# *Standard Model: status & recent theory highlights*

Emanuele Re

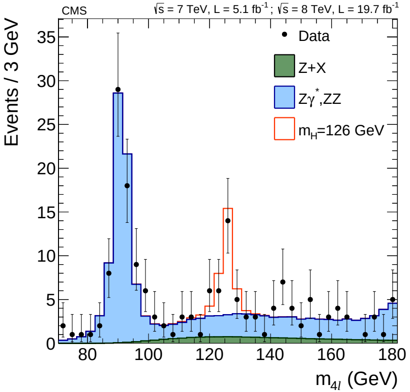
LAPTh Annecy

Rencontre de Physique des Particules

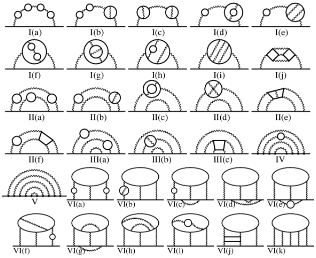
LAPTh, Annecy-le-Vieux, 25 January 2016

- at a first glance, the SM looks in as good a shape as it ever was...

## Higgs boson discovery




## quantum effects at 5 loops




$$a_e = \frac{(g-2)_e}{2} [\times 10^{-13}]$$

$$115\,965\,218\,17.8 \pm 8 \quad [\mathrm{TH}]$$

$$115\,965\,218\,07.3 \pm 2.8 \quad [\mathrm{EX}]$$

# the Standard Model today

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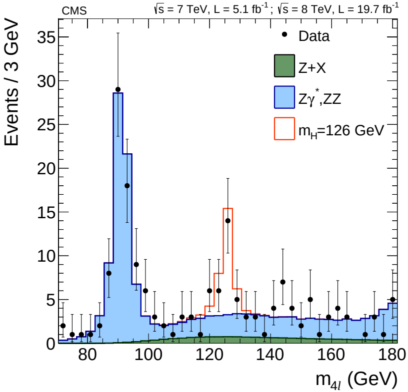


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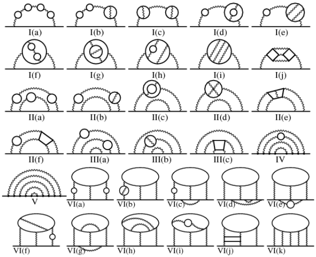


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$115\,965\,218\,17.8 \pm 8$ [TH]

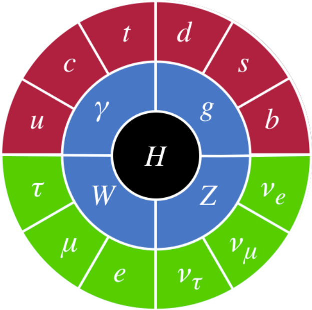
$115\,965\,218\,07.3 \pm 2.8$ [EX]

however a lot still remains to be understood...

# plan of the talk

1. electroweak and strong sectors
   . overview and selection of recent results

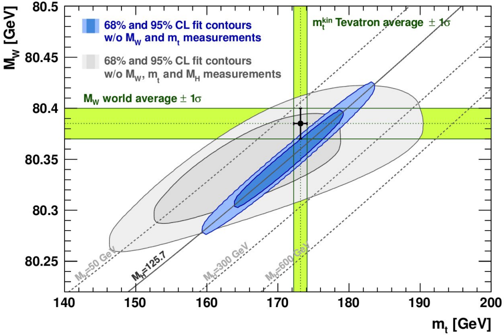
2. LHC Phenomenology
   . highlights from last couple of years

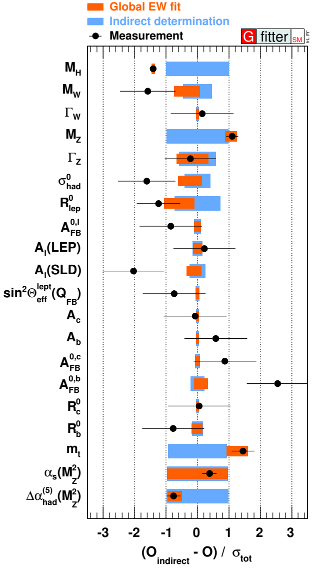



disclaimer:

- by no means this talk is fully comprehensive (especially on 1.)
- the choice of presented results is biased
- apologies if I have left out some very relevant results (possibly yours)

# the EW sector: precision observables




- test EW sector at the quantum level
- small tensions, but overall good agreement
- TH accuracy: $\geq 2$ loops

☞ measuring $m_W$ and $m_t$ becomes relevant
. as for Higgs properties, TH input is needed

# muonic $g-2$

[for more details: M. Passera talk at LFC15, Sep ’15]

- long standing $3\sigma$ discrepancy for $(g-2)_\mu$

$$a_\mu^{\mathtt{EX}} = 116\,592\,091 \pm 63\ (\times 10^{-11}) \qquad \text{BNL-E821}$$
$$a_\mu^{\mathtt{TH}} = 116\,591\,809 \pm 66\ (\times 10^{-11}) \qquad \text{[Jegerlehner,Nyffeler]}$$

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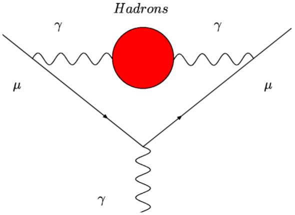
TH challenges: Hadronic LO (vacuum polarization)

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}\,K(s)\,R_{e^+e^-\to\mathrm{had}}(s)$$
$$K(s) = \int_0^1 dx\,\frac{x^2(1-x)}{x^2+(1-x)(s/m^2)}$$




- HLO: from EXP, using dispersion relations
- different determinations are compatible
  however $\delta a_\mu^{\mathrm{HLO}} \simeq 40\ (\times 10^{-11})$
- dominated by low-energy data (below 2 GeV)

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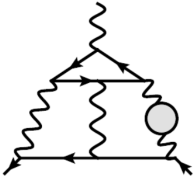
TH challenges: Hadronic (N)NLO

- diagrams with hadronic vacuum polarization insertions: now known up to $\mathcal{O}(\alpha^4)$

[Kurz,Marquard et al. '14]



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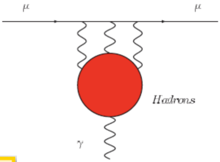
- Hadronic ligh-by-light (H-lbl): relies on theory ...and it had a troubled life!




| | |
|---|---|
| $a_\mu^{\mathrm{HNLO}}(\mathrm{lbl}) = +80\,(40) \times 10^{-11}$ | Knecht & Nyffeler '02 |
| $a_\mu^{\mathrm{HNLO}}(\mathrm{lbl}) = +136\,(25) \times 10^{-11}$ | Melnikov & Vainshtein '03 |
| $a_\mu^{\mathrm{HNLO}}(\mathrm{lbl}) = +105\,(26) \times 10^{-11}$ | Prades, de Rafael, Vainshtein '09 |
| $a_\mu^{\mathrm{HHO}}(\mathrm{lbl}) = +116\,(39) \times 10^{-11}$ | Jegerlehner & Nyffeler '09 |

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TH challenges: Hadronic LO (vacuum polarization) / Hadronic (N)NLO

- today: TH error about the same as EXP
- last couple of years:
  - HLO: extract $a_\mu^{\rm HLO}$ from small-angle Bhabha scattering [C-Calame,Passera et al. '15]
  - H-lbl from lattice [Blum et al. '15] and dispersive approach [Colangelo et al. '14]
- "E989" (FNAL) and J-PARC target to achieve $\delta a_\mu^{\rm EX} \simeq 15\ (\times 10^{-11})$

