Title: Precision Physics for Run II

Date: May 26, 2015 01:00 PM

URL: http://pirsa.org/15050029

Abstract: <p>In this talk Iâ€™ll discuss some of the recent developments in precision physics which will be useful for extracting the best physics results we can from LHC run II. Iâ€™ll mostly focus on a specific example regarding anomalous interactions of the Higgs boson.</p>

Precision Physics for Run II

Ciaran Williams (SUNY Buffalo)


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UB
"Physics world celebrates Higgs boson discovery"
CBS NEWS

“Physics world celebrates Higgs boson discovery” CBS NEWS

“Physicists Find Elusive Particle Seen as Key to Universe” The New York Times

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The New York Times

Scientists at the Fermilab in Batavia, Ill., on Wednesday watched the presentation about the discovery of the Higgs boson, which was shown from Geneva.

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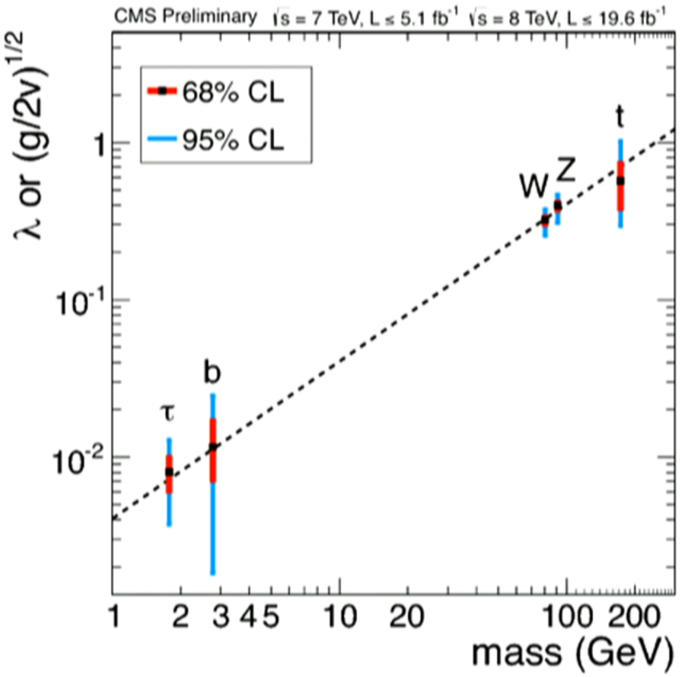
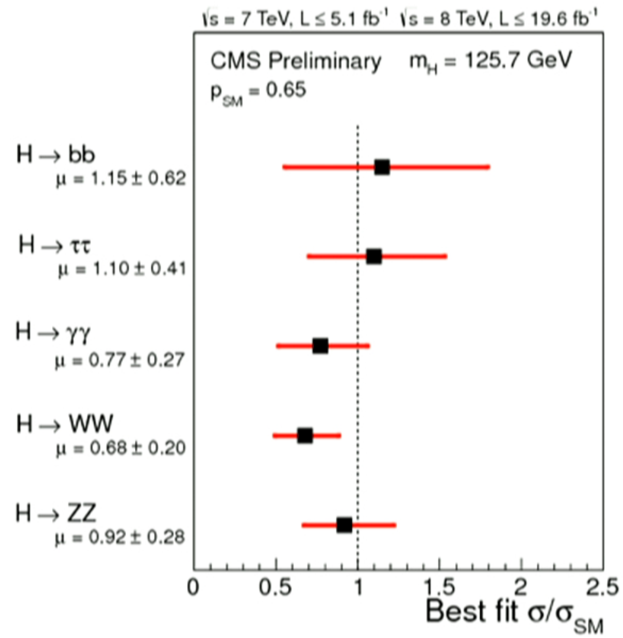
Constraining the Higgs





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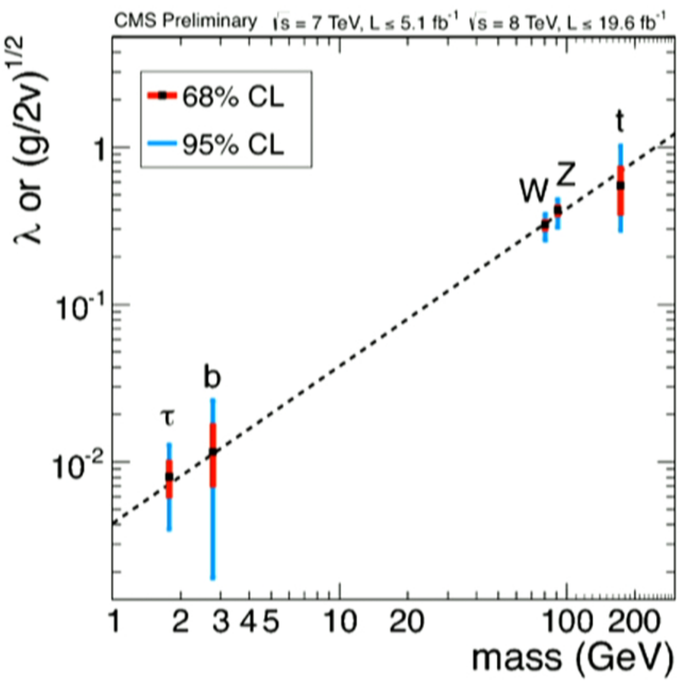

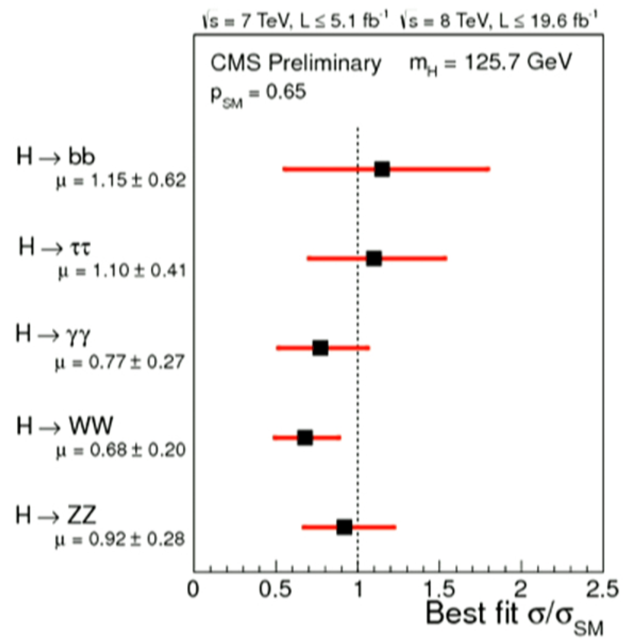

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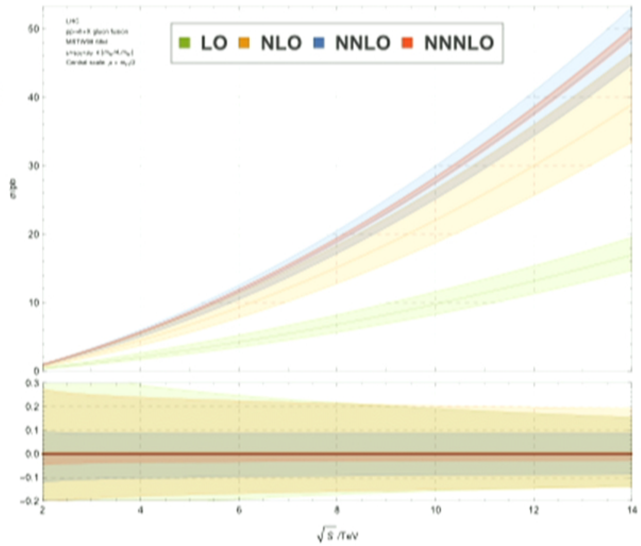
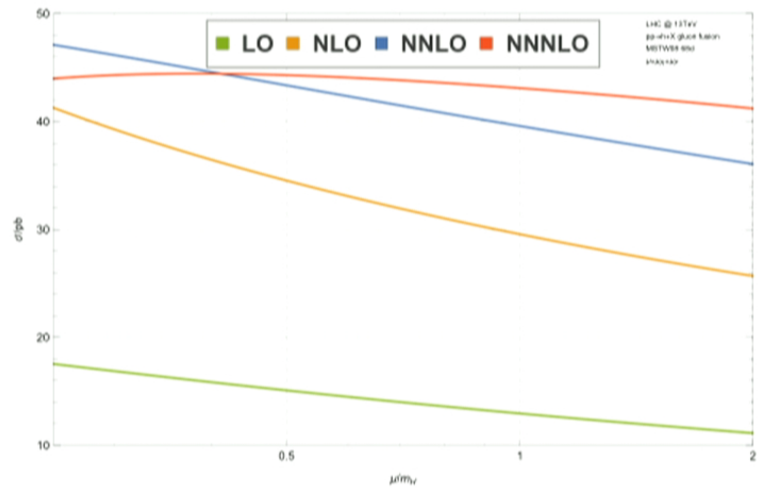
Higgs at N3LO

Anastasiou , Duhr, Dulat, Herzog
Mistlberger 1503.04110



Exciting recent theory developments!



