Brief physics summary of the Monte Carlo generator workshop

[Hadron Collider Physics Summer School 2010]

Jan Winter

– Fermilab –

- *Monte Carlo event generation*
- *Vector boson production and parton showers*
- *V + n-jets using tree-level ME+PS merging*
- *V + n-jets @ next-to-leading order*

Monte Carlo modelling of a (high-p_T) event

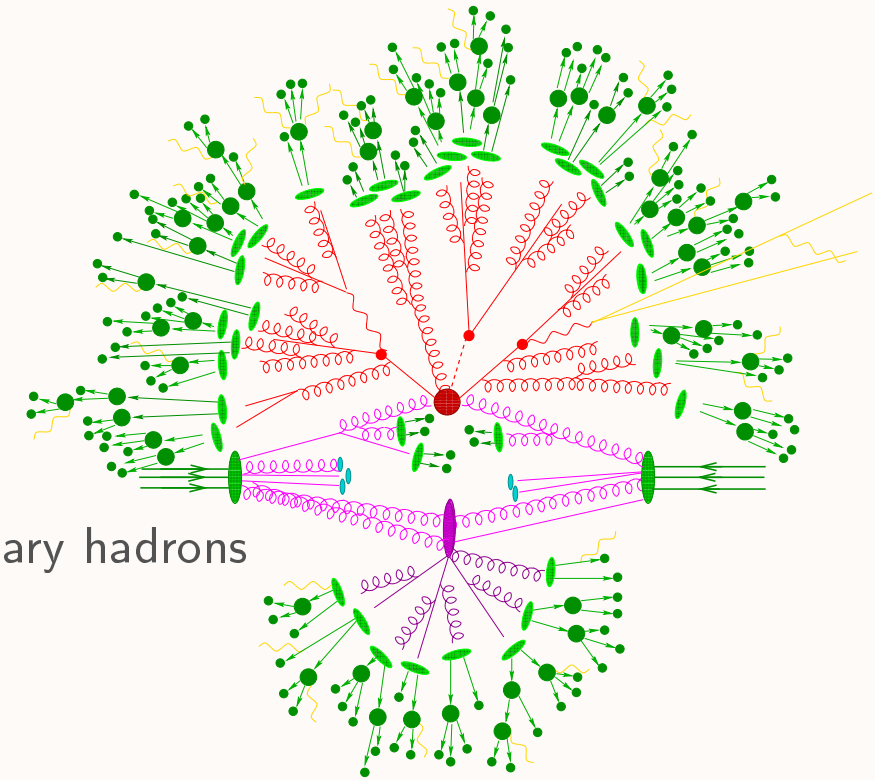
➔ ***Factorization approach: divide jet simulation into different phases***

➡ ***Perturbative Phases:*** *[parton jets]*

- ***Hard process/interaction (hard jet production)***
  exact matrix elements $|\mathcal{M}|^2$
- ***QCD bremsstrahlung (soft/coll multiple emissions)***
  initial- and final-state parton showering
- ***Multiple/Secondary interactions***
  modelling the underlying event

➡ ***Non-perturbative Phases:*** *[jet confinement – particle jets]*

- ***Hadronization***
  phenomenological models to convert partons into primary hadrons
- ***Hadron decays***
  phase-space or effective models to decay unstable into stable hadrons as observed in detectors



➔ predictions at hadron level – comparable to experimental data if corrected for detector effects

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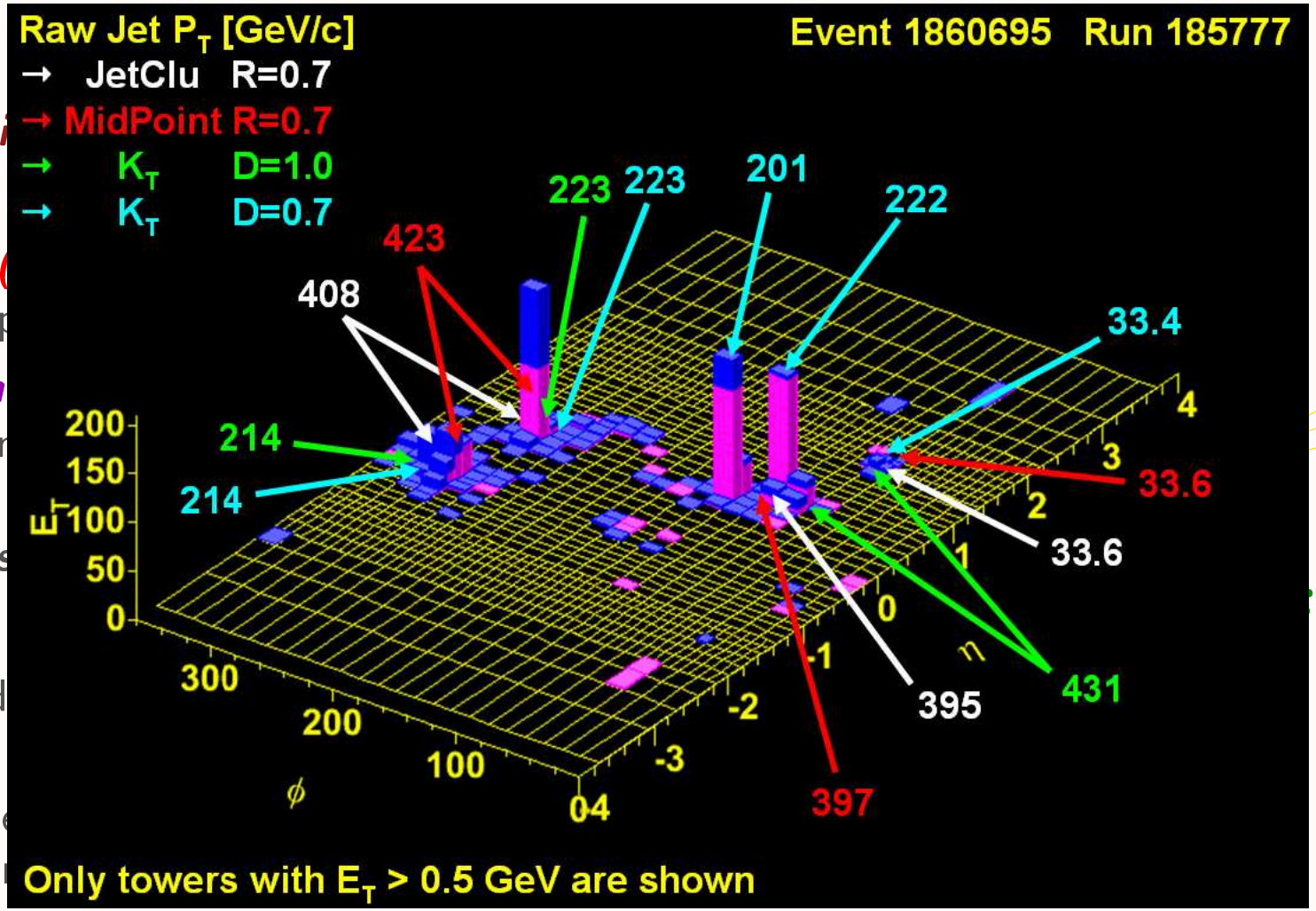
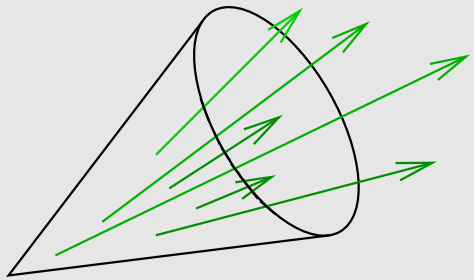


➔ predictions at hadron level – comparable to experimental data if corrected for detector effects

Monte Carlo modelling of a (high-p_T) event

Precise and compatible jet definition is necessary on theoretical and experimental level.



- Type: cone
  maximize energy within a cone
  $\Rightarrow$ radius $\times$ (pseudo-)rapidity $\times$ azimuthal angle

- Type: cluster
  identification and combination of nearest neighbouring particles
  infra-red safe k_T-measure: find minimal value of

$$Q_{ij}^2 = \min\{k_{T,i}^2, k_{T,j}^2\} \cdot (\Delta R_{ij}^2 / D^2) \quad \textit{and}$$

$$Q_{iB}^2 = k_{T,i}^2$$

where e.g. $\Delta R_{ij}^2 = 2\,[\cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)]$

➔ predictions at hadron level – comparable to experimental data if corrected for detector effects

Vector boson production

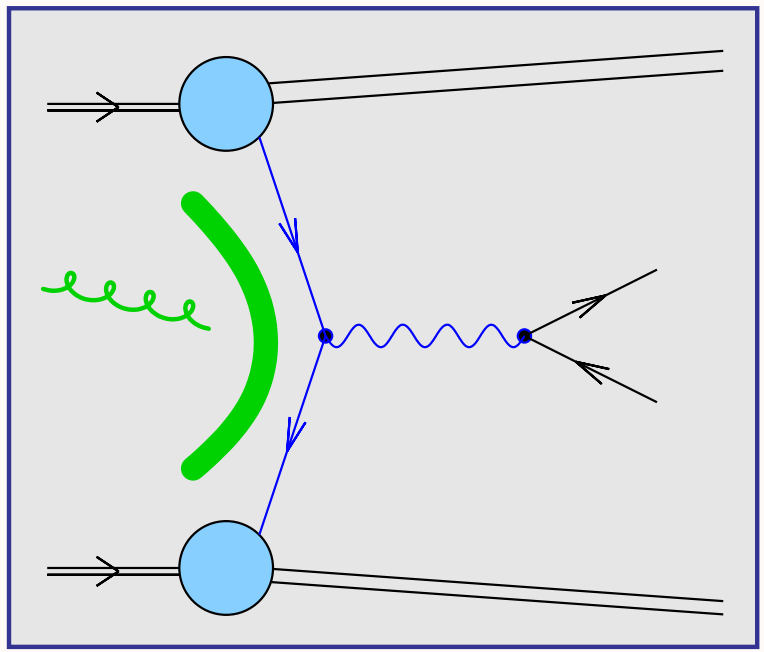
- calculation of the hadronic cross section relying on factorization theorem
  ... ... expected to hold for $A + B \to V + X$ [COLLINS, SOPER, STERMAN, 2004 REVIEW]

$$\sigma_{\rm hadr} = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, \mu_{\rm F}) \; f_j(x_2, \mu_{\rm F}) \; \sigma_{\rm part}(ij \to V \to \ldots)$$

$\sigma_{\rm part}$ ... calculable in pQCD; f_i = parton density functions (PDFs) ... extracted from data;
separation of perturbative and non-perturbative regimes ➡ pQCD used to predict cross sections in complicated hadron collider environment

- V production @ LO: two initial-state partons fuse to make either $W^\pm \to \ell\nu$ or $Z/\gamma^* \to \ell^+\ell^-$
  vector boson has no transverse momentum

- V + n-jet production @ LO: vector boson recoils against one or more jets (parton-level jets)
  ⬅ highly automated ME generators @ tree level
  - Alpgen, MadGraph, Helac, Amegic, Comix, Whizard, LO MCFM

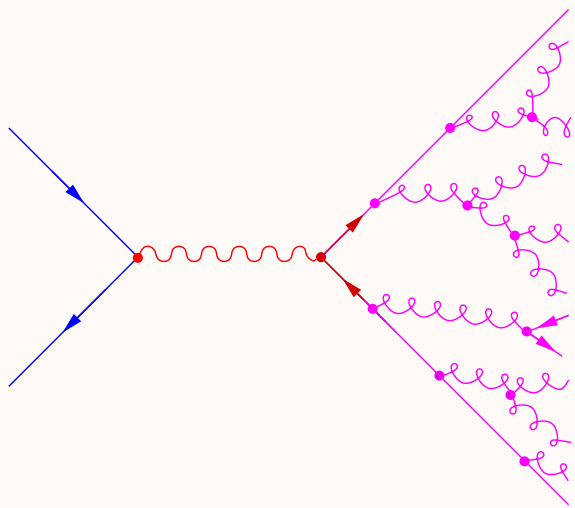


Parton shower concept

Traditional approach: describe additional jet activity by parton showers.

