Hard QCD at the LHC

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“Particle Phys. on the Verge of Discovery?”

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Hard QCD at the LHC: Outline

- Introduction. Observables: Jets, (di)photons, W,Z bosons, heavy-Q, Higgs

- Data vs. state-of-the-art (N)NLO+(N)NLL pQCD:

- (N)NLO PDFs & FFs improvements:

- (N)NLO QCD coupling extraction:
Hard QCD at the LHC: Outline

- Introduction. Observables: Jets, (di)photons, W,Z bosons, heavy-Q, Higgs

- Data vs. state-of-the-art (N)NLO+(N)NLL pQCD:

DISCLAIMER: This talk does NOT contain a comprehensive (but representative) selection of all ATLAS/CMS/LHCb results

- (N)NLO PDFs & FFs improvements:

- (N)NLO QCD coupling extraction:
“All” LHC p-p physics “is” QCD physics

Full Quantum Chromodynamics at work:

1. Hard scattering (large $p_T$, mass): perturbative matrix elements, DGLAP evol., Resummations, Parton Distribution Functions, Fragmentation Functions
2. Semi-hard dynamics: Multiparton interactions, Generalized PDFs
3. Soft: Beam remnants, diffractive scatterings,...

High-precision (experimental & theoretical) studies of QCD are key to understand production of all (B)SM signals & bckgds at the LHC:
"All" LHC p-p physics "is" QCD physics

Full Quantum Chromodynamics at work:

1. Hard scattering (large $p_T$, mass): perturbative matrix elements, DGLAP evol., Resummations, Parton Distribution Functions, Fragmentation Functions

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3. Soft: Beam remnants, diffractive scatterings,

High-precision (experimental & theoretical) studies of QCD are key to understand production of all (B)SM signals & bckgds at the LHC:

[Douglas M Schaefer, Friday]
Organization of the talk

- What have learned from the hard QCD data at the LHC about...

- The total and differentional cross sections for any new particle(s) at the LHC (SUSY, DM, Z', S(750)...) are affected by such crucial hard QCD ingredients.
“Master formula” for hard QCD cross sections

- Collinear factorization for hard process cross sections in p-p collisions:
  - Convolution of non-perturbative objects + parton-parton matrix elements:

\[ \sigma^{AB\rightarrow h} = f_A(x_1, Q^2) \otimes f_B(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{i\rightarrow h}(z, Q^2) \]

1) Initial state:
   - Universal PDFs fitted from data + DGLAP evolution

2) Hard scattering:
   - Matrix elements computed at (N)NLO in $\alpha_s$ expansion + (N)NLL resummation of logs

3) Final-state hadronization ($q,g,Q\rightarrow\pi,k,p,D,B$) or bound-state formation (ccbar,bbar):
   - Universal FFs fitted from data + DGLAP evolution
Hard $\sigma$-sections: Perturbative $\alpha_s$ expansion

Theoretical cross section calculations obtained via $\alpha_s$ expansion with increasing number of real parton emissions (legs) + virtual corrections (loops):

- **LO**
  - $q\bar{q} \rightarrow Z$
  - $O(1-10)$ diagrams
  - TH uncert.~50-100%

- **NLO**
  - $gq \rightarrow Z$
  - $O(100)$ diagrams
  - TH uncertainty~20%
  - $pp \rightarrow \text{jets}+X$ (upcoming NNLO)
  - $pp \rightarrow \gamma+X$

- **NNLO**
  - $gg \rightarrow H+X$ (upcoming N3LO)
  - $O(1.000)$ diagrams
  - TH uncert.~5%
  - $pp \rightarrow W,Z+X$ (+jet)
  - $pp \rightarrow \gamma\gamma+X$
  - $pp \rightarrow t\bar{t}+X$
  - $pp \rightarrow H+X=\text{jets},V,t\bar{t}$

First-ever $N^3LO$: $gg\rightarrow H+X$ ($\sim 10^5$ diags.~2% uncert.)
Hard cross sections: Soft gluon resummations

