Karlsruhe Institute of Technology

New developments in the APPLfast project

xFitter External meeting | CERN, Geneva, Switzerland

Lucas Kunz (with Fazila Ahmadova, Daniel Britzger, Xuan Chen, Claire Gwenlan, Gudrun Heinrich, Alexander Yohei Huss, João Ramalho Pires, Klaus Rabbertz, Mark R. Sutton) | 04/05/2023

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Motivation

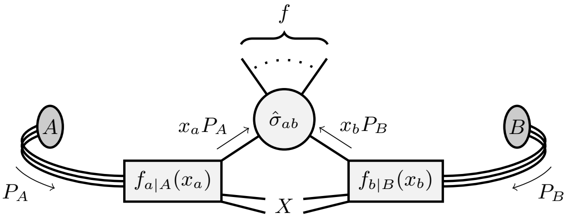

Figure by A. Huss

$$\mathrm{d}\sigma_{pp\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_a(x_a, \alpha_s(\mu_R), \mu_F)\, f_b(x_b, \alpha_s(\mu_R), \mu_F)$$

$$\times \, \mathrm{d}\hat{\sigma}_{ab\to X}(x_a, x_b, \alpha_s(\mu_R), \mu_R, \mu_F) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)^p$$

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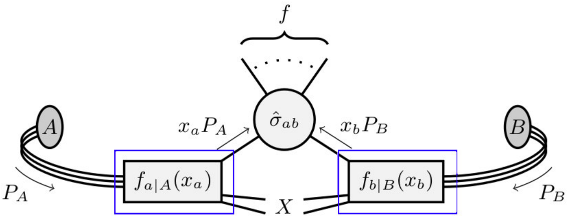

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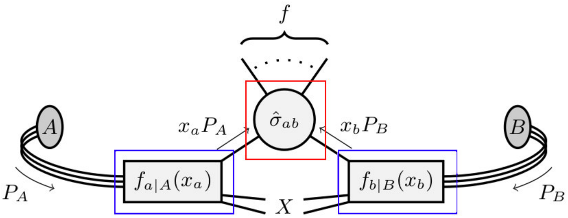

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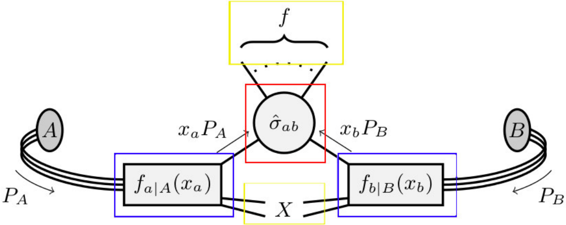

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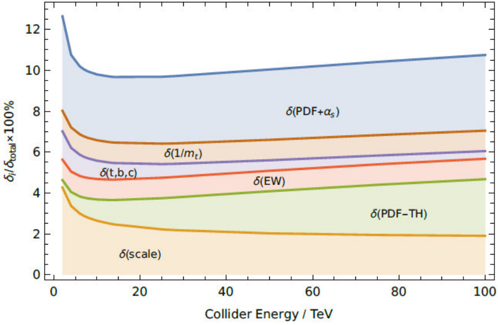
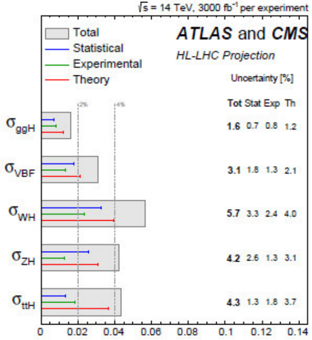


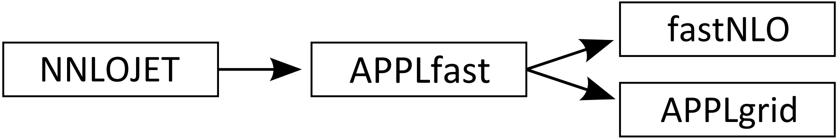


Relative uncertainty of the Higgs boson production cross section [Dulat, Lazopoulos, Mistlberger '18]

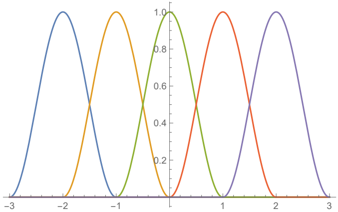
Higgs production uncertainty estimates for the HL-LHC [HL-LHC Working Group 2 '19]

