QCD for LHC

Gavin P. Salam* Rudolf Peierls Centre for Theoretical Physics All Souls College

* on leave from CERN and CNRS





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THE ROYAL SOCIETY

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what are we trying to learn at the LHC?

Z = - + FAL FMU + iFDY $+ \chi_i \mathcal{Y}_{ij} \chi_j \phi + h.c.$ $+ \left| D_{m} \varphi \right|^{2} - V(\phi)$ GAN www.cam.dt

what is the underlying Lagrangian of particle physics?





Z = - + FAUFMU + iFDY $- \chi_{i} \chi_{ij} \chi_{j} \phi + h.c.$ $- |D_{m} \phi|^{2} - V(\phi)$

LHC is first machine to directly access Higgs sector Is it the minimal version hypothesised in the SM? origin of mass for W/Z origin of mass for fermions via Yukawa couplings a potential V(ϕ) that is theorists' favourite toy (φ⁴), but yet to be confirmed in nature











Z = - + FAL FMU + iFDY + $\chi_i \mathcal{Y}_{ij} \chi_j \phi + h.c.$ $+ \left| D_{m} \varphi \right|^{2} - V(\phi)$

Is there anything else at the ~TeV scale?

If not, then many people worry about fine tuning









Z = - + FAUFMU + iFDY + $\chi_i y_{ij} \chi_j \phi + h.c.$ + $|D_{m}g|^2 - V(\phi)$ (AN) www.cam.dt

what are the values of the parameters of the SM? couplings (esp. strong coupling) masses (e.g. top & W masses)









 $\frac{M_h}{\text{GeV}} > 124.2 - \frac{190}{\log_{10}^2 \frac{T_{\text{RH}}}{G_{\text{eV}}}} + 2.0 \left(\frac{M_t}{\text{GeV}} - 173.34\right) - 0.6 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.$

what are the values of the parameters of the SM? couplings (esp. strong coupling) masses (e.g. top & W masses)

arXiv:1505.04825









A proton-proton collision: INITIAL STATE













A proton-proton collision: FINAL STATE



(actual final-state multiplicity ~ several hundred hadrons)





A PIOLUII - PIOLUII COUISIUII. I IMAL OIAIL

UNDERLYING THEORY

 $\begin{aligned} \mathcal{I} &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i F \mathcal{N} \mathcal{V} \end{aligned}$ + $\mathcal{Y}_{ij}\mathcal{Y}_{j}\phi$ +h.c + $|\mathcal{D}_{m}\phi|^{2} - V(\phi)$

how do you make quantitative connection?

through a chain of experimental and theoretical links

EXPERIMENTAL DATA







What are the links? ATLAS and CMS (big LHC expts.) have written ~1000 articles since 2014 links \equiv papers they cite

Pileup subtraction

Herwig 6 MC

MWLO ttbar

PDF4LHC (2011)

Muddress Pors

Cl(s) technique

MNDDF30 PDFS

Likelihood tests for hew physics

Sherba 1.1

Madgraph 5

to02++

Fastuer Manual

quantum chromodynamics (QCD) theory papers

experimental & statistics papers



Perugia tunes (2010)

this lecture: 7 small parts

- 1. structure of QCD Lagrangian
- 2. a master formula
- 3. the strong coupling
- 4. parton distribution functions
- 5. fixed order calculations
- 6. Monte Carlo event generators

7. jets

the QCD lagrangian and lattice QCD

Quarks — 3 colours: $\psi_a = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$

Quark part of Lagrangian:

 $\mathcal{L}_{q} = \bar{\psi}_{a} (i \gamma^{\mu} \partial_{\mu} \partial_{\mu}$

 $SU(3) \text{ local gauge symmetry} \leftrightarrow 8$ corresponding to 8 gluons $\mathcal{A}^{1}_{\mu} \dots$ A representation is: $t^{A} = \frac{1}{2}\lambda^{A}$, $\lambda^{1} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \ \lambda^{2} = \begin{pmatrix} 0 & -i \\ i & 0 \\ 0 & 0 \end{pmatrix}$ $\lambda^{5} = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \ \lambda^{6} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix}$



$$\delta_{ab} - g_s \gamma^{\mu} t^{C}_{ab} \mathcal{A}^{C}_{\mu} - m) \psi_b$$

$$\mathcal{B} \ (= 3^2 - 1) \ ext{generators} \ t_{ab}^1 \dots t_{ab}^8$$

 \mathcal{A}^8_μ .

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \ \lambda^{3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \ \lambda^{4} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$
$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \ \lambda^{7} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \ \lambda^{8} = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix},$$



Lagrangian:

 $\mathcal{L}_{G} =$



Field tensor: $F^{A}_{\mu\nu} = \partial_{\mu}A^{A}_{\nu} - \partial_{\nu}A^{A}_{\nu} - g_{s}f_{ABC}A^{B}_{\mu}A^{C}_{\nu}$ $[t^{A}, t^{B}] = if_{ABC}t^{C}$

 f_{ABC} are structure constants of SU(3) (antisymmetric in all indices — SU(2) equivalent was e^{ABC}). Needed for gauge invariance of gluon part of

$$-rac{1}{4}F^{\mu
u}_{A}F^{A\,\mu
u}$$





The only complete solution uses lattice QCD

- put all quark & gluon fields on a 4d lattice (NB: imaginary time)
- Figure out most likely configurations (Monte Carlo sampling)

QCD ttice



image credit <u>fdecomite [flickr]</u>

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For LHC reactions, lattice would have to Resolve smallest length scales (2 TeV ~ 10⁻⁴ fm) > Contain whole reaction (pion formed on timescale ~ 1fm, with boost of $10^4 - i.e. 10^4$ fm) That implies 10⁸ nodes in each dimension, i.e. 10³² nodes — inconceivable



Durr et al, arXiv:0906.3599

the strong coupling, *a*_s *it feeds into everything else in collider QCD*

for more info see <u>arXiv:1712.05165</u>, <u>arXiv:1902.08191</u>

All couplings run: the QCD coupling runs fastest

Solve
$$Q^2 \frac{d\alpha_s}{dQ^2} \simeq -b_0 \alpha_s^2 \Rightarrow \alpha_s (C)$$

 $\Lambda \simeq 0.2 \text{ GeV}$ (aka Λ_{QCD}) is the fundamental scale of QCD, at which perturbative coupling blows up.

