Constraining heavy flavor PDFs at hadron colliders

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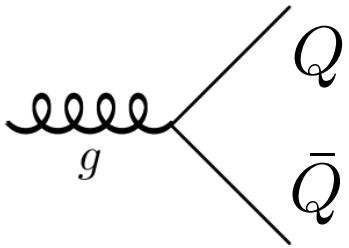
Constraining heavy-flavor PDFs: what does it mean?

Here ``constraining'' has a twofold meaning:

- Corresponds to the ability of a specific QCD framework (scheme) to give correct predictions for the cross section of observables involving the third generation of quarks. Charm, bottom, and even the top quark are tied to the gluon:



Heavy quarks are perturbatively generated.
Constraints reflect our ability to access gluon splitting
and when one of the heavy quarks goes along the beampipe
with proton's remnant: heavy quark inside the proton

Basically, the ability of our scheme to capture heavy flavor perturbative dynamics.

- Corresponds to the possibility of directly accessing heavy-quark PDFs parametrized at the initial scale:
  - intrinsic/fitted charm, bottom, and top in the proton
  Assuming that these contributions factorize…

PDF fits may include a ``fitted charm'' PDF

``Fitted charm'' = ``intrinsic charm''

+ other (possibly not universal)

higher O(αs) / Higher power terms

We don't have an agreed definition/framework to factorize intrinsic HQ contributions.

DIS HQ factorization by Collins PRD(1998) was proved only for radiative HQ

Intrinsic HQ are correction that scales like $\frac{\Lambda_{QCD}^2}{m_Q^2} \ln\left(\frac{Q^2}{\mu^2}\right)$

There is no consensus on how to factorize these contributions.

New precision measurements at LHC run II, EIC, and future collider programs will help shed light

(Recent discussion in: CT14-IC JHEP 2018, NNPDF3.1 EPJC 2017)

…with this in mind, in the next slides I have put together a few thoughts

<u>Questions</u>:

- Can we set tighter ``constraints'' on heavy-flavor PDFs with new LHC and future collider measurements?
- What process?
- What scheme?
- Can we improve on our current knowledge of intrinsic heavy flavors by using processes from LHC run II (and future colliders)?
- Will future colliders be helpful to shed new light on this?

Heavy flavor schemes

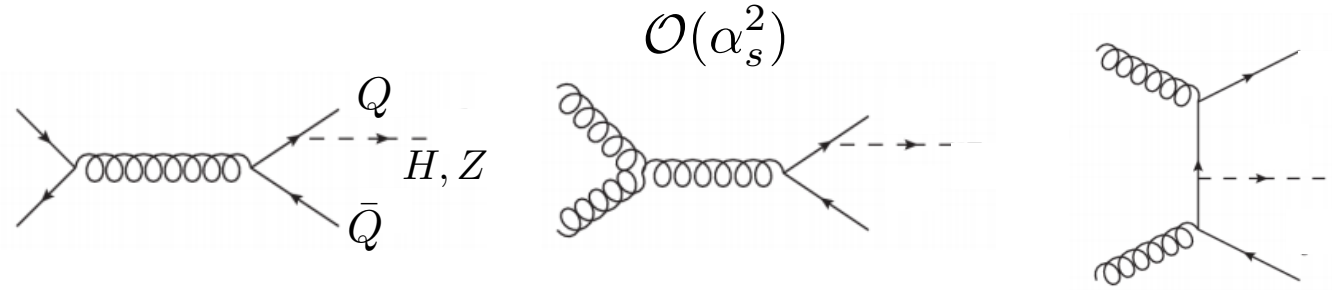
(it goes back a long way: Barnett, Haber, Soper, NPB 1988; Olness, Tung, NPB 1988)

- Massive and Massless schemes: different ways to organize the perturbation series

Massive schemes: $Q \approx m_Q \gg m_P \Longrightarrow$ heavy quarks can only be created in pairs in high-Q^2 interactions.
Give a correct description in the threshold region.

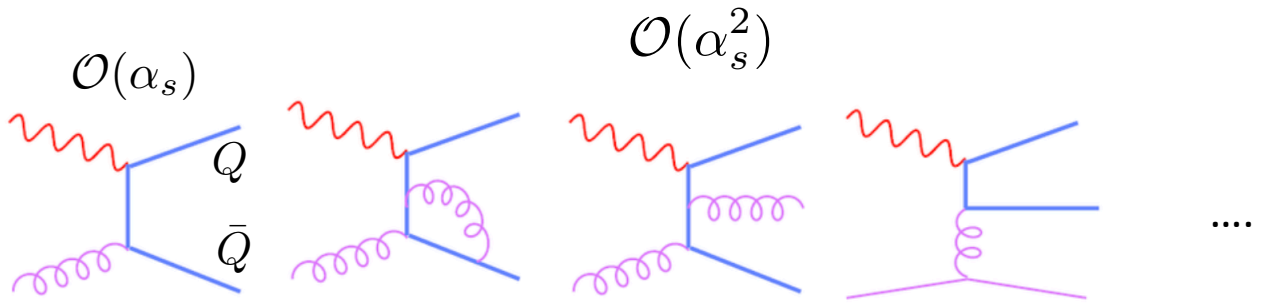
No heavy-quark PDF in the proton. Heavy flavors generated as massive final states. m_Q is an infrared cut-off.