Grid Technique - Logic

- NNLOJET: fixed order Monte Carlo calculations
- fastNLO/APPLgrid: grid libraries
- APPLfast: interface connecting the two sides



Grid Technique - Interpolation



- Split interval $I = [a, b]$ into $N + 1$ nodes, $a = x^{[0]}$, $b = x^{[N]}$
- Partition of unity into a set of functions:
  - $1 = \sum_{i=0}^{N} E_i(x) \;\; \forall x \in I$
  - $E_i\left(x^{[i]}\right) = 1 \;\; \forall i \in \{0, \ldots, N\}$
- $\Rightarrow$ Functions on the interval can be approximated: $f(x) \simeq \sum_{i=0}^{N} f^{[i]} E_i(x)$ where $f^{[i]} = f(x^{[i]})$
- $\Rightarrow$ Integrals can also be approximated: $\int_a^b f(x) g(x)\, \mathrm{d}x \simeq \sum_{i=0}^{N} f^{[i]} g_{[i]}$ with $g_{[i]} := \int_a^b E_i(x) g(x)\, \mathrm{d}x$

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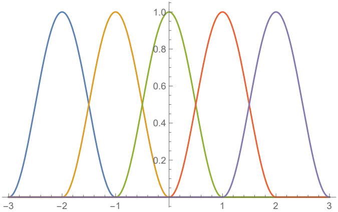

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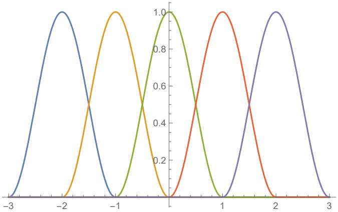

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Grid Technique - Formulae

$$\mathrm{d}\hat{\sigma}_{ab\to X}(x, \alpha_s, \mu) = \sum_k \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^{k+r} \mathrm{d}\hat{\sigma}^{(k)}_{ab\to X}(x, \alpha_s, \mu)$$

Evaluation with Monte Carlo event generator:

- Fixed-order ($k = 0, 1, ...$) parton level calculations
- Phase-space samples (x_m, Φ_m) with weights $w^{(k)}_{ab\to X,\,m}$

$$\Rightarrow \sigma_{pp\to X}(x, \alpha_s, \mu) = \sum_{a,b} \sum_k \sum_{m=1}^{M_p} \left(\frac{\alpha_s(\mu_{R,m})}{2\pi}\right)^{k+r} \hat{\sigma}^{(k)}_{ab\to X,\,m}$$

$$\times\, w^{(k)}_{ab\to X,\,m}\, f_a(x_{a,m}, \mu_{F,m})\, f_b(x_{b,m}, \mu_{F,m})$$

Grid Technique - Formulae

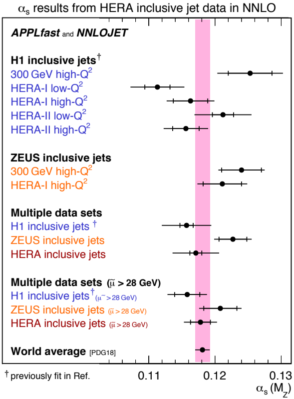
For pp collisions: 4 functions $E_i(x_a)$, $E_j(x_b)$, $E_v(\mu_R)$, $E_w(\mu_F)$

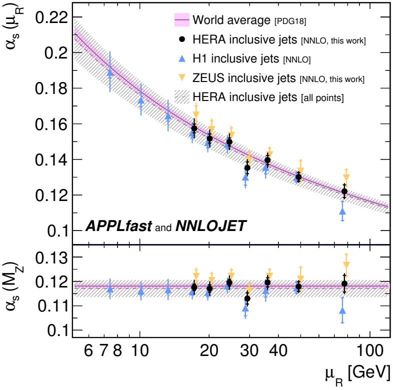
$$\Rightarrow \sigma_{pp\to X}(x,\alpha_s,\mu) = \sum_{i,j,v,w=0}^{N} \sum_{a,b} \sum_{k} \left(\frac{\alpha_s^{[v]}}{2\pi}\right)^{k+r} f_a^{[i,w]}\, f_b^{[j,w]} \times \hat{\sigma}^{(k)}_{ab\to X\;[i,j,v,w]}$$

with

$$\hat{\sigma}^{(k)}_{ab\to X\;[i,j,v,w]} := \sum_{m=1}^{M_p} E_i(x_{a,m})\, E_j(x_{b,m})\, E_v(\mu_{R,m})\, E_w(\mu_{F,m}) \times w^{(k)}_{ab\to X,\,m}\, \hat{\sigma}^{(k)}_{ab\to X,\,m}$$

