Theory in Copenhagen

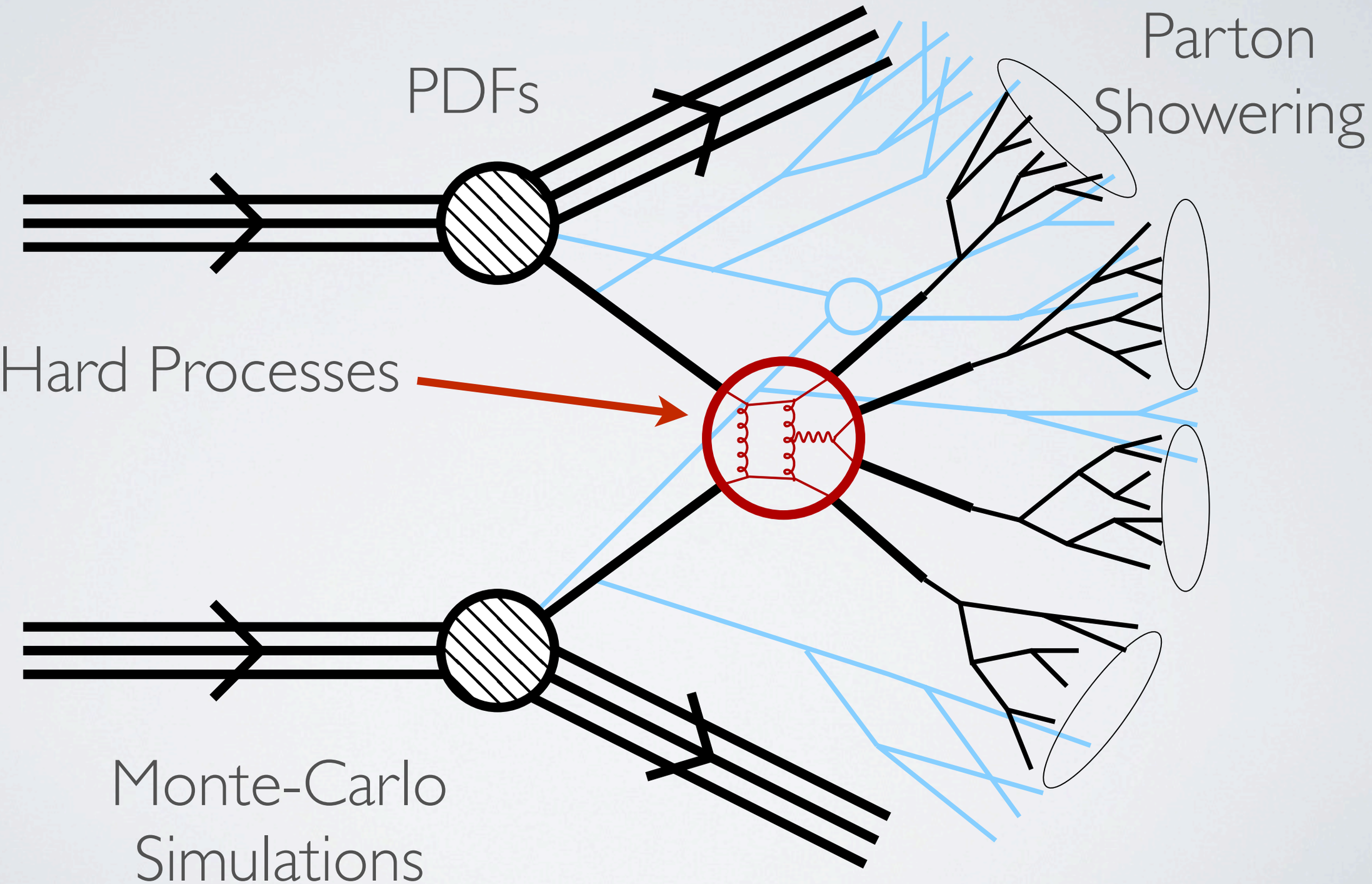
Simon Badger

RECFA meeting, Copenhagen, 3rd May 2013

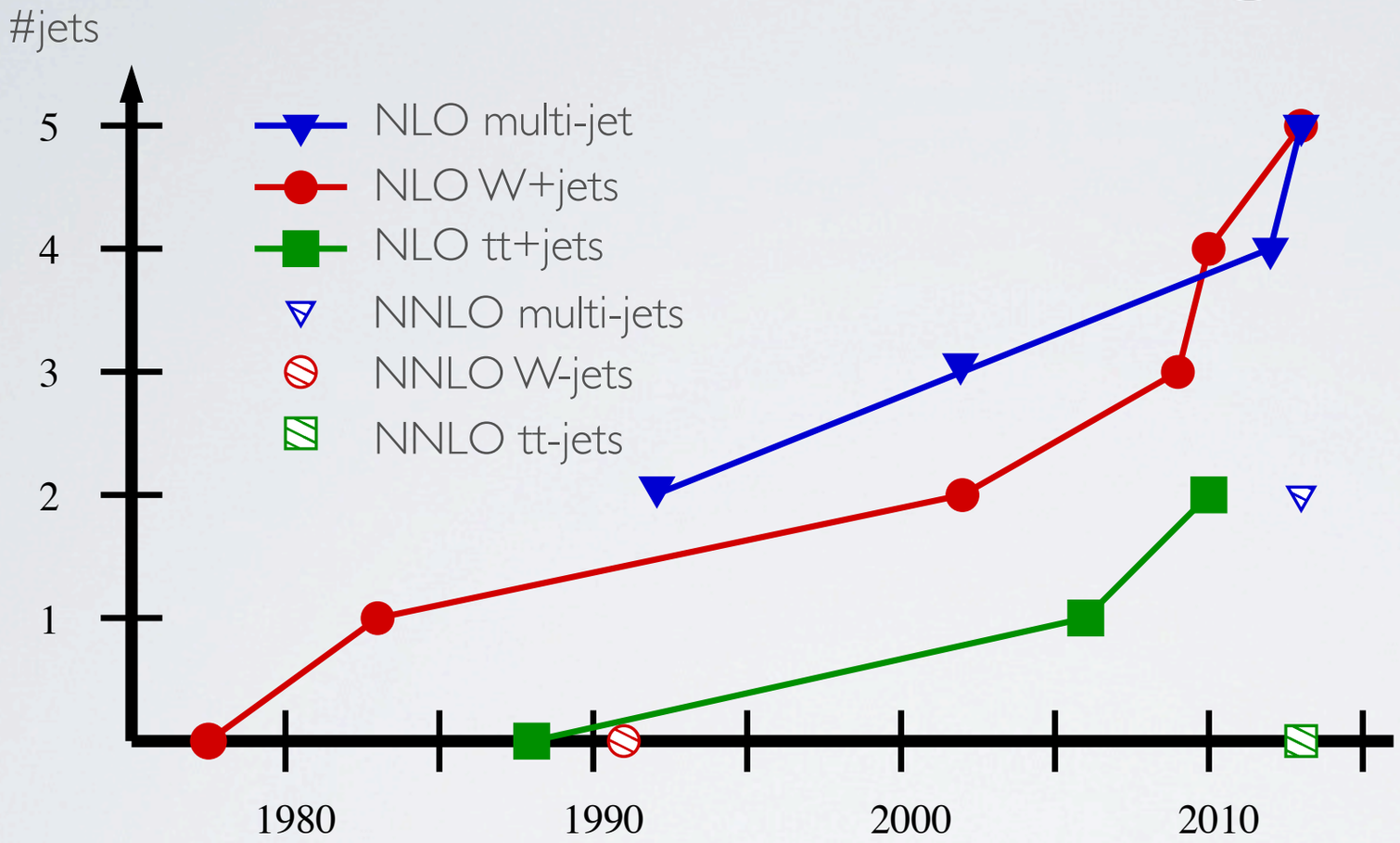
Overview

- Scattering amplitude methods and computations
- Gravity and string theories
- Collider Phenomenology
  - Precision QCD
  - Parton Distribution Functions

QCD at Hadron Colliders



Precision Backgrounds



NNLO 2→2 in 2013

pp→tt Czakon et a.

gg→gg Pires et al.

gg→Hg Bougezhal et al.

