

# NNLO Jets for DIS

James Currie

in collaboration with T. Gehrmann and J. Niehues

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**MC@NNLO**

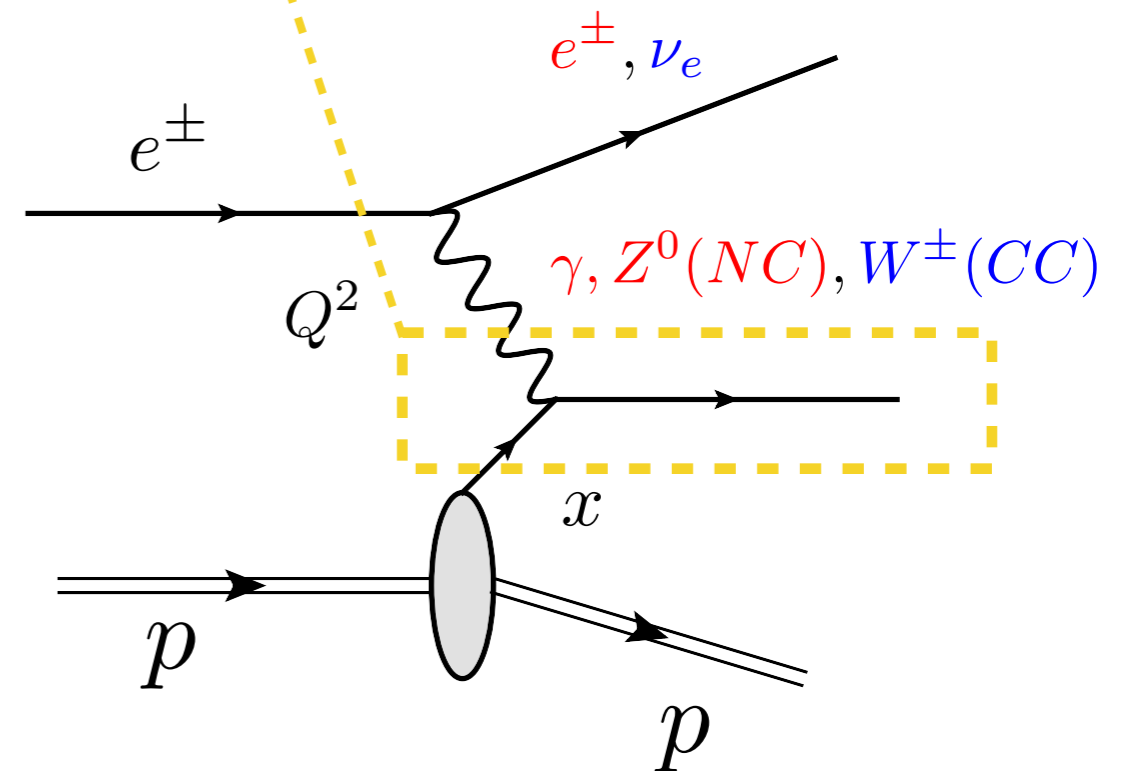
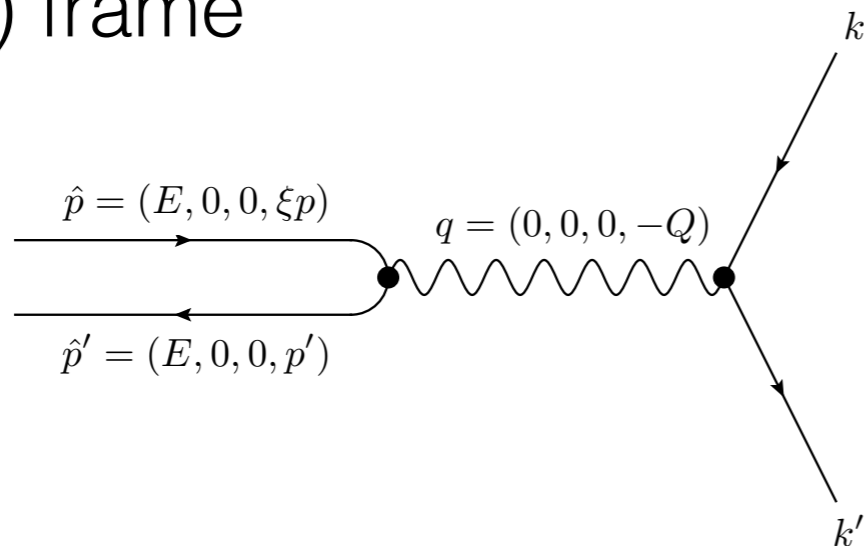
# Outline

- DIS and HERA's legacy
- Antenna Subtraction at NNLO
- *NNLOJET*
- Results and analysis
- Summary and outlook

# Deep Inelastic Scattering

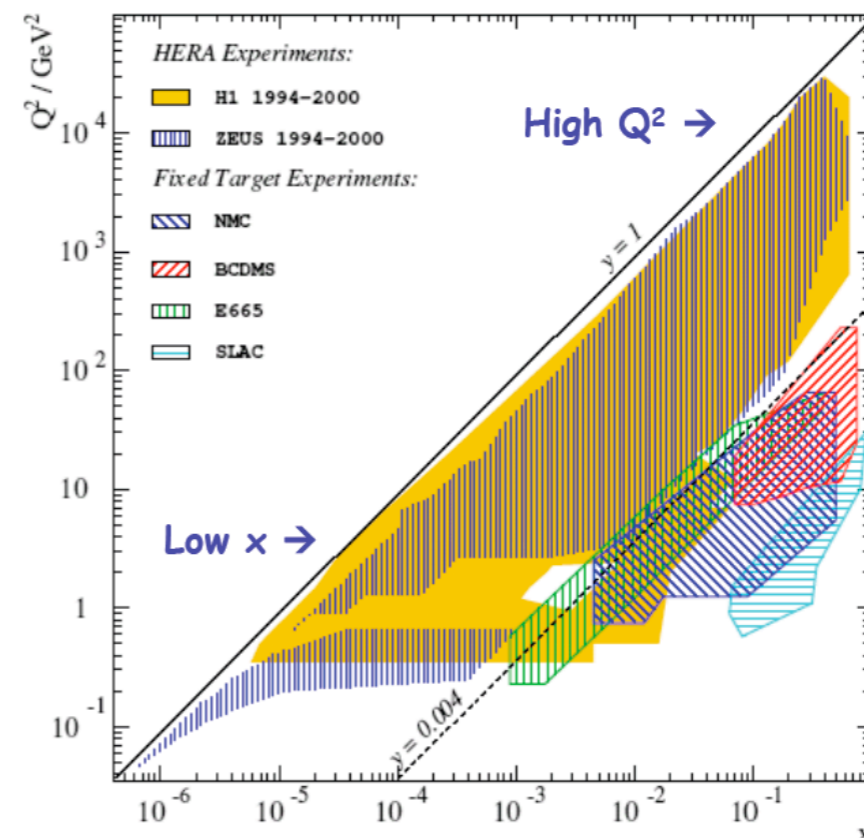
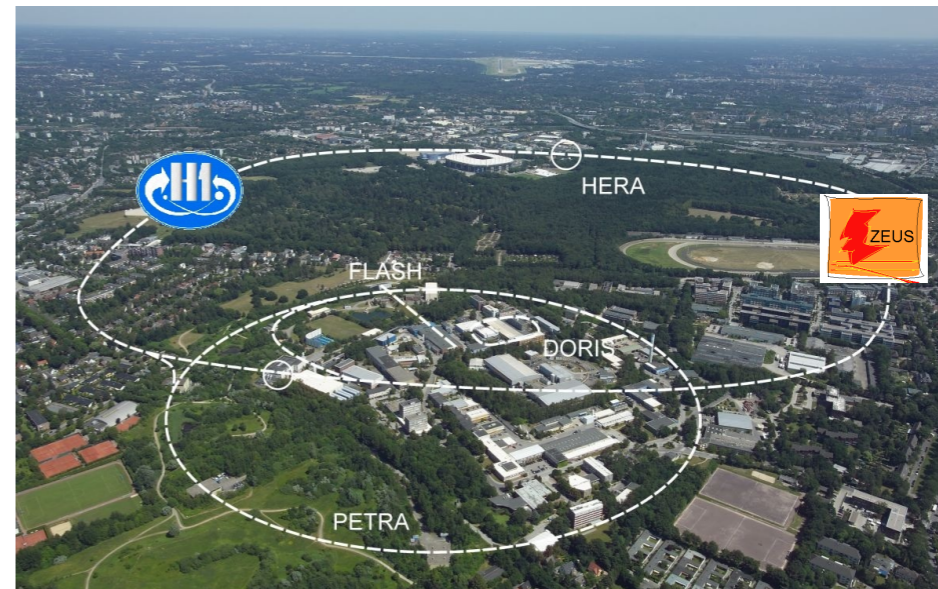
$$d\sigma = \int \frac{d\xi}{\xi} \sum_a f_a(\xi) d\sigma_a$$

- clean probe of proton structure (PDFs)
- two independent variables,  $(x, Q^2)$
- Clear exposition in “Breit” (brick-wall) frame



# HERA's legacy

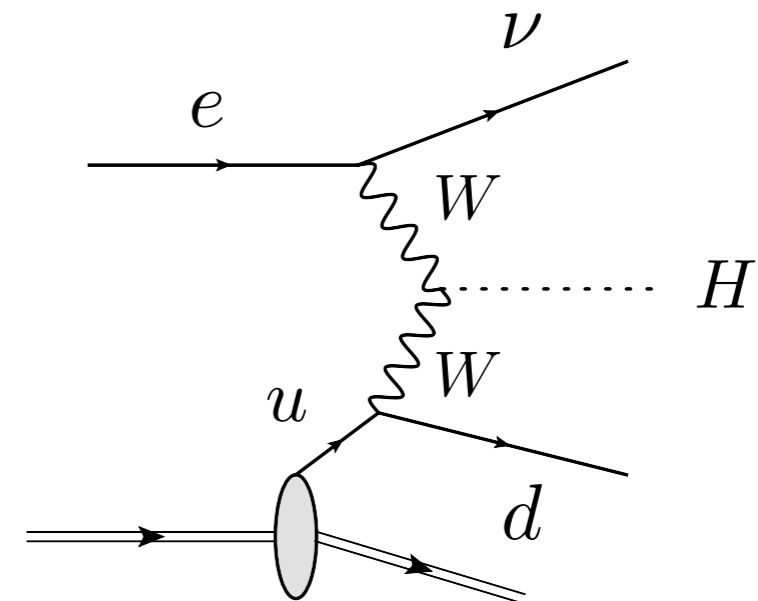
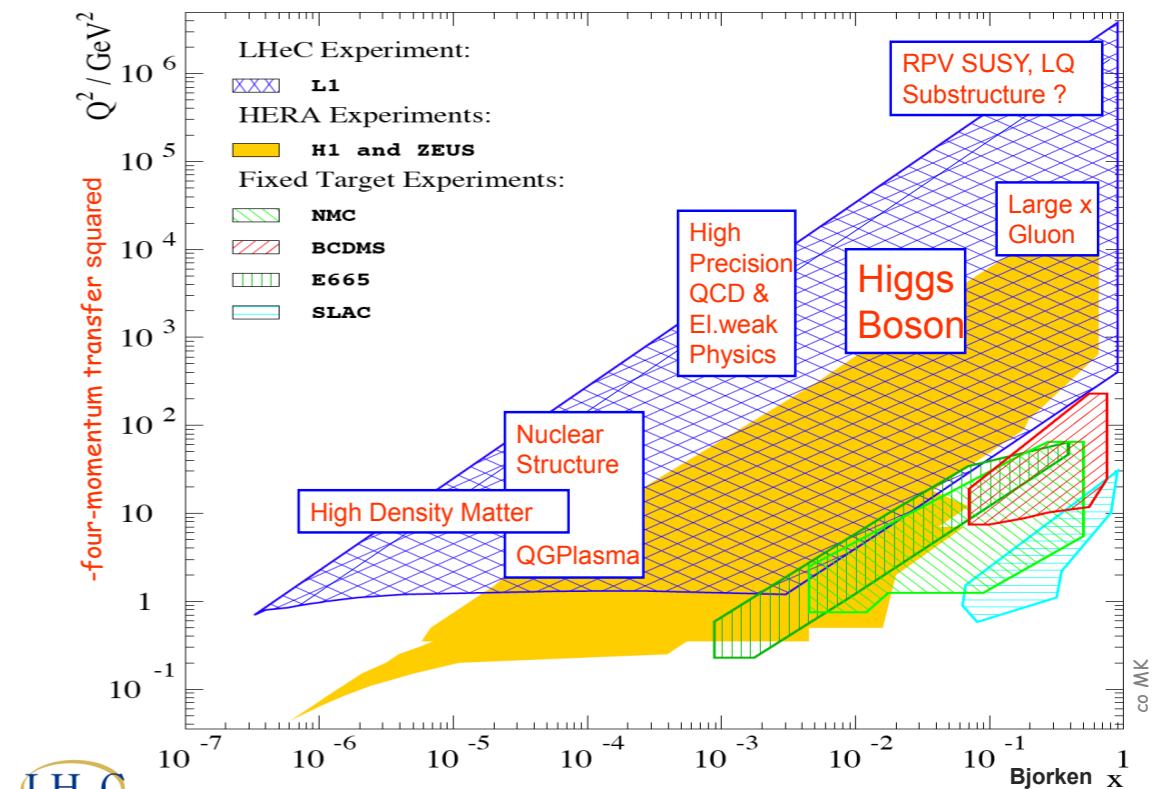
- 1994-2000 HERA I
- 2000-2007 HERA II
- H1 and Zeus experiments  $0.5\text{fb}^{-1}$  each
- $e^{\pm}$  (27.5 GeV) + p (460, 575, 820, 920 GeV)  $\rightarrow \sqrt{s} \sim 225\text{-}318$  GeV
- huge impact on PDFs (esp quark)
- large set of jet data over broad kinematic range... *not yet fully exploited*