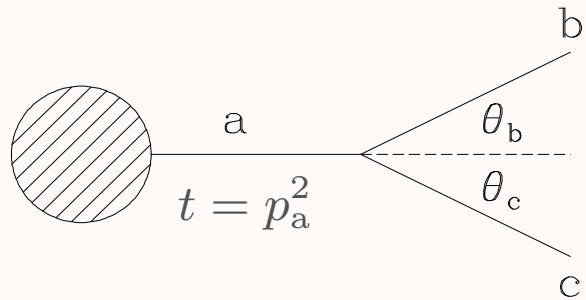
➡ ***QCD emissions preferably populate collinear and soft phase-space regions.***

[Pythia, Herwig, Ariadne]



- QCD amplitudes factorize in the coll/soft limit.
- ➡ Recursive definition of multiple emissions:

$$d\sigma_{n+1} \;=\; d\sigma_n \, \frac{\alpha_s(t)}{2\,\pi} \, \frac{dt}{t} \; dz \, P_{a\to bc}(z) \qquad \text{(e.g. coll limit)}$$

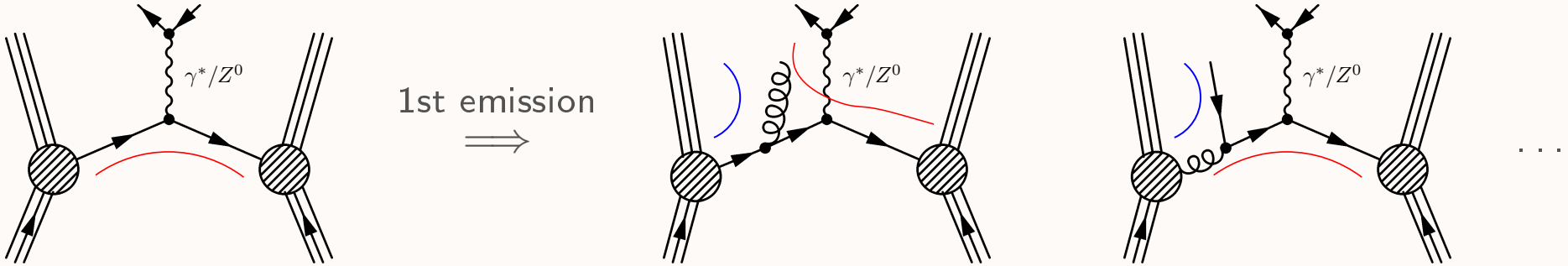


- coll/soft parton emissions iteratively added to the initial/final states *[LL resummation]*
- good description of bulk of radiation and particle multiplicity growth
- partonic ensemble evolved down to hadronization scale *[ordering variable Q, ϑ, p_T]*
  - ➡ provides suitable input for universal hadronization models *[$\mathcal{O}(1\ \text{GeV})$]*

➡ <u>vector boson production:</u> inclusive V + n-jets prediction @ LO+LL

Example: Sherpa's Catani–Seymour shower

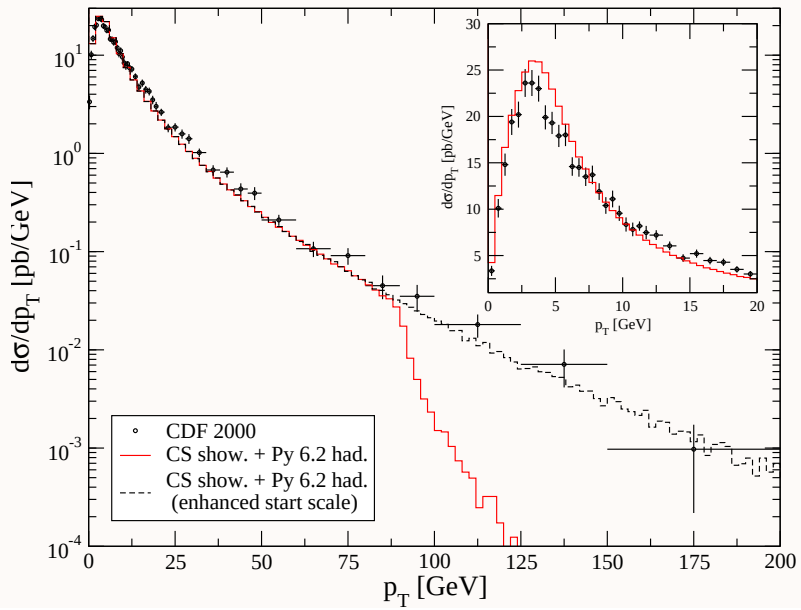
- universal dipole terms describe $1 \to 2$ parton splittings, exponentiated in Sudakov form factor
- correct soft & coll. limits; $2 \to 3$ kinematics: spectator used to conserve E, $\vec{p}$ locally
- Drell–Yan production:



- hard scale fixed by $M_{ee}^2 \Rightarrow \mathbf{k}_{\perp,\max}^2$

CS Shower [SCHUMANN, KRAUSS, JHEP 03 (2008),038]

- transverse momentum of lepton-pair determined by multiple QCD emissions



- comparison with Tevatron CDF data
  - rate normalised to data
  - dominant contribution for p_T^{ee}
  - Sudakov damping for $p_T^{ee} \to 0$
  - hardest emission below $\mathbf{k}_{\perp,\max}$
    $\hookrightarrow p_T^{ee} > \mathbf{k}_{\perp,\max}$ matrix-element regime
- ME corrections can be implemement to improve 1st emission

V + n-jet predictions @ LO+LL and beyond

Examples for shower Monte Carlos

- Pythia – virtuality ordering, $1 \to 2$ (old) and p_T ordering, $2 \to 3$ [SJÖSTRAND, SKANDS, MRENNA]
- Herwig – angular ordering, $1 \to 2$ [WEBBER, MARCHESINI, SEYMOUR, RICHARDSON]
- Ariadne – Lund colour-dipole model, p_T ordering, full $2 \to 3$ [LÖNNBLAD, GUSTAFSON, ANDERSSON]
- Sherpa's CS shower – based on CS subtraction terms, p_T ordering, $2 \to 3$ [SCHUMANN, KRAUSS]

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Limitations

- shower seeds are LO (QCD) processes only
- lack of high-energetic large-angle emissions
- semi-classical picture; quantum interferences and correlations only approximate
- shower evolution proceeds in the limit of large N_{C} (number of colours)

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Possible improvements

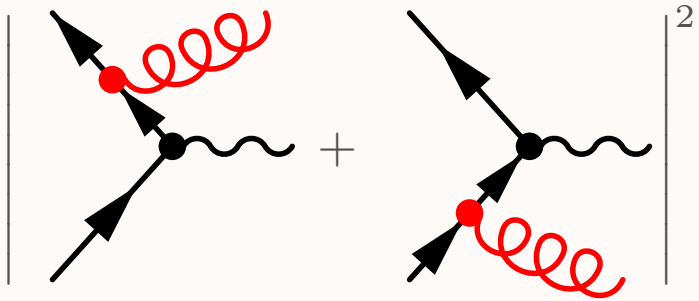
- first few hardest emissions given by tree-level MEs ➡ improved LO+LL predictions

  [called (tree-level/LO) ME+PS merging – CKKW, L-CKKW, MLM, ME&TS – No NLO xsecs!]

- use NLO QCD core processes and match to parton showers ➡ NLO+LL predictions

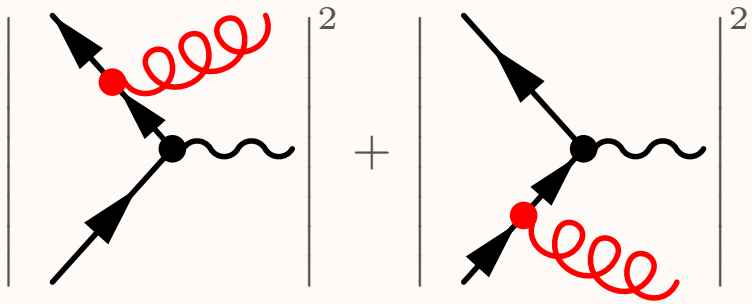
  [called NLO+PS matching – MC@NLO, POWHEG – Full NLO xsecs!]

matrix element:



$$|A_R|^2 + |B_R|^2 + 2\,\mathrm{Re}(A_R B_R^*)$$

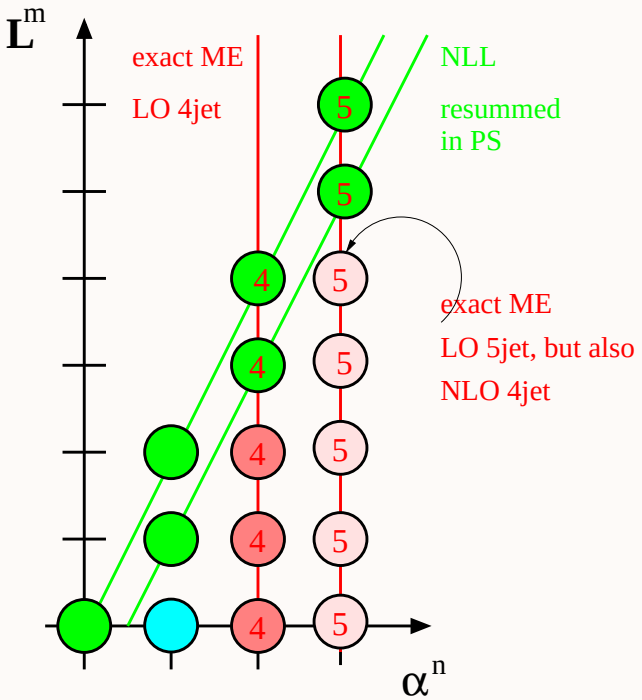
parton shower:



$$|A_R|^2 + |B_R|^2$$

Combine ME&PS advantages, remove ME&PS weaknesses.