- Theoretical challenges - combat growth in complexity
- Keep theory uncertainties in line with experiments

HELAC-NLO Bevilacqua et al.

Dittmaier, Uwer, Wienzierl

Nagy Giele, Glover, Kosower

MCFM - Campbell, Ellis, **Williams**

BLACKHAT Berger et al.

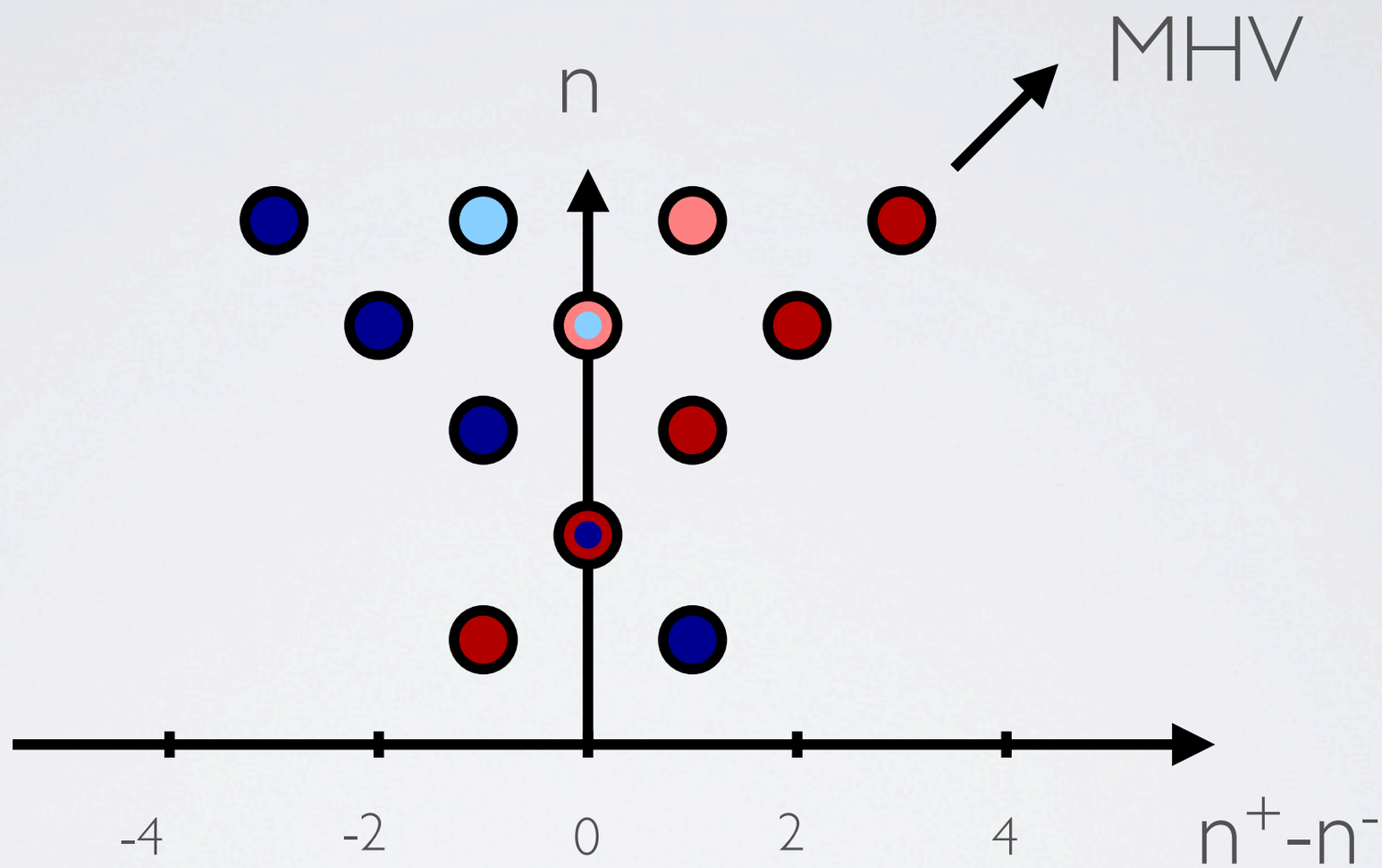
NGLUON/NJET **SB**, Biedermann, Uwer, **Yundin**

On-shell Methods

n	4	5	6	7	8	9
gluons	4	25	220	2485	34300	559405
qq+gluons	3	16	123	1240	15495	231280

- Feynman diagram expansion grows quickly
- On-shell amplitudes are much simpler
- All ingredients are gauge invariant with physical d.o.f

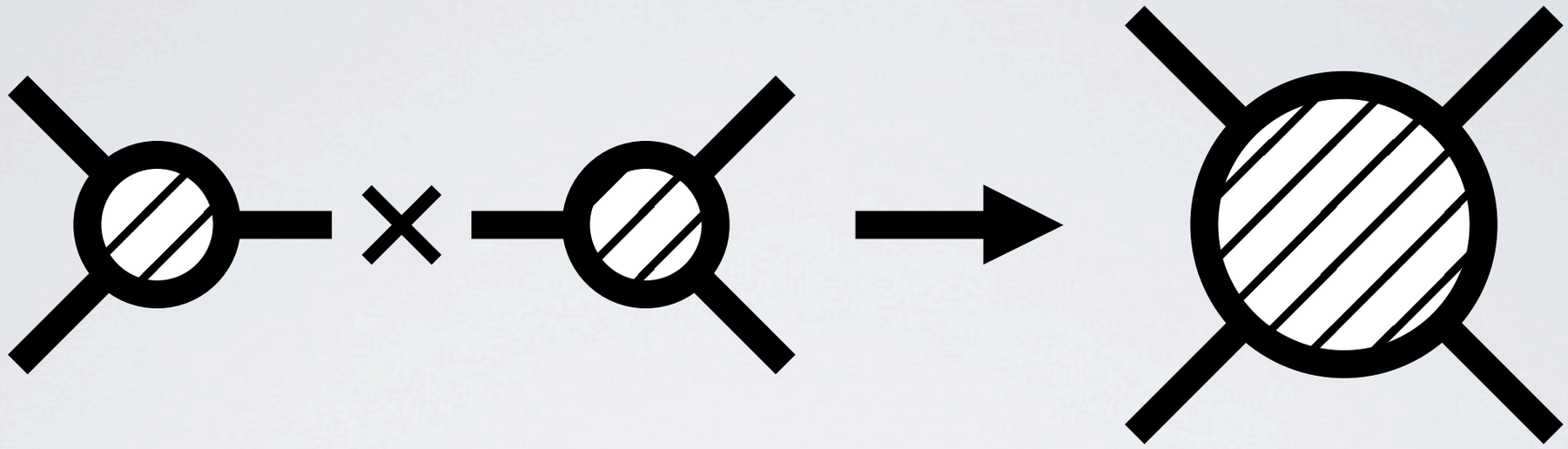
Tree-level simplicity



$$A^{\text{tree}}(1^-,2^-,\ldots,n^+) = \frac{\langle 12\rangle^4}{\prod_{i=1}^{n}\langle i\, i+1\rangle}$$

