Summary of WG4

Hadronic and EW observables

P. Ferrari, A. Grebenyuk, D. Pagani

Overview

33 talks + 1 joined session with WG2
17 theory, 16 experiment

A large variety of topics:

- DIS, VV, VVV, V + jets, VBS, (di)jet, ttbar+gamma, light-by-light scattering
- ((N)N)NLO corrections, NLL, showers: both techniques and pheno results
- (I)TMD: shower, p-Pb collisions, techniques
- EFT for BSM interpretation

DIS$_{1J}$ @ N^{3}LO using Projection-to-Born

DIS 2 jet

@ NNLO

[Currie, Gehrmann, Niehues '16]
[Currie, Gehrmann, AH, Niehues '17]
CC: [Niehues, Walker '18]

Projection-to-Born

$\oplus$

[Cacciari, et al. '15]

DIS structure function

@ N^{3}LO

[Moch, Vermaseren, Vogt '05]

$=$

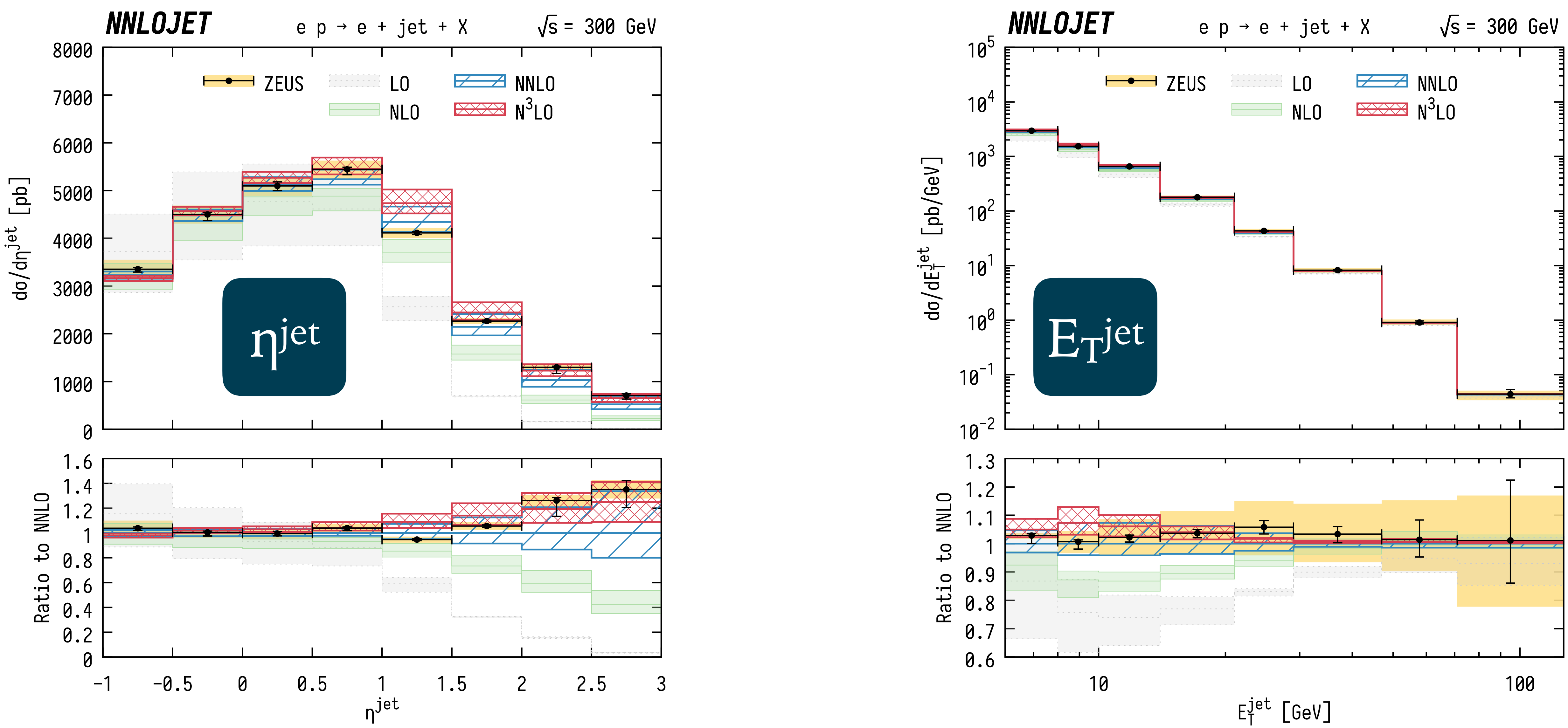
DIS fully differential @ N^{3}LO

[Currie, Gehrmann, Glover, AH, Niehues, Vogt. '18]
CC: [Gehrmann, Glover, AH, Niehues, Walker, Vogt '18]

A. Huss' talk

INCLUSIVE JETS (NC DIS$_{1J}$)

[Currie, Gehrmann, Glover, AH, Niehues, Vogt. '18]



- ➤ for the first time: overlapping bands (agreement with data)
- ➤ reduction of scale uncertainties

A. Huss' talk

DIS with KaTıe

Andreas van Hameren
Institute of Nuclear Physics
Polish Academy of Sciences
Kraków

presented at

DIS 2019

10-04-2019, University of Turin, Turin

This work was supported by grant of National Science Center, Poland, No. 2015/17/B/ST2/01838 and DEC-2017/27/B/ST2/01985.

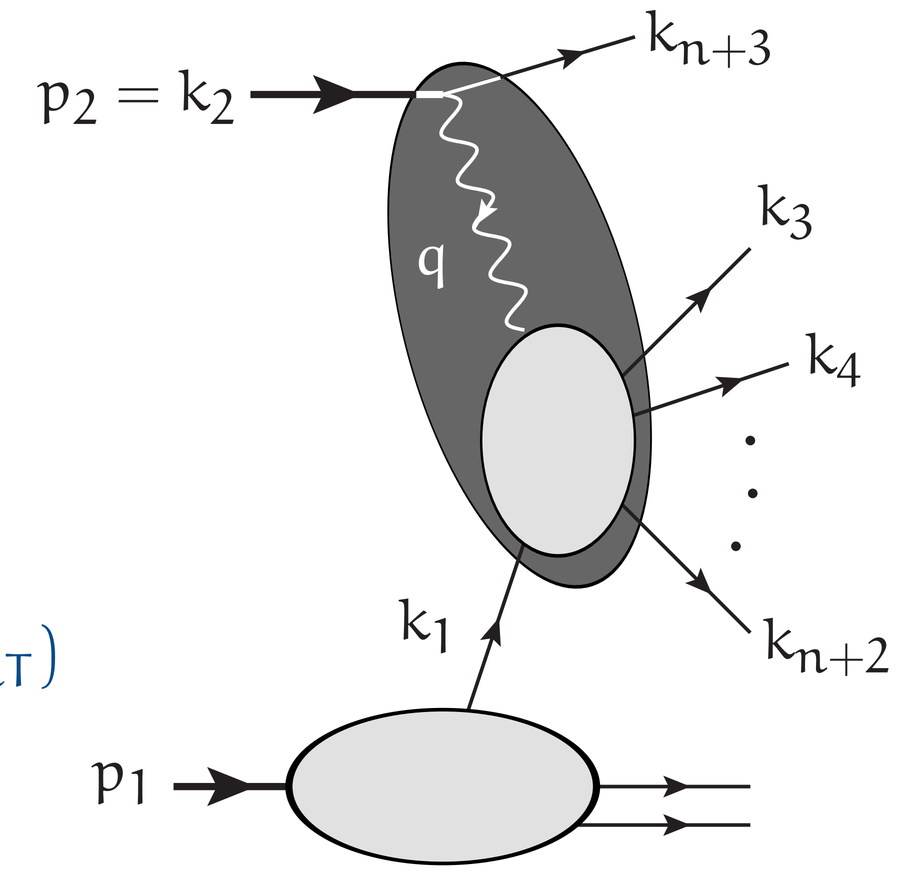
What does KaTie do?

Let $Y = \{y = y_1 y_2 \to y_3 y_4 \cdots y_n\}$ be a list of partonic processes contributing to a eh-scattering process with a multi-jet final state, with differential cross section

$$d\sigma_Y(p_1, p_2; k_3, \ldots, k_{3+n}) = \sum_{y \in Y} \int d^4k_1\, \mathcal{P}_{y_1}(k_1) \qquad d\hat{\sigma}_y(k_1, k_2; k_3, \ldots, k_{3+n})$$

Collinear factorization:

$$\mathcal{P}_{y_i}(k_i) = \int \frac{dx_i}{x_i} f_{y_i}(x_i, \mu)\, \delta^4(k_i - x_i p_i)$$



k_T-dependent factorization factorization:

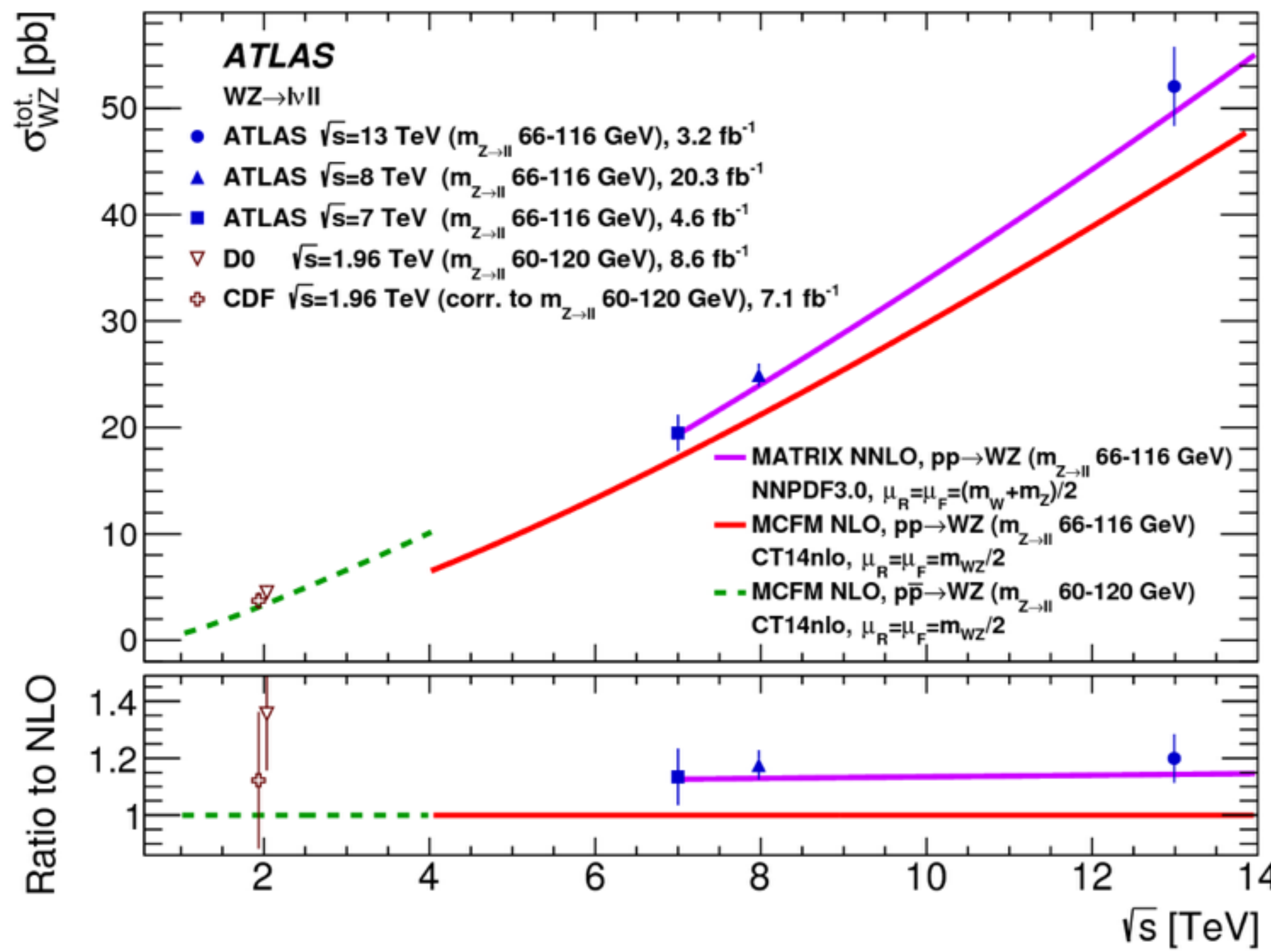
$$\mathcal{P}_{y_i}(k_i) = \int \frac{d^2\mathbf{k}_{iT}}{\pi} \int \frac{dx_i}{x_i} \mathcal{F}_{y_i}(x_i, |\mathbf{k}_{iT}|, \mu)\, \delta^4(k_i - x_i p_i - k_{iT})$$

Differential partonic cross section:

$$d\hat{\sigma}_y(k_1, k_2; k_3, \ldots, k_{3+n}) = d\Phi_Y(k_1, k_2; k_3, \ldots, k_{3+n})\, \Theta_Y(k_3, \ldots, k_{3+n}) \times \text{flux}(k_1, k_2) \times \mathcal{S}_y\, |\mathcal{M}_y(k_1, \ldots, k_{3+n})|^2$$

KaTie creates tree-level event files corresponding to $d\sigma_Y$, if supplied with f_y and/or $\mathcal{F}_y$.

Importance of QCD corrections
(example WZ)

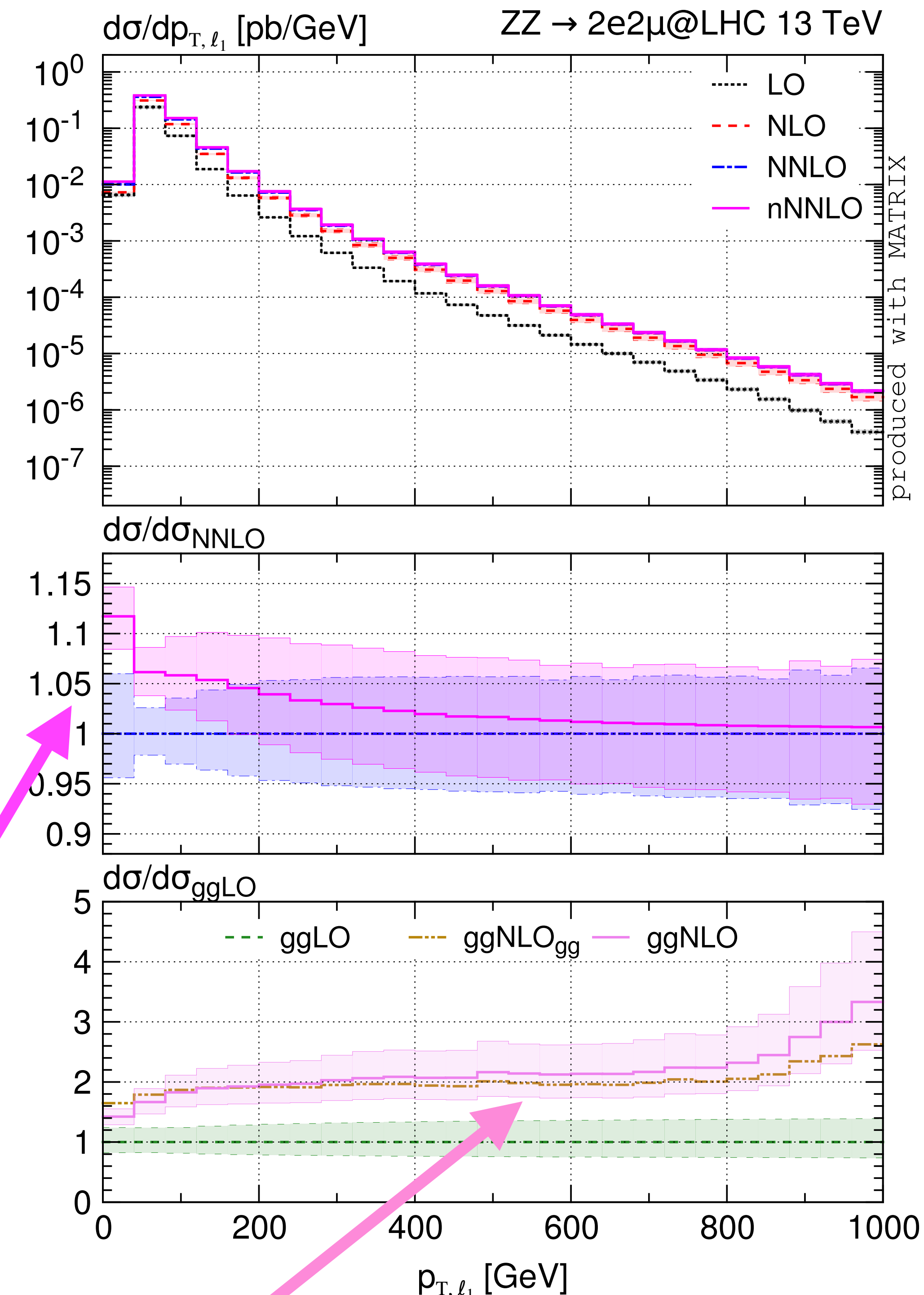


NNLO crucial for accurate description of data

M. Wiesemann's talk

$gg \to ZZ \to 4\ell$ at NLO [Grazzini, Kallweit, MW, Yook '18]

$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}}-1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(7)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.08(3)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+6.9\%$	$+8.6\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{ggLO}}-1$	
ggLO	$0.79354(8)^{+28.2\%}_{-20.9\%}$	$2.0054(2)^{+23.5\%}_{-17.9\%}$	0%	0%
ggNLO$_{gg}$	$1.4810(9)^{+16.0\%}_{-13.2\%}$	$3.627(3)^{+15.2\%}_{-12.8\%}$	$+86.6\%$	$+80.9\%$
ggNLO	$1.3901(9)^{+15.4\%}_{-13.6\%}$	$3.423(3)^{+13.9\%}_{-12.0\%}$	$+75.2\%$	$+70.7\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}}-1$	
NNLO	$12.87(3)^{+2.8\%}_{-2.1\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	$+13.9\%$	$+18.7\%$
nNNLO	$13.47(3)^{+2.6\%}_{-2.2\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	$+19.2\%$	$+25.8\%$



+5-6% effect due to NLO correction to gg compared to NNLO

NLO gg correction large+not flat; moves nNNLO outside uncertainty band of NNLO

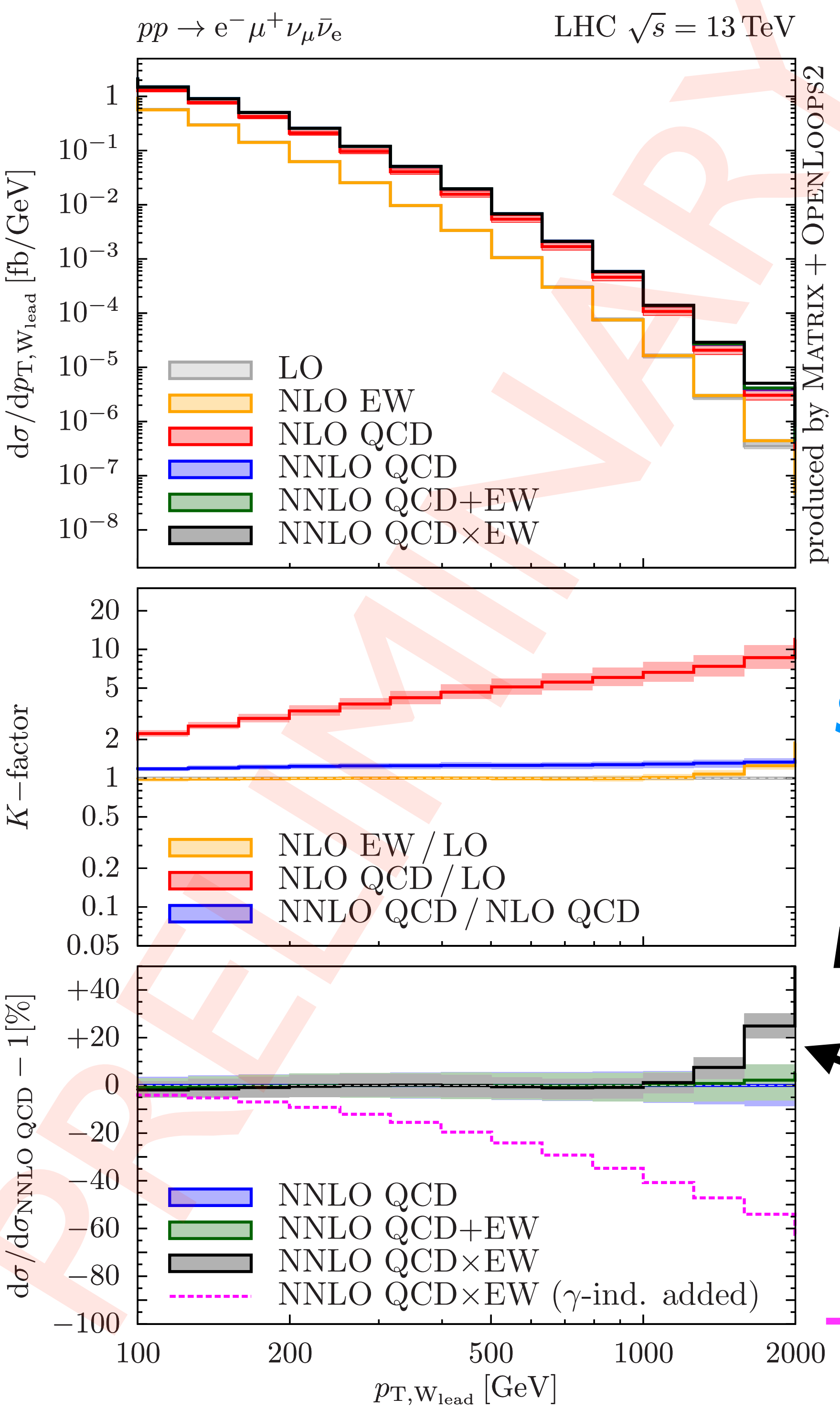
huge NLO gg K-factor (~2 & more); impact of newly computed fermionic channels clearly visible

M. Wiesemann's talk

Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

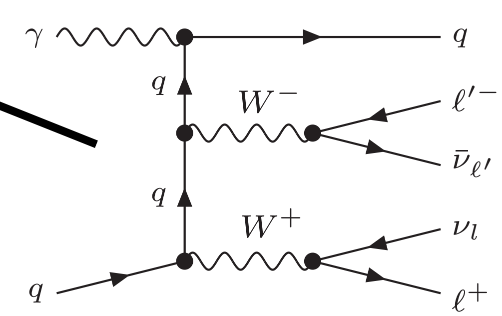
- *let's look in detail on one interesting aspect:* ***photon-induced + giant K-factor***



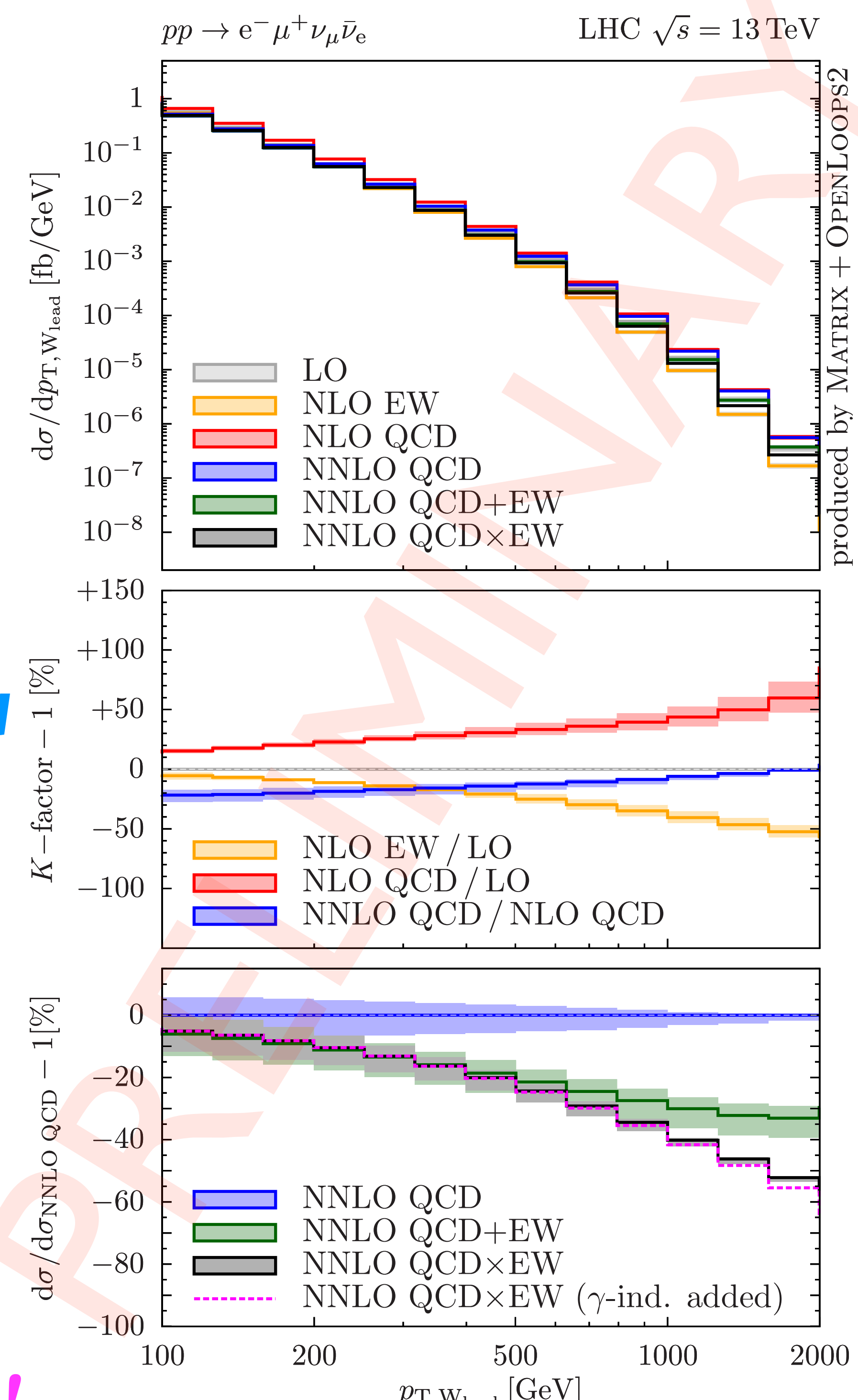
jet-veto ($H_{T,jet}$< 0.2 $H_{T,lep}$)

Sudakov suppression restored

high p_T dominated by V+jet



→ don't include γ in multiplicative combination!



UNIVERSITÀ DEGLI STUDI DI TORINO

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Local Analytic Sector Subtraction at NNLO

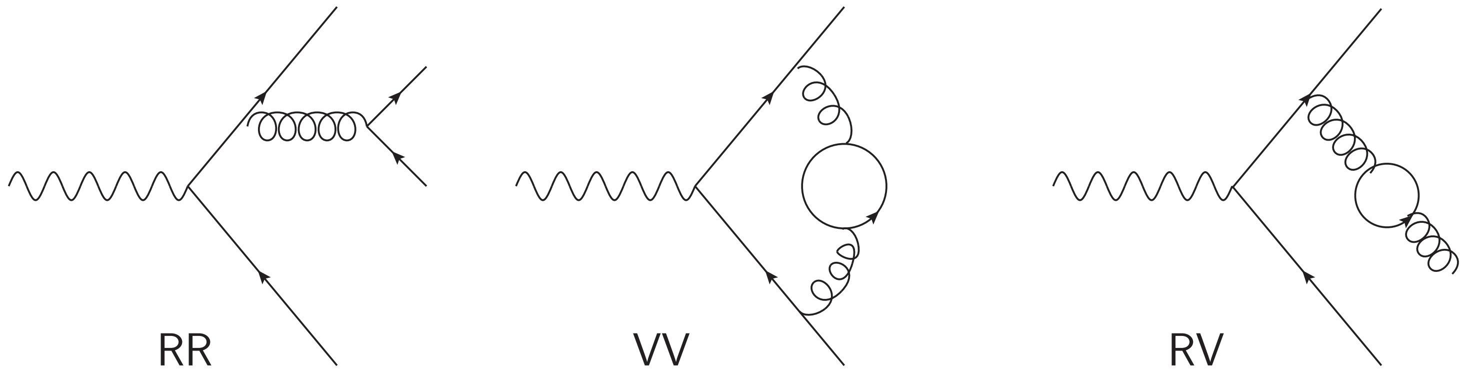
Giovanni Pellicciolì
University and INFN of Torino

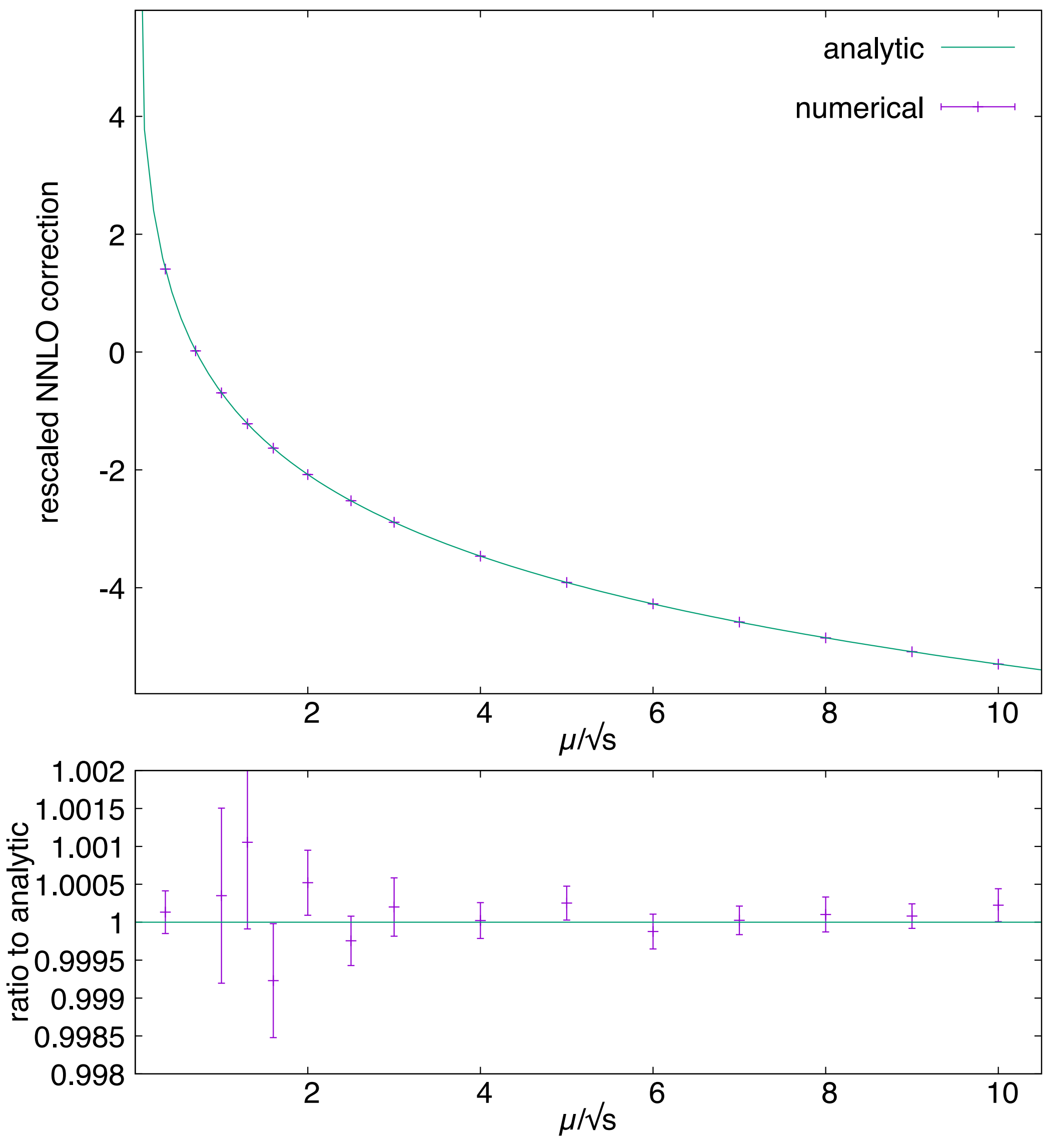
in collaboration with:
L. Magnea, E. Maina, C. Signorile-Signorile, P. Torrielli and S. Uccirati

based on [Magnea et al., arXiv:1806.09570, arXiv:1809.05444]

Proof-of-concept

$T_R\, C_F$ contributions to $e^+e^- \to jj$ @ NNLO





Inclusive cross-section (NNLO correction) obtained via numerical implementation of the subtraction scheme, compared with the analytic result,

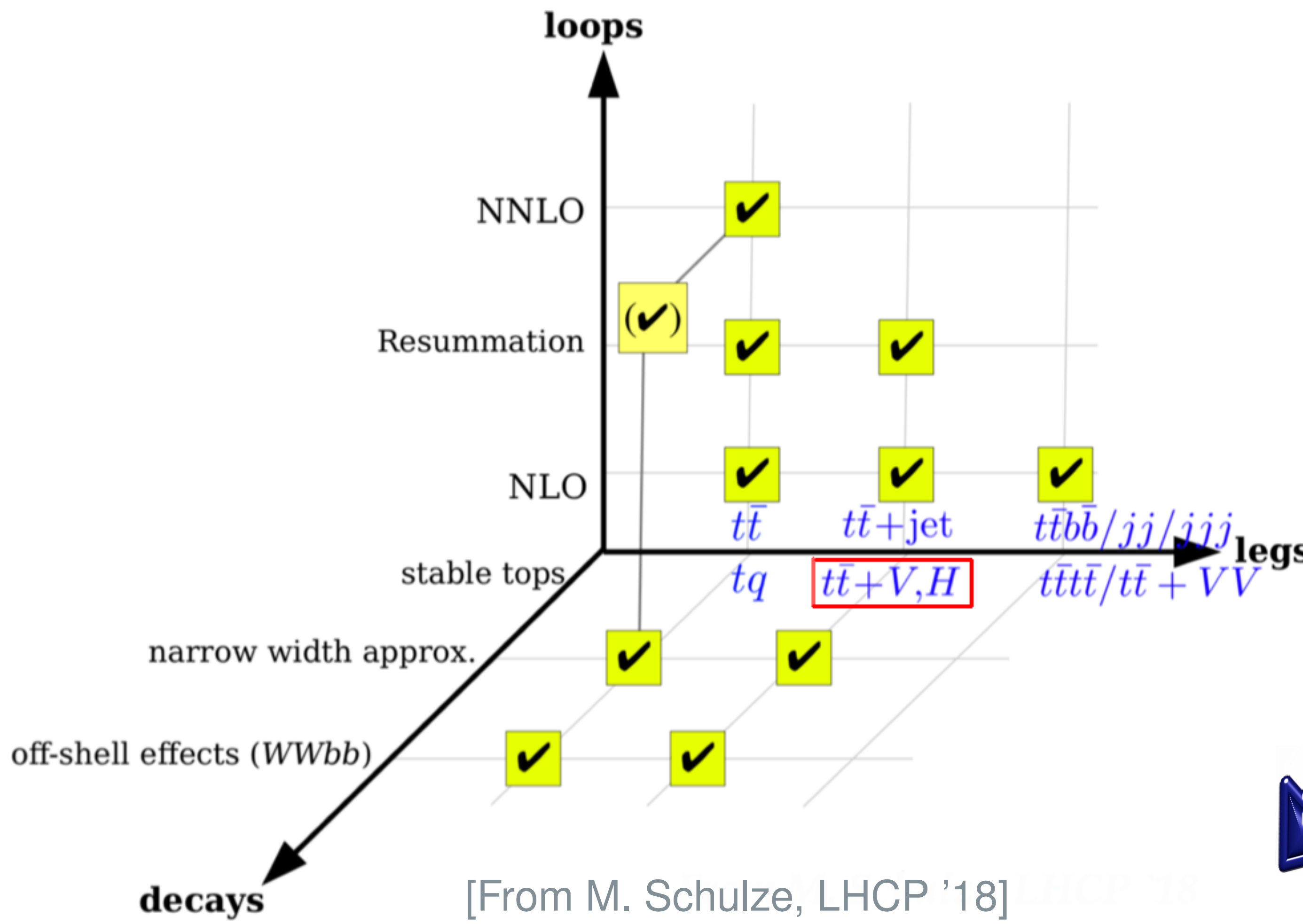
$$\frac{\sigma_{\rm NNLO}}{\sigma_{\rm LO}\left(\frac{\alpha_s}{2\pi}\right)^2 T_R\, C_F} = \left(-\frac{11}{2} + 4\,\zeta_3 - \log\frac{\mu^2}{s}\right)$$

with the renormalization-scale dependence.

Very good agreement ($\lesssim 0.1\%$ differences).

G. Pelliccioli's talk

Towards higher precision



[From M. Schulze, LHCP '18]

improving accuracy

improving final state shaping

At present, the best theoretical accuracy available for offshell $t\bar{t}\gamma$ production is NLO QCD. NNLO is out of reach.

$\hookrightarrow$ Concentrate on observables which can help reducing the theoretical uncertainties: cross section ratios

The cross section ratio

G. Bevilacqua's talk

Instead of considering the *absolute* "$t\bar{t}\gamma$" cross section, normalize to "$t\bar{t}$":

$$\mathcal{R} = \frac{\sigma(pp \to b\bar{b}WW\gamma)}{\sigma(pp \to b\bar{b}WW)}$$

$[p_T(\gamma) > 25$ GeV$]$

Advantages:

- Experiment $\to$ more accurate measurement

  $\hookrightarrow$ common systematics cancel in $\mathcal{R}$
  (e.g. b-tagging efficiency, luminosity ...)

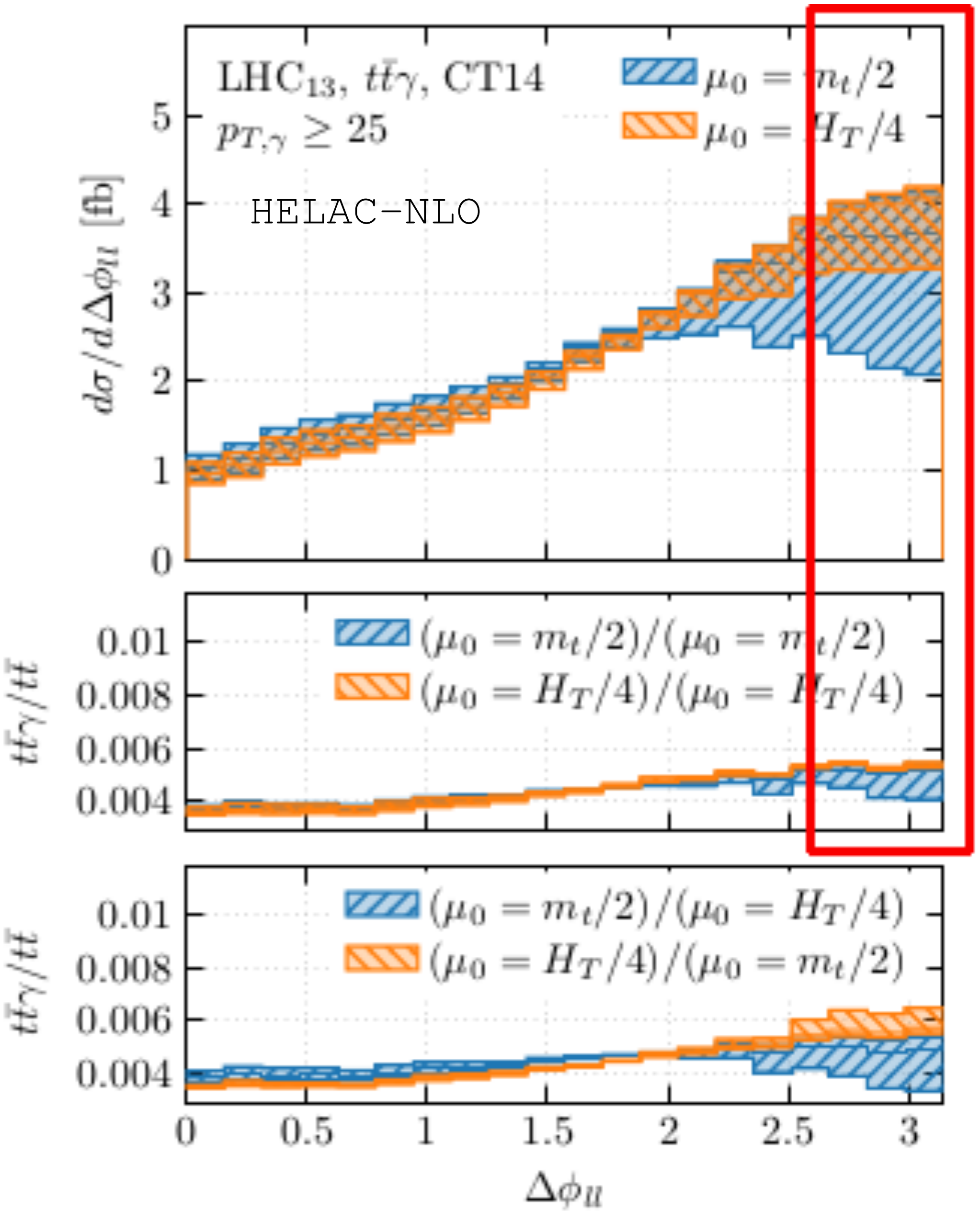
- Theory $\to$ more accurate prediction (?)

  $\hookrightarrow$ theory uncertainties on $\mathcal{R}$ (dominated by scale variation) can be dramatically reduced *if* the two processes are *correlated*

  Melnikov, Scharf, Schulze '11; Mangano, Rojo '12; G.B, Worek '14; Schulze, Soreq '16 ...

How strongly correlated are $t\bar{t}\gamma$ and $t\bar{t}$ production ?

Differential cross section ratios



$\longrightarrow$ absolute $t\bar{t}\gamma$ prediction

$\longrightarrow$ correlated $t\bar{t}\gamma/t\bar{t}$ ratio

$\longrightarrow$ uncorrelated $t\bar{t}\gamma/t\bar{t}$ ratio (example)

Correlation reduces uncertainty bands

$\Delta\phi_{ll} \approx 3$: $\underbrace{\mathcal{O}(50\%)}_{abs(m_t/2)} \rightarrow \underbrace{\mathcal{O}(20\%)}_{abs(H_T/4)} \Leftrightarrow \underbrace{\mathcal{O}(30\%)}_{rat(m_t/2)} \rightarrow \underbrace{\mathcal{O}(3\%)}_{rat(H_T/4)}$

An Introduction to HEJ

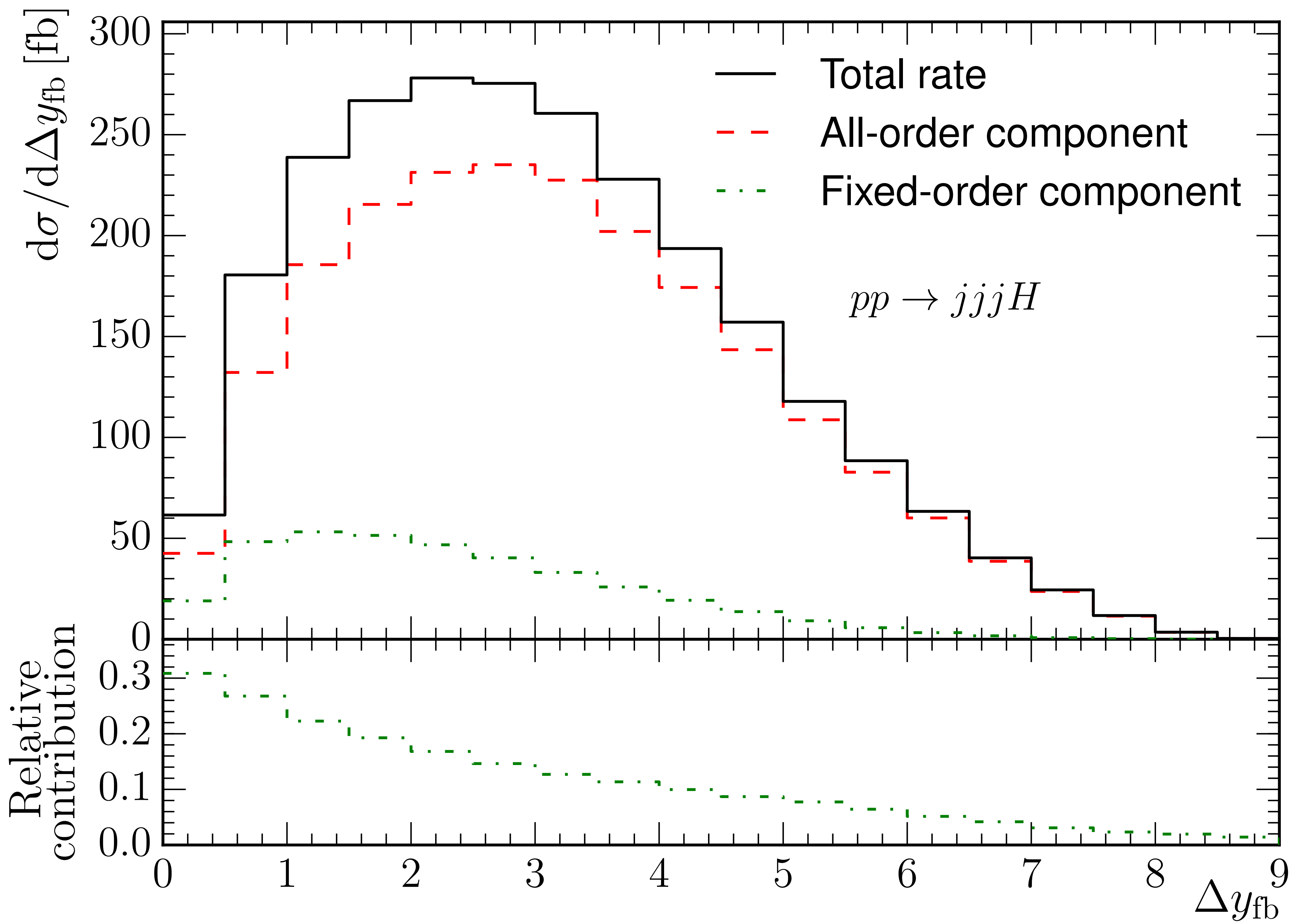
J. Black's talk

High Energy Jets

- A Partonic Monte Carlo Generator which aims to describe **high multiplicity events**.
- Provides perturbative predictions at LL accuracy ($\log(\hat{s}/|\hat{t}|)$) with **resummation of hard corrections to all orders**.
- Hard corrections are α_s suppressed but phase space enhanced in the **large invariant mass limit**.

Motivation: H+Jets FKL Only

J. Black's talk



Resumed

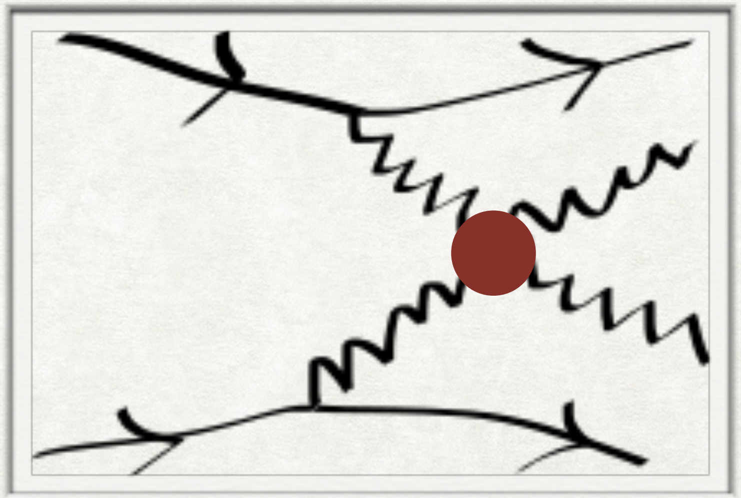
- FKL

Processes at FO

- Unordered
- Extremal $q\bar{q}$
- Other

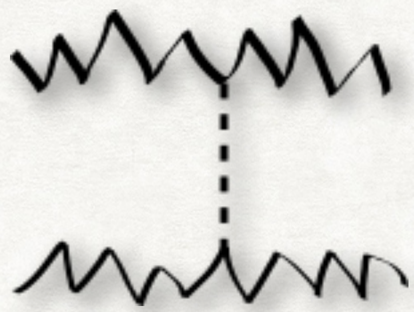
VECTOR BOSON SCATTERING

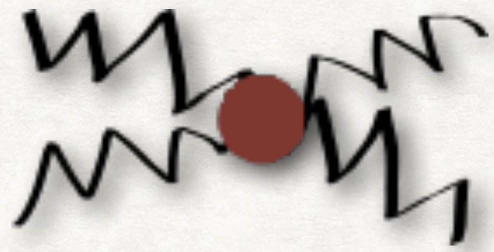
- Family of processes of the type: $q_1\,\bar{q}_2 \rightarrow V\,V\,q_3\,\bar{q}_4$
    - Fundamental for tests of the EWSB mechanism
    - Only way to access Quartic Gauge Couplings (QGC) at LHC



INGREDIENT 2: SMEFT

- Effective field theory: Decoupling heavy states from the *light* energy regime





$$\sim \frac{1}{p^2+M^2} \quad \rightarrow \quad M^2 \gg p^2 \quad \rightarrow \quad \frac{1}{M^2}\left(1-\frac{p}{M^2}+\frac{1}{2}\left(\frac{p}{M^2}\right)^2+\ldots\right)$$

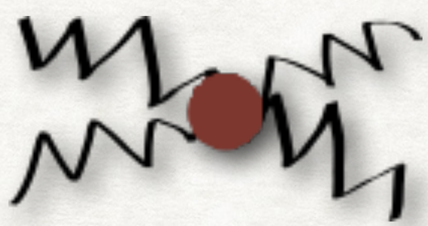
- Assuming linear representation for the Higgs, no new light particles, and SM symmetries:
  - $\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$
  - The most general basis in dim-6 has 2499 Operators, 59 if we assume some flavour symmetries: Here we will use the so-called Warsaw Basis

Compatible with NLO corrections!
(unlike kappa/anomalous approach)

R. Gomez Ambrosio's talk

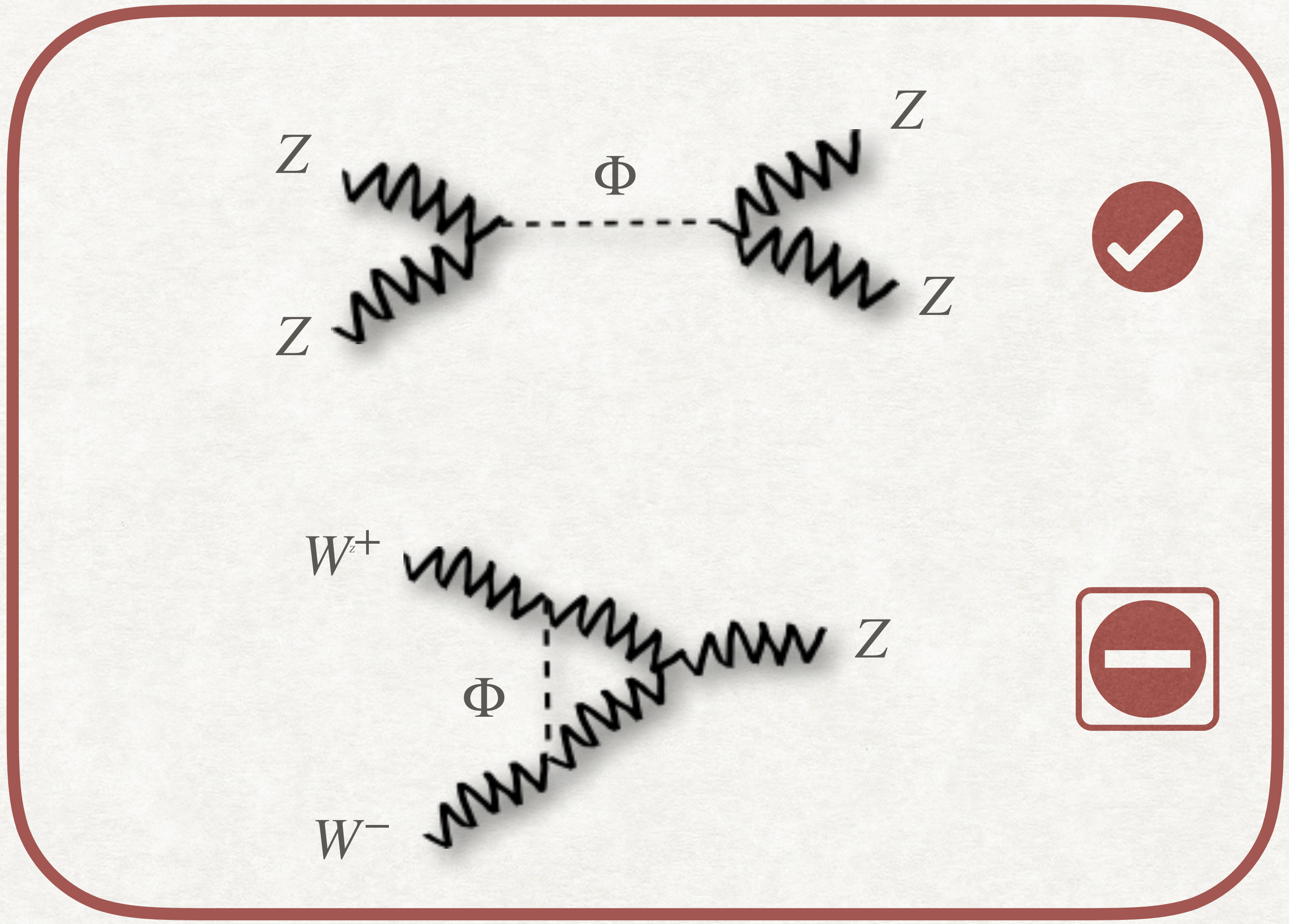
TRADITIONAL VBS INTERPRETATION: DIM 8

- One has to think which UV completion is compatible with this behaviour: only generating QGC and not TGC, predicting ZZZZ interactions....



$Z_\mu Z_\nu Z_\rho Z_\sigma$

If we assume the Higgs is a Doublet in a linear representation, we are implicitly assuming EWSB, where TGC and QGC are generated simultaneously



Possible UV completion..
not very model independent

Summary and Outlook

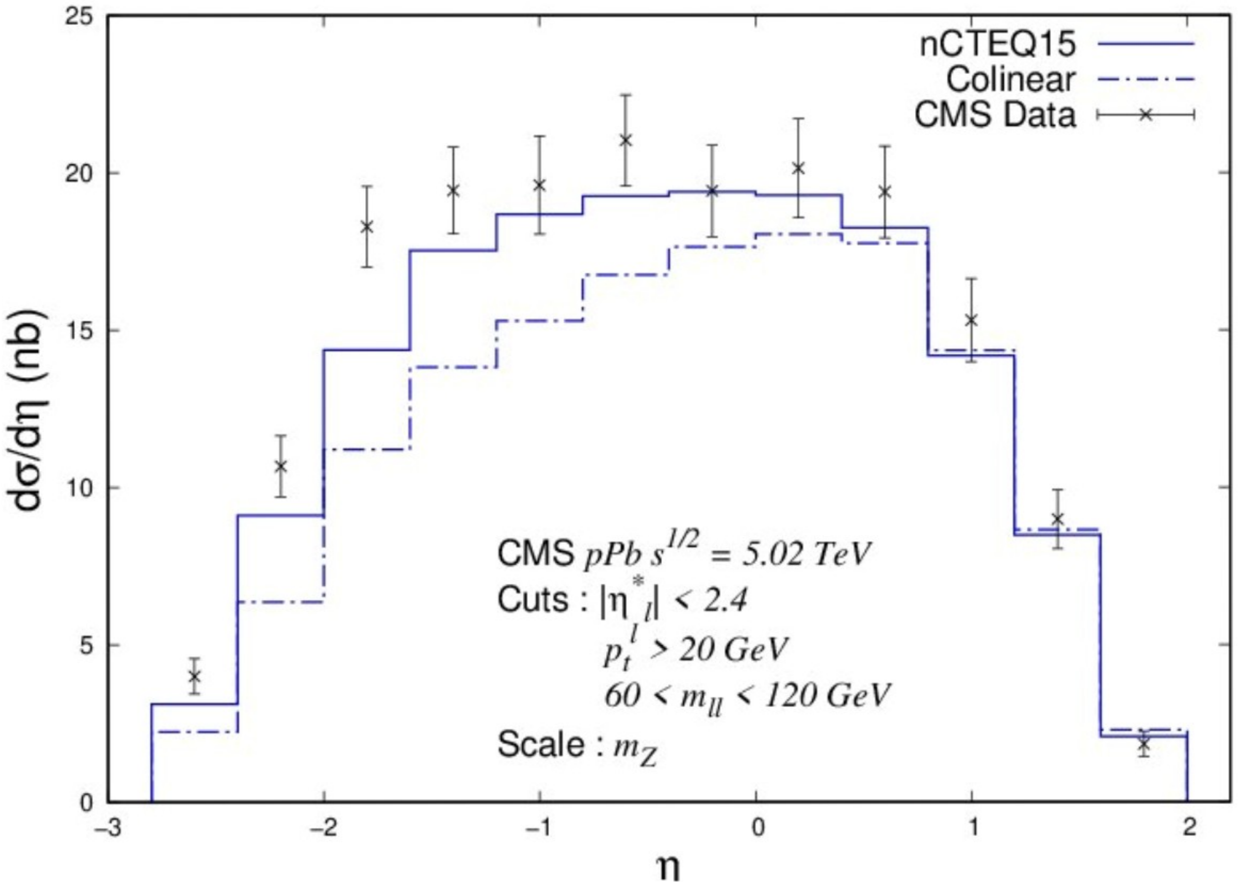
A. Kusina's talk

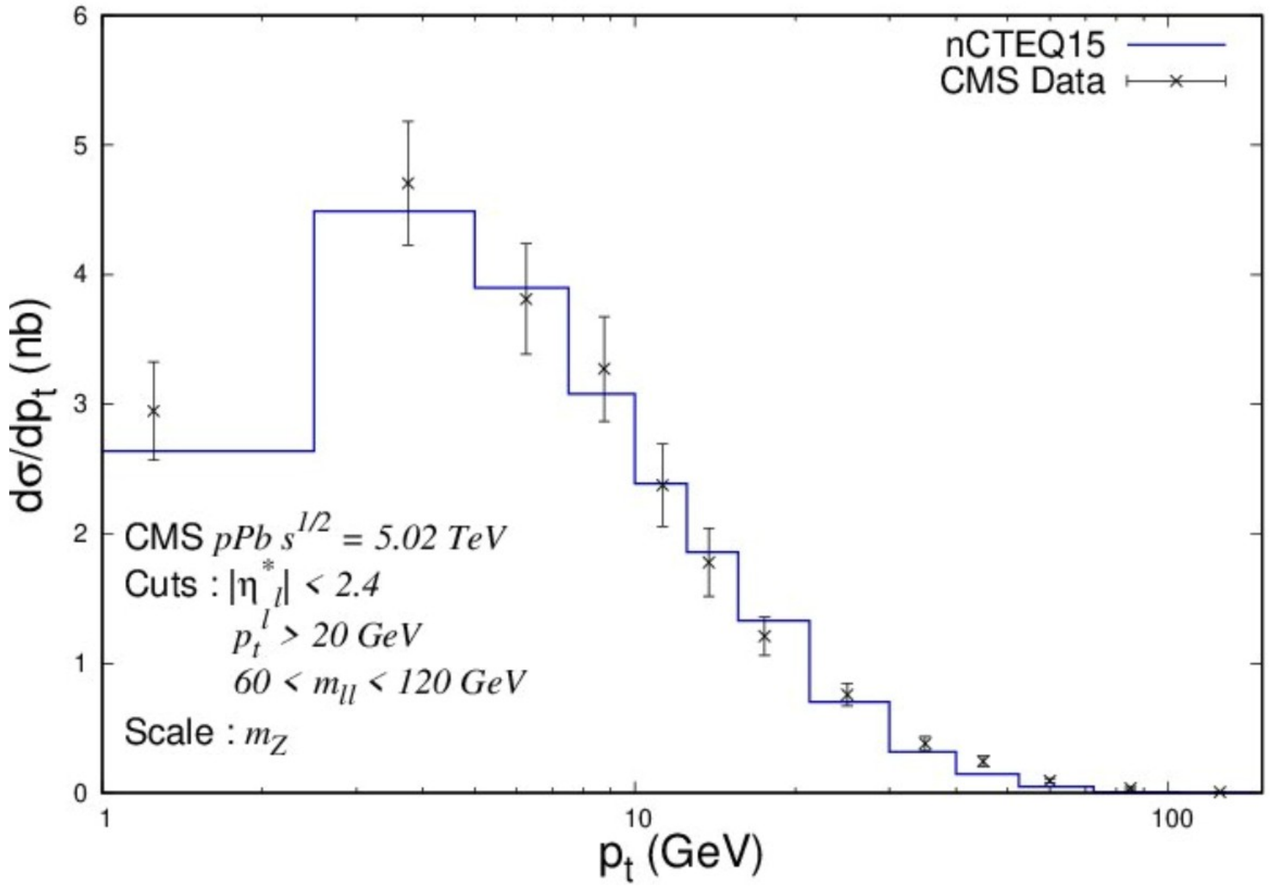
- We successfully extended method of Curci, Furmanski and Petronzio to the TMD case using gauge invariant vertices.
  - The essential subtleties which prevent the Catani-Hautmann generalisation from being directly extended to the P_{gg} case were uncovered and worked out.
- With the new projectors we have reproduced our earlier results for real emission $k_\perp$-dependent P_{qq}, P_{gq} and P_{qg} splitting functions confirming our formalism.
- We used the formalism to calculate P_{gg} TMD splitting function which feature correct
  - collinear limit (DGLAP kernels)
  - high-energy limit (BFKL kernel)
  - soft limit (CCFM kernel)
- We are in the process of calculating the virtual corrections.
- The next step will be to construct a complete set of evolution equations.

TMD vs. collinear

$$p + Pb \to Z^* \to \mu^+ + \mu^-$$

preliminary results





Calculated using KaTie i.e. TMD by Monte Carlo by A. van Hameren

K. Krzysztof's talk

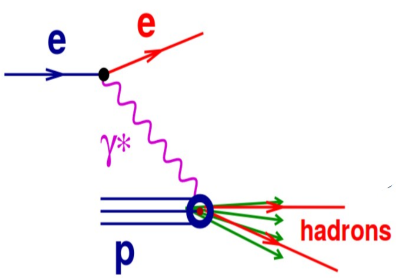
Experimental results

Iris Abt

Azimuthal particle correlations in DIS with ZEUS

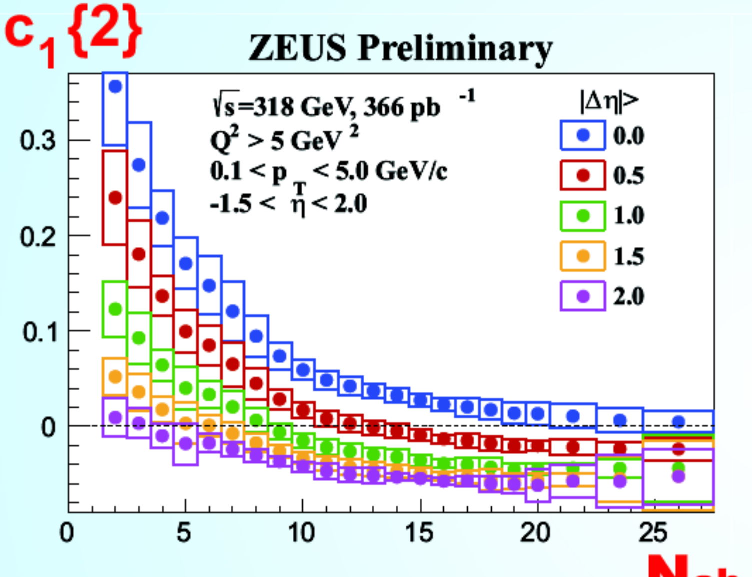
Correlations for charged hadrons as a function of multiplicity, rapidity separation and $\langle p_T \rangle$

- Study of collective particle production in small collision systems
- Limits on possible collective effects in high-multiplicity ep collisions



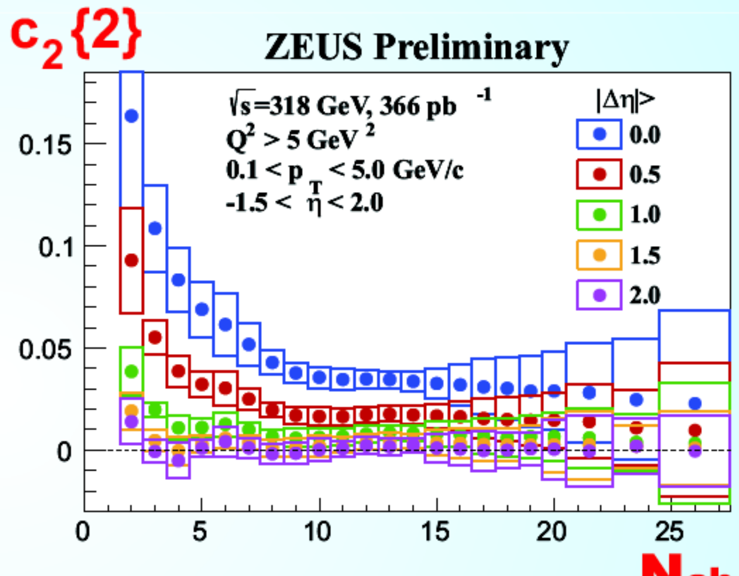
$$c_n\{2\} = \langle\langle \cos(n(\varphi_\alpha - \varphi_\beta))\rangle\rangle$$

The inner brackets denote the average in a single event.
The outer brackets the average over all events.



| Δη >2 | ==>

sign change reflects momentum conservation



| Δη >2 | ==>

consistent with zero

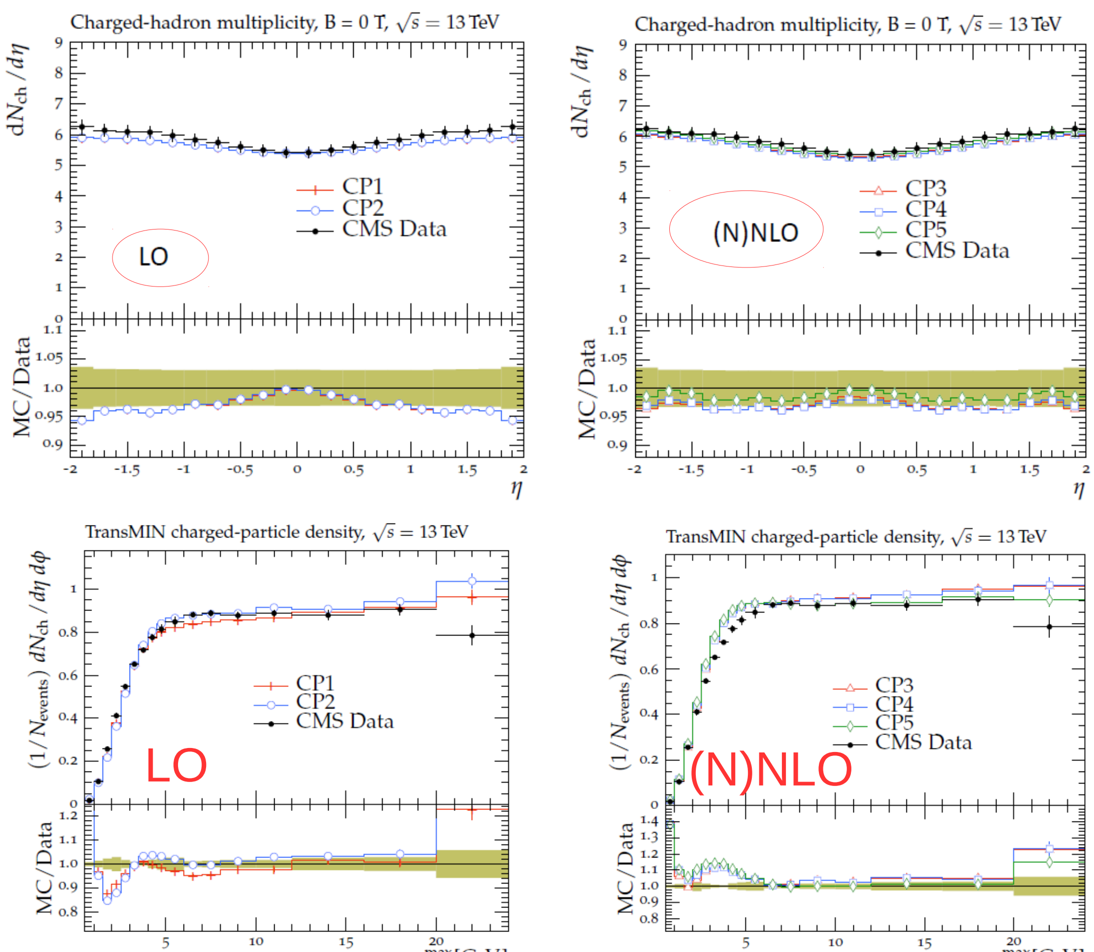
No long range correlations for any multiplicity observed

QCD Monte Carlo model tuning studies in CMS

Why do we tune?

- Good physics predictions: Correct evaluation of physics effects
- Correct description of the data: Pile-up simulation, detector effects and unfolding, estimation of the background in the MC-driven approach

- Using the same PDF set and $\alpha_s(M_Z)$ value in the ME and in the simulation of the PS components in matched configurations advocated Cooper et al. EPJC72 (2012) 2078
  - i.e. If ME is at NLO, then use $N^{\geq 1}LO$ PDF in ME and PS.



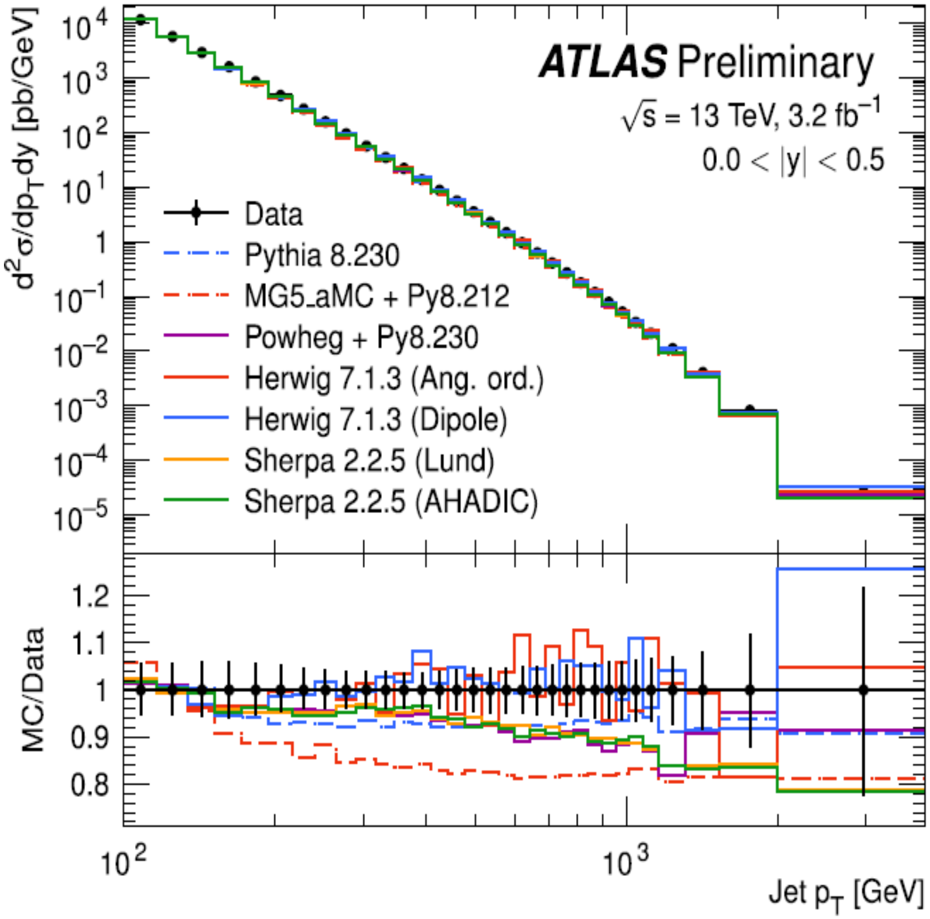
arXiv:1903.12179

- New CMS Tunes for Pythia8 using LO PDF and (N)NLO PDFs

The tunes are able to describe UE and MB observables with NNLO PDF sets as well as LO PDF set

Evelin Meoni

Inclusive jets:

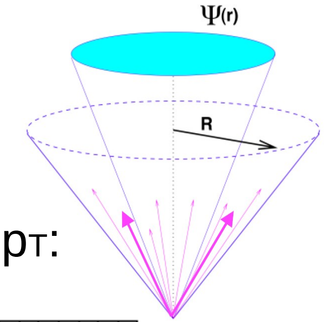


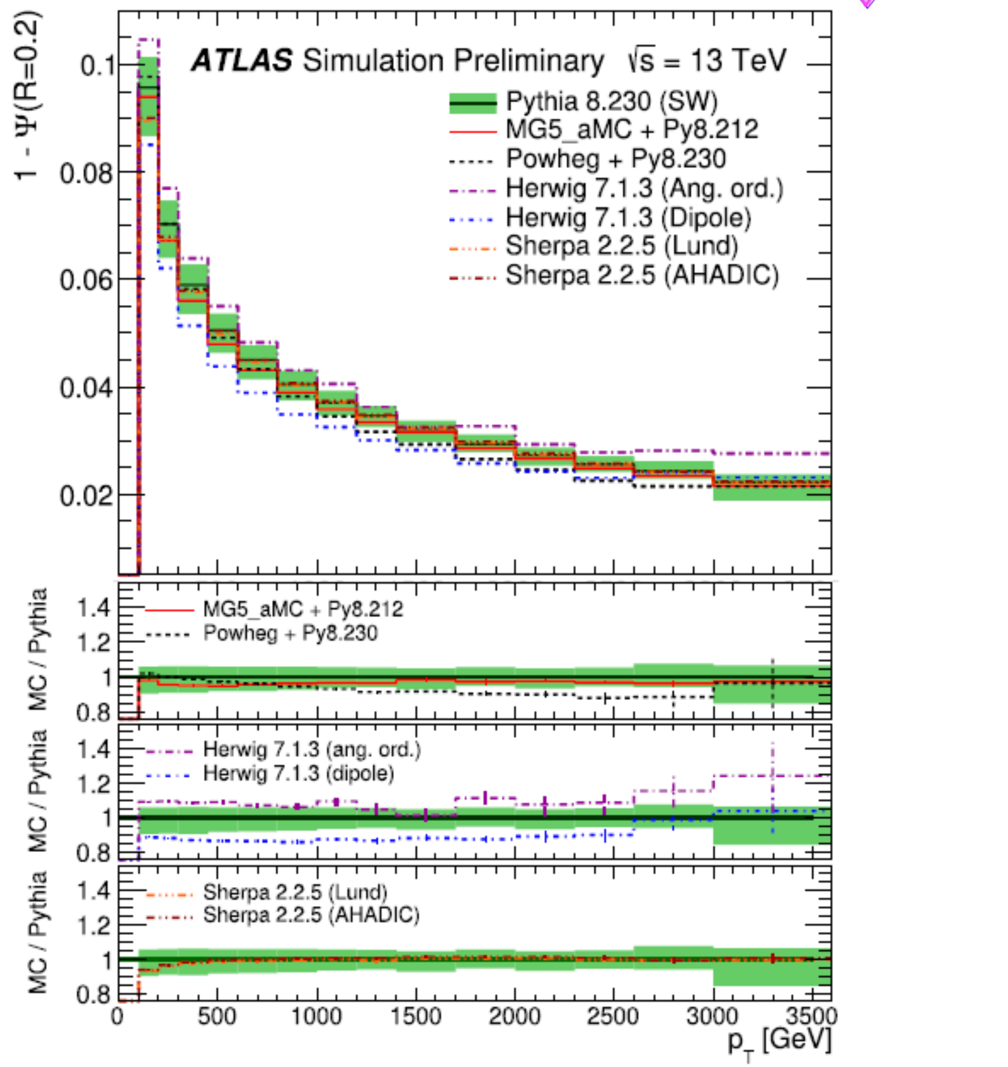
Explored impact of different aspects:

- QCD orders of ME (LO vs NLO)
  → **Hard to make a strong conclusion**
- PS: pT ordered, angular ordered, dipole PS
  → **small effect**
- Factorisation and hadronisation (Lund vs cluster)
  → **small effect**

Jet Shape:

Fraction of the jet p_T outside a cone of 0.2 as a function of the jet p_T:



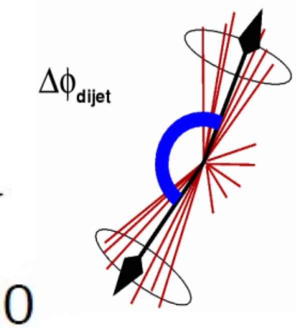


Large sensitivity to the PS models

Radek Zlebcik

Dijet azimuthal correlations

- Sensitive to the QCD resummation effects ($\Delta\varphi \sim \pi$) as well as to higher orders and multi-leg ME (lower $\Delta\varphi$)
- Possibility to study the strong coupling constant

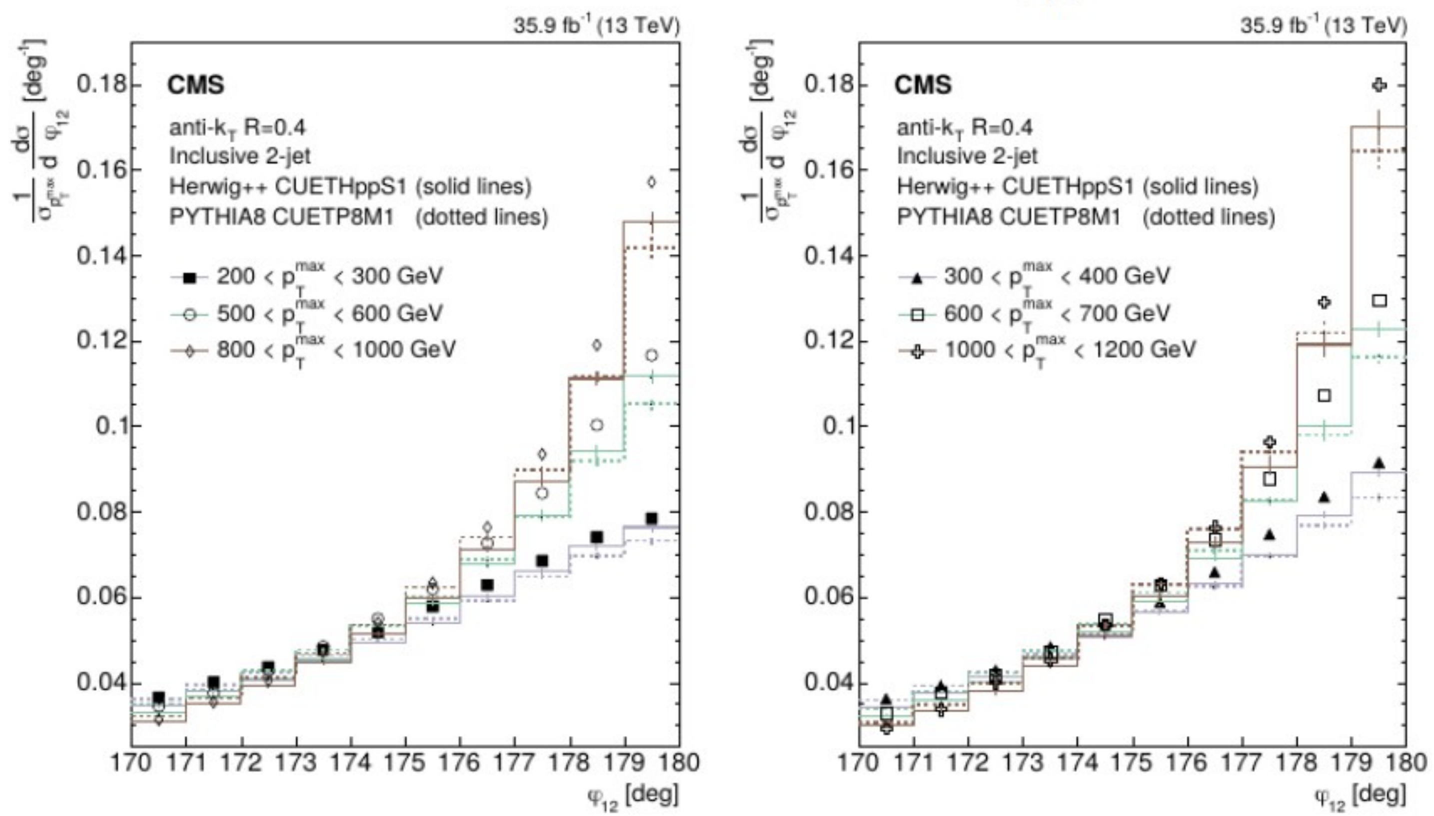


Azimuthal correlations in back-to-back region (>=2 jets vs LO)

$p_T^{jet} > 100\,\mathrm{GeV}$

$170° < \Phi_{1,2} < 180$

- The normalized spectra for various p_T ranges differ mostly in the back-to-back region
- Higher p_T enhances $\Phi_{1,2} \sim \pi$
- This has never been investigated before



