SINLO Sudakov Improved NLO

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Benefits of NLO

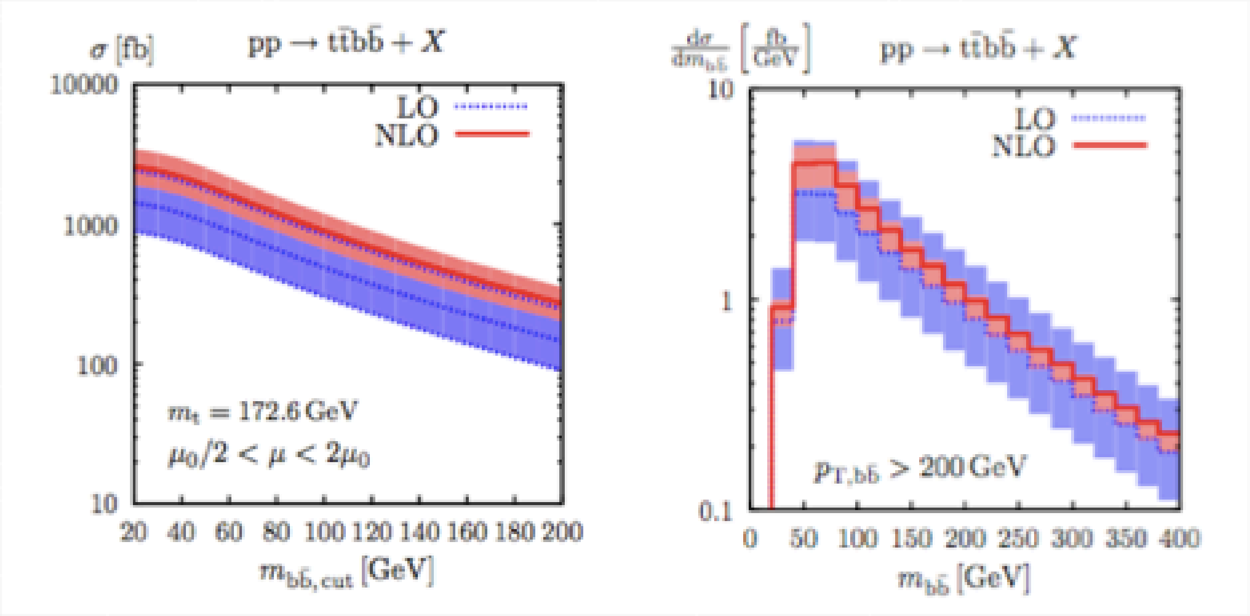
- Leading Order is often a quite crude approximation
  - normalization can float arbitrarily up and down by just changing α_s (more so with more jets in the final state)
  - poor description of jets, without any internal substructure (1jet=1parton)
  - poor control on shapes of distributions (***but BSM searches rely heavily on a solid control of shapes to extrapolate backgrounds from control regions to signal regions***)
- Next-to-Leading order is just "a better approximation" to data: this is manifest in reduced theory uncertainties (often estimated by varying renormalization and factorization scales)

BUT: even at NLO the scale choice is an issue and different choices can lead to a different picture/contrasting conclusions

