(Some) recent advances in top theory

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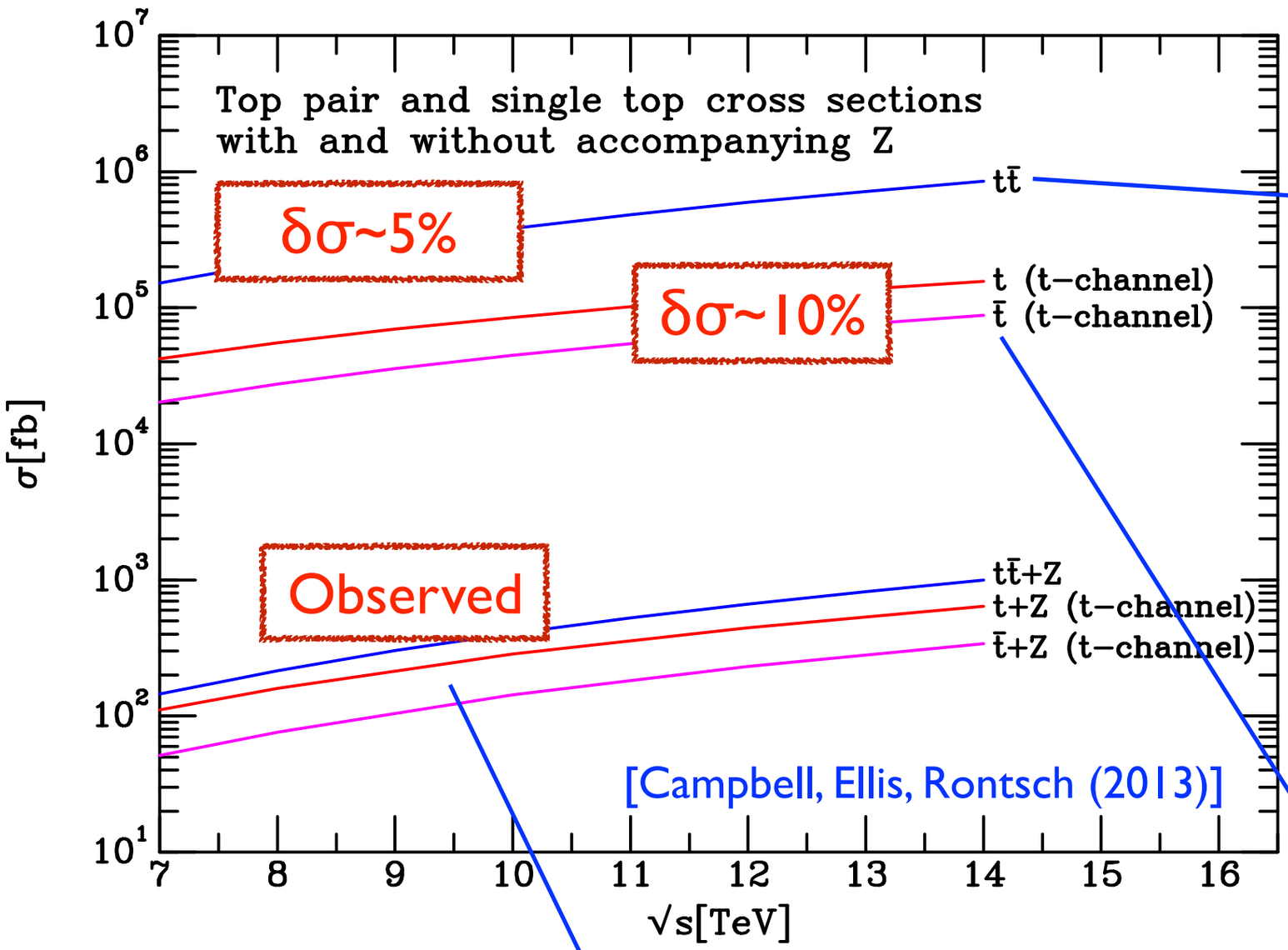
PARTICLE PHYSICS AT THE VERGE OF ANOTHER DISCOVERY? ASPEN, JAN. 10TH 2016

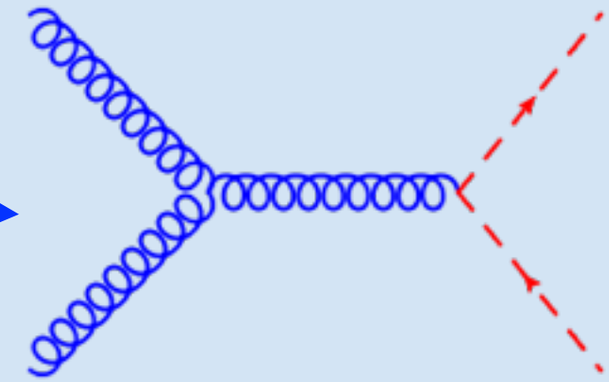
[Many thanks to K. Melnikov for countless discussions on these topics]

Why top?

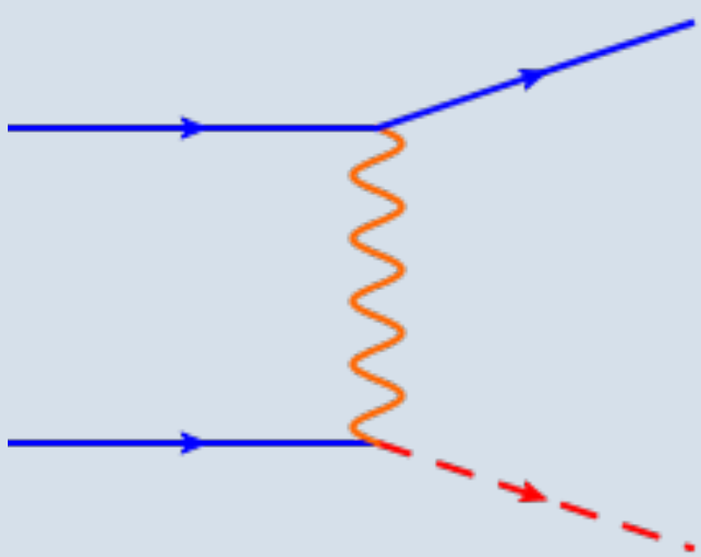
- Top is interesting: heaviest particle in the SM
  - expect deep connections with EWSB (Higgs sector, naturalness, vacuum stability…)
  - key role in BSM (natural SUSY, compositeness, flavor…)
- Top is relevant:
  - involved in many BSM searches
  - top decays into lepton, jets and missing energy → poster child for collider phenomenology (top tagging…)
- Top is easy: $\Lambda_{QCD} << \Gamma_t << m_t$
  - most tops decay before hadronization
  - its properties (polarization) are not washed out by QCD effects
  - production and decay stages are well-separated

LHC is a top factory





Largest yield
Probe QCD



Sizable yield
Probe EW (V_{tb},Γ_t)

Information about the tZ/tγ, among the least constrained

You've made your bed… now lie in it

or the price of precision

- We need to deal with ~few percent precision for tops
- $\alpha_s \sim 0.1 \rightarrow$ NNLO predictions. Fancy computations in QCD, for a long time conceptual problems barred us from performing them [see Kirill's talk on Wednesday]

Now we have them both for top production

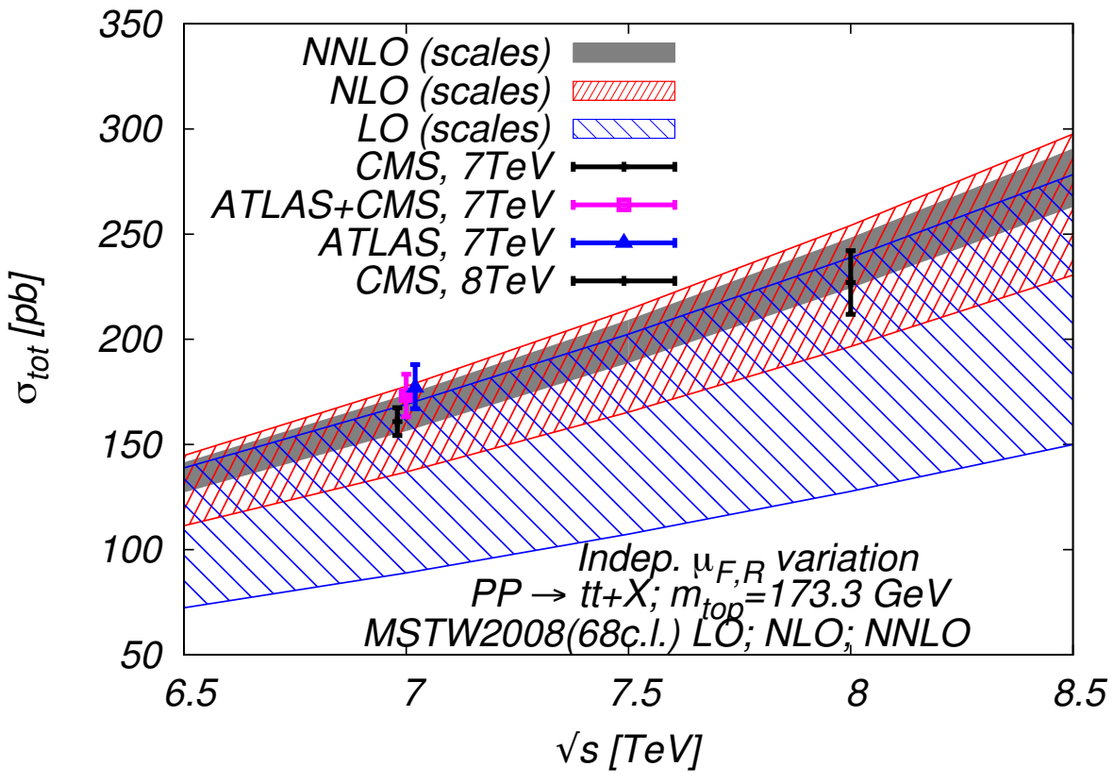
- top pair total cross-section [Czakon, Fiedler, Mitov (2013); Czakon, Heymes, Mitov (2015)]
- t-channel single-top [Brucherseifer, FC, Melnikov (2013)]

