Presentation based on arXiv:1711.09845 [hep-ph]

- Coauthored with **Qiang Li**
- With special thanks to **Kaoru Hagiwara**

Probing the Dark Sector through Mono-Z Boson Leptonic decays

Daneng Yang

School of Physics, Peking University

The Third China LHC Physics Workshop,
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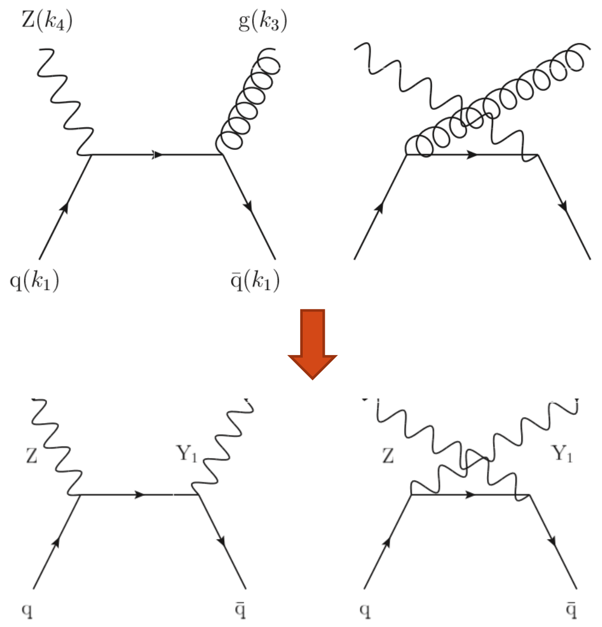
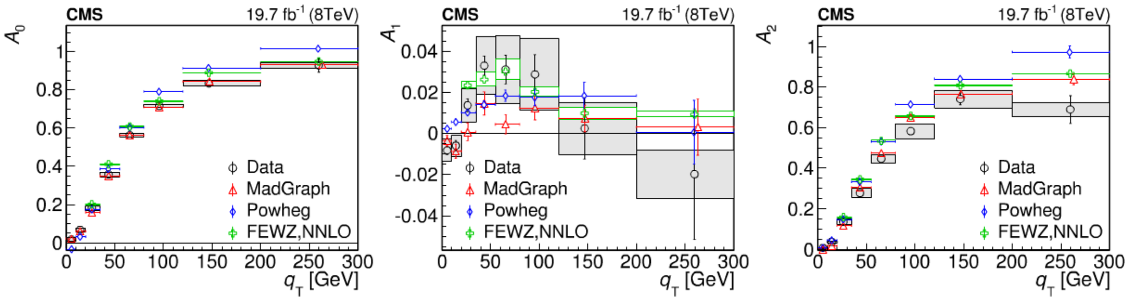
Background

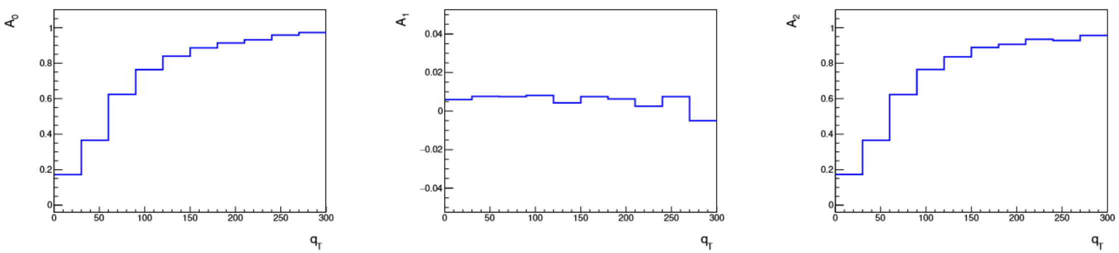


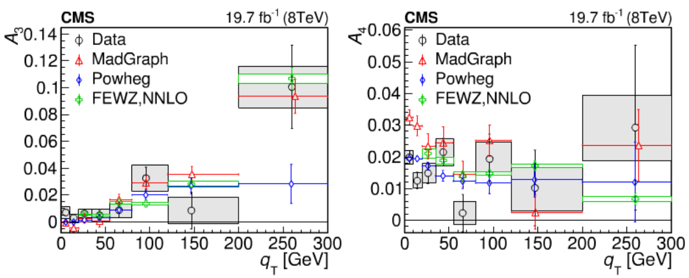
Measuring angular coefficients of high pT Z boson leptonic decays

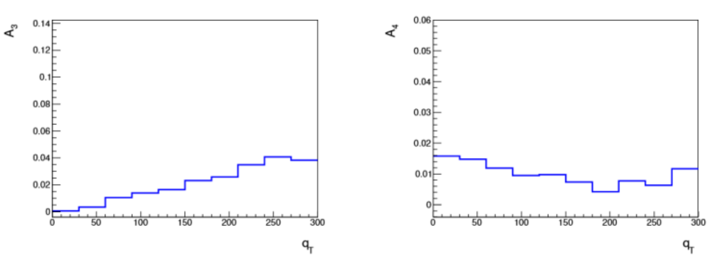
Z boson pT balanced by **jets** → Z boson pT balanced by **missing energy**

Recent experimental results on the angular coefficients of Z boson leptonic decays at the LHC









CMS: Phys. Lett. B 750 (2015) 154

ATLAS: JHEP08(2016)159

Order in QCD

0th A4 only, from qqbar->Z

1st A0-A4,

Lam–Tung relation: A0=A2

2nd A0-A7, all appear

Comparing the measured angular coefficients and the parton level predictions (L.O.)

