Drell-Yan production at NNLO+PS

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mini-workshop: “ATLAS+CMS+TH on M_W”

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Outline

- brief motivation
- method used (POWHEG+MiNLO)
- results:

  - "validation" / standard observables

  - comparison with data and analytic resummation

  - comparison with original POWHEG (NLOPS)
- other available methods
- conclusions & discussion

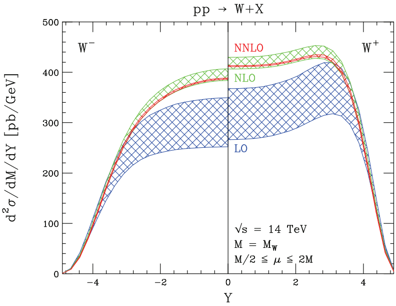
NNLO+PS: why and where?

NLO not always enough: NNLO needed when

1. large NLO/LO “K-factor”
   [as in Higgs Physics]

2. very high precision needed
   [e.g. Drell-Yan]

- last couple of years:
  huge progress in NNLO



plot from [Anastasiou et al., ’03]

Q: can we merge NNLO and PS?

NNLO+PS: why and where?

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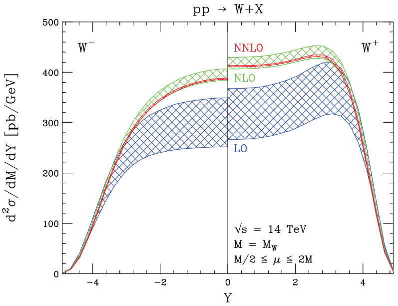

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Q: can we merge NNLO and PS?

☞ realistic event generation with state-of-the-art perturbative accuracy !
☞ could be important for precision studies in Drell-Yan events

- method presented here: based on POWHEG+MiNLO, used so far for
  - Higgs production [Hamilton,Nason,ER,Zanderighi, 1309.0017]
  - neutral & charged Drell-Yan [Karlberg,ER,Zanderighi, 1407.2940]
- I will also present some results obtained with UNNLOPS [Hoeche,Li,Prestel, 1405.3607]
- preliminary results also from the GENEVA group [Alioli,Bauer,et al. →”PSR2014”]

towards NNLO+PS

- what do we need and what do we already have?

	V (inclusive)	V+j (inclusive)	V+2j (inclusive)
V @ NLOPS	NLO	LO	shower
VJ @ NLOPS	/	NLO	LO
V-VJ @ NLOPS	NLO	NLO	LO
V @ NNLOPS	NNLO	NLO	LO

☞ a merged V-VJ generator is almost OK

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- many of the multijet NLO+PS merging approaches work by combining 2 (or more) NLO+PS generators, introducing a merging scale

- POWHEG + MiNLO: no need of merging scale: it extends the validity of an NLO computation with jets in the final state in regions where jets become unresolved

(what you have been using so far is V @ NLOPS)

MiNLO

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation
- non-trivial task: hierarchy among scales can spoil accuracy (large logs can appear, without being resummed)
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

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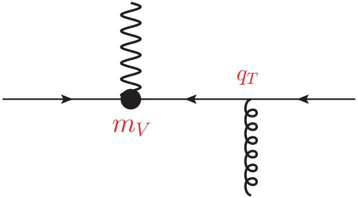

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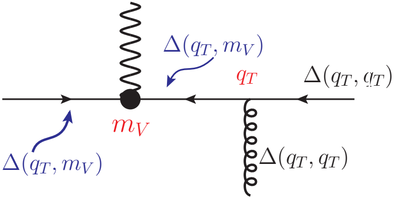

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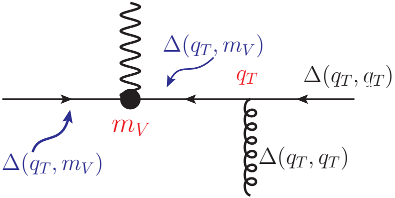

- $\bar{\mu}_R = q_T$
- $\log \Delta_{\rm f}(q_T, m_V) = -\int_{q_T^2}^{m_V^2} \frac{dq^2}{q^2} \frac{\alpha_{\rm S}(q^2)}{2\pi}\Big[A_f \log\frac{m_V^2}{q^2} + B_f\Big]$
- $\Delta_{\rm f}^{(1)}(q_T, m_V) = -\frac{\alpha_{\rm S}^{\rm (NLO)}}{2\pi}\Big[\frac{1}{2}A_{1,\rm f}\log^2\frac{m_V^2}{q_T^2} + B_{1,\rm f}\log\frac{m_V^2}{q_T^2}\Big]$
- $\mu_F = q_T$

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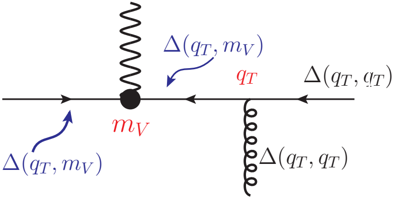

☞ Sudakov FF included on $V+j$ Born kinematics

- MiNLO-improved VJ yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\rm MiNLO}$ ideal to extend validity of VJ−POWHEG [called "VJ−MiNLO" hereafter]

“Improved” MiNLO & NLOPS merging

- formal accuracy of `VJ-MiNLO` for inclusive observables carefully investigated

  [Hamilton et al., 1212.4504]

- `VJ-MiNLO` describes inclusive observables at order α_S
- to reach genuine NLO when fully inclusive (NLO$^{(0)}$), “spurious” terms must be of relative order α_S^2, *i.e.*

$$O_{\mathrm{VJ-MiNLO}} = O_{\mathrm{V@NLO}} + \mathcal{O}(\alpha_S^2) \qquad \text{if } O \text{ is inclusive}$$

- “Original `MiNLO`” contains ambiguous “$\mathcal{O}(\alpha_S^{1.5})$” terms

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- Possible to improve $\texttt{VJ-MiNLO}$ such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of $V+j$ (NLO$^{(1)}$).
- accurate control of subleading small-p_T logarithms is needed
  (scaling in low-p_T region is $\alpha_S L^2 \sim 1$, *i.e.* $L \sim 1/\sqrt{\alpha_S}$!)

