A journey to LHC physics from proton structure to Higgs pair production

Juan Rojo
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MSc Theoretical Physics Master Lunch
Amsterdam Science Park, 19/01/2017

A gentle introduction

BSc+MSc+PhD
Barcelona (1998-2006)

A gentle introduction

Postdoc @ LPTHE (Paris VI)
Paris (2006-2008)

A gentle introduction

Postdoc @ INFN
Milano (2008-2011)

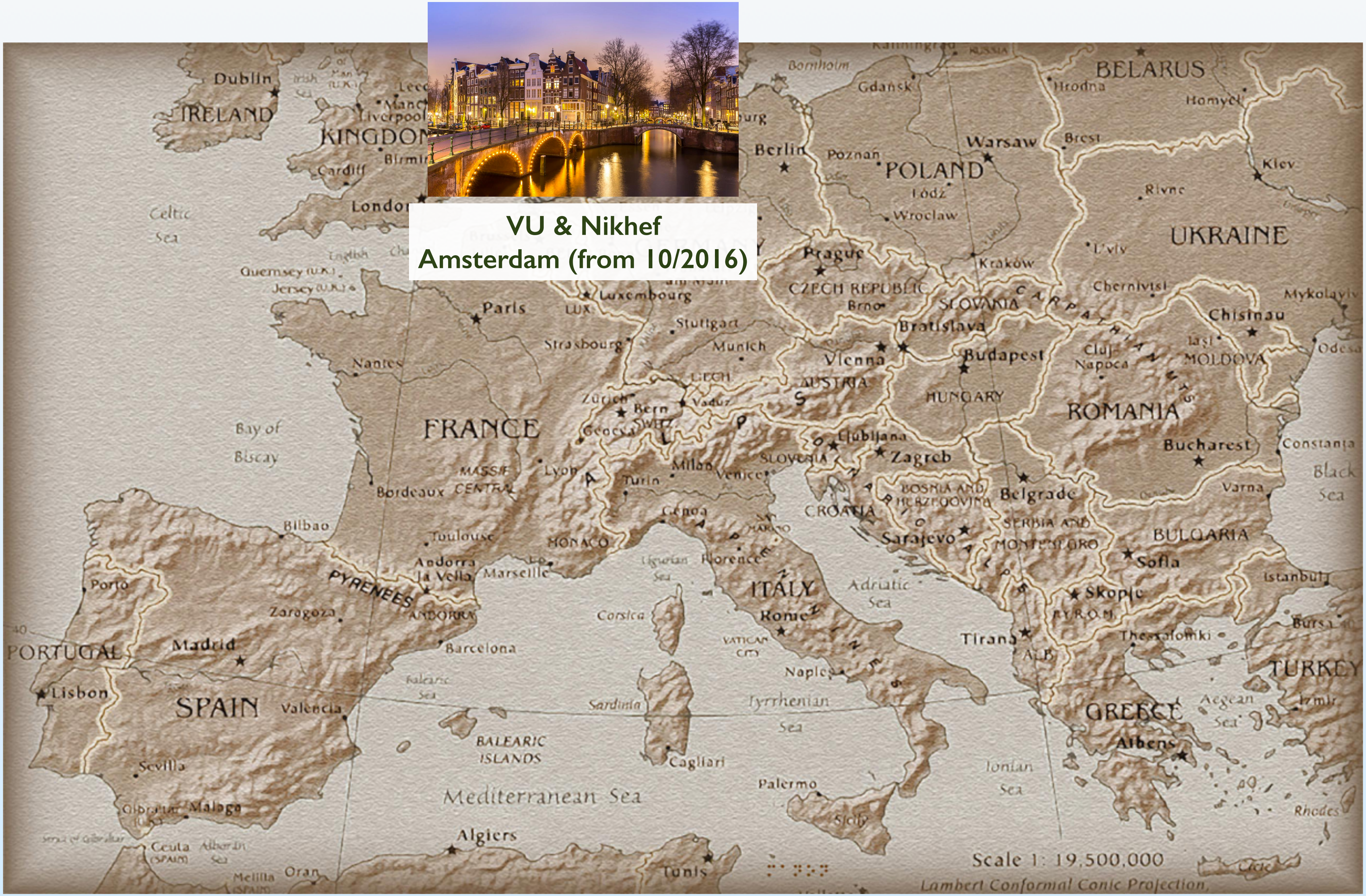
A gentle introduction

Marie Curie Fellow @ CERN
Geneva (2011-2013)

A gentle introduction

Junior Faculty
Oxford (2014-2016)

A gentle introduction



VU & Nikhef
Amsterdam (from 10/2016)

Group

http://juanrojo.com/

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Funding:

PDF4BSM
Parton Distributions in the Higgs Boson Era
erc European Research Council

Science & Technology Facilities Council

Teaching

- ***Von Quantum tot Molecuul***, 2nd year Bs Medical Physics, VU, together with Erwin (replacing John K)

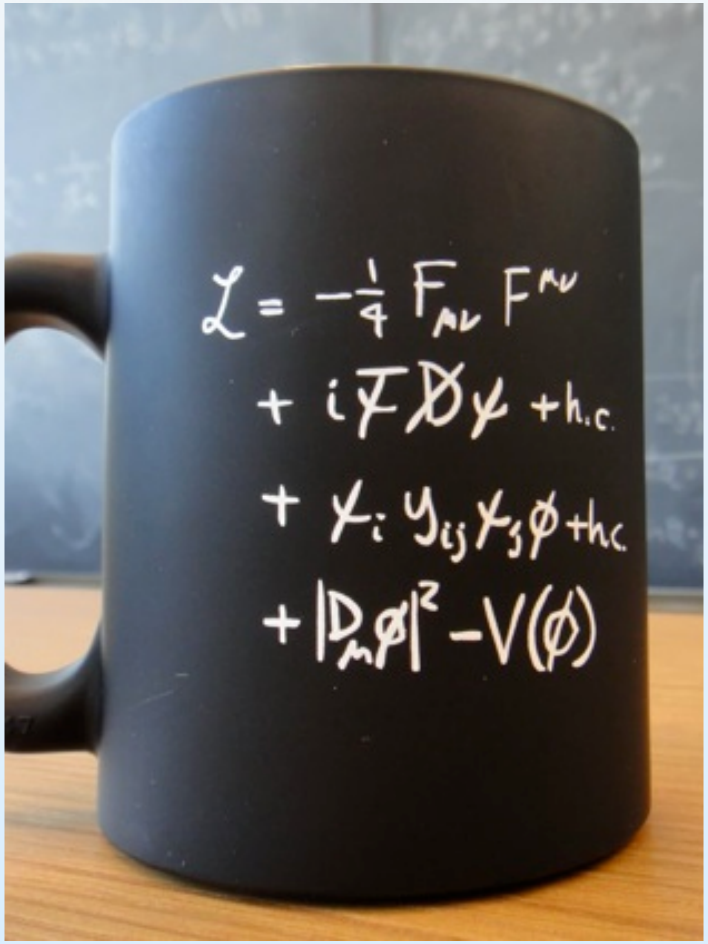
- ***Subatomic Physics Workshop***, 3rd year BSc Physics, UvA with Nikhef

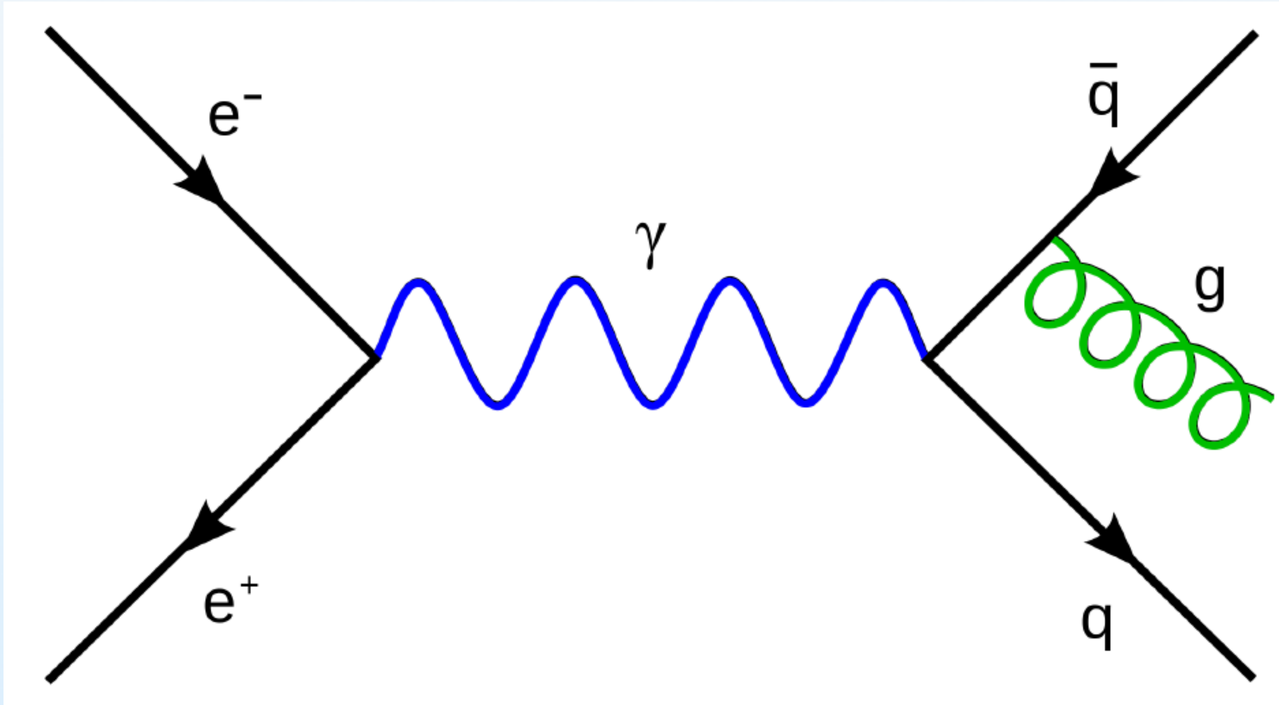
- ***Quantum Field Theory Extension***, **MSc Physics and Astronomy**, VU+UvA, Theoretical Physics Track (from 2017-2018)

Outreach

Lepton vs Hadron Colliders

High-energy **lepton colliders** such as **LEP** involve **elementary particles** without substructure