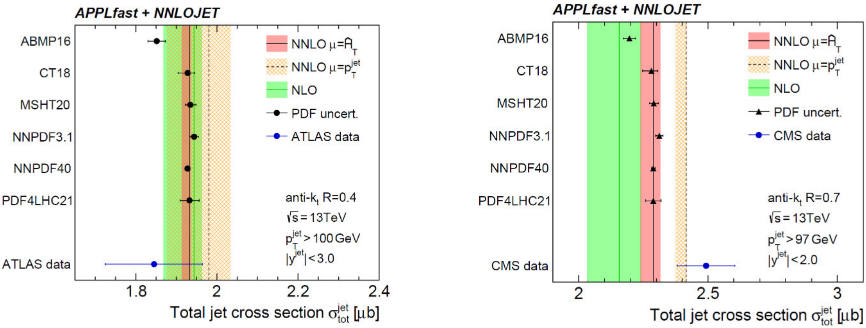
Phenomenology modules 1





Determination of the strong coupling constant from HERA data
[Britzger, Gehrmann, Huss, Rabbertz, et al. '19]

Phenomenology modules 1



Comparison of the total jet cross section using different PDFs
[Britzger, Gehrmann, Huss, Rabbertz, et al. '22]

New Interface

- Interface adapted to use modules 2 of NNLOJET
  - better colour sampling
  - full colour dijet code
  - printout of intermediate results during production step
    ⇒ workflow can better detect problematic phase space points
  - more flexible decomposition of logarithmic scale coefficients
    ⇒ no need for „magical numbers“ in scale setup any more

```
   muf = 1.0 * mll          mur = 1.0 * mll
   muf = 0.5 * mll          mur = 0.5 * mll
   muf = 2.0 * mll          mur = 2.0 * mll
   muf = 1.0 * mll          mur = 0.5 * mll
   muf = 0.5 * mll          mur = 1.0 * mll
   muf = 1.0 * mll          mur = 2.0 * mll
   muf = 2.0 * mll          mur = 1.0 * mll

!  muf =              mll   mur =              mll
!  muf =    90.0171313005   mur =    90.0171313005
!  muf =    54.5981500331   mur =    54.5981500331
!  muf =   148.4131591026   mur =   148.4131591026
!  muf =    54.5981500331   mur =    90.0171313005
!  muf =    90.0171313005   mur =    54.5981500331
!  muf =   148.4131591026   mur =    90.0171313005
```

Phenomenology modules 2 - dijet fc

- Two different dijet full colour data sets produced (so far):
  - CMS at 7 TeV, anti-kt, R=0.6
  - double differential in $m_{12} \in [260.0, 5040.0]$ and $y^* \in [0.0, 3.0]$
  - PDF set: NNPDF31 nnlo as 0118

  - ATLAS at 13 TeV, anti-kt, R=0.4
  - double differential in $m_{12} \in [260.0, 9066.0]$ and $y^* \in [0.0, 3.0]$
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  - $\Rightarrow$ plots shown on the following slides

