Transverse Momentum Resummed Calculations in `reSolve` and Z' searches

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Work done in collaboration with F. Coradeschi, C. Voisey, E. Accomando, J. Fiaschi, F. Hautmann, S. Moretti, C. Shepherd-Themistocleous.

Resummation, Evolution, Factorization: Edinburgh 2020

Outline

Work based on our paper and references therein: "Production of Z’-boson resonances with large width at the LHC", Physics Letters B 803 (2020) 135293, arXiv:1910.13759.

Introduction

- Increasing amounts of data coming out of the LHC, with greater precision and more differential.
- Necessitates precise theoretical predictions, including transverse momentum (q_T) resummed calculations.
- This is particularly true for standard canonical channels, e.g. DY.
- E.g. Precision measurements of W mass rely on precise predictions of q_T spectrum for Z and W.
- Many recent developments in making such theoretical predictions and proliferation of codes able to produce such q_T resummed predictions at the LHC via many different approaches:
  - Standard (CSS) q_T resummation
  - Parton Branching
  - TMDs
  - SCET

  Currently being benchmarked for DY (see Daniel's talk).
- These codes calculate the q_T resummed spectra for DY up to NNLO+NNLL'/N3LL.

reSolve - q_T resummation code

- reSolve is a Monte Carlo program set up to calculate the resummed component of the cross-section (i.e. low q_T part) for any generic process with a colourless final state F.*
- So far it has been explicitly set-up and tested for Diphoton, Drell-Yan and Z' final states.
- Uses CSS/CFG q_T resummation formalism. Catani et. al, 1311.1654
- Performs the resummation in b-space and Mellin space, calculates spectra up to NNLL'.
- Matching to finite component being developed now - soon ready for NLO, NNLO ongoing development. Can be provided externally.
- Involved in benchmarking effort for DY at the LHC in EW working group. See my talk at https://indico.cern.ch/event/941711/timetable/?print=1

*Manual and paper available at CPC Vol. 238 pgs 262-294 and at arXiv:hep-ph/1711.02083. F. Coradeschi and T.C., Nov '17

Setup in CSS q_T resummation

Collins, Soper, Sterman, '85
Catani, de Florian, Grazzini, '01
Bozzi, Catani, de Florian, Grazzini, '05
....

$$\frac{d\sigma^F_{res}(p_1,p_2,Q^2,\mathbf{q}_T,y,\mathbf{\Omega})}{dQ^2 d^2\mathbf{q}_T dy d\mathbf{\Omega}} = \int \frac{d^2 b}{(2\pi)^2} \int_{x_1}^1 \frac{dz_1}{z_1} \int_{x_2}^1 \frac{dz_2}{z_2} W^F(\mathbf{b}, z_1, z_2, \ldots)$$

$$\equiv \frac{Q^2}{s} \left[d\hat{\sigma}^{F,\,\mathrm{LO}}_{c\bar{c}} \right] \int \frac{d^2 b}{(2\pi)^2} e^{i\mathbf{b}\cdot\mathbf{q}_T} \underbrace{S_c(Q^2, b_0^2/b^2)}_{Sudakov}$$

$$\times \int_{x_1}^1 \frac{dz_1}{z_1} \int_{x_2}^1 \frac{dz_2}{z_2} \overbrace{H^F}^{\text{Hard Factor}} \underbrace{C_1 C_2}_{\text{Collinear Factors}} f_{a_1/h_1}(x_1/z_1, b_0^2/b^2) f_{a_2/h_2}(x_2/z_2, b_0^2/b^2) \,.$$

Perturbative Coefficients
- Universal

where

$$S_c(\mu_2^2,\mu_1^2) = \exp\left\{ - \int_{\mu_1^2}^{\mu_2^2} \frac{dq^2}{q^2} \left[A_c(\alpha_s(q^2)) \log \frac{\mu_2^2}{q^2} + B_c(\alpha_s(q^2)) \right] \right\},$$

$$H^F_q = \frac{|\tilde{M}_{q\bar{q}\Rightarrow F}|^2}{|M_{q\bar{q}\Rightarrow F^{(0)}}|^2}. \quad C_{qa}(z,\alpha_s) = \delta_{qa}\delta(1-z) + \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n C^{(n)}_{qa}(z).$$

Beyond Standard Model - Z's

- These resummed calculations are now in widespread use in SM precision calculations.
- However little effort has been made examining their effects on BSM calculations given these tend to require less precision.
- At LHC searching for heavy Z's with $M_{Z'} \sim \mathcal{O}(TeV) \rightarrow$ naturally in the kinematic regime where $q_T/M_{ll} \ll 1$, i.e. where the QCD corrections can be treated by resummation.
- Spectrum peaked strongly at low $q_T \ll M_{ll}$ therefore majority of contribution included in resummed component.
- Use `reSolve` to examine searches for Z's with predictions up to NNLL'.

Z's in phenomenology

- Z's arise in a large variety of theories and models:
  - "Top-down" models based on GUT extended gauge groups (e.g. E_6).
  - "Bottom-up" models add small changes to SM (e.g. LR models).
- From phenomenological perspective we can just parameterise this as an effective description at low energy with an additional Z' at scales above EW scale:

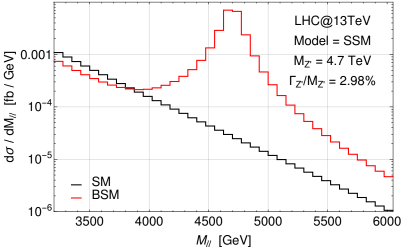
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{Z'}$$

$$\mathcal{L} \supset g' Z'_\mu \bar{\psi} \gamma^\mu (a_V - a_A \gamma_5) \psi$$

- Free parameters are then the Z' mass ($M_{Z'}$), width ($\Gamma_{Z'}$), and fermion couplings (a_V^ψ, a_A^ψ).
- Try to search for/rule out Z's based on mass, width, couplings rather than models.
- Different models will set different relations between these free parameters and can then be interpreted in terms of these searches.

Z' searches

- Experimentally, the typical search for these is to "bump-hunt".
- Search in dilepton invariant mass spectrum:
  - Clean, free of QCD background.
  - Easy to detect.
  - Very precisely measured kinematics.

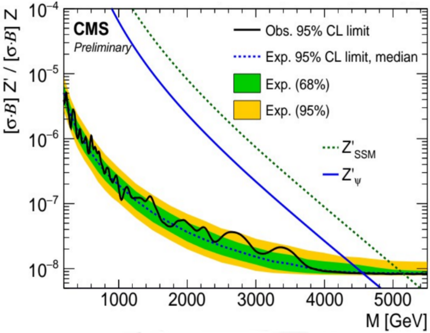


- Largely model-independent, just gives mass and width of Z'
- Doesn't depend on precise details of theoretical predictions/corrections.
- However, assumes narrow BW resonances, $\Gamma/M \lesssim 5\%$
- But many Z' models can have large widths - models with exotic decays, DM portals, non-universal models, ...

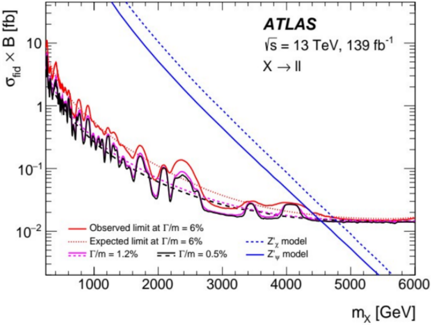
Current Z' limits - LHC

Accomando et al., JHEP, 01 (2016), 127

- Projected approx. sensitivities - Current luminosity 3.5 - 4TeV, Run III (300fb^{-1}) 4 - 5TeV, HL-LHC (3000fb^{-1}) 5 - 6.5TeV.



CMS collaboration, CMS-PAS-EXO-19-019

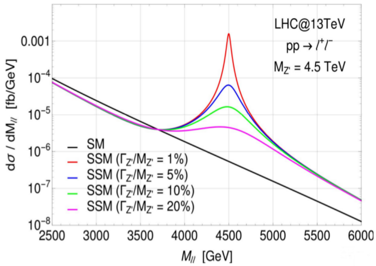


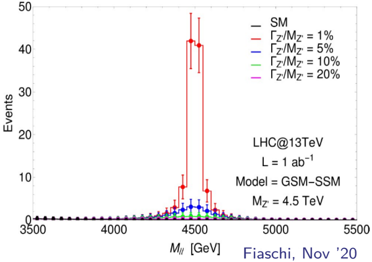
ATLAS collaboration, Phys. Lett. B 796 (2019) 68-87

- 13TeV data with 139 fb^{-1}, Z' excluded up to 4.5 - 5TeV.
- Projected approx. exclusions - Current luminosity 4.5 - 5.5TeV, Run III (300fb^{-1}) 5 - 6TeV, HL-LHC (3000fb^{-1}) 6 - 6.5TeV.

Large width Z's

- Many models have "wide" Z' resonances with $\Gamma_{Z'}/M_{Z'} > 5\%$.
- No longer have clear resonance peak but rather smeared "shoulder" of excess over SM background.
- Instead rely on just counting excess events above SM background.
- Requires precise knowledge and control of SM backgrounds/extrapolations.
- Additional small effects must therefore be considered:
  - Finite Width effects.
  - Interferences with Z's.
  - QCD corrections.





Fiaschi, Nov '20

- Want search strategies for heavy wide Z's robust to these effects.

Resummed calculation in reSolve

- Kinematic regime of such heavy Z' searches is naturally that of resummed part of spectrum, $q_T/M_{ll} \ll 1$.
- reSolve code modified to include Z's on top of SM Drell-Yan, including finite width and interference effects.
- Calculate multi-differential cross-sections $\frac{d\sigma}{dM_{ll}dq_T dy_{ll}d\Omega}$ including resummation up to NNLL'.
- Focus on two exemplar cases in Sequential Standard Model (SSM), both are heavy wide Z's currently not excluded:
  - "SSM-wide" - 10% width, enlarged by extra invisible decay modes.
  - "SSM-enhanced" - 27% width, SM couplings enlarged.

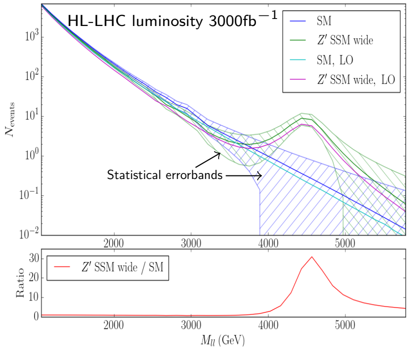
Standard Z couplings

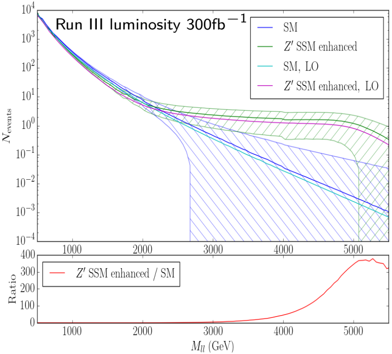
$U(1)'$	$M_{Z'}$(GeV)	$\Gamma_{Z'}/M_{Z'}$	g'	g_V^u	g_A^u	g_V^d	g_A^d	g_V^e	g_A^e	g_V^ν	g_A^ν
SSM wide	4500	10%	0.76	0.193	0.5	−0.347	−0.5	−0.0387	−0.5	0.5	0.5
SSM enhanced	5000	27%	2.28	0.193	0.5	−0.347	−0.5	−0.0387	−0.5	0.5	0.5

Paper: E. Accomando, F. Coradeschi, T.C., J. Fiaschi, F. Hautmann, S. Moretti, C. Shepherd-Thmistocleous., C. Voisey. "Production of Z'-boson resonances with large width at the LHC", Physics Letters B 803 (2020) 135293 and arXiv:1910.13759.

Differential M_{ll} cross-sections for SSM wide/enhanced

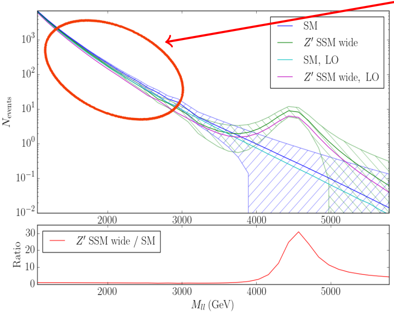
- SSM wide model (below left) has 10% width,
  - still some reduced resonance shape remains in invariant mass.
- SSM enhanced (below right) has 27% width,
  - broad "shoulder" of excess events - must simply count events above background - sensitive to model and corrections.

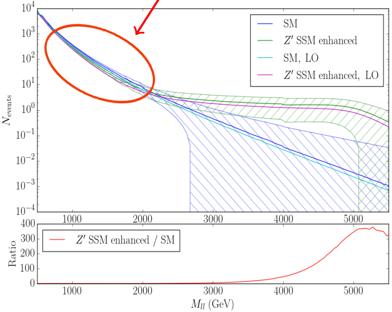




Depletion of events?

- Looking at the M_{ll} spectra before the Z' peak/shoulder appears shows the effects of interference of the Z' with SM.
- See small, but statistically significant depletion of events, particularly in SSM enhanced case:





- Interference effects may reveal potential presence of Z' at lower M_{ll} than peak/shoulder, but need good control of backgrounds and corrections to see it.

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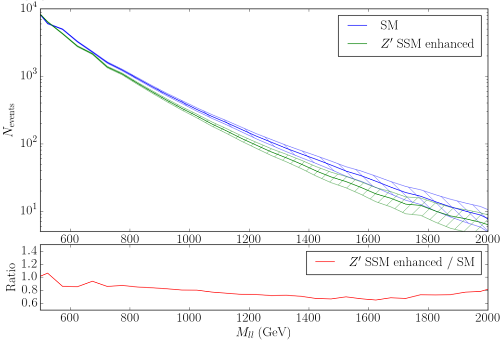

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Forward-Backward Asymmetry, A_{FB}

- Forward-backward asymmetry:

$$\boxed{A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}}$$

N.B. A_{FB} relies on knowing θ angle between l^- and q in CoM frame, we can't know the quark direction in hadron collider $\Rightarrow$ use direction of boost of dilepton system, this defines related A^*_{FB}.

where $\sigma_{F,B} = \int_a^b \frac{d\sigma}{d\cos\theta} d\cos\theta$ with $[a, b] = [0, 1]/[-1, 0]$ for F/B.

- Sensitive to different combination of couplings relative to cross-section:

$$\Sigma|M|^2 \sim \Sigma_{i,j}|P_i^* P_j|[\underbrace{(1+\cos^2\theta)C_S^{ij}}_{\text{Cross-section}} + \underbrace{2\cos\theta C_A^{ij}}_{A_{FB}}]$$

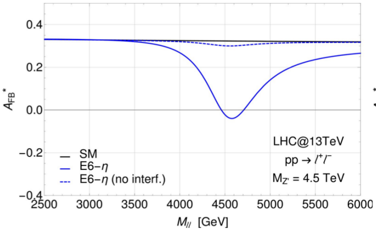
$$C_{S/A}^{ij} = (a_{V_i} a_{V/A_j} + a_{A_i} a_{A/V_j})_L (a_{V_i} a_{V/A_j} + a_{A_i} a_{A/V_j})_Q$$

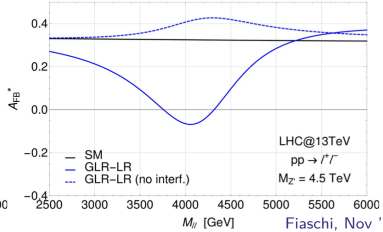
- A_{FB} usually suggested as diagnostic tool to determine Z' model after discovery $\Rightarrow$ offers complementary information.

Accomando et al, 1504.03168, 1510.05892, ...

Forward-Backward Asymmetry, A_{FB} shape

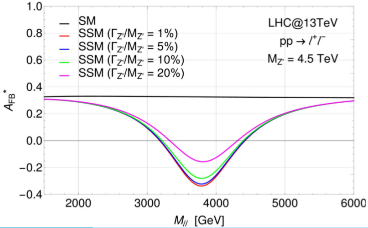
- A_{FB} shape is coupling-sensitive and dominated by interference effects, occur at $M_{ll} < M_{Z'}$ $\Rightarrow$ diagnostic and search tool:





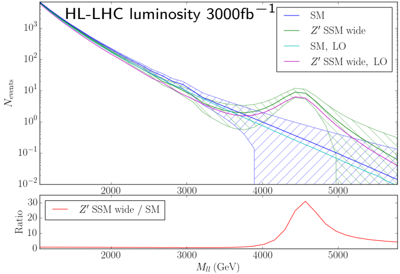
Fiaschi, Nov '20

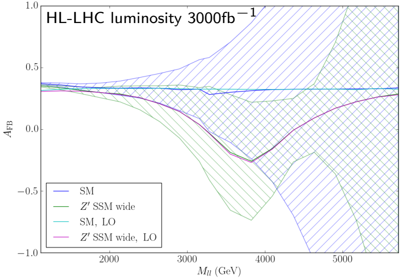
- Very model dependent shape, hence utility to distinguish models.
- Also maintains a clear line shape, even for wide Z's $\Rightarrow$ search tool when M_{ll} searches are insensitive.
- Systematics partially cancel (e.g. PDFs, lumi) at cost of increased stat errors.



Accomando et al., JHEP, 01 (2016), 127

SSM wide A_{FB}



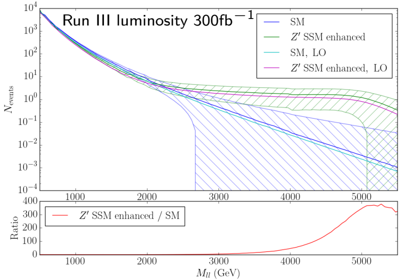


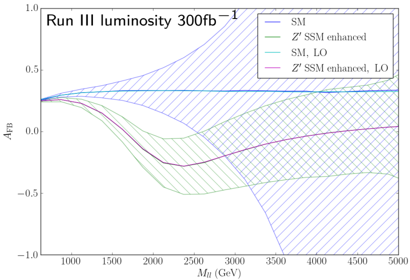
- Only stat errors shown here as at high M_{ll} these dominate. A_{FB} has larger stat errors.

$$\Delta A_{FB}^{stat} = \frac{\sqrt{1 - A_{FB}^2}}{\sqrt{N}}$$

- Scale variation errors from resummed prediction negligible in comparison to stat errors, also reduced in A_{FB}.
- A_{FB} is more robust against resummation effects $\Rightarrow$ good variable.
- Cross-section search shows more promise, A_{FB} stat limited but could confirm the signal/enhance sensitivity to it.

SSM enhanced A_{FB}

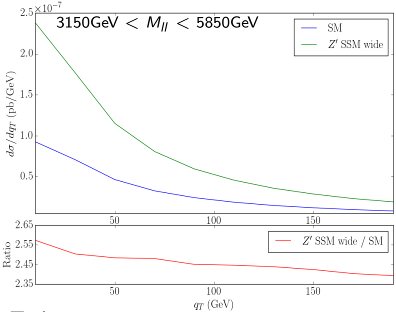


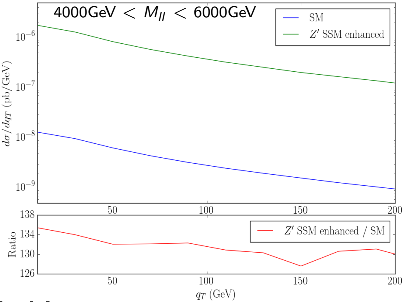


- Now A_{FB} clearly deviates from SM at much lower invariant masses than the cross-section ⇒ due to interference effect.
- Whilst A_{FB} generally has larger stat errors at same M_{ll}, it's deviations occur at lower M_{ll} than the shoulder in cross-section, more events here ⇒ error-bands in search regions are smaller.
- A_{FB} a better probe of this Z' model than differential cross-section.
- Invariant mass spectrum and A_{FB} may offer complementary information and enhanced sensitivity.

Further Variables: q_T

- Given potential for A_{FB} to detect heavy wide Z's, whether at or before $M_{Z'}$, are there other potentially useful variables?
- `reSolve` calculates fully differential cross-section for dilepton system and leptons so many variables to look at...
- Now we have resummed predictions we can look at the q_T spectrum in the high M_{ll} window around the peak/shoulder:

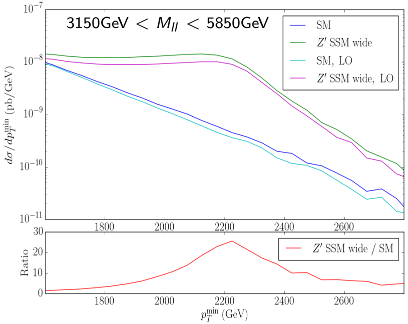


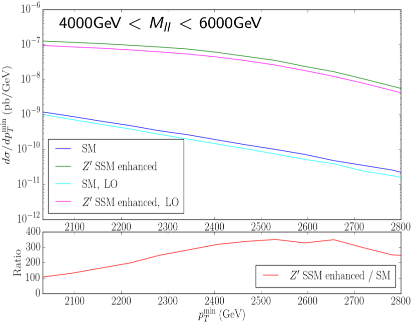


- Enhancement in q_T spectrum at high M_{ll}.

Further Variables: p_T^{min}

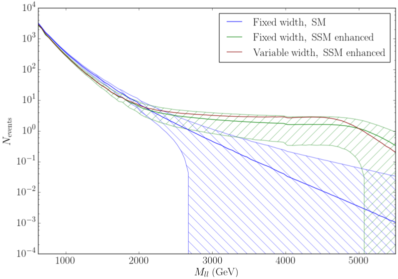
- Examine spectrum of minimum transverse momentum of leptons.
- Jacobian peak clear at $M_{Z'}/2$, potential for mass measurement via this effect.
- Still clear, although smeared, for SSM enhanced which has shoulder in M_{ll} rather than resonance, clearer "peak" in p_T^{min} than in M_{ll}.
- Need resummed calculation to see this. Similar for p_T^{max}.





Variable Width effects

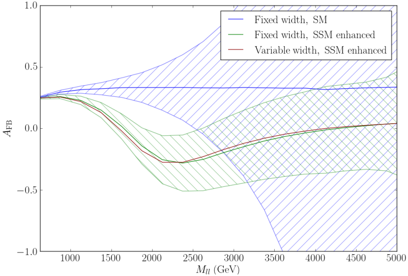
- Given large $\Gamma_{Z'}/M_{Z'}$, Breit-Wigner constant width approximation may not hold true.
- Examine effects of "variable width" via phenomenological LEP* treatment, in propagator $m_{Z'}\Gamma_{Z'} \rightarrow \hat{s}\Gamma_{Z'}/m_{Z'}$.
- The running width then is identical at $\hat{s} = M_{Z'}^2$ whilst is smaller/higher than the fixed width for $\hat{s}/M_{Z'}^2 < / > 1$.
- Cross-section rises/lowers before/after $M_{Z'}$, consider for SSM enhanced model (right).
- Effect within stat error-bands.
- Enhances the "shoulder" of excess events moves it away from SM slightly in lower mass, greater number of events region.



*G. Altarelli, R.H.P. Kleiss, C. Verzegnassi, CERN-89-08-V-1, https://cds .cern .ch / record /116932, 1989.

Variable Width effects

- As differential cross-section changes, so will A_{FB}.
- Expect A_{FB} less affected as it's a ratio, indeed we see this:
- Small effect well within stat errors.
- Again slightly enhances the difference in shape compared to the SM.



- Negative Z'-SM interference contribution increased, therefore A_{FB} amplitude enhances in the lower M_{ll} region relevant for A_{FB} deviations from SM.
- Results shown therefore independent of the precise form of the partial width we assumed.

Conclusions

- Shown how for heavy, wide Z's "bump-hunting" in M_{ll} spectra may be insensitive to "shoulder" of excess events.
- Alternative approaches, these require more precise calculations.
- Calculated resummed differential cross-sections and A_{FB} up to NNLL' for two exemplar models.
- Saw that the A_{FB} is robust against resummation and other effects and could offer a more promising search option.
- Interference effects mean A_{FB} may show impact of Z' at much lower M_{ll} than cross-section, in same region as depletion of events.
- Considered further differential variables as probes of Z' models, q_T of dilepton system and individual lepton p_T $\Rightarrow$ all show impact of Z', could enhance sensitivity to these wide Z's.
- In future will add finite piece in order to consider further variables and also wish to follow-up on these initial observations.

"Production of Z'-boson resonances with large width at the LHC", Physics Letters B 803 (2020) 135293 and arXiv:1910.13759.

Thank you for your attention!

- "Production of Z'-boson resonances with large width at the LHC", Physics Letters B 803 (2020) 135293 and arXiv:1910.13759, E. Accomando, F. Coradeschi, T.C., J. Fiaschi, F. Hautmann, S. Moretti, C. Shepherd-Themistocleous, C. Voisey.
- "reSolve - A Transverse Momentum Resummation Tool" CPC Vol. 238 pgs 262-294 and arXiv:1711.02083, F. Coradeschi and T.C. .

Backup Slides

Z's in theory

- Z's arise in a large variety of theories, both "top-down" models based on GUT extended gauge groups and "bottom-up" models adding small changes to the SM to explain additional features:
  - E_6 models, e.g. broken via $E_6 \to SO(10) \times U(1) \to (SU(5) \times U(1)) \times U(1)$.
  - Generalised Left-Right symmetric models where $SU(2)_L \times SU(2)_R \times U(1) \to SU(2)_L \times U(1)_Y$.
  - Little Higgs Models, where Higgs is a pseudo-Goldstone boson of an approximate symmetry, divergences in Higgs mass cancelled by new TeV scale bosons, fermions, scalars.
  - Extra dimension models with Kaluza-Klein excitations of Z and other SM gauge bosons.
  - Generalised/Sequential Standard Model (SSM), here you just have a heavier copy of the SM Z boson, useful reference case.
- Can be used to explain many things - naturalness, neutrino masses, dark matter, gauge unification, charge quantisation, etc... .

All schematic!

Different Z' Models

Different models give different mixings and couplings at the low scale:

$U(1)'$	$Parameter$	a_V^u	a_A^u	a_V^d	a_A^d	a_V^e	a_A^e	a_V^ν	a_A^ν
$E6(g'=0.462)$	θ								
χ	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
ψ	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
η	-0.29π	0	-0.516	-0.388	-0.129	0.388	-0.129	0.129	0.129
S	0.129π	0	-0.130	-0.581	0.452	0.581	0.452	0.516	0.516
I	0.21π	0	0	-0.5	0.5	0.5	0.5	0.5	0.5
N	0.42π	0	0.317	-0.157	0.474	0.157	0.474	0.316	0.316
$GLR(g'=0.592)$	ϕ								
R	0	0.5	-0.5	-0.5	0.5	-0.5	0.5	0	0
$B-L$	0.5π	0.333	0	0.333	0	-1	0	-0.5	-0.5
LR	-0.130π	0.326	-0.459	-0.591	0.459	-0.06	0.459	0.199	0.199
Y	0.25π	0.589	-0.354	-0.118	0.354	-1.061	0.354	-0.354	-0.354
$GSM(g'=0.762)$	α								
SM	-0.072π	0.186	0.487	-0.336	-0.487	-0.035	-0.487	0.487	0.487
$T3L$	0	0.5	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
Q	0.5π	1.333	0	-0.667	0	-2	0	0	0

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Different approaches to resummation

Schematic!

- CSS q_T resummation:

$$\frac{d\sigma_{res}}{dq_T} \sim e^S \times [(HC_1C_2) \otimes f_1 \otimes f_2]$$

- TMD resummation:

$$\frac{d\sigma_{res}}{dq_T} \sim H \times F_1 \times F_2$$

- SCET resummation:

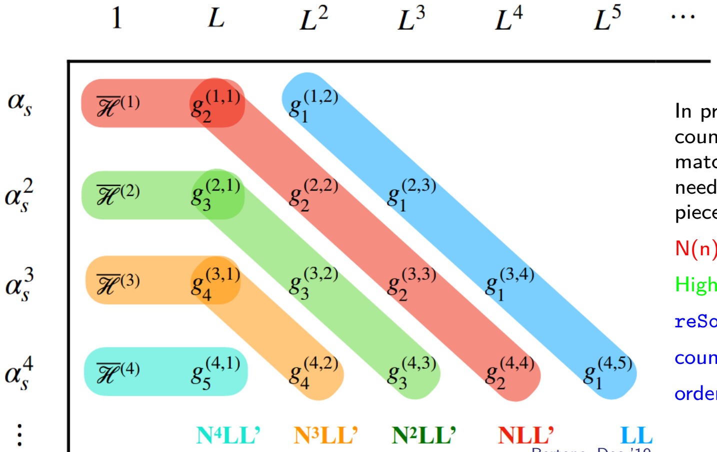
$$\frac{d\sigma_{res}}{dq_T} \sim H \times B_1 \times B_2 \times S$$

- Parton Shower-like (parton branching):
  - Parton shower based with Sudakov factor S denoting probability of no resolvable branching emissions.
  - Ordered emissions ensure control of sub-leading logs.

These different approaches are equivalent for the resummed piece at each order (up to power corrections $\mathcal{O}[(q_T/Q)^n]$).

q_T resummation - Log. Counting - primed N(n)LL'

$$\ln\left(\frac{d\sigma}{dq_T}\right) \propto \ln\left(1 + \sum_{m=1}^{\infty} \alpha_s^m \mathcal{H}^{(m)}\right) + \sum_{n=1}^{\infty} \alpha_s^n \sum_{k=1}^{n+1} g^{(n,k)} L^k \qquad \alpha_S L \sim 1$$



Bertone, Dec '19

In primed (original) counting the order matches the order needed in the finite piece for matching:

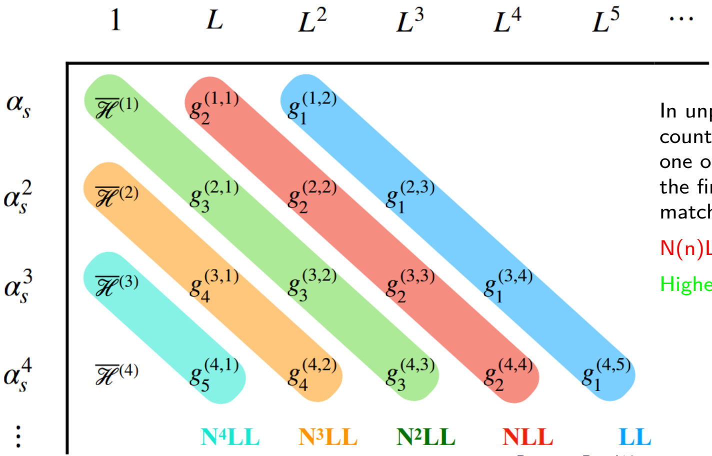
N(n)LL' + N(n)LO.

Highest order NNLL'.

`reSolve` uses primed counting, highest order NNLL'.

q_T resummation - Log. Counting - unprimed N(n)LL

$$\ln\left(\frac{d\sigma}{dq_T}\right) \propto \ln\left(1+\sum_{m=1}^{\infty}\alpha_s^m\mathcal{H}^{(m)}\right)+\sum_{n=1}^{\infty}\alpha_s^n\sum_{k=1}^{n+1}g^{(n,k)}L^k \qquad \alpha_S L \sim 1$$



Bertone, Dec '19

In unprimed (new) counting you need one order lower in the finite piece for matching:

N(n)LL + N(n-1)LO.

Highest order N3LL.

LHC EW q_T Resummation benchmarking

See my talk at https://indico.cern.ch/event/941711/timetable/?print=1

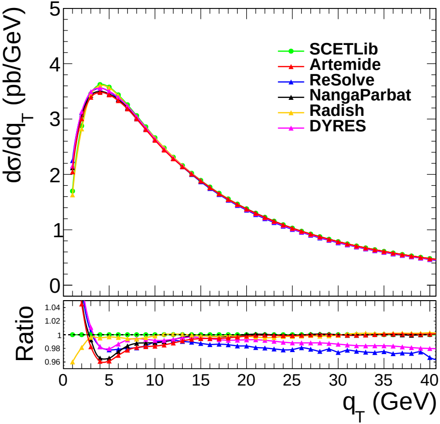
Level 1 - Essentially consistency in settings wherever possible!