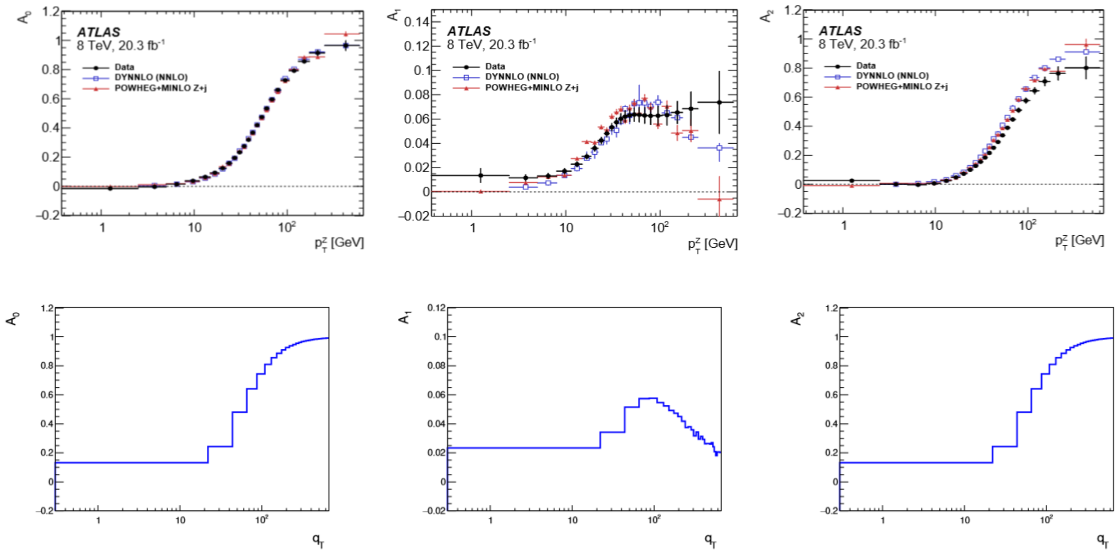
Nice agreement!

- The Z boson e/mu decays have very clean signatures
- QCD corrections to angular coefficients are very small

Angular coefficients in the Collins-Soper frame

$$\frac{d\sigma}{dq_T dy_Z ds_Z d\cos\theta d\phi} = \left(\int d\cos\theta d\phi \frac{d\sigma}{dq_T dy_Z ds_Z d\cos\theta d\phi}\right)\frac{3}{16\pi} \left\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\sin 2\theta\cos\phi +\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta\right\}$$

Recent experimental results on the angular coefficients of Z boson leptonic decays at the LHC



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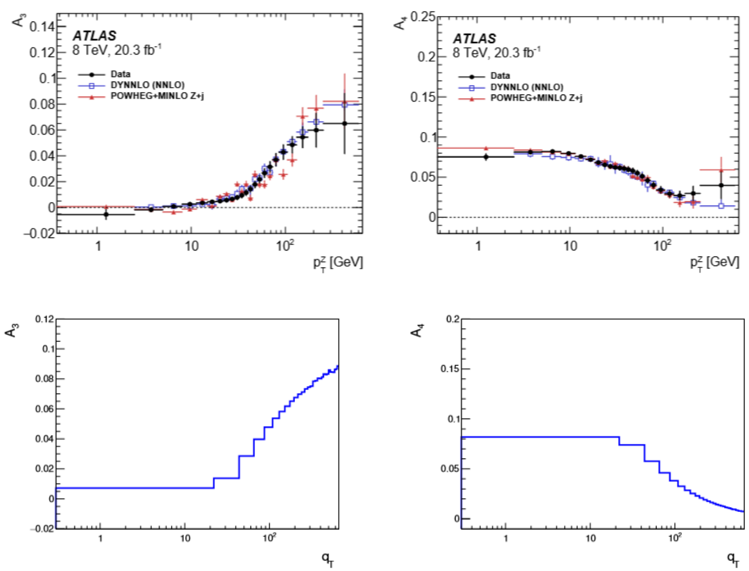

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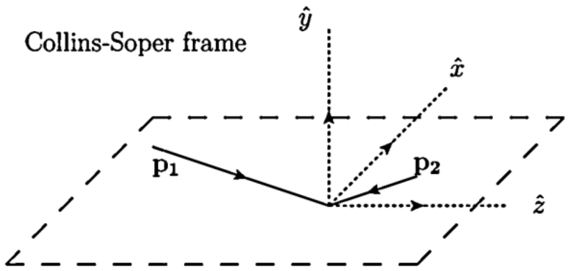
$$\left\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi\right.$$

$$\left. + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta\right\}$$



Parametrization of the lepton angular distribution

Measuring angular coefficients of high pT Z boson leptonic decays

Z boson pT balanced by **jets** → Z boson pT balanced by **missing energy**

Parametrization of the lepton angular distribution

We parametrize the phase space such that the visible part is $\mathbf{x} = (y_Z, q_T, \cos\theta_{CS}, \phi_{CS})$ and the invisible part is $(y_Y, s_Y, \cos\theta_\chi, \phi_\chi)$

$$\int d\Phi_4(k_l, k_{\bar{l}}, k_\chi, k_{\bar{\chi}}) = \int \frac{ds_Z}{2\pi}\frac{ds_X}{2\pi}\int d\Phi_2'(p_Y, p_Z)\, d\Phi_2(k_l, k_{\bar{l}})\, d\Phi_2(k_\chi, k_{\bar{\chi}}),$$

$$\int d\Phi_2'(p_Y, p_Z) = \int \frac{d^3 p_Z}{(2\pi)^3 2p_Z^0}\frac{d^3 p_Y}{(2\pi)^3 2p_Y^0}(2\pi)^4\delta^4(p_1 + p_2 - p_Z - p_Y),$$

$$= \frac{1}{4\pi s}\int \boxed{dy_Z dy_Y dq_T}\cdot q_T$$

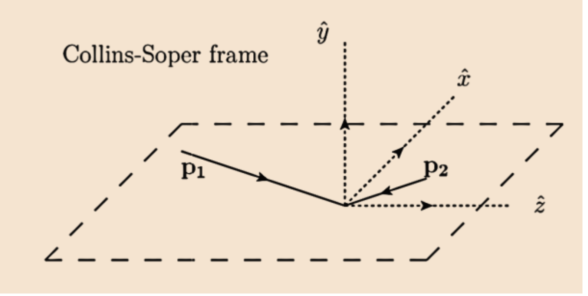
$$\boxed{\delta\left(x_1 - \frac{x_{T,Z}}{2}e^{y_Z} - \frac{x_{T,Y}}{2}e^{y_Y}\right)\delta\left(x_2 - \frac{x_{T,Z}}{2}e^{-y_Z} - \frac{x_{T,Y}}{2}e^{-y_Y}\right)}$$