- Theory calculations with increasing # of real emissions + virtual corrections + soft & collinear log resummations (improves $p_T$ differential distributions):

  - **LO**
    - $q \rightarrow Z$
  - **+LL**
    - $O(1-10)$ diagrams
      - TH uncertainty ~50-100%
    - pp $\rightarrow$ jets+X (upcoming NNLO)
    - pp $\rightarrow$ $\gamma$+X
  - **NLO**
    - $q \rightarrow Z$
  - **+NLL**
    - $O(100)$ diagrams
      - TH uncertainty ~20%
    - pp $\rightarrow$ $W,Z$+X (+jet)
    - pp $\rightarrow$ $\gamma\gamma$+X
    - pp $\rightarrow$ ttbar+X
    - pp $\rightarrow$ H+X=jets,V,ttbar
  - **NNLO**
    - $g \rightarrow Z$
  - **+NNLL**
    - $O(1.000)$ diagrams
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    - pp $\rightarrow$ $\gamma\gamma$+X
    - pp $\rightarrow$ ttbar+X
    - pp $\rightarrow$ H+X=jets,V,ttbar

(State-of-the-art pQCD calculations include also QED+EWK corrections)
Hard cross sections: Higher-order corrections

- Theory calculations with increasing # of real emissions + virtual corrections:
  (i) (usually) increased x-sections, (ii) reduced theoretical uncertainties

\[ \sigma(pp \rightarrow Z, \gamma^*) \text{ at NNLO:} \]

\[ \sigma_{ggH} = 19.47 \text{ pb (} +0.3\%-3.0\% \text{)} \]

[Higgs \( \sigma(gg \rightarrow H) \) at \( N^3\text{LO} \):]


\[ \text{[Grazzini, Kidonakis, Petriello, Melnikov, ...]} \]

+10^5 diagrams more
Hard cross-sections: Resummations

- Theory calculations include increasing number of real emissions + virtual corrections:
  + soft & collinear log resummations:
    1. (usually) increased $\sigma$-sections,
    2. reduced theoretical uncertainties,
    3. improved $p_T$ differential distributions:

\[ \sigma(pp \rightarrow \text{ttbar}) \text{ at NNLO+NNLL:} \]

\[ \text{Higgs } d\sigma/dp_T \text{ at NNLO+NNLL:} \]

[DeFlorian et al. arXiv:1203.6321]  
[Mitov, Czakon, ...]  
[DeFlorian et al. arXiv:1203.6321]
Hard QCD: LHC Data
Wealth of hard QCD data: jets, $\gamma$, diphotons

- $\sqrt{s}=2.76,7,8,13$ TeV (central):
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- $\sqrt{s}=7,8,13$ TeV (central):

\[ \text{NEW} \]
Wealth of hard QCD data: charm, bottom

\[ \sqrt{s} = 7, 8, 13 \text{ TeV (central rapidities):} \]

\[ \sqrt{s} = 7, 8, 13 \text{ TeV (forward):} \]

[arXiv: 1510.01707] [NPB871 (2013) 1]
Wealth of hard QCD data: W, Z bosons

\( \sqrt{s} = 7, 8, 13 \text{ TeV (central rapidities):} \)

- CMS Preliminary, 43 pb^{-1} (13 TeV)
- CMS, 18 pb^{-1} (8 TeV)
- CMS, 36 pb^{-1} (7 TeV)
- CDF Run II
- D0 Run I
- UA2
- UA1

\[ \sigma \times B = 10^{3} \text{ pb} \]

Center-of-mass energy [TeV]

\[ \sqrt{s} = 7, 8 \text{ TeV (forward):} \]

CMS Preliminary

18.4 pb^{-1} at \( \sqrt{s} = 8 \text{ TeV} \)

W^+ \rightarrow \mu^+ \nu

\[ \sigma_{WW} \times \sigma_{Z(W)} \]

\[ \frac{1}{\sigma_{WW}} \times \frac{d\sigma}{dp_T} \]

ATLAS Preliminary

Data 2015 (\( \sqrt{s} = 13 \text{ TeV} \))

MSTW2008 NNLO

NEW
Wealth of hard QCD data: top-pairs

\[ \sqrt{s} = 7, 8, 13 \text{ TeV (central rapidities)}: \]

\[ \sqrt{s} = 7, 8 \text{ TeV (forward)}: \]

\[ \sqrt{s} = 7, 8 \text{ TeV (forward)}: \]
Wealth of hard QCD data: Higgs boson

- $\sqrt{s} = 7, 8$ TeV (central rapidities):

ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^* \rightarrow 4l$ comb. data syst. unc.