Scale choice at NLO

Example where a scale choice leads to a different picture at NLO

Bredenstein et al. 0905.0110, 1006.2653



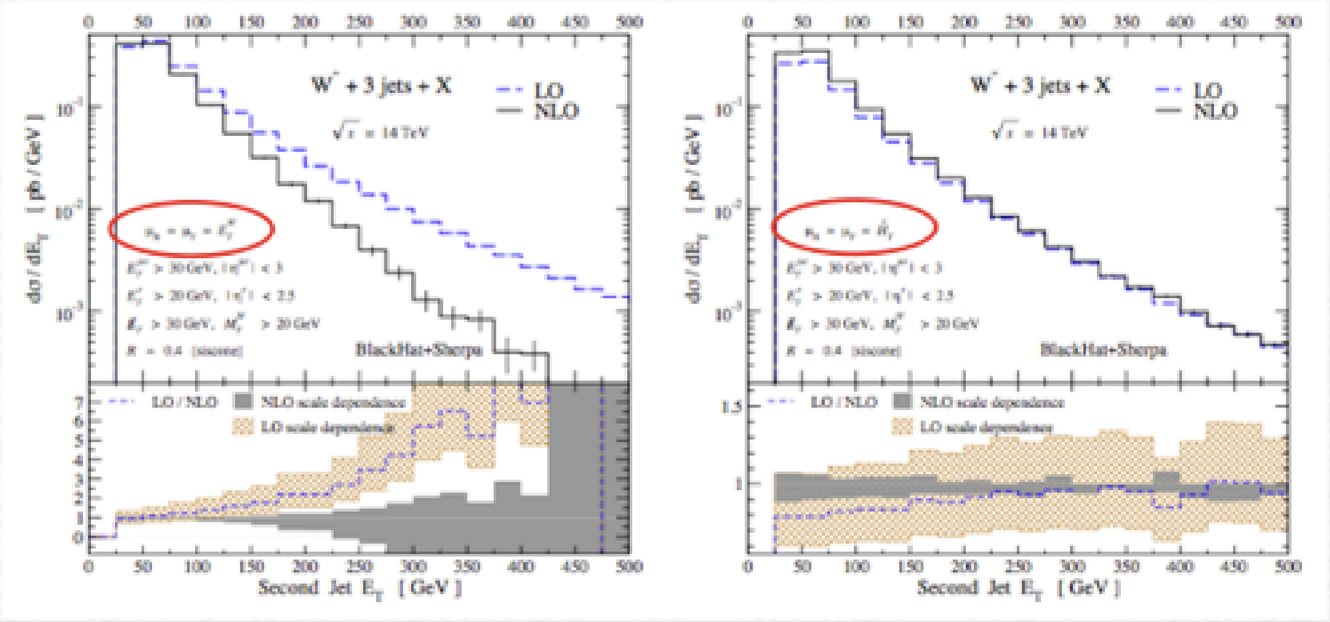
$\mu_0 = m_t + m_{bb,\mathrm{cut}}/2$ $\qquad$ $\mu_0^2 = m_t\sqrt{p_{t,b}p_{t,\bar{b}}}$

ttbb important background to ttH with H → bb. Whether or not we can control this background to better than 20% makes a crucial difference (ttH is unique to measure the ttH Yukawa coupling)

