MENLOPS

Getting the most out of POWHEG & MEPS methods.

K.Hamilton

Università degli Studi di Milano-Bicocca

Outline:

- NLOPS & MEPS features.
- Theoretical considerations for MEPS $\rightarrow$ MENLOPS.
- How close can you get just combining today's tools?
- New SHERPA implementation.
  [S.Höche, F.Krauss, M.Schönherr, F.Siegert]

Outline:

Throughout this talk

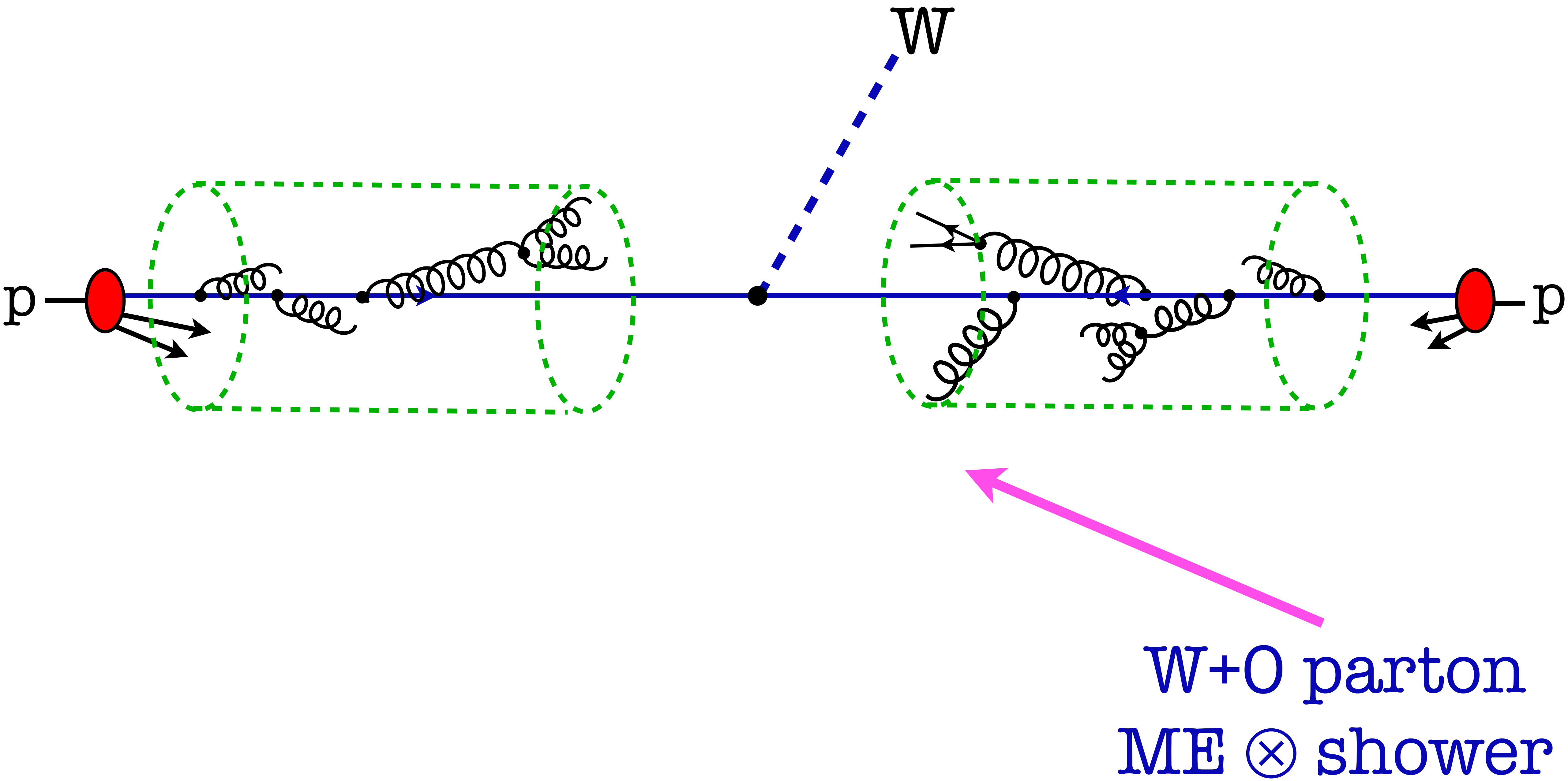
NLO = NLO with respect to the X+0 jets process

Outline:

- NLOPS & MEPS features.
- Theoretical considerations for MEPS → MENLOPS.
- How close can you get just combining today's tools?
- New SHERPA implementation.
  [S.Höche, F.Krauss, M.Schönherr, F.Siegert]

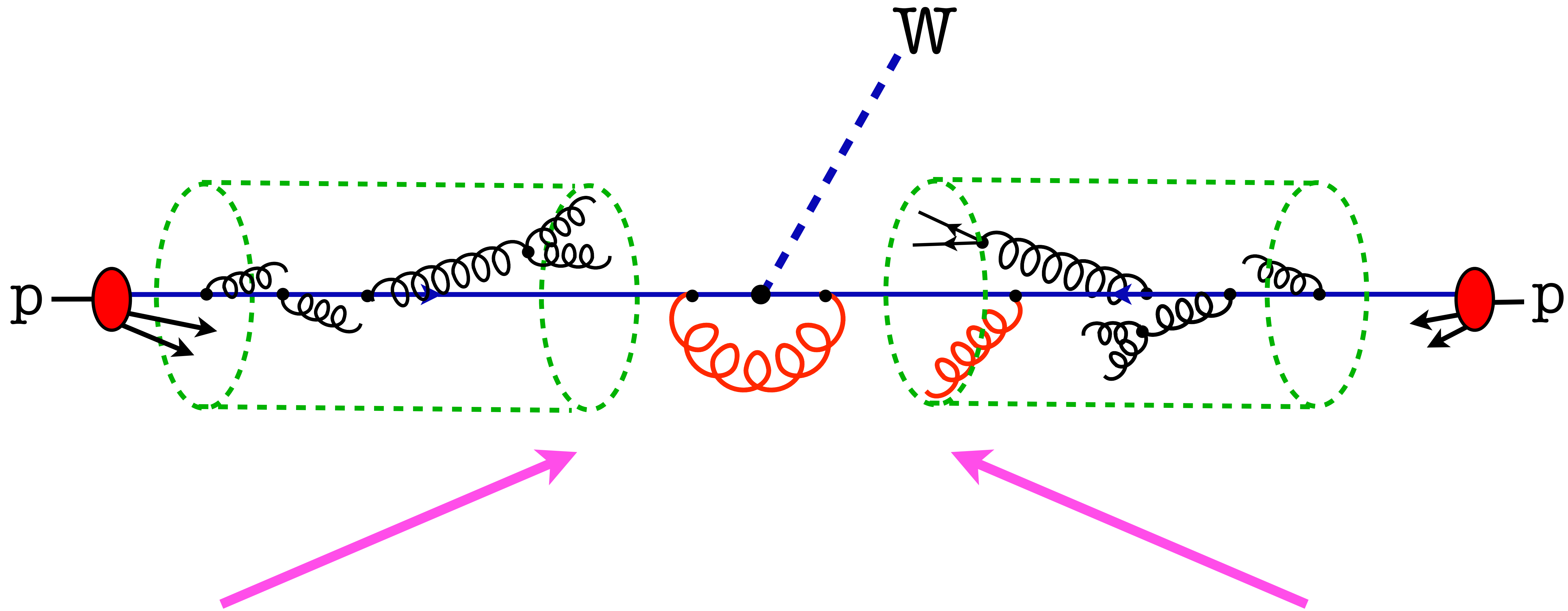
pp → W + 0 jets

MEPS



pp → W + 0 jets

NLOPS



NLO Born kinematics

W+1 parton ME ⊗ shower

NLOPS & MEPS features

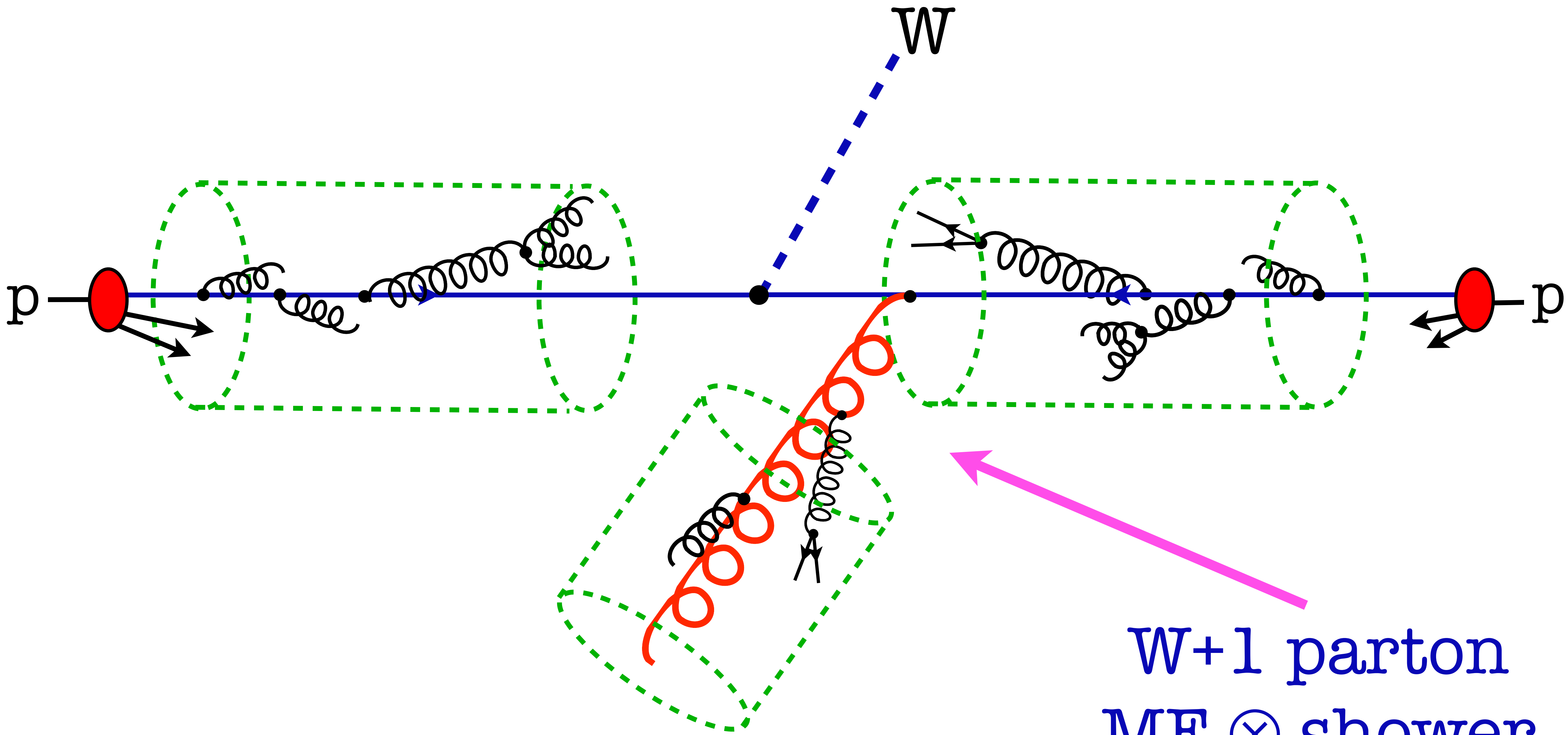
Accuracy†	MEPS	NLOPS
0-jet events	LO	NLO
1-jet events	...	...
2-jet events	...	...

☞ NLOPS is best for hard X+0 jet description.

† For hard jets.

pp → W + 1 jets

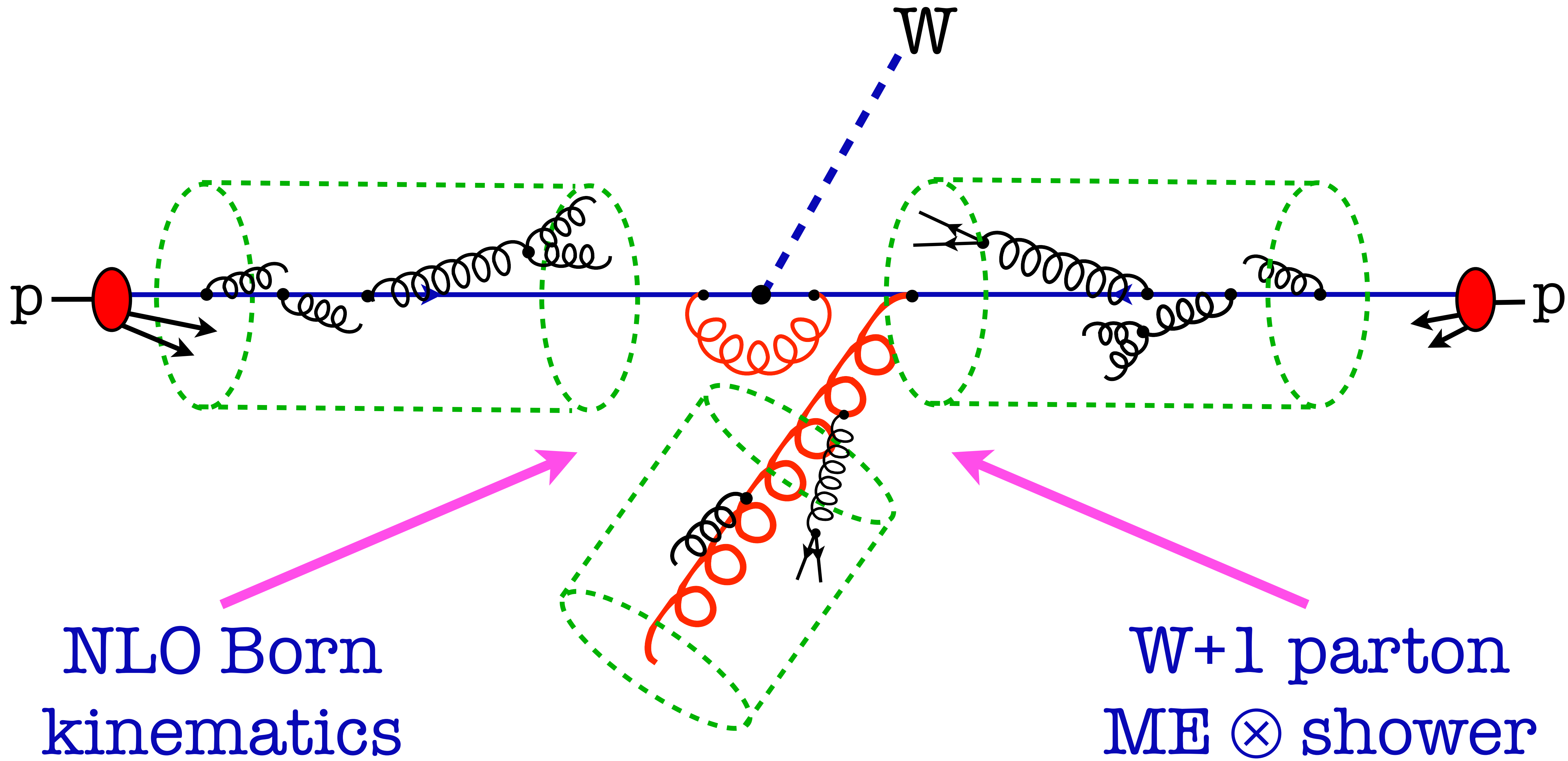
MEPS



W+1 parton
ME ⊗ shower

pp → W + 1 jets

NLOPS



NLOPS & MEPS features

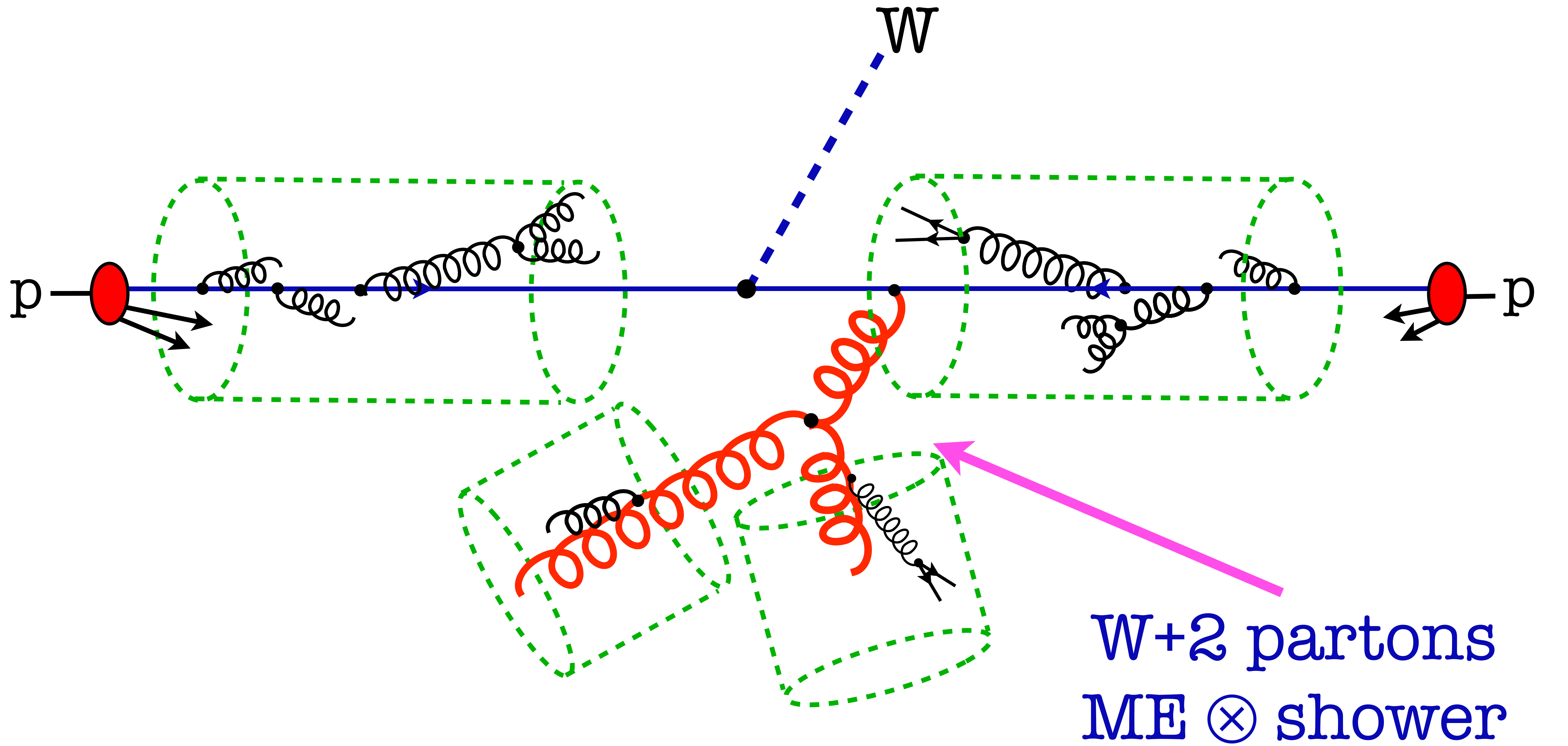
Accuracy†	MEPS	NLOPS
0-jet events	LO	NLO
1-jet events	LO	LO
2-jet events	...	...