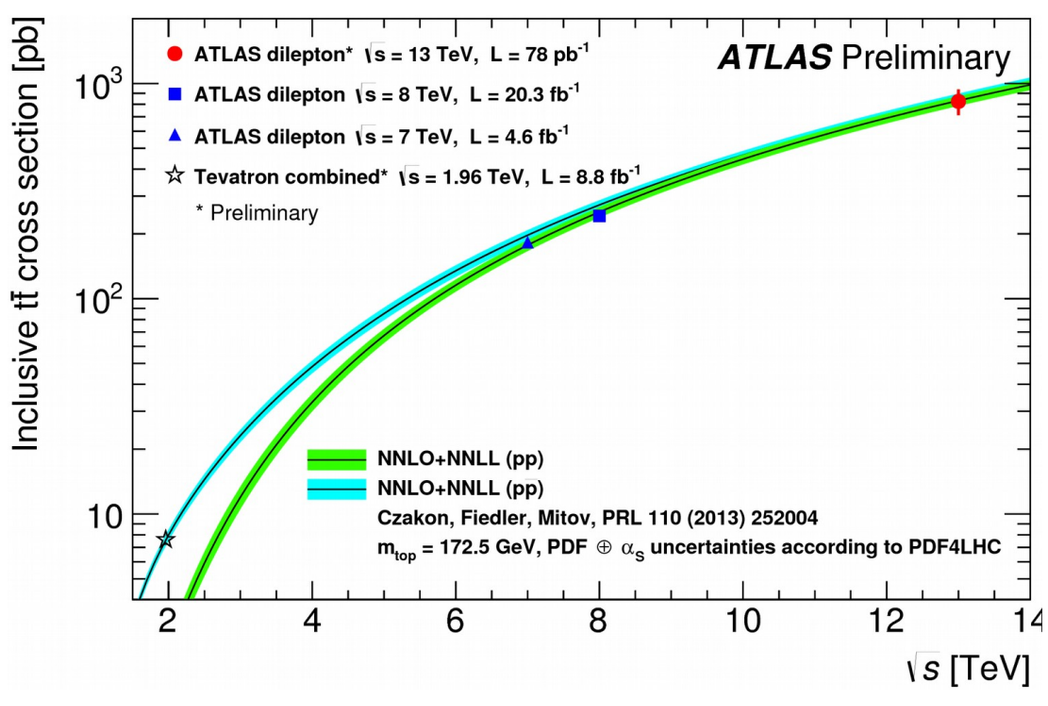
and decay

- fully differential decay [Gao, Li, Zhu (2012), Brucherseifer, FC, Melnikov (2013)]
- helicity fractions [Czarnecki, Körner, Piclum (2010); Gao, Li, Zhu (2012), Brucherseifer, FC, Melnikov (2013)]

$t\bar{t}$ predictions at NNLO

[Czakon, Fiedler, Mitov (2013); Czakon, Heymes, Mitov (2015)]



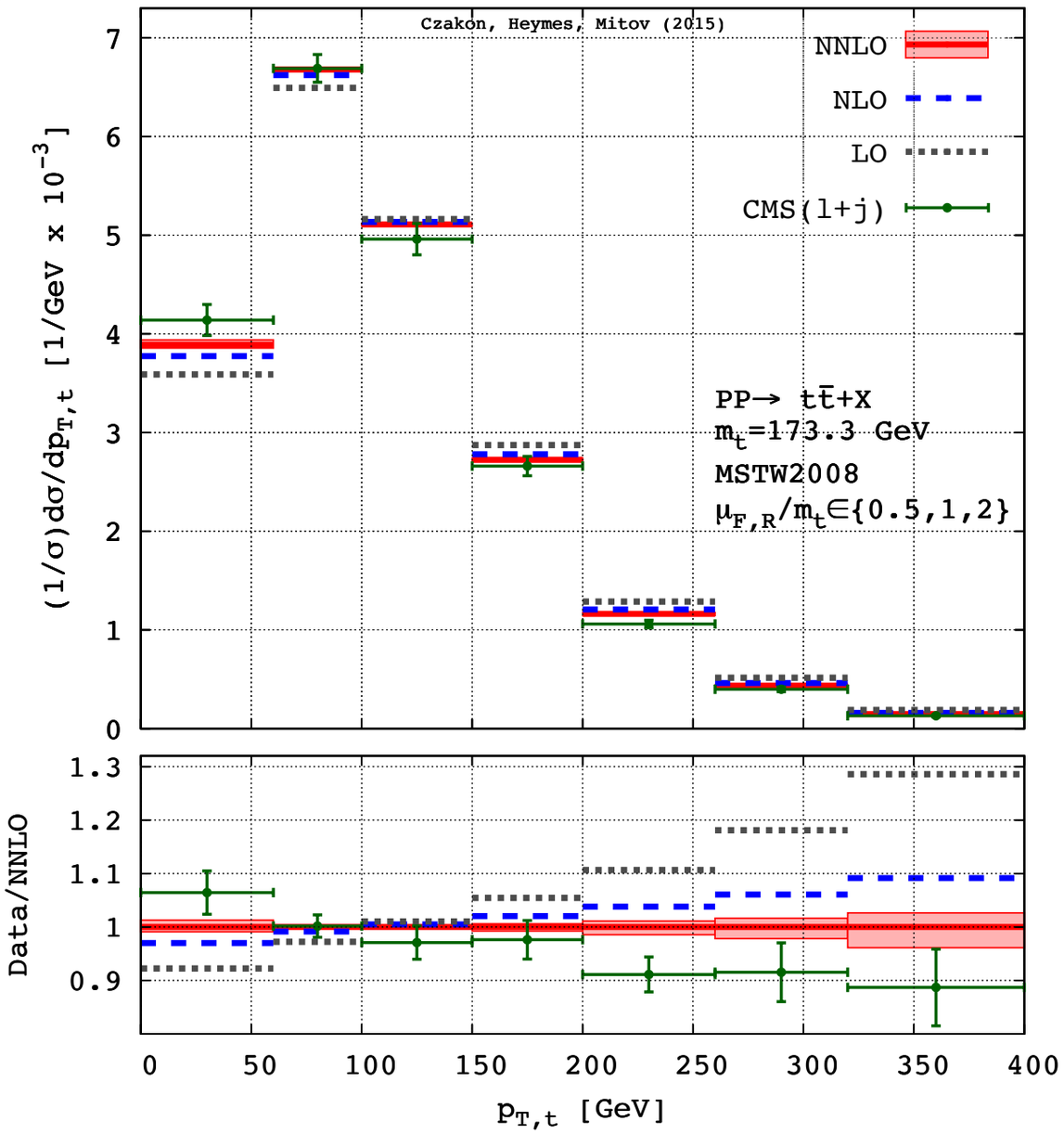


NNLO+NNLL

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

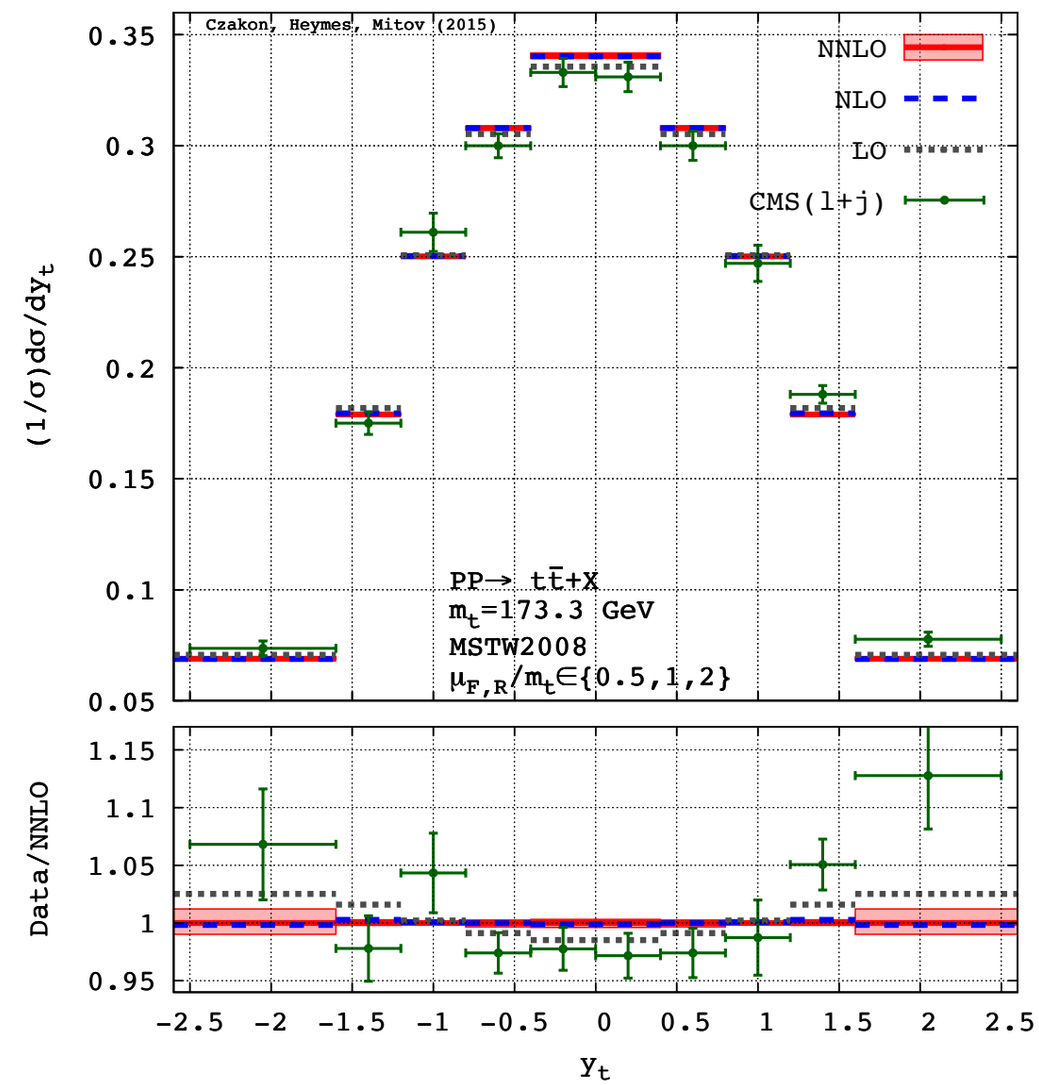
- Milestone result in pQCD
- residual ~4% uncertainty, comparable with exp
- perfect agreement with data at 7, 8 and 13 TeV
- recently LHC differential distributions presented