- ► it sets the mass scale for most hadrons
- perturbation theory only valid for $Q \gg \Lambda$, where a_s is small

PDG World Average: $\alpha_{s}(M_{Z}) = 0.1181 \pm 0.0011 (0.9\%)$





tau	⊢∎ PDF	Collider
Lattice	Event-Shapes	Electroweak



 a_{s}

strong-coupling determinations

Bethke, Dissertori & GPS in PDG '16

- Most consistent set of independent determinations is from lattice
- Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169) $a_s(M_Z) = 0.1183 \pm 0.0007 (0.6\%)$ [heavy-quark] correlators

- Many determinations quote small uncertainties ($\leq 1\%$). Most are disputed!
- Most robust is perhaps ALPHA lattice result $a_s(M_Z) = 0.1185 \pm 0.00084 \ (0.7\%)$
 - Some determinations quote anomalously small central values (~0.113 v. world avg. of 0.1181±0.0011). Also disputed











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factorisation

and perturbative expansions

a proton-proton collision: FILLING IN THE PICTURE

. . .



proton

Why is simplification "allowed"?

- > Proton's dynamics occurs on timescale $O(1-10^4 \text{ fm/c})$ Final-state hadron dynamics occurs on timescale $O(1-10^4 \text{ fm/c})$
- Production of Higgs, Z (and other "hard processes") occurs on timescale $1/M_{\rm H} \sim 1/125 \text{ GeV} \sim 0.002 \text{ fm/c}$

all the hadronic dynamics

key idea #1 FACTORISATION



That means we can separate — "factorise" — the hard process, i.e. treat it as independent from





Why is simplification "allowed"?

- > On timescales $1/M_{\rm H} \sim 1/125$ GeV ~ 0.002 fm you can take advantage of asymptotic freedom
- constant $a_s(125 \text{ GeV}) \sim 0.11$



key idea #2 USE PERTURBATION THEORY

▶ i.e. you can write results in terms of an expansion in the (not so) strong coupling



Why is simplification "allowed"? key idea #2 short-distance QCD corrections are perturbative

- > On timescales $1/M_{\rm H} \sim 1/125$ GeV ~ 0.002 fm you can take advantage of asymptotic freedom
- constant $a_s(125 \text{ GeV}) \sim 0.11$

 $\hat{\sigma} = \hat{\sigma}_0 (1 + c_1 \alpha_s + c_2 \alpha_s^2 + \cdots)$

(Next-to-next-to-Leading Order)

▶ i.e. you can write results in terms of an expansion in the (not so) strong coupling









$$\begin{split} &\sum_{i,j} \int dx_1 dx_2 f_{i/h_1} \left(x_1, \mu_F^2 \right) f_{j/h_2} \left(x_2, \mu_F^2 \right) \\ &x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left(\frac{\Lambda^2}{M_W^4} \right) \,, \end{split}$$





$$\sum_{i,j} \int dx_1 dx_2 f_{i/h_1} \left(x_1, \mu_F^2 \right) f_{j/h_2} \left(x_2, \mu_F^2 \right)$$
$$x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left(\frac{\Lambda^2}{M_W^4} \right) ,$$

Parton distribution function (PDF): e.g. number of up antiquarks carrying fraction x₂ of proton's momentum

proton

U





$\sigma(h_1 h_2 \to ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n \left(\mu_R^2\right) \sum_{i,j} \int dx_1 dx_2 \frac{f_{i/h_1}\left(x_1, \mu_F^2\right)}{f_{j/h_2}\left(x_2, \mu_F^2\right)} f_{j/h_2}\left(x_2, \mu_F^2\right)$ $\times \hat{\sigma}_{ij \to ZH+X}^{(n)} \left(x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O}\left(\frac{\Lambda^2}{M_W^4} \right) \,,$ Parton distribution function (PDF): e.g. number of up quarks carrying fraction x_1 of proton's momentum U proton





Perturbative sum over powers of the strong coupling: typically we use first 2-4 orders

$$\sum_{i,j} \int dx_1 dx_2 f_{i/h_1} \left(x_1, \mu_F^2 \right) f_{j/h_2} \left(x_2, \mu_F^2 \right) x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left(\frac{\Lambda^2}{M_W^4} \right) ,$$





$$\begin{split} &\sum_{i,j} \int dx_1 dx_2 f_{i/h_1} \left(x_1, \mu_F^2 \right) f_{j/h_2} \left(x_2, \mu_F^2 \right) \\ &x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O} \left(\frac{\Lambda^2}{M_W^4} \right) \,, \end{split}$$

At each perturbative order n we have a specific "hard matrix element" (sometimes several for different subprocesses)

proton

U



 $\sigma(h_1 h_2 \to ZH + X) = \sum_{n=0}^{\infty} \alpha_s^n \left(\mu_R^2\right) \sum_{i=i}^{\infty} \int dx_1 dx_2 f_{i/h_1}\left(x_1, \mu_F^2\right) f_{j/h_2}\left(x_2, \mu_F^2\right)$





 $\times \hat{\sigma}_{ij \to ZH+X}^{(n)} \left(x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + \mathcal{O}\left(\frac{A^2}{M_W^4}\right) , \checkmark$

proton

Additional corrections from nonperturbative effects: higher "twist", suppressed by powers of QCD scale (Λ) / hard scale





parton distribution functions (PDFs)

For visualisations of PDFs and related quantities, a good place to start is <u>http://apfel.mi.infn.it/</u> (ApfelWeb)






knowing what goes into a collision i.e. proton structure



Deep Inelastic Scattering — the simpler context to determine PDFs









two major kinematic variables: $\mathbf{x} \simeq \text{longitudinal}$

momentum fraction of struct quark

> $Q^2 \simeq photon$ virtuality \rightarrow

transverse

resolution at which

is probes proton

structure





Parton distribution and DGLAP

Write up-quark distribution in proton as

running coupling.