Beware of double counting, preserve universality of hadronization.



α_S *vs. Log*

Tree-level ME+PS merging

- combine parton-shower pros (soft emissions) $+$
  ME pros (hard emissions, quantum interferences, correlations)
- avoid double counting and missing phase-space regions

Divide multi-jet phase space into two regimes:

- tree-level MEs: jet seed (hard parton) production $Q > Q_{\rm jet}$
- parton showers: (intra-)jet evolution $Q_{\rm jet} > Q > Q_{\rm cut-off}$

Examples for ME+PS merging Monte Carlos:

- Alpgen – MLM; interfaced to Pythia or Herwig [Mangano et al.]
- MadGraph – MLM, cone or k_T jets; interfaced to Pythia [Maltoni et al.]
- Sherpa – CKKW, ME&TS from vs1.2; truly interconnected with PSs [Krauss et al.]

Methods mainly differ in:

- the jet definition used to define/regularize the MEs,
- the way of accepting/rejecting jet configurations stemming from the MEs,
- the details concerning the starting conditions of the parton showering and the jet vetoing inside the shower algorithm.

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  - Alpgen – ML
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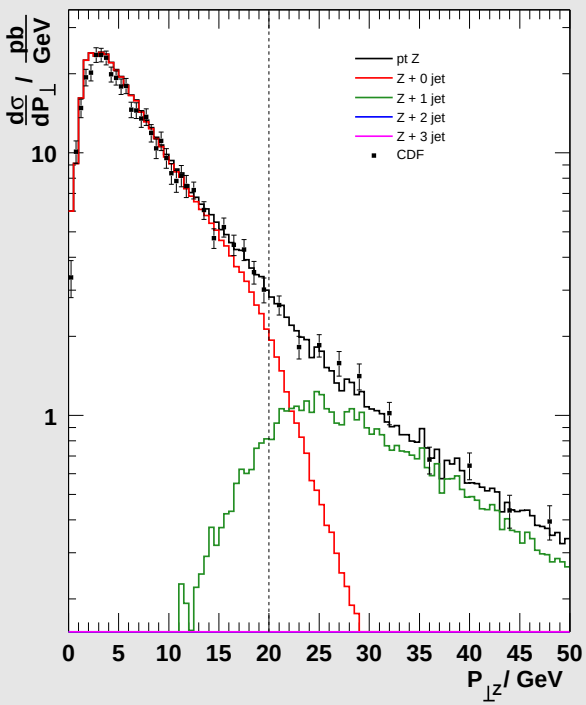
    - the jet
    - the way
    - the det
      the jet

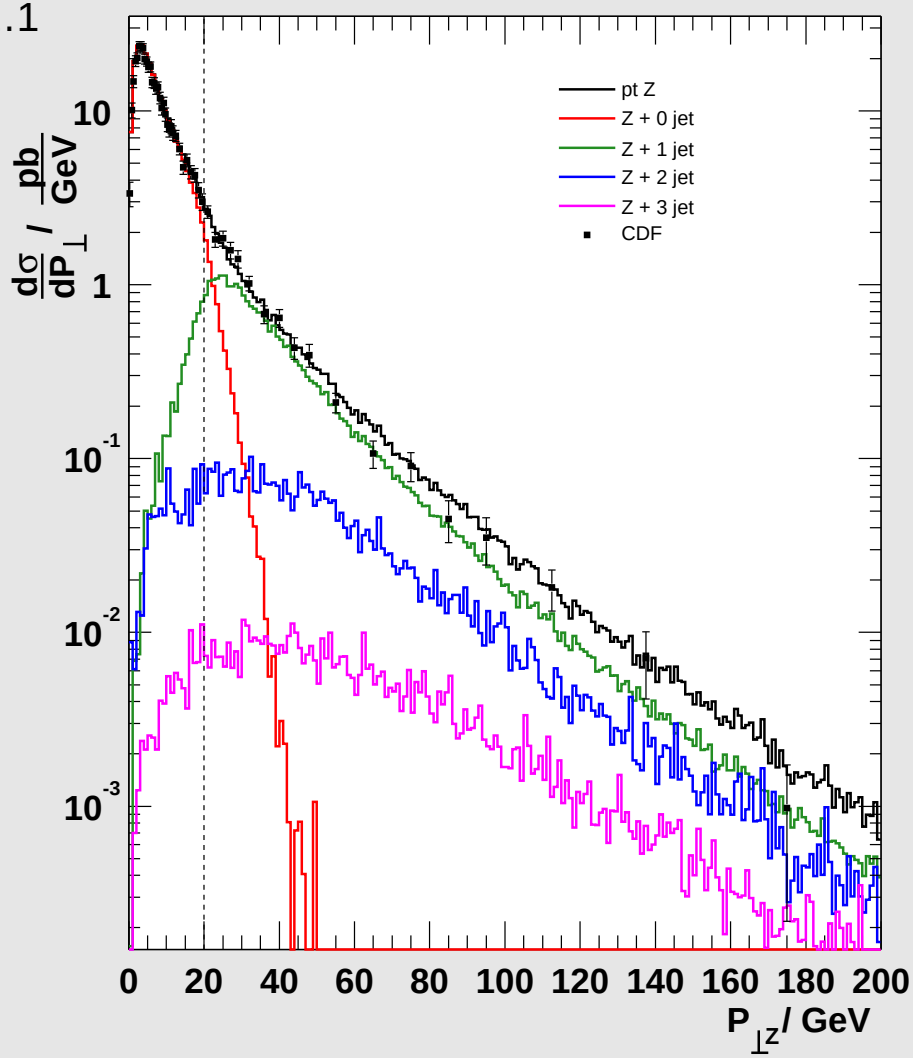
CKKW

[Catani, Krauss, Kuhn, Webber, JHEP 11 (2001) 063]
[Krauss, JHEP 08 (2002) 015]

⇒ in Sherpa vs1.0 and vs1.1
e.g. Z + jets @ 1.8 TeV

- AMEGIC + APACIC
- constant K-factor
- intrinsic k_T-smearing of order 1 GeV





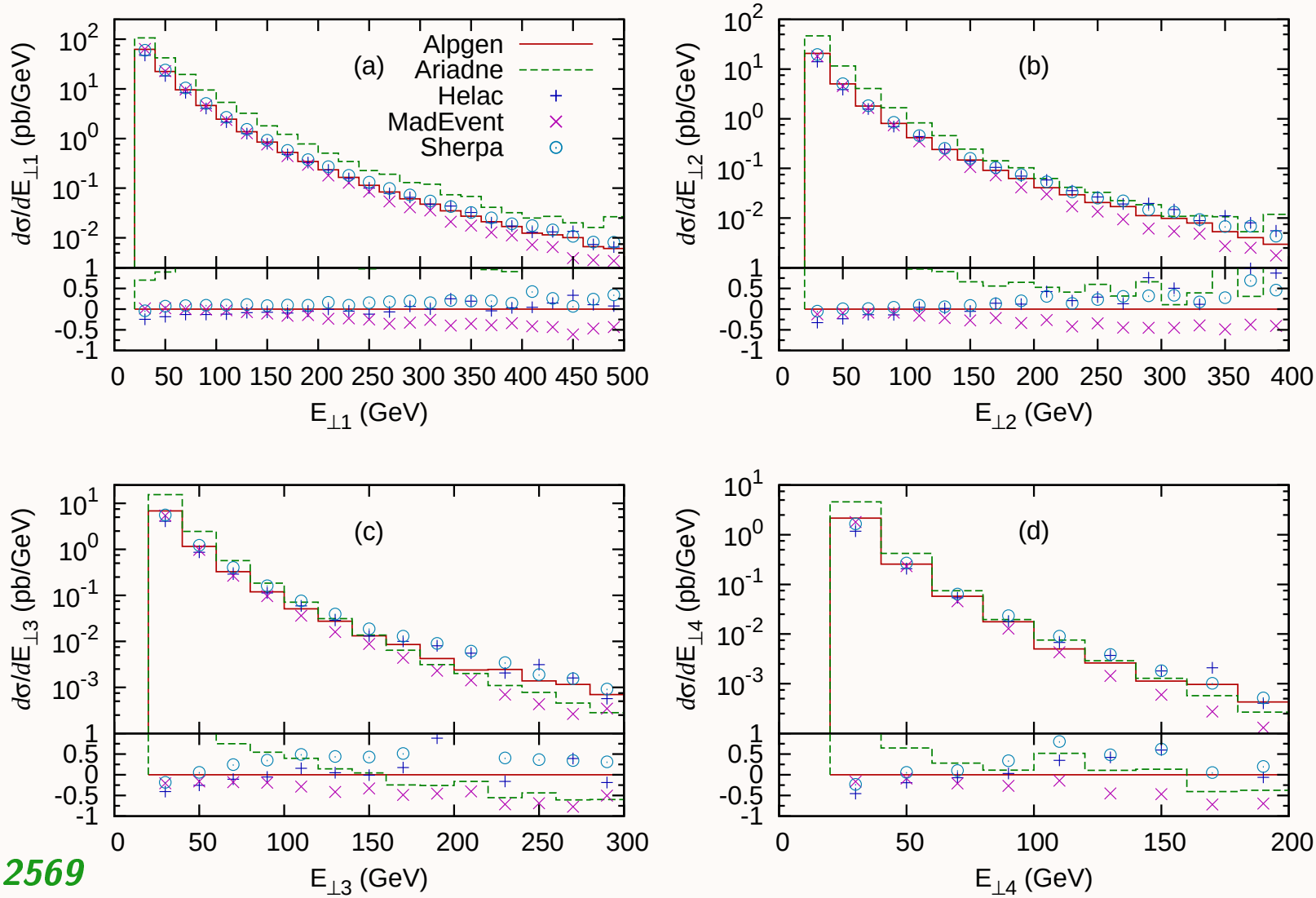
Krauss et al. PRD 70 (2004) 114009

Comparison between merging approaches

➡ *Tree-level ME+PS merging predictions of Alpgen, Ariadne, Helac, MadEvent and Sherpa.*

$W^+ + X$

- *jet E_T spectra at the LHC*
- *similar pattern wrt Tevatron*
- *extrapolation to LHC energies makes differences more pronounced*
- *Results in arXiv:0706.2569 (EPJC 53 (2008) 473)*



