α_s from $\sigma_{t\bar{T}}$ at the LHC

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Why extract α_S from top data?

- ✓ Top production naturally involves scales ~ m_{top}=173GeV
- ✓ This way we have direct access to the running of $\alpha_S(\mu_R)$ at scales $\mu_R \geq m_{top}$.
- ✓ As far as direct measurement of $\alpha_S(\mu_R)$ at large scales is concerned, top production is a leading collider candidate.

The other being jet production; see Joao Pires' talk

- ✓ NNLO accuracy available
  - Any distribution with stable tops (more later).
- ✓ The top cross-section is very sensitive to α_S:
- ✓ Plenty of top data, especially in the long run (say LHC 13)
  - $0 < P_T < 1$TeV will be plentiful
  - $P_T > 1$TeV will also be accessible
- ✓ This offers a <u>major opportunity</u>: direct measurement of the running of α_S at scales up to 1TeV (easily) and beyond (this is for LHC; at a 100 TeV collider an order of magnitude more!)
  - More details in the following.

See also Francesco Sannino's talk

What are the problems when extracting α_s from top data?

✓ Very observable dependent question:

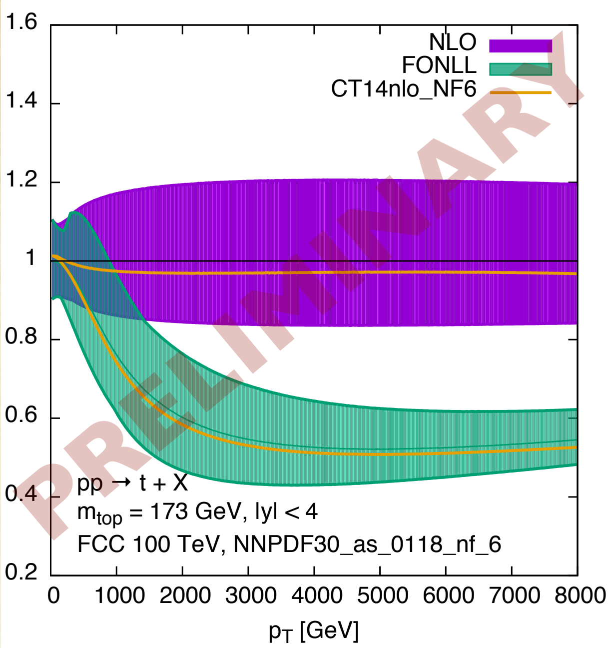
- Total cross-section
- Differential distributions

✓ PDF's

- Different pdf's differ (often) more than their pdf errors
- Much less of a problem in normalized distributions

✓ Top mass

- Both the normalization of the total cross-section and the shape of differential distributions depend strongly on it.



FONLL talk by Matteo Cacciari at the FCC workshop last week

✓ Theoretical precision: even at NNLO it may be limited in some observables, especially for scales above 1 TeV (see fig).

- All current calculations done with nf=5 active flavours.
- Likely this will be the case for anything computed to scales <1TeV.
- Above 2TeV it might be reasonable to consider tops as massless (effect of collinear resummation becomes significant – see fig).

What scales are accessible from top data?

- ✓ Observable dependent, too:
- ✓ The total cross-section is dominated by "low" scales (low ~ m_{top} ~ 175 GeV)
- ✓ Differential distributions allow access to much larger scales:
  - ✓ P_T spectrum: $\mu_R = \sqrt{(m_t^2 + P_T^2)}$
- ✓ How to identify the "running" scale?
  - The scale at which the coupling is evaluated when compared with data!
  - This is the renormalisation scale
  - In top physics it is usually defined as above (or similar)
- ✓ Do we know the scale precisely?
  - Of course not!
  - But the usefulness of high-precision calculations, NNLO for example, is that the choice doesn't matter much. A change by a factor of 2 would change the cross-section by few percent (few permil, for normalized distributions) – comparable to α_S error (more later)
  - Alternatives to the usual scale setting procedures exist; BLM/PMC is one of them.