$t\bar{t}$ predictions at NNLO: LHC distributions



[Czakon, Heymes, Mitov (2015)]

- NNLO results has a p_t-dep. shape
- no significant tension with data
- NNLO accuracy make discussions about 'right' scale largely irrelevant

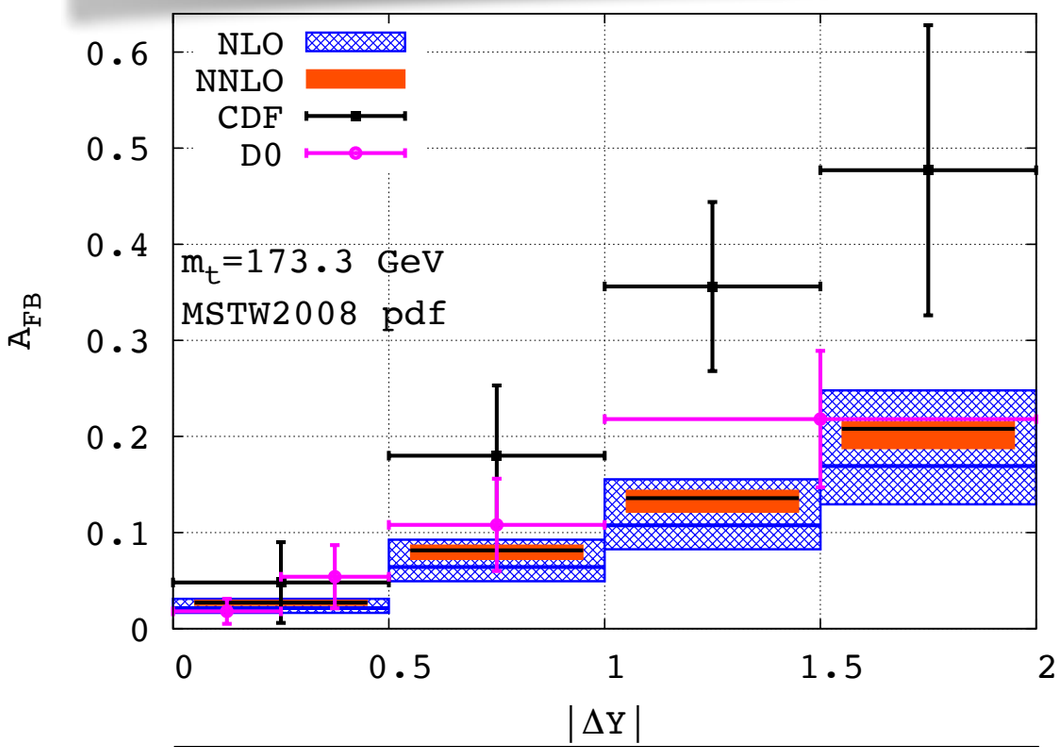


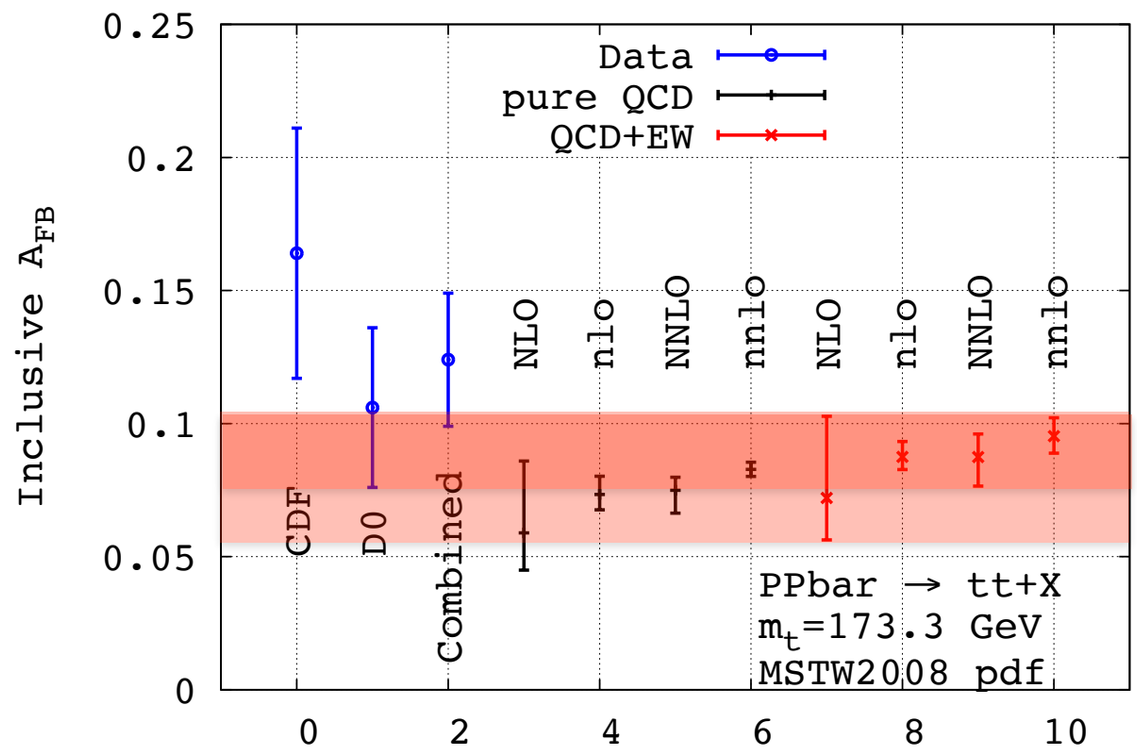
- rapidity: very flat corrections

Can SIGNIFICANTLY Constrain the Gluon PDF

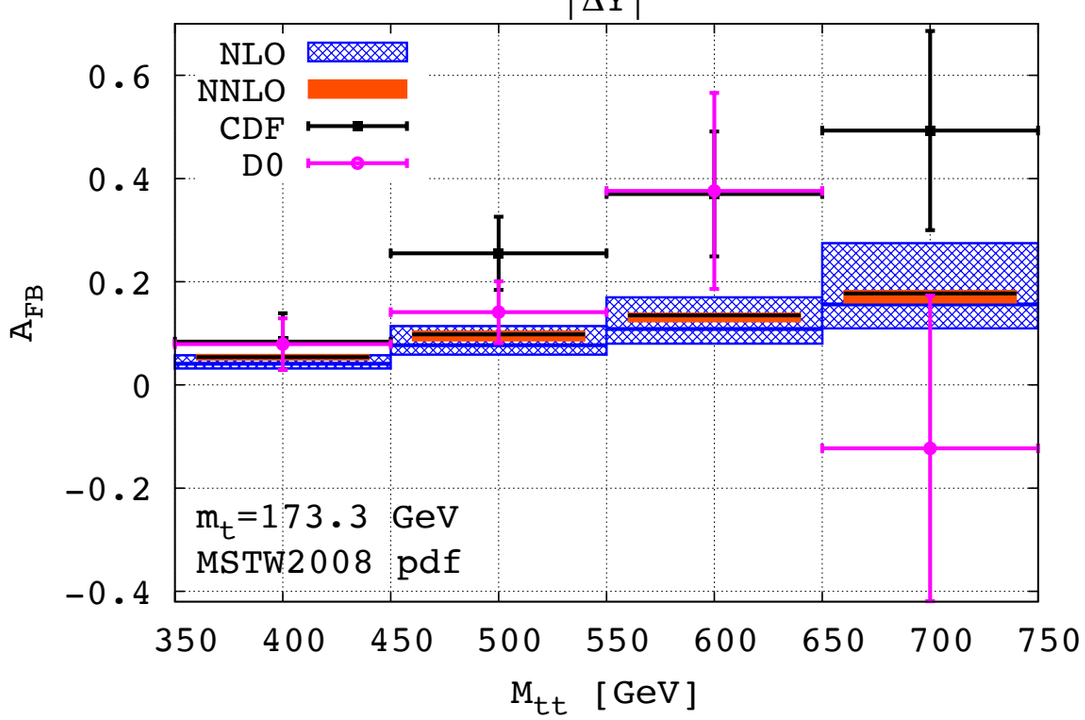
NNLO and the Tevatron A_{FB}

Nothing pathological is going on in our description of the asymmetry → SM PREDICTION SEEMS SOLID





[Czakon, Fiedler, Mitov (2015)]



- no clear tension
- funny feature in CDF ΔY that we will probably never understand
- curious m_{tt} shape, but large errors

Precision as a tool for discovery: stealthy stops

[Czakon, Mitov, Papucci, Ruderman, Weiler (2014)]

$$\tilde{t} \to t + \chi_1^0/\tilde{G}, \quad m_{\tilde{t}} \sim m_t \gg m_{\chi_1^0,\tilde{G}}, \quad \sigma_{\tilde{t}} \approx 0.15 \cdot \sigma_t$$

VERY SIMILAR TO TOPS 😞

- very hard to separate from SM $t\bar{t}$ production
- different spin correlations, but lepton rapidity/angular correlations either have large theory uncertainties or require lots of statistics

VERY SIMILAR TO TOPS 😀

- almost indistinguishable from top → contaminate σ_t
- if exp. and th. uncertainty on σ_t are good enough, DEVIATIONS FROM SM BEHAVIOR COMING FROM STOPS ARE DETECTABLE

SIDE REMARKS: this kind of reasoning is one of the BEST APPLICATIONS OF HIGH QUALITY PREDICTIONS. Ideally, we would like to do the same for large classes of observables, and cross-correlate → HUNT DOWN NEW PHYSICS