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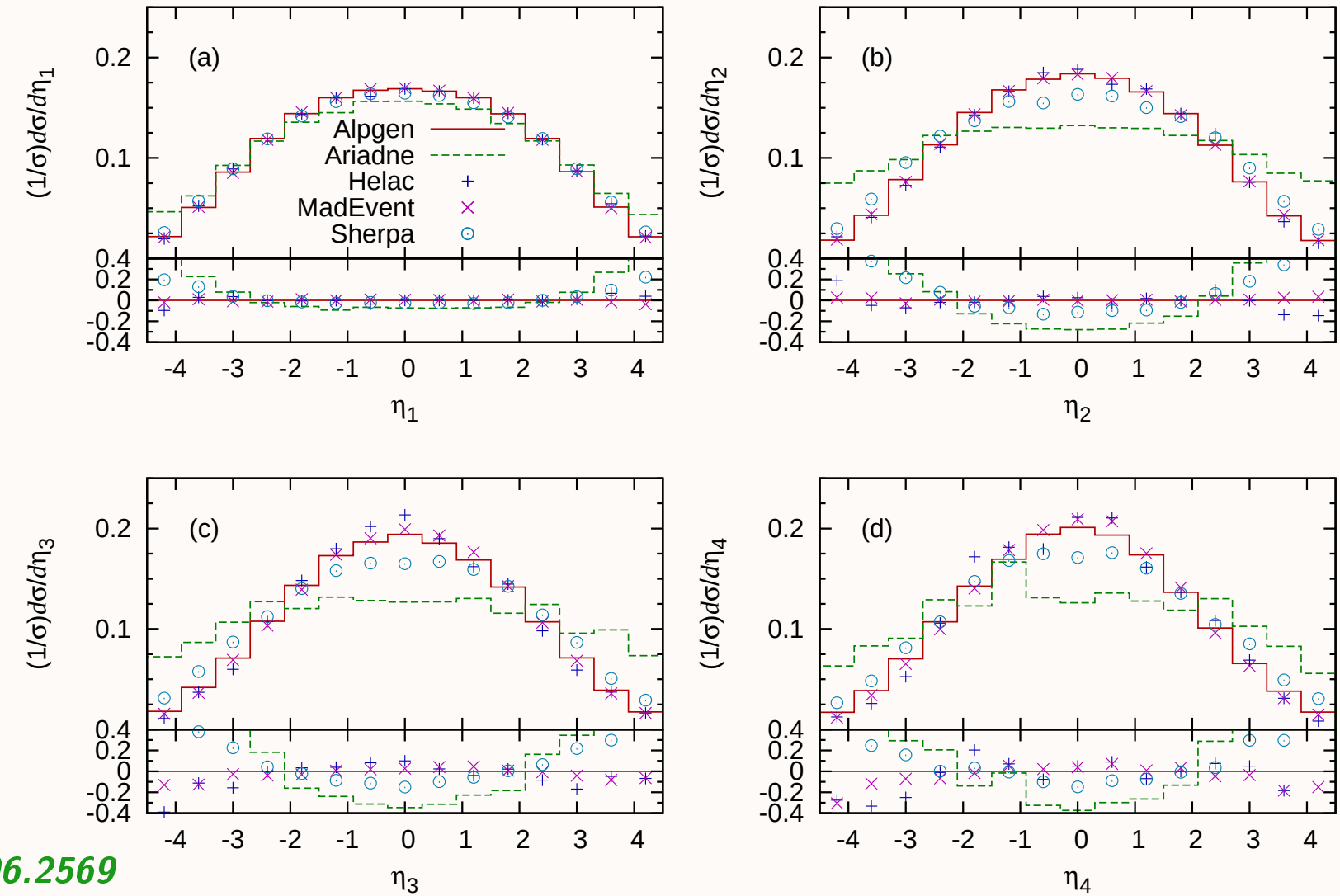
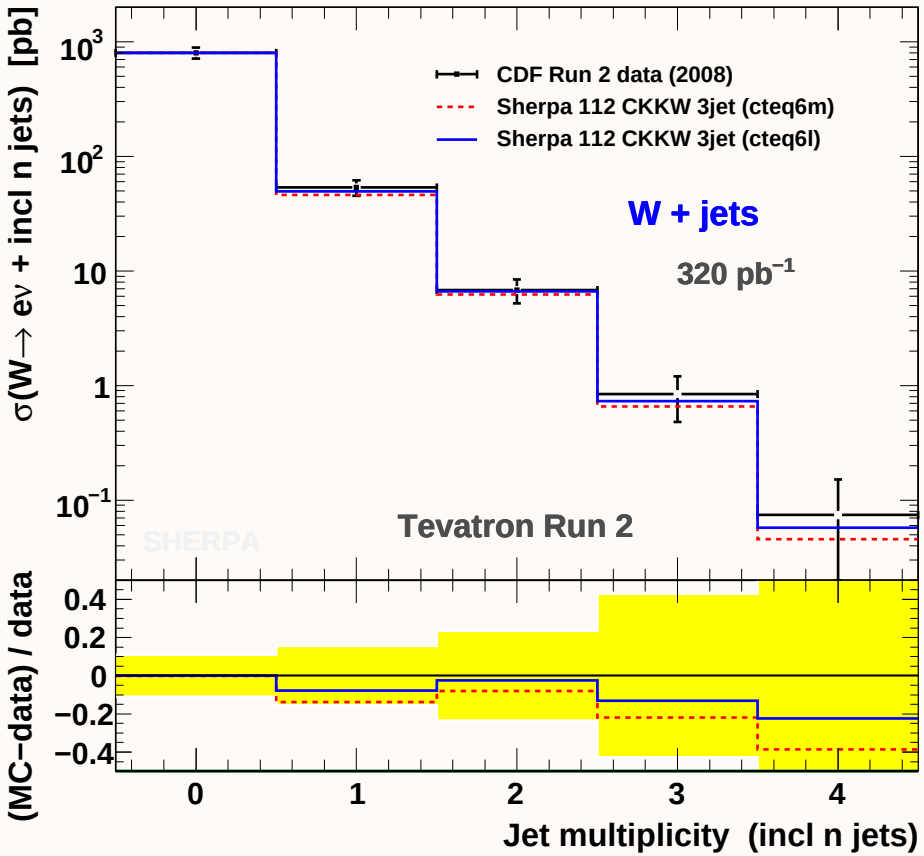
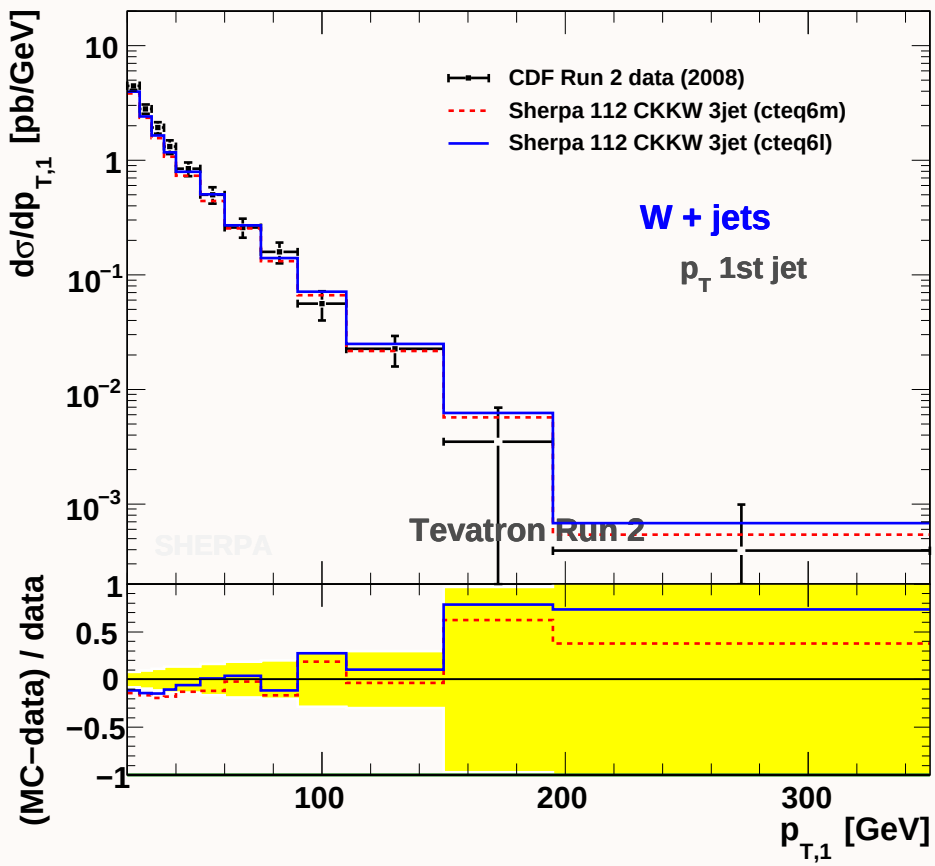


Comparison with CDF data: W+jets production

[T. AALTONEN ET AL., PRD **77** (2008) 011108]

- Monte Carlos need to be validated and tuned against most recent Tevatron data.
- Sherpa vs1.1.3 predictions normalized to total inclusive cross section. Two choices of PDFs.
- Tree-level ME+PS can reproduce W+>=n-jet xsecs to 20% after applying overall K-factor.





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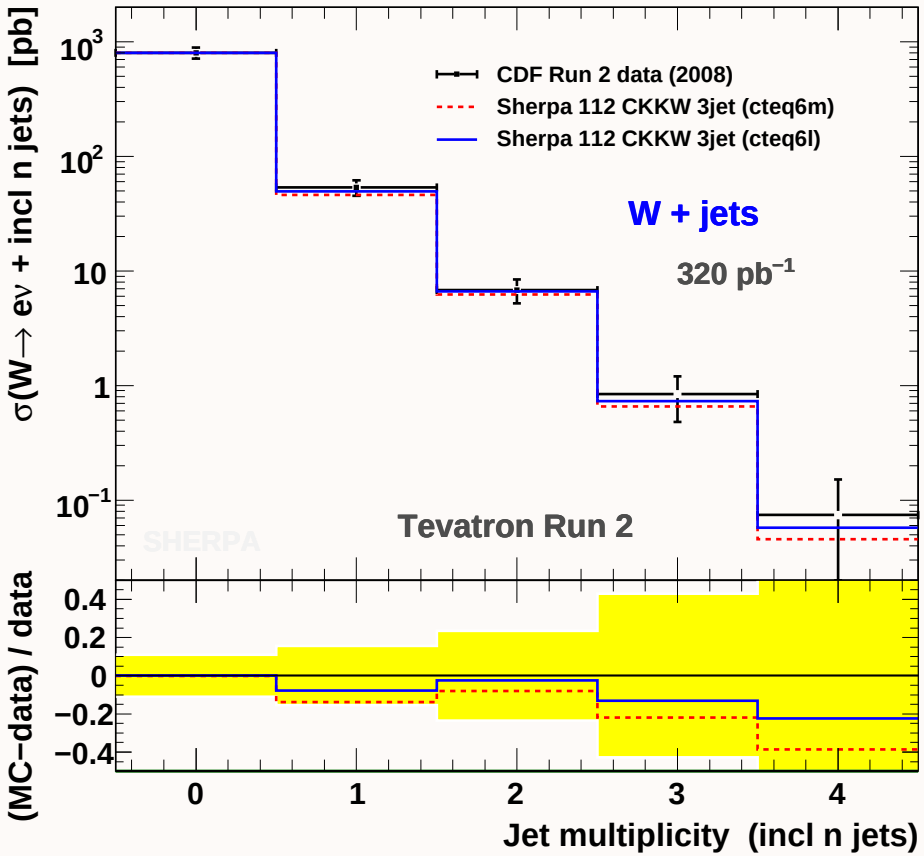

