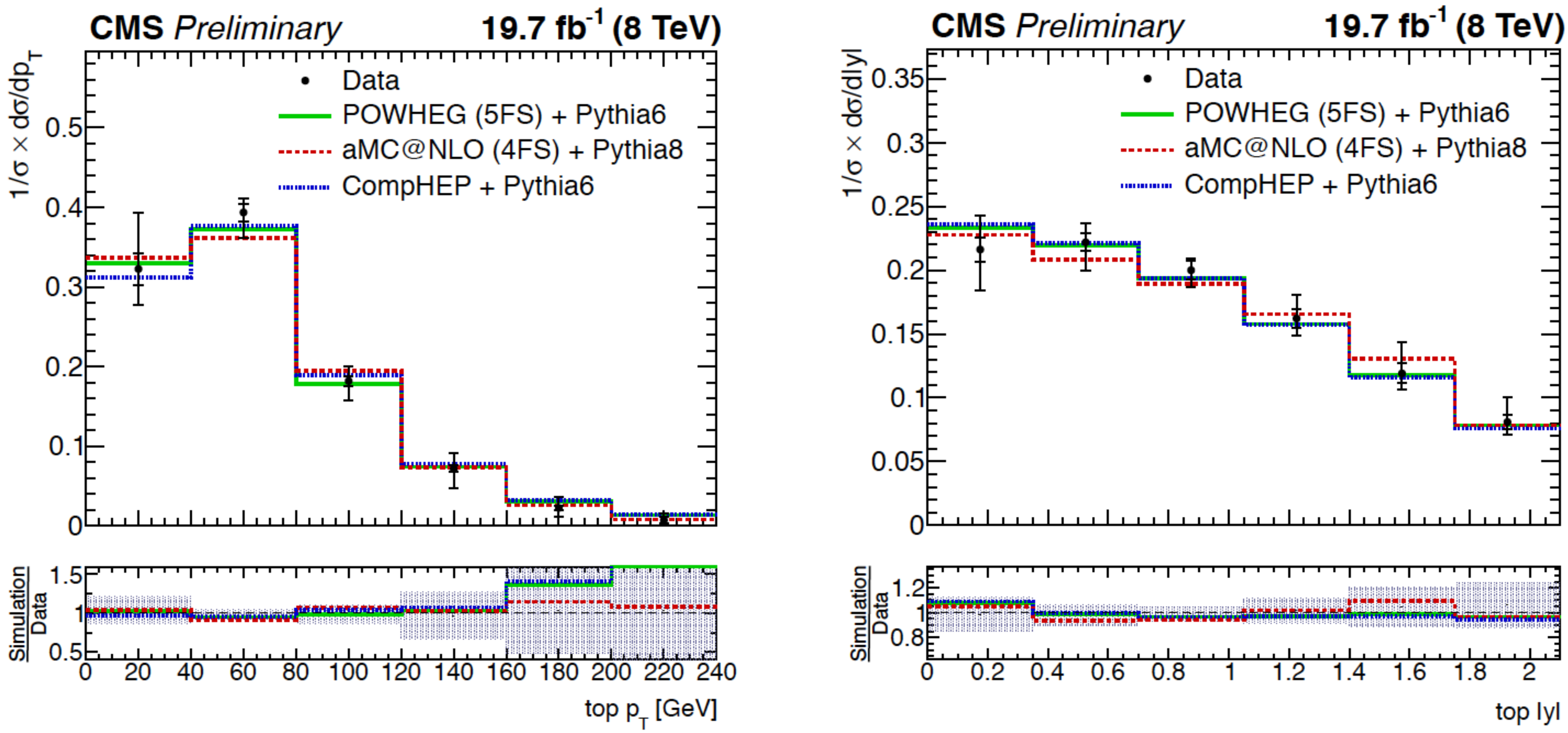
Top Physics: single top exp

- ✓ Differential measurements also available from ATLAS and CMS
- ✓ Large statistics for t-ch
- ✓ Good agreement with MC's