- $\sigma_{gg} + \sigma_{XH}$
- $\sigma_{XH} = 3.0 \pm 0.1$ pb
- $XH = VBF + VH + tH + bbH$

QCD scale uncertainty
- Total uncertainty (scale $\times$ PDF-$c_{\alpha_s}$)

CMS $5.1$ fb$^{-1}$ (7 TeV), $19.7$ fb$^{-1}$ (8 TeV)

- Data (stat. $\times$ sys. unc.)
- Systematic uncertainty
- Model dependence
- Standard model ($m_H = 125$ GeV)

$pp \rightarrow (H \rightarrow 4l) + X$

CMS $19.7$ fb$^{-1}$ (8 TeV)

$H \rightarrow$ (Higgs + X)

- Data (stat. + sys. unc.)
- Systematic uncertainty
- Model dependence
- Standard model ($m_H = 125$ GeV)
Higher-order & resummations

Soft & collinear
Gluon resummations

Higher-order (NNLO) corrections
NNLO calculations in excellent agreement with all measured total x-sections:

Total hard cross sections: Data vs. pQCD

Standard Model Production Cross Section Measurements

Status: Nov 2015
NNLO calculations in excellent agreement with all measured total x-sections:

CMS Preliminary

Dec 2015

Production Cross Section, $\sigma$ [pb]

All results at: http://cern.ch/go/pNj7

7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
13 TeV CMS measurement ($L \leq 1.3$ fb$^{-1}$)
Theory prediction
CMS 95%CL limit
Higgs x-sections: Data vs. NNLO+NNLL

- Theory calculations include increasing # of real emissions + virtual corrections + soft & collinear log resummations (improves $p_T$ differential distributions).
- Higgs production is paradigmatic example:

  Higgs $\sigma(pp\rightarrow H)$ vs $N^{2,3}LO$:
  
  $\sigma_{ppH} = 33\pm5.3$(stat)$\pm1.6$(sys) pb
  
  $\sigma_{ppH} = 22.5 \pm 0.1$ pb

- Decent agreement within still large experimental statistical uncertainties

$\sigma(pp\rightarrow H)$ vs $N^{2,3}LO$:

$\sigma_{ggF + \sigma_{XH}} \sigma_{XH} = 3.0 \pm 0.1$ pb

$XH = VBF + VH + t\bar{t}H + bbH$

QCD scale uncertainty

Total uncertainty (scale $+ PDF + \alpha_s$)

$pp\rightarrow H, \ m_H = 125.4$ GeV

$H\rightarrow \gamma\gamma \ H\rightarrow ZZ^*\rightarrow 4l$

comb. data syst. unc.

ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Higgs $d\sigma/dp_T$ vs NNLO+NNLL:

Decent agreement within still large experimental statistical uncertainties
Theory calculations include increasing # of real emissions + virtual corrections + soft & collinear log resummations (improves $p_T$ differential distributions).

Higgs production is paradigmatic example:

Higgs $\sigma(pp\to H)$ vs N$^{2,3}$LO:

$5.1 \text{ fb}^{-1} (7 \text{ TeV}), 19.7 \text{ fb}^{-1} (8 \text{ TeV})$

Higgs $d\sigma/dp_T$ vs NNLO+NNLL:

$19.7 \text{ fb}^{-1} (8 \text{ TeV})$

Decent agreement within still large experimental statistical uncertainties
Diphoton x-sections: Role of NNLO corrections

- NLO largely underestimates increasingly collinear $\gamma$'s ($\Delta \phi < 2.5$):