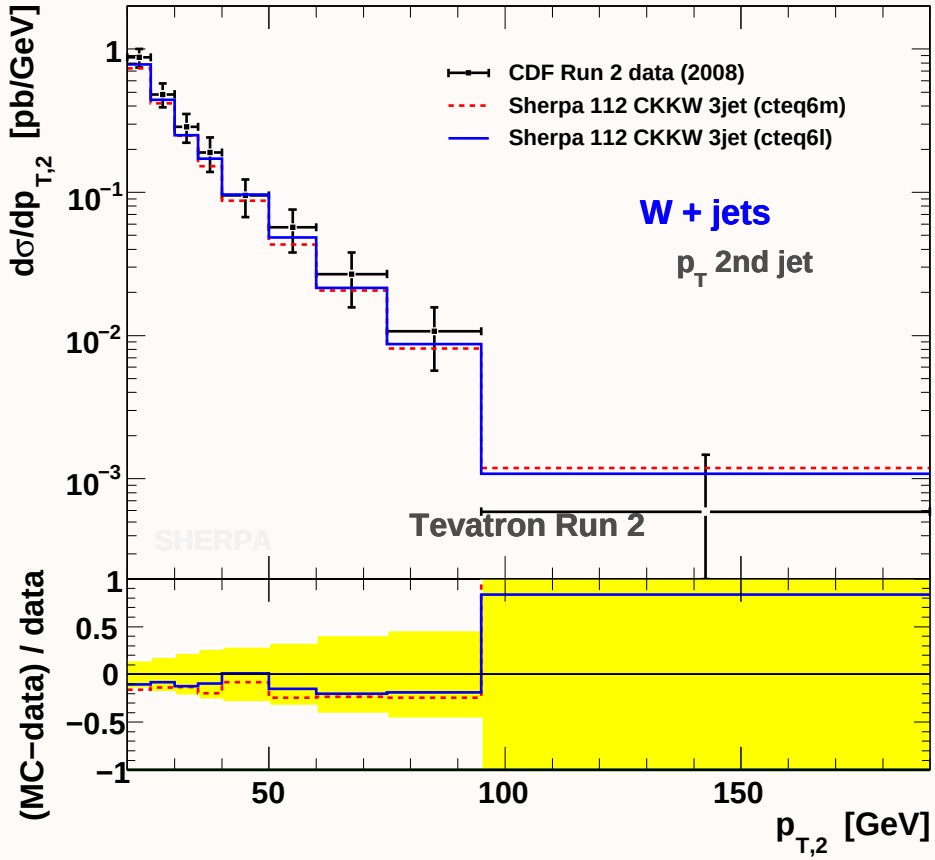

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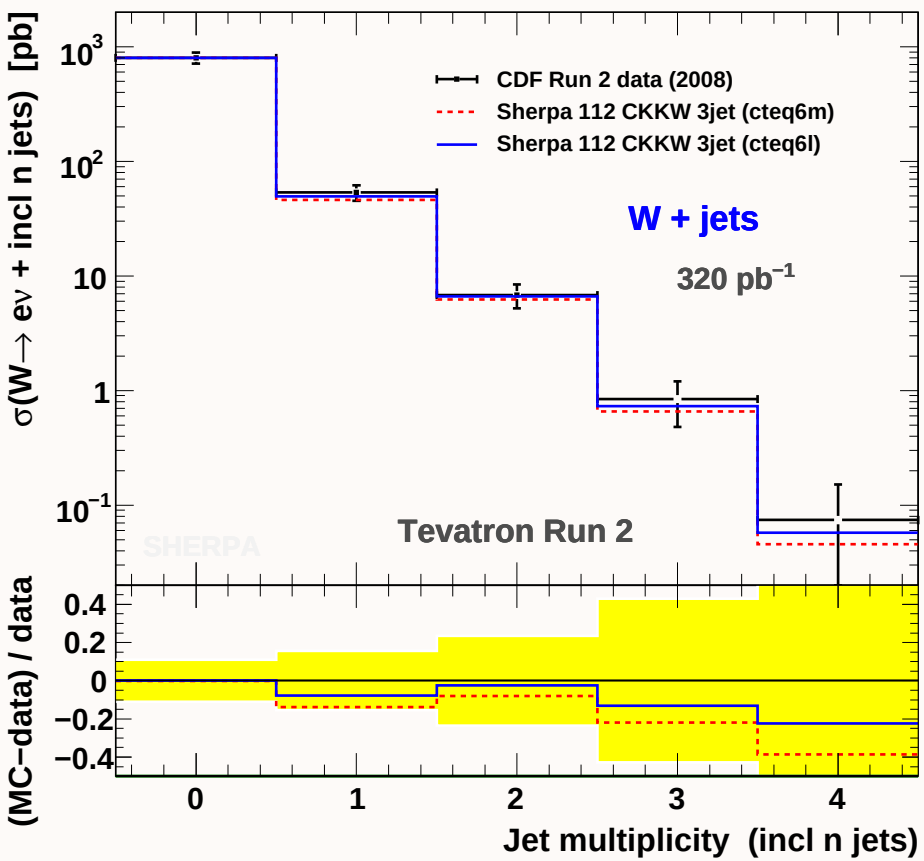
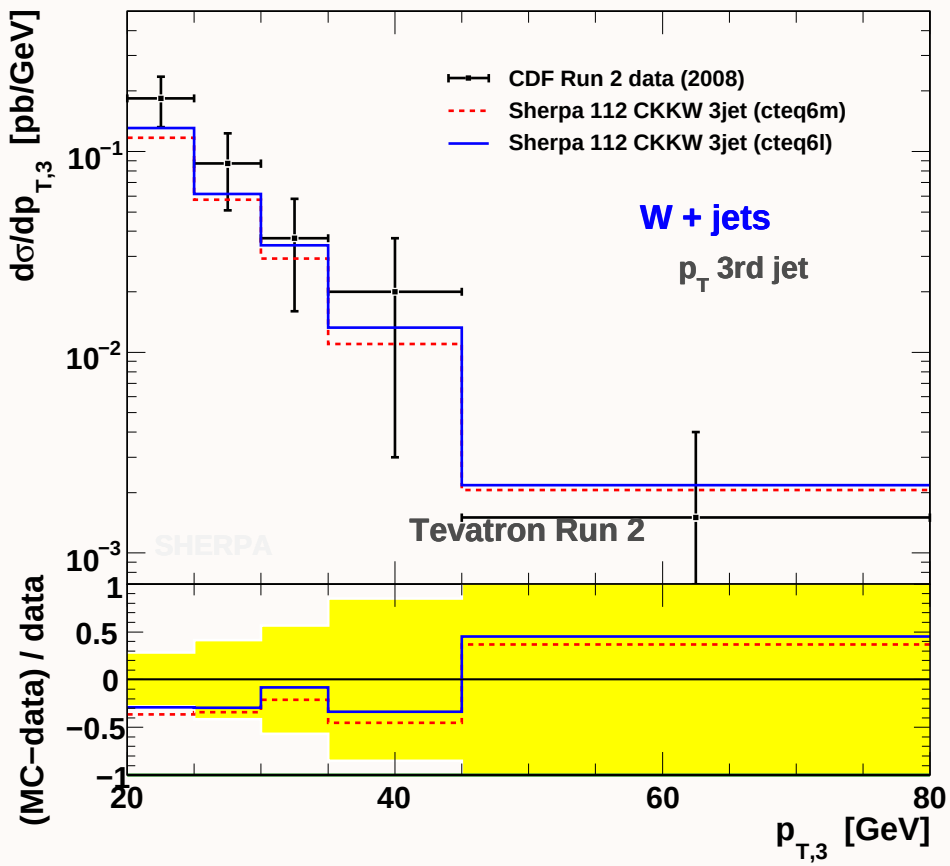
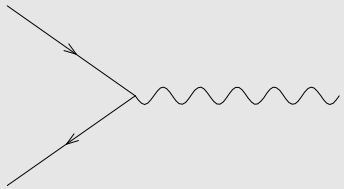




V + n-jets ....

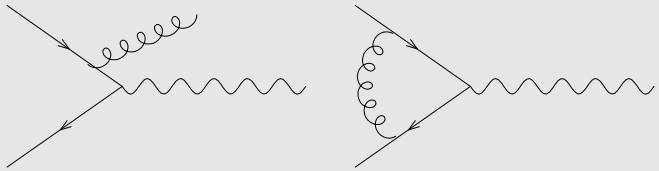
at & beyond NLO ... ..

LO



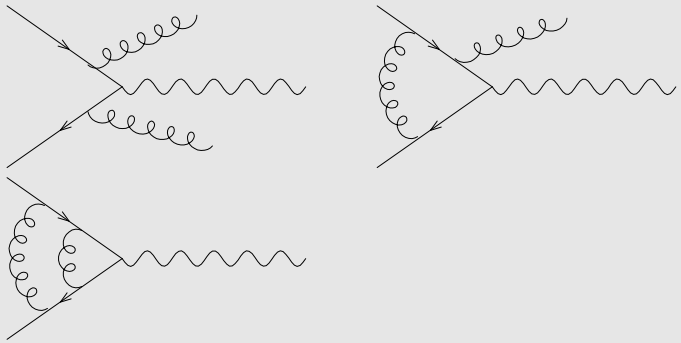
$$\left|\mathcal{A}^{(0)}_{q\bar{q}'}\right|^2$$

NLO



$$\left|\mathcal{A}^{(0)}_{q\bar{q}'}\right|^2, \quad \Re(\mathcal{A}^{(0)}_{q\bar{q}'}\mathcal{A}^{(1)\star}_{q\bar{q}'})$$

NNLO



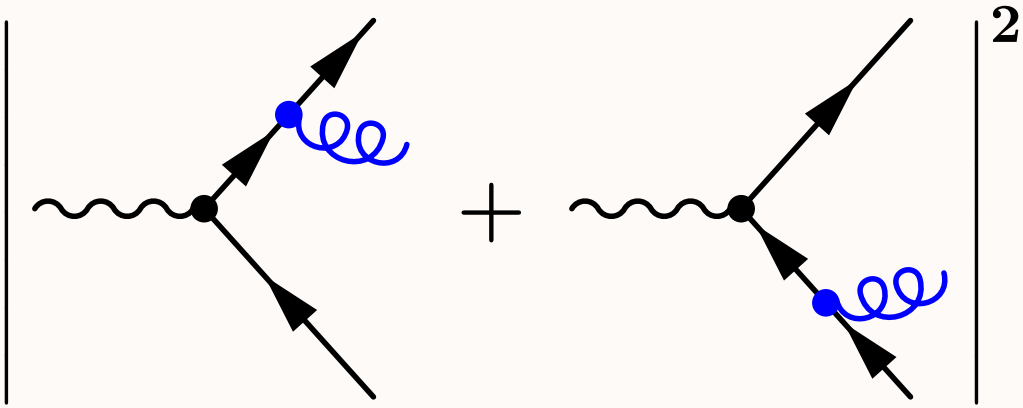
$$\left|\mathcal{A}^{(0)}_{q\bar{q}'}\right|^2, \quad \Re(\mathcal{A}^{(0)}_{q\bar{q}'}\mathcal{A}^{(1)\star}_{q\bar{q}'}),$$
$$\Re(\mathcal{A}^{(0)}_{q\bar{q}'}\mathcal{A}^{(2)\star}_{q\bar{q}'}), \quad \left|\mathcal{A}^{(1)}_{q\bar{q}'}\right|^2$$

and so forth...

