LES HOUCHES 2019 SM THEORY

N^xLO, Multi-legs, Jets WG

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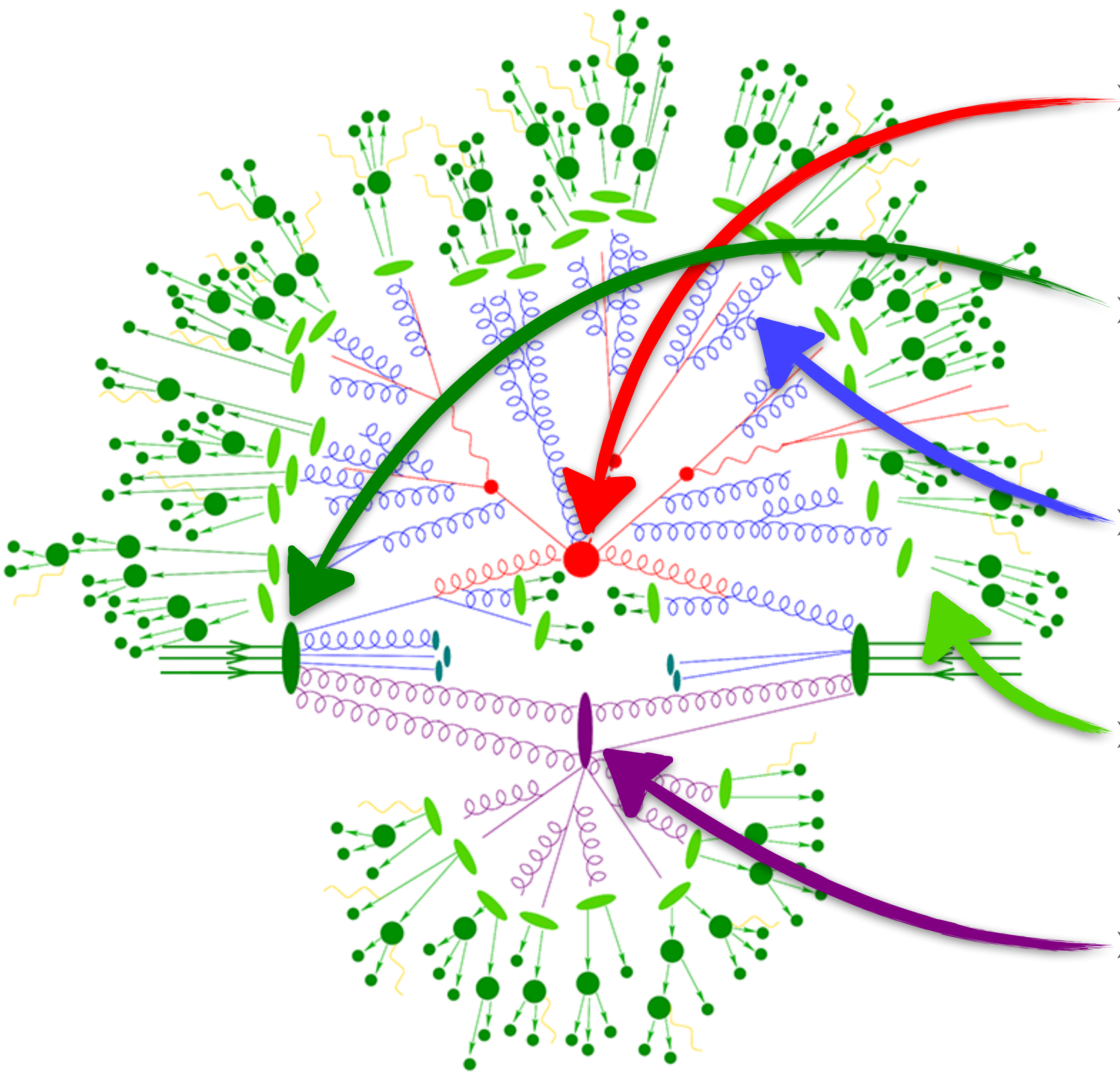
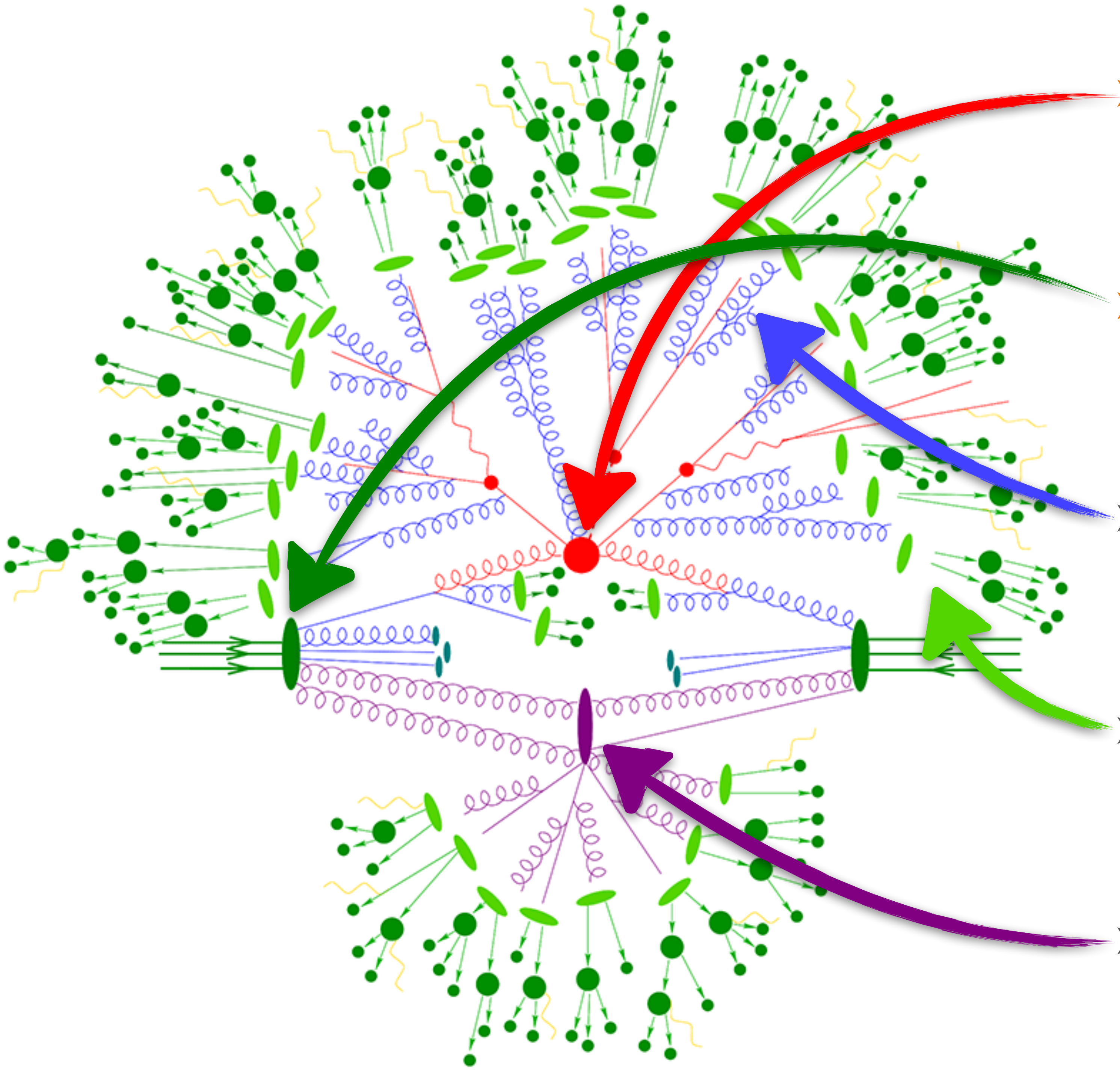
June 11th 2019, Les Houches

Predictions @ LHC



- Hard subprocess
- PDFs
- Parton shower
- Hadronization + decays
- Underlying event
- Jets, substructure, res.

Predictions @ LHC



- Hard subprocess (less Higgs)
- PDFs
- Parton shower
- Hadronization + decays
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- Jets, substructure, res.

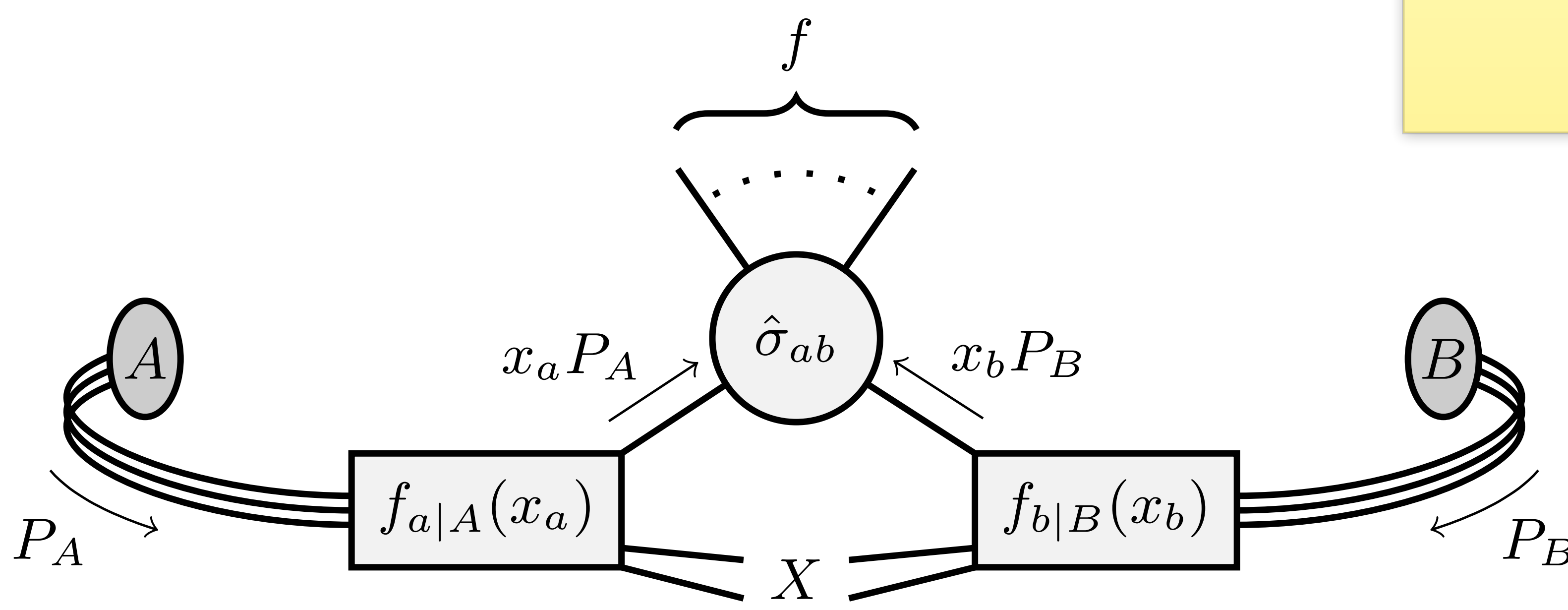
{Higgs Theory}

{Tools & MC}

{Jets}

THE PRECISION FRONTIER

NP: intrinsic limitation?
PDF: for central EW production %-level



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a|A}(x_a) \, f_{b|B}(x_b) \, \hat{\sigma}_{ab}(x_a, x_b) \, \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

parton distribution functions
(in principle, improvable)
few % at LHC

hard scattering
(systematically improvable)
aim for few % level!

