Les Houches 2017
SM N^{x}LO, NLO (multi-legs+EW) WG
TH and EXP summary

Stefan Kallweit

LHC and the Standard Model: Physics and Tools
CERN, Switzerland, June 12–July 7, 2017

Overview of SM WG topics discussed in session I of Les Houches 2017

1. NNLO IR subtraction schemes
2. Methods to provide results from NNLO calculations
3. NLO EW automation
4. Amplitudes and ingredients of higher-order calculations
5. Wishlist
6. Scale choices in inclusive jet production
7. NLO ME+PS vs. fixed order in inclusive jet production
8. Non-perturbative effects in inclusive jet production
9. QCD resummation studies on TeV Z's
10. Uncertainties in cross-section ratios

NNLO IR subtraction schemes

Different NNLO IR subtraction schemes are on the market and have been (partially) implemented into public programs:

- Antenna subtraction (NNLOJET) [talk by J. Pires]

- Sector-improved residue subtraction (TOP++, ...)
- Iterative subtraction [talk by R. Röntsch]

- q_{T} subtraction/slicing (HqT, DYNNLO, 2γNNLO, MATRIX, ...)
- N-jettiness subtraction/slicing (MCFM, GENEVA, ...) [talk by F. Tackmann]

- Projection to Born/structure function approach

- Colorful subtraction

Different approaches lead to (dis-)advantages of the respective methods:

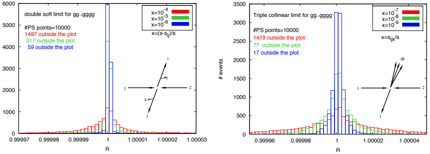
- Restriction to special process classes/kinematics
- Dependence on cut parameters in slicing approaches
- More or less staightforward automation

Antenna subtraction

- Implementation in NNLOJET program
- Applied to $pp \to jj/Hj/Zj$ production (also: $pp \to H/W/Z$, $ep \to jj$)
- (Nearly) local subtraction method with analytic IR pole cancellation
- No additional building blocks needed for higher multiplicities (massless quarks)
- Many subtraction terms needed, bookkeeping complicated
- Colour-ordered amplitudes needed (not easily available from public tools)

[talk by J. Pires]

Antenna subtraction at work



Double unresolved emission

- Generate phase space trajectories that approach singular region of the phase space
- Infrared behaviour of subtraction term mimics the behaviour of the matrix element

$$R = \frac{d\sigma^R_{NNLO}}{d\sigma^S_{NNLO}} \xrightarrow{l_g, k_g \to 0} 1$$

Pros and cons

Antenna subtraction

- local method with phase space averaging → good control on the numerical accuracy of the final result, RR, RV, VV separately finite
- analytic IR pole cancellation at NNLO → good control on the correctness of the pole cancellation
- double precision
- universal method works for general jet multiplicity → no additional building blocks needed
- pp→jj,Hj,Zj @ NNLO
- subtraction terms for a fixed colour structure reusable
- involves many mappings/subtraction terms as expected for a local method → needs caching system to store mappings

Iterative subtraction

- Extension of FKS to NNLO by adding sectors to separate singularities
- Simplified implementation — focussed on gauge-invariant matrix elements

- Local; process independent; clear origin of singularities
- Explicit pole cancellation; 4-dimensional matrix elements sufficient

- Numerical pole cancellation; intermediately not Lorentz invariant
- Some work required for extension to colored final states and masses

[talk by R. Röntsch]

Soft and collinear singularities

BUT: we are dealing with gauge-invariant matrix elements (as opposed to individual Feynman diagrams):

- **Can regulate soft and collinear singularities independently.**
- Order energies $E_4 > E_5$: either double soft ($\mathbb{S}$) or gluon 5 soft.
- Regulate soft singularities:

$$\langle F_{LM}(1,2,4,5)\rangle = \langle \mathbb{S} F_{LM}(1,2,4,5)\rangle + \langle S_5(I-\mathbb{S})F_{LM}(1,2,4,5)\rangle + \langle (I-S_5)(I-\mathbb{S})F_{LM}(1,2,4,5)\rangle.$$

then regulate collinear singularities in each term

Les Houches 6 June 2017 — Raoul Röntsch (KIT) A Primer on Iterative Subtraction at NNLO — 10

Combining partitions

Rename the resolved gluon 4 in the first term and combine:

$$\langle [I-\mathbb{S}]\,[I-S_5]\,[C_{41}[\mathrm{d}g_4]w^{14,25} + C_{51}[\mathrm{d}g_4]w^{15,24}F_{LM}(1,2,4,5)\rangle$$
$$= -\frac{[\alpha_s]s^{-\epsilon}}{\epsilon}\int_0^1 \frac{\mathrm{d}z}{(1-z)^{1+2\epsilon}}\langle \tilde{w}_{5||1}^{15,24}\Big(\hat{\mathcal{P}}_{qq}^{(-)}(z)\,[I-S_4]\,F_{LM}(z\cdot 1,2,4) +$$
$$\theta(z_4-z)2C_F\,[I-S_4]\,F_{LM}(1,2,4) + \theta(z_4-z)\hat{\mathcal{P}}_{qq}^{(-)}(z)S_4F_{LM}(z\cdot 1,2,4)\Big)\rangle.$$

Similar simplifications on combining terms from **double** & **triple** collinear partitions.

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N-jettiness subtraction/slicing

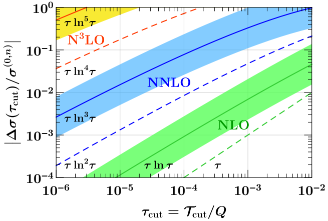
- Differential 0-jettiness subtractions implemented in GENEVA Monte Carlo
- Global 0-/1-jettiness in MCFM 8: V/H, VH, $\gamma\gamma$; $V/H/\gamma$+jet
- Not local in slicing approach; result dependent on slicing parameter $\tau_{\rm cut}$
- $\tau_{\rm cut}$ dependence can be well controlled by
  - power corrections that can be analyzed and computed in SCET
  - Born+jet NLO calculations that remains stable deep into the IR-singular region
- Straightforward to be automated if NNLO beam/jet/soft functions are known

[talk by F. Tackmann]

Estimating Size of Missing Power Corrections.