☞ NLOPS & MEPS equal for hard X+1 jet description

† For hard jets.

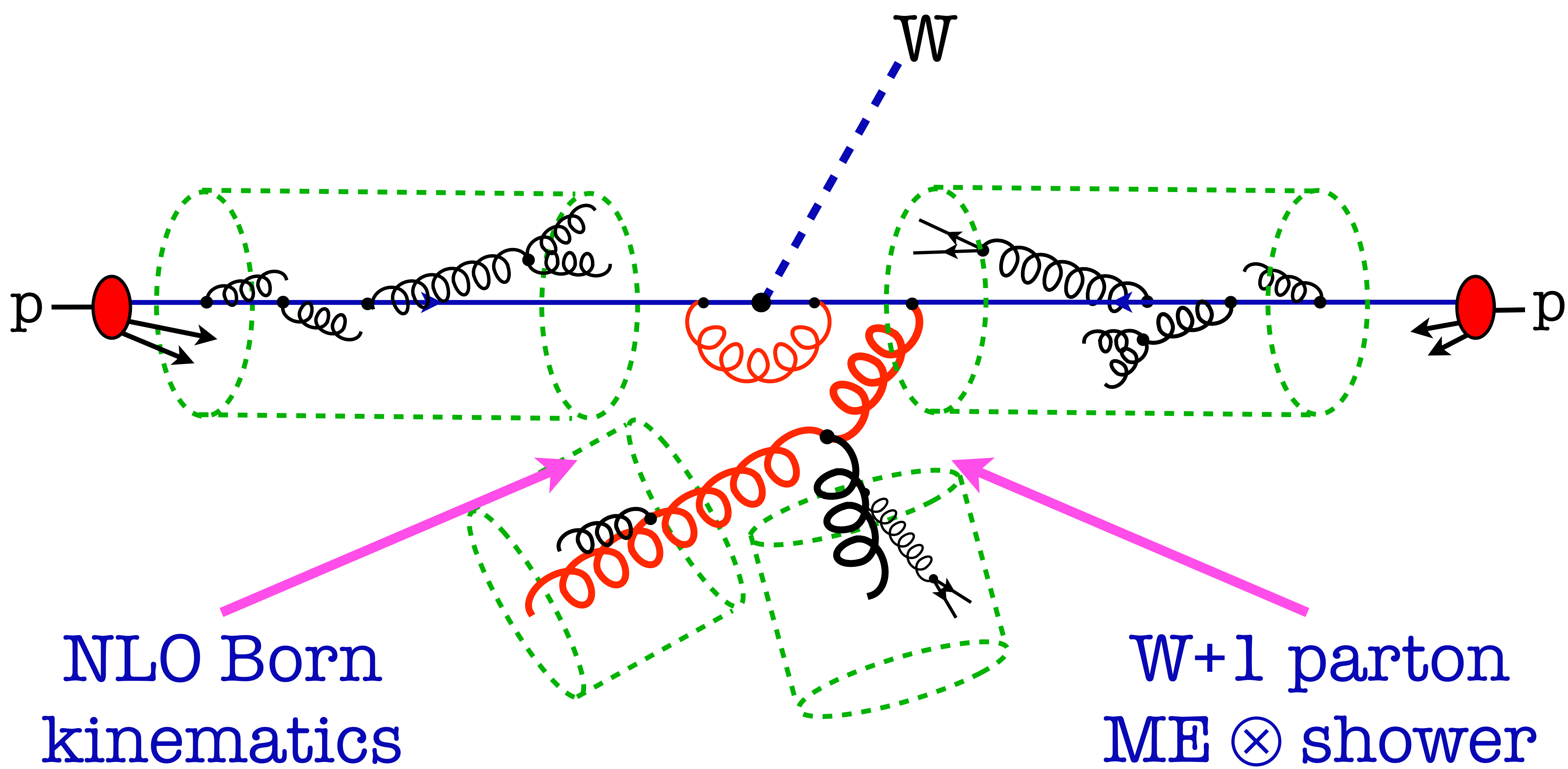
pp → W + 2 jets

MEPS



pp → W + 2 jets

NLOPS



NLOPS & MEPS features

Accuracy†	MEPS	NLOPS
0-jet events	LO	NLO
1-jet events	LO	LO
2-jet events	LO	LL

☞ MEPS best for hard X+≥2 jet description.

† For hard jets.

NLOPS & MEPS features

Accuracy†	MEPS	NLOPS
0-jet events	LO $\otimes$ LL	NLO $\otimes$ LL
1-jet events	LO $\otimes$ LL	NLO $\otimes$ LL
2-jet events	LO $\otimes$ LL	NLO $\otimes$ LL

Remember disclaimer: In this talk NLO means w.r.t. to X+0.

[soft emission in NLOPS shouldn't affect IR safe observables]

† For soft jets.

NLOPS & MEPS features

MEPS:

- Inclusive event sample ✔
- LO description of hardest emission: X+1 jet events ✔
- X+n jet [n ≥ 2] events LO ✔ ← - -
- LL resummation of multiple soft collinear emission ✔
- LO normalisation and shape - no virtuals ✘ ← - -
- LO sensitivity to μ_R and μ_F ✘ ← - -
- Lots of mature, trusted, highly automated codes ✔ ✔

NLOPS & MEPS features

NLOPS:

- Inclusive event sample ✔
- LO description of hardest emission: X+1 jet events ✔
- X+n jet [n ≥ 2] events shower approx ✘ ⇠
- LL resummation of multiple soft collinear emission ✔
- NLO normalisation and shape - virtuals ✔ ⇠
- NLO sensitivity to μ_R and μ_F ✔ ⇠
- Lots of well tested codes, automation in progress ✔ ✔

NLOPS & MEPS features

MENLOPS:

- Inclusive event sample ✔
- LO description of hardest emission: X+1 jet events ✔
- X+n jet [$n \geq 2$] events LO ✔ ⟵ - -
- LL resummation of multiple soft collinear emission ✔
- NLO normalisation and shape - virtuals ✔ ⟵ - -
- NLO sensitivity to μ_R and μ_F ✔ ⟵ - -

Outline:

- NLOPS & MEPS features.
- Theoretical considerations for MEPS → MENLOPS.
- How close can you get just combining today's tools?
- New SHERPA implementation.
  [S.Höche, F.Krauss, M.Schönherr, F.Siegert]

POWHEG oversimplified

POWHEG hardest emission x-sec:

$$d\sigma = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T) \underbrace{\frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)}} d\Phi_R \right]$$

Integrand in $\overline{\Delta}(p_T)$ is exactly

☞ $$\int d\Phi_R\, [\ \dots\ ] = \overline{\Delta}(p_{T,min}) + \int_{\overline{\Delta}(p_{T,min})}^{1} d\overline{\Delta}(p_T) = 1$$

MEPS in the POWHEG language

From general arguments the MEPS x-sec is:

[For Sudakovs red hats → blue hats]

Born x-sec [LO]

$$d\sigma = B(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_{T,min}) + \bar{\Delta}(p_T) \frac{\bar{R}(\Phi_B, \Phi_R)}{B(\Phi_B)} d\Phi_R \right]$$

Effective Sudakov form factor; same LL accuracy as PS

Real emission x-sec ÷ Born x-sec

N.B. Integrand in $\bar{\Delta}(p_T)$ is not $\bar{R}(\Phi_B,\Phi_R)/B(\Phi_B)$!

KH, P.Nason 04/2010

MEPS in the POWHEG language

From general arguments the MEPS x-sec is:

[For Sudakovs red hats → blue hats]

Born x-sec [LO]

$$d\sigma = B(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_{T,min}) + \bar{\Delta}(p_T) \frac{\bar{R}(\Phi_B, \Phi_R)}{B(\Phi_B)} d\Phi_R \right]$$

Effective Sudakov form factor; same LL accuracy as PS

Real emission x-sec ÷ Born x-sec

☞ $$\int d\Phi_R [\ \dots\ ] \equiv N(\Phi_B) \neq 1$$

MEPS in the POWHEG language

Unitarity breaking manifest as $\overline{B}_{ME}(\Phi_B)$ fn in MEPS:

$$d\sigma = \overline{B}_{ME}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T)\, \frac{\overline{R}(\Phi_B, \Phi_R)}{B(\Phi_B)}\, d\Phi_R}{N(\Phi_B)} \right]$$

Integrates to 1

$$\overline{B}_{ME}(\Phi_B) \equiv B(\Phi_B) \times N(\Phi_B)$$
$$= B(\Phi_B) \times [1 + O(\alpha_s)]$$

Turning MEPS into MENLOPS

Promoting MEPS → MENLOPS:

$$d\sigma = \overline{B}_{ME}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T) \dfrac{\overline{R}(\Phi_B, \Phi_R)}{B(\Phi_B)} d\Phi_R}{N(\Phi_B)} \right]$$

Integrates to 1

calculate $\overline{B}_{ME}(\Phi_B)$ and reweight MEPS by: $\dfrac{\overline{B}(\Phi_B)}{\overline{B}_{ME}(\Phi_B)}$

KH, P.Nason 04/2010

Turning MEPS into MENLOPS

Promoting MEPS → MENLOPS:

$$d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \left[\frac{\bar{\Delta}(p_{T,min}) + \bar{\Delta}(p_T) \frac{\bar{R}(\Phi_B, \Phi_R)}{B(\Phi_B)} d\Phi_R}{N(\Phi_B)} \right]$$

Integrates to 1

calculate $\bar{B}_{ME}(\Phi_B)$ and reweight MEPS by: $\dfrac{\bar{B}(\Phi_B)}{\bar{B}_{ME}(\Phi_B)}$

KH, P.Nason 04/2010

Turning MEPS into MENLOPS

Promoting MEPS → MENLOPS:

$$d\sigma = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T)\, \frac{\overline{R}(\Phi_B, \Phi_R)}{B(\Phi_B)}\, d\Phi_R}{N(\Phi_B)} \right]$$

Integrates to 1

N.B. We do not claim this is a general solution to the problem of NLOPS-MEPS merging; only for simple processes.

Outline:

- NLOPS & MEPS features.
- Theoretical considerations for MEPS → MENLOPS.
- How close can you get just combining today's tools?
- New SHERPA implementation.
  [S.Höche, F.Krauss, M.Schönherr, F.Siegert]

How close can you get just combining today's tools?

Basic idea:

- Choose 'MENLOPS jet merging scale' such that for X+≥2 jets MEPS is always at least as good as NLOPS.

- I.E. MEPS is not allowed to generate events in which two or more jets can be considered soft.

- For X+0 jets take events from an NLOPS
- For X+1 jets take events from an NLOPS
- For X+≥2 jets take events from an MEPS

Surely this destroys NLO accuracy?

- You get a sample of NLOPS events and replace the 2-jet events with ones from your MEPS.
- Sounds pretty crude ...
- But think about the 2-jet events come from the point of view of a perturbative expansion of the x-section ...

From earlier:

MENLOPS:

$$d\sigma = \overline{B}(\Phi_B)\, d\Phi_B \left[\underbrace{\frac{\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T)\, \dfrac{\overline{R}(\Phi_B, \Phi_R)}{B(\Phi_B)}\, d\Phi_R}{N(\Phi_B)}}_{\text{Integrates to 1}} \right]$$

How close can you get just combining today's tools?

MENLOPS:

$$d\sigma^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q<q^*)\, d\Phi_R}{N(\Phi_B)} \right]$$

$$d\sigma^{[X+1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] \Delta_{ME}(q^*)$$

$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

Approximating MENLOPS:

$$d\sigma^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T)\frac{\overline{R}}{B}\Theta(q<q^*)\, d\Phi_R}{N(\Phi_B)} \right]$$

$$d\sigma^{[X+1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T)\frac{\overline{R}}{B}\Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] \Delta_{ME}(q^*)$$

$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T)\frac{\overline{R}}{B}\Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

Approximating MENLOPS:

[X+0 formally equivalent to exact method - by definition]

$$d\sigma_{PW}^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q<q^*)\, d\Phi_R \right]$$

$$d\sigma^{[X+1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] \Delta_{ME}(q^*)$$

$$d\sigma^{[X+\gtrsim 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

Approximating MENLOPS:

[X+0 formally equivalent to exact method - by definition]

$$d\sigma_{PW}^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q<q^*)\, d\Phi_R \right]$$

[X+1 formally equivalent to exact method - by definition]

$$d\sigma_{PW}^{[X+1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*)\, d\Phi_R \right] \Delta_{MC}(q^*)$$

$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

Approximating MENLOPS:

[X+0 formally equivalent to exact method - by definition]

$$d\sigma^{[X+0]}_{PW} = \bar{B}(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_{T,min}) + \bar{\Delta}(p_T)\, \frac{\bar{R}}{B}\, \Theta(q<q^*)\, d\Phi_R \right]$$

[X+1 formally equivalent to exact method - by definition]

$$d\sigma^{[X+1]}_{PW} = \bar{B}(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_T)\, \frac{\bar{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right] \Delta_{MC}(q^*)$$

[Equivalent to exact method neglecting irrelevant $O(\alpha_s^2)$]

$$d\sigma^{[X+\geq 2]}_{ME} = K\, B(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_T)\, \frac{\bar{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

Approximating MENLOPS:

[X+0 formally equivalent to exact method - by definition]

$$d\sigma_{PW}^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q<q^*)\, d\Phi_R \right]$$

Not so fast !
What about unitarity and inclusive quantities ?!

[X+1 forma ... definition]

$$d\sigma_{PW}^{[X+1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right] \Delta_{MC}(q^*)$$

[Equivalent to exact method neglecting irrelevant $O(\alpha_s^2)$]

$$d\sigma_{ME}^{[X+\geq 2]} = K\, B(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \overline{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\overline{B}(\Phi_B)} \left[1 - \frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}} \right] \right]$$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma^{[X+\geq 2]}_{MEPS} - d\sigma^{[X+\geq 2]}_{PW}$$

Unitarity breaking

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma^{[X+\geq 2]}_{MEPS}}{\bar{B}(\Phi_B)} \left[1 - \frac{\int_{\Phi_R} d\sigma^{[X+\geq 2]}_{PW}}{K \int_{\Phi_R} d\sigma^{[X+\geq 2]}_{MEPS}} \right] \right]$$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)} \left[1 - \frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{\underbrace{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}} \right] \right]$$

At LL $d\sigma_{MEPS}^{[X+\geq 2]} = d\sigma_{PW}^{[X+\geq 2]}$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)} \left[1 - \underbrace{\frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}}_{1 + O(\alpha_S)} \right] \right]$$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \underbrace{\frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)}}_{} \left[1 - \underbrace{\frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}}_{1 + O(\alpha_S)} \right] \right]$$

Insist this be $\leq \alpha_S$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \underbrace{\frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)}}_{O(\alpha_S)} \left[1 - \frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{\underbrace{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}_{1+O(\alpha_S)}} \right] \right]$$

How close can you get just combining today's tools?