Precision as a tool for discovery: stealthy stops

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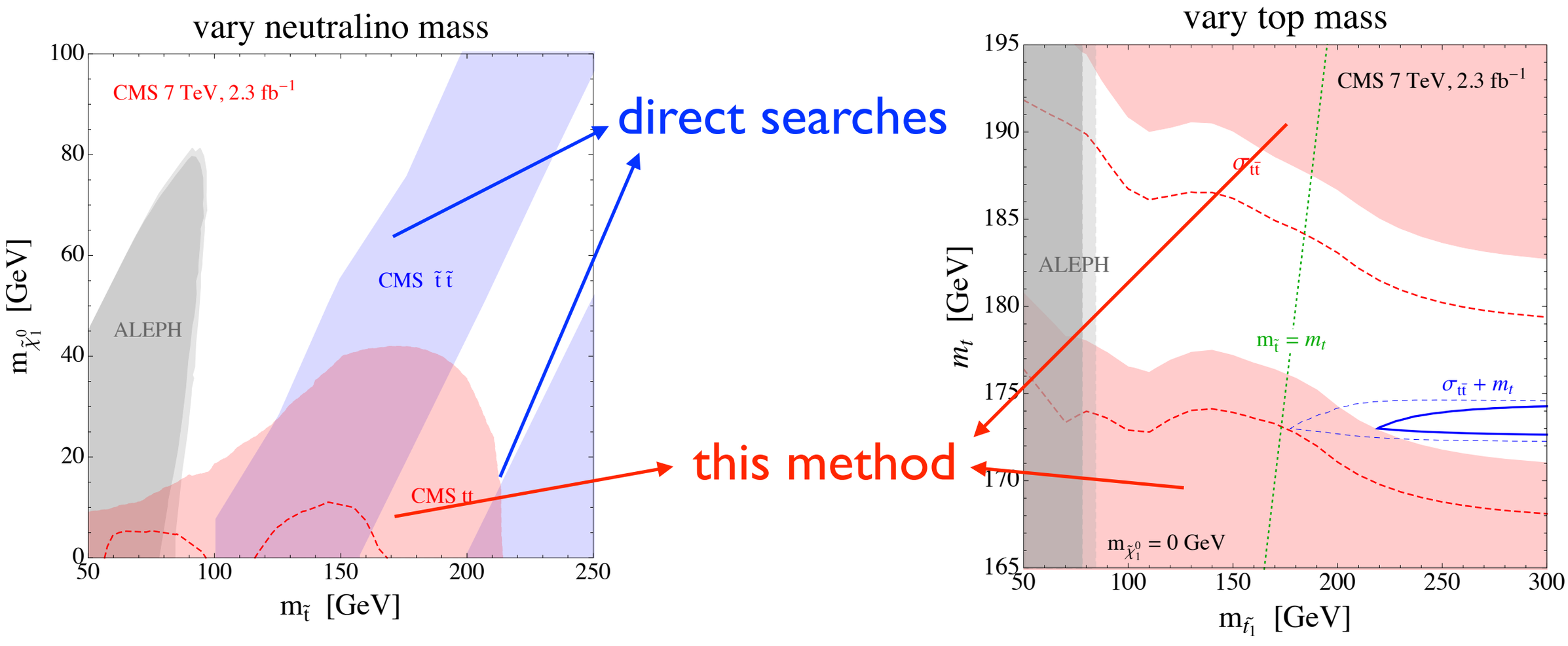
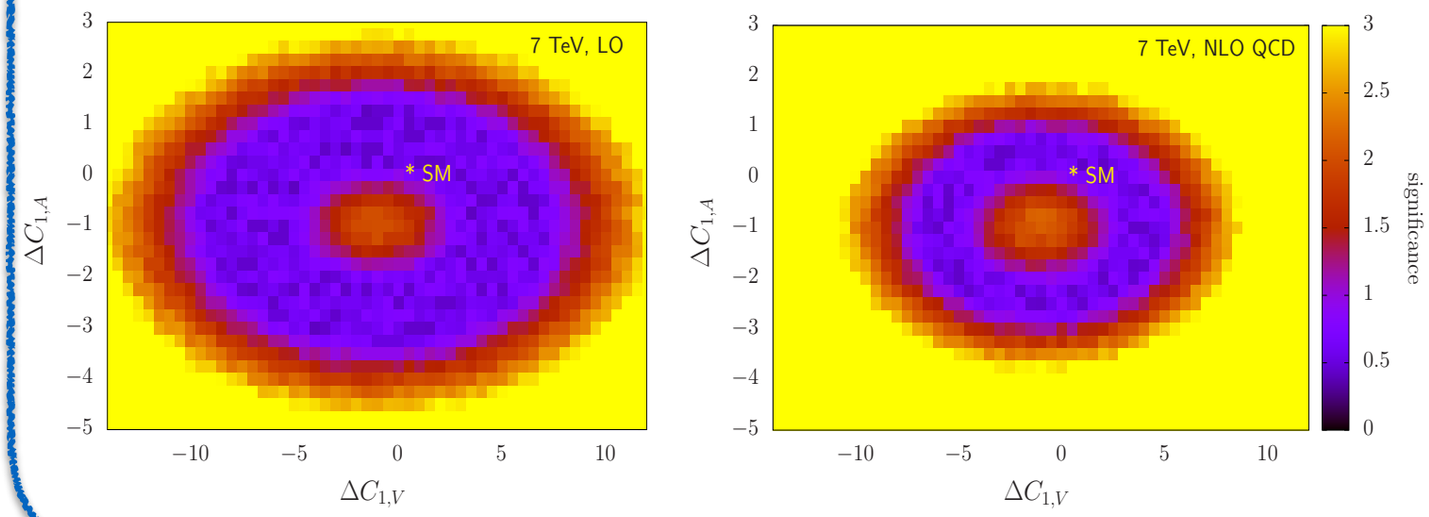
- CMS di-lepton analysis, $\delta\sigma_{exp} \sim 4.5\%$
- NNLO SM prediction, $\delta\sigma_{th} \sim 4\%$
- SIGNIFICANT DISCOVERY POWER



An orthogonal approach: EFT formalism

Vector/axial couplings



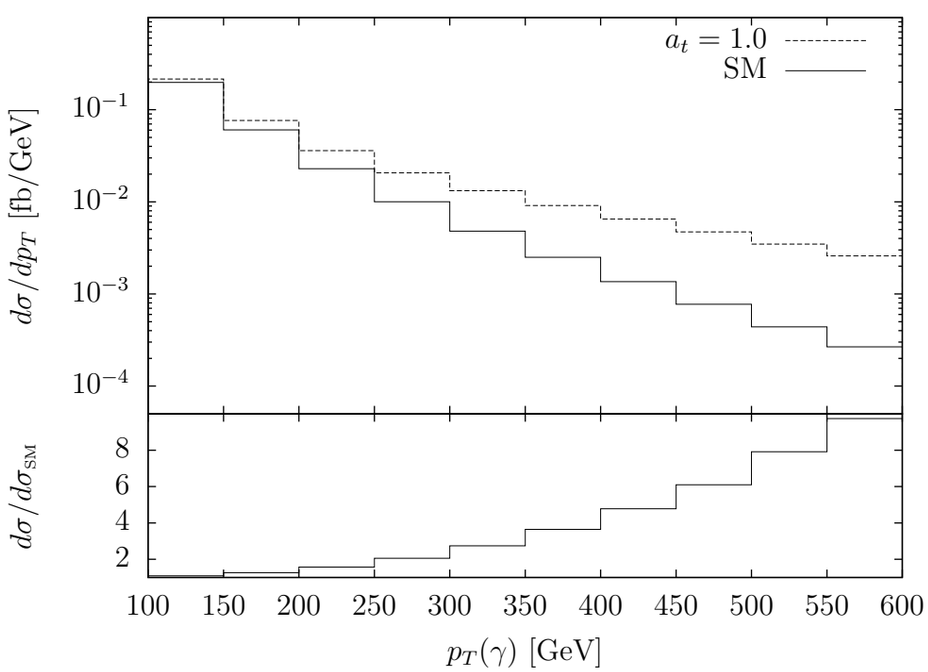
[Röntsch, Schulze (2015)]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

$\Lambda \propto \delta\sigma_{\rm exp,th}$ →NLO

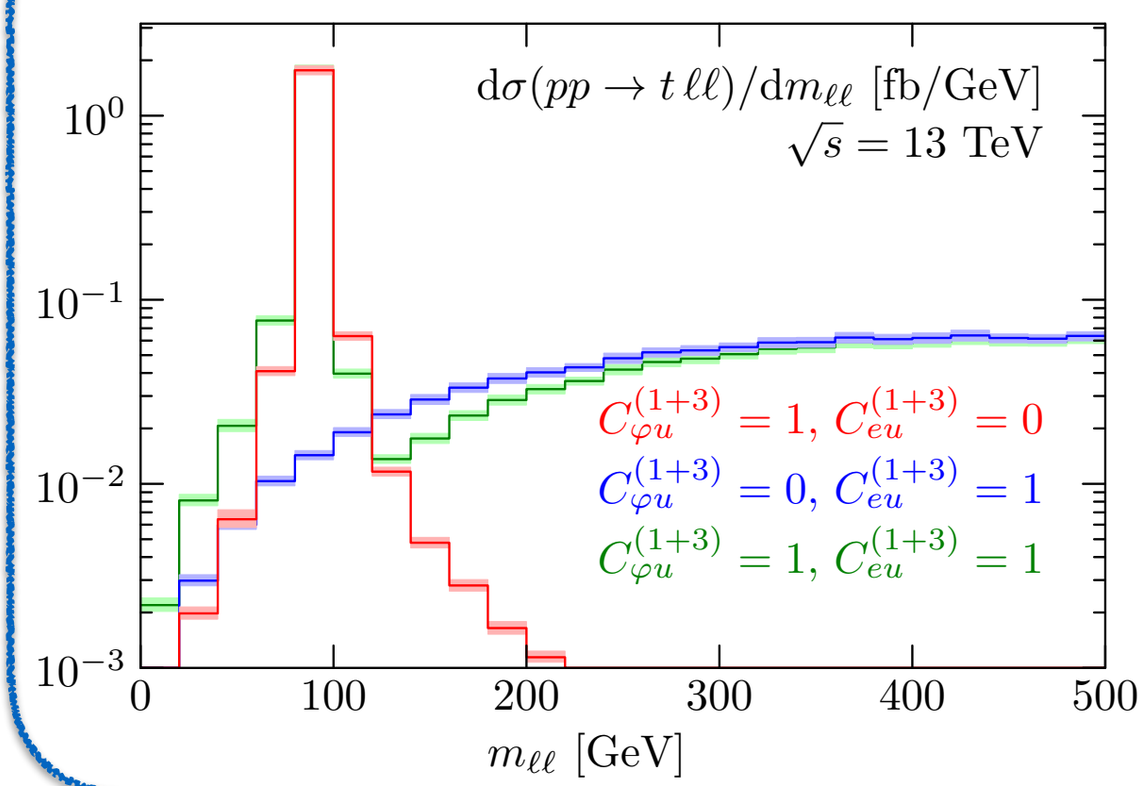
Scales probed now:
$\Lambda \lesssim 1$ TeV