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Effectively as if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).

Drell-Yan at NNLO+PS

- VJ−MiNLO+POWHEG generator gives V-VJ @ NLOPS

	V (inclusive)	V+j (inclusive)	V+2j (inclusive)
✓ V-VJ @ NLOPS	NLO	NLO	LO
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- reweighting (differential on Φ_B) of "MiNLO-generated" events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm VJ-MiNLO}}$$

  - by construction NNLO accuracy on fully inclusive observables ($\sigma_{\rm tot}, y_V, M_V, ...$) [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of VJ−MiNLO in 1-jet region [ ]

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  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{3/2})$ terms in V-VJ @ NLOPS
- Variants for reweighting ($W(\Phi_B, p_T)$) are also possible:
  - freedom to distribute "NNLO/NLO K-factor" only over medium-small p_T region

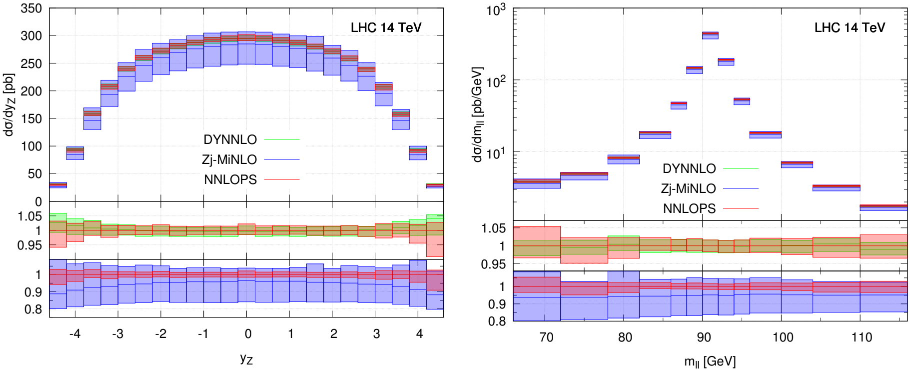
settings for plots shown

inputs for following plots:

- used p_T-dependent reweighting ($W(\Phi_B, p_T)$), smoothly approaching 1 at $p_T \gtrsim m_V$

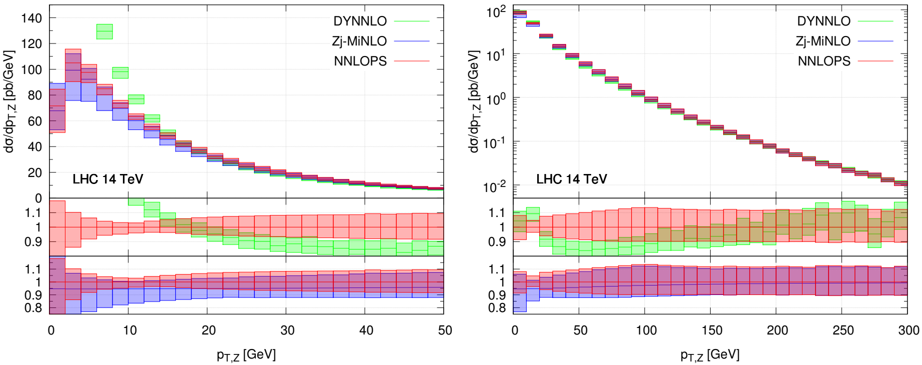
- scale choices: NNLO input with $\mu = m_V$, VJ-MiNLO has its own scale
- PDF: everywhere MSTW2008 NNLO
- NNLO from DYNNLO [Catani,Cieri,Ferrera et al., '09]
  (3pts scale variation, but 7pts in pure NNLO plots)
- MiNLO: 7pts scale variation (using POWHEG BOX-V2 machinery)
- events reweighted at the LH level: 21-pts scale variation $(7_{\mathrm{Mi}} \times 3_{\mathrm{NN}})$
- tunes: Pythia6: "Perugia P12-M8LO" , Pythia8: "Monash 2013"

Z@NNLOPS, PS level



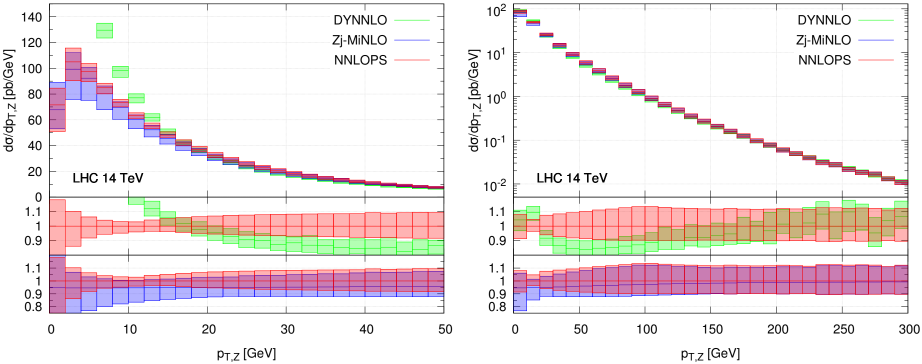
- $(7_{\mathrm{Mi}} \times 3_{\mathrm{NN}})$ pts scale var. in NNLOPS, 7pts in NNLO
- agreement with DYNNLO
- scale uncertainty reduction wrt ZJ-MiNLO