Simple estimate of $\Delta\sigma(\tau_{\rm cut})$ at N^{n}LO

- relative to full N^{n}LO coefficient

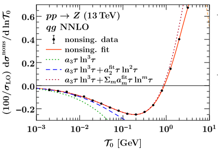


Typical values in current implementations are in $\tau_{\rm cut} \simeq 10^{-4}\ldots10^{-3}$ range

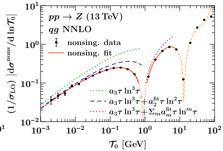
Frank Tackmann (DESY) | N-jettiness Subtractions | 2017-06-07 | 15 / 27

Numerical Results at NNLO.

linear scale



log scale



channel and coefficient		fitted	calculated
$q\bar{q}$ NNLO	a_3	-0.01112 ± 0.00150	-0.01277
qg NNLO	a_3	$+0.02373 \pm 0.00247$	$+0.02256$
$q\bar{q}$ NNLO	a_2	-0.04662 ± 0.00180	
qg NNLO	a_2	$+0.04234 \pm 0.00242$	

Frank Tackmann (DESY) | N-jettiness Subtractions | 2017-06-07 | 23 / 27

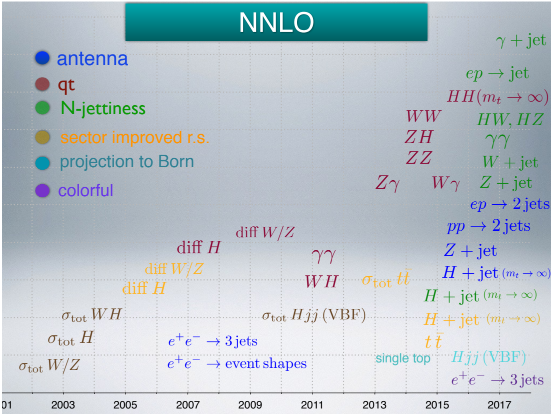
NNLO IR subtraction schemes

Planned proceeding projects

- Discussion of different IR subtraction schemes
- Drell-Yan as benchmark between applicable schemes
  - inclusive results
  - maybe a benchmark distribution
  - runtime estimate (only partially useful, as process is quite trivial)

Methods to provide results from NNLO calculations

[introductory talk by G. Heinrich]



How can these NNLO results be made fully available for non-authors?

- Public NNLO codes to be run by anyone
- nTuples output written by the programs, to be provided to anyone
- Interface to FASTNLO/APPLGRID/APPLFASTNNLO

nTuples

- nTuples have proven useful for NLO — can they be as useful for NNLO?
- Same advantages and same disadvantages but amplified:
  - Programs are more complex, i.e. more runtime can be saved
  - Larger files: more pieces in the calculation, more logarithm coefficients
- Main question: is the size reasonable?
  - studied on $e^+e^- \to$ 3jets, hadron–hadron in development
  - modifications to reduce required storage under investigation

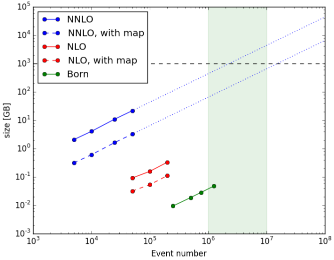
[talk by D. Maitre]

Using mapping information

- The most space-consuming part is the double real part
  - More final state momenta
  - Need much statistics because of subtraction terms
- For each real-real phase-space point we have many subtraction terms
- Each of them has a different set of momenta given by a (n+2)→ n or (n+1) →n map
- We can save much space if we simply record the mapping that was used instead of the momenta
- The downside is that
  - there is more calculation at the moment of reading the nTuple
  - More coupling between nTuple file and code that produced it

Loops and Legs 2016 9

Extrapolated file size

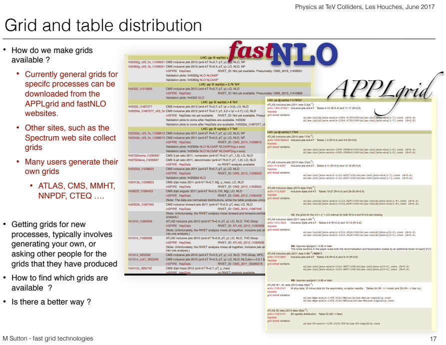


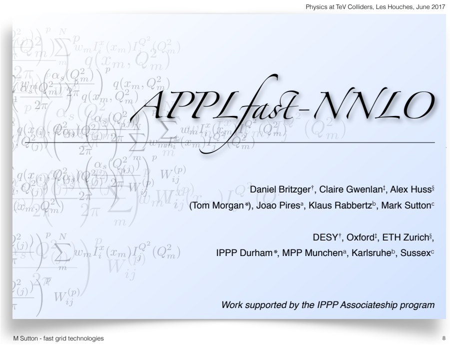
Loops and Legs 2016 10

Fast grid technologies

- FASTNLO and APPLGRID provide intermediate output formats
  - that allow for a-posteriori variation of scales and PDFs,
  - that need the original code to be run only once.
- Fast a-posteriori convolution, original calculation reproduced very precisely
- Analysis cuts and observables cannot be changed a-posteriori
- APPLFAST-NNLO interface to NNLOJET has been established.

[talk by M. Sutton]





Methods to provide results from NNLO calculations

Planned proceeding projects

- APPLFast Tables: come up with common interface for input to Tables, such that N(N)LO code providers can stick to standards as guidelines for the output format they provide (**Les Houches APPLcord**?)
- Working out standards for communication between nTuples at NNLO and users
- Working out standards for output format of (NNLO) fixed order results to pass to parton showers (at runtime)

NLO EW automation

Status of NLO EW matrix element generators (and their implementation into full (parton-level) Monte Carlo programs):

- GoSam [talk by N. Greiner]
- NLOX [talk by C. Reuschle]
- MadLoop [talk by V. Hirschi]
- OpenLoops [talk by M. Schönherr]
- Recola [talk by M. Pellen]
- . . . (?)

