# QCD Physics at the LHC

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# Remarkable experimental performance

- Overall good agreement with the SM, over 14 orders of magnitude!
- Many differential/inclusive cross-sections are known at permil precision! i.e. better than the theories.



# A precision era!

# Limitations due to QCD predictions



#### How to turn to the pole mass? Theory error could be ~ 1GeV

Large ED (ADD) : monojet Large ED (ADD) : diphotor Mg (GRW cut-of ATLAS UED :  $\gamma\gamma + E$ Compact, scale 1/R (SPS8) RS with  $k/M_{m} = 0.1$  : diphoton, m. Graviton mass RS with  $k/M_{\rm Pl} = 0.1$  : dilepton, m Graviton mass  $Ldt = (0.04 - 5.0) \text{ fb}^{-1}$ RS with  $k/M_{pl} = 0.1$  : ZZ resonance,  $m_{m}$ RS with g / g = -0.20 :  $t\bar{t} \rightarrow l+jets$ , nADD BH ( $M_{TH}^{qqK}/M_{D}=3$ ) : multijet,  $\Sigma p_{T}$ ,  $N_{ie}$ IS = 7 TeV KK aluon ma ADD BH (MTH /MD=3) : SS dimuon, N (δ=6 ADD BH  $(M_{TH}/M_{D}=3)$  : leptons + jets,  $\Sigma p$ Quantum black hole : dijet, F (n gggg contact interaction : 2(m aall CI : ee. uu combined. I uutt CI : SS dilepton + jets +  $E_{T}$ SSM Z Z 21 TeV Z' mass SSM W': m W' mas Scalar LQ pairs ( $\beta$ =1); kin, vars, in eeii, ev gen. LQ mass calar LQ pairs ( $\beta$ =1) : kin. vars. in  $\mu\mu$ jj,  $\mu\nu$ j Tev q\* mas Excited quarks : dijet resonance, Excited electron : e-y resonance, m Excited muon : µ-y resonance, m  $\mu^*$  mass ( $\Lambda = m(\mu^*)$ ) Techni-hadrons : dilepton, men  $m(\pi_{\rm T}) = 100 \, {\rm GeV}$ adrons : WZ resonance (vIII),  $m_{\tau}^{e}$  $ss(m(o)) = m(\pi_{\pi}) + m_{uv} \cdot m(a) = 1.1 m(o)$ neutr. (LRSM, no mixing) : 2-lep + jets  $M mass (m(W_) = 2 TeV)$ W<sub>R</sub> (LRSM, no mixing) : 2-lep + jets d., BR( $H^{\pm\pm} \rightarrow \mu\mu$ )=1) : SS dimuon, m  $W_{o}$  mass (m(N) < 1.4 GeV)prod., BR(H Color octet scalar : dijet resonance. m Vector-like quark : CC. m. Q mass (coupling  $\kappa_{qQ} = v/m_Q$ ) Q mass (coupling  $\kappa_{qQ} = v/m$ 10<sup>2</sup> 10 10 Mass scale [TeV] \*Only a selection of the available mass limits on new states or phen

### Precision measurements of the SM param.

•  $m_{\rm top}, m_W, \sin^2 \theta_w, \ldots$ 

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• (partially) dominated by the QCD uncertainties

 $m_t^{\text{pole}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{theory}) \text{ GeV}$ 

Similar story for constraining new physics and hard probing hadrons



# Theorists are catching up

W/Z total, H total, Harlander, Kilgore H total, Anastasiou, Melnikov H total, Ravindran, Smith, van Neerven WH total, Brein, Djouadi, Harlander H diff., Anastasiou, Melnikov, Petriello H diff., Anastasiou, Melnikov, Petriello W diff., Melnikov, Petriello W/Z diff., Melnikov, Petriello H diff., Catani, Grazzini W/Z diff., Catani et al

# explosion of calculations in past 24 months

2002 2004 2006 2008 2010 2012 2014 2016 Fixed Order:

- $LO + NLO + NNLO + \cdots$
- the most powerful tool for LHC physics

as of April 2017, let me know of omissions

VBF total, Bolzoni, Maltoni, Moch, Zaro WH diff., Ferrera, Grazzini, Tramontano Hj (partial), Boughezal et al. ttbar total, Czakon, Fiedler, Mitov Z-γ, Grazzini, Kallweit, Rathlev, Torre jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires ZZ, Cascioli it et al. ZH diff., Ferrera, Grazzini, Tramontano WW, Gehrmann et al. ttbar diff., Czakon, Fiedler, Mitov Z-y, W-y, Grazzini, Kallweit, Rathlev Boughezal et al. Wj, Boughezal, Focke, XL, Petriello Hj, Boughezal, Focke, Giele, XL, Petriello VBF diff.. Cacciari et al. Zj, Gehrmann-De Ridder et al. ZZ, Grazzini, Kallweit, Rathlev Hj, Caola, Melnikov, Schulze Zi, Boughezal, Focke, XL, Petriello + MCFM WH diff., ZH diff., Campbell, Ellis, Williams y-y, Campbell, Ellis, Li, Williams WZ, Grazzini, Kallweit, Rathlev, Wiesemann WW, Grazzini et al. MCFM at NNLO, Boughezal, Focke, XL, Petriello + MCFM ptz, Gehrmann-De Ridder et al. single top, Berger, Gao, C.-Yuan, Zhu HH, de Florian et al. ptH, Chen et al. pt7, Gehrmann-De Ridder et al. jj, Currie, Glover, Pires yX, Campbell, Ellis, Williams yj, Campbell, Ellis, Williams

Gavin P. Salam, 2017

y-y, Catani et al.

# Fixed Order Calculations

### Virtual

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- IBP + improvements Larporta, + ...
- Differential eqn. Kotikov
- Difference eqn. Larporta
- SecDec. Binoth, Heinrich
- Mellin Barnes Usyukina, Smirnov
- Series representation Ma, et.al
- Parameter expansions Yang, et.al
- Quasi-Monte Carlo Li, et. al.

### Real

- Antenna subtraction Gehrmann, Glover, et.al
- STRIPPER Czakon, et.al
- N-jettiness subtraction Boughezal, XL, et.al
- qT-subtraction Catani, et.al
- Inclusive jet mass subtraction Gao, Li, Zhu
- P2B Salam, et. al.
- • •

### Both loops and real corrections are important for predictions at the LHC

e.g., 2- loops for di-jet production are known for long ( $\sim$ 2001), but no methods to deal with the real before 2015.

## Resummation

Standard approaches to the predictions: FO + Res.

...... Fixed order (b)-----NLO ----Asy • Breaks down in the soft--Res -Pythia 3 collinear dominated regions -----Y-piece do/dq\_ [pb/ pp→t+jet  $\mu = H_T$  $P_{J\perp} > 30 \text{ GeV}$  $3 < |y_J| < 4.5, |y_t| < 3$ Resummation to rescue •  $LL + NLL + NNLL + \cdots$ • Parton shower (~ LL) 50 10 20 30 40 • Analytic — SCET …  $q_{\perp}[\text{GeV}]$ 

Cao, Sun, Yan, Yuan, Feng 2018

# Outlines

- LHC phenomenology and available tools
  - Higgs, vector bosons and jets
- Summary

VBE total, Bolzoni, Maltoni, Moch, Zaro W/Z total, H total, Harlander, Kilgore WH diff., Ferrera, Grazzini, Tramontano H total, Anastasiou, Melnikov v-v. Catani et al. H total, Ravindran, Smith, van Neerven Hj (partial), Boughezal et al. WH total, Brein, Djouadi, Harlander ttbar total, Czakon, Fiedler, Mitov H diff., Anastasiou, Melnikov, Petriello Z-v. Grazzini, Kallweit, Rathlev, Torre H diff., Anastasiou, Melnikov, Petriello /jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires W diff., Melnikov, Petriello ZZ. Cascioli it et al. W/Z diff., Melnikov, Petriello ZH diff., Ferrera, Grazzini, Tramontano diff., Catani, Grazzin WW, Gehrmann et al. ttbar diff., Czakon, Fiedler, Mitov -Z-γ, W-γ, Grazzini, Kallweit, Rathlev Hj, Boughezal et al. -Wi, Boughezal, Focke, XL, Petriello Hj, Boughezal, Focke, Giele, XL, Petriello VBF diff., Cacciari et al. explosion of calculations Zj, Gehrmann-De Ridder et al. -ZZ, Grazzini, Kallweit, Rathlev Hj, Caola, Melnikov, Schulze in past 24 months Zj, Boughezal, Focke, XL, Petriello + MCFM WH diff., ZH diff., Campbell, Ellis, Williams y-y, Campbell, Ellis, Li, Williams 2002 2004 2006 2008 2010 2012 2014 2016 WZ, Grazzini, Kallweit, Rathlev, Wiesemann WW, Grazzini et al. MCFM at NNLO, Boughezal, Focke, XL, Petriello + MCFM ptz, Gehrmann-De Ridder et al. single top, Berger, Gao, C.-Yuan, Zhu HH, de Florian et al. ptH, Chen et al. ptz, Gehrmann-De Ridder et al. ii. Currie, Glover, Pires YX, Campbell, Ellis, Williams as of April 2017, let me know of omissions yj, Campbell, Ellis, Williams

# Higgs



- The only fundamental scalar in the SM
- Potential? Completely unknown!
- Yukawa? Only on the 3rd generations
- Portals to New physics
- ••



All measurements are consistent with the SM

$$\sigma_{ggH} = 48.58 \text{ pb}_{-6.72\%}^{+4.56\%} \text{(theory)} \pm 3.2\% \text{(PDF} + \alpha_s)$$
Anastasou, et.al., 2016
Precision is the key!