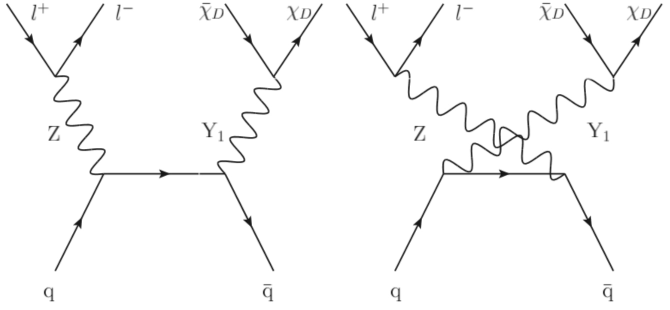
$$\int d\Phi_2(k_1, k_2) = \frac{1}{8\pi}\bar{\beta}\left(\frac{m_1^2}{s_{12}}, \frac{m_2^2}{s_{12}}\right)\frac{d\cos\theta}{2}\frac{d\phi}{2\pi},$$

$$\bar{\beta}(a, b) = \sqrt{\lambda(1, a, b)} = \sqrt{1 + a^2 + b^2 - 2a - 2b - 2ab}.$$

$$x_{T,Z} = \frac{2\sqrt{s_Z + q_T^2}}{\sqrt{s}},\quad x_{T,Y} = \frac{2\sqrt{s_Y + q_T^2}}{\sqrt{s}}$$

x_1, x_2 fixed through delta functions





- The z-axis is defined as the bisector of the angle θ_{12} between $\mathbf{p_1}$ and $-\mathbf{p_2}$.
- $\tan\frac{\theta_{12}}{2} = \frac{q_T}{\sqrt{s_Z}}$, $q_T \equiv |\mathbf{q_T}|$:
  - θ_{12} independent of longitudinal boost
  - Minimize the impact of incoming quark transverse momentum
- Rotate around the x-axis by π for events with $y_Z < 0$:
  - Avoid possible dilutions by the initial states swapped processes
  - Angular coefficients have symmetric y_Z distributions

Parametrization of the lepton angular distribution

We consider the Z boson decay as a probe of the underlying production structure with a narrow width approximation.

$$\frac{d\sigma}{dy_Z dq_T ds_Y d\Phi_2(k_\chi, k_{\bar\chi}) d\cos\theta d\phi} = \frac{d\sigma_P}{dy_Z dq_T ds_Y d\Phi_2(k_\chi, k_{\bar\chi})} \cdot \mathrm{Br}(Z \to l^+ l^-) \cdot 3 \sum_{s,s'} \rho^P_{ss'} \rho^D_{ss'}$$

$$\mathrm{Tr}\rho^P = \int_{\mathcal{R}} d\Phi_2'(p_Y, p_Z) d\Phi_2(k_\chi, k_{\bar\chi}) \sum_{a,b} f_a(x_1, \mu_F) f_b(x_2, \mu_F) \frac{1}{2\hat{s}} \overline{\sum_{\mathrm{ext}}} \sum_s |\mathcal{M}_s|^2 ,$$

$$\rho^P_{ss'} = \frac{1}{\mathrm{Tr}\rho^P} \int_{\mathcal{R}} d\Phi_2'(p_Y, p_Z) d\Phi_2(k_\chi, k_{\bar\chi}) \sum_{a,b} f_a(x_1, \mu_F) f_b(x_2, \mu_F) \frac{1}{2\hat{s}} \overline{\sum_{\mathrm{ext}}} \mathcal{M}_s \mathcal{M}^*_{s'}$$

→ Angular coefficients

$$\rho^{P,CS}_{ss'} = \sum_{\alpha,\beta} d^{J=1}_{\alpha s}(-\omega) d^{J=1}_{\beta s'}(-\omega) \rho^{P,HEL}_{\alpha\beta}$$

$$\cos\omega = \frac{2\sqrt{\tau_Z}\sinh y_Z}{\sqrt{x^2_{T,Z}\cosh^2 y_Z - 4\tau_Z}},$$

- Analytic implementation (ALOHA generated HELAS subroutines): allows application of matrix element method (MEM).
- All evaluated angular coefficients checked with toy measurements based on MadGraph5 generated events.

Parameter	Value
$\sin^2\theta_W$	0.23129
$1/\alpha$	127.95
m_Z	91.1876 GeV
Γ_Z	2.4952 GeV
α_s	0.13 (NNPDF 23)
m_W	$m_Z \cos\theta_W$
Br(Z→ll), l=e,μ	6.73%
μ_F	$E_T = \sqrt{s_Z + q_T^2}$

We will show $y_Z - q_T$ distributions of A_{0-4} in different scenarios

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_\mathrm{T}\mathrm{d}y_\mathrm{Z}\mathrm{d}s_\mathrm{Z}\mathrm{d}\cos\theta\mathrm{d}\phi} = \left(\int \mathrm{d}\cos\theta\mathrm{d}\phi\frac{\mathrm{d}\sigma}{\mathrm{d}q_\mathrm{T}\mathrm{d}y_\mathrm{Z}\mathrm{d}s_\mathrm{Z}\mathrm{d}\cos\theta\mathrm{d}\phi}\right)\frac{3}{16\pi}$$
$$\left\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\sin 2\theta\cos\phi\right.$$
$$\left.+\frac{1}{2}A_2\sin^2\theta\cos 2\phi+A_3\sin\theta\cos\phi+A_4\cos\theta\right\}$$

Angular coefficients with dark sector models

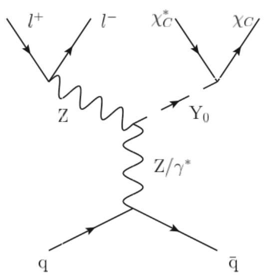
- **SM ZZ→2l 2v background**
- **Spin-0 mediator**
- **Spin-1 mediator**
- **Spin-2 mediator**

Angular coefficients with dark sector models

Spin-0 models

$$\mathcal{L}^{Y_0}_{SMEW} = \frac{1}{\Lambda} g^S_{h3} (D^\mu\phi)^\dagger (D_\mu\phi) Y_0 + \frac{1}{\Lambda} B_{\mu\nu}\left(g^S_B B^{\mu\nu} + g^P_B \tilde{B}^{\mu\nu}\right) Y_0 + \frac{1}{\Lambda} W^i_{\mu\nu}\left(g^S_W W^{i,\mu\nu} + g^P_W \tilde{W}^{i,\mu\nu}\right) Y_0,$$

$$\mathcal{L}^{Y_0}_{X} = m_{X_C} g^S_{X_C} X_C^* X_C Y_0 + \bar{X}_D (g^S_{X_D} + i g^P_{X_D}\gamma_5) X_D Y_0,$$