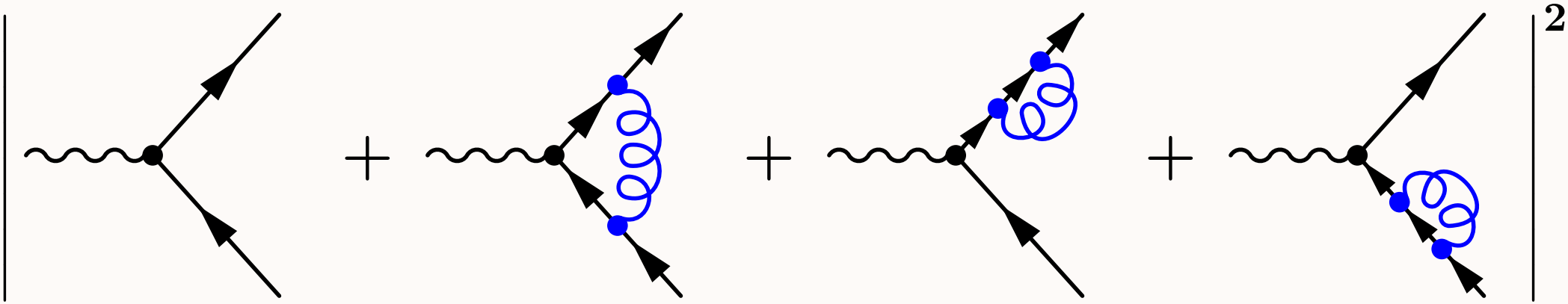
Inclusion of all diagrams contributing at a given order in α_s leads to LO, NLO, NNLO, ... results.

A well known example

➡ ***$\mathcal{O}(\alpha_s)$ corrections to virtual-photon decay to quark–antiquark pair, $\gamma^* \to q\bar{q}$:*** $K = 1 + \frac{\alpha_s(\mu_R^2)}{\pi}$



- real gluon emission, real $\to \mathcal{O}(g_s)$
- Born + one additional leg
- infrared divergencies
- $|A_R|^2 + |B_R|^2 + 2\,\mathrm{Re}(A_R B_R^*)$

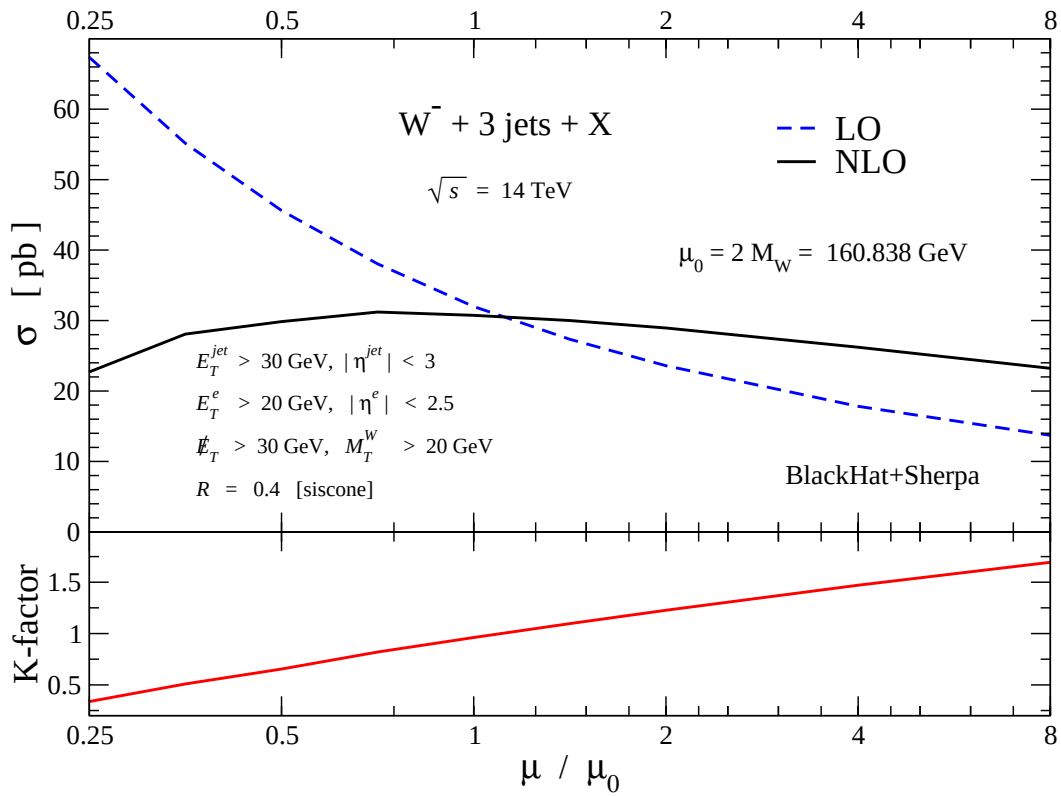


- virtual gluon corrections, virtual $\to \mathcal{O}(g_s^2)$, Born + one additional loop
- infrared (soft & collinear) and ultraviolet divergencies (removed by renormalization)
- $|A_0|^2 + 2\,\mathrm{Re}(A_0 A_V^* + A_0 B_V^* + A_0 C_V^*) + |A_V + B_V + C_V|^2$

Need for NLO calculations

➡ ***Lessons learned from LEP, HERA, Tevatron:***
LO predictions are fine, yet often only give rough estimates

@ NLO: 1st real prediction of normalization of many observables
less sensitivity to unphysical input scales (factorization and renormalization scales, $\mu_{\rm F}$ & $\mu_{\rm R}$)
more physics (parton merging, jet substructure, ISR, more IS parton species)



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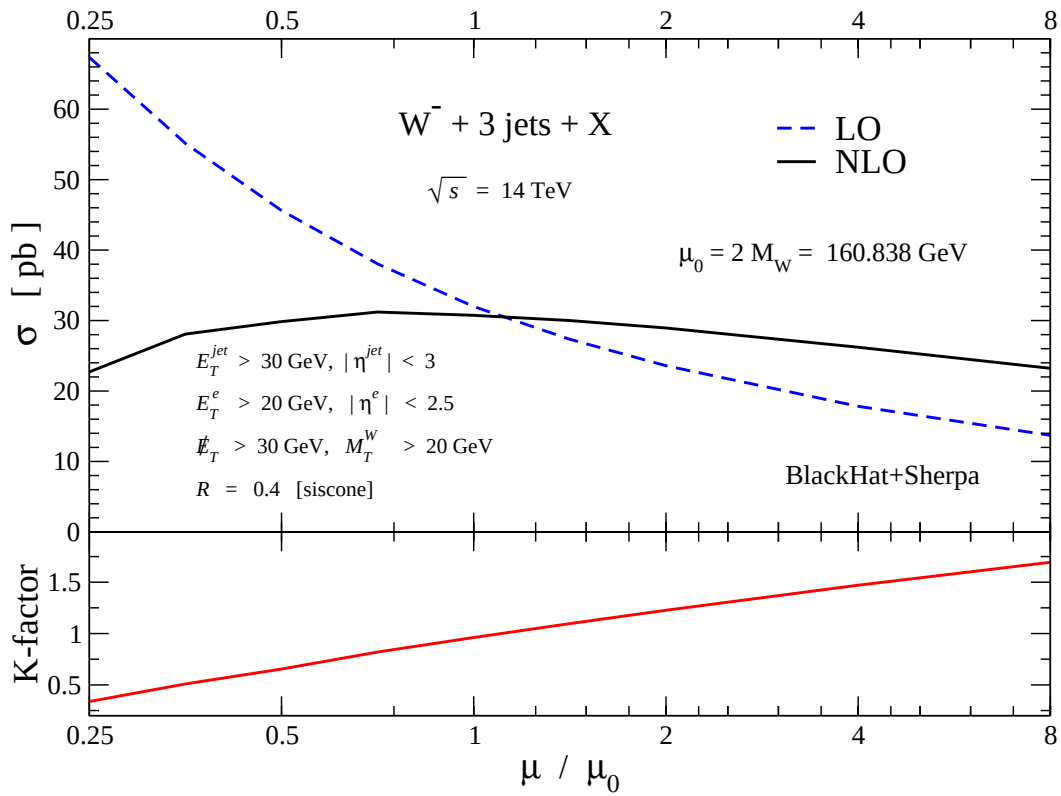
➡ ***Components of NLO calculations***

- tree-level amplitudes (LO & real radiation)
- \+ one-loop correction to Born level
- \+ subtraction terms to handle and combine singularities
- \+ phase-space generator



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➡ for example, BLACKHAT+SHERPA

$$\sigma = \int_m d\sigma^B + \int_{m+1} (d\sigma^R - d\sigma^A) + \int_m (d\sigma^V + \int_1 d\sigma^A)$$