Scale choice at NLO

Example where a scale choice leads to a different picture at NLO

Bern et al. 0907.1984

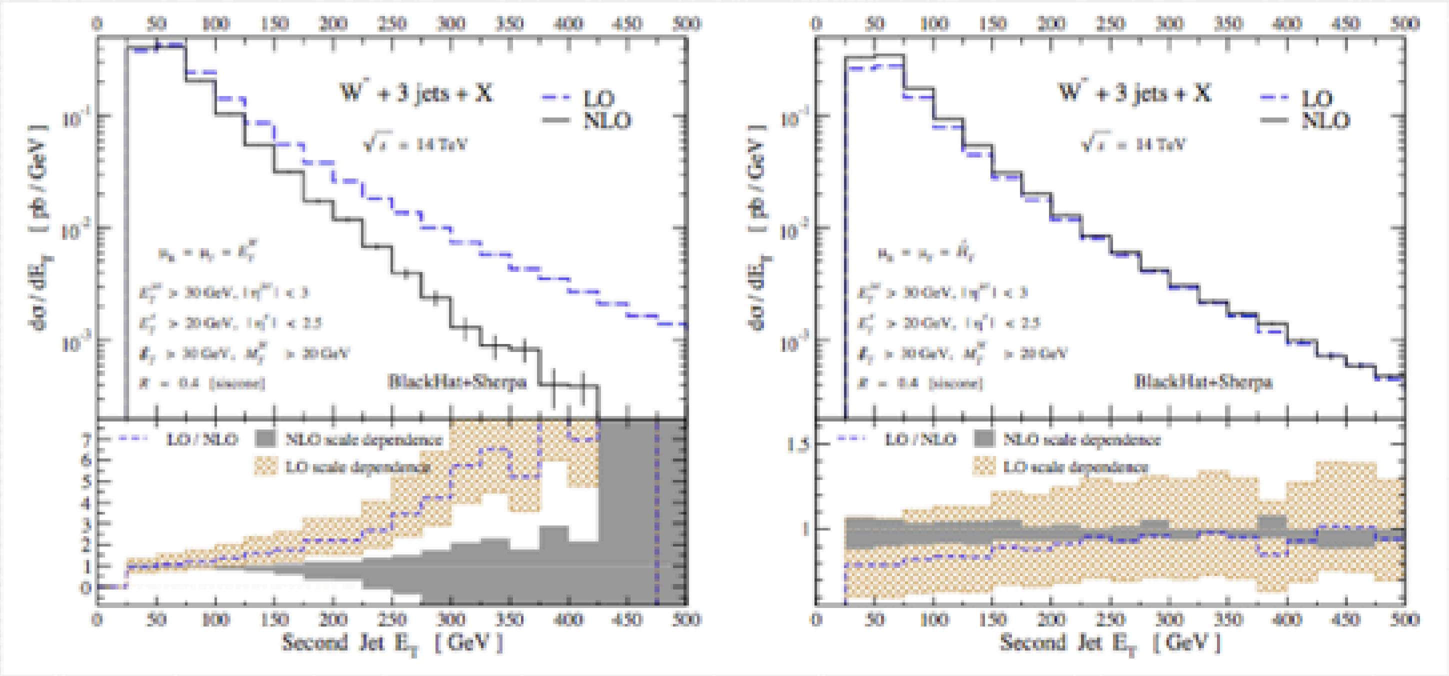


W+ multi-jet processes are important backgrounds to SUSY searches at high transverse energies

Could quote many more examples. In general the problem is more severe as the number of jets increases (as more scales enter into play)

Scale choice at NLO

Often a "good scale" is determined ***a posteriori***, either by requiring NLO corrections to be small, or by looking where the sensitivity to the scale is minimized



bad scale

good scale

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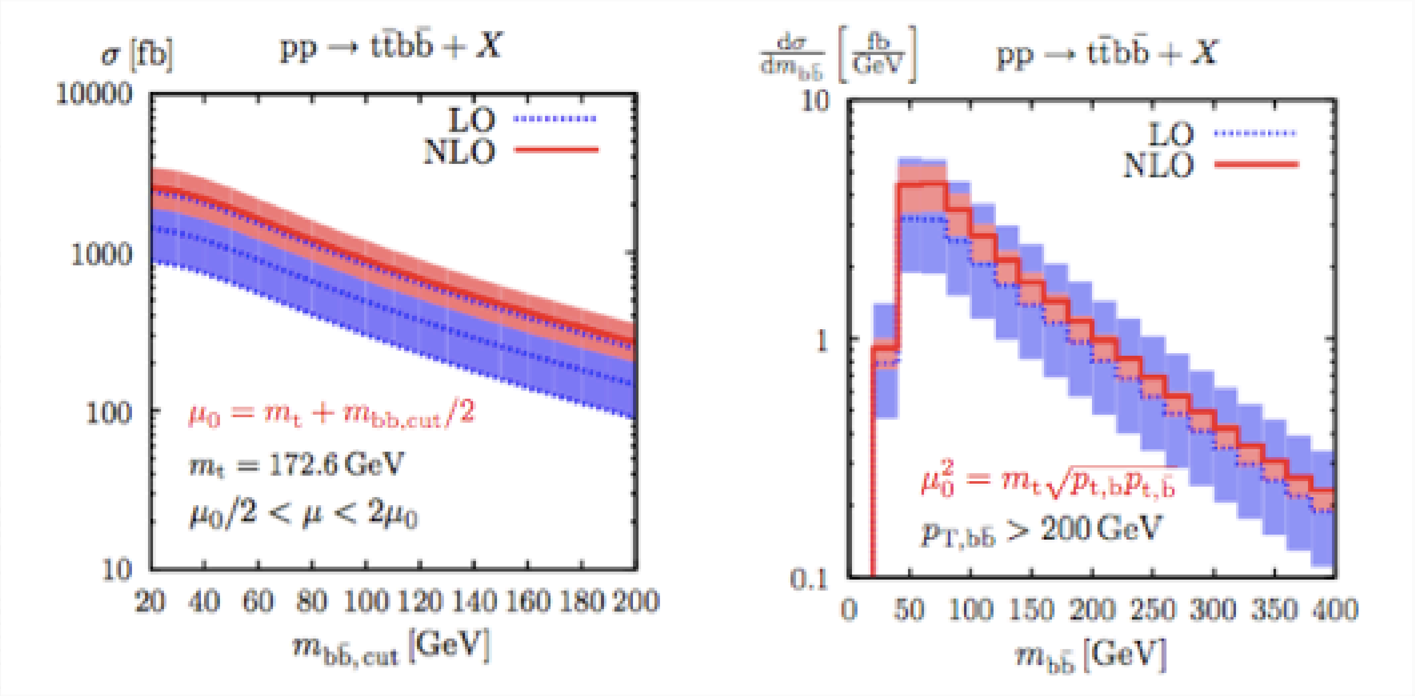