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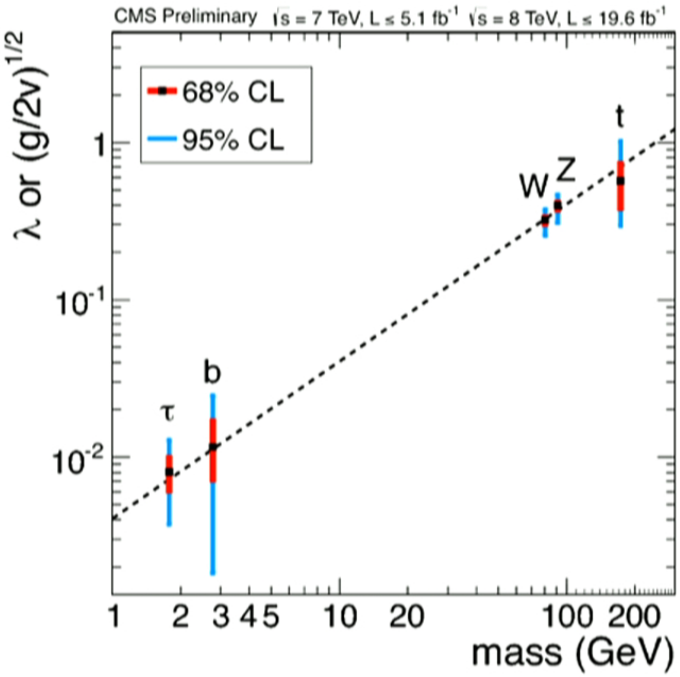
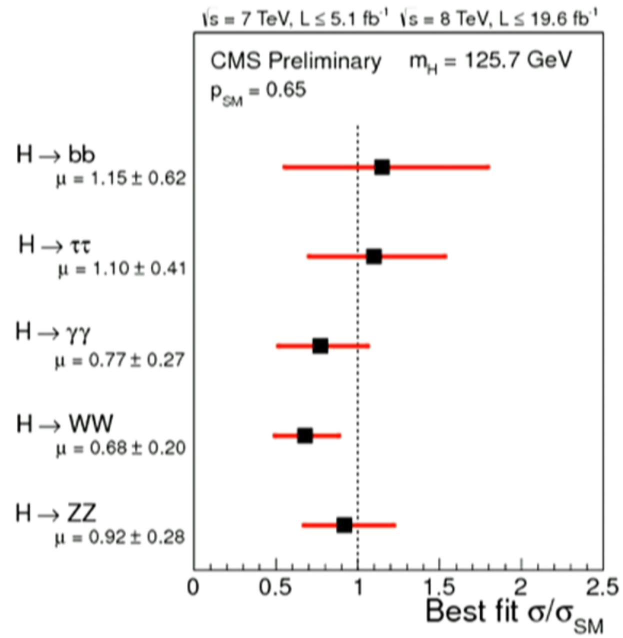
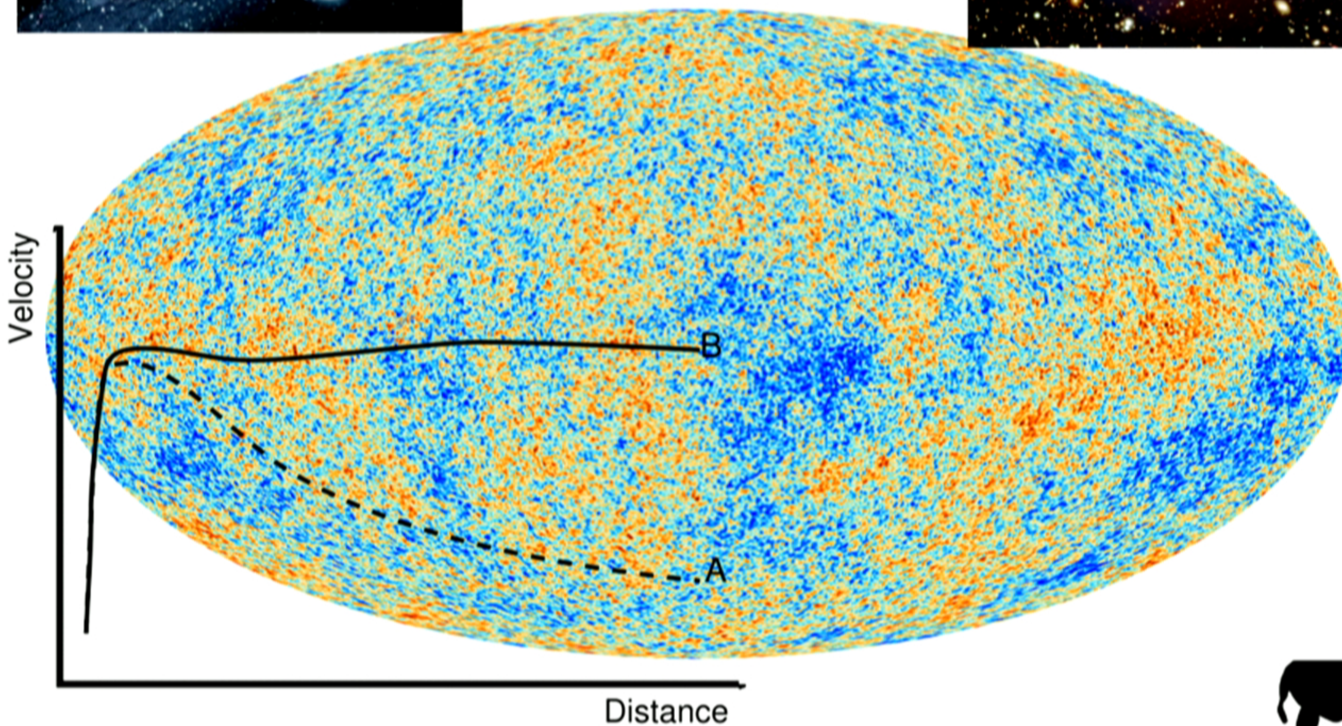
Constraining the Higgs

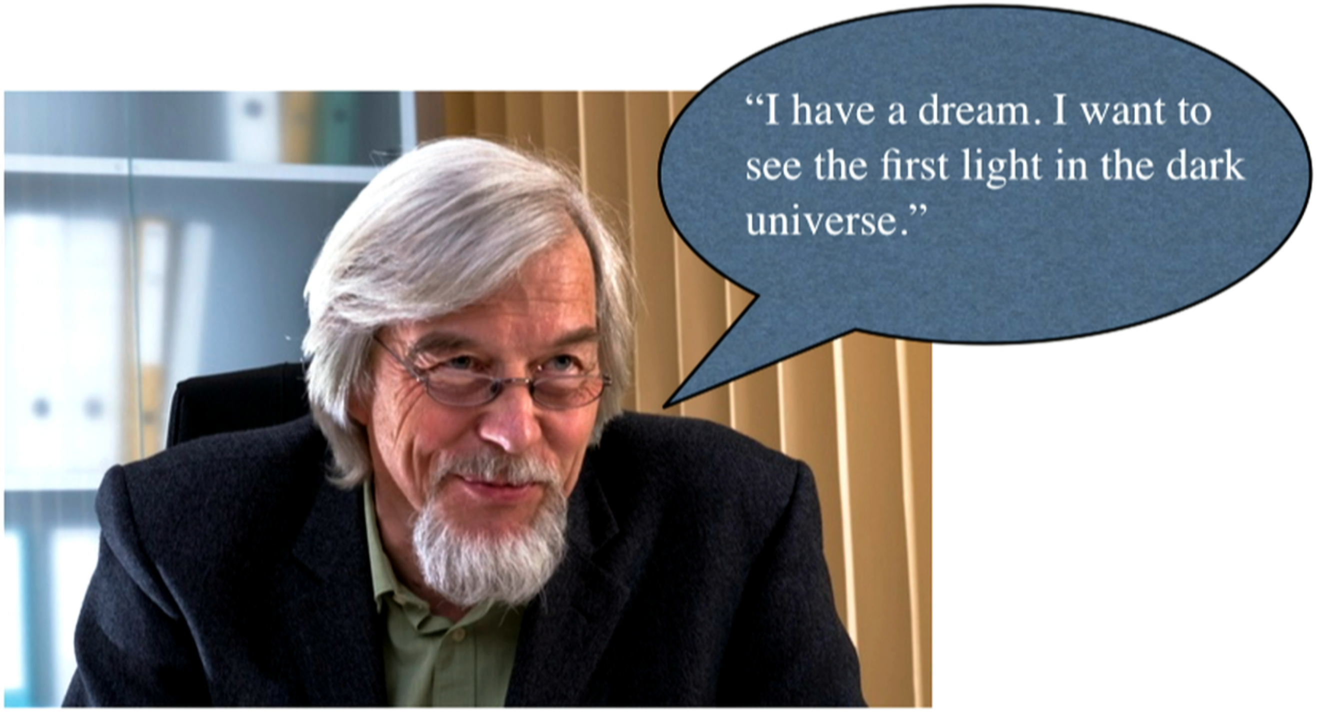




Dark Matter

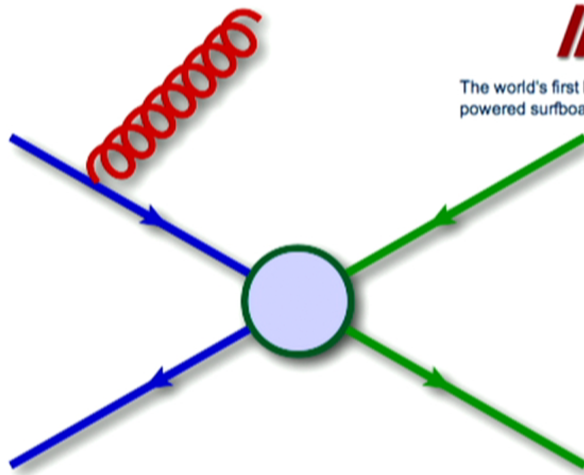


Dark Matter at the LHC?



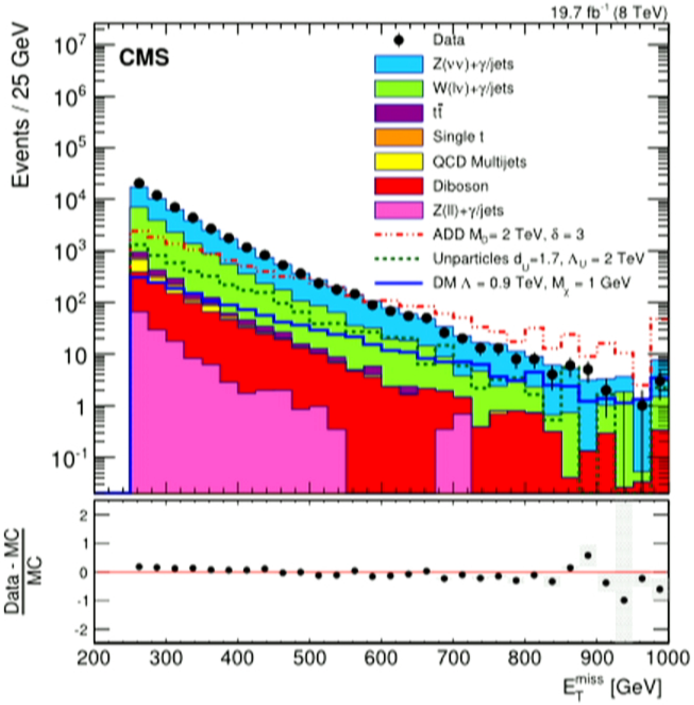
Rolf Heuer (at least according to the Guardian website)

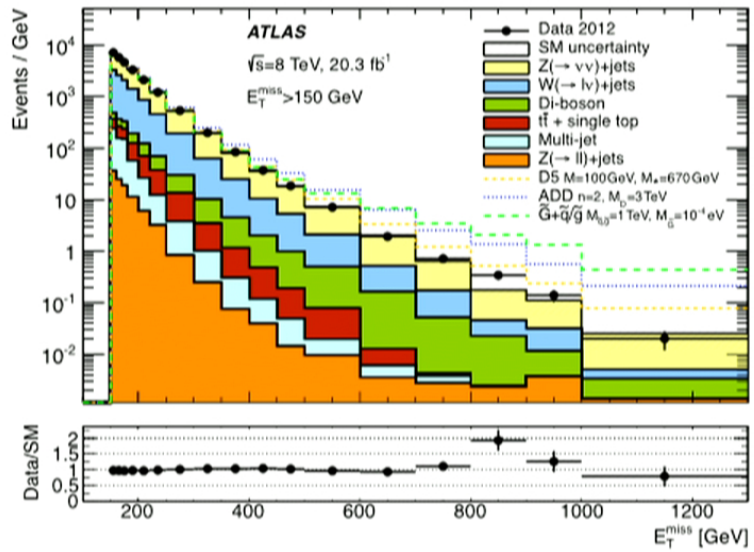
Dark Matter at Colliders



We need instead to look for DM produced in association with something we can see, i.e. a “monojet” topology.