Integrate approximate x-sec over Φ_R :

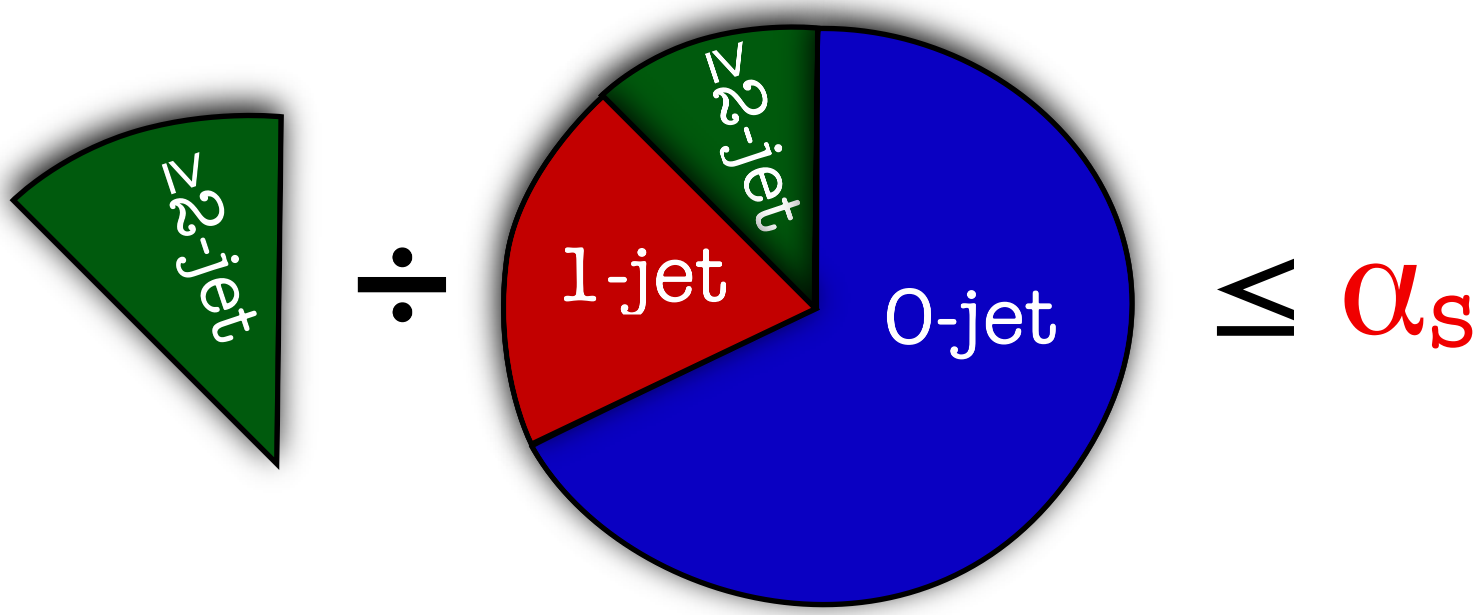
$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \underbrace{\frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)}}_{O(\alpha_S)} \left[1 - \underbrace{\frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}}_{1+O(\alpha_S)} \right] \right]$$

$$= \bar{B}(\Phi_B)\, d\Phi_B\, [1 + O(\alpha_S{}^2)]$$

How close can you get just combining today's tools?

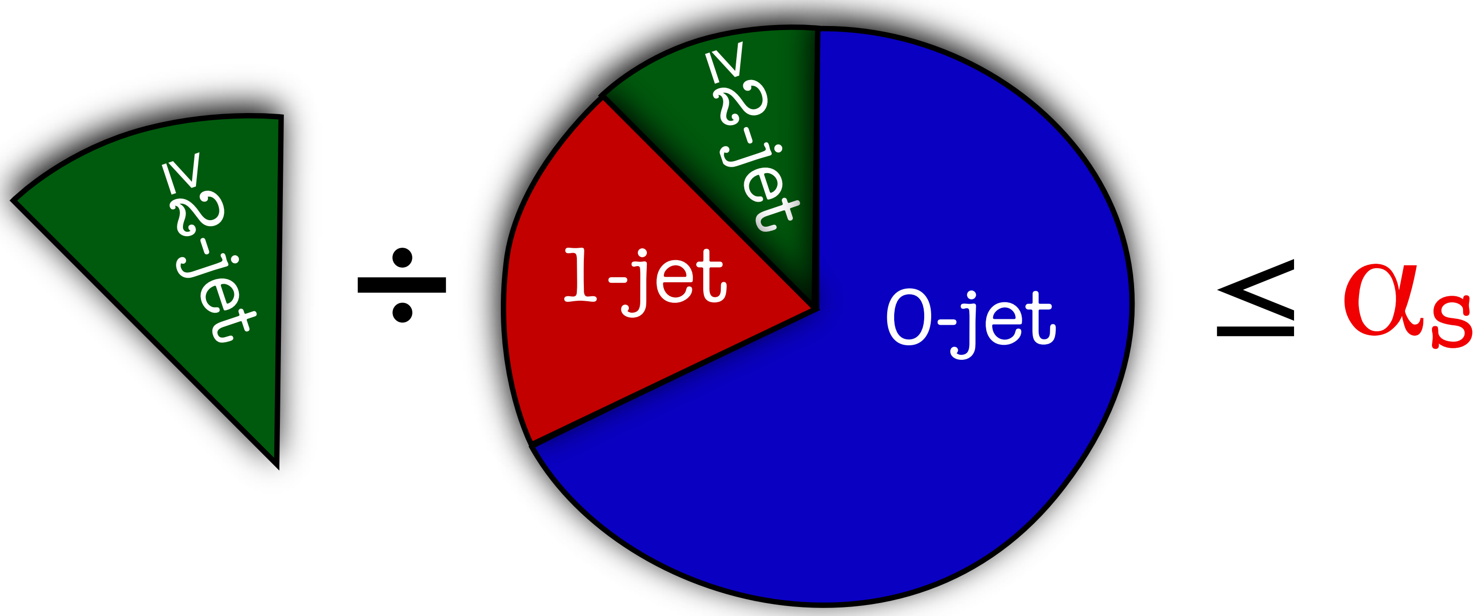
NLO accuracy will be safe if the fraction of X+≥2 jet events in the MENLOPS sample is less than α_s :



Seen differently this is equivalent to confining the 2-jet phase space to the region where MEPS is always at least as good as NLOPS: it avoids the 'double-soft' region which would result in the 2-jet x-sec becoming O(1)!

Exact MENLOPS vs approximate MENLOPS

- Requiring,

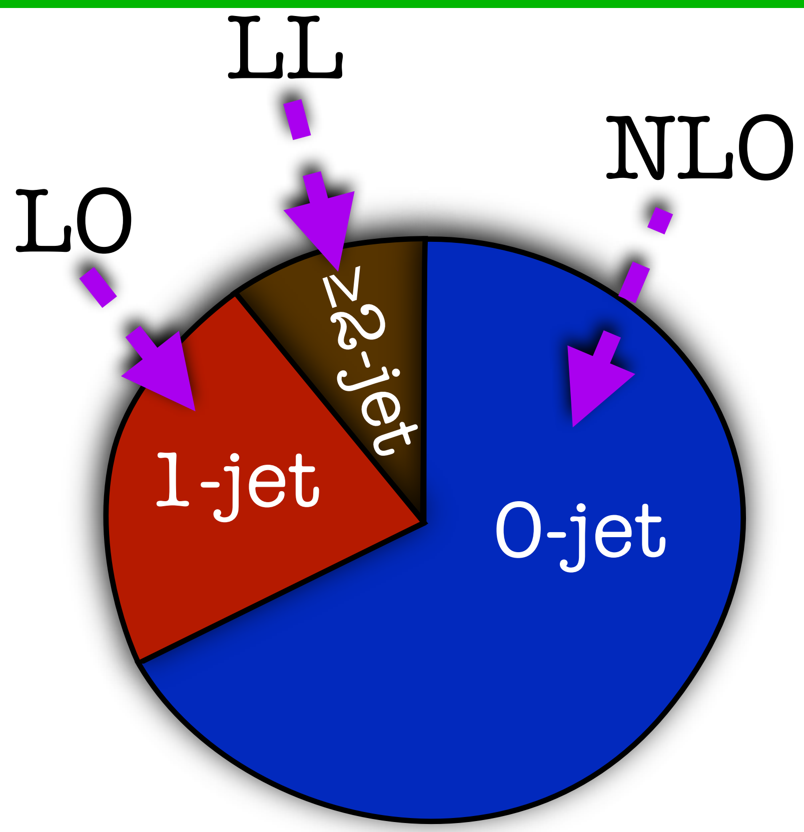


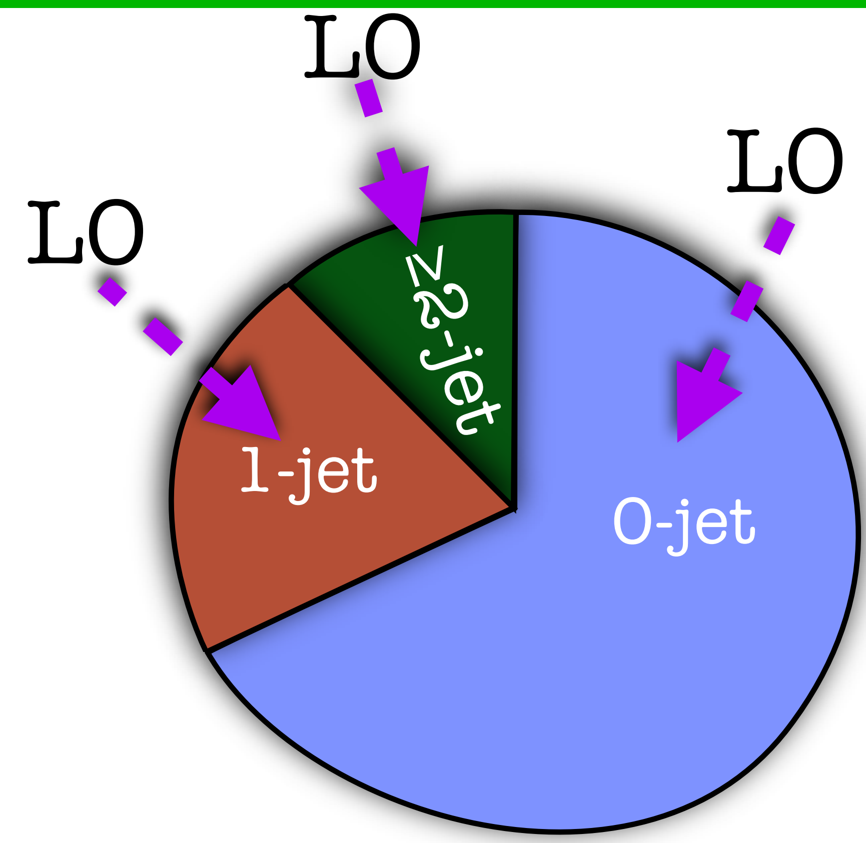
means that you can't merge MEPS & NLOPS at whatever MENLOPS scale you want ← limitation of the approximation!

- The MENLOPS merging scale q^* is bounded from below: if the scale gets too small P(≥2-jets) gets bigger than O(α_S) spoiling NLO accuracy.

- In the exact method there is no MENLOPS scale dependence [there is no such thing - just the MEPS scale].

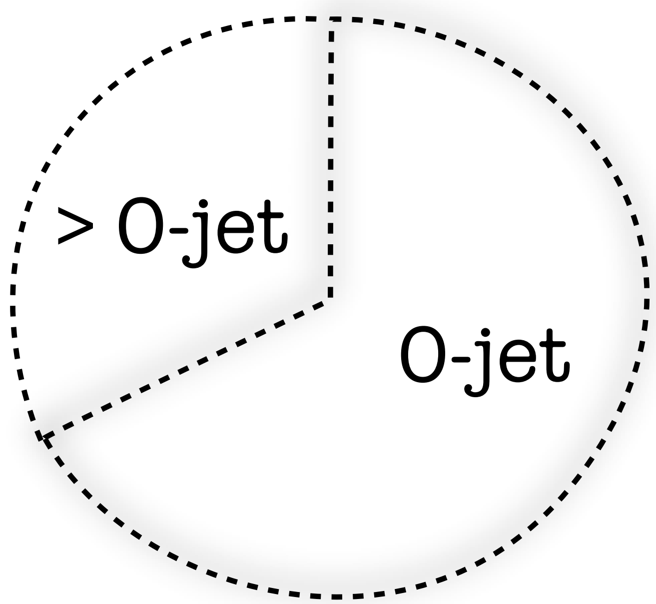
How close can you get just combining today's tools?

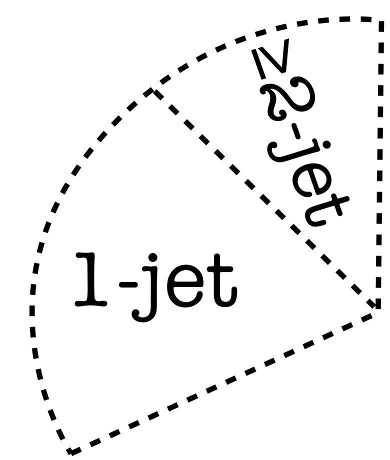




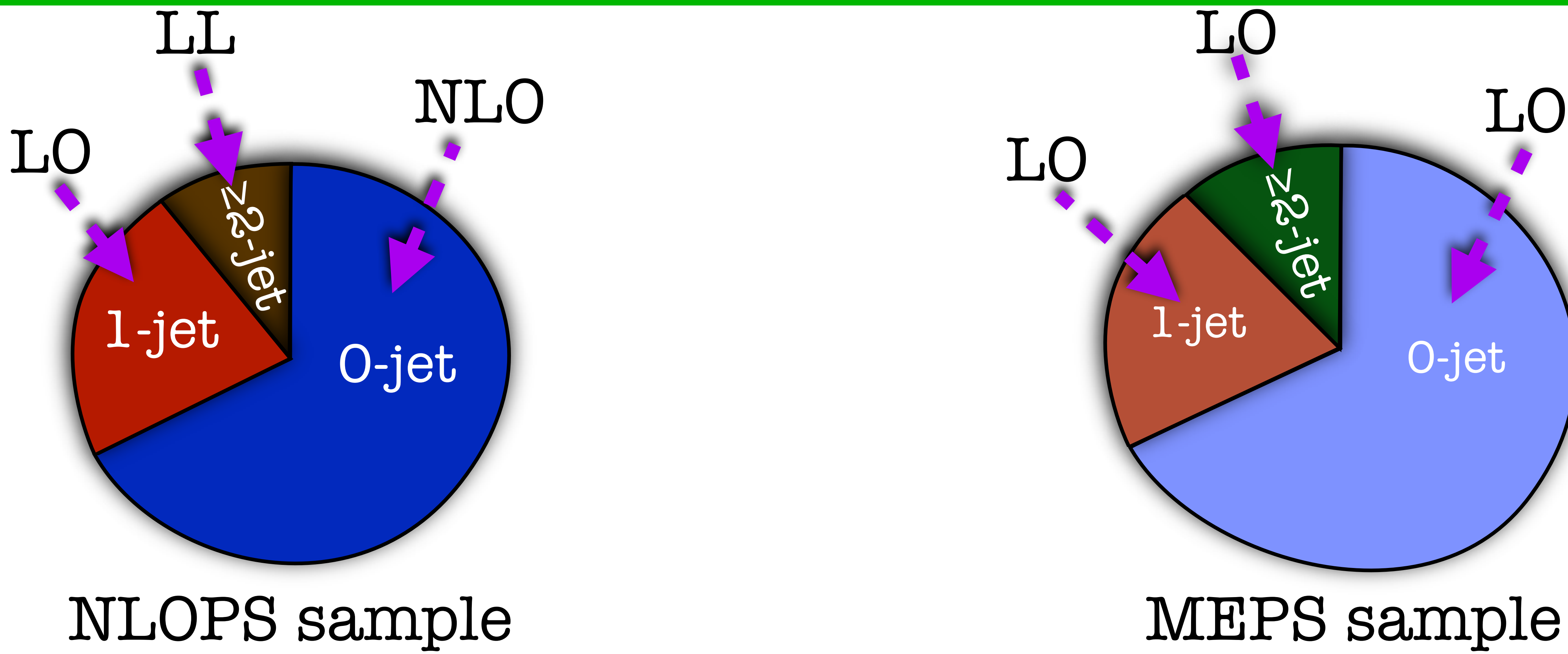
1. compute P[0-jets] from NLOPS [NLO]

2. compute P[1-jet|≥1-jet] from MEPS [LO]





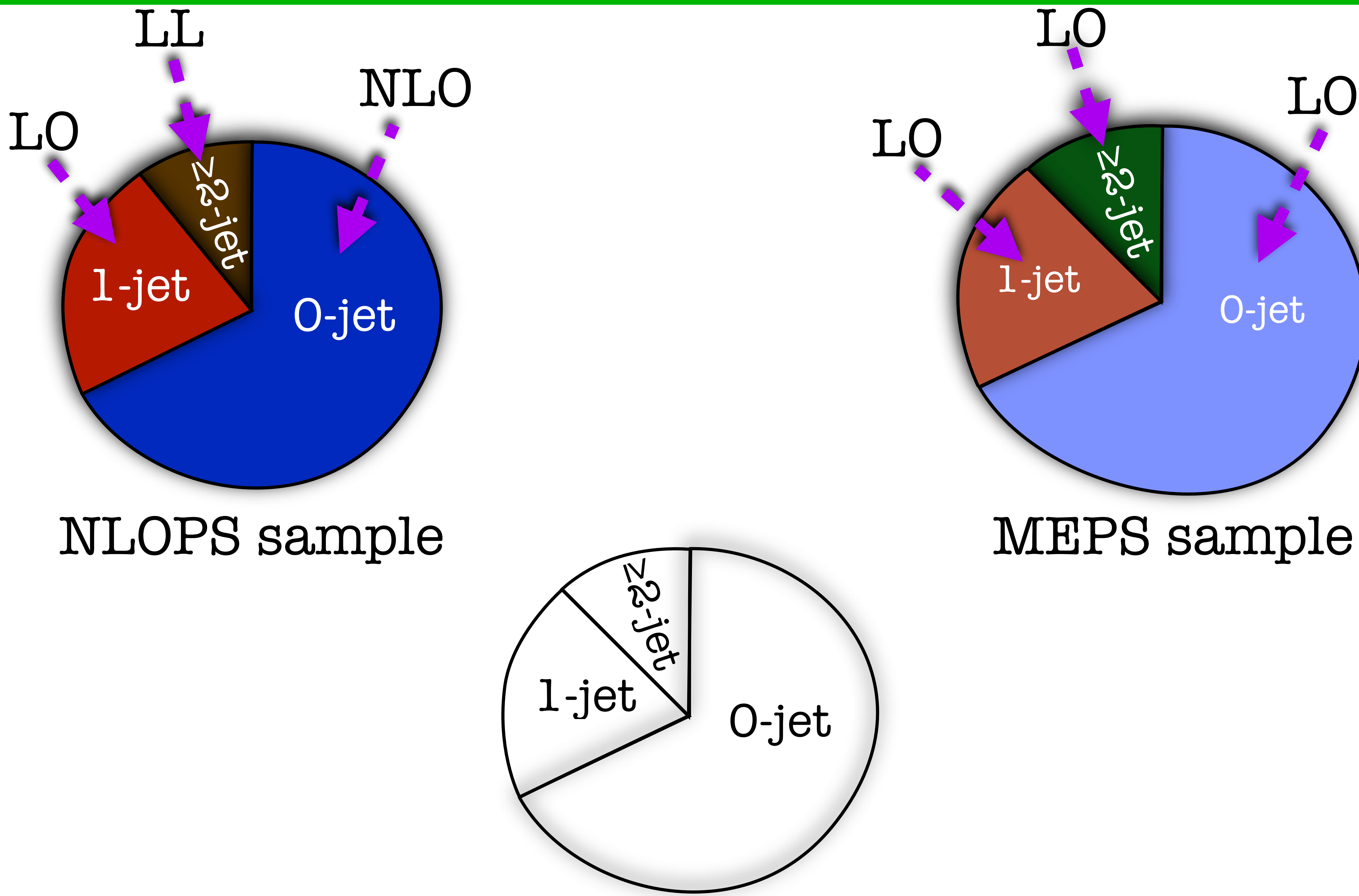
How close can you get just combining today's tools?