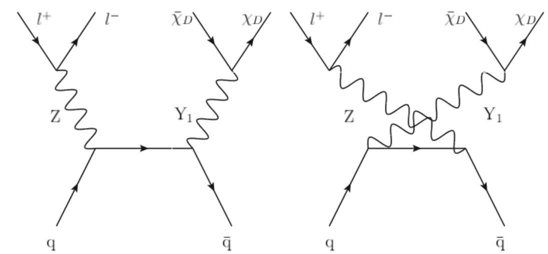


Benchmark	$S0_a$	$S0_b$	$S0_c$
$g^S_{X_D}$	1	0	0
$g^P_{X_D}$	0	1	0
$g^S_{X_C}$	0	0	1
g^S_W	0.25	0	0
g^P_W	0	0.25	0
g^S_{h3}	0	0	1
Λ (GeV)	3000	3000	3000
Interaction	CP-even	CP-odd	CP-even
m_χ (GeV)	10	10	10
m_{Y_0} (GeV)	1000	1000	1000
Γ_{Y_0} (GeV)	41.4	41.4	1.05
Cross section (fb)	0.0103	0.00977	2.98e-08

Spin-1 models

$$\mathcal{L}^{Y_1}_{X_D} = \bar{\chi}_D \gamma_\mu \left(g^V_{X_D} + g^A_{X_D}\gamma_5\right) \chi_D Y_1^\mu$$

$$\mathcal{L}^{Y_1}_{SM} = \bar{d}_i \left(g^V_{d_{ij}} + g^A_{d_{ij}}\gamma_5\right) d_j Y_1^\mu + \bar{u}_i \left(g^V_{u_{ij}} + g^A_{u_{ij}}\gamma_5\right) u_j Y_1^\mu$$



Benchmark	$S1_a$ Spin independent	$S1_b$ Right handed	$S1_c$ Left handed	$S1_0$ SM ($ZZ \to 2l2\nu$)
$g^V_{X_D}$	1	$1/\sqrt{2}$	$1/\sqrt{2}$	-
$g^A_{X_D}$	0	$1/\sqrt{2}$	$-1/\sqrt{2}$	-
$g^V_{X_C}$	0	0	0	-
g^V_u	0.25	$\sqrt{2}/8$	$\sqrt{2}/8$	-
g^A_u	0	$\sqrt{2}/8$	$-\sqrt{2}/8$	-
g^V_d	0.25	$\sqrt{2}/8$	$\sqrt{2}/8$	-
g^A_d	0	$\sqrt{2}/8$	$-\sqrt{2}/8$	-
m_χ (GeV)	10	10	10	-
m_{Y_1} (GeV)	1000	1000	1000	-
Γ_{Y_1} (GeV)	56.3	55.9	55.9	-
Cross section (fb)	2.50	0.533	4.50	239

Spin-2 models

$$\mathcal{L}^{Y_2}_X = -\frac{1}{\Lambda} g^T_X T^X_{\mu\nu} Y_2^{\mu\nu}$$

$$\mathcal{L}^{Y_2}_{SM} = -\frac{1}{\Lambda} \sum_i g^T_i T^i_{\mu\nu} Y_2^{\mu\nu}$$

Benchmark	$S2_a$	$S2_b$	$S2_c$
$g^T_{X_D}$	1	0	0
$g^T_{X_R}$	0	1	0
$g^T_{X_V}$	0	0	1
g^T_{SM}	1	1	1
m_χ (GeV)	10	10	10
m_{Y_2} (GeV)	1000	1000	1000
Λ	3000	3000	3000
Γ_{Y_2} (GeV)	95.3	93.7	97.7
Cross section (fb)	2.73	0.0462	0.578

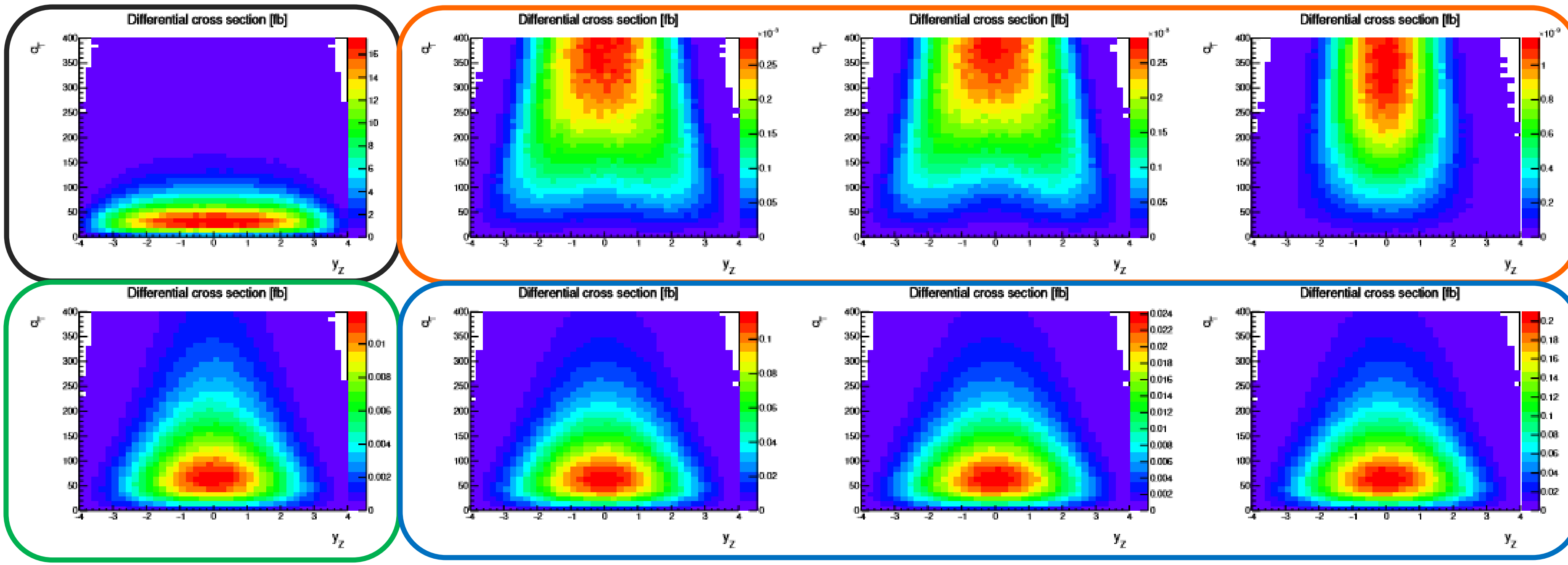
- *JHEP 02 (2016) 082*
- *Report of the ATLAS/CMS Dark Matter Forum, 1507.00966*
- *Eur. Phys. J. C77 (2017) 326*