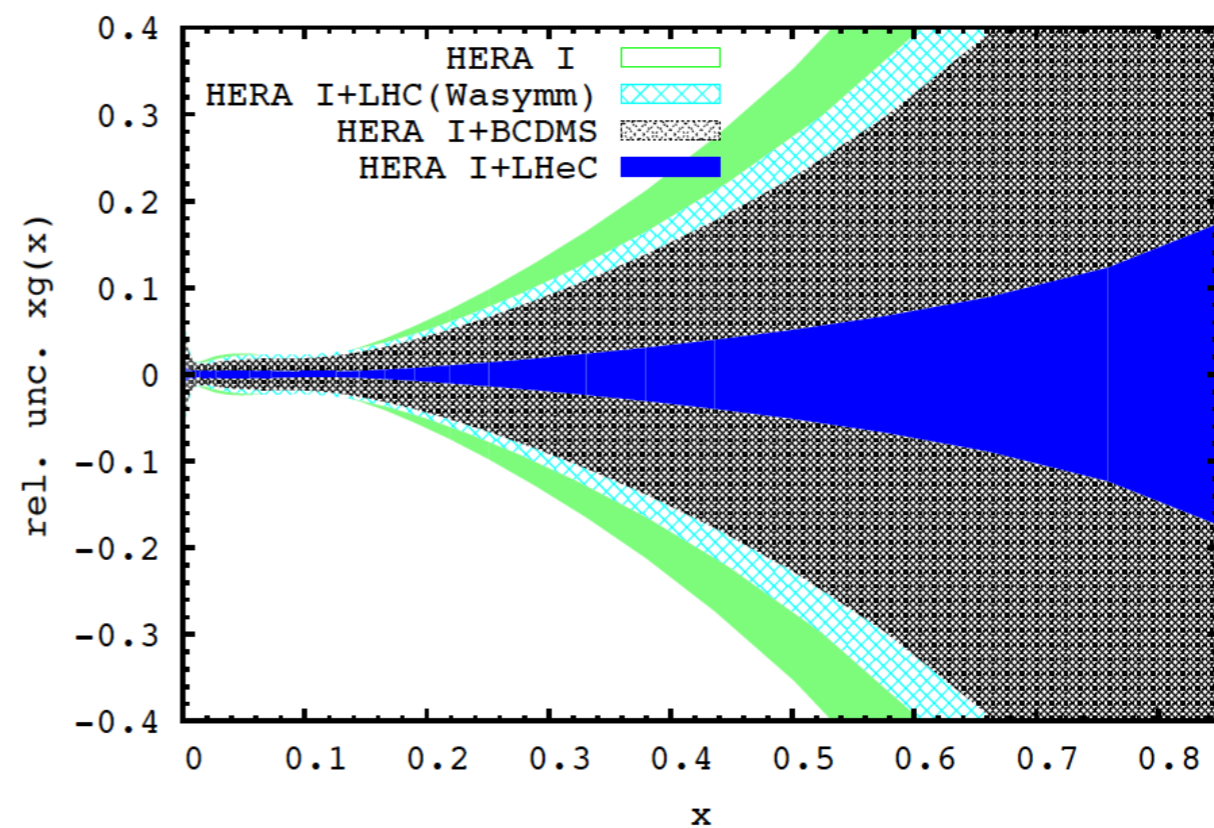
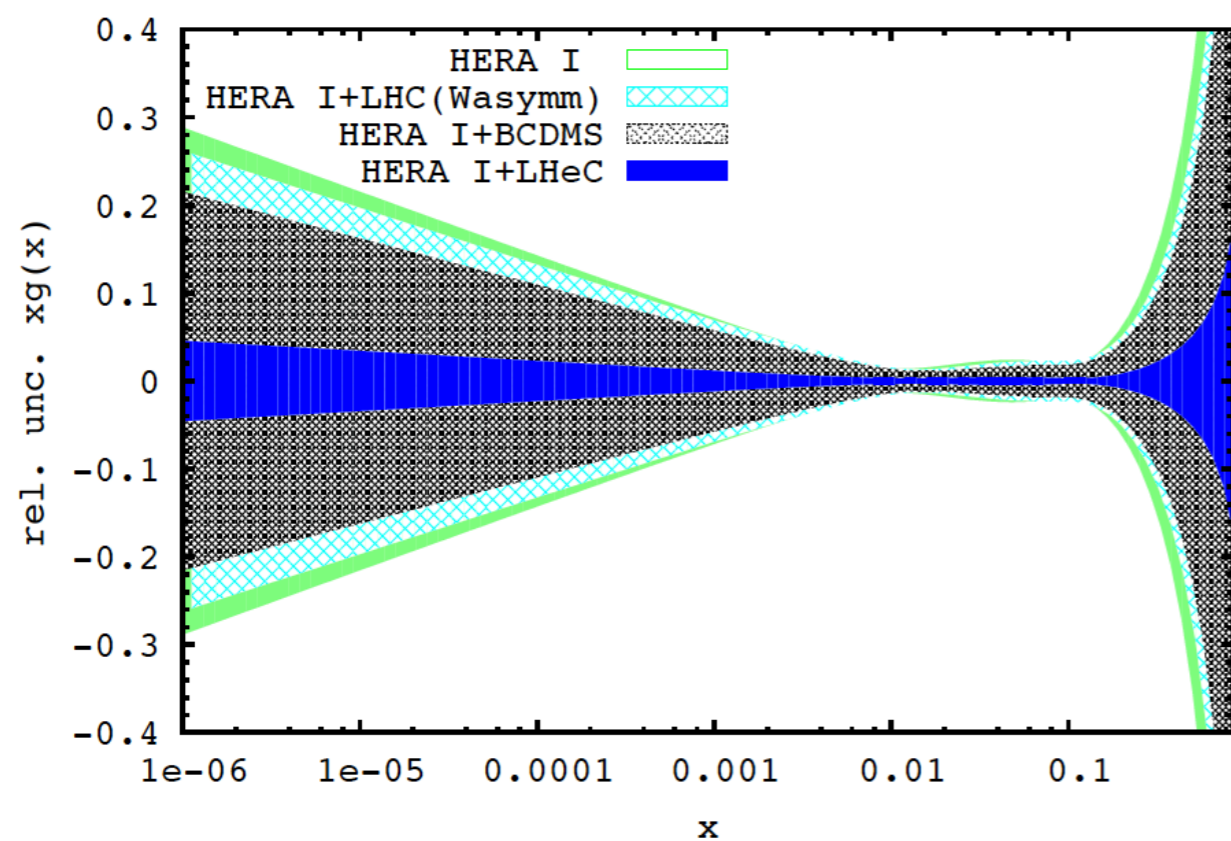
# A future e-p collider (LHeC)

Prospect for e-p collider to run with HL-LHC:

- $Q^2 > 1 \text{ TeV}^2$ ,  $x \sim 0.5$
- precision QCD  $\delta\alpha_s \sim 0.1\%$
- PDF uncertainties  $\sim 1\%$
- boosts value of LHC (and VLHC) data
- $x \sim 10^{-6}$  gluon saturation?
- (CC) H+J+ME disentangle WWH from ZZH

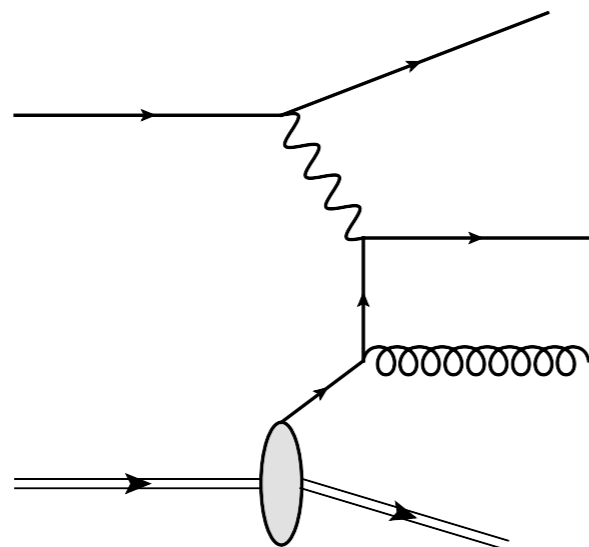
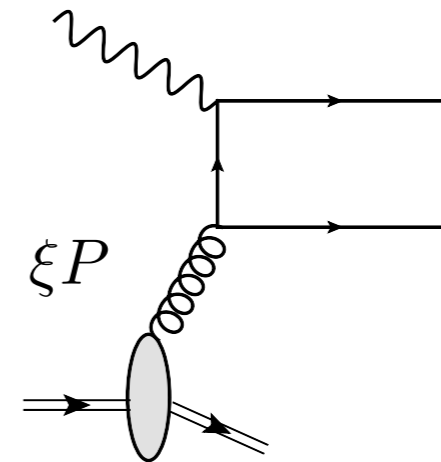


# LHeC gluon

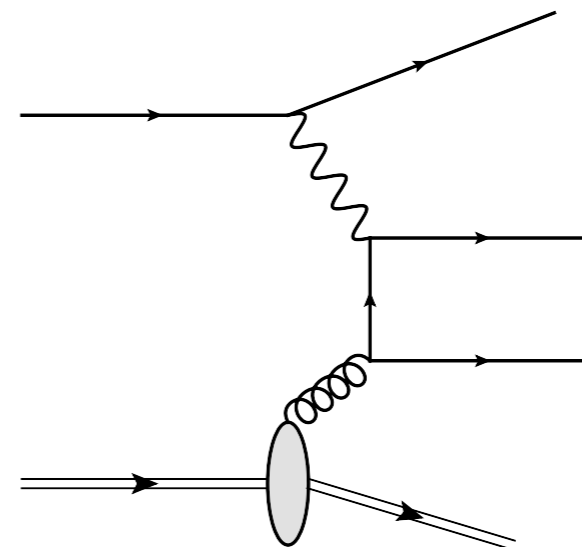


# Jet production

- Dijet production in BGF channel at LO
- rare handle on gluon PDF and  $\alpha_s$  at HERA
- Inclusive jet production, measure  $P_T^{jet}$
- dijets, measure  $\langle P_T \rangle_2 = \frac{1}{2}(P_{T,1} + P_{T,2})$  and  $\xi_2 = x(1 + M_{12}^2/Q^2)$
- normalized distributions (relative to NC DIS) for clean measurements