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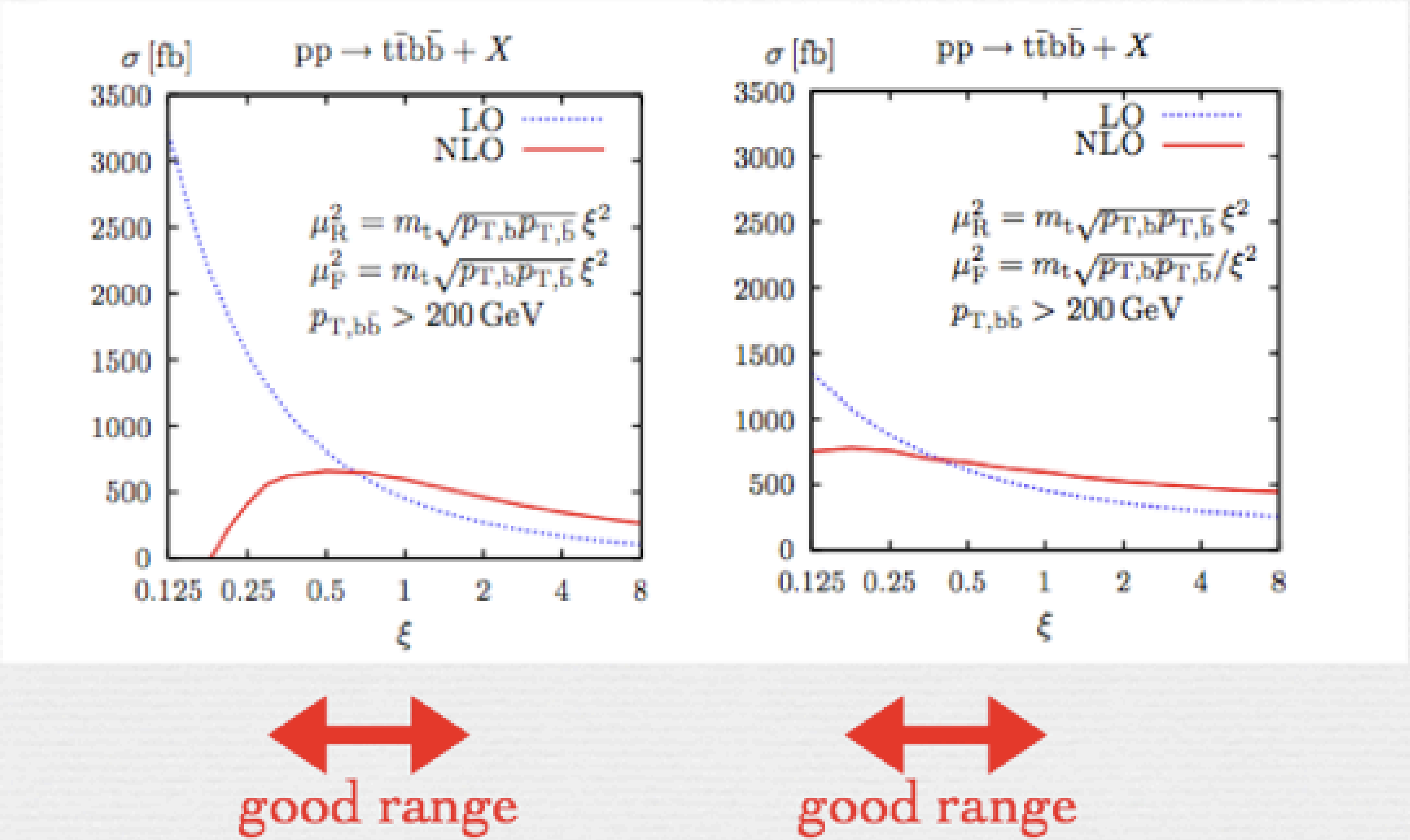