$\Rightarrow$ theoretically very challenging

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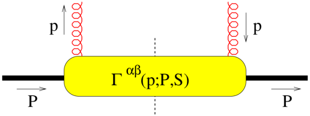
- $\alpha_S$ measurement (important per se + implication for all LHC phenomenology)
  - from pion decay constant [Kneur,Neveu '15]
- high-energy scattering and saturation of PDFs [→ talk by S. Munier]
- heavy ions
- partonic distribution functions:
  - integrated PDFs (unpolarized partons / unpolarized hadrons)
    - fundamental for all LHC Pheno (enter everywhere)
    - now up to NNLO + more and more consistent
    - MSTW/MMHT, CT(EQ), NNPDF,... [PDF4LHC WG]
  - polarised distributions (proton spin, unpolarised partons)
  - other degrees of freedom can be retained:
    - GPDs [→ talk by R. Boussarie]
    - TMDs
  - nuclear PDFs

# TMD at the LHC

- polarized gluons in upolarized protons
  - perturbatively ($g \to gg$)
  - potentially also intrinsic non-perturbative component
- can be described by TMD PDFs



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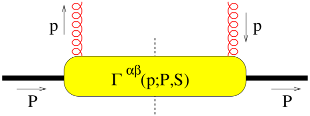


$$\Phi_g^{\alpha\beta}(x, k_T; P) \simeq \Bigg\{ + \quad g_T^{\alpha\beta} \quad f_1^g(x, k_T^2)$$ ← related to usual PDF

$$- \left( \frac{k_T^\alpha k_T^\beta}{M^2} + g_T^{\alpha\beta} \frac{|\vec{k}_T|^2}{2M^2} \right) h_1^{\perp g}(x, k_T^2) \Bigg\}$$ ← essentially unknown

☞ second term: linearly polarized $g$ (and helicity flipping)

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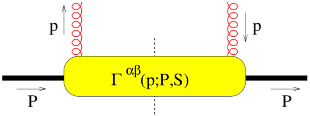


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- very little is known about $f_1^g$ and $h_1^{\perp g}$, especially at small $p_T$

- typically: $f_1^g$ gaussian ; model independent bound on $h_1^{\perp g}$: $|h_1^{\perp g}| \leq (2M^2/k_T^2) f_1^g$
- by measuring them, distinguish among different underlying models!

doable also at the LHC!

# TMD at the LHC from quarkonium production

$f_1^g$ and $h_1^{\perp g}$ can be probed by measuring $pp \to \mathcal{Q}[Q\bar{Q}] + X$

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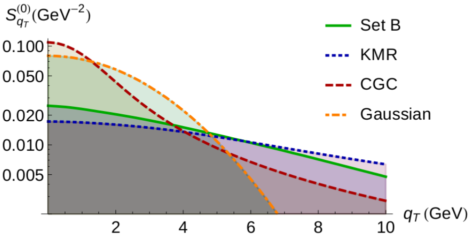
- only transverse momentum of $(\mathcal{Q} + \gamma)$ system need be small
- best onium: $\Upsilon$ ($gg$-fusion + CS dominated) $\Upsilon = b\bar{b}[^3S_1]$

$$\frac{d\sigma}{dQdY\,d^2q_T d\Omega} \propto A\ (\mathbf{f_1^g} \otimes \mathbf{f_1^g}) + B\ \ (f_1^g \otimes h_1^{\perp g})\ \cos(2\phi) + C\ (h_1^{\perp g} \otimes h_1^{\perp g})\ \cos(4\phi)$$

- disentangle contributions:

$$S_{q_T}^{(n)} \equiv \frac{\int d\phi \cos(n\,\phi)\, \frac{d\sigma}{dQdYd^2\boldsymbol{q}_T d\Omega}}{\int d\boldsymbol{q}_T^2 \int d\phi \frac{d\sigma}{dQdYd^2\boldsymbol{q}_T d\Omega}}$$



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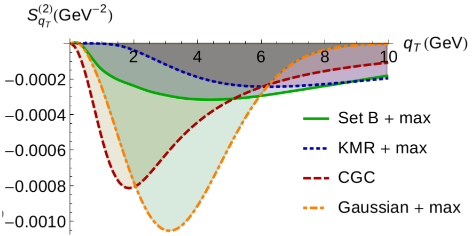