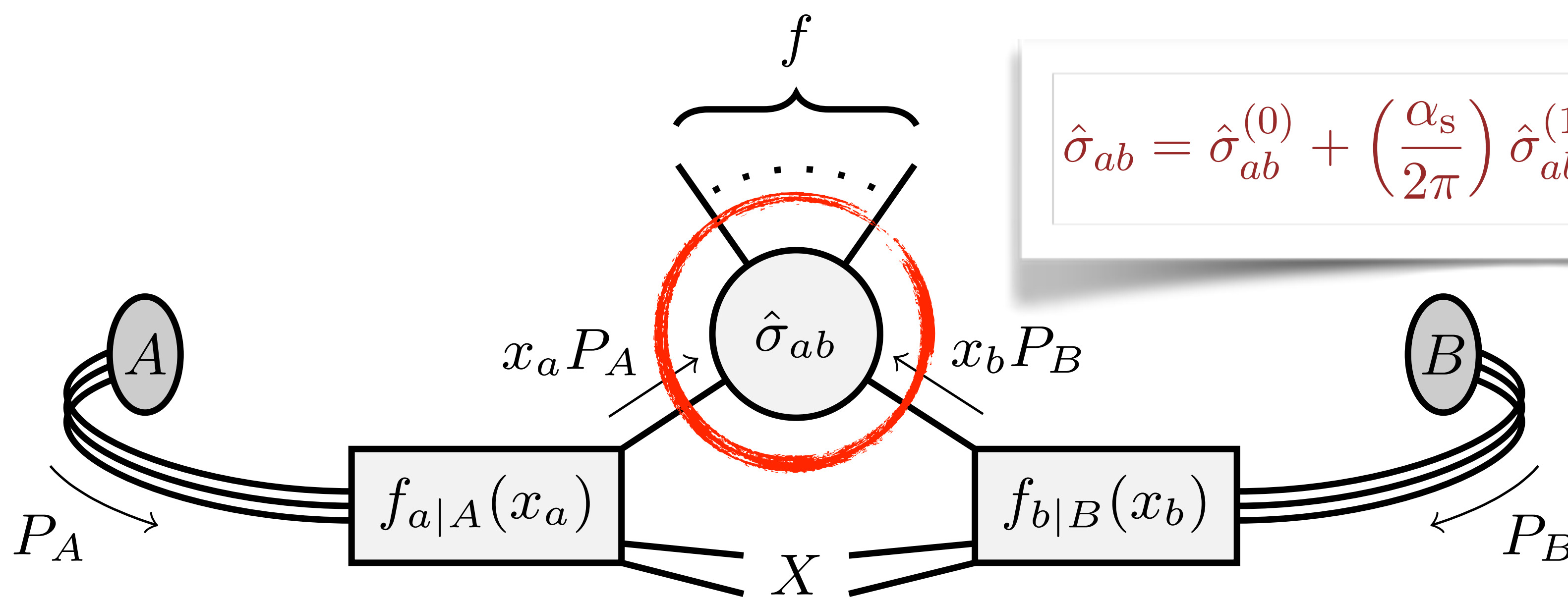
non-perturbative effects
(no good understanding)
$\sim$ few %?

OUTLINE.

1. *The NNLO revolution(?)*
2. *N^{3}LO differential*
3. *off-shell EW corrections*
4. *Theory uncertainties*

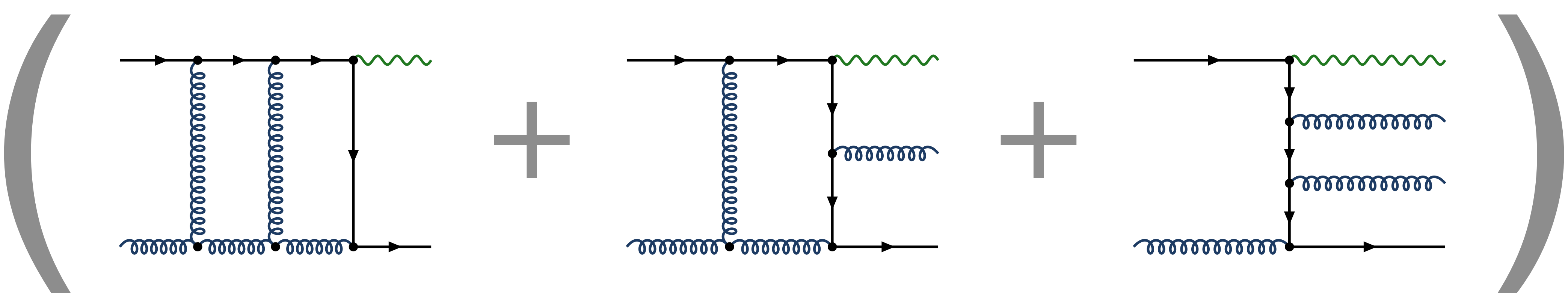
- *NNLO comparison*
- *Distribution of NNLO results*
- *one-loop RV amplitudes in NNLO*
- *Photon Isolation*
- *TH uncert. in PDFs*
- *Scales in ratios*

HARD SCATTERING @ NNLO



$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0)}_{ab} + \left(\frac{\alpha_s}{2\pi}\right)\hat{\sigma}^{(1)}_{ab} + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{(2)}_{ab} + \dots$$

next-to-next-to-leading order (NNLO)



"double virtual" *"real-virtual"* *"double real"*

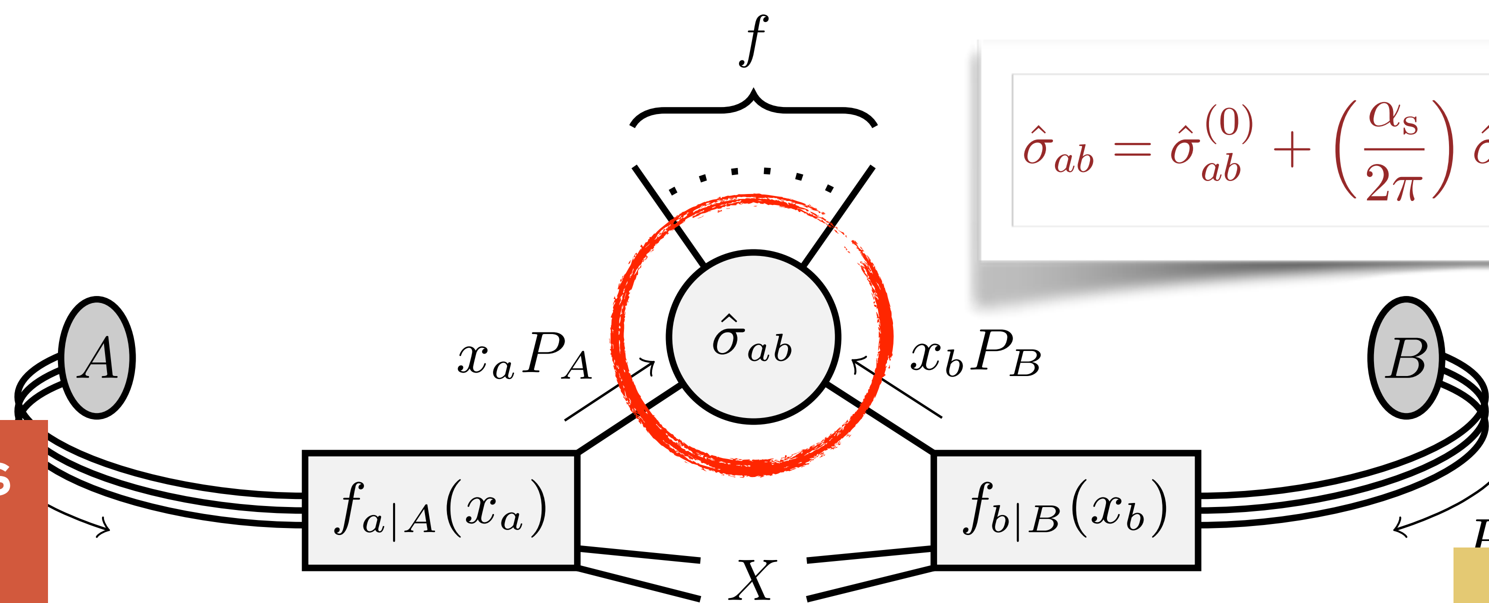
- *$1/\varepsilon^4$, $1/\varepsilon^3$, $1/\varepsilon^2$, $1/\varepsilon$*

- *$1/\varepsilon^2$, $1/\varepsilon$*
- *single unresolved*

- *double unresolved*
- *single unresolved*

NNLO — Bottle Necks

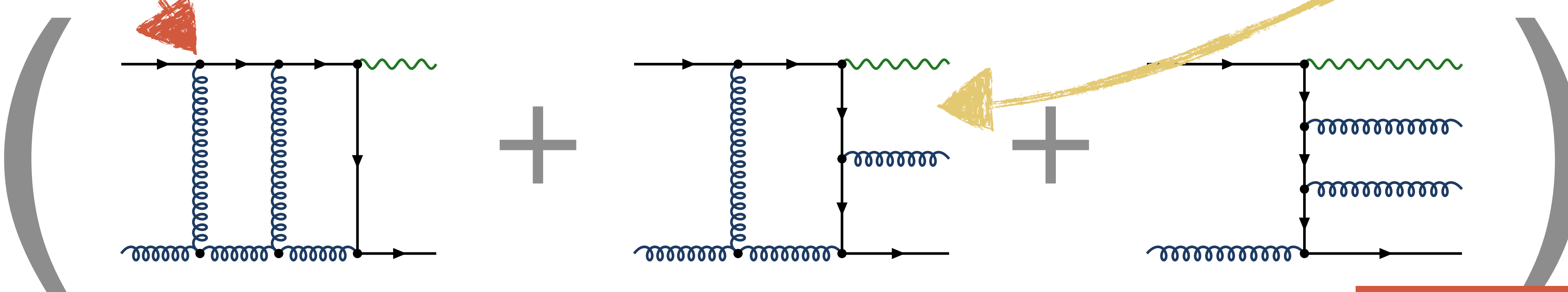
$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0)}_{ab} + \left(\frac{\alpha_s}{2\pi}\right)\hat{\sigma}^{(1)}_{ab} + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}_{ab} + \ldots$$



two-loop amplitudes
(new class of functions, combinatoric & algebraic complexity)

one-loop amplitudes
(evaluation in singular & unstable regions)

next-to-next-to-leading order (NNLO)



"double virtual" *"real-virtual"* *"double re…"*

IR subtraction
(involved IR structure, numerical stability, construction)

infrared singularities

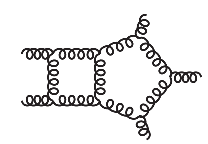
Two-Loop Amplitudes

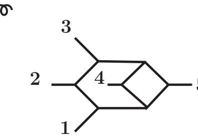
- What we can do: $2 \to 1$ and $2 \to 2$ (mainly massless, 2 massive legs)
- What we want: 3j, V+2j, γγj, ttH, EW corrections, …

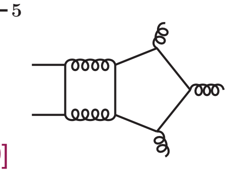
LH '17 wishlist

$pp \to 3\,\text{jets}$	NLO_{QCD}	$\text{N}^2\text{LO}_{\text{QCD}}$

1. Progress in 5-parton amplitudes [from LC 5-point gluon (all plus)]
   - LC 5-point gluon (one minus) [Badger, Brønnum-Hansen, Hartanto, Peraro '18]
   - LC 5-point gluon (all helicities) [Abreu, Dormans, Febres Cordero, Ita, Page '18]
   - all masters (planar & non-planar) [Chicherin, Gehrmann, Henn, Wasser, Zhang, Zoia '18]
   - LC 5-point parton (all helicities) [Abreu, Dormans, Febres Cordero, Ita, Page, Sotnikov '19]
   - full 5-point gluon (all plus) [Badgera, Chicherinb, Gehrmannc, Heinrichb, M. Hennb, Peraroc, Wasserd, Zhangb, Zoia, '19]







2. Understanding of elliptic integrals

$$G(\{c_n, \vec{c}_{n-1}\}, x) = \int_0^1 \frac{dt}{t - c_n}\, G(\vec{c}_{n-1}, t) \longrightarrow K(x, a) = \int_0^x \frac{dt}{\sqrt{(1-t^2)\,(1-at^2)}}$$

[Remiddi, Tancredi]
[Adams, Chaubey, Weinzierl]
[Broedel, Duhr, Dulat, Penante, Tancredi]

3. numerical approaches: tt [Chen, Czakon, Poncelet '17], pySecDec (HH, H+j) [Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk '19]

** more painful with masses & scales*

One-Loop in an NNLO context

- many automated one-loop providers:
  - Recola, OpenLoops(2), MadLoop, GoSam, NLOX, …
- LH ’17 technical comparison: $pp \to ZZ$ & $pp \to WW$

- As Real-Virtual amplitudes in NNLO calculations:
  1. numerical stability — probe unresolved regions
  2. evaluation time (quad precision rescue system?)