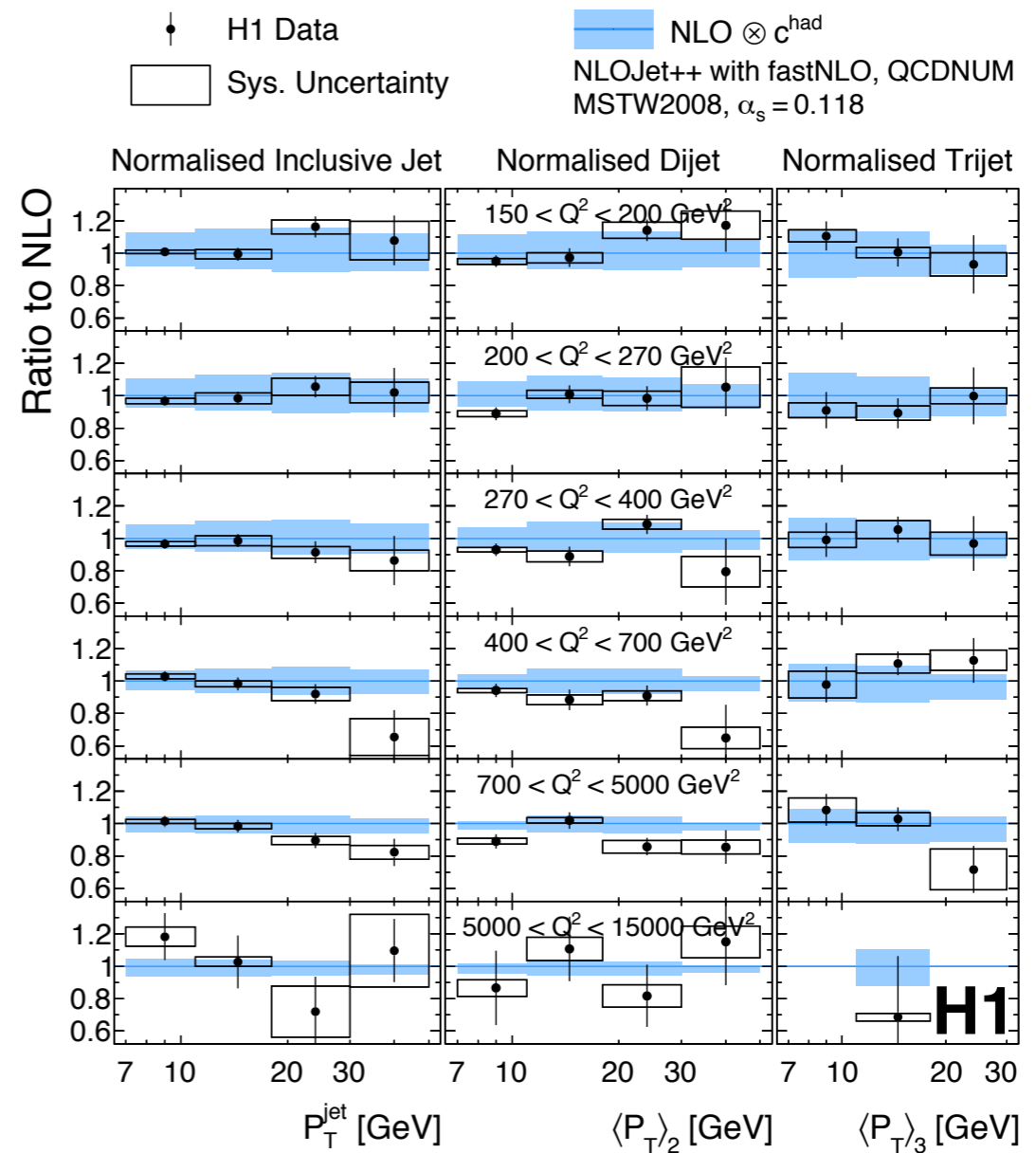
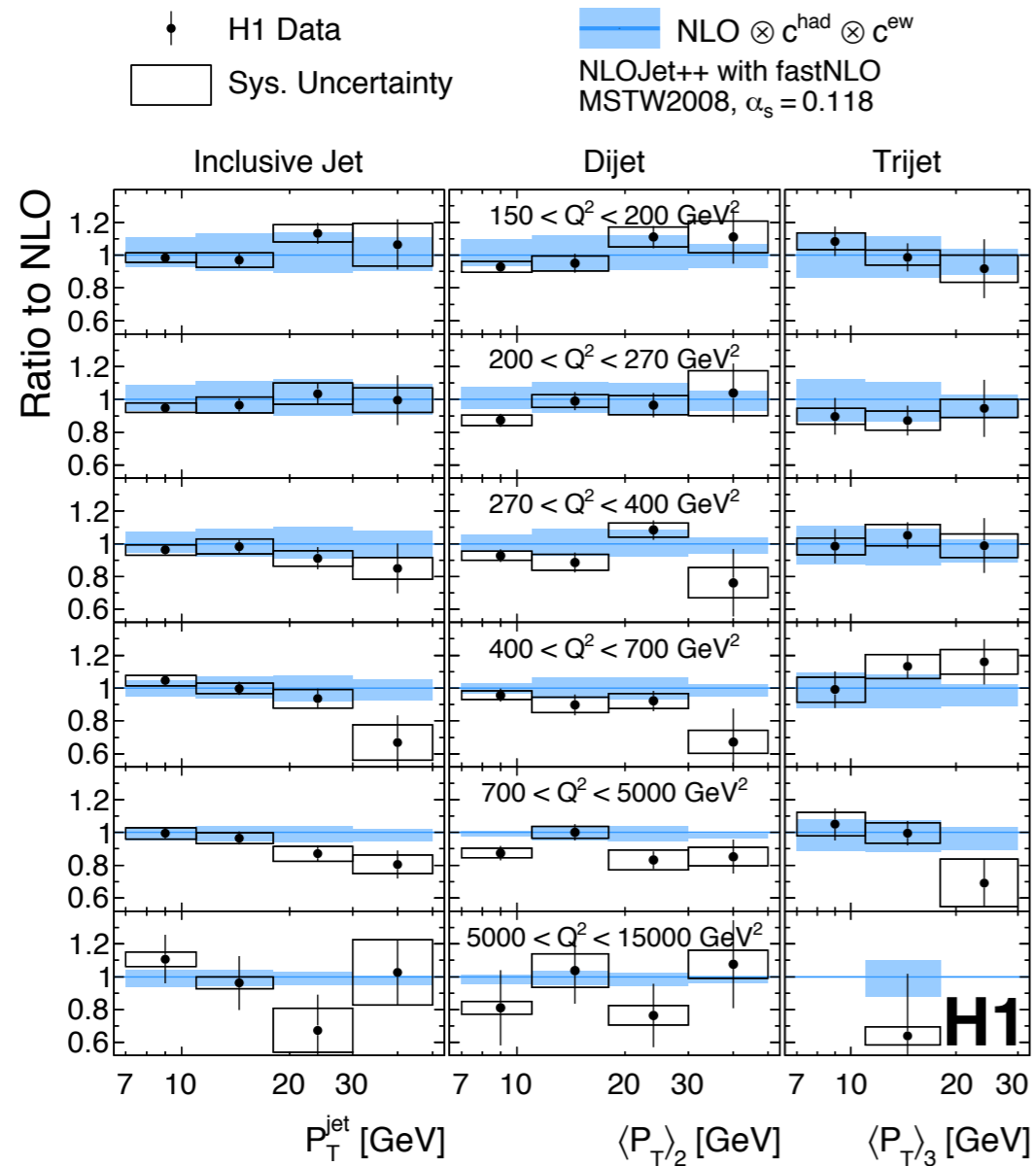


QCD Compton scattering



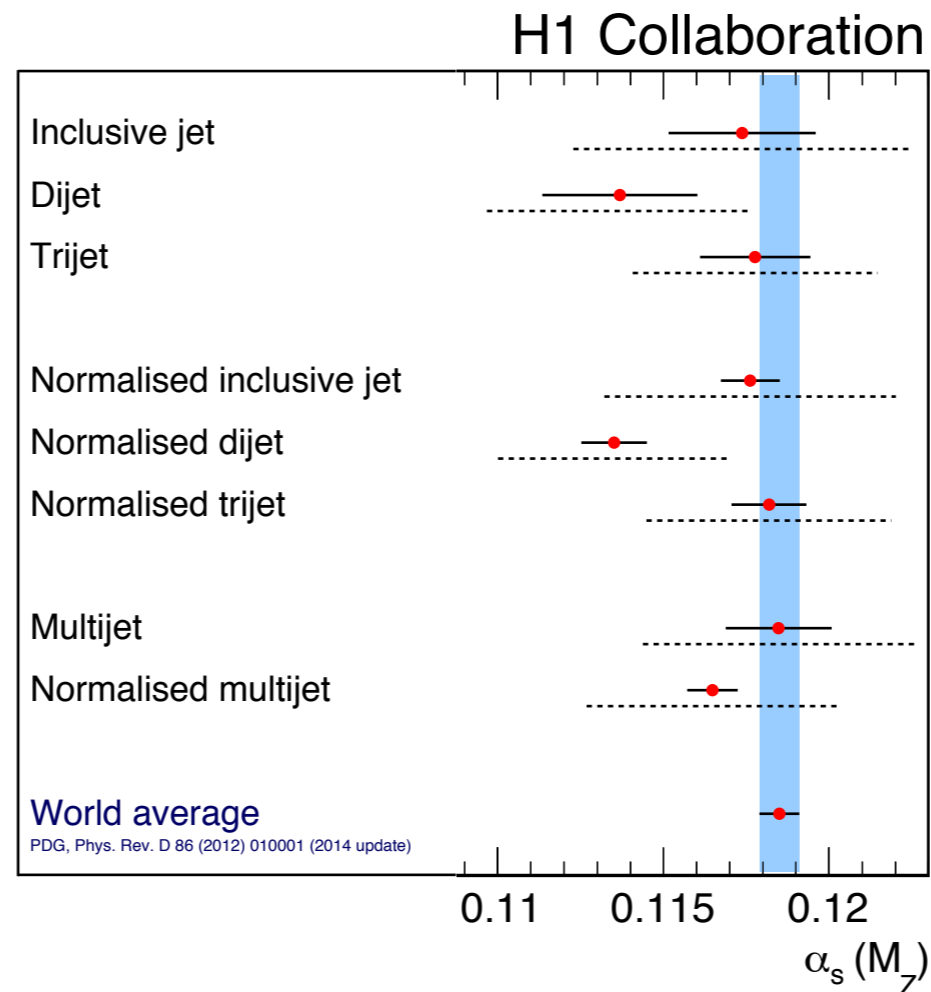
Boson-gluon fusion

# NLO at HERA



- Good description of data by NLO
- dominated by scale uncertainty...need for NNLO

# NLO at HERA



- extraction of strong coupling dominated by NLO scale uncertainty
- experimental accuracy of normalised jet data close to world average
- would like to include jet data in NNLO average, less reliant on lattice studies

# Subtraction at NLO

$$d\sigma_{a,NLO} = \int_{\Phi_{m+1}} d\sigma_a^R + \int_{\Phi_m} d\sigma_a^V + d\sigma_a^{MF}$$