3. From 1. & 2. compute:

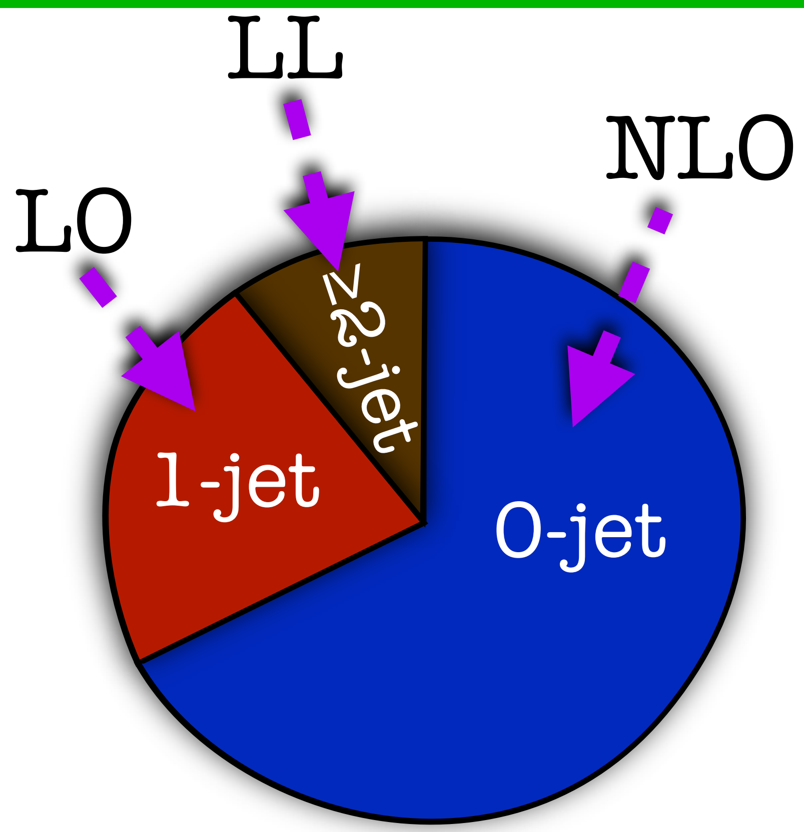
P[0-jet] ← - - NLO
P[1-jet] ← - - LO
P[≥2-jet] ← - - LO

How close can you get just combining today's tools?

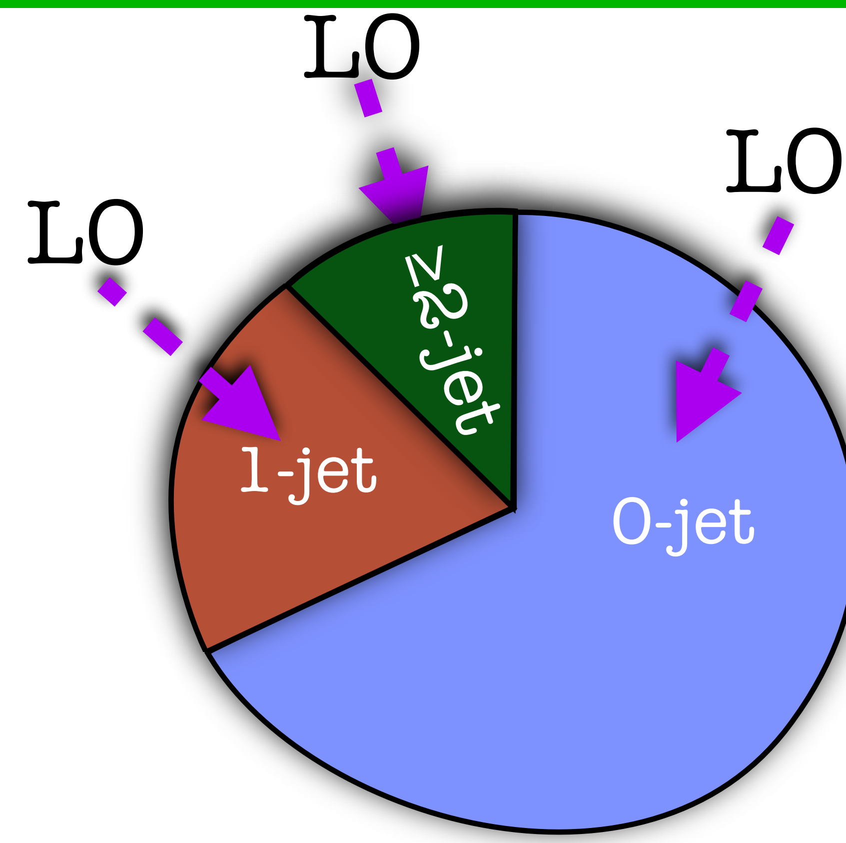


☞ Defines proportions for MENLOPS sample

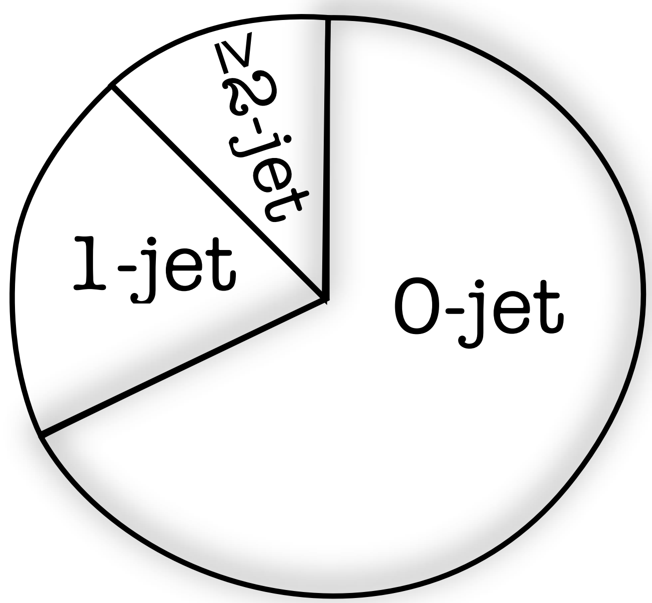
How close can you get just combining today's tools?



NLOPS sample

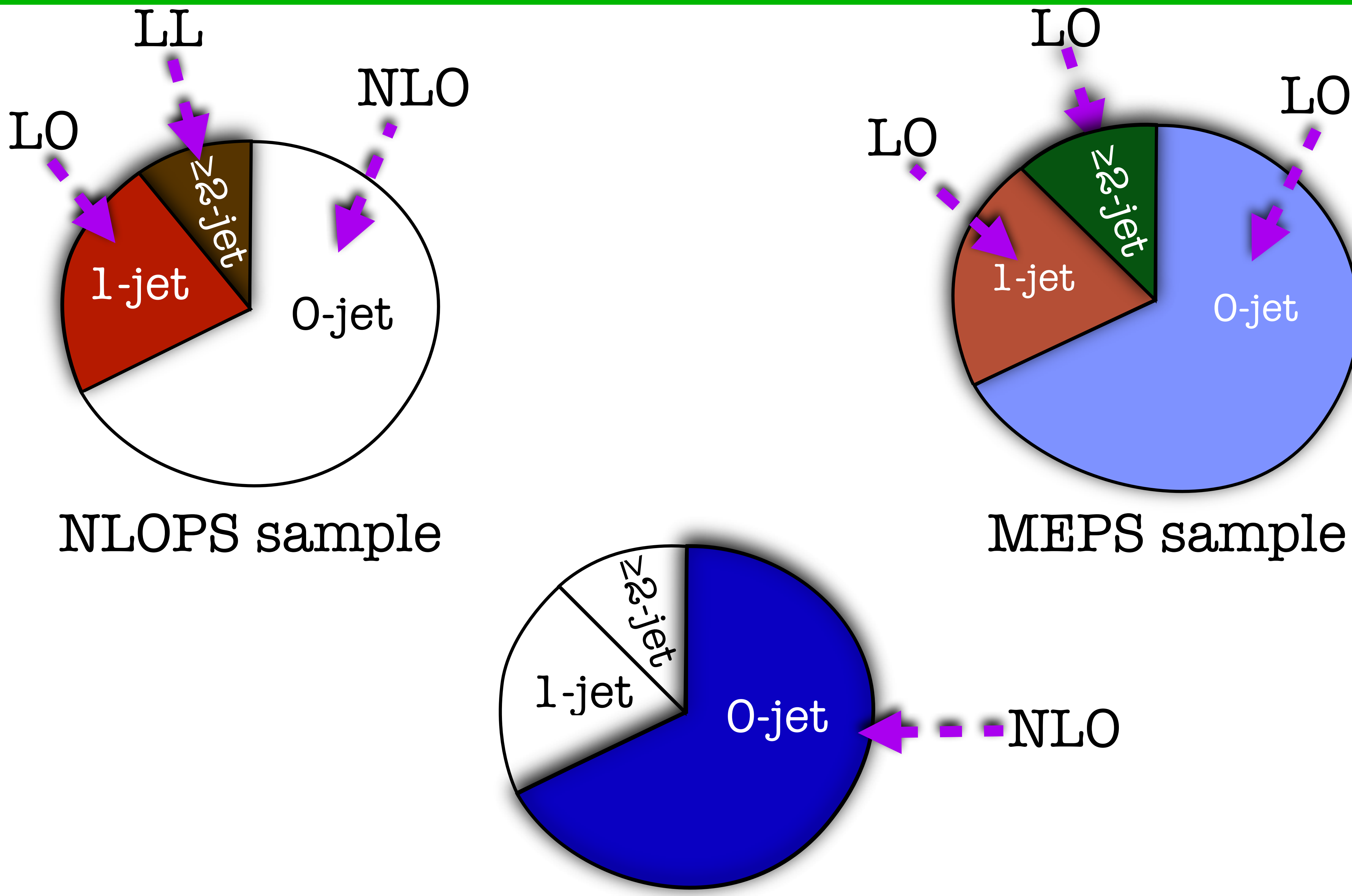


MEPS sample



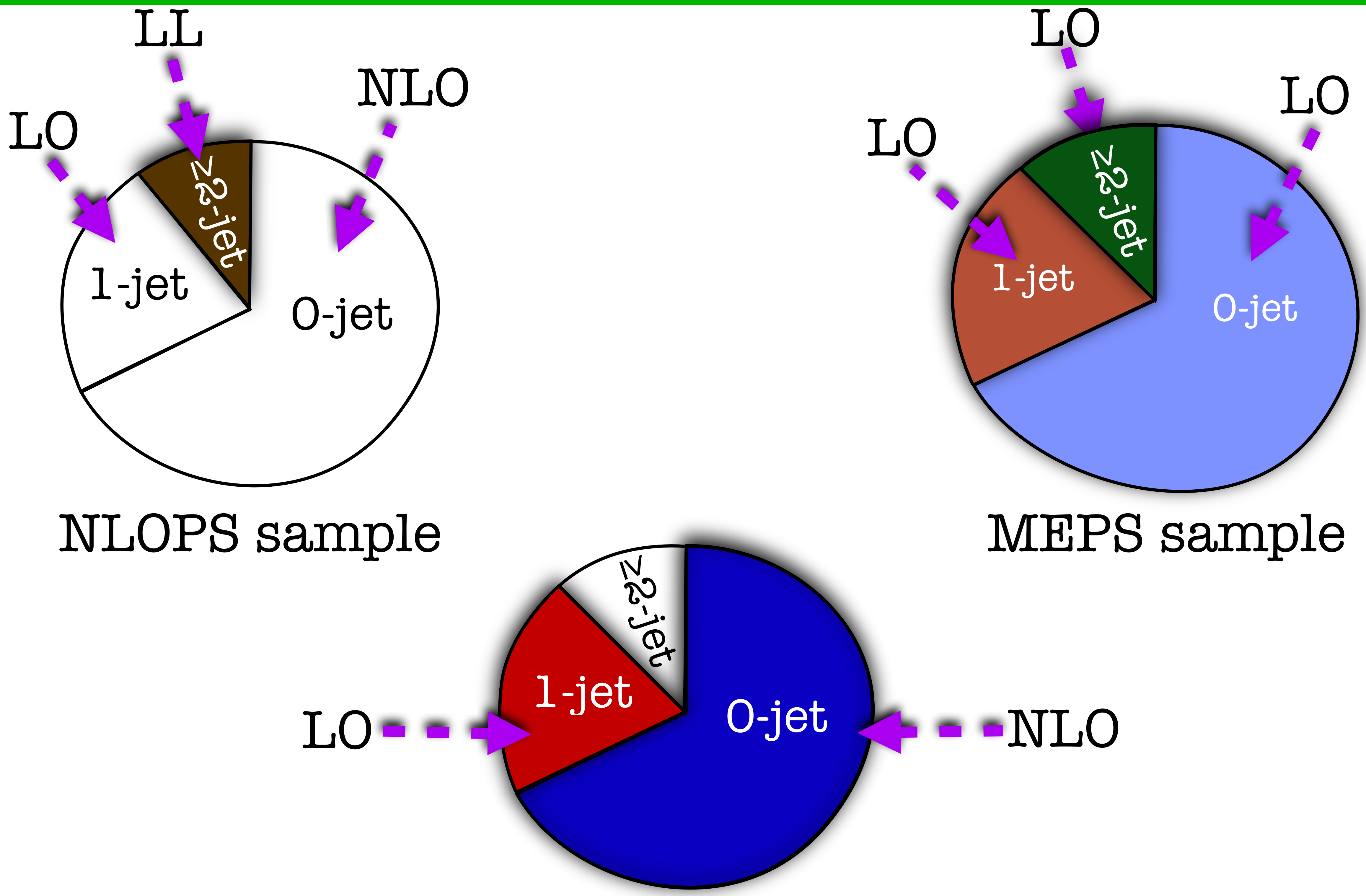
☞ Take 0-jet events from NLOPS [NLO]

How close can you get just combining today's tools?



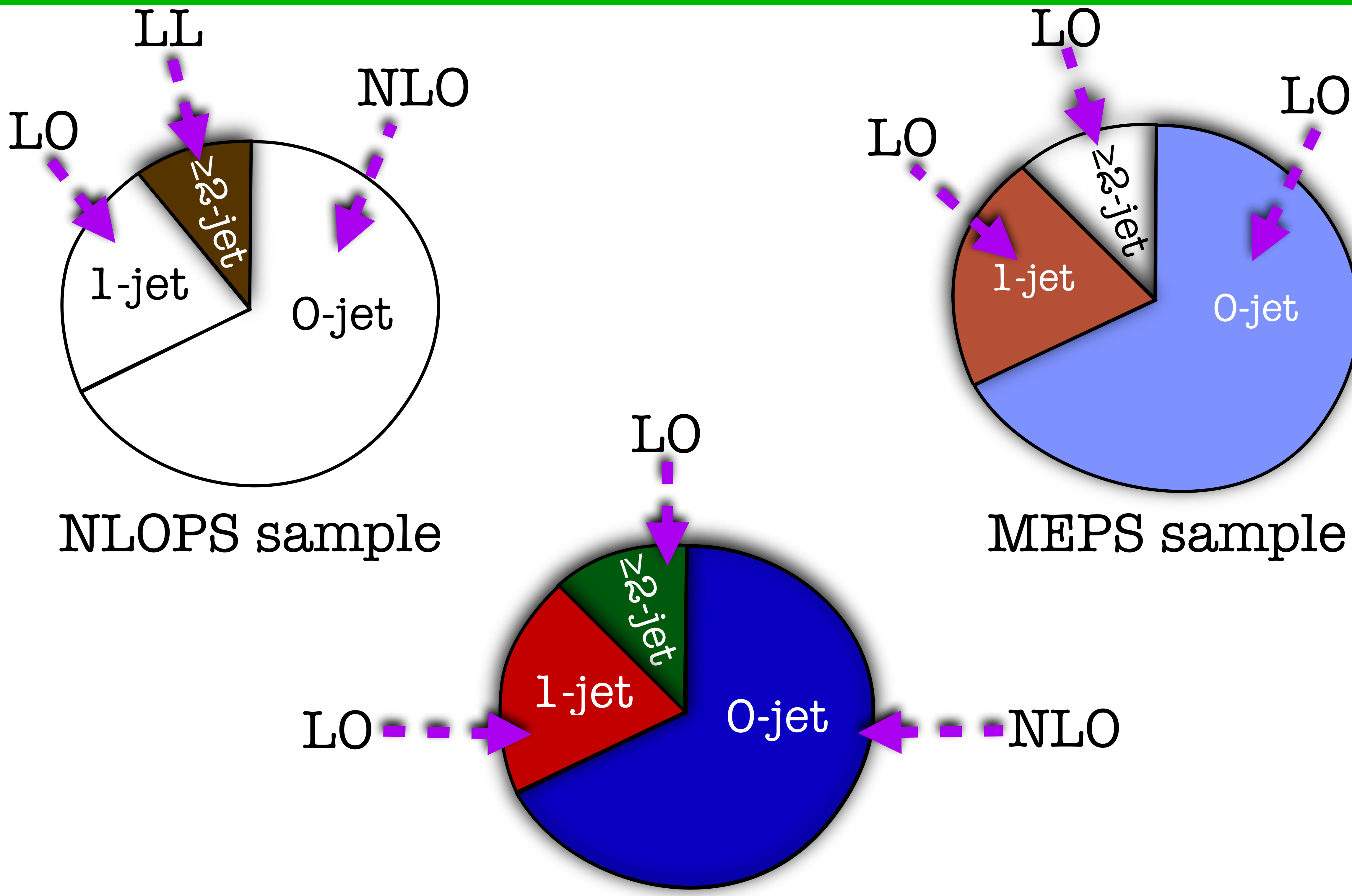
☞ Take 0-jet events from NLOPS [NLO]

How close can you get just combining today's tools?