Dark Matter at the LHC?



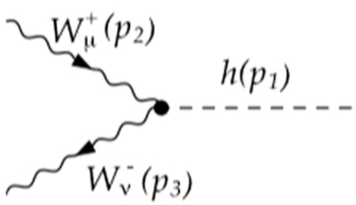


(b)

Challenging to see signal over background.

Assuming Baryon number and lepton number conservation the lowest higher dimensional operators start at 6 dimensions.

We are primarily interested in the modifications to the HWW vertex.



$$i\Big[\eta^{\mu\nu}\big(g m_W + g^{(1)}_{hww} p_2\cdot p_3 + g^{(2)}_{hww}(p_2^2+p_3^2)\big) - g^{(1)}_{hww} p_2^\nu p_3^\mu - g^{(2)}_{hww}\big(p_2^\nu p_2^\mu + p_3^\nu p_3^\mu\big) - \epsilon^{\mu\nu\rho\sigma}\tilde{g}_{hww} p_{2\rho} p_{3\sigma}\Big]$$

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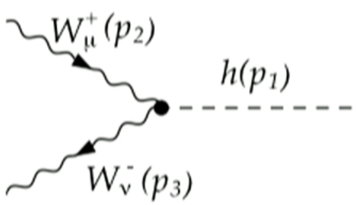

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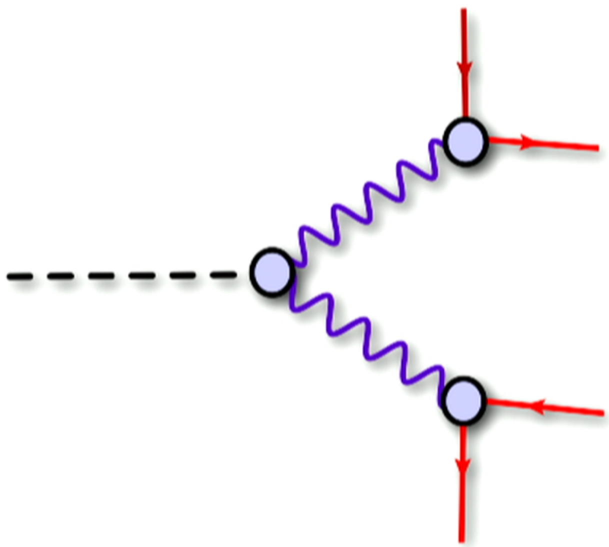
Probing anomalous couplings

It seems most logical to probe the vertex by looking at the decays of the Higgs bosons to the vector bosons themselves in as much detail as possible.



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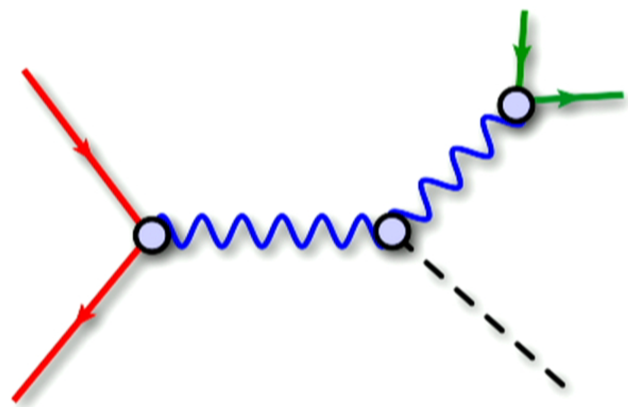
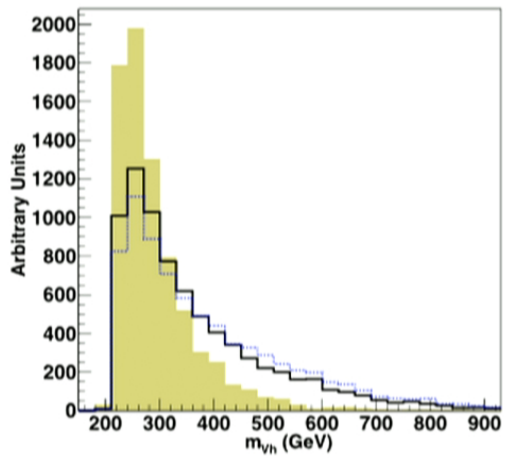
Probing anomalous couplings

Using associated production to probe the vertex is then rather appealing since the s-channel diagram allows access to high energy behaviour, whilst keeping the Higgs on-shell





eg. Alloul, Fuks and Sanz 1310.5150

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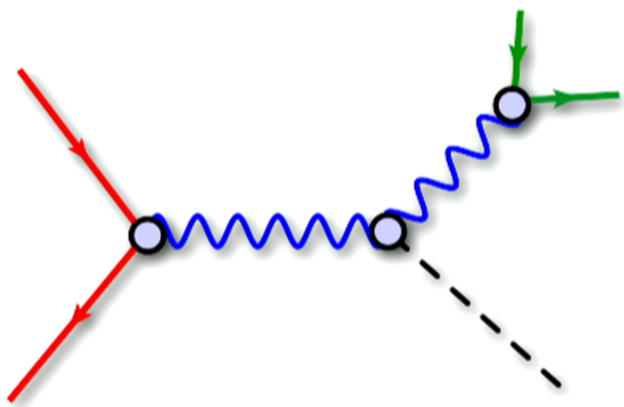

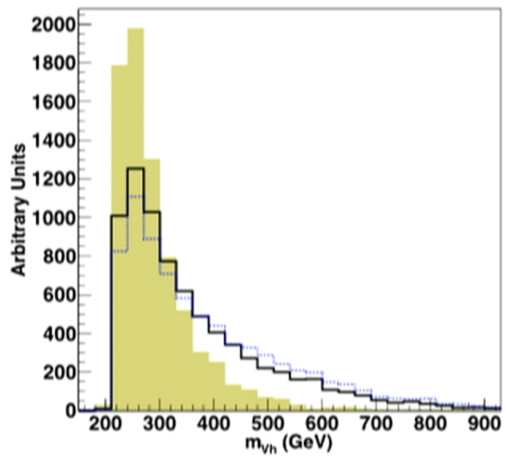

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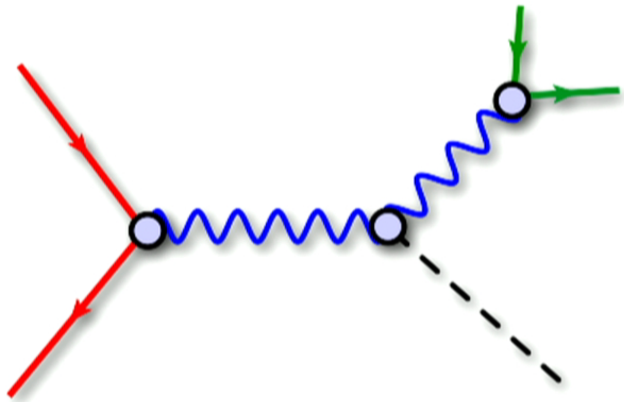

