

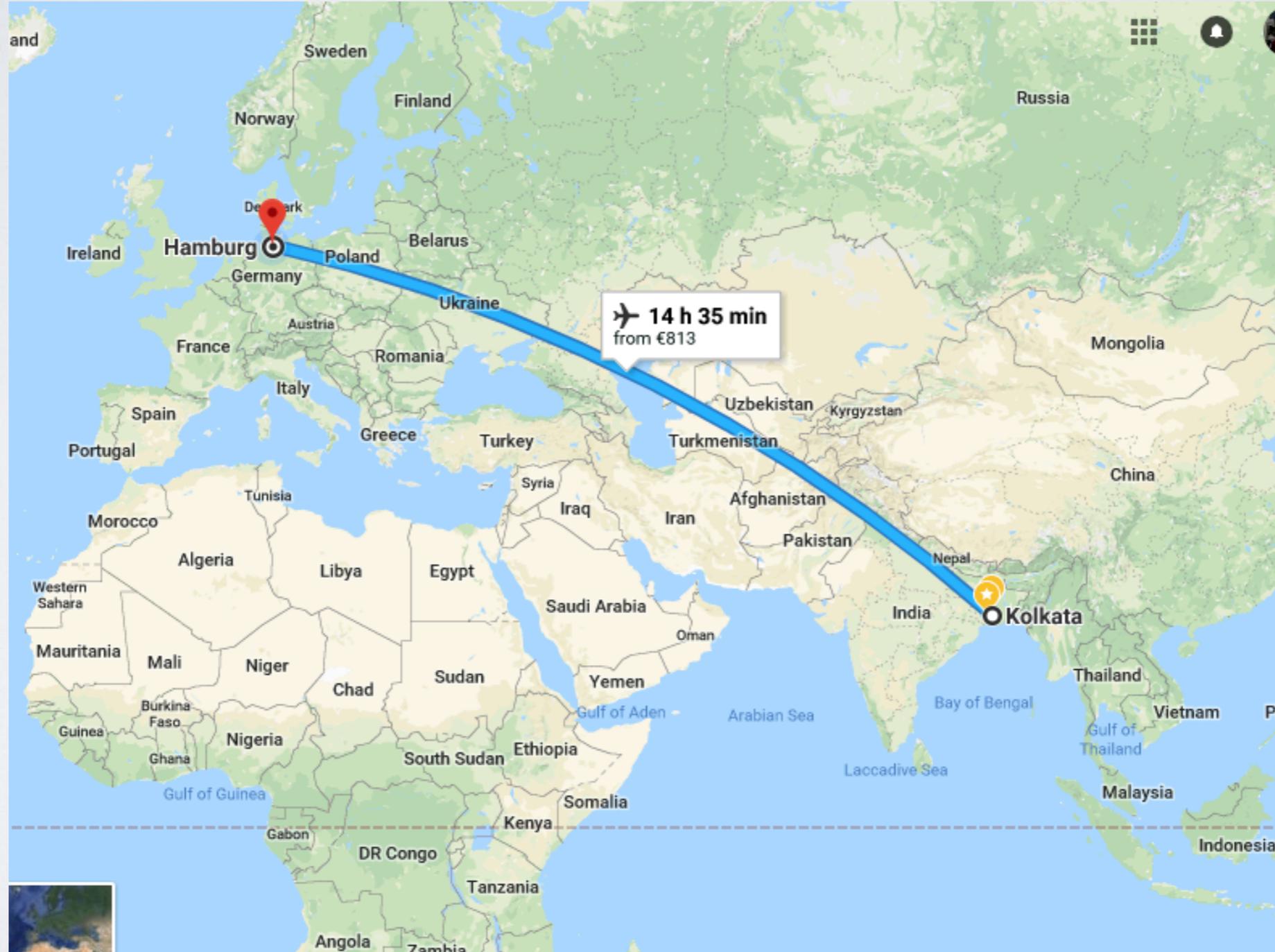


# QCD corrections in the SM and Beyond

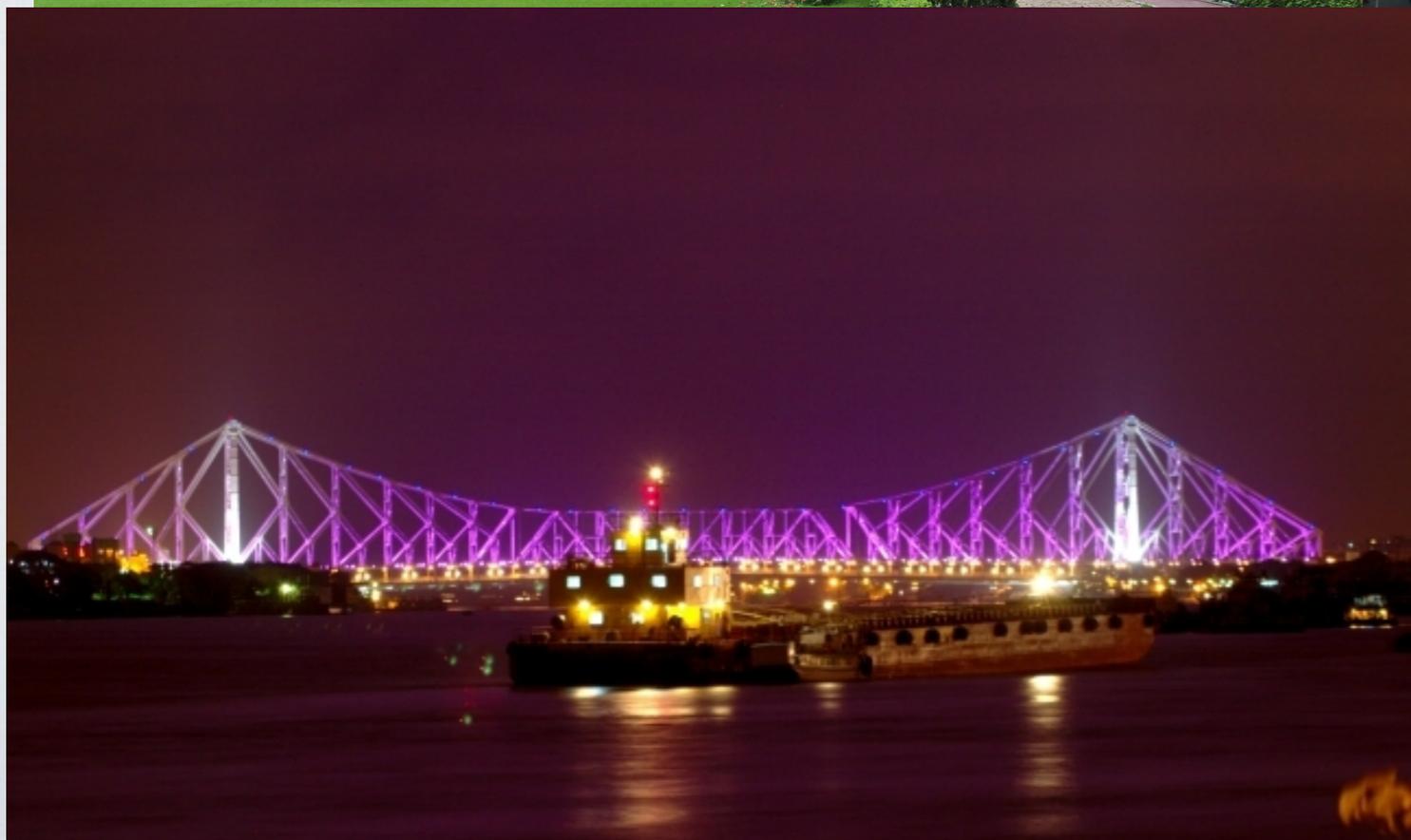
Goutam Das  
DESY, Hamburg

Theory Fellow Meeting, December 2017

# Where did I come from?



# Kolkata (Kalkutta)-City of Joy



# Activities

## Sports:

Cricket, Table Tennis.

Moto GP, F1

## Others:

Movies, Music

Motorbiking, Foodie  
Doglover

# Academic Carrier

- PhD: Saha Institute of Nuclear Physics, Kolkata, (2017)
- PDF: The Institute of Mathematical Sciences, Chennai, 2017(Feb-Oct)
- PDF: DESY, Hamburg (2017, Oct- Present)  
(Office: 204/1b)

# Research So Far

- Precision Spin-2 searches at the LHC



- Threshold Resummation

# Precision Spin-2 study at LHC

## Spin-2 in the context of LHC

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PhysicsResults > PhysicsResultsEXO (2017-12-05, SlavaValuev)

### CMS Exotica Public Physics Results

This page is still maintained on a best-effort basis, but please see the official CMS Publications page for the fully up-to-date list of results

#### CMS EXO Conveners

- Oliver Buchmueller, Ivan Mikulic (former Slava Valuev)

#### CMS EXO Summary Plots and Supporting L

- EXO summary plots:**
  - Resonances, extra dimensions, etc. (Aug 2016): [p](#)
  - Searches for long-lived particles (Aug 2016): [pdf](#), [p](#)
  - Searches for dark matter (Jul 2017) **NEW**: [pdf](#) [tar](#) [t](#)
- Note on the usage of simplified likelihood for the rein

#### Journal Publications - Run 2

##### Analysis

- Search for new long-lived particles **NEW**
- Search for excited states of light and heavy flavor quarks in the final state **NEW**

## ATLAS EXPERIMENT — PUBLIC RESULTS

### Exotic Physics Searches

This page contains public results from the ATLAS Exotics Working Group, which is searching for physics beyond the Standard Model with a signature-based pr... experimentally viable signatures focusing on non-supersymmetric models from Extra Dimensions and mini Black Holes to Dark Matter, extended Higgs models

ATLAS EXPERIMENT

If you have any question, please contact the group conveners (currently Gabriel Facini and Marie-Helene Genest): [atlas-phys-exotics-conveners](mailto:atlas-phys-exotics-conveners).