> As you vary the factorisation scale, the parton distributions evolve with a renormalisation-group type equation



Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations

$$f_{u/p}(x,\mu_F^2)$$

 $\succ \mu_F$ is the factorisation scale — a bit like the renormalisation scale (μ_R) for the





Today's PDF fits









► LHC EW physics probes x $\sim m_{\rm H}/\sqrt{s} \sim 0.01$

► gluon distribution is ~ 10× larger than (up) quark distribution

10 3 0.3 0.1

 $x f_{i/p}(x)$

30

(number per unit log x)



carried by quark/gluon



► LHC EW physics probes $x \sim m_{\rm H}/\sqrt{s} \sim 0.01$

30

10

3

0.3

0.1

 $x f_{i/p}(x)$

- gluon distribution is ~
 10× larger than (up)
 quark distribution
- viewing proton at scales
 from 2 GeV to 100 GeV,
 DGLAP evolution modifies
 PDFs by ~ ×2–10

quark & gluon distributions inside proton (number per unit log x)



X = fraction of proton momentum carried by quark/gluon





fixed-order calculations

LO

 $\sigma \sim \sigma_2 \alpha_s^2 + \sigma_3 \alpha_s^3 + \sigma_4 \alpha_s^4 + \sigma_5 \alpha_s^5 + \cdots$ NLO NNLO N3LO







fixed order calculations (only modestly represented in plot, but arguably the core of the field)











to illustrate the concepts, we don't care what the particles are — just draw lines

+ complex conj.







doing better than Feynman diagrams to calculate individual terms



amp =

```
+ F(CiE1,Ci2,CiE4)*F(CiE2,Ci2,CiXX)*F(CiE3,CiE5,CiXX) * (
   - e1.e3*e2.e5*e4.p1*s14^-1
   - 1/2*e1.e3*e2.e5*e4.p4*s14^-1
   - 1/2*e1.e4*e2.e3*e5.p1*s14^-1
   + 1/2*e1.e4*e2.e3*e5.p4*s14^-1
   + 1/2*e1.e4*e2.e5*e3.p1*s14^-1
   - 1/2*e1.e4*e2.e5*e3.p4*s14^-1
   + e1.e5*e2.e3*e4.p1*s14^-1
   + 1/2*e1.e5*e2.e3*e4.p4*s14^-1
   - 1/2*e1.p1*e2.e3*e4.e5*s14^-1
   + 1/2*e1.p1*e2.e5*e3.e4*s14^-1
   - e1.p4*e2.e3*e4.e5*s14^-1
   + e1.p4*e2.e5*e3.e4*s14^-1
+ F(CiE1,Ci2,CiE4)*F(CiE2,Ci2,Ci4)*F(CiE3,CiE5,Ci4) * (
   - 2*e1.e2*e3.e5*e4.p1*p1.p3*s14^-1*s124^-1
   - 2*e1.e2*e3.e5*e4.p1*p1.p4*s14^-1*s124^-1
   + 2*e1.e2*e3.e5*e4.p1*p2.p3*s14^-1*s124^-1
   - 2*e1.e2*e3.e5*e4.p1*p3.p4*s14^-1*s124^-1
   - e1.e2*e3.e5*e4.p4*p1.p3*s14^-1*s124^-1
   - e1.e2*e3.e5*e4.p4*p1.p4*s14^-1*s124^-1
   + e1.e2*e3.e5*e4.p4*p2.p3*s14^-1*s124^-1
   - e1.e2*e3.e5*e4.p4*p3.p4*s14^-1*s124^-1
   + e1.e2*e3.p1*e4.p1*e5.p1*s14^-1*s124^-1
   - 3*e1.e2*e3.p1*e4.p1*e5.p2*s14^-1*s124^-1
   + e1.e2*e3.p1*e4.p1*e5.p3*s14^-1*s124^-1
   + e1.e2*e3.p1*e4.p1*e5.p4*s14^-1*s124^-1
   + 1/2*e1.e2*e3.p1*e4.p4*e5.p1*s14^-1*s124^-1
   - 3/2*e1.e2*e3.p1*e4.p4*e5.p2*s14^-1*s124^-1
   + 1/2*e1.e2*e3.p1*e4.p4*e5.p3*s14^-1*s124^-1
   + 1/2*e1.e2*e3.p1*e4.p4*e5.p4*s14^-1*s124^-1
   + 3*e1.e2*e3.p2*e4.p1*e5.p1*s14^-1*s124^-1
```

slide adapted from Fabrizio Caola

+ 22 similar terms



Massive simplification!

 $A_5^{\text{tree}}(1^{\pm}, 2^{+}, 3^{+}, 4^{+}, 5^{+}) = 0$ $A_5^{\text{tree}}(1^-, 2^-, 3^+, 4^+, 5^+) = i \frac{\langle 12 \rangle}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle}$ $\langle 13 \rangle^4$ $A_5^{\text{tree}}(1^-, 2^+, 3^-, 4^+, 5^+) = i_{\overline{a}}$