PP



For example

DIS



- 3FFS c production
- 4FFS b production
- 5FFS t production

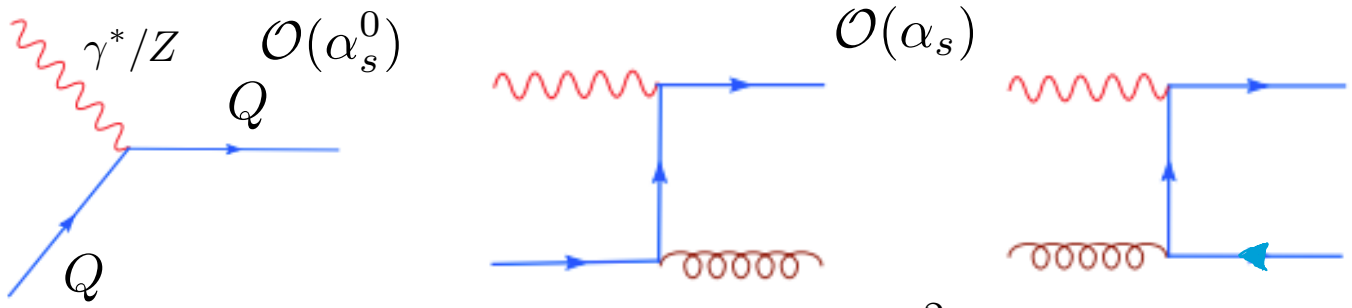
Heavy flavor schemes

- Massive and Massless schemes: different ways to organize the perturbation series

Massless schemes: $Q^2 \gg m_Q \gg m_P \Longrightarrow$ appearance of log terms $\log\left(Q^2/m_Q^2\right)$ where Q is one typical scale in the process (e.g. pT, etc). The heavy quark is considered essentially massless and enters also the running of α_s. These logs may spoil the convergence of the fixed order expansion.

➡ Need to resum these logs with DGLAP: initial-state logs resummed into a heavy-quark PDF, final-state logs resumed into a fragmentation function (FF)

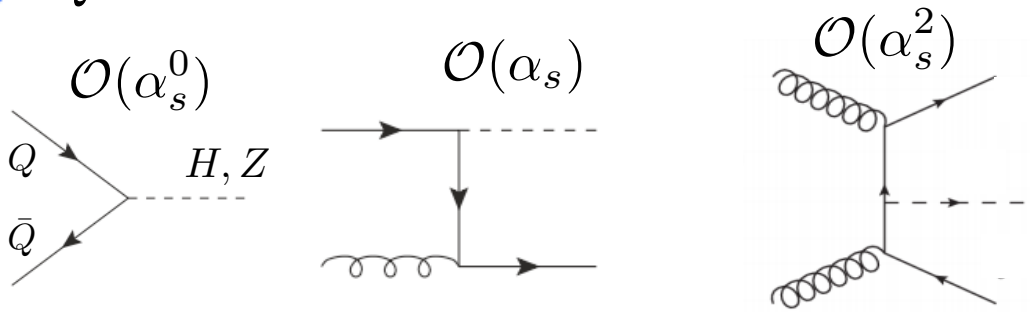
DIS



For example

+ ....

PP



+ ....

4FFS, 5FFS, 6FFS

Interpolating schemes

- **In DIS**: we have factorization schemes with VFN of active quarks. They interpolate between massless (ZM) and massive (FFN) schemes:

ACOT: Aivazis, Collins, Olness, Tung PRD 1994 (later modifications of it: S-ACOT, and S-ACOT-χ);