- Sherpa+GoSam
- MG5_aMC@NLO
- Herwig+OpenLoops
- Munich+OpenLoops
- Powheg+OpenLoops
- Sherpa+OpenLoops
- "in-house MC"+Recola
- Sherpa+Recola

General issues in EW corrections (NLO EW and subleading orders)

- Realistic uncertainty estimate for EW corrections
  - Estimate of missing higher EW orders
  - Additive/multiplicative combination of QCD and EW results
- Democratic clustering (photons+QCD partons)
- Treatment of photons (IS/FS/identified)
- Treatment of (pseudo-)resonances
  - in particular pseudo-resonances in interference contributions without CMS
  - actual resonances in CMS only potential numerical problem at fixed order
- Issues with the complex mass scheme
  - complex α wrong in subleading EW corrections: consistent use of $|\alpha|$?
  - renormalization of (stable) top in presence of complex W mass

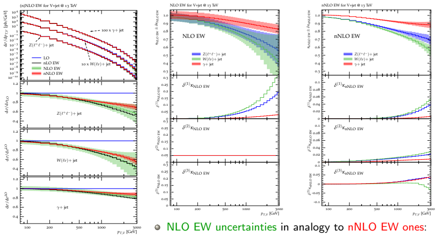
Realistic uncertainty estimate for EW corrections

- EW correction large in high-energy tails of distributions (Sudakov regime)
- NNLO Sudakov corrections dominant source of EW uncertainty
  - ↪ use in uncertainty estimate, or even include as nNLO EW
- NNLO Sudakov corrections also relevant for combined QCD–EW uncertainty
  - ↪ multiplicative approach as nominal prediction, plus uncertainty estimate
- But: Sudakov corrections do not dominate EW uncertainties everywhere!

[talk by SK]

Uncertainty assessment and numerical results | Higher-order EW corrections

EW uncertainties of V+jet $p_{\mathrm{T,V}}$ distributions



- $\mathrm{d}\sigma_{\mathrm{nLO\ EW}} \approx \mathrm{d}\sigma_{\mathrm{NLO\ EW}}$!
- $\mathrm{d}\sigma_{\mathrm{nNLO\ EW}}$ well covered by NLO EW uncertainty.
- NLO EW uncertainties in analogy to nNLO EW ones:

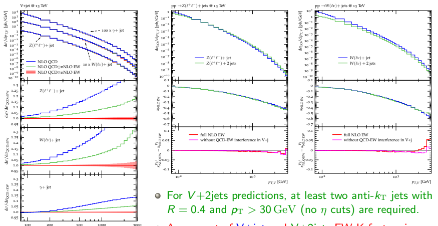
$$\delta^{(1)}\kappa^{(V)}_{\mathrm{NLO\ EW}}(x) = \frac{2}{2}\left[\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)\right]^2,$$

$$\delta^{(2)}\kappa^{(V)}_{\mathrm{NLO\ EW}}(x) = 0.05, \qquad \delta^{(3)}\kappa^{(V)}_{\mathrm{NLO\ EW}}(x) = 0.$$

Stefan Kallweit (CERN) | Precise predictions for V+jets | Les Houches workshop, June 9, 2017 | 14 / 20

Uncertainty assessment and numerical results | Combination of QCD and electroweak corrections

Combined $p_{\mathrm{T,V}}$ distributions and NLO EW comparison of V+1,2jets



- large difference between multiplicative and additive combination
- For V+2jets predictions, at least two anti-k_{T} jets with $R = 0.4$ and $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ (no η cuts) are required.
- Agreement of V+jet and V+2jets EW K-factors is better than 2% almost in full $p_{\mathrm{T,V}}$ range.
- Factorization slightly disturbed by finite mixed QCD–EW bremsstrahlung interference contributions.

Stefan Kallweit (CERN) | Precise predictions for V+jets | Les Houches workshop, June 9, 2017 | 17 / 20

Democratic clustering

- Exemplary situation: $gq \to gq + \gamma$ contribution to di-jet production
- QCD and QED singularity structures favours democratic treatment of q, g, γ
  - ↪ implies presense of γq initial state at Born level
- But: Experiment would not consider photon-jets as jets
  - ↪ democratic clustering, and discard jets with $E_\gamma > z_{\rm cut} E_{\rm jet}$
- But: E_γ not well-defined in perturbative QED ($\gamma \to q\bar{q}$)
  - ↪ fragmentation function approach . . .

[talk by V. Hirschi]

Need for democratic jets

[Slides onwards from S.Frixione]

Need to compute "QED corrections": then, include photon emission

But: soft photons induce singularities; one must treat them inclusively

Solution: sum over all configurations

However: (QCD) IR safety demands $E_{gluon} \to 0$ to be a smooth limit.
This implies a $q\gamma$ final state must exist at the Born level.
That's OK: treat q's, g's and γ's democratically

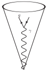
Valentin Hirschi, ETHZ | Mixed NLO QCD-EW | Les Houches | 09.06.2017

Issues with democratic jets

But experimentalists typically do not consider photon-jets as jets.

Solution: cluster democratically, but discard jets where $E_\gamma > z_{cut} E_{jet}$

However: E_γ is not a well-defined quantity in pQED ($\gamma \to q\bar{q}$)



This is a problem only at $\Sigma_{\rm NLO,3}$ and beyond (at least two EW couplings are needed): in principle it can be ignored at NLO EW.

Still, it is much cleaner to devise a solution which is universally valid

Valentin Hirschi, ETHZ | Mixed NLO QCD-EW | Les Houches | 09.06.2017

Treatment of photons

- Distinction between different photon types
  - initial state: unresolved → short-distance scheme (G_μ , $\alpha(m_Z)$, $\bar{MS}$, ...)
  - final state: identifed → $\alpha(0)$ scheme, no $\gamma \to f\bar{f}$ splittings
  - final state: democratic → short-distance scheme, include $\gamma \to f\bar{f}$ splittings
    ↪ identify photon through fragmentation function
- Other descriptions could also work reasonably.