➡ ***Componen***

- tree-level a
(LO & real

\+ one-loop co

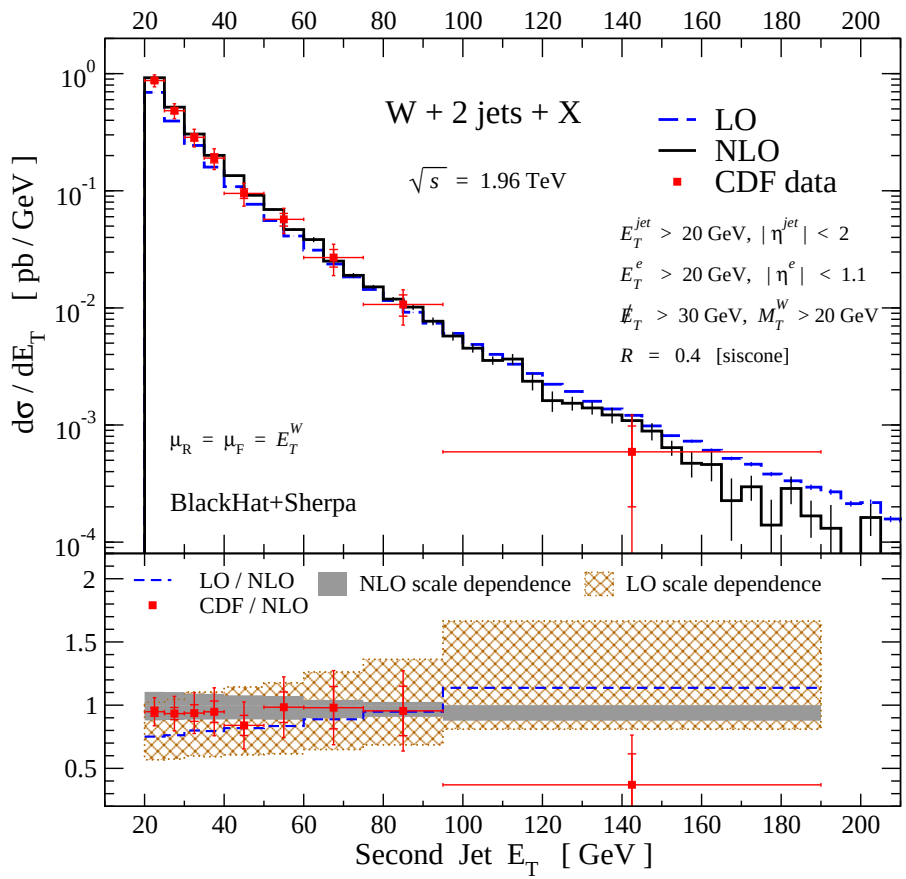
\+ subtraction
combine si

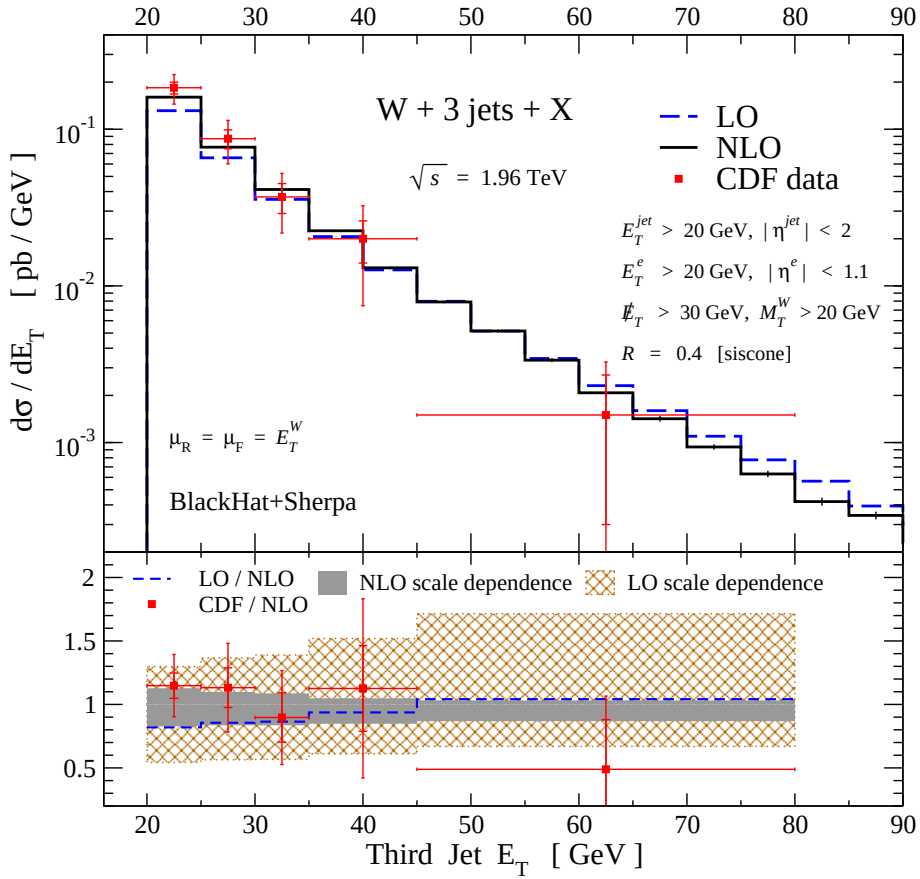
\+ phase-spac

BlackHat+Sherpa W+2,3-jets predictions

[Gleisberg, Krauss, EPJC53 (2008) 501] [Berger et al., Phys Rev D80 (2009) 074036]

- Reduced scale uncertainties: grey NLO bands are smaller wrt yellow LO bands
- LO rates are too low: first few bins contain $\lesssim$ cross section (log plot!) where LO undershoots
- LO shapes are distorted: Data/NLO is consistent with one.

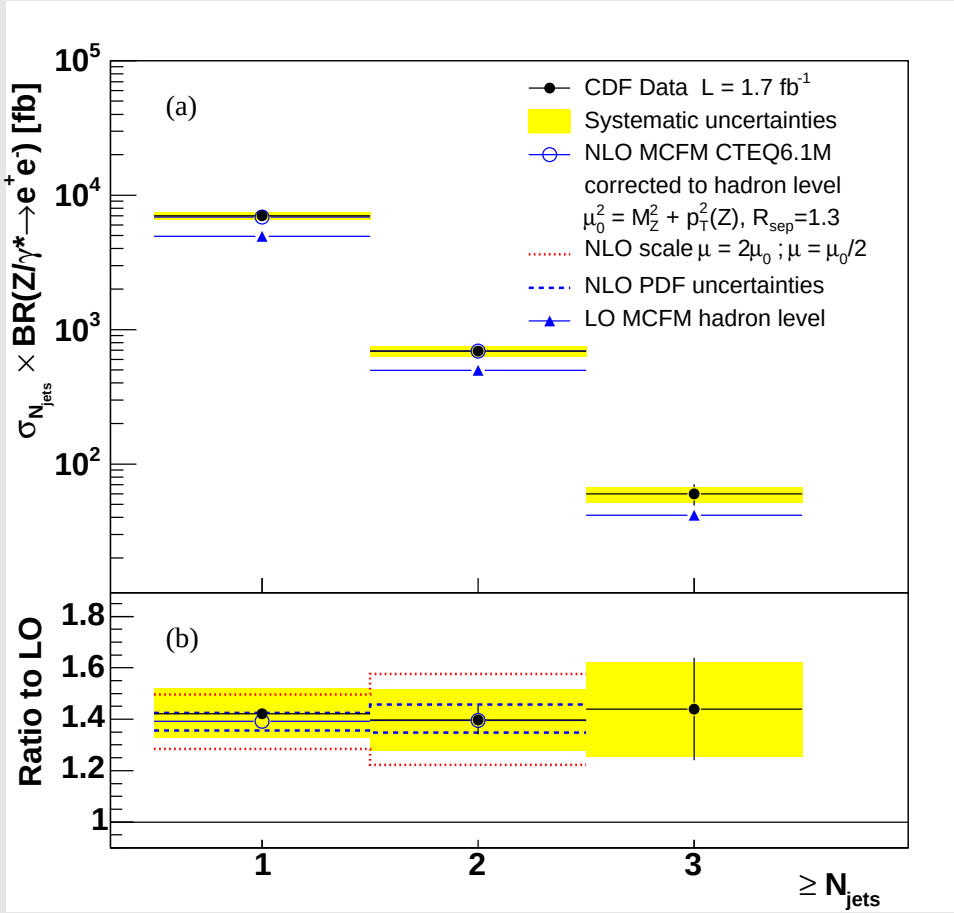


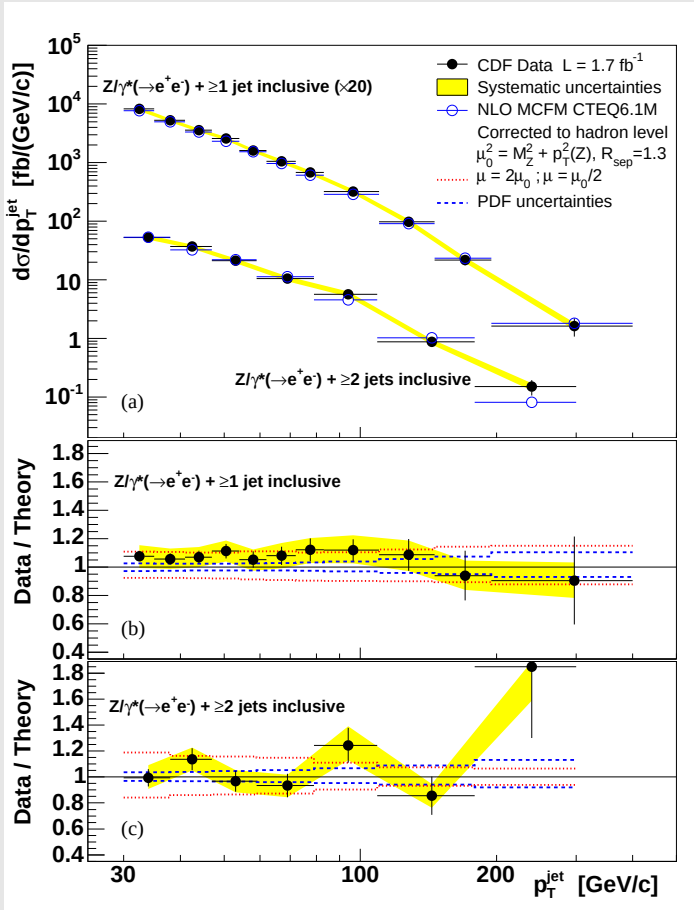


MCFM

[Campbell, Ellis, http://mcfm.fnal.gov/] [T. Aaltonen et al., PRL **100** (2008) 102001]

- NLO parton-level event generator for a range of processes at hadron colliders.
- Anybody can study V + 0,1,2 jets @ NLO (and LO) by running MCFM themselves.
- Spin correlations maintained in decays. Helicity amplitudes. Slightly modified CS subtraction.





