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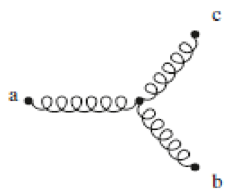
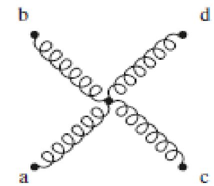
Théorie de la production des jets et des bosons W et Z au LHC

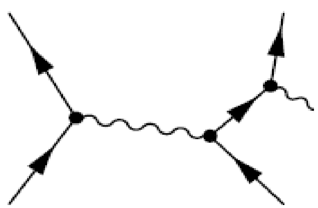
1) Fixed order calculations.
2) Resummations
3) EW corrections
4) Summary

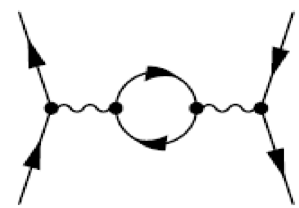
Slides taken from F. Petriello, M. Mangano, D. Kosower, P. Skands





Fixed order calculations





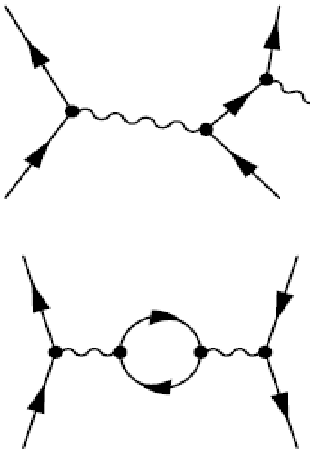
1.1) Fixed order pQCD

- Basic concept of the fixed order calculations: develop the observable in a serie in strong coupling α_s

$$\mathcal{R} = \sum_{j=0}^{\infty} M_j \alpha_s^j$$

- For each observable LO is defined as minimal “j” value for which M_j != 0.

- At NLO you find two kind of contributions:
  – Real emissions: positive contribution to M_{j+1}.
  – Loop contributions.



1.2) NLO

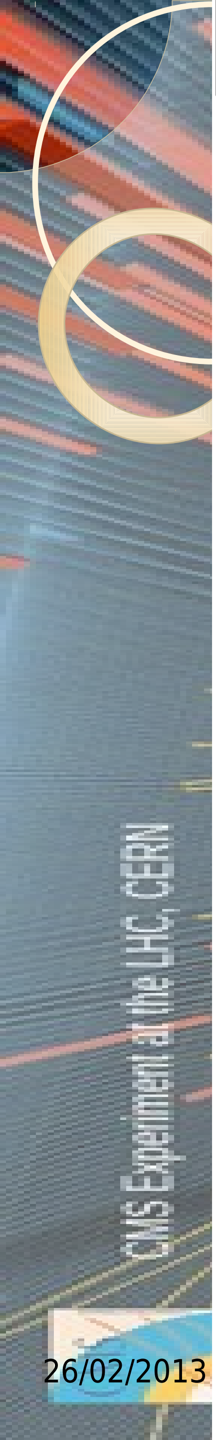
$$\sigma_{\text{n-jet}} = \sigma^{LO}_{\text{n-jet}} + \sigma^{NLO}_{\text{n-jet}} = \sigma^{LO}_{\text{n-jet}} + \left[\int_{n+1} \mathrm{d}\sigma^{R} + \int_{n} \mathrm{d}\sigma^{V}\right]$$

- NLO emission terms are divergent IR and collinear:
  - If the observable is IR and collinear safe: ok for inclusive obs.
    - collinear divergences factorize out into the observable and PDF definition.
    - Infrared divergences cancel out between virtual and real corr.
  - Need to use “dipole substraction” to make the observable practically “calculable” and produce differential predictions.

$$\sigma^{NLO}_{\text{n}-\text{jet}} = \int_{n+1} \left[\mathrm{d}\sigma^{R} - \mathrm{d}\sigma^{A}\right] + \int_{n} \left[\mathrm{d}\sigma^{V} + \mathrm{d}\sigma^{A}\right]$$

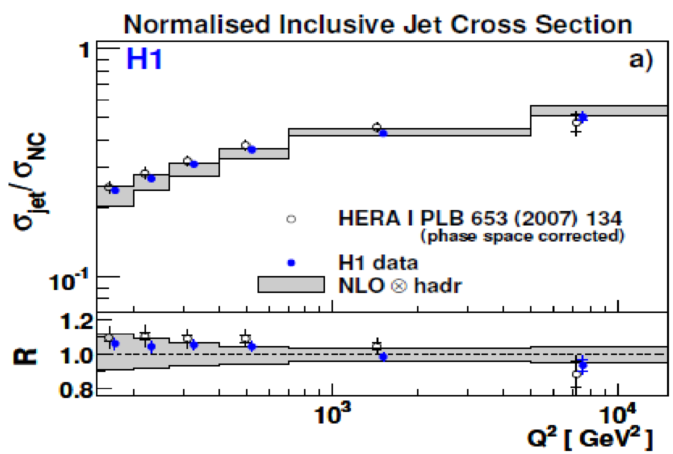
Approximate real-emission matrix elements in all singular limits so this difference is integrable.

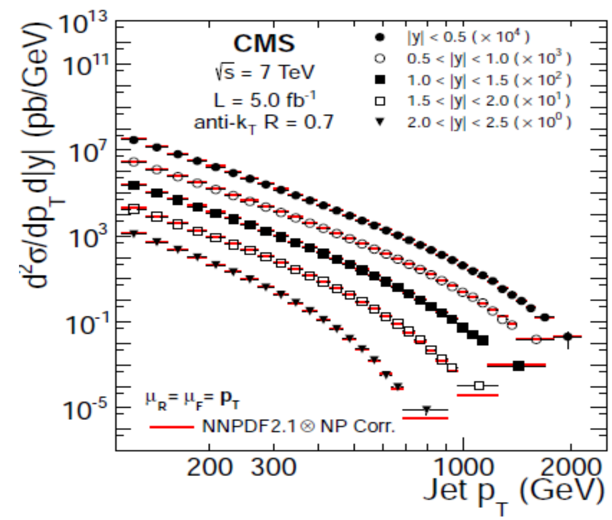
Simple enough to integrate so that 1/ε poles can be canceled against virtual corrections



1.3) NLO

- This method is applied since 90's. For example NLOJET++ is used for 2-jet and 3-jet cross sections in ee, *ep* or *pp* collisions:





- But this method requests to build « by hand » the dipole substraction elements. We arrive now at the stage where this approach might be « automatized ».