Recast into a finite form using auxiliary subtraction terms

$$d\sigma_{a,NLO} = \int_{\Phi_{m+1}} \left[ d\sigma_a^R - d\sigma_a^S \right] \\ + \int_{\Phi_m} \left[ d\sigma_a^V - d\sigma_a^T \right]$$

# Subtraction at NNLO

At NNLO more terms to regulate

$$\begin{aligned} d\sigma_{a,NNLO} = & \int_{\Phi_{m+2}} \left[ d\sigma_{a,NNLO}^{RR} - d\sigma_{a,NNLO}^S \right] \\ & + \int_{\Phi_{m+1}} \left[ d\sigma_{a,NNLO}^{RV} - d\sigma_{a,NNLO}^T \right] \\ & + \int_{\Phi_m} \left[ d\sigma_{a,NNLO}^{VV} - d\sigma_{a,NNLO}^U \right] \end{aligned}$$

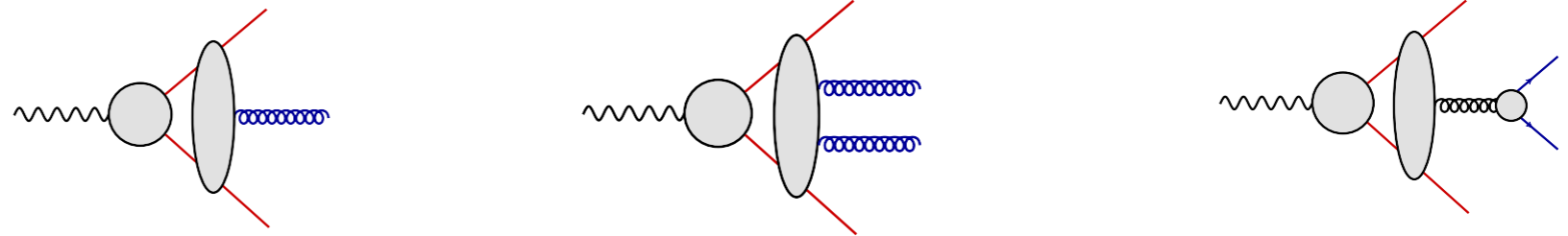
# Antennae

Antenna functions built from matrix elements:

$$X_3^0(i, j, k) \sim \frac{|\mathcal{M}_3^0(i, j, k)|^2}{|\mathcal{M}_2^0(I, K)|^2}, \quad X_4^0(i, j, k, l) \sim \frac{|\mathcal{M}_4^0(i, j, k, l)|^2}{|\mathcal{M}_2^0(I, L)|^2}$$

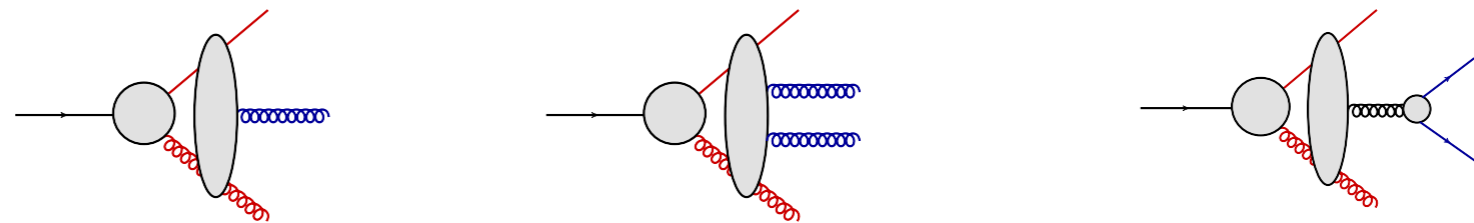
Quark-antiquark:

$$\gamma^* \rightarrow q\bar{q} + \dots$$



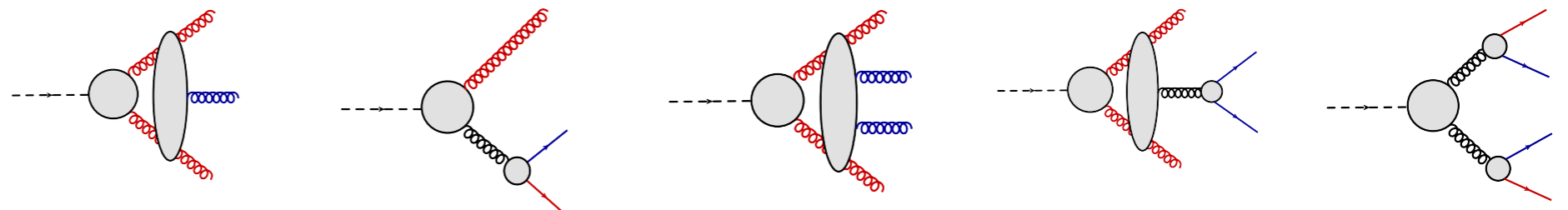
Quark-gluon:

$$\bar{\chi}^0 \rightarrow \tilde{g}g + \dots$$

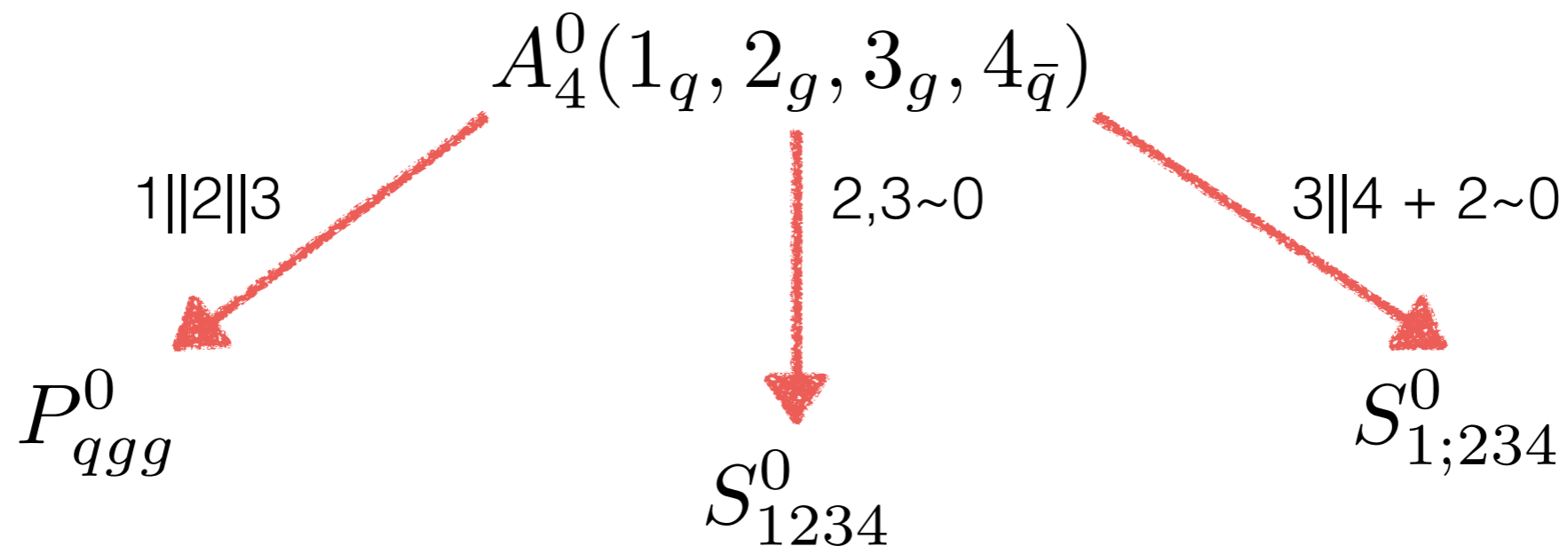


Gluon-gluon:

$$H \rightarrow gg + \dots$$



Antenna mimics all singularities of QCD



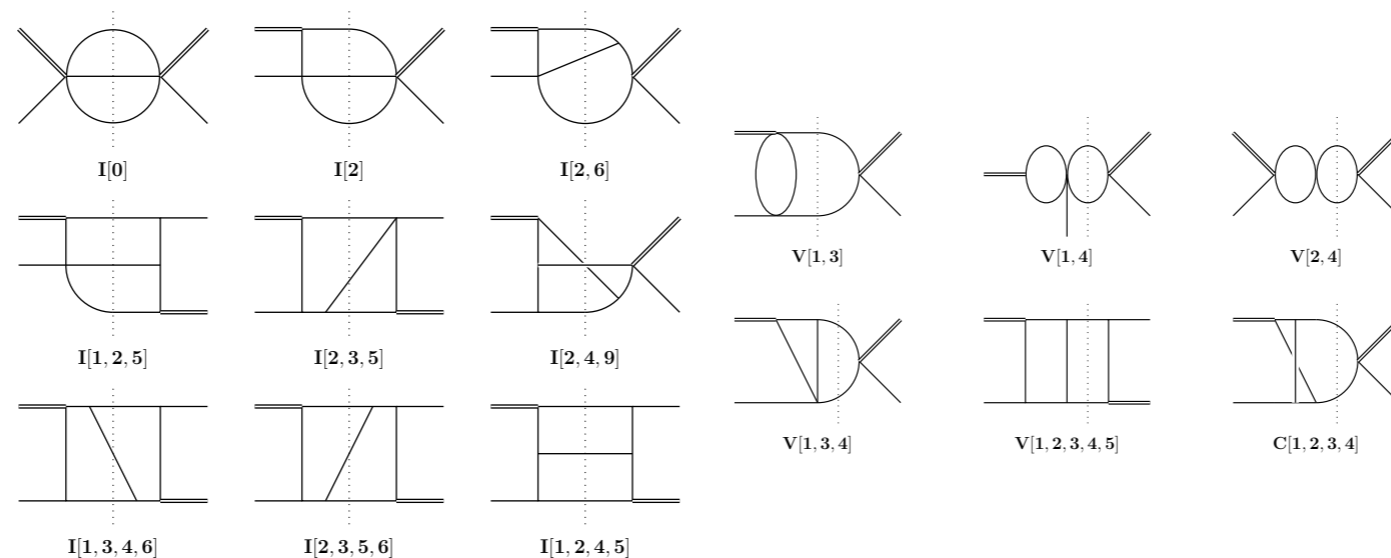
Phase space map smoothly interpolates momenta for reduced matrix element between limits