Parke, Taylor (1986)

Recursion Relations



- Recursion for on-shell amplitudes

  Britto, Cachazo, Feng, Witten (2005)

- Make use of complex momenta

- Compact analytic forms for wide variety of processes

- Exploring hidden structures in field theories

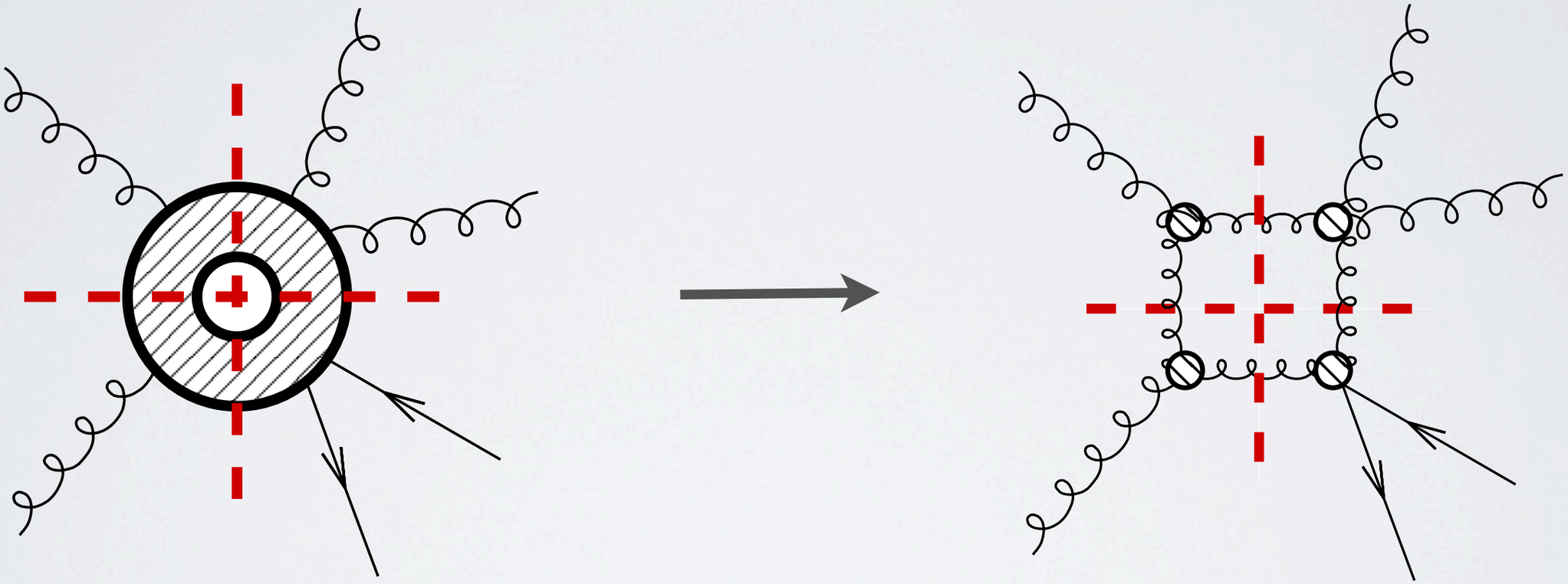
  e.g. simplicity in QED and gravity SB, Bjerrum-Bohr, Vanhove (2009)

Generalized Unitarity

Bern, Dixon, Dunbar, Kosower (1994)

Britto, Cachazo, Feng (2004)

Factorize loops into tree-level amplitudes with complex momenta



combining with known scalar integrals ⇒

purely algebraic construction for all 1-loop amplitudes

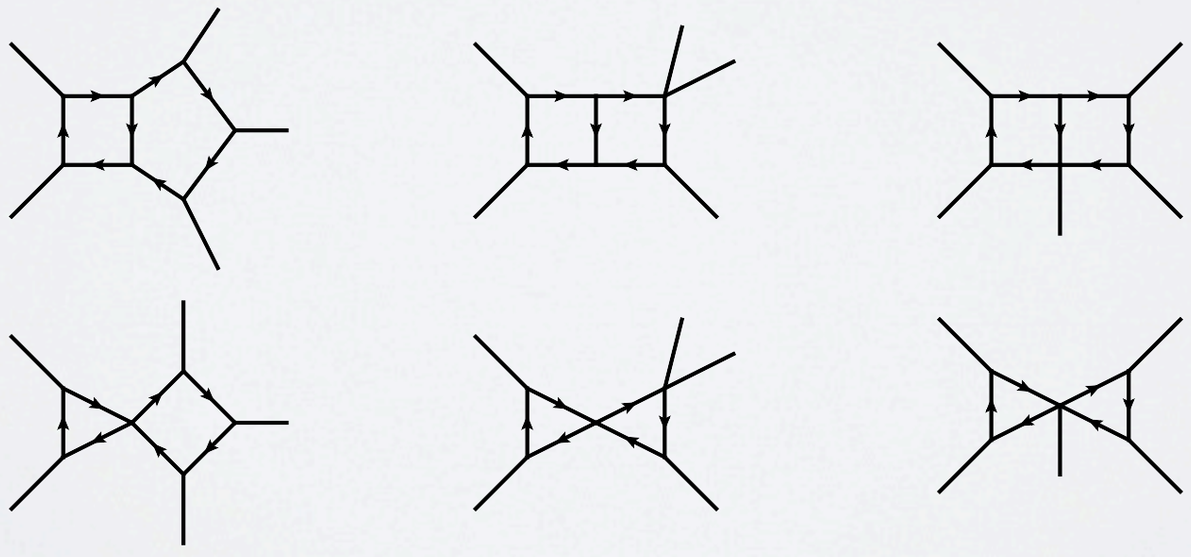
Multi-loop methods

- Generalized unitarity methods for multi-loop QCD amplitudes
- Algorithm based on computational algebraic geometry

Zhang (2012)

SB, Frellesvig, Zhang (2012)

- First applications towards 2→3 process in pure QCD



Connection To Gravity

Bjerrum-Bohr, Damgaard, Dennen, O'Connell, Monteiro

- Gauge-Gravity duality: $(\text{N=4 SYM})^2 \leftrightarrow \text{N=8 SUGRA}$

- Re-cycling QCD-like amplitudes gives access to amplitudes impossible with Feynman diagrams

- Colour/kinematic duality and double-copy for loop amplitudes

- Is N=8 SUGRA UV finite?