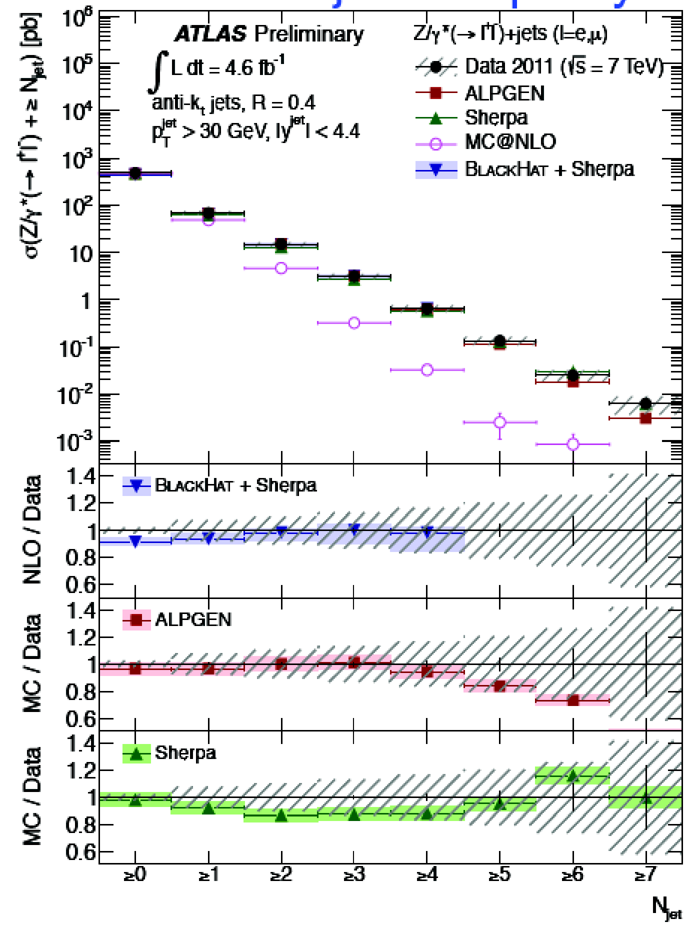
CMS Experiment at the LHC, CERN

1.4) Automatized NLO

- Different groups invested in this industry which has good records: BlackHat, Rocket, Samurai, NGluon, MadLoop etc...
- Enters into the composition of new generation of MC generators: POWHEG, MC@NLO Sherpa@NLO.
- V+n-jets, n-jets (n = 1..4).

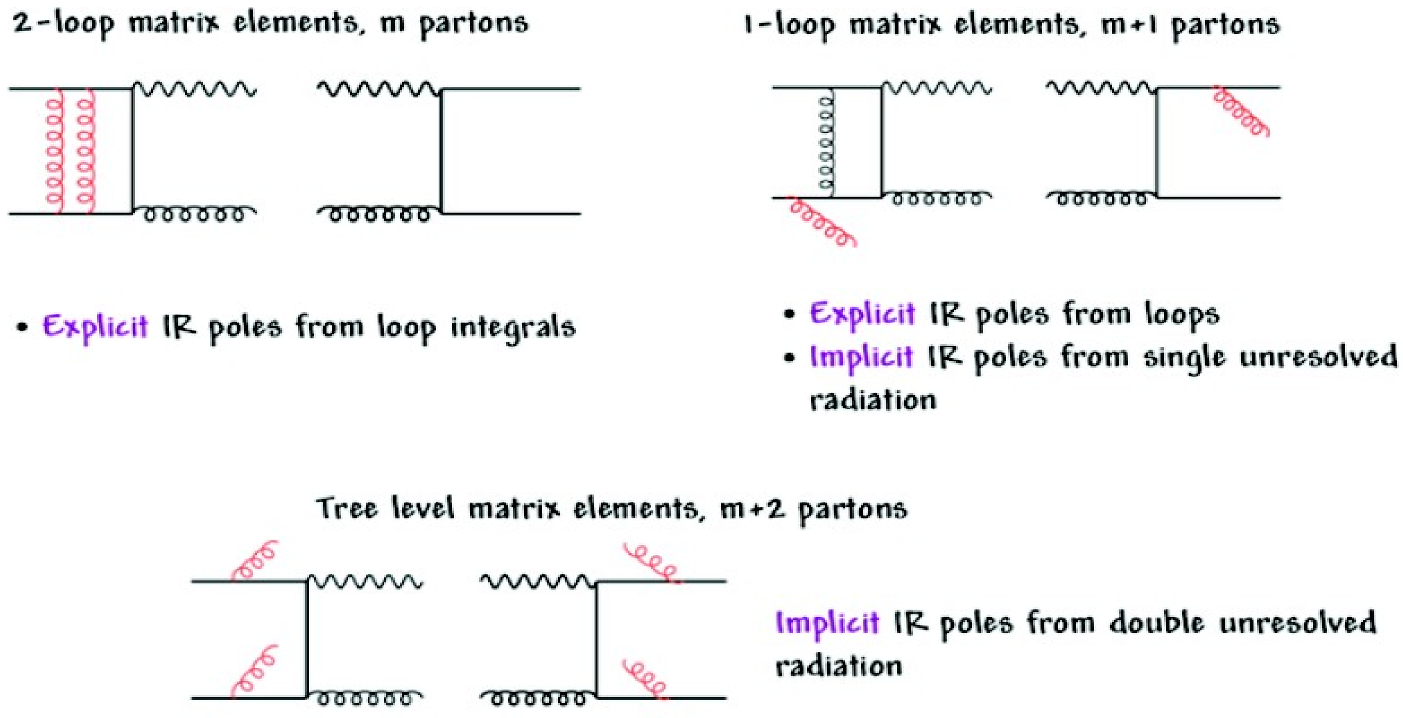
The limiting factor is the computing time.

inclusive jet multiplicity



1.5) NNLO

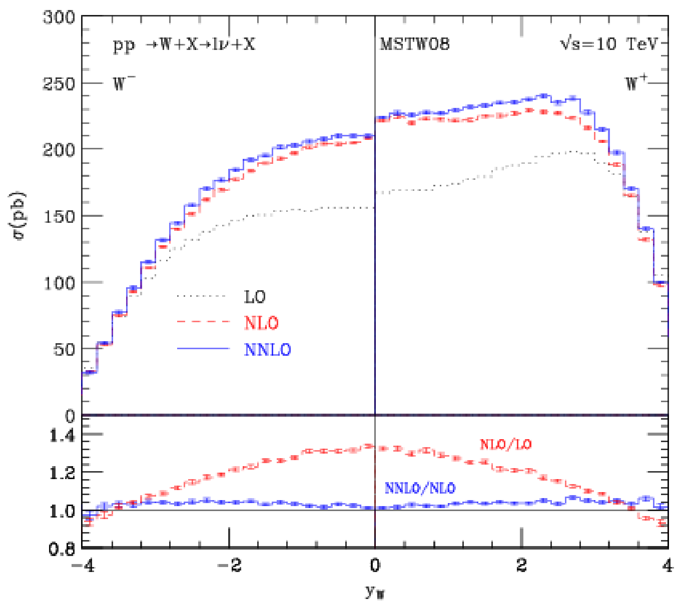
- Structure of NNLO calculations (From Franck Petrillo talk):