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LHC is a discovery machine

- optimize as much as possible our knowledge of the SM to make the most out of this experiment (particularly so if no BSM smoking-gun discovery)

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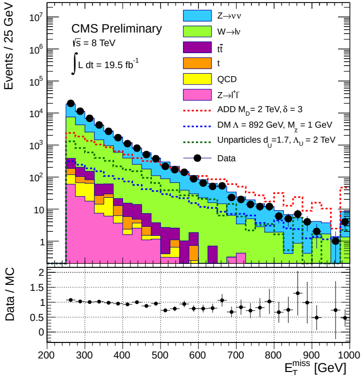
  . detect small deviations from SM backgrounds

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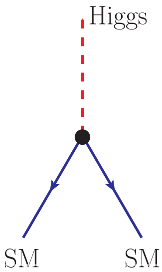


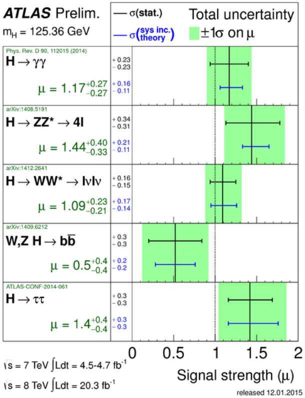


- accurate measurement of Higgs couplings
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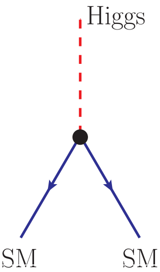


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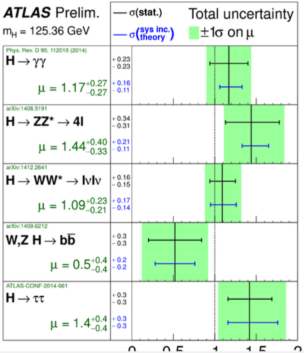
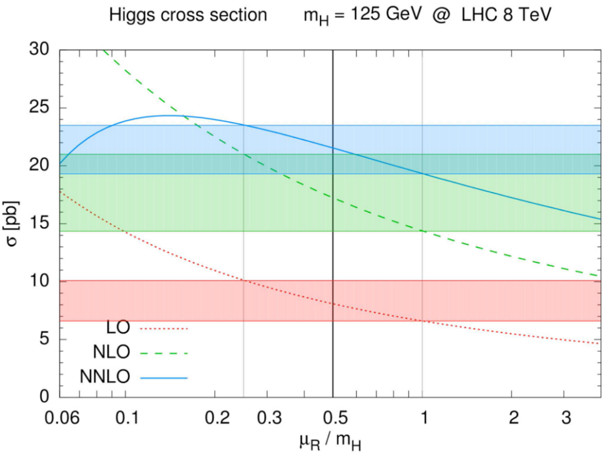
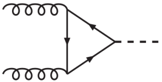


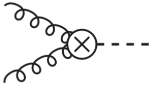

**important also in presence of new discovery**

# the Higgs cross section

- to measure Higgs properties, need to know Higgs production cross section
  - $gg \to H$ is the dominant production mechanism at the LHC
- known at NLO [Dawson; Djouadi et al.] and NNLO [Harlander,Kilgore; Anastasiou,Melnikov; Ravindran et al.]





- perturbative series: converges very slowly
- large perturbative uncertainties (estimated by scale variation)

# Higgs production at N3LO

- the $gg \to H$ cross section is now know at N3LO !