Amplitudes at Work

$$\hat{\sigma}_{NLO} = \int_n d\sigma_B + d\sigma_V + \int_{n+1} d\sigma_R$$

$$d\sigma_B = \sum_{h,i,j} A_i^{h,(0),\dagger} \boldsymbol{C_{ij}^{(0)}}(N_c) A_j^{h,(0)}$$

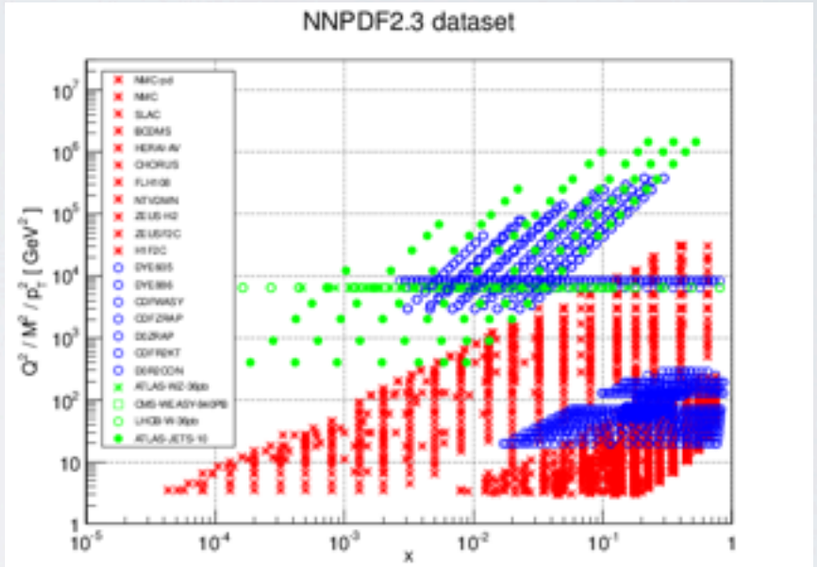
$$\sigma = \int dx_1 \int dx_2 \sum_{i,j} f_i(x_1,\mu_F) f_j(x_2,\mu_F) \hat{\sigma}_{ij}(\hat{s},\mu_R,\mu_F)$$

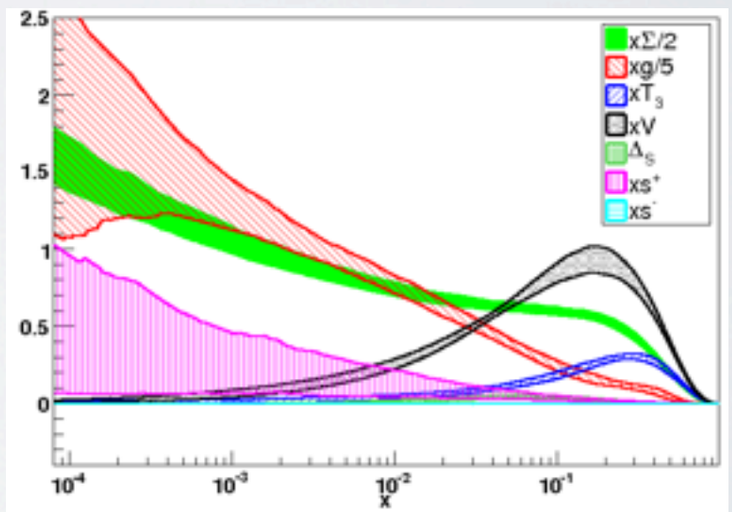
- Requires efficient **colour** and **helicity** summations
- Convolution with **parton distribution functions**
- Cancellation of IR divergences - Catani-Seymour/Frixone-Kunszt-Signer

NNPDF

Slide from A. Guffanti

- ★ **Innovative methodology** for determination of Parton Distribution Functions (based on **Monte Carlo methods** and **Neural Networks**)
- ★ **NNPDF methodology** addresses shortcomings of standard PDF determinations (statistical meaning of uncertainties, parametrization bias)
- ★ **First** global fit (**NNPDF2.3**) to include **LHC data** constraining PDFs





The **most up-to-date PDF set** available to **LHC experiments**

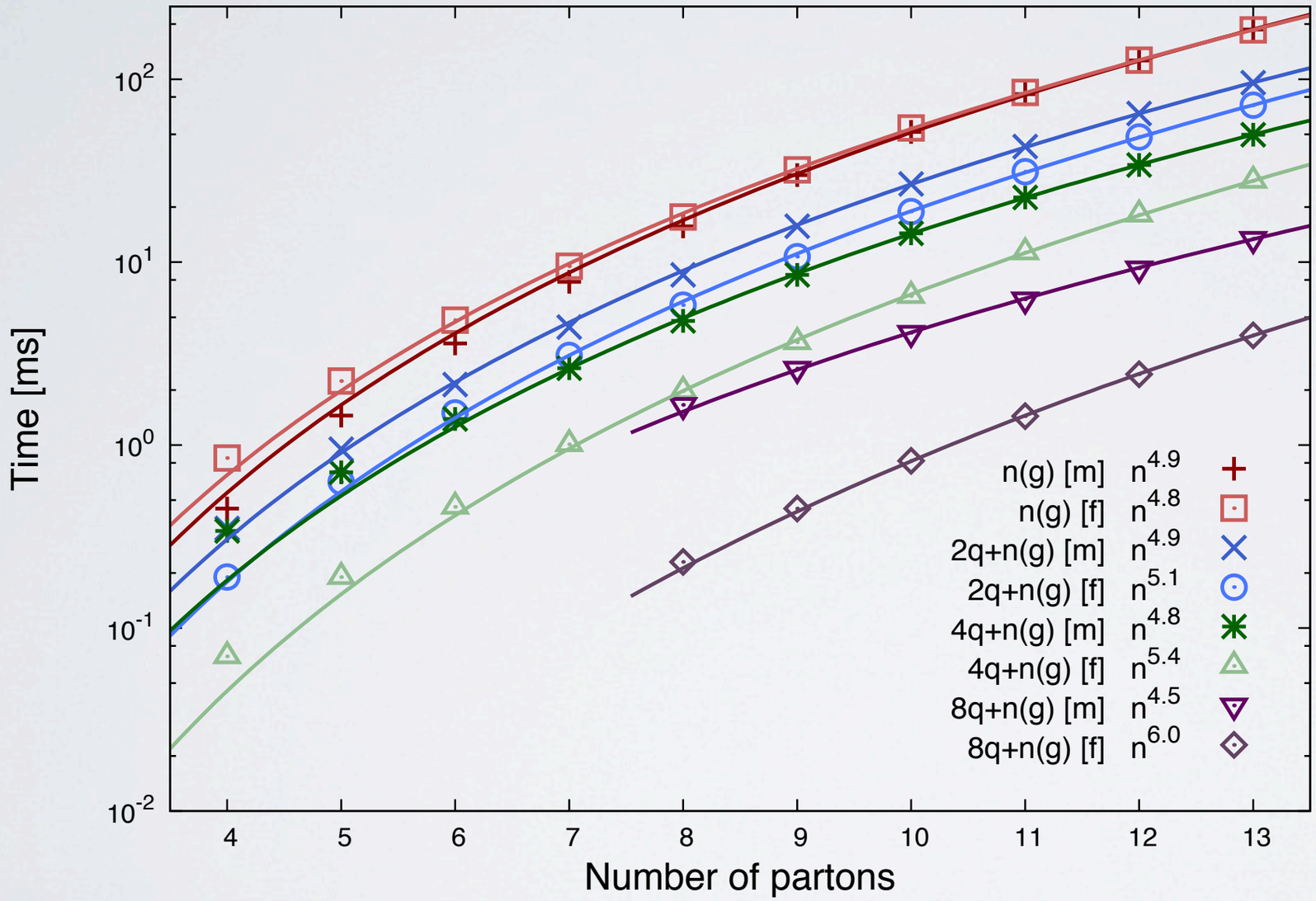
Automated NLO

BlackHat	Berger, Bern, Dixon, Ferbes-Cordero, Forde, Hoeche, Ita, Kosower, Mâitre
GoSam	Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
MadLoop/aMC@NLO	Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau
OpenLoops	Cascoli, Maierhofer, Pozzorini
Helac-NLO	Bevilacqua, Czakon, Garzelli, Kardos, Papadopoulos, Pittau, van Hameren, Worek
NJet	SB, Biedermann, Uwer, Yundin

- Multi-leg NLO now ready for LHC phenomenology!
- Increasing number of automated numerical tools

Speed $\longleftrightarrow$ Flexibility

Numerical Efficiency



Polynomial scaling with time!