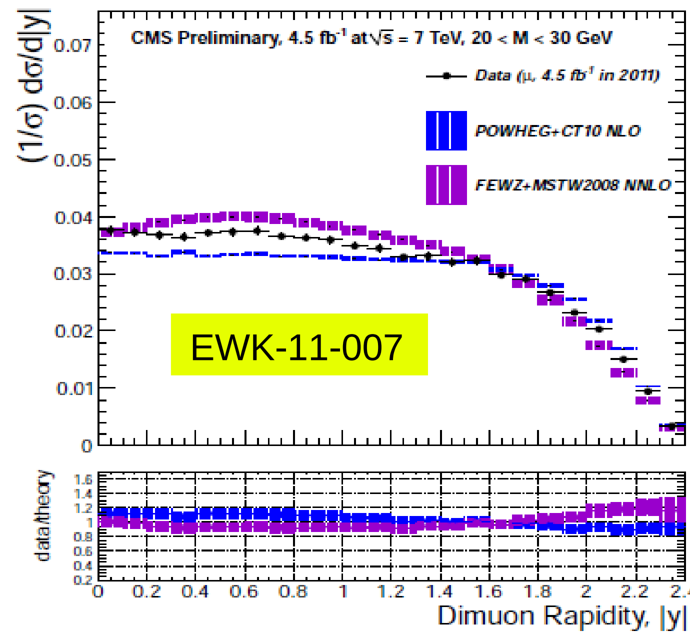


- Two loop amplitudes quite well known for V+jet since 10 years.
- One loop correction also well known (similar concept to NLO).
- Double singular real emission is the bottleneck especially for differential cross sections.

1.6) NNLO inclusive V production

- Inclusive V production with leptonic final sate is an easier case since the final sate is not colored: qq→V→ll.
- NNLO is important at the level of precision we have now in inclusive V, V* production O(1%).





- This is a similar situation to : ee->V->qq.
- The PDFs are known to NNLO.

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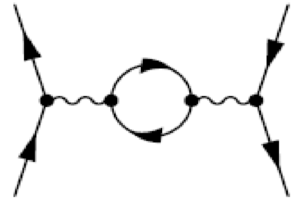
1.7) Loops and scale dependance

- Loop contributions:



- Divergences when allowing infinite momentum in the loop:
  - Apply a renormalization procedure, for example loop energy cut off scale μ. Arbitrary scale affecting truncated serie but not the total cross section

$$L = \ln \frac{\mu_r}{\mu_0} = \ln x_r \quad \text{et} \quad \alpha(\mu_r) = \frac{\alpha_s(\mu_r)}{4\pi}$$

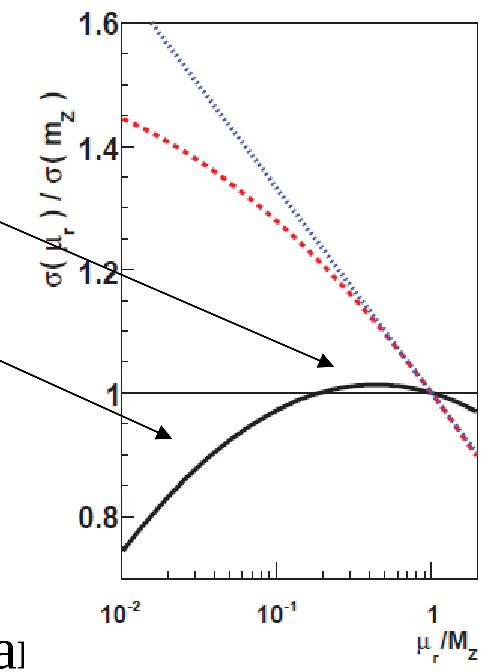
$$\left(\frac{\partial}{\partial L} + \frac{\partial \alpha_s}{\partial L} \frac{\partial}{\partial \alpha_s} \right) \mathcal{R} = 0$$

  - Equation above is true for any cross section. This gives the famous « running constant » beta function:

$$\frac{\partial \alpha_s}{\partial L} = \beta(\alpha_s)$$

1.9) Scale dependance and missing orders

- The scale dependance arise from a non-complete cancellation of the strong coupling running and virtual loops: $\frac{\mathrm{d}\mathcal{R}_n}{\mathrm{d}L} = \mathcal{O}(\alpha^{n+1})$
  - LO μ L : the predicted cross section is a priori « whatever »
  - NLO: reduced scale dependence
    « Maximal cross section »
    and
    a « non-physical » region.



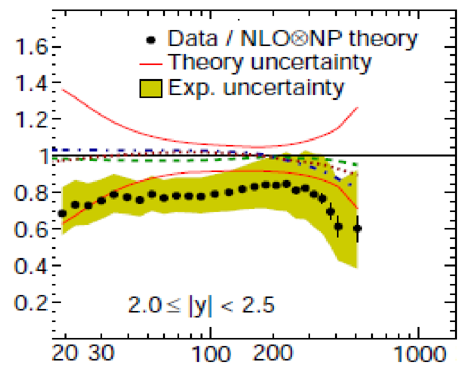
- The experience shows :
  μ_r = typical physical scale (p_T, M_V, etc...) seems frequently to fasten the convergence.

- Missing orders: $\Delta R = R-R_n$ size estimated by va scale by an arbitrary factor ½ and 2. $\frac{\mathrm{d}\mathcal{R}_n}{\mathrm{d}L} = \mathcal{O}(\alpha^{n+1})$

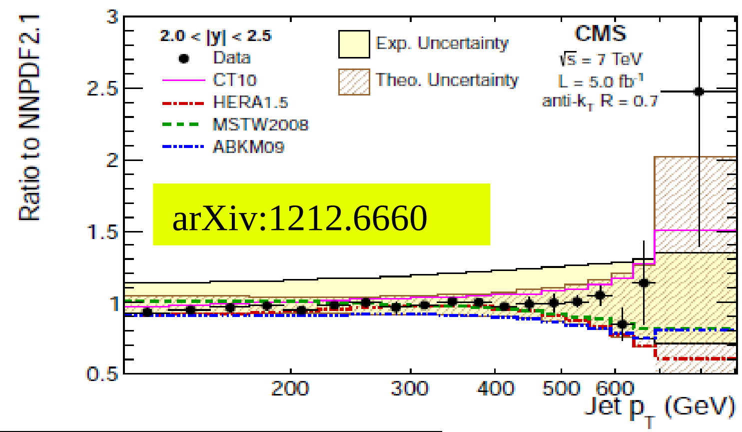
Naively: a smaller k-factor make think about a faster convergence.