- Benchmark study specifically targeted towards this use case?

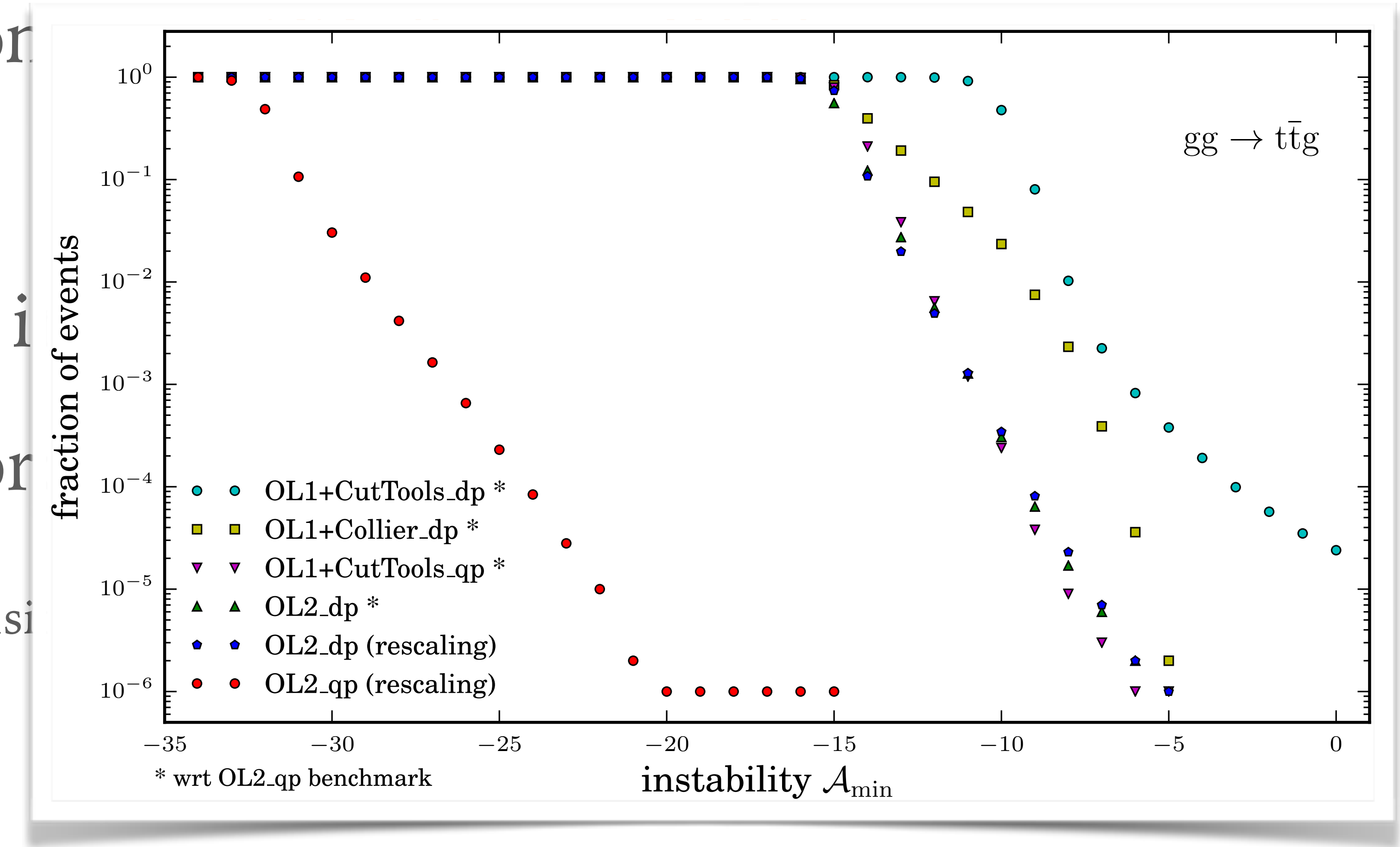
  analytical amplitudes from numerical evaluations [De Laurentis, Maître ’19]

One-Loop in an NNLO context

- ➤ many automated one-loop providers:
  - Recola, OpenLoops(2), MadLoop, GoSam, NLOX, …

[Buccioni, Lang, Pozzorini, Zhang, Zoller ’17]

- ➤ LH ’17 technical comparison



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- ➤ Benchmark study specifically targeted towards this use case?

analytical amplitudes from numerical evaluations [De Laurentis, Maître ’19]

SUBTRACTION METHODS

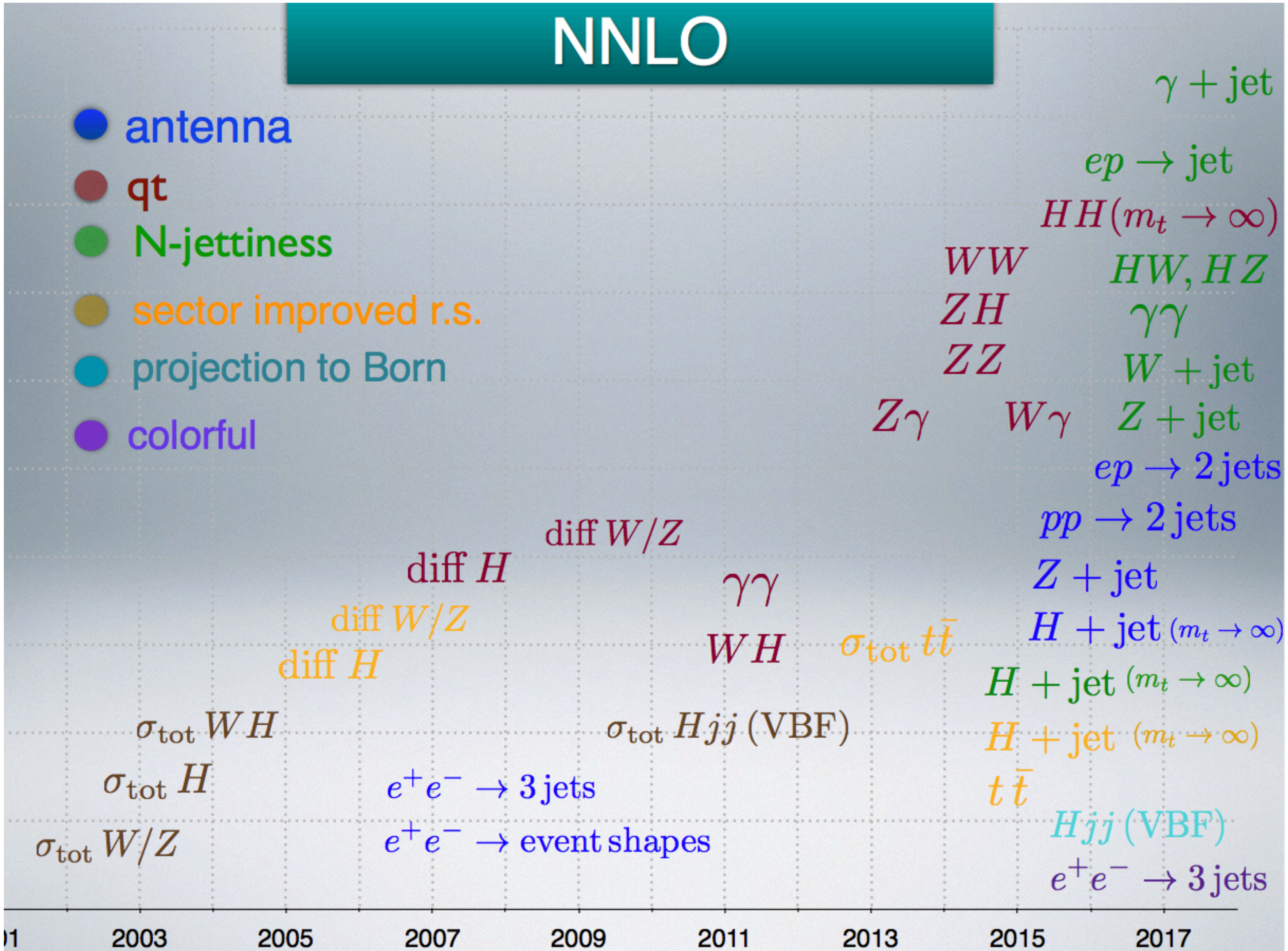
{session Thu morning}

➤ Remarkable progress in the development of methods to perform NNLO computations!

(not an exhaustive list)	local subtraction	analytic	pp collisions	final-state jet(s)
Antenna	✗ (local after rot^{n})	✓	✓	✓
CoLorFul	✓	✓	✗	✓
q_T-Subtr.	✗	✓	✓	✗ (only t)
STRIPPER / nested soft–coll.	✓	✗ / ✓	✓	✓
N-jettiness	✗	✓	✓	✓ ($\leq$ 1 jet so far)

- Projection-to-Born, Local Analytic Sectors, Geometric, …

* *more painful with massless particles*



[slide by Gudrun Heinrich]

W + jet ('17)
Hjj(VBF) ('18)
HHjj(VBF) ('19)
$t\bar{t}$ ('19)
γ + jet ('19)

combination of (production) $\times$ (decay):

- (t-channel single-t) $\times$ ($t \to W^+ b$) .... [Berger, Gao, Yuan, Zhu '16]
- (VH) $\times$ (H $\to$ bb) .... [Ferrera, Somogyi, Tramontano '17]
- (WH) $\times$ (H $\to$ bb) .... [Caola, Luisoni, Melnikov, Röntsch '17]
- ($t\bar{t}$) $\times$ ($t \to Wb$)^2 .... [Behring, Czakon, Mitov, Papanastasiou, Poncelet, '19]

NNLO Benchmarks?

- Calculations @ NNLO very complex
- Independent methods and/or implementation

  $\Rightarrow$ cross validation!

- Many processes computed by at least two groups
  - perform tuned comparisons
  - validation points for future calculations/methods
  - Drell-Yan, … ?