NJET SB, Biedermann, Uwer, Yundin (2012)

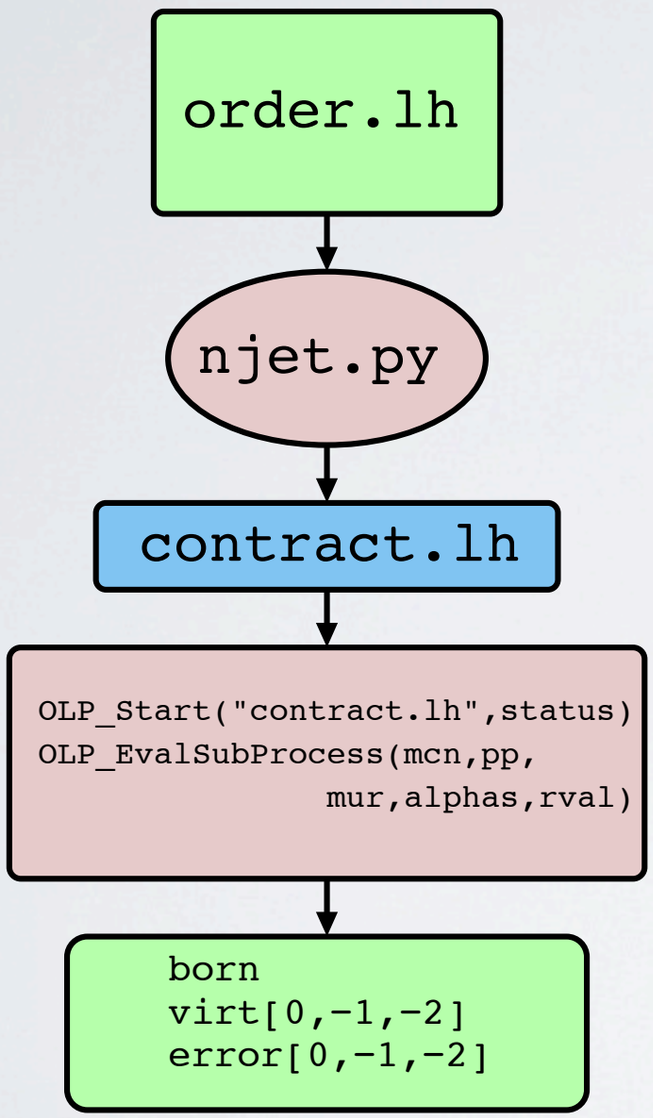
Public Tools

- NJET - C++ library for NLO virtual corrections to multi-jet production in QCD
  - Full colour matrix elements
  - Simple interface to commonly used MC event generators
  - Fast evaluation for up to 5 final state jets

http://bitbucket.org/njet/njet

SB, Biedermann, Uwer, Yundin (2012)

Interface with MC tools

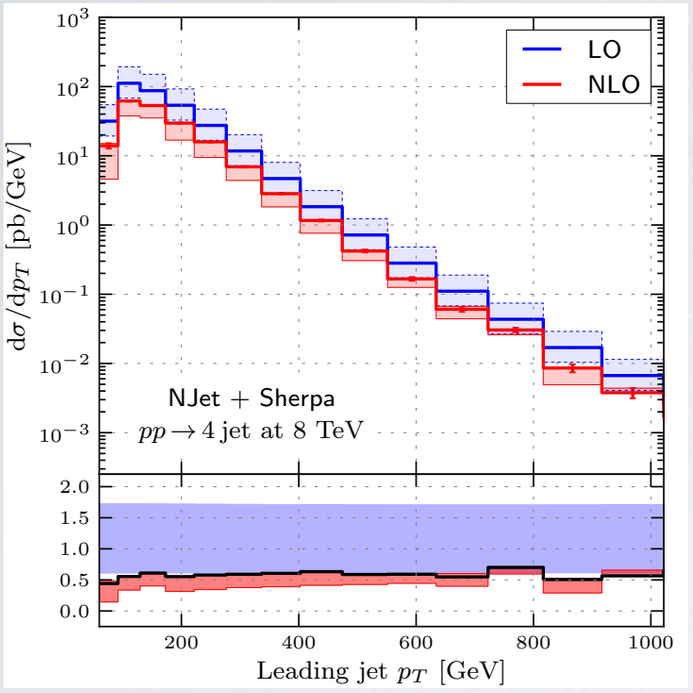


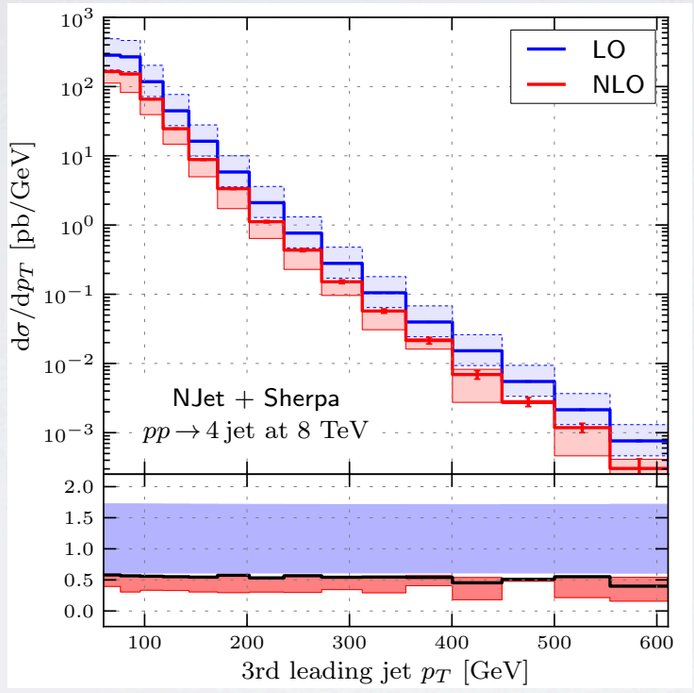
- Monte-Carlo simulations for phase-space integration etc.
- Binoth Les Houches Accord - a universal interface for MC tools

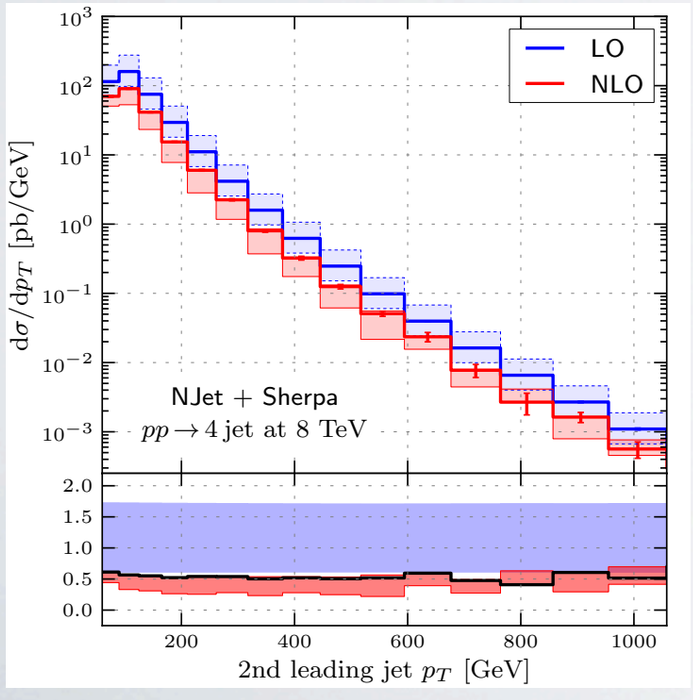
e.g. SHERPA Gleisberg et al.