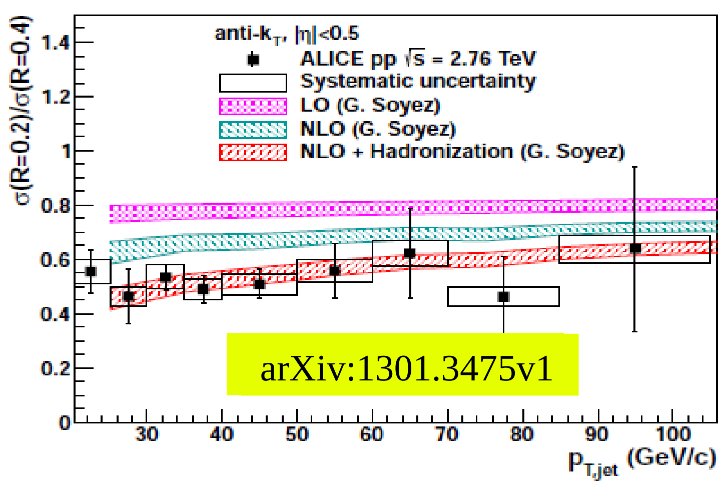
1.10) Does it always works?

- In pp collisions large small angle corrections: described by ISR and FSR.
- Visible when the small jet radius (R <~ 0.5) is used.
- Explicitly visible when jet radius ratio is calculated.
- Effects not covered by scale variations.



arXiv:1106.0208





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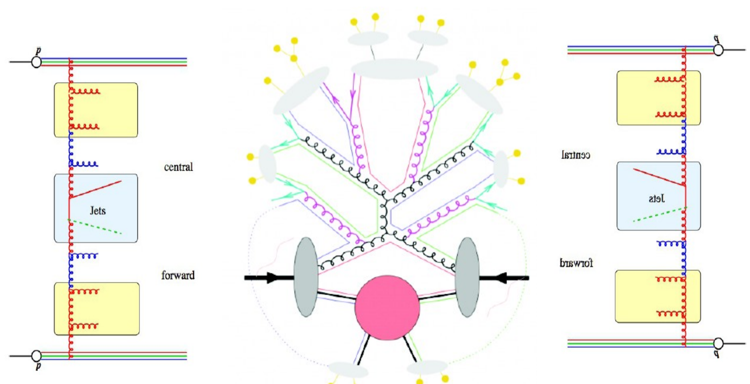
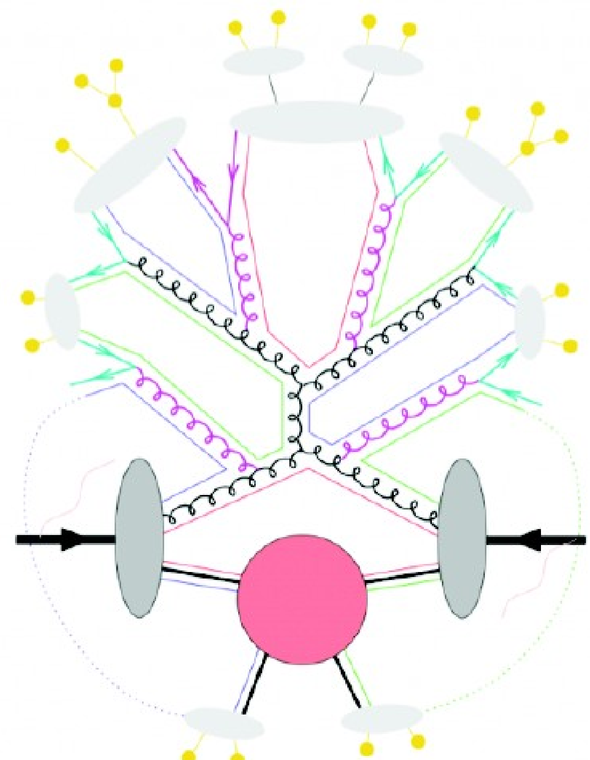
Resummations



2.1) Collinear and IR effects

- Measured cross sections are sensitive to:
  - non-perturbative effects and small angle radiations.
  - Large logarithms contribution when more than one different scale is involved: log (μ_1/μ_2)
- One need to coherently connect:

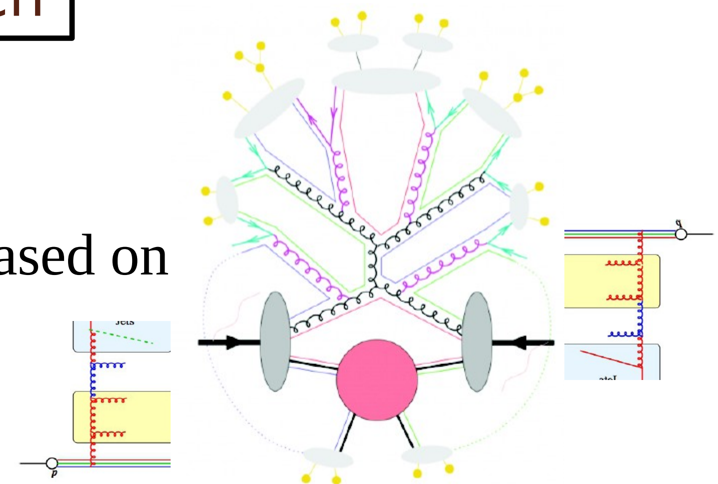
Hard scattering ME +
Soft and collinear rad. +
hadronisation + UE