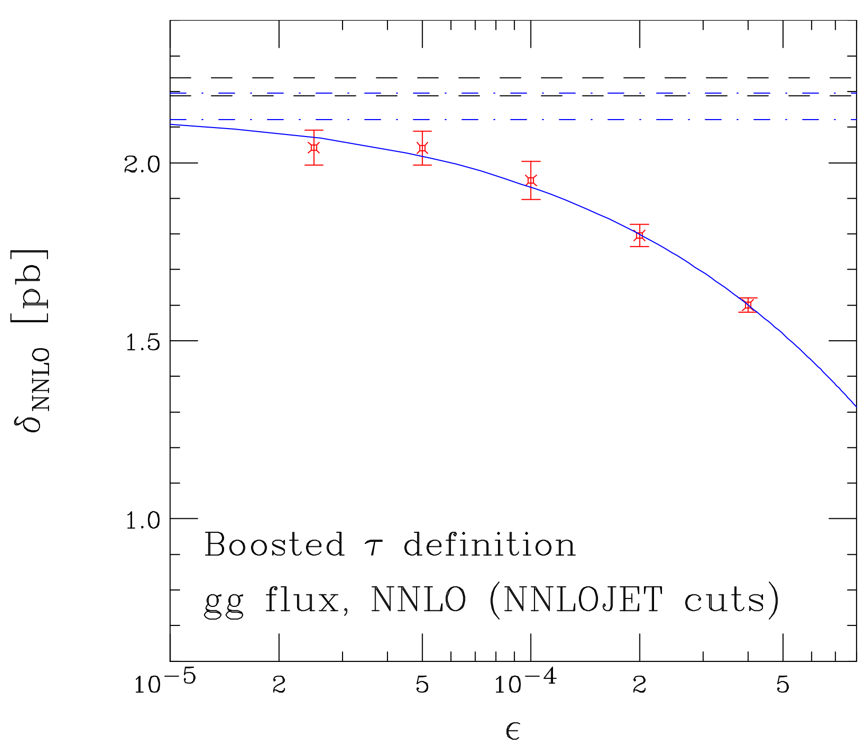
NNLO BENCHMARKS!

➤ Long-standing tension between NNLO H+jet calculations

[Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '16]

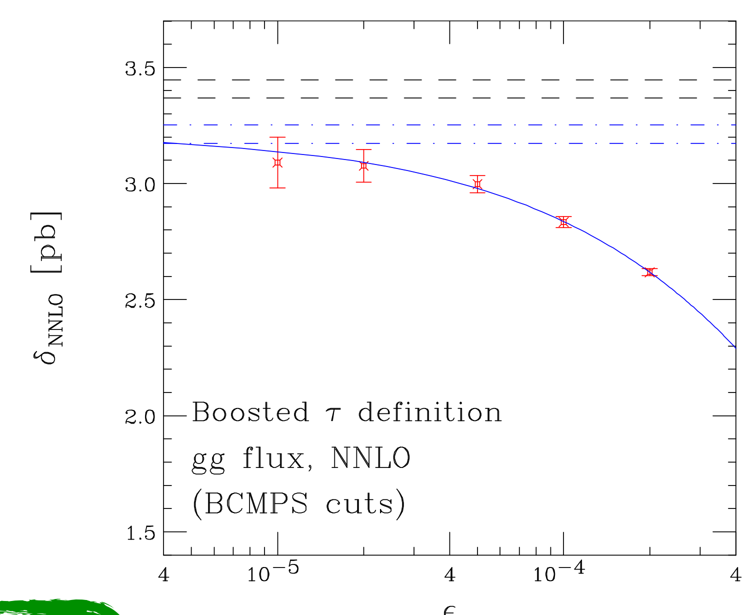
		$\sigma^{EFT}_{H(\to\gamma\gamma)+\geq 1jet,\text{NNLO}}$	$\sigma^{EFT}_{H+\geq 1jet,\text{NNLO}}$	$\sigma^{EFT}_{H+\geq 1jet,\text{NNLO}}$
	NNLOJET	$9.44^{+0.59}_{-0.85}$ fb	$16.8^{+0.9}_{-1.5}$ pb	$5.81^{+0.51}_{-0.62}$ pb
Sector-imp.	Results from [18]	$9.45^{+0.58}_{-0.82}$ fb	-	-
residue subtr.	Results from [39]	-	$16.7^{+1.0}_{--}$ pb	-
τ_N slicing	Results from [17]	-	-	$5.5^{+0.3}_{-0.4}$ pb

➤ Finally resolved [Campbell, Ellis, Seth '19]



$$\sigma_{NNLO}(\text{NNLOJET}) = 16.73 \pm 0.05\,^{+1.00}_{-1.51}\ \text{pb}$$

$$\sigma_{NNLO}(\text{MCFM, fit}) = 16.71 \pm 0.05\,^{+1.03}_{-1.52}\ \text{pb}$$



Distribution of Results.

- Full $2 \to 2$ @ NNLO calculation: $\mathcal{O}(100\text{k})$ CPUh

  $\Rightarrow$ prohibitive in applications such as PDF & α_s fits!

DISTRIBUTION OF RESULTS.

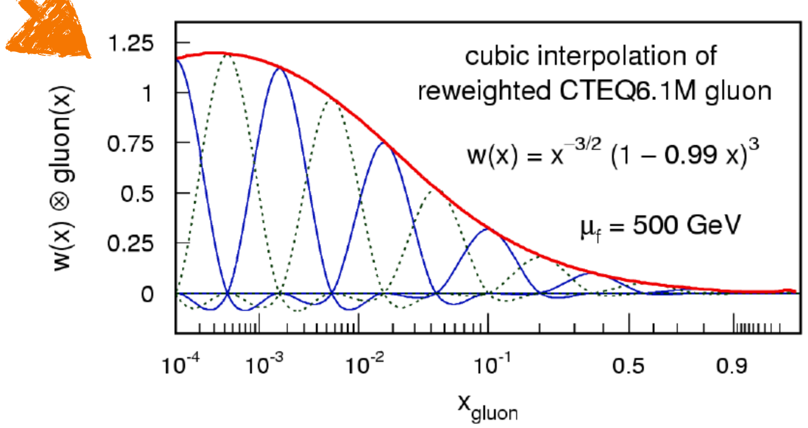
- Full $2 \to 2$ @ NNLO calculation: O(100k) CPUh

  $\Rightarrow$ prohibitive in applications such as PDF & α_s fits!

- Fast interpolation grids: APPLfast [APPLgrid, fastNLO, NNLOJET '19]

sum: cheap!

$$\sigma = \int_0^1 \mathrm{d}x\, f_a(x)\, \alpha_s^n\, \hat{\sigma}_a(x) \simeq \sum_i f_a(x^{(i)})\, \alpha_s^n \underbrace{\left[\int_0^1 \mathrm{d}x\, \hat{\sigma}_a(x)\, E^{(i)}(x)\right]}_{\hat{\sigma}_a^{(i)}}$$



$$f_a(x) \simeq \sum_i f_a(x^{(i)})\, E^{(i)}(x)$$

DISTRIBUTION OF RESULTS.

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- Fast interpolation grids: APPLfast [APPLgrid, fastNLO, NNLOJET '19]

- nTuples @ NNLO [LH '15, '17]

For each event store the weight decomposition:

$$\omega = \alpha_S^n \,\mathrm{pdf}(x_1, id_1, \mu)\,\mathrm{pdf}(x_2, id_2, \mu) \times \Big(c_0 + c_1 \log(\mu^2) + c_2 \log^2(\mu^2) + \dots\Big)$$

  - *$e^+e^- \to 3j$* *O(few TB)* [LH '15]
  - *$pp \to 2j$* *O(100 TB)* [LH '17 (estimate)]
  - *input from different NNLO groups; benchmark using Drell-Yan?*

Distribution of Results.

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- Fast interpolation grids: APPLfast [APPLgrid, fastNLO, NNLOJET '19]

- nTuples @ NNLO [LH '15, '17]

★ Common interface standard for both?

★ Study impact on fits: NNLO[grid] vs. NLO[grid] $\times$ K_{NNLO}

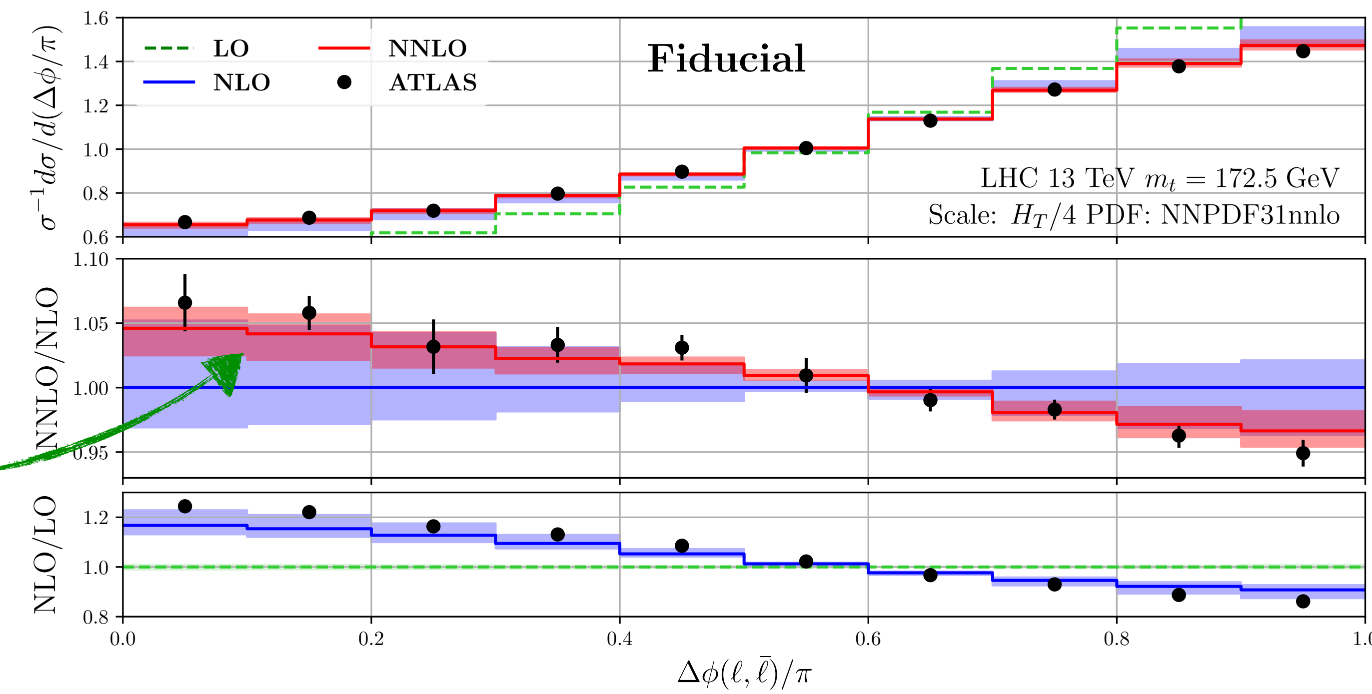
rapid decay: spin info from tops transferred to leptons

REFERENCE

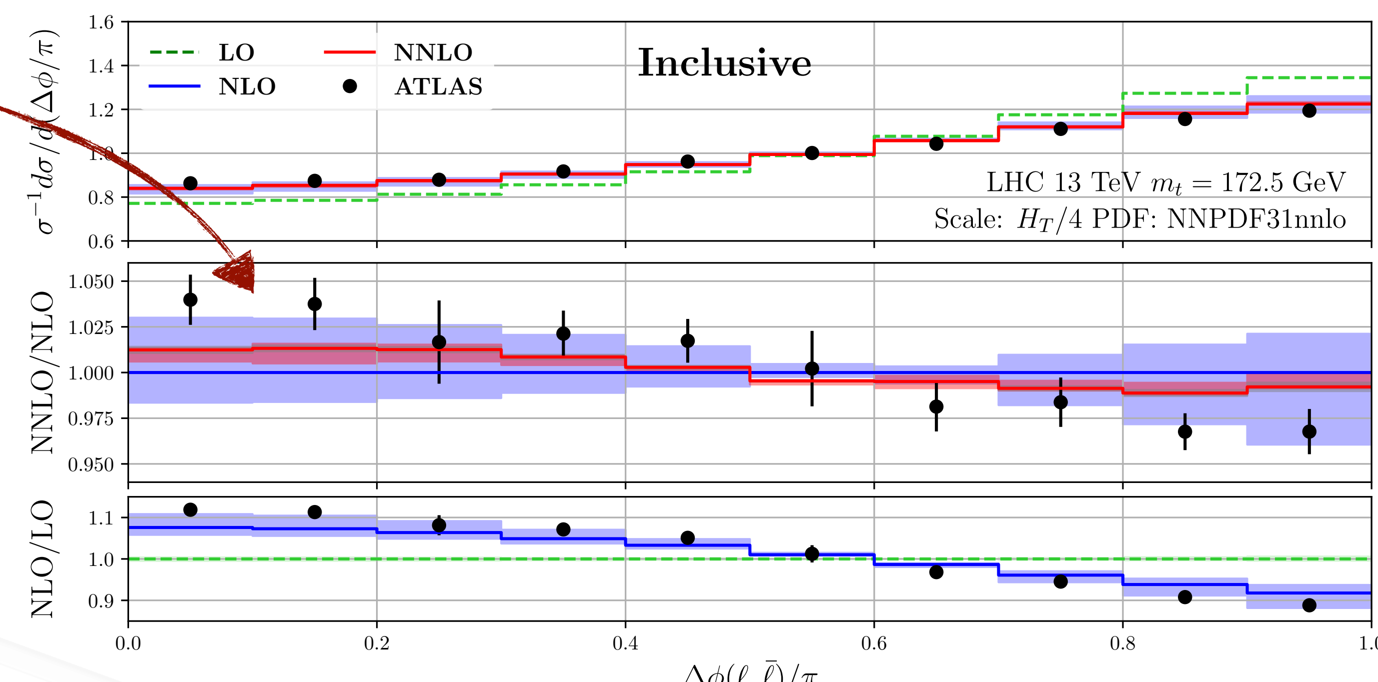
Top Quark Spin Correlation at NNLO

[Behring, Czakon, Mitov, Papanastasiou, Poncelet `19]