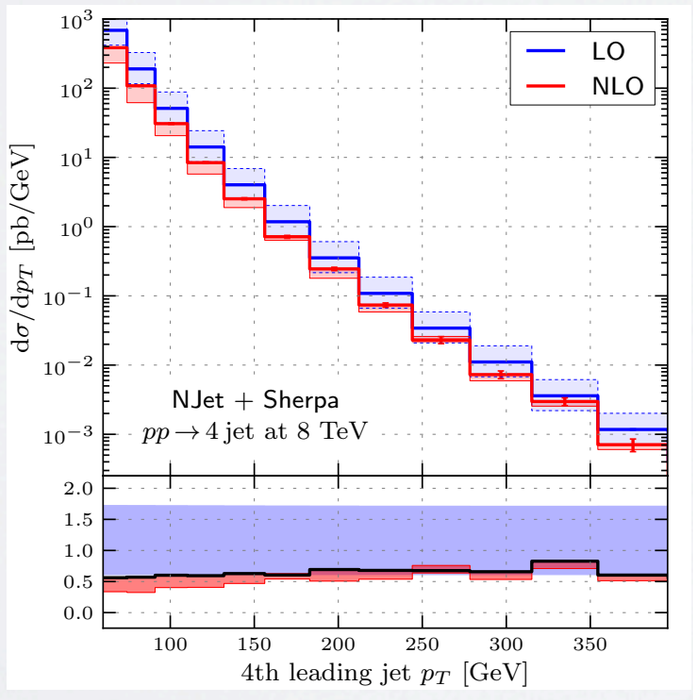
aMC@NLO Frederix et al.

Multi-jet production @ NLO









ATLAS 2011
Eur. Phys. J. C 71 (2011)

pp → 4j @ 7/8 TeV

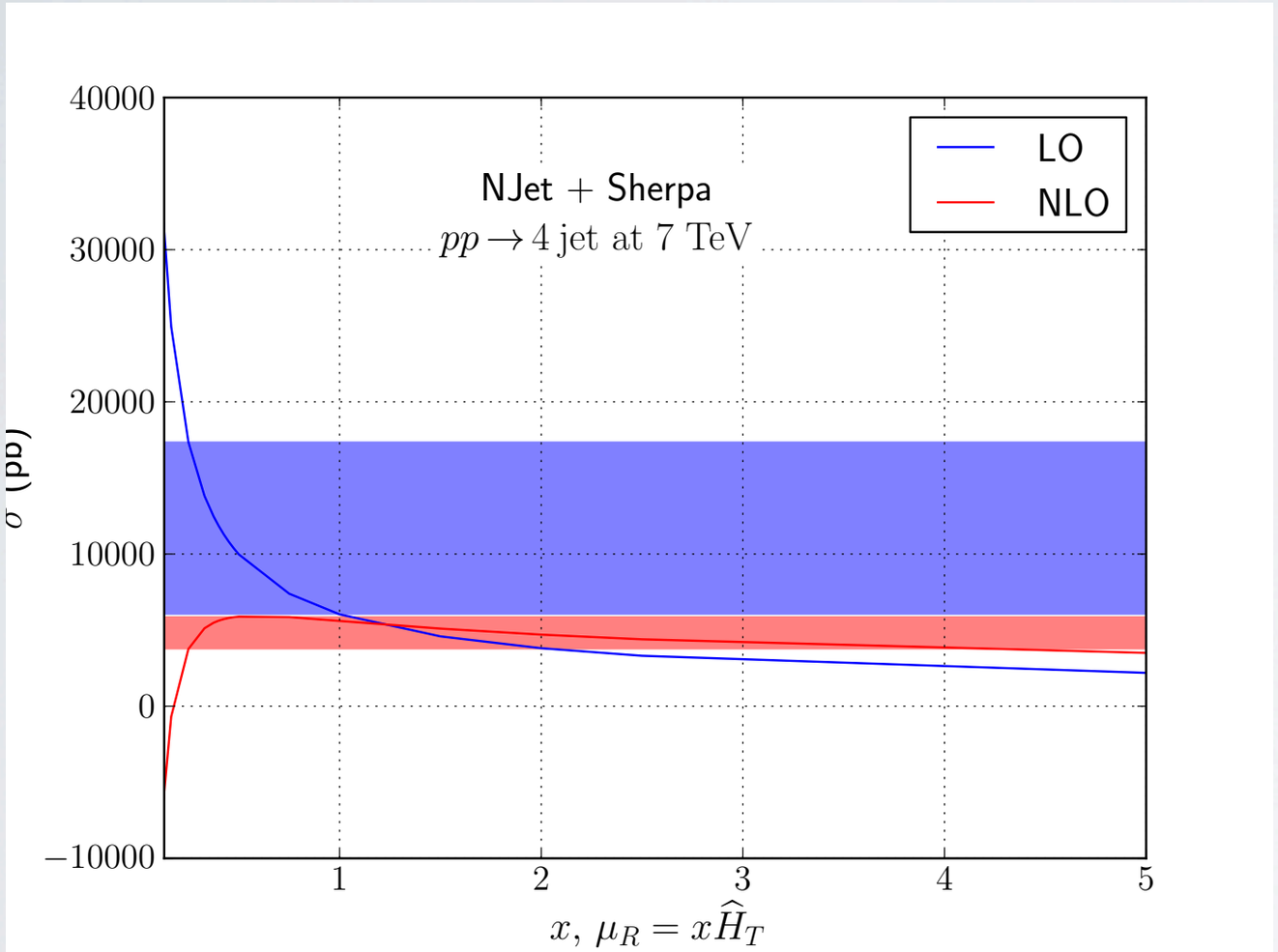
$p_T^{1st} > 80$ GeV $p_T > 60$ GeV

$|\eta| < 2.8$

BLACKHAT Bern et al. (2011)

SB, Biedermann, Uwer, Yundin (2012)