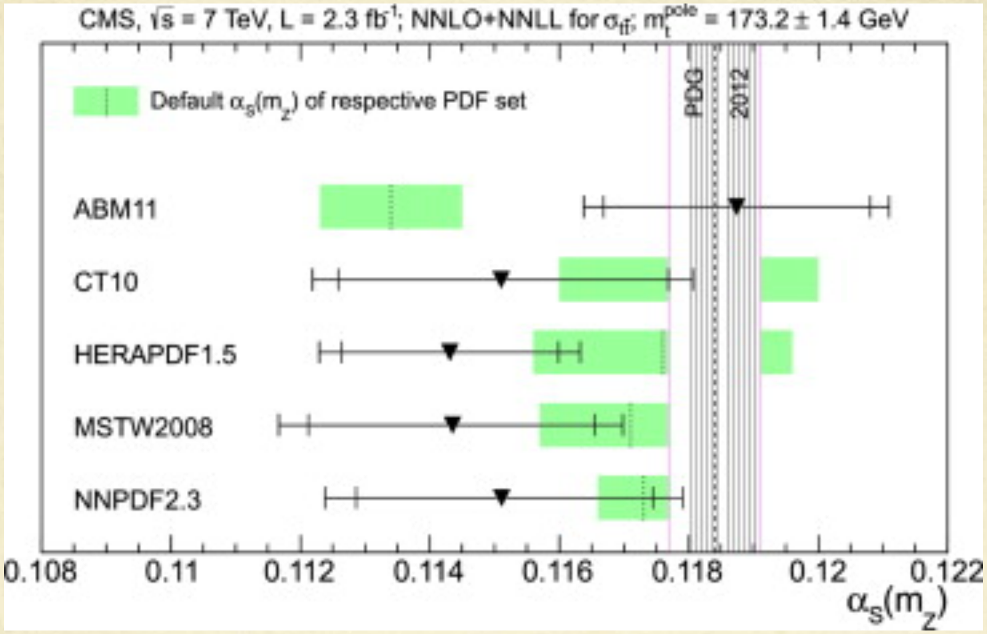
Brodsky, Lepage and Mackenzie '83
Brodsky, Mojaza, Wu (number of papers)

  - Actively developed in top physics

See: Wang, Wu, Si, Brodsky 1508.03739

First direct measurement of α_S in top production

CMS: 1307.1907



- ✓ Extraction of α_S together with m_{top}
- ✓ For a number of pdf sets

- ✓ Note: compare the extracted value (black), with the assumed value (green) of α_S for each set, and look for consistency.

- ✓ Precision is good:

$$\alpha_S (m_Z) = 0.1151 + 0.0028 - 0.0027$$

- ✓ Subtleties: pdf, m_{top}, modeling…

More details: see talk by Gavin Salam

Indirect measurement of α_S in top production through PDF's

- ✓ MMHT2014 global PDF analysis

Harland-Lang, Martin, Motylinski, Thorne 1506.05682

- ✓ The analysis is sensitive to m_{top} through the (rather minimal) inclusion of LHC top data
- ✓ From the previous discussion one should expect a correlation between m_{top} and α_S.
- ✓ Some of the findings in this paper:
  - *"There is a particularly strong, but also complicated, relationship between the value of $\alpha_S(M_Z)$ and the fit to data on the inclusive cross section for tt production."*
  - *"Indeed, nominally σ_{tt} provides one of the strongest constraints of any data set for the lower limit of $\alpha_S(M_Z)$ at NLO and the upper limit of $\alpha_S(M_Z)$ at NNLO."*
  - *"However, the picture is more complicated than for other data sets due to the very strong correlation with the value of the mass m_t of the top quark."*

Clearly, top data at the LHC is powerful enough to strongly influence global fits.