Z@NNLOPS, PS level



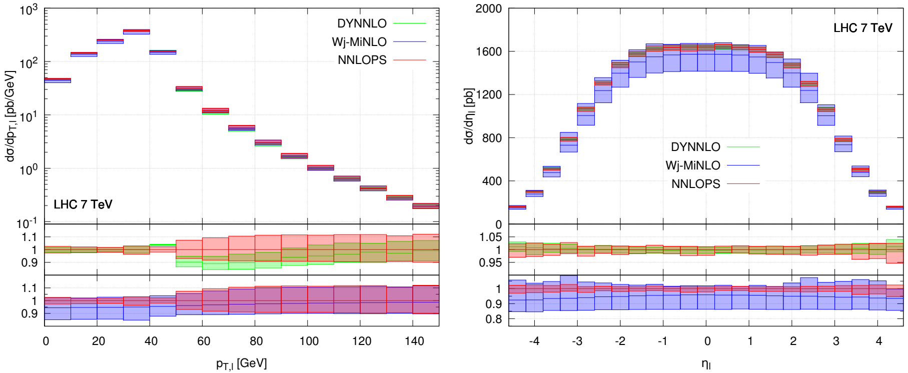
- NNLOPS: smooth behaviour at small k_{T}, where NNLO diverges
- at high p_T, all computations are comparable (band size similar)
- at very high p_T, DYNNLO and ZJ-MiNLO (and hence NNLOPS) use different scales !

Z@NNLOPS, PS level



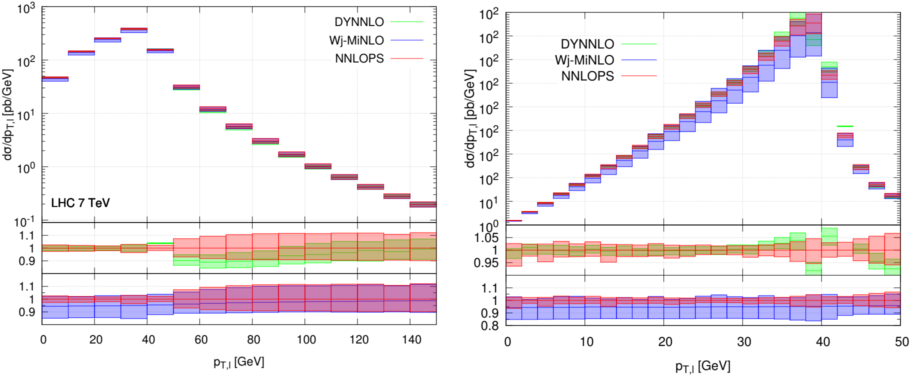
- NNLO envelope shrinks at ~ 10 GeV; NNLOPS inherits it
- notice that in Sudakov region, NNLO rescaling doesn't alter shape from `MiNLO`
- at $p_T \simeq m_V/2$, NNLOPS has an uncertainty twice as large as fixed-order:
  - I will show how it compares with analytic resummation

W@NNLOPS, PS level



- **not** the observables we are using to do the NNLO reweighting
  - observe exactly what we expect:
    $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$
  - η_ℓ is NNLO everywhere

W@NNLOPS, PS level



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  - smooth behaviour when close to Jacobian peak (also with small bins)
    (due to resummation of logs at small $p_{T,V}$)

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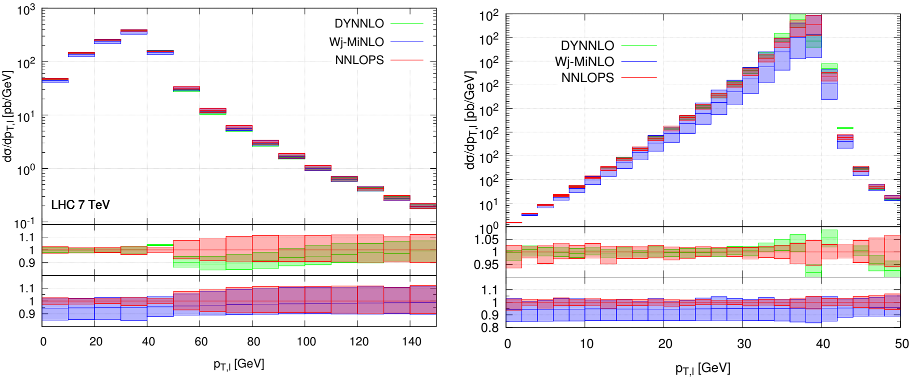

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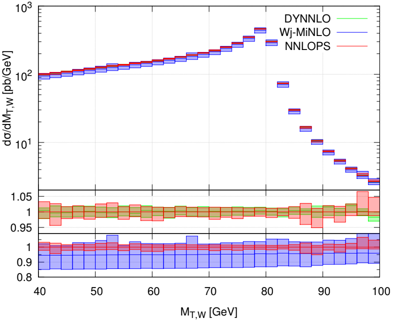
  - smooth behaviour when close to Jacobian peak (also with small bins)
    (due to resummation of logs at small $p_{T,V}$)
- just above peak, `DYNNLO` uses $\mu = M_W$, `WJ-MiNLO` uses $\mu = p_{T,W}$
  - here $0 \lesssim p_{T,W} \lesssim M_W$ (so resummation region does contribute)

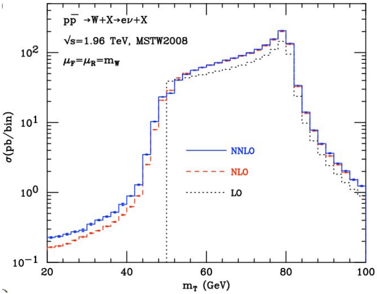
W@NNLOPS, PS level



- only cut here: $M_{T,W} > 40$ GeV:

$$M_{T,W} = \sqrt{2p_{T,\ell}p_{T,\nu}(1-\cos\Delta\phi)}$$

- all well-behaved: important for M_W determination



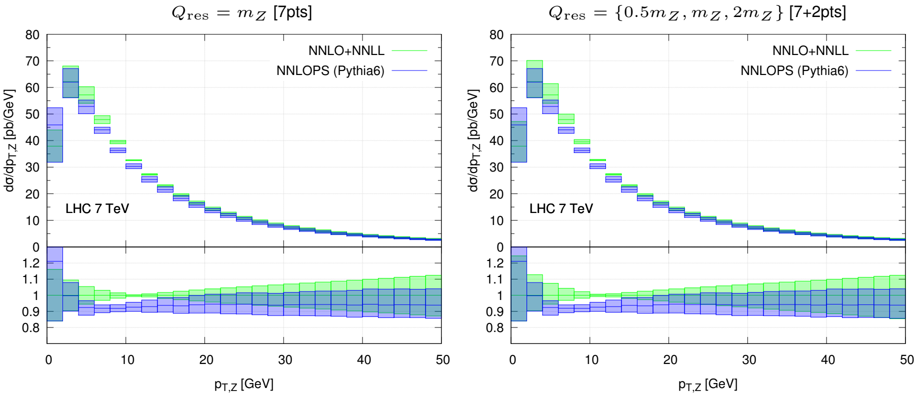
- with leptonic cuts, situation is more subtle:

$$p_{T,\ell} > 20 \text{ GeV} \quad , \quad p_{T,\nu} > 25 \text{ GeV}$$

- perturbative instabilities [Catani,Webber, '97]
- should be better using a (N)NLO+PS approach

plot from [Catani et al., 0903.2120]

Vector boson p_T: resummation



- DyQT: NNLL+NNLO [Bozzi,Catani,Ferrera, et al., '10]
  $\mu_R = \mu_F = m_Z$ [7pts], $Q_{\rm res} = m_Z$ [+ $Q_{\rm res} = 2m_Z, m_Z/2$]
- agreement with resummation good (PS only), but not perfect
  - formal accuracy not the same!
  - shrinking of bands at 10 GeV makes it looking perhaps "worse" than what it is...
  - at 30-50 GeV, bands similar to DyQT

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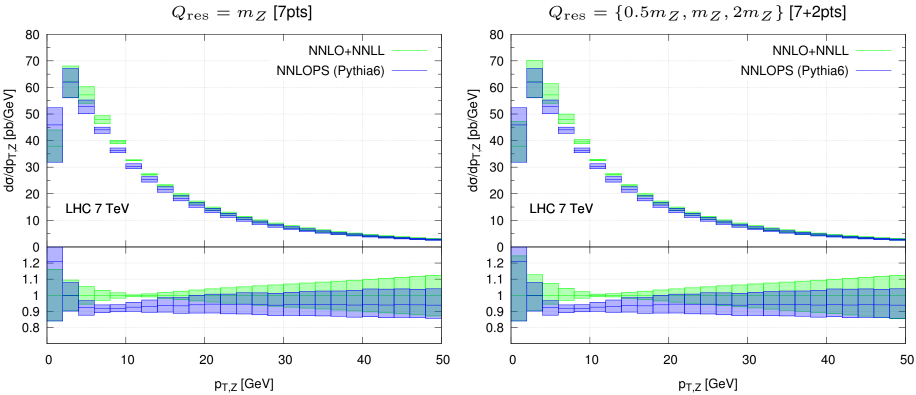

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- agreement with resummation good (PS only), but not perfect
  - ☞ understanding (or improving) the formal logarithmic accuracy of NNLOPS is an open issue. Nevertheless, the observed pattern seems (to me) qualitatively consistent with known differences between LL, NLL, and NNLL resummation

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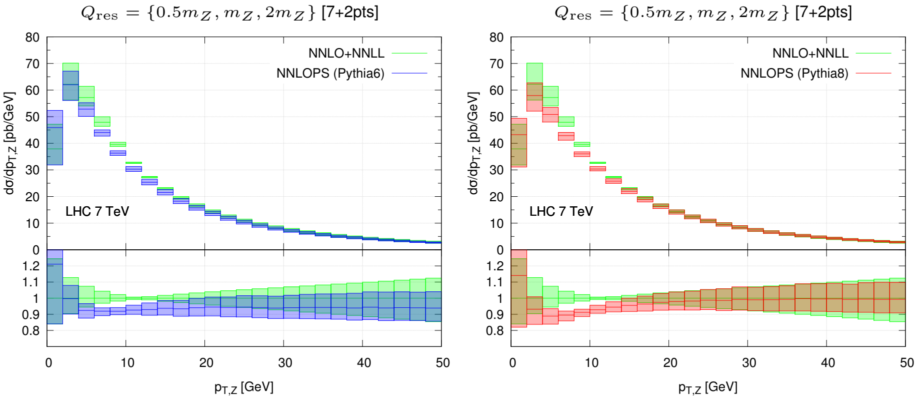
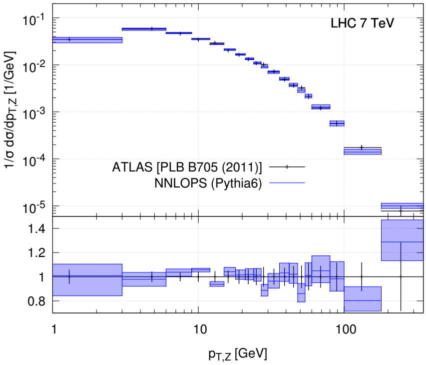
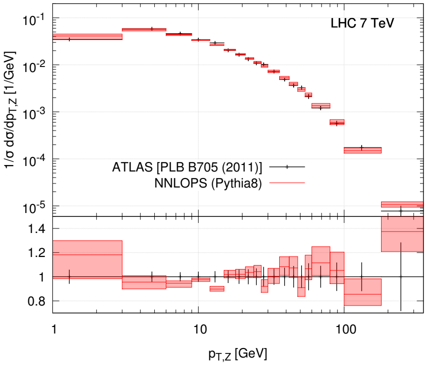


- similar pattern, although some differences visible between `Pythia6` and `Pythia8`
- NP/tune effects are not negligible

