Transfer of status

F. Giuli – Particle Phenomenology Forum
University of Oxford

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22/10/2015

Oxford Physics

PDF4BSM
Parton Distributions in the Higgs Boson Era

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ATLAS

First of all…

- ATLAS member - half theoretical and half experimental DPhil
- The research projects in which I have been involved so far included:
  - Searches of New Physics in the Drell-Yan process at 13 TeV (ATLAS paper in preparation)
  - Involved in the analysis on PDF fit to ATLAS 2011 jets data (paper ongoing)
  - Qualification task within ATLAS: implementation and validation of aMC@NLO FxFx in ATLAS software

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Implementation and validation of MG5_aMC@NLO + Pythia8 with FxFx merging in Athena, the off-line ATLAS analysis software

- To reproduce ATLAS results regarding W/Z+jets @7 TeV (Pythia8 stand-alone validation)
- Validation of inclusive W/Z samples in Athena using MG5_aMC@NLO and Pythia8
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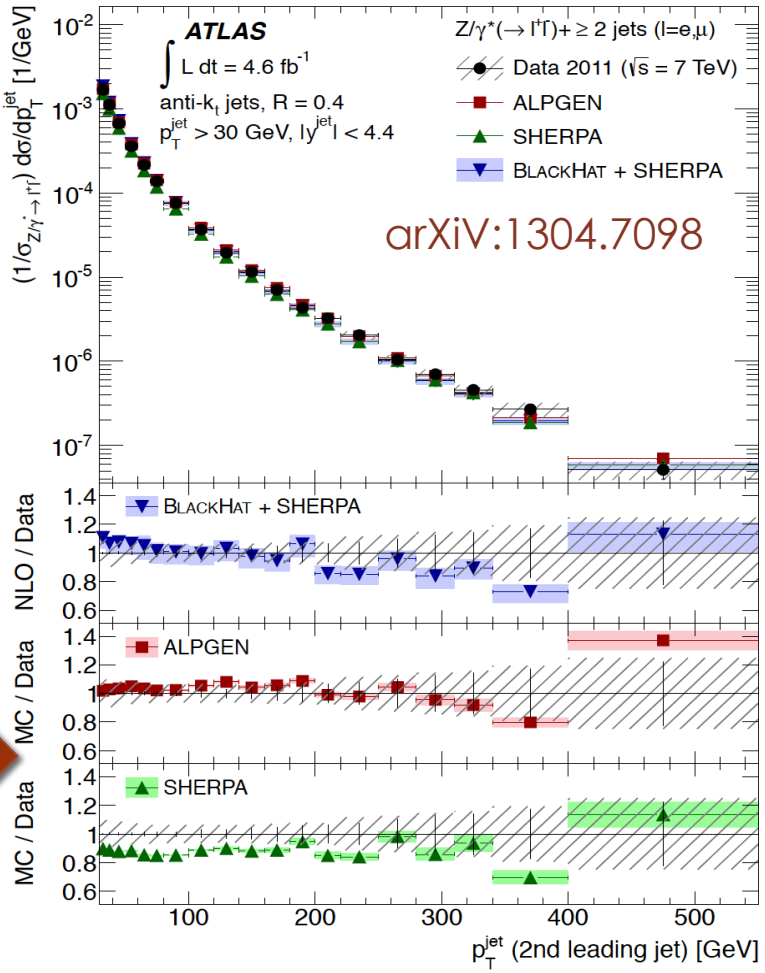
Ongoing

Outline

- I will present the validation of NLO merged calculations of W and Z boson inclusive production at $\sqrt{s}$ =7 TeV
- Events generated in Athena with MG5_aMC@NLO (including next-to-leading order perturbative corrections) and showered with Pythia8 (always in Athena)
- Simulated events analysed with several Rivet routines
- **W/Z + jets processes fundamental for Montecarlo tuning**

7 TeV ATLAS data

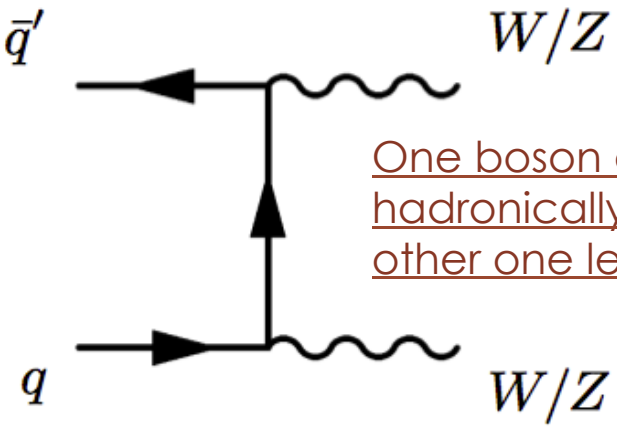
2nd leading jet transverse momentum distribution



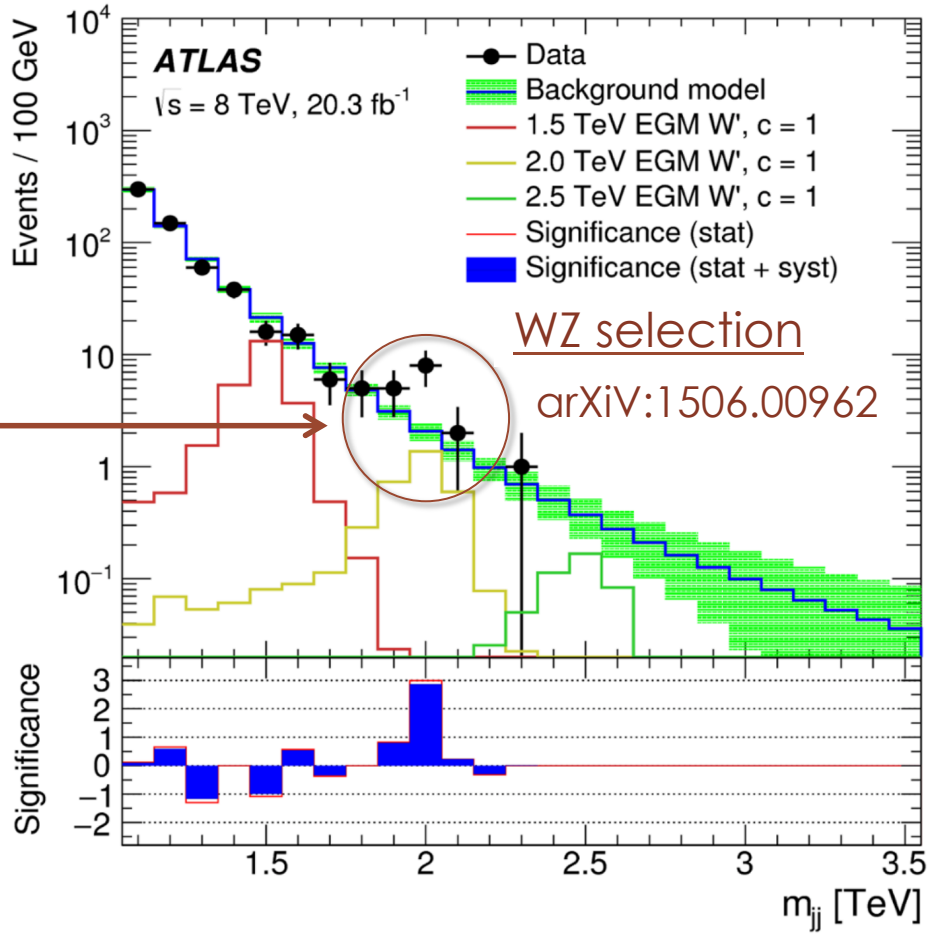
Why MC validation is so important?

- One needs reliable and trustful MonteCarlo (MC) simulations for estimating SM backgrounds, especially in the Beyond-the-SM searches
- Furthermore, careful modelling of SM backgrounds is essential to understand the output of searches
- As you can see here…

Bump in dijet invariant mass ~2 TeV with a significance of 3.4 σ



One boson decays hadronically and the other one leptonically



MadGraph5_aMC@NLO (arXiv:1405.0301)

- An automated cross section calculator that contains all the features relevant to the computation of LO and NLO cross sections, with also the matching to the Parton Shower (PS)
- Why automation?
  - Time: Less tools, means more time for physics
  - Robust: Easier to test and to debug
  - Easy: One framework/tool to learn
- Why NLO?
  - Reliable prediction of the physics quantities
  - Reduction of the theoretical uncertainty
- Why matched to the PS?
  - Partons are not an detector observables

Going NLO

$$d\sigma = \sum_{a,b} \int dx_1 dx_2 \; f_a(x_1, \mu_F) f_b(x_2, \mu_F) \, d\hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$

Cross section at hadron collider

Parton density functions

Parton-level (differential) cross section

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter:

$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left(\frac{\alpha_s}{2\pi} \right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi} \right)^3 \sigma^{(3)} + \dots \right)$$

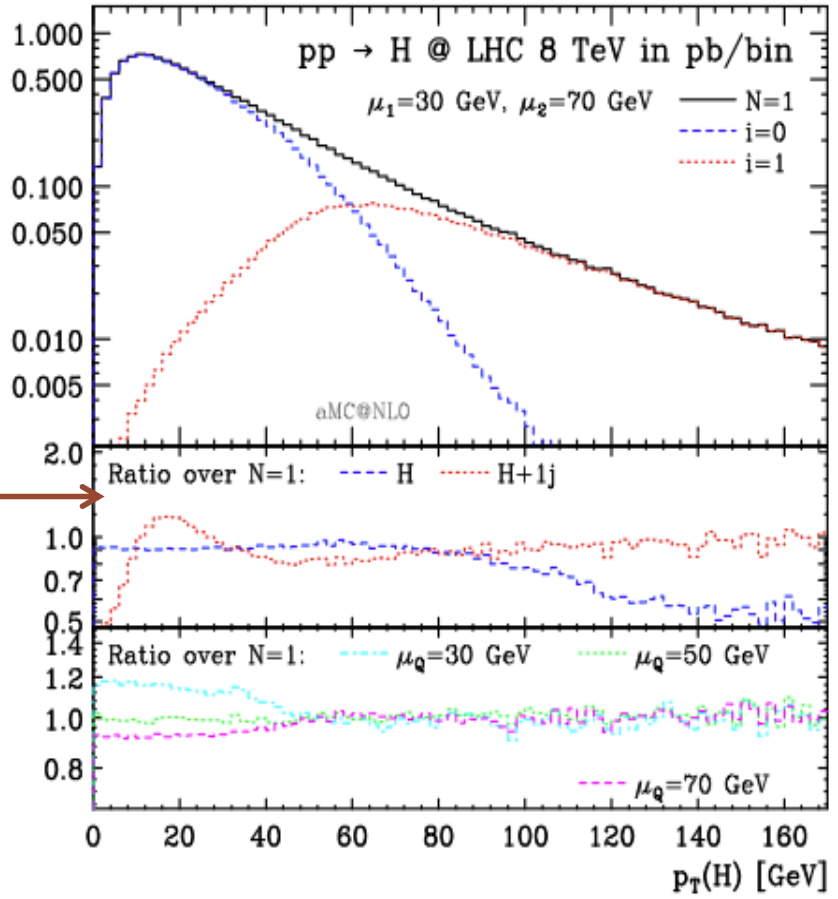
- **Including higher corrections improves predictions and reduces theoretical uncertainties**
- σ^{Born} represents prediction on cross section at LO, while $\sigma^{(1)}$, $\sigma^{(2)}$ and $\sigma^{(3)}$ are NLO, NNLO and NNNLO (or N^{3}LO) corrections
- NLO is the first order where we have first reliable estimate of the total cross section, as well as of the theoretical uncertainties

Matching and merging

- Matching in MCs: To match matrix-element calculations and parton shower simulation in order to attain NLO precision (needed because NLO predictions predict rates much more precisely and because we have correct estimates for PDF uncertainties)
- **Matched computations are some of the most accurate/realistic predictions currently available**

arXiv:1209.6215

- What is this NLO FxFx merging? A prescription which allows for the consistent merging of event files of various jet multiplicities at NLO accuracy, avoiding double counting
- In this way, **by including higher multiplicity matrix elements, a better description of the events is achieved**



Higgs boson p_T

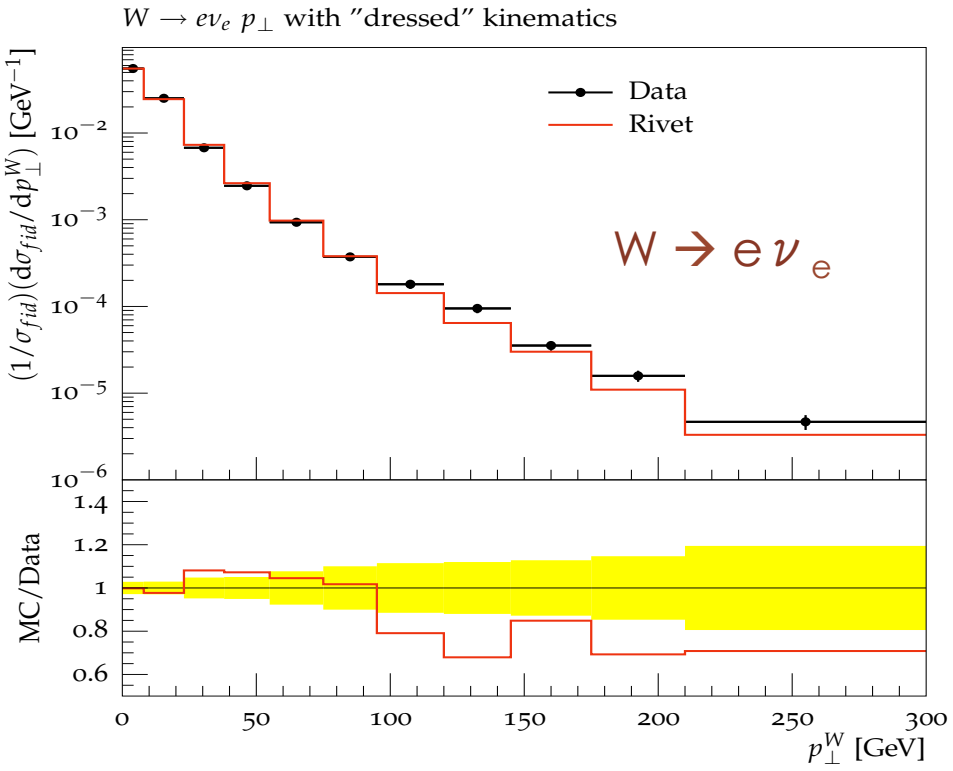
Higgs + 0 jet sample: fails at higher p_T
Higgs + 1 jet sample: fails at lower p_T
Merged sample: works in the whole range

Athena framework

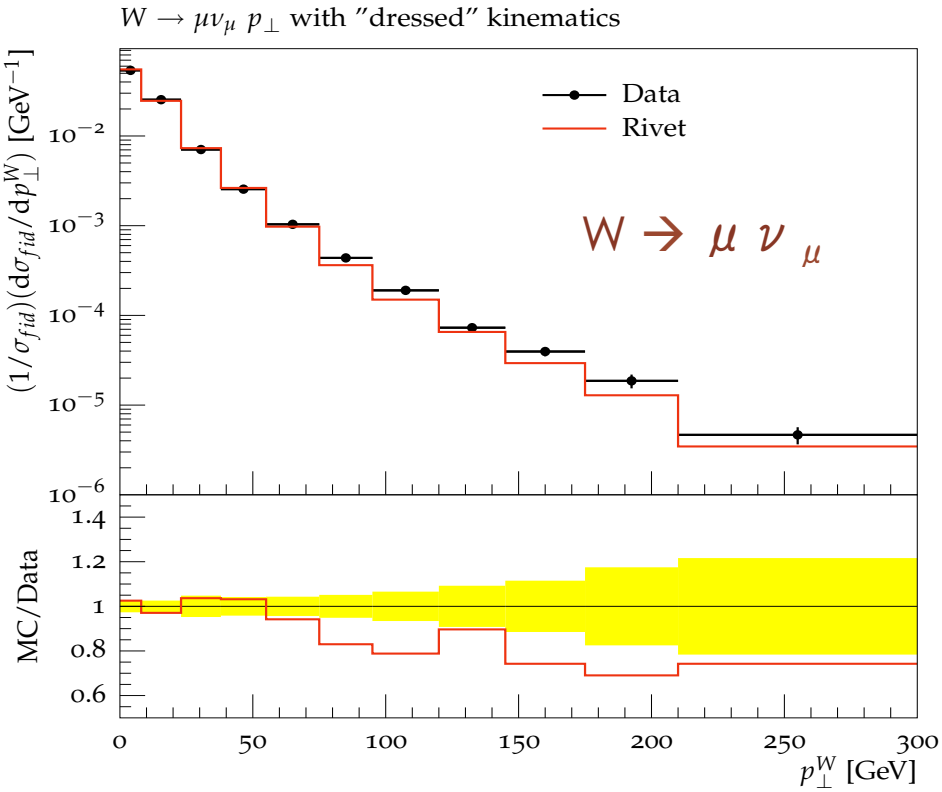
- This is the ATLAS off-line analysis software
- **C++ control *framework*** designed for a wide range of physics and data processing applications
- Basically, a skeleton of an application into which developers plug in their code (component-based)
- Athena uses **Python as scripting language**
- All of the offline processing is done in the Athena framework… but this flexibility comes at the expense of user-friendliness (unfortunately)
- Thousand and thousand lines of code
- Several different components in Athena
- Implementation of new functionalities very challenging

Summarizing… Working in this framework **NOT EASY AT ALL!!!**

W boson inclusive production

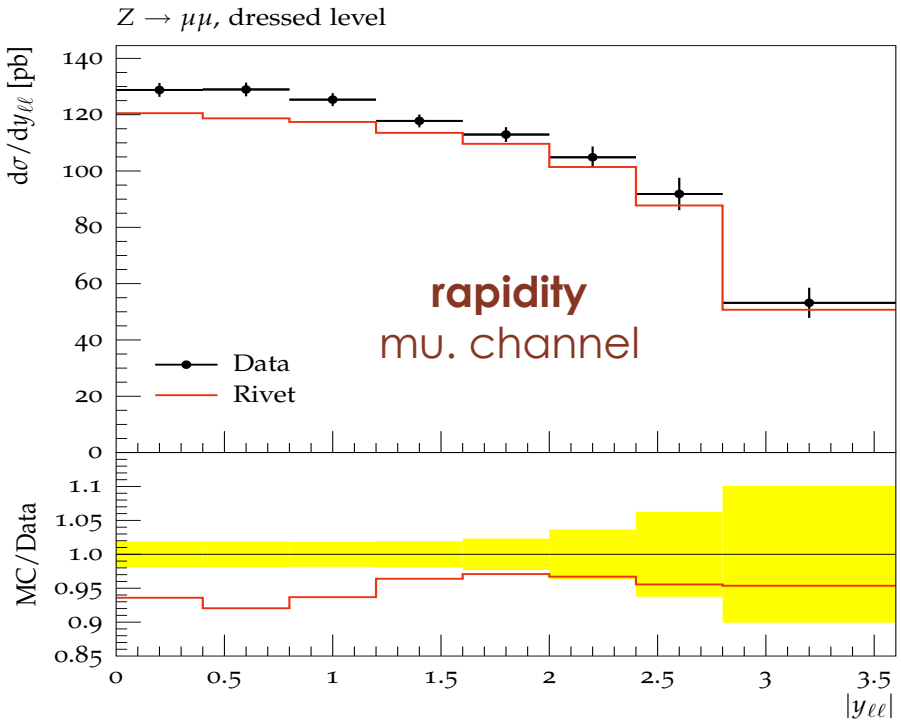


Comparison of aMC@NLO NLO+PS predictions in Athena and the ATLAS 7 TeV data (no merging yet)



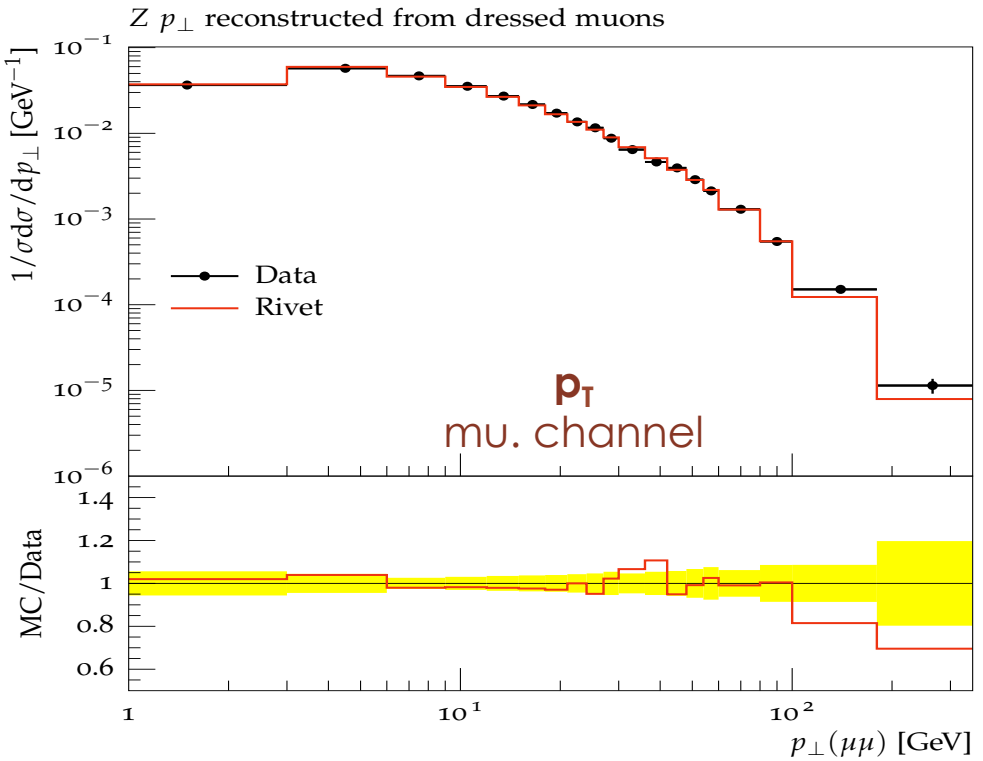
- Nice agreement between aMC@NLO predictions and data
- The yellow band represents quadratic sum of stat. + syst. errors

Z boson inclusive production



- Results for the muon channel shown
- Nice agreement as well in the electron channel

- Nice agreement between aMC@NLO predictions and data
- The yellow band represents quadratic sum of stat. + syst. errors



Conclusion and outlook

- In this talk I have illustrated the implementation of NLO+PS aMC@NLO calculations of W and Z boson production at $\sqrt{s}$ =7 TeV in Athena
- The agreement between MC predictions and data is good
- Agreement can be further improved by including higher multiplicity matrix element (FxFx merging)
- No physics validation! Check that the tool worked without any unexpected problems in the ATLAS software → **FxFx merging should be used for any serious data/theory comparison**
- **FxFx merging in Athena very recently implemented** (validation studies ongoing)

BACK-UP SLIDES

Theory Settings

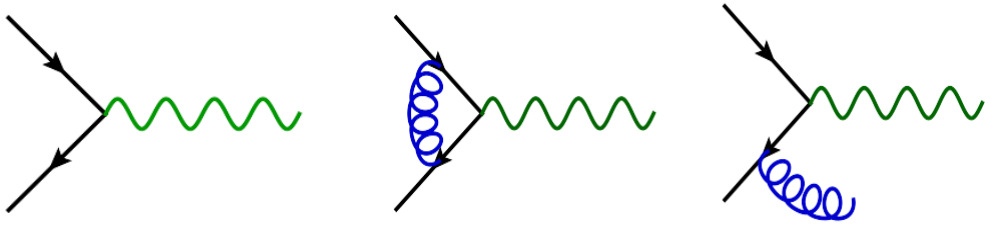
- The theory settings are the same of the "official" samples generated for an stand-alone independent study by the MG5_aMC@NLO authors (S. Frixione, S. Prestel, P. Torrielli et al)
  - **NNPDF-2.3 NLO** (lhaid = 230000) has been used as input PDF set for the event generation
  - F = fixed_ren_scale ! If .true. use fixed renormalisation scale
  - F = fixed_fac_scale ! If .true. use fixed factorisation scale
  - .true. = reweight_PDF → for including PDF uncertainties
  - 5 = maxjetflavor (all quarks – except for top quark – treated as light quarks)
  - 8 GeV = min. jet transverse momentum; no cut on η jet
  - 0 GeV = min. lepton transverse momentum; no cut on η lepton
  - 40 GeV = min. inv. mass of all possible sign lepton pairs
  - In the Pythia8 shower, the PDF set used is NNPDF-2.3 LO (**PY8_A14 tune** – ATLAS default tune in parton shower)
- Same theory setting in both event generation and parton shower in order to make a comparison between my results (obtained in Athena) and the ones from MG5_aMC@NLO collaboration

Going NLO (2)

- At NLO the dependence on the renormalization and factorization scales is reduced
- First order where scale dependence in the running coupling and the PDFs is compensated for via the loop corrections
- **First reliable estimate of the total cross section** which provides a better description of the final state

$$\sigma^{\mathrm{NLO}} = \int_m d\sigma^B + \int_m d\sigma^V + \int_{m+1} d\sigma^R$$

Cross section at NLO

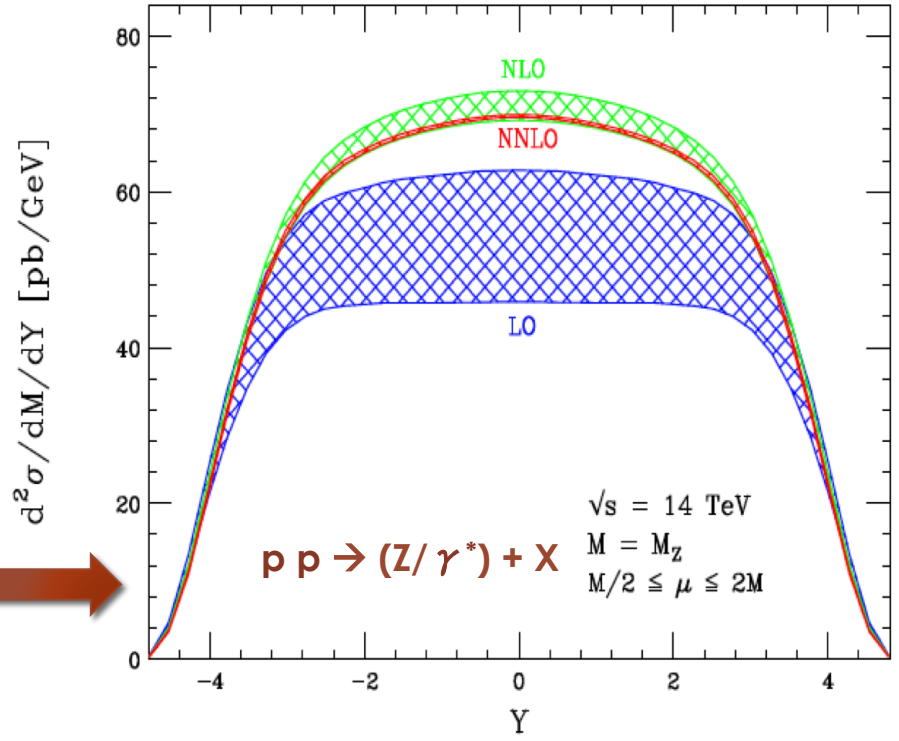


- NLO corrections have three parts:
  - Born contribution (LO)
  - Virtual (or Loop) corrections: formed by an amplitude with a closed loop of particles interfered with the Born amplitudes
  - Real emission corrections: formed by amplitudes with one extra parton compared to the Born process
- Both Virtual and Real emission have one power of α_s extra compared to the Born process

Going NNLO…?