- leptons carry spin information of the tops
- fiducial: good agreement



- inclusive: some tension



In our view the most plausible explanation for this discrepancy lies in the extrapolation of the fiducial measurement to the full phase space.

Fiducial vs. Inclusive

➤ When possible, report physical cross sections

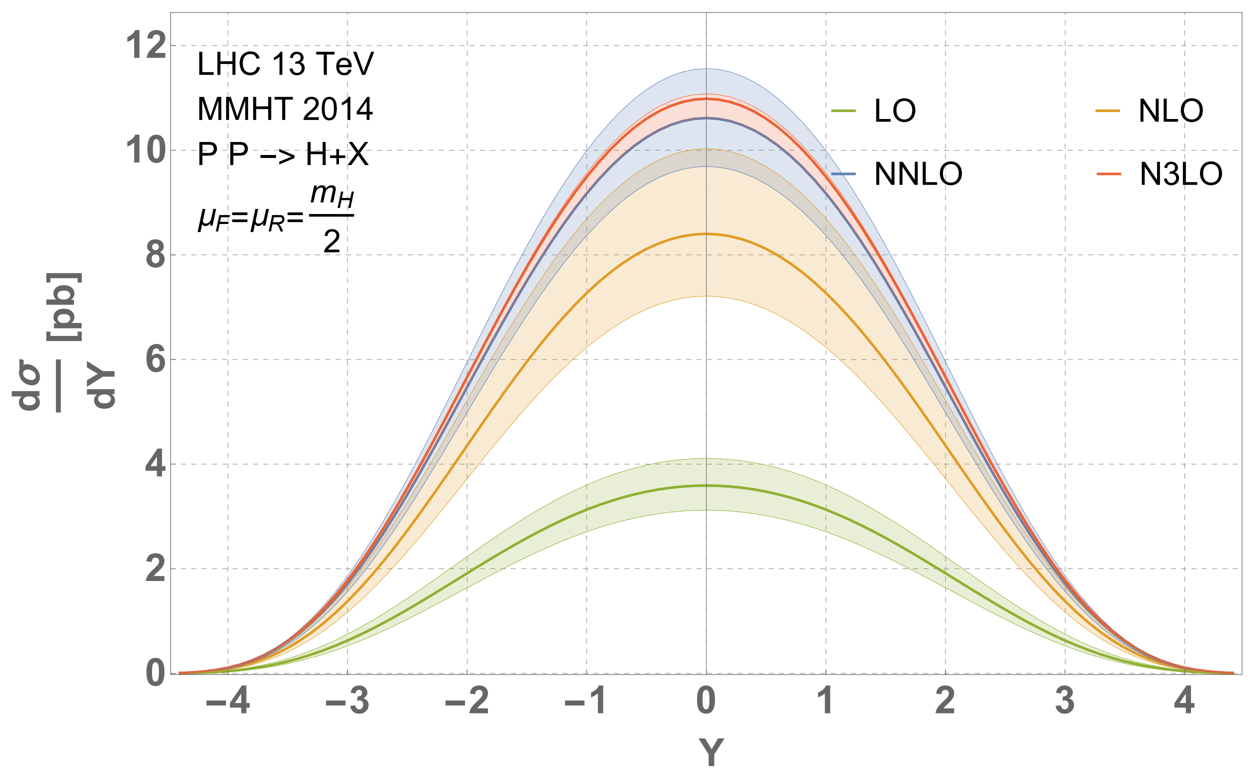
1. infamous WW example [Monni, Zanderighi '13]
   - jet-veto efficiency overestimated Sudakov suppression
2. $H \to 4l$ acceptances CMS vs. ATLAS **{Talk by S. Jones}**
   - isolation prescription can impact pert. stability
3. angular coefficients A_i to extrapolate to full lepton acceptance

➤ study acceptances/extrapolations with state-of-the-art tools?

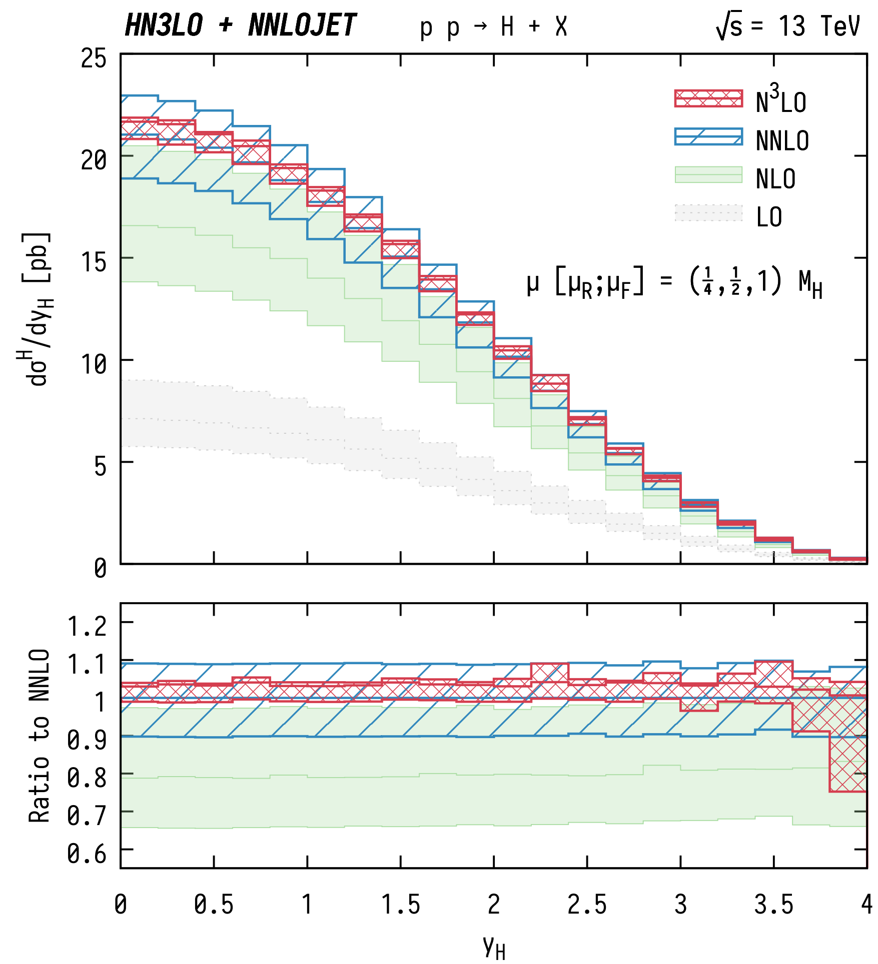
N^{3}LO — GOING DIFFERENTIAL

➤ Inclusive results: H [Anastasiou et al. '15] [Mistlberger '18], H(VBF) [Dreyer, Karlberg '16], HH(VBF) [Dreyer, Karlberg '18]

➤ Differential results: y_H



analytic [Dulat, Mistlberger, Pelloni '18]



q_T subtraction [Cieri, Chen, Gehrmann, Glover, AH '18]

- DIS [Currie, Gehrmann, Glover, AH, Niehues, Vogt, Walker], H→bb [Mondini, Schiavi, Williams '19]

➤ N^{3}LO beam function: RRV [Melnikov, Rietkerk, Tancredi, Wever '17] RRR [Melnikov, Rietkerk, Tancredi, Wever '19]