Scale Dependence



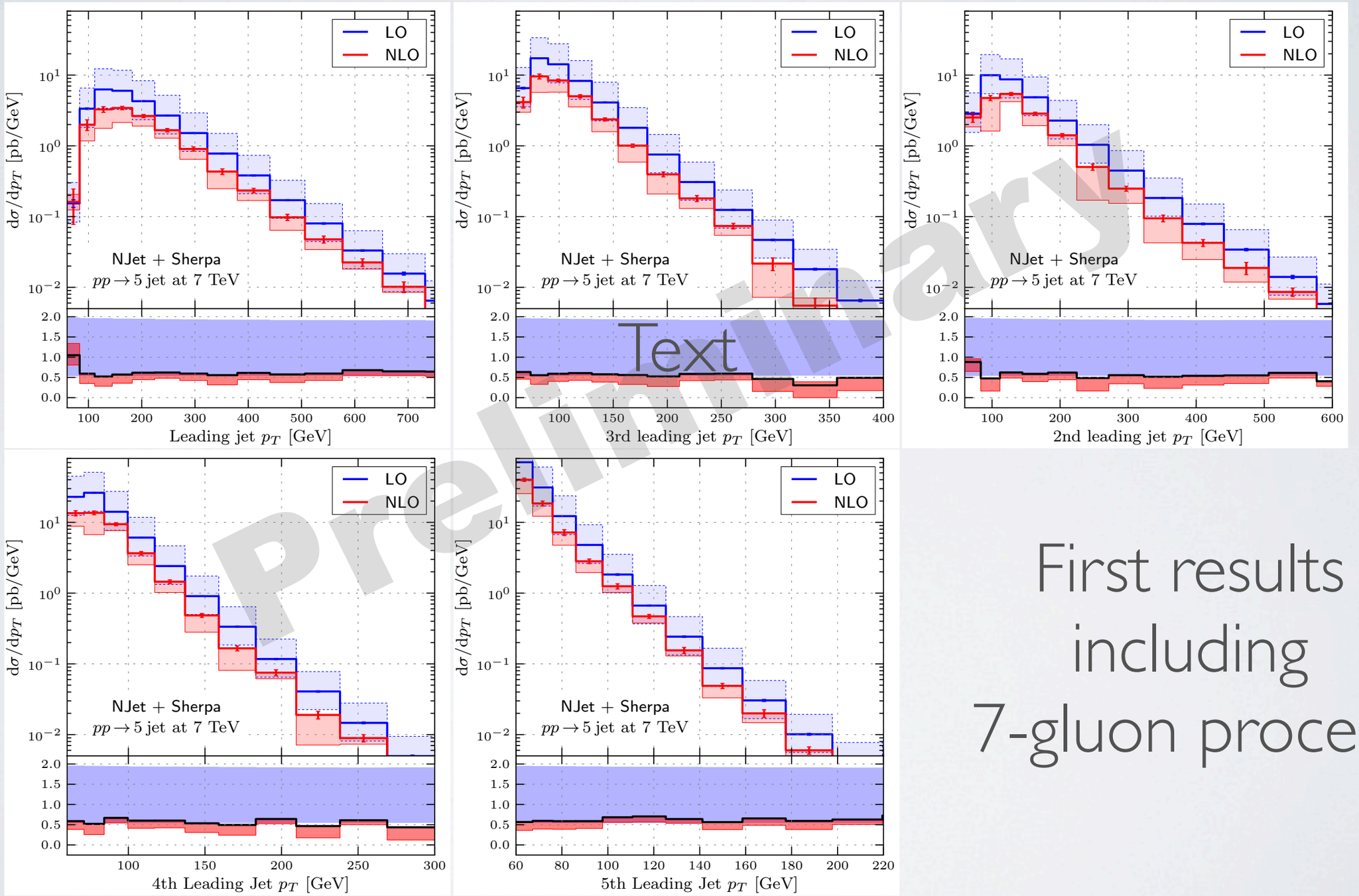
NLO reduces theoretical uncertainty

Central scale $\hat{H}_t / 2$

$$\hat{H}_t = \sum_{\text{final}} p_T$$

Dynamical scale stabilizes NLO corrections

NLO corrections to pp→5j



First results including 7-gluon process

SB, Biedermann, Uwer, Yundin (in preparation)

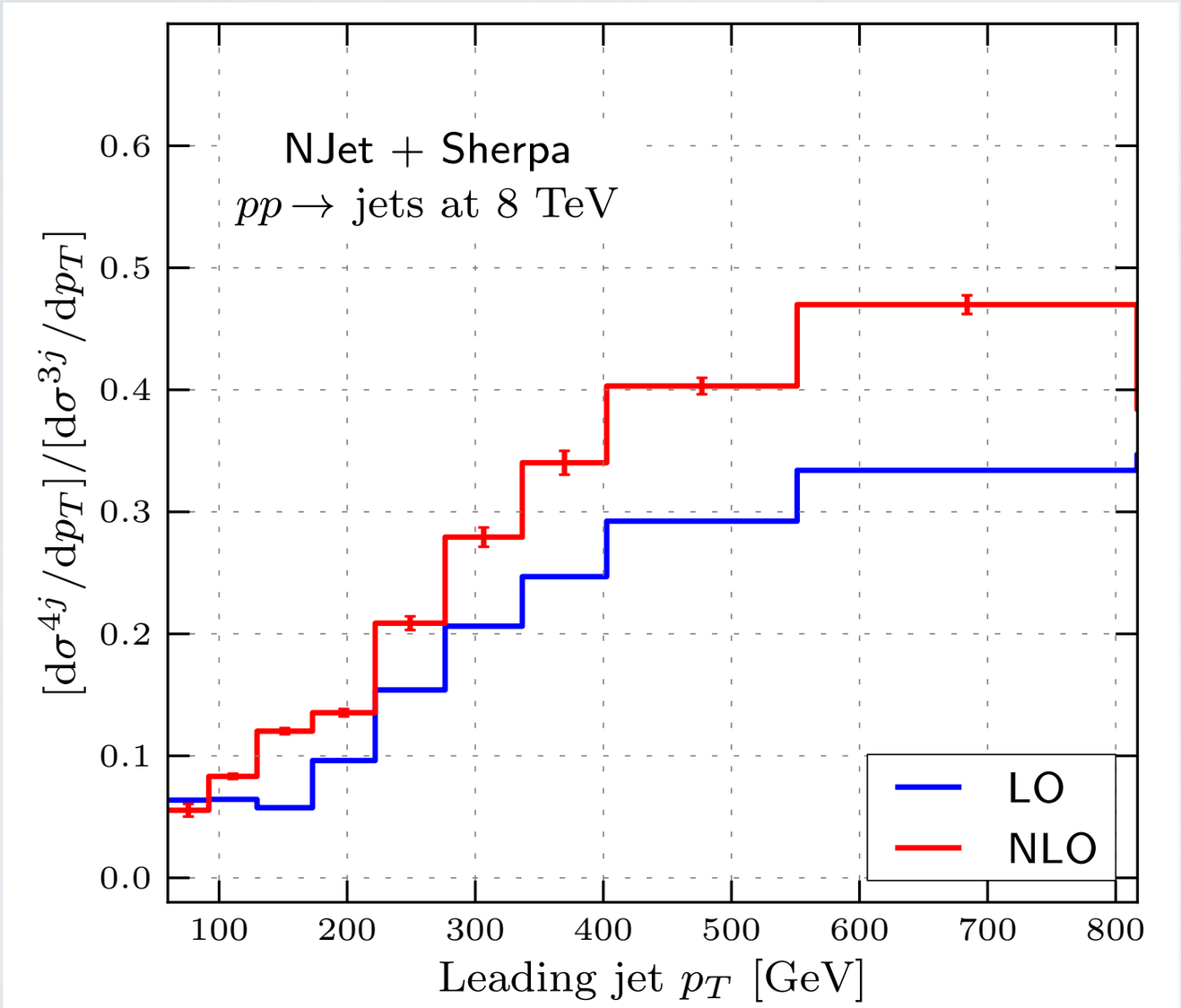
Outlook

- Looking forward to further precision QCD for LHC@14TeV
  - Constraining PDFs
  - Parton shower and merging at NLO
- Precision backgrounds to new physics searches