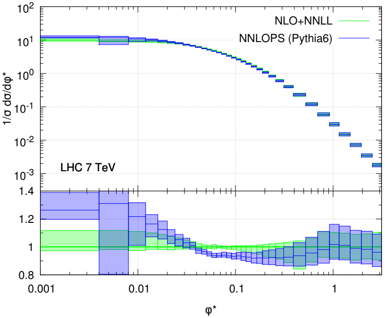
Vector boson: comparison with data ($p_{T,Z}$)

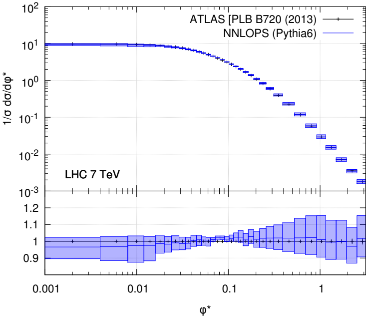




- good agreement with data (PS+hadronisation+MPI)
- band shrinking at ~ 10 GeV
- `Pythia8` is slightly harder at large p_T, and in less good agreement at small p_T
  - part of this can be considered a genuine uncertainty (different shower)
  - specific tune likely to have an impact at small p_T

ϕ^*: resummation and data



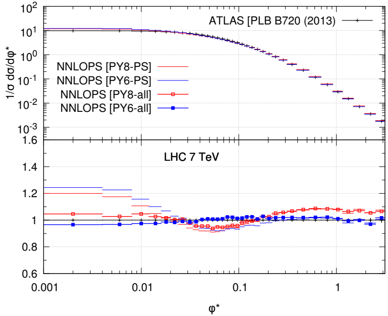


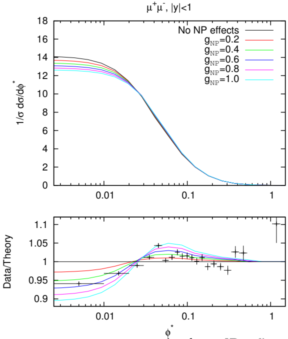
$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \sin\theta^*$$

- θ^*: angle between electron and beam axis, in Z boson rest frame
- ATLAS uses slightly different definition: $\cos\theta^* = \tanh((y_{l^-} - y_{l^+})/2)$

- NLO+NNLL resummation [Banfi et al., '11]
- agreement not very good at small ϕ^*
- NP effects seem quite important here; comparison with data much better when they are included

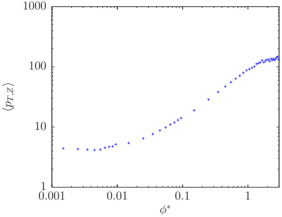
ϕ^*: NP effects



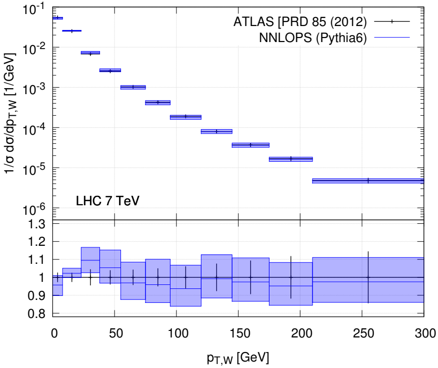


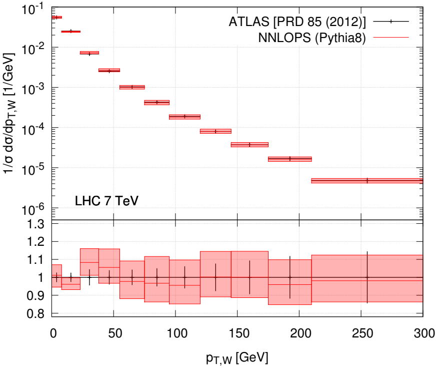
plot from [Banfi et al., 1102.3594]

- NP effects observed here have same pattern as those discussed in Banfi et al.
- large interval of ϕ^* is dominated by low values of $p_{T,Z}$
- looking at $\langle p_T \rangle$ vs. ϕ^*, difference `Pythia8` vs. `Pythia6` is consistent with $p_{T,Z}$ result



Vector boson: comparison with data ($p_{T,W}$)

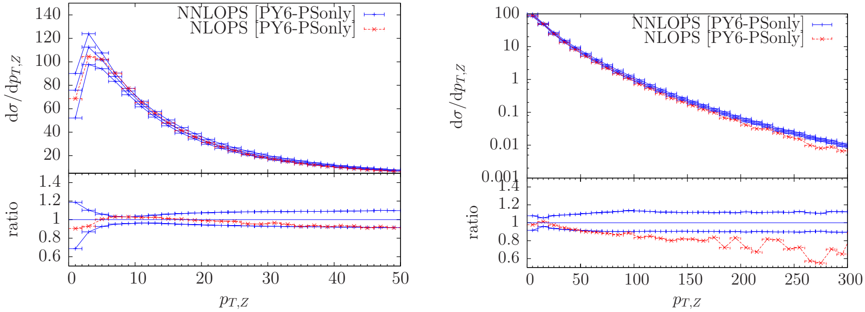




- data comparison both with `Pythia6` and `Pythia8`
- differences small (but visible) at low p_T: different showers, different tunes...

☞ in the contest of M_W measurement, a detailed study and tune (like *e.g.* the one performed recently by ATLAS [1406.3660]) probably useful. To be discussed...