[talk by M. Schönherr]

External photons – initial state

Harland-Lang et.al. arXiv:1605.04935, Kallweit et.al. arxiv:1705.00598

- **initial state photons** are not resolved, treat them identically to any other parton
- both elastic and inelastic photons evolve according to DGLAP
  → splittings $\gamma \to \gamma$, $\gamma \to q\bar{q}$, $q \to q\gamma$
- the photon PDF (at NLO QED) contains renormalisation factors that must be cancelled by the partonic cross section

⇒ renormalisation in short-distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...)

External photons – final state

- **final state photons** may be resolved or not
  strictly speaking: differentiate between short-distance photon and indentified, measurable photon

⇒ if treated as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \to ff$ splittings
→ renormalisation contains IR poles

⇒ if treated democratically (just another parton), renormalise in short distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \to ff$ splittings
→ pure UV renormalisation
→ identify photon through fragmentation function $D^p_\gamma(z,\mu)$

i.e. $D^\gamma_\gamma(z,\mu) = \frac{\alpha(0)}{\alpha_{\text{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha)$

all others $D^q_\gamma(z,\mu) = \mathcal{O}(\alpha)$, $D^g_\gamma(z,\mu) = \mathcal{O}(\alpha^2)$

- identical at NLO EW, if fragmentation D^q_γ on Born is negligible

Issues with the complex mass scheme

- Complex α spoils IR factorization and KLN cancellation
  - ↪ only in subleading (below NLO EW) corrections
- possible solution: assign a phase to G_μ to make α real?

- Example with stable top quarks and unstable W bosons
  - ↪ imaginary residue of UV pole remains uncancelled
- solution: always consider fully decayed particles?

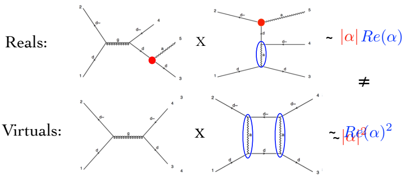
[talk by V. Hirschi]

How to handle the complex phase of α?

‣ In the G_μ-scheme for example, α is defined as:

$$\alpha^{(CMS,G_\mu)} = \frac{\sqrt{2}G_f}{\pi} \frac{M_W^{(CMS)2} - M_W^{(CMS)4}}{M_Z^{(CMS)2}} \longrightarrow \text{Should be complex!}$$

‣ In practice the complex phase is irrelevant because the matrix elements factorize |α|. However, in subleading blobs, one can have:



Complex mass scheme issues

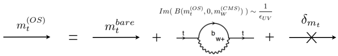
‣ Is there anyway to salvage the CMS with unstable final states?

Relevant case: p p > t t~ (+jets)

p p > t t~ : Can set all widths to zero, so OK.

p p > t t~ j : Must retain the weak bosons width. Is **WT=0** ok?

Probably not! Because the following bubble has an imaginary residue of UV pole that remains uncancelled:



Any easy solution within the CMS? Or is one forced to always consider fully decayed particles?
Notice that the top width offshell effect ($\mathcal{O}(\Gamma_t/m_t)$) are anyway of the same order.

Treatment of (pseudo-)resonances

- Pseudo-resonances arise in QCD–EW interference contributions
  (no squared propagator; in CMS regularized by respective particle width)
- Ways out if external on-shell W bosons need to be used (CMS not applicable):
  - introduce small (gauge-invariance breaking) regulator width
  - apply technical phase-space cuts around the propagator poles
- Other (best?) way out: Never treat unstable particles as stable external states!

[talk by C. Reuschle]

$Wb\bar{b}$ FOR PROOF OF CONCEPT: PSEUDO-RESONANCES 18

- In our contributions: interferences with massive VB propagators, e.g. in g^2e^1 tree $\times$ g^2e^3 loop.
- Singular when massive VB propagator momentum turns on-shell.
- These pop up in only one diagrammatic side of the interferences, e.g. in g^2e^3 loop but not g^2e^1 tree
  $\Rightarrow$ there are no physical resonances, but the integrator still has to integrate over singular regions.

- Technical resonance cuts with $\delta_r = 0.25$ GeV:

$$m_t - \delta_r < \sqrt{|(p_W + p_b)^2|} < m_t + \delta_r$$
$$m_h - \delta_r < \sqrt{|(p_b + p_b)^2|} < m_h + \delta_r$$
$$m_Z - \delta_r < \sqrt{|(p_b + p_b)^2|} < m_Z + \delta_r$$

- Why? No complex-mass (CM) scheme yet.
  Used zero widths for now.

- In the literature, for on-shell W the question is:
  - W^* with CM connected to on-shell W without CM (via γ-radiation or -exchange) $\rightarrow$ soft sing. turn into logs of widths.
  - Polarization sums: What to use for M_W for an on-shell W in CM scheme?
  - Literature: In the CM scheme "the on-shell prescription should be abandoned".

- Various approaches to regulate pseudo-resonant Z, H and t if not using CM scheme:
  - Cut on events with large K-factor [GoSam (+MadDipole), Chiesa, Greiner, Tramontano, arXiv:1507.08579]
  - Implement technical width in critical propagators
    [OpenLoops (+Sherpa,+Munich), Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr, arXiv:1412.5157]
  - We cut on inv. masses in all contributions: no gauge inv. violation, but restricts phase space.
- So:
  - With CMs regulating soft singularities, one should not worry about soft $W^* \rightarrow W\gamma$: soft sing. turn into logs of widths; they will pop up also in virt and one accepts them. Simple in PS slicing: leave out soft eikonal for $W^* \rightarrow W\gamma$. How about in a subtraction scheme?
  - What about other issues if wanting to use CM, like gauge inv. violation due to polarizations of on-shell Ws? Is the only way to always run (computationally expensive) fully off-shell?