mathematically equivalent

VBF total, Bolzoni, Maltoni, Moch, Zaro WH diff., Ferrera, Grazzini, Tramontano W/Z total, H total, Harlander, Kilgore γ-γ, Catani et al. H total, Anastasiou, Melnikov Hj (partial), Boughezal et al. H total, Ravindran, Smith, van Neerven ttbar total, Czakon, Fiedler, Mitov /WH total, Brein, Djouadi, Harlander Z-γ, Grazzini, Kallweit, Rathlev, Torre jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires /H diff., Anastasiou, Melnikov, Petriello ZZ, Cascioli it et al. H diff., Anastasiou, Melnikov, Petriello ZH diff., Ferrera, Grazzini, Tramontano W diff., Melnikov, Petriello WW, Gehrmann et al. /W/Z diff., Melnikov, Petriello ttbar diff., Czakon, Fiedler, Mitov - Z-γ, W-γ, Grazzini, Kallweit, Rathlev H diff., Catani, Grazzini Hj, Boughezal et al. /W/Z diff, Catani et al Wj, Boughezal, Focke, Liu, Petriello Hj, Boughezal et al. VBF diff., Cacciari et al. Gehrmann-De Ridder et al. QQ ZZ, Grazzini, Kallweit, Rathlev X **S** Hi, Caola, Melnikov, Schulze É, Zj, Boughezal et al. WH diff., ZH diff., Campbell, Ellis, Williams γ-γ, Campbell, Ellis, Li, Williams WZ, Grazzini, Kallweit, Rathlev, Wiesemann p_{t7}, Gehrmann-De Ridder et al. WW, Grazzini et al. MCFM at NNLO, Boughezal et al. single top, Berger, Gao, C.-Yuan, Zhu HH, de Florian et al. p_{tH}, Chen et al. p_{tZ}, Gehrmann-De Ridder et al. jj, Currie, Glover, Pires γX, Campbell, Ellis, Williams yj, Campbell, Ellis, Williams VH, H->bb, Ferrera, Somogyi, Tramontano single top, Berger, Gao, Zhu HHZ, Li, Li, Wang 2020 2012 2014 2016 2018 2004 2006 2008 2010 DIS jj, Žlebčík et al. VH, H->bb, Caola, Luisoni, Melnikov, Roentsch p_{tW}, Gehrmann-De Ridder et al. WBF diff., Cruz-Martinez, Gehrmann, Glover, Huss Wj, Zj, Gehrmann-De Ridder et al. ttbar total, Catani et al. γj, Chen et al. H->bbj, Mondini, Williams ttbar diff., Catani et al.

major advances in NNLO calculations v. time 2002 as of 2019-05, with input from Fabrizio Caola





Higher precision needs more legs & more loops

Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD

S. Abreu,^{*a*} J. Dormans,^{*b*} F. Febres Cordero,^{*b*,*c*} H. Ita,^{*b*} B. Page,^{*d*} and V. Sotnikov^{*b*}

ABSTRACT: We present the analytic form of all leading-color two-loop five-parton helicity amplitudes in QCD. The results are analytically reconstructed from exact numerical evaluations over finite fields. Combining a judicious choice of variables with a new approach to the treatment of particle states in D dimensions for the numerical evaluation of amplitudes, we obtain the analytic expressions with a modest computational effort. Their systematic simplification using multivariate partial-fraction decomposition leads to a particularly compact form. Our results provide all two-loop amplitudes required for the calculation of next-tonext-to-leading order QCD corrections to the production of three jets at hadron colliders in the leading-color approximation.

Order in perturbation theory:

 $\alpha_s^{n_{\rm legs}+n_{\rm loops}-2}$



57

perturbative series for Higgs production (gg \rightarrow H)



results from <u>arXiv:1503.06056</u>

ggF, hE qq ω Φ <PDF4L Ъ, μ_0 :m_H/2, $\mu_{F}=\mu_{0}$

even though $as(m_H) \approx 0.11$, perturturbative series requires a number of orders in order to start converging

a similar phenomenon holds for almost all hadron collider cross sections (though not usually quite this bad)

NB: here, only the renorm. scale $\mu(\equiv \mu_R)$ has been varied to estimate uncertainty. In real life you need to change renorm. and factorisation (μ_F) scales.





Monte Carlo event generators see e.g. <u>arXiv:1202.1251</u>, PDG <u>review</u>







predicting what collider events look like IN DETAIL

QCD Parton Shower [parton = quark or gluon]







QCD Parton Shower [parton = quark or gluon]











Pattern of branching usually simulated with a Monte Carlo Parton Shower algorithm

Experiments always compare data to Monte Carlo simulations to establish fundamental hypotheses

Robustness & accuracy of multi-scale properties of these simulations is one of the open questions of the field





At its simplest: the perturbative part of event generators



iteration of $2 \rightarrow 3$ (or $1 \rightarrow 2$) splitting kernel

in what sense does it give the right answer when you ask arbitrary questions about the final state? cf. <u>arXiv:1805.09327</u>



parton-hadron transition ("hadronisation") can, today, only be modelled

reorganise coloured partons into coloursinglet hadrons

String Fragmentation (Pythia and friends)















jets: organising event information







what shou



projection to jets should be resilient to QCD effects

of energy flow





73



anti-kt jet algorithm

- successive recombination of closest pair of particles (with some distance measure)
- parameter for reach in angle (R)
- parameter for minimum energy of jet
 (p_{t,min})

7



anti-k_t jet algorithm

- successive recombination of closest pair of particles (with some distance measure)
- parameter for reach in angle (R)
- parameter for minimum energy of jet $(p_{t,min})$



using full event information: jet substructure for W tagging



QCD rejection with use of full jet substructure 5–10x better

taken from Dreyer, GPS & Soyez '18











THE PREPRINT SERVER FOR BIOLOGY

For identifying spatial clusters, we have implemented both centroidlinkage hierarchical clustering using FastJet [...]

Via the qSR software, FastJet can analyze a typical super-resolution dataset within a few seconds. By storing the full tree structure, the user can quickly re-cluster data and compare the resulting clusters at varying characteristic sizes.