# Spin-2 at the LHC

## Models:

- Generic Spin-2
  - Arkani-Hamed-Dimopoulos-Dvali (ADD)
  - Randall-Sundrum (RS)
  - Universal Extra-Dimension (UED)
- } Extra Dimensions

# Spin-2 at the LHC

## Idea:

- Built an EFT and study low energy phenomena
- Impact of gravity on quantum phenomena on first approximation, relying on semi-classical description of gravity.

# Randall-Sundrum

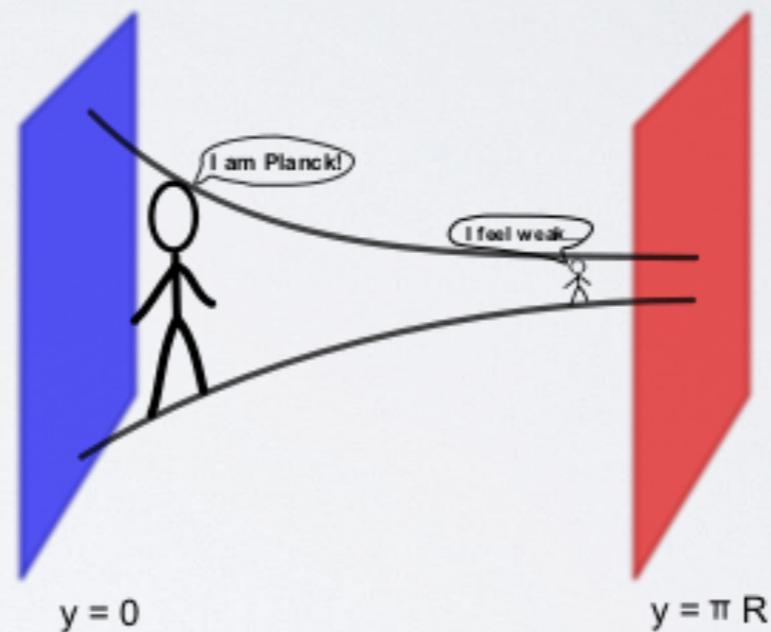
## Naive description:

- One extra spatial dimension compactified on a  $S^1/Z_2$  orbifold.
- SM is confined in TeV brane, Gravity propagates in 4+1 D
- 5-D gravity appears as a tower of Kaluza-Klein states from the SM brane.

# Randall-Sundrum

- 5-D non-factorisable warped metric

$$ds^2 = e^{-2\kappa r_c |\phi|} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2$$



- Interaction Lagrangian

$$\mathcal{L}_{RS} = -\frac{1}{\overline{M}_{Pl}} T^{\mu\nu}(x) G_{\mu\nu}^{(0)}(x) - \frac{\bar{c}_0}{m_0} T^{\mu\nu}(x) \sum_{n=1}^{\infty} G_{\mu\nu}^{(n)}(x)$$

# Perturbative QCD

- N-particle scattering cross-section:

$$\sigma_N = \sigma_N^{(0)} + \left(\frac{\alpha_s}{2\pi}\right) \sigma_N^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma_N^{(2)} + \dots$$

LO > NLO > NNLO

# Precision Spin-2 Study at LHC

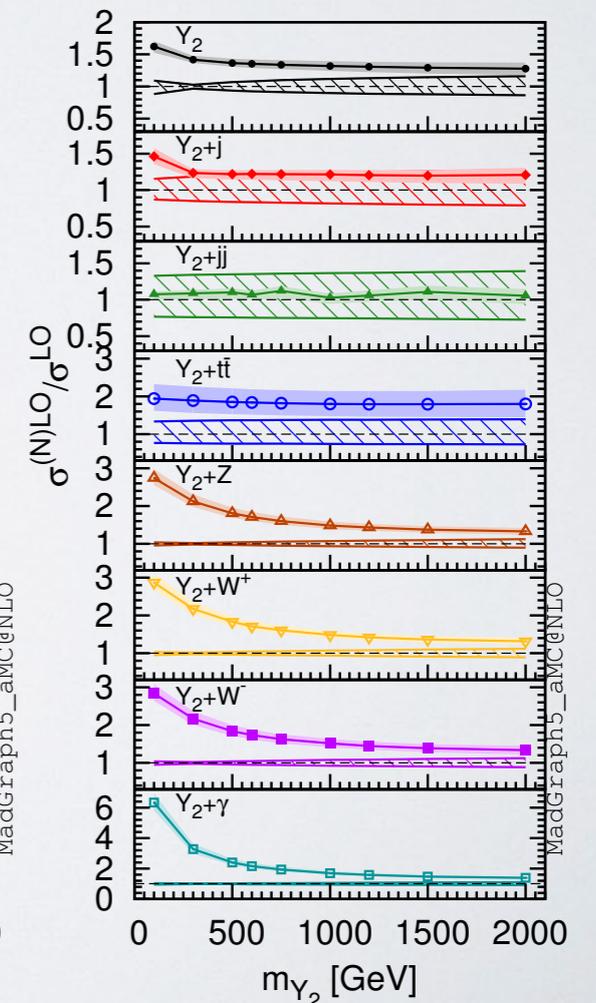
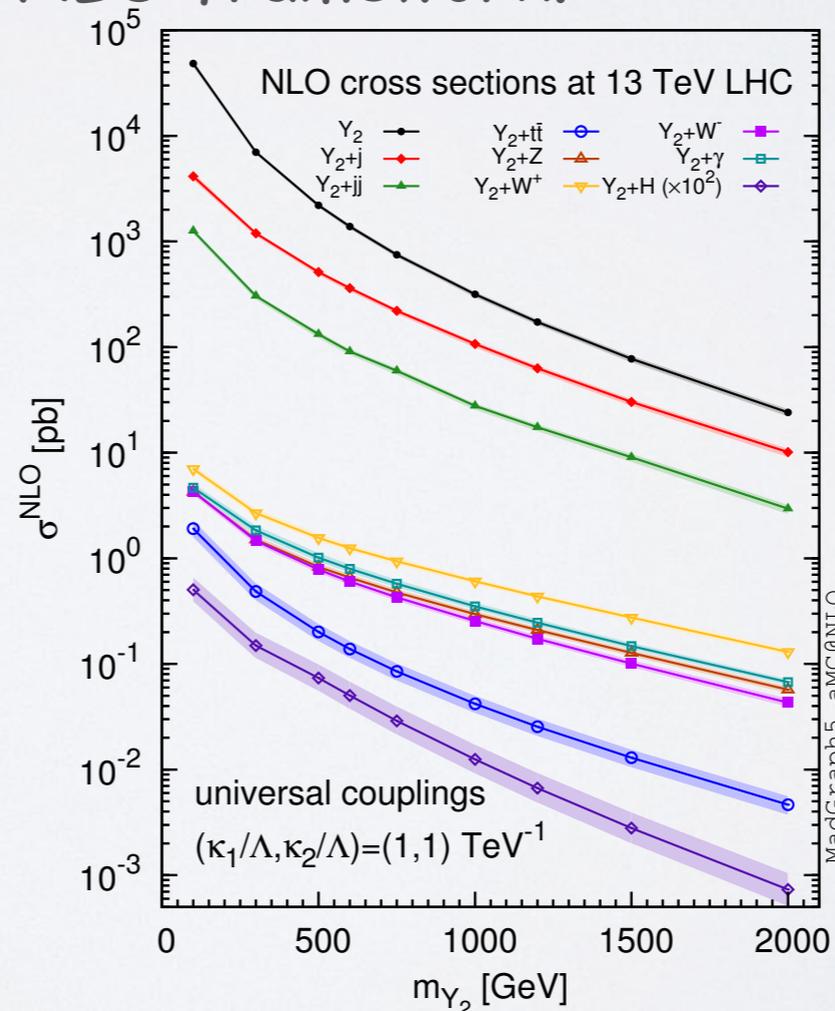
- Automation MC tools:

Implementation of a generic spin-2 model in  
FeynRules - MadGraph5\_aMC@NLO framework.

(<http://feynrules.irmp.ucl.ac.be/wiki/Spin2>)

Phenomenology study at  
NLO+PS for inclusive and  
associated production with

$$j, jj, \gamma, Z, W^{\pm}, t\bar{t}$$



# Precision Spin-2 Study at LHC

- Automation MC tools:

Implementation of RS model in MadGraph5\_aMC@NLO at

NLO+PS

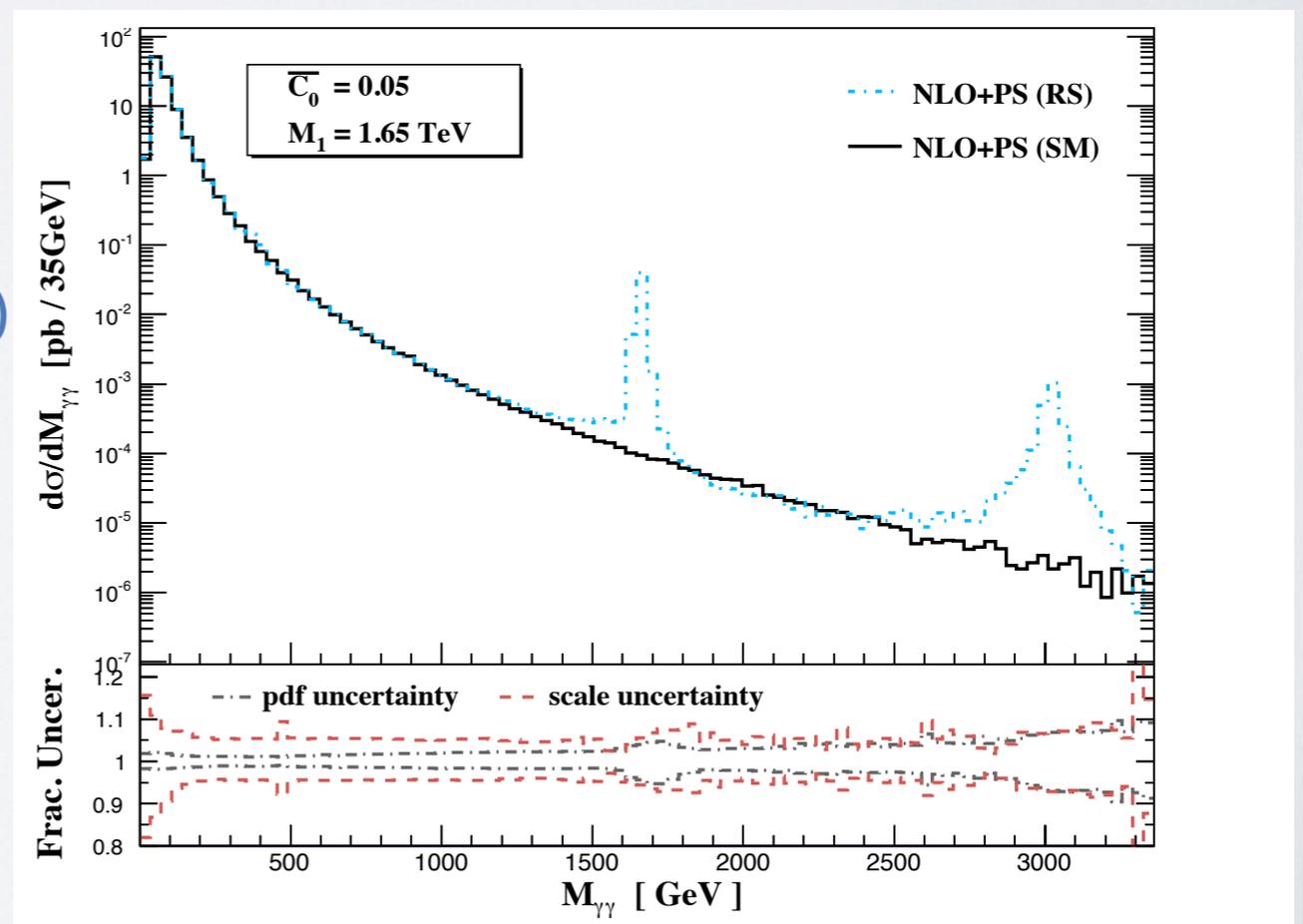
Standalone codes:

<http://amcatnlo.web.cern.ch/amcatnlo/>

Phenomenology study for

$\gamma\gamma, l^+l^-, ZZ, W^+W^-$

$\gamma\gamma\gamma, \gamma\gamma Z, \gamma ZZ, ZZZ$



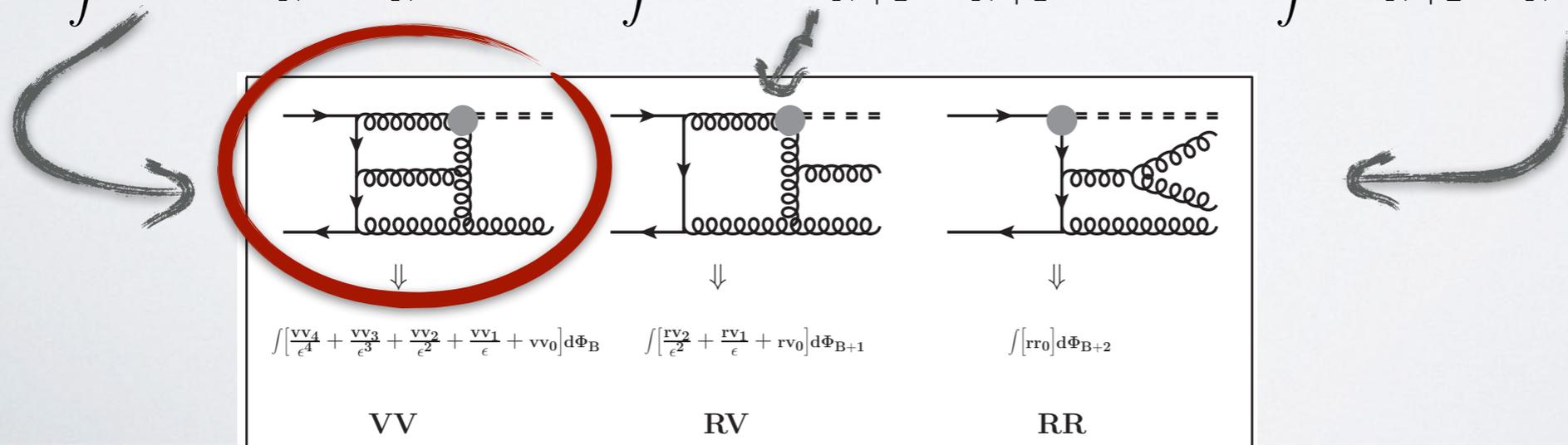
# Precision Spin-2 Study at LHC

- Multiloop computation:  
N-particle cross-section

$$\sigma_N = \sigma_N^{(0)} + \left(\frac{\alpha_s}{2\pi}\right) \sigma_N^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma_N^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma_N^{(3)} + \dots$$

LO > NLO > NNLO > NNNLO

$$\sigma_N^{(2)} = \int 2 \operatorname{Re} \langle M_N^{(0)} | M_N^{(2)} \rangle d\phi_N + \int 2 \operatorname{Re} \langle M_{N+1}^{(0)} | M_{N+1}^{(1)} \rangle d\phi_{N+1} + \int \langle M_{N+2}^{(0)} | M_{N+2}^{(0)} \rangle d\phi_{N+2}$$



# Precision Spin-2 Study at LHC

- Multiloop computation:



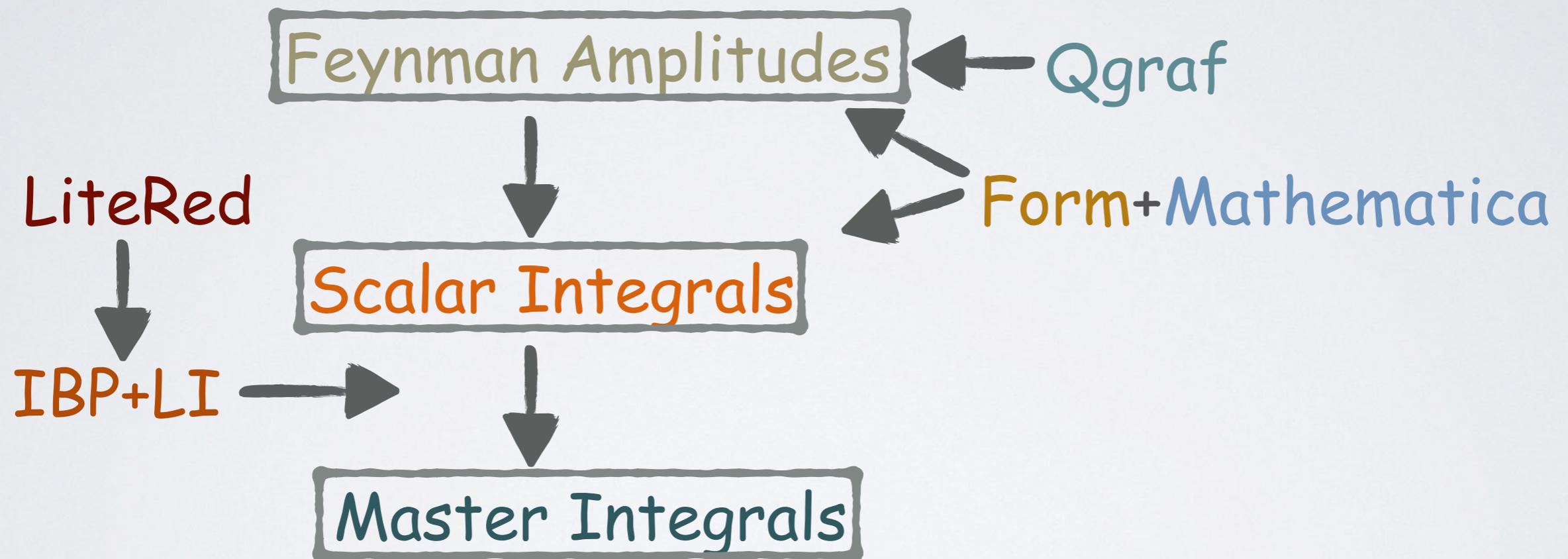
Inclusive Spin-2 production  
at NNNLO

Mono-jet at NNLO

Thousands of diagrams!!