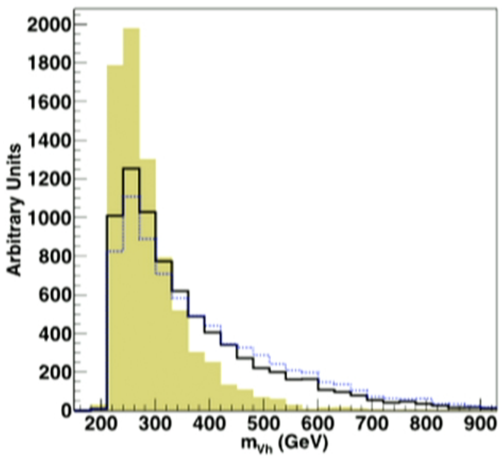

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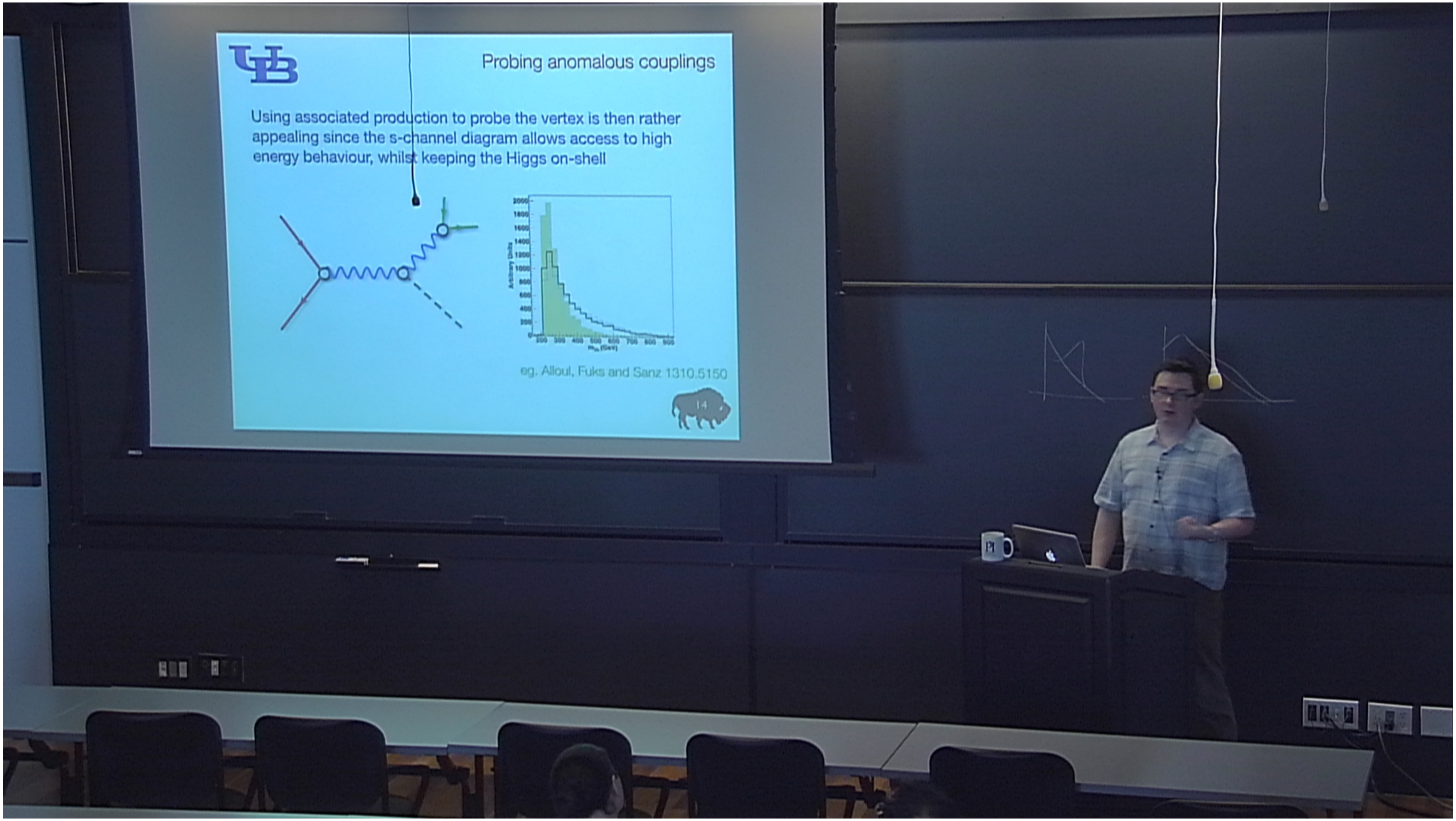
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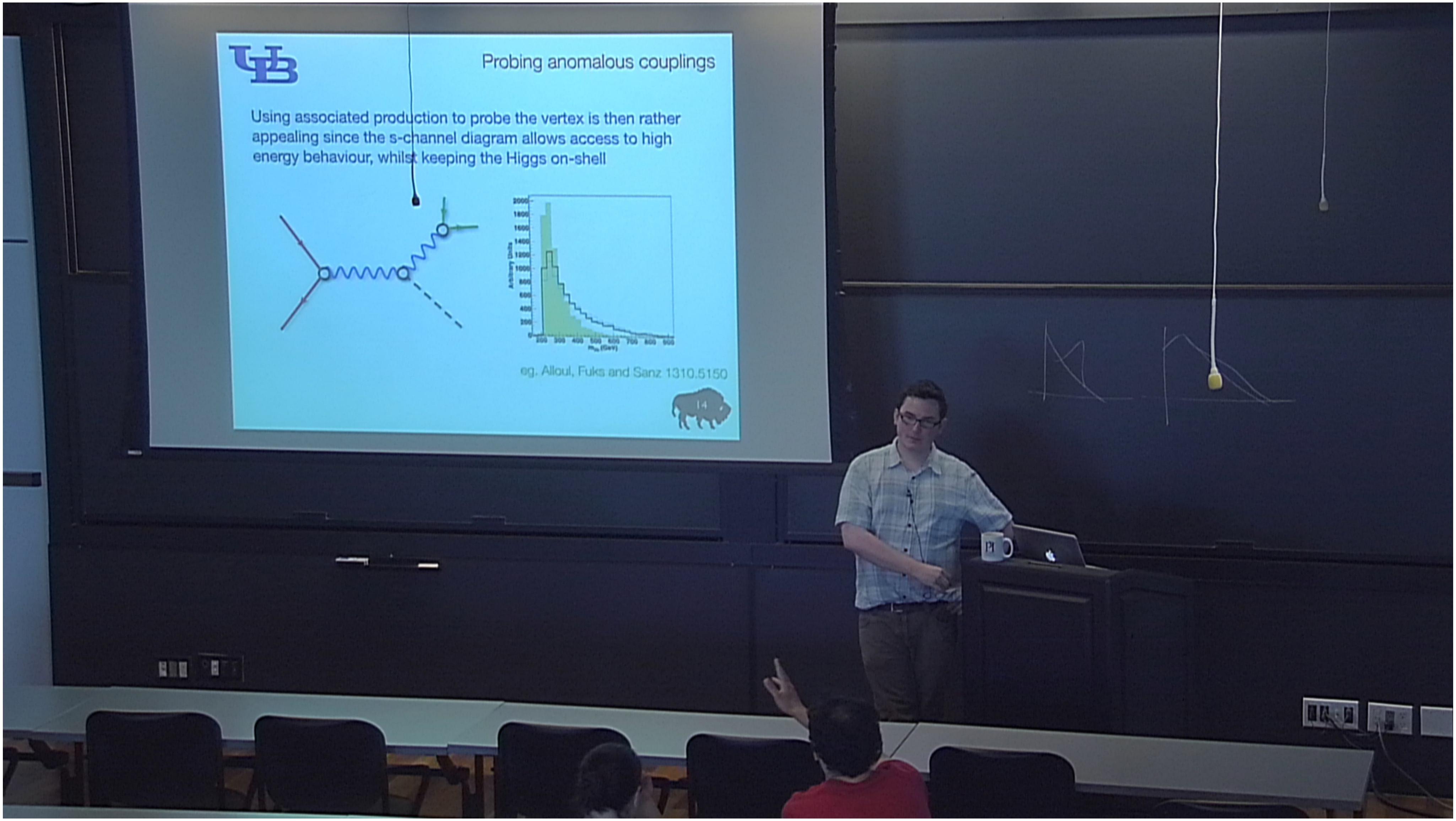

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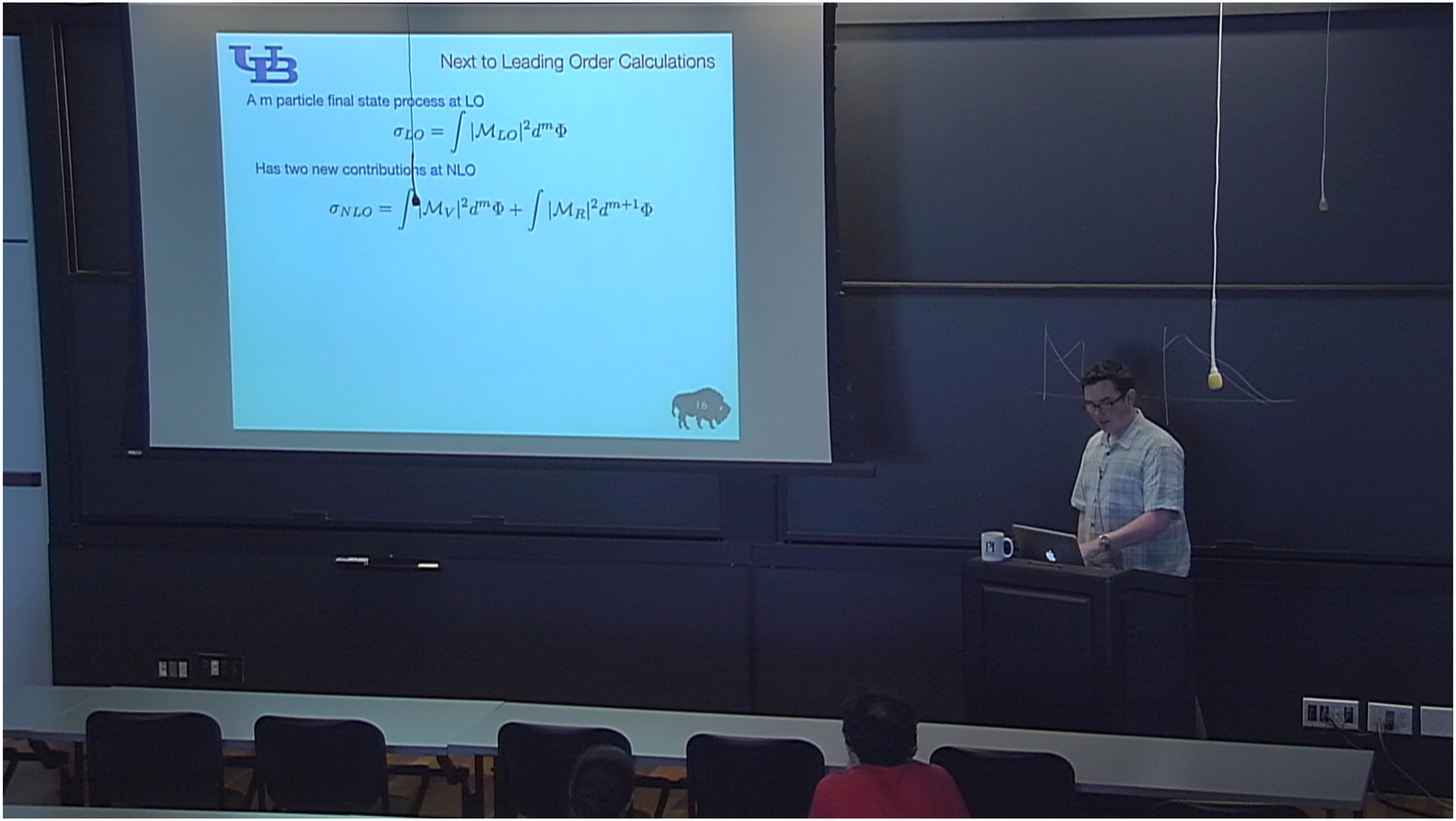

Next to Leading Order Calculations
A m particle final state process at LO
$\sigma_{LO} = \int |\mathcal{M}_{LO}|^2 d^m\Phi$
Has two new contributions at NLO
$\sigma_{NLO} = \int |\mathcal{M}_V|^2 d^m\Phi + \int |\mathcal{M}_R|^2 d^{m+1}\Phi$
16