  - $p_{T_{\gamma_1,\gamma_2}} > 25,40$ GeV

- Cured by latest state-of-the-art NNLO diphoton calculations:

  - Enhanced NNLO production of collinear $\gamma$'s (e.g. $qq \rightarrow qq\gamma\gamma$).
  - When $\gamma-\gamma$ not back-to-back: NLO~$1^{\text{st}}$ order

[CMS, EPJC 74 (2014) 3129]
Diphoton x-sections: Role of NNLO corrections

- NLO largely underestimates increasingly collinear $\gamma$'s ($\Delta \phi < 2.5$):

- Cured by latest state-of-the-art NNLO diphoton calculations:

Enhanced NNLO production of collinear $\gamma$'s (e.g. $q\bar{q} \rightarrow q\bar{q}\gamma\gamma$) “fills” out relevant regions of phase-space.
**Z boson x-sections: Role of resummations**

- Very precise differential measurement (uncert. <1% in $\phi^*$) strongly constrains modeling of soft/collinear gluon emission.

- NLO+NNLL resummations are crucial to reproduce the $Z$ spectra at low-$p_T$:

  - NLO+parton-showers (effective LL or NLL*) also reproduce well low-$p_T$ spectra:

  ![Graphs showing differential measurements and resummation effects](image)

  **Note:**
  - Very precise differential measurement (uncert. <1% in $\phi^*$) strongly constrains modeling of soft/collinear gluon emission.
  - NLO+NNLL resummations are crucial to reproduce the $Z$ spectra at low-$p_T$.
  - NLO+parton-showers (effective LL or NLL*) also reproduce well low-$p_T$ spectra.

*ATLAS, arXiv:1512.02192*
At high energies, negative W,Z corrections increasingly reduce by O(10-30%) the $\gamma$ x-sections. Explanation of the data/theory<1 for $m_{\gamma j}>1.5$ TeV?

\[\text{[arXiv:1512.05910]}\]

\[\text{[J.H.Kuhn et al., JHEP 0603 (2006) 059]}\]
Parton distribution functions
Extraction of PDFs via global fits

- Fixed-target & collider DIS ($\ell^{\pm}, \nu$-$p$) and $p$-$p$ data:
  \[ \sigma_{\text{data}} \sim \sigma_{\text{partons}} \otimes \text{PDF}_{\text{fitted}} \]

**Diagram:**

- **Energy scale ($Q^2$)**
- **Parton momentum fraction ($x$)**
- **$Q^2/M^2/p_T^2$ [GeV^2]**
- **$\ell^\pm p \rightarrow$ hadrons**
- **$\nu p \rightarrow$ hadrons**
- **$pp \rightarrow W, Z$**
- **$pp \rightarrow \ell^+\ell^-$**
- **$pp \rightarrow$ ttbar, jets, $\gamma$**

**Legend:**

- $q$
- $q'$
- $h_{\lambda}$
- $Z (W)$
- $l$
Gluon PDF constraints from jets

- Inclusive jet $p_T$ spectra:
  $p_T = 20$ GeV up to 2–3 TeV
  Exp. uncertainty: ~10% (JES)

- NLO pQCD describes data over 14 orders-magnitude!

- Improved knowledge of gluon PDF:

[Diagram showing $x \cdot g(x, Q^2)$ and data/theory comparison]

[CMS, EPJC 75 (2015) 186] [CMS-SMP-14-001]
Gluon PDF constraints from $\gamma$, charm, t-tbar

- **Isolated photon $p_T$ spectra:**
  - Figure showing PDF vs CT10 (NLO) with $1.52 < h_\gamma^2 < 2.37$
  - CT10 (NLO)
  - NNPDF 2.3(100)
  - HERAPDF 1.5
  - [ATLAS, PRD89 (2014) 052004]

- **Top-pair differential x-sections (NNLO):**
  - Diagram showing top-pair production
  - [NPB 871 (2013) 1]

- **Forward D-mesons (LHCb):**
  - Figure showing forward D-meson production
  - LHCb data, FONLL, GMVFNs, GMVFNs intr. charm
  - [ATLAS, PRD90 (2014) 072004]
Gluon PDF constraints from $\gamma$, charm, t-$\bar{t}$