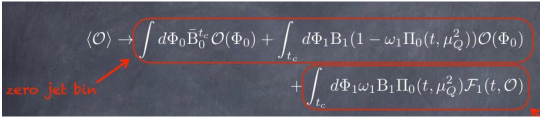
NNLOPS vs. NLOPS



- different terms in Sudakov, although both contain NLL terms in momentum space
  - in NLOPS: α_S in radiation scheme; in NNLOPS: MiNLO Sudakov
- formally they have the same logarithmic accuracy (as supported by above plot)
- at large p_T, difference as expected

NNLOPS Drell-Yan with UNNLOPS

- NNLOPS obtained also upgrading `UNLOPS` to `UNNLOPS` [Hoeche,Li,Prestel '14]

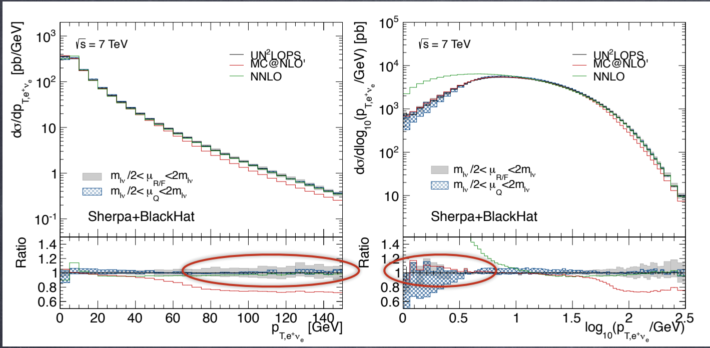


$$\bar{B}_0^{t_c}(\Phi_0) = B_0(\Phi_0) + V_0(\Phi_0) + \int^{t_c} B_1 d\Phi_1$$

- inclusive NLO recovered
- notice: contributions in “zero-jet” bin are not showered:
  - in `POWHEG(+MiNLO)` , all “no-radiation” bin is Sudakov-suppressed
- scheme pushed to NNLO

NNLOPS Drell-Yan with UNNLOPS

Hoeche, YL, Prestel arXiv:1405.3607



Comparison with MC@NLO in Sherpa (S-MC@NLO)

- UN2LOPS essentially merges MC@NLO for H/W/Z + 0 jet with H/W/Z + 1jet, and retains inclusive NNLO accuracy for H/W/Z + 0 jet
  - Good agreement with MC@NLO at low W pT
  - W + 1 jet K factor at high W pT

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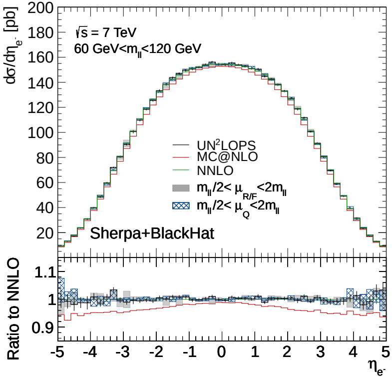
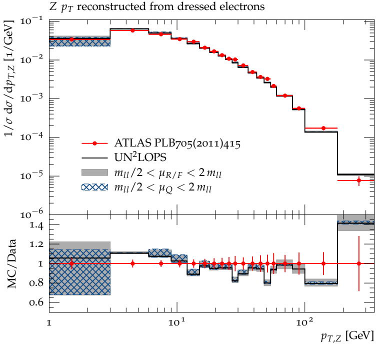
courtesy of Ye Li

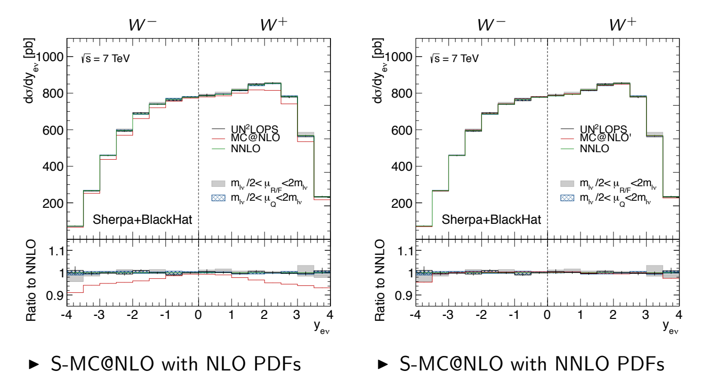
NNLOPS Drell-Yan with UNNLOPS





Impact of PDFs

Impact of PDFs



- Using NNLO PDF for MC@NLO also gives rise to rapidity distribution of W boson identical to NNLO result

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courtesy of Ye Li

Conclusions / discussion

- shown results for Drell-Yan at NNLOPS using MiNLO+POWHEG
- distributions and theoretical uncertainties match NNLO where they have to
- resummation effects important when close to Sudakov regions
  - good agreement with data
  - with resummation good agreement, but not always as good as one would have hoped (especially for ϕ^*)
- shown also how NNLOPS compare with NLOPS
- other approaches on the market

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1. at the level of precision needed for M_W measurement, (dedicated ?) tune on Z data ?
2. how strong is the case for including inclusively NLO QED/EW corrections ?
3. other theory uncertainty not mentioned: β (NNLO/NLO K-factor), include other NNLL terms [notice: will not improve any formal claim]
4. subtleties and subleading effects in (N)NLOPS:
   some of these issues can be addressed by comparing with analytic resummation as well as by having many measurements available
5. ...

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Thank you for your attention!

Extra slides

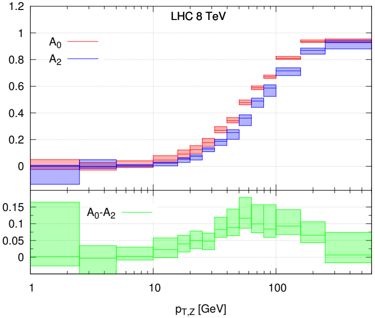
few technical details

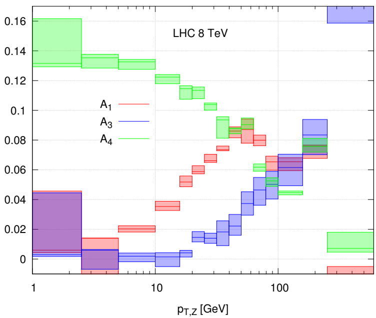
Code will be out very soon

- we use as input distributions from `DYNNLO`
- `POWHEG+MiNLO` events generation is highly parallelizable: grids (30 cores) + generating 20M events (+ reweighting to have 7-pts scale uncertainty) (400 cores): ~ 2 days
- "`MiNLO-to-NNLO`" rescaling takes few hours (for all 20M events)
- showering (+ hadronisation + MPI): ~ 2 M events/day (on 1 core)