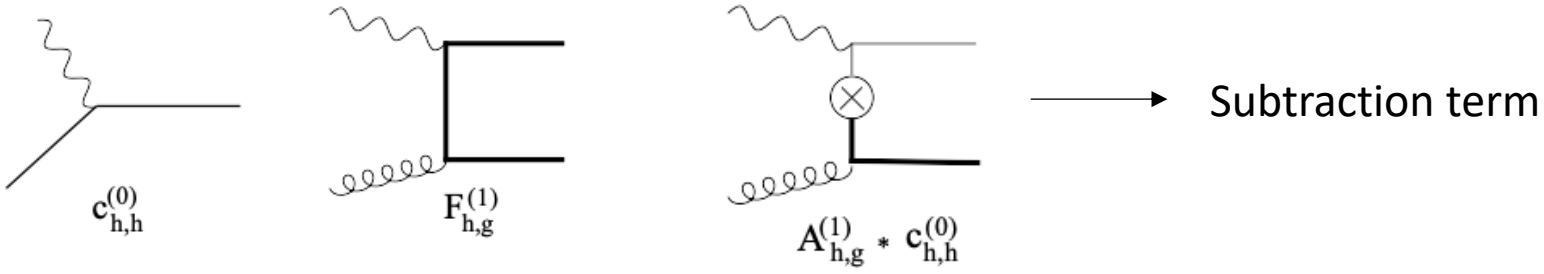
BMSN: Buza, Matiounine, Smith, Van Neerven, EPJC 1998;

TR': Thorne, Roberts, PRD 1998;

FONLL: Forte, Laenen, Nason, Rojo, NPB 2010;

Hybrid Scheme: Kusina, Olness, Schienbein, Jezo, Kovarik, Stavreva, Yu, PRD 2013.

They require a subtraction mechanism to avoid double-counting in the collinear region



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TR': Thorne, Roberts, PRD 1998; (MMHT)

FONLL: Forte, Laenen, Nason, Rojo, NPB 2010; (NNPDF)

Hybrid Scheme: Kusina, Olness, Schienbein, Jezo, Kovarik, Stavreva, Yu, PRD 2013.

- Most of these GMVFN schemes are now known up to $O(\alpha_s^2)$.
- They are crucial for a correct treatment of heavy flavor structure functions in DIS and to accurately predict key scattering rates at the LHC $\longrightarrow$ crucial in global PDF analyses
- DIS data constitute the backbone of PDF determination

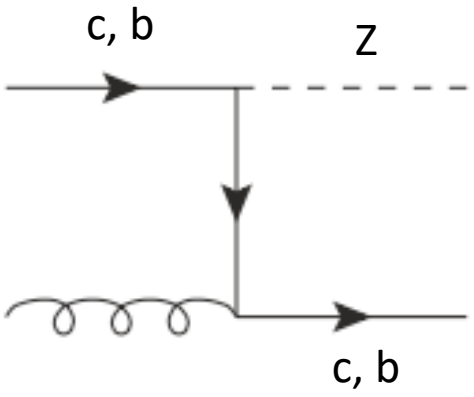
Selected heavy flavors in PP collisions

- Associated production of a Z boson with charm or bottom quark jets in proton-proton collisions provide direct access to charm and bottom PDFs:

- What is the best scheme?

- can we probe initial scale intrinsic/fitted heavy-flavors ?

Recent Xsec measurements from **CMS** 2001.06899 and **ATLAS** 2003.11960 at **13 TeV**



- NNLO Theory prediction with full mass dependence not yet available.
- But a lot of work has been done at NLO, especially regarding the intricacies due to the interplay between 4FS and 5FS
- massive-b scheme and EW corrections also studied

(Figueroa, Honeywell, Quackenbush, Reina, Reuschle, Wackeroth, PRD 2018)

A PDF analysis could in principle be attempted,
fast tables for theory predictions needed,
which account for matching between schemes

It would be interesting to apply/validate S-ACOT-χ for such a process

Matching various hq flavor schemes in Z/H+b

A lot of work has been done in trying to understand the interplay between 4FS and 5FS in single and double bottom-quark initiated processes relevant for Higgs and Z production.

The list here is of course not exhaustive:

- Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2005.03016:
  (FO calculation for Z+ b-jet at O(α_s^3) in QCD, combines ZM NNLO and FFNS NLO)
- Forte, Giani, Napoletano EPJC 2019: (massive b-scheme)
- Figueroa, Honeywell, Quackenbush, Reina, Reuschle, Wackeroth, PRD 2018:
  (massive b-scheme, Z + b-jet at O($\alpha_s^2\alpha$) and O($\alpha_s\alpha^2$) within ACOT and S-ACOT)
- Forte, Napoletano, Ubiali EPCJ 2018:
  (FONLL method to match 5FS with massless b to 4FS with massive b)
- Krauss, Napoletano, Schumann, PRD 2017: (Z/H + b with SHERPA);
- Lim, Maltoni, Ridolfi, Ubiali JHEP 2016: (b-bbar-initiated processes at the LHC);
- Bonvini, Papanastasiou, Tackmann, JHEP 2015, JHEP 2016: (4 matched calculation b-bar-H);
- Forte, Napoletano, Ubiali, PLB 2015;
- Maltoni, Ridolfi, Ubiali JHEP 2012: (b-initiated processes at the LHC);
- Campbell, Caola, Cordero, Reina, Wackeroth, PRD 2012;
- Campbell, Ellis, Cordero, Maltoni, Reina, Wackeroth, Willenbrock, PRD 2009;
- Dawson, Jackson, Reina, Wackeroth PRD 2004;
- Maltoni, Sullivan, Willenbrock, PRD 2003;
- ……

Matching various hq flavor schemes in in Z/H+$b\bar{b}$

PP-> Z$b\bar{b}$ and PP-> H$b\bar{b}$ are sensitive to two bottom quarks in the initial state.