$$\widetilde{(123)} = xp_1 + r_1p_2 + r_2p_3 + zp_4$$

$$\widetilde{(234)} = (1-x)p_1 + (1-r_1)p_2 + (1-r_2)p_3 + (1-z)p_4$$

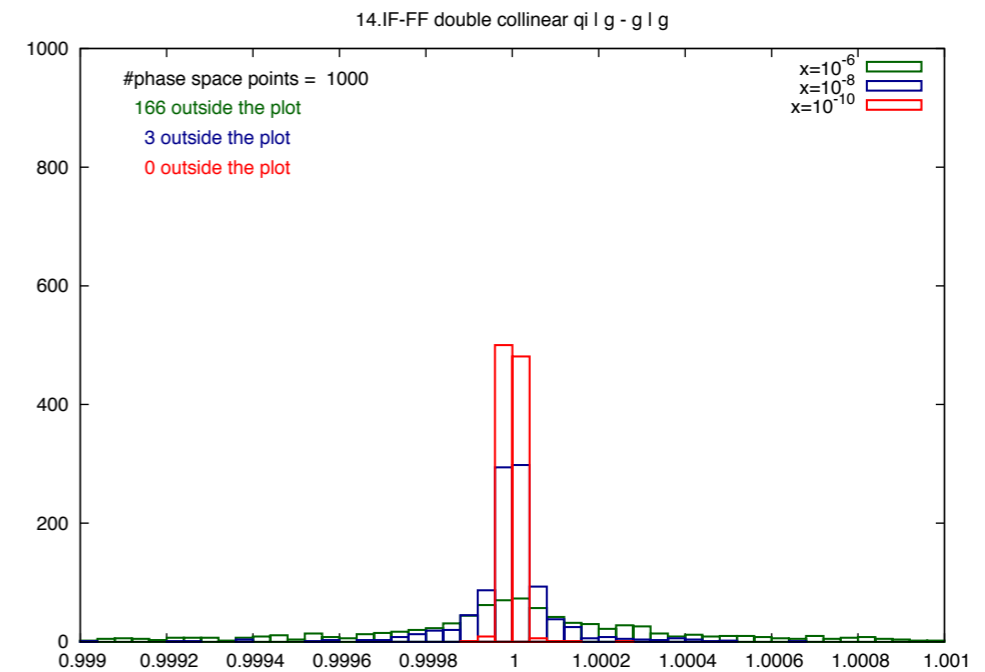
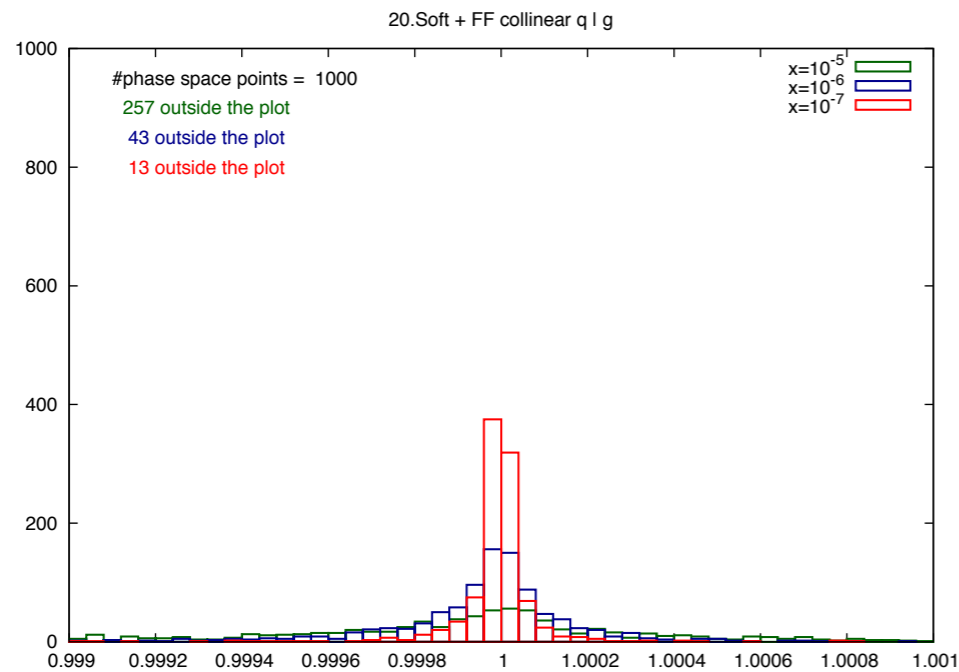
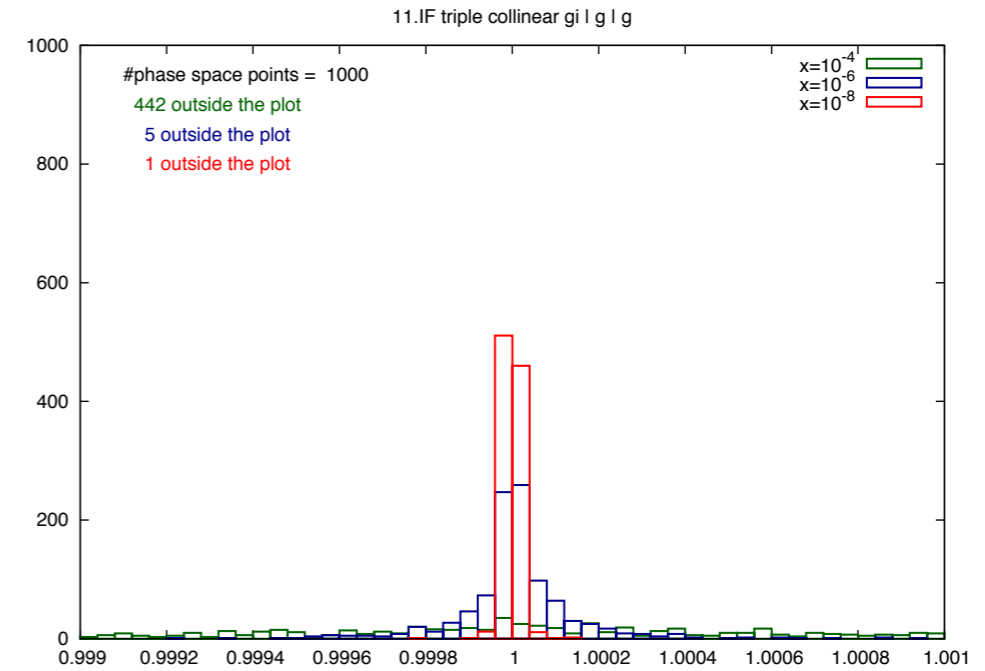
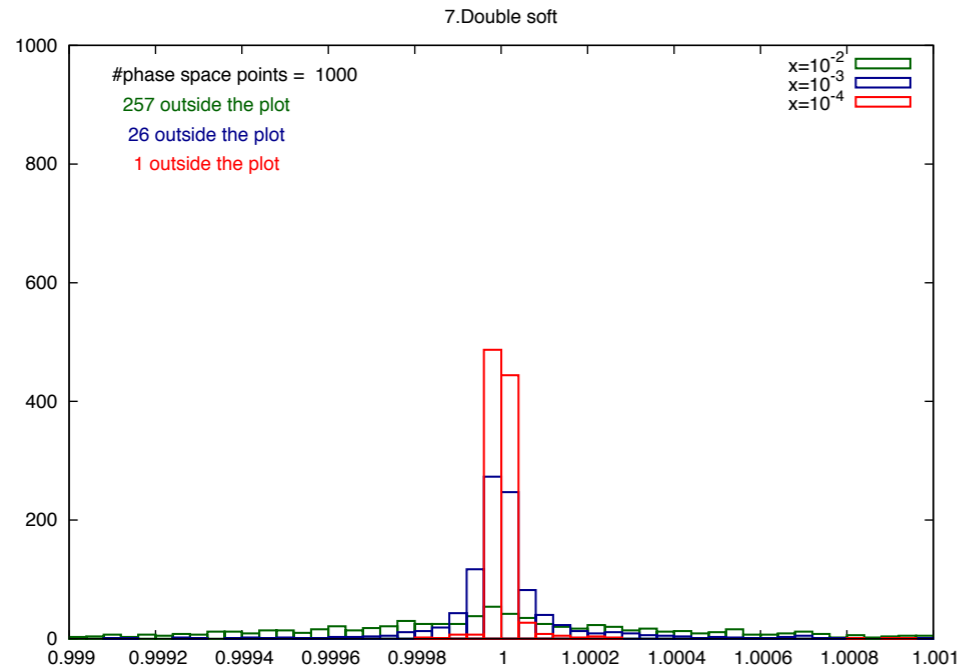
# Integrating the Antennae

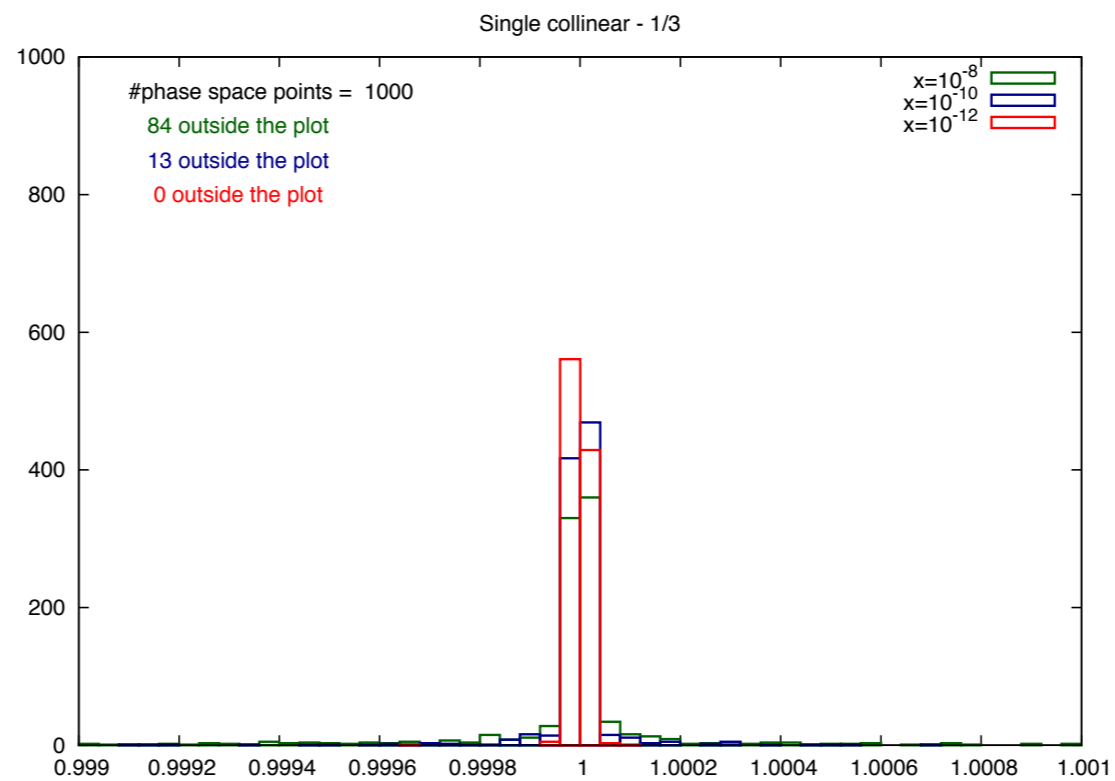
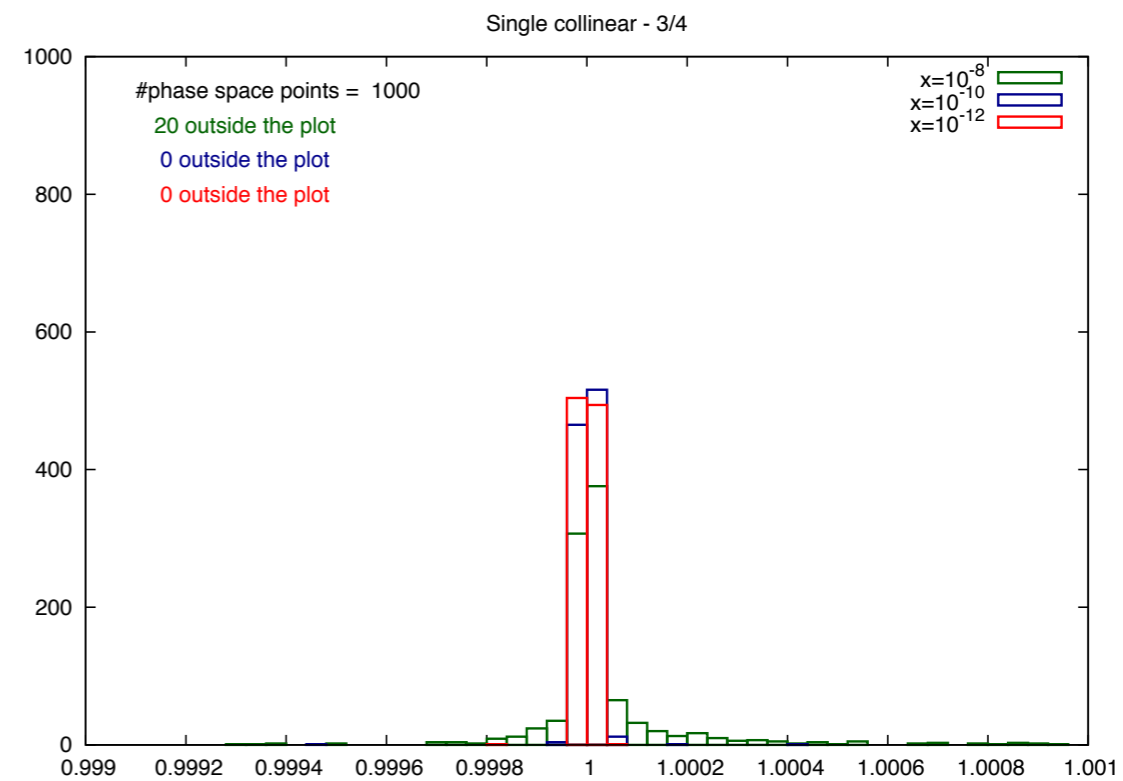
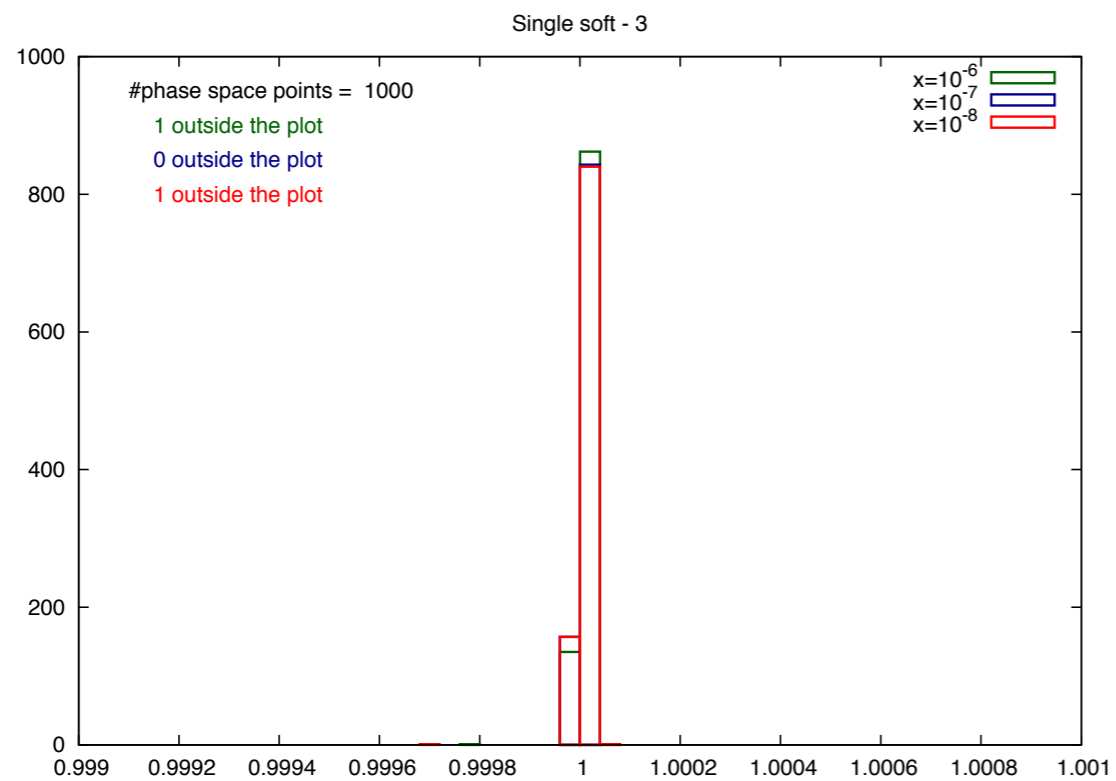
- Relate phase space integrals to multiloop integrals via optical theorem
- apply well developed techniques IBP LI to masters



- Final-Final [Gehrman, Gehrmann-De Ridder, Glover '04, '05]
- Initial-Final [Daleo, Gehrmann-De Ridder, Gehrmann, Luisoni '10]
- Initial-Initial [Gehrmann, Monni '11; Boughezal, Gehrmann-De Ridder, Ritzmann '11; Gehrmann, Ritzmann '12]

# Testing the subtraction terms





# Analytic pole cancellation against 2-loop and 1-loop matrix element

```
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoA4g2XU.frm
FORM 4.1 (Mar 13 2014) 64-bits                               Run: Wed May  4 18:13:43 2016
#-
```

```
poles = 0;
```

```
19.40 sec out of 20.04 sec
```

```
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoA4g2YU.frm
FORM 4.1 (Mar 13 2014) 64-bits                               Run: Wed May  4 18:14:10 2016
#-
```

```
poles = 0;
```

```
7.43 sec out of 7.50 sec
```

```
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoAh4g2XU.frm
FORM 4.1 (Mar 13 2014) 64-bits                               Run: Wed May  4 18:14:42 2016
#-
```

```
poles = 0;
```

```
8.83 sec out of 8.88 sec
```

```
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoAh4g2YU.frm
FORM 4.1 (Mar 13 2014) 64-bits                               Run: Wed May  4 18:14:55 2016
#-
```

```
poles = 0;
```

```
5.37 sec out of 5.41 sec
```

```
James@Jamess-MacBook-Pro-4:~/hepforge/maple/process/jet$ form autoqgB2g2XU.frm
FORM 4.1 (Mar 13 2014) 64-bits                               Run: Wed May  4 18:15:25 2016
#-
```

```
poles = 0;
```

# *NNLOJET*

Semi-automated Monte Carlo for NNLO phenomenology (see Mark Sutton's talk)

- completely standalone code at LO, NLO, NNLO
- fully differential parton level event generator
- many processes now included at NNLO:
  - $H(\gamma\gamma) + 0, 1, 2$  jets
  - $Z(l^+l^-) + 0, 1$  jet
  - DIS jets
  - LHC+Tevatron dijet
- is being 'Appl-tised' for pheno studies

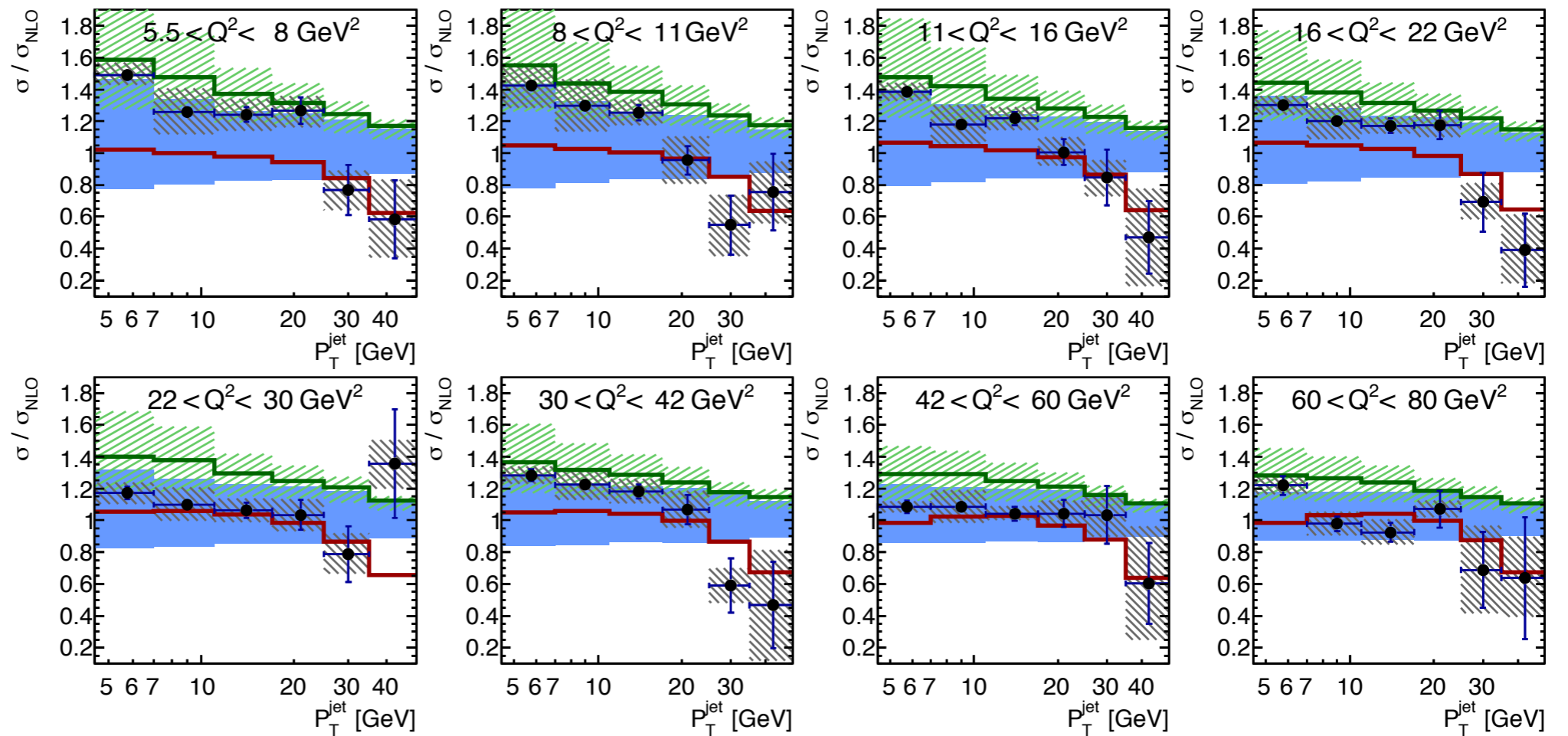
# H1 low $Q^2$ inclusive jet

## Norm. inclusive jet

- H1 HERA-II (prel.)
- ↑ H1 HERA-II  
Eur. Phys. J. C75 (2015) 65
- ▨ Systematic uncertainty
- NLO ⊗ hadr. corr.