# Precision Spin-2 Study at LHC

- Multiloop computation:



- Form-Factors satisfy Sudakov integro-differential equation
- Universal infrared pole behaviour.

# Threshold resummation

- Developed a formalism to resum threshold logarithms for Rapidity distribution of any colorless particle.
- Resummation in two-dimensional Mellin space.

# Threshold resummation

- Rapidity distribution

$$\frac{d\sigma^I}{dy} = \sigma_B^I(x_1^0, x_2^0, q^2, \mu_R^2) \sum_{ab=q, \bar{q}, g} \int_{x_1^0}^1 \frac{dz_1}{z_1} \int_{x_2^0}^1 \frac{dz_2}{z_2} \mathcal{H}_{ab}^I \left( \frac{x_1^0}{z_1}, \frac{x_2^0}{z_2}, \mu_F^2 \right) \Delta_{d,ab}^I(z_1, z_2, q^2, \mu_F^2, \mu_R^2).$$

Hadronic rapidity:  $y = \frac{1}{2} \ln(x_1^0/x_2^0)$

Scaling variable:  $z_i = x_i^0/x_i$

Soft-Virtual part:

$$\left[ \frac{\delta(1-z_i) \ln^{m-1}(1-z_i)}{(1-z_i)} \right]_+ \quad m \leq 2n$$

Exponentiates the threshold logs through cusp anomalous dimension and collinear functions

# Threshold resummation

- Double Mellin transformation

$$\tilde{\Delta}_d^{I,SV}(\omega) = \int_0^1 dz_1 z_1^{N_1-1} \int_0^1 dz_2 z_2^{N_2-1} \Delta_d^{I,SV}(z_1, z_2)$$

Resummed rapidity distribution

$$\tilde{\Delta}_d^{SV,I}(\omega) = \tilde{g}_{d,0}^I(a_s) \exp(g_d^I(a_s, \omega))$$

Ni dependent

Ni independent

$$\omega = a_s \beta_0 \ln(\bar{N}_1 \bar{N}_2)$$

# Threshold resummation

Resummed rapidity distribution

$$g_d^I(a_s, \omega) = g_{d,1}^I(\omega) \ln(\bar{N}_1 \bar{N}_2) + \sum_{i=0}^{\infty} a_s^i g_{d,i+2}^I(\omega)$$

$$= g_{d,1}^I(\omega) \ln(\bar{N}_1 \bar{N}_2) + g_{d,2}^I(\omega) + a_s g_{d,3}^I(\omega) + \dots$$



Resummed Logs

LL	→	$\alpha_s^n \ln^{n+1}(\bar{N}_1 \bar{N}_2)$
NLL	→	$\alpha_s^n \ln^n(\bar{N}_1 \bar{N}_2)$
NNLL	→	$\alpha_s^{n+1} \ln^n(\bar{N}_1 \bar{N}_2)$

$$\delta(1 - z_i) \rightarrow 1$$

$$\frac{\ln^i(1 - z_j)}{1 - z_j} \rightarrow \ln^i \bar{N}_j$$

# Threshold resummation

Logarithms that are resummed

$$\mathcal{O}(a_s)$$

$$\mathcal{O}(a_s^2)$$

$$\mathcal{O}(a_s^3)$$

$$\ln^2(\bar{N}_1 \bar{N}_2)$$

$$\ln^3(\bar{N}_1 \bar{N}_2)$$

$$\ln^4(\bar{N}_1 \bar{N}_2)$$

LL

$$a_s^m \ln^{m+1}(\bar{N}_1 \bar{N}_2)$$

$$g_{d,1}^I \ln(\bar{N}_1 \bar{N}_2)$$

$$\ln(\bar{N}_1 \bar{N}_2)$$

$$\ln^2(\bar{N}_1 \bar{N}_2)$$

$$\ln^3(\bar{N}_1 \bar{N}_2)$$

NLL

$$a_s^m \ln^m(\bar{N}_1 \bar{N}_2)$$

$$g_{d,2}^I$$

$$\ln(\bar{N}_1 \bar{N}_2)$$

$$\ln^2(\bar{N}_1 \bar{N}_2)$$

NNLL

$$a_s^{m+1} \ln^m(\bar{N}_1 \bar{N}_2)$$

$$a_s g_{d,3}^I$$

Resummed terms:

Functions that  
resums:

# Threshold resummation

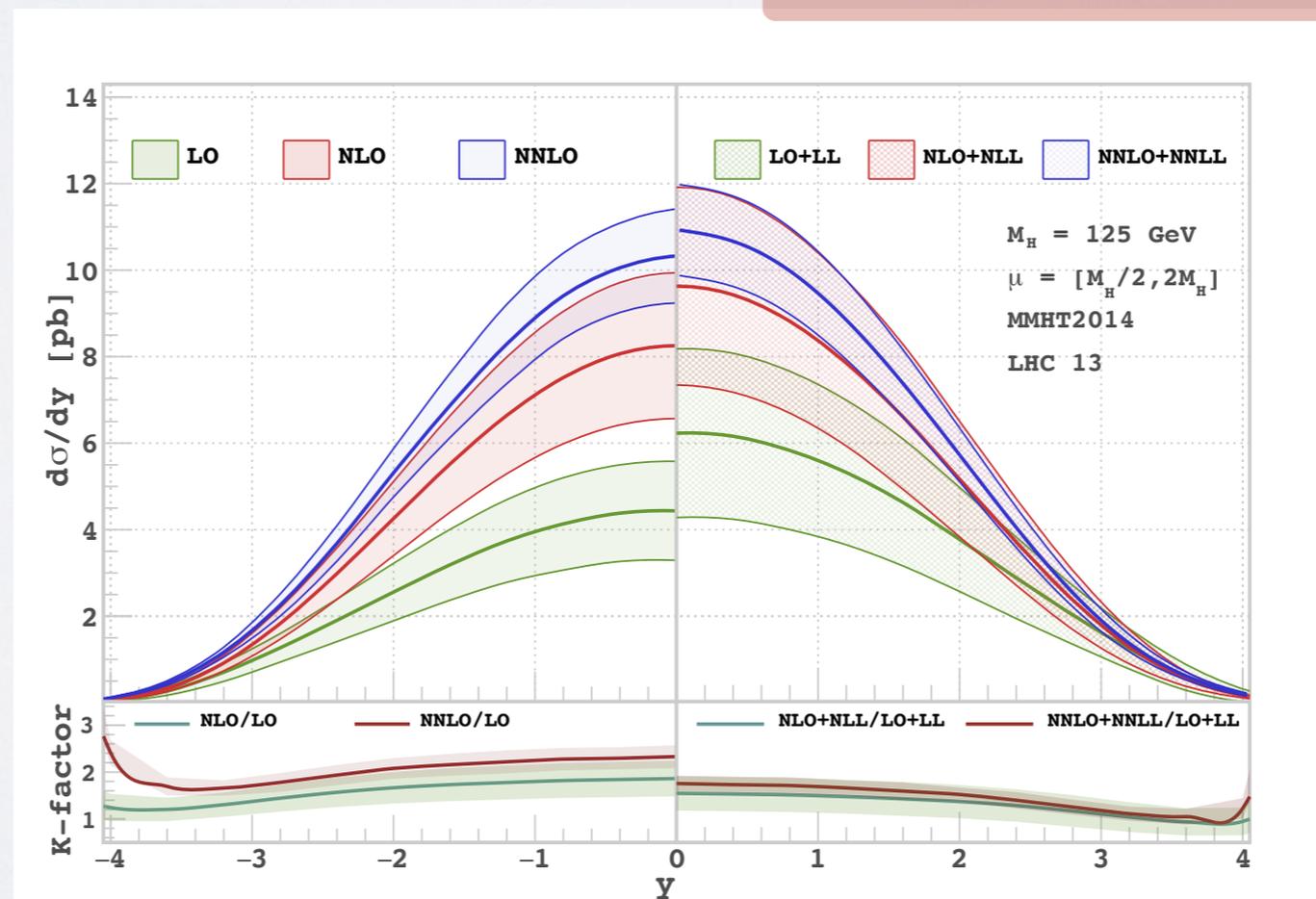
- Matching at NNLO+NNLL:

$$\frac{d\sigma^{g,\text{res}}}{dy} = \frac{d\sigma^{g,\text{f.o.}}}{dy} + \sigma_B^I \int_{c_1-i\infty}^{c_1+i\infty} \frac{dN_1}{2\pi i} \int_{c_2-i\infty}^{c_2+i\infty} \frac{dN_2}{2\pi i} e^{y(N_2-N_1)} \times (\sqrt{\tau})^{-2-N_1-N_2} \tilde{f}_g(N_1) \tilde{f}_g(N_2) \left[ \tilde{\Delta}_{d,g}^{\text{SV},N_1,N_2} - \left( \tilde{\Delta}_{d,g}^{\text{SV},N_1,N_2} \right)_{\text{trunc}} \right]$$

Matching with FO

Case study: Higgs rapidity

1. Resum result gives better perturbative convergence.
2. NNLO+NNLL result stabilises with respect to the choice of central scale.



# Current Research

- Study DY threshold resummation.
- $q_T$  resummation.
- Resummation in Soft-Collinear Effective theory.
- N-Jettiness
- ...



thank you!