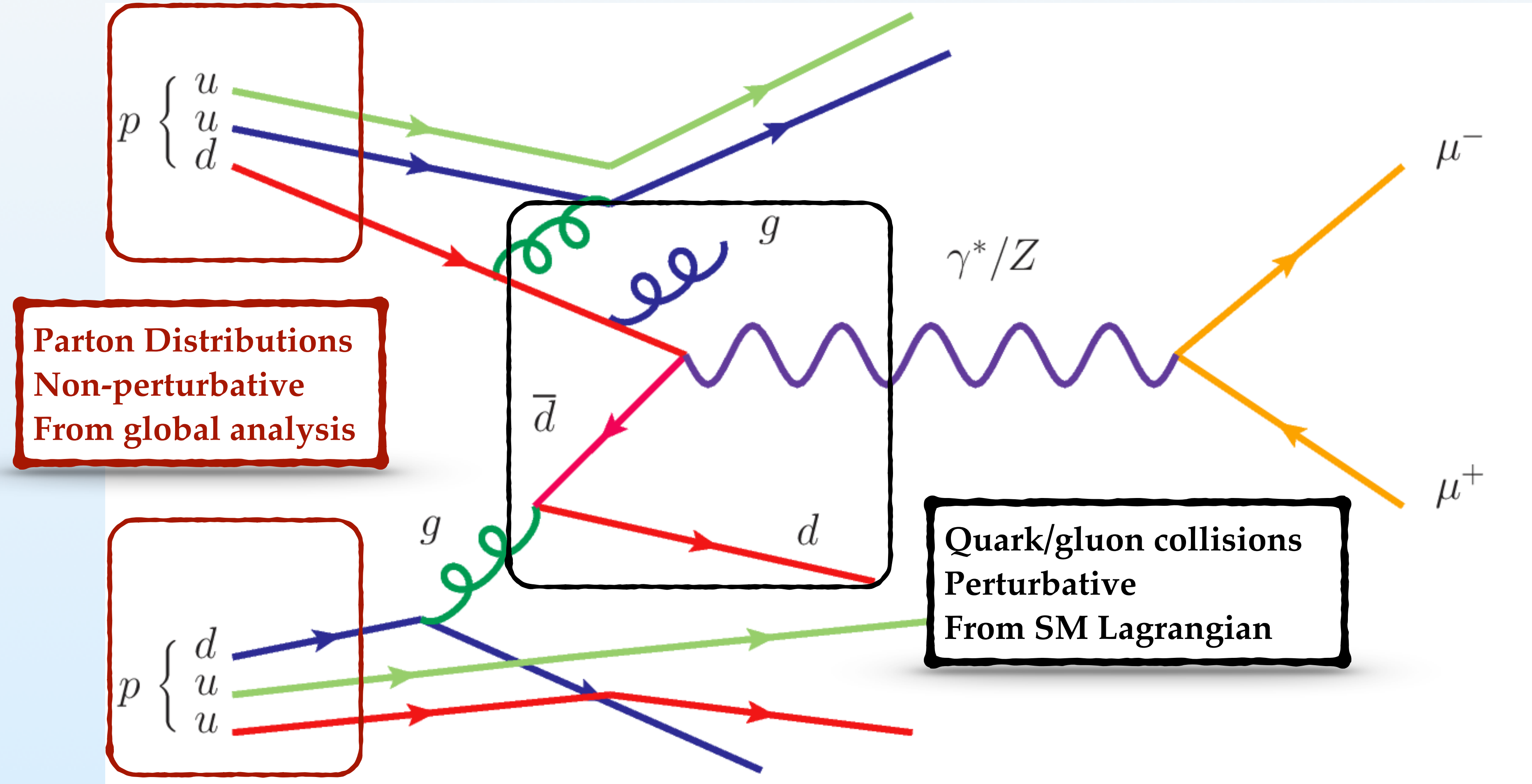




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

Lepton vs Hadron Colliders

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with **internal structure** (quarks and gluons)



Calculations of **cross-sections** in hadron collisions require the combination of **perturbative, quark/gluon-initiated processes**, and **non-perturbative, parton distributions**, information

Parton Distributions

The distribution of energy that **quarks and gluons carry inside the proton** is quantified by the **Parton Distribution Functions (PDFs)**

$$g(x, Q)$$

g(x,Q): **Probability** of **finding a gluon inside a proton**, carrying a fraction *x* of the proton momentum, when probed with energy *Q*

x: **Fraction of the proton's momentum**

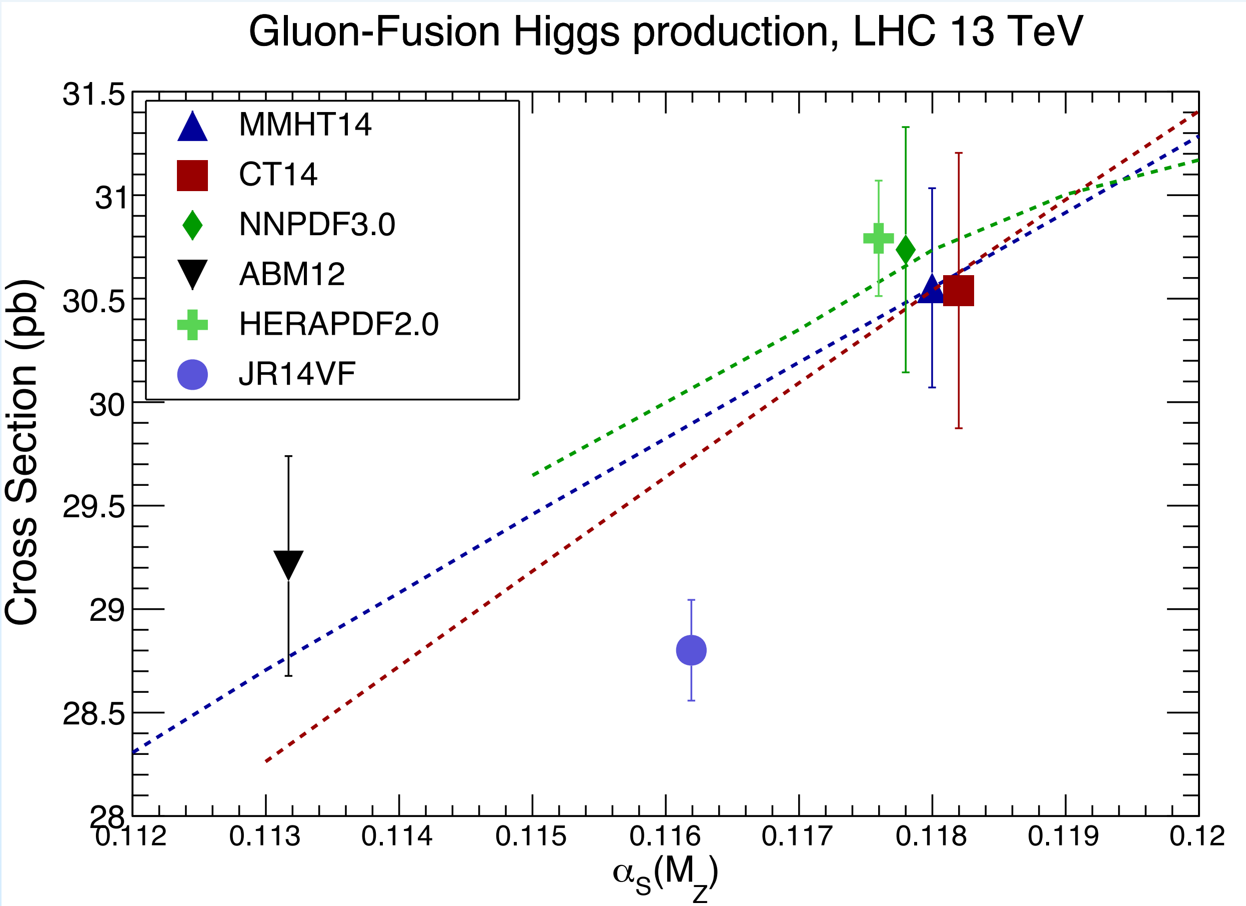
Q: **Energy of the quark/gluon collision**
Inverse of the resolution length

PDFs are** determined by **non-perturbative QCD dynamics,** cannot be computed from first principles, and therefore need to be **extracted from experimental data** with a **global analysis

PDFs and LHC phenomenology

Uncertainties from Parton Distributions** are one of the limiting factors of theory predictions of Higgs production, **degrading the exploration of the Higgs sector

$$\sigma_{exp} = \mu_{bsm} \cdot \sigma_{SM} = \boxed{\mu_{bsm}} \cdot \sigma_{gg\to h} \cdot \boxed{g(x_1,m_h) \cdot g(x_2,m_h)}$$