Anomalous magnetic moment



[Fael, Gehrmann (2013)]

FCNC

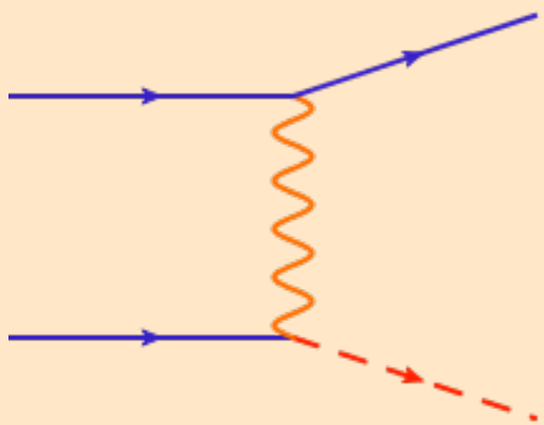


[Durieux, Maltoni, Zhang (2015)]

Precision for single-top

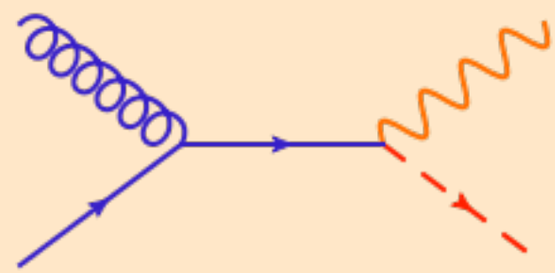
Classical picture: 3 production mechanism

T-CHANNEL



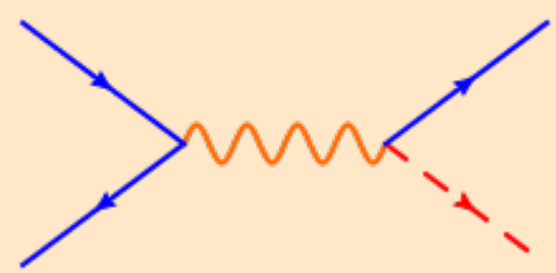
LHC: ~ 80%

ASSOCIATED PRODUCTION



LHC: ~ 15%

S-CHANNEL



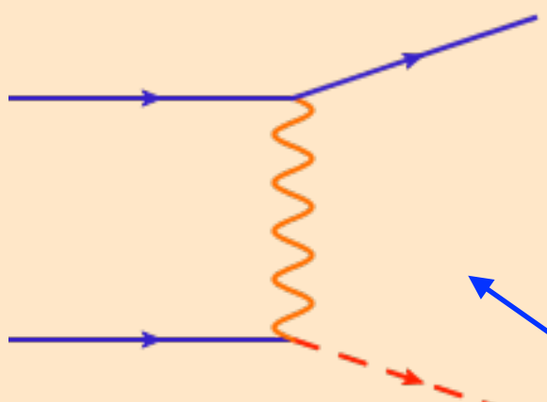
LHC: ~ 5%

With stable tops and at tree-level:
clear separation / hierarchy among different channels

The price of precision

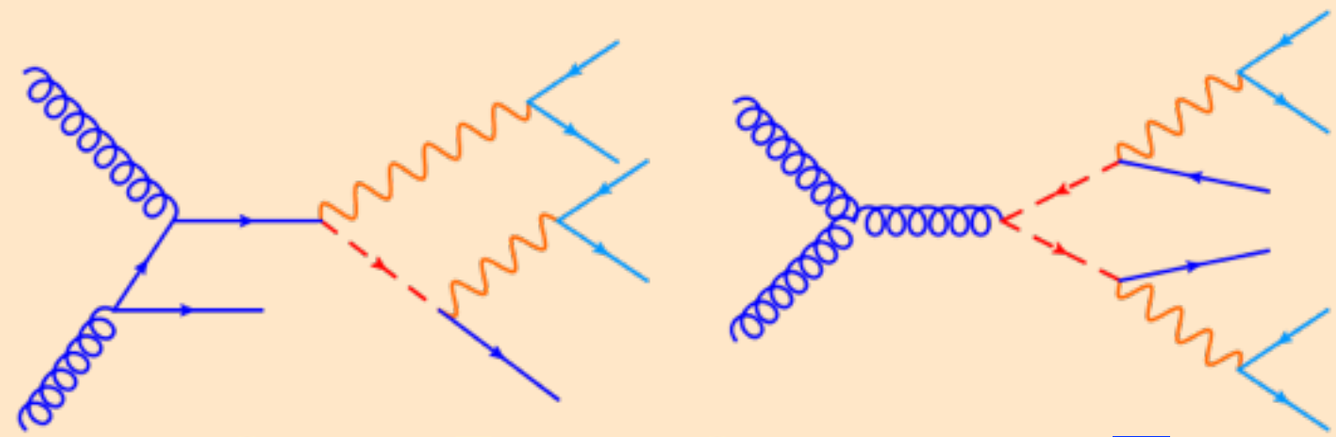
Mixing at the quantum level

T-CHANNEL



LHC: ~ 80%

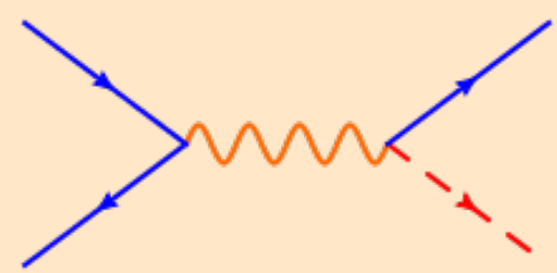
ASSOCIATED PRODUCTION



SAME FINAL STATE OF $t\bar{t}$

INTERFERENCE

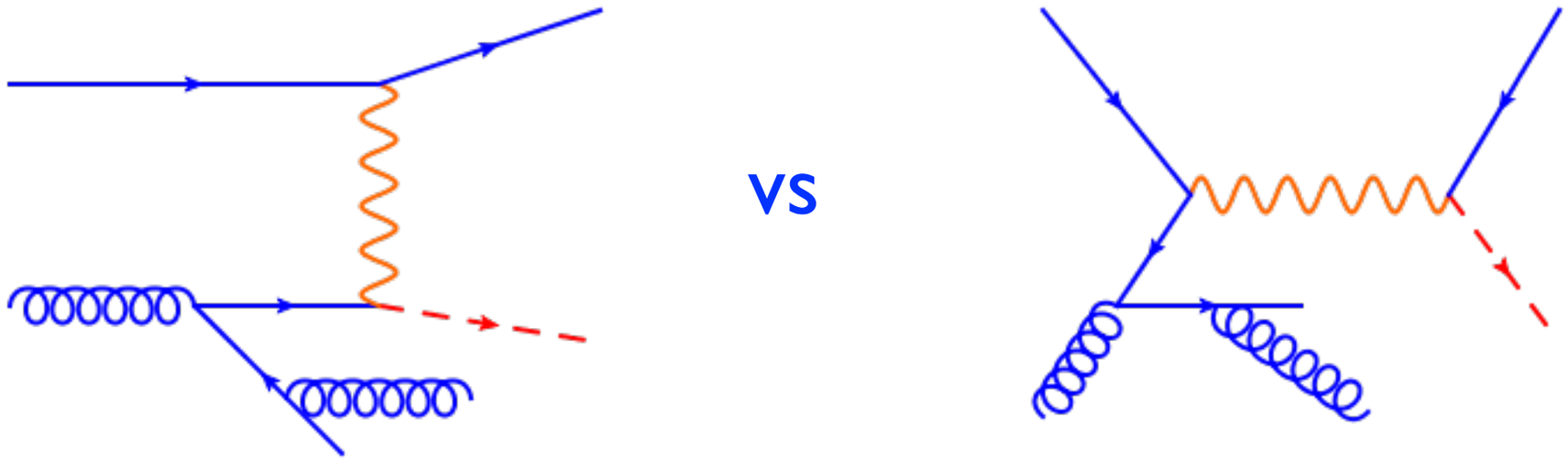
S-CHANNEL



LHC: ~ 5%

Rigid separation: good for the old 'pioneering' days,
must be taken with care if precision is sought/needed

t- vs s- channels: it still makes sense



IN PRINCIPLE:

- beyond LO t- and s- channels same initial/final states -> interferences, no well defined distinction

HOWEVER IN PRACTICE:

- thanks to color, interference starts at NNLO (in the 5FNS)
- suppressed (color / kinematics)