  [Anastasiou,Duhr,Dulat,Herzog,Mistlberger (+Furlan,Gehrmann) '14-'15]

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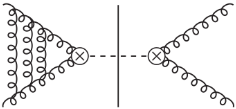
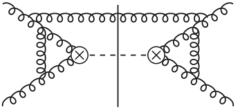
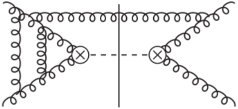


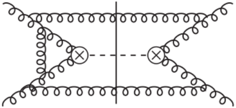
Triple virtual



Real-virtual squared



Double virtual real



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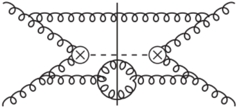

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from C. Duhr talk at Higgs Hunting '15

# Higgs production at N3LO

[Anastasiou,Duhr,Dulat,Herzog,Mistlberger (+Furlan,Gehrmann) '14-'15]



Tri

| | NNLO | N3LO |
|---|---|---|
| # diagrams | ~ 1.000 | ~ 100.000 |
| # integrals | ~50.000 | 517.531.178 |
| # masters | 27 | 1.028 |

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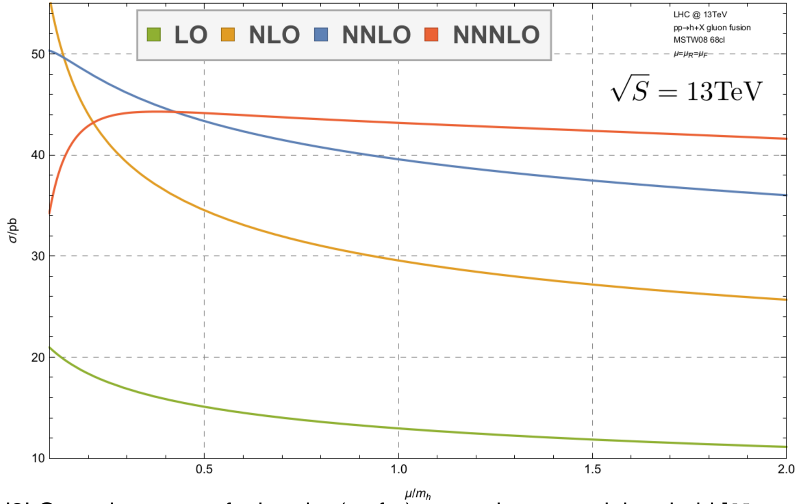


- N3LO result: exact soft-virtual + (so far) expansion around threshold [$N \simeq 30$]

$$\frac{\hat{\sigma}_{ij}(z)}{z} = \hat{\sigma}^{\text{SV}}\delta_{ig}\delta_{jg} + \sum_{N=0}^{\infty} \hat{\sigma}_{ij}^{(N)}(1-z)^N \quad \text{where} \quad z = m_H^2/\hat{s}$$

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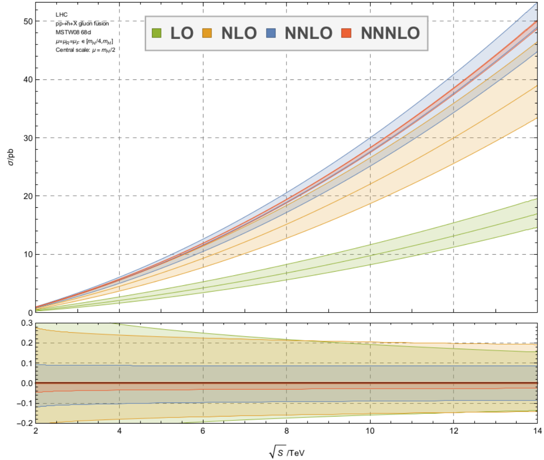


- N3LO result: perturbative uncertainties drastically reduced [$\pm 2$ %]
- consider residual effects: $(1/m_t)$ , threshold resummation , missing N3LO PDFs , PDFs+$\alpha_S$ , EW effects...
- preliminary results:

  [+4.3%,-6.5%] [TH]

  [3.15%] [PDFs+$\alpha_S$]

  [A. Lazopoulos,HXSWG Jan '16]