New Results

qSR: A software for quantitative analysis of single molecule and super-resolution data

J. Owen Andrews, Arjun Narayanan, Jan-Hendrik Spille, Won-Ki Cho, Jesse D. Thaler, Ibrahim I. Cisse

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Abstract	Info/History	Metrics	Data Supplements	Preview PD
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Abstract

We present a software for quantitative analysis of single molecule based super-resolution data. The software serves as an opensource platform integrating multiple algorithms for rigorous spatial and temporal characterizations of protein clusters in superresolution data of living, or fixed cells.



signs mark the centroids of each cluster. Scale Bars – A: 5 µm B - D: 500 nm







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closing

does it work? does it work sufficiently well?



vast array of LHC data agrees with **QCD** predictions

PIP $\sigma = 95.33 \pm 0.128 \pm 1.3 \operatorname{rm}(\operatorname{deta})$ COMPETE HPRIG2(Neary)A1W $\sigma = 190.1 \pm 0.2 \pm 6.4 \operatorname{rb}(\operatorname{deta})$ DYNNLO + C114NNLO (theory) $\sigma = 98.11 \pm 0.028 \pm 2.191 \operatorname{rb}(\operatorname{deta})$ DYNNLO + C114NNLO (theory) $\sigma = 28.12 \pm 0.03 \pm 2.191 \operatorname{rb}(\operatorname{deta})$ DYNNLO + C114NNLO (theory) $\sigma = 28.42 \pm 0.03 \pm 0.02 \operatorname{rb}(\operatorname{deta})$ DYNNLO + C114 NNLO (theory) $\sigma = 29.25 \pm 0.03 \pm 0.07 \operatorname{rh}(\operatorname{deta})$ DYNNLO + C114 NNLO (theory) $\sigma = 29.25 \pm 0.03 \pm 0.07 \operatorname{rh}(\operatorname{deta})$ $\text{DYNNLO + C114 NNLO (theory)}$ A1T $\sigma = 58.42 \pm 0.03 \pm 0.03 \operatorname{cl}(\operatorname{deta})$ $\text{DYNNLO + C114 NNLO (theory)}$ $\sigma = 29.23 \pm 1.6 \operatorname{ab}(\operatorname{deta})$ $\text{DYNNLO + C114 NNLO (theory)}$ $\sigma = 247 \pm 5 \pm 46 \operatorname{pb}(\operatorname{deta})$ $\text{DY + NNLO + NNLL (theory)}$ T $\sigma = 182.9 \pm 3.1 \pm 6.4 \operatorname{pb}(\operatorname{deta})$ $\text{DY + NNLO + NNLL (theory)}$ $\sigma = 182.9 \pm 3.1 \pm 6.4 \operatorname{pb}(\operatorname{deta})$ $\text{NLO + NNLL (theory)}$ $\sigma = 182.9 \pm 3.1 \pm 6.4 \operatorname{pb}(\operatorname{deta})$ $\text{NLO + NNLL (theory)}$ $\sigma = 142 \pm 5 \pm 31 \operatorname{pD}(\operatorname{deta})$ $\text{NLO + NNLL (theory)}$ $\sigma = 142 \pm 5 \pm 31 \operatorname{pD}(\operatorname{deta})$ NLO (theory) $\sigma = 142 \pm 5 \pm 31 \operatorname{pD}(\operatorname{deta})$ NLO (theory) $\sigma = 57 \pm 5 \pm 32 \pm 2.4 \operatorname{c}0 \operatorname{pb}(\operatorname{deta})$ NLO (theory) $\sigma = 57 \pm 5 \pm 32 \pm 2.4 \operatorname{c}3 \operatorname{pb}(\operatorname{deta})$ NLO (theory) $\sigma = 57 \pm 5 \pm 32 \pm 3.2 \pm 3.2 \operatorname{c}7 \operatorname{pb}(\operatorname{deta})$ $\text{LHC + HXSWG YR 4 (theory)}$ $\sigma = 57 \pm 5 \pm 32 \pm 2.4 \operatorname{c}3 \operatorname{pb}(\operatorname{deta})$ NLO (theory) $\sigma = 142 \pm 5 \pm 31 \operatorname{pD}(\operatorname{deta})$ NLO (theory) $\sigma = 142 \pm 32 \pm 32 \operatorname{p}3 (\operatorname{deta})$ NLO (theory) $\sigma = 142 \pm 32 \pm 32 \operatorname{p}3 (\operatorname{deta})$ NLO (theory) $\sigma = 142 \pm 32 \pm 32 \operatorname{p}3 (\operatorname{deta})$ NLO (HOOY) $\sigma = 142 \pm 32 \pm 32 $	
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$ \begin{array}{c} \overline{\mathbf{t}} = 247 \pm 6 \pm 46 \text{ po} (\text{cata}) \\ \text{NLC4-NLL (theory)} \\ \overline{\mathbf{\sigma}} = 89.6 \pm 1.7 + 7.2 - 6.4 \text{ pb} (\text{data}) \\ \text{NLC4-NLL (theory)} \\ \overline{\mathbf{\sigma}} = 68 \pm 2 \pm 8 \text{ pb} (\text{data}) \\ \text{NLC4-NLL (theory)} \\ \overline{\mathbf{\sigma}} = 68 \pm 2 \pm 1.2 \pm 4.6 \text{ pb} (\text{data}) \\ \text{NNLO (theory)} \\ \overline{\mathbf{\sigma}} = 51.9 \pm 2 \pm 4.4 \text{ pb} (\text{data}) \\ \text{NNLO (theory)} \\ \overline{\mathbf{\sigma}} = 51.9 \pm 2 \pm 4.4 \text{ pb} (\text{data}) \\ \text{LHC-HXSWG YR4 (theory)} \\ \overline{\mathbf{\sigma}} = 57 + 6 - 5.9 \pm 4 - 3.3 \text{ pb} (\text{data}) \\ \text{LHC-HXSWG YR4 (theory)} \\ \overline{\mathbf{\sigma}} = 27.7 \pm 3 + 2.3 - 1.9 \text{ pb} (\text{data}) \\ \text{LHC-HXSWG YR4 (theory)} \\ \overline{\mathbf{\sigma}} = 22.1 \pm 6.7 - 5.3 \pm 3.3 - 2.7 \text{ pb} (\text{data}) \\ \text{LHC-HXSWG YR4 (theory)} \\ \overline{\mathbf{\sigma}} = 23 \pm 1.3 \pm 3.4 - 3.7 \text{ pb} (\text{data}) \\ \text{NLO+NNLL (theory)} \\ \overline{\mathbf{\sigma}} = 23 \pm 1.3 \pm 3.4 - 3.7 \text{ pb} (\text{data}) \\ \text{NLO+NNLL (theory)} \\ \overline{\mathbf{\sigma}} = 23 \pm 1.3 \pm 3.4 - 3.7 \text{ pb} (\text{data}) \\ \text{NLO+NNLL (theory)} \\ \overline{\mathbf{\sigma}} = 16.8 \pm 2.9 \pm 3.9 \text{ pb} (\text{data}) \\ \text{NLO+NLL (theory)} \\ \overline{\mathbf{\sigma}} = 16.8 \pm 2.9 \pm 3.9 \text{ pb} (\text{data}) \\ \text{NLO+NLL (theory)} \\ \overline{\mathbf{\sigma}} = 16.8 \pm 2.3 \text{ pb} (\text{data}) \\ \text{MATRX} (\text{NNLO}) (\text{theory}) \\ \overline{\mathbf{\sigma}} = 10 \pm 1.4 \pm 1.3 \pm 1.0 \text{ td} \text{ cat}) \\ \overline{\mathbf{m}} \text{ MATRX} (\text{NNLO}) (\text{theory}) \\ \overline{\mathbf{\sigma}} = 17.3 \pm 0.6 \pm 0.8 \text{ pb} (\text{data}) \\ \text{MATRX} (\text{NNLO}) (\text{theory}) \\ \overline{\mathbf{\sigma}} = 17.3 \pm 0.4 \pm 0.4 \pm 0.3 \text{ pb} (\text{data}) \\ \text{MATRX} (\text{NNLO}) (\text{theory}) \\ \overline{\mathbf{\sigma}} = 17.3 \pm 0.4 \pm 0.4 \pm 0.3 \text{ pb} (\text{data}) \\ \text{MATRX} (\text{NNLO}) (\text{theory}) \\ \overline{\mathbf{\sigma}} = 6.7 \pm 0.7 \pm 0.5 \pm 0.4 \text{ pb} (\text{data}) \\ \text{MATRX} (\text{NNLO}) (\text{theory}) \\ \overline{\mathbf{\sigma}} = 6.7 \pm 0.7 \pm 0.5 \pm 0.4 \text{ pb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 369 \pm 80 \pm 100 \text{ pb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 369 \pm 80 \pm 100 \text{ pb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 369 \pm 80 \pm 100 \text{ tb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 0.68 \pm 0.16 - 0.15 \text{ pb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 0.68 \pm 0.16 - 0.15 \text{ pb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 0.49 \pm 0.14 \pm 0.14 \pm 0.13 \text{ pb} (\text{data}) \\ \text{MACFM} (\text{theory}) \\ \overline{\mathbf{\sigma}} = 0.49 \pm 0.14 \pm 0.14 - 0.13 \text{ pb}$	
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	
$\sigma = 142 \pm 3 \pm 13 \text{ pb}$ (data) NNLO (lineory) $\sigma = 68.2 \pm 1.2 \pm 4.6 \text{ pb}$ (data) NNLO (lineory) $\sigma = 57 + 6 - 5.9 + 4 - 3.3 \text{ pb}$ (data) LHC-HXSWG YR4 (lineory) $\sigma = 27.7 \pm 3 \pm 2.3 - 1.9 \text{ pb}$ (data) LHC-HXSWG YR4 (lineory) $\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7 \text{ pb}$ (data) LHC-HXSWG YR4 (lineory) $\sigma = 94 \pm 10 \pm 28 - 23 \text{ pb}$ (data) NLO+NNLL (lineory) $\sigma = 94 \pm 10 \pm 28 - 23 \text{ pb}$ (data) NLO+NNLL (lineory) $\sigma = 94 \pm 10 \pm 28 - 3.7 \text{ pb}$ (data) NLO+NNLL (lineory) $\sigma = 16.8 \pm 2.9 \pm 3.9 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 142.3 \pm 0.6 \pm 0.9 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 17.3 \pm 0.6 \pm 0.9 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 17.3 \pm 0.6 \pm 0.8 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 17.3 \pm 0.6 \pm 0.8 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 17.3 \pm 0.6 \pm 0.8 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 7.3 \pm 0.4 \pm 0.4 - 0.3 \text{ pb}$ (data) MATRIX (NNLO) (lineory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb}$ (data) MATRIX (lineory) $\sigma = 870 \pm 130 \pm 140 \text{ tb}$ (data) MATRIX (lineory) $\sigma = 870 \pm 130 \pm 140 \text{ tb}$ (data) MATRIX (lineory) $\sigma = 269 \pm 86 - 79 \pm 44 \text{ lo}$ (data) MATRIX (lineory) $\sigma = 269 \pm 80 \pm 100 \text{ tb}$ (data) MATRIX (lineory) $\sigma = 269 \pm 80 \pm 100 \text{ tb}$ (data) MATRIX (lineory) $\sigma = 269 \pm 80 \pm 100 \text{ tb}$ (data) MATRIX (lineory) <td></td>	
WW $\sigma = 60.2 \pm 1.2 \pm 4.0 \text{ pb}$ (data) NNLO (theory) $\sigma = 51, 9 \pm 2 \pm 4.4 \text{ pb}$ (data) NNLO (theory) $\sigma = 57, 6-5.9 \pm 4-3.3 \text{ pb}$ (data) LHC-HXSWG YR4 (theory) $\sigma = 27, 7 \pm 3 \pm 2.3 - 1.9 \text{ pb}$ (data) LHC-HXSWG YR4 (theory) $\sigma = 22.1 \pm 6.7 - 5.3 \pm 3.3 - 2.7 \text{ pb}$ (data) LHC-HXSWG YR4 (theory) $\sigma = 94 \pm 10 \pm 28 - 23 \text{ pb}$ (data) NLO+NNLL (theory) $\sigma = 94 \pm 10 \pm 28 - 23 \text{ pb}$ (data) NLO+NNLL (theory) $\sigma = 16.8 \pm 2.9 \pm 3.9 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 51 \pm 0.8 \pm 2.3 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 51 \pm 0.6 \pm 0.3 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.3 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.3 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.3 \text{ pb}$ (data) Matrix (NNLO) & Shorpa (NLO) (theory) $\sigma = 6.7 \pm 0.7 \pm 0.5 \pm 0.3 \text{ pb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 369 \pm 36 \pm 79 \pm 44 \text{ b}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 369 \pm 86 \pm 79 \pm 44 \text{ b}$ (data) Madgraph5 + aMCNLO (theory) $\tau = 176 \pm 52 \pm 48 \pm 24 \text{ b}$ (data) Madgraph5 + aMCNLO (theory) $\tau = 176 \pm 52 \pm 0.10 \pm 0.16 \pm 0.15 \text{ pb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 369 \pm 30 \pm 100 \text{ tb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 166 \pm 0.16 \pm 0.15 \pm 0.16 \pm 0.15 \text{ pb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 166 \pm 2.22 \text{ (theory)}$ WWW $\sigma = 0.49 \pm 0.14 \pm 0.14 \pm 0.13 \text{ pb}$ (data) Sherpa 2.22 (theory)WWWZ	
$III = 3 + 3 \pm 2 \pm 3 \pm 3 \pm 2 \pm 3 \pm 3 \pm 2 \pm 3 \pm 3 \pm$	
$IHC-HXSWG YR4 (theory)$ $\sigma = 27.7 \pm 3 \pm 2.3 = 1.9 \text{ pb (data)}$ $UHC-HXSWG YR4 (theory)$ $\sigma = 22.1 \pm 6.7 \pm 5.3 \pm 2.7 \text{ pb (data)}$ $UHC-HXSWG YR4 (theory)$ $\sigma = 94 \pm 10 \pm 28 \pm 2.3 \text{ pb (data)}$ $NLO+NLL (theory)$ $\sigma = 23 \pm 1.3 \pm 3.4 \pm 3.7 \text{ pb (data)}$ $NLO+NLL (theory)$ $\sigma = 16.8 \pm 2.9 \pm 3.9 \text{ pb (data)}$ $NLO+NLL (theory)$ $\sigma = 51 \pm 0.8 \pm 2.3 \text{ pb (data)}$ $MATRIX (NNLO) (theory)$ $\sigma = 19 \pm 1.4 \pm 1.3 \pm 1 \text{ pb (data)}$ $MATRIX (NNLO) (theory)$ $\sigma = 17.3 \pm 0.5 \pm 0.6 \text{ pb (data)}$ $MATRIX (NNLO) (theory)$ $\sigma = 17.3 \pm 0.4 \pm 0.4 \pm 0.3 \text{ pb (data)}$ $NNLO (theory)$ $\sigma = 6.7 \pm 0.7 \pm 0.5 \pm 0.4 \text{ pb (data)}$ $NNLO (theory)$ $\sigma = 870 \pm 1.30 \pm 140 \text{ tb (data)}$ $MCFM (theory)$ $\tau = 369 \pm 86 \pm 79 \pm 44 \text{ fb (data)}$ $MCFM (theory)$ TZZ $\sigma = 950 \pm 80 \pm 100 \text{ tb (data)}$ $MCFM (theory)$ $\sigma = 176 \pm 2.2 \text{ th (data)}$ $MCFM (theory)$ $\sigma = 369 \pm 8.5 \pm 100 \text{ tb (data)}$ $MCFM (theory)$ $\sigma = 369 \pm 8.5 \pm 100 \text{ tb (data)}$ $MCFM (theory)$ $\sigma = 950 \pm 80 \pm 100 \text{ tb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.13 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 950 \pm 80 \pm 100 \text{ tb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.15 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.15 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.13 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.15 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.15 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.13 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.13 \text{ pb (data)}$ $MCFM (theory)$ $\sigma = 0.68 \pm 0.16 \pm 0.13 \text{ pb (data)}$	
HLHC-HXSWG YR4 (Incory) $\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7 pb (data)LHC-HXSWG YR4 (Incory)\sigma = 94 \pm 10 + 28 - 23 pb (data)NLO+NNLL (theory)\sigma = 23 \pm 1.3 + 3.4 - 3.7 pb (data)NLO+NLL (theory)\sigma = 16.8 \pm 2.9 \pm 3.9 pb (data)MATRIX (NNLO) (theory)\sigma = 51 \pm 0.8 \pm 2.3 pb (data)MATRIX (NNLO) (theory)\sigma = 19 \pm 1.4 - 1.3 \pm 1 pb (data)MATRIX (NNLO) (theory)\sigma = 17.3 \pm 0.6 \pm 0.9 pb (data)MATRIX (NNLO) (theory)\sigma = 17.3 \pm 0.6 \pm 0.8 pb (data)MATRIX (NNLO) (theory)\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 pb (data)NNLO (theory)\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 pb (data)NNLO (theory)\sigma = 4.8 \pm 0.8 \pm 1.6 - 1.3 pb (data)NNLO (theory)\sigma = 369 \pm 80 \pm 100 fb (data)Madgraph5 \pm aMCNLO (theory)\sigma = 369 \pm 80 \pm 100 fb (data)Madgraph5 \pm aMCNLO (theory)\sigma = 77 \pm 1.30 \pm 140 fb (data)Madgraph5 \pm aMCNLO (theory)\sigma = 369 \pm 80 \pm 100 fb (data)Madgraph5 \pm aMCNLO (theory)\sigma = 262 \pm 170 \pm 160 fb (data)Madgraph5 \pm aMCNLO (theory)\sigma = 0.68 + 0.16 - 0.15 + 0.16 - 0.15 pb (data)Madgraph5 \pm 2.2 (theory)WVW\sigma = 0.49 \pm 0.14 + 0.14 - 0.13 pb (data)Sherpa 2.2.2 (theory)WVVZ$	