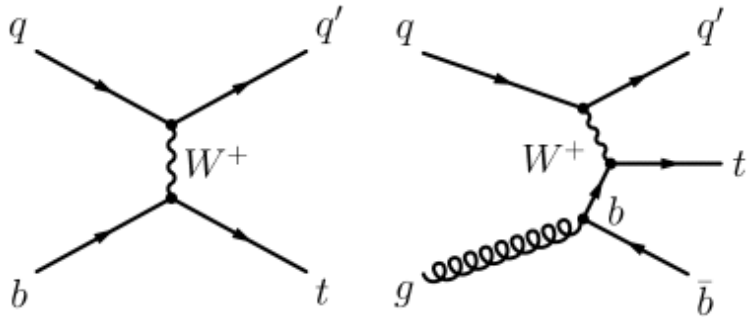
Recent measurements from **ATLAS** 2003.11960 at **13 TeV**

- The 4FS NLO and 5FS NNLO Xsec calculations provide complementary information. Matching has been tried in several ways (FONLL, EFT, etc). Results are in agreement (Handbook of LHC Higgs 1610.07922).
- Massive b-scheme (Forte, Giani, Napoletano EPJC 2019) for Higgs production
- 5-flavor massive scheme (5FMS) for MC implementation (Krauss, Napoletano PRD 2018).

- Need to be generalized to NNLO.
- Test intrinsic heavy flavor impact
- Validate with other schemes?

Preliminary PDF analyses feasible ?

Single top



- <u>NNLO predictions:</u>
  Berger, Gao, Zhu JHEP 2017
  Berger, Gao, Yuan, Zhu, PRD 2016;
  Brucherseifer, Caola, Melnikov, PLB 2014;
  Kidonakis, PRD 2011, PRD 2016 (Soft gluon corrections)

- <u>Interplay between 4FS and 5FS</u>
  Gao, Berger, 2005.12936 -> excellent agreement between 4FS and 5FS
  Maltoni, Ridolfi, Ubiali JHEP 2012;
  Campbell, Frederix, Maltoni, Tramontano, PRL 2009;

- <u>NNLO PDF analysis using the 5FS and 4FS scheme</u>
  in the NNPDF-like framework already attempted: Nocera, Ubiali, Voise JHEP 2020

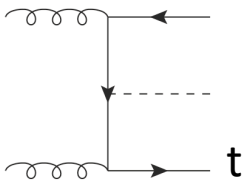
- 4FS with full Mass dependence not yet available.

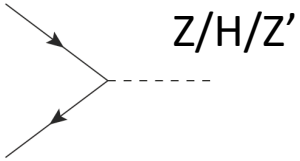
-Sensitive to the gluon and b-quark.
-Interesting to see the impact of intrinsic c, b

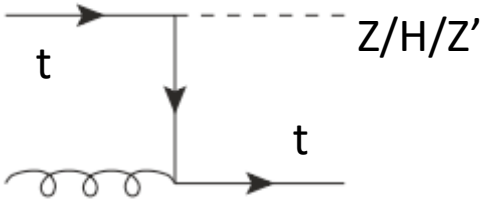
Future colliders

- Top-quark initiated processes

Dawson, Ismail, Low PRD 2014
Han, Sayre, Westhoff JHEP 2015;







Re-examine of whether the top quark is a parton in the proton = 6FS

Effects of collinear resummation at lowest order:
Interplay between 6FS t tb -> H and t g-> t H
and 5FS gg-> t tb H

The study of Han, Sayre, Westhoff JHEP 2015
uses an amended version of the ACOT (mACOT) scheme
to treat heavy-quark masses in hadronic collisions with two
initial top quarks

Several new BSM analyses and analyses at future colliders may
require the use of Nf=6 PDFs. These are currently provided by NNPDF only.

tZ' production at hadron colliders (Soft gluon corrections),
M.G., Kidonakis EPJC 2020

Summary

- Precision measurements at the LHC run II already offer the possibility of probing heavy flavors using novel processes
- A lot of work has been done already in trying to understand the interplay between 4FS and 5FS in single and double bottom-quark initiated processes relevant for Higgs and Z production, and also in single top production.
- Progress in higher-order calculations is fast, missing pieces to investigate the interplay between HQ schemes will be available in the near future.
- HL LHC, EIC, and Future colliders will offer new opportunities to ``constrain'' HQ in unprecedented kinematic scenarios
- Future is exciting!