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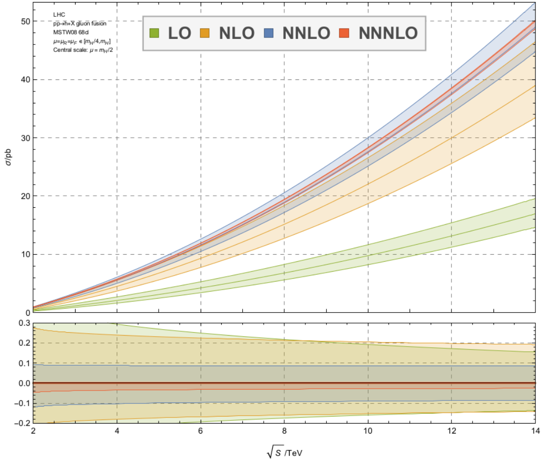


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  [3.15%] [PDFs+$\alpha_S$]
  [A. Lazopoulos,HXSWG Jan '16]

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- $e^+e^- \to t\bar{t}$ : crucial to measure $m_t$ ultra precisely
- N$^3$LO in threshold region + non-relativistic resummation [Beneke et al. '15]

# fully differential NNLO

- differential distributions essential to compare EX (after cuts) and TH
- last 3 years: huge progress in computing $2 \to 2$ LHC processes at NNLO in QCD

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**matrix elements**

- $2$-loops $2 \to 2$ amplitudes $\sim$ known for years

**subtraction scheme**

- $\mathcal{O}(\alpha_s^2)$ matrix-elements live in different phase spaces

$\Downarrow$

- numerical algorithm to combine them: cancellation of IR divergences for a generic observable

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☞ first partial results for $2$-loops $2 \to 3$
- $gg \to ggg$, planar, all + helicities

[Badger et al. '13-'15, Gehrmann,Henn et al. '15]

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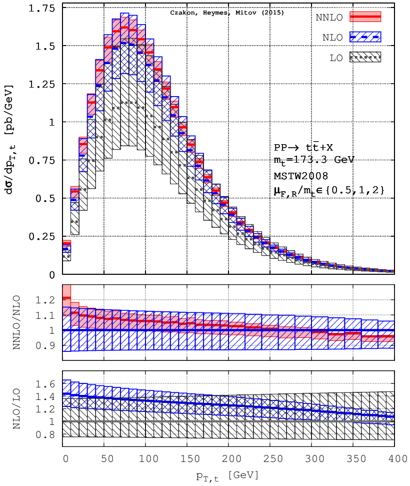
[Czakon,Heymes,Mitov '15]







- good perturbative convergence
- K-factors are non flat

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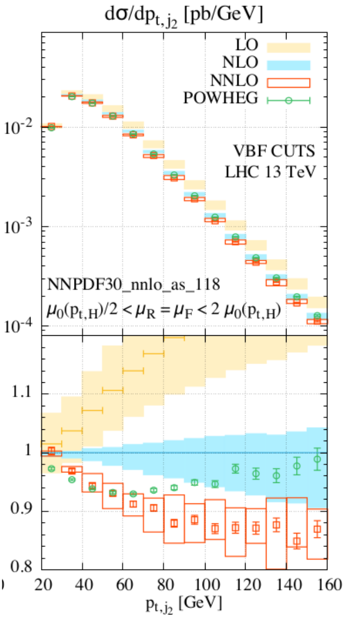


- NNLO fully inclusive
  - extremely stable under scale variation (1-2%)
- NNLO fully differential, VBF cuts
  - corrections are up to 10-12% !

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi '15]

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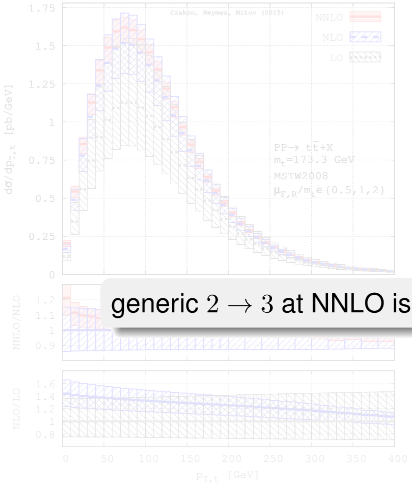