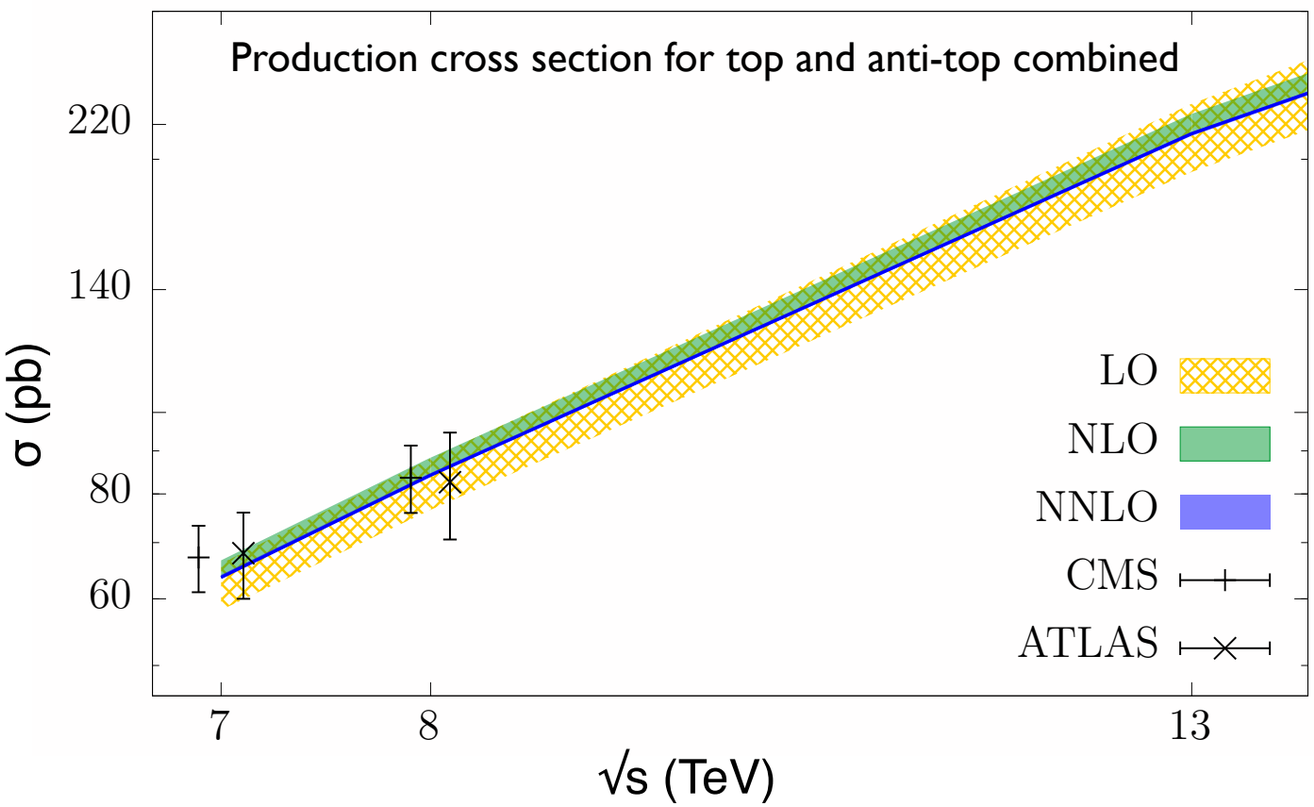
CAN STILL TALK MEANINGFULLY ABOUT T (AND S) CHANNEL

- Talking about FIDUCIAL CROSS SECTION is much better
- Ideally for REALISTIC FINAL STATES

t-channel single top at NNLO

[Brucherseifer, FC, Melnikov (2013)]

$$\sigma_{t+\bar{t}}^{\rm NLO} = 85.2^{+2.5}_{-1.4}\ {\rm pb}, \qquad \sigma_{t+\bar{t}}^{\rm NNLO} = 83.9^{+0.8}_{-0.3}\ {\rm pb}$$



At NLO, small corrections, but:

- large cancellations among different channels -> small K-factor accidental
- large corrections at high p_T

NNLO stabilizes the result

- small (non flat) ~ 1% corrections through the full spectrum
- reduced scale uncertainty

Good theoretical control on the Wtb vertex

- top decay width
- V_{tb}

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

t-channel single top at NNLO

[Brucherseifer, FC, Melnikov (2013)]

top/anti-top ratio very stable

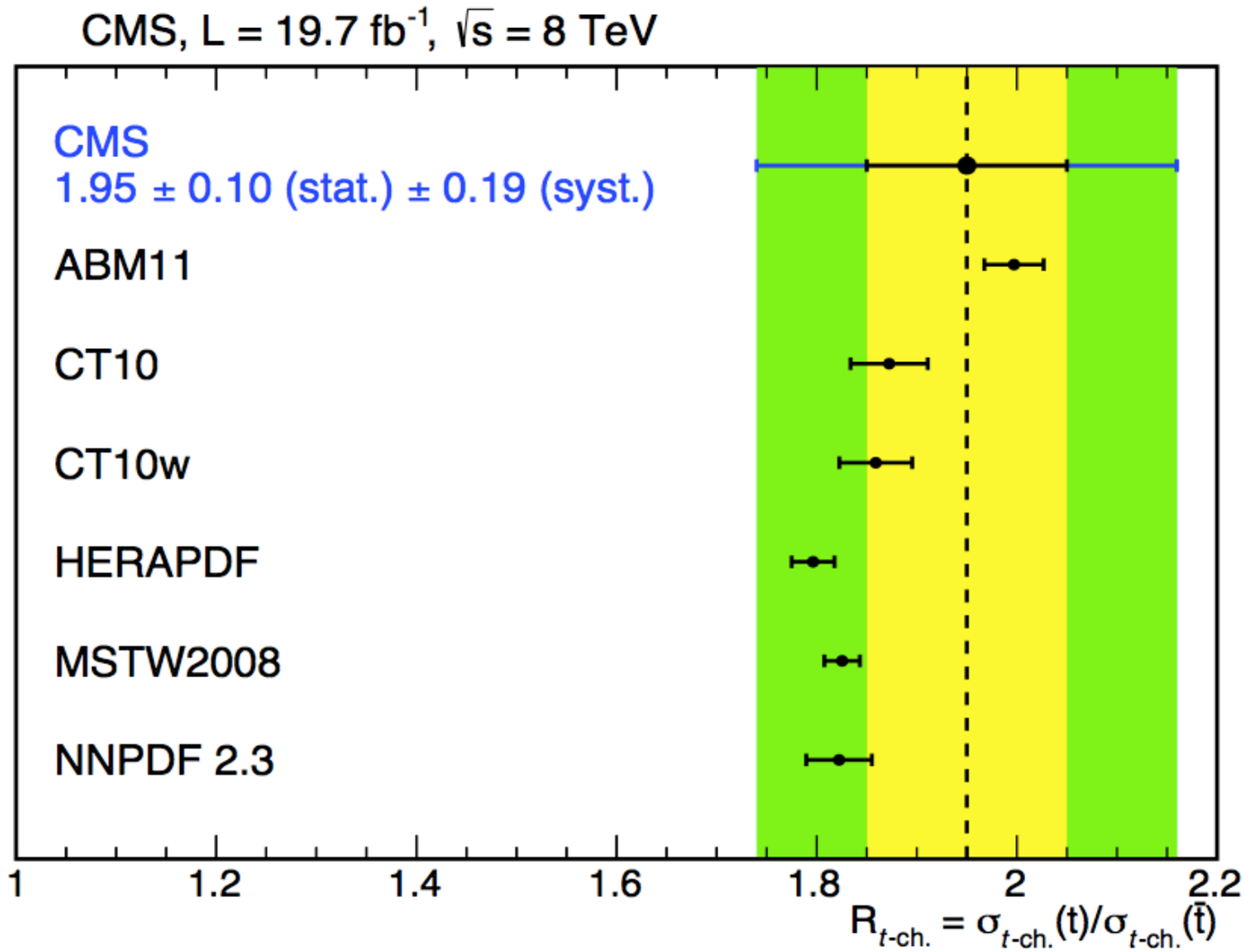
$$\sigma_{t,\mathrm{LO}}/\sigma_{\bar{t},\mathrm{LO}} = 1.85$$

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

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

No substantial modification w.r.t. NLO →

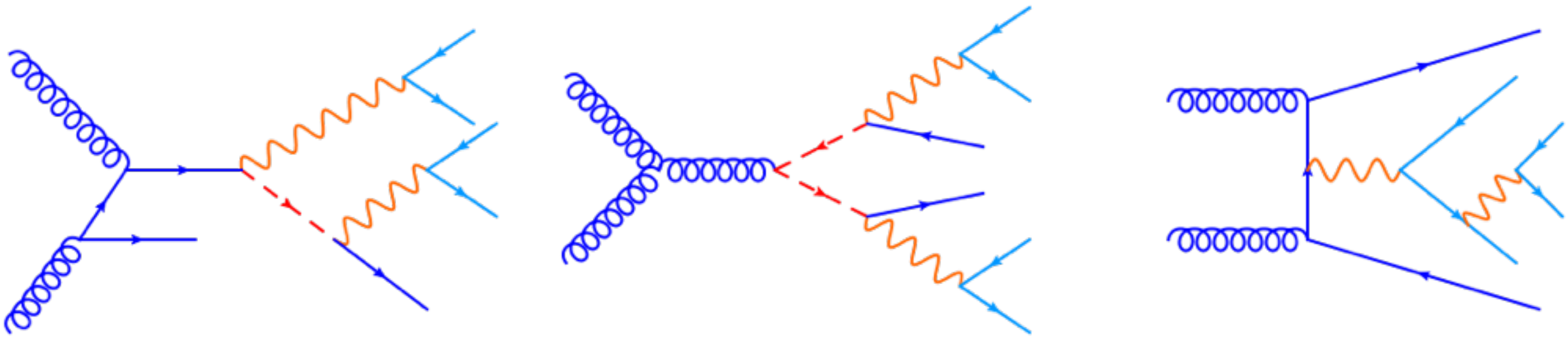
HANDLE ON B CONTENT IN THE PROTON



Can also give interesting information on the light quarks content [Moch…]

What about Wt?

Already at NLO, Wt, $t\bar{t}$ and WW 'background' share the same initial/final states -> interferences, cannot be separated



If you want to consider massive b (b-tagging…) and work in the 4FNS -> LO problem