- *NNLO is the current state-of-the-art*
- Why do we need it?
  - Provide more reliable estimation of the total cross section
  - Control of the uncertainties in a calculation
  - It is "mandatory" if NLO corrections are really large in order to check the behaviour of the perturbative expansion (if it is convergent or not)
  - It is needed for Standard Model candles and very precise tests of the perturbation theory, exploiting all the possible information, e.g. for determining NNLO PDF sets

In this plots, the dashed bands represent the theoretical uncertainty



Rivet

- A tool to produce physics plots from an MC generator code which can produce HepMC events
- All the "most famous" generators can do that: C++ Pythia 8, Sherpa, Herwig++ etc
- This is useful for validating generators – only need to write the analysis once and it can be used to validate and compare every generator that should be able to simulate it
- In these analyses, one could compare MC predictions with a large (and ever growing) set of experimental analyses (including ATLAS, CMS, …, data) useful for MC generator development, validation, tuning, BSM studies and so on
- Latest version: Rivet_2.2.4 (one can download it from the following link: https://rivet.hepforge.org/trac/wiki/GettingStarted)
- One of the latest tutorial can be found here: http://indico.cern.ch/event/281744/material/slides/0.pdf

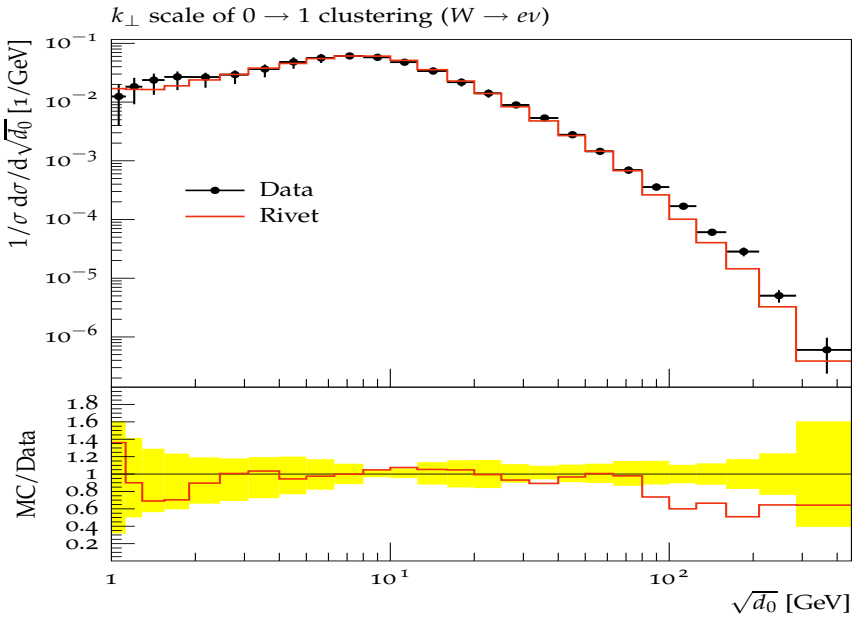
Rivet routines used

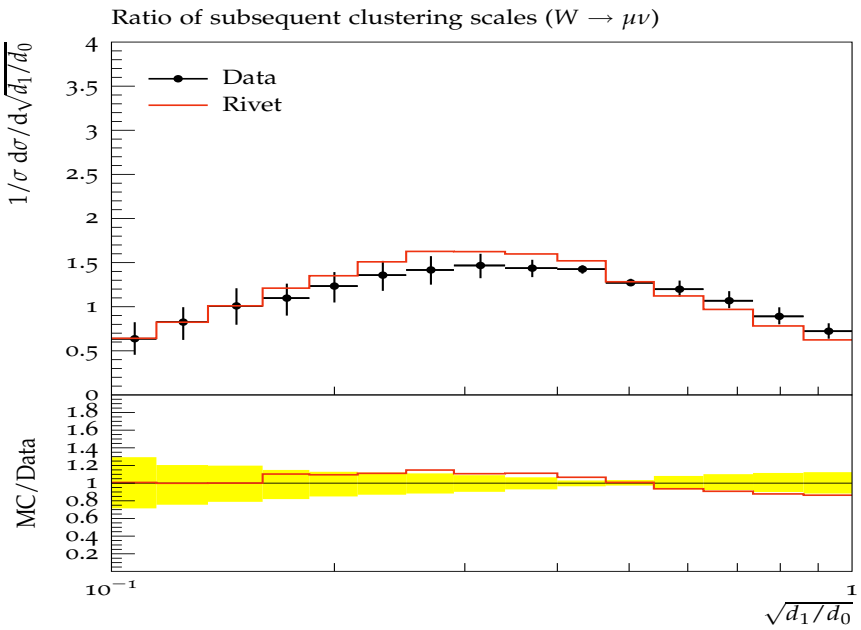
- Some already in Rivet, other copied from the following repository on SVN: svn+ssh://svn.cern.ch/reps/atlasphys-comm/Physics/Generators/Notes/MC14/VJetsNote/Rivet

- **W boson inclusive production:**
  - ATLAS_2011_I925932 (W p_T distribution)
  - ATLAS_2013_I1210867 (Cluster splitting scales in events with W bosons decaying to electrons or muons)
  - ATLAS_2011_S9002537 (Muon charge asymmetry in W events at 7 TeV in ATLAS)
  - MC_WINC
- **Z boson inclusive production:**
  - ATLAS_2011_I928289_Z (Z rapidity distribution)
  - ATLAS_2011_S9131140 (Z p_T distribution)
  - ATLAS_2014_I1315949 (Distributions sensitive to the underlying event in Z boson inclusive production at 7 TeV)
  - ATLAS_2012_I1204784 (Measurement of angular correlations in Drell-Yan lepton pairs to probe Z/γ^* boson transverse momentum)
  - CMS_2012_I941555 (Measurement of differential Z/γ^* p_T and y)
  - CMS_2012_I1107658 (Measurement of the underlying event activity in the Drell-Yan process at a centre-of-mass energy of 7 TeV)
  - MC_ZINC

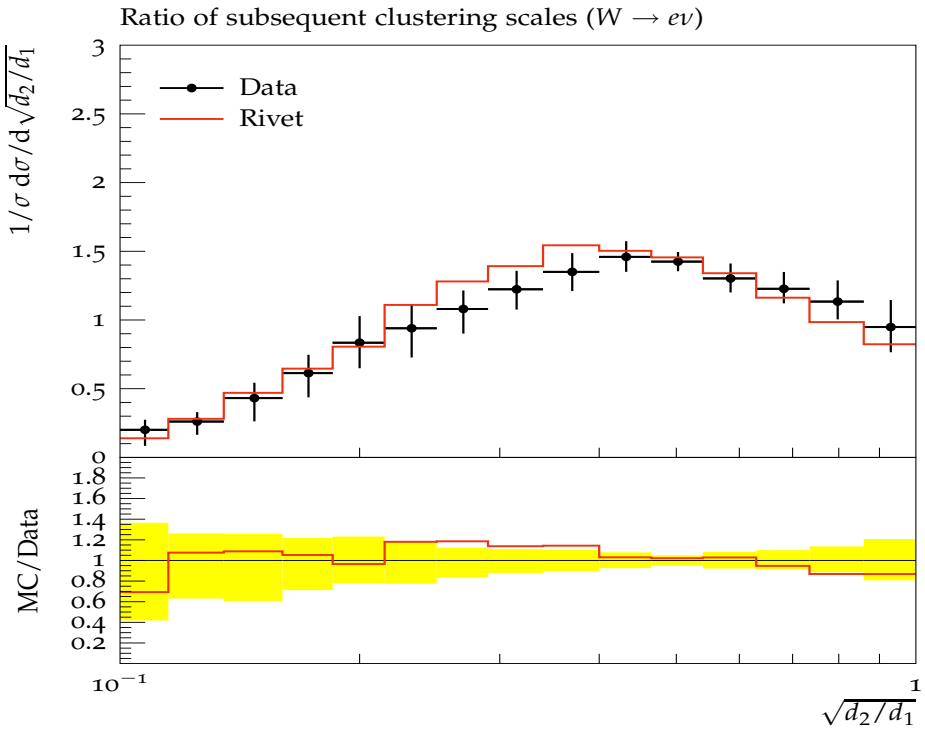
- In each sample, *5M of events* generated and showered (~2 weeks of CPU time do to both the generation and the shower part)

W boson inclusive production (2)

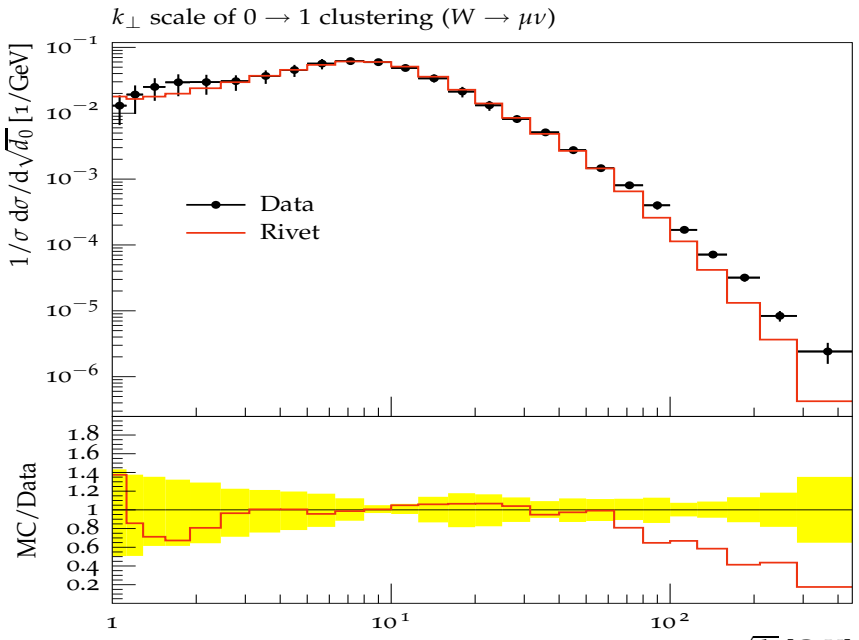


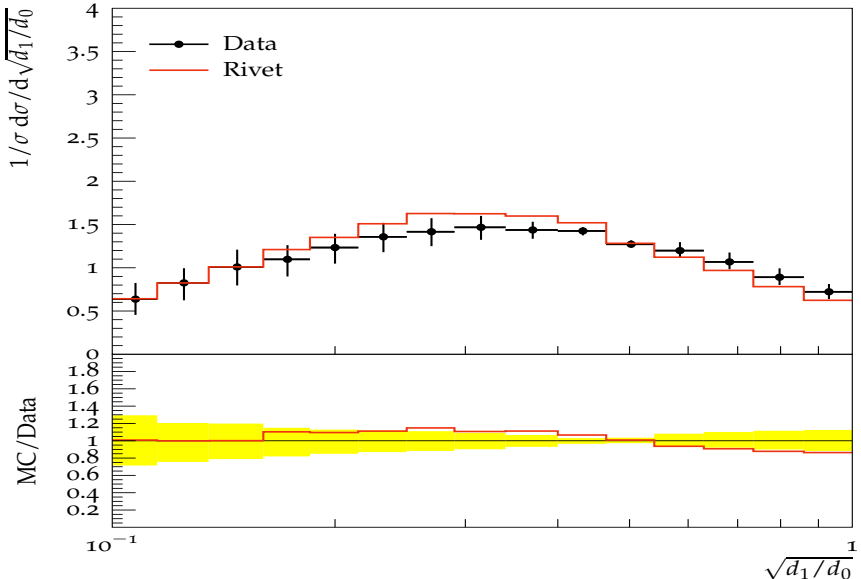


- This Rivet analysis comprises the four hardest splitting scales in a k_T cluster sequence of the hadronic activity accompanying the W boson, and the ratio of theses splitting scales
- Nice agreement between aMC@NLO prediction and data



W boson inclusive production (3)





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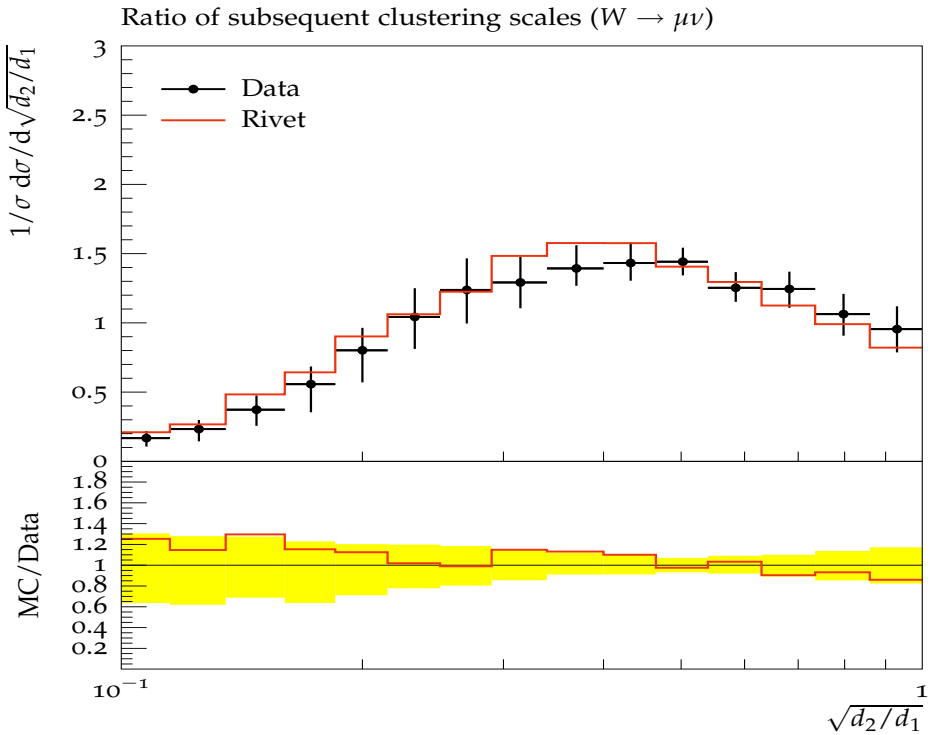
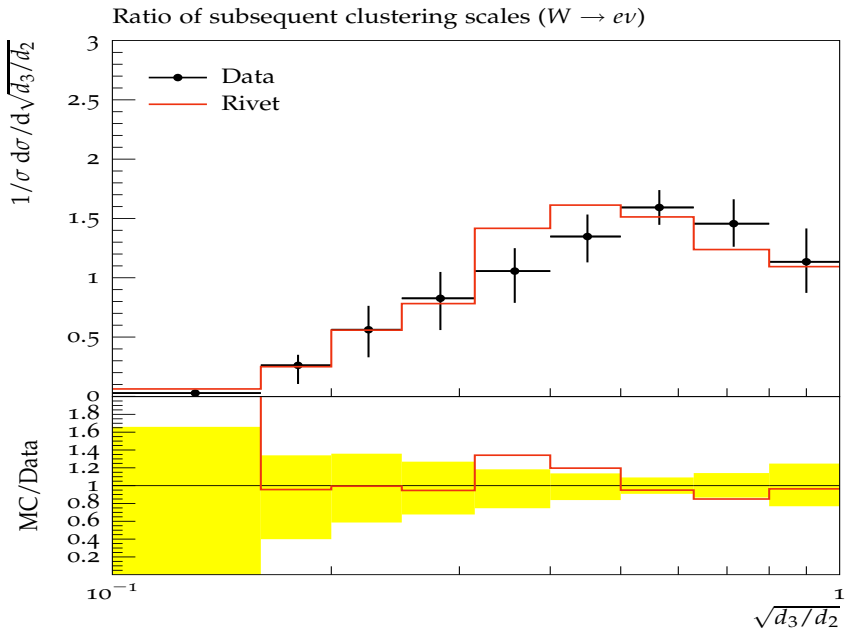
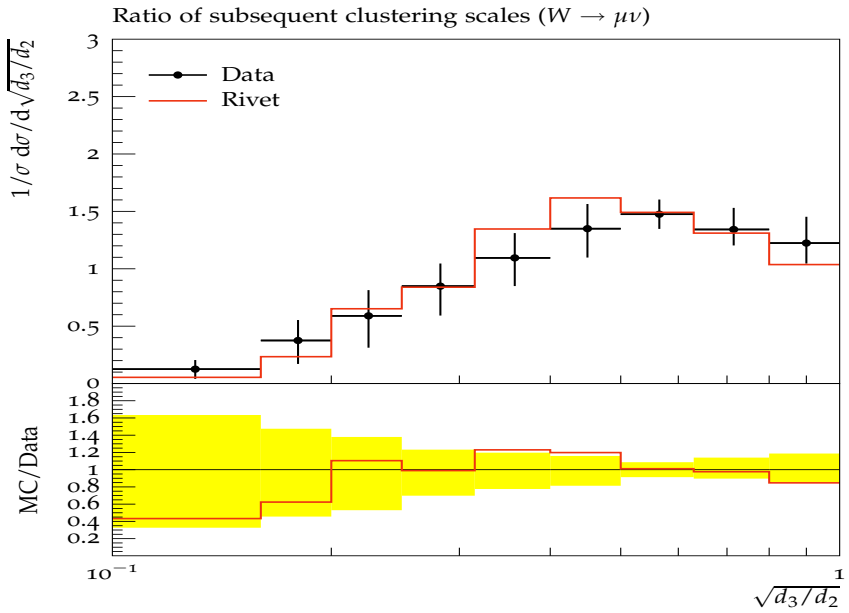
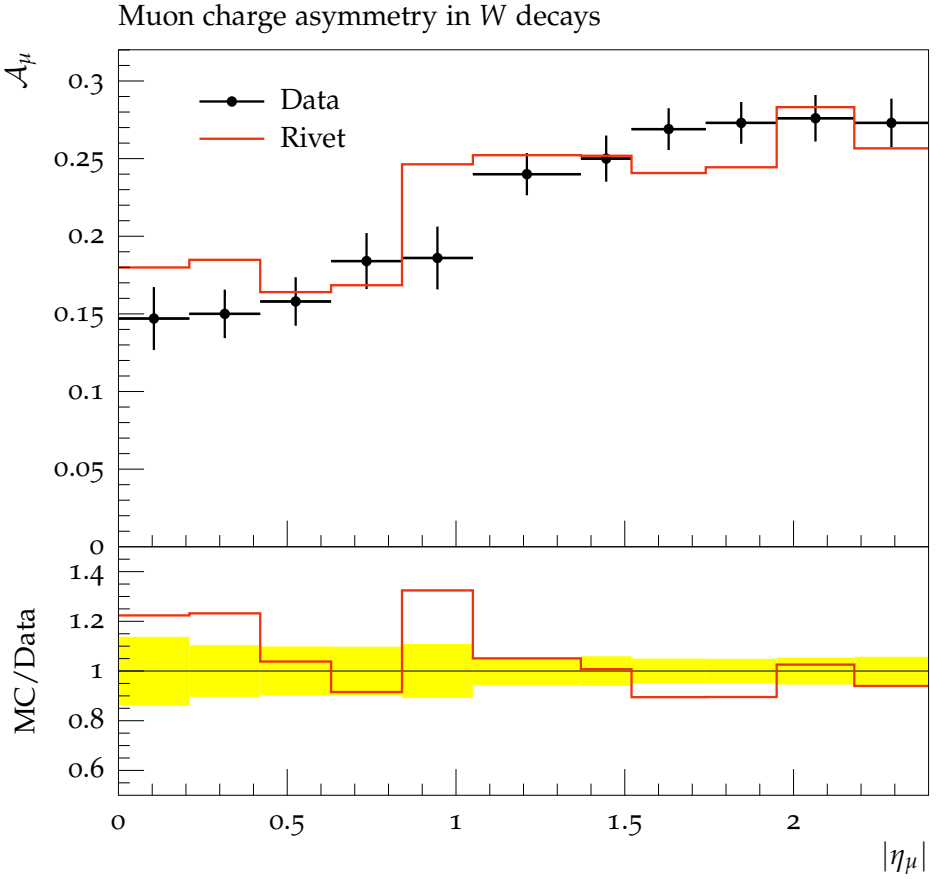


W boson inclusive production (4)

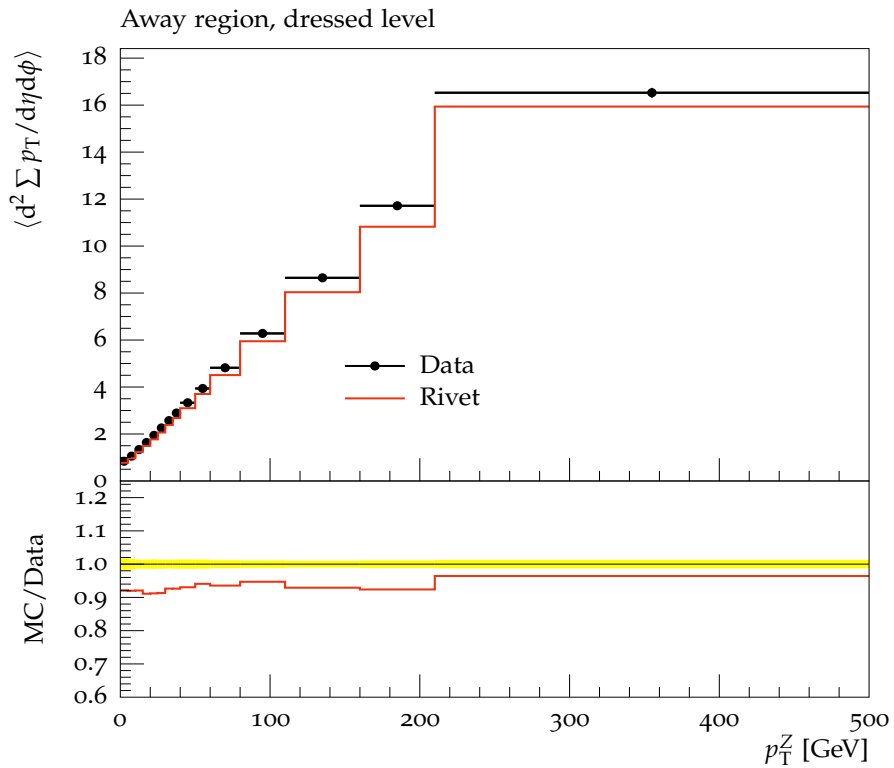




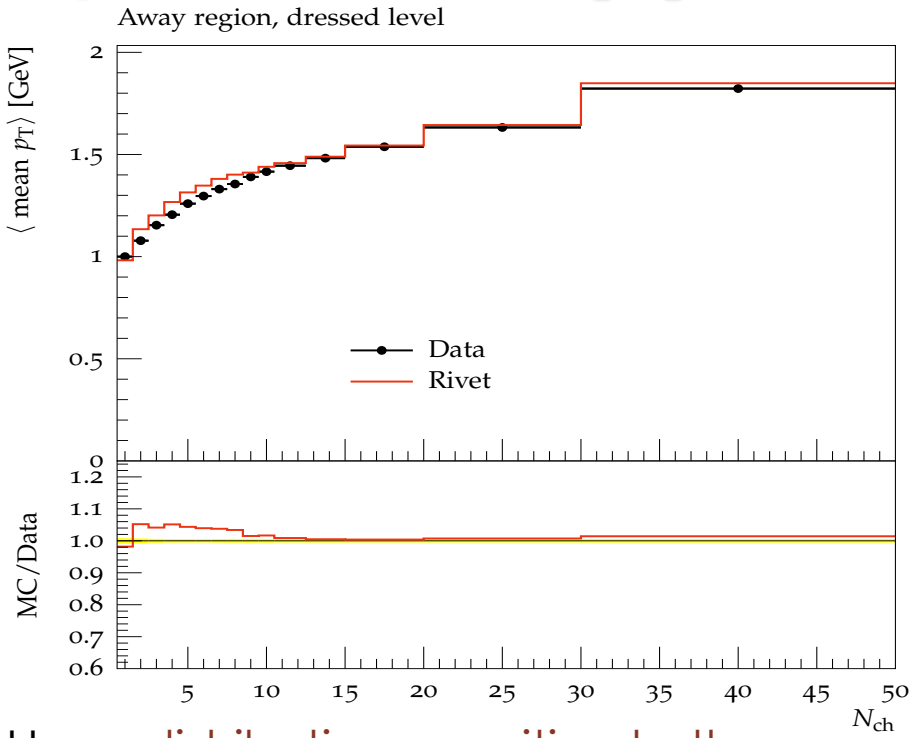
- Ratio $\sqrt{(d_3/d_2)}$ and μ charge asymmetry in W decays
- Nice agreement between aMC@NLO prediction and data