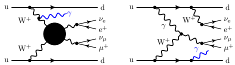
[talk by M. Pellen]

RECOLA: a one-loop matrix element generator
Automation: SHERPA+RECOLA
NLO EW corrections to VBS

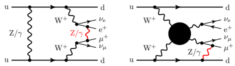
→ NLO EW corrections are of order $\mathcal{O}(\alpha^7)$

→ Include all possible real photonic corrections

$pp \rightarrow \mu^+\nu_\mu e^+\nu_e jj\gamma$



→ Include all virtual corrections
(with up to 8-point functions)



Mathieu PELLEN | Electroweak: RECOLA, Automation, VBS | 15 / 22

NLO EW automation

Planned proceeding projects

- Discussion and solutions for the before-mentioned topics (and relates ones)
  - suggestion for realistic EW (and mixed QCD–EW) uncertainty estimates
- Numerical investigation of the impact of "democratic clustering" against other possible prescriptions, on di-jet or $W(\to l\nu)$+jet (or even $W(\to l\nu)$+2jets) as a sample process.
- Numerical investigation of the impact of different pseudo-resonance treatments in processes with external vector bosons treated as stable, on W+2jets as a sample process

Amplitudes and ingredients of higher-order calculations

[introductory talk by G. Heinrich]

Prospects in amplitudes and four-dimensional approaches:

- Distribution of multi-loop results
- Four-dimensional methods at NLO/NNLO
- Progress in two-loop amplitudes

Distribution of multi-loop results

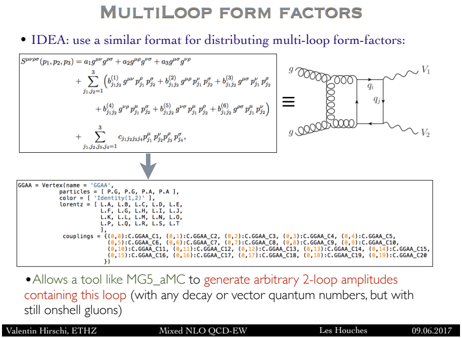
- Idea to build a database for master integrals
  - easy search for Feynman graphs
  - links to literature
  - explicit results ready for download

$\Rightarrow$ **Loopedia**

- Extension beyond only integrals proposed (e.g. multiloop form factors)

$\Rightarrow$ use **UFO** format

[talk by V. Hirschi]



MultiLoop form factors

- IDEA: use a similar format for distributing multi-loop form-factors:

$$S^{\mu\nu\rho\sigma}(p_1,p_2,p_3) = a_1 g^{\mu\nu}g^{\rho\sigma} + a_2 g^{\mu\rho}g^{\nu\sigma} + a_3 g^{\mu\sigma}g^{\nu\rho} + \sum_{j_1,j_2=1}^{3}\Big(b^{(1)}_{j_1j_2}\, g^{\mu\nu}\, p^{\rho}_{j_1}\, p^{\sigma}_{j_2} + b^{(2)}_{j_1j_2}\, g^{\mu\rho}\, p^{\nu}_{j_1}\, p^{\sigma}_{j_2} + b^{(3)}_{j_1j_2}\, g^{\mu\sigma}\, p^{\nu}_{j_1}\, p^{\rho}_{j_2} + b^{(4)}_{j_1j_2}\, g^{\nu\rho}\, p^{\mu}_{j_1}\, p^{\sigma}_{j_2} + b^{(5)}_{j_1j_2}\, g^{\nu\sigma}\, p^{\mu}_{j_1}\, p^{\rho}_{j_2} + b^{(6)}_{j_1j_2}\, g^{\rho\sigma}\, p^{\mu}_{j_1}\, p^{\nu}_{j_2}\Big) + \sum_{j_1,j_2,j_3,j_4=1}^{3} c_{j_1j_2j_3j_4} p^{\mu}_{j_1}\, p^{\nu}_{j_2} p^{\rho}_{j_3}\, p^{\sigma}_{j_4},$$

$\equiv$


```
GGAA = Vertex(name = 'GGAA',
         particles = [ P.G, P.G, P.A, P.A ],
         color = [ 'Identity(1,2)' ],
         lorentz = [ L.A, L.B, L.C, L.D, L.E,
                     L.F, L.G, L.H, L.I, L.J,
                     L.K, L.L, L.M, L.N, L.O,
                     L.P, L.Q, L.R, L.S, L.T
                     ],
          couplings = {(0,0):C.GGAA_C1, (0,1):C.GGAA_C2, (0,2):C.GGAA_C3, (0,3):C.GGAA_C4, (0,4):C.GGAA_C5,
                       (0,5):C.GGAA_C6, (0,6):C.GGAA_C7, (0,7):C.GGAA_C8, (0,8):C.GGAA_C9, (0,9):C.GGAA_C10,
                       (0,10):C.GGAA_C11, (0,11):C.GGAA_C12, (0,12):C.GGAA_C13, (0,13):C.GGAA_C14, (0,14):C.GGAA_C15,
                       (0,15):C.GGAA_C16, (0,16):C.GGAA_C17, (0,17):C.GGAA_C18, (0,18):C.GGAA_C19, (0,19):C.GGAA_C20
                      })
```

- Allows a tool like MG5_aMC to generate arbitrary 2-loop amplitudes containing this loop (with any decay or vector quantum numbers, but with still onshell gluons)

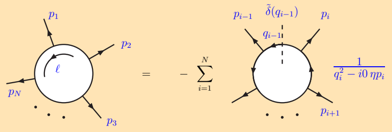
Valentin Hirschi, ETHZ | Mixed NLO QCD-EW | Les Houches | 09.06.2017

The Loop-Tree Duality

- New algorithm/regularization scheme for higher-orders in perturbative QFT
- Local cancellation of IR and UV singularities (IR unsubtracted and 4-dim.)
- Simultaneous generation of real and virtual corrections advantageous, particularly for multi-leg processes (at NLO level, so far).
- Outlook: automation and fully differential multi-leg at NNLO (and beyond)

[talk by G. Chachamis]

A graphical representation of the Loop-Tree Duality



[talk by F. Driencourt-Mangin]