Polarisation coefficients

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta^*)d\phi^*} = \frac{3}{16\pi}\Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin 2\theta^*\cos\phi^*$$
$$+ A_2\frac{1}{2}\sin^2\theta^*\cos 2\phi^* + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^*$$
$$+ A_5\sin\theta^*\sin\phi^* + A_6\sin 2\theta^*\sin\phi^* + A_7\sin^2\theta^*\sin 2\phi^*\Big],$$





- all angles in Collins-Soper frame
- no dedicated comparison, but reasonable qualitative agreement with results obtained by `FEWZ` authors [Gavin,Li,Petriello,Quackenbush, '10]
- we have also reproduced quite well recent study on "naive-T-odd" asymmetry in W+jets [Frederix,Hagiwara, et al., '14]

Differential cross section in cosθ and ϕ

- Collins-Soper frame : the center of mass frame of dilepton

$$q\bar{q} \to Z/\gamma* \to \ell^+\ell^-$$

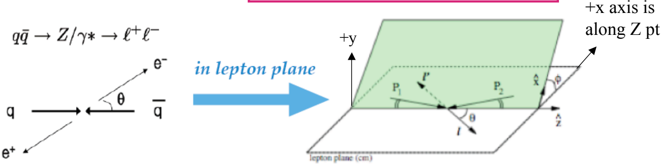


FIG. 1: The Collins-Soper frame.

- Differential cross section of cosθ and ϕ

$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta) \quad \longrightarrow \quad \textit{LO term}$$

$$+ \frac{1}{2}A_0(1-3\cos^2\theta) \quad \longrightarrow \quad \cos^2\theta\text{: higher order term}$$

$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi \quad \longrightarrow \quad (\theta, \phi) \text{ terms}$$

$$+ A_4 \cos\theta \quad \longrightarrow \quad \textit{LO term : determine } A_{fb}$$

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \quad \longrightarrow \quad \text{small terms -> zero when we add positive and negative Phi}$$

****All higher order terms are zero at Pt=0*

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slide from A. Bodek's talk [2010]

UNLOPS

UNLOPS

- To implement NLO matching
  - use actual matrix element for the first emission

"w" adjusts the renormalization and factorization scale of the real radiation matrix element to match parton shower

$$\mathrm{B}_0\mathrm{K}_0 \to w_1\mathrm{B}_1 \qquad w_1 = \frac{\alpha_S(t)}{\alpha_S(\mu_R^2)}\frac{f_a(x_a,t)}{f_a(x_a,\mu_F^2)}\frac{f_b(x_b,t)}{f_b(x_b,\mu_F^2)}$$

$$\langle\mathcal{O}\rangle \to \int d\Phi_0\mathrm{B}_0\mathcal{O}(\Phi_0) - \int_{t_c} d\Phi_1 w_1\mathrm{B}_1\Pi_0(t,\mu_Q^2)\mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1 w_1\mathrm{B}_1\Pi_0(t,\mu_Q^2)\mathcal{F}_1(t,\mathcal{O})$$

  - add virtual correction to the zero bin by using jet-vetoed NLO cross section: achieve NLO accuracy

$$\mathrm{B}_0 \to \bar{\mathrm{B}}_0 = \bar{\mathrm{B}}_0^{t_c} + \int_{t_c} d\Phi_1\mathrm{B}_1$$

the "bar" on "B" denotes inclusively NLO accurate prediction of the corresponding Born process

$$\langle\mathcal{O}\rangle \to \int d\Phi_0\bar{\mathrm{B}}_0^{t_c}\mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1\mathrm{B}_1(1-w_1\Pi_0(t,\mu_Q^2))\mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1 w_1\mathrm{B}_1\Pi_0(t,\mu_Q^2)\mathcal{F}_1(t,\mathcal{O})$$

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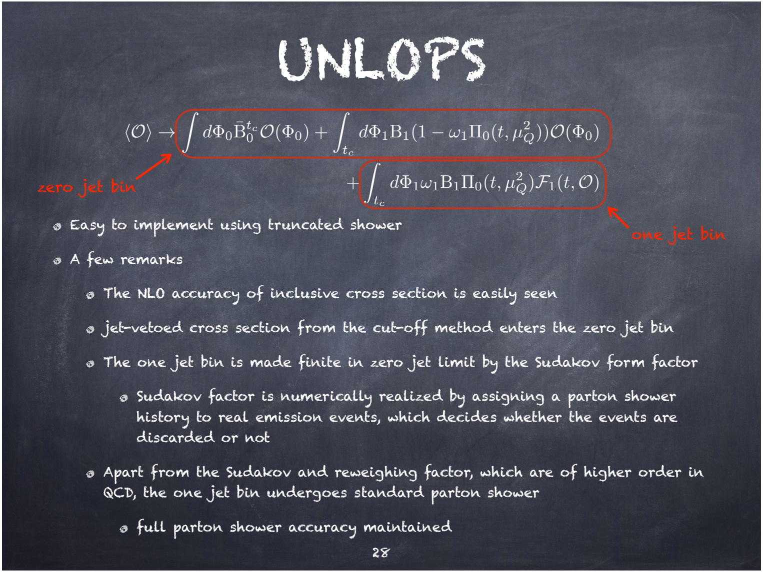
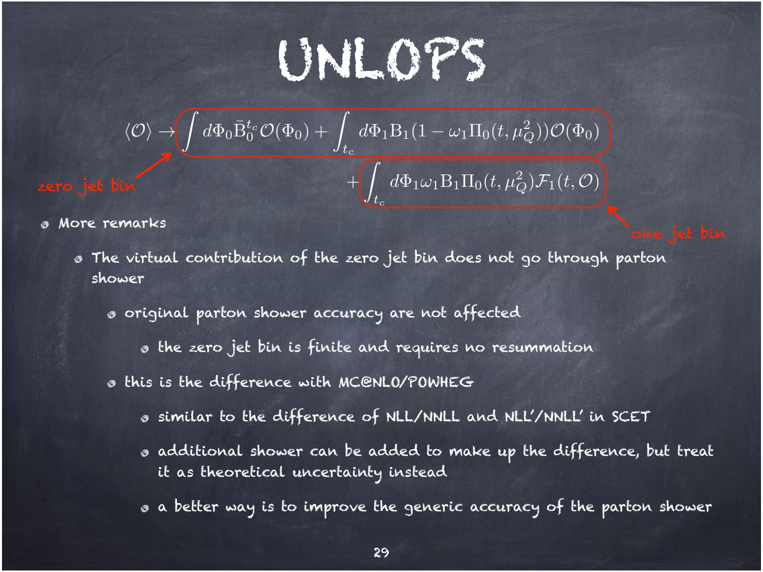
courtesy of Ye Li