Z boson inclusive production (2)



The dressed leptons definition uses photons clustered in a cone around the charged leptons (while the bare lepton definition uses the post-FSR charged leptons only in the Z reconstruction)



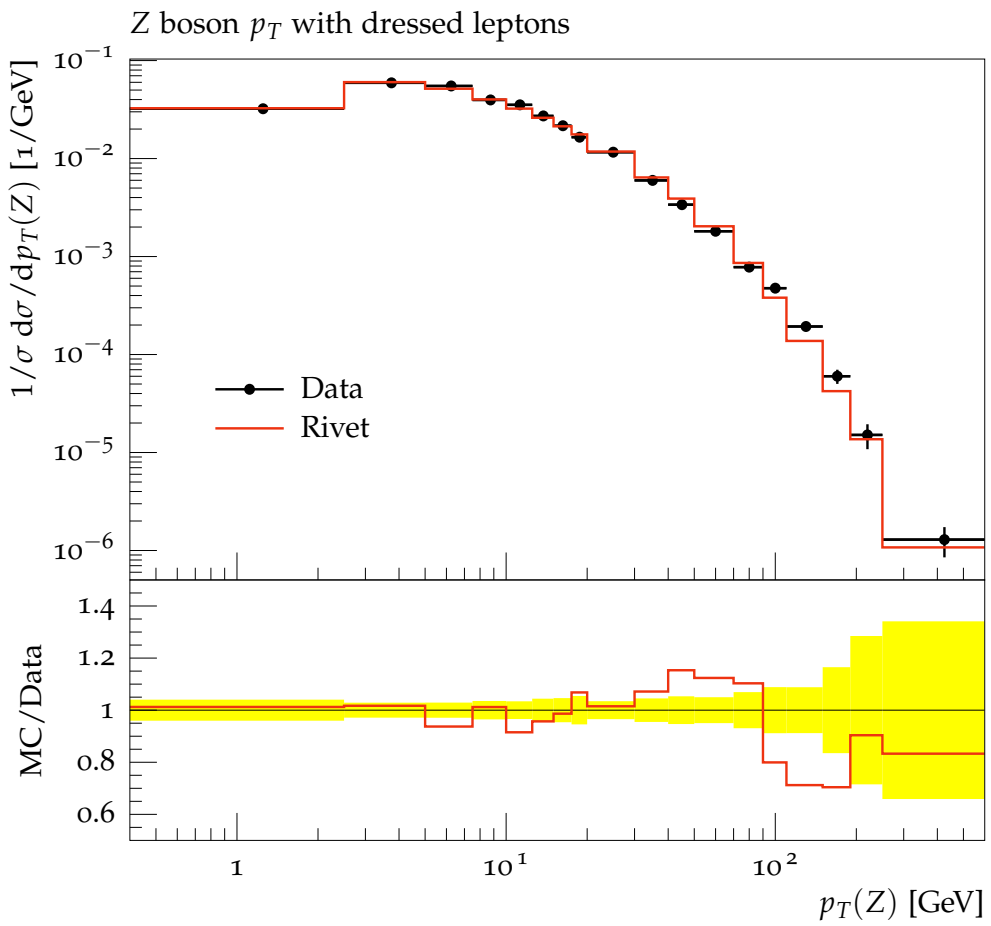
Here, distributions sensitive to the underlying event

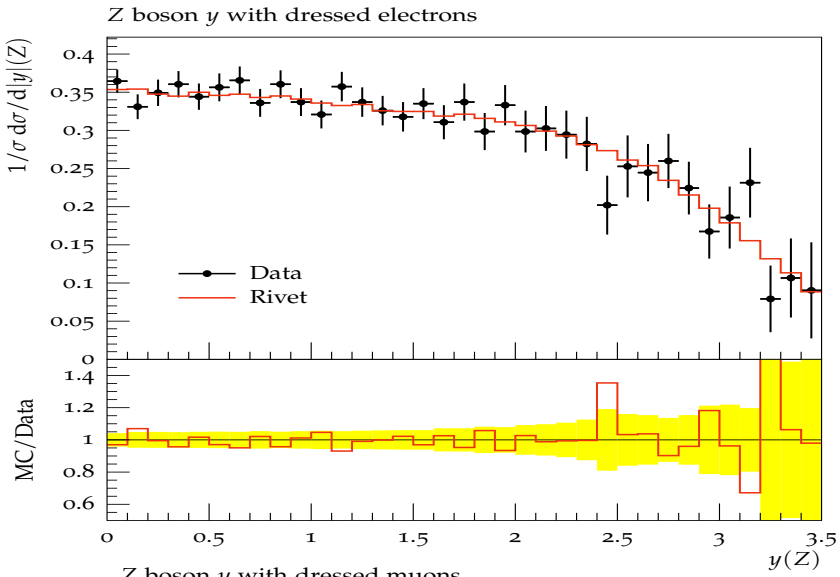
Nice agreement too! Also in the distributions shown in the previous slide:

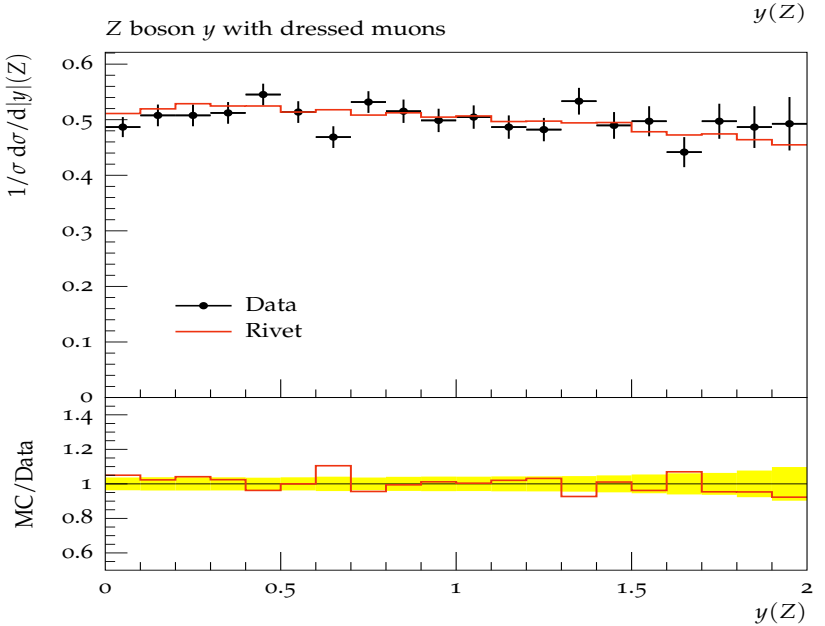
- pT of the Z boson
- Z boson rapidity
- Additional cut: $60 < m_{ll} < 120$ GeV

Z boson inclusive production (3)

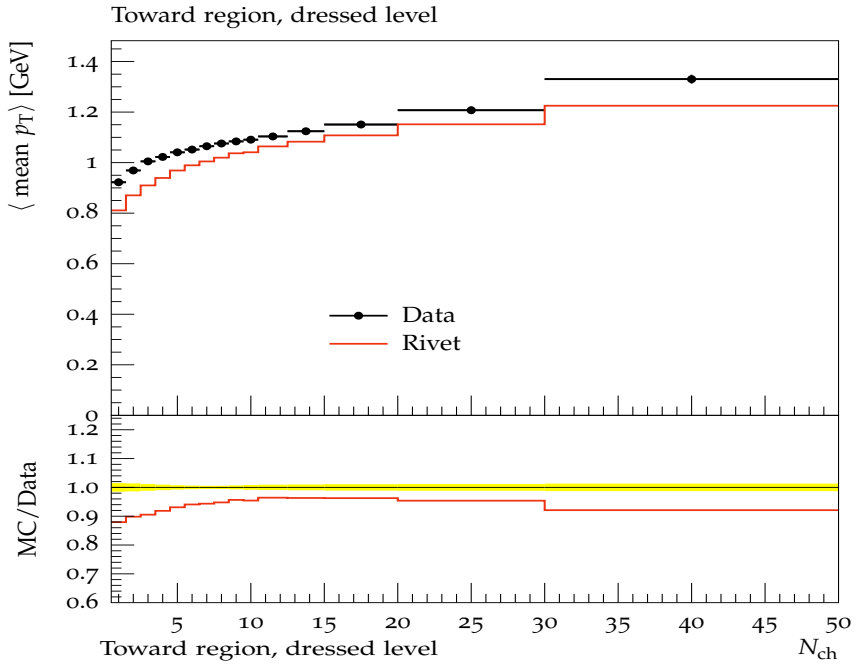
Some kinematical distribution compared to CMS data: Z/γ^* p_T and y (more plots in back-up slides)

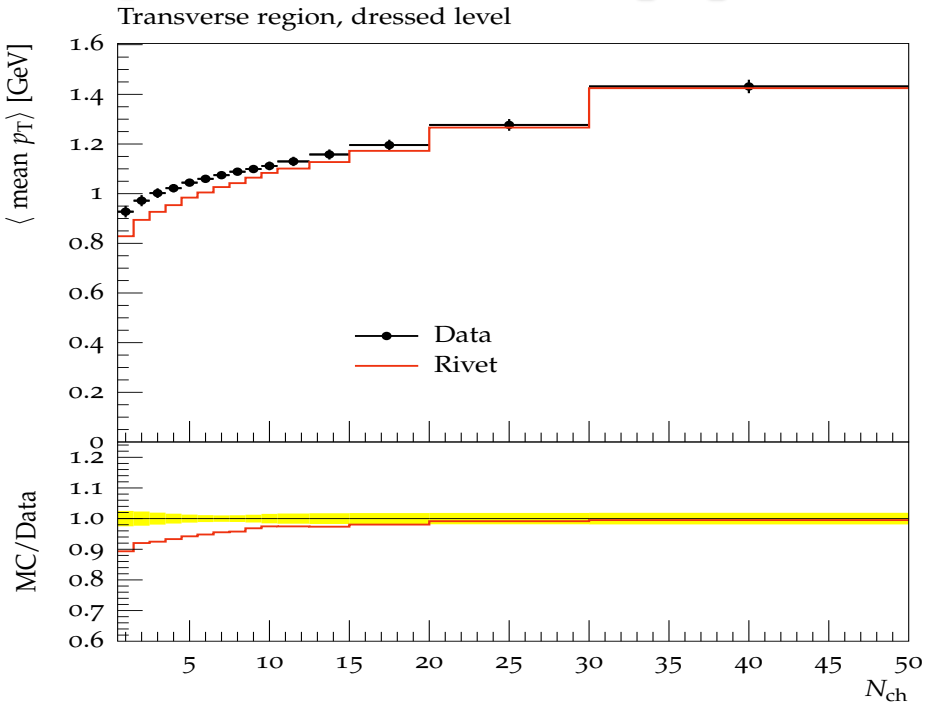


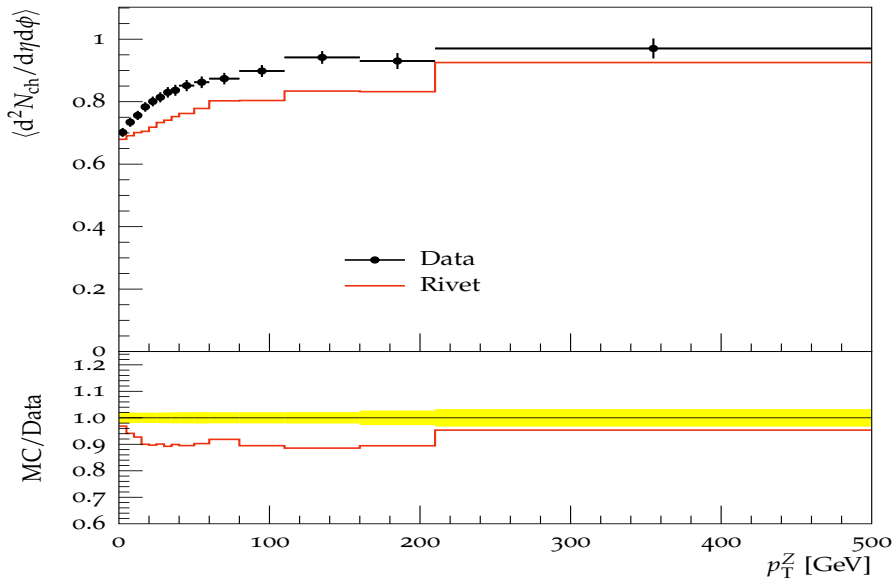




Z boson inclusive production (4)





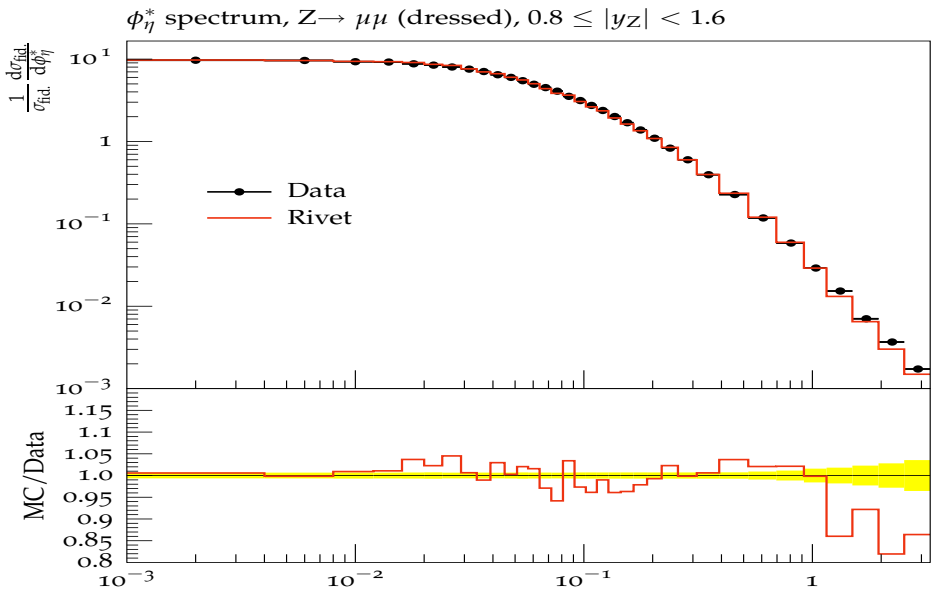


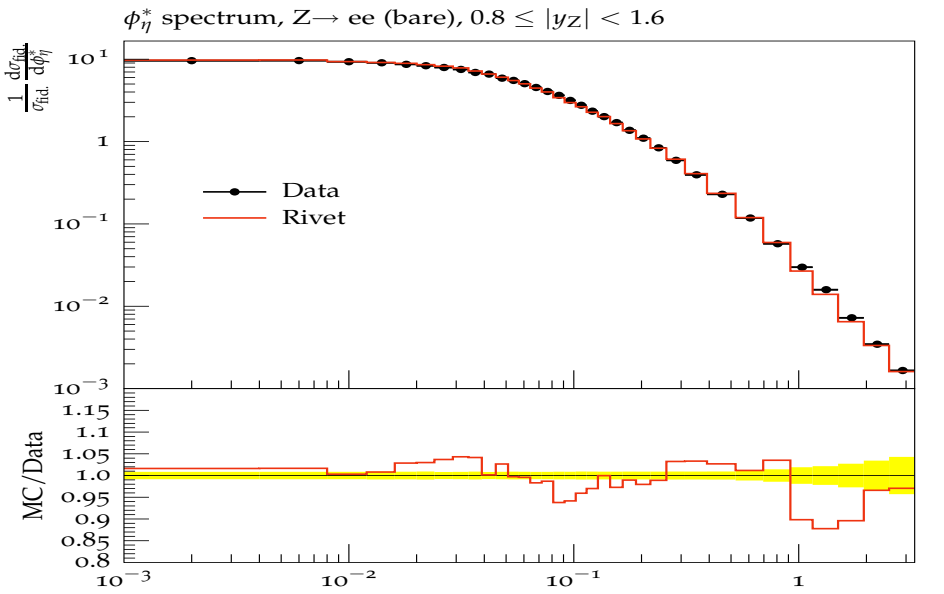
Here and in slide 15, distributions sensitive to the underlying event in Z boson inclusive production at $\sqrt{s}$ = 7 TeV are shown

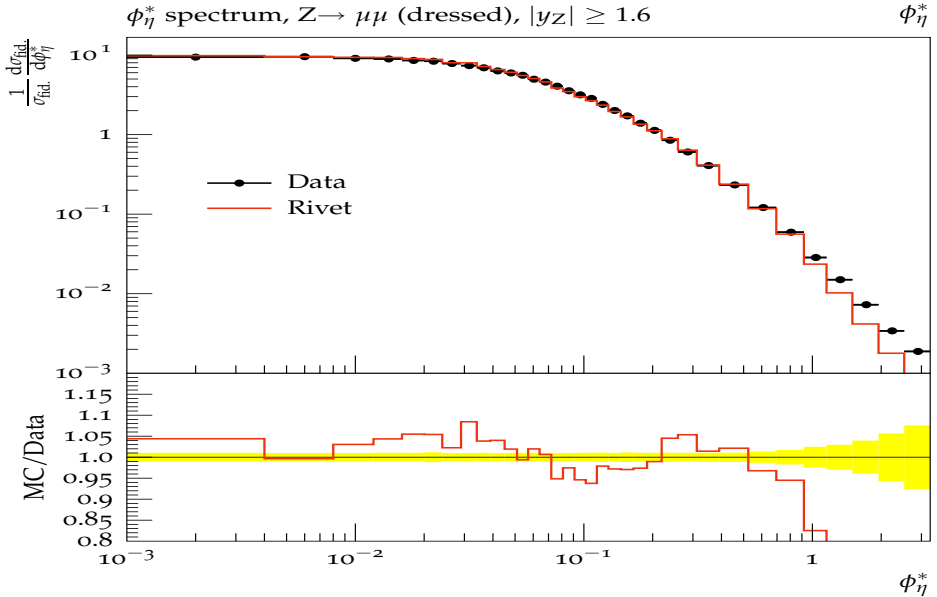
Once again, **nice agreement!**

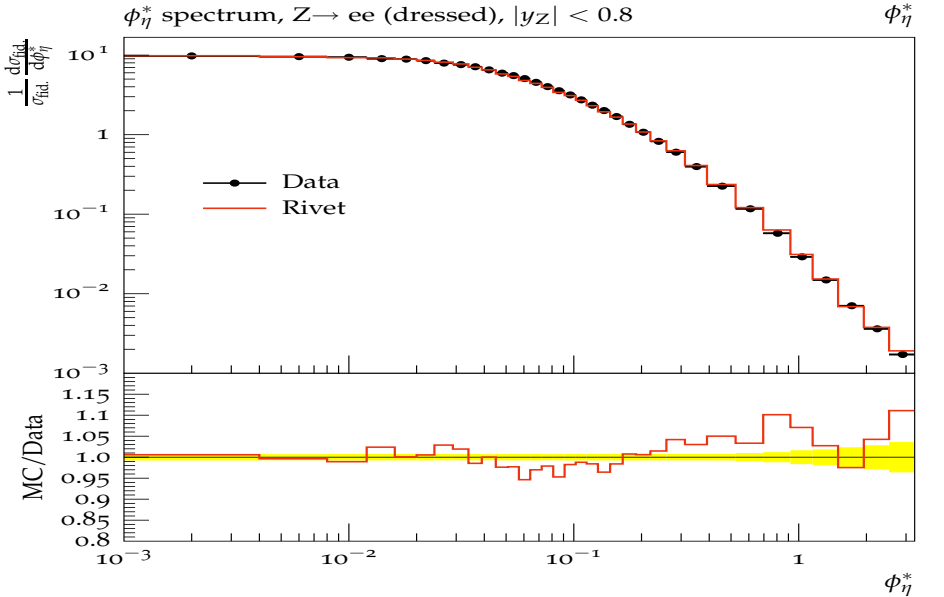
Z boson inclusive production (5)