Z+jets
CDF data
2007
1.7/fb

Comparison between MCFM and ME+PS merging

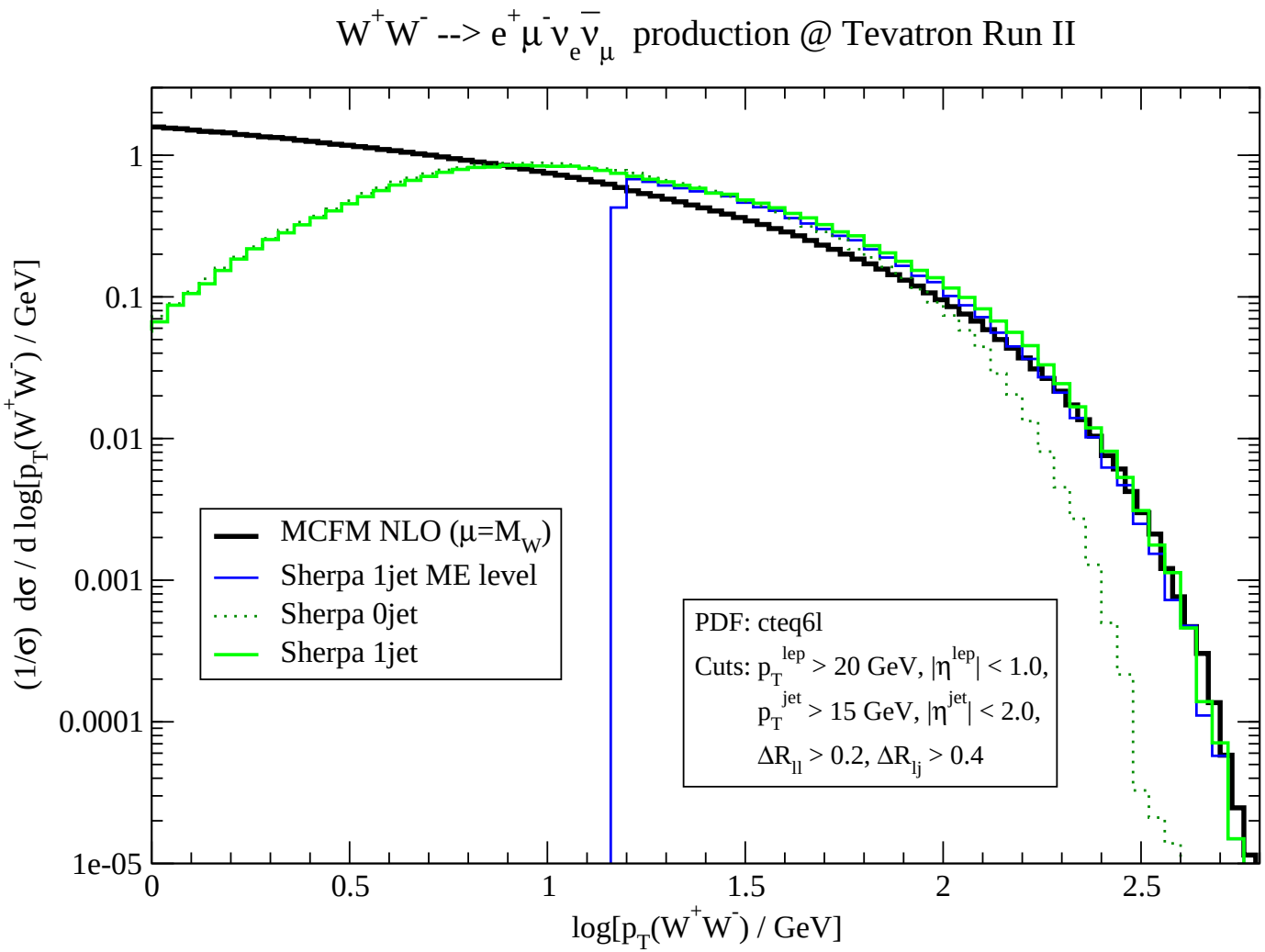
J.M. Campbell and R.K. Ellis, Phys. Rev. D ***60*** (1999) 113006

➡ $p\bar{p} \to W^+W^- + X$ @ Tevatron Run II: • p_T of the WW system

➡ MCFM @ parton level *vs.* Sherpa @ shower level

- @ LO, distribution described by delta peak at 0
- @ NLO, the p_T of the WW system "diverges" for soft p_Ts.

  ME+PS accounts for multiple soft-parton emission leading to a Sudakov suppression for $p_T \to 0$
- for large p_T, shapes of NLO and ME+PS agree well, since both include real-emission corrections @ same order



Beyond NLO

NLO+PS matching

- match PS to NLO preserving good features of PS (Sudakov suppression at small p_T, multiple soft/coll emissions) and NLO (rate, high-p_T shape, reduced scale dependence)
- among other processes, V production + decays fully correlated
- MC@NLO: http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/
  [Frixione, Webber; ...]
- POWHEG: http://moby.mib.infn.it/ nason/POWHEG/
  [Nason; Oleari, ...] work on Z+1jet under way

NNLO

- $pp \to Z/\gamma^* \to \ell^+\ell^-$ calculated by Petriello and Melnikov,
  show scale dependence is further reduced

q_T resummation + matching to higher orders

- calculations taylored to describe specific observable very accurately, e.g. p_T of V
- for example ResBos [C.-P. Yuan et al.]

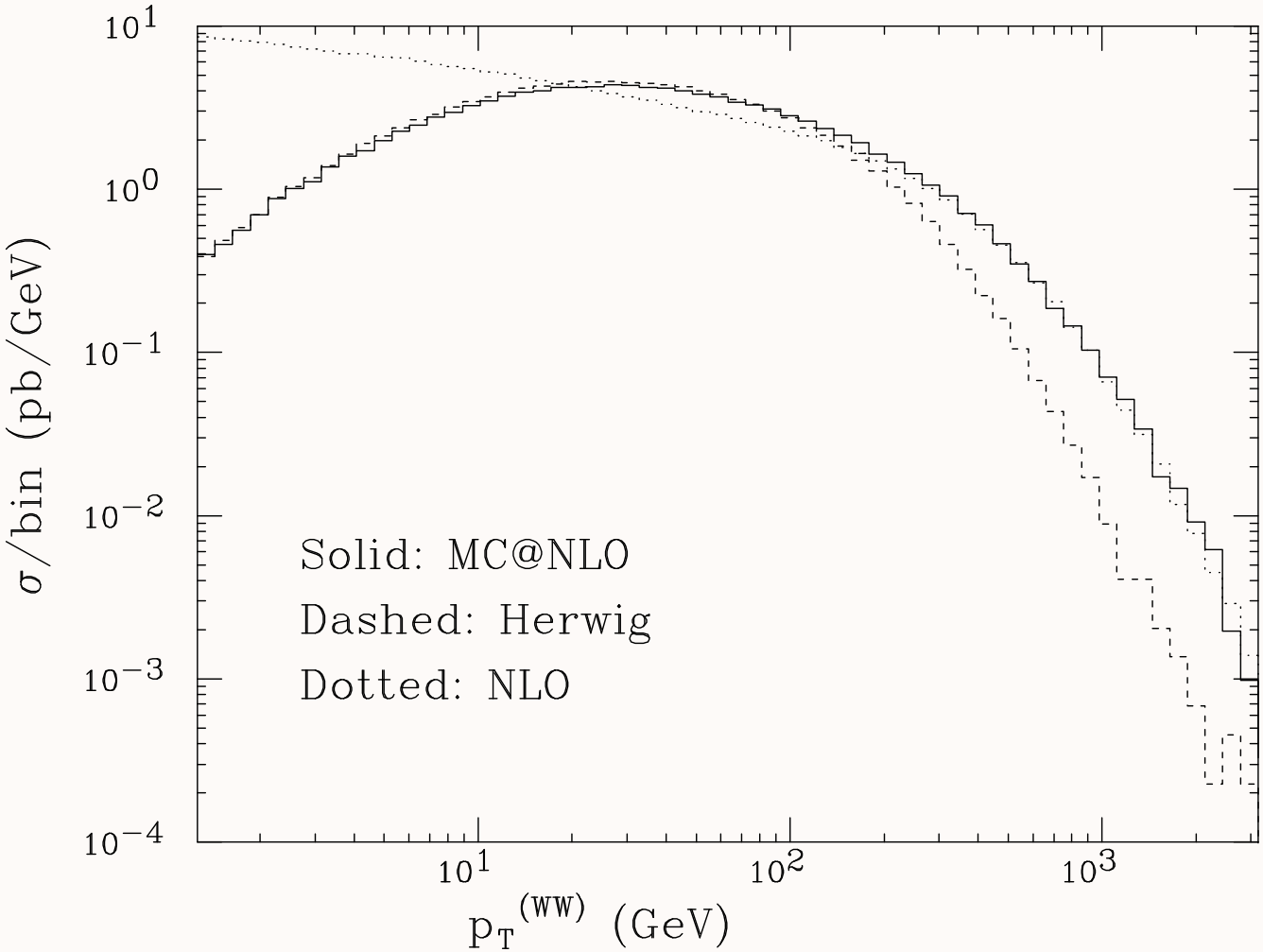
NLO+PS matching

for example MC@NLO: S. Frixione and B.R. Webber, JHEP ***0206*** (2002) 029

➡ $pp \to W^+W^- + X$ @ 14 TeV LHC: • p_T of the WW system

➡ rate & shape comparison

MC@NLO *vs.* Herwig PS and NLO prediction



- naive NLO+PS leads to double counting
- PS has real-emission contribution due to final-state branching
- PS has virtual contribution due to no-branching probability
- solution: subtract PS evolution terms from $2 \to n+1$ and add back to $2 \to n$
- NLO results recovered upon expansion of NLO+PS in α_s, matching is smooth, no phase-space separation cut, final states can be hadronized

Summary

- In a high-energy hadron collider environment the production of W/Z bosons is always affected by QCD radiation.

  $\Rightarrow$ recoiling against "QCD" generates the vector boson's p_T distribution.

- Parton showers can capture the leading effects of soft and collinear emissions.

  $\Rightarrow$ for certain observables, e.g. $p_{T,V}$, analytic resummations go beyond these limits

- Vector bosons often come with additional hard jets.

  $\Rightarrow$ V + n-jets is a major background to all new physics searches.

- Parton showers can be improved by merging them with real-emission MEs for hard radiation.

  $\Rightarrow$ CKKW, MLM, ...

  Comparison with data: differences are on 20–40% level if an overall K-factor is used to correct for the total inclusive cross section as measured in the experiment.

- V + n-jets @ NLO: not only predicts shapes but also total rate @ NLO.
  Observables that are sensitive to multiple soft parton emission cannot be described.
  Hadronization and jet corrections are needed to compare to data.

  $\Rightarrow$ NLO+PS matching improves on these last two points.

Summary

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- Parton showers c

  $\Rightarrow$ for cer

- Vector bosons of

  $\Rightarrow$ V + n-

- Parton showers c

  $\Rightarrow$ CKKW

  Comparison with
  correct for the to

- Please do not hesitate to ask your questions now (and later during the school).
- Look forward to hear and learn more in John Campbell's lectures on QCD.

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