- Consider triple differential cross-section $\frac{d\sigma}{dQdYdq_T}$.
- Z/γ^* production at 13TeV.
- Across values of $Q = m_Z, 1\,TeV$ and $y = 0, 2.4$; but focusing on $Q = m_Z, y = 0$.
- Consider all logarithmic orders up to NNLL'/N3LL.
- Only "Canonical" logs, i.e. unmodified $L = \log(Q^2 b^2)$.
- Resummed piece only.
- Across q_T range of 0 to 100GeV, focus though on low q_T where resummed piece relevant.
- No non-perturbative function S_{NP}, Landau pole regularisation treated differently but common value b_0/b_{max} used.
- Scales fixed to Q where naturally at hard scale.
- Same PDF choice, same $\alpha_s(m_Z) = 0.118$, same EW settings, no lepton cuts.

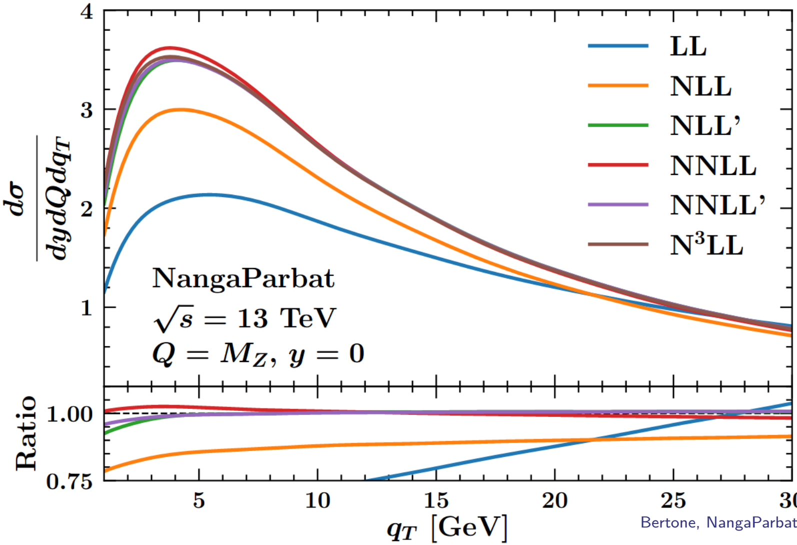
Comparison of q_T resummation codes at NNLL'

See my talk at https://indico.cern.ch/event/941711/timetable/?print=1

- Comparison of several different methods and codes of q_T resummation for SM Z/γ^* production at LHC at 13TeV at $Q = m_Z$, $y = 0$ at NNLL'. (Level 1 of benchmarking).



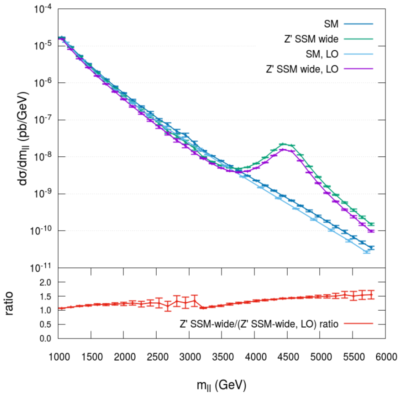
Perturbative convergence with Log resummation order

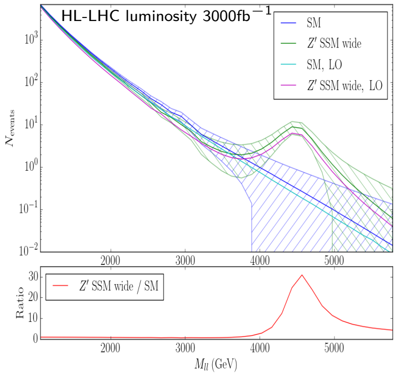


Bertone, NangaParbat, Dec '19

Differential M_{ll} cross-sections for SSM wide

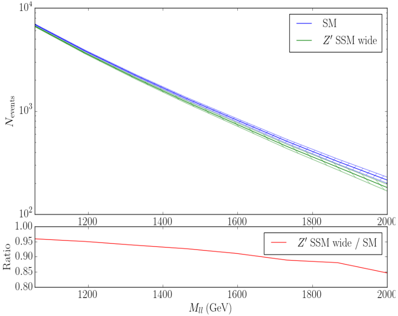
- SSM wide model (below left) has 10% width, enlarged by additional invisible decay modes
  - still some resonance shape remains in invariant mass.

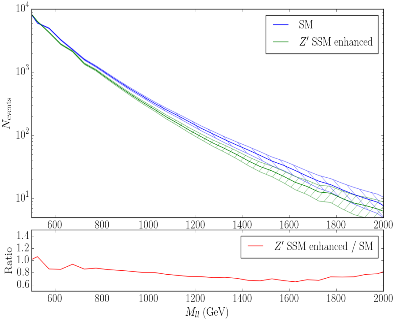




Depletion of events?

- Looking at the M_{ll} spectra before the Z' peak/shoulder appears shows the effects of interference of the Z' with SM.
- See small, but statistically significant depletion of events, particularly in SSM enhanced case:

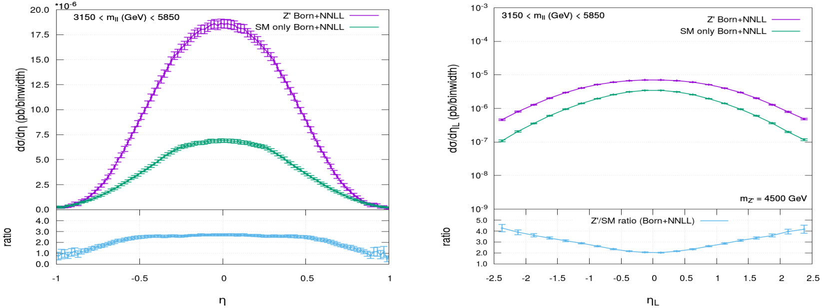




- Interference effects may reveal potential presence of Z' at lower M_{ll} than peak/shoulder, but need good control of backgrounds and corrections to see it.