- Φ^* distributions (ATLAS_2012_I1204784) – angular correlation



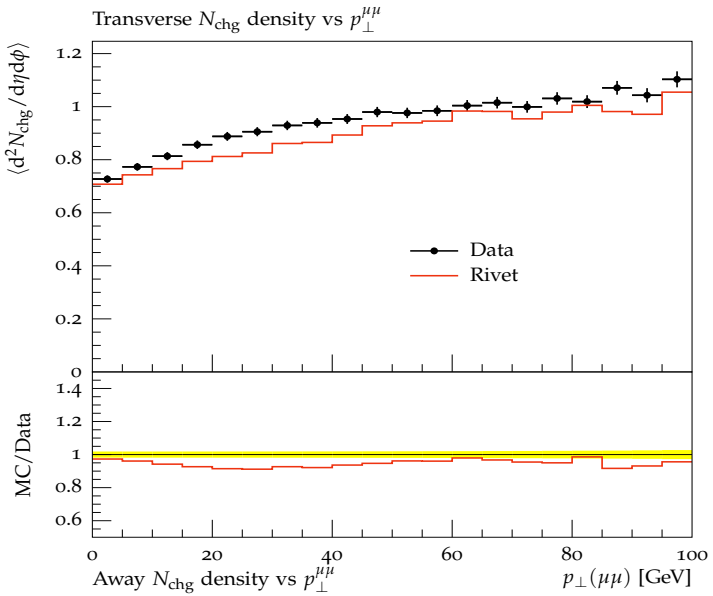


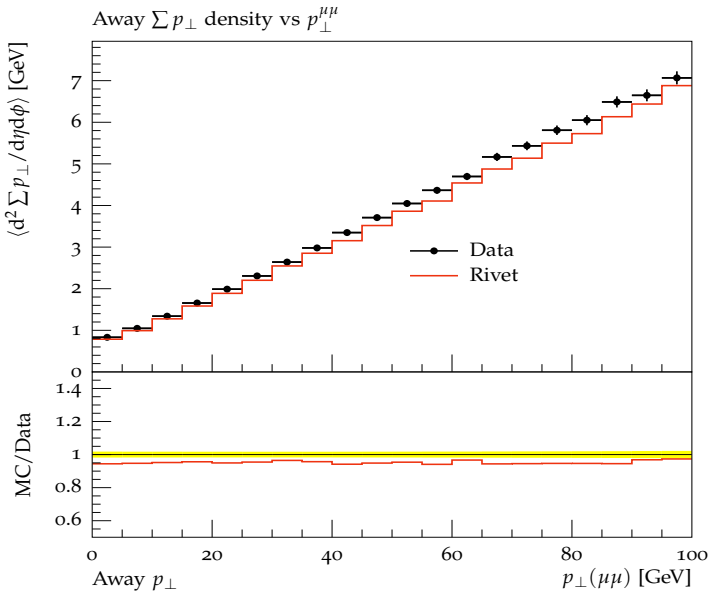


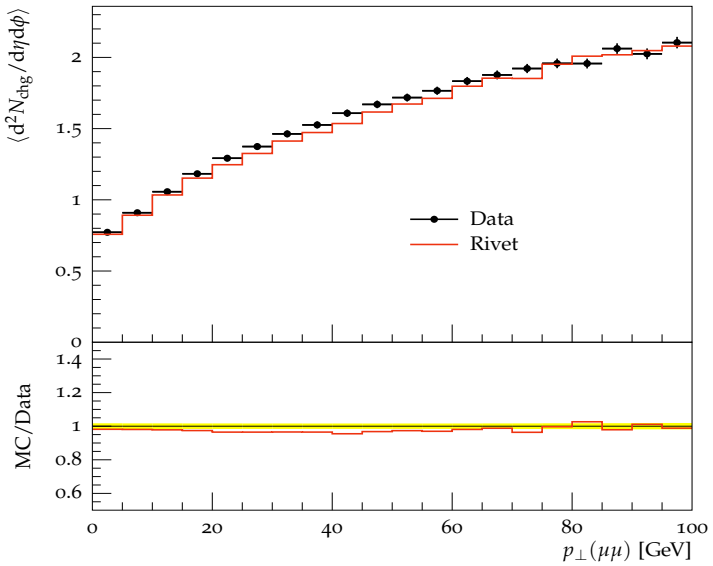


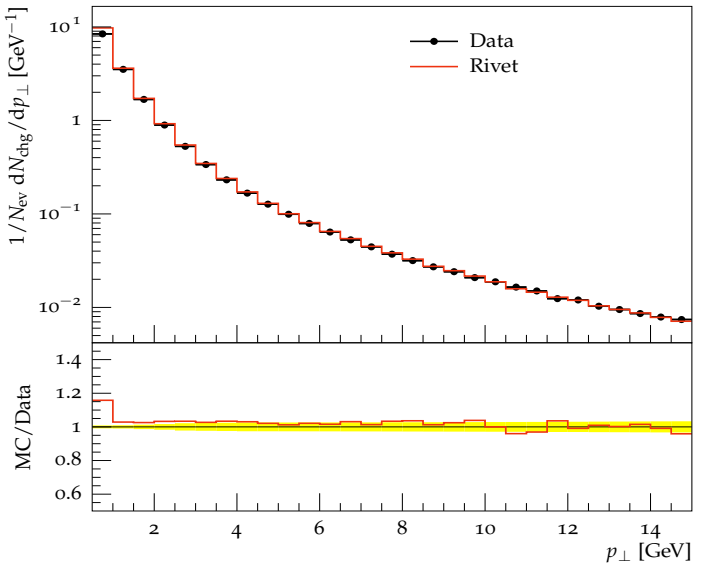
Other kinematical distributions

- Rivet routine: CMS_2012_I1107658



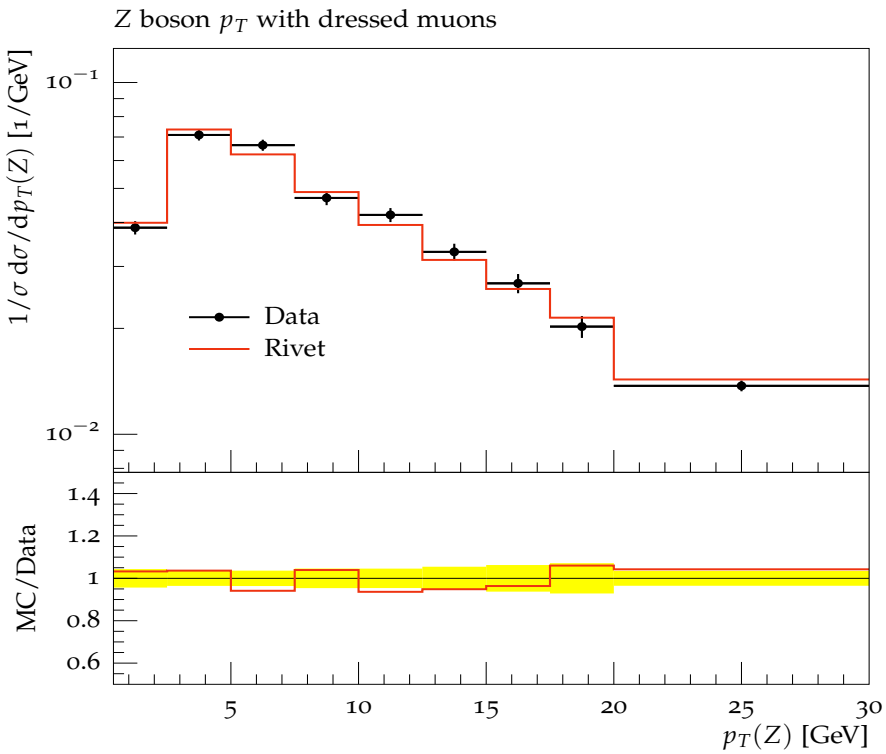




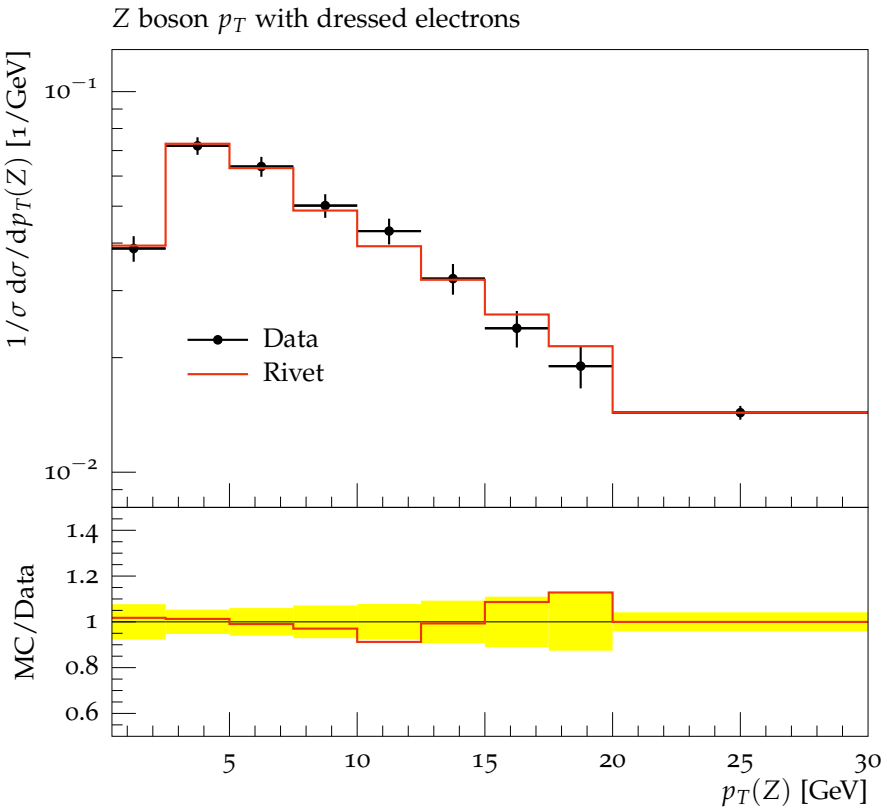


Other kinematical distributions (2)

- Rivet routine: CMS_2012_I941555



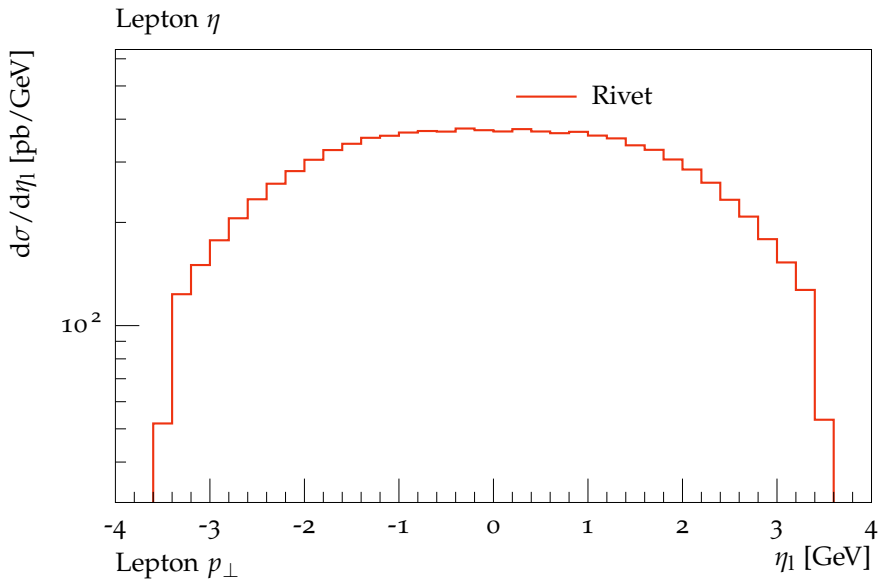
At slide 13, I showed Z boson transverse momentum for dressed leptons…

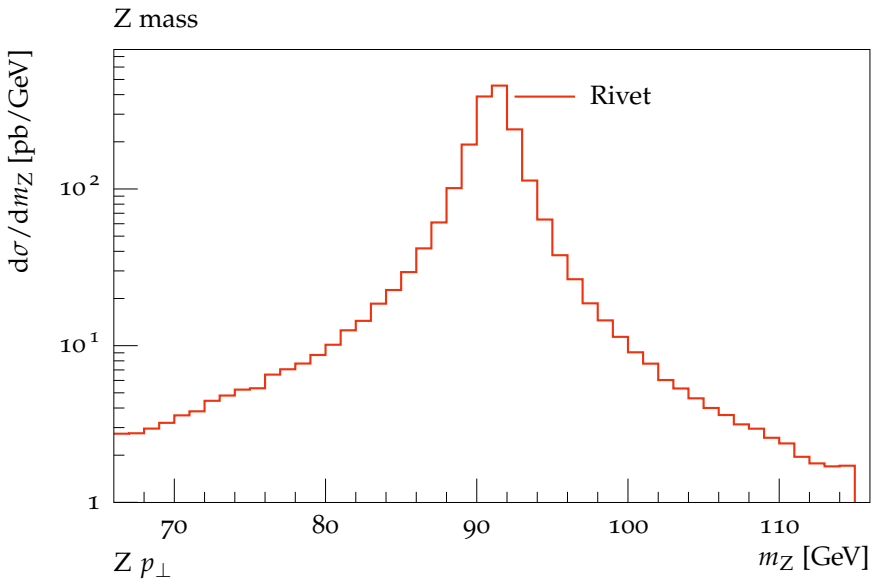


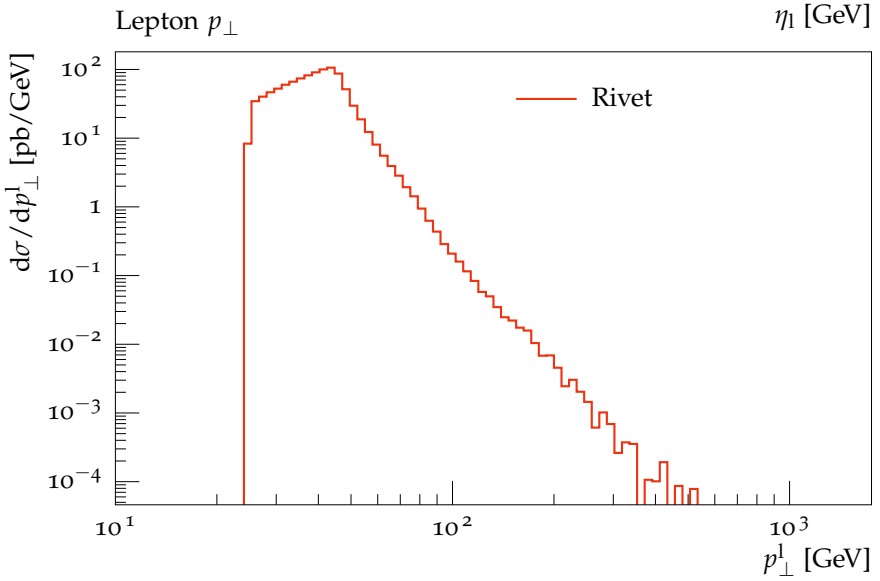
… here the Z boson p_T for the two different channels: dressed electrons and muons

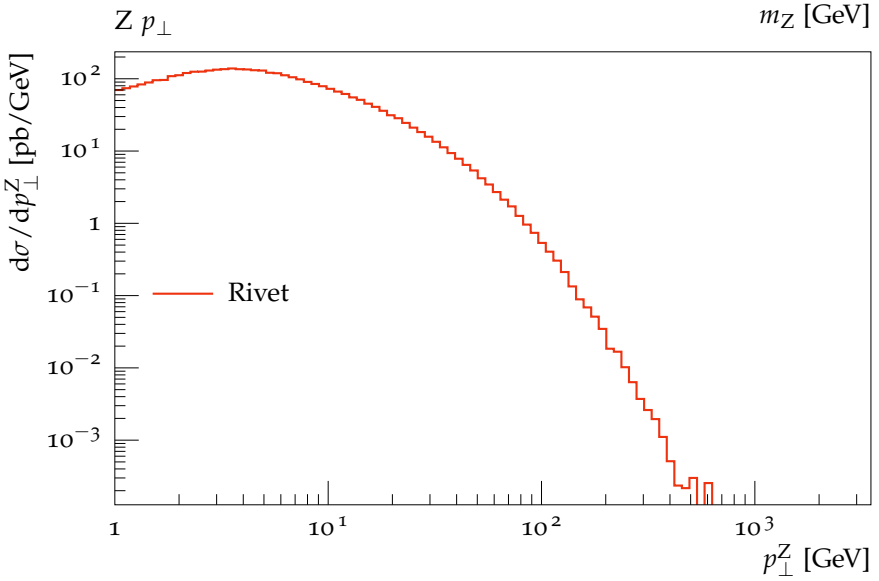
MonteCarlo-ONLY routine

- Rivet routine: MC_ZINC (Z boson inclusive production – MC only)









Parton Distributions with Threshold Resummation

Luca Rottoli

Rudolf Peierls Center for Theoretical Physics, University of Oxford

Particle Phenomenology Forum, 22 October 2015

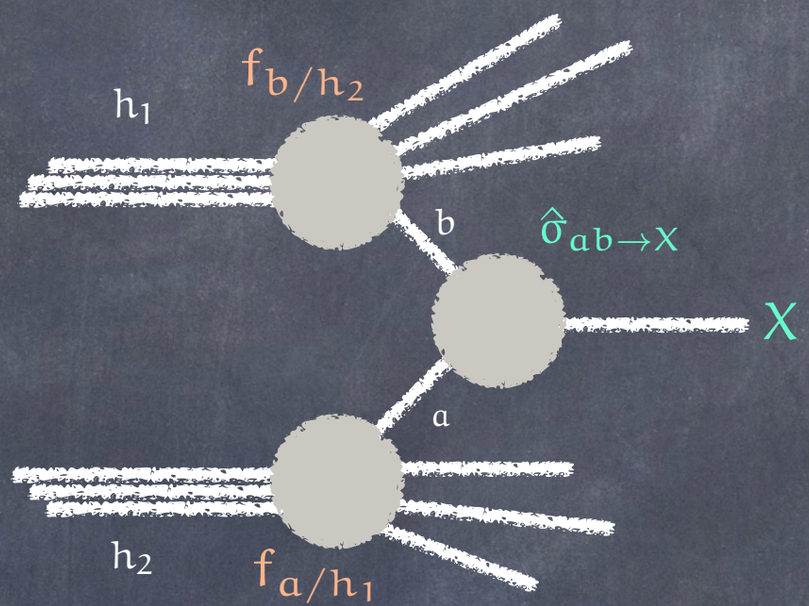
Based on

M. Bonvini, S. Marzani, J. Rojo, LR, M. Ubiali et al,

JHEP 1509 (2015) 191

Parton Distribution Functions

Collinear Factorization



$$\sigma = x\sigma_0 \sum_{a,b} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2)\, C_{ab}(z)$$

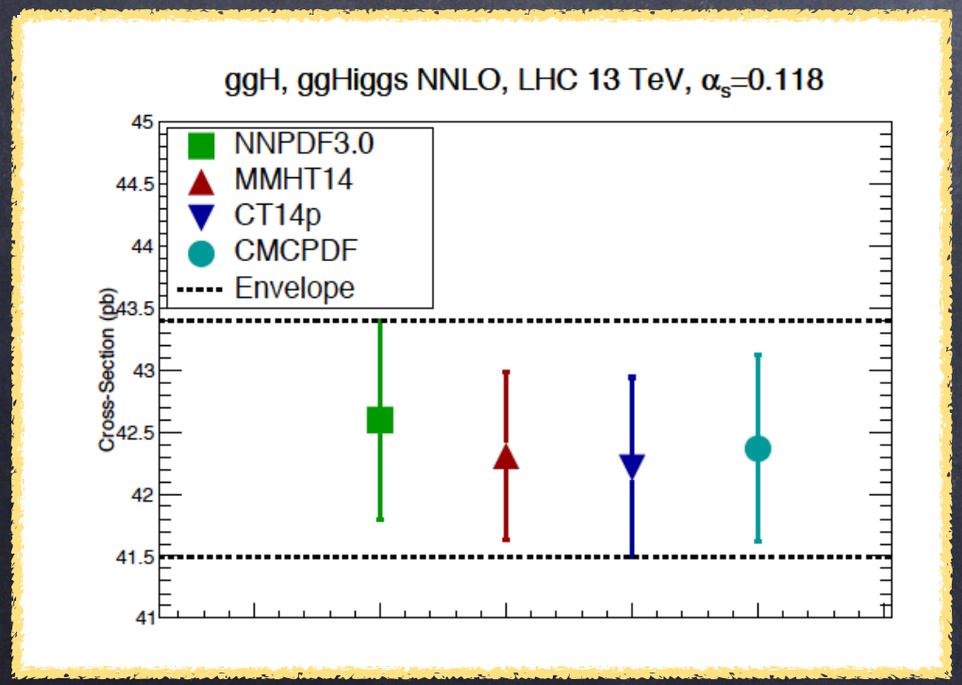
extracted from experiment

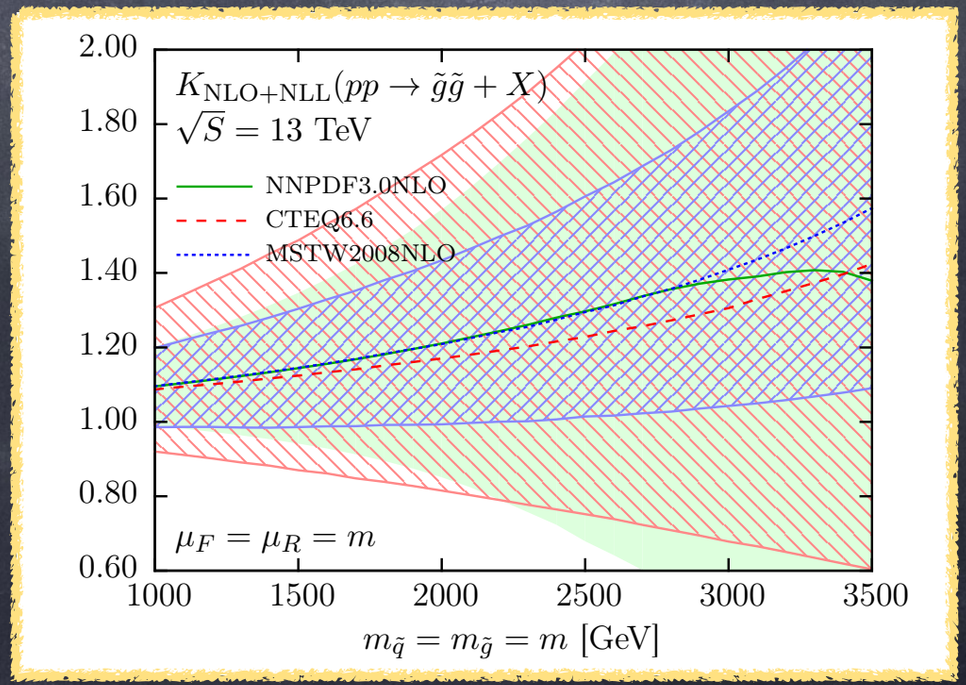
pQCD

- Parton distribution functions (PDFs) contain the information about the substructure of nucleons in terms of quarks and gluons (partons)
- PDFs cannot be computed from first principles, but are extracted from experiments
- Scale dependence is perturbative (DGLAP evolution)

Parton Distribution Functions

- PDFs fits extract information on the proton structure by comparison of experimental data and pQCD predictions
- Global fits include data from several processes: Deep Inelastic Scattering (DIS) experiments, Drell-Yan production, jets data, top data
- PDFs are a necessary tool for precision physics at LHC
- Open questions in proton structure: anti-symmetric sea quarks distributions, intrinsic charm…
- Knowledge of PDFs at large-x essential for New Physics $x \sim \frac{M^2}{s}$





PDFs with Threshold Resummation

Cross sections may contain several (logarithmically) enhanced contributions

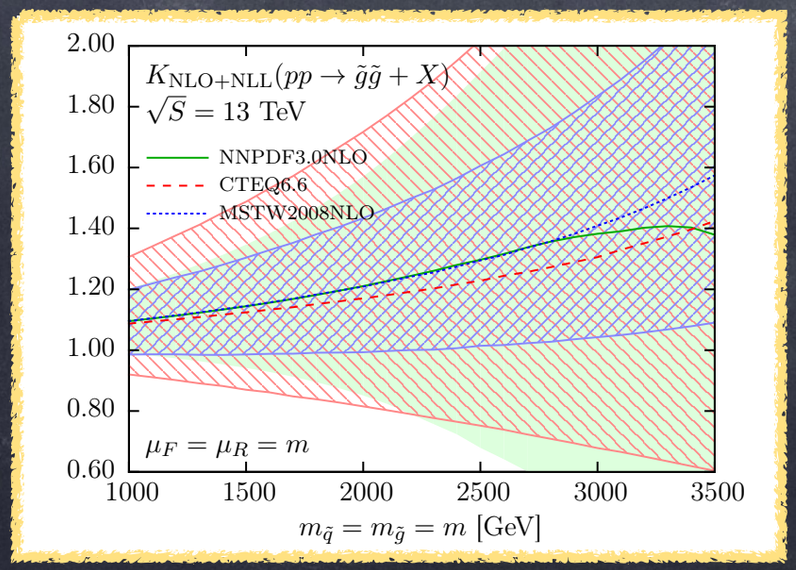
Logarithmic contributions may become large in some kinematic regions, thus spoiling the perturbative expansions

RESUMMATION

Large-x resummation: logarithmic enhancement close to threshold, $x \to 1$ $\quad x \sim \frac{M^2}{s}$

- Resummed calculations provide the state of the art accuracy for many processes at LHC

- Resummed PDFs are necessary to obtain full N^{k}LO+N^{k}LL accuracy at the level of hadronic observables



PDFs with Threshold Resummation

Resummation consists in a reorganization of the perturbative expansion by performing an all order summation of classes of logs

$$
\begin{array}{cccccc}
\alpha_s L^2 & \alpha_s L & \cdots & & \mathcal{O}(\alpha_s) & \\
\alpha_s^2 L^4 & \alpha_s^2 L^3 & \alpha_s^2 L^2 & \alpha_s^2 L & \cdots & \mathcal{O}(\alpha_s^2) \\
\vdots & \vdots & \vdots & \vdots & & \vdots \\
\alpha_s^n L^{2n} & \alpha_s^n L^{2n-1} & \cdots & & & \mathcal{O}(\alpha_s^n)
\end{array}
$$

Fixed order expansion

$$
\sum_{n=1}^{\infty} \qquad \sum_{n=1}^{\infty} \qquad \cdots
$$

LL NLL $\cdots$ N^{k}LL

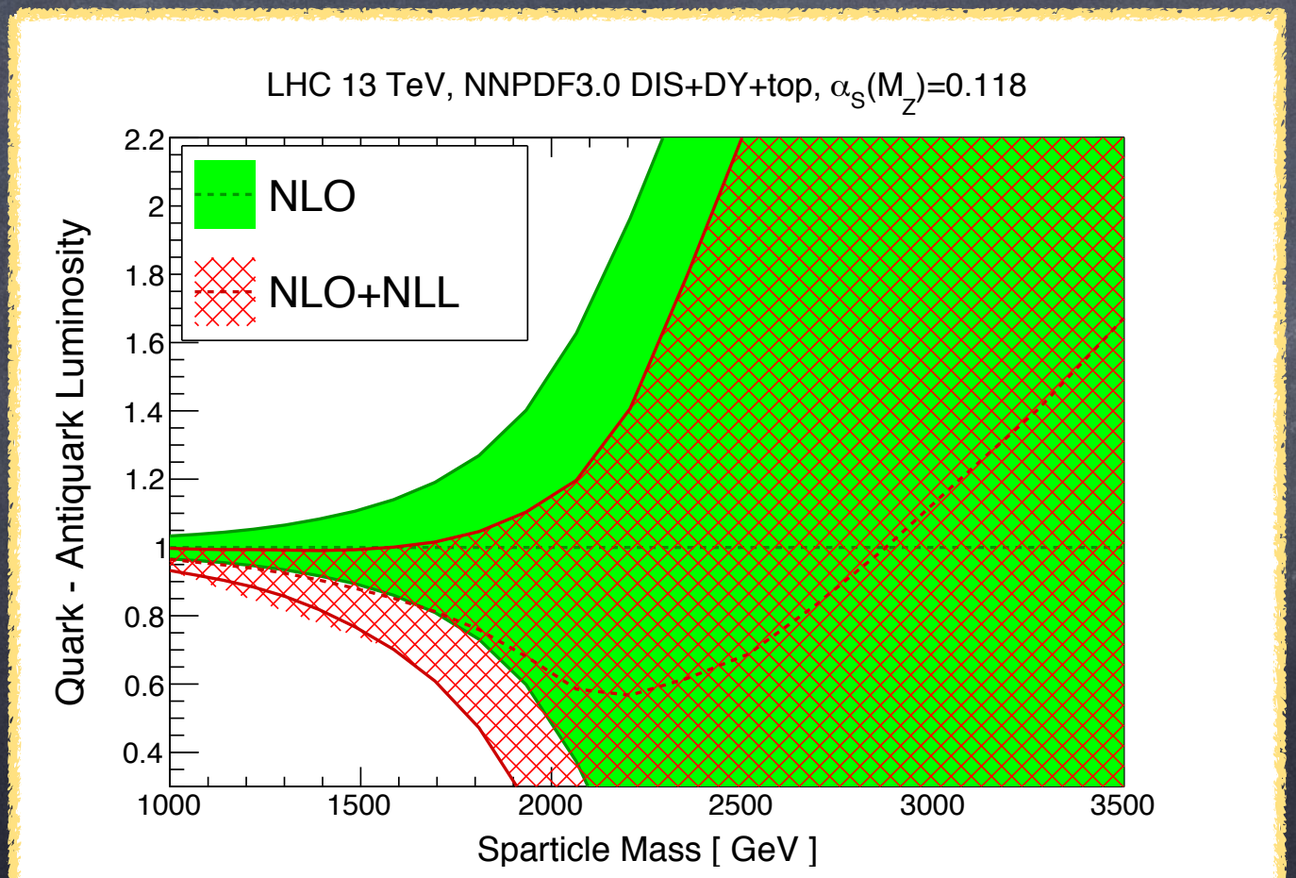
Resummed expansion $\alpha_s L^2 \sim 1$

$$
C(z) \longrightarrow C^{\text{res}}(z)
$$

PDFs with Threshold Resummation

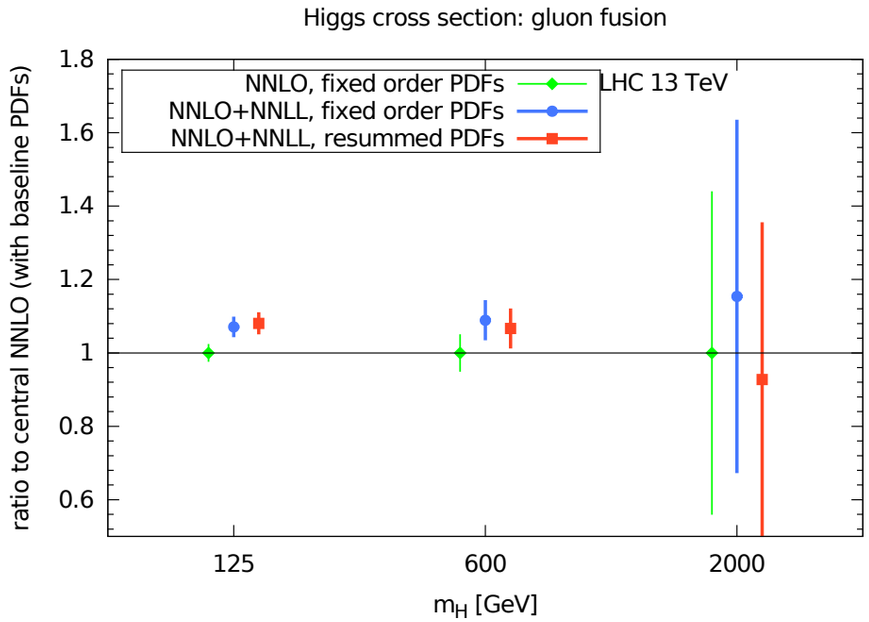
$$\sigma = x\sigma_0 \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} f_1(x_1,Q^2) f_2(x_1,Q^2) C(z) = x\sigma_0 \int_x^1 \frac{dz}{z} \mathcal{L}\left(\frac{x}{z},Q^2\right) C(z)$$

$$\sigma(x,Q^2) = x\sigma_0 \int_x^1 \frac{dz}{z} \mathcal{L}\left(\frac{x}{z},Q^2\right) C(z) \qquad \sigma(x,Q^2) = x\sigma_0 \int_x^1 \frac{dz}{z} \mathcal{L}\left(\frac{x}{z},Q^2\right) C^{\text{res}}(z)$$