UNLOPS



courtesy of Ye Li

UNLOPS



courtesy of Ye Li

UNNLOPS

UN2LOPS

$$\langle \mathcal{O} \rangle \to \int d\Phi_0 \bar{\mathrm{B}}_0^{t_c} \mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1 \mathrm{B}_1 (1 - \omega_1 \Pi_0(t, \mu_Q^2)) \mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1 \omega_1 \mathrm{B}_1 \Pi_0(t, \mu_Q^2) \mathcal{F}_1(t, \mathcal{O})$$

- Extension to NNLO
  - the zero jet bin is promoted to NNLO with a cut-off
  - the one jet bin is promoted to NLO and showered using MC@NLO/POWHEG
  - the one jet bin is no longer finite in zero jet limit in UN2LOPS because the Sudakov form factor does not contain enough logarithms
    - the Sudakov is numerically generated by the parton shower, which is only partially NLL accurate
      - the parton shower has no unordered emissions
    - consequence: sub-leading logs of the cutoff not resummed
    - however, minimum impact given a reasonable cut-off value

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courtesy of Ye Li

UNNLOPS

Final Formula

$$
\begin{aligned}
\langle O \rangle = & \int \mathrm{d}\Phi_0 \, \bar{\bar{\mathrm{B}}}_0^{t_c} \, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2) \left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1 \, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \, \Pi_0(t_1,\mu_Q^2) \left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1 \, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}} \, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_1 \Pi_0(t_1,\mu_Q^2) \, \tilde{\mathrm{B}}_1^{\mathrm{R}} \, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{t_c} \mathrm{d}\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}} \, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_2 \, \Pi_0(t_1,\mu_Q^2) \, \mathrm{H}_1^{\mathrm{R}} \, \mathcal{F}_2(t_2, O) \\
& + \int_{t_c} \mathrm{d}\Phi_2 \, \mathrm{H}_1^{\mathrm{E}} \, \mathcal{F}_2(t_2, O)
\end{aligned}
$$

- Tree level amplitude and subtraction from Amegic or Comix
  [Krauss,Kuhn,Soff] hep-ph/0109036, [Gleisberg,Krauss] arXiv:0709.2881, [Gleisberg,Hoeche] arXiv:0808.3674
- One loop virtual matrix element from Blackhat, or internal Sherpa
  [Berger et al.] arXiv:0803.4180, [Berger et al.] arXiv:0907.1984 arXiv:1004.1659 arXiv:1009.2338
- NNLO vetoed cross section using recent SCET results
  [Becher,Neubert] arXiv:1007.4005 arXiv:1212.2621, [Gehrmann,Luebbert,Yang] arXiv:1209.0682 arXiv:1403.6451 arXiv:1401.1222
- Parton shower based on Catani-Seymour dipole
  [Schumann,Krauss] arXiv:0709.1027
- Combined in Sherpa event generation framework
  [Gleisberg et al.] hep-ph/0311263 arXiv:0811.4622

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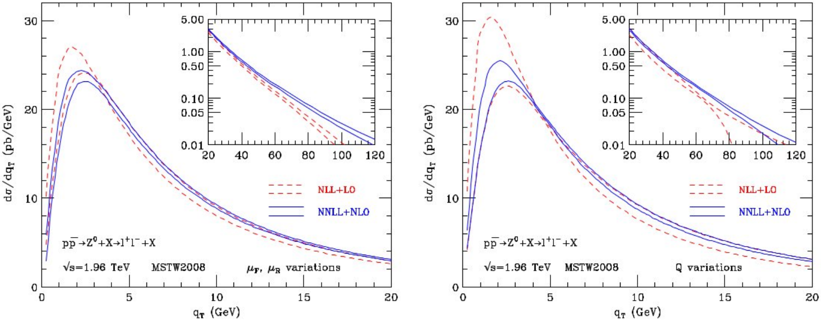
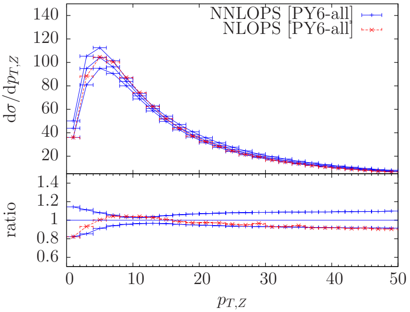
courtesy of Ye Li

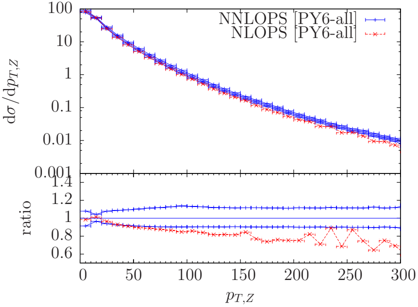
NNLL vs. NLL (analytic resummation)



plot from [Bozzi,Catani et al., 1007.2351]

NNLOPS vs. NLOPS (all included)





PY8 vs PY6: small p_T