Scale choice at NLO

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Reason: bad scale ➠ large logs ➠ large NLO and large scale dependence

But we also know that large NLO ~~➠~~ bad scale choice, since NLO corrections can have a "genuine" physical origin (new channels opening up, Sudakov logs, color factors, large gluon flux ...)

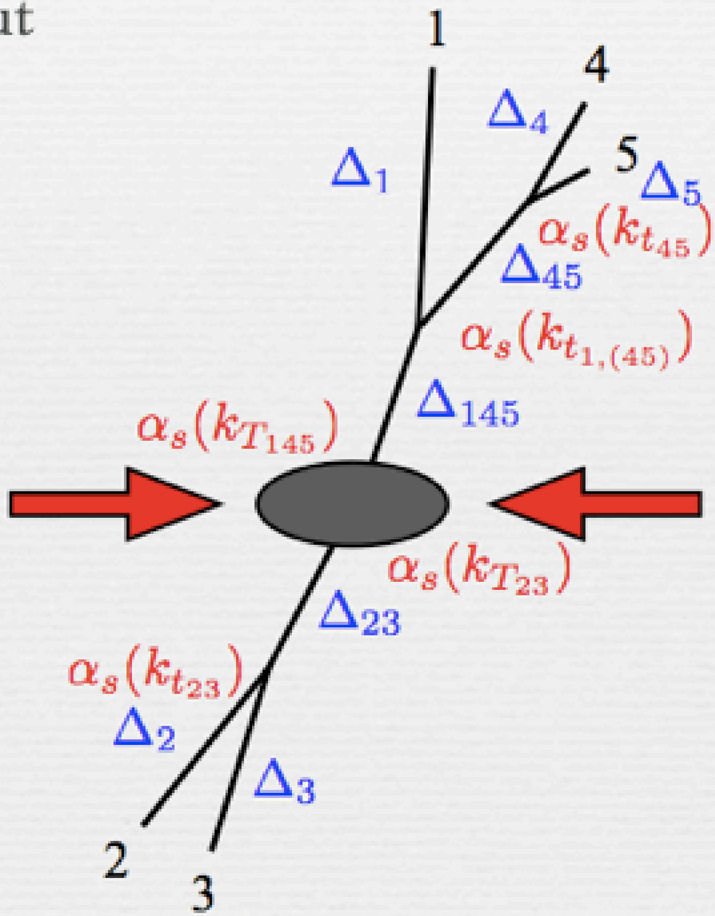
Furthermore, double logarithmic corrections can never be absorbed by a choice of scale (single log). So a "stability criterion" can be misleading.

On the other hand, LO calculations in matrix elements generators are quite sophisticated: they use optimized scales and Sudakov form factors

Recap of CKKW

A breakthrough in LO calculations came about with the CKKW prescription:

- use the k_t algorithm to reconstruct a branching history
- evaluate each α_s at the local transverse momentum of the splitting
- for each internal line include a Sudakov form factor $\Delta = D(Q_0,Q_i)/D(Q_0,Q_j)$ that encode the probability of evolving from scale Q_i to scale Q_j without emitting. For external lines include $\Delta = D(Q_0,Q_i)$
- match to a parton shower to include radiation below Q_0



Catani,Krauss, Kuehn, Webber '01
extension to hh collisions *Krauss '02*

Aim of this work

- At LO we have a sensible prescription to include Sudakov effects and a solid presciption for choosing the scales. This means we are getting the most out of LO calculations
- NLO calculations are very hard (not so much conceptually challenging today, but technically difficult/computer intensive)
- So, once you do a hard NLO calculation, you should try to exploit it as much as possible (i.e. not spoil your result with a bad scale choice)