Comparison with DREG

DREG	LTD / FDU
Modify the dimensions of the space-time to **d = 4-2e**	Computations without altering the **d=4 space-time** dimensions[1]
Singularities manifest **after** integration as **1/e poles:** ▪ **IR** cancelled through suitable **subtraction terms,** which need to be integrated over the unresolved phase-space ▪ **UV** renormalized	Singularities killed **before** integration: ▪ **Unsubtracted** summation over degenerate IR states at integrand level through a suitable **momentum mapping** ▪ **UV** through local counter-terms
Virtual and real contributions are considered **separately:** phase-space with **different number of final-state particles**	Virtual and real contributions are considered **simultaneously:** more efficient Monte Carlo implementation and fully differential

[1] Gnendiger et al., *To d, or not to d: Recent developments and comparisons of regularization schemes,* arXiv:1705.01827

F. Driencourt-Mangin   Les Houches Workshop Series 2017

Loop amplitudes: The numerical approach

- Local subtraction terms for loop amplitudes
- Loop-tree duality to re-write cyclic-ordered one-loop amplitude
- Contour deformation
- Cancellations at the integrand level
  (with UV divergences, non-zero spins and initial-state partons)
- only simple integrals analytically, to reproduce the finite terms associated to a given renormalisation/factorisation scheme

[talk by S. Weinzierl]

Cancellations at the integrand level

$$\int_{n+1} d\sigma^{\mathrm{R}} + \int_{n} d\sigma^{\mathrm{V}} \;=\; \int_{n+1} \left(d\sigma^{\mathrm{R}} - d\sigma^{\mathrm{A}}_{\mathrm{R}}\right) + \underbrace{\int_{n} (\mathbf{I}+\mathbf{L}) \otimes d\sigma^{B}}_{\text{numerical integrable?}} + \int_{n+\mathrm{loop}} \left(d\sigma^{\mathrm{V}} - d\sigma^{\mathrm{A}}_{\mathrm{V}}\right)$$

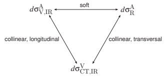
- At NLO both $d\sigma^{\mathrm{A}}_{\mathrm{R}}$ and $d\sigma^{\mathrm{A}}_{\mathrm{V}}$ are easily integrated analytically.
- This is no longer true at NNLO and beyond.

$$\int_{n} (\mathbf{I}+\mathbf{L}) \;=\; \int_{n} \left[\int_{1} d\sigma^{\mathrm{A}}_{\mathrm{R}} + \int_{\mathrm{loop}} d\sigma^{\mathrm{A}}_{\mathrm{V}} + d\sigma^{\mathrm{V}}_{\mathrm{CT}} + d\sigma^{\mathrm{C}} \right].$$

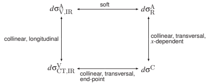
- Unresolved phase space is $(D-1)$-dimensional.
- Loop momentum space is D-dimensional
- $d\sigma^{\mathrm{V}}_{\mathrm{CT}}$ counterterm from renormalisation
- $d\sigma^{\mathrm{C}}$ counterterm from factorisation

Cancellations of infrared singularities

Only final-state particles:



With initial-state particles:



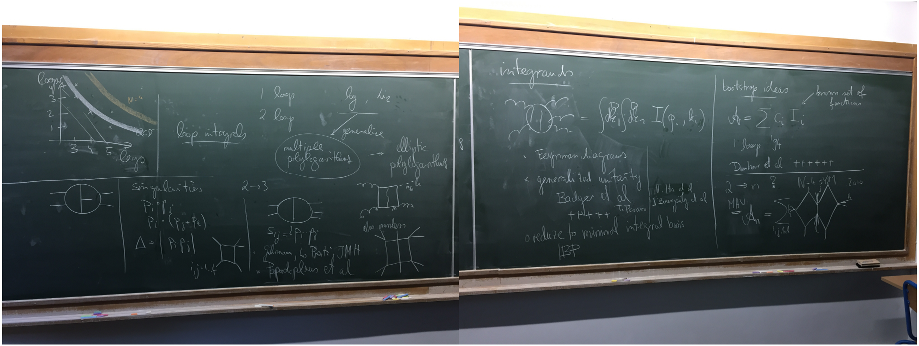
Amplitudes and ingredients of higher-order calculations

Planned proceeding projects

- Standards for public multi-loop results: come up with Drell-Yan as an example for tool-chain at various levels in UFO format
    - Merge this approach with the Loopedia project (original plan: only integrals)?
- Working out standards for providing two-loop amplitudes to combine them with other building blocks making up a NNLO fixed-order calculation
- Reasonable project on four-dimensional methods under discussion

Progress in two-loop amplitudes

[talk by J. Henn]



- "State of the art is moving towards 2 → 3 processes"

Wishlist

Planned proceeding projects

- Update the processes computed since release of the last wishlist (correct for out-dated process information, make some details more precise)
- Add new required processes to the new wishlist
- Provide references for the calculations
- Provide links to relevant measurements
- Add information on required experimental precision
- **Promote the Les Houches wishlist to a reference for SM processes, saying which fixed-order calculations are available at which order (make sure that also applied approximations are visible)**

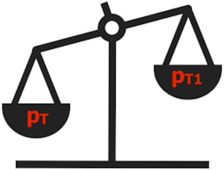
N(N)LO, Multi-legs SM group
experimental summary

K. Theofilatos
J. Huston (co-convener)

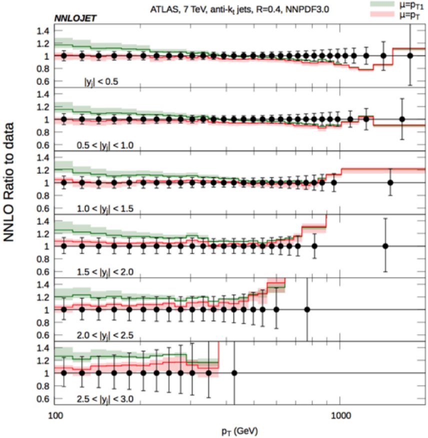
ETH zürich

Les Houches
14 June 2017

From questions arising from the

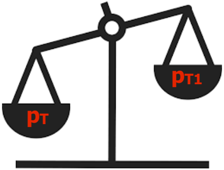


NNLO scale ?