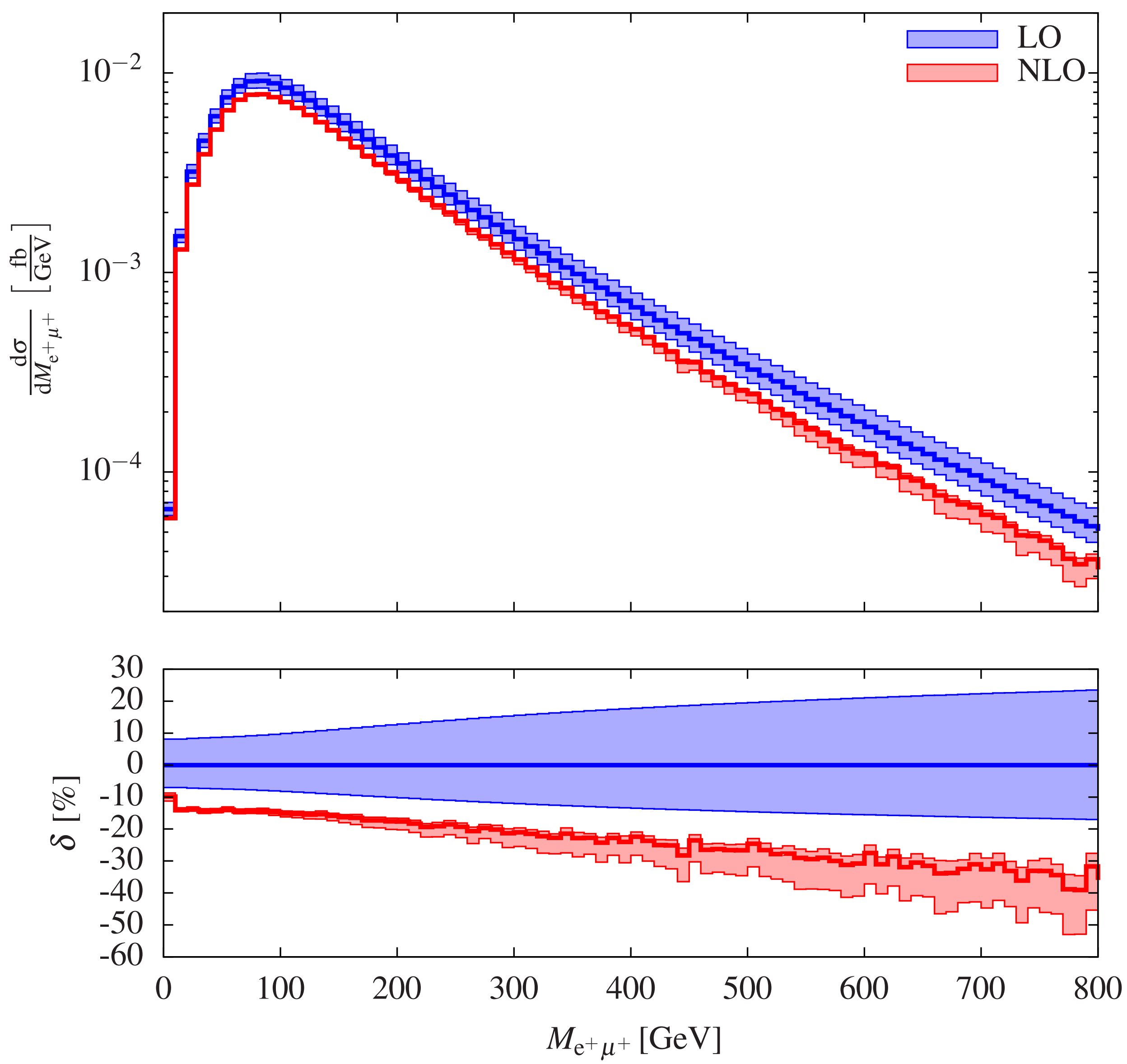
Unitarisation of Higg: EWWSB,

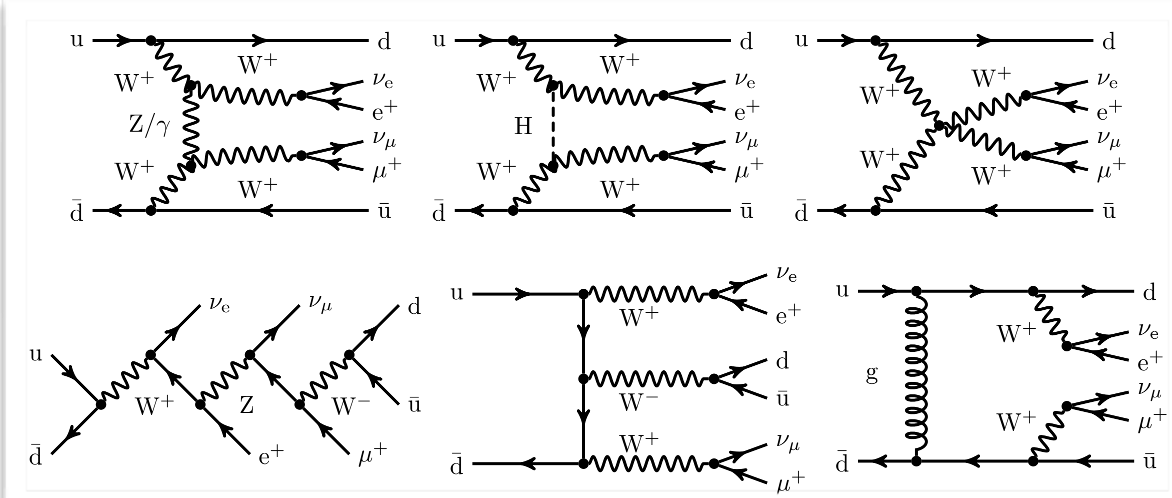
4 = # ext. W's

large SU(2) gauge coupling & casimir

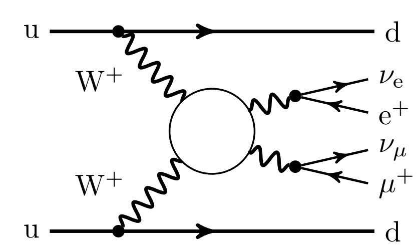
EW — GOING OFF-SHELL

- now up to $2 \to 6$: WWW [Schönherr '18], W^+W^+ scattering [Biedermann, Denner, Pellen '17]
- full NLO VBS(W^+W^+):





- EW corrections dominant!



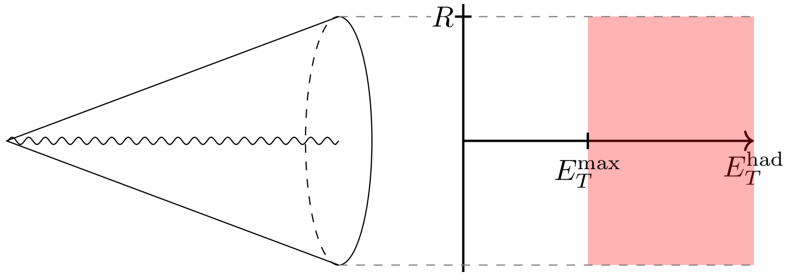
$$\sigma_{LL} = \sigma_{LO}\left[1 - \frac{\alpha}{4\pi} 4C_W^{ew} \log^2\left(\frac{Q^2}{M_W^2}\right) + \frac{\alpha}{4\pi} 2b_W^{ew} \log\left(\frac{Q^2}{M_W^2}\right)\right],$$

+ PS [Chiesa, Denner, Lang, Pellen '19]

Photon Isolation

{session Fri afternoon}

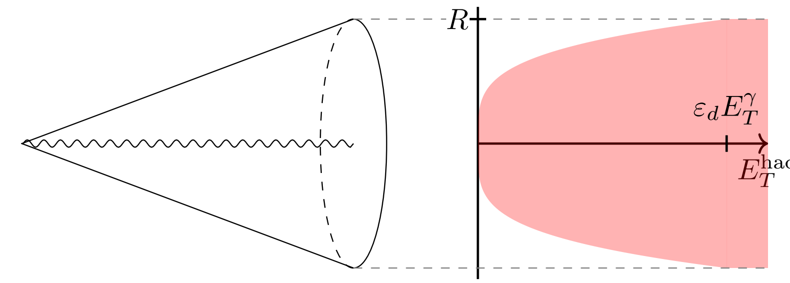
Hard cone



$$E_{\mathrm{T}}^{\mathrm{had}} \leq \epsilon\, p_{\mathrm{T}}^{\gamma} + E_{\mathrm{T}}^{\mathrm{thresh}}$$

- fragmentation
- used in experiment

Smooth cone [Frixione '98]



$$E_{\mathrm{T}}^{\mathrm{had}} \leq \epsilon\, p_{\mathrm{T}}^{\gamma} \left(\frac{1-\cos r}{1-\cos R} \right)^{n} \quad \forall r \leq R$$

- no fragmentation (theory 😀)
- cannot be used in experiment

➤ Tight isolation accord (γγ, γ+jet) [LH '13, '15]

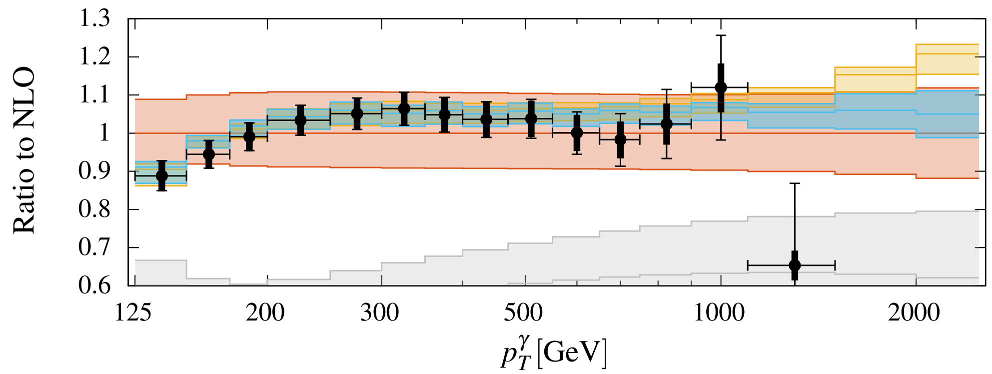
For $\epsilon \lesssim 0.1$ hard vs. smooth $\sim O(\text{few}\ \%)$

looser: $O(10\%)$

PHOTON ISOLATION CONT.

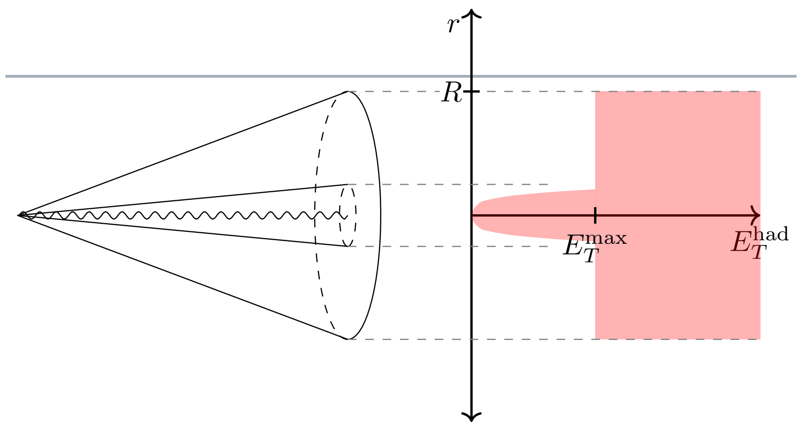
{session Fri afternoon}

- NNLO: O(few %) matters!



- Isolation with smaller mismatch
  - get away with looser cuts?
  - soft-drop [Hall, Thaler '18], …

HYBRID ISOLATION [Siegert '16] [Chen et al. '19]



- connection to Tools & MC?

- fragmentation @ NNLO & how to measure them?

Theory uncertainties

- increasingly urgent to have more robust uncertainty estimates
- scale ambiguities in jets **{Talk by J. Huston}**
- theory uncertainties in PDF fits **{session on Fri morning}**
- scales in ratios:

THEORY UNCERTAINTIES

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- scale ambiguities in jets {Talk by }
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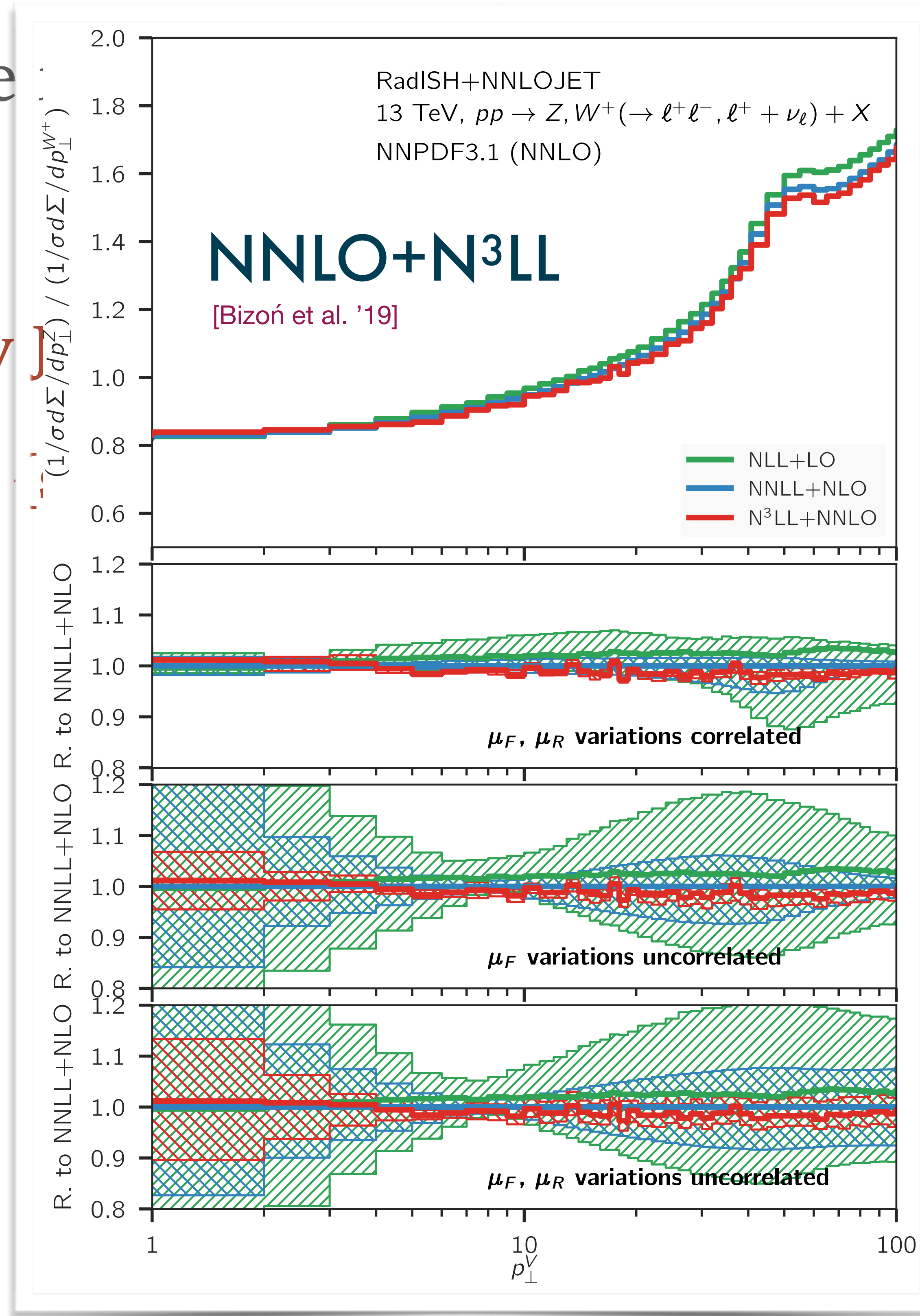
  - $p_T(Z)$ / $p_T(W)$