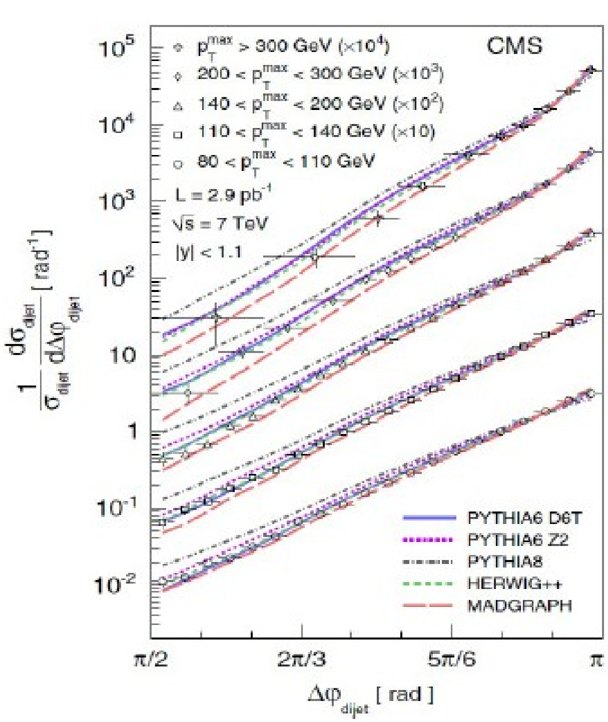


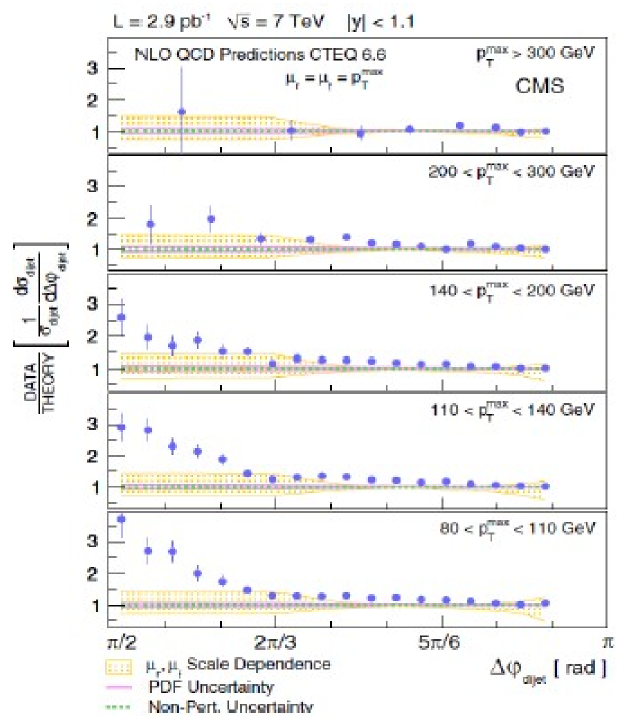
- 2 solutions:
  - Parton showering
  - N^pLL Resummation

2.2) Parton showering approach

- The usual solution is to use the parton showering: ordered real (Q2, pT2...) emissions based on Sudakov form factors.
- Equivalent to the collinear resummation.
- Use by: PYTHIA, SHERPA, HERWIG...







2.3) ME+PS matching

- PS under-produce hard pT jets wrt to the multi-partom ME.
- Idea: Match multi-parton ME to the Parton shower.

Shower off X already contains LL part of all X+n

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

Adding back full ME for X+n would be overkill

Solution I: "Additive" (most widespread)

Seymour (Herwig), CPC 90 (1995) 95
CKKW (Sherpa), JHEP 0111 (2001) 063
Lönnblad (Ariadne), JHEP 0205 (2002) 046
Frixione-Webber (MC@NLO), JHEP 0206 (2002) 029
+ many more recent ...

Add event samples, with modified weights

$$w_X = |M_X|^2 \quad + \text{Shower}$$

$$w_{X+1} = |M_{X+1}|^2 - \text{Shower}\{w_X\} \quad + \text{Shower}$$

$$w_{X+n} = |M_{X+n}|^2 - \text{Shower}\{w_X, w_{X+1}, \ldots, w_{X+n-1}\} \quad + \text{Shower}$$

Only CKKW and MLM

HERWIG: for X+1 @ LO (Shower = 0 in dead zone of angular-ordered shower)

MC@NLO: for X+1 @ LO and X @ NLO (note: correction can be negative)

CKKW & MLM : for all X+n @ LO (force Shower = 0 above "matching scale" and add ME there)
SHERPA (CKKW), ALPGEN (MLM + HW/PY), MADGRAPH (MLM + HW/PY), PYTHIA8 (CKKW-L from LHE files), …

- Solution II: Multiplicative. Used for example by POWHEG. See for details in backup.