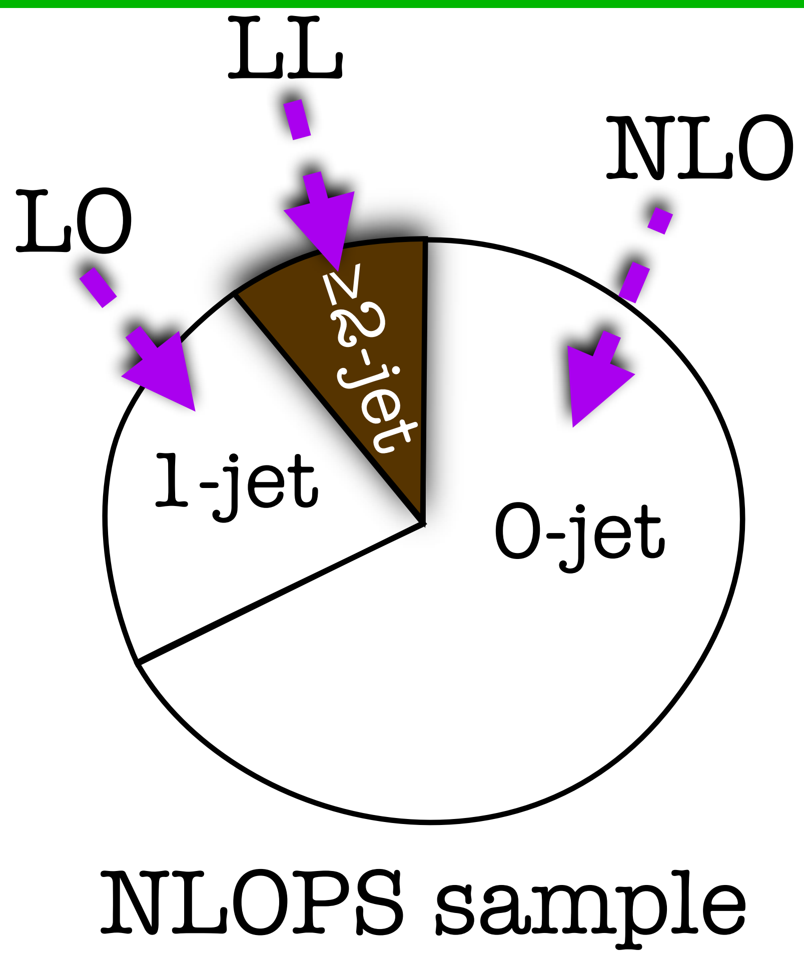
☞ Take 1-jet events from NLOPS [~LO]

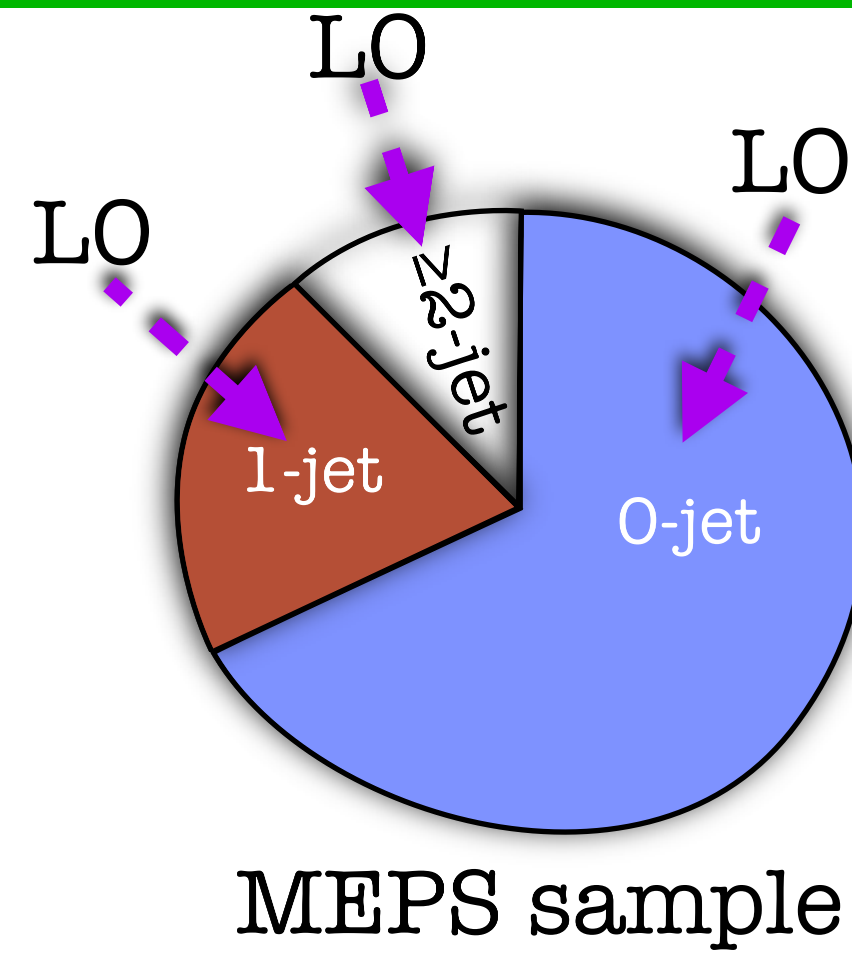
How close can you get just combining today's tools?

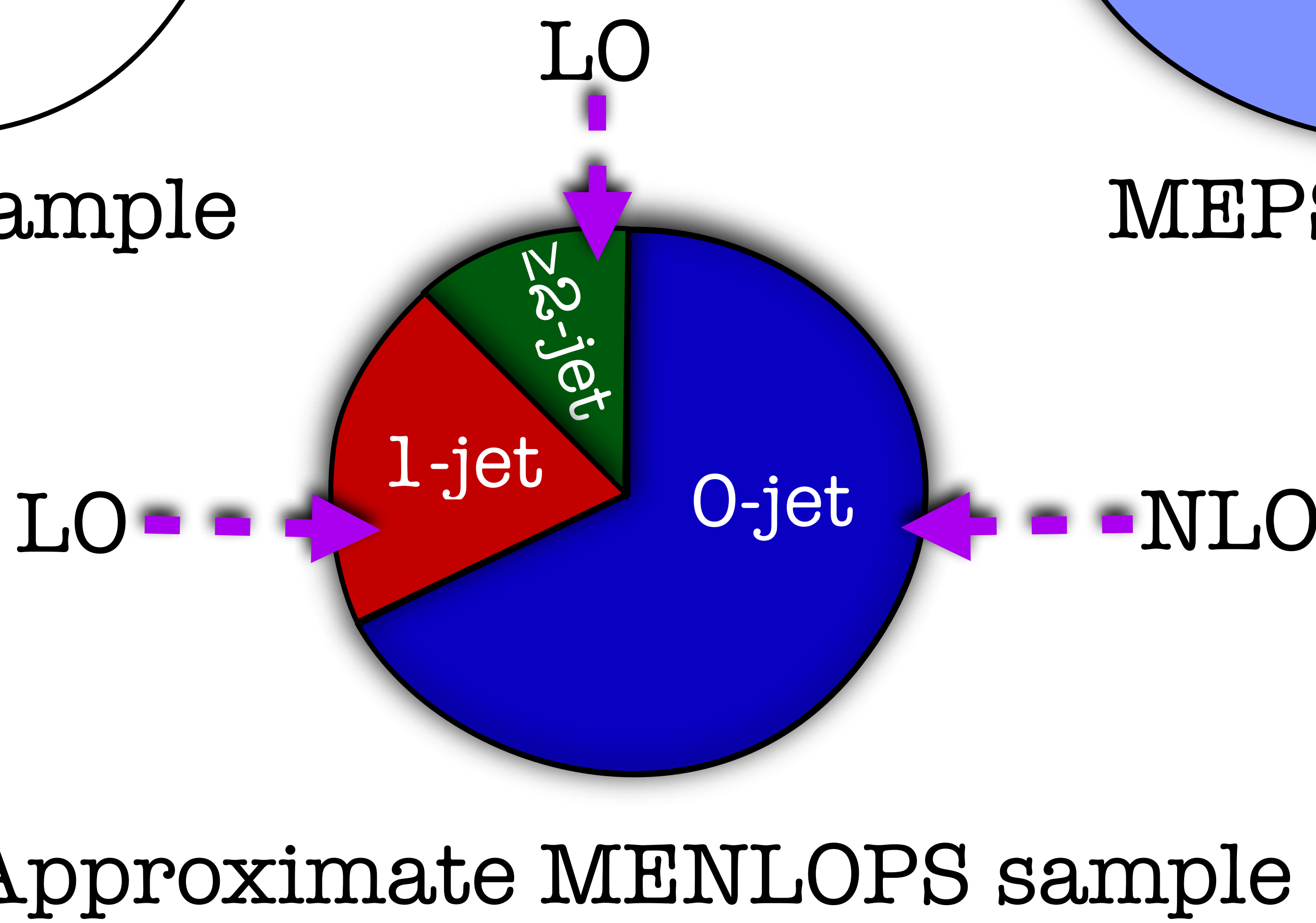


☞ Take ≥2-jet events from MEPS [LO]

How close can you get just combining today's tools?







Case studies: $t\bar{t}$ and W production

- MEPS: MadGraph with 'MLM-k_T' scheme
- NLOPS: POWHEG-hvq [$t\bar{t}$, tops set stable]
- NLOPS: POWHEG-w [$W^- \rightarrow e^- \bar{\nu}_e$]
- PYTHIA: Q^2 ordered shower in MEPS
- PYTHIA: p_T ordered shower for NLOPS
- PDF: MRST 2002 NLO used everywhere
- LHC nominal C.O.M. energy $\sqrt{S}$ = 14 TeV

Case studies: $t\bar{t}$ and W production

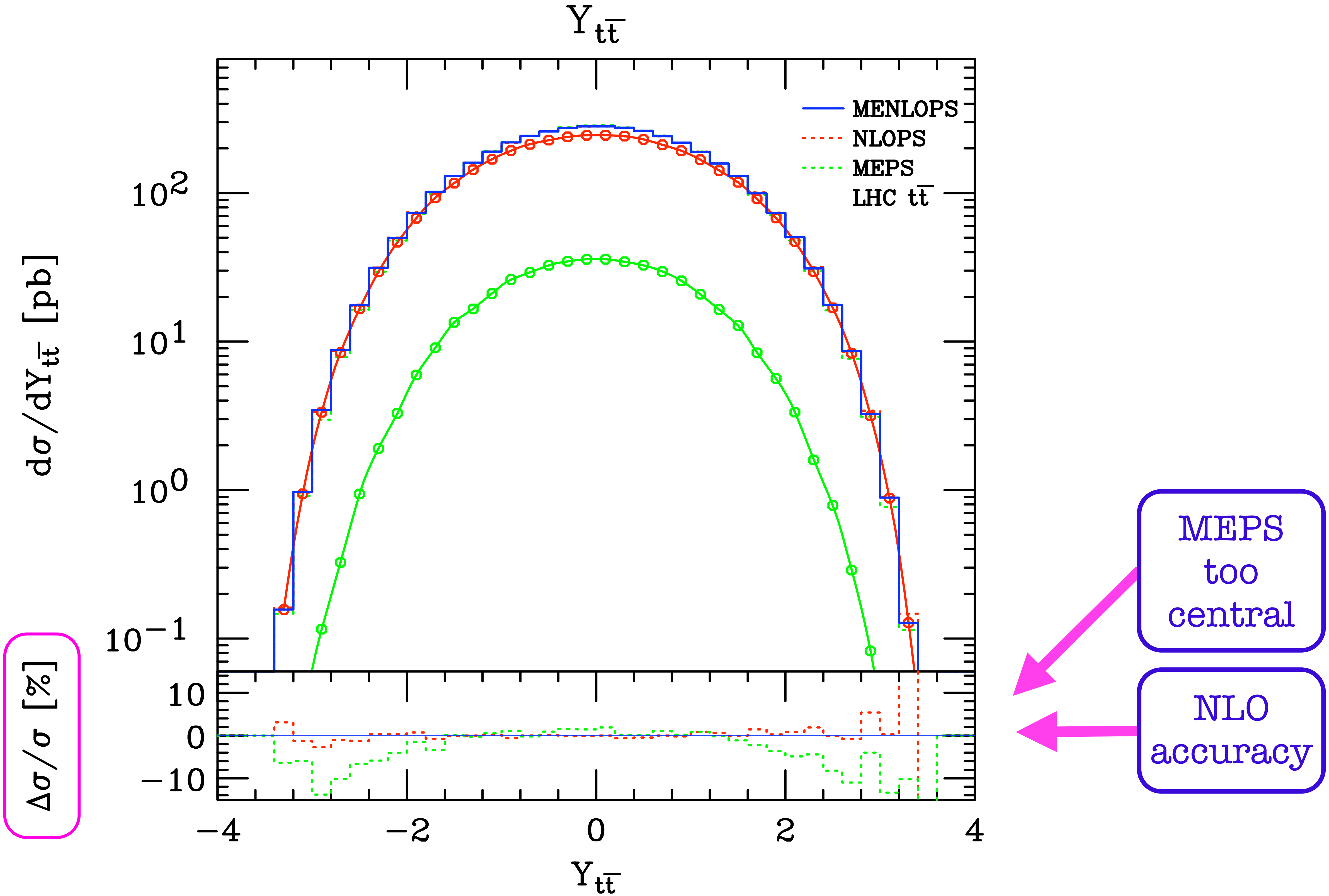
$t\bar{t}$ production:

- MEPS merging scale: 30 GeV
- MENLOPS clustering scale: 60 GeV
- MENLOPS MEPS content: 12.5 %

W^- production:

- MEPS merging scale: 20 GeV
- MENLOPS merging scale: 25 GeV
- MENLOPS MEPS content: 5 %

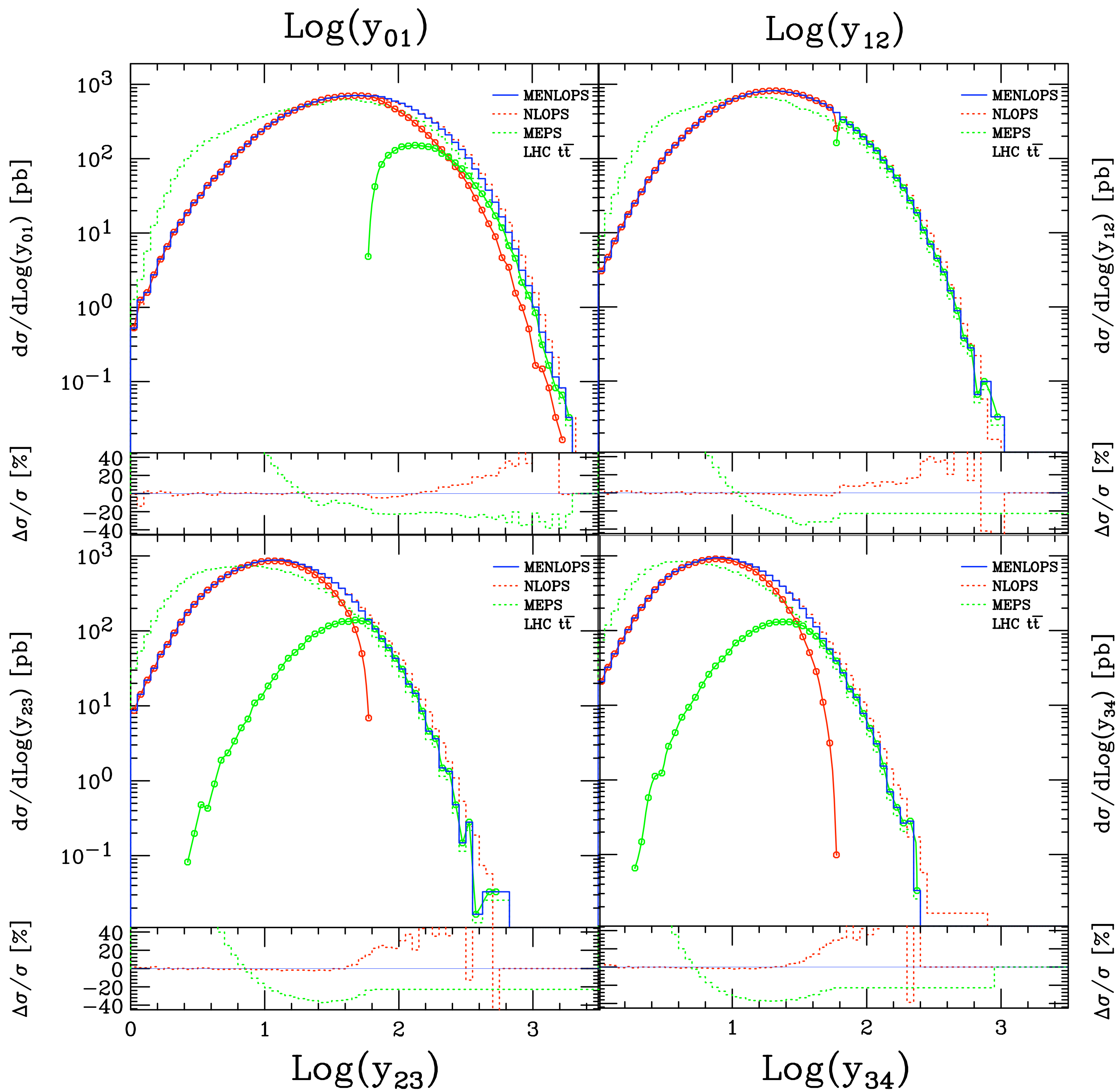
Inclusive quantities: $t\bar{t}$ rapidity



MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default MEPS default × K

Log[y_{nm}] differential jet rates in $t\bar{t}$ events

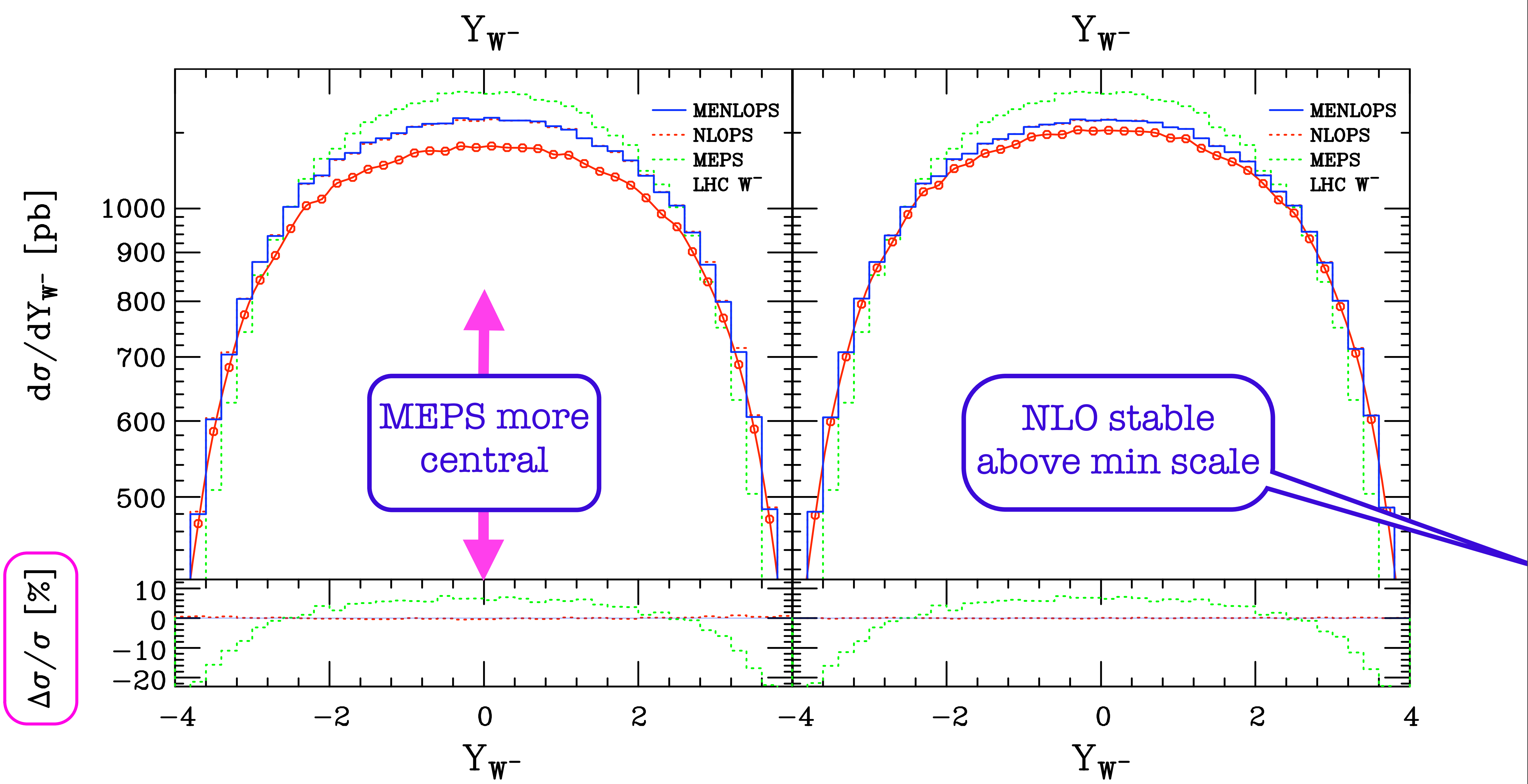


No kinks

MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default   MEPS default × K

Inclusive quantities: W⁻ rapidity



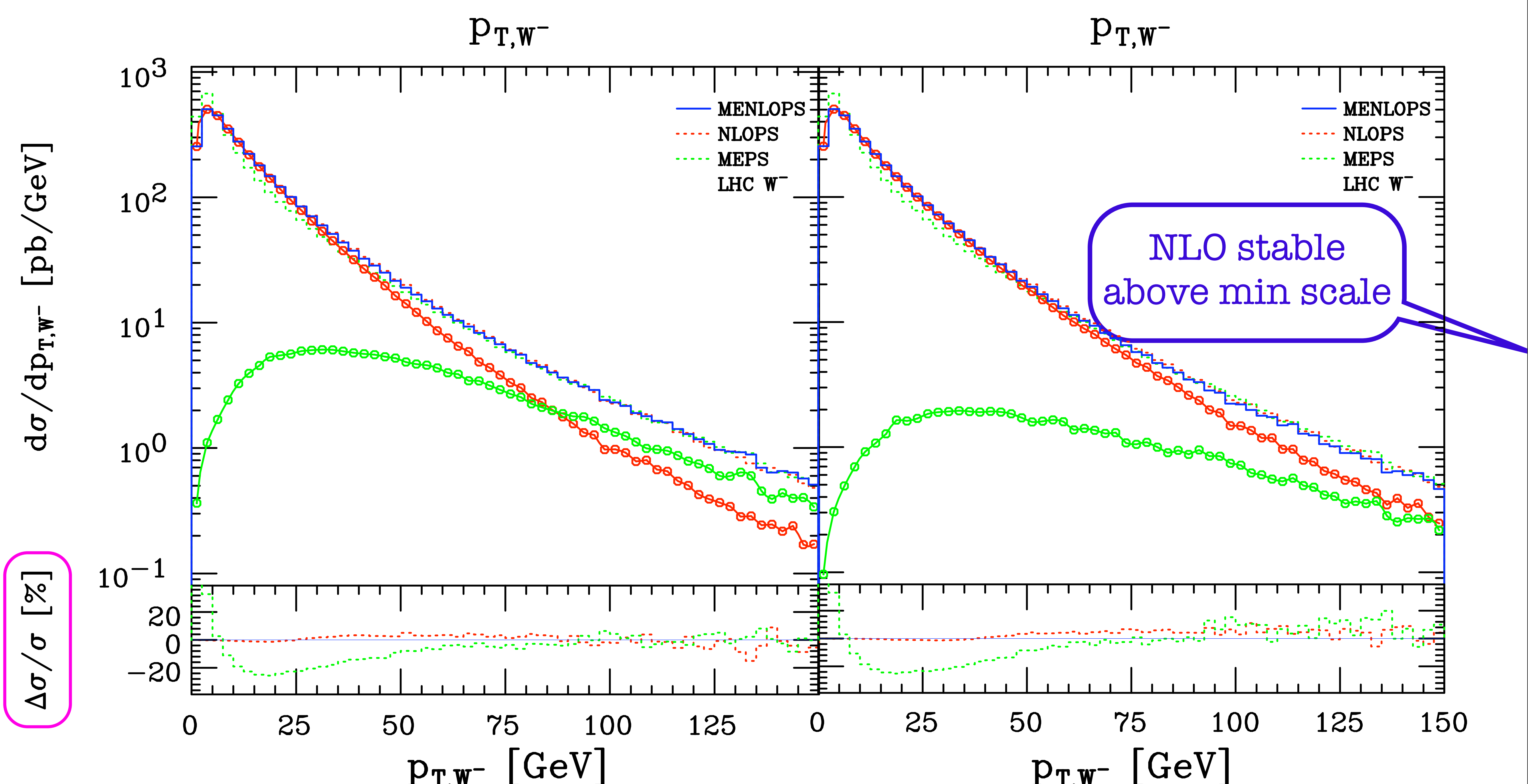
25 GeV MENLOPS scale

40 GeV MENLOPS scale

MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default MEPS default × K

Inclusive quantities: W^- p_T



25 GeV MENLOPS scale

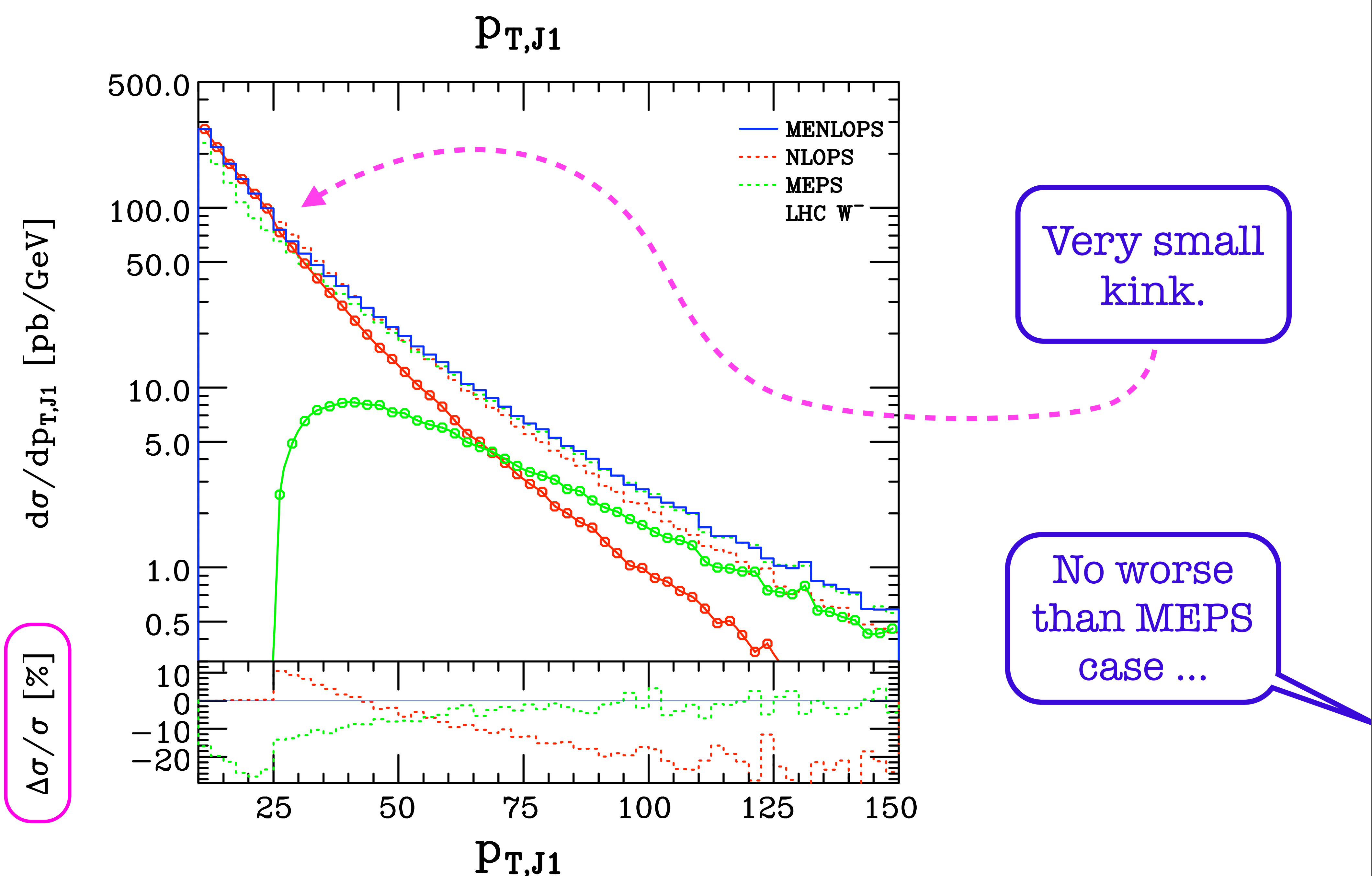
40 GeV MENLOPS scale

MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default

MEPS default × K

p_T of hardest Jet in W^- production

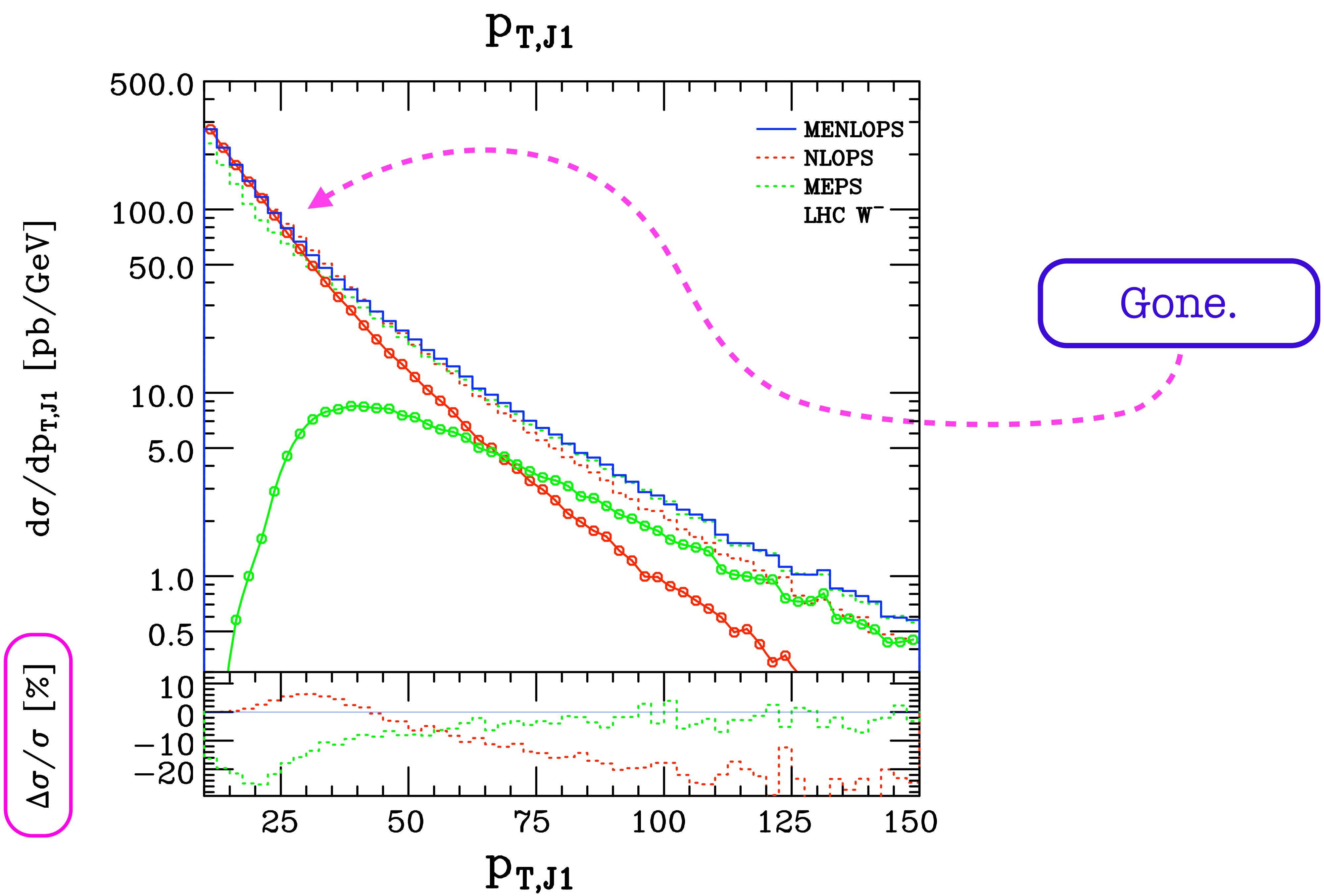


MENLOPS merge scale 25 GeV, jets resolved at 10 GeV.

MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default MEPS default × K

p_T of hardest Jet in W^- production



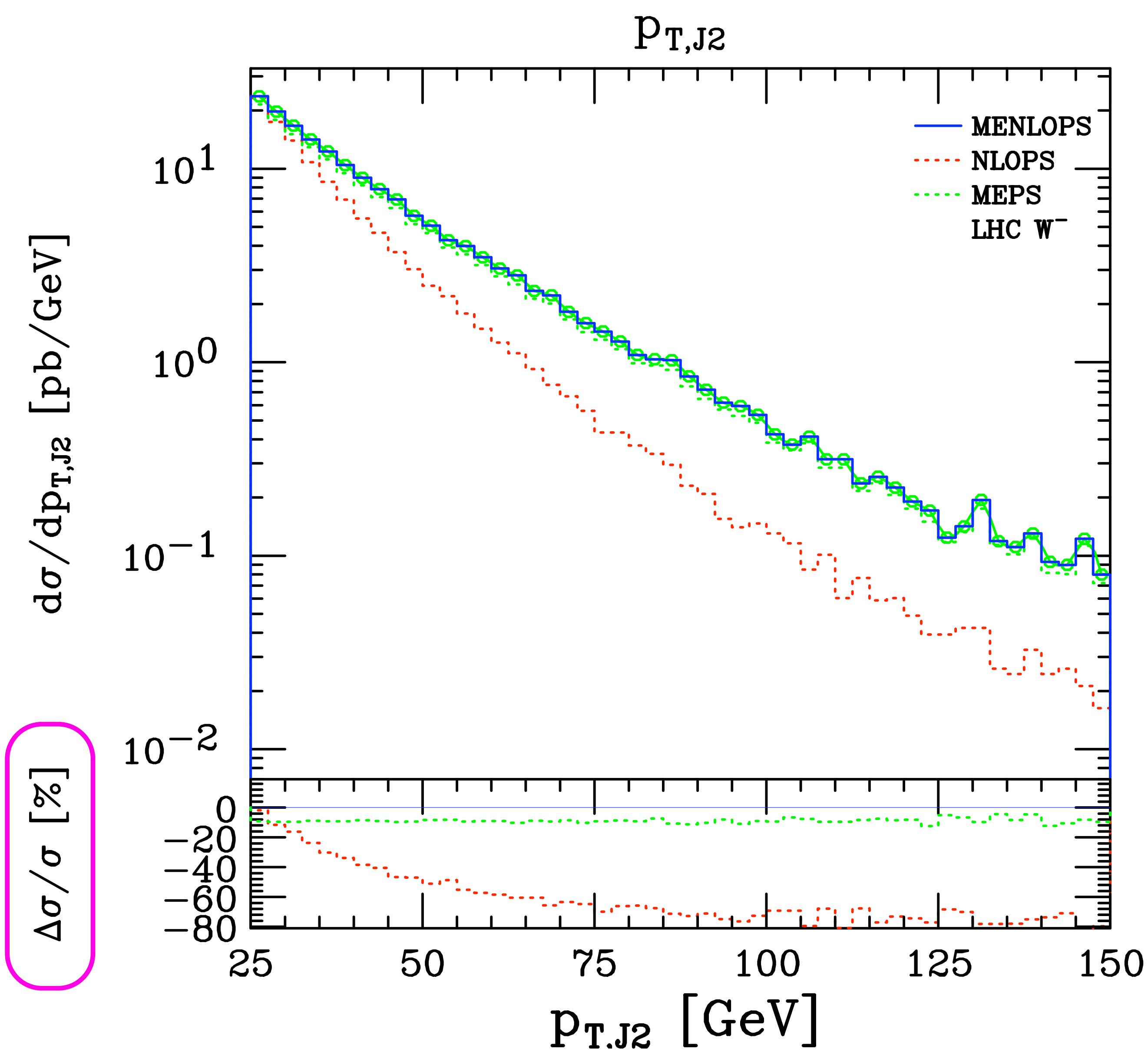
Same again but MENLOPS scale floating: N[25 GeV,5^2 GeV^2]

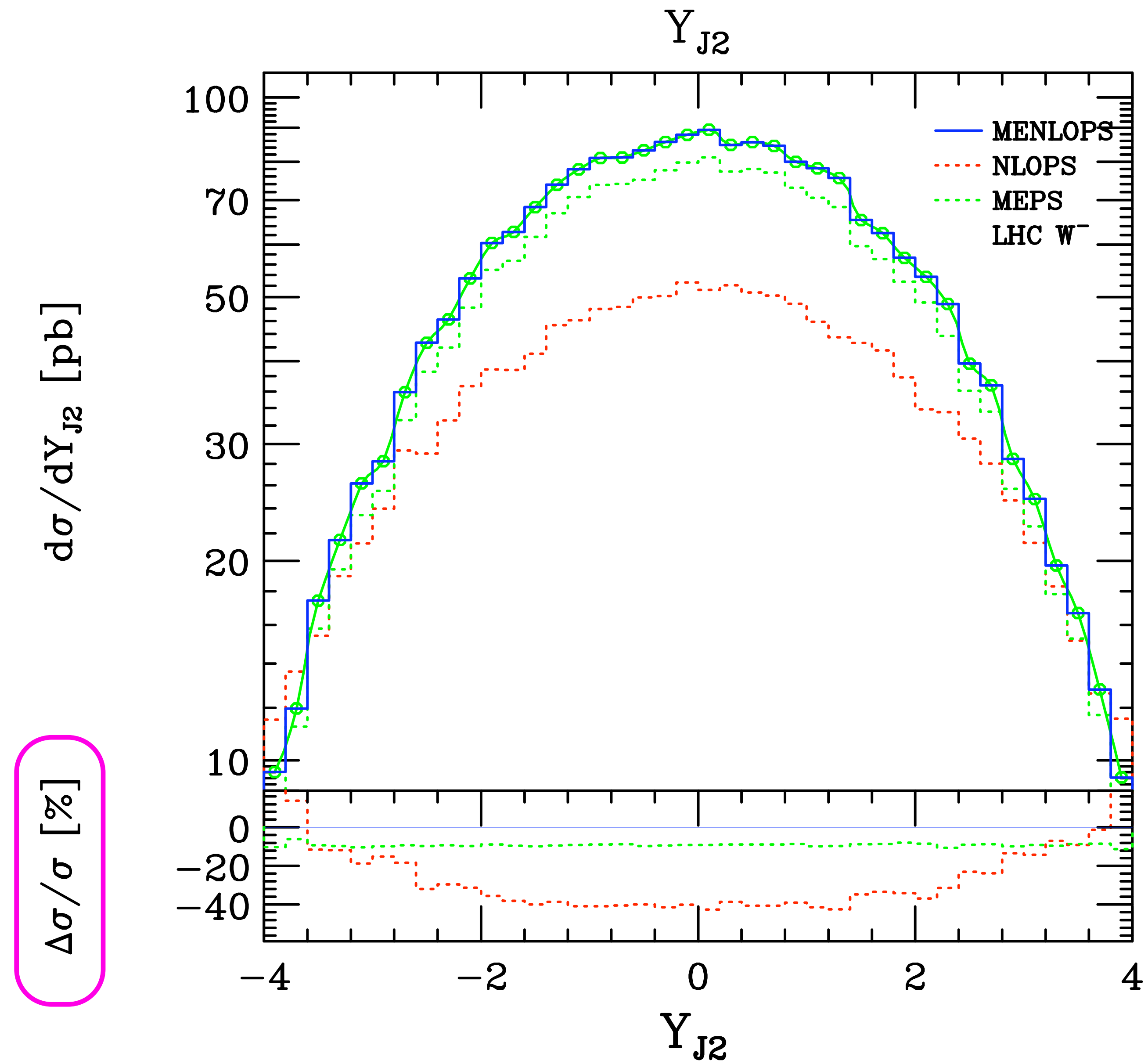
MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default MEPS default × K

2nd Jet p_T and rapidity in W^- events

Here jet scale = MENLOPS scale = 25 GeV; MEPS = 20 GeV





Jet 2 much softer in NLOPS

MEPS/MENLOPS 50 % more central

MENLOPS = NLOPS subsample + MEPS subsample

NLOPS default MEPS default × K

Outline:

- NLOPS & MEPS features.
- Theoretical considerations for MEPS → MENLOPS.
- How close can you get just combining today's tools?
- New SHERPA implementation.
  [S.Höche, F.Krauss, M.Schönherr, F.Siegert]

New SHERPA implementation [S.Höche et al]

- Aims at the same exact 'master formula'.
- Slightly different perspective: POWHEG examined from the MEPS point of view instead of the other way round.

$$\langle O\rangle^{(\mathrm{MENLOPS})} = \sum_{\{\vec{f}\}} \int \mathrm{d}\Phi_B(\{\vec{p}\})\,\bar{\mathrm{B}}(\{\vec{a}\}) \Bigg[\underbrace{\Delta^{(\mathrm{ME})}(t_0,\mu^2;\{\vec{a}\})}_{\text{virtual/unresolved}} O(\{\vec{a}\})$$

$$+ \sum_{\{\widetilde{\imath\jmath},\tilde{k}\}} \sum_{f_i=\{\bar{f}_{\widetilde{\imath\jmath}},g\}} \frac{1}{16\pi^2} \int_{t_0}^{\mu^2} \mathrm{d}t \int_{z_{\min}}^{z_{\max}} \mathrm{d}z \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi} J_{ij,k}(t,z,\phi)$$

$$\times \frac{1}{S_{ij}} \frac{S(r_{\widetilde{\imath\jmath},\tilde{k}}(\{\vec{f}\}))}{S(\{\vec{f}\})} \frac{\mathrm{R}_{ij,k}(r_{\widetilde{\imath\jmath},\tilde{k}}(\{\vec{a}\}))}{\mathrm{B}(\{\vec{a}\})} O(r_{\widetilde{\imath\jmath},\tilde{k}}(\{\vec{a}\}))$$

$$\times \Bigg(\underbrace{\Delta^{(\mathrm{ME})}(t,\mu^2;\{\vec{a}\})\,\Theta\left(Q_{\mathrm{cut}} - Q_{ij,k}\right)}_{\text{resolved, PS domain}} + \underbrace{\Delta^{(\mathrm{PS})}(t,\mu^2;\{\vec{a}\})\,\Theta\left(Q_{ij,k} - Q_{\mathrm{cut}}\right)}_{\text{resolved, ME domain}} \Bigg) \Bigg] .$$

Höche et al
[this weeks arXiv]

- MENLOPS scale implicit as MEPS merging scale Q_{cut}.

New SHERPA implementation [S.Höche et al]

SHERPA MENLOPS

[X+0 formally equivalent to exact method - by definition]

$$d\sigma_{PW}^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q<q^*) d\Phi_R \right]$$

[MEPS for [X+≥1] but with $B(\Phi_B) \rightarrow \overline{B}(\Phi_B)$]

$$d\sigma^{[X+\geq 1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q>q^*) d\Phi_R \right]$$

New SHERPA implementation [S.Höche et al]

SHERPA MENLOPS

[X+0 formally equivalent to exact method - by definition]

$$d\sigma_{PW}^{[X+0]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_{T,min}) + \overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q<q^*)\, d\Phi_R \right]$$

[MEPS for [X+≥1] but with $B(\Phi_B) \rightarrow \overline{B}(\Phi_B)$]

$$d\sigma_{SHERPA}^{[X+\geq 1]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right]$$

But remember MEPS [...] isn't unitary in Φ_B. Need to make sure integral over Φ_R in $d\sigma_{SHERPA}^{[X+\geq 1]}$ is $O(\alpha_S)$. So, again q^* is bounded from below to preserve NLO accuracy.

New SHERPA implementation [S.Höche et al]

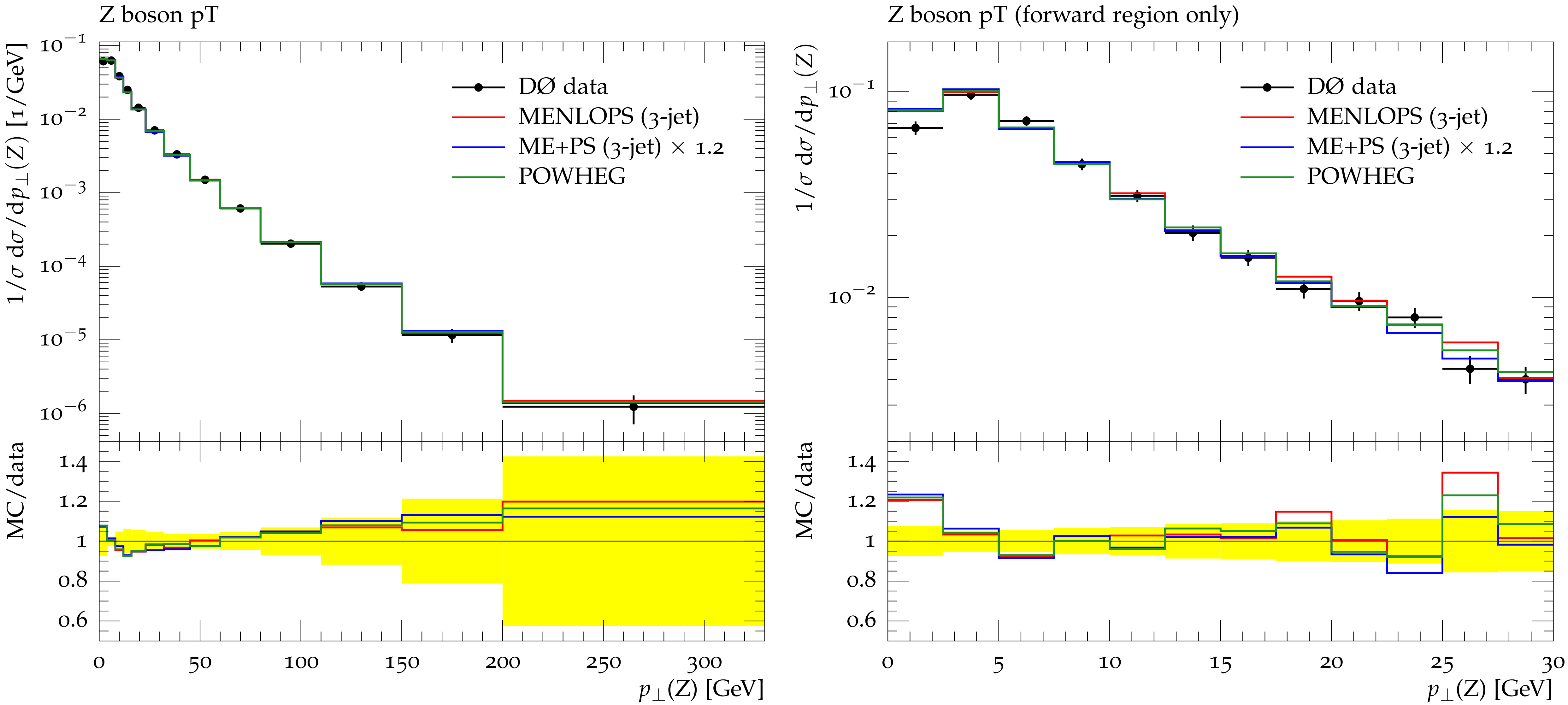


Figure 9: The transverse momentum of the reconstructed Z boson in Drell-Yan production at the Tevatron at $\sqrt{s} = 1.96$ TeV. Experimental data stem from the DØ experiment [35, 36] and are described in the text.

New SHERPA implementation [S.Höche et al]

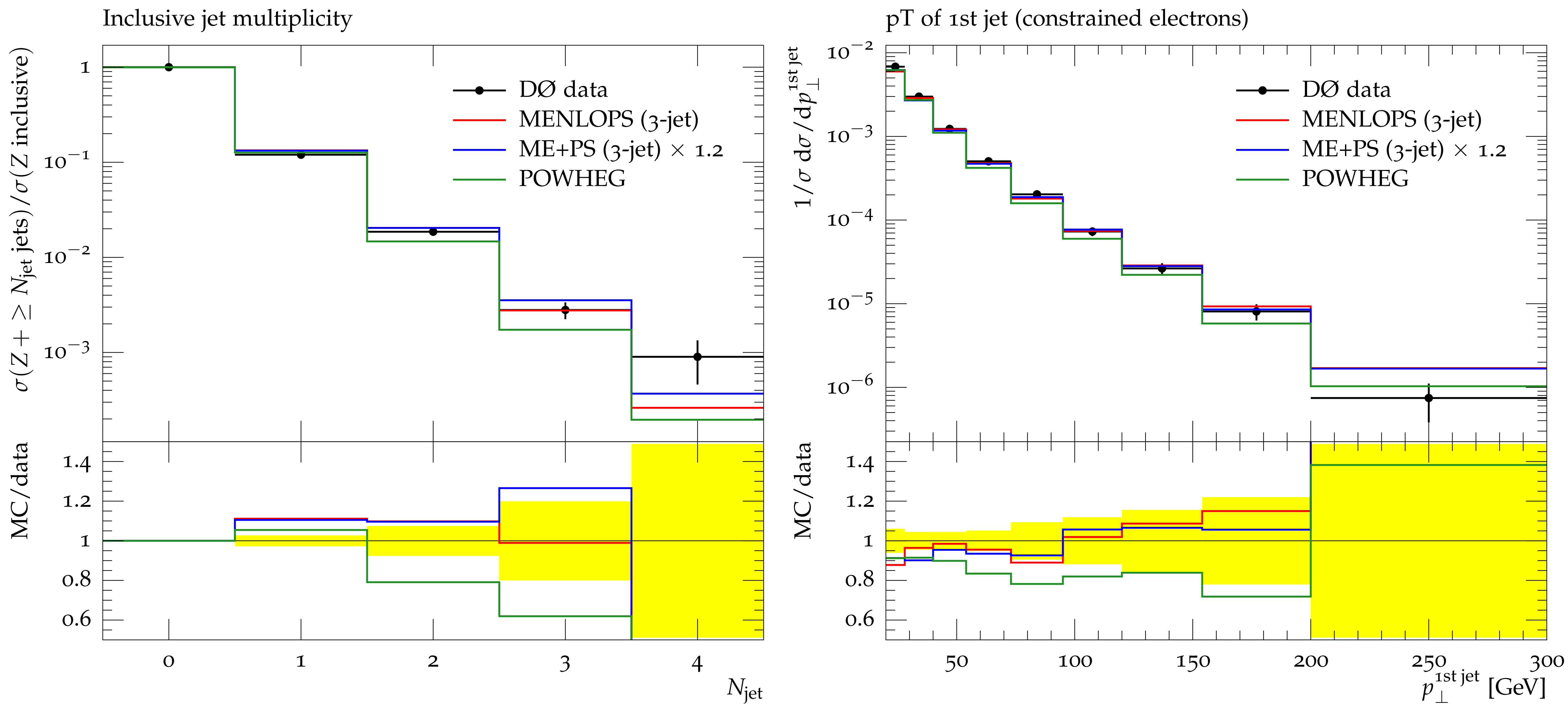


Figure 11: Inclusive jet multiplicity [39] (left) and transverse momentum of the leading jet [41] (right) in Z+jets events at the Tevatron at $\sqrt{s} = 1.96$ TeV.