Angular coefficients with dark sector models

$y_Z - q_T$ differential cross section

SM ZZ→2l2ν

Spin-0 mediator (a-c)



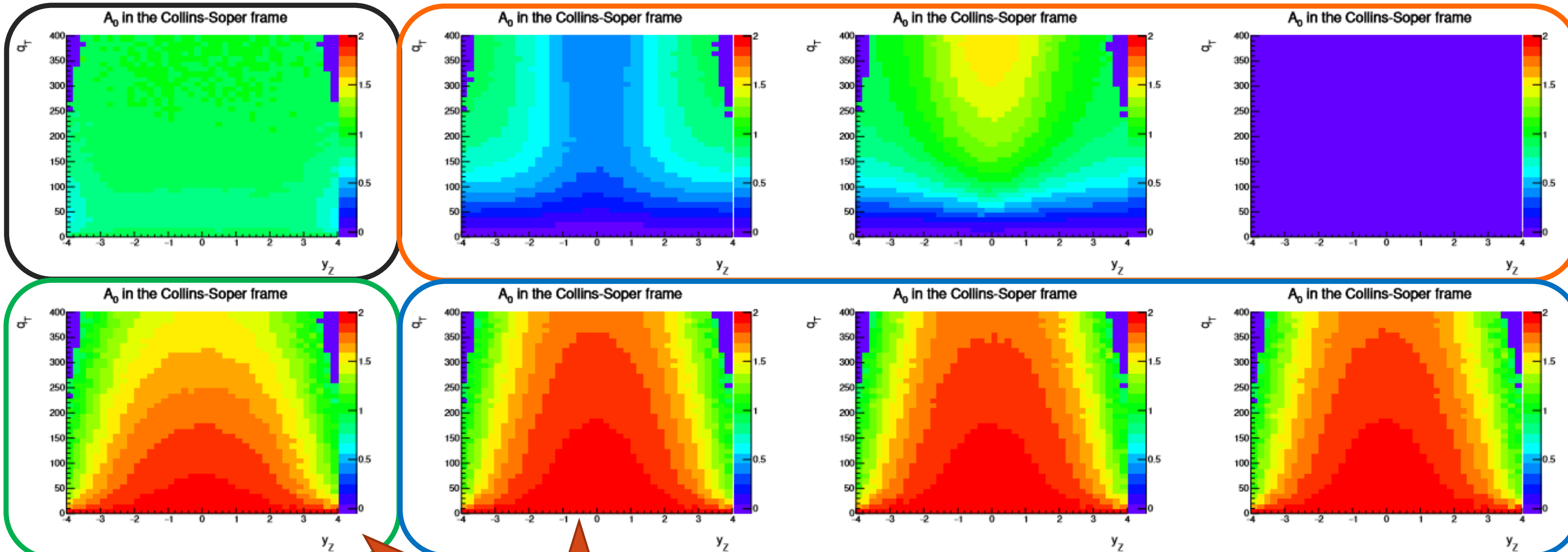
Spin-2 mediator

Spin-1 mediator (a-c)

A0 in the $y_Z - q_T$ plane

SM ZZ→2l2ν

Spin-0 mediator (a-c)



Spin-2 mediator

Spin-1 mediator (a-c)

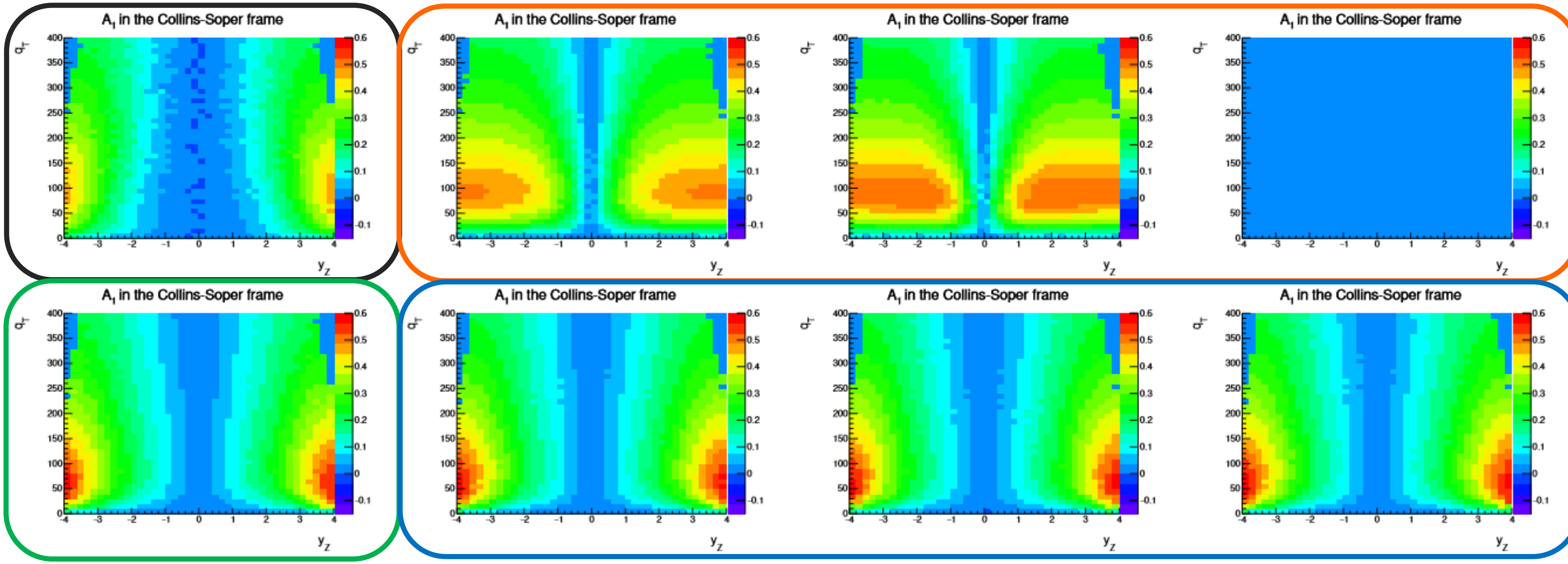
The A0 distribution can distinguish spins of the mediators

Angular coefficients with dark sector models

A1 in the $y_Z - q_T$ plane

SM ZZ→2l2ν

Spin-0 mediator (a-c)



Spin-2 mediator

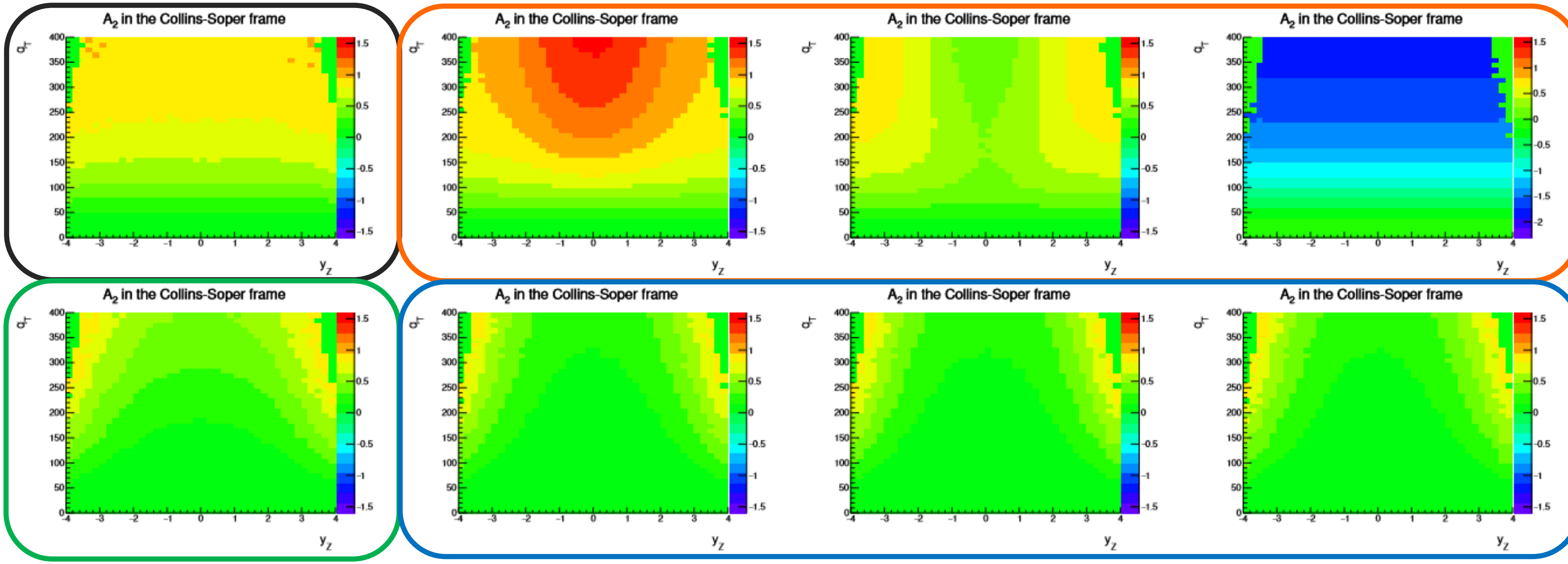
Spin-1 mediator (a-c)

Distributions look similar
Exception: A1 in S0c = 0

A2 in the $y_Z - q_T$ plane

SM ZZ→2l2ν

Spin-0 mediator (a-c)



Spin-2 mediator

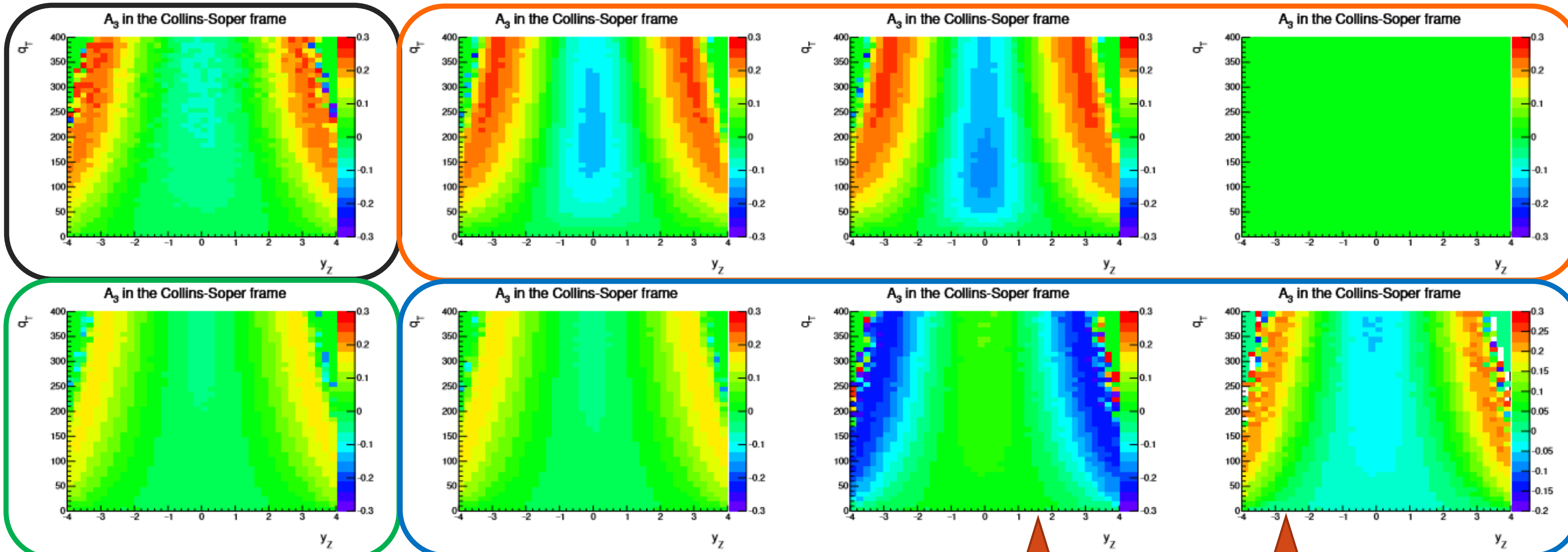
Spin-1 mediator (a-c)

Sensitive to spin-0 models
Spin-2 signature similar but different from the one of the spin-1 model

A3 in the $y_Z - q_T$ plane

SM ZZ→2l2ν

Spin-0 mediator (a-c)