CMS Experiment at the LHC, CERN

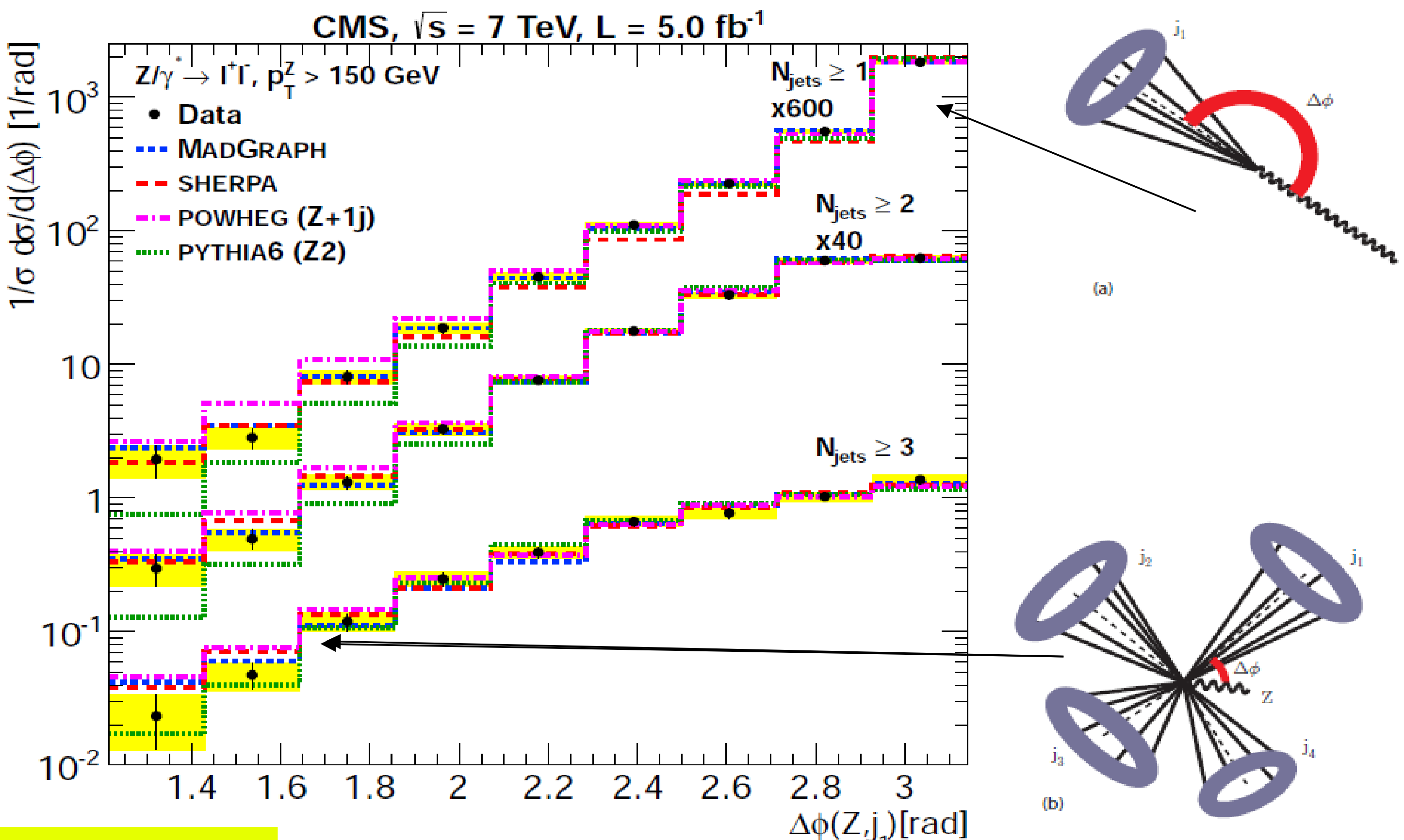
2.4) Z+jets event shapes

- Effect of ME+PS seen here:

PYTHIA (2 partons LO+ PS)

MadGraph, Sherpa (2,3,4 partons LO + PS);

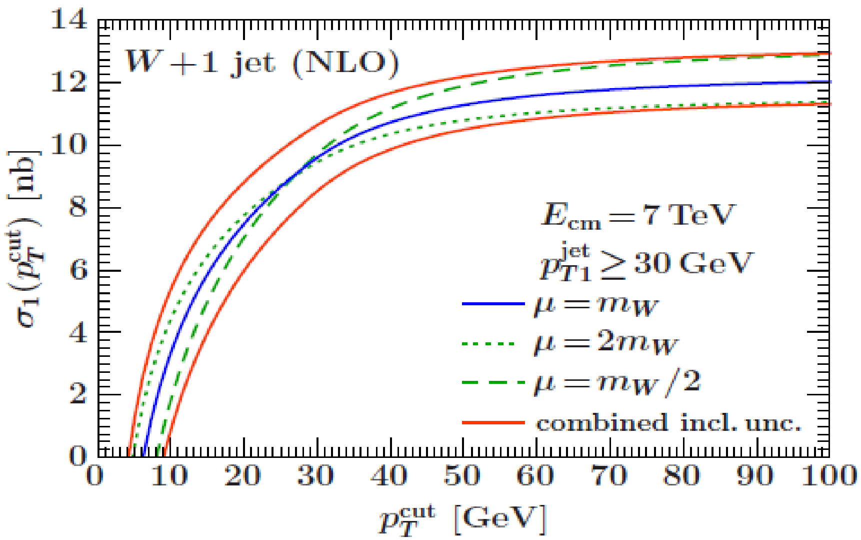
POWHEG (2 part. NLO+PS)



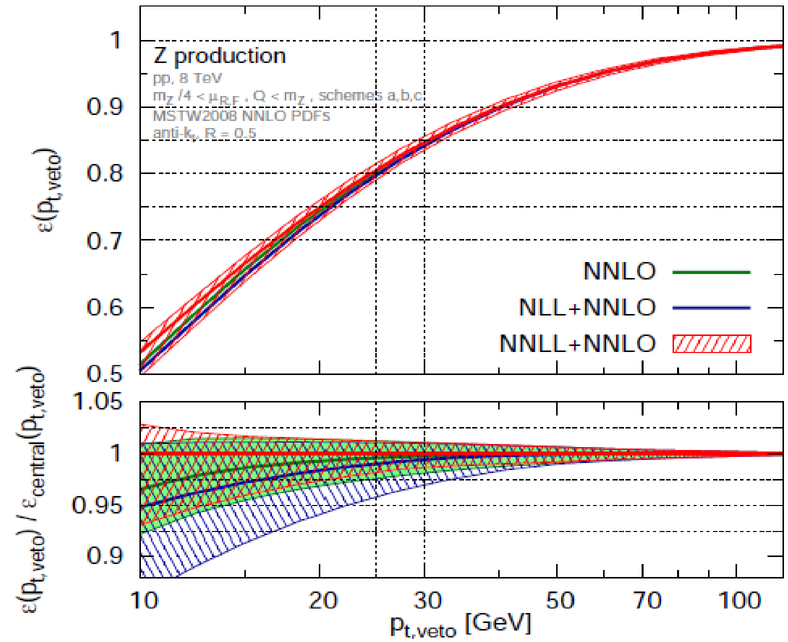
arXiv:1301.1646

2.5) Resummation

- An other way to correct for soft radiation effects is to carry out explicit analytical resummation. For example:
  - Jet veto used for Higgs searches or VV production. Tested on Z production.
  - Large terms in $\alpha_s^n L^{2n}$ $\quad L = \ln(M/p_{\mathrm{t,veto}})$
  - NLO uncertainty estimation may fai. Need to bootstrap it or use resummations.