The goal: formulate a procedure to compute the actual NLO correction to matrix element style LO calculations with Sudakov form factors, such that the procedure to choose the scale is unbiased and choosen ***a priori***

Two observations

1. A generic NLO cross-section has the form

$$\alpha_S^n(\mu_R)\,B + \alpha_S^{n+1}(\mu_R)\left(V(Q) + n b_0 \log\frac{\mu_R^2}{Q^2}B(Q)\right) + \alpha_S^{n+1}(\mu_R)\,R$$

   Adopting CKKW scales at LO, this becomes naturally

$$\alpha_s(\mu_1)\ldots\alpha_s(\mu_n)B + \alpha_s^{n+1}(\mu_R')\left(V(Q) + b_0 \log\frac{\mu_1^2\ldots\mu_n^2}{Q^{2n}}B\right) + \alpha_s^{n+1}(\mu_R'')R$$

   and the scale choices μ_R' and μ_R'' are irrelevant for the scale cancelation

2. Sudakov corrections included at LO via the CKKW procedure lead to NLO corrections that need to be subtracted to preserve NLO accuracy

Arbitrariness

When trying to extend the CKKW procedure to NLO there is arbitrariness in

1. the arguments of α_s in the real and virtual term
2. the exact definition of the subtraction terms of the NLO terms in the Born Sudakovs
3. whether or not to include Sudakovs in the real and virtual

Our guiding principle is that the virtues of the CKKW result at leading order are maintained once radiative corrections are included

The SINLO method

1. Find the clustering scales $q_1 < \ldots < q_n$ (and q_0 for the real term). Set $Q_0 = q_1$, since radiation is inclusive below q_1 and the hard scale Q to the invariant mass after clustering

2. Evaluate n coupling constants at the scales q_i, and the $(n+1)$ α_s in the virtual and real term at the arithmetic average of the $\alpha_s(q_i)$

3. Set μ_F to the soft scale q_1, and μ_R to the geometric average of the q_i

4. Include Sudakov form factors for all Born and NLO terms

5. Subtract the NLO bit present in the CKKW Sudakov of the Born

Properties of SINLO

SINLO satisfies the following requirements

- the result is accurate at NLO, i.e. the scale dependence is NNLO
- the accuracy in the Sudakov region is Leading Log (LL) or better, according to the form of the Sudakov used
- the smooth behaviour of the CKKW scheme in the singular regions is preserved
  - X+n-jet cross-sections are finite even without jet cuts (do not need generation cuts or Born suppression factors)
  - X+n-jet cross-sections reproduce the inclusive cross-section accurate to LO
- the procedure is simple to implement in any NLO calculation, i.e. the improvement requires only a very modest amount of work