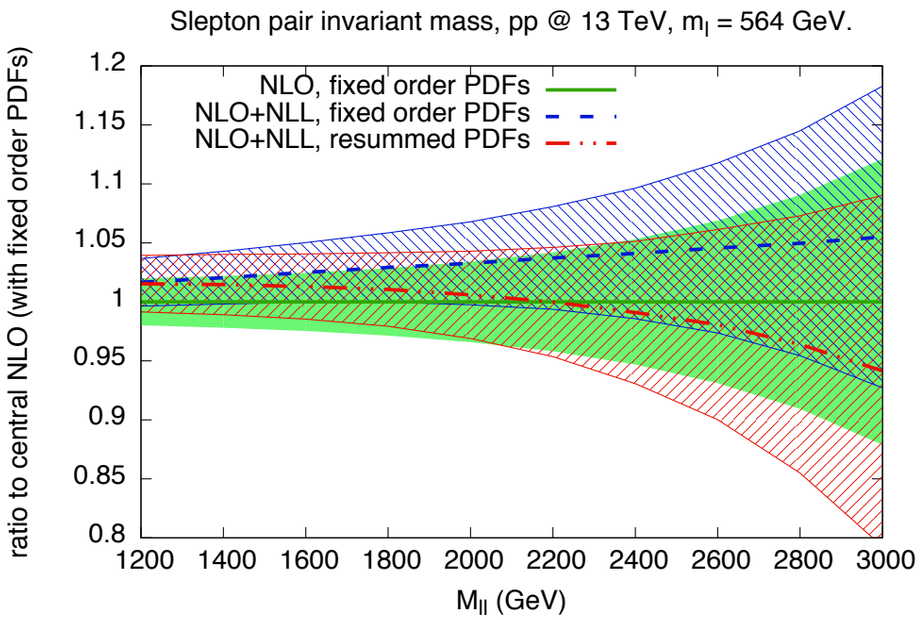


PDFs with Threshold Resummation

Phenomenology



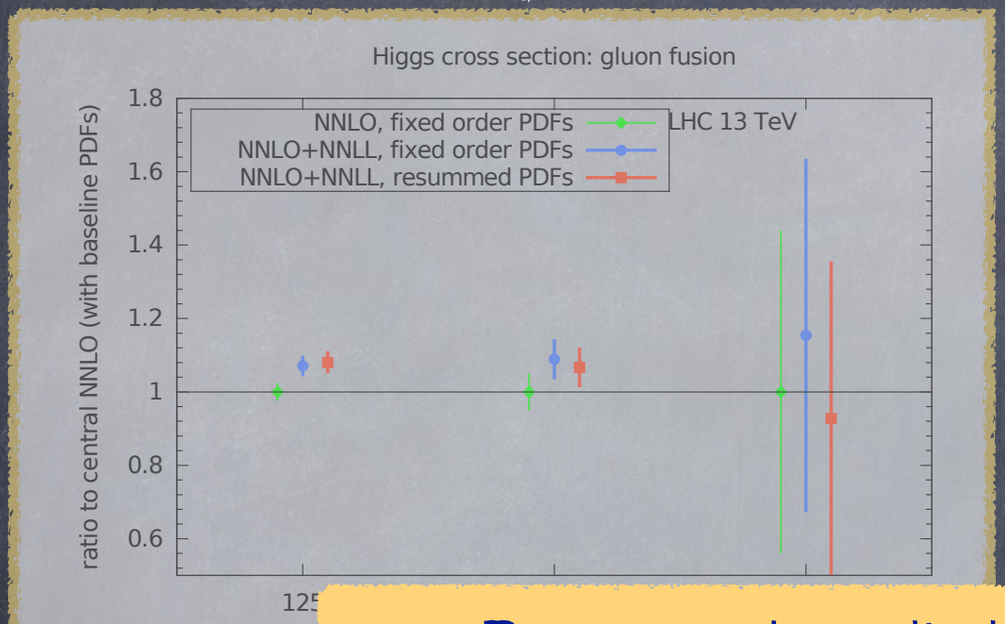
- SM Higgs not affected by resummation of PDFs
- m_H ~600 GeV cancellation of 1/2 of the enhancement



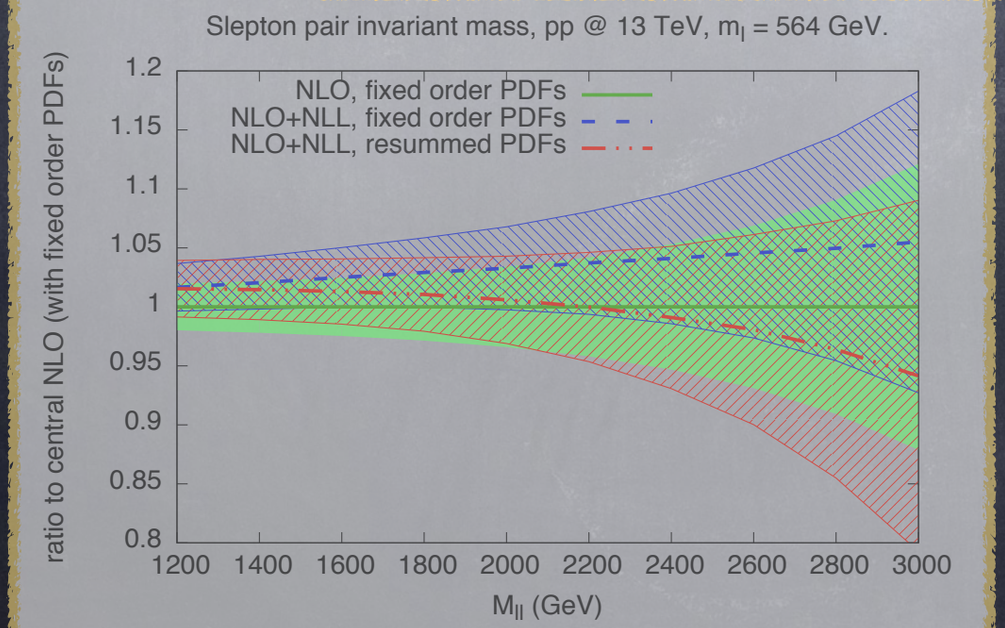
- 2-5% enhancement NLO+NLL calculation with FO PDFs
- 1-2% enhancement NLO+NLL calculation with resummed PDFs only of M_{ll}<2000 GeV
- At higher masses suppression of NLO+NLL calculation with resummed PDFs

PDFs with Threshold Resummation

Phenomenology



Resummed result closer to the fixed order calculation at large invariant masses



- SM Higgs not affected by resummation of PDFs
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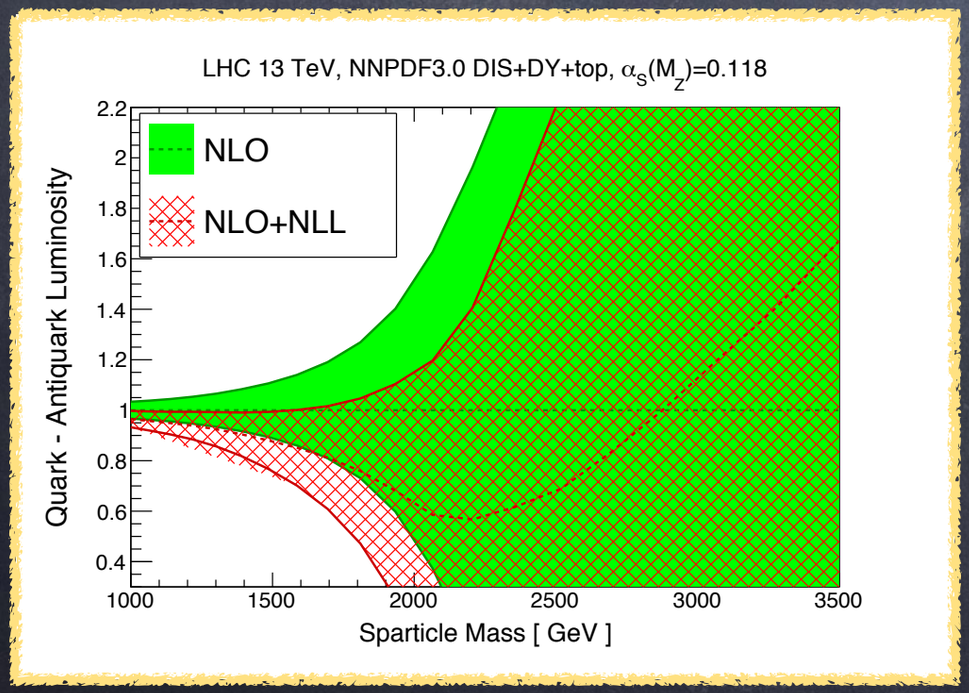
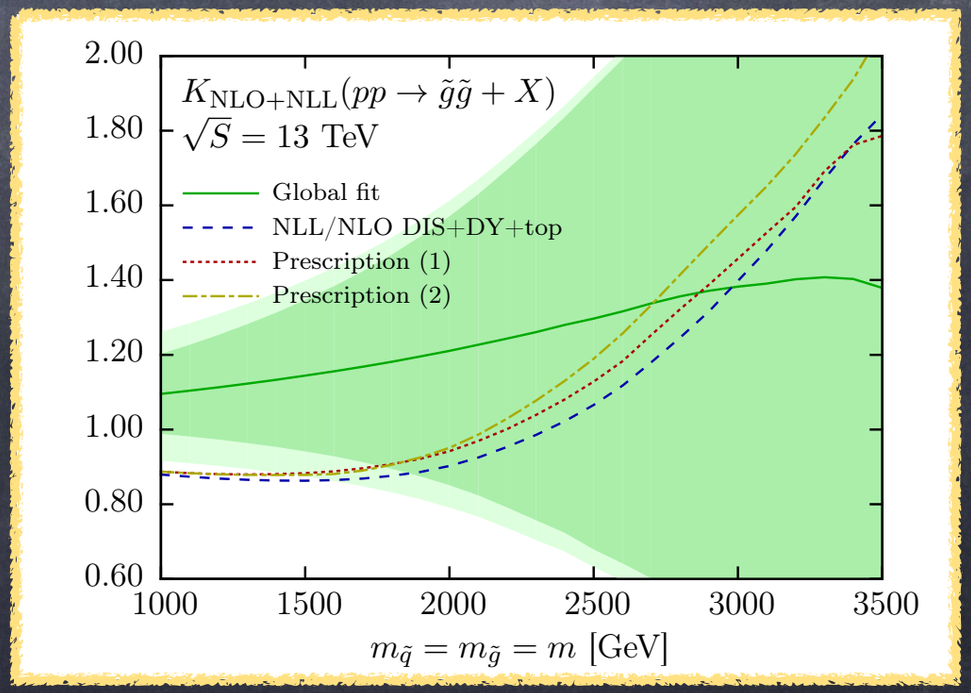
PDFs with Threshold Resummation

Summary

- First ever (global) fit of PDFs with threshold resummation
- Inclusion of resummation in PDFs compensates the enhancement from resummation in partonic cross sections for when M_X is large
- Importance of using the same perturbative order in all components when calculating hadronic cross sections: full N^kLO+N^kLL accuracy at the level of hadronic observables only possible with resummed PDFs





W. Beenakker et al, arXiv:1510.00375

Other works

- Three loop soft function for N^{3}LL' gluon fusion Higgs production in soft-collinear effective theory, M. Bonvini, LR, Phys.Rev. D91 (2015) 5, 051301.
- Charm production in the forward region: constraints on the small-x gluon and backgrounds for neutrino astronomy, R. Gauld, J. Rojo, LR, J. Talbert, arXiv: 1506.08025 [hep-ph].
- Intrinsic charm in a matched general-mass scheme, R. D. Ball, V. Bertone, M. Bonvini, S. Forte, P. G. Merrild, J. Rojo, LR, arXiv:1510.00009 [hep-ph].
- Charm in Deep-Inelastic Scattering, R. D. Ball, M. Bonvini, LR, arXiv:1510.02491 [hep-ph].

Ongoing projects

- Prompt atmospheric neutrino fluxes validated with LHC data with R. Gauld, J. Rojo, J. Talbert and S. Sarkar
- Resummation of a Pseudo-Scalar Particle at N^{3}LL' in dQCD and in SCET, with M. Bonvini, V. Ravindran et al.
- NNPDF related projects: PDFs with small-x resummation, Fitted charm PDF, general code development and maintenance, etc.

PDFs with Threshold Resummation

Threshold Resummation in a nutshell

$$\sigma(x, Q^2) = x\sigma_0 \int_x^1 \frac{dz}{z} \mathcal{L}\left(\frac{x}{z}, Q^2\right) C(z)$$

Convolution integral diagonalised in Mellin space

$$f(N) = \int_0^1 dx\, x^{N-1} f(x)$$

Mellin Transform

$$\sigma(N, Q^2) = \mathcal{L}(N, Q^2)\sigma_0(N, Q^2) C(N)$$

Double logarithmic enhancement due to soft gluon emission

$$C(N) = 1 + \sum_{n=1}^{\infty} \alpha_s^n \sum_{k=0}^{2n} c_{nk} \ln^k N + \mathcal{O}(1/N)$$

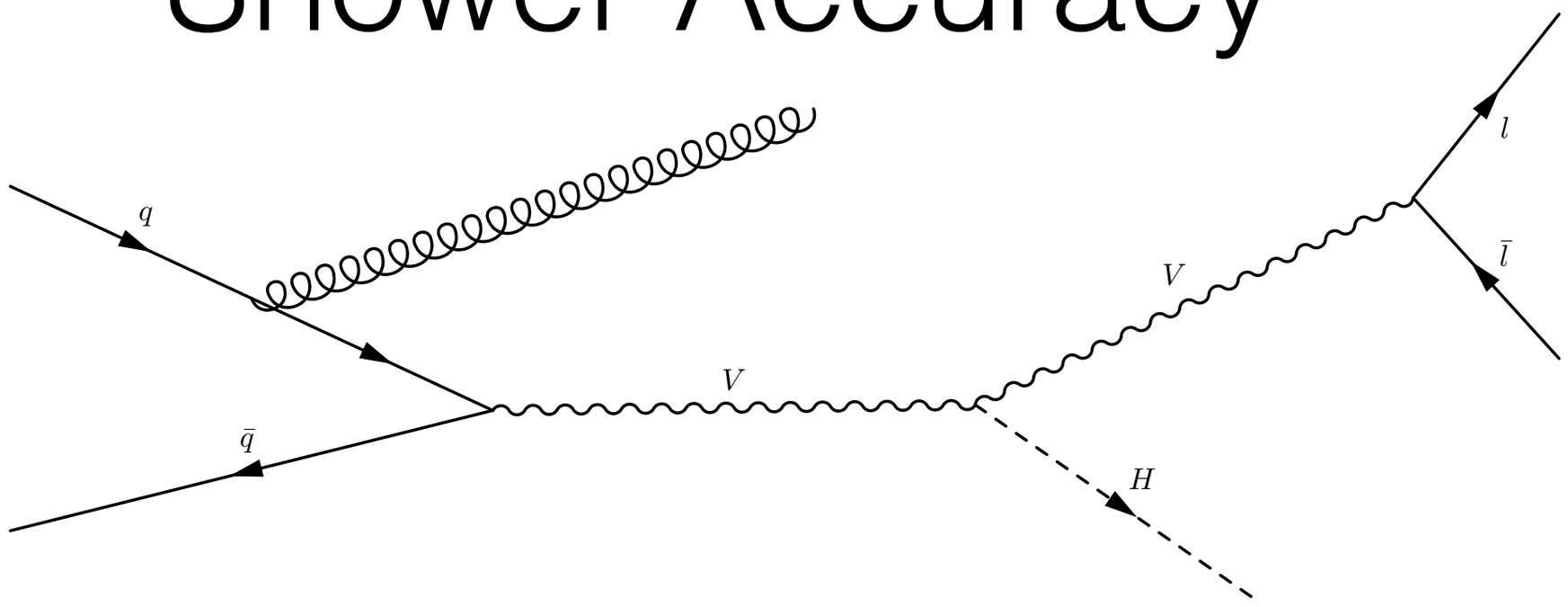
N-soft approximation

Exponentiation

$$C(N) = g_0(\alpha_s) \exp\left[\frac{1}{\alpha_s} g_1(\alpha_s \ln N) + g_2(\alpha_s \ln N) + \alpha_s\, g_3(\alpha_s \ln N) + \dots\right]$$

The functions g_i resum $\alpha_s^n \ln^n N$ to all orders

Associated Higgs Production and a Jet at NNLO+Parton Shower Accuracy



William Astill
Supervisor: Giulia Zanderighi

Why we need precision calculations?

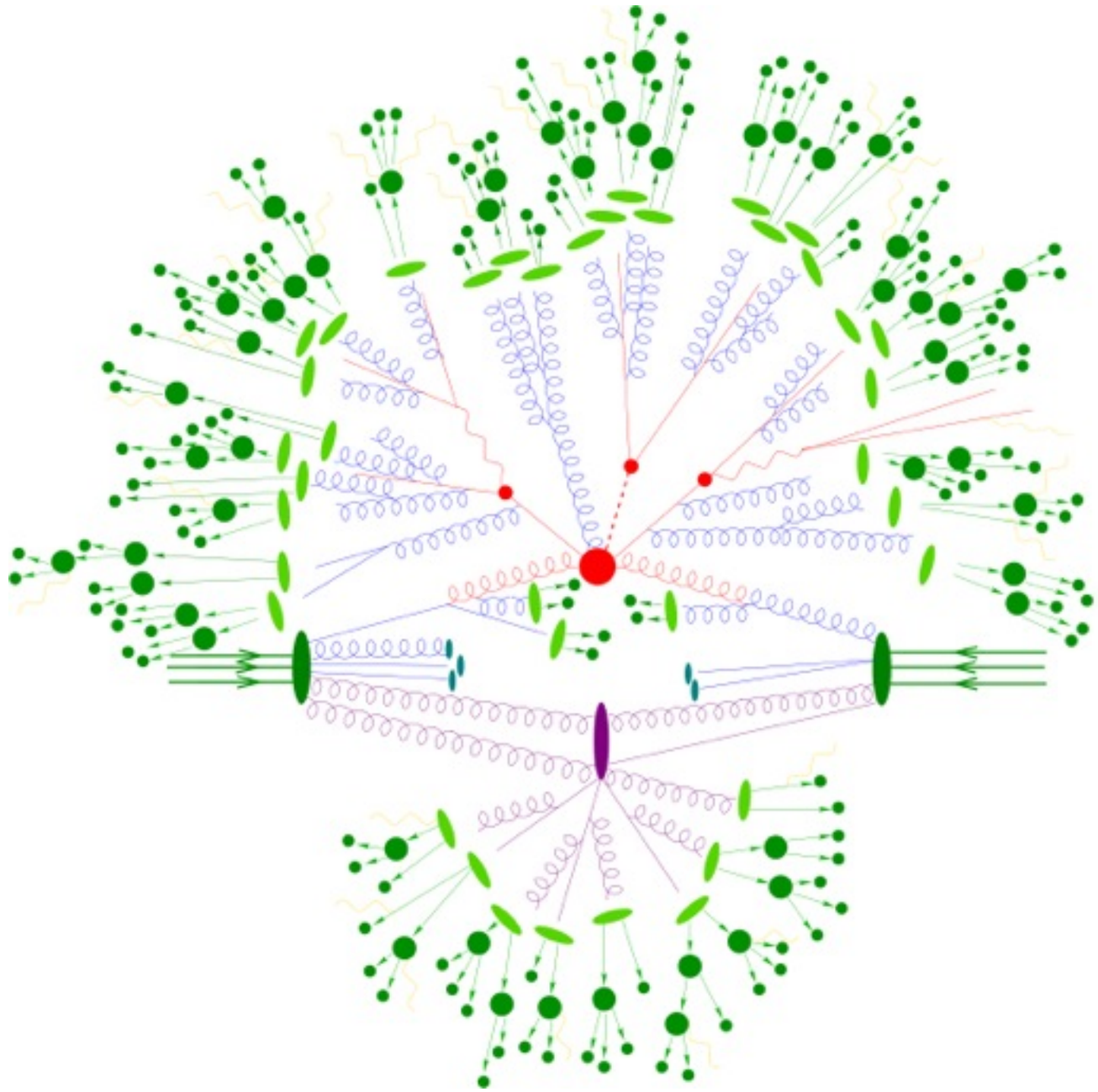
- Lots of current and future experiments are testing limits of standard model and looking for new physics

  - LHC, DESY, SLAC, Tevatron, FCC, etc.