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Wt $NLO+NNLL (theory)$ $\sigma = 23 \pm 1.3 + 3.4 - 3.7 \text{ pb (data)}$ $NLO+NLL (theory)$ $\sigma = 16.8 \pm 2.9 \pm 3.9 \text{ pb (data)}$ $NLO+NLL (theory)$ $\sigma = 51 \pm 0.8 \pm 2.3 \text{ pb (data)}$ MATRIX (NNLO) (theory) $\sigma = 24.3 \pm 0.6 \pm 0.9 \text{ pb (data)}$ MATRIX (NNLO) (theory) $\sigma = 19 \pm 1.4 - 1.3 \pm 1 \text{ pb (data)}$ MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.8 \text{ pb (data)}$ MATRIX (NNLO) & Sherpa (NLO) (theory) $\sigma = 7.3 \pm 0.4 + 0.4 - 0.3 \text{ pb (data)}$ NNLO (theory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ NNLO (theory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ NNLO (theory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ NLO+NNL (theory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ NLO+NNL (theory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ $MATRIX (NNLO) (theory)$ $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ $MLO (theory)$ $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)}$ $MATRIX (NNLO (theory))$ $\sigma = 6.7 \pm 130 \pm 140 \text{ tb (data)}$ $MATRIX (NNLO (theory))$ $\sigma = 369 \pm 86 - 79 \pm 44 \text{ tb (data)}$ $MATRIX (NOLO (theory))$ $\sigma = 950 \pm 80 \pm 100 \text{ tb (data)}$ $MATRIX (NOLO (theory))$ $\sigma = 176 \pm 52 - 48 \pm 24 \text{ tb (data)}$ $MATRIX (theory)$ $\sigma = 0.68 + 0.16 - 0.15 + 0.16 - 0.15 \text{ pb (data)}$ $NUC4-NUL (theory)$ $\sigma = 0.49 \pm 0.14 + 0.14 - 0.13 \text{ pb (data)}$ $Sherpa 2.2.2 (theory)$ $MU = 1.14 + 0.14 + 0.13 \text{ pb (data)}$ <td></td>	
VVLNLO+NLL (theory) $\sigma = 16.8 \pm 2.9 \pm 3.9 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 51 \pm 0.8 \pm 2.3 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 24.3 \pm 0.6 \pm 0.9 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.9 \text{ pb}$ (data) MATRIX (NNLO) (theory) $\sigma = 17.3 \pm 0.6 \pm 0.8 \text{ pb}$ (data) Matrix (NNLO) & Sherpa (NLO) (theory) $\sigma = 17.3 \pm 0.4 + 0.4 - 0.3 \text{ pb}$ (data) Matrix (NNLO) & Sherpa (NLO) (theory) $\sigma = 7.3 \pm 0.4 + 0.4 - 0.3 \text{ pb}$ (data) Matrix (NNLO) (theory) $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb}$ (data) NNLO (theory) $\sigma = 4.8 \pm 0.8 + 1.6 - 1.3 \text{ pb}$ (data) NLO+NNL (theory) $\sigma = 4.8 \pm 0.8 + 1.6 - 1.3 \text{ pb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 369 + 86 - 79 \pm 44 \text{ fb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 369 + 86 - 79 \pm 44 \text{ fb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 950 \pm 80 \pm 100 \text{ fb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 950 \pm 80 \pm 100 \text{ fb}$ (data) Madgraph5 + aMCNLO (theory) $\sigma = 0.68 + 0.16 - 0.15 \text{ pb}$ (data) NLO+NLL (theory) $\sigma = 0.68 + 0.16 - 0.15 \text{ pb}$ (data) Sherpa 2.2.2 (theory)WWZ $\sigma = 0.49 \pm 0.14 + 0.14 - 0.13 \text{ pb}$ (data) Sherpa 2.2.2 (theory)	
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WZMATRIX (NNLO) (theory) $\sigma = 24.3 \pm 0.6 \pm 0.9 \text{ pb} (data)MATRIX (NNLO) (theory)\sigma = 19 \pm 1.4 \pm 1.3 \pm 1 \text{ pb} (data)MATRIX (NNLO) (theory)ZZ\sigma = 17.3 \pm 0.6 \pm 0.8 \text{ pb} (data)Matrix (NNLO) & Sherpa (NLO) (theory)\sigma = 7.3 \pm 0.4 \pm 0.4 \pm 0.3 \text{ pb} (data)NNLO (theory)ZZ\sigma = 17.3 \pm 0.4 \pm 0.4 \pm 0.3 \text{ pb} (data)NNLO (theory)\sigma = 6.7 \pm 0.7 \pm 0.5 \pm 0.4 \text{ pb} (data)NNLO (theory)ts-chan\sigma = 4.8 \pm 0.8 \pm 1.6 \pm 1.3 \text{ pb} (data)NLO+NNL (theory)\sigma = 870 \pm 130 \pm 140 \text{ th} (data)Madgraph5 \pm aMCNLO (theory)\sigma = 369 \pm 86 \pm 79 \pm 44 \text{ tb} (data)Madgraph5 \pm aMCNLO (theory)\sigma = 950 \pm 80 \pm 100 \text{ tb} (data)Madgraph5 \pm 4MCNLO (theory)\sigma = 176 \pm 52 \pm 48 \pm 24 \text{ tb} (data)Madgraph5 \pm 0.16 \pm 0.15 \text{ pb} (data)ttZj\sigma = 620 \pm 170 \pm 160 \text{ tb} (data)NLO+NLL (theory)\sigma = 0.49 \pm 0.14 \pm 0.14 \pm 0.13 \text{ pb} (data)Sherpa 2.2.2 (theory)WWZ\sigma = 0.49 \pm 0.22 \text{ (theory)}$	
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CMS Preliminary



Higgs cross-sections v. QCD theory



Higgs precision (H $\rightarrow \gamma\gamma$) : optimistic estimate v. luminosity & time

extrapolation of μ_{vv} precision from 7+8 TeV results



Today, Higgs coupling precisions are in the 10-20% range.

The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

 $1 \text{ fb}^{-1} = 10^{14} \text{ collisions}$

HL-LHC official Higgs coupling projections (by ~2036)

We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings

HL-LHC official Higgs coupling projections (by ~2036)

We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings if theoretical interpretations can be

made sufficiently accurate

theory (QCD) uncertainty dominates, even with an assumption of ×2 improvement by 2030s

can we ensure that QCD is up to the task?

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