It is then interesting to see how the method fares in practice

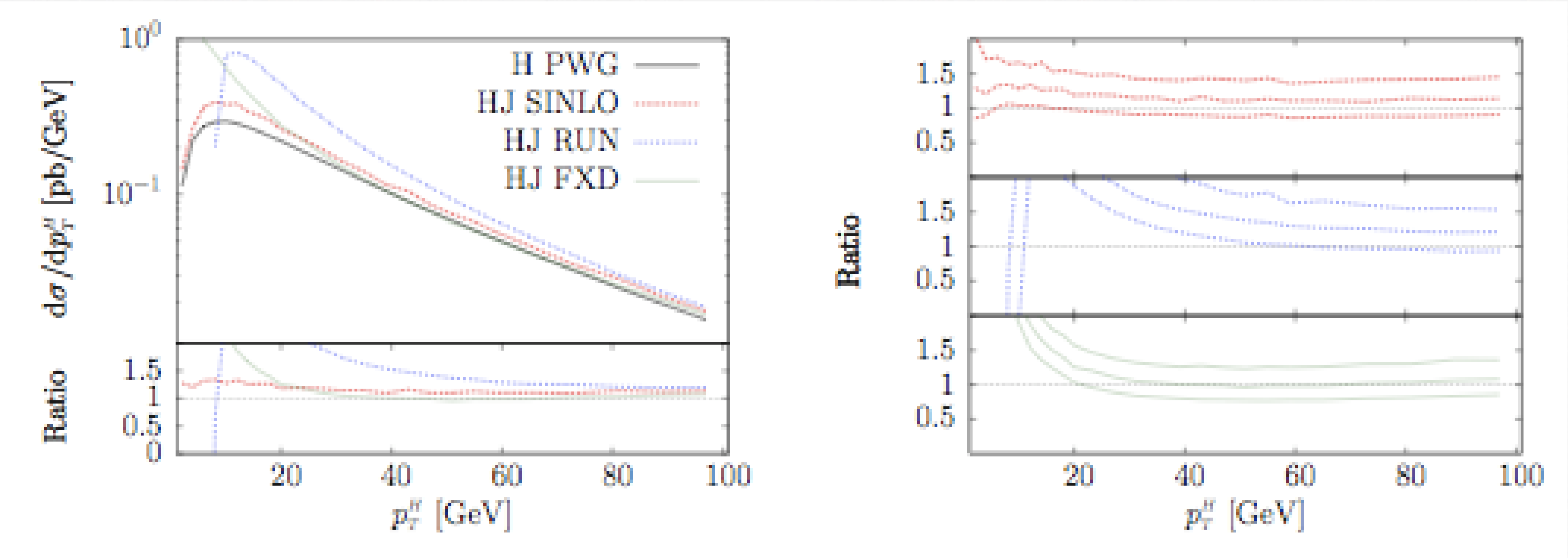
Phenomenology

To asses how the method fares in practice, we considered the following processes

- H+1jet, H+2jets,W+1jet, W+2jets (we implemented the latter ourself in POWHEG using automated MadGraph4 interface and taking virtual corrections from MCFM)
- we compare the SINLO predictions to standard NLO results with a number of common scales used for these processes
- we compare the SINLO predictions with POWHEG results with (n-1) jets

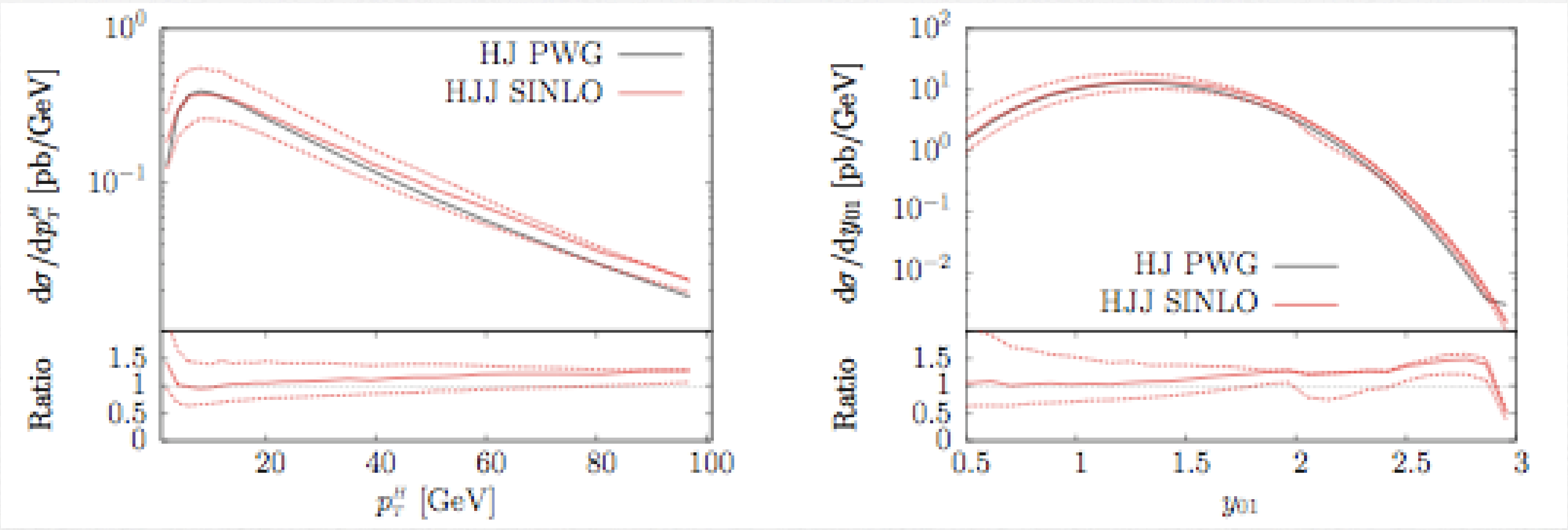
We use a standard LHC setup, but since SINLO includes Sudakov form factors, **we do not need to impose any jet cut**. We generated hundreds of distributions, I'll just show 3 examples here.