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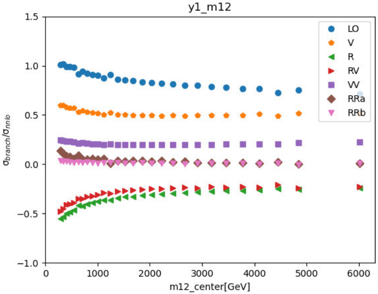
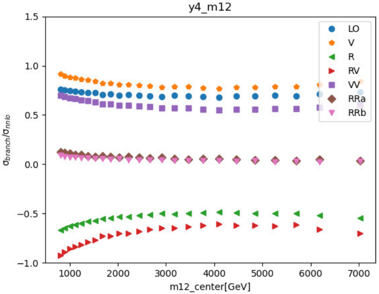
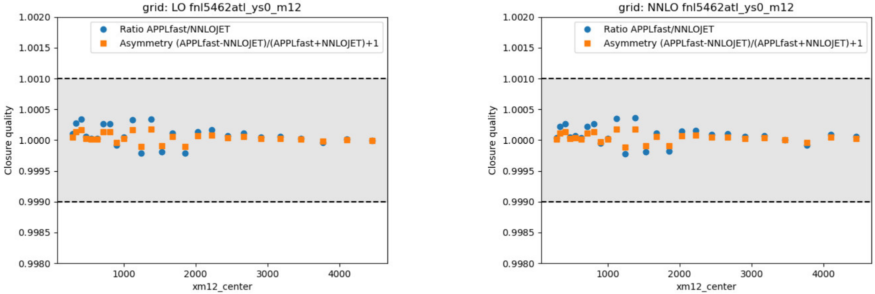
Phenomenology modules 2 - channels





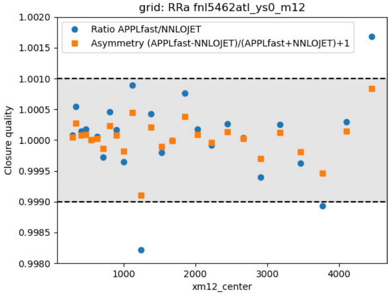
Plot of relative contributions of different channels shows large cancellations between real and virtual parts for higher y^*

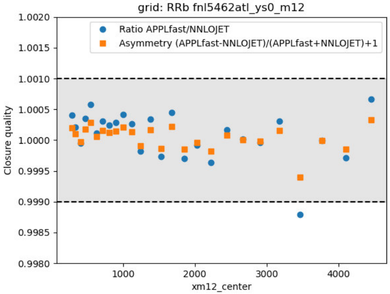
Phenomenology modules 2 - closure



Overall we find good closure at sub-permille accuracy

Phenomenology modules 2 - closure





Even the most problematic channels (double real) show nice behaviour

Phenomenology modules 2 - runtimes

	Event	Jobs	neval	Tot Time	Cross section	Error
LO	$0.5*10^9$	27*8	$108*10^9$	$4.7*10^3$h	5.249331E+08	1.315478E+04
V	$8*10^6$	28*8	$1.792*10^9$	$3.6*10^3$h	4.089646E+08	1.072727E+05
R	$4*10^6$ $10*10^6$	84*8	$5.088*10^9$	$22.9*10^3$h	-3.296991E+08	2.205647E+05
VV	$15*10^6$	55*8	$6.006*10^9$	$4.8*10^3$h	2.200059E+08	7.435571E+04
RV	$0.67*10^6$ $1.7*10^6$	100*8	$1.1952*10^9$	$41.6*10^3$h	-3.385389E+08	8.122503E+05
RRa	$0.69*10^6$	300*8	$1.656*10^9$	$116*10^3$h	5.278204E+07	2.521830E+06
RRb	$3.75*10^6$ $11.2*10^6$	81*8	$3.436*10^9$	$19*10^3$h	2.386325E+07	1.117482E+06

	LO	*NLO*	*NLO_only*	*NNLO*	*NNLO_only*
Number of evaluations	$108*10^9$	$\sim 114.9*10^9$	$\sim 6.9*10^9$	$\sim 127.2*10^9$	$\sim 12.3*10^9$
Cross-section	5.249331E+08	6.041986E+08	7.926550E+07	5.623109E+08	-4.188771E+07
error	1.315478E+04	4.835966E+05	2.452676E+05	2.886867E+06	2.876399E+06

Next steps

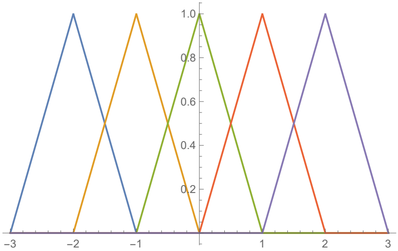
- finalize validation of NNLO code
  - optimize workflow and runtime
  - make sure closure works in all channels
  - reproduce results in [Britzger, Gehrmann, Huss, Rabbertz, et al. '22]
- calculate di-jet differential distributions at full colour
- $\alpha_s(\mathrm{M_Z})$ determination from LHC data
- provide setup for further developments and calculations

Thank you for your attention!