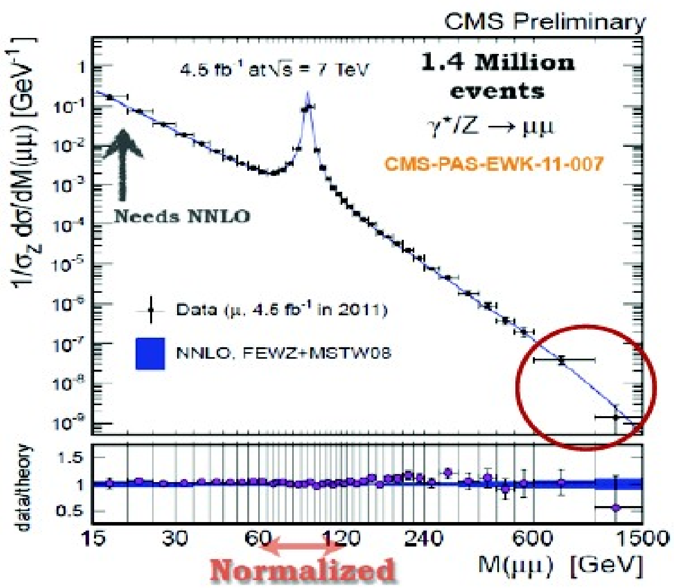


arXiv::1107.2117v2



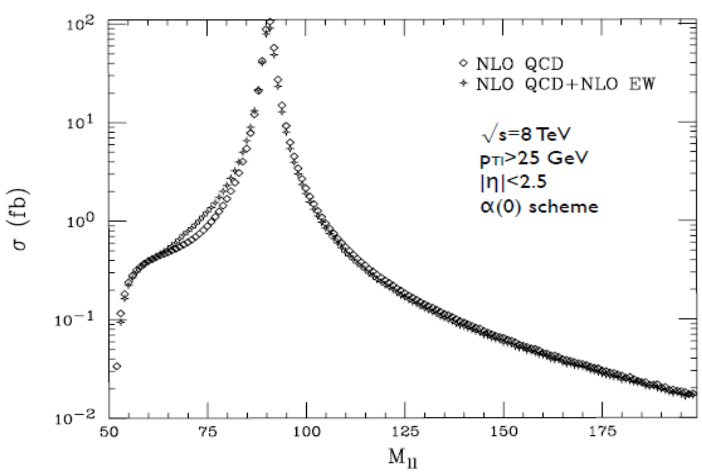
arXiv:1206.4998

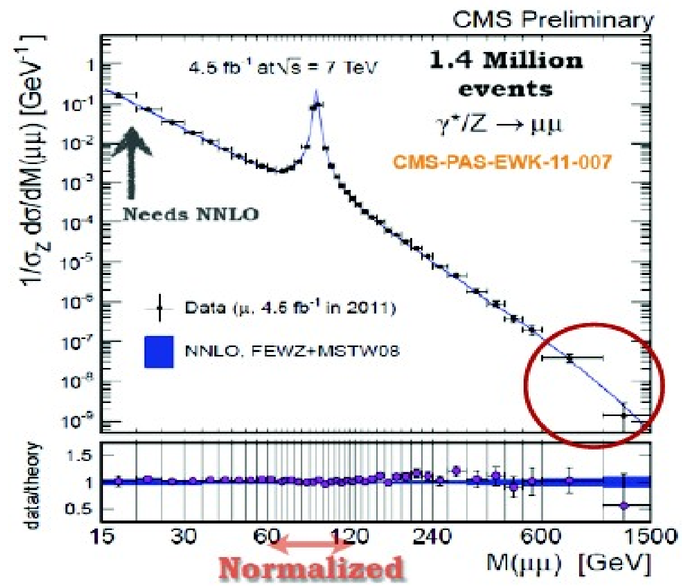
EW corrections



3.1) Few examples

- Important around the M(Z) and MT(W) peaks. Very precise measurements. One of the key points for W mass measurement at O(10 MeV) precision.
- The precision of DY at high mass is sufficient to be sensitive to EW corrections.





- Numbers for 14 TeV LHC:

  $\gamma\gamma \to ll$: $\delta_{\gamma\gamma} \approx +5\%$
  QED: $\delta_{QED} \approx -(3\text{-}4)\%$

3.2) General situation for EW corrections

$$d\sigma = d\sigma_0 + d\sigma_{\alpha_s} + d\sigma_\alpha + d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + \dots$$

Fixed order MC:

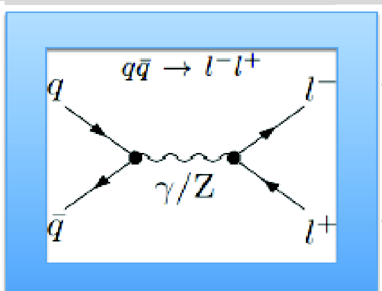
- FEWZ: $\alpha_s^2 (+\alpha$ for neutral DY) — Melnikov & Petriello, PRL 96 (2006) 231803; Li & Petriello, arXiv:1208.5967
- SANC: $\alpha_s + \alpha$ — Bardin & al., arXiv:1207.4400

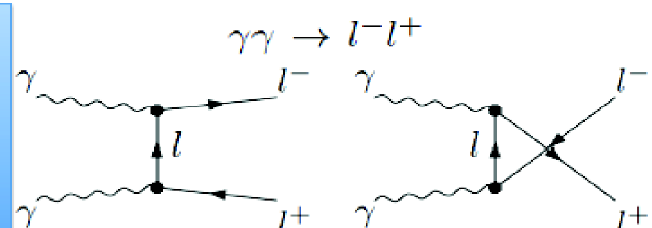
Matching realized using different generators:

- PYTHIA8/HERWIG++ $\oplus$ SANC — Richardson & al., JHEP 1206 (2012) 090
- MC@NLO $\oplus$ HORACE — Balossini & al., JHEP 1001 (2010) 013

NLO matched to PS (POWHEG):

- W_EW-BMNNP — L. B. & al., JHEP 1204 (2012) 037
- W_EW-BW — Bernaciack & Wackeroth, PRD 85 (2012) 093003





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SUMMARY

	NLO	NNLO	NNLO+ NLO EW	NNLO + NNLL	LO+ PS	NLO+PS
W, Z, DY		DY NNLO	FEWZ PWHG	Banfi @ *Al*.		PPWHEG
W,Z+0..1 jet excl.				Banfi @ *Al*.		POWHEG
2-jets	NLOJET++					POWHEG
W+1..5-jets	BLACK HAT				MDG	SHERPA aMC@NLO
Z+1..4-jets	BLACK HAT				MDG	SHERPA aMC@NLO
1..5-jets	BLACK HAT				MDG	SHERPA aMC@NLO
W,Z+1 jet					PTIA	PWHG

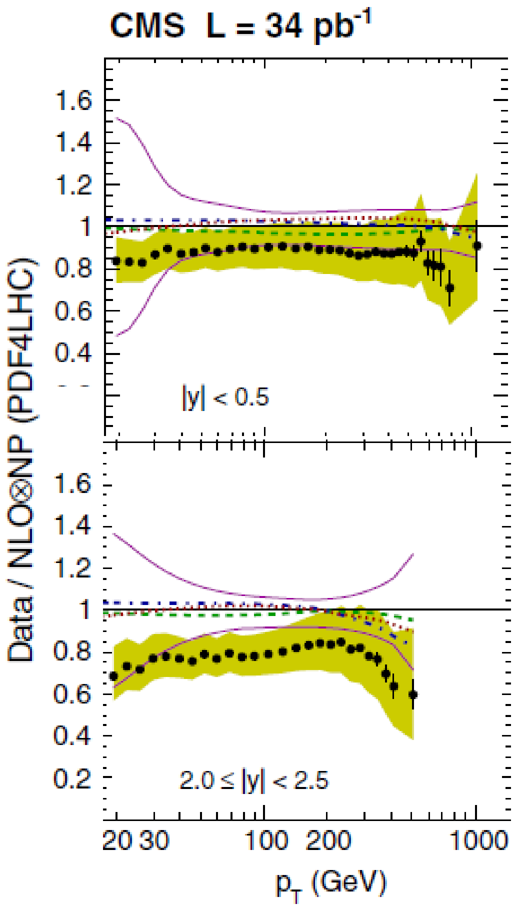
- Fact 1: this table is intentionally not complete to keep it light.
- Fact 2: even if it was complete it would not be complete is few weeks: the field is very actively developing. This development is fueled by the active LHC SM program.