- To claim a discovery it is crucial to distinguish between SM background and New Physics signals

- Making this distinction requires a good understanding of the experimental and theoretical errors

Calculating Cross Sections



Representation of a proton-proton collision, Frank Krauss, Durham University

Fixed Order Calculations

- Cross section is calculated as a power expansion in order of the coupling constant
- The higher the order of the calculation the more powers of the coupling constant you have

$$\frac{d\sigma}{d\Phi} = \text{LO} + \alpha_s \left[\text{NLO} \right] + \alpha_s^2 \left[\text{NNLO} \right] + \ldots$$

Fixed Order Calculations

- Give a finite value (if all diagrams up to your given order are included) for infrared and collinear safe observables

- Provides a very clean view of a specific process but have a very limited final state multiplicity compared to real events seen in LHC

    - Don’t resemble what is actually seen in detector

- Are affected by infrared and collinear divergences

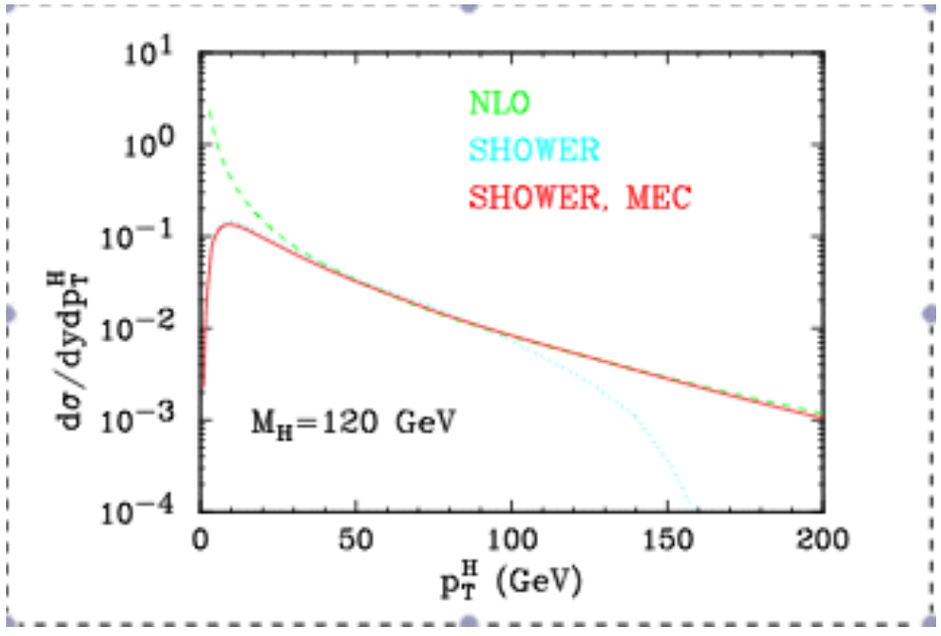
    - Results in predictions that are not reliable in certain corners of phase space

Parton Shower Approximation

- Hadron collisions produce a lot of soft QCD radiation
- Parton shower takes parton content from hard scattering process and calculates additional radiation through multiple soft and collinear splittings
- Keeps splitting until parton virtualities are ~GeV
- Result is well behaved close to divergences but is not accurate in regions dominated by hard emissions

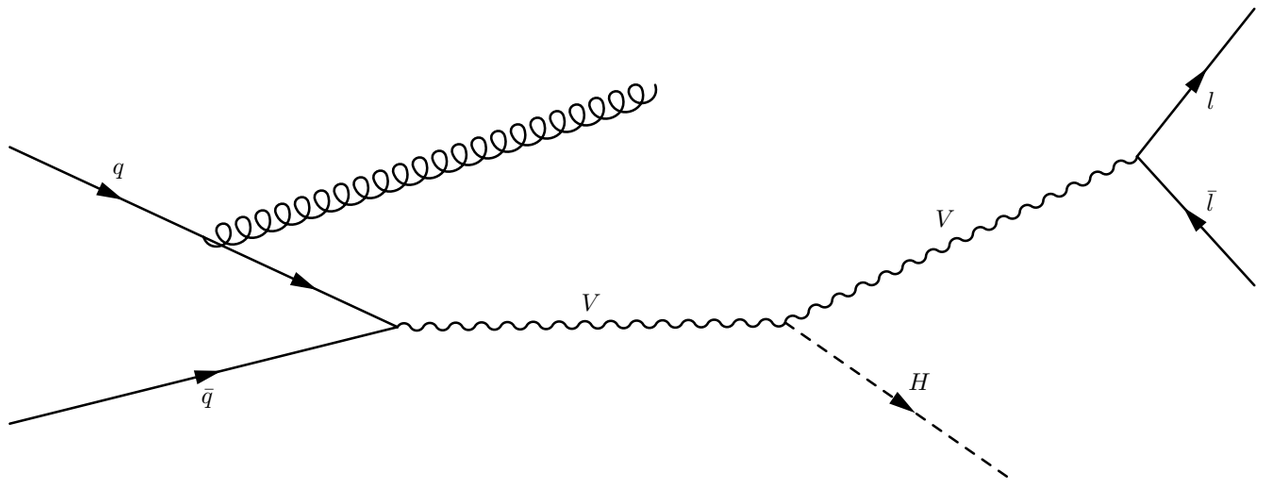
Matching fixed order calculation with parton shower

- Matching fixed order calculations with parton shower provides good accuracy across all phase space
- At low pT keeps smooth shape of shower
- At high pT result matches fixed order result
- Inclusive cross section matches that of fixed order



Transverse momentum distribution of the Higgs at NLO, in a shower algorithm, and in a MEC shower
Source:1202.1251 Nason and Weber

P P → H V + J



- Associated Higgs production, a.k.a. Higgsstrahlung, is when a $W^{\pm}$ or Z boson emit a Higgs boson

- One of 4 main Higgs production channels at the LHC

  - Gluon gluon fusion, vector boson fusion, and ttH are the other three

- Final state particles contains at least 1 jet plus decay products of vector and Higgs bosons

Current Accuracy Limits

- POWHEG can currently calculate HV+J events at NLO+PS accuracy
- Calculation is done with the MiNLO (multi-scale improved NLO) prescription
    - MiNLO allows integration over the whole range of jet pT without any cut on the jet transverse momentum by resumming the hardest jet
    - Preserves NLO accuracy of inclusive HV production
- NNLO accuracy has been achieved for HV production (Ferrera et al. 1312.1669)
- By comparing NNLO results for HV production with MiNLO results for HV +J one can reweight event files to increase the HV+J accuracy to NNLO

Reweighting Procedure

- NNLO accuracy is obtained by reweighting NLO HVJ events from POWHEG

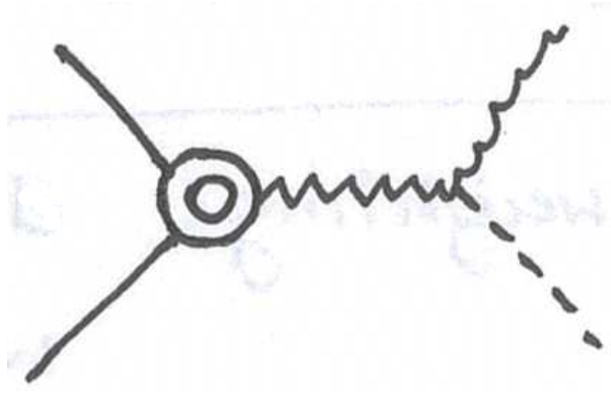
$$\frac{\mathrm{d}\sigma^{NNLO}}{\mathrm{d}\Phi_B} = W\left(\Phi\right) \cdot \frac{\mathrm{d}\sigma^{MiNLO}}{\mathrm{d}\Phi_B}$$

- Reweighting function obtained from ratio of cross sections of NNLO fixed order HV cross section and NLO

$$W\left(\Phi_B\right) \equiv \frac{\frac{\mathrm{d}\sigma^{NNLO}}{\mathrm{d}\Phi_B}}{\frac{\mathrm{d}\sigma^{MiNLO}}{\mathrm{d}\Phi_B}}$$

NNLO Accuracy of Result

- When comparing HVJ at NLO with HV at NNLO there is one additional diagram type (double virtual corrections)



- The reweighting function introduces correction at NNLO accuracy without spoiling NLO accuracy (no O(α_s) term)

$$W(\Phi_B) \equiv \frac{\frac{d\sigma^{NNLO}}{d\Phi_B}}{\frac{d\sigma^{MiNLO}}{d\Phi_B}} = 1 + O(\alpha_s^2)$$

- Parton shower does not affect accuracy as it only gives correction at higher orders of α_s

$$\frac{\frac{d\sigma^{NNLOPS}}{d\Phi_B}}{\frac{d\sigma^{NNLO}}{d\Phi_B}} = 1 + O(\alpha_s)$$

Conclusion

- High precision calculations are necessary for obtaining a good understanding of standard model background

- With recent discovery of Higgs, and subsequent focused study on its properties, Higgsstrahlung is an important process to know to high precision

- NNLO+PS accuracy can be obtained by reweighting NLO HV+J events obtained from existing event generator (POWHEG)

- To be continued by Wojtek…

NNLO+Parton Shower "Higgs + Vector Boson"

Part 2

Wojciech Bizoń
Supervisor: Giulia Zanderighi

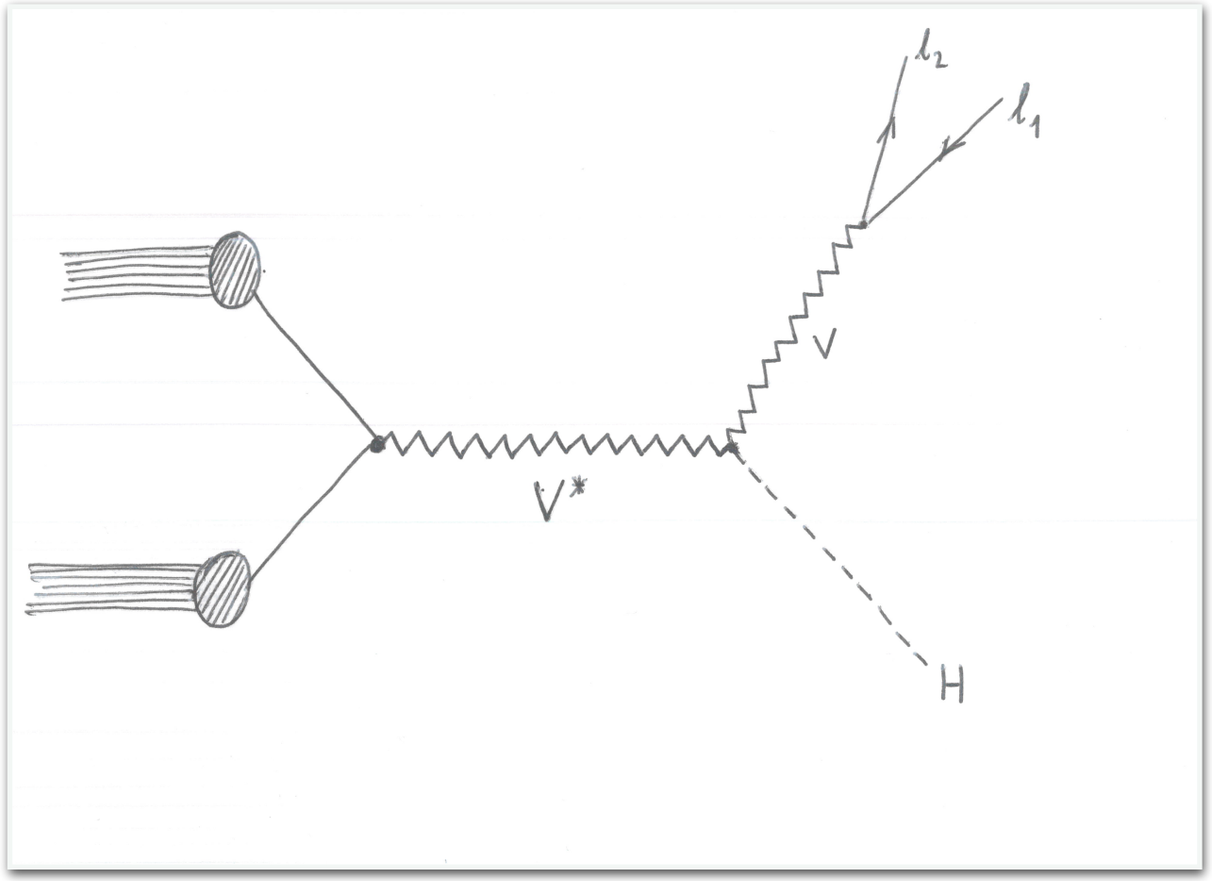
Kinematics

How to describe this process?

- we have 6 degrees of freedom

- need 6 variables:

  [m_V, $p_{t,H}$, y_{VH}, $\Delta y_{VH} = y_H - y_V$, θ_{CS}, ϕ_{CS}]
- the last two variables — Collins-Soper angles
- these variables seem to be fairly uncorrelated

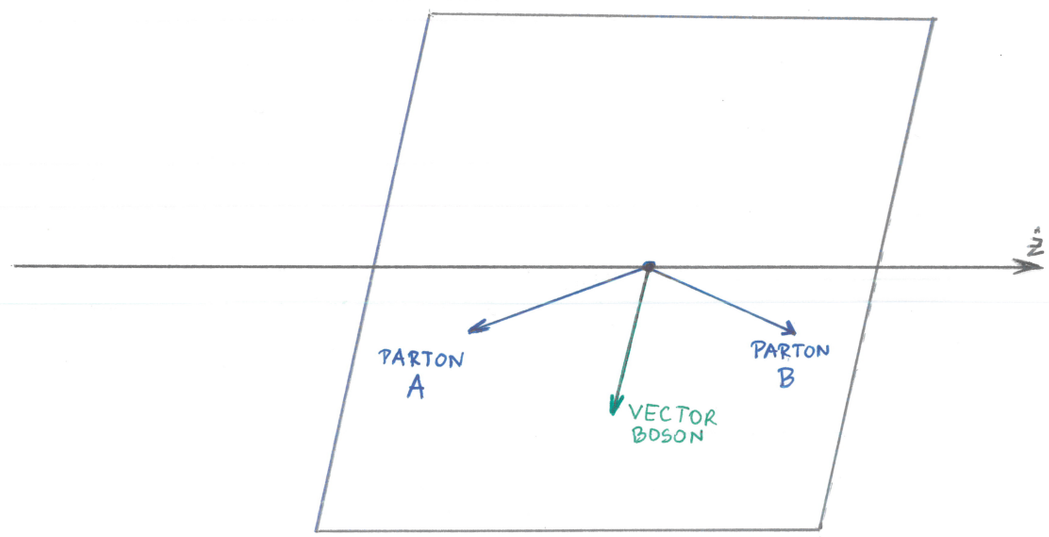


$pp \to HW^+ \to H\ell^+\nu_\ell$	σ [fb]	Increase
LO	81.92	—
NLO	96.42	+17.7%
NNLO	96.78	+0.4%

Collins-Soper frame

Definition:

- vector boson at rest
- **z-axis:** bisects angle between [PARTON A] and –[PARTON B]
- **x-axis:** –([PARTON A] + [PARTON B])



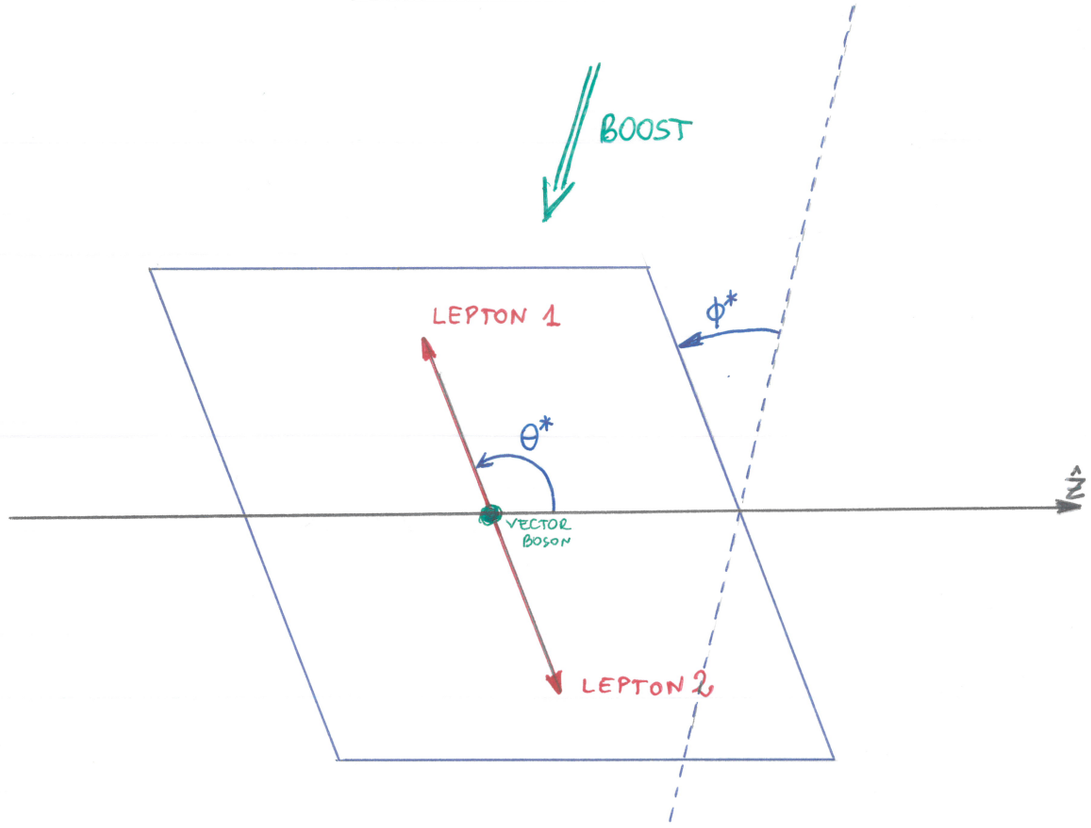
Why use this frame?

- cross-section in terms of 8 coefficients:

Instead of 25^2=**125** bins we have **8** numbers.

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

- analytical expressions are usually better than numbers
- frame often used in experiment



Reweighting

Recipe for NNLO+PS events:

- take sample of HWJ events generated with POWHEG-BOX

```
<event>
      8  10001  1.82114E-01  6.94413E+01 -1.00000E+00  1.29605E-01
       2    -1     0     0   501     0  0.000000000E+00  0.000000000E+00  1.441082126E+02  1.441082126E+02  0.000000000E+00  0.00000E+00  9.000E+00
      21    -1     0     0   512   502  0.000000000E+00  0.000000000E+00 -1.476970750E+03  1.476970750E+03  0.000000000E+00  0.00000E+00  9.000E+00
      25     1     1     2     0     0 -1.418561541E+02 -1.053865810E+02 -4.933175534E+01  2.220077737E+02  1.249973184E+02  0.00000E+00  9.000E+00
      24     2     1     2     0     0  1.647652149E+02  2.133528996E+01 -1.587445458E+02  2.433469199E+02  8.009445656E+01  0.00000E+00  9.000E+00
     -11     1     4     4     0     0  1.415677625E+02  4.403528840E+01 -1.471366045E+02  2.088772807E+02  5.110000000E-04  0.00000E+00  9.000E+00
      12     1     4     4     0     0  2.319745242E+01 -2.269999843E+01 -1.160794129E+01  3.446963923E+01  6.951036328E-07  0.00000E+00  9.000E+00
      21     1     1     2   501   502  4.560909504E+01  7.276636642E+01 -1.148698566E+02  1.434232115E+02  3.568322551E-06  0.00000E+00  9.000E+00
       3     1     1     2   512     0 -6.851815583E+01  1.128492460E+01 -1.009916380E+03  1.012301058E+03  5.000000000E-01  0.00000E+00  9.000E+00
```

- provide 3D-histograms containing [A_i] coefficients both at:
  - NNLO obtained from HV@NNLO
  - NLO obtained from HWJ in POWHEG-BOX
- rescale every single weight according to formula:

$$w_{\text{NNLO}} = w_{\text{POWHEG}} \cdot \frac{(d\sigma^{\text{NNLO}}/d\Omega_B)}{(d\sigma^{\text{POWHEG}}/d\Omega_B)}$$

$\frac{d\sigma^{\text{NNLO}}}{d\Omega_B}$ HV@NNLO

$\frac{d\sigma^{\text{POWHEG}}}{d\Omega_B}$ HWJ-POWHEG

- play with new events in any way you can imagine…

Reweighting

Formula:

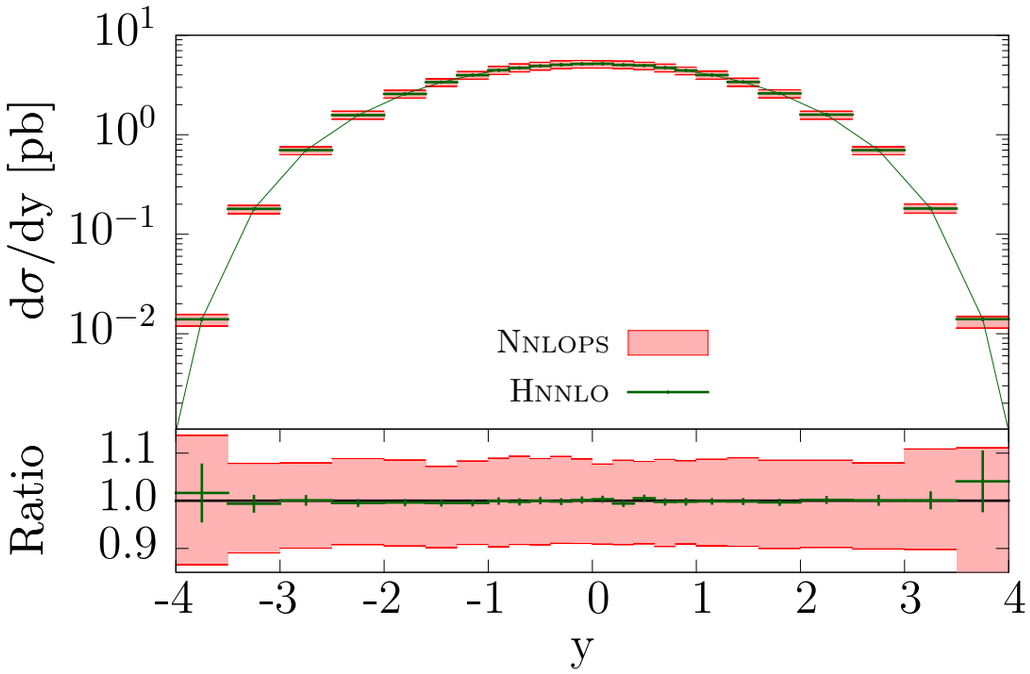
$$w_{\text{NNLO}} = w_{\text{POWHEG}} \cdot \frac{(d\sigma^{\text{NNLO}}/d\Omega_B)}{(d\sigma^{\text{POWHEG}}/d\Omega_B)}$$

Why does reweighting get harder?

- Higgs production (1-dim)

  1 variable = one histogram (y_H, **25 bins**)

  [arxiv: 1309.0017]



Reweighting

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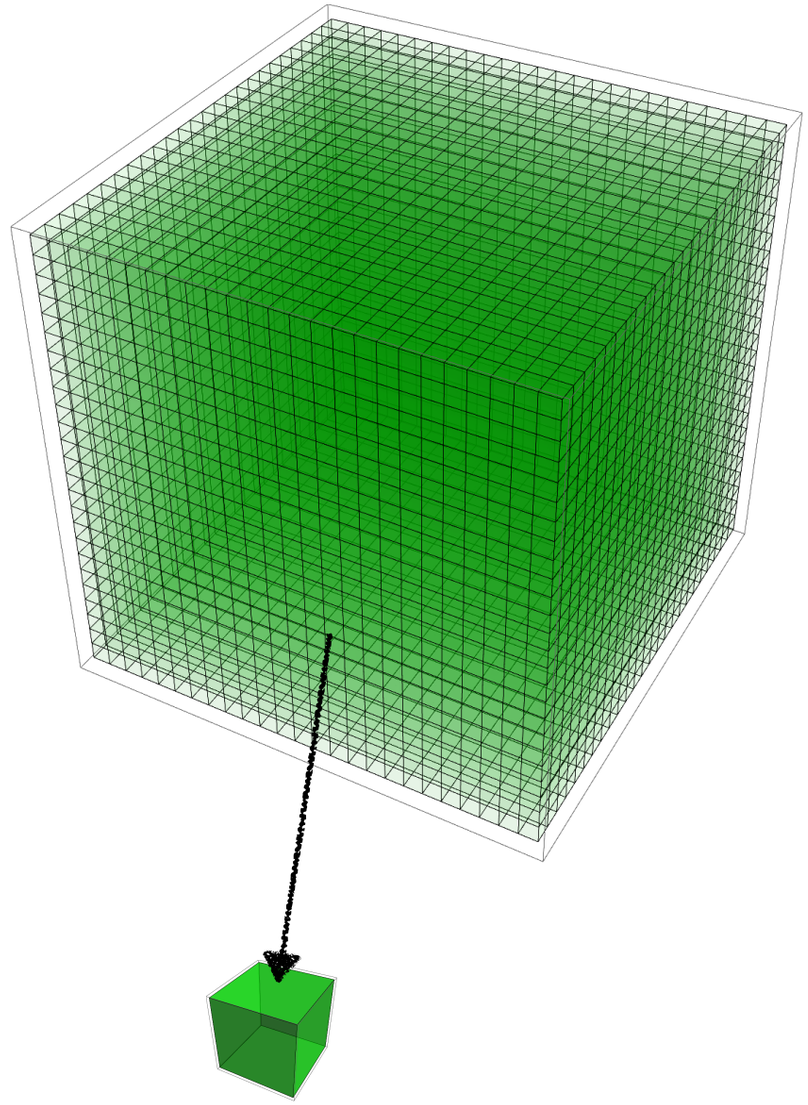
  3 variables = one 3D-histogram (**15 625 bins**)

  [arxiv: 1407.2940]



$$\frac{d^3\sigma}{dy_V\, d\theta_l\, dm_V} = \texttt{SINGLE-NUMBER}$$

Reweighting

Formula:

$$w_{\mathtt{NNLO}} = w_{\mathtt{POWHEG}} \cdot \frac{(d\sigma^{\mathtt{NNLO}}/d\Omega_B)}{(d\sigma^{\mathtt{POWHEG}}/d\Omega_B)}$$

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  [arxiv: 1309.0017]

- Drell-Yan process (3-dim)

  3 variables = one 3D-histogram (**15 625 bins**)

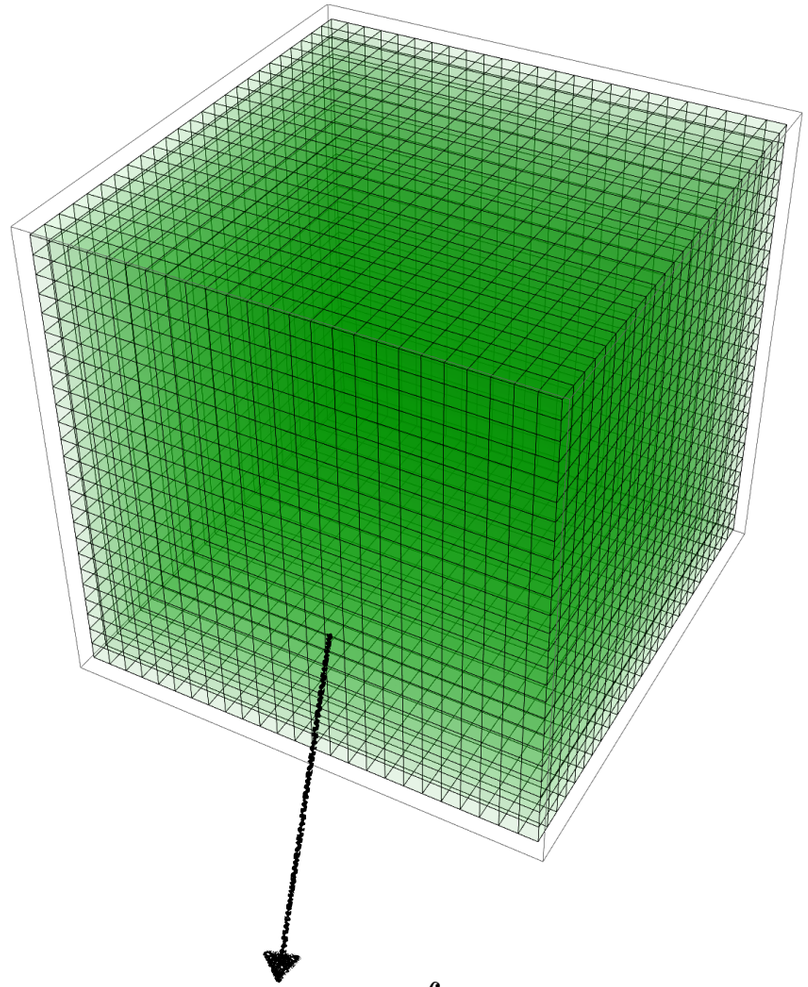
  [arxiv: 1407.2940]

- Higgs-strahlung process (6-dim)

  3 variables = eight 3D-histograms (**15 625 bins**)