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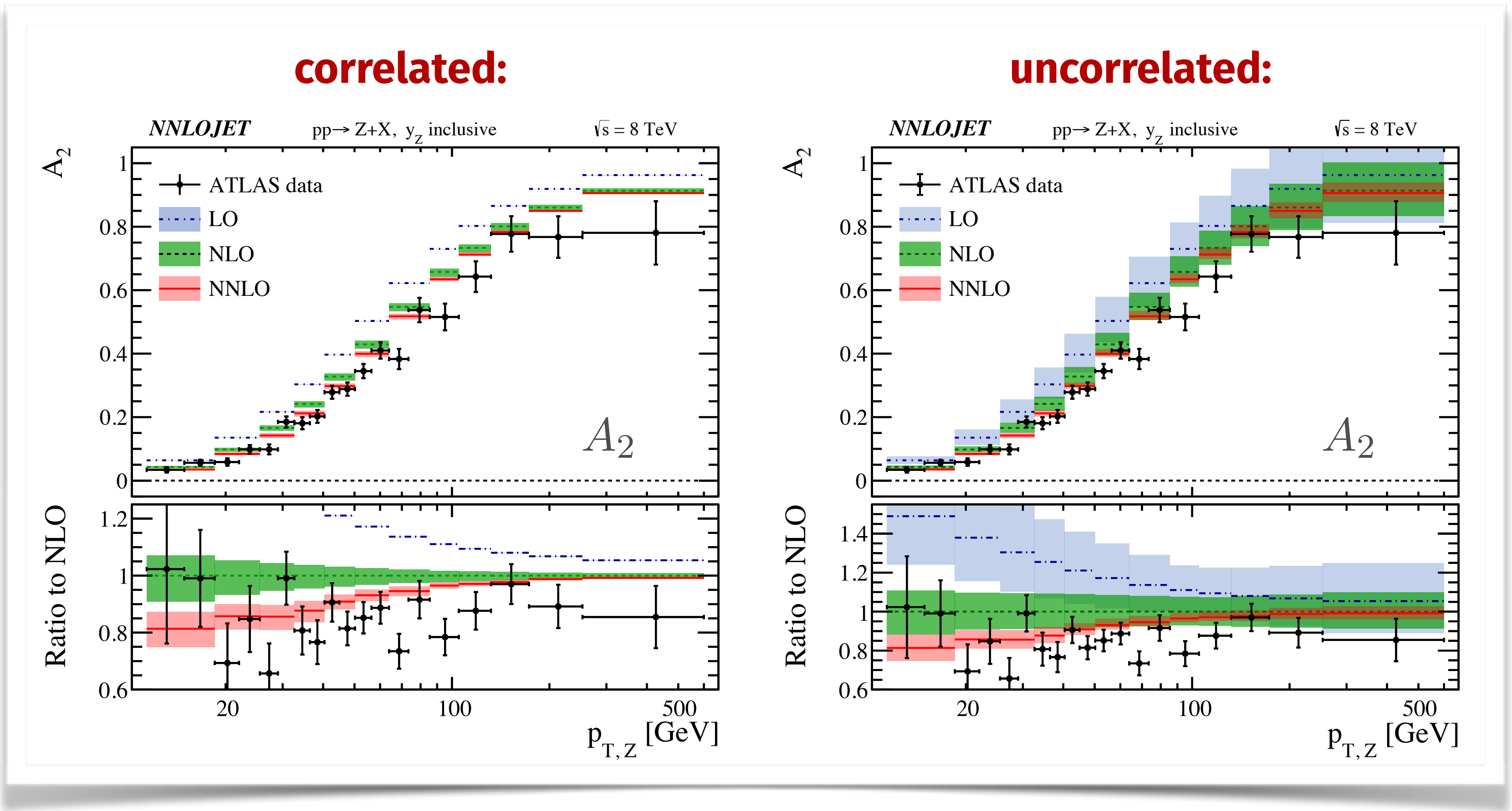
  - $p_T(Z)$ / $p_T(W)$
  - ang. coefficients A_i

$$\langle f(\theta,\phi)\rangle = \frac{\int \mathrm{d}\Omega\, \mathrm{d}\sigma(\mu_F^{\text{num.}}, \mu_R^{\text{num.}})\, f(\theta,\phi)}{\int \mathrm{d}\Omega\, \mathrm{d}\sigma(\mu_F^{\text{den.}}, \mu_R^{\text{den.}})}$$



[Gauld et al. '17]

THEORY UNCERTAINTIES

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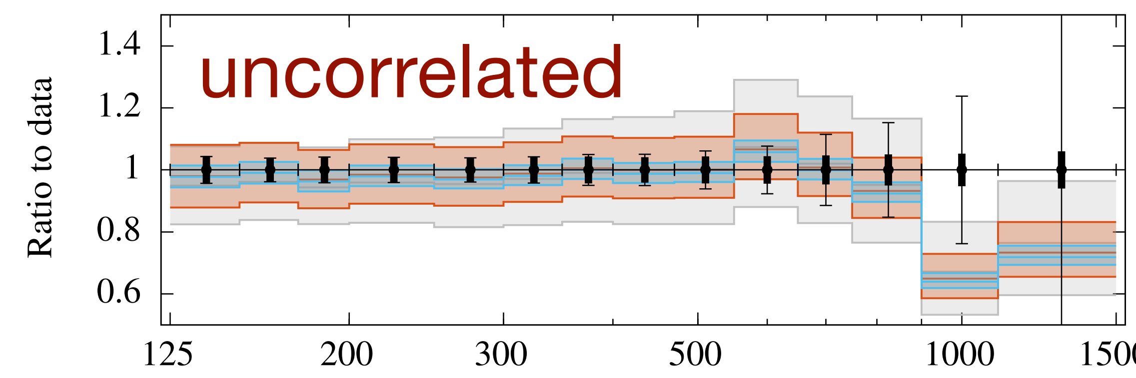
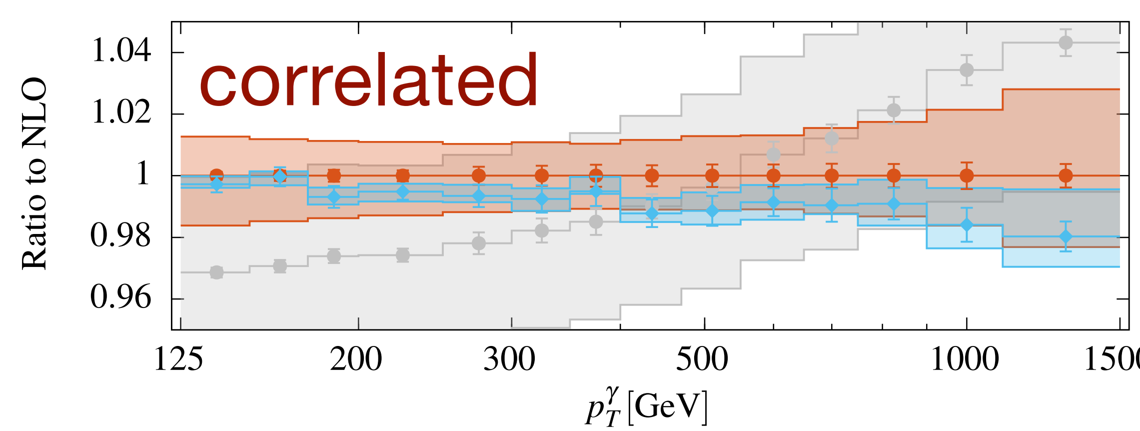
  - $p_T(\gamma)$: 13 TeV / 8 TeV



[Chen et al. '19]



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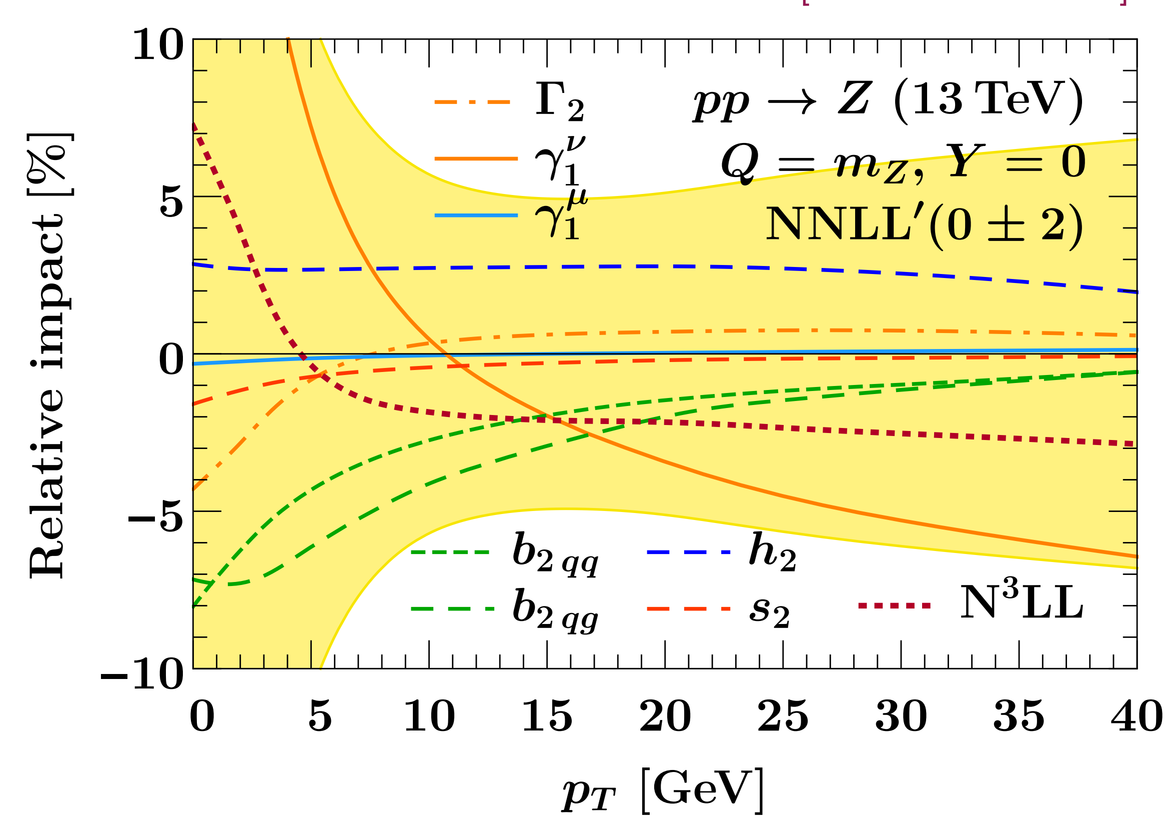
  - ang. coefficients A_i
  - $p_T(\gamma)$: 13 TeV / 8 TeV
- nuisance parameters in p_T res.