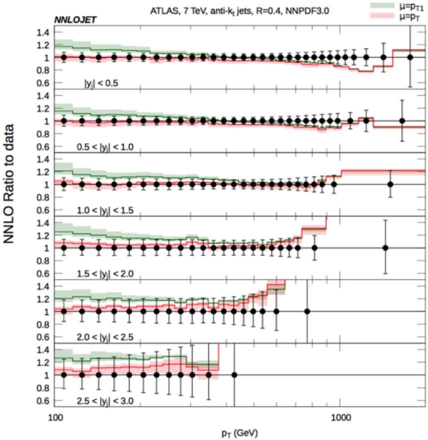


2

From questions arising from the



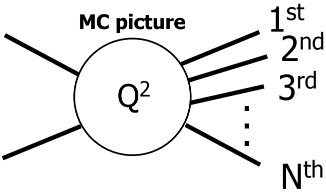
NNLO scale ?



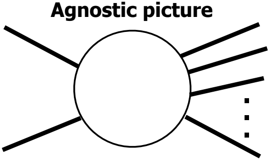
to wondering if AK04 is sufficiently wide enough and if the inclusive jet observable makes sense to start with ...

3

Two pictures



<u>each event</u> has a specific scale Q^2



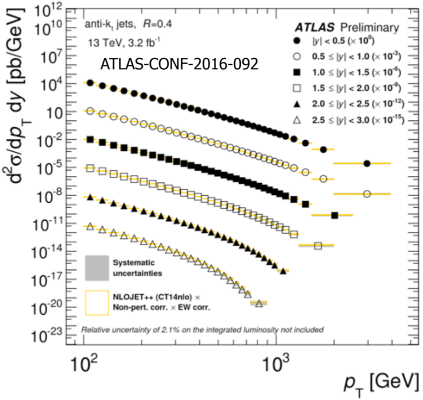
$Q^2 = p_T^2$

<u>each jet</u> is agnostic what happens elsewhere, it only knows its very own p_T

4

Inclusive jet cross section

- A N-jet event will contribute N-times in the same distribution (histogram)
- Alternative would be: order them and use each event once, e.g., a 4-jet event will just go in the 4-jet distribution

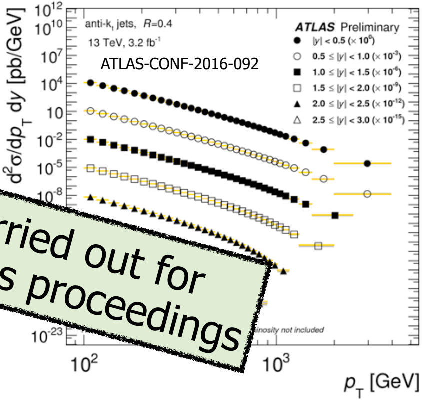


a bet has been placed that peculiarities of the different scale differences will reside on high N_{jet} that gets a soft scale for $\mu = p_T$

Inclusive jet cross section

- A N-jet event will contribute N-times in the same distribution (histogram)
- Alternative ... ld be: order them and ... once, e.g. ... just go in the ... distribution

Study to be carried out for the Les Houches proceedings

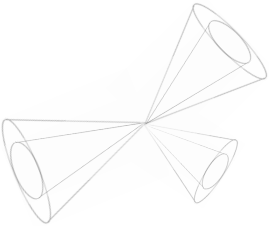


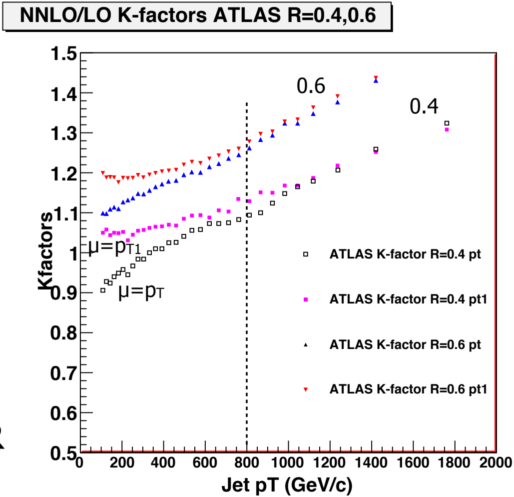
a bet has been placed that peculiarities of the different scale differences will reside on high N_{jet} that gets a soft scale for $\mu=p_T$

6

But is this discussion

independent of
the cone size ?

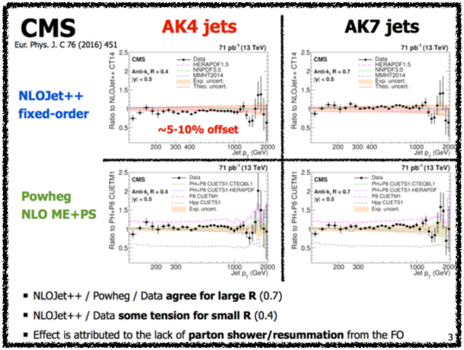




scale choice
differences get
larger for smaller R

7

partonic vs hadronic x-sections

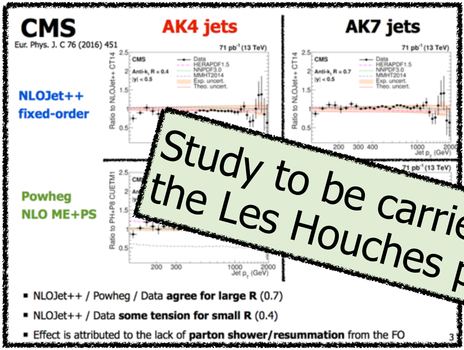


NLO ME+PS vs Fixed Order agree for large R but not for small, data always good with NLO ME+PS

quantify resummation/shower effects affecting small cones for FO predictions comparing ME with ME+PS for (N)LO using MCs

8

partonic vs hadronic x-sections



Study to be carried out for the Les Houches proceedings

NLO ME+PS vs Fixed Order agree for large R but not for small, data always good with NLO ME+PS

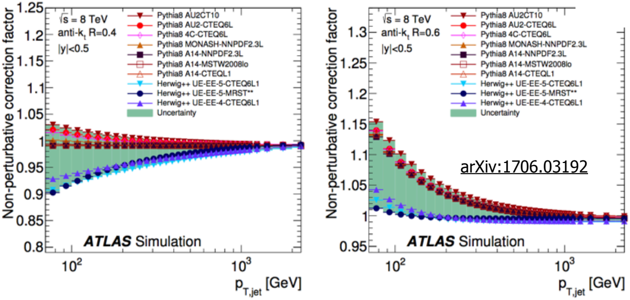
quantify resummation/shower effects affecting small cones ... s for (N) ...