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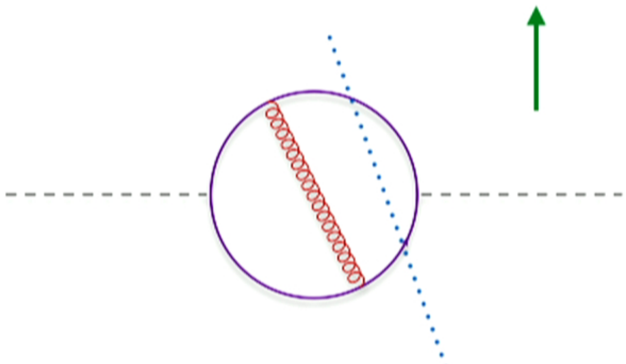
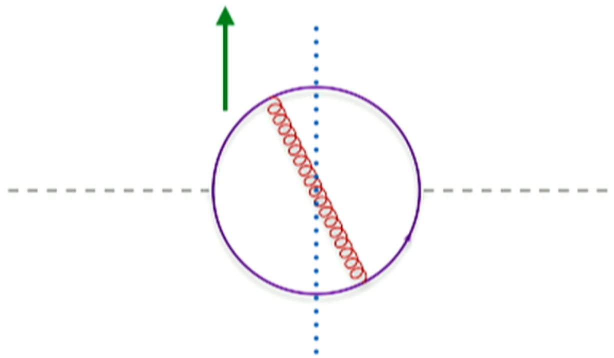


Virtual



Real

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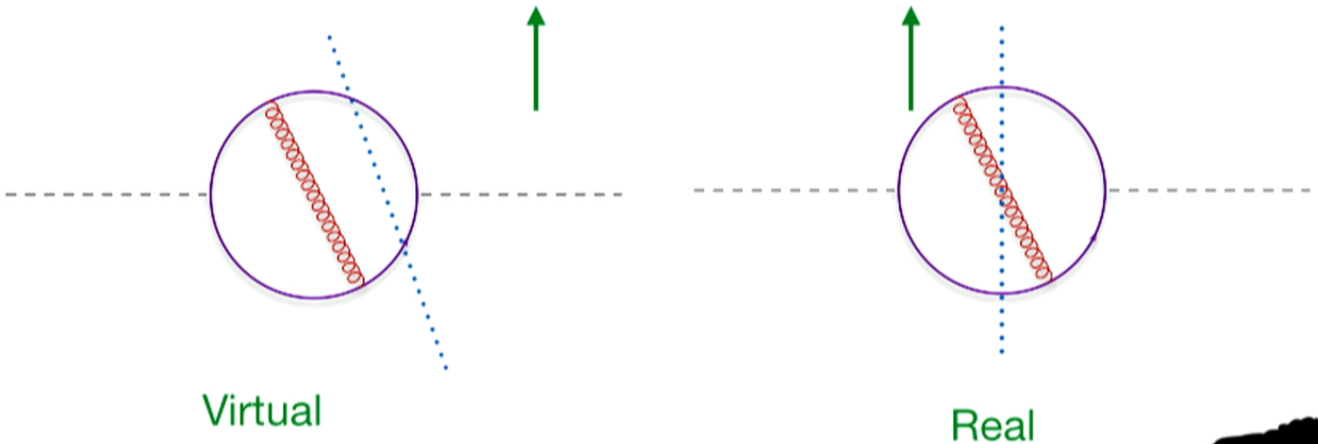

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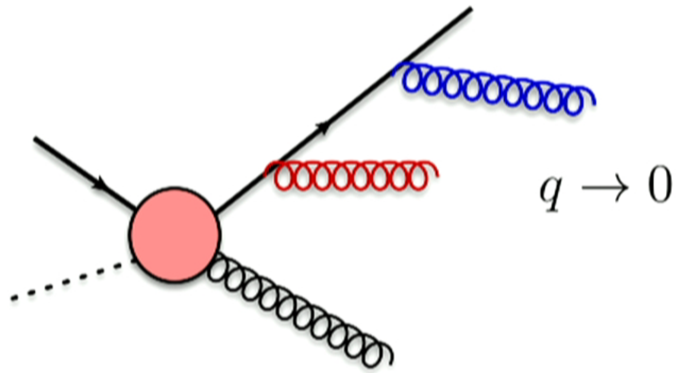
Infrared divergences : Soft

See e.g. Catani and Grazzini hep-ph/9908523

We first consider the soft limit of an amplitude,



We re-write the matrix element in terms of the color and spin basis.

$$\mathcal{M}^{c_1 \ldots c_n ; s_1 \ldots s_n}(p_1 \ldots p_n) = (\langle c_1 \ldots c_n | \otimes \langle s_1 \ldots s_n |) \mathcal{M}(p_1 \ldots p_n) \rangle$$

So $\mathcal{M}(p_1 \ldots p_n)$ is a vector in color and spin space.

Then when a gluon with color c and spin mu, goes soft the amplitude factorizes as follows,

$$\langle c;\mu|\mathcal{M}(q,p_1\ldots p_n)\rangle = g_s\mu^\epsilon J^\mu_c|\mathcal{M}(p_1\ldots p_n)\rangle$$

where we have introduced the following Eikonal current,

$$\mathbf{J}^\mu(q) = \sum_{i=1}^{n}\mathbf{T_i}\frac{p_i^\mu}{p_i\cdot q}$$

and defined the color charge operators as follows,

$$\mathbf{T}_i^c = \langle c|T_i^c \quad \text{with} \quad \mathbf{T}_i\cdot\mathbf{T}_j = \mathbf{T}_j\cdot\mathbf{T}_i \quad \mathbf{T}_i^2 = C_i$$

and C_i is a Casimir of SU(3).

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Infrared divergences : Soft

Squaring the Eikonal current and inserting the soft gluon polarization tensor $d_{\mu\nu} = -g_{\mu\nu} + \ldots$

$$[\mathbf{J}^\mu(q)]^\dagger d_{\mu\nu}(q)\mathbf{J}^\nu(q) = -\sum_{i,j=1}^{n} \mathbf{T}_i \cdot \mathbf{T}_j \frac{p_i \cdot p_j}{(p_i \cdot q)(p_j \cdot q)}$$

So that the Matrix element squared factorizes as follows

$$|\mathcal{M}(q, p_1, \ldots p_n)|^2 = -4\pi\alpha_s\mu^{2\epsilon} \sum_{i,j=1}^{n} S_{ij}(q)|\mathcal{M}^{(i,j)}(p_1 \ldots p_n)|^2$$

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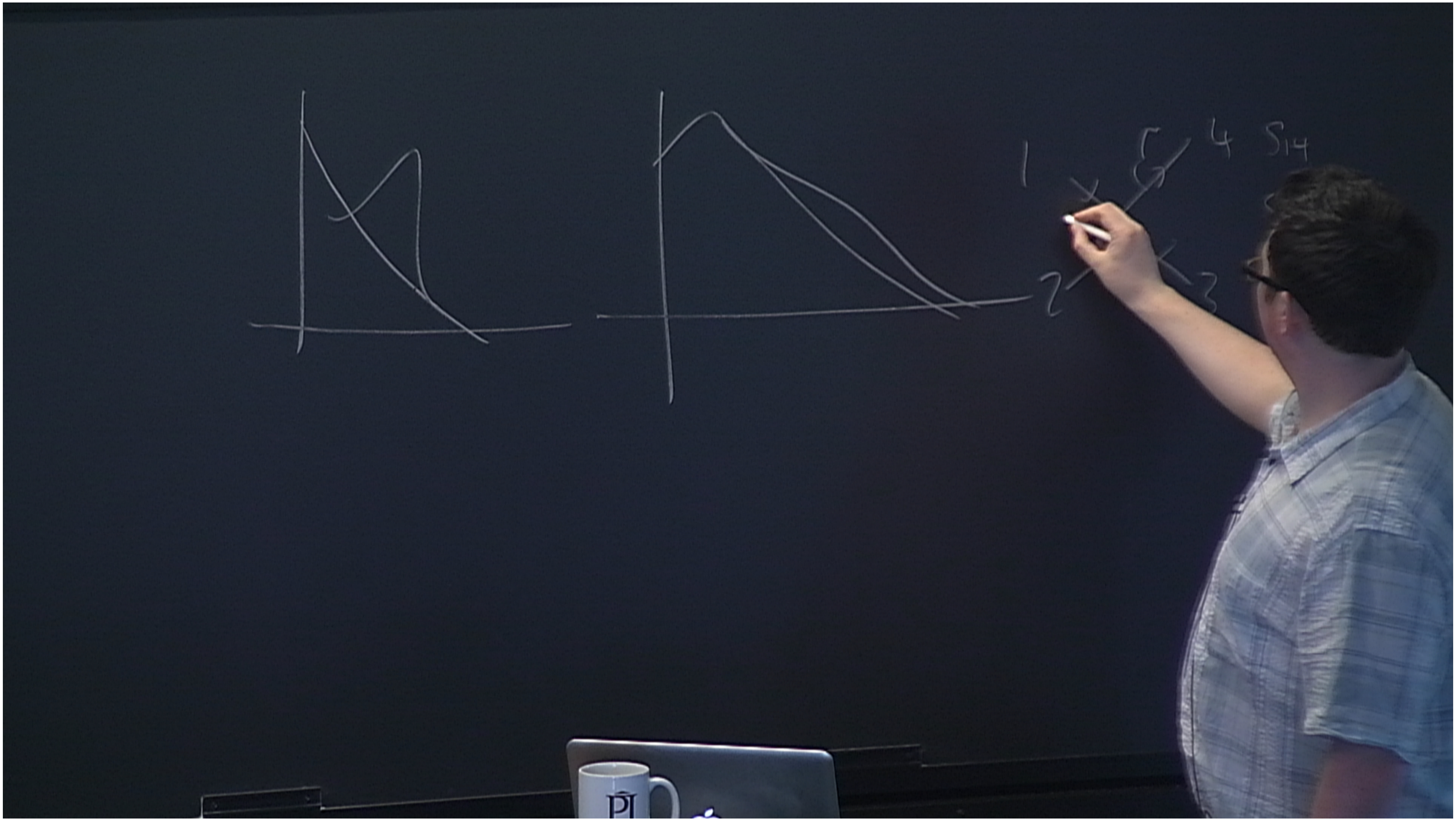

1
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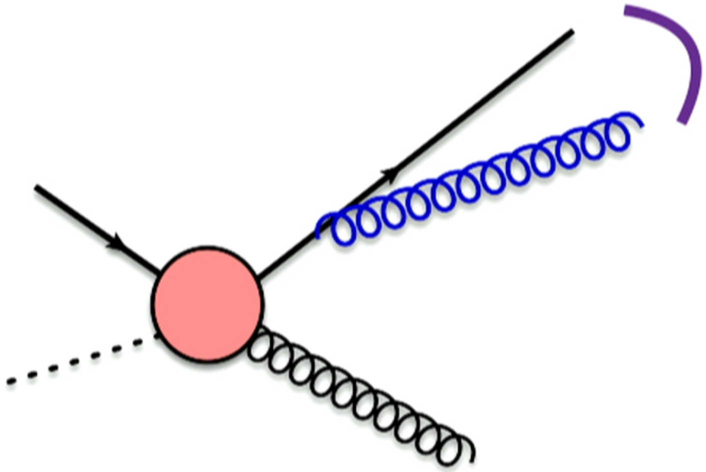
s_{14}

Infrared divergences : Collinear

$$\theta \to 0$$



Collinear divergences occur when the angle between two massless partons goes to zero.

The limit is defined as follows

$$p_1^\mu = z p^\mu + k_\perp^\mu - \frac{k_\perp^2}{z}\frac{n^\mu}{2(p\cdot n)} \qquad p_2^\mu = (1-z)p^\mu - k_\perp^\mu - \frac{k_\perp^2}{1-z}\frac{n^\mu}{2(p\cdot n)}$$

with $\quad s_{12} = -\frac{k_\perp^2}{z(1-z)} \quad k_\perp^2 \to 0$

Anatomy of a higher order correction : NNLO

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Next to Next to Leading Order Calculations

At NNLO we have three types of final state phase spaces

$$\sigma_{NLO} = \int |\mathcal{M}_{VV}|^2 d^m\Phi + \int |\mathcal{M}_{RV}|^2 d^{m+1}\Phi + \int |\mathcal{M}_{RR}|^2 d^{m+2}\Phi$$

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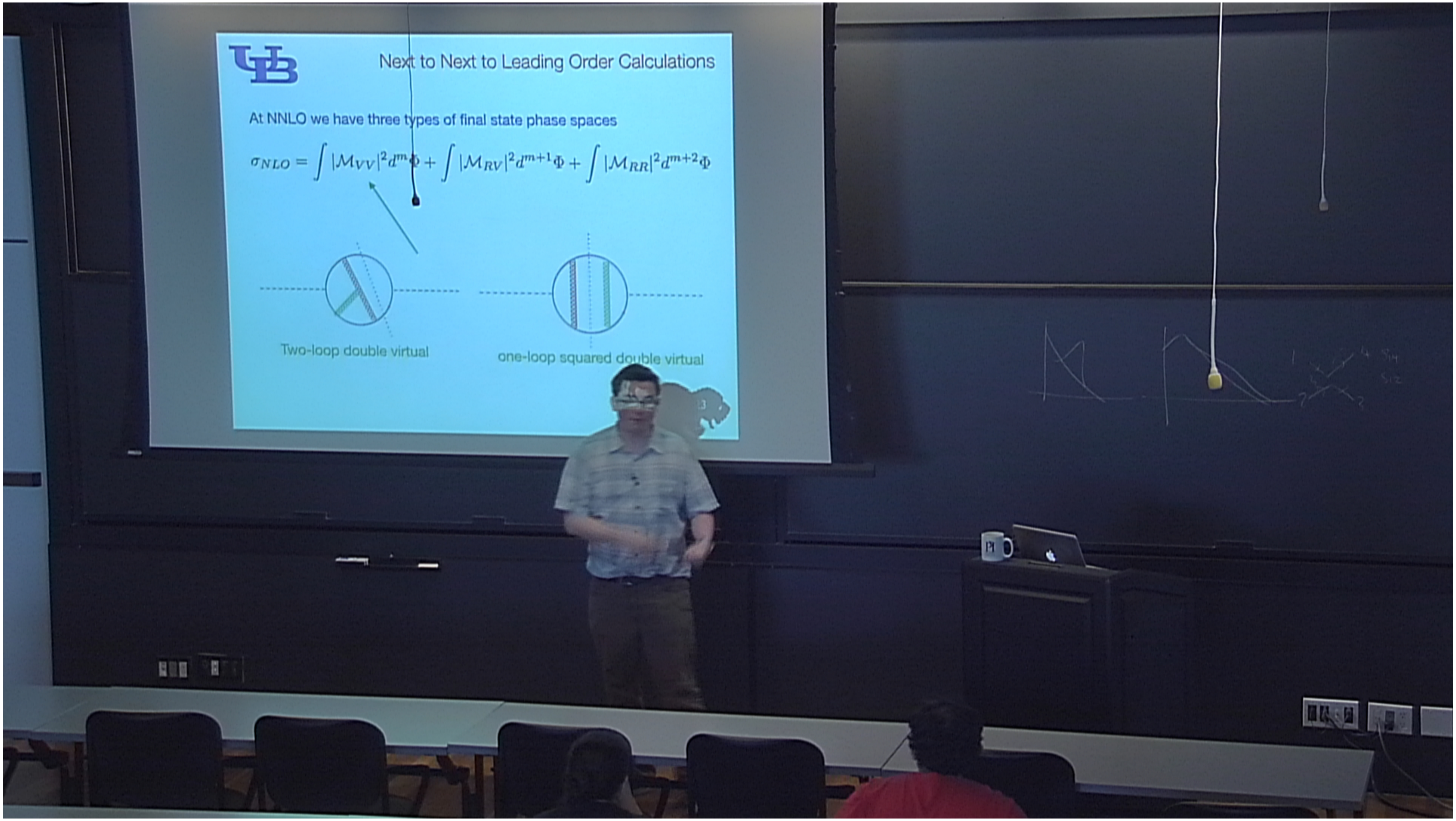
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Two-loop double virtual
one-loop squared double virtual

Next to Next to Leading Order Calculations

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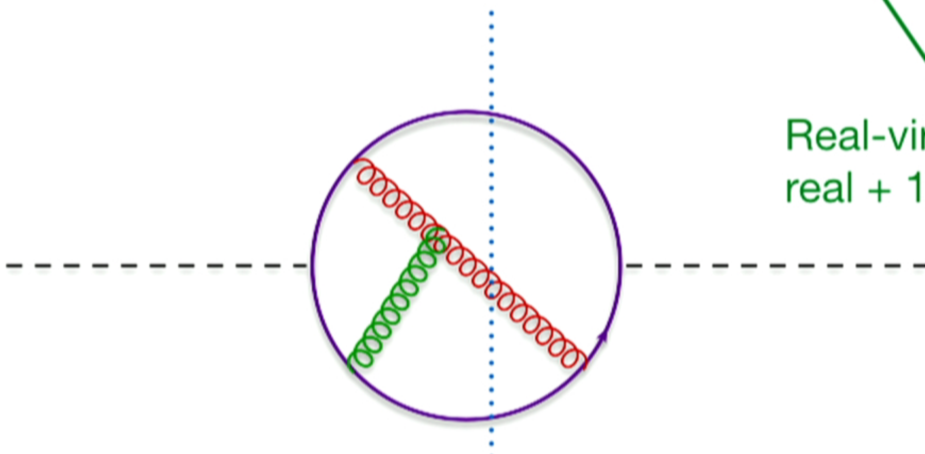
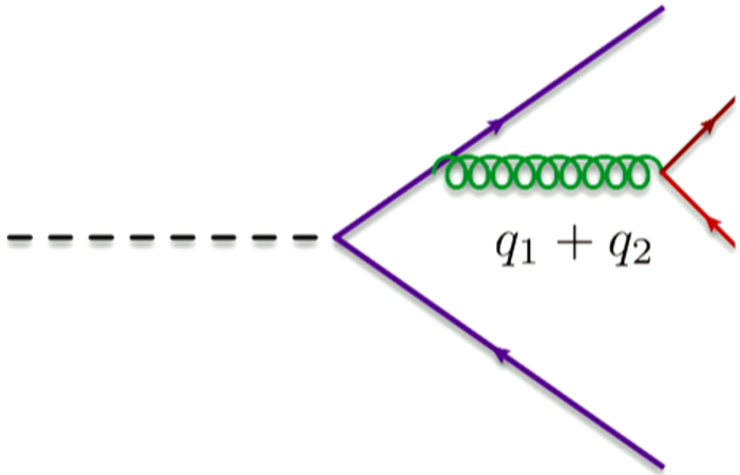


Real-virtual (one-loop +1 x real + 1)

Infrared singularities at NNLO : Double Soft

Catani and Grazzini hep-ph/9908523



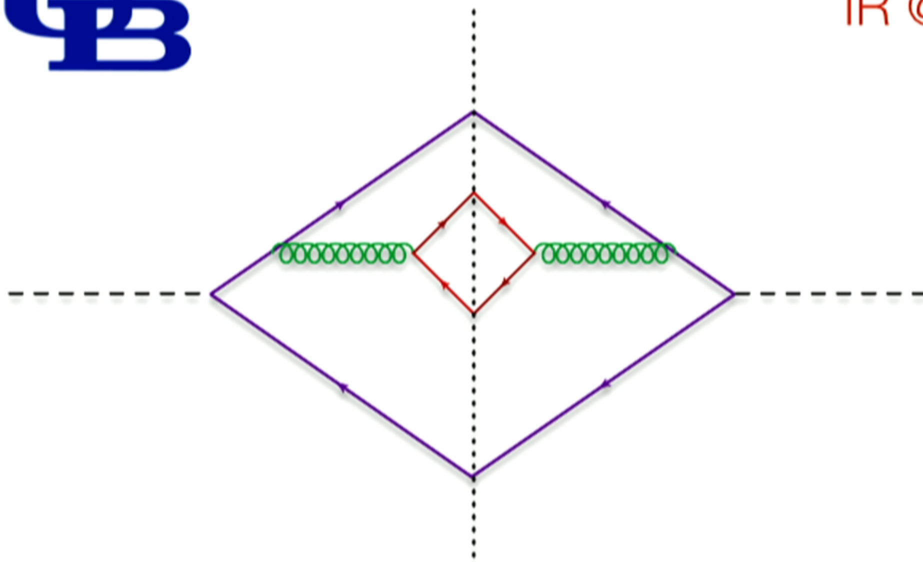
For our example, the soft physics we have to consider will arise from the emission of a soft quark pair i.e.

$$(q_1, q_2) \to 0 \quad \text{with } \frac{q_1}{q_2} \text{ fixed}$$

Our factorization result now becomes,

$$|\mathcal{M}(q_1, q_2; p_1, \dots p_n)|^2 = (4\pi\mu^{2\epsilon}\alpha_s)^2 \langle \mathcal{M}(p_1 \dots p_n)|\mathbf{I}_{(q\bar{q})}(q_1, q_2)|\mathcal{M}(p_1 \dots p_n)\rangle$$

IR @ NNLO : Double Soft



We build the soft insertion operator from the eikonal currents and the quark loop discontinuity contribution to the gluon propagator.

$$\mathbf{I}_{q\bar{q}}(q_1, q_2) = [\mathbf{J}_\mu(q_1 + q_2)]^\dagger \Pi^{\mu\nu}(q_1, q_2)\mathbf{J}_\nu(q_1 + q_2)$$

where

$$\Pi^{\mu\nu}(q_1, q_2) = \frac{T_R}{(q_1 \cdot q_2)^2}\left(-g^{\mu\nu}(q_1 \cdot q_2) + q_1^\mu q_2^\nu + q_1^\nu q_2^\mu\right)$$

IR @ NNLO : Double Soft

Putting this all together the soft behaviour of the matrix element with a soft quark anti-quark pair is as follows,

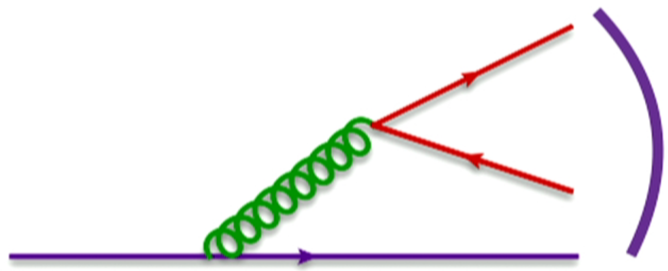
$$|\mathcal{M}(q_1, q_2; p_1 \ldots p_n)|^2 = (4\pi\alpha_S\mu^{2\epsilon})^2 T_R \sum_{i,j=1}^{n} \mathcal{I}_{ij}(q_1, q_2)|\mathcal{M}(p_1 \ldots p_n)|^2$$

where the quark pair soft function is given by,

$$\mathcal{I}_{ij}(q_1, q_2) = \frac{(p_i \cdot q_1)(p_j \cot q_2) + (p_j \cdot q_1)(p_i \cdot q_2) - (p_i \cdot p_j)(q_1 \cdot q_2)}{(q_1 \cdot q_2)^2 (p_i \cdot (q_1 + q_2))(p_j \cdot (q_1 + q_2))}$$

which can be evaluated simply from the formulae on the previous slide.

Infrared subtractions at NNLO : Triple Collinear



$$\theta \to 0$$

A further type of IR singularity we will deal with arises from a triple collinear singularity in which three partons all become collinear to one another.

The factorization is analogous to the double collinear splitting

$$|\mathcal{M}(q_1, q_2, q_3, p_1 \ldots p_n)|^2 = \left(\frac{8\pi\mu^{2\epsilon}\alpha_S}{s_{123}}\right)^2 \mathcal{T}^{ss'} \hat{P}^{ss'}_{q_1 q_2 q_3}$$

Now, P represents the triple-collinear splitting function

Putting it all together.

We would like to now build a Monte-Carlo code which is capable of integrating the +2 parton phase space. In which the two new partons can be un-resolved.

We know how the Matrix element behaves in the singular limits (as we've just discussed). So the problem should be easy right?

You might guess that a good way to proceed is to simply subtract the relevant singular limit from the matrix element, and then integrate the subtraction analytically over the unresolved parton phase space.

The resulting analytic terms, as a series in epsilon, should then cancel the relevant poles in the loop amplitudes via the KLN theorem.

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Putting it all together.

This approach, whilst extremely successful at NLO has several major difficulties when attempted at NNLO,

- Multiple singular regions, how to successfully separate them?
- Integration of subtractions over the unresolved phase space is extremely difficult.
- Some issues with angular correlations in the most successfully subtraction approach so far (Antenna subtraction) which will affect some differential distributions.

However, an alternative approach to analytic integration of the subtractions was put forward by Czakon in 2010. We'll look at that now.

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This approach, whilst extremely successful at NLO has several major difficulties when attempted at NNLO,

- Multiple singular regions, how to successfully separate them?
- Integration of subtractions over the unresolved phase space is extremely difficult.
- Some issues with angular correlations in the most successfully subtraction approach so far (Antenna subtraction) which will affect some differential distributions.

However, an alternative approach to analytic integration of the subtractions was put forward by Czakon in 2010. We'll look at that now.

The STIRPPER routine for double real emission

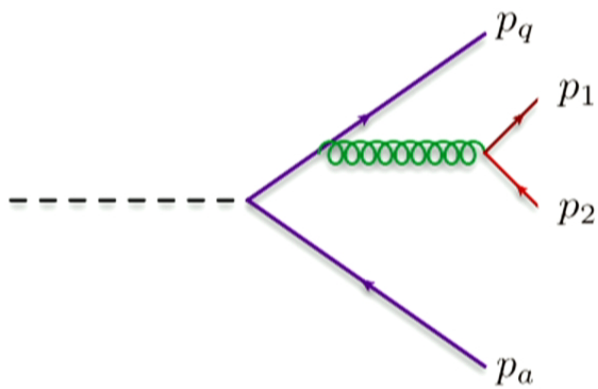
Czakon 1005.0274 and 1101.0642

See also Boughezal Melnikov and Petriello 1111.0741

IR singularities at NNLO : The Stripper routine

We are considering decays of the Higgs boson to bb, and in particular we are interested in the bbQQ amplitudes as an example.

We want to write a fully differentiable Monte Carlo code, which can integrate over the full phase space of the matrix element, i.e. where the quark pair becomes unresolved we define,



$$d\Phi(H \to p_q + p_1 + p_2 + p_q)$$

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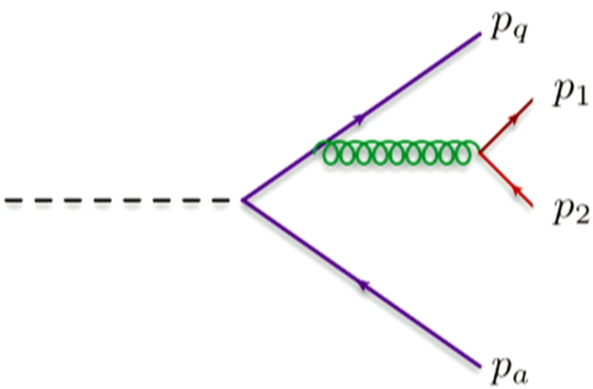

$$d\Phi(H \to p_q + p_1 + p_2 + p_q)$$

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To begin we note the following at first rather trivial, but actually rather useful identity.

$$1 = \frac{s_{q12}}{s_{q12} + s_{a12}} + \frac{s_{a12}}{s_{q12} + s_{a12}} = \delta_q + \delta_a$$

Then

$$d\Phi = d\Phi\delta_q + d\Phi\delta_a$$

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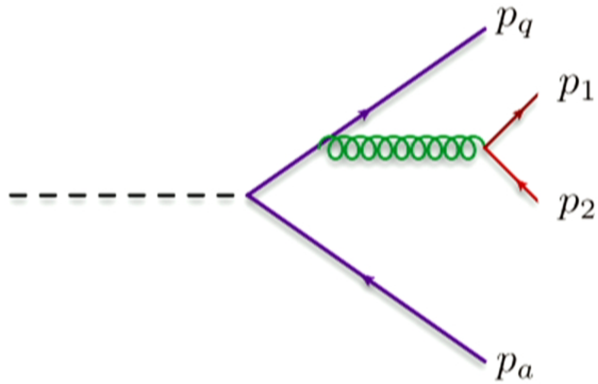

$$d\Phi(H \rightarrow p_q + p_1 + p_2 + p_q)$$

The singular phase space

Exploiting Lorentz invariance we can define the phase space in a frame in which the b-quark moves along the x-axis. Then the two other quarks can be written as follows,

$$p_1 = \xi_1(1, \sin\theta_1, 0, \cos\theta_1)$$
$$p_2 = \xi_2(1, \sin\theta_2 \sin\phi, \sin\theta_2 \cos\phi, \cos\theta_2)$$

We will find it convenient to introduce the following two parameters,

$$\eta_1 = \frac{1}{2}(1-\cos\theta_1) \quad \eta_2 = \frac{1}{2}(1-\cos\theta_2)$$

Note that already the set of parameters, $\xi_1\ \xi_2\ \eta_1\ \eta_2$ naturally describe nearly all of the kinematic limits we are interested in.

Collinear parameterization

We now have 5 variables which completely specify all of the kinematic IR limits we are interested in,

$$\xi_1 \; \xi_2 \; \eta_1 \; \eta_2 \; x_5$$

ξ_i : Particle i is soft

η_i : Particle i is collinear to the b-quark

$\eta_1 = \eta_2$: Particles 1 and 2 are collinear

So our next and final task is to separate out the various overlapping singularities.

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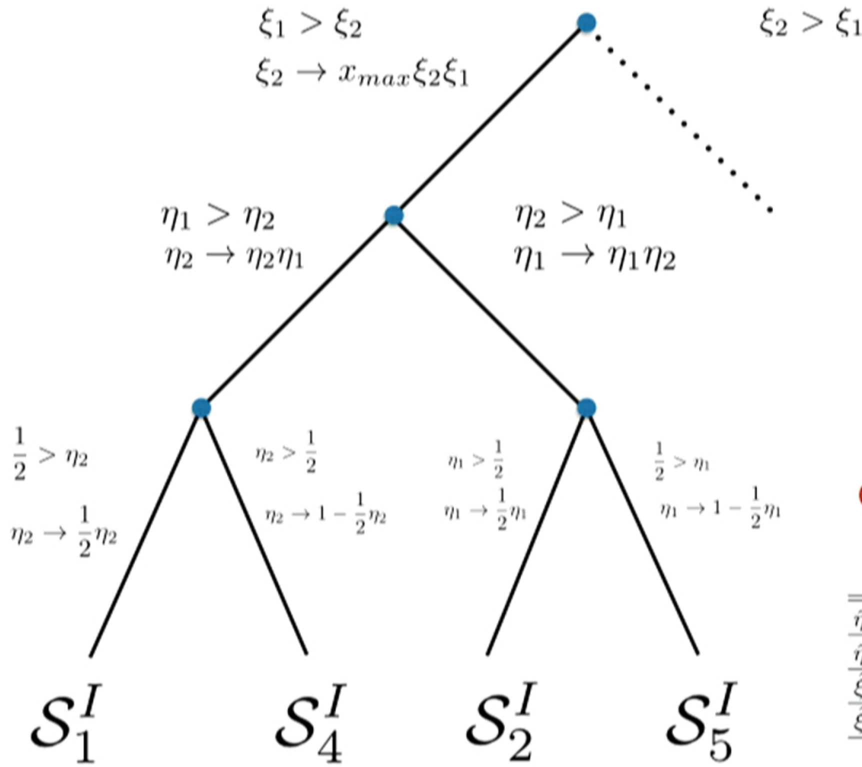
Sector Decomposition for H=>bbQQ



We order the variables, and in each new sector re-map the variables such that the new variables are in the unit hypercube.

Our final integration variables are

	$\mathcal{S}_1^I$	$\mathcal{S}_2^I$	$\mathcal{S}_4^I$	$\mathcal{S}_5^I$
$\hat{\eta}_1$	x_3	$\frac{1}{2}x_3x_4$	x_3	$\frac{1}{2}x_3(2-x_4)$
$\hat{\eta}_2$	$\frac{1}{2}x_3x_4$	x_3	$\frac{1}{2}x_3(2-x_4)$	x_3
$\hat{\xi}_1$	x_1	x_1	x_1	x_1
$\hat{\xi}_2$	$x_1x_2x_{max}$	$x_1x_2x_{max}$	$x_1x_2x_{max}$	$x_1x_2x_{max}$

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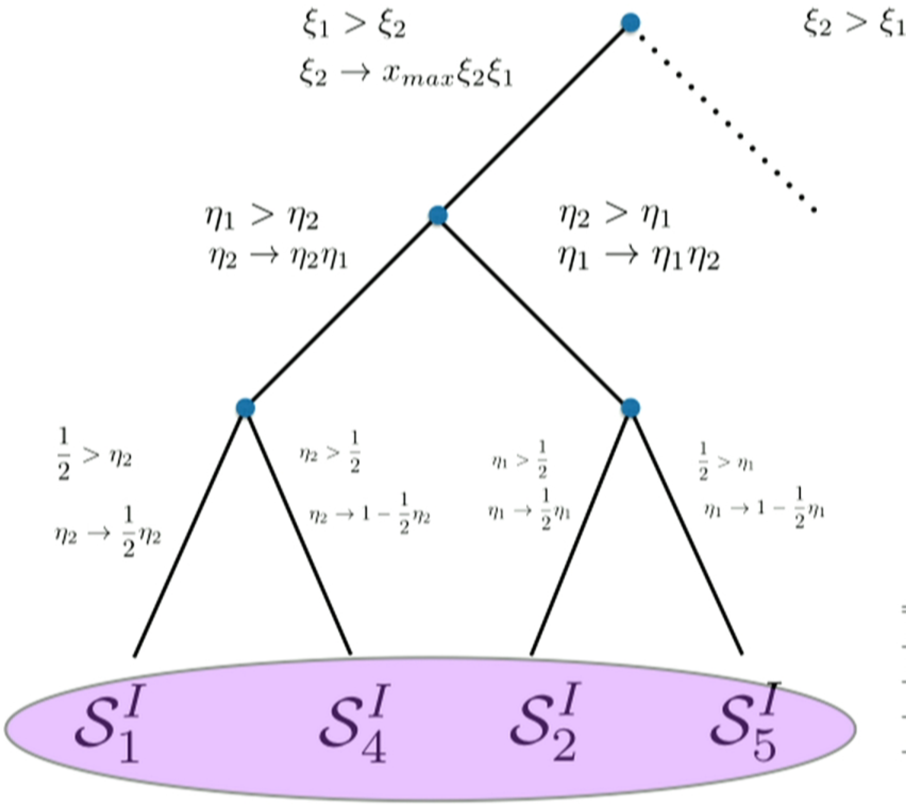
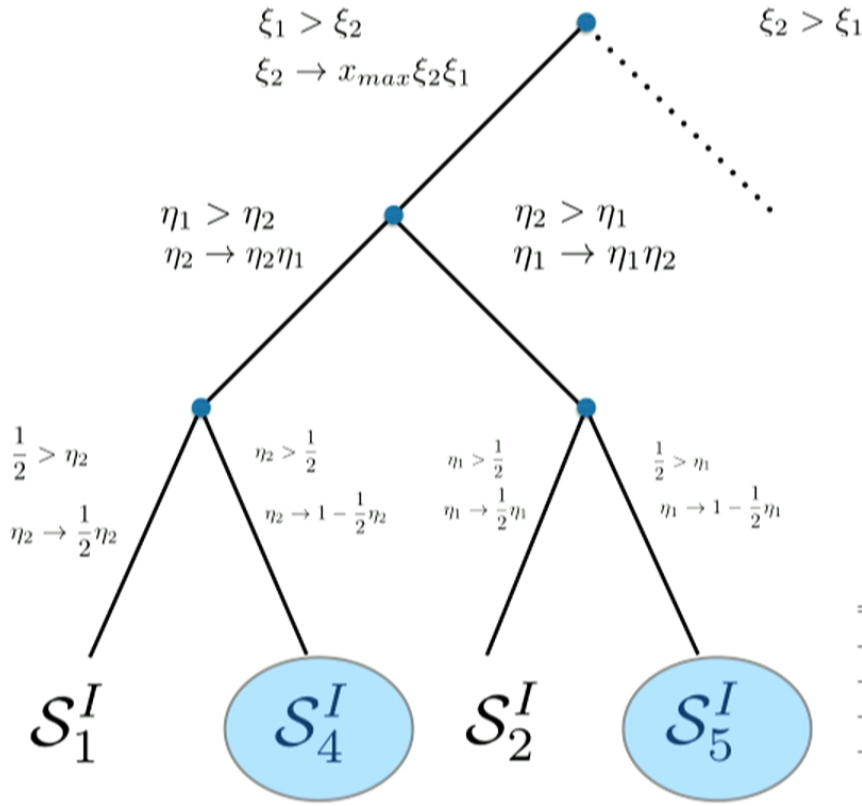
H=>bbQQ Limits in Each sector



Every sector has a Double Soft singularity which corresponds to x_1 = 0

	$\mathcal{S}_1^I$	$\mathcal{S}_2^I$	$\mathcal{S}_4^I$	$\mathcal{S}_5^I$
$\hat{\eta}_1$	x_3	$\frac{1}{2}x_3x_4$	x_3	$\frac{1}{2}x_3(2-x_4)$
$\hat{\eta}_2$	$\frac{1}{2}x_3x_4$	x_3	$\frac{1}{2}x_3(2-x_4)$	x_3
$\hat{\xi}_1$	x_1	x_1	x_1	x_1
$\hat{\xi}_2$	$x_1x_2x_{max}$	$x_1x_2x_{max}$	$x_1x_2x_{max}$	$x_1x_2x_{max}$

H=>bbQQ Limits in Each sector



If x_4 = 0, sectors 4 and 5 have a double collinear singularity. Sectors 1 and 2 have no singularity in this limit.

	$\mathcal{S}_1^I$	$\mathcal{S}_2^I$	$\mathcal{S}_4^I$	$\mathcal{S}_5^I$
$\hat{\eta}_1$	x_3	$\frac{1}{2}x_3x_4$	x_3	$\frac{1}{2}x_3(2-x_4)$
$\hat{\eta}_2$	$\frac{1}{2}x_3x_4$	x_3	$\frac{1}{2}x_3(2-x_4)$	x_3
$\hat{\xi}_1$	x_1	x_1	x_1	x_1
$\hat{\xi}_2$	$x_1x_2x_{max}$	$x_1x_2x_{max}$	$x_1x_2x_{max}$	$x_1x_2x_{max}$

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Example : S4

As an example, lets consider the sector S4, after appropriate Jacobian transformations the phase space measure is as follows,

$$d\Phi_{S4qq} = \mathrm{PS}\ \mathrm{PS}^{-\epsilon} \frac{dx_1}{x_1^{1+4\epsilon}} \frac{dx_2}{x_2^{1+2\epsilon}} \frac{dx_3}{x_3^{1+2\epsilon}} \frac{dx_4}{x_4^{1+2\epsilon}} dx_5 [x_1^4 x_2^2 x_3^2 x_4^2]$$

Ultimately we want to integrate the Matrix element squared over the phase space, so we define

$$d\Phi_{S4qq} |\mathcal{M}|^2 = \mathrm{PS}\ \mathrm{PS}^{-\epsilon} \frac{dx_1}{x_1^{1+4\epsilon}} \frac{dx_2}{x_2^{1+2\epsilon}} \frac{dx_3}{x_3^{1+2\epsilon}} \frac{dx_4}{x_4^{1+2\epsilon}} dx_5 F[x_1, x_2, x_3, x_4, x_5]$$

where

$$F[x_1, x_2, x_3, x_4, x_5] = x_1^4 x_2^2 x_3^2 x_4^2 |\mathcal{M}|^2$$

is a regular function, and finite for all x_i values!

Evaluating the limits

This is where the beauty of the method comes in! We **know** exactly what F[x_i] looks like with any of the x_i's zero, since this corresponds to one of our factorization formula of QCD.

For example, in our sector the x_1 = 0 limit is exactly given by the soft factorization formula we derived above, e.g. with x_1 and x_4 =0 we are in the double soft limit,

$$F[0, x_2, x_3, 0, x_5] = \left(x_1^4 x_2^2 x_3^2 x_4^2 \; \mathcal{I}_{b\bar{b}}(p_1, p_2)|\mathcal{M}(H \to b\bar{b}|^2\right)_{x_1 \to 0 x_4 \to 0}$$

which is,

$$F[0, x_2, x_3, 0, x_5] = \frac{(4\pi\alpha_S)^4 T_R x_2(-1+x_3)x_5(-2x_2^2(2-2x_3)+4(-1+x_3)-2x_2(4-8x_5+2x_3(-2+4x_5))}{(2+x_2)^2(2+x_2(2-2x_3)-2x_3)^2}$$

$$\times|\mathcal{M}_{LO}|^2$$

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Combining all of the sectors together we find the following numerical result for the H=>bbQQ double-real contribution to H=>bb at NNLO

$$\mathcal{R}\mathcal{R}_{H\to b\bar{b}q\bar{q}} = S_\Gamma^2\left(-\frac{0.333328}{\epsilon^3} - \frac{1.5557}{\epsilon^2} - \frac{1.62429}{\epsilon} + 5.15843\right)$$

An analytic calculation for the inclusive quantity from reverse unitarity yields

$$\mathcal{R}\mathcal{R}^{exact}_{H\to b\bar{b}q\bar{q}} = S_\Gamma^2\left(-\frac{0.333333}{\epsilon^3} - \frac{1.5556}{\epsilon^2} - \frac{1.62397}{\epsilon} + 5.15993\right)$$

Note that the exact numbers above, cannot be used to write a fully exclusive differential Monte Carlo code, while the top ones can easily do so!

Conclusions/Outlook

Today I've presented some partial results for the NNLO calculation of associated production using the Stripper algorithm for IR pole cancelation. In general:

- Constructing fully differential MC codes at NNLO is no trivial task, the Stripper routine developed by Czakon provides a physically intuitive way of constructing this. I've outlined this today.
- Once completed the code will be able to handle pp=> H(=>bb) + V(=>leptons), at NNLO
- The code will include potential BSM corrections which manifest themselves as deviations from the SM vertex.
- After that more processes will be implemented!