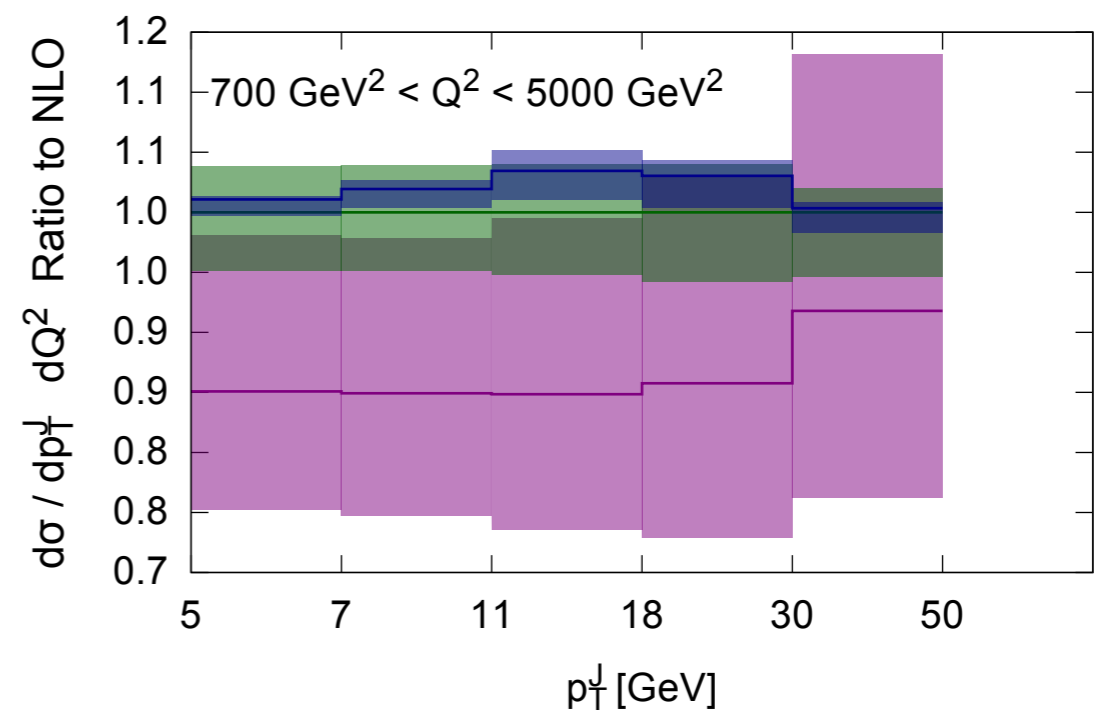
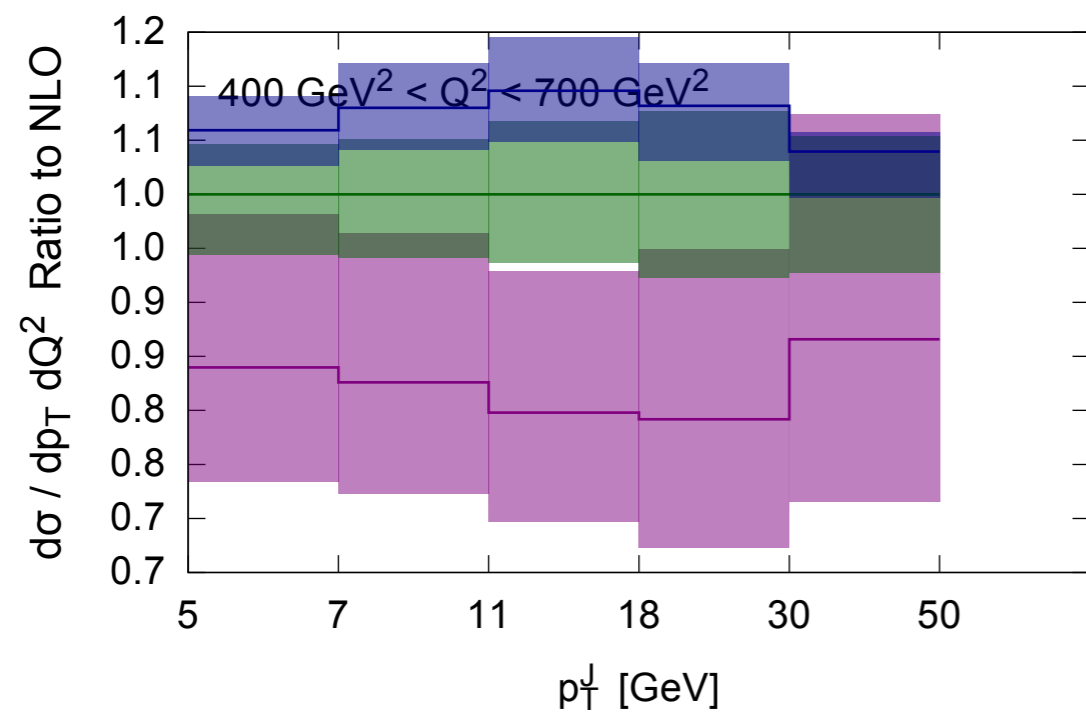
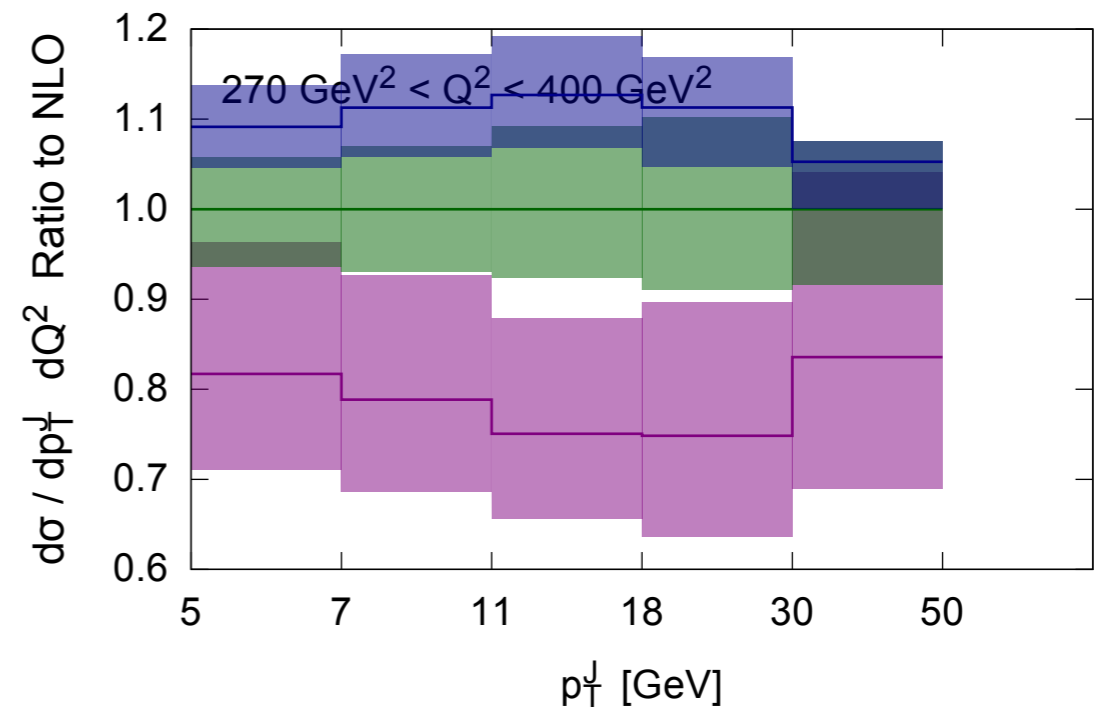
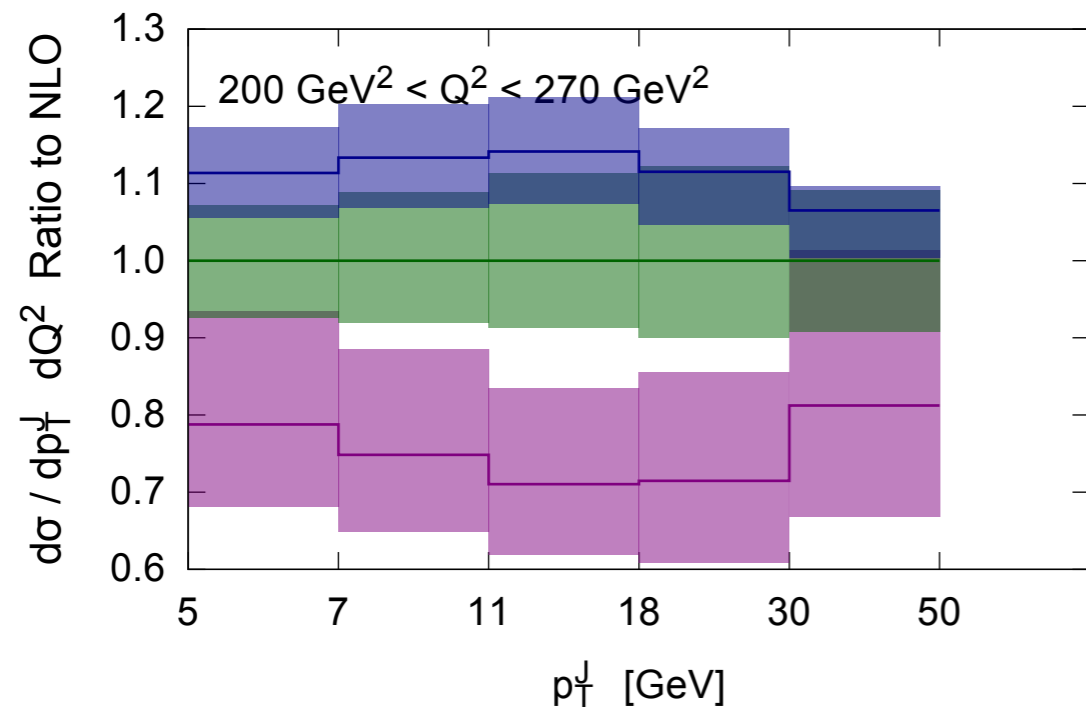
## New predictions

- ▨ NNLO ⊗ hadr. corr.  
Phys. Rev. Lett. 117 (2016) 042001
- aNNLO ⊗ hadr. corr.  
Phys. Rev. D 92 (2015) 074037

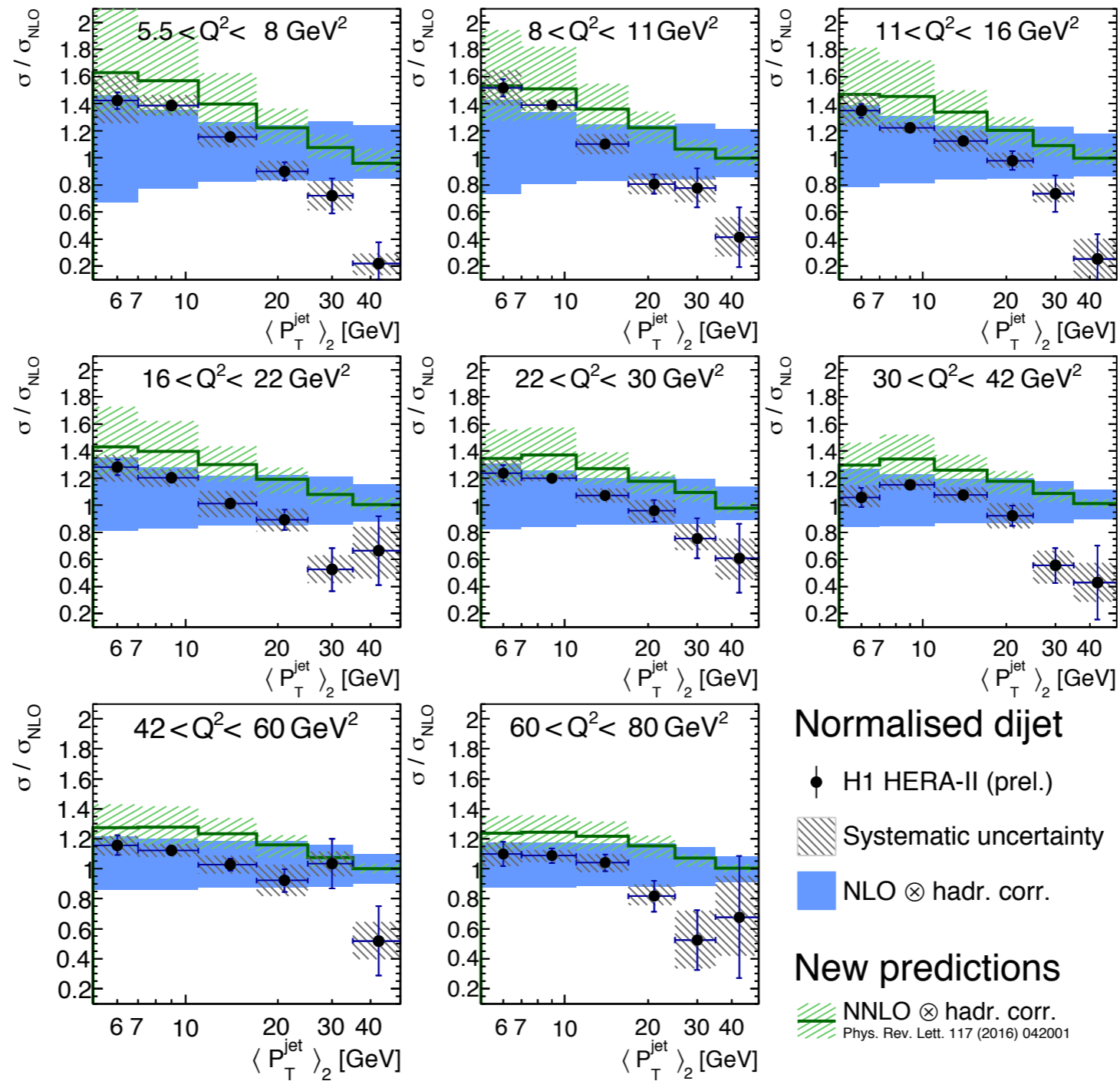


H1prelim-16-062

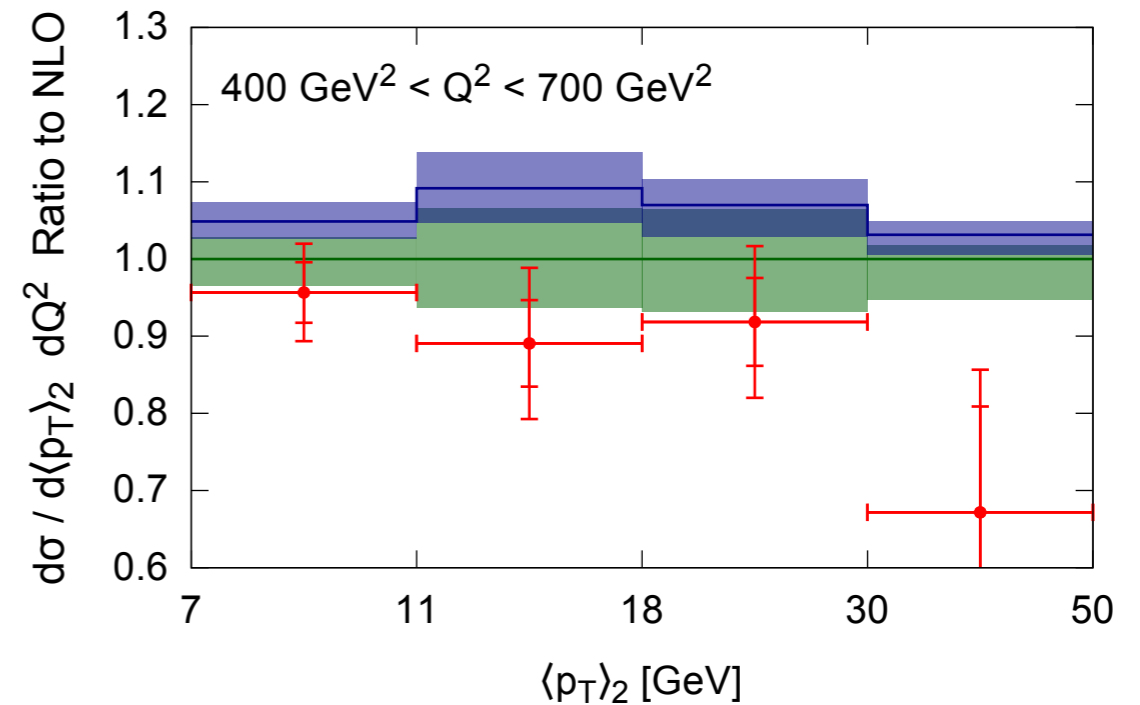
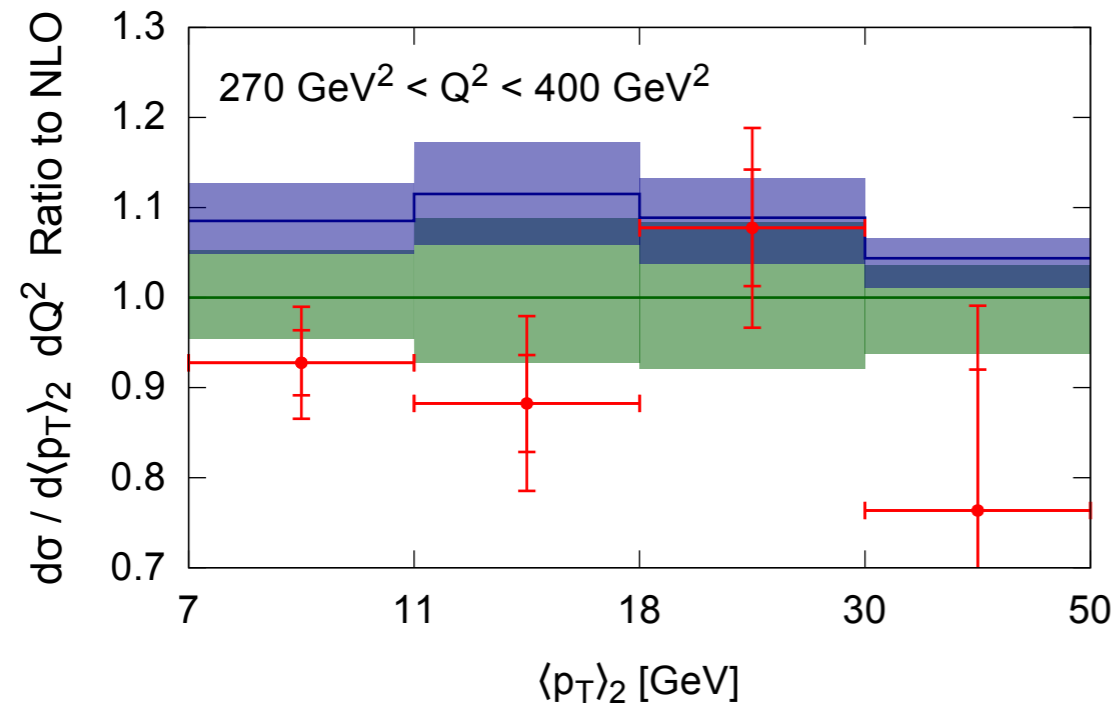
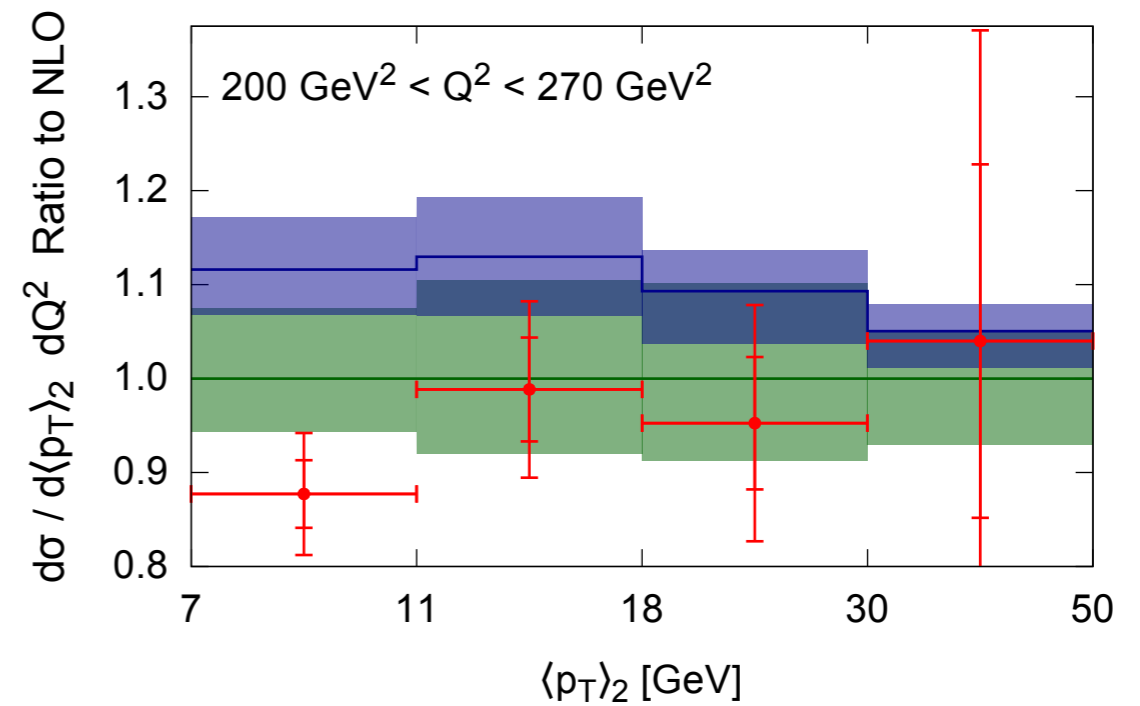
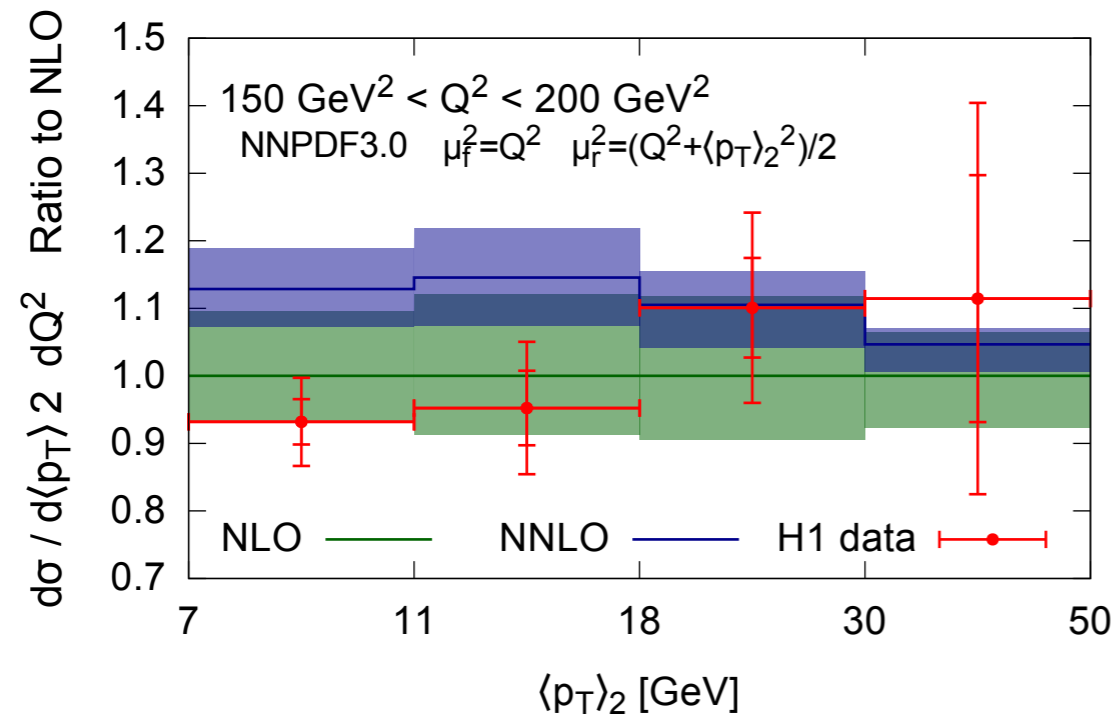
# H1 high $Q^2$ inclusive jet



# H1 low $Q^2$ dijet



# H1 high $Q^2$ dijet



# Discussion

- NNLO inclusive jet improves scale uncertainty relative to NLO (see H1prelim-16-062 and Daniel Britzger's talk for normalized low  $Q^2$  analysis)
- NNLO high  $Q^2$  dijet reduces scale dependence but shows some tension with data (see Daniel Britzger's talk for normalised low  $Q^2$  analysis)
- potential for impact on PDF fits
- high  $Q^2$  dijet analysis uses symmetric  $P_t$  jet cuts and additional  $M_{jj}$  cut to mitigate known perturbative instability
- $M_{jj}$  cut vetoes LO phase space in section of lowest  $P_t$  bin, large K-factors
- also, possibly insufficient to remove perturbative instability at high rapidity
- more comprehensive investigation of cuts warranted (no  $M_{jj}$ , asymmetric cuts)

# Summary and outlook

- HERA data provides vital information on strong coupling and gluon PDF, not yet fully exploited
- prospect of future precision e-p machine demands NNLO accurate jet calculations
- we have used Antenna Subtraction method in *NNLOJET* framework to calculate fully differential NNLO dijets for the first time
- NNLO significantly improves scale dependence of inclusive jet and dijet predictions relative to NLO
- interesting interplay of cuts requires further investigation to maximise impact of data
- comparison with Zeus analysis forthcoming
- preparation of grids for PDF and strong coupling phenomenology