Discovery through precision:
Perturbative QCD at the dawn of LHC Run II

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Seminari del Departament d'Estructura i Constituents de la Materia
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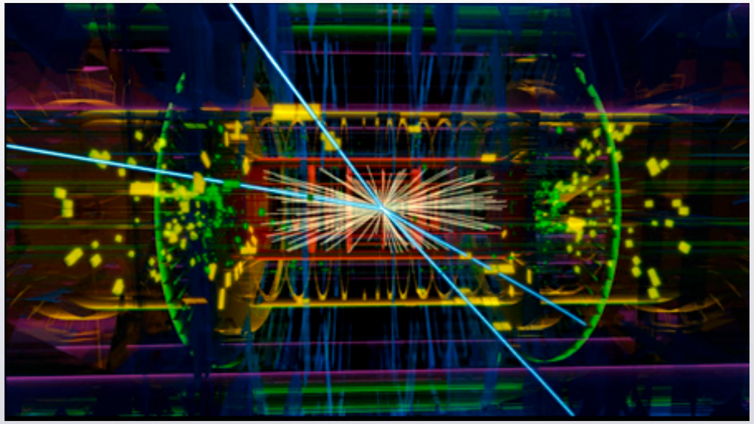
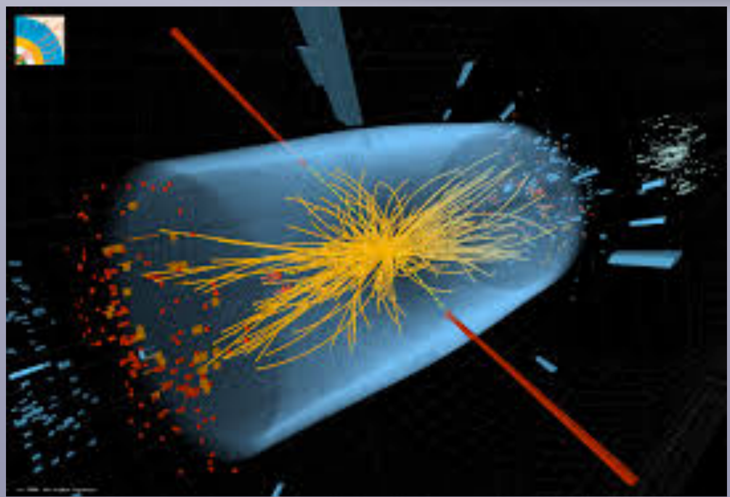


Particle Physics at the Dawn of the LHC Run II



Particle Physics in the headlines

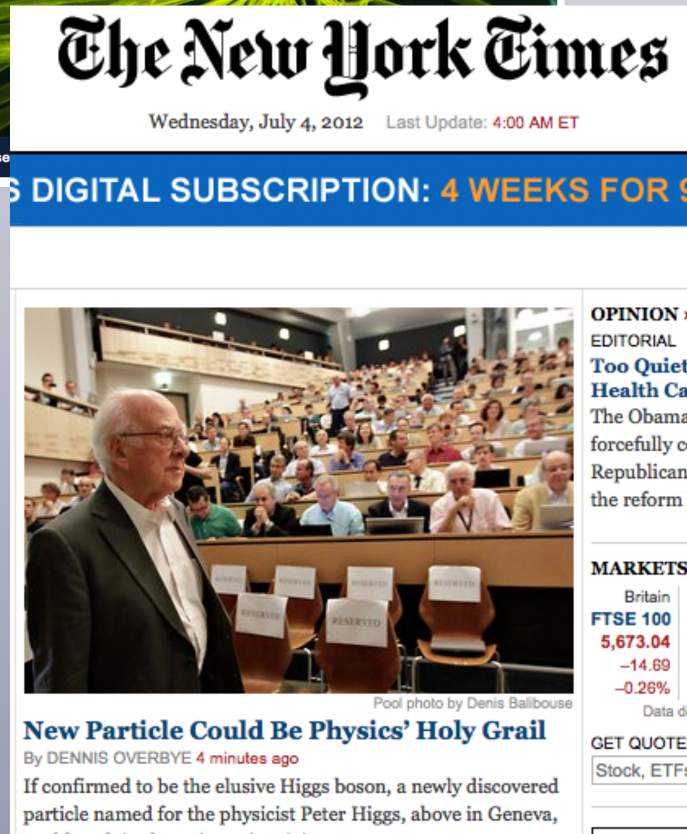
- The **Higgs Boson** is the **most important discovery in particle physics** in 25 years
- The Higgs completes the **extremely successful Standard Model of particle physics**, but at the same time **opens a number of crucial questions** for the field that we need to address
- The **LHC** will play a crucial role in **exploring the energy frontier in the next 20 years**


El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs

El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs, cuya existencia está predicha por el modelo estándar de la física de partículas

Ciencia | 04/07/2012 - 09:46h | Actualizado el 04/07/2012 - 11:27h

El bosón de Higgs podría se


The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET

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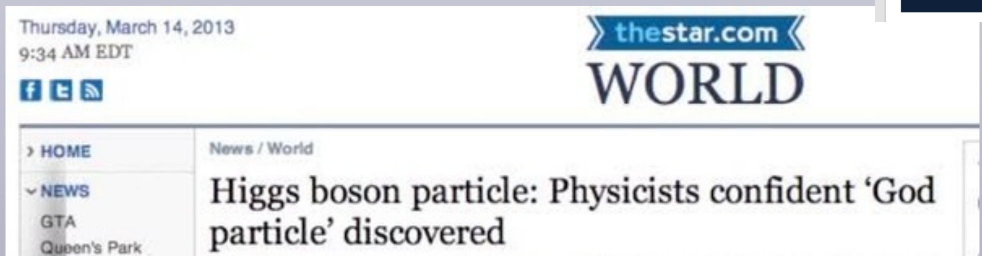
New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva,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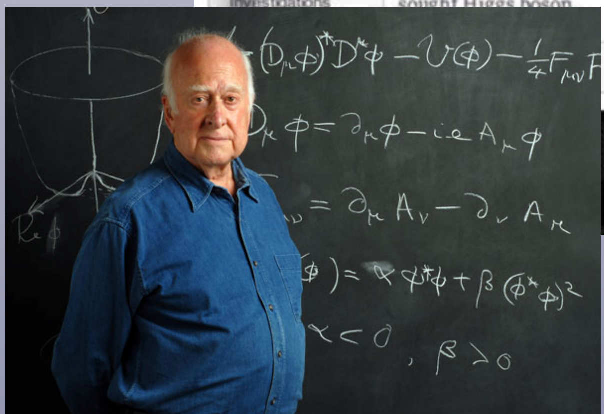
Higgs boson particle: Physicists confident 'God particle' discovered

Scientists announced Thursday that the parti
CMS experiments at the Large Hadron Collid
sought Higgs boson



Towards a new paradigm in high-energy physics?

- **Hadron colliders** are typically regarded as **discovery machines,** while the cleaner **lepton colliders** are often seen as **precision machines for characterisation**