Spin-2 mediator

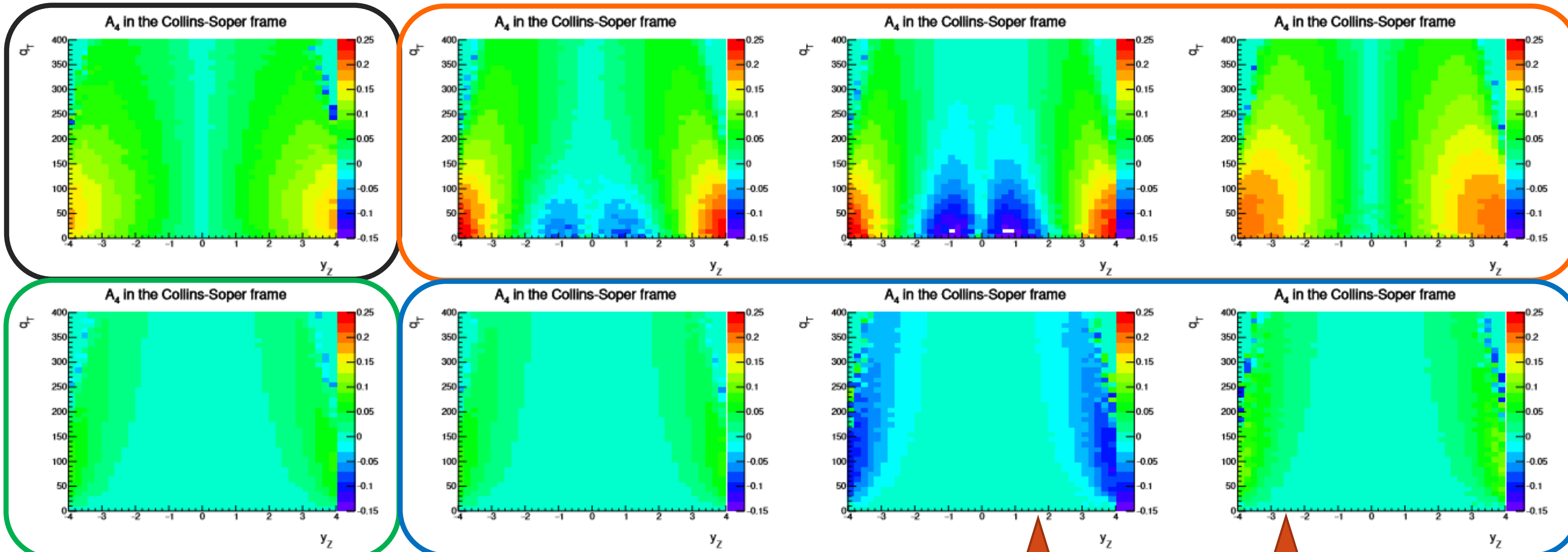
Spin-1 mediator (a-c)

A3, **A4**: Sensitive to the left- and right- handed couplings

A4 in the $y_Z - q_T$ plane

SM ZZ→2l2ν

Spin-0 mediator (a-c)



Spin-2 mediator

Spin-1 mediator (a-c)

A3, **A4**: Sensitive to the left- and right- handed couplings

Visible part: $\mathbf{x} = (y_{\mathrm{Z}}, q_{\mathrm{T}}, \cos\theta_{CS}, \phi_{CS})$

Invisible part (integrated): $(y_{\mathrm{Y}}, s_{\mathrm{Y}}, \cos\theta_{\chi}, \phi_{\chi})$

Setting limits on the coupling strength parameters

- **Benchmark scenarios S0a, S0b, S0c**
- **Benchmark scenarios S1a, S1b, S1c**

Setting limits on the coupling strength parameters

We exploit a dynamically constructed matrix element based likelihood function to set limits on the coupling strength parameters:

$$\rho(\mathbf{p}^{\mathrm{vis}}|\lambda) = \frac{1}{\sigma_\lambda}\sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F)\int d\Phi \frac{d\hat{\sigma}}{d\Phi}\prod_{i\in\mathrm{vis}}\delta(\mathbf{p}_i - \mathbf{p}_i^{vis})$$

Visible part: $\mathbf{x} = (y_Z, q_T, \cos\theta_{CS}, \phi_{CS})$

Invisible part (integrated): $(y_Y, s_Y, \cos\theta_\chi, \phi_\chi)$

λ scales couplings of the dark mediator to the dark matter and the SM particles at the same time

An unbinned likelihood fit is performed to extract limit

$$\mathcal{L}(\mathrm{data}|\lambda,\boldsymbol{\theta}) = \mathrm{Poisson}(N|S(\lambda,\boldsymbol{\theta}) + B(\boldsymbol{\theta}))\rho(\boldsymbol{\theta})\prod_i \rho(\mathbf{x}^i|\lambda,\boldsymbol{\theta}),$$

$$\rho(\mathbf{x}|\lambda,\boldsymbol{\theta}) = \frac{S(\lambda,\boldsymbol{\theta})\rho_s(\mathbf{x}^i,\lambda) + B(\boldsymbol{\theta})\rho_b(\mathbf{x}^i)}{S(\lambda,\boldsymbol{\theta}) + B(\boldsymbol{\theta})},$$

Evaluate test statistics in the large sample limit

Dual integration
- Integrate over the invisible part
- Evaluate the KL divergence term

$$t_\lambda = -2\ln\frac{\mathcal{L}(\mathrm{data}|\lambda,\hat{\boldsymbol{\theta}}_\lambda)}{\mathcal{L}(\mathrm{data}|\hat{\lambda},\hat{\boldsymbol{\theta}})}$$

$$t_\lambda \xrightarrow{N\to\infty} -2\ln\frac{\mathrm{Poisson}(N|S(\lambda)+B)}{\mathrm{Poisson}(N|B)} + 2N\int d\mathbf{x}\rho(\mathbf{x}|\lambda=0)\ln\frac{\rho(\mathbf{x}|\lambda=0)}{\rho(\mathbf{x}|\lambda)}$$

$$= -2\ln\frac{\mathrm{Poisson}(N|S(\lambda)+B)}{\mathrm{Poisson}(N|B)} + 2N\cdot D(\rho(\mathbf{x}|\lambda=0)||\rho(\mathbf{x}|\lambda)).$$