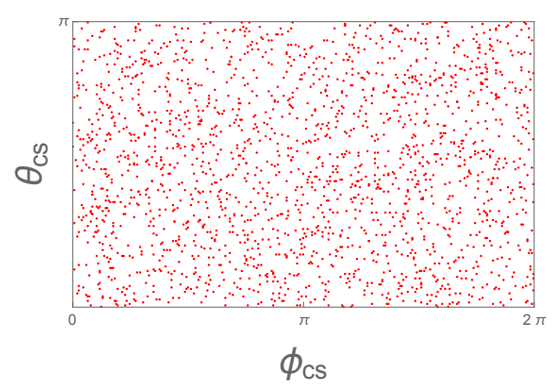
  + 2D-integration (θ_{CS},ϕ_{CS})

  + one more variable (m_V)



x 8

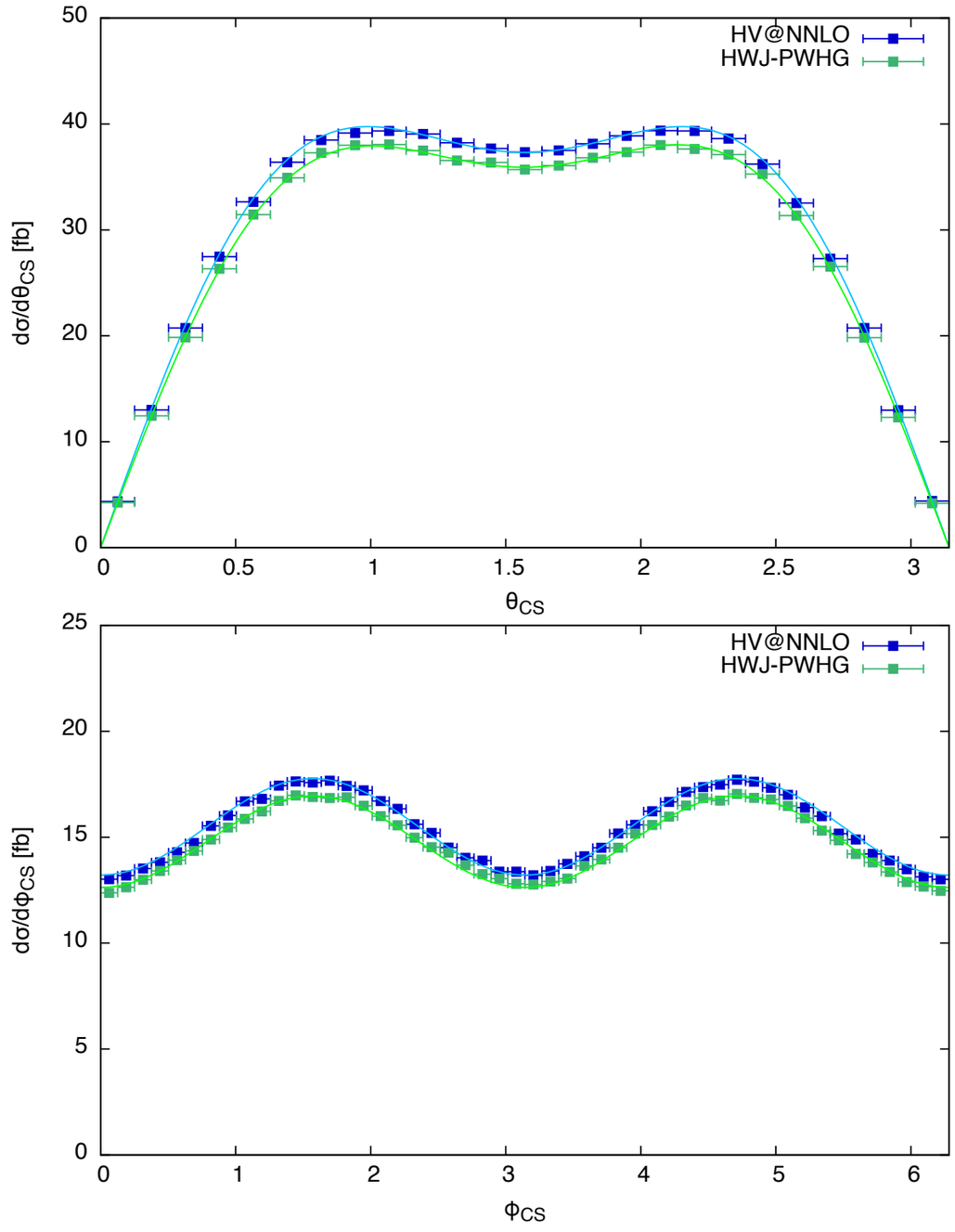
$$< A_i >= \int d\phi^* d\theta^* \ldots$$



Results

Conclusions about CS coefficients:

- CS coefficients describe cross-section in Higgs-strahlung well

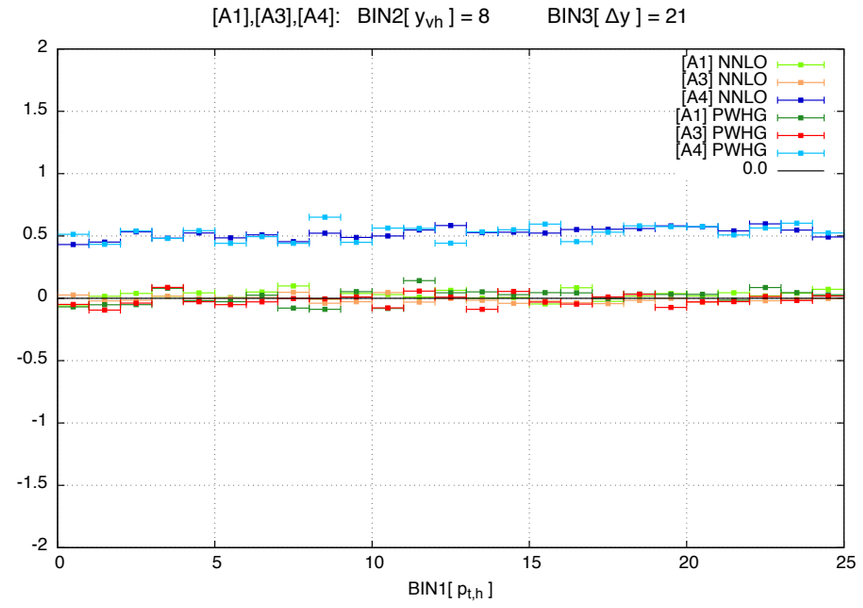


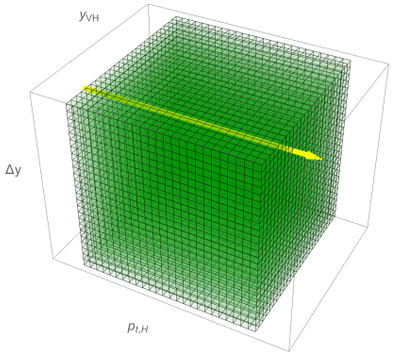
Results

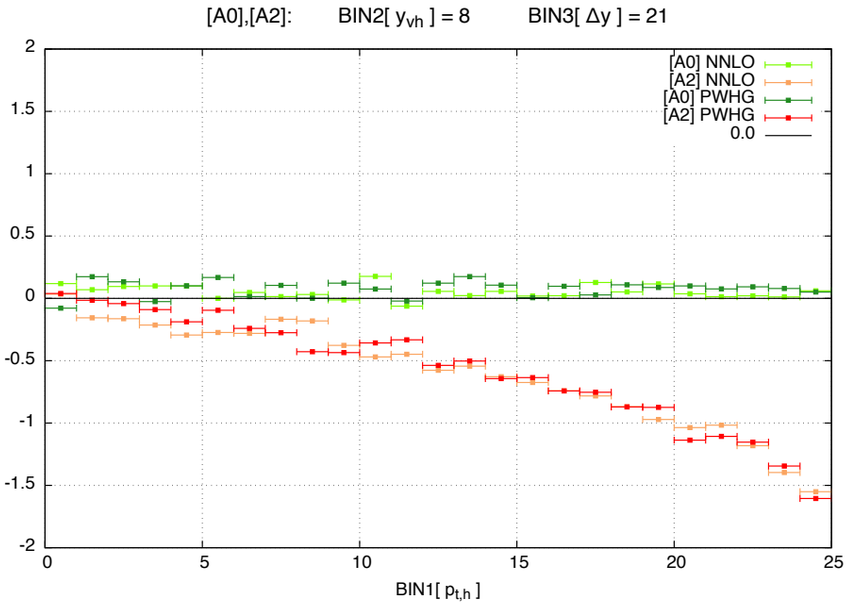
Conclusions about CS coefficients:

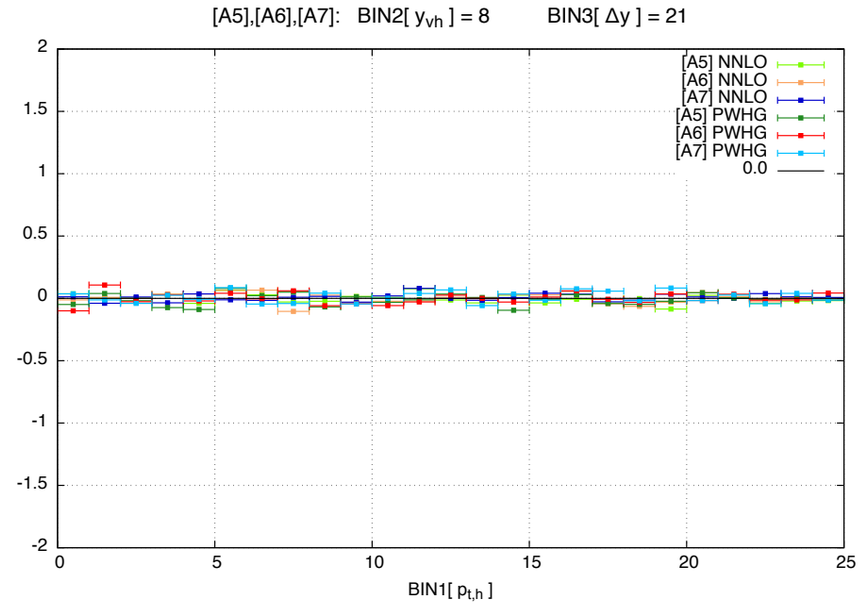
- CS coefficients describe cross-section in Higgs-strahlung well
- the leading role played by A_0, A_2, A_4
- large statistical fluctuations

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









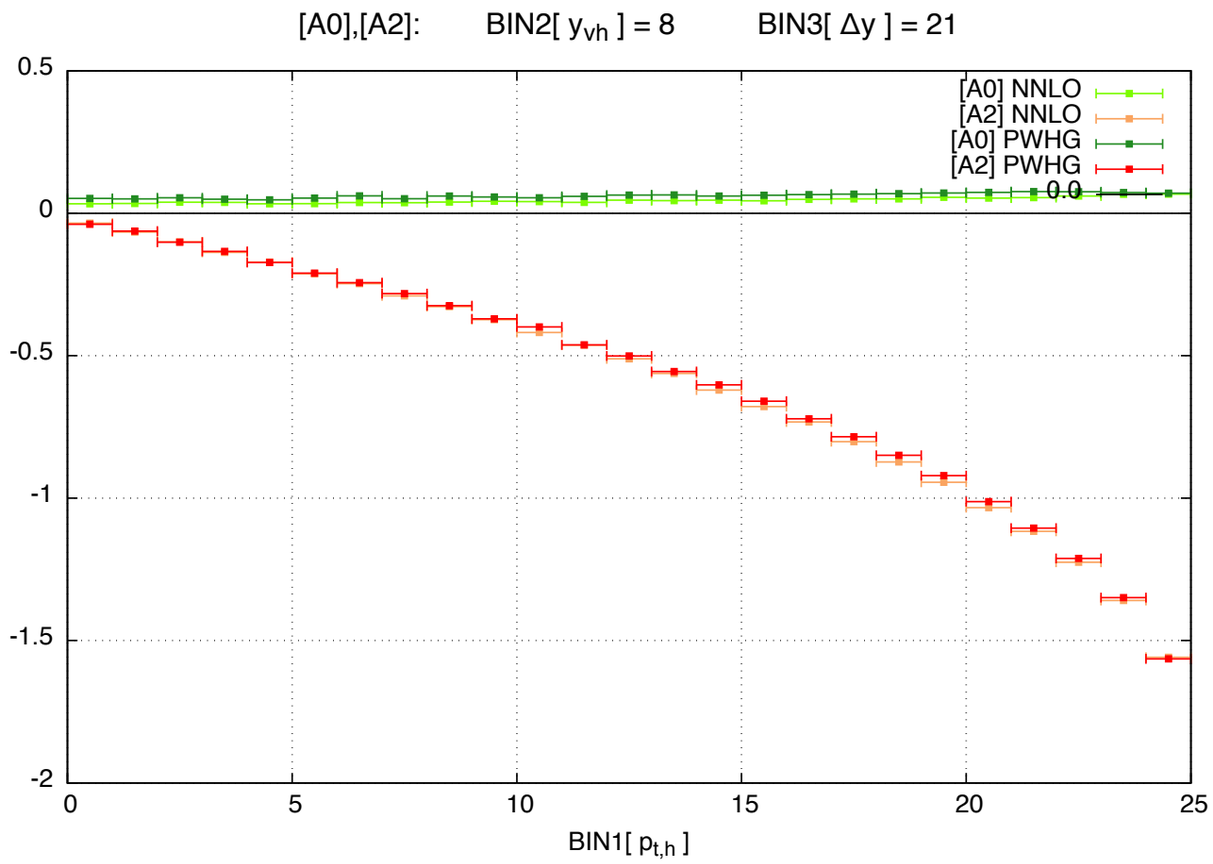
Results

Conclusions about CS coefficients:

- CS coefficients describe cross-section in Higgs-strahlung well
- the leading role played by A_0, A_2, A_4
- large statistical fluctuations
- [quick-check]: integrated over two dimensions we see slight difference between coefficients at NNLO and coefficients from HWJ-POWHEG

we're on a good track:

reweighting indeed changes distributions slightly



Results

Summary:

- sorry for not showing any actual histograms for HW (work in progress)
- we have “working” algorithm that enables us to reweight HWJ events == **HW@NNLO+PS**
  (we still need to verify if NNLO+PS distributions match fixed order NNLO)
- we need to increase statistics in order to reduce statistical fluctuations
  (especially time consuming in NNLO computations, easier in POWHEG)
- interesting question arises about the most appropriate way to combine many datasets with fluctuations
  (issue: how to remove large fluctuations, that spoil an average, without introducing bias)

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THANK YOU!

Searching for a 3.55 keV line in radio galaxies

Nicholas Jennings

Supervisor: Professor Joe Conlon

Contents

- Introduction to the 3.55 keV line
- DM $\rightarrow a \rightarrow \gamma$ model
- Radio galaxies

The 3.55 keV line

- Bulbul et al. (2014) found line in stacked spectrum of 73 galaxy clusters.
- Boyarsky et al. (2014) found the line in Perseus cluster and Andromeda galaxy.
- Many papers since detect a line, some don’t.

The 3.55 keV line

- Possible explanations:
  - Statistical fluctuations
  - Systematic effects
  - Astrophysical
  - Dark Matter decay

Dark matter decay models

- Sterile neutrinos from split flavour mechanism, sterile neutrinos from decaying of single scalar, sterile neutrinos from decays of light vector boson, sterile neutrinos decaying due to transition magnetic moment, sterile neutrinos decaying due to transition electric dipole moment, sterile neutrinos from Inverse Seesaw mechanism, sterile neutrinos due to E6 grand unification, sterile neutrinos from U(1)R-lepton number model, sterile neutrinos from dark matter-philic Higgs boson decay, sterile neutrinos from PeV scale supersymmetry, one-loop induced radiative neutrinos, Dirac neutrino dark matter, minimal decaying dark matter, nonabelian dark matter, axions, axion-like particles (ALPs), axinos, new scalar/pseudoscalar field from the effective field theory, vector dark matter, nonthermal two component dark matter, millicharged dark matter particles, moduli with low cutoff scale, new almost degenerate Standard Model singlets with mass at GeV scale, dark gauginos, gravitinos, pseudo-Nambu-Goldstone bosons, majorons, dark matter scalars, extra light fermions in E6-inspired U(1) extension of the Standard Model, local U(1)B−L extension of Zee-Babu model, nearly-degenerate decaying WIMPs, spin-3/2 dark matter, and lepton flavored dark matter[1].

[1] Dmytro Iakubovskyi, 2015

DM $\rightarrow a \rightarrow \gamma$ model

- Dark Matter (e.g. sterile neutrino) decays to an axion-like particle (light pseudoscalar).
- ALPs couple to electromagnetism via the Lagrangian term

$$\frac{a}{M}\mathbf{E}\cdot\mathbf{B}$$

- An ALP in a magnetic field converts to photon with probability

$$P_{a\rightarrow\gamma} = \frac{1}{4}\left(\frac{B_{\perp}L}{M}\right)^2$$

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Radio Galaxies

- Elliptical galaxy with AGN.
- Jets feed lobes with a relativistic plasma.
- Lobes extend for 100-1000 kpc, $B \sim \mu$G.

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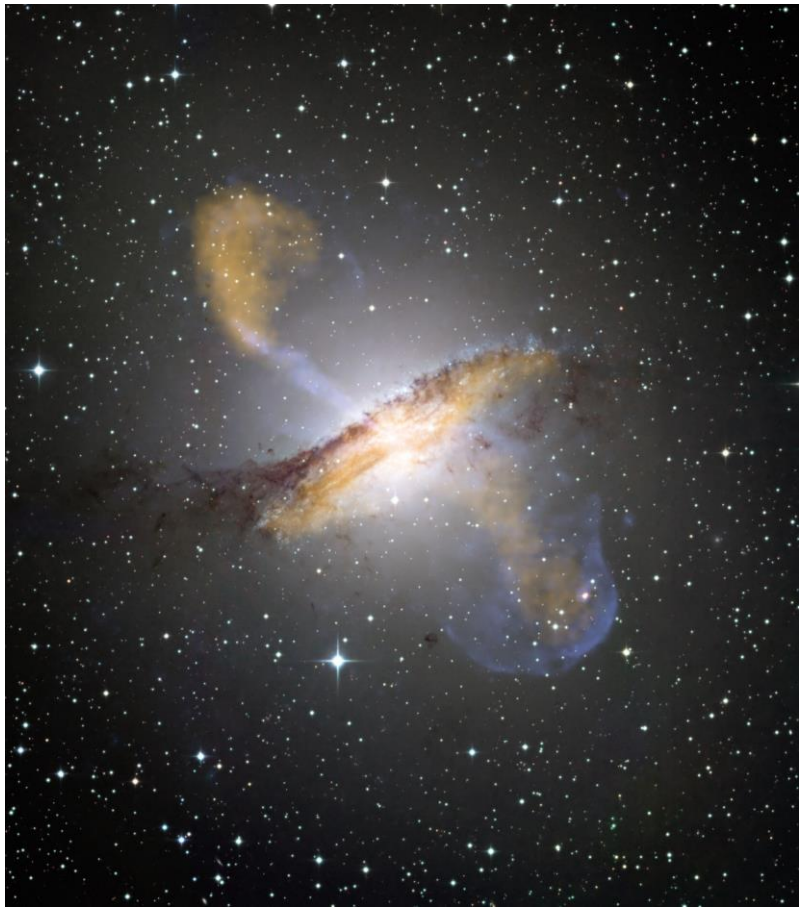
Centaurus A

Centaurus A	
Distance	3.7 Mpc
Angular size	$5° \times 9°$
Lobes	600kpc × 200kpc
Lobe Mag. field strength	$B \sim 1\mu$G
Coherence length	> 10 kpc
Thermal electron density	$n_{e,th} \leq 10^{-15}\mathrm{cm}^{-3}$



http://www.eso.org/public/images/eso0903a/

ALP to photon conversion in lobes

- Far from jets random magnetic field component dominates.
- X-Ray background from lobes < 10% of the CXB.
- Therefore calculate conversion of 3.55keV ALP to photon in 200 kpc^3 volume. Result:

$$P_{a\to\gamma} \sim 10^{-5} \text{ for } M = 10^{13}$$

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Signal from dSphs behind lobes?

- Dwarf spheroidal galaxies exist behind the lobes of Centaurus A.
- They would produce negligible X-Ray backgrounds.
- Estimate their DM density profiles from the profiles of the ‘classical’ dSphs.

Results

- Assuming DM decay lifetime $\tau \sim 5 \times 10^{24}$s, expected signal < 1% of CXB.
- Radio galaxies not a good environment to look for a 3.55keV line.
- Future direction: Studying ALP-photon conversion in galaxy clusters to put bounds on ALP coupling strength.

Thanks for listening!

Any questions?

Holomorphic Yukawa Couplings in Heterotic String Theory

Stefan Blesneag

University of Oxford

Work done in collaboration with: Andre Lukas, Evgeny I. Buchbinder, and Philip Candelas

Motivation

- Calabi-Yau compactifications of heterotic string theories can lead to models with the MSSM spectrum.
- Yukawa couplings determine particle mass and interactions $\Rightarrow$ they are crucial for understanding the theory's phenomenology.
- So far, Yukawa couplings have been calculated only for a small number of cases: orbifold compactifications and heterotic models with "standard embedding" (i.e. models where the gauge bundle is chosen to be the tangent bundle of the Calabi-Yau manifold, with SU(3) structure group).
- Aim: develop methods to calculate Yukawa couplings for heterotic models with general vector bundles (non-standard embedding).

Geometric ingredients

- Start from $E_8 \times E_8$ heterotic string theory with a Calabi-Yau 3-fold X, which has a nowhere vanishing holomorphic $(3,0)-$form Ω.
- Define a vector bundle $V \to X$ with structure group G embedded into E_8.
- The "visible sector" E_8 breaks into $G \times H$ at low energies. Here, H is the gauge group of the resulting GUT theory.
- Phenomenologically interesting structure groups are $G = SU(3)$, $SU(4)$, and $SU(5)$, because they lead to low-energy groups $H = E_6$, $SO(10)$, and $SU(5)$ respectively.
- The branching of the adjoint representation of E_8 under $G \times H$

$$\mathbf{248} \to \left[(\mathrm{Adj}_G, \mathbf{1}) \oplus (\mathbf{1}, \mathrm{Adj}_H) \oplus \bigoplus (\mathcal{R}_G, \mathcal{R}_H)\right]_{G\times H}$$

- The matter multiplets originate from the $E_8 \times E_8$ gauge fields and the associated gauginos and transform as representations $\mathcal{R}_H$ under H.

Deformations of the Calabi-Yau space

- $h^{(1,1)}$ Kähler moduli and $h^{(2,1)}$ complex structure moduli - from deformations of the metric around the $M_4 \times X$ vacuum .
- Matter fields and bundle moduli - from fluctuations of the $E_8 \times E_8$ gauge boson A.
- Example: $SU(5)$ GUT

$$\begin{aligned} \mathbf{10} &\leftrightarrow \nu_2 \in H^1(X,V) && \Rightarrow n_{\mathbf{10}} = h^1(X,V) \\ \mathbf{5} &\leftrightarrow \nu_1 \in H^1(X,\wedge^2 V^*) && \Rightarrow n_{\mathbf{5}} = h^1(X,\wedge^2 V^*) \\ \mathbf{1} &\leftrightarrow \nu_3 \in H^1(X,V\wedge V^*) && \Rightarrow n_{\mathbf{1}} = h^1(X,V\wedge V^*) \end{aligned}$$

- The Yukawa couplings in $4d$ arise from the $A \cdot \chi \cdot \chi$ couplings in $10d$ which are provided by the gaugino kinetic terms $\overline{\hat{\chi}^a}\Gamma^M D_M \hat{\chi}^a$.

The holomorphic Yukawa coupling

- For three representations $(\mathcal{R}_G^I, \mathcal{R}_H^I)$ of the split group $G \times H$, $I = 1, 2, 3$, with associated vector bundles V_I and harmonic bundle valued $(0,1)-$ forms $\nu_I \in H^1(X, V_I)$:

$$\lambda(\nu_1, \nu_2, \nu_3) = \int_X \Omega \wedge \nu_1 \wedge \nu_2 \wedge \nu_3$$

  so that $\mathcal{R}_G^1 \otimes \mathcal{R}_G^2 \otimes \mathcal{R}_G^3$ contains a singlet.

- This function is holomorphic and independent of the choice of harmonic representatives (it is quasi-topological):

$$\lambda(\nu_1 + \bar{\partial}\xi_1, \nu_2 + \bar{\partial}\xi_2, \nu_3 + \bar{\partial}\xi_3) = \lambda(\nu_1, \nu_2, \nu_3),$$

  which means it can be computed purely algebraically.

The physical Yukawa coupling

- However, the previous expression is **not** the **physical** Yukawa coupling: the theory was not yet normalized
- The effective kinetic terms of the matter fields are non-canonical:

$$S_{\text{matter fields}} \sim \int_{M_4} G_{ij} dC^{i\alpha} \wedge *d\overline{C}^{j\alpha}$$

and the Kähler metric is not a holomorphic function:

$$G_{ij} = \int_X \omega_i \wedge *_X \omega_j, \quad \omega_i, \omega_j \in H^1(X, V)$$

- Normalization would require knowledge of the specific Calabi-Yau metric $\Rightarrow$ calculations have to rely on differential geometry, rather than pure algebraic calculations.