- **Isolated photon** $p_T$ spectra:
  - LHC 7 TeV isolated-$\gamma$ data
  - NNPDF2.1 NLO
  - NNPDF2.1 NLO + IsoPhotons
  - $Q = 100$ GeV

- **Top-pair** differential $x$-sections (NNLO):
  - Reduced gluon uncertainties at different $(x,Q^2)$

- **Forward D-mesons** (LHCb):
  - Low-$x$ region
  - Mid-$x$ region
  - Large-$x$ region

J.Rojo'15

NNPDF3.0 NLO $\alpha_s = 0.118$

J. Rojo'15

J. Rojo'15

NNPDF2.3

NNPDF2.3 + Top Data

Q$^2 = 100$ GeV$^2$
Quark PDF constraints from W, Z “std. candles”

- Differential DY+Z x-section in accord with NNLO over 9 orders-of-magnitude & forward:

- W electron charge asymmetry vs $|\eta|$ measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

$$A(\eta) = \frac{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) - d\sigma/d\eta(W^- \rightarrow \ell^−\overline{\nu})}{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) + d\sigma/d\eta(W^- \rightarrow \ell^−\overline{\nu})}$$

- W electron charge asymmetry vs $|\eta|$

$\sqrt{s}=7$ TeV

- ATLAS+CMS+LHCb Preliminary

$|\eta| > 20$ GeV

- ATLAS (extrapolated data, $W \rightarrow l\nu$) 35 pb$^{-1}$
- CMS ($W \rightarrow l\nu$) 36 pb$^{-1}$
- LHCb ($W \rightarrow l\nu$) 36 pb$^{-1}$
- MSTW08 prediction (MC@NLO, 90% C.L.)
- CTEQ66 prediction (MC@NLO, 90% C.L.)
- HERAPDF1.5
- HERA1.0 prediction (MC@NLO, 90% C.L.)

~2.5% uncertainty(!)
Quark PDF constraints from W, Z “std. candles”

- Differential $\text{DY}+\text{Z} \times$-section in accord with NNLO over 9 orders-of-magnitude & forward:

$$\text{CMS}$$

$$\frac{d\sigma}{dm} [\text{pb/GeV}]$$

$$\gamma^{*}/Z \rightarrow e^{+}e^{-}, \mu^{+}\mu^{-}$$

- $W$ electron charge asymmetry vs $|\eta|$ measured to $\sim1\%$. Many uncertainties cancel in ratio. Constrains $u/d$ PDF ratio:

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^{+} \rightarrow \ell^{+}\nu) - \frac{d\sigma}{d\eta}(W^{-} \rightarrow \ell^{-}\bar{\nu})}{\frac{d\sigma}{d\eta}(W^{+} \rightarrow \ell^{+}\nu) + \frac{d\sigma}{d\eta}(W^{-} \rightarrow \ell^{-}\bar{\nu})}$$

- $W$+charm constrains $s/d$ PDF ratio:

- Mid-x region

$$r_s = 0.5 \ (s/d)$$

$Q^2 = m_W^2$

$\text{ATLAS}$

HERAPDF1.5 + ATLAS $Wc$-jet/$WD^{(*)}$ data

ATLAS-epWZ12

HERAPDF1.5

$\sim2.5\%$ uncertainty(!)
Quark PDF constraints from W, Z “std. candles”

- Differential DY+Z x-section in accord with NNLO over 9 orders-of-magnitude & forward:
  - CMS
  - W electron charge asymmetry vs $|\eta|$ measured to $\sim 1\%$. Many uncertainties cancel in ratio. Constrains $u/d$ PDF ratio
  $\frac{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) - d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) + d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}$
  - W+charm constrains $s/d$ PDF ratio:
    - Mid-x & large-x region

- [EPJC 75 (2015) 147]
- [JHEP 08 (2015) 039]