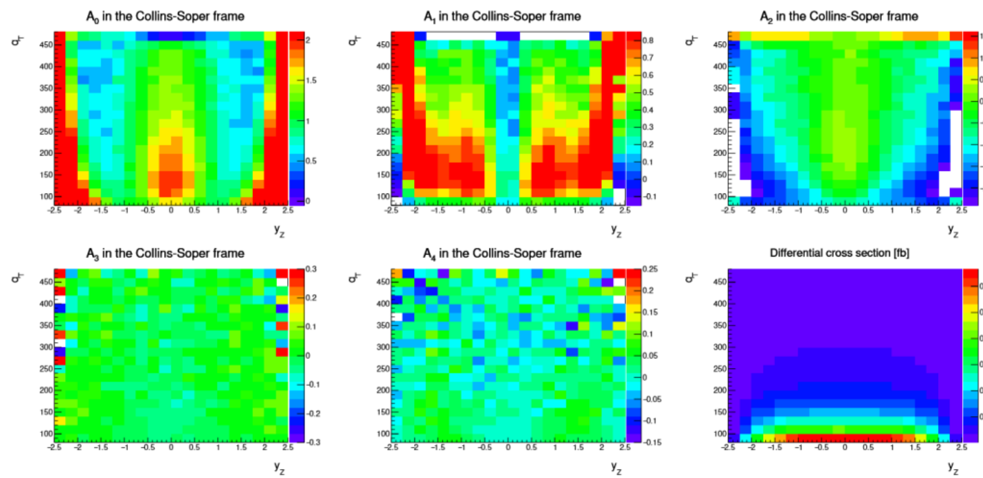
Background modeling and event selections

Consider the same selections as in the 13 TeV CMS measurement:
JHEP 03 (2017) 061

Selections implemented in numerical integration (BL-selections):

Variable	Requirements
p_T^l	> 20 GeV
s_Z	NWA
E_T^{miss}	> 80 GeV
$\|\eta_l\|$	< 2.4
ΔR_{ll}	> 0.4
$\|y_Z\|$	< 2.5

Distributions distorted by selections. Shown for background only hypothesis

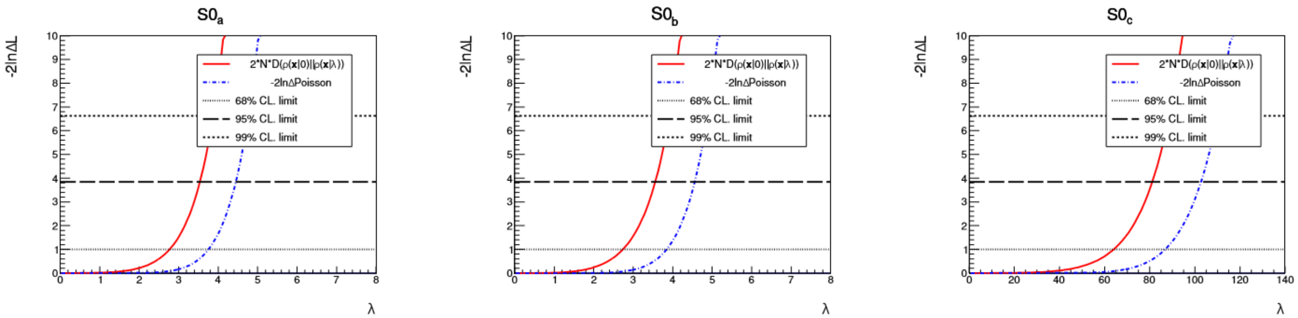


Other selection effects are included through an ancillary $A \cdot \epsilon$ factor.
Event rate corresponds to 13 TeV LHC with 150 fb^{-1} data.

	Process	Cross section with BL-selections (fb)	Ancillary $A \cdot \epsilon$	Events
Matrix Element	ZZ$\rightarrow 2l2\nu$	27.7	0.488	2028
Phase space	Non-resonant-ll	1.57×10^3	5.80×10^{-3}	1370
Matrix Element	WZ($\rightarrow e\nu 2l$)	17.05	0.296	757
Matrix Element	$Z/\gamma^* \rightarrow l^+l^-$	3.61×10^4	1.23×10^{-4}	665

Setting limits on the coupling strength parameters

Upper limits on the coupling strength parameters of the S0 benchmark scenarios.



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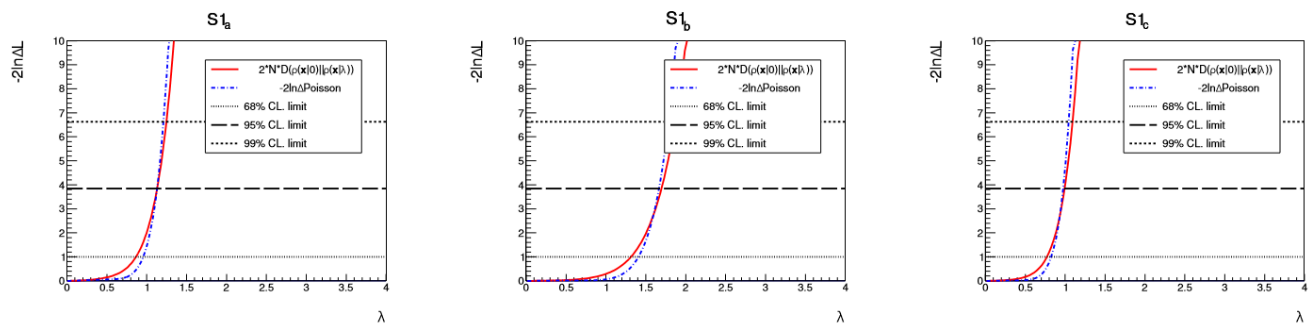

Benchmark	$S0_a$	$S0_b$	$S0_c$	$S1_a$	$S1_b$	$S1_c$
Limit from the normalization term (λ_1)	4.4	4.6	103	1.1	1.7	0.97
Signal cross section at λ_1 (fb)	1.86	1.87	1.86	1.87	1.87	1.87
Limit from the KL-divergence term (λ_2)	3.5	3.6	81	1.1	1.7	0.99
Signal cross section at λ_2 (fb)	0.75	0.70	0.72	1.9	2.0	2.0
Combined limit (λ_0)	3.5	3.5	79	1.0	1.5	0.89

Close

Quantify the shape improvements

Summary and outlook

- Simplified dark sector models with scalar, vector, and tensor mediators have different signatures in the distribution of A0-A4.
- Angular coefficients can be used to distinguish different scenarios of the spin-0 and spin-1 models, including the ones with P- and CP-odd operators.
- Shape differences provide significant improvements in the limits, especially for the scalar mediator models.

  - Example Matrix Element Kinetic Discriminator results available in a new version of the paper.
  - W boson leptonic decay channel

Thanks for your attention!