Ideally we would like Pythia, Herwig, Powheg, Sherpa, aMC@NLO people subscribing if not done that already, Rivet routines from CMS are waiting in the wiki

9

Unboxing NP effects

$$C_{\mathrm{NP}} = \frac{d\sigma^{\mathrm{ME+PS+HAD+MPI}}/dp_{\mathrm{T}}}{d\sigma^{\mathrm{ME+PS}}/dp_{\mathrm{T}}}$$



- Herwig alone predicts **small δC_{NP}** when varying its tunes
- Pythia alone predicts **small δC_{NP}** when varying its tunes
- But Pythia/Herwig **disagree on C_{NP}**

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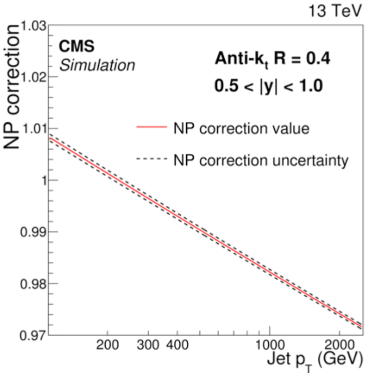
NP at CMS



- Herwig/Pythia and Powheg+Pythia used for envelopes
- Uncertainties become larger (a bit) at high P_T for R=0.7

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Philosophical (?) questions

- Why the procedure of assessing $\mathbf{C_{NP}}$, $\mathbf{\delta C_{NP}}$ can't be made ~identical between ATLAS/CMS
- Why Pythia and Herwig predict so much different C_{NP} ? What about Sherpa ?
- What is the best cone size, interplay for NP and soft pertubative effects (resummation)
- Are these purely theoretical aspects on the interpretation having nothing to do with the experimental-measurements@hadron-level?

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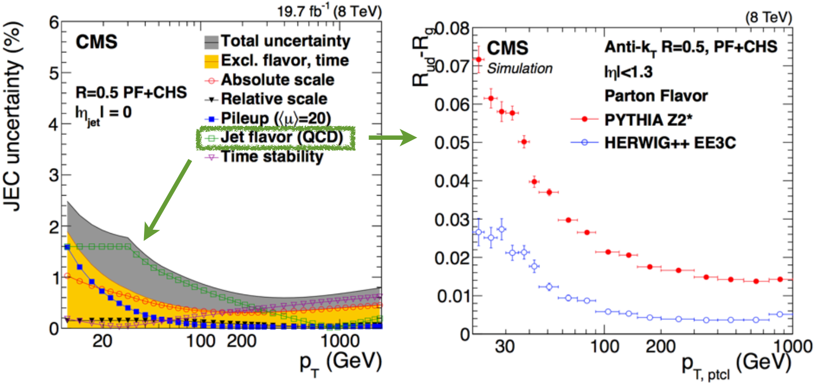
Interplay with the jet group



Pythia vs Herwig gluon response is a dominant experimental uncertainty

What about UE/PU area subtraction (offset JEC) ?

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Les Houches accord on NP/cone?

- Les Houches accord on MPI+HAD assessment (C_{NP}, δC_{NP})
- Understand why Pythia vs Herwig predict different C_{NP}
  - Can we get Sherpa also ? Yes we can
  - "jet flavor uncertainties" upon calibrating the jets ? (dominant experimental uncertainties on the cross section)
- Rivet routines for tuning observables **jet mass, width and LH angularities** have been provided in the LH wiki (interplay with jet group) -- can these be also measured by ATLAS/CMS for **Les Houches 2019** ?
- **3-rd dimension of the problem**, evaluate these for different cone sizes, suggested R=0.3, 0.4, 0.6, 0.7, 1.0

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Les Houches accord on NP/cone?

- Les Houches accord on MPI+HAD assessment (C_{NP}, δC_{NP})
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Study to be carried out for the Les Houches proceedings

https://phystev.cnrs.fr/wiki/2017:working_groups:incljets

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~TeV Z's are useful

for QCD resummation studies

Idea behind this exercise:

- **mZ'** sets high scale the scale of **Z' + jets**
- check down to which $\mathbf{p_{T1}^{min}}$ the FO predictions are alone sufficient to describe the leading jet $\mathbf{p_T}$ spectrum by contrasting them with resummed predictions

- project to be added soon in the wiki, would be nice to compare predictions with some real Z' data ;-)

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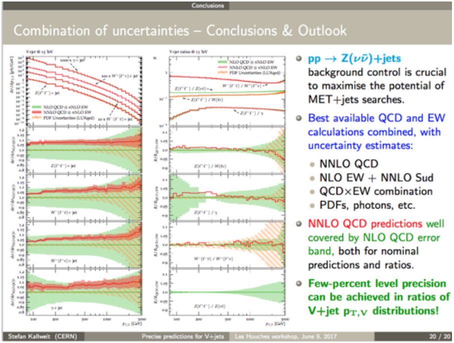
Uncertainties in ratios

- scale choices in ratios e.g., W+>=1 jet/Z+>=1 jet, H+>=1 jet/Z+>=1 jet at NLO and at NNLO
- paradigm from V+jets background for DM searches was discussed (W/Z, Z/γ)
- :-(from discussion at LH not easy to do similar tricks for VV, VV+2j VBSs



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Summary of the summary

unknotting the knot (reducing uncertainties)

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subscribe to the wiki and become a contributor to the SM studies !