~2.5% uncertainty(!)
Updated PDF sets with LHC Run-1 data

- Run-1 data constraints: New generation PDFs (global fit) for Run-2:
  - NNPDF2.0 → NNPDF3.0
  - MSTW08 → MMHT14
  - CT10 → CT14
  - HERAPDF1.0 → HERAPDF2.0

- Parton-parton luminosities pre- and post-LHC Run-1:
  
  ![Graphs showing gluon and quark luminosities pre- and post-LHC Run-1.](image)

  - Small-x: Precision physics
  - New physics
Parton fragmentation functions
NLO pQCD overpredicts high-p$_T$ hadron cross sections by factor $\times 2$:

- All Fragmentation Functions (FFs) fail.
  Disagreement increases from $\sqrt{s} = 0.9$ to 7 TeV
- “Old” Kretzer FF shows best agreement:

  [Dd'E et al, NPB883 (2014) 615]

- Same NLO calculations reproduce well high-p$_T$ jet and photon spectra:
  Problems in current parton-to-hadron FFs obtained from $e^+e^-\rightarrow$hadrons data.
Badly-known gluon-to-hadron FFs

- Dominant gluon production & fragmentation up to $p_T \approx 50$ GeV with $<z> \approx 0.3-0.6$

Very large differences on gluon-to-hadron FFs

Current NLO gluon FFs are too hard. Need to refit them with newer data.
Improved gluon-to-hadrons FFs

- Refitting of recent BaBar/Belle $e^+e^-\rightarrow$hadrons data yields softer FFs & better agreement with high-$p_T$ LHC hadron spectra:

[DeFlorian et al, PRD91 (2015) 014035]
Strong coupling determination
**Determination of the QCD coupling $\alpha_s$**

$\alpha_s = \text{Single free parameter in QCD (in the } m_q \to 0 \text{ limit).}$

Determined at a given reference scale (usually $m_Z$).

Decreases as $\sim 1/\ln(Q^2/\Lambda^2)$, with $\Lambda \sim 0.25 \text{ GeV}$

- Least precisely known of all couplings: $\delta\alpha_s \sim 1\% (!), \delta\alpha \sim 3 \cdot 10^{-10}, \delta G_F \sim 5 \cdot 10^{-8}, \delta G \sim 10^{-5}$

- Impacts all LHC cross-sections.

- Key for precise SM studies. Uncertainties: $\pm 4\% \sigma(ggH), \pm 7\% H\rightarrow cc, \pm 4\% H\rightarrow gg$

- BSM physics (e.g. new coloured sectors).

- Determined through comparison of various experimental ($ee, ep, pp$) observables to associated pQCD predictions at NNLO accuracy.

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**Graph**

- $\tau$ decays (N$^3$LO)
- DIS jets (NLO)
- Heavy Quarkonia (NLO)
- $e^+e^-$ jets & shapes (res. NNLO)
- e.w. precision fits (NNLO)
- $pp \rightarrow$ jets (NLO)
- $pp \rightarrow t\bar{t}$ (NNLO)

$QCD \quad \alpha_s(M_Z) = 0.1177 \pm 0.0013$
QCD coupling from jet observables (CMS)

- Ratio of 3-jets of 2-jets, 3-jet mass & inclusive jets x-sections constrain $\alpha_s$ (at NLO accuracy only) up to so-far unprobed scales $Q \sim 1.4$ TeV:

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014 \text{ (exp.)}$$

$$\pm 0.0018 \text{ (PDF)} \pm 0.0050 \text{ (theory)}$$

- Measurements dominated by TH uncertainty: PDF & (asym.) scale uncertainty.