Complete Intersection Calabi-Yau Manifolds (CICYs)

- Define the Calabi-Yau 3-fold X to be the common zero locus of K homogeneous polynomials $\{p_j\}_{j=1,\ldots,K}$ in an ambient space $\mathcal{A} = \mathbb{P}^{n_1} \times \ldots \times \mathbb{P}^{n_m}$.
- The tetra-quadric manifold, defined by a $(2,2,2,2)$ homogeneous polynomial in $\mathbb{P}^1 \times \mathbb{P}^1 \times \mathbb{P}^1 \times \mathbb{P}^1$:

$$\tilde{p} = c_1 u_0 u_1 v_0 v_1 x_0 x_1 y_0 y_1 + c_2 (u_1^2 v_0^2 x_0 x_1 y_0 y_1 + u_0^2 v_1^2 x_0 x_1 y_0 y_1) + \text{etc.}$$

- $\tilde{p}$ must be invariant under $\Gamma = \mathbb{Z}_2 \times \mathbb{Z}_2$. $\Rightarrow$ GUT is broken to the SM group
- The bundle V descends to the quotient Calabi-Yau X/Γ in the low energy limit (Wilson line symmetry breaking).

Splitting the bundle

- The vector bundle is fully split into a direct sum of n line bundles:

$$V = \bigoplus_{a=1}^{n} L_a \Rightarrow c_1(V) = \bigoplus_{a=1}^{n} c_1(L_a) \stackrel{!}{=} 0$$

- Tautological bundle $\mathcal{O}(-1) \Rightarrow$ the fiber over vector space W is W itself
- For a line bundle $\mathcal{O}_X(\mathbf{k}) \equiv (\mathcal{O}(-1)^*)^{\otimes k_1} \otimes ... \otimes (\mathcal{O}(-1)^*)^{\otimes k_m}$:

$$c_1(\mathcal{O}_X(\mathbf{k})) = \sum_{i=1}^{m} k^i J_i, \quad \text{where } J_i = \text{Kähler form on } \mathbb{P}^{n_i}$$

- Replace the structure group $SU(n)$, with an abelian group $S(U(1)^n)$ (n charges with one trace condition).
- For a term to be phenomenologically possible: it has to have neutral charge under $S(U(1)^n)$.

An example: $SU(5) \times S(U(1)^5)$ GUT group

$V = \bigoplus_{a=1}^{5} L_a$

$$\begin{aligned} L_1 &= \mathcal{O}_X(-1,0,0,1) \quad , \quad L_2 = \mathcal{O}_X(-1,-3,2,2) \quad , \quad L_3 = \mathcal{O}_X(0,1,-1,0) \\ L_4 &= \mathcal{O}_X(1,1,-1,-1) \quad , \quad L_5 = \mathcal{O}_X(1,1,0,-2)\,. \end{aligned}$$

At the GUT level the only superpotential terms allowed by the gauge symmetry are:

$$W = \lambda_{IJK}\mathbf{5}^{(I)}_{2,5}\mathbf{10}^{(J)}_{2}\mathbf{10}^{(K)}_{5} + \rho_{IJK}\mathbf{1}^{(I)}_{2,4}\overline{\mathbf{5}}^{(J)}_{4,5}\mathbf{5}^{(K)}_{2,5}$$

$\downarrow$ "downstairs" spectrum

$$W = \lambda^{(u)}_{IJ}\overline{H}_{2,5}u^{(I)}Q^{(J)} + \rho_{IJ}\mathbf{1}^{(I)}_{2,4}L^{(J)}_{4,5}\overline{H}_{2,5}$$

$$\lambda^{(u)} = \frac{i\pi^3}{6}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \qquad \rho = -\frac{i\pi^3}{360}\begin{pmatrix} 0 & (c_3-c_5)\left(4c_4^2 + c_1\left(c_3+c_5-2c_6\right)\right)\left(c_3+c_5+2c_6\right) \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

Conclusions

- We have developed methods to calculate holomorphic Yukawa couplings for heterotic line bundle models, focusing on CICYs like the tetra-quadric in $\mathbb{P}^1 \times \mathbb{P}^1 \times \mathbb{P}^1 \times \mathbb{P}^1$.
- Even though we restricted ourselves to a relatively narrow class of Calabi-Yau manifolds, our calculations can lead to several generalisations:
  - higher co-dimension CICYs,
  - non-Abelian bundles
  - hypersurfaces in toric varieties.
- Important task: calculate the matter field Kähler metric, in order to determine the physical Yukawa couplings and normalise the theory.

HOLOGRAPHIC ENTANGLEMENT TEMPERATURE IN CHARGED CFT

NIKOLA IVANOV GUSHTEROV

Oxford Holography Group

Supervised by:

A. *O'Bannon, University of Southampton*

A. Starinets, Oxford University

In collaboration with*:*

R. Rodgers, University of Southampton

OUTLINE

- **Holography & Gauge/Gravity duality**
- **Gapless Quantum Matter**
- **Holographic Entanglement Entropy (HEE)**
- **Charged solutions, PEAK!**
- **Physical Interpretation?**
- **Other directions**

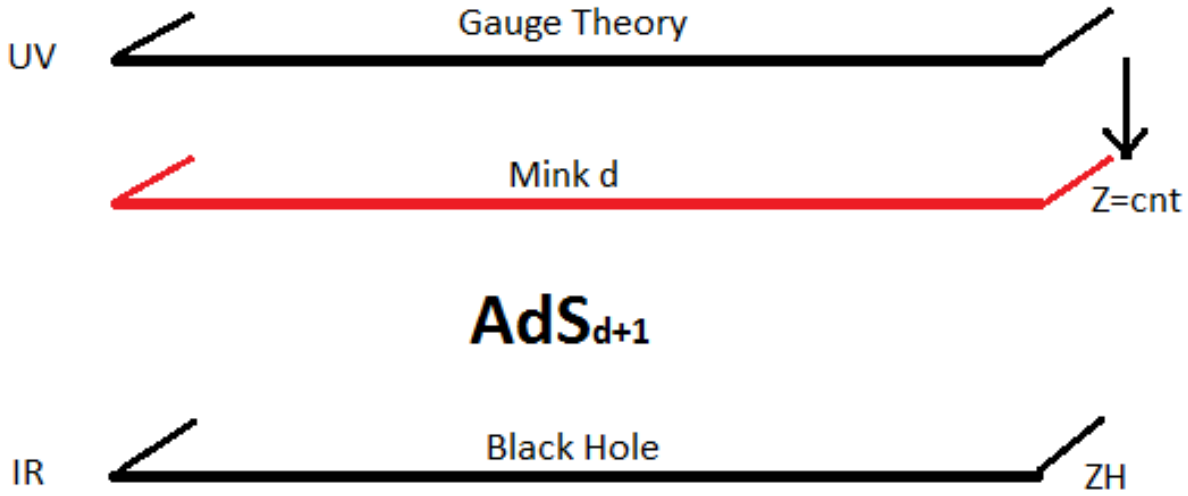
HOLOGRAPHY & GAUGE/GRAVITY DUALITY

{d-Dimensional Strongly coupled Gauge Theory in flat Space-time}

↕

{ d+1-Dimensional Classical Gravity in AdS_{d+1} Space-time }

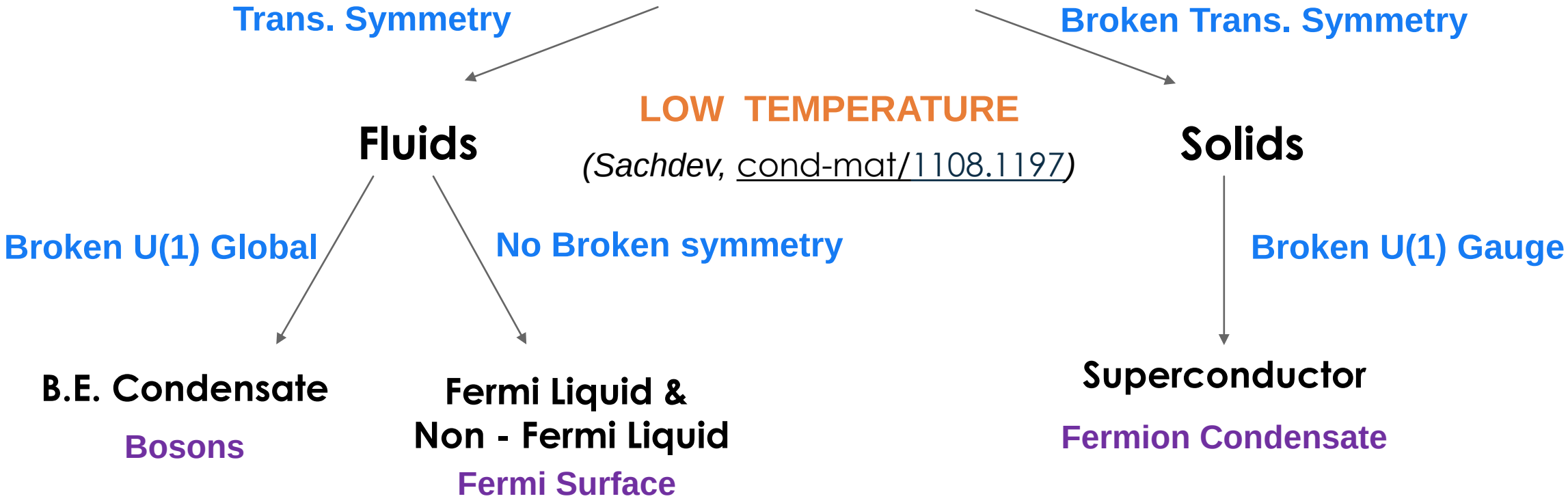
- **Geometrized RG flow** (Z acts as an RG scale relating the Gauge theory at UV and IR)



Holographic Dictionary

Gauge Theory		**AdS_{d+1}**
Conserved current	⟷	*Gauge field*
Stress Energy Tensor	⟷	*Space-time metric*
Thermodynamics	⟷	*BH Thermodynamics*

Gapless Quantum Matter



Gapless Quantum Matter

Trans. Symmetry

Broken Trans. Symmetry

LOW TEMPERATURE

(*Sachdev*, cond-mat/1108.1197)

Fluids

Solids

Broken U(1) Global

No Broken symmetry

Broken U(1) Gauge

B.E. Condensate

Bosons

Fermi Liquid & Non - Fermi Liquid

Fermi Surface

Superconductor

Fermion Condensate

No Broken Symmetry

Strongly coupled Holographic Fluids?

No Fermi Surface & Quasiparticles

Finite Entropy Ground State

We need some Non-Local Observable

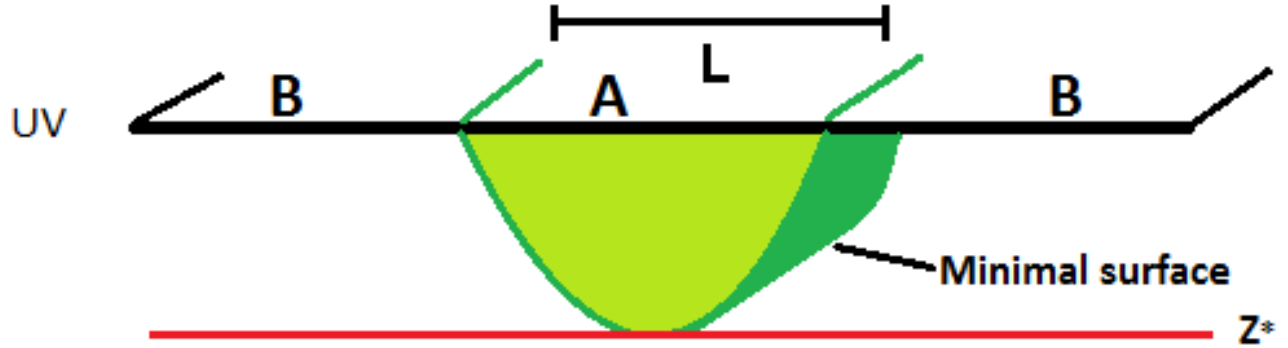
HOLOGRAPHIC ENTANGLEMENT ENTROPY (HEE)

- *In any QFT, for subsystems A and B, the Entanglement Entropy (EE) is a measure of their quantum entanglement defined as:*

$$S(A) = -Tr_A(\rho_A \, Log \, \rho_A) \quad \text{where} \quad \rho_A = Tr_B(\rho) \text{ is the Reduced density matrix}$$

- *In holography, the EE is related to a **geometric** concept using* (Ryu, Takayanagi hep-th/0603001)

$$S(A) = \frac{\text{Area minimal surface}}{4 \text{ Planck area}}$$



Z= Turning point of the surface*

ZH= Black hole horizon position

HOLOGRAPHIC ENTANGLEMENT ENTROPY (HEE)

- *In the case of small subsystem compared to the energy density ($\varepsilon L^d \ll 1$), we can calculate the change to leading order in ε*

$$Energy(Strip) \sim \varepsilon L Vol_{d-2} \qquad S(Strip) \sim \left(\frac{1}{a^{d-2}} - \frac{\#}{L^{d-2}} + \#\varepsilon L^2\right) Vol_{d-2}$$

- *As in the QFT case, we need to regulate the HEE by introducing a small UV cut off a*
- *Define the **Inverse Entanglement Temperature (IET)** β_{Ent}*

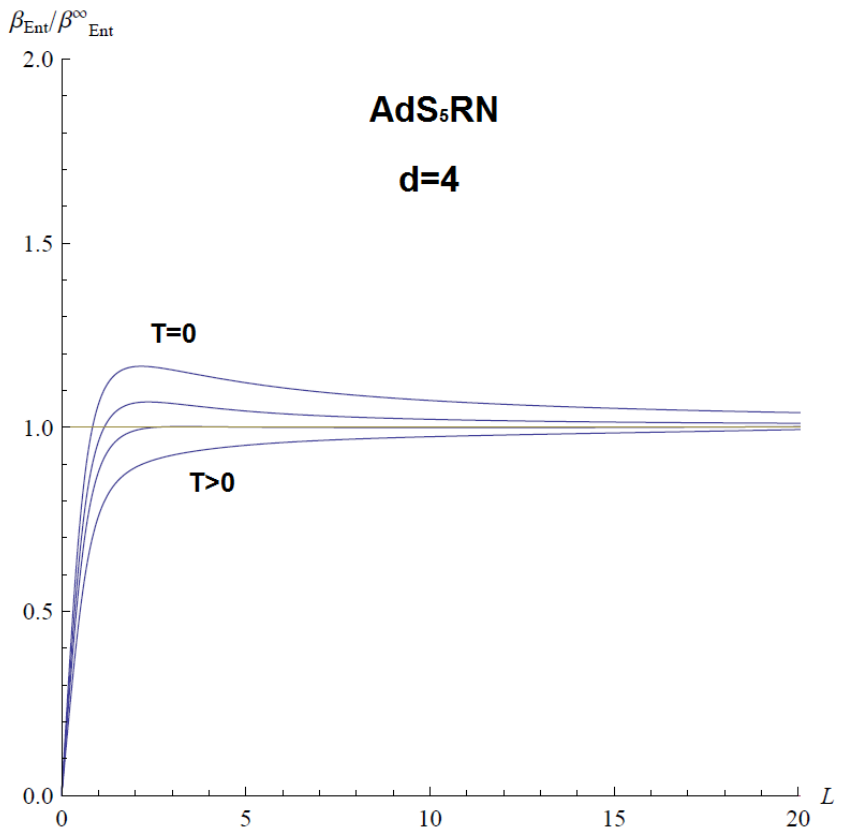
(Takayanagi, et al., hep-th/1212.1164)

$$\frac{\mathbf{\Delta S(A)}}{\mathbf{\Delta E(A)}} \equiv \beta_{\mathbf{Ent}} \qquad \beta_{\mathbf{Ent}} \sim \mathbf{L} \qquad \varepsilon L^d \ll 1$$

- *In analogy with thermodynamics, we define this as the inverse of the ET*
- *For small A, **universal slope** only depending on the **dimension** d and its **shape***
- *This ratio can tell us how ΔS scales with L and how it becomes extensive $\Delta S \sim S_{TH} \sim L Vol_{d-2}$*

CHARGED SOLUTIONS, PEAK!

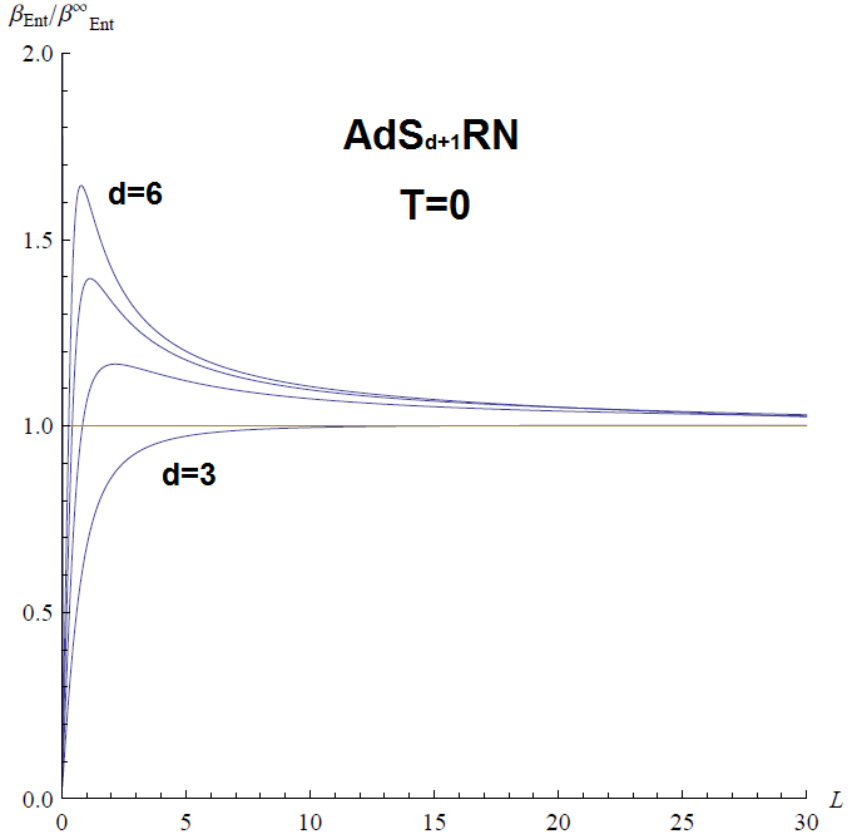
- *The normalized β_{Ent} is computed as function of the size of L in horizon units. At fixed dimension, when we **lower the temperature** observe a **peak** developing for AdS5RN or greater space-time dimension*



We expect

$$L_{Peak} \sim \frac{1}{\mu(T=0)}$$

(Only scale at T=0)



- *Expected behaviour: Under Extensive ⟶ Extensive (AdS4,5...SC , AdS4,RN,)*
- *Observed T=0: Under Extensive ⟶ **?!Over Extensive !?** ⟶ Extensive (AdS5,6...RN, AdS4,5...DBI)*

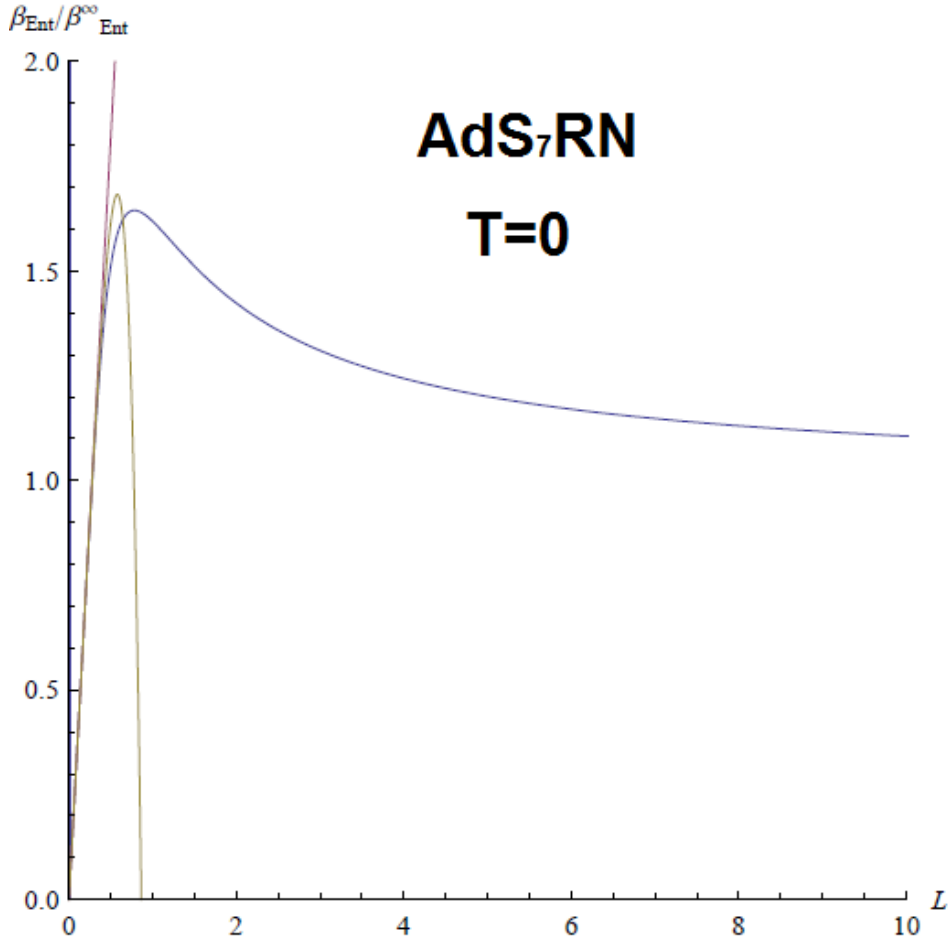
PHYSICAL INTERPRETATION?

- *To understand what is happening, we do perturbation theory for small ε and charge density q*

$$\frac{\Delta S(A)}{\Delta E(A)} = \#\, L \;\; - \#\, \frac{q^2}{\varepsilon} L^{(d-1)} + \ldots \qquad \varepsilon L^d \ll 1 \;\; , \;\; q L^{d-1} \ll 1$$

- *The analytic position of the maximum for T=0:*

$$L_{Peak} \sim \left(\frac{\varepsilon}{q^2}\right)^{1/(d-2)} \sim \frac{1}{\mu(T=0)}$$



- ***Gets more accurate as $d \gg 1$***

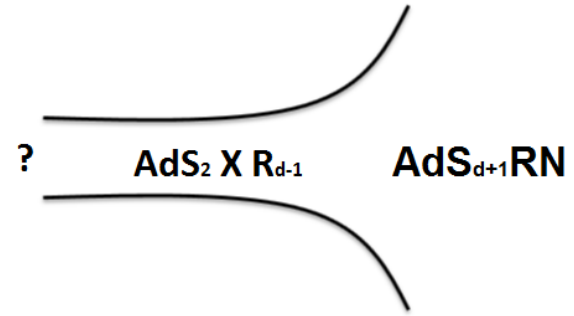
  (Emparan, Suzuki, Tanabe, hep-th/1302.6382)

- ***Predicts a peak even for AdS4RN***
- ***Similar for different A and charged solutions***

PHYSICAL INTERPRETATION?

- *The boundary QFT has **one UV and one "IR" fixed point**. The "IR" fixed point comes from the fact that **T=0** charged solutions have a **near horizon geometry** ≈ **AdS_2 X R_{d-1}***
- ***Semi-Local Quantum Liquid (SLQL)*** *(Hong Liu et al. hep-th/1105.4621)*

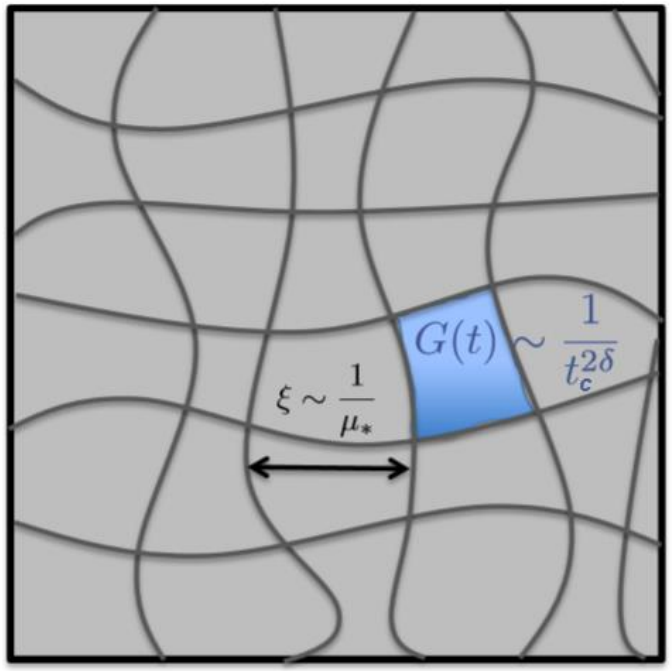
  - *Intermediate state of theories dual to Asymptotic $AdS_{d+1}RN$*
  - *Correlation length* $\xi \sim 1/\mu(T=0)$
  - $L \gg \xi$ ***Collective behaviour** of small regions **(0+1)-CFT***
  - $L \ll \xi$ *Controlled by a higher dimensional **CFT***



- ***The position of the peak (when present): Definition of correlation length for the SLQL?***

$$\xi \sim L_{Peak} \sim 1/\mu(T=0)$$

- ***Entanglement Temperature: Another Criteria to classify states in whether they have a peak or not?***



OTHER DIRECTIONS

- *In the future, we can study the system in the large D limit and maybe obtain some more accurate analytic results* *(Emparan, Suzuki, Tanabe,* hep-th/1302.6382*)*

- *We also considered a two parameter family of BH and found some interesting structure in the parameter space:*

d=3					j>p			
					RN			
	p\j	2,5	3	3,5	**4**	4,5	5	5,5
	2	No *	No *	No *	No *	No *	No *	Yes *
	2,5	X	Yes	Yes	Yes	Yes	Yes	No
RN	**3**	X	X	Yes	**No**	No	No	No
	3,5	X	X	X	No	No	No	No
	4	X	X	X	X	No	No	No

- *Explore Low energy excitation of the other Charged solution (AdS$_{d+1}$DBI) such as Zero sound*

THANK YOU FOR YOUR ATTENTION!