[Tackmann EWWG '19]



Final remarks.

- **Remarkable progress** in precision calculations:
  - $2 \to 2$ @ NNLO, $2 \to 1$ @ N^3LO, off-shell EW $2 \to 6$
- still many **issues** & **challenges** $\Rightarrow$ let's tackle some here!
- More topics to consider:
  - mixed QCD-EW corrections; how to combine QCD & EW?
  - $p_T(Z)$—in the world of per-cent precision **{EWWG June 18th}**
    - ➡ m_b effects, QED ISR, NP effects, …
  - fixed-order vs. resummation vs. showers
  - … **your ideas!**

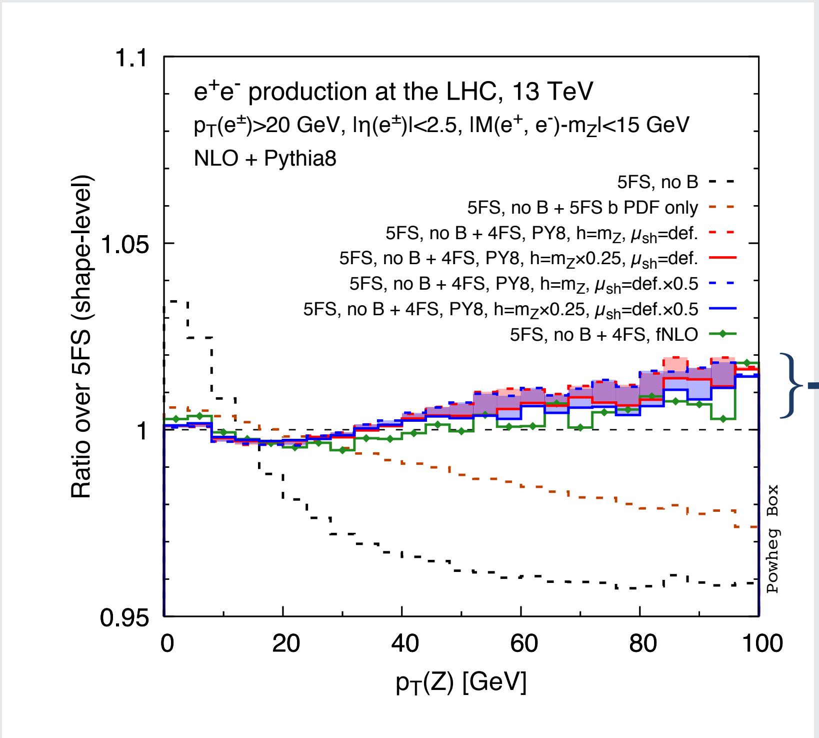
Enjoy Les Houches!

Backup.

$P_T(Z)$ @ THE PER-CENT LEVEL

Bottom-quark effects

[Bagnaschi, Maltoni, Vicini, Zaro '18]



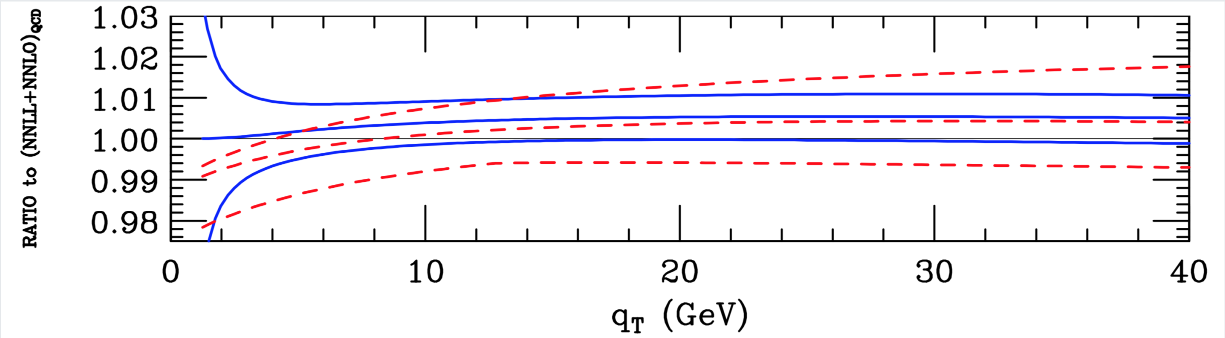
$$\frac{d\sigma^{m_b}}{dp_T^Z} = \frac{d\sigma^{5\,FS}_{b\,veto}}{dp_T^Z} + \frac{d\sigma^{4\,FS}_{m_b>0}}{dp_T^Z}$$

} → different PS approx.

- shape distortion @ $\pm 0.5\%$ level
- impact on M_W extraction
  $\hookrightarrow \Delta M_W < 5$ MeV

Small-p_T QED ISR effects

[Cieri, Ferrera, Sborlini '18]



(LL)$_{QED}$ $-1\% \to +0.5\%$
$\hookrightarrow$ uncertainty: 2–3%

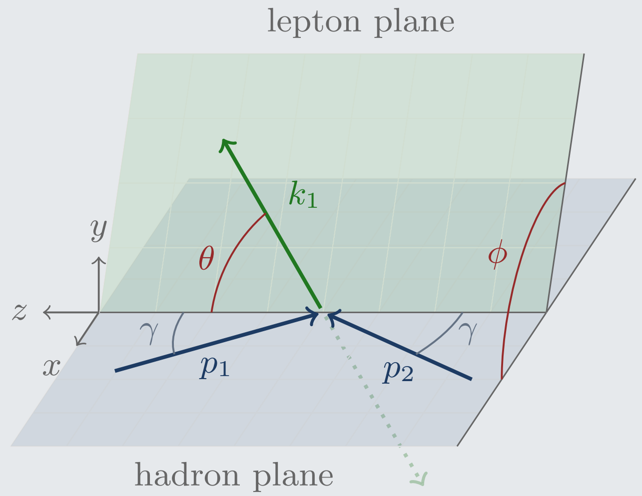
(NLL+NLO)$_{QED}$ $\sim 0.5\%$
$\hookrightarrow$ uncertainty: $\sim 1\%$

PDF and non-perturbative effects

[Catani, de Florian, Ferrera, Grazzini '15]

PDF $\sim \pm 3\%$ **NP** $\lesssim 2\%$ $(p_T^Z > 15$ GeV$)$, more sizeable for $p_T^Z < 3$ GeV

Angular Coefficients



$$\mathrm{p\,p} \to \mathrm{Z}/\gamma^* + X \to \ell^-\ell^+ + X$$

- lepton angular distributions (θ, ϕ)
- probe production dynamics & polarisation
- M_W & $\sin^2\theta_\mathrm{w}$ measurement

[Gauld, Gehrmann–De Ridder, Gehrmann, Glover, AH '17]

Angular coefficients: $A_i(p_\mathrm{T}^\mathrm{Z}, y^\mathrm{Z}, m_{\ell\ell})$ $\qquad Y_{lm}(\theta,\phi),\ l = 0,1,2$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\text{unpol.}}}{\mathrm{d}^4q}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0\,(1-3\cos^2\theta)$$
$$+ A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}A_2\,\sin^2\theta\,\cos(2\phi)$$
$$+ A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi)$$
$$+ A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\}$$

$A_i(q)$ $+\ \sigma^{\text{unpol.}}$

production dynamics

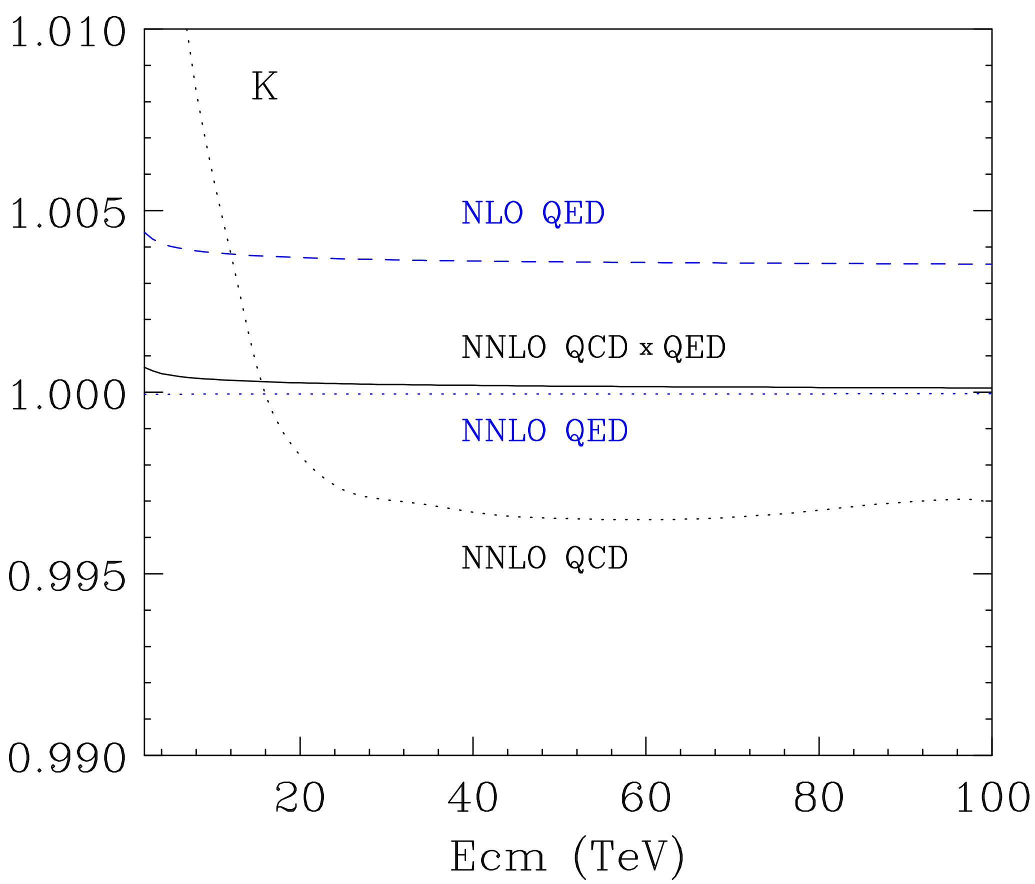
$Y_{lm}(\theta,\phi)$

lepton kinematics

$l = 0:$	$m = 0$
$l = 1:$	$m = \pm1,\ 0$
$l = 2:$	$m = \pm2,\ \pm1,\ 0$
total:	9

MIXED QCD–EW FOR DRELL-YAN

- **Pole approximation** (around resonance) .... [Dittmaier, AH, Schwinn '14, '15]
- **Altarelli–Parisi splitting functions** .... [de Florian, Sborlini, Rodrigo '16]
- **2-loop master integrals** .... [Bonciani, Di Vita, Mastrolia, Schubert '16]
  [von Manteuffel, Schabinger '17]
- **Double-real** (production, inclusive) .... [Bonciani, Buccioni, Mondini, Vicini '16]
- **QCD–QED** (on-shell Z, inclusive) .... [de Florian, Der, Fabre '18]



[de Florian, Der, Fabre '18]

- *trick*: start with **NNLO QCD**
  $\hookrightarrow SU(3)_{\text{colour}} \to U(1)_{\text{QED}}$
  $\Leftrightarrow$ W and off-shell decay ✗

- $\mathcal{O}(\alpha_s\alpha_{\text{QED}}) < 1‰$
- $\mathcal{O}(\alpha_{\text{QED}}^2)$ $\mathcal{O}(10^{-5})$
- but for $M_W \Leftrightarrow$ *shape*!