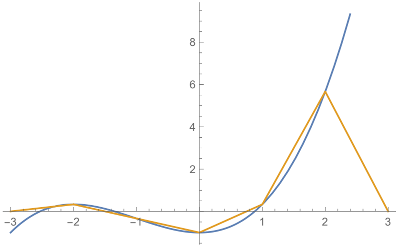
Backup - Interpolation

Example: $f(x) = \frac{1}{3}x^3 + x^2 - 1$ on the Interval $I = [-2, 2]$

Five nodes $\{-2, -1, 0, 1, 2\}$



$\Rightarrow$



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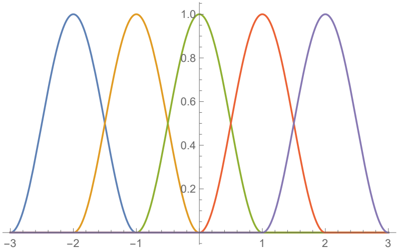

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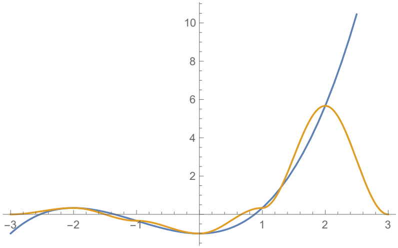

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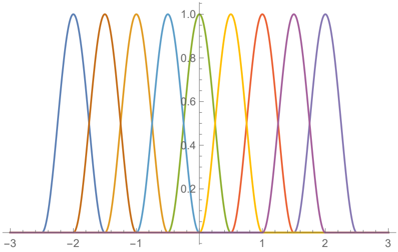
Example: $f(x) = \frac{1}{3}x^3 + x^2 - 1$ on the Interval $I = [-2, 2]$

Nine nodes $\{-2, -1.5, \ldots, 1.5, 2\}$



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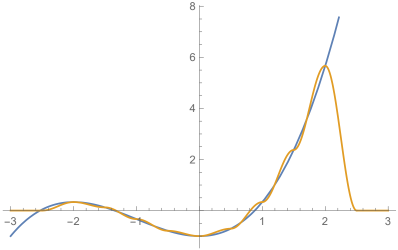

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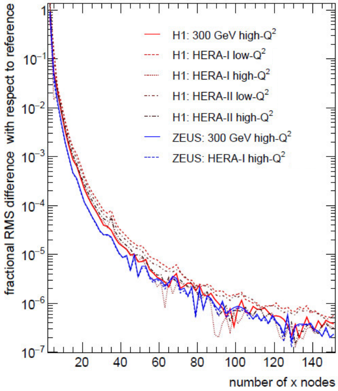

Fractional root mean square difference between interpolation and reference [Britzger, Gehrmann, Huss, Rabbertz, et al. '19]

Backup - Logarithm decomposition

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$$\sigma_{pp\to X}(x,\alpha_s,\mu) = \sum_{i,j,v,w=0}^{N} \sum_{a,b} \sum_{k} \left(\frac{\alpha_s^{[v]}}{2\pi}\right)^{k+r} f_a^{[i,w]} \, f_b^{[j,w]} \, \hat{\sigma}^{(k)}_{ab\to X\;[i,j,v,w]}$$

$$\mathrm{d}\hat{\sigma}^{(k)}_{ab\to X\;[i,j,v,w]}\left(\mu_R^2,\mu_F^2\right) = \sum_{\alpha+\beta\leq k} \mathrm{d}\hat{\sigma}^{(k|\alpha,\beta)}_{ab\to X\;[i,j,v,w]} \ln^{\alpha}\left(\frac{\mu_R^2}{\mu_0^2}\right) \ln^{\beta}\left(\frac{\mu_F^2}{\mu_0^2}\right)$$

$$\hat{\sigma}^{(k|\alpha,\beta)}_{ab\to X\;[i,j,v,w]} = \sum_{m=1}^{M_p} E_i(x_{a,m})\, E_j(x_{b,m})\, E_v(\mu_{R,m})\, E_w(\mu_{F,m})\, w^{(k)}_{ab\to X,\,m}\, \hat{\sigma}^{(k|\alpha,\beta)}_{ab\to X,\,m}$$