  (W+jets, tt+jets, H+jets)
- Understanding theoretical uncertainties at NNLO

Backup Slides

Jet Production Ratios

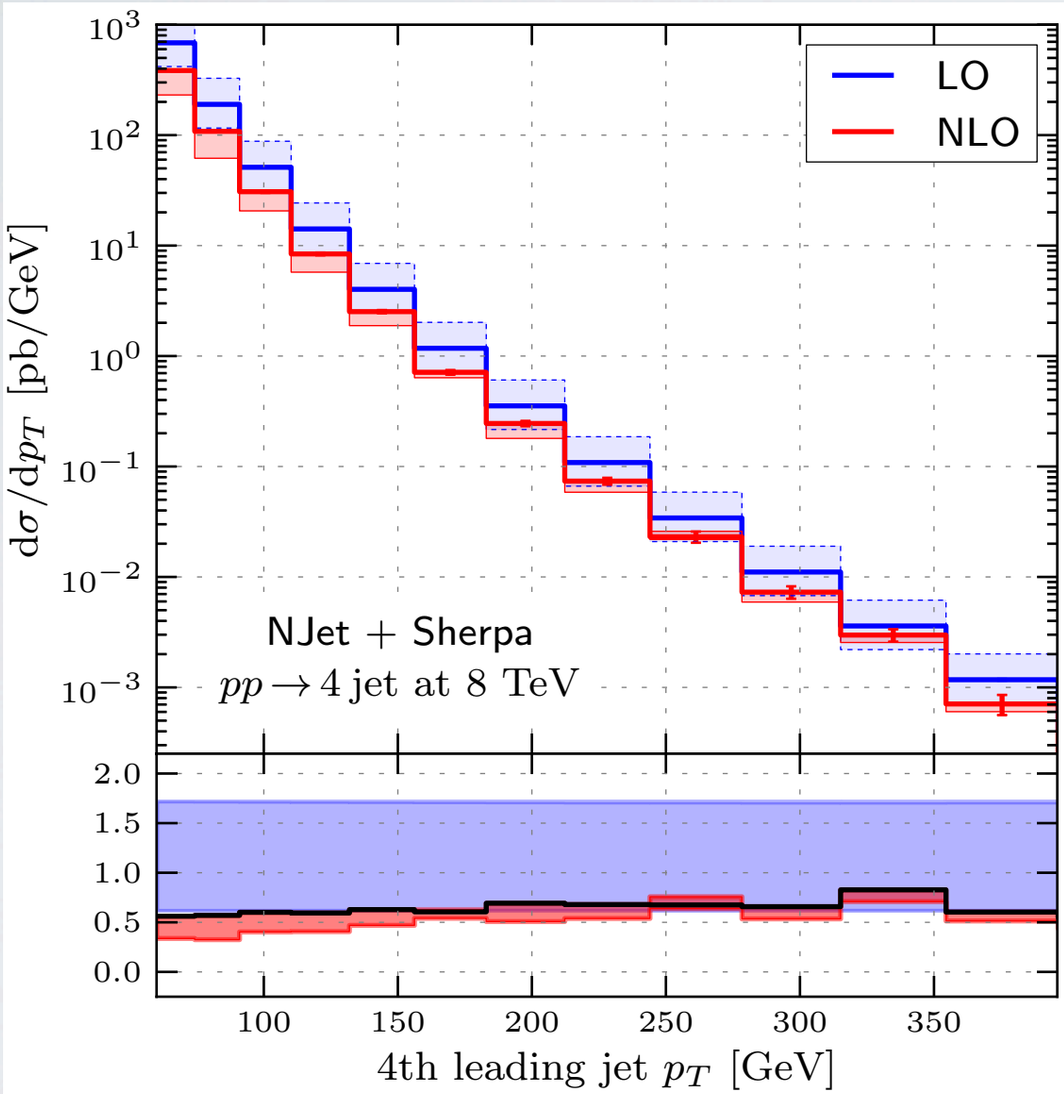


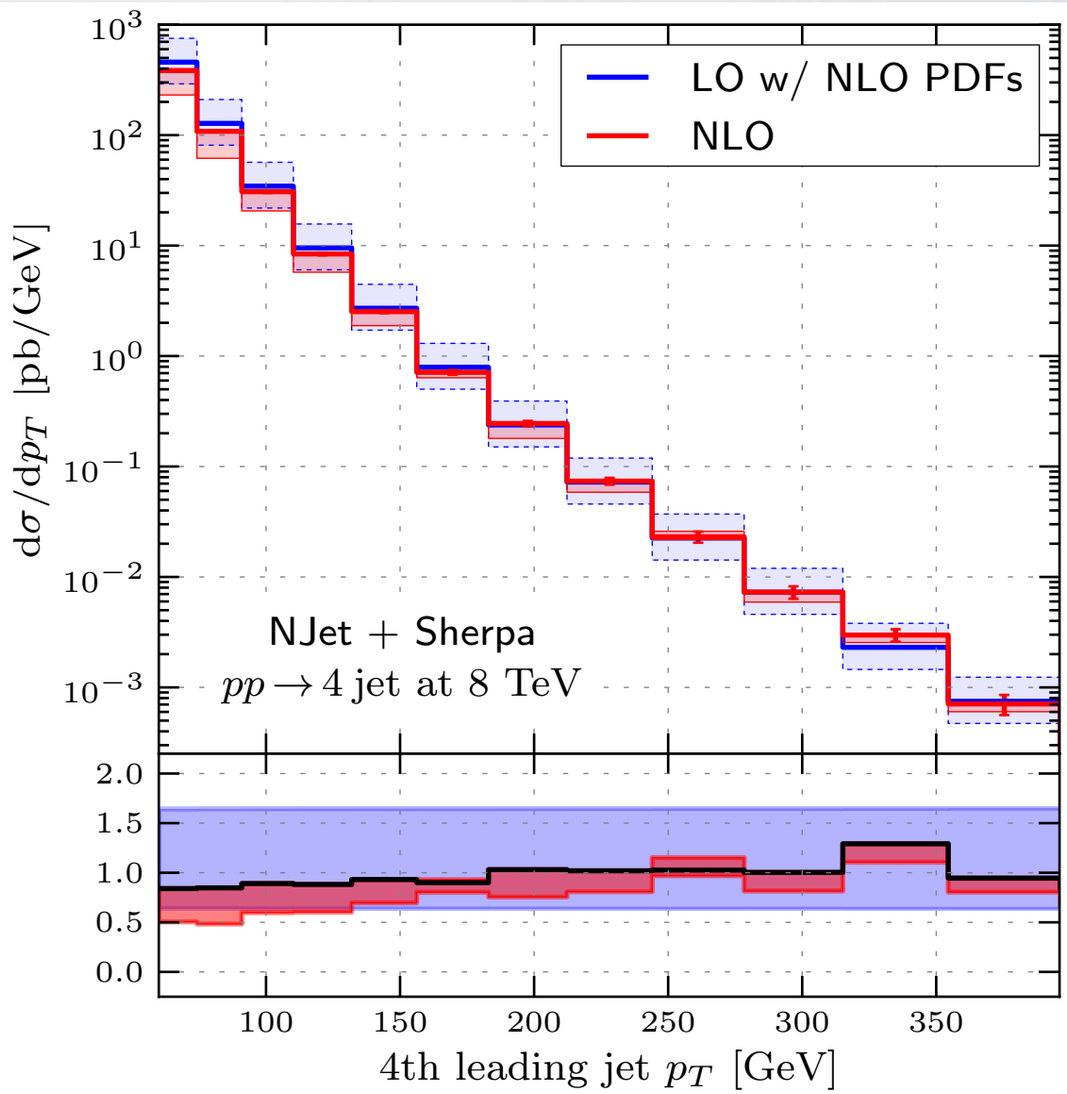
Cancellation of many exp. uncertainties

Extraction of strong coupling

see recent ATLAS study of 3/2j ratio

α_s dependence





Strong dependence on NLO evolution of α_s