Higgs Cross-Section Working Group Yellow Report 4, 16

PDFs and LHC phenomenology

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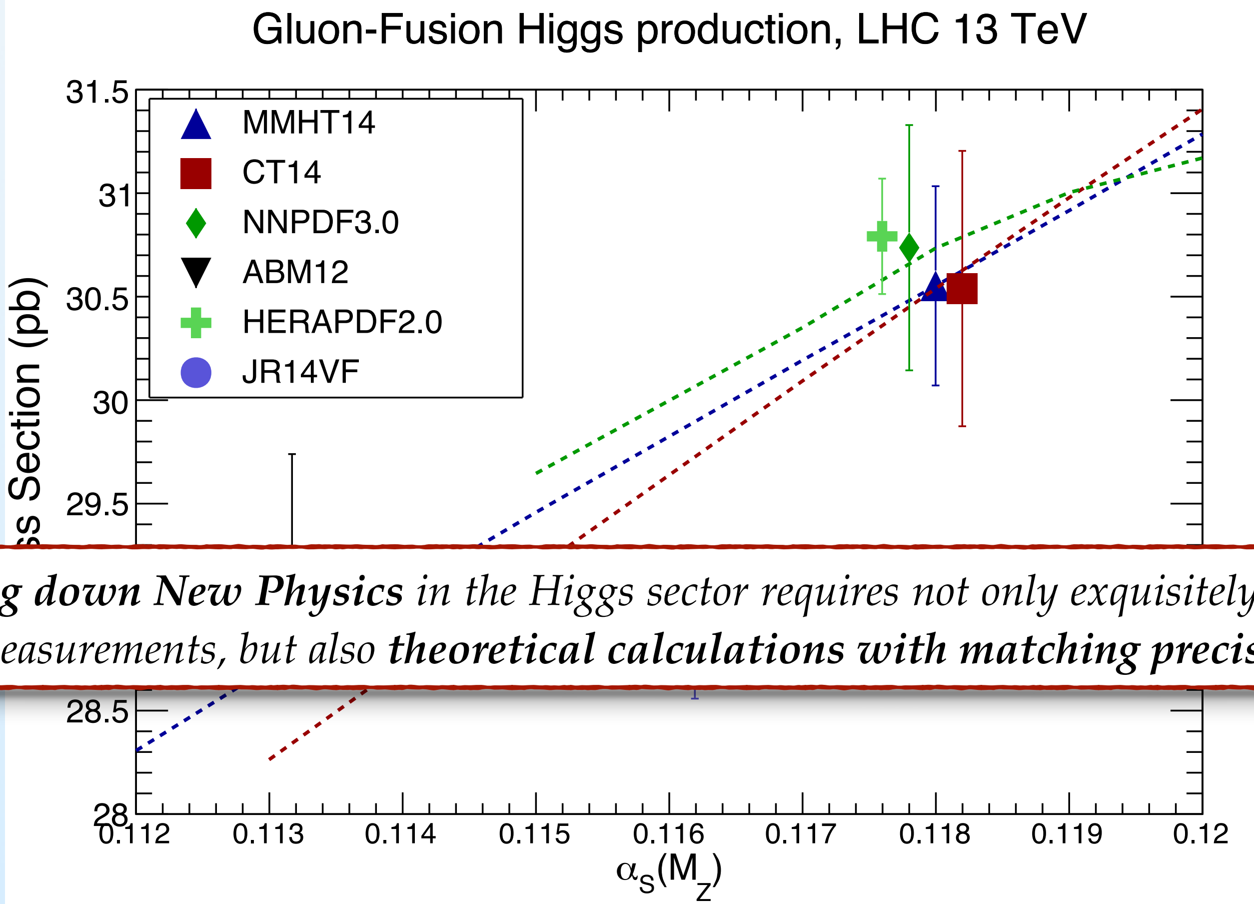
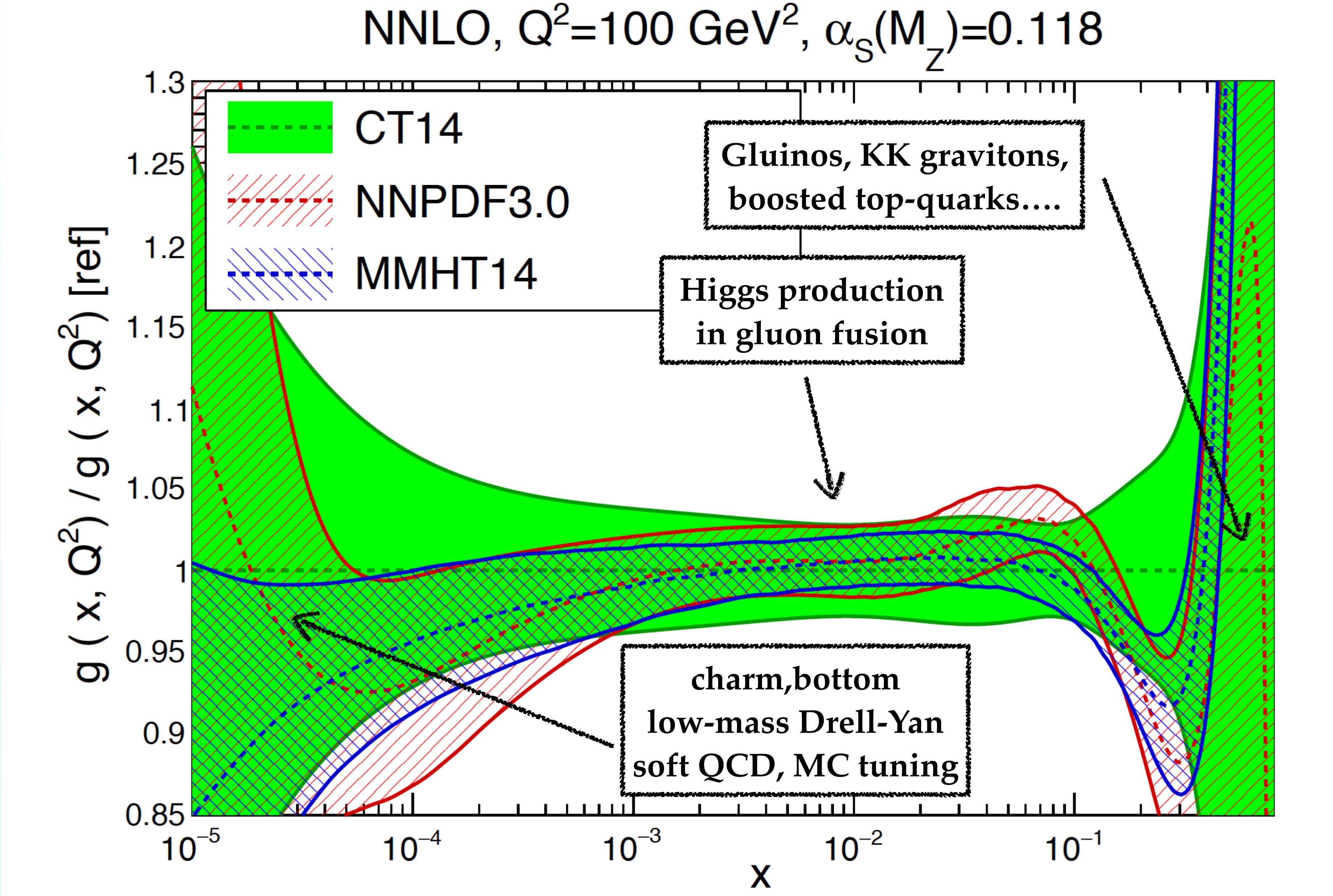


Pinning down New Physics *in the Higgs sector requires not only exquisitely precise LHC measurements, but also* ***theoretical calculations with matching precision***

Higgs Cross-Section Working Group Yellow Report 4, 16

One glue to bind them all



Exploit PDF-sensitive LHC measurements to **constrain the gluon from small to large-x**

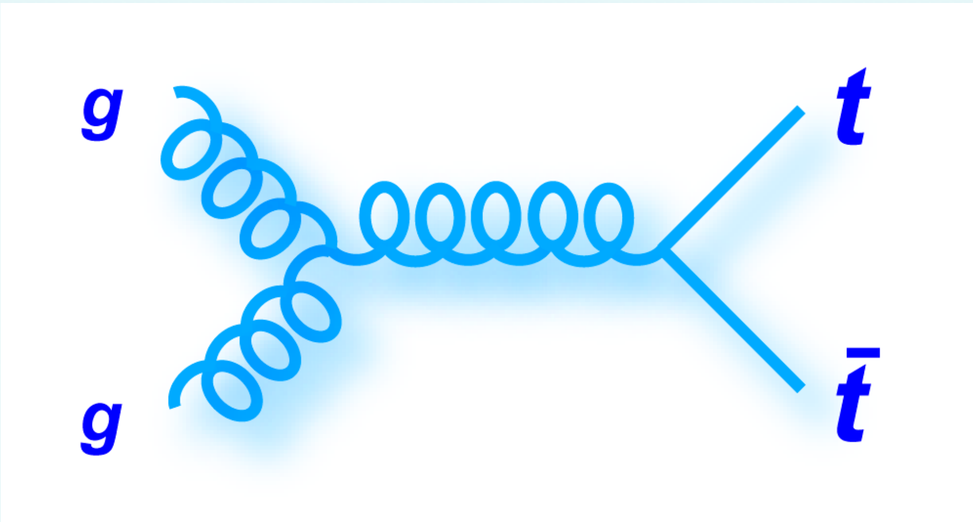
The large-x gluon from top-quark production

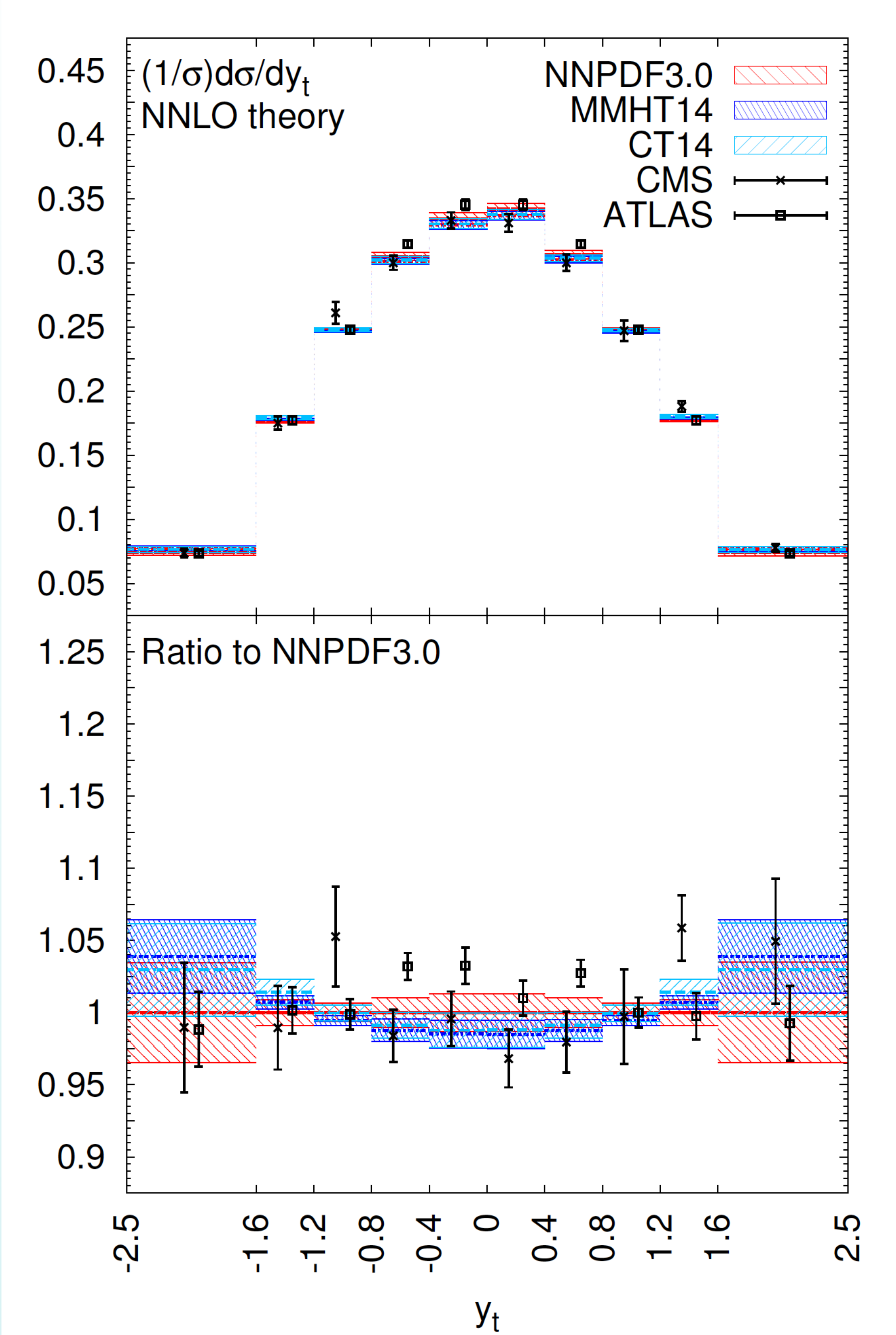
- Top-quark pair production driven by the **gluon-gluon luminosity**

- **NNLO calculations for stable top quarks** available (with decays in the pipeline)

- Recent **precision data from ATLAS and CMS at 8 TeV** with full breakdown of statistical and systematic uncertainties

- For the first time, included ATLAS+CMS 8 TeV differential top measurements into the **global PDF fit**