QCD coupling from jet observables (ATLAS)

- Ratio of 3-jets of 2-jets, 3-jet mass & inclusive jets x-sections as well as angular correlations in multijet events constrain $\alpha_s$ (at NLO accuracy):

$$\int L \, dt = 37 \text{ pb}^{-1}$$

$\sqrt{s} = 7 \text{ TeV}$

$\text{anti-k}_t$ jets, $R=0.6$

$0.1151 + 0.0047 - 0.0047$

[Malaeescu & Starovoitov, EPJC72(12)2041]

Upcoming jet x-sections NNLO calculations will provide improved $\alpha_s$ extractions.
QCD coupling from t-tbar cross sections

Total top-antitop cross section (theoretically known at NNLO+NNLL) is the 1\textsuperscript{st} p-p collider observable to constrain $\alpha_s$ at NNLO accuracy:

Data-theory x-section comparison for varying PDF+$\alpha_s$ as a function of $m_{\text{top}}$:

Precise measurement dominated by associated PDF uncertainty ($\pm 2.5\%$)

$\alpha_s(M_Z^2) = 0.1151^{+0.0028}_{-0.0027}$
Total top-antitop cross section (theoretically known at NNLO+NNLL) is the 1\textsuperscript{st} p-p collider observable to constrain $\alpha_s$ at NNLO accuracy:

Data-theory x-section comparison for varying PDF+$\alpha_s$ as a function of $m_{\text{top}}$:

Inclusion of full set of t-tbar data increases the extracted $\alpha_s(m^2_Z)$ value.
Summary: Hard-QCD at the LHC

- Wealth of (differential, central & fwd) data: Jets, (di)γ, W,Z, heavy-Q, Higgs

- Good data–pQCD (N)NLO+(N)NLL accord for total and differential cross sections:

- Improved (N)NLO PDFs via jets, γ, W,Z, charm, ttbar:

- Refitted (N)NLO gluon-to-hadron FFs

- High-precision $\alpha_s$ extractions (asymptotic freedom tested up to ~2 TeV)

- Hard-QCD precision ~5% = Cornerstone for all (B)SM signals & bckgds. studies.
Back up slides
Quantum Chromodynamics

- Quantum Field Theory describing the strong interaction between quarks & gluons via local gauge symmetry: non-Abelian SU(3) color group

**QCD sector in the Standard Model:**

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} + \sum_f \bar{\psi}_i^f \left( i \gamma^\mu D_\mu - m_f \right) \psi_i^f
\]

- Gluon dynamics
- Quark-gluon dynamics + quark mass

\[
F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g s f_{abc} A_\mu^b A_\nu^c
\]

\[
D_\mu = \partial_\mu \pm i g s t_\alpha A_\mu^\alpha
\]

**Infrared confinement = Hadrons**

**Asymptotic freedom = quarks & gluons**

\[
\alpha_s(M_Z) = 0.1189 \pm 0.0010
\]

(lattice QCD) vs (perturbative QCD)
Quantum Chromodynamics

\[ \mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{8} \text{tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2} \text{tr}(G_{\mu\nu} G^{\mu\nu}) \]

- \sqrt{2} \left[ (\bar{\nu}_L, \bar{e}_L) \phi M e_R + \bar{e}_R \tilde{M} e_L \right] \frac{1}{v} \left[ \pmatrix{\nu_L \\ e_L} \right] - \sqrt{2} \left[ (-\bar{e}_L, \bar{\nu}_L) \phi^* M^\nu e_R + \bar{e}_R \tilde{M}^\nu e_L \right] \frac{1}{v} \left[ \pmatrix{-\nu_L \\ e_L} \right]

- \frac{1}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi M d_R + \bar{d}_R \tilde{M} d_L \right] \frac{1}{v} \left[ \pmatrix{u_L \\ d_L} \right] - \sqrt{2} \left[ (-\bar{d}_L, \bar{u}_L) \phi^* M^u u_R + \bar{u}_R \tilde{M}^u u_L \right] \frac{1}{v} \left[ \pmatrix{-d_L \\ u_L} \right]

- (D_{\mu} \phi) D^\mu \phi - m_\pi^2 [\phi \phi - v^2/2] \frac{1}{2v^2}.