New SHERPA implementation [S.Höche et al]

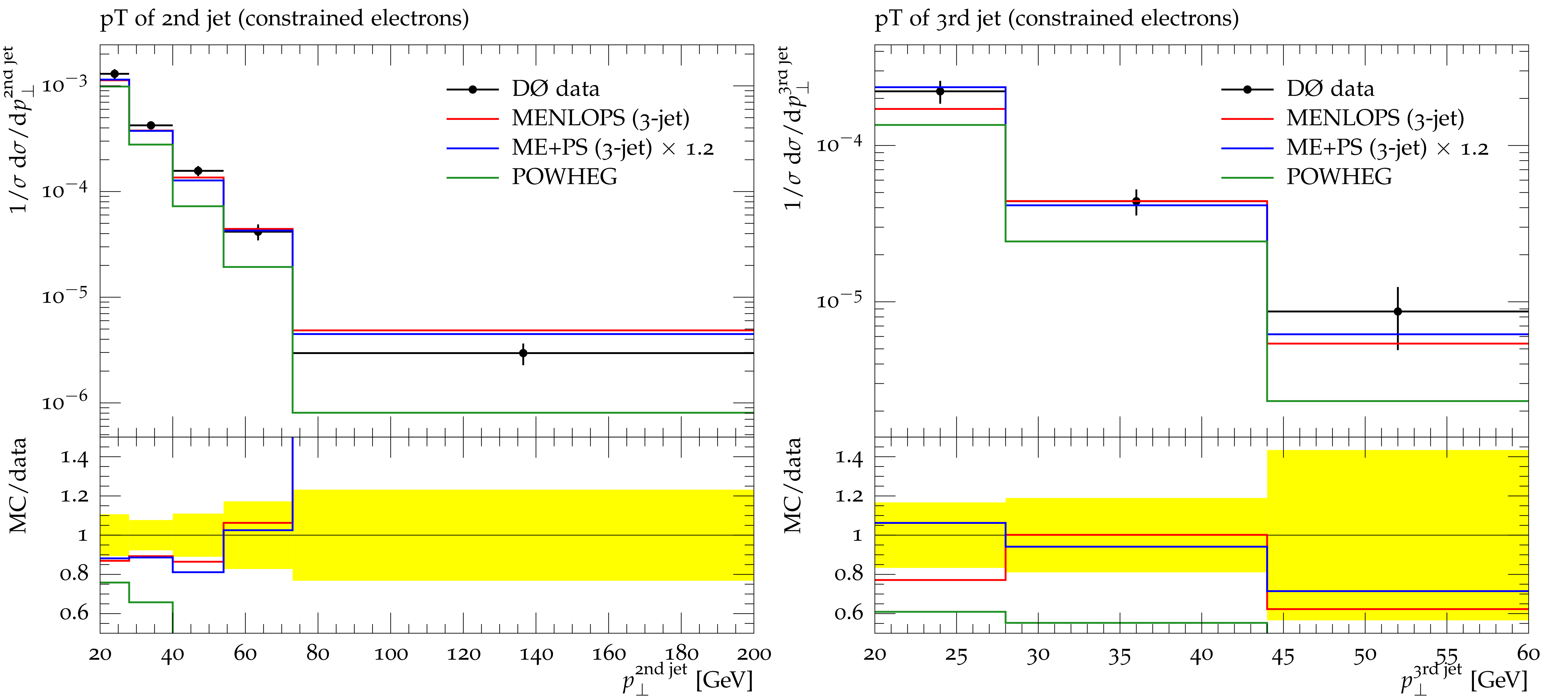


Figure 12: Transverse momentum of the second and third jet [41] in Z+jets events at the Tevatron at $\sqrt{s} = 1.96$ TeV.

New SHERPA implementation [S.Höche et al]

NLO matrix elements and truncated showers

Stefan Höche[1], Frank Krauss[2,3], Marek Schönherr[4], Frank Siegert[2,5]

- Higgs production
- WW production at LHC
- Comparison to TVT W/Z+jets data
- Comparison to LEP data
- Comparison to HERA data

Summary:

- NLOPS & MEPS features:

  NLOPS is great except if you are as interested in X+≥2 jet events as you are in X+0 & X+1 jet events then MEPS is better.

- Theoretical considerations for MEPS → MENLOPS.

  MENLOPS combines the accuracy of a *SINGLE* NLOPS with that of an MEPS. Key point: in the general case you need to make MEPS unitary [at least up to terms $O(\alpha_S^2)$]!

Summary:

- New SHERPA implementation.

  Fresh perspective and first attempt at theoretical extension of original exact MENLOPS theory to general case of multiple momentum mappings! Implementation too [see this weeks arXiv].

- Approximating MENLOPS using today's tools.

  Works great too! NLO accuracy provided X+≥2 jet fraction is less than α_S. Easy to do: we just ran codes off the shelf, out of the box; could've used Alpgen / Sherpa / Helac / Herwig++ / MC@NLO. In W events for MENLOPS scale = MEPS scale: P[X+≥2-jets] < 8%.

New SHERPA implementation [S.Höche et al]

- Original exact MENLOPS scheme $\overline{B}$ / $\overline{B}_{ME}$ only considered for simplest case of ONE inverse momentum mapping $\Phi_R \to \Phi_B$ i.e. old plus function / new FKS subtraction, with simple processes in mind†: hh → V / H / VH / VV / tt.

- Non-trivial theoretical extension needed for general case of multiple inverse mappings $\Phi_R \to \Phi_B$ [need Sudakov FFs & real ME's to pick which mapping ...].

- First attempt by Höche, Krauss, Schönherr, Siegert for dipole subtraction method! Implemented in SHERPA [see the arXiv this week ...].

† Processes with only two genuine collinear singularities

How close can you get just combining today's tools?

For the description of events with two hard jets the distributions in the approximate & exact methods tend to the tree order 2-jet cross section:

$$d\sigma^{[X+\geq 2]} = \bar{B}(\Phi_B)\, d\Phi_B \left[\frac{\bar{\Delta}(p_T)\,\frac{\bar{R}}{B}\,\Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1-\Delta_{ME}(q^*)]$$

$$d\sigma_{ME}^{[X+\geq 2]} = K\, B(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_T)\,\frac{\bar{R}}{B}\,\Theta(q>q^*)\, d\Phi_R \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

For the description of events with two hard jets the distributions in the approximate & exact methods tend to the tree order 2-jet cross section:

$$d\sigma^{[X+\geq 2]} = R_2(\Phi_B,\Phi_R,\Phi_{R'})\, d\Phi_B\, d\Phi_R\, d\Phi_{R'}$$

$$d\sigma_{ME}^{[X+\geq 2]} = R_2(\Phi_B,\Phi_R,\Phi_{R'})\, d\Phi_B\, d\Phi_R\, d\Phi_{R'}$$

Both agree neglecting terms $O(\alpha_s^3)$.

How close can you get just combining today's tools?

For the description of events with two soft jets the distributions in the approximate & exact methods factorise in Φ_B and Φ_R:

$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1-\Delta_{ME}(q^*)]$$

$$d\sigma_{ME}^{[X+\geq 2]} = K\, B(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T)\, \frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right] [1-\Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

For the description of events with two soft jets the distributions in the approximate & exact methods factorise in Φ_B and Φ_R:

$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, U(\Phi_R)\, d\Phi_B\, d\Phi_R$$

$$d\sigma_{ME}^{[X+\geq 2]} = K\, B(\Phi_B)\, U(\Phi_R)\, d\Phi_B\, d\Phi_R$$

The exact method is NLO in Φ_B but the approximate one is LO. Moreover for $q^* \to 0$ the integral over Φ_R is $O(1)$ i.e. big unitarity violation. Avoid $q^* \to 0$ for have NLO accuracy.

How close can you get just combining today's tools?

For the description of events with one hard and one soft jet [or two moderately soft jets] the distributions in the approximate & exact methods basically tend to:

$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q > q^*)\, d\Phi_R}{N(\Phi_B)} \right] [1 - \Delta_{ME}(q^*)]$$

$$d\sigma_{ME}^{[X+\geq 2]} = K\, B(\Phi_B)\, d\Phi_B \left[\overline{\Delta}(p_T) \frac{\overline{R}}{B} \Theta(q > q^*)\, d\Phi_R \right] [1 - \Delta_{ME}(q^*)]$$

How close can you get just combining today's tools?

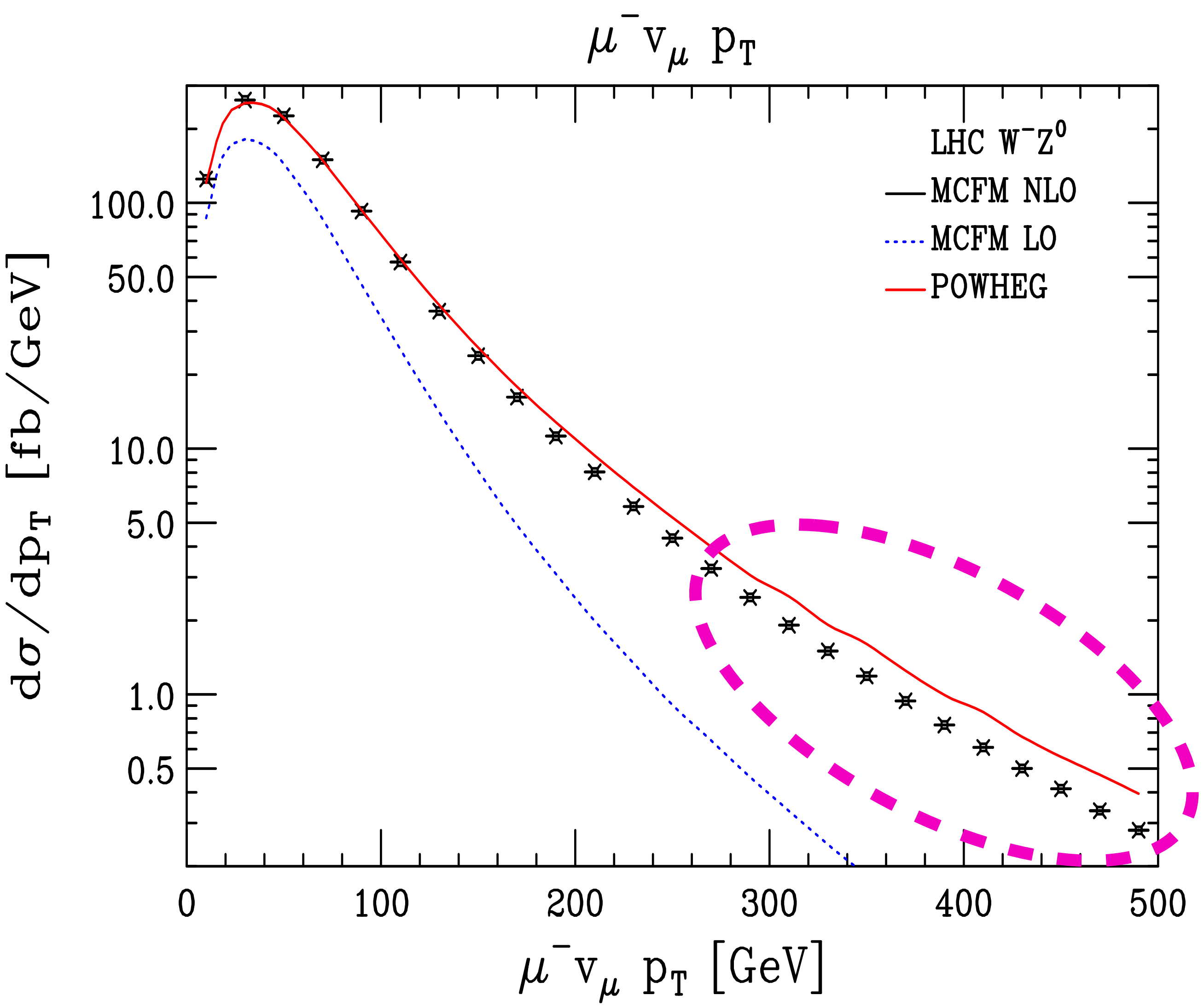
For the description of events with one hard and one soft jet [or two moderately soft jets] the distributions in the approximate & exact methods basically tend to:

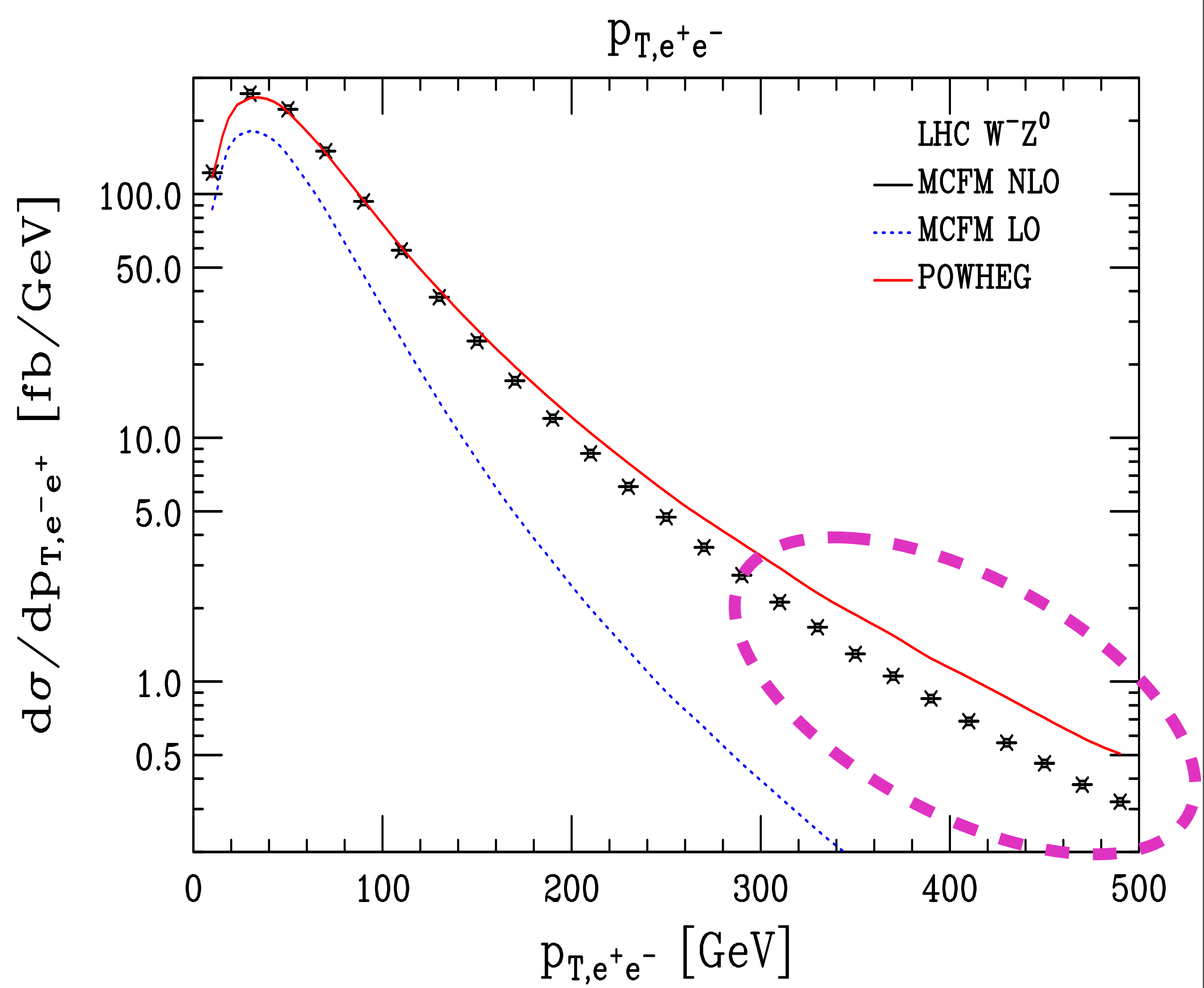
$$d\sigma^{[X+\geq 2]} = \overline{B}(\Phi_B)\, d\Phi_B \left[\frac{\frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R}{N(\Phi_B)} \right]$$

$$d\sigma_{ME}^{[X+\geq 2]} = K\, B(\Phi_B)\, d\Phi_B \left[\frac{\overline{R}}{B}\, \Theta(q>q^*)\, d\Phi_R \right]$$

Both agree neglecting terms $O(\alpha_s^2)$. Fine for NLO. So insisting that the total 2-jet fraction is $\leq \alpha_s$ this should be the limiting behaviour in the 2-jet subsample.

What about inclusive observables at high energy?





$$d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \left[\bar{\Delta}(p_{T,min}) + \bar{\Delta}(p_T) \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)} d\Phi_R \right]$$

What about inclusive observables at high energy?

Integrate approximate x-sec over Φ_R :

$$d\sigma = d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

What about inclusive observables at high energy?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)} \left[1 - \frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}} \right] \right]$$

What about inclusive observables at high energy?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

Unitarity breaking

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)} \left[1 - \frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}} \right] \right]$$

What about inclusive observables at high energy?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)} \left[1 - \underbrace{\frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}}_{1 + O(\alpha_S)} \right] \right]$$

What about inclusive observables at high energy?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)} \left[1 - \underbrace{\frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}}_{1+O(\alpha_S)} \right] \right]$$

I.E. if this goes $\geq \alpha_S$ in a high energy regime it's OK as POWHEG doesn't give you exactly the same as NLO result anyway there.

What about inclusive observables at high energy?

Integrate approximate x-sec over Φ_R :

$$d\sigma = \int_{\Phi_R} d\sigma_{PW} + K\, d\sigma_{MEPS}^{[X+\geq 2]} - d\sigma_{PW}^{[X+\geq 2]}$$

$$= \bar{B}(\Phi_B)\, d\Phi_B \left[1 + \underbrace{\frac{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}{\bar{B}(\Phi_B)}}_{O(\alpha_S)} \left[1 - \frac{\int_{\Phi_R} d\sigma_{PW}^{[X+\geq 2]}}{\underbrace{K \int_{\Phi_R} d\sigma_{MEPS}^{[X+\geq 2]}}_{1+O(\alpha_S)}} \right] \right]$$

Just some reassurance in case you thought I messed up the NLO calculation on the last slide: