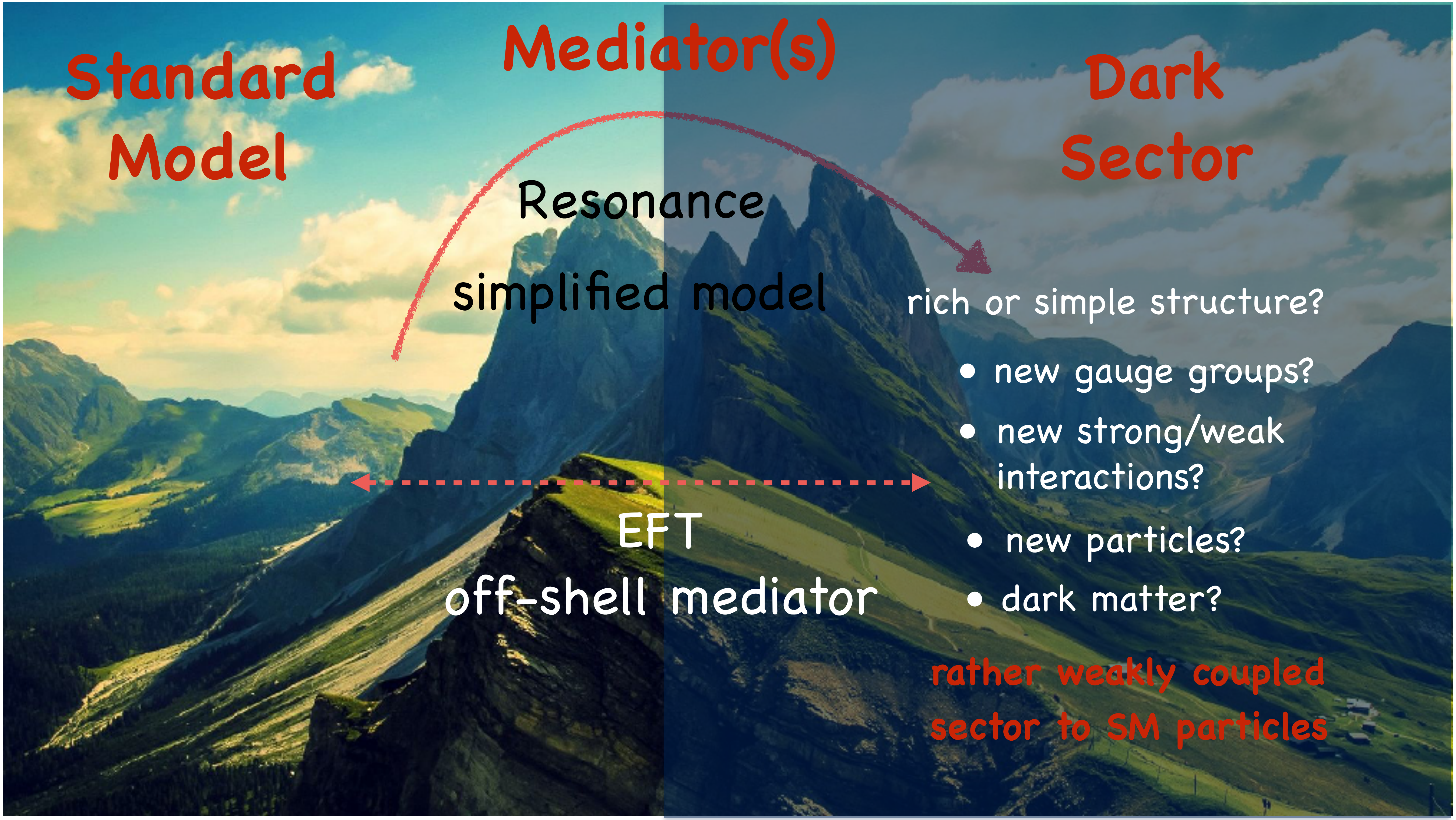
FCC
hh ee he

Probing Dark Sectors at Future Colliders

Michael Spannowsky

IPPP, Durham University



Resonant phenomenology rather one-directional
- its difficult to excite particles in the dark sector directly

How to study structure of dark sector?

Incomplete list how to receive echoes from dark sectors

It depends on **nature of mediator** and **dark sector structure**

Gravity

- **direct**, e.g. Planck, velocity of galaxies
- **indirect**, e.g. grav. waves from first-order phase transition

vector mediator

(new gauge group)

- **direct**, e.g. hidden valley phenomenology, comp. dark matter, …
- **indirect**, e.g. running of gauge coupling

scalar mediator

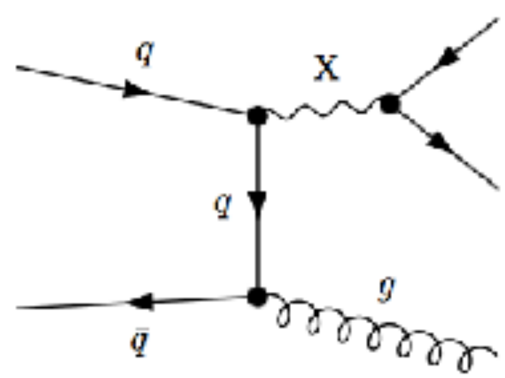
- **direct**, e.g. hidden valley phenomenology, …
- **indirect**, e.g. running of mixing angles,…

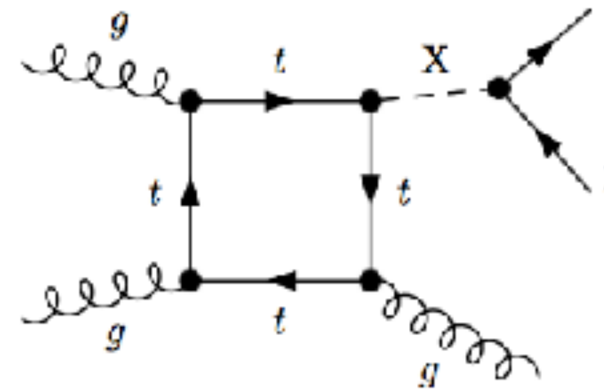
See talks by D. Curtin, S. Iwamoto, A. Katz, M. McCullough, J. Zurita

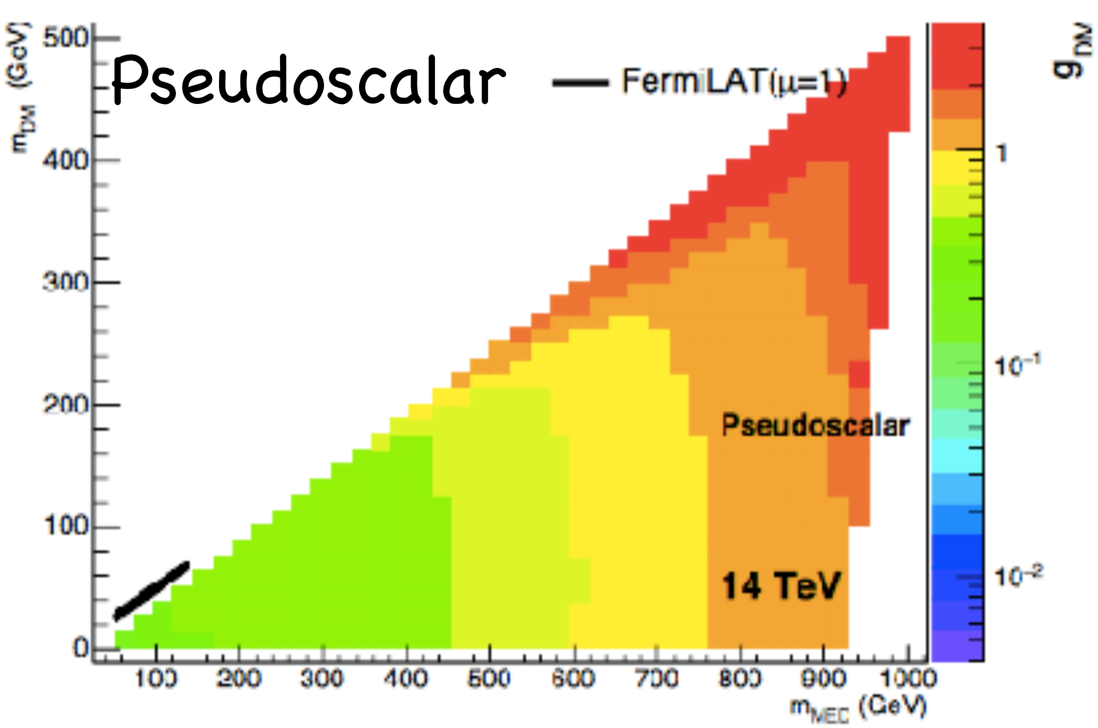
Window to dark sector at HL-LHC

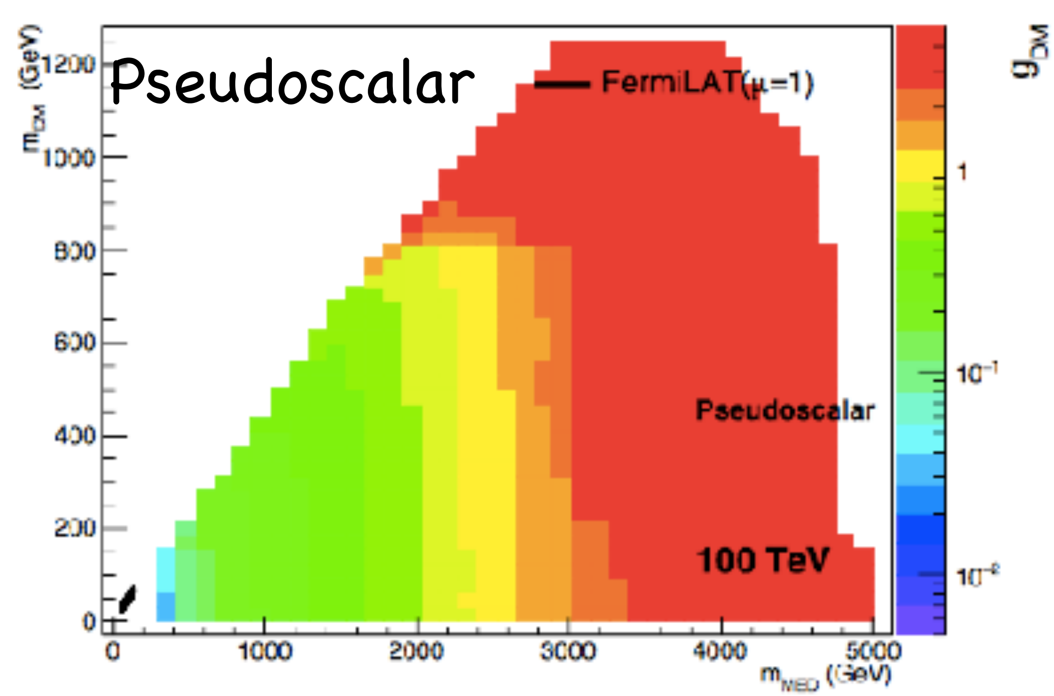
Let's first discover dark sector...

monojet and multijet searches can establish existence of dark sector









Direct dark sector spectroscopy at e+e- colliders

- Can we access the quantum numbers of the mediator and dark sector particle, e.g. spin or masses?

[Dreiner, Huck, Kraemer, Schmeier, Tattersall '12]
[Andersen, Rauch, MS '13]
[Chacko, Cui, Hong '13]

- Let us pick a benchmark simplified model

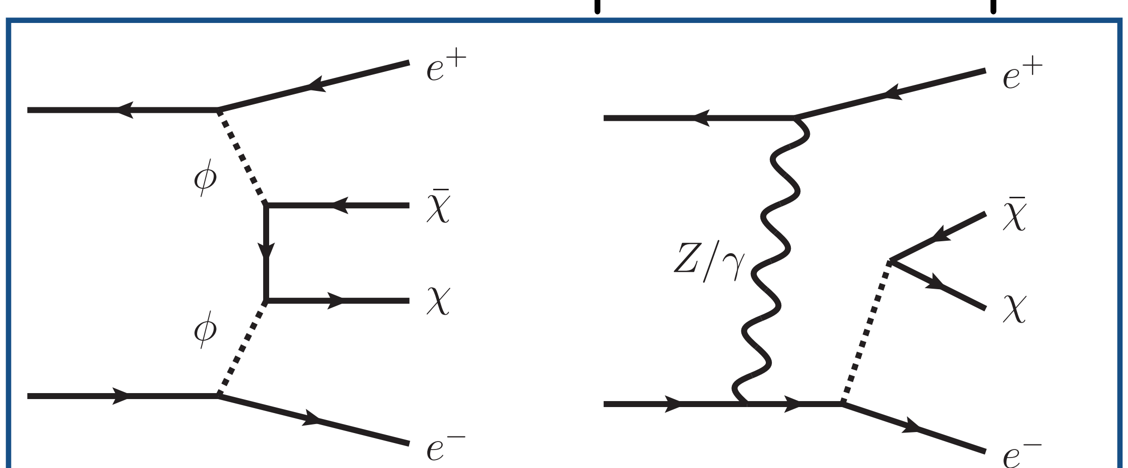
assume mediator couples between electron and dark sector particle

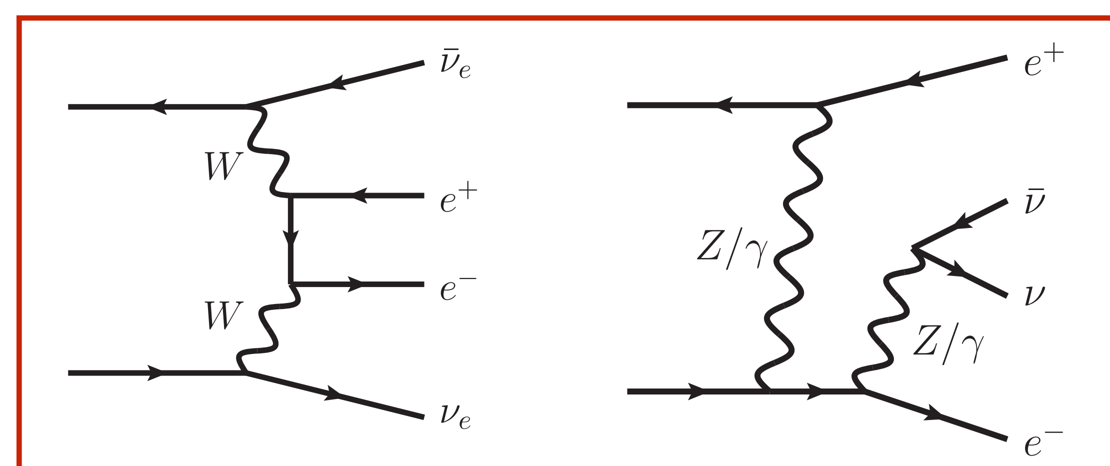
	scalar	vector
e	$i\, g_{ee\phi,S}\ \bar{e}e\ \phi_S$	$i\, g_{ee\phi,V}\ \bar{e}\gamma_\mu e\ \phi_V^\mu$
χ	$i\, g_{\chi\chi\phi,S}\ \bar{\chi}\chi\ \phi_S$	$i\, g_{\chi\chi\phi,V}\ \bar{\chi}\gamma_\mu\chi\ \phi_V^\mu$

$$M_* = \frac{M_\phi}{\sqrt{g_{ee\phi}\, g_{\chi\chi\phi}}}$$

model	mediator mass	mediator spin	WIMP mass	M_*
LSL	8 GeV	0 (scalar)	5 GeV	30 GeV
LVL	8 GeV	1 (vector)	5 GeV	30 GeV
LSH	8 GeV	0 (scalar)	120 GeV	27.4 GeV
LVH	8 GeV	1 (vector)	120 GeV	21 GeV
HSL	200 GeV	0 (scalar)	5 GeV	1250 GeV
HVL	200 GeV	1 (vector)	5 GeV	1250 GeV
HSH	200 GeV	0 (scalar)	120 GeV	332.4 GeV
HVH	200 GeV	1 (vector)	120 GeV	511.8 GeV

- In VBF-like final state possible to exploit kinematic distributions





Direct dark sector spectroscopy at e+e- colliders

- The **spin of the mediator** can be probed directly in this multi-Regge kinematic limit, where the invariant mass bigger than prop. momentum $s_{ij} \gg |t_i|$

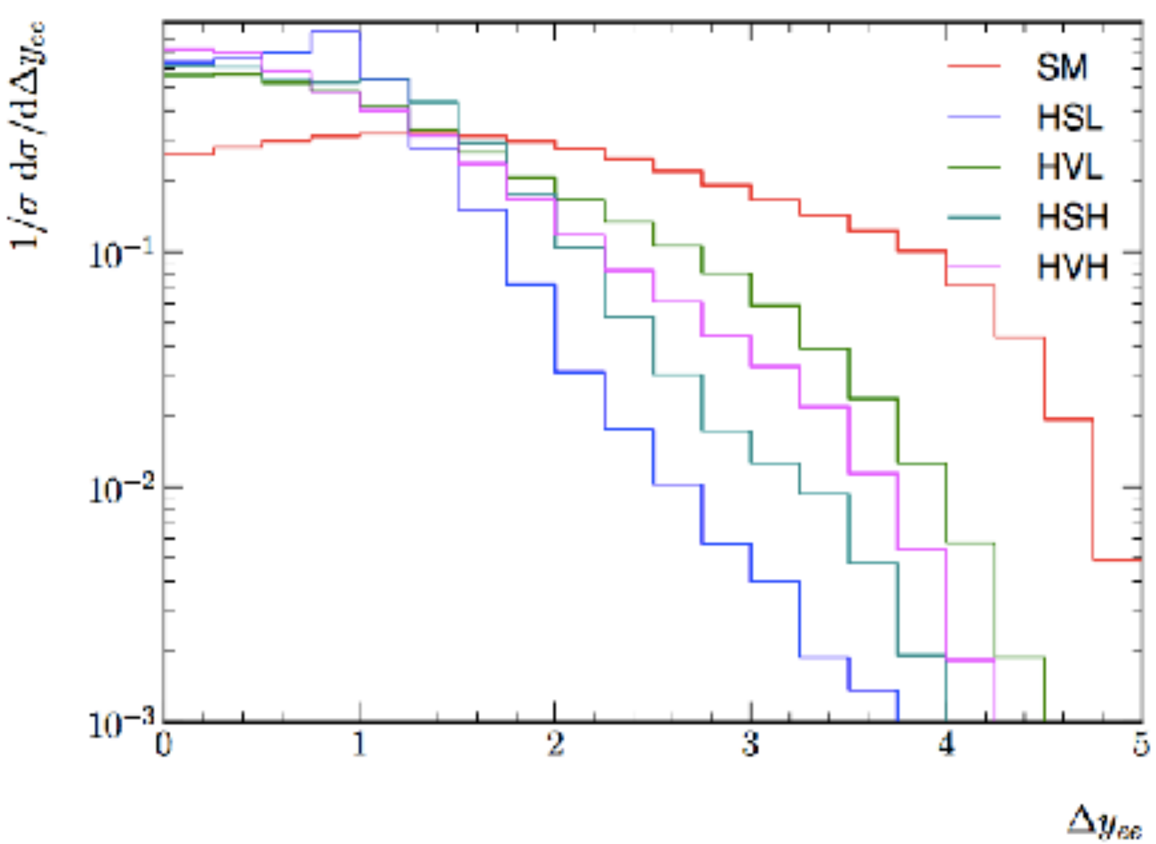
Behaviour of 2->n scattering is for rapidity ordered momenta p determined by

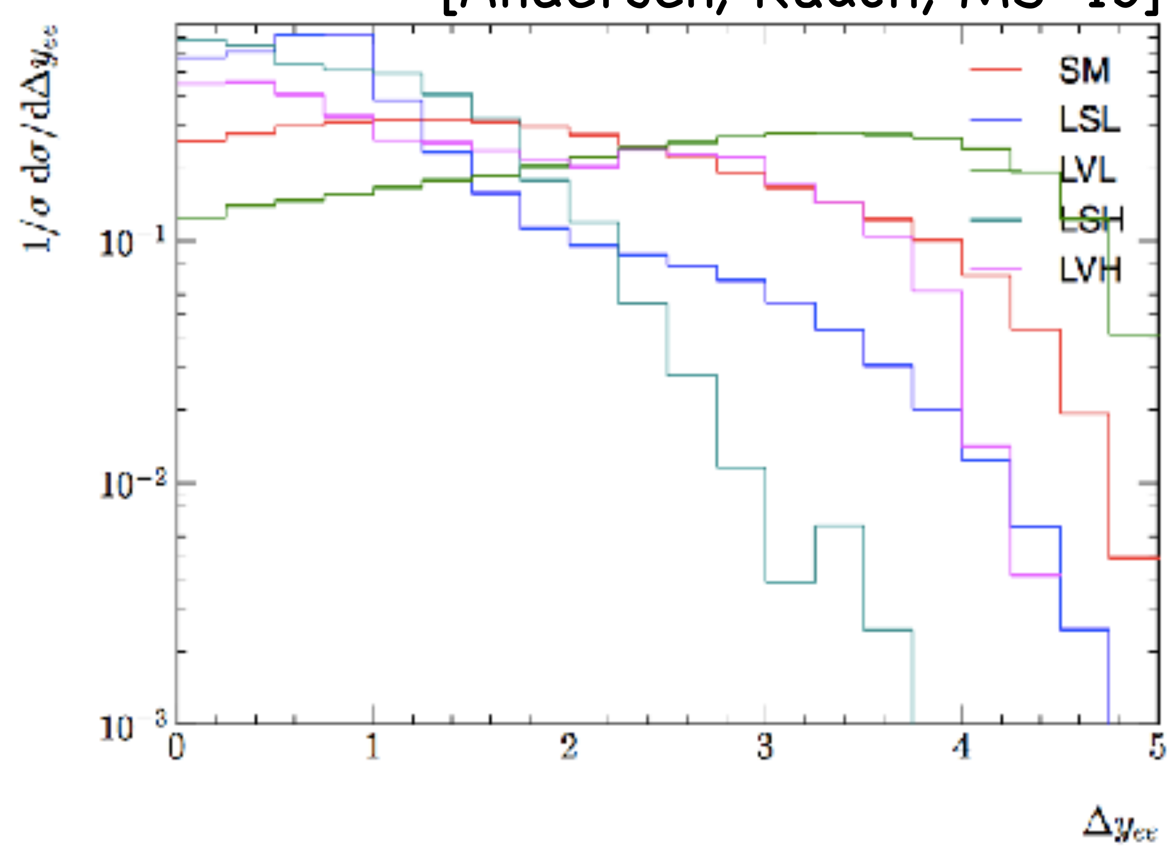
[Regge 1959]

$$\mathcal{M}^{p_a p_b \to p_1 p_2 p_3 p_4} \to s_{12}^{\alpha_1(t_1)}\ s_{23}^{\alpha_2(t_2)}\ s_{34}^{\alpha_3(t_3)}\ \gamma$$

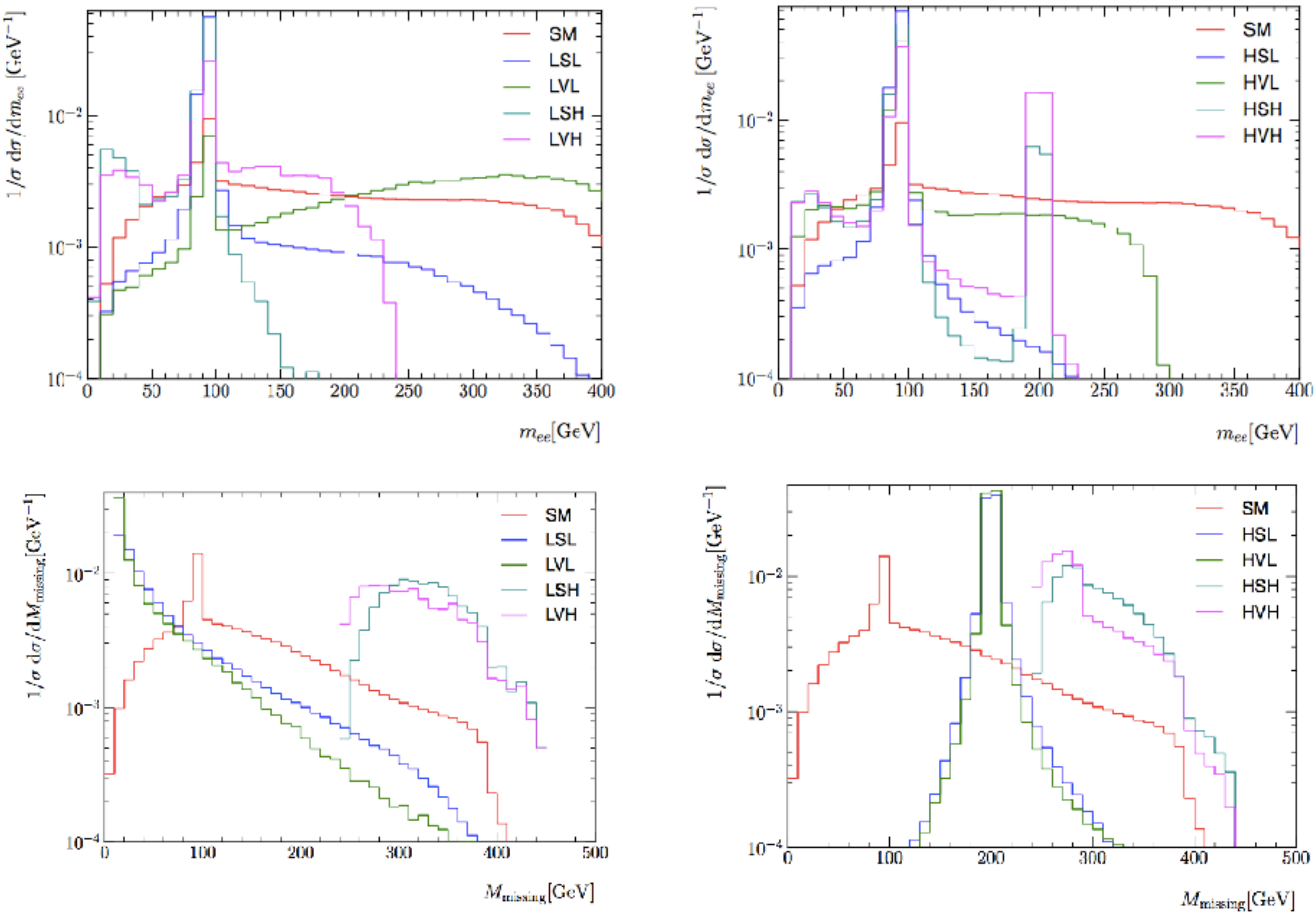
Powers determined by spin $\alpha_i = J_i$ → can probe spin in mjj or yjj

[Andersen, Rauch, MS '13]





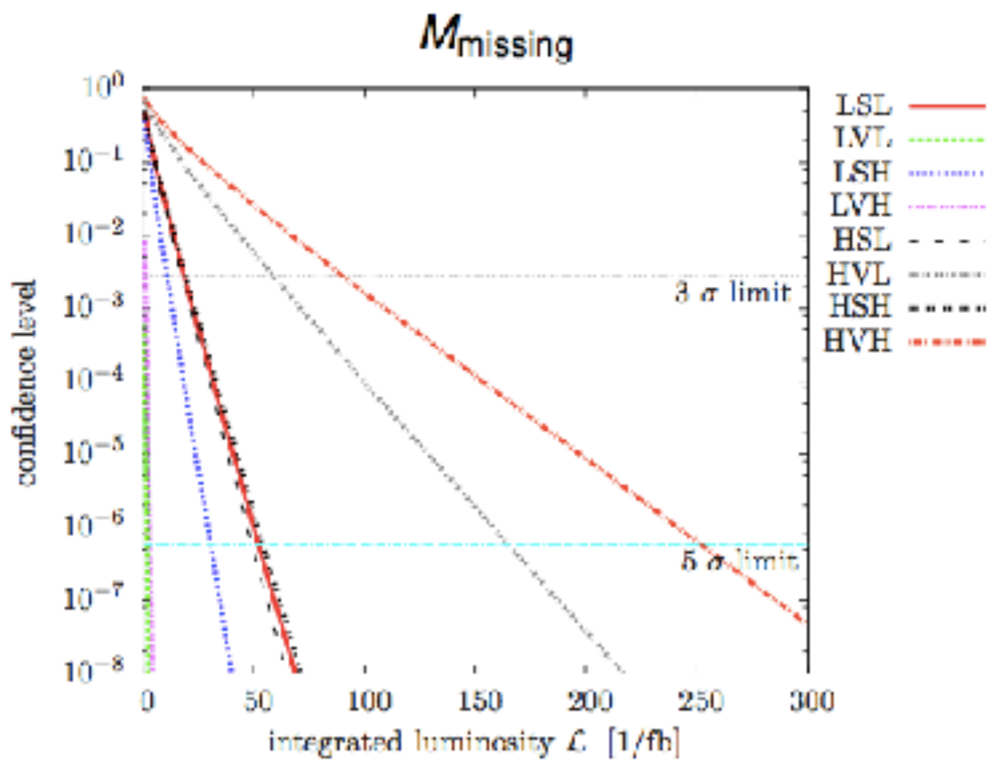
Direct dark sector spectroscopy at e+e- colliders

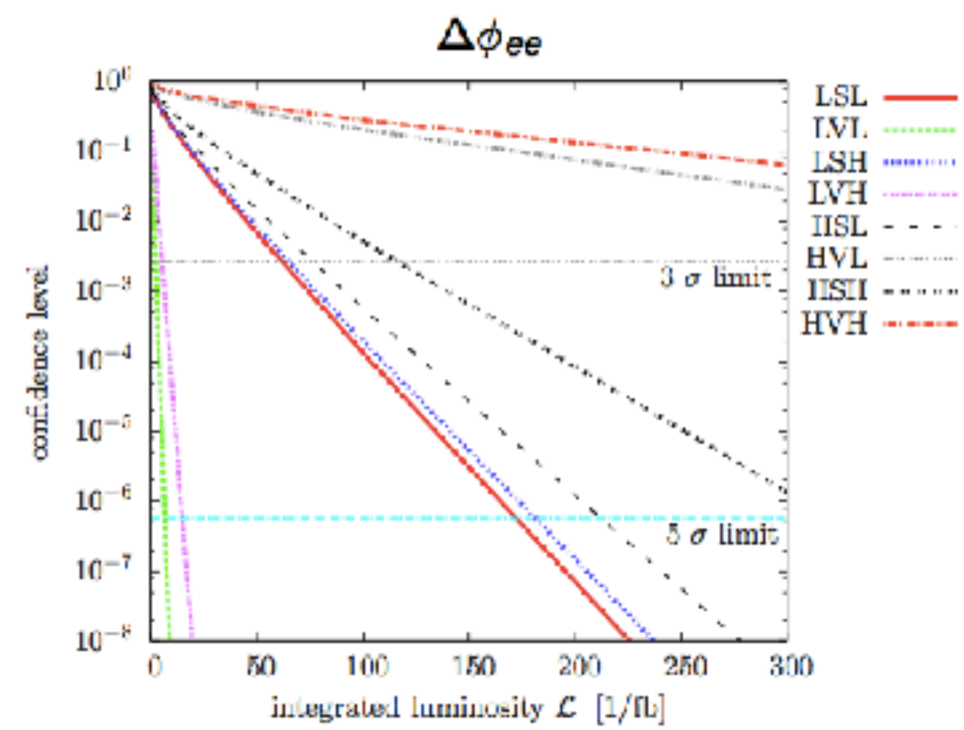


Direct dark sector spectroscopy at e+e- colliders

ILC, binned log-likelihood

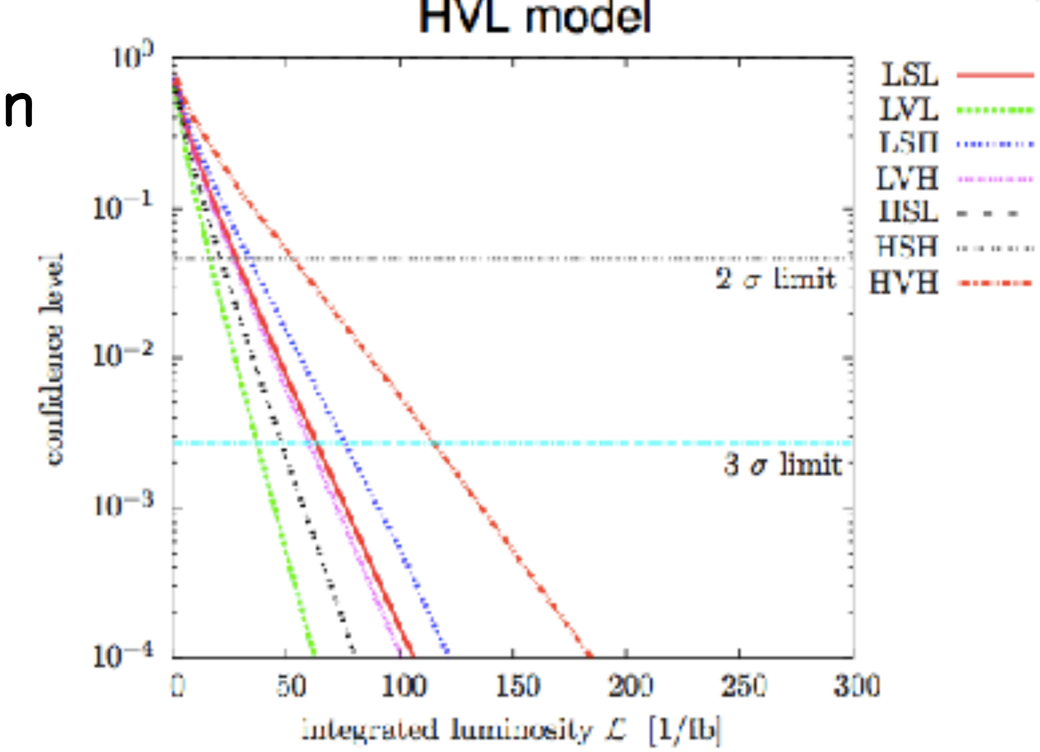
discovery

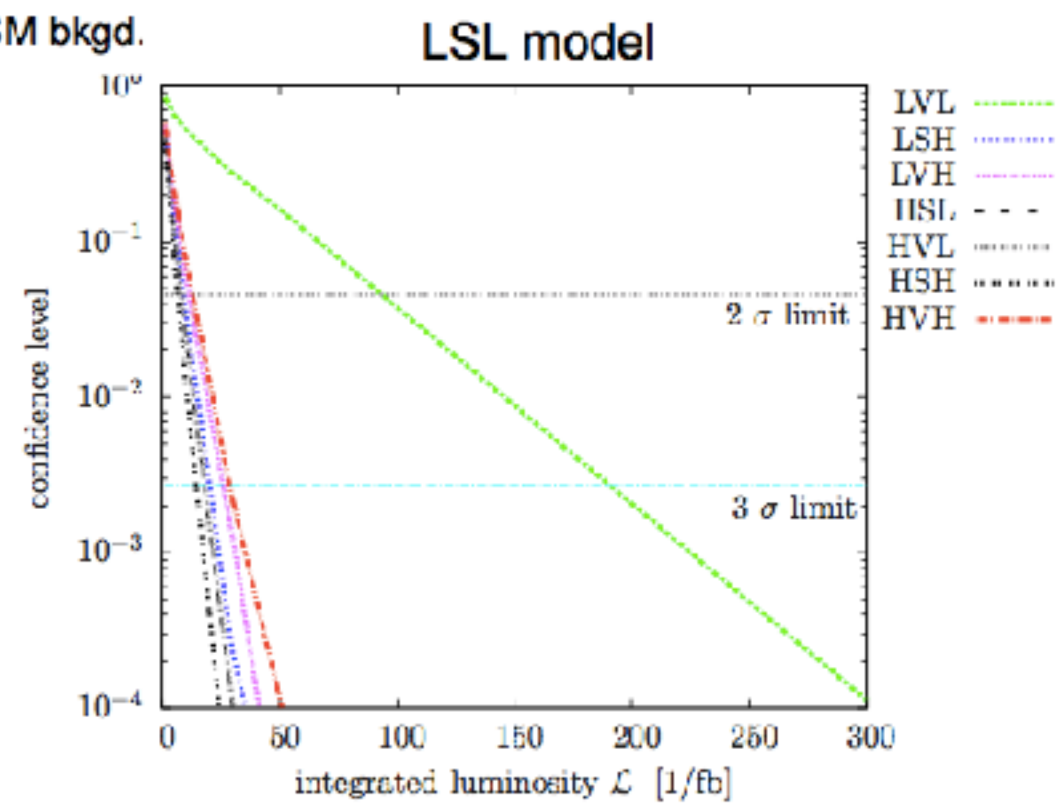




$\sigma = 2.5\% \times \sigma_{\text{SM bkgd.}}$

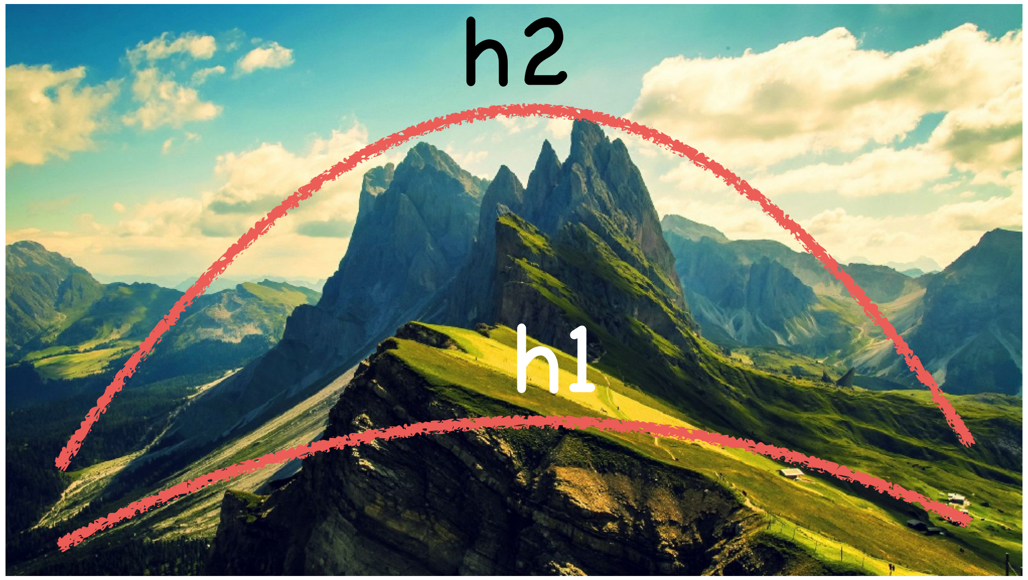
model discrimination

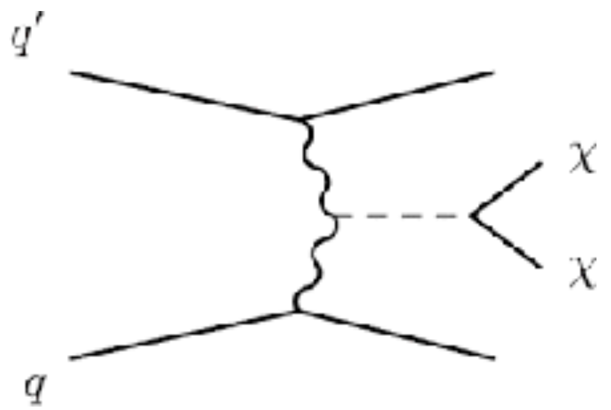




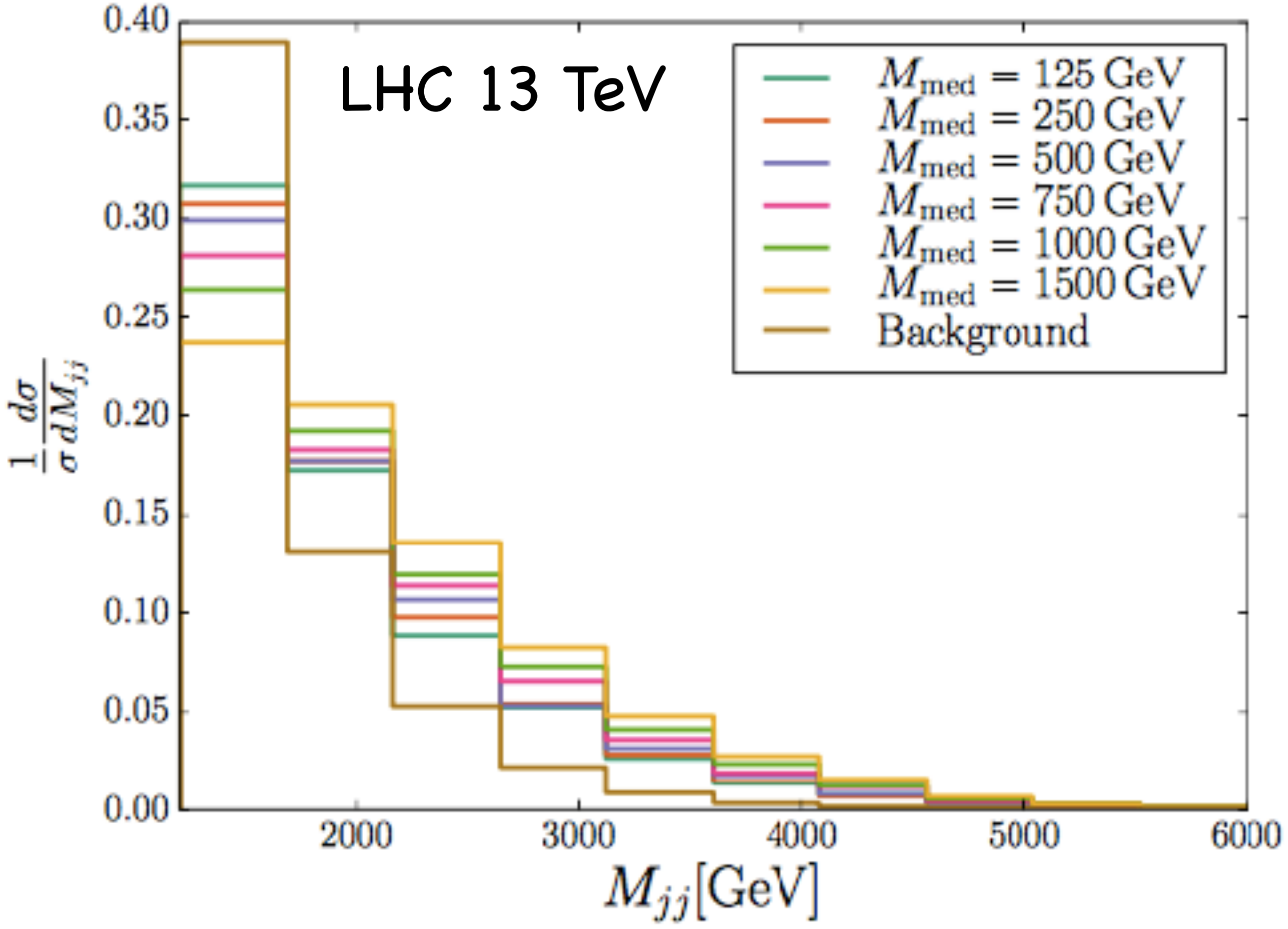
[Khoze, Ro, MS '15]

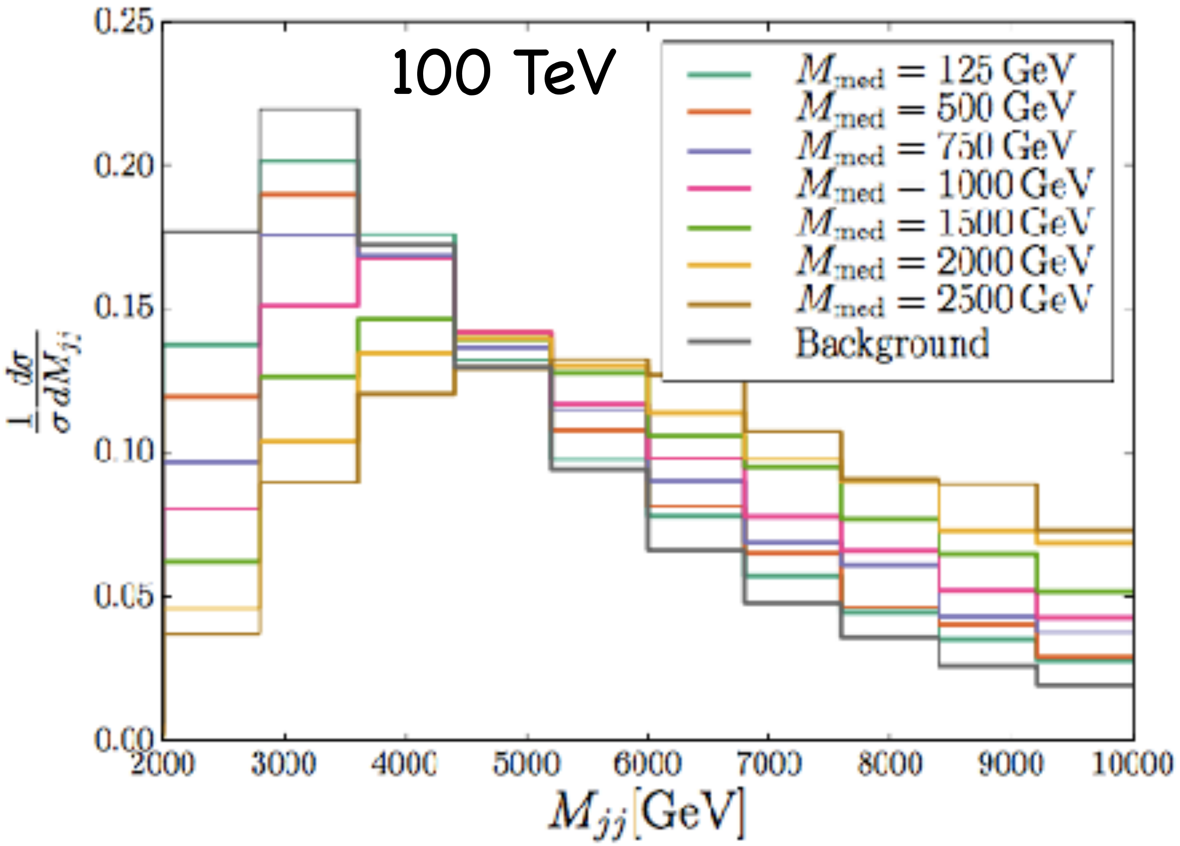
Measuring the mediator mass at the LHC



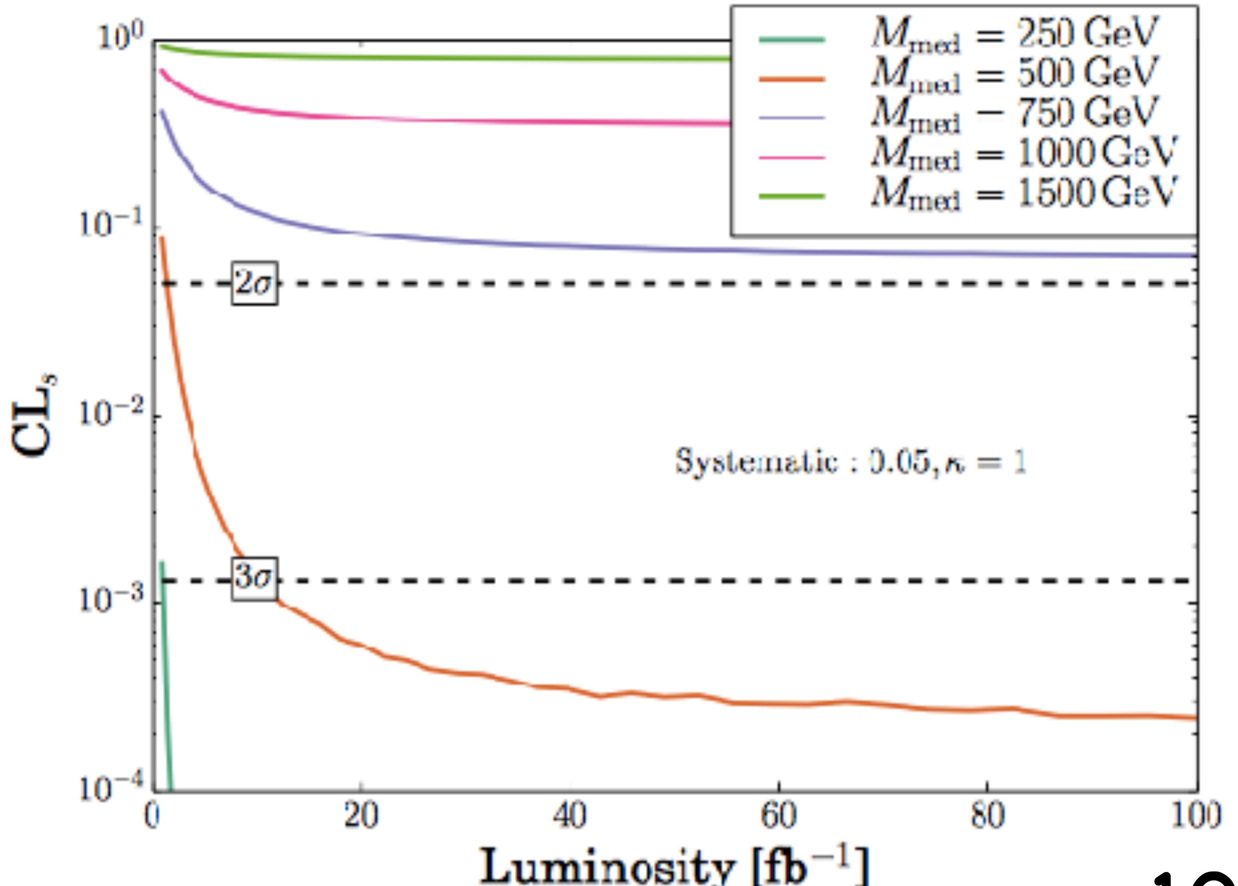


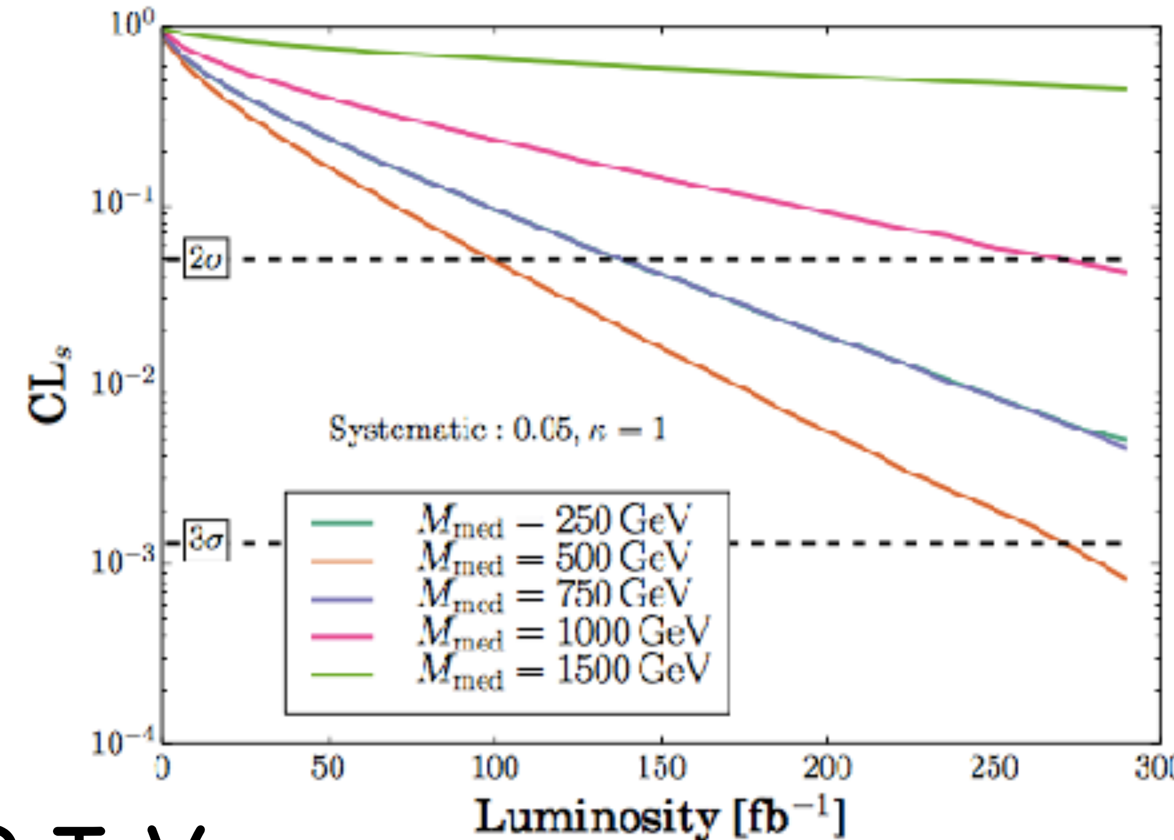
$$\mathcal{L} = \sqrt{\kappa}\left(\frac{2M_W^2}{v}W_\mu^+W^{-\mu} + \frac{M_Z^2}{v}Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\bar{f}f\right)\phi - g_{\rm DM}\bar{\chi}\chi\phi - \frac{1}{2}M_{\rm med}^2\phi^2 - m_\chi\bar{\chi}\chi$$



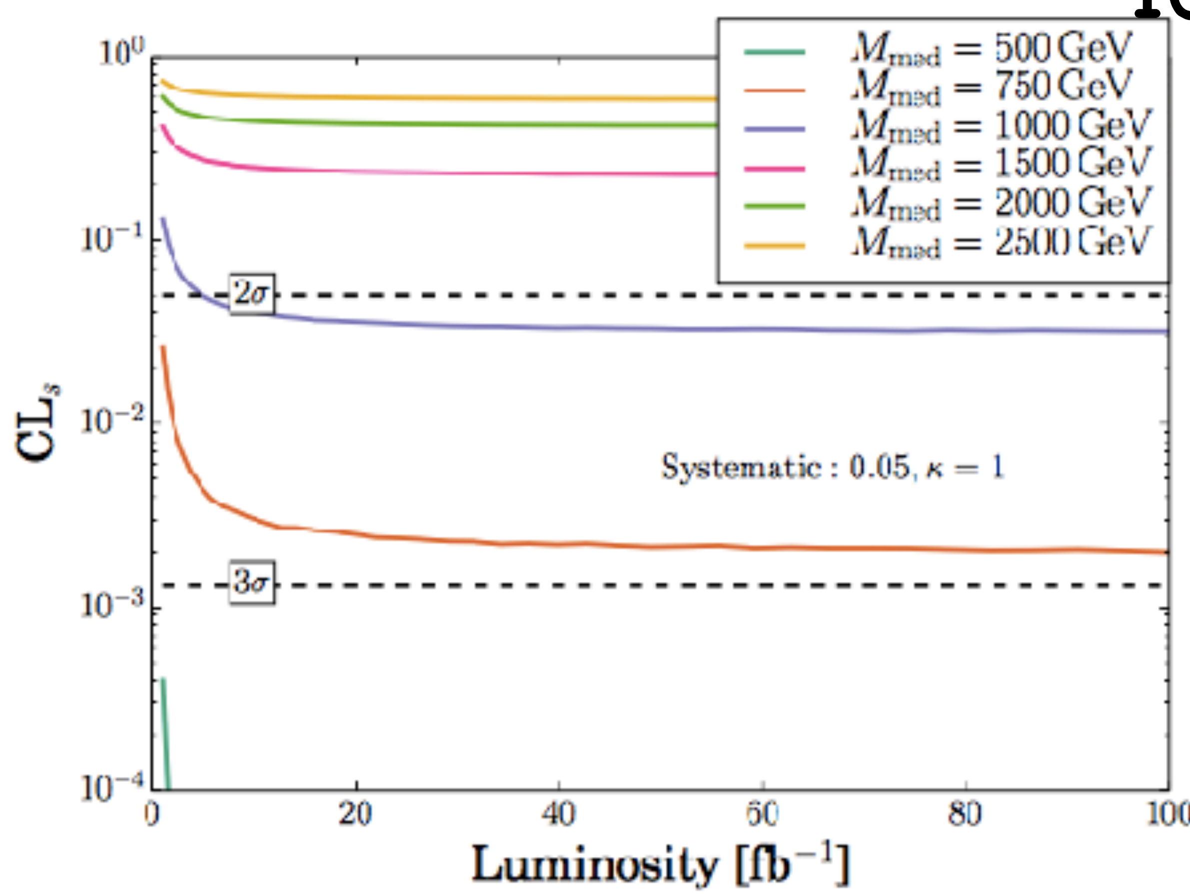


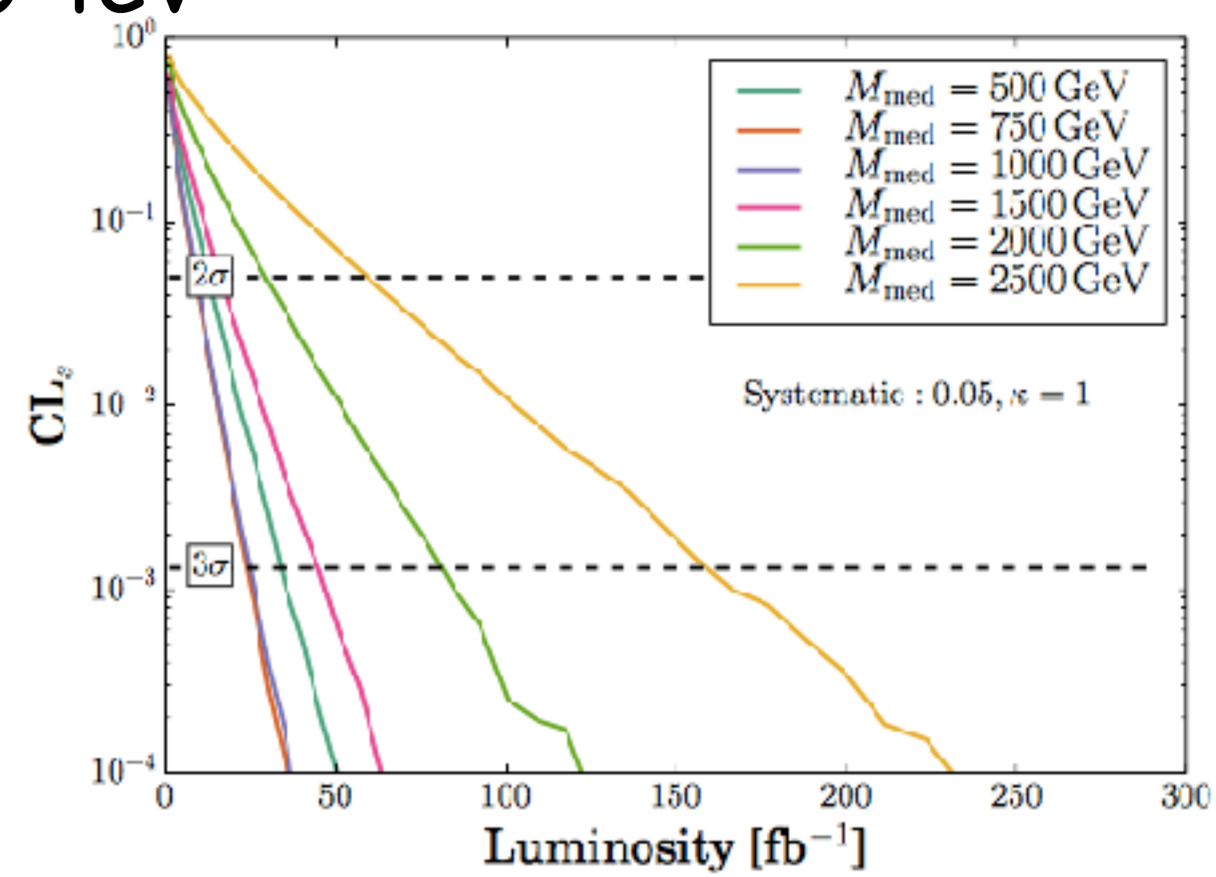
vs SM LHC vs M = 125 GeV





100 TeV





Indirect dark sector spectroscopy through scale dependence

[Englert, Nordstrom, MS '16]

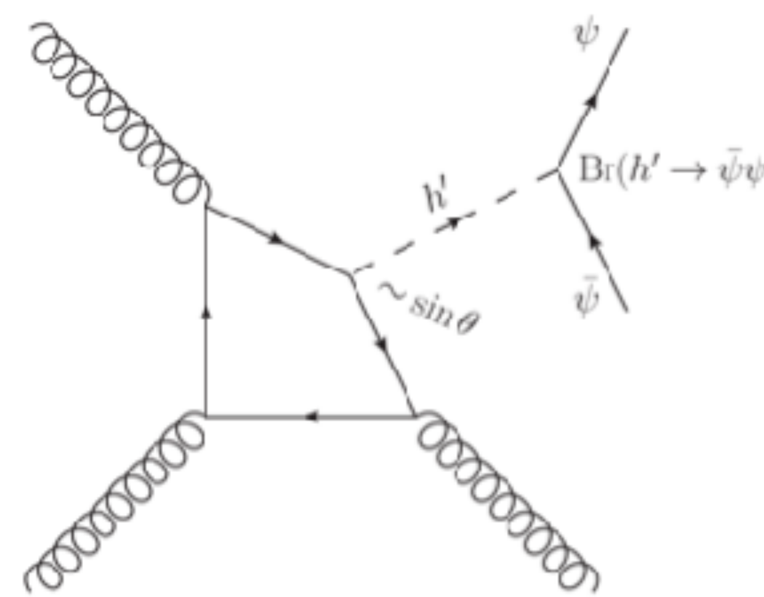
- assume UV model with vector and scalar mediators
- proton-collider experiments better in excluding vector than scalar mediators
  see talks by M. Chala and P. Harris
- In vector case coupling to dark sector and SM needs to be gauge couplings, e.g.

$$\mathrm{SM} \times U(1)_{\mathrm{mediator}} \times SU(N)_{\mathrm{dark}}$$

mediator coupling running according to

$\longrightarrow$ $$\mu \frac{\mathrm{d}g'}{\mathrm{d}\mu} \propto \frac{(g')^3}{16\pi^2}$$

$\longrightarrow$ only total nr contributing degrees of freedom to running, see α_s and α_W [Becciolini et al '14] [Alves et al '14]



- Instead scalar mediator interaction sensitive to internal dynamics of dark sector

In SM 1-loop RGE of top Yukawa

$$\mu \frac{\mathrm{d}y_t^{\rm SM}}{\mathrm{d}\mu} = \frac{y_t^{\rm SM}}{16\pi^2}\left(\frac{9}{2}(y_t^{\rm SM})^2 - \frac{17}{12}g_Y^2 - \frac{9}{4}g_L^2 - 8g_3^2\right)$$

$$\mu \frac{\mathrm{d}g'}{\mathrm{d}\mu} \propto \frac{(g')^3}{16\pi^2}$$

dials sensitivity on QCD sector into Higgs-top interaction

For scalar mediators, can expect echo of dynamics in dark sector in mediator cross section

Let us assume for the following extended scalar sector:

See talks by M. Ramsey-Musolf and D. Buttazzo

$$V(H,\phi) = -m_H^2 H^\dagger H - \frac{m_\phi^2}{2}\phi^2 + \lambda_1 (H^\dagger H)^2 + \frac{\lambda_2}{4}\phi^4 + \frac{\lambda_3}{2}\phi^2 H^\dagger H.$$

$$H = \begin{pmatrix} 0 \\ (v+h_1)/\sqrt{2} \end{pmatrix}, \quad \phi = (x + h_2),$$

vevs

$$\begin{pmatrix} h \\ h' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$\tan 2\theta = \frac{\lambda_3 v x}{\lambda_2 x^2 - \lambda_1 v^2}$$

effect visible in SM sector

Example: **Scalar mediator with SU(N) in dark sector**

$$\mathcal{L}_{\rm dark} = -Y_\psi^{i,j}\phi\bar\psi^i\psi^j + \text{h.c.} + i\bar\psi\gamma^\mu D_\mu\psi - \frac{1}{4g_d^2}G^a_{\mu\nu}G^{a,\mu\nu}\,.$$

With 3 generations of Dirac fermions transform in the representation **M**

free parameters are $Y_\psi^{3,3}, g_d, \theta, m(h'), x$

we choose in agreement with existing constraints:

$x = 100$ GeV, $Y_\psi^{3,3} = 0.7$, $\theta = 0.5^\circ$ and $m(h') = 150$ GeV

$$\longrightarrow \quad \text{Br}(h' \to \psi\bar\psi) \approx 1$$

much like in SM mutual dependence of free parameters

$$\mu\frac{\mathrm{d}g_d}{\mathrm{d}\mu} = -\left(\frac{11}{3}C(\mathbf{A}) - 4\,T(\mathbf{M})\right)\frac{g_d^3}{16\pi^2} \qquad \mu\frac{\mathrm{d}x}{\mathrm{d}\mu} = -2\,\text{Dim}(\mathbf{M})\,(Y_\psi^{3,3})^2\frac{x}{16\pi^2}$$

$$\mu\frac{\mathrm{d}Y_\psi^{3,3}}{\mathrm{d}\mu} = \left(-6\,C(\mathbf{M})\,g_d^2 + (2\,\text{Dim}(\mathbf{M})+3)(Y_\psi^{3,3})^2\right)\frac{Y_\psi^{3,3}}{16\pi^2}$$

$$\mu\frac{\mathrm{d}\lambda_2}{\mathrm{d}\mu} = \left(18\lambda_2^2 + 2\lambda_3^2 + 8\,\text{Dim}(\mathbf{M})\,\lambda_2(Y_\psi^{3,3})^2 - 8\,\text{Dim}(\mathbf{M})\,(Y_\psi^{3,3})^4\right)\frac{1}{16\pi^2}$$

$$\mu\frac{\mathrm{d}\lambda_3}{\mathrm{d}\mu} = \left(-\frac{3}{2}g_1^2 - \frac{9}{2}g_2^2 + 12\lambda_1 + 6\lambda_2 + 4\lambda_3 + 4\,\text{Dim}(\mathbf{M})\,(Y_\psi^{3,3})^2 + 6y_t^2\right)\frac{\lambda_3}{16\pi^2}$$

Example: **Scalar mediator with U(1) in dark sector**

$$\mathcal{L}_{\rm dark} = -Y_u^{i,j}\phi^\dagger \bar{u}_d^i q_d^j - Y_d^{i,j}\phi \bar{d}_d^i q_d^j + \text{h.c.}$$
$$+ i\bar{q}_d\gamma^\mu D_\mu q_d + i\bar{u}_d\gamma^\mu D_\mu u_d + i\bar{d}_d\gamma^\mu D_\mu d_d - \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu}\,.$$

to avoid anomalies we add dark fermion field with charges $q_d \sim 0$, $u_d \sim 1/2$, $d_d \sim -1/2$, and for complex scalar $\phi \sim 1/2$

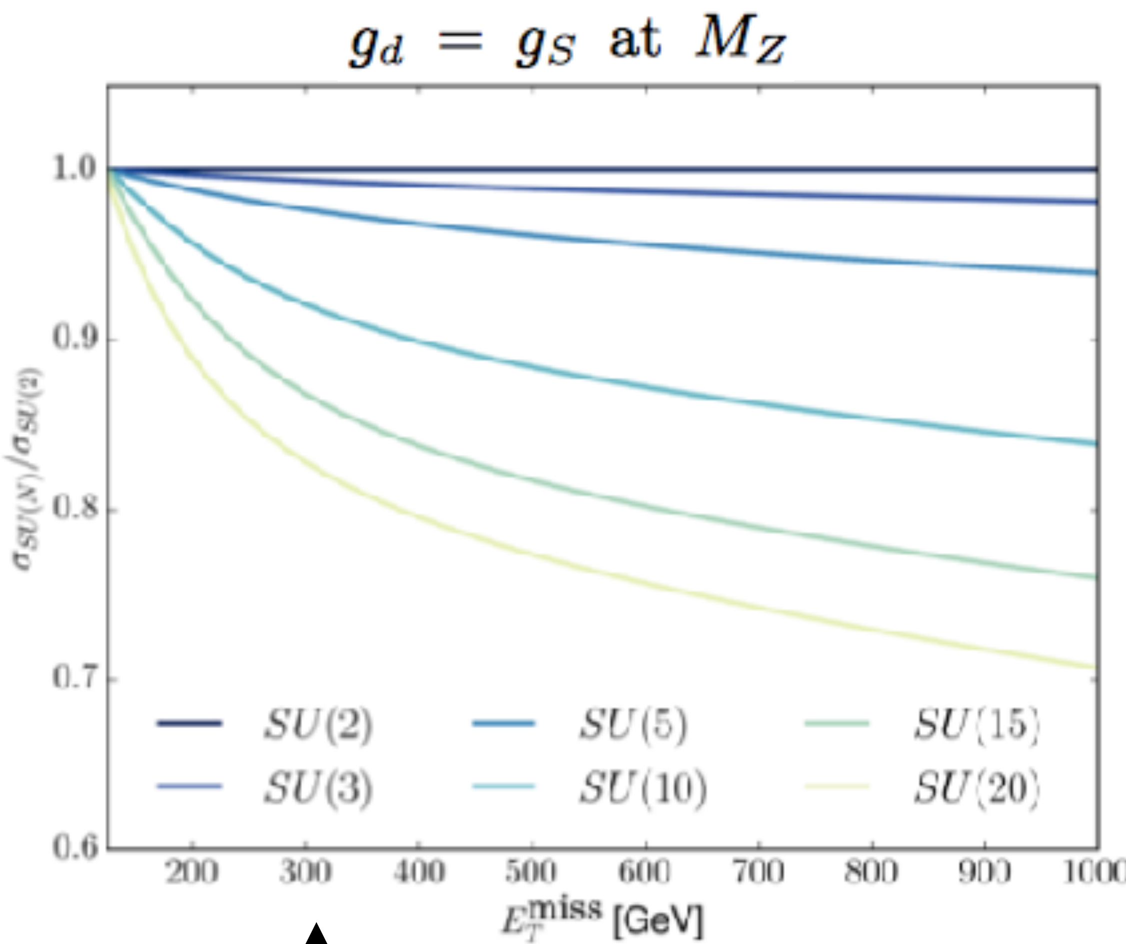
(no kinetic mixing between U(1) and U(1)$_Y$)

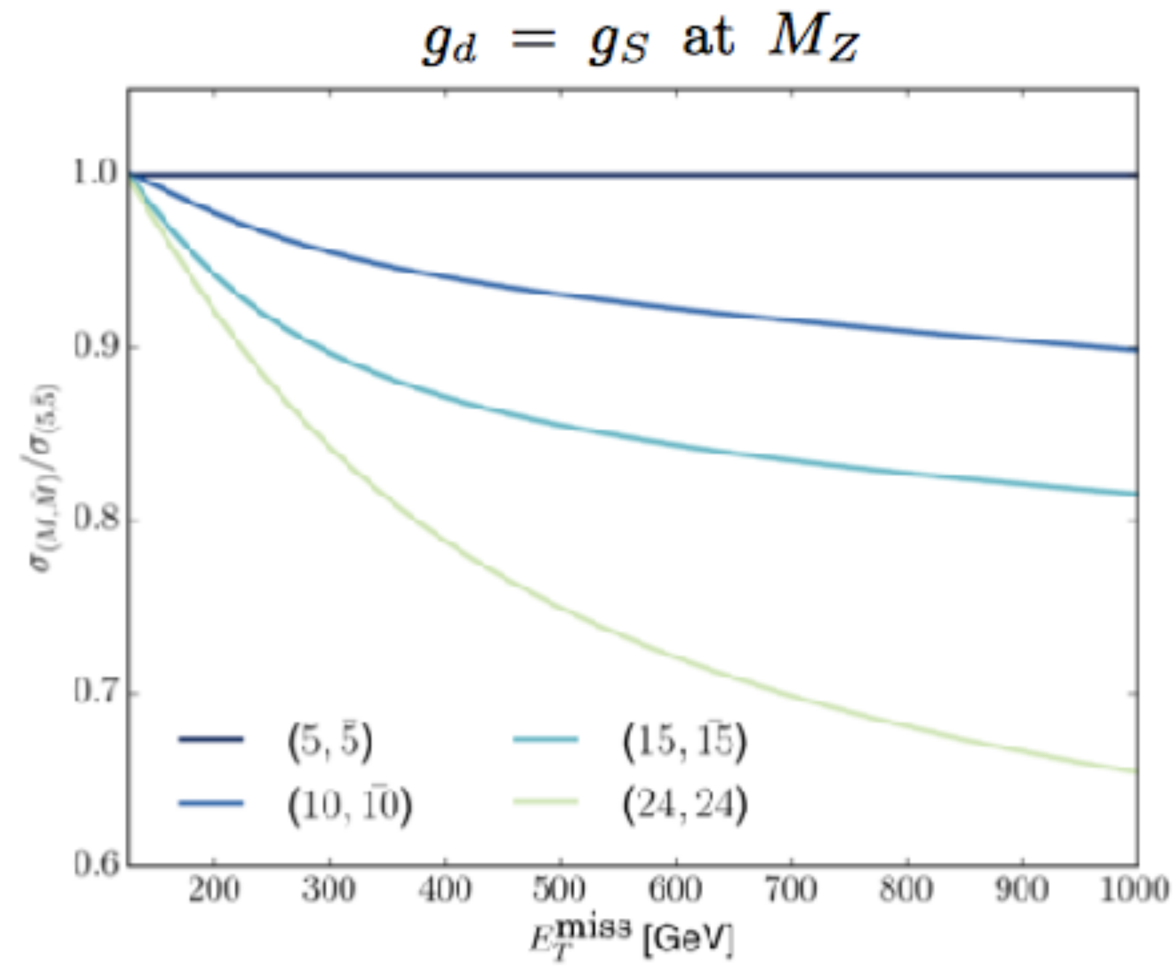
$$\mu\frac{\mathrm{d}g}{\mathrm{d}\mu} = \frac{13}{12}\frac{g^3}{16\pi^2}\,, \qquad \mu\frac{\mathrm{d}x}{\mathrm{d}\mu} = -(Y_u^{3,3})^2\frac{x}{16\pi^2}$$

$$\mu\frac{\mathrm{d}Y_u^{3,3}}{\mathrm{d}\mu} = \left(-\frac{3}{4}g^2 + 2(Y_u^{3,3})^2\right)\frac{Y_u^{3,3}}{16\pi^2}\,,$$

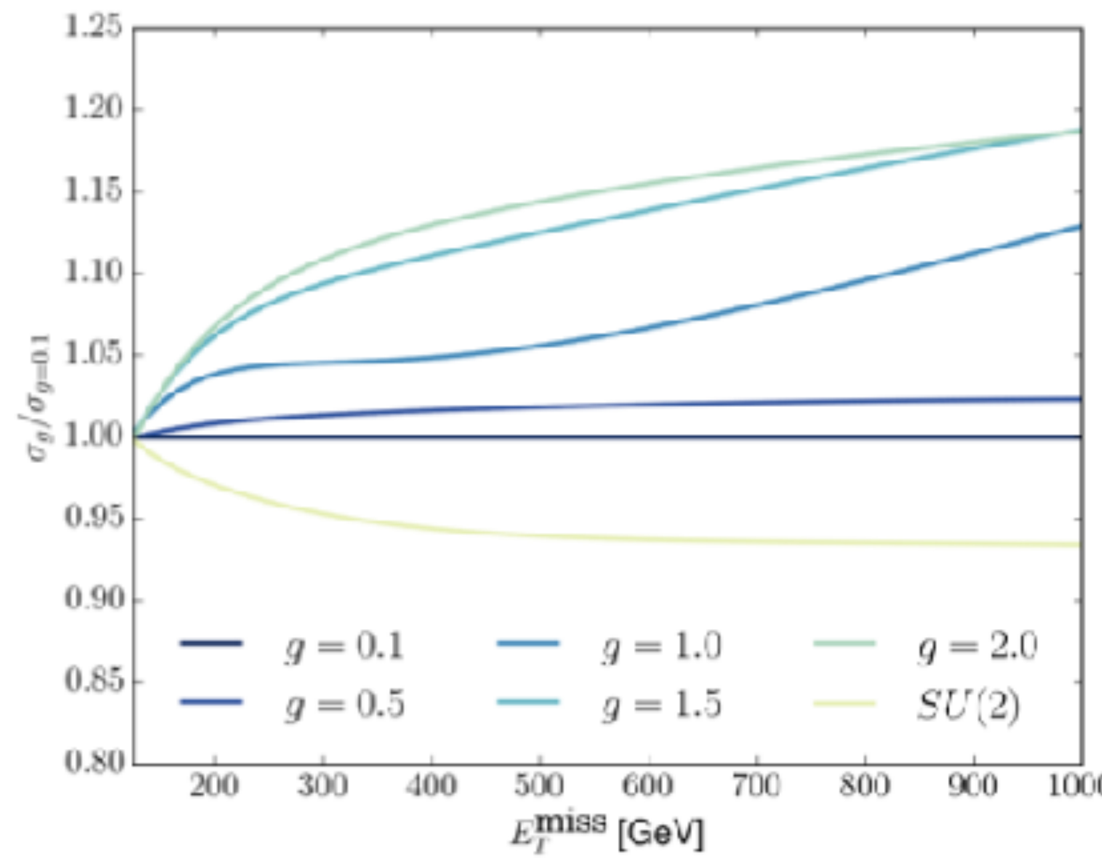
$$\mu\frac{\mathrm{d}\lambda_2}{\mathrm{d}\mu} = \left(20\lambda_2^2 + 2\lambda_3^2 + \frac{3}{8}g^4 - 3g^2\lambda_2 + 4\lambda_2(Y_u^{3,3})^2 - 2(Y_u^{3,3})^4\right)\frac{1}{16\pi^2}\,,$$

$$\mu\frac{\mathrm{d}\lambda_3}{\mathrm{d}\mu} = \left(-\frac{3}{2}g_1^2 - \frac{9}{2}g_2^2 - \frac{3}{2}g^2 + 12\lambda_1 + 8\lambda_2 + 4\lambda_3 + 2(Y_u^{3,3})^2 + 6y_t^2\right)\frac{\lambda_3}{16\pi^2}\,,$$

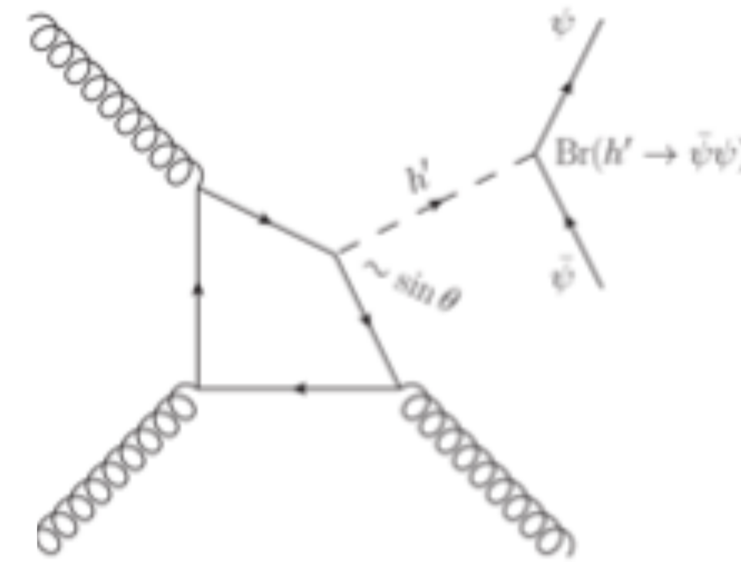




- varying gauge groups with dark quarks in fundamental rep.
- SU(5) gauge group with varying representations of dark quarks
- U(1) model with varying values for dark coupling g at MZ



Measurement in jet+MET at 100 TeV



Higgs signal-strength measurements set tight limits on θ ⟶ No sensitivity at LHC

Cross sections at 100 TeV

Cut	$U(1)$	$SU(2)$	$SU(25)$	Bgd.
$E_T^{miss} > 200$ GeV	1.84 pb	1.70 pb	1.45 pb	432 pb
$E_T^{miss} > 500$ GeV	0.0411 pb	0.0359 pb	0.0271 pb	18.0 pb
signal Ratio	44.8 ± 1.47	47.3 ± 1.78	53.5 ± 2.66	

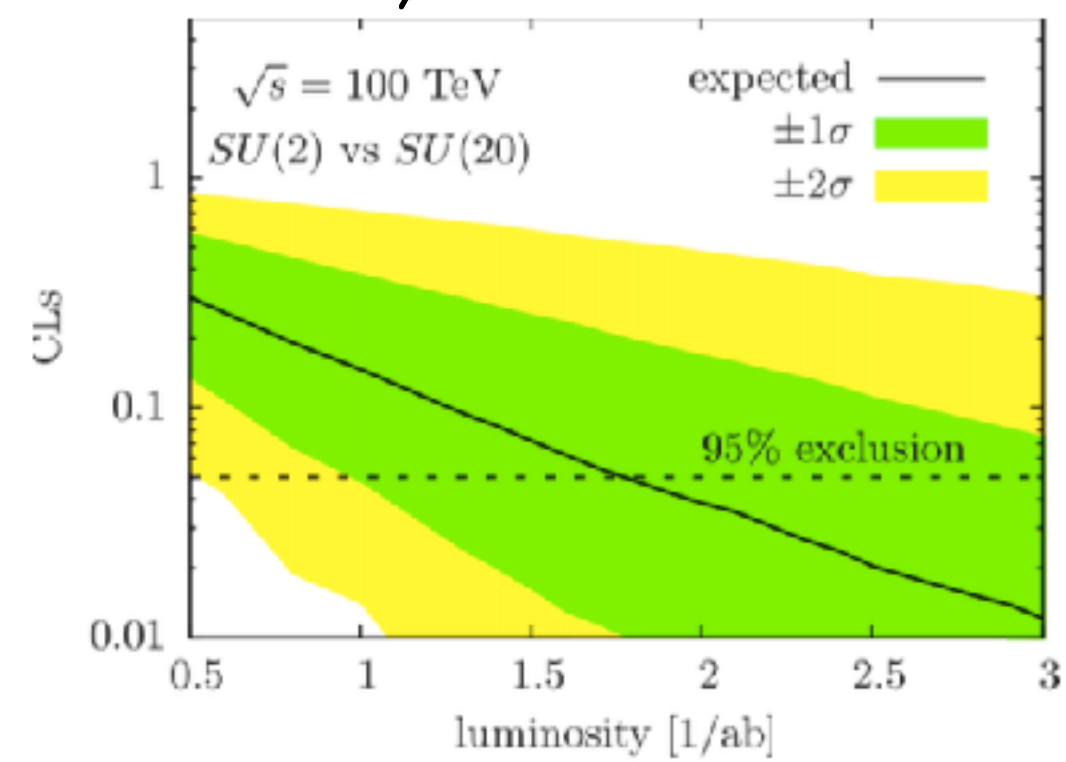
Biggest challenge S/B

Data-driven extrapolation from (Z->ll)+jets and gamma+jets

5 sigma discovery of SU(2) with ~ 100 ifb

discrimination SU(2) vs SU(20) with ~ 1.6 iab

only stat. uncertainties



A few remarks:

- **For indirect scalar dark sector spectroscopy:**
  - we do not rely on dark Higgs phenomenology, but could use SM Higgs (which scales with $\cos\theta$). However, for small mixing angles, this translates to sub-permille cross section differences.
  - Future lepton collider are sensitive to running in weak-boson fusion, but needs photon ISR radiation. But then background free… requires ELW corrections to be taken into account
- **In general, future colliders FCC-hh, FCC-he or FCC-ee can for some scenarios be only chance to establish the existence and to study the structure of dark sectors directly**