• Gauge-fermion dynamics via covariant derivatives:

\[ D_{\mu} \left( \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right) = \begin{pmatrix} \partial_{\mu} - \frac{i g_1}{2} B_{\mu} + \frac{i g_2}{2} W_{\mu} \\ \partial_{\mu} \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad D_{\mu} \left( \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right) = \begin{pmatrix} \partial_{\mu} + \frac{i g_1}{6} B_{\mu} + \frac{i g_2}{2} W_{\mu} + i g G_{\mu} \\ \partial_{\mu} \end{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \]

\[ D_{\mu} \nu_R = \partial_{\mu} \nu_R, \quad D_{\mu} e_R = \left[ \partial_{\mu} - i g_1 B_{\mu} \right] e_R, \quad D_{\mu} u_R = \left[ \partial_{\mu} + \frac{2 g_2}{3} B_{\mu} + i g G_{\mu} \right] u_R, \quad D_{\mu} d_R = \left[ \partial_{\mu} - \frac{g_1}{3} B_{\mu} + i g G_{\mu} \right] d_R. \]

\[ D_{\mu} \phi = \begin{pmatrix} \partial_{\mu} + \frac{g_1}{2} B_{\mu} + \frac{g_2}{2} W_{\mu} \end{pmatrix} \phi. \]

• Gauge-boson field strength tensors:

\[ B_{\mu\nu} = \partial_{\mu} B_{\nu} - \partial_{\nu} B_{\mu}, \quad W_{\mu\nu} = \partial_{\mu} W_{\nu} - \partial_{\nu} W_{\mu} + i g_2 (W_{\mu} W_{\nu} - W_{\nu} W_{\mu}) / 2, \quad G_{\mu\nu} = \partial_{\mu} G_{\nu} - \partial_{\nu} G_{\mu} + i g (G_{\mu} G_{\nu} - G_{\nu} G_{\mu}). \]

«Issues»: no CP-violation (axion?), confinement, non-perturbative structure/dynamics,...
Higgs cross sections: pQCD predictions

- Theory calculations include increasing # of real emissions + virtual corrections + soft&collinear log resummations (improves $p_T$ differential distributions).

- Higgs production is paradigmatic example:

  Higgs $\sigma(gg\rightarrow H)$ at $N^3$LO:

  Higgs $d\sigma/dp_T$ at NNLO+NNLL:

  $\sigma_{ggH} = 19.47$ mb (+0.3%-3.0%)


  [DeFlorian et al. arXiv:1203.6321]
Gluon PDF constraints via LHC $\gamma$, charm, t-tbar

- **Isolated photon $p_T$ spectra:**
  
  - LHC: $pp \sqrt{s} = 2.76, 7$ TeV
  - Tevatron: $p\bar{p} \sqrt{s} = 1.96$ TeV
  - Tevatron: $pp \sqrt{s} = 1.8$ TeV
  - SpS, Tevatron: $pp \sqrt{s} = 630$ GeV
  - SpS: $pp \sqrt{s} = 546$ GeV
  - RHIC: $pp \sqrt{s} = 200$ GeV

- **Forward D-mesons (LHCb):**

- **Top-pair total x-sections (NNLO):**

- Reduced gluon uncertainties at different $(x, Q^2)$
Searches of “Beyond DGLAP” evolution

- **DGLAP** equations describe parton radiation as a function of $Q^2$:
  \[ f(Q^2) \sim \alpha_s \ln \left( \frac{Q^2}{Q_0^2} \right)^n \]  
  [fixed-order PDFs, collinear factorization]

- **BFKL**, saturation evolutions: At low-$x$ & mid $Q^2$, parton emission in $p_L, \eta$
  \[ f(x) \sim \alpha_s \ln(1/x)^n \]  
  [uPDFs, $k_T$-factorization]

- Mueller-Navelet dijets with large $y$ separation very sensitive to BFKL:
  \[ \Delta \eta \sim 10 \]  
  (Atlas, CMS)

- Extra radiation in rapidity?
- Enhanced azimuthal decorrelation?
“Beyond DGLAP” in LHC Mueller-Navelet dijets?

MN dijet azimuthal decorrelations over large $\Delta y$:
Absolute $\Delta \phi$ distributions & ratio moments vs $\Delta y$

HERWIG = DGLAP + (N)LL parton-shower not doing bad ...

Latest NLL+ BFKL also consistent with results... Final word at lower $p_T$?