CMS, 8 TeV, 19.7 fb^{-1}

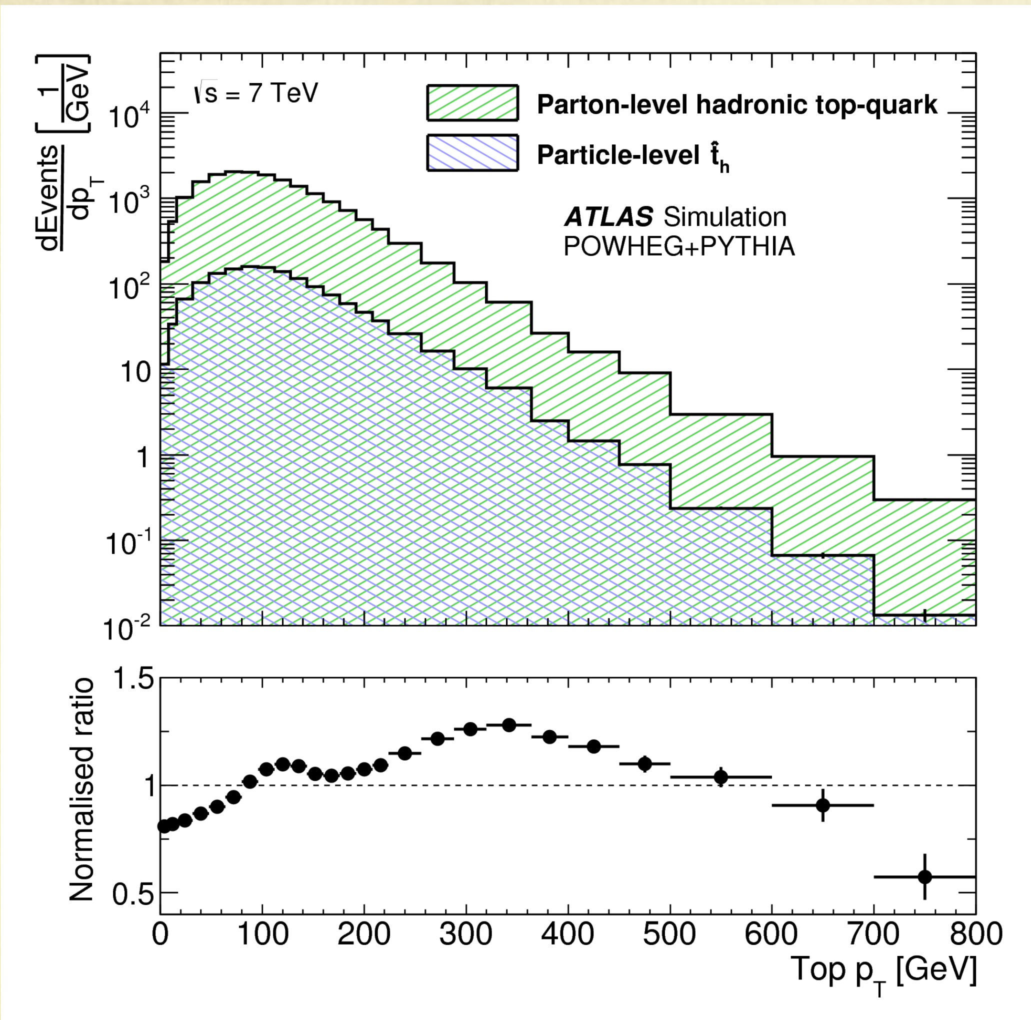
CMS PAS TOP-14-004

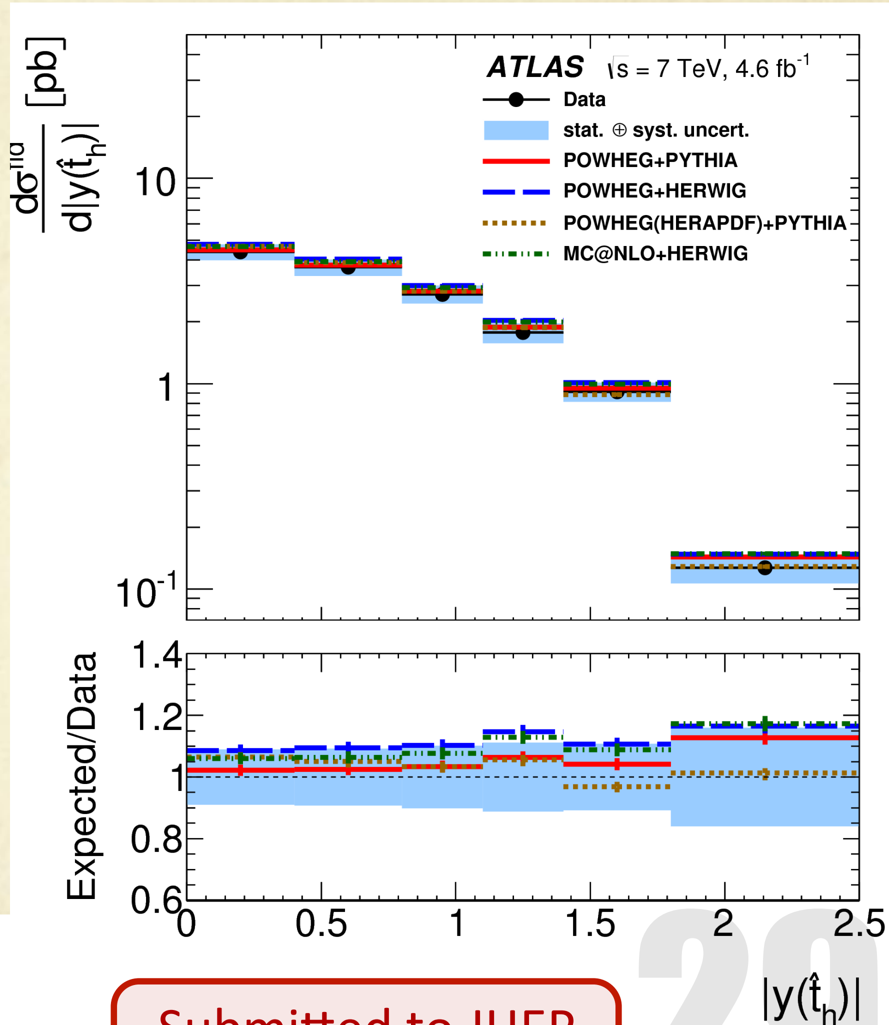
Top Physics: New concepts: pseudo top

✓ Differential measurements start to probe the tricky question:

"How to compare measurements and predictions at the level of top quarks"

✓ Operational definition is to combine particles (jets, leptons, …) to an object closely related to top quarks: *pseudo-top*.