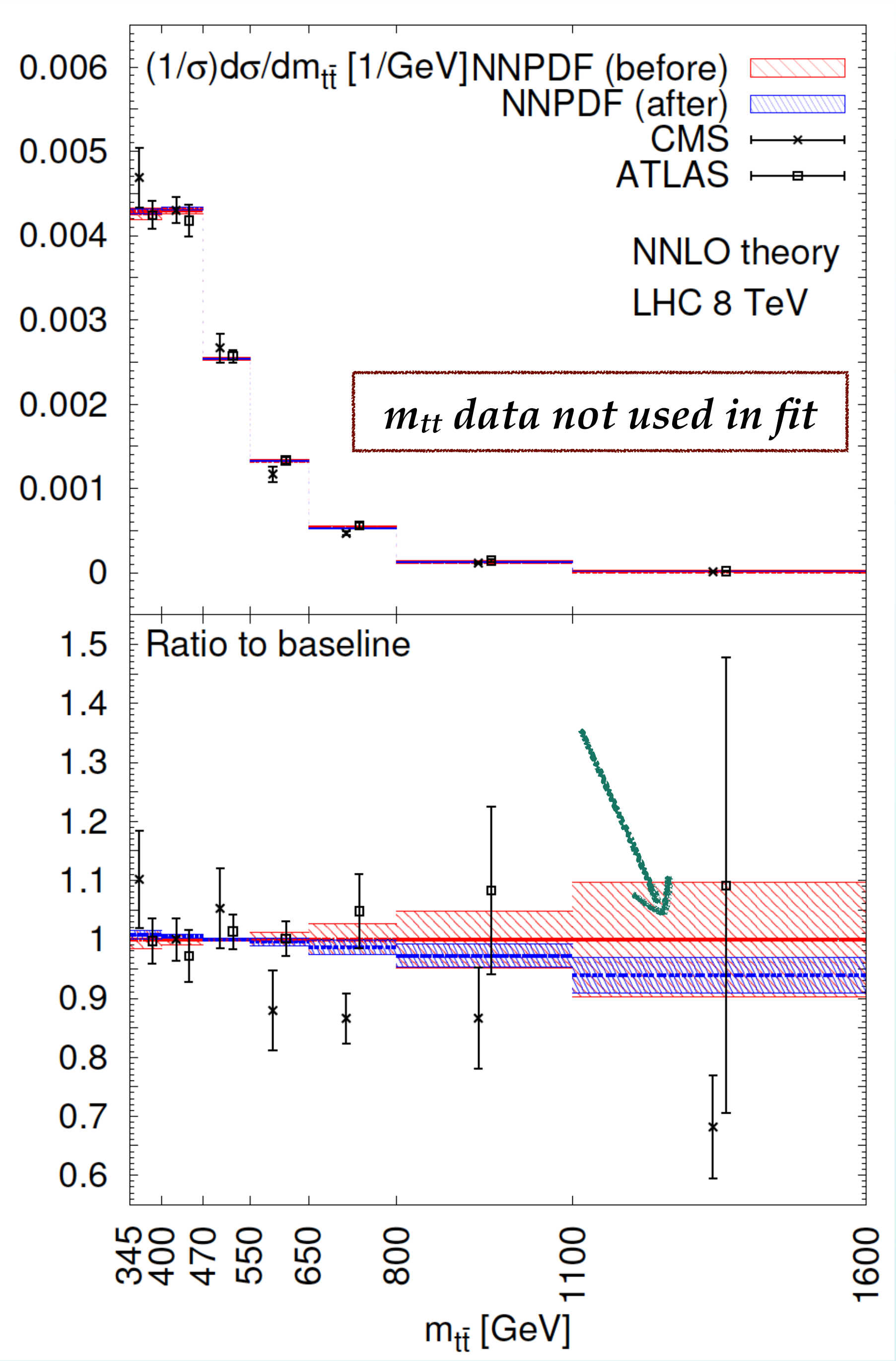
The large-x gluon from top-quark production

- PDF uncertainties reduced by more than a factor two for $\mathbf{m_{tt} \gtrsim 500}$ **GeV**

- Our choice of fitted distributions, $\mathbf{y_t}$ and $\mathbf{y_{tt}}$, reduces the **risk of *BSM contamination*** (kinematical suppression of resonances), which might show up instead in $\mathbf{m_{tt}}$ and $\mathbf{p^t_T}$, where PDF uncertainties are now much smaller

- Self-consistent program to **use top data to provide better theory predictions**

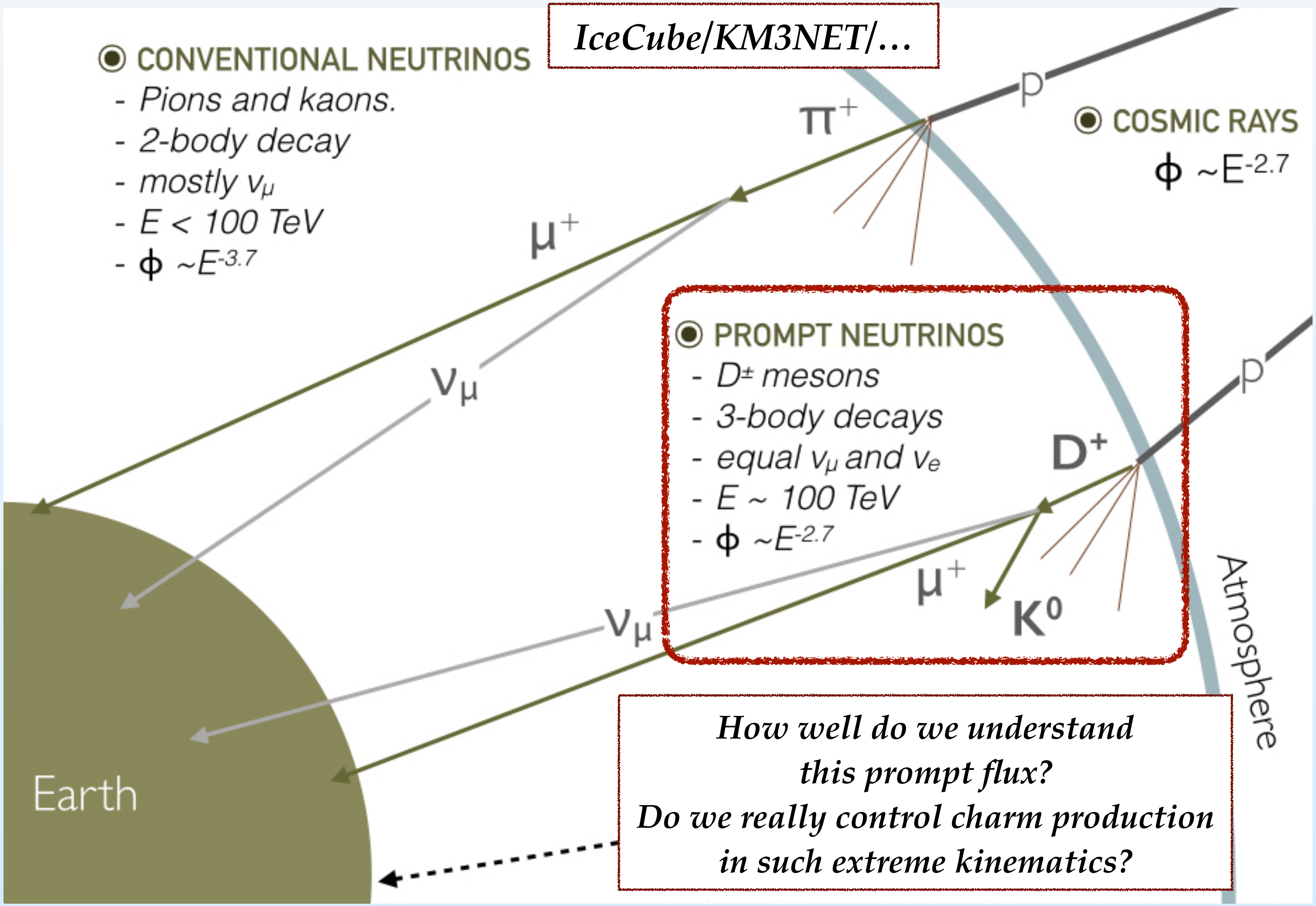
Improved sensitivity to BSM dynamics with top-quark final states!