H+1jet



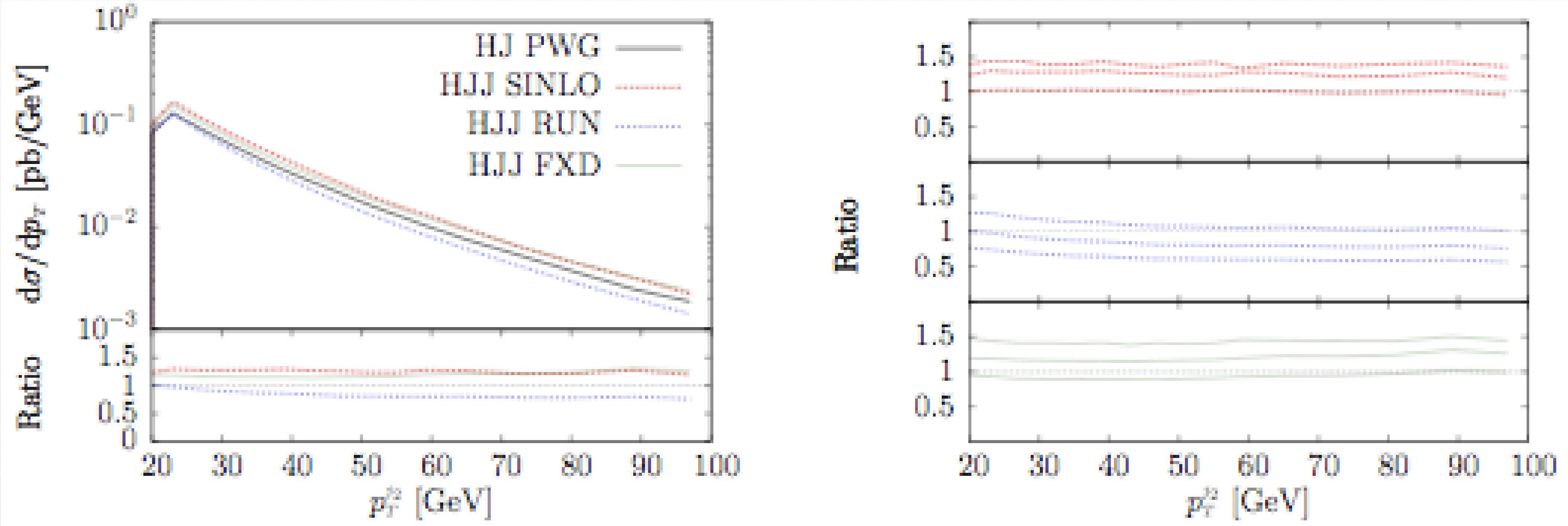
- SINLO mimics POWHEG all the way down to very small $p_{T,H}$ where standard H+1j order results diverge
- SINLO uncertainty band compatible with POWHEG all the way down to low transverse momenta
- SINLO more compatible with fixed rather than running scales (surprising? No, running scale misses Sudakov)

H+2jets



- without cuts impossible to compare to Standard NLO
- again, SINLO uncertainty band compatible with POWHEG all the way down to low transverse momenta

H+2jets



- running scale (H_T) outside the band of SINLO
- using $H_T/2$ leads to much better agreement
- $H_T/2$ has becomes the preferred scale because it leads to an improved scale stability
- the SINLO result confirms, independently, this choice

Conclusions

The choice of scale in NLO calculation has since a while being a debated issue

Matrix element calculations have a natural choice via the CKKW procedure, but they also include double logs from Sudakov form factors

SINLO is a simple procedure to extend the CKKW method to NLO

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- the procedure is simple to implement in any NLO calculation, i.e. the improvement requires only a very modest amount of work