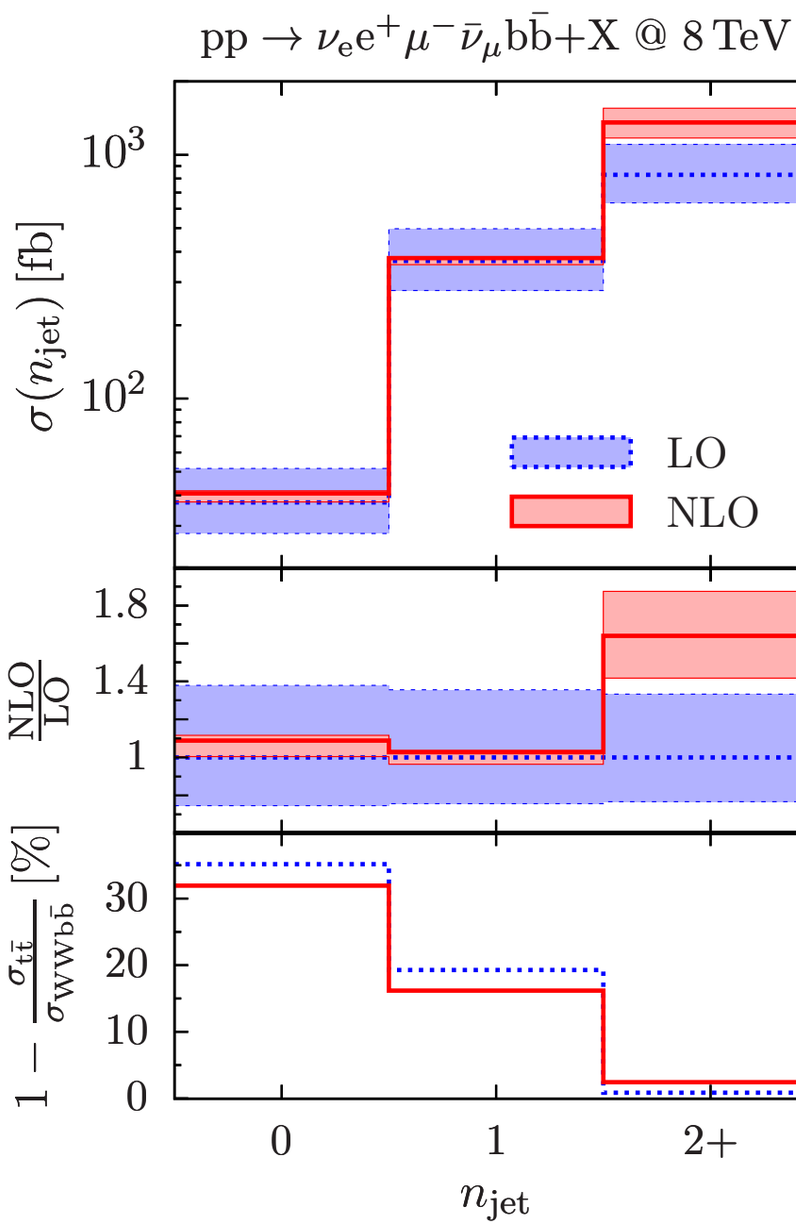
In the past, full computation was out of question -> must cook up some add-hoc recipe to deal with it (DR,DS,PR…)

NONE OF THEM IS THEORETICALLY FULLY SOUND

Wt and $t\bar{t}$: separation

A full NLO computation in terms of final state decay products is now doable [Frederix (2013), Cascioli, Maierhoefer, Kallweit, Pozzorini (2013)]

[Cascioli, Maierhoefer, Kallweit, Pozzorini (2013)]



NLO(LO) 4F NNPDFSs, $p_{T,j} = 30\,\mathrm{GeV}$

$$d\sigma_{WWb\bar{b}} \sim \frac{1}{\Gamma_t^2} d\sigma_{t\bar{t}} + \frac{1}{\Gamma_t} d\sigma_t + d\sigma_{bkg}$$

Wt: single-resonant contribution. Devise cuts to enhance it

- Non tt effects very jet-bin dependent, concentrated in the 0/1 jet bins
- Large in phase space regions with unresolved b-quarks

Put physical intuition on a precise quantitative level

tops vs physical objects (lepton, jets)

In general, it is highly preferable to include top decay in predictions

- reduce reconstruction biases
- we know many cases when omitting corrections to decay lead to bad mismodeling [Melnikov, Schulze (2011)]

Since $\Gamma_t/m_t \ll 1$, production/decay do not talk → factorization

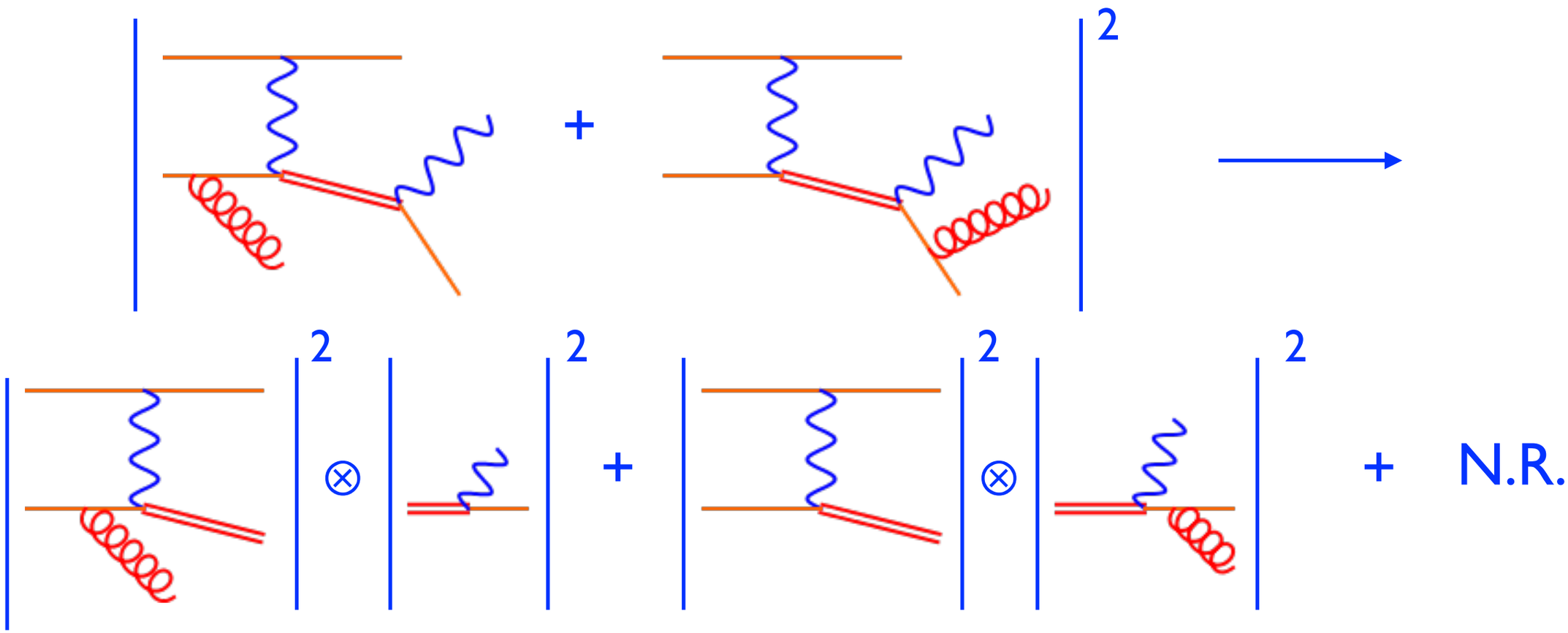
- this has been now confirmed [Pittau (1996), Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]
- very important → reliable predictions at NNLO, reliable predictions for complicated final states (ttV/H, ttγγ, ttJ, ttJJ…)

In certain situations, we may want to go beyond the $\Gamma \to 0$ limit

- Wt, kinematics edges, m_{Wb}…
- current NLO groups are getting there: WWbb, WWbbH [Denner, Feger, Scarf (2015)]
- for narrow resonances, one should be careful with parton showers (PS emissions destroy the quasi-resonant structure). Since recently, problem seems under control [Ježo, Nason (2015) + work in progress])

Narrow resonances in PS: problem…

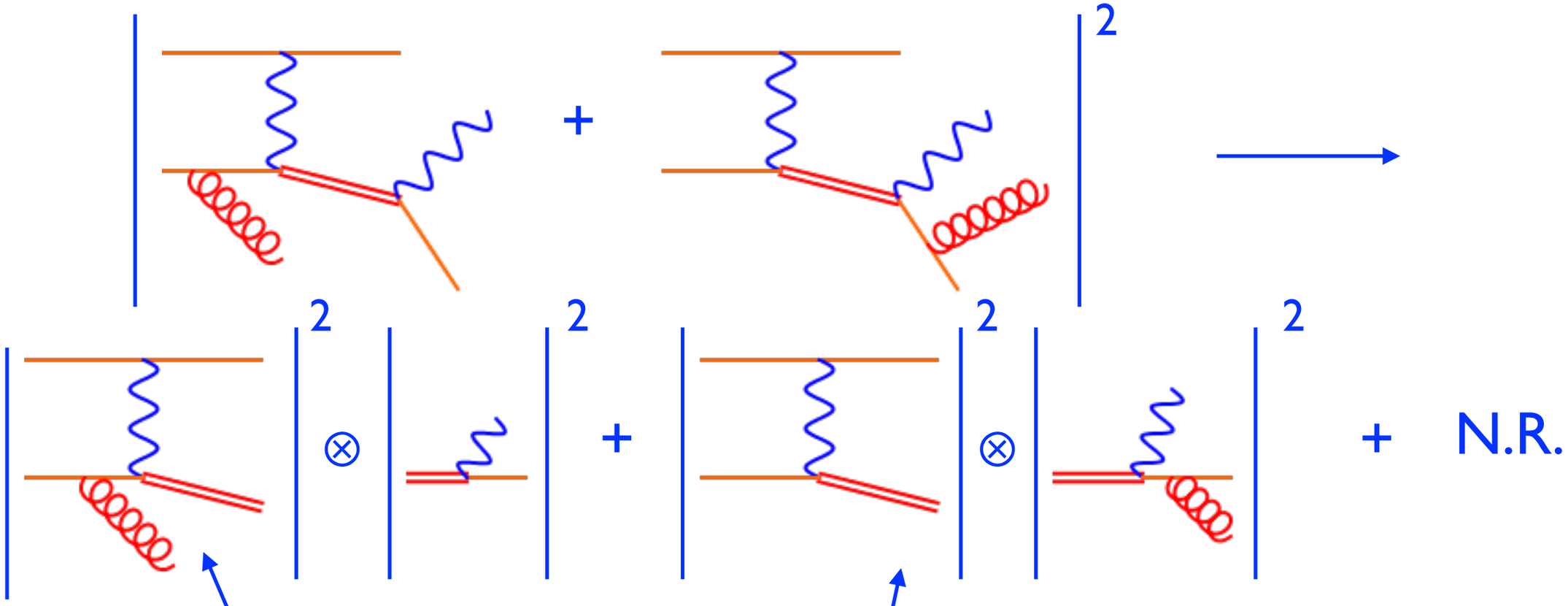
What we would like



- In general, PS will emit multiple gluons which will destroy this structure → MORALLY WRONG RESULT (i.e. expect unphysical features)
- It is trivial to force emission to conserve any given invariant mass. How to select the 'right' mass to constrain (m_{Wb} vs m_{WbJ})?