- ✓ Future pdf extractions from differential NNLO predictions will increase significantly the importance of top data in pdf's and, from there, the top quark effect on α_S from pdf fits.

Future prospects for measurement of α_S in top at the LHC

- ✓ Measurements of α_S from the total cross-section, event at different collider energies, will be beneficial but hardly much better that what we have seen so far.

- ✓ Alternatively, one may explore top differential distributions. Say, top P_T

- ✓ Two options:

  - ✓ Distributions with absolute normalization: $\sigma(P_{T,top} > P_{T,cut})$

    - They are ~ $(\alpha_S)^2$ and, therefore, sensitive to α_S
    - At large P_T give access to $\alpha_S(P_T)$
    - Suffer from larger pdf, m_{top} and perturbative uncertainties.

  - ✓ Normalized distributions: $\frac{\sigma(P_{T,top} > P_{T,cut})}{\sigma_{tot}}$

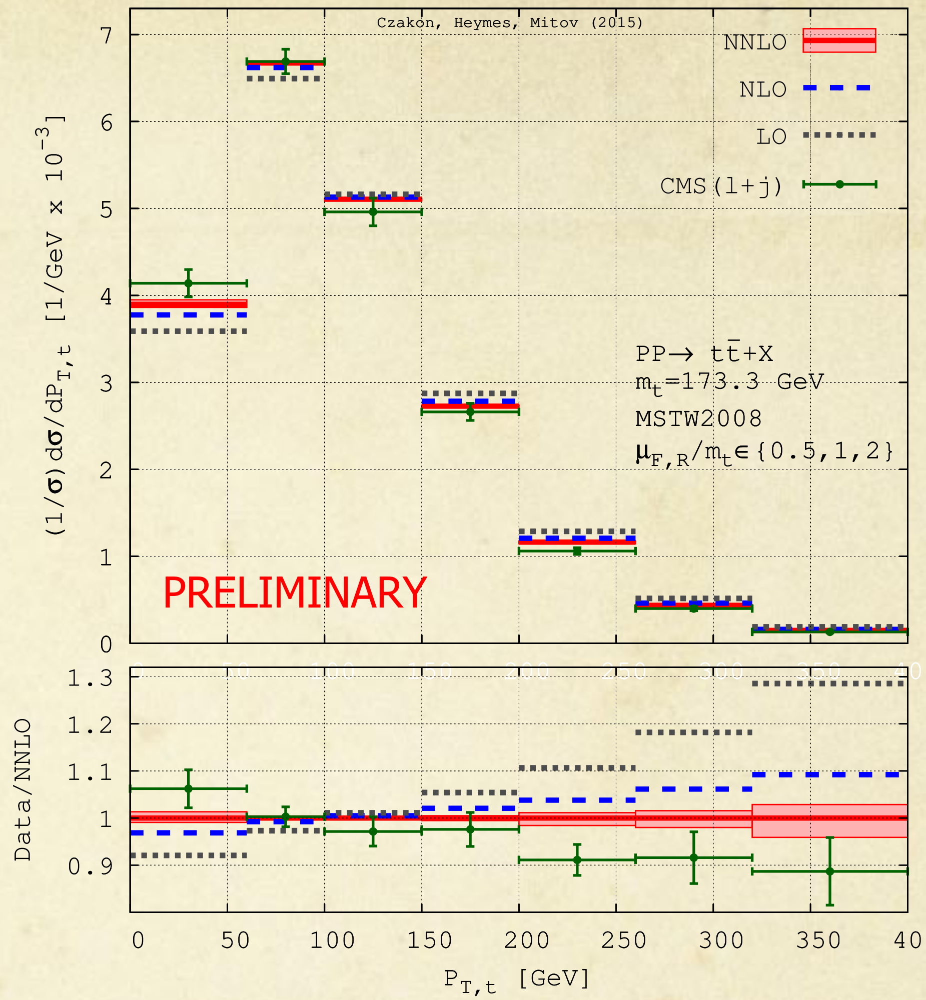
    - They are ~ $(\alpha_S(P_T)/\alpha_S(m_{top}))^2$.
    - At large P_T also give access to $\alpha_S(P_T)$.
    - Much weaker pdf, m_{top} and perturbative uncertainties.
    - How to disentangle pdf dependence? Fit pdf's from M_{tt}, measure from top P_T.