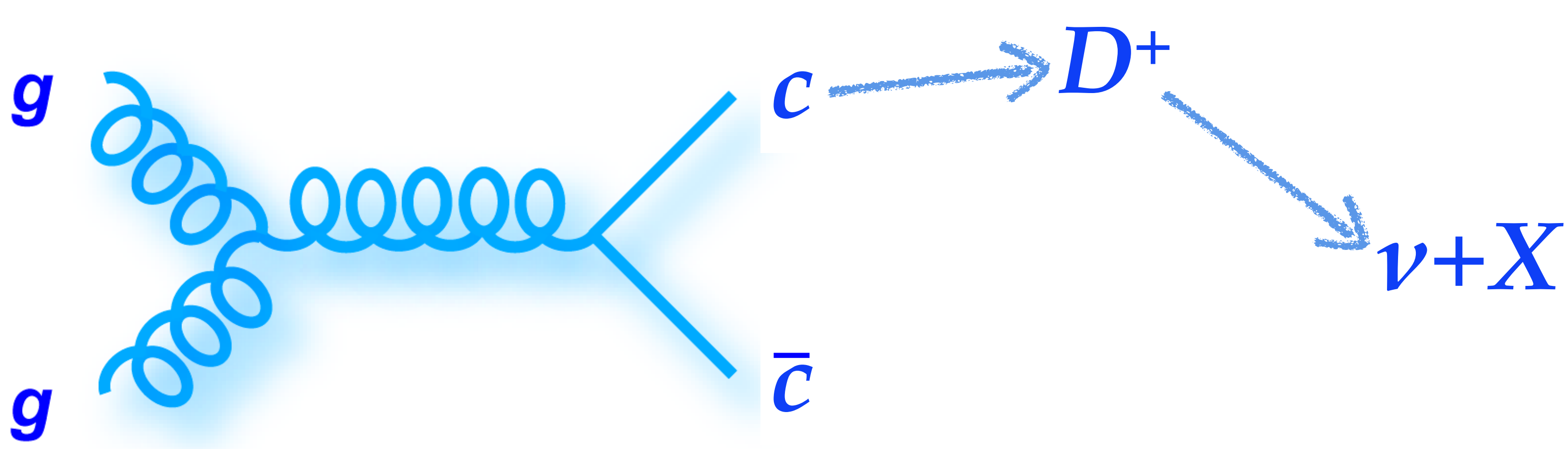
The prompt flux at neutrino telescopes

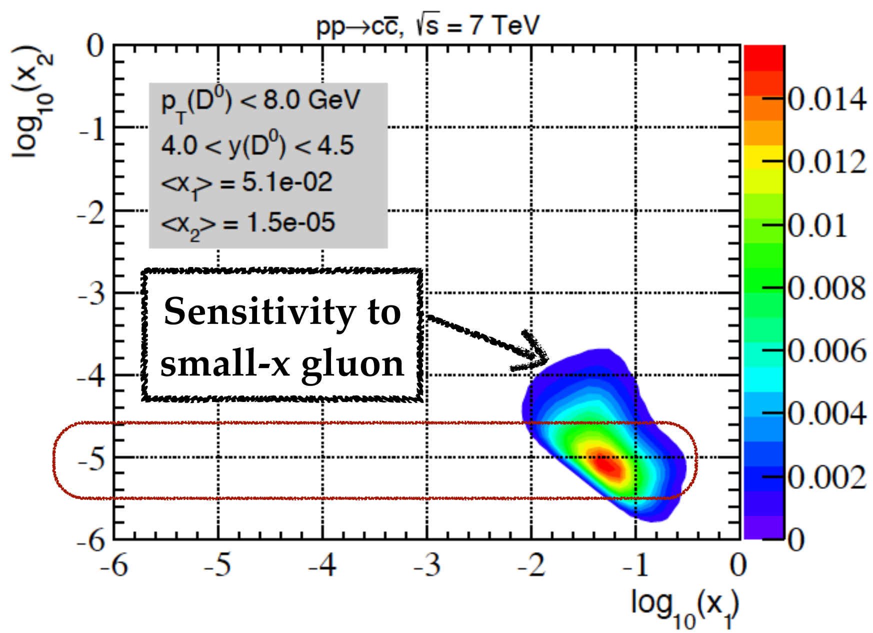
Observation of Ultra-High Energy (UHE) neutrino events heralds start of **Neutrino Astronomy**

New window to the Universe, but interpretation of UHE data requires **control over backgrounds**



The low-x gluon from charm production





Lab frame $E_{lab} = (2m_pE_{CR})^{1/2}$

$E_{CR} = 100$ PeV $\longrightarrow E_{lab} \approx 14$ TeV

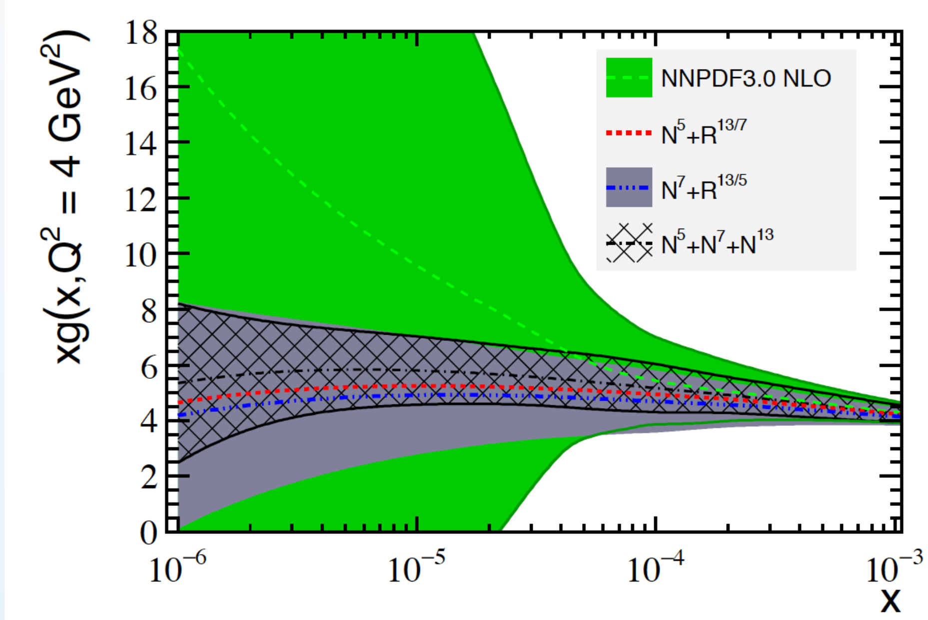
Overlap kinematics between charm production in UHE cosmic rays and at the LHC

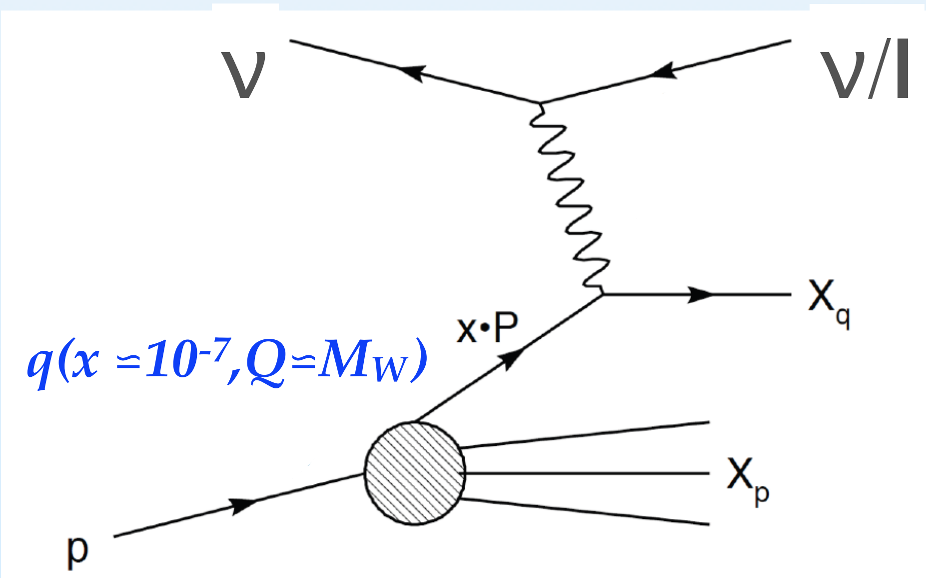
UHE neutrino-nucleus cross-sections

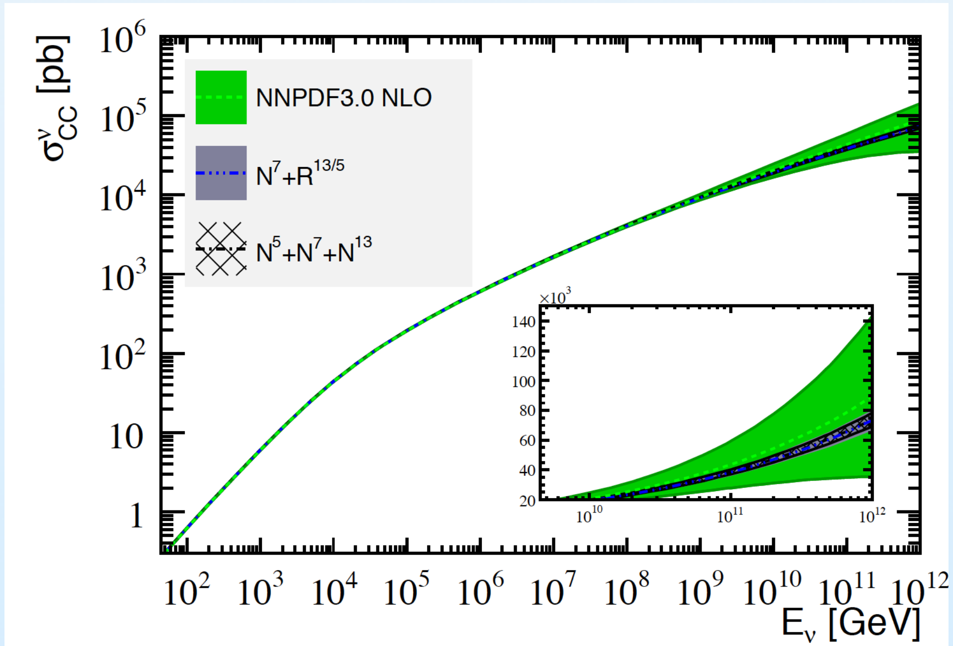
- Combine **LHCb 5 TeV and 13 TeV with 7 TeV** data to achieve a reduction of gluon PDF errors **by an order of magnitude at x=10^{-6}**

Gauld, Rojo 16

- High-precision QCD predictions of **neutrino-nucleus cross-section up to 10^6 PeV** (low-x sea quarks driven by gluon through DGLAP evolution)

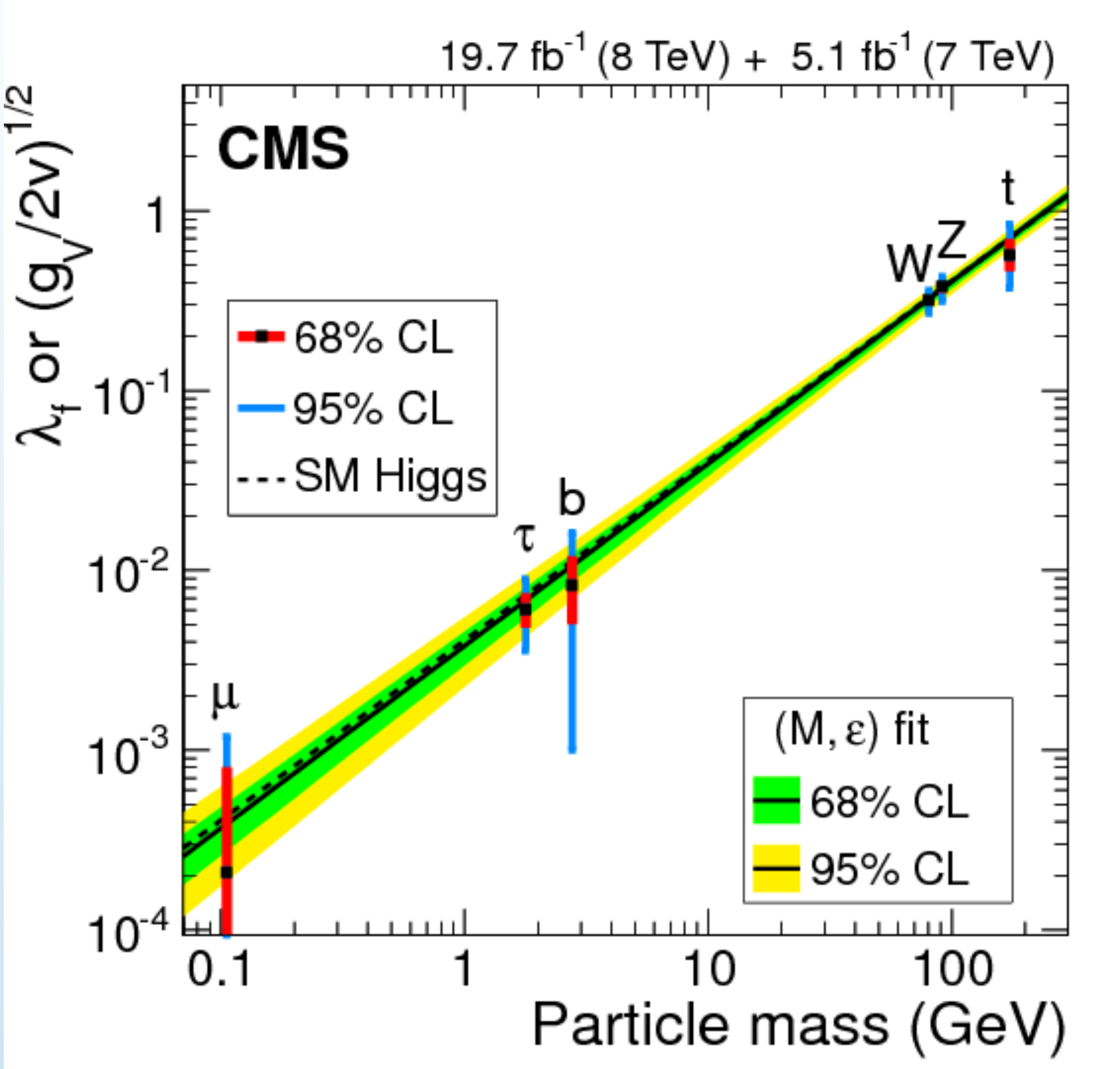






Precision studies of extreme QCD with IceCube/KM3NET: the ultimate DIS experiments