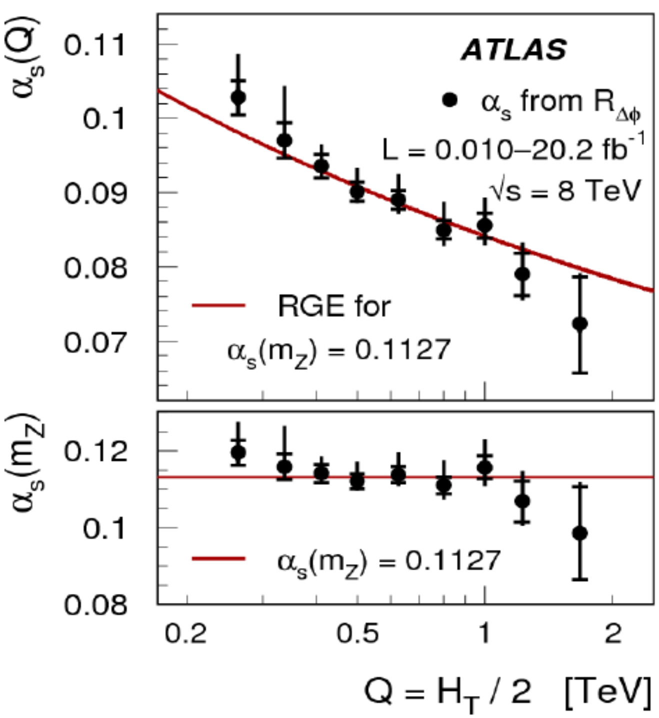
Zdenek Hubacek

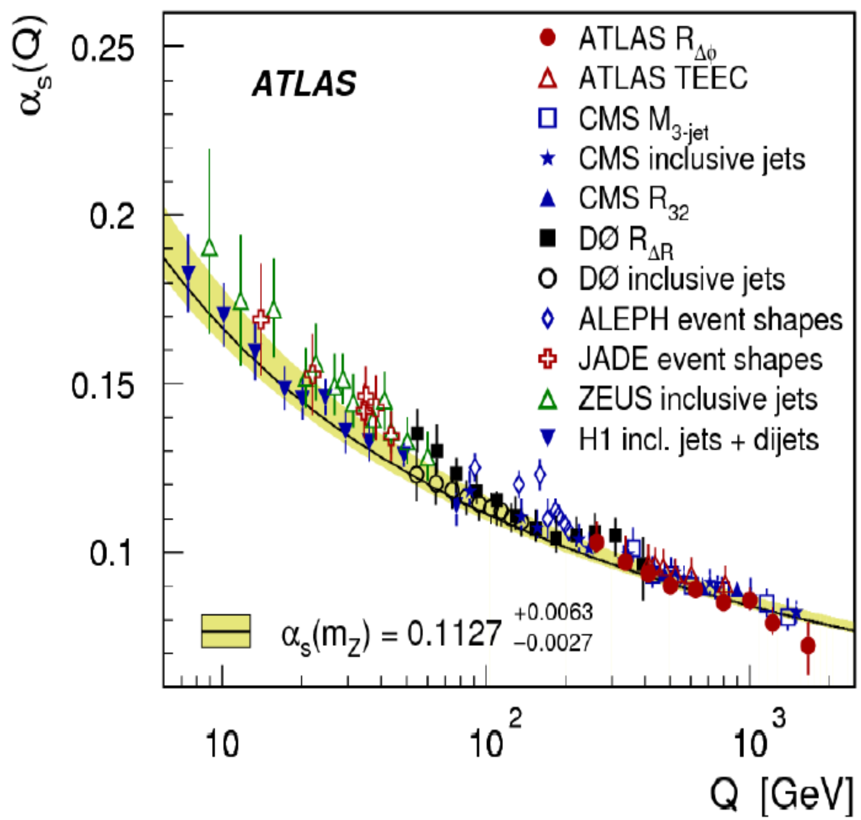
Strong coupling contrant extraction

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max}) = \frac{\dfrac{d^2\sigma_{dijet}(\Delta\phi_{dijet} < \Delta\phi_{max})}{dH_T\, dy^*}}{\dfrac{d^2\sigma\, dijet(inclusive)}{dH_T\, dy^*}}$$

Fraction of dijet events where the azimuthal difference between two leading jets is smaller than some $\Delta\Phi_{max}$ value w.r.t. to the inclusive dijet cross section

- 9 intervals selected for $\alpha_S(Q)$ with $Q = H_T/2$ extraction over the range $262 < Q < 1675$ GeV
- Combined analysis results in $\alpha_S(m_Z) = 0.1127^{+0.0063}_{-0.0027}$ dominated by the scale dependence of the NLO pQCD predictions





Toward W mass with LHCb

Precision electroweak tests are a powerful probe of physics beyond the Standard Model

- Mw measurements at the LHC are largely affected by PDF uncertainties
- PDF uncertainties would be partially anticorrelated with those of ATLAS and CMS → **Significant impact of LHCb on the LHC average**

Analysis Strategy:

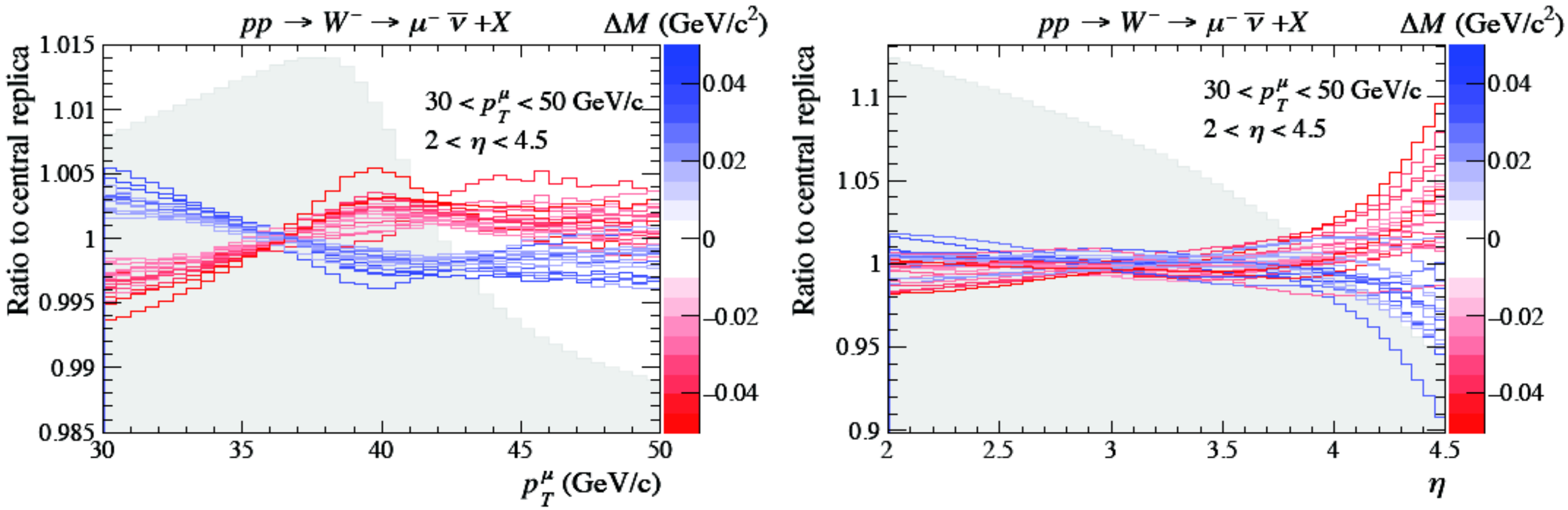
- Monte Carlo sample of $W \to \mu\nu$ decays (Powheg + Pythia)
  - Selected $\mathcal{O}(10^7)$ events in $30 < p_T < 50\,\mathrm{GeV/c}$ and $2 < \eta < 4.5$
- Toy dataset: scaled to LHCb collected luminosity during Run 2 ($6\,\mathrm{fb}^{-1}$)
- Templates: $M_W \times$ PDF hypothesis weights (using NNPDF3.1, 1000 *replicas*)

Template fit to a single toy dataset: for each PDF replica scan over all the Mw hypotheses

Martina Pili

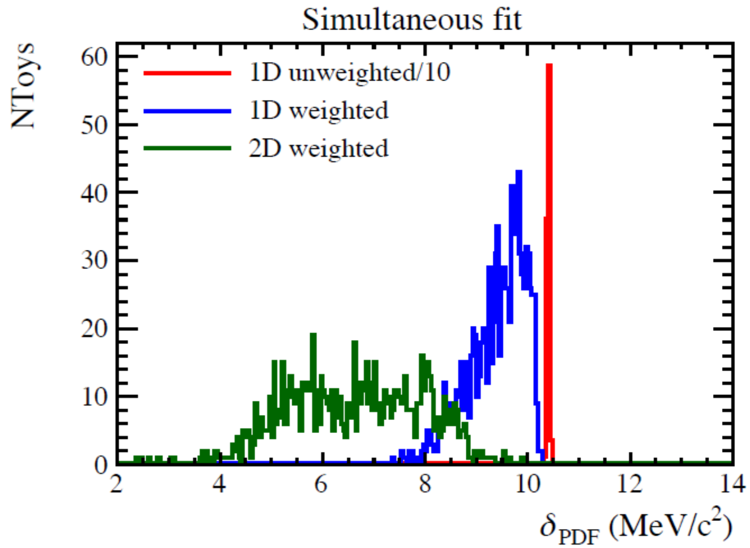
Toward W mass with LHCb

Looking at the distributions of *measurable* quantities: p_T^μ, η



! The replicas with the largest $|\Delta M|$ lead to variations of several percent in the shape of the η distribution

$\Rightarrow$ **2D (p_T^μ, η) fit with PDF replica reweighting**, already suggested by [5]



- Simultaneous fit of the W+ and W− data
- The PDF uncertainties are extracted for multiple toy datasets
- δ_{PDF} is the width of the PDF spread in the M_W values extracted with each replica

2D fit with weighting reduce δ_{PDF} on average by roughly a factor of 2

Effect of flavor-dependent partonic transverse momentum on the determination of the W mass

Marco Radici

- Quark intrinsic transverse momentum can be flavor dependent → additional uncertainty on Mw, not considered so far

- we use a modified version of **DYRes** (Catani, De Florian, Ferrera, Grazzini (2015))
- we implement into the cross section an explicit dependence on quark intrinsic k_T through Transverse Momentum Distributions (TMD)

$$f_1^q(x, k_T; \mu^2) = \frac{1}{2\pi} \int d^2 b_T \, e^{-i b_T \cdot k_T} \, \tilde{f}_1^q(x, b_T; \mu^2)$$

$$\tilde{f}_1^q(x, b_T; \mu^2) = \sum_i \left(\tilde{C}_{q/i} \otimes f_1^i \right)(x, b_*; \mu_b^2) \, e^{\tilde{S}(b_*; \mu_b, \mu)} \, f_{1\mathrm{NP}}^q(x, b_T)$$

$$f_{1\mathrm{NP}}^q(x, b_T) \approx f_{1\mathrm{NP}}^q(b_T) \propto e^{-\overbrace{\left[g_{evo} \log(Q^2/Q_0^2) + g_q\right]}^{g_{NP}^q} b_T^2}$$

flavor-independent (gluon radiation): $g_{evo} \log(Q^2/Q_0^2)$

flavor-dependent: g_q

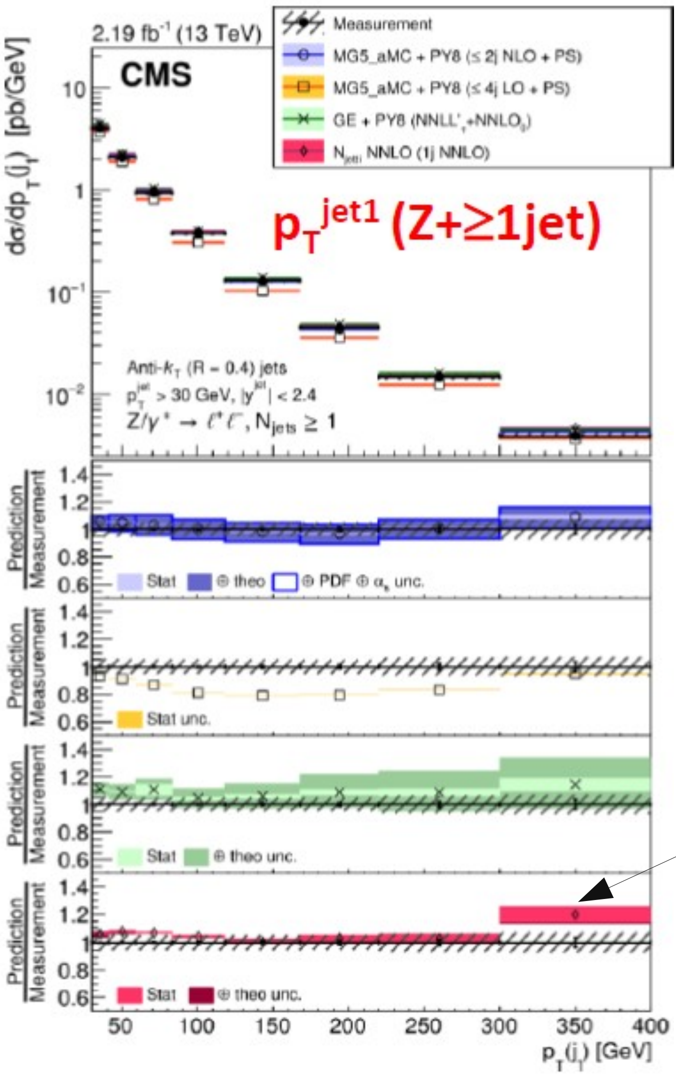
$-15 \leq \Delta m_{W^+} \leq 9$ MeV

$-10 \leq \Delta m_{W^-} \leq 10$ MeV

Evelin Meoni
M. Isabel Josa

V+jets

- Possibility to study correlations between colorless W/Z and colored object (jet)



NNLO

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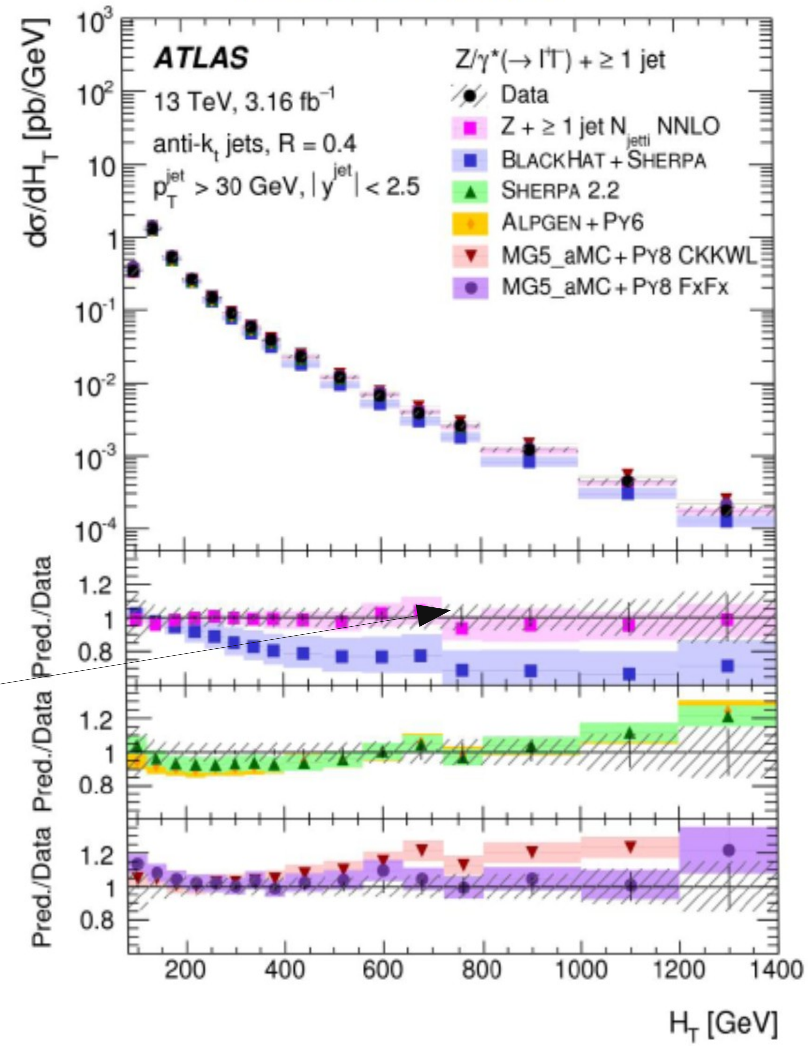