Frontier of the Precision Frontier, from 2016 to 2018

$$\sigma_{ggH} = 48.58 \text{ pb}_{-6.72\%}^{+4.56\%} \text{(theory)} \pm 3.2\% \text{(PDF} + \alpha_s)$$



Small discrepancies mainly due the slow soft convergence of the qq channels

Frontier of the Precision Frontier, from 2016 to 2018

NOT ONLY inclusive x-sec!

Dulat, et.al., 2018



- Fully exclusive N3LO available
- Perturbative uncertainties reduced to 4%
- N3LO distribution

   (left) well
   reproduced by
   assuming a flat
   correction (right)

Cieri, et.al., 2018

Frontier of the Precision Frontier, from 2016 to 2018

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pT spectrum at NNLO + N3LL
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- Res. is crucial for small pT
- Further reduce the theory errors



NNLO see also Boughezal, et. al., 2015

Boughezal, Focke, Giele, XL, Petrillo, 2015

# Vector Bosons

- Benchmark process at the LHC
- Clean signature, exp. uncertainty < 1%
- Irreducible background for NP searches
- Sensitive to PDFs





Independent calculations by different groups with different methods



Boughezal, Focke, XL, Petriello + MCFM, 2016



NLO underestimates the data by 50% !

NNLO recovers agreement with data by add on missing high orders.

Boughezal, Focke, XL, Petriello + MCFM, 2016



### Z pT distribution

- Clean and very small exp. uncertainty  $\sim 1\%$
- therefore standard candle at the LHC

# NNLO agrees much better than NLO.



	Before $p_T^Z$ data	After $p_T^Z$ data
$\sigma_{gg \to H} \text{ [pb]}$	$48.22\pm0.89~(1.8\%)$	$48.61 \pm 0.61 \ (1.3\%)$
$\sigma_{\rm VBF} \ [{\rm pb}]$	$3.92\pm 0.06~(1.5\%)$	$3.96 \pm 0.04 \; (1.0\%)$

#### Error reduced by 30% when NNLO Z pT included

# Jet

- Anther benchmark process at the LHC
- Related to new physics searches, PDF fitting …





Overall good agreements with data, but  $\cdots$ 

Long time systematic discrepancies between theory and the data

Holds for 7, 8, 13,  $\cdots$  TeV



NNLO seems to help, but Strongly depends on the scale choices!



Currie, Glover, Pires, 2018

Resummation (small R + threshold) helps here

- Small R res. reduces the cross section
- Threshold enhances the cross section
- After resummation, the theory describes the data well



XL, Moch, Ringer, 2018

# Tools

Available tools for NNLO predictions Grazzini, et.al.

- MATRIX (qT-subtraction, public)
  - zero-jet ggH, Drell-Yan …
- MCFM 8.0 @ NNLO (N-jettiness-subtraction) Boughezal, Focke, XL, Petriello + MCFM
  - zero-jet ggH, Drell-Yan … (public)
  - Z/W/photon/H+1-jet (private)
- NNLOJET (antenna subtraction, private) Gehrmann et. al.
  - Lots of NNLO and N3LO + res. Results
- Already used in experimental analysis In general, good agreements are found

# Sorry for not covering

- Inclusive VBF @ N3LO Dreyer, Karlberg, 18
- VBF distribution @ N2LO Cacciari, et.al., 15, Cruz-Martinez, et. al., 18
- Full top mass dependent NLO HH Borowka, et. al., 16
- Full top mass dependent NLO H + jet production Jones, et. al., 18
- Top quarks Czakon, et, al; Li, Gao, Zhu; Wang, Yang; Gao, Liu …
- VV' productions a lot since 2014
- Jet substructures Kang, Marzani, Larkoski, Lee, XL, Ringer, Salam, Soyez, Thaler, Wang, …
- Other relevant topics, e.g. DIS @ N3LO, N2LO …

Gehrmann, et.al.; Berger, Li, Liu, Zhu, Abelof, Boughezal, XL, Petriello …

## Summaries

- A competitive and highly active area
- Precision is important (test QCD + new physics searches)
- A lots for 2 -> 2 processes have been pushed to NNLO or even beyond, public tools are also available now
- Beyond that, the predictions are limited by the unknown virtual corrections, e.g., 3jet,  $V + 2j \cdots$

# Thanks!