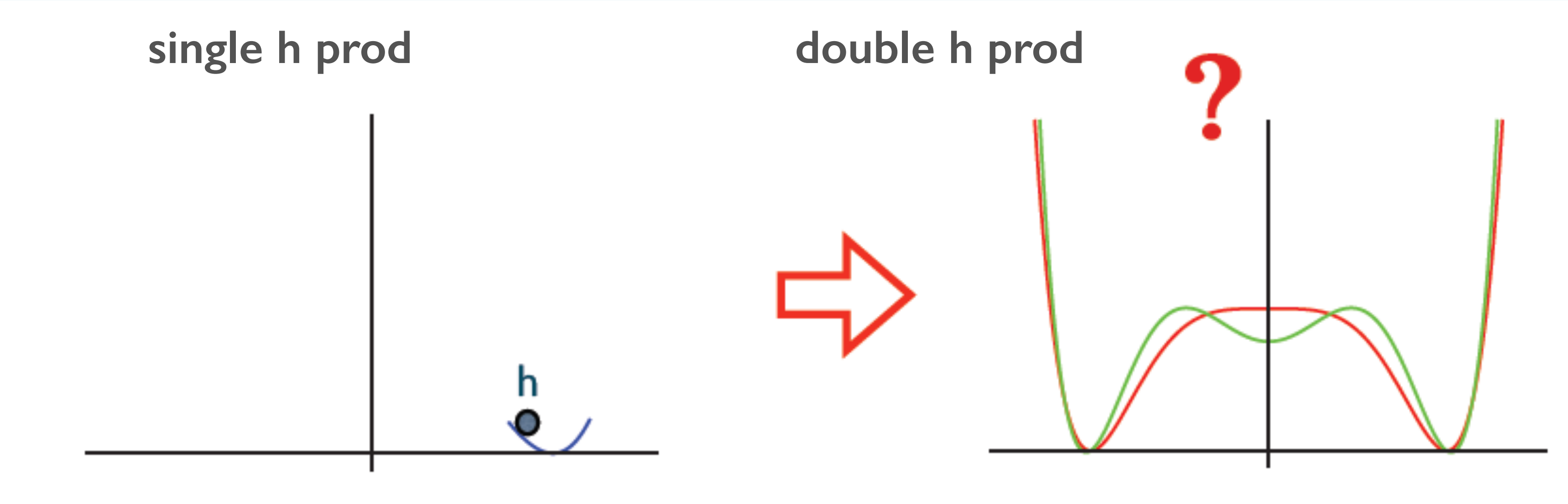
EW symmetry breaking: what do we know



- **Yukawa/Couplings** between Higgs and SM particles **proportional to mass**
- The Higgs boson is **responsible to break EW symmetry and give particles mass**
- However, we still lack understanding of ***why and how*** EWS is broken
- What are the **dynamics** underlying EW symmetry breaking?

EW symmetry breaking: what we don't know

- **Current measurements** (couplings in single Higgs production) probe **Higgs potential close to minimum**
- **Double Higgs production** essential to **reconstruct the full Higgs potential** and clarify EWSB mechanism
- The Higgs potential is *ad-hoc*: **many other EWSB mechanisms conceivable**



Higgs mechanism

$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda(h^\dagger h)^2$$

Coleman-Weinberg mechanism

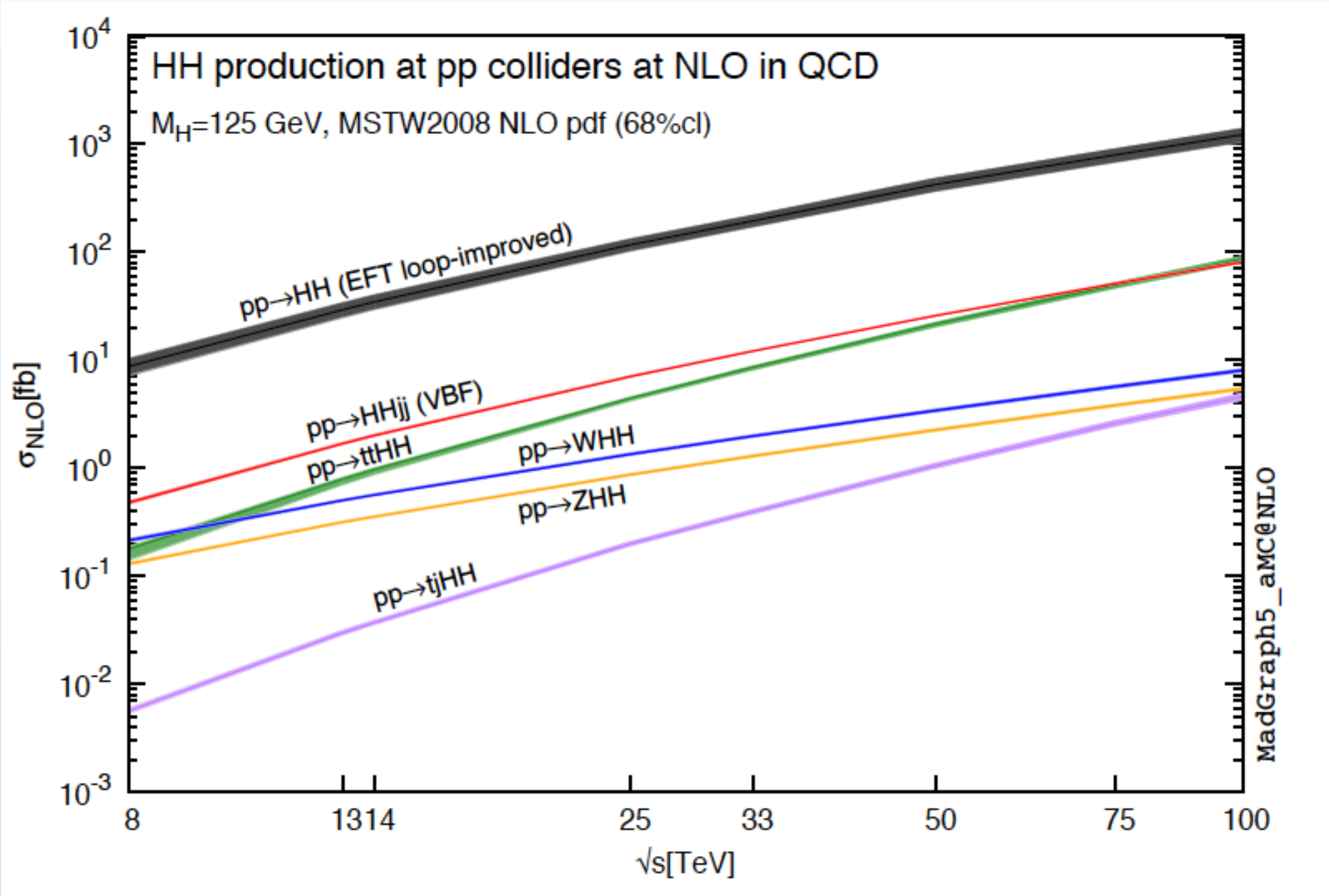
$$V(h) \to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

Each possibility associated to **completely different EWSB mechanism**, with crucial implications for the **hierarchy problem**, the structure of quantum field theory, and **New Physics at the EW scale**

Arkani-Hamed, Han, Mangano, Wang, arxiv:1511.06495

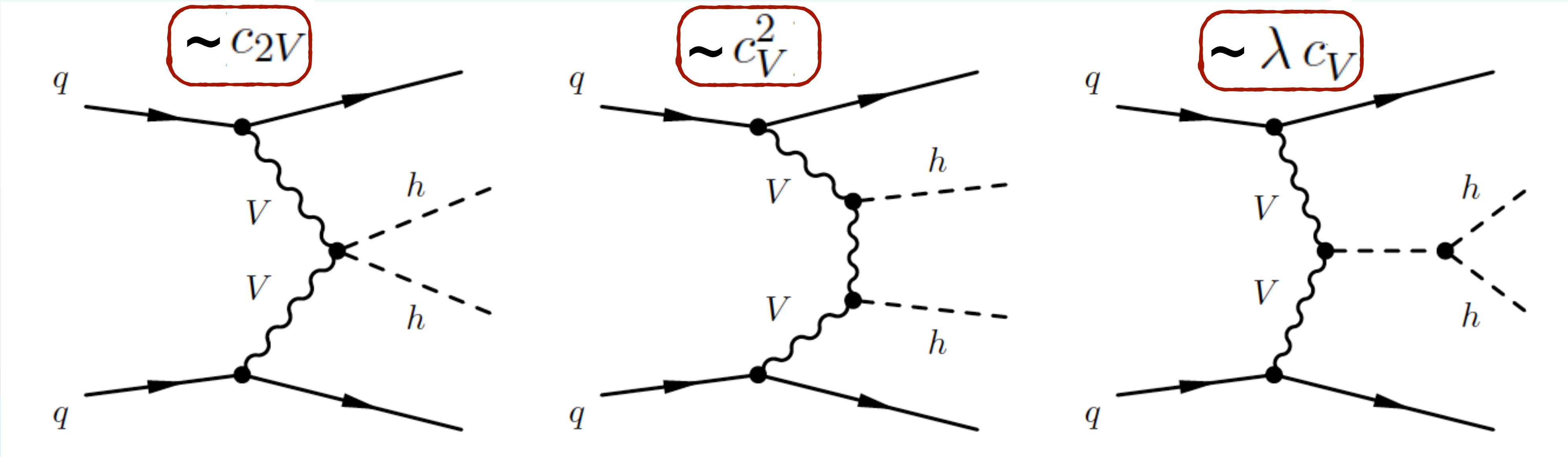
Higgs Pair Production at the LHC

- **Double Higgs production** allows accessing **crucial components of the Higgs sector**:
  - ☑ Reconstruct the **full electroweak symmetry breaking potential**
  - ☑ Probe the **Higgs self-interaction**
  - ☑ Probe the **doublet nature** of the Higgs by means of the **hhVV coupling**
- In the SM, **hh rates are small:** in the leading gluon-fusion production mode, the **cross-section at 14 TeV** is only **40 fb,** further suppressed by branching fractions