Further Variables: η_{ll}, η_l

- Look at rapidity spectra of dilepton system/individual leptons.
- Z' produced at much higher masses than SM DY, requires PDFs at larger x and more balanced $\Rightarrow$ peaked at narrower η_{ll}.
- Z' therefore also less boosted, therefore it produces leptons minimally along $\cos\theta = \pi/2 \to \eta_L = 0$, SM Z boosted and so minima off-axis (i.e. away from $\eta_L = 0$). Ratio minimum at $\eta_L = 0$.



- All differences between Z' and SM signals $\Rightarrow$ could aid Z' searches.

Cut efficiencies

- Single lepton p_Ts and rapidities η_l are usually cut on in searches.
- Given their distributions are affected by the presence of Z's $\Rightarrow$ need to check this does not bias our search.
- Consider SSM wide case - question is whether fraction of total events (acceptances) for Z' passing these cuts is same as for SM:

$U(1)'$	$p_T^1, p_T^2 \geq 20$ GeV	$\eta_1, \eta_2 \leq 2.5$	$p_T^1, p_T^2 \geq 20$ GeV; $\eta_1, \eta_2 \leq 2.5$
$U(1)_{\mathrm{SM}}$	0.99	0.95	0.95
$U(1)_{\mathrm{SSMwide}}$	0.99	0.96	0.96

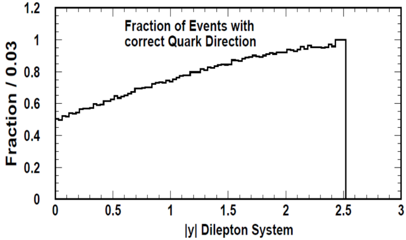
- The mass window $3150 \text{ GeV} \leq M_{ll} \leq 5850 \text{ GeV}$ is selected. Label 1(2) refers to the highest(lowest) transverse momentum lepton.
- Fortunately very limited differences, so whilst ratio of Z'/SM shows differences the Z' and SM show similar behaviours within their spectra with p_T and η_l.

A^*_{FB}

- In actuality we show the "reconstructed A_{FB}", A^*_{FB} throughout the slides/results.

Accomando et al., 1503.02672

- A_{FB} is purely a theoretical object, relies on knowing angle θ between l^- and q in parton Centre of Mass (CoM) frame.
- In hadron collider no access to parton CoM frame experimentally!
- Instead take direction of boost of dilepton system as indicating quark direction $\Rightarrow A^*_{FB}$.
- A^*_{FB} and A_{FB} equivalent in large dilepton boost limit.
- A^*_{FB} is diluted compared to A_{FB}.

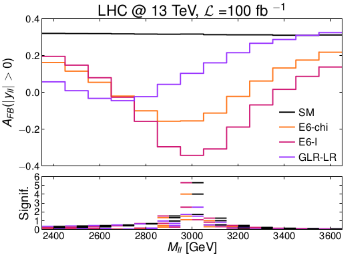


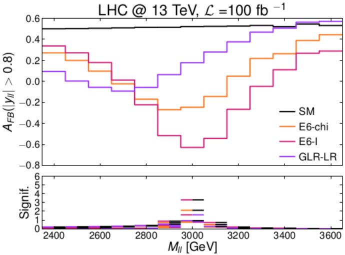
Dittmar, Phys.Rev.D55:161-166 (1997)

- Particularly important for heavy objects, these are less boosted so chance of direction "mismatch" greater.
- Can extend definition to higher orders via Collins-Soper frame.

Effect of rapidity cuts

- As a result of fact $A^*_{FB} \to A_{FB}$ for large y_{ll}, rapidity cuts are often put on the dilepton system in searches.
- However this alters flavour composition as momentum of $u_V > d_V$ on average, also reduces stats.
- Could use rapidity cuts to probe flavour couplings...
- For our heavy Z's suggest no rapidity cut to maximise sensitivity to small effects. Also preserves flavour independence.

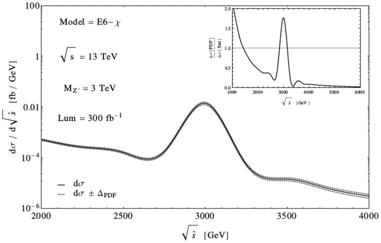


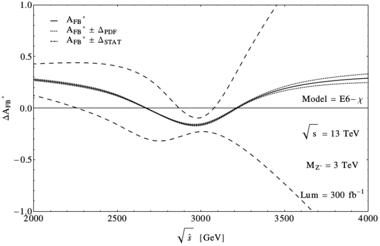


PDF effects

- Two considerations - firstly PDF systematic errors at large M_{ll} can spoil sensitivity to heavy Z's, provided there are enough stats.
- A_{FB} being a ratio of cross-sections, is robust against PDF systematic errors as they largely cancel in the ratio:

$$\Delta A^*_{FB} = \frac{1}{2}(1 - {A^*_{FB}}^2)\left|\frac{\Delta\sigma_F}{\sigma_F} - \frac{\Delta\sigma_B}{\sigma_B}\right|$$





- Secondly can use rapidity cuts to give sensitivity to individual PDFs, may be useful in future for PDF determinations.

Accomando et al., 1503.02672,1906.11739