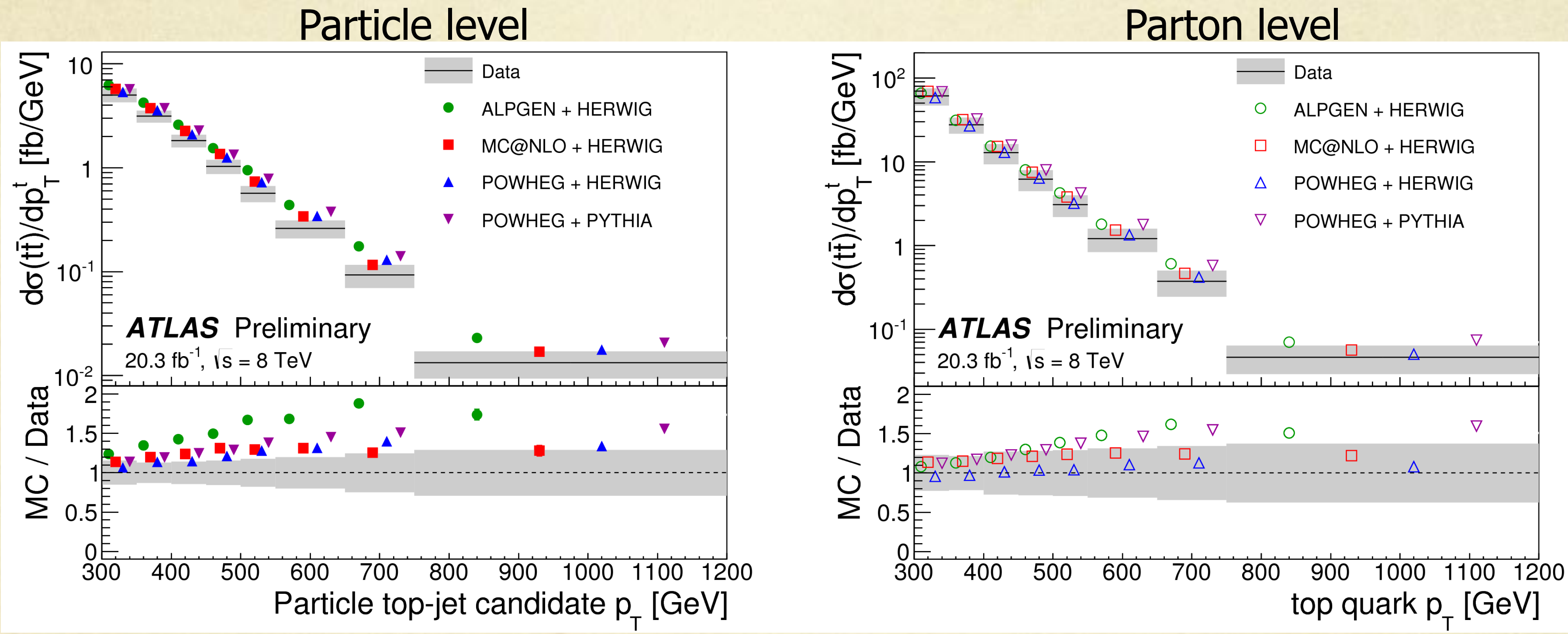
Submitted to JHEP
arXiv:1502.05923

! Could be relevant for the top P_T

Top Physics: New regimes : boosted top

✓ First differential cross-section measurement for boosted top:

- Using lepton + jets events in √s = 8 TeV data
- Hadronic top decay reconstructed as jet with R=1.0 with substructures



✓ So far we observe a persistent feature: at high P_T data is lower than theory

✓ Is it:

- NNLO QCD? Or (2→ n merged @ NLO) → matched to PS ?
- EW?
- Shower modeling?

Summary: Where do we go from here?

✓ Top Physics:

- So far good agreement with SM everywhere
- Will be a dominant topic at Run II due to its omnipresence in SM and bSM analyses
- Expect fully differential NNLO QCD
- Combined with EW (fully differential)
- Top decay with NNLO QCD is not unlikely within 1 year's time
- Single top fully differential with top decay to be expected
- Anticipate activity towards NNLO matched to showers (builds nicely on existing work on multijet merging in top).
- More measurements on 8 TeV data underway, Run-II data coming
- NLO 2-to-n MC's are being commissioned for the new data
- Expect to scrutinize, for the first time, top production in the TEV range.
- First evidence for top pair production in association with boson (Z,W).

✓ Bottom and Charm Physics:

- Overall agreement with SM but two 3σ deviations. Something to follow but may still go away…
- The SM predictions for b/c predictions are NLO. Fiducial NNLO predictions can be expected reasonably soon; detailed predictions may take more time.
- Interplay with top is very interesting; something to pay more and more attention to.
- Their contribution to PDF's will become ever more important, within the Precision Frontier