Vector-Boson Fusion Higgs Pair production

- In the absence of the Higgs boson, the amplitude for **vector-boson scattering** (VBS) **grows** with the partonic center-of-mass energy, until eventually **unitarity is violated**
- In the SM, the Higgs boson **unitarizes the high-energy behaviour** of VBS amplitudes



at high energies

$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)\,,$$

Is this **cancellation exact** (as in SM, $c_{2V} = c_V^2$) or only **approximate (BSM, $c_{2V} \neq c_V^2$)?**

No model-independent information on c_{2V} available so far at the LHC

Even for small deviation of the SM couplings, **striking signals within the reach of Run II!**

Vector-Boson Fusion Higgs Pair production

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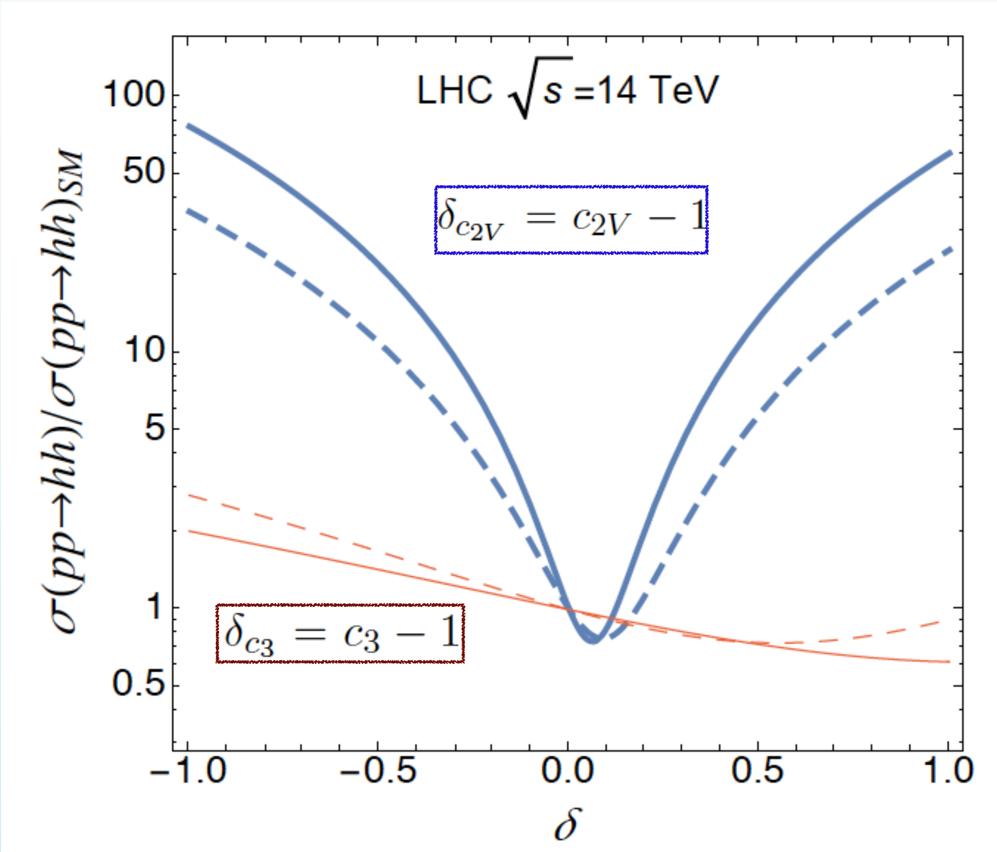


On the other hand, VBF production has **very little sensitivity to the Higgs self-coupling …**

at high energies

$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)\,,$$

Exploiting the VBF channel for di-Higgs

- Signal generation with **MadGraph5** using customized UFO model
- **Event rates** can increase by **up to a factor 30** as compared to SM if new physics is present
- At a 100 TeV collider, $\mathbf{10^5}$ **events before cuts** even for SM couplings

Signal: VBF $hh \to b\bar{b}b\bar{b}$					
$\{c_V, c_{2V}, c_3\}$		LHC 14 TeV		FCC 100 TeV	
		σ (fb)	$N_{\rm ev}(\mathcal{L} = 3\,{\rm ab}^{-1})$	σ (fb)	$N_{\rm ev}(\mathcal{L} = 10\,{\rm ab}^{-1})$
{1,1,1}	SM	0.26	780	14.8	$1.5 \cdot 10^5$
{1,0,1}		4.4	$1.3 \cdot 10^4$	593	$5.9 \cdot 10^6$
{1,2,1}		2.5	$7.5 \cdot 10^3$	471	$4.7 \cdot 10^6$
{1,0,0}		5.8	$1.7 \cdot 10^4$	656	$6.6 \cdot 10^6$
{1,0,-1}		7.5	$2.3 \cdot 10^4$	731	$7.3 \cdot 10^6$
{1,1,0}		0.64	$1.9 \cdot 10^3$	29.8	$3.0 \cdot 10^5$
{0.84,0.40,0.48}	MCHM5 $\xi = 0.3$	0.78	$2.3 \cdot 10^3$	75.7	$7.6 \cdot 10^5$

Exploiting the VBF channel for di-Higgs

- Generation of **QCD multijet backgrounds** highly CPU time-intensive
- Generated at LO with **Sherpa** (weighted and unweighted events), **cross-checked with ALGEN**
- **Gluon-fusion di-Higgs** production now background to VBF production
- The **irreducible 4b multijet background** is **seven orders of magnitude larger than the SM signal** at the generation level. How to overcome this huge difference?

Background processes

Process	Program	Generation	$\sigma_{\rm LO}$ (fb) LHC14	$\sigma_{\rm LO}$ (fb) FCC100	K–factor LHC14	K–factor FCC100
$4b$	`Sherpa2.2`	$N_{\rm ev}$ = 50M weighted	$1.1 \cdot 10^6$	$1.6 \cdot 10^7$	1.7	1.7
$2b2j$	`Sherpa2.2`	$N_{\rm ev}$ = 50M weighted	$2.6 \cdot 10^8$	$3.8 \cdot 10^9$	1.3	1.3
$t\bar{t}jj$	`Sherpa2.2`	$N_{\rm ev}$ = 10M weighted	$1.9 \cdot 10^4$	$1.6 \cdot 10^6$	1.6	1.6
$4b2j$	`ALPGEN`	$N_{\rm ev}$ = 6M(2M) unweighted	$5.4 \cdot 10^4$	$2.4 \cdot 10^6$	1.7	1.7
$2b4j$	`ALPGEN`	$N_{\rm ev}$ = 260k unweighted	10^7	$5.2 \cdot 10^8$	1.3	1.3
$gg \to hh \to b\bar{b}b\bar{b}$	`aMC@NLO`	$N_{\rm ev}$ = 1M unweighted	6.2	272	2.4	2.2

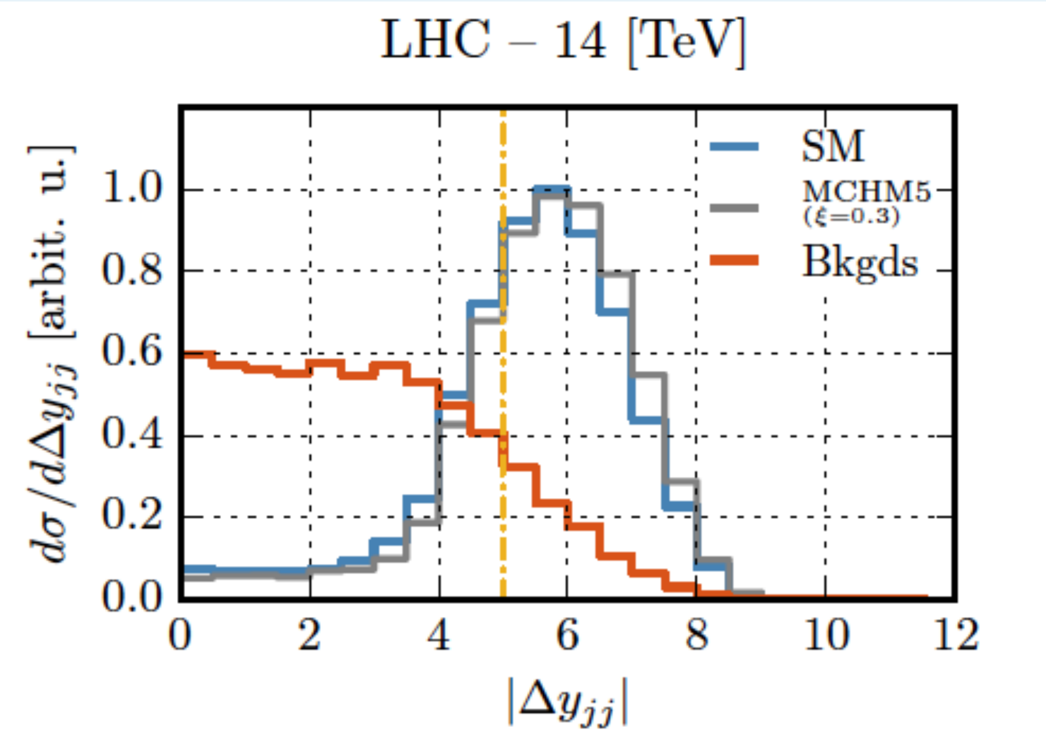
Killing backgrounds with VBF topology

The huge QCD jet backgrounds can be **reduced by exploiting the VBF topology**

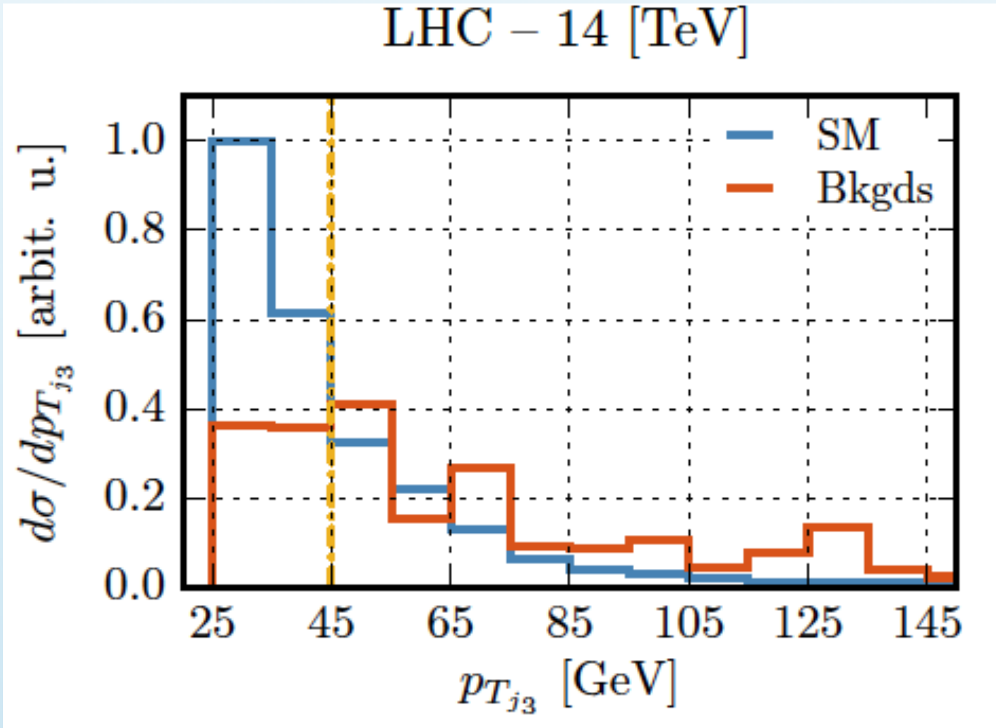
Require **two forward jets**, **separated in rapidity**, plus a **veto in hadronic activity** in the central region

Additional cuts in the r**econstructed Higgs invariant mass** and the **di-Higgs invariant mass m_{hh}** further reduce the QCD multijet cross-sections

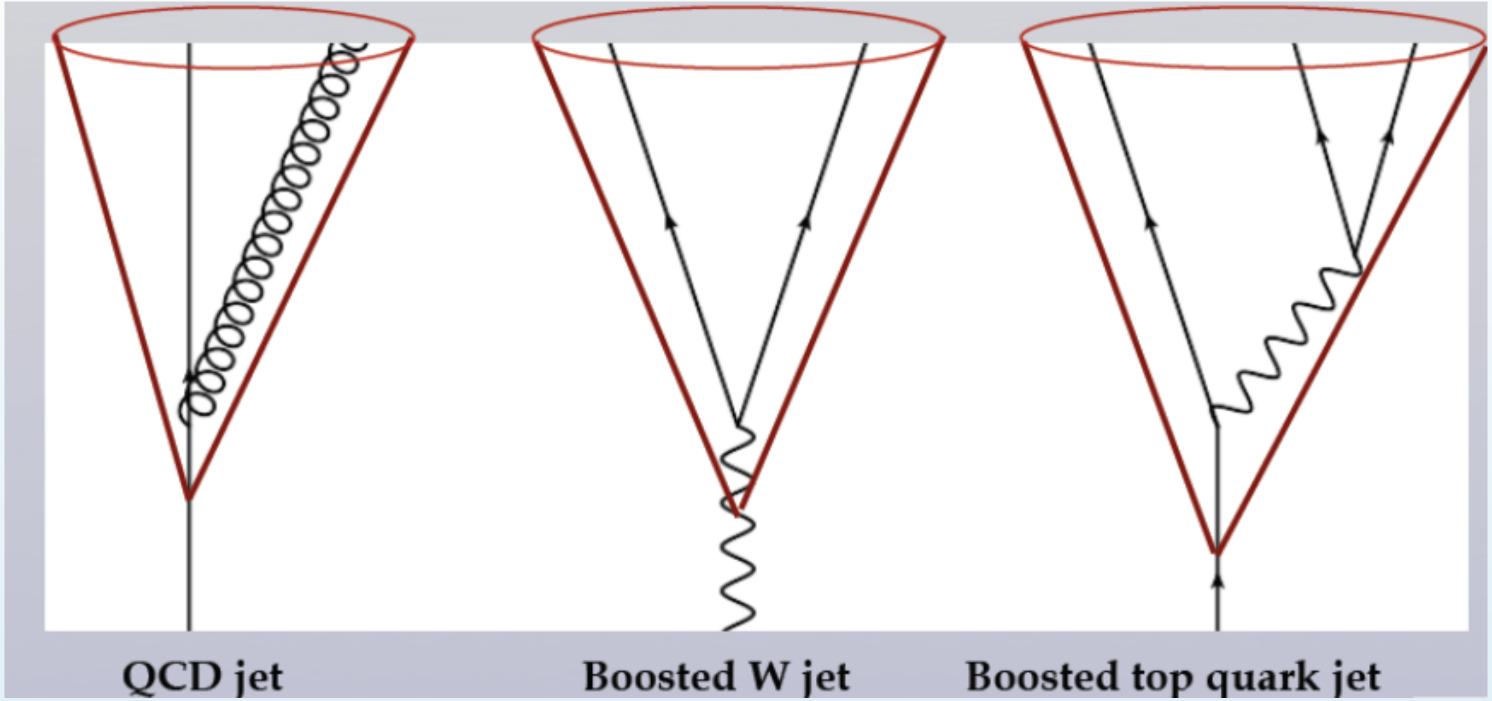
Dijet rapidity separation cut



Central jet veto cut

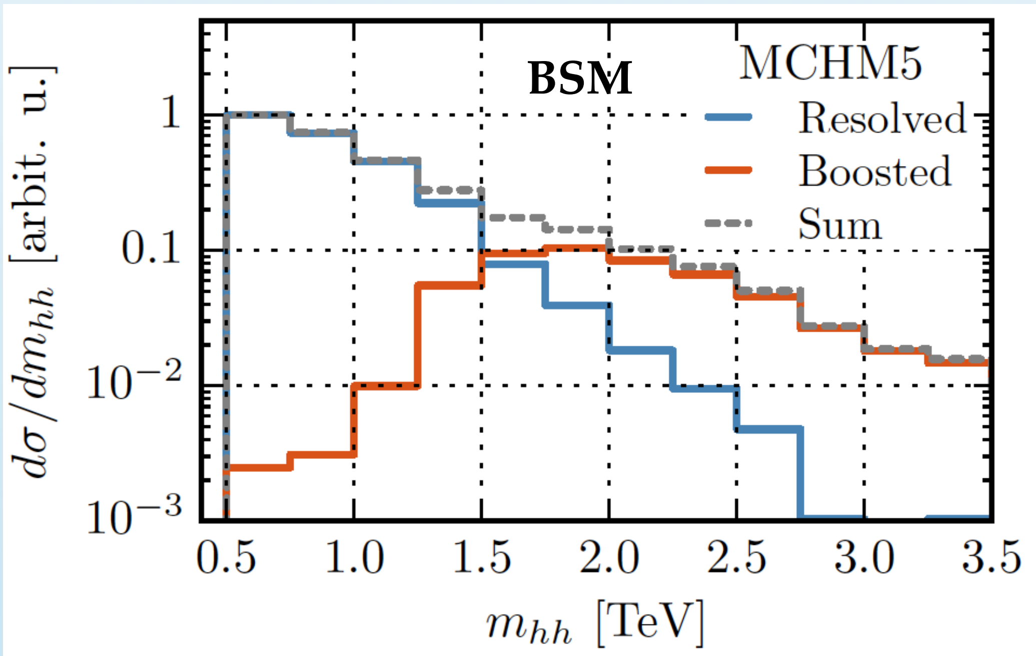


Boosted jets and BSM physics

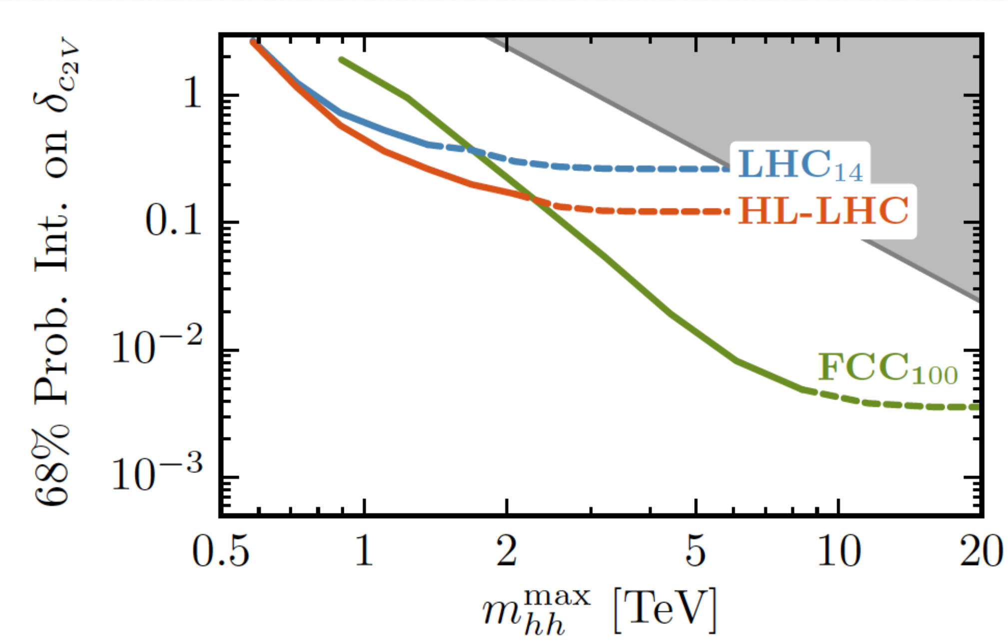


In the **SM, resolved selection** dominates

For **BSM couplings**, **boosted topology** becomes important and eventually dominates



Sensitivity to the hhVV coupling



	68% probability interval on δ_{c2V}	
	$1 \times \sigma_{bkg}$	$3 \times \sigma_{bkg}$
LHC$_{14}$	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC$_{100}$	$[0, 0.01]$	$[-0.01, 0.01]$

The **sensitivity to c_{2V}** improves significantly the **higher the values of m_{hh} that can be probed**

In the absence of new resonances, **c_{2V}** can be constrained **down to 45% (20%) of its SM value at the 1-sigma level** at the LHC (HL-LHC), assuming SM couplings

Take-away message

Searches for **di-Higgs production in the vector-boson-fusion channel** should start already during **Run II**, without waiting for the HL-LHC!

Master Projects

Available MSc projects in my group cover a wide range of topics in **LHC phenomenology**, including:

- ☑ *Constraining the proton structure with Run II LHC data*
- ☑ *A three-dimensional imaging of the proton with Neural Networks*
- ☑ *Higgs coupling measurements from Double Higgs production*
- ☑ *Parton Distributions at a future 100 TeV hadron collider*

A more **detailed description** of some of these MSc projects is available from

http://juanrojo.com/vacancies

together with several other possibilities. If you would like to know more, please contact me!

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Nikhef

UNIVERSITEIT VAN AMSTERDAM

Constraining the proton structure with Run II LHC data

Master project, Theoretical Physics & GRAPPA tracks, MSc Physics and Astronomy

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Thanks for your attention!

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Constraining the proton structure with Run II LHC data

Master project, Theoretical Physics & GRAPPA tracks, MSc Physics and Astronomy