Thanks to Juan Rojo for the suggestion!

Future prospects for measurement of α_s in top at the LHC

✓ Differential top distributions available

Czakon, Heymes, Mitov, to appear



✓ Calculation is for fixed scales, so not very appropriate for extraction of α_s just yet.

✓ However, notice the scale variation error:

- At P_T = 400 GeV the NNLO normalized distribution changes by around 2%.
- Running scales will reduce it further.

Future prospects for measurement of α_S in top at the LHC

✓ What sensitivity to α_S would a normalized differential distribution have?

✓ In absence of differential calculation with a running scales (will not take long though) one can try to estimate the sensitivity based on an NLO calculation.

✓ Setup: create templates for

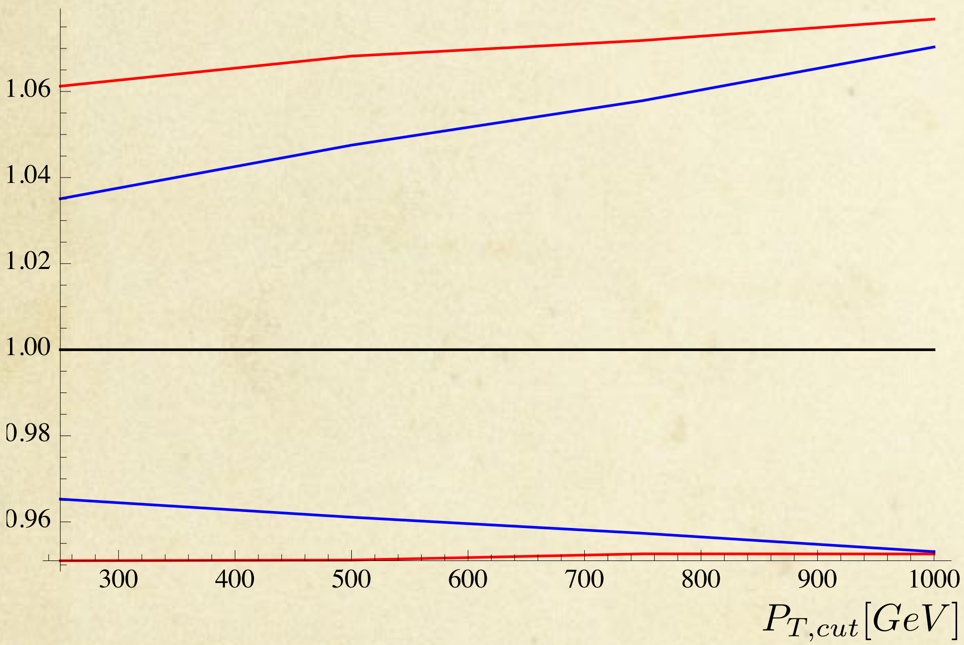
- $\sigma(P_T > P_{T,cut})/\sigma_{tot}$
- Two pdf sets with varying values of α_S
  - NNPDF30_nnlo_as_(0115; 0118; 0121)
  - CT14nnlo_as_(0115; 0118; 0121)
- Choice of scales:
  - $\sigma(P_T > P_{T,cut})$: $\mu_F = \mu_R = P_{T,cut}$
  - σ_{tot}: $\mu_F = \mu_R = m_{top}$

Future prospects for measurement of α_s in top at the LHC

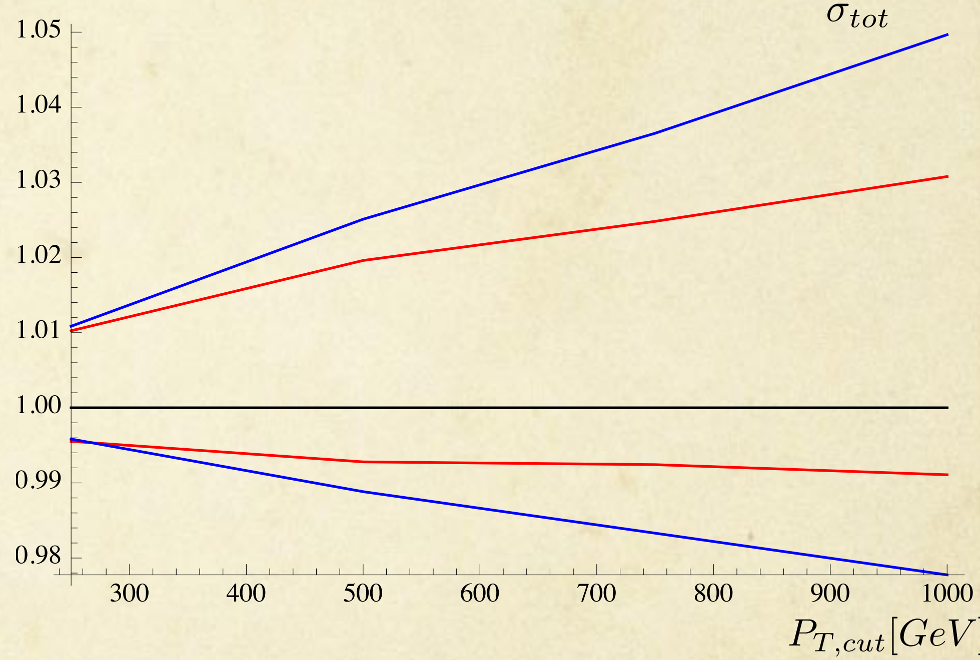
- ✓ What sensitivity to α_s would differential distributions have?
- ✓ Look at ratios for
  - (as=0.115)/(as=0.118) (LOWER bands in figs. below)
  - (as=0.121)/(as=0.118) (UPPER bands in figs. below)

- CT14NNLO
- NNPDF30NNLO

- NLO absolute normalization $\sigma(P_{T,top} > P_{T,cut})$



- NLO normalized distribution $\frac{\sigma(P_{T,top} > P_{T,cut})}{\sigma_{tot}}$



- ✓ Good news: sensitivity to α_s variation is comparable to expected NNLO perturbative error!
- ✓ Above figures remain almost the same in LO (same pdf's)
- ✓ The wild card would be the m_{top} sensitivity (not estimated here).
- ✓ Non-negligible pdf dependence

Conclusions

- ✓ Due to the opportunity to access very high scales α_S measurement form top data will weigh heavily in the discussion e^+e^- versus VLHC (favorably for VLHC).

  - Indeed at a 100 TeV collider top quarks will be produced at scales of O(10 TeV) (and beyond) giving us the unprecedented opportunity to directly test the running of α_S to scales O(10 TeV).

- ✓ So far at the LHC:

  - α_S extracted from the total cross-section σ_{tot}:
    - Extraction of α_S (m_{top})
    - Competitive errors
    - "Contamination" from m_{top}, pdf, perturbative errors:
      - Errors due to (m_{top},pdf,scales)=3%; α_S(68cl) = 2-3%

- ✓ Future LHC

  - (slight) improvement in the σ_{tot}-based extraction possible
  - Available NNLO $P_{T,top}$ distributions offer the opportunity to measure α_S up to 1 TeV or so.
  - Estimates show that α_S sensitivity is competitive with NNLO scale errors.
  - Pdf errors can be reduced after top data is used in the pdf fits (from M_{tt} and y_t)
  - Strong interplay with m_{top} will likely remain.

    - Detailed study needed to quantify this and try to disentangle the two.
    - Work is in progress