- NNLO (Njetti) ME models are available with significantly reduced theory uncertainties
  → current precision of the measurement do not allow to conclude on gain in using NNLO vs multipaton NLO ME calculations

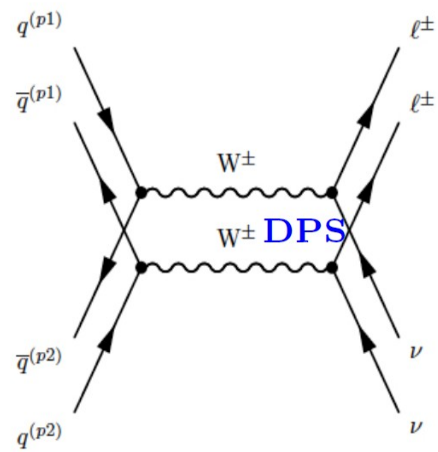
Ankita Mehta

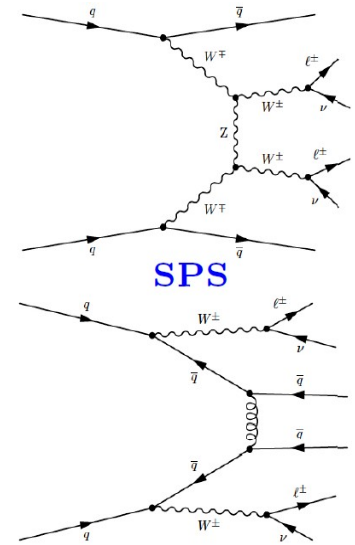
DPS is SSWW

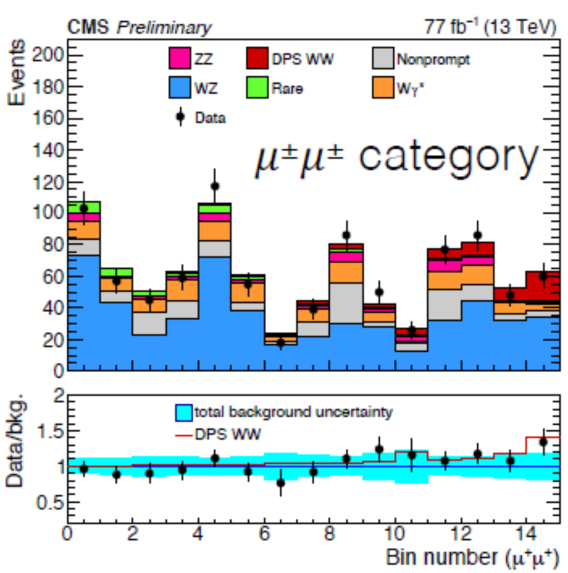
- Provides information about hadron structure in transverse plane
- Understanding of background contributions to interesting SM & BSM processes

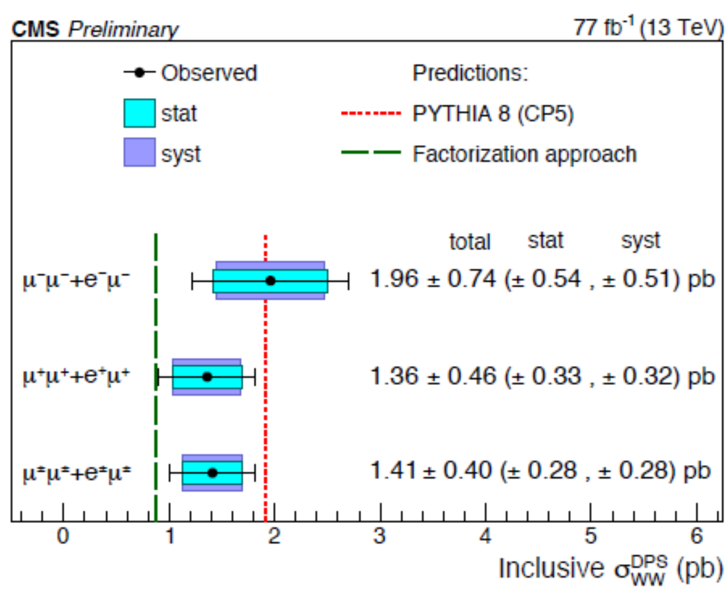
First evidence for WW production from double-parton scattering (DPS) from CMS

- Signal: two same-sign leptons (dimuon or electron-muon pairs)
- Main backgrounds from WZ and samples with non-prompt leptons
- Signal & background discrimination based on BDT classifiers; trained separately against dominant backgrounds









- first evidence of the DPS WW process, with 3.9 s.d.

$\sigma_{DPS\ WW}=1.41\pm0.28\ (stat)\pm0.28 (syst)$ pb

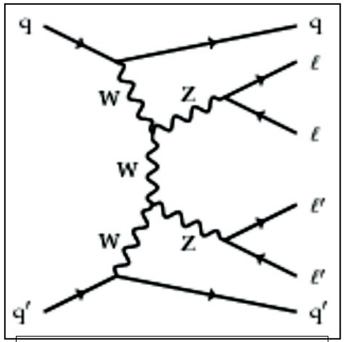
$\sigma_{eff}=12.7^{+5}_{-2.9}$ mb

Pietro Govoni

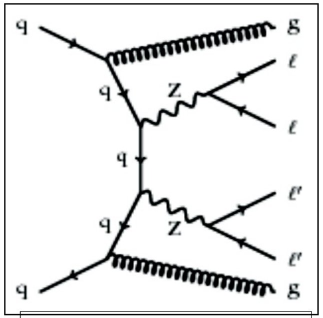
VBS: ZZ

Vector Boson Scattering (VBS): Two forward jets separated in rapidity, with low hadronic activity in between

- Probes electroweak symmetry breaking
- BSM searches with VBS

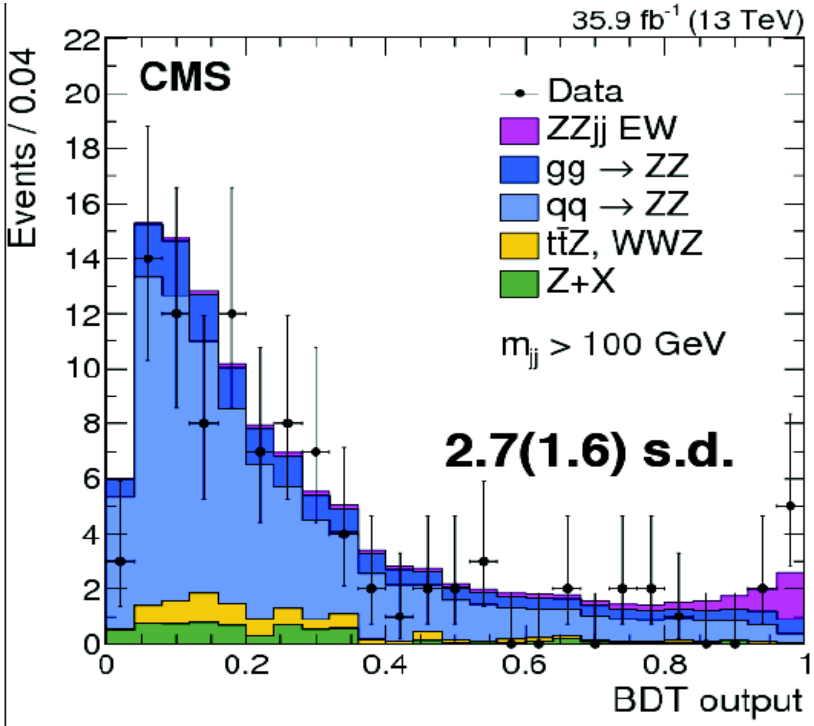


signal example



irreducible background

- four charged leptons (e± or μ±) in the final state
- train BDT with 7 variables for EW vs. QCD discrimination



$$-0.46 < f_{T0}/\Lambda^4 < 0.44$$
$$-0.61 < f_{T1}/\Lambda^4 < 0.61$$
$$-1.2 < f_{T2}/\Lambda^4 < 1.2$$
$$-0.84 < f_{T8}/\Lambda^4 < 0.84$$
$$-1.8 < f_{T9}/\Lambda^4 < 1.8 \ .$$

the **most stringent limits** on the T0, T1, T2, T8, and T9 anomalous quartic gauge couplings to date

$$\sigma^{EW}_{(fid)} = 0.40^{+0.21}_{-0.16}(\mathrm{stat})\ ^{+0.13}_{-0.09}(\mathrm{syst})\ \mathrm{fb}$$

Andrea Sciandra

Triboson production

VVV production is a rare process, sensitive to new physics

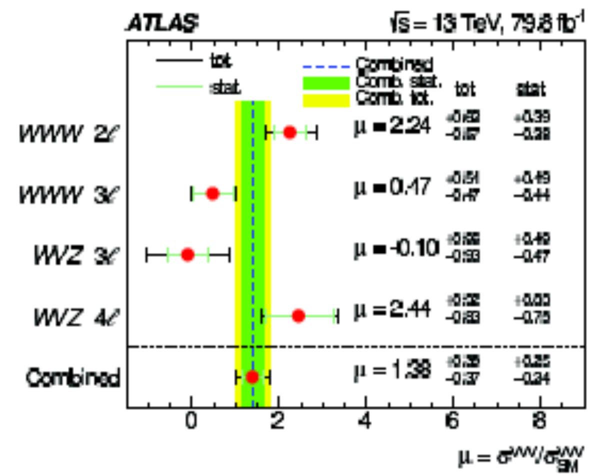
First evidence of VVV by ATLAS with 80 fb^{-1}

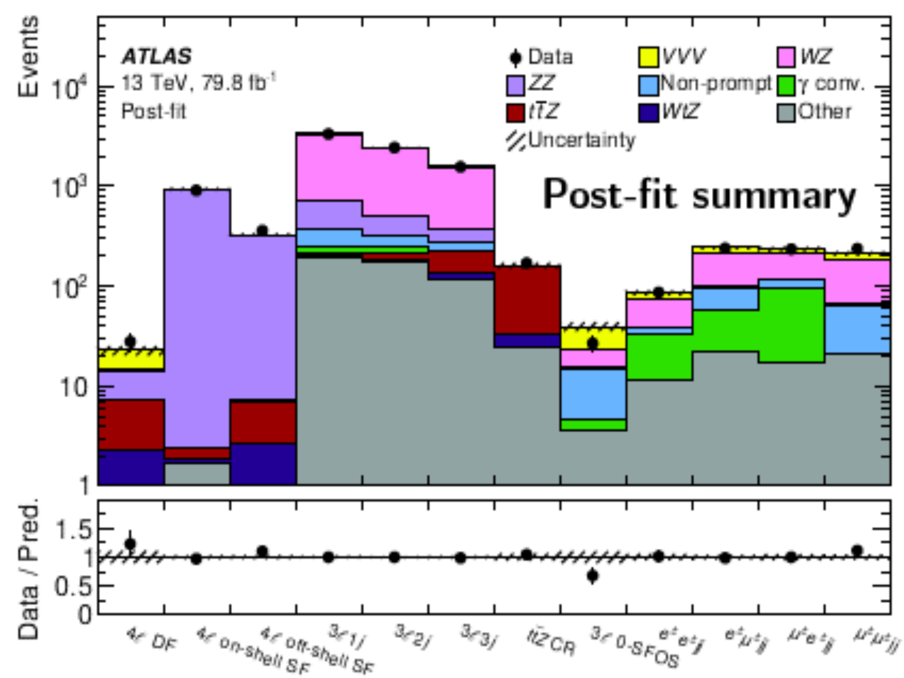
WWW/WZZ/WWZ (ATLAS): same-sign 2ℓ with at least 2 jets or 3ℓ (WWW), or 3ℓ, 4ℓ (WZZ/WWZ).

WWW – cut-based, WVZ – MVA-based

- Expected: $\mu_{VVV}^{\text{Asimov}} = 1^{+0.36}_{-0.34} = 1^{+0.24}_{-0.24}\,(\text{stat.})\ ^{+0.27}_{-0.24}\,(\text{syst.})$
- Observed: $\mu_{VVV}^{\text{Data}} = 1.38^{+0.39}_{-0.37} = 1.38^{+0.25}_{-0.24}\,(\text{stat.})\ ^{+0.30}_{-0.27}\,(\text{syst.})$
- Exclusion of background-only hypothesis: **evidence**
  - VVV (expected and observed)
  - $WWW \to 2\ell$ and $WVZ \to 4\ell$ (observed)

Decay channel	Significance Observed	Significance Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ





Outlook

- Without precision there will be no certainty on discovery
- In the quest of precision the experiments are continuously improving and the full LHC Run2 statistics is yet to be analysed
- Systematics will be soon the dominant one for many processes
- From the theoretical point of view, for a correct interpretation of current and future measurements and the possible identification of BSM effects, precise predictions and therefore radiative corrections are paramount
- Many new precise calculations were presented and discussed in our session
- Interesting analyses stepping out from the standard ones and exploring the challenging phase space were presented, where new things can be tested (for ex. TMD approach)