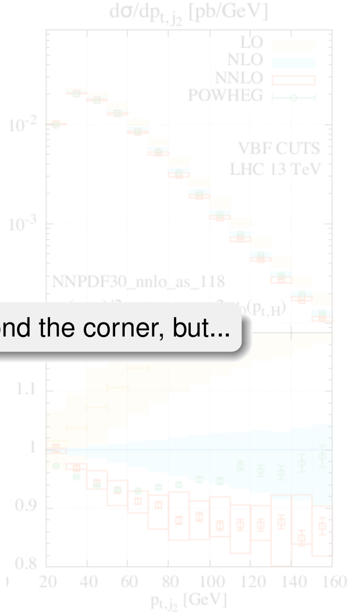


generic $2 \to 3$ at NNLO is not beyond the corner, but...

# NLO corrections at the LHC

- all high-multiplicity processes relevant at the LHC are known at NLO QCD!
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- often computations done linking together $1$-loop codes with tree-level/MC program [BLHA]

. BLACKHAT: $W$ + 5 jets [+Sherpa] [Bern,Dixon et al. '13]

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[→ talk by H-S. Shao]

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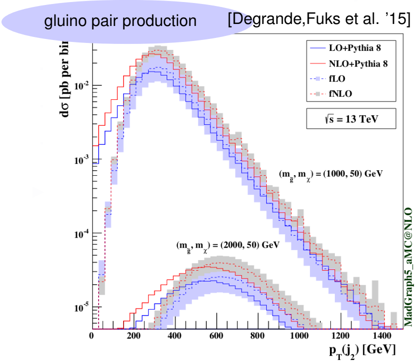


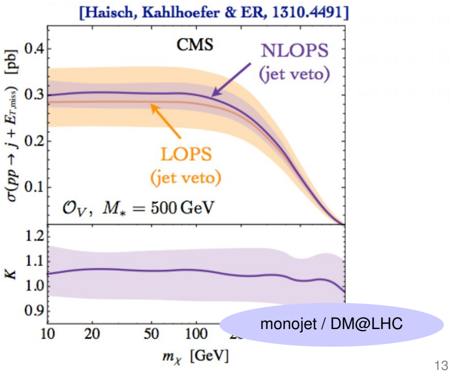

# MC tools

1. fully-consistent NLO+PS simulation of $WWb\bar{b}$, with exact decays at NLO and offshellness effects




figure from R. Franceschini

- extract $m_t$ looking into the kinematics of visible particles from top-decay

2. merging NLO+PS simulations for different jet multiplicities

- describe simultaneously (and at NLO+PS) $pp \to X + 0, 1, 2, \ldots$ jets
- important for
  - BSM searches
  - match NNLO with parton showers
- requires detailed understanding of logarithmic accuracy

☞ very active field ! `MEPS@NLO`, `FxFx`, `UNLOPS`, `Geneva`, `POWHEG+MiNLO`

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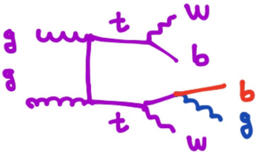


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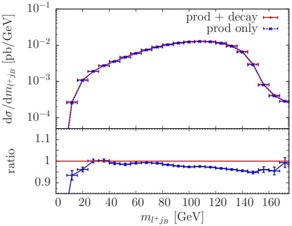


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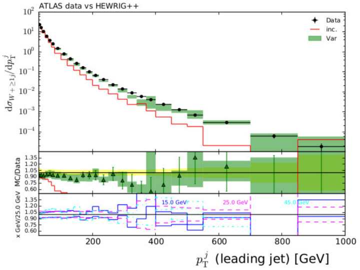
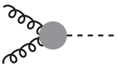
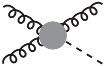


# NNLO+PS [with POWHEG+MiNLO]



# loops: 0 1 2



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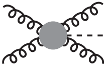