BACKUP

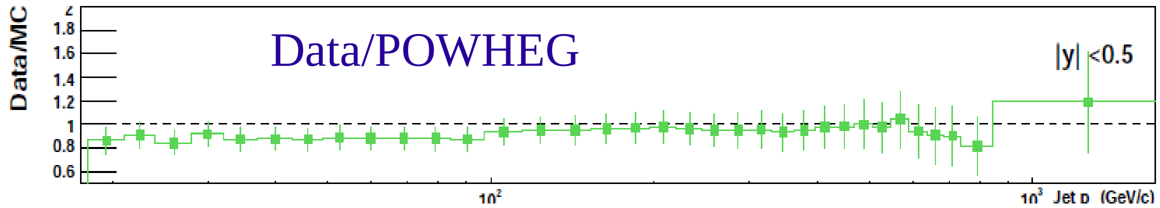
3.3) POWHEG vs NLO+NP

Phys. Rev. Lett. 107 (2011) 132001

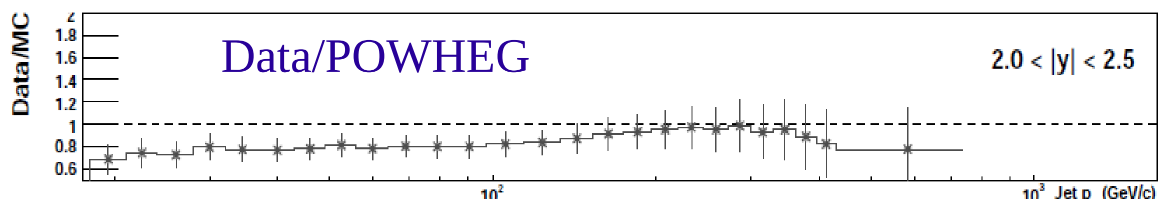
S. Dooling, H. Jung



R=0.5 |y|<0.5



R=0.5 2.0<|y|<2.5



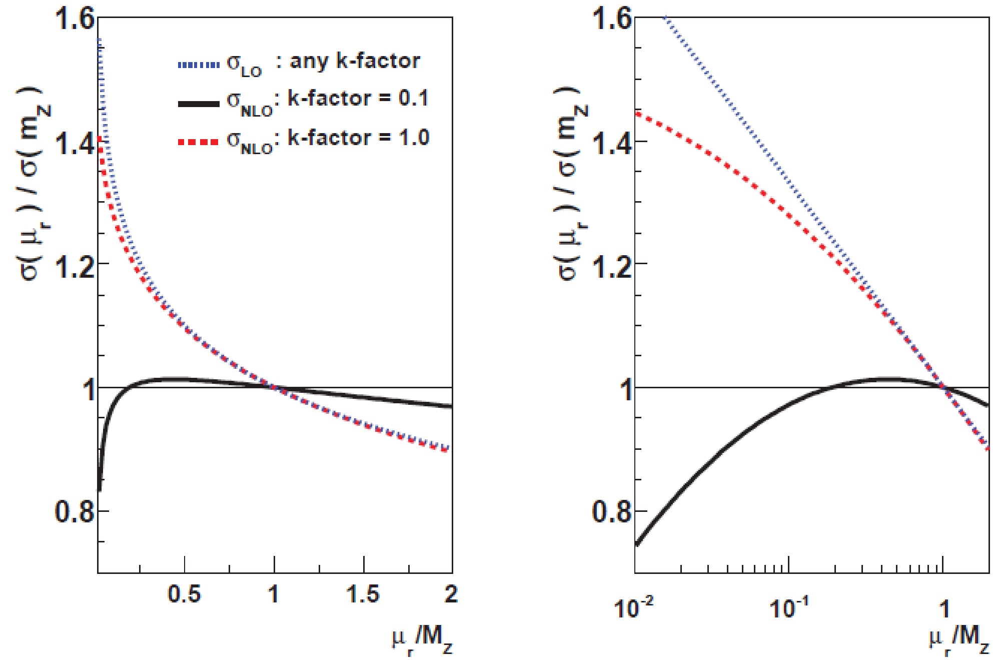
- POWHEG by itself describes better R=0.5 data than NLO+NP. PS represent part of the missing orders.
- Agreement not perfect at large y, but covered by systematics.

1.8) Scale dependance

-

$$\frac{\mathrm{d}\mathcal{R}_n}{\mathrm{d}L} = \mathcal{O}(\alpha^{n+1})$$

- If you know matrix elements you know analytically the scale dependence ($k_{factor}=M_{j+1}/M_j$):



$$\frac{\mathcal{R}_1(L)}{\mathcal{R}_1(L=0)} = 1 - \beta_0 L\,,$$

$$\frac{\mathcal{R}_2(L)}{\mathcal{R}_2(L=0)} = 1 - \frac{(\beta_1 L + \beta_0^2 L^2) + \frac{2\beta_0}{\alpha(L)} L \cdot k_2}{1+k_2}\alpha^2(L)$$

2.3) ME+PS matching

- PS under-produce hard pT jets wrt to the multi-partom ME.
- Idea: Match multi-parton ME to the Parton shower.

Shower off X already contains LL part of all X+n

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

Adding back full ME for X+n would be overkill

Solution 2: "Multiplicative"

Bengtsson-Sjöstrand (Pythia), PLB 185 (1987) 435 + more
Bauer-Tackmann-Thaler (GenEva), JHEP 0812 (2008) 011
Giele-Kosower-Skands (Vincia), PRD84 (2011) 054003

One event sample

$w_X = |M_X|^2$ + *Shower*

Make a "course correction" to the shower at each order

$R_{X+1} = |M_{X+1}|^2/Shower\{w_X\}$ + *Shower*

$R_{X+n} = |M_{X+n}|^2/Shower\{w_{X+n-1}\}$ + *Shower* **Only VINCIA**

PYTHIA: for X+1 @ LO (for color-singlet production and ~ all SM and BSM decay processes)

POWHEG: for X+1 @ LO and X @ NLO (note: positive weights) POWHEG Box HERWIG++ ...

VINCIA: for all X+n @ LO and X @ NLO (only worked out for decay processes so far)

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