Narrow resonances in PS: … and solution

[Ježo, Nason (2015) + work in progress]



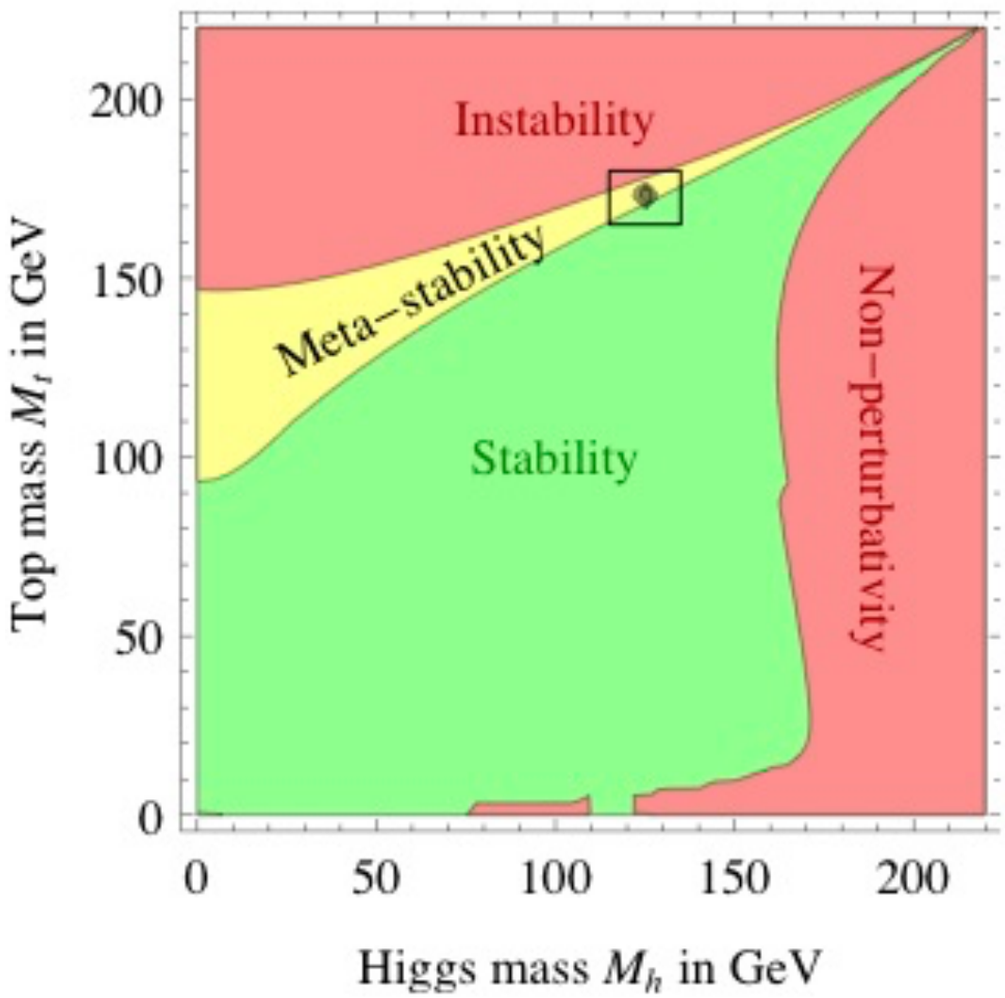
- 'Sum over resonance history', i.e. introduce partition of unity which effectively project onto the right structures (i.e. BW-FKS)

$$1 = \frac{P(s_{Wb})}{P(s_{Wb}) + P(s_{WbJ})} + \frac{P(s_{WbJ})}{P(s_{Wb}) + P(s_{WbJ})} \qquad P(s) = \frac{m_t^4}{(s - m_t^2)^2 + m_t^2 \Gamma_t^2}$$

- For each term, force the 'right' invariant mass to be fixed
- Resonances are properly taken care of, n.r. terms are spread

The top mass

- Top: heaviest particle of the SM → top mass is a privileged parameter in many respect (stability…)
- Given the amount of tops produced at the LHC, it is already now possible to perform to very good accuracy many measurements strongly correlated to the top mass → the Monte Carlo mass ~ sub percent level



Two natural questions:

- can we measure the actual top mass (or equivalently, can we precisely relate the result of these measurements to a clean theoretical parameter)?
- to which precision?

A step back: quark masses in QCD

- Top mass is a parameter in the SM Lagrangian, which undergoes renormalization → ITS DEFINITION REQUIRES SOME CARE

- The simplest possible definition of the top mass is the value of the pole of top propagator. Closely related to kinematics boundaries… Perfectly fine definition order by order in perturbation theory, but famously problematic at the NP level ('renormalon ambiguities', PT series is asymptotic and does not converge to a finite number)
- In *b* physics, we observe that this reflects in a poor convergence of the perturbative series if the top mass is used →new definition of 'short distance' masses (MSbar…). Related to the pole mass by a scheme change, order by order in PT
- IS CHOOSING THE 'RIGHT' DEFINITION IMPORTANT FOR TOP PHYSICS?

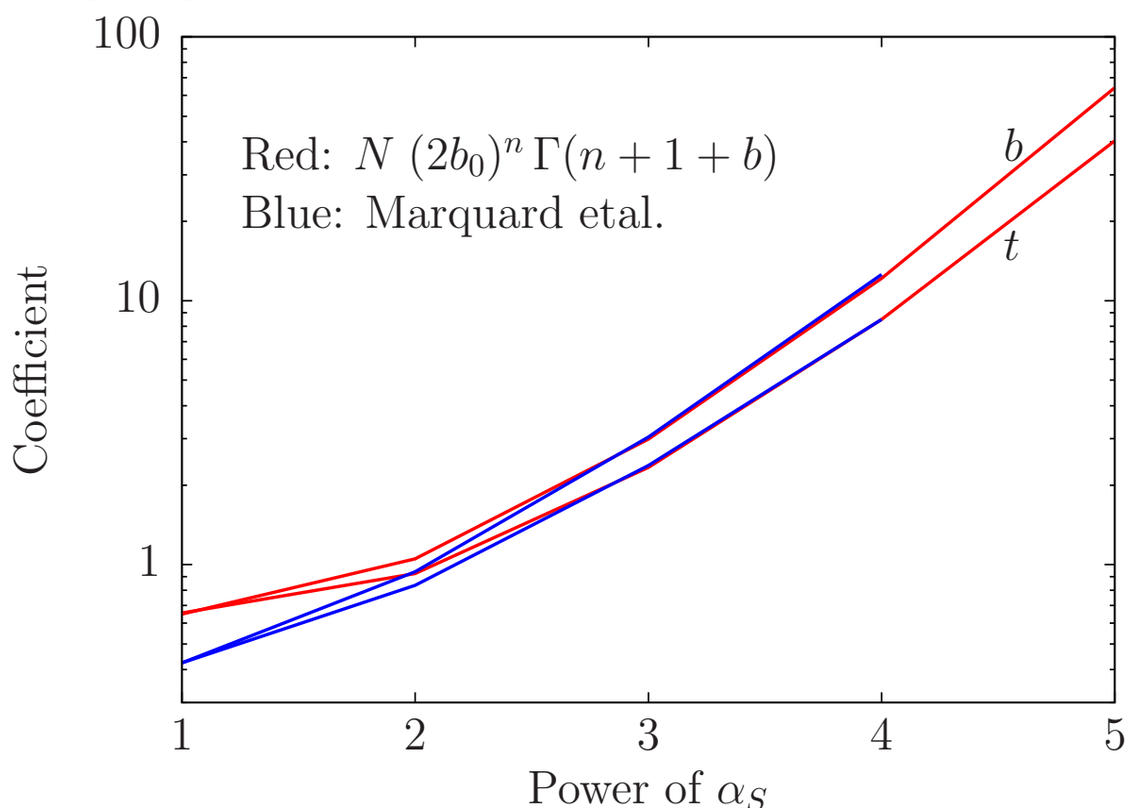
Pole vs MSbar mass

Recently, the 4-loop conversion between MSbar and pole mass was computed [Marquard, Smirnov, Smirnov, Steinhauser (2015)]

$$M_{pole} = 163.643 + 7.557 + 1.617 + 0.501 + 0.195 \text{ GeV}$$

- $\alpha s(m_t) \ll \alpha s(m_b) \rightarrow$ top pole mass does not show pathological behavior
- same behavior seen in other observables (top decay)
- last shift ~ 200 MeV, to be compared with world average error ~ 760 MeV

Furthermore, the perturbative series seems to have reached its asymptotic → can estimate next orders, and ultimate precision



- next term would be +0.10 GeV
- final ambiguity could be as low as 43 MeV

[Nason, Steinhauser, Beneke et al., work in progress]

The top mass at the LHC

- Although a proper choice of the theoretical definition of the top quark does not seem to be a problem, unfortunately THIS DOES NOT MEAN THAT WE KNOW HOW TO MEASURE IT AT THE LHC
- Indeed, the LHC is a hadron collider, and as such we are ultimately limited in our prediction by non-perturbative QCD effects. This affects all observables (i.e. also lepton ones)

$$\mathrm{d}\sigma = \int dx_1 dx_2 f_1(x_1) f_2(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2)(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$

- Right now we heavily rely on how these effects are modeled in PS. Comparing different PS may give an idea of the size of uncertainties, (but beware that different PS share many common features)
- Improving our understanding of NP effects (which observables are less affected, what is the first power contributing…) is likely to be REQUIRED TO DETERMINE THE TOP MASS AT THE LHC TO VERY HIGH PRECISION [Corcella, Hoang, Mangano, Melnikov… work in progress]

Conclusions

- The remarkable experimental program at the LHC is allowing for top quark investigation at the percent precision
- This already allowed to scrutinize the top sector to very good accuracy, in the future the situation can only improve
- This require very sophisticated theoretical computations. Along with Higgs, top-physics is pushing further the frontier of collider phenomenology
  - for simple processes, we now have fully differential NNLO predictions. It will be very interesting to let the top decay
  - NLO predictions are now a standard, both for very complicated final state and for generic BSM theories. (NLO EW is coming as well)
  - First investigation beyond the NWA approximation are appearing
- The top mass still represents a big challenge for theorists
  - Perturbative part seems under control
  - Can we say anything meaningful about non-perturbative effects?

Thank you for your attention!