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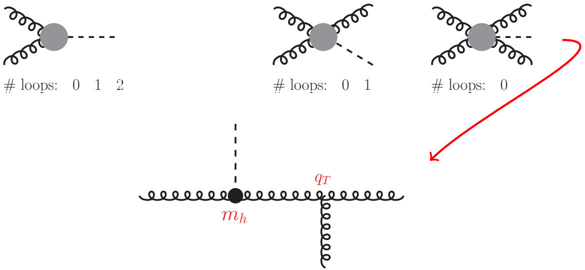


(a) 1 and 2 jets: POWHEG H+1j [NLO+PS matching]

$$\bar{B}_{\rm NLO} = \alpha_{\rm S}^3(\mu_R)\Big[B + \alpha_{\rm S} V(\mu_R) + \alpha_{\rm S}\int d\Phi_{\rm r} R\Big]$$

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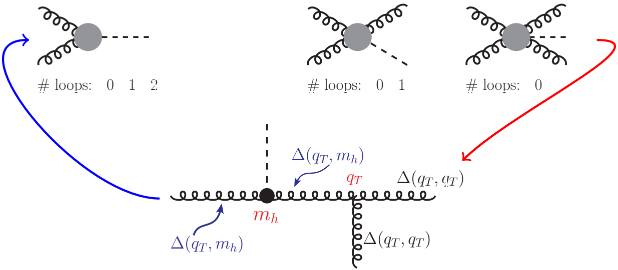


(b) integrate down to $q_T = 0$ with MiNLO [H-HJ NLO+PS merging]

$$\bar{B}_{\mathrm{MiNLO}} = \alpha_{\mathrm{S}}^2(m_h)\alpha_{\mathrm{S}}(q_T)\Delta_g^2(q_T, m_h)\left[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_{\mathrm{S}}\, V(\bar{\mu}_R) + \alpha_{\mathrm{S}}\int d\Phi_{\mathrm{r}} R\right]$$

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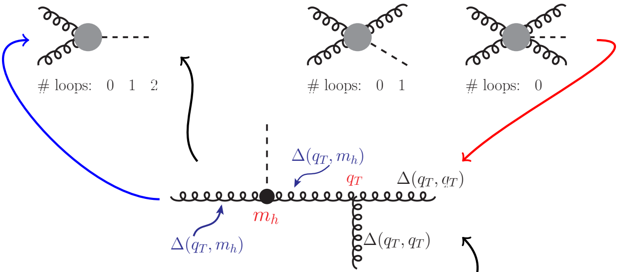


(c) 2 loops missing: from exact fixed-order NNLO [NNLO+PS]

$$W(y) = \frac{d\sigma(y)_{\text{NNLO}}}{d\sigma(y)_{\text{MiNLO}}}$$

[Hamilton,Nason,ER,Zanderighi '13]

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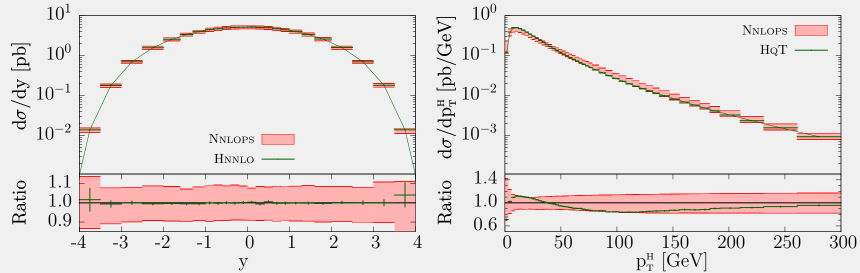


- applied also to Drell-Yan [Karlberg,ER,Zanderighi '14]
- other methods: UNNLOPS [Hoeche,Li,Prestel, '14] , Geneva [Alioli,Bauer et al.,'15]

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  - all backgrounds and many signals known at NLO+PS
  - several $2 \to 2$ NNLO fully differential computations performed, more to come
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...but of course, I hope that the 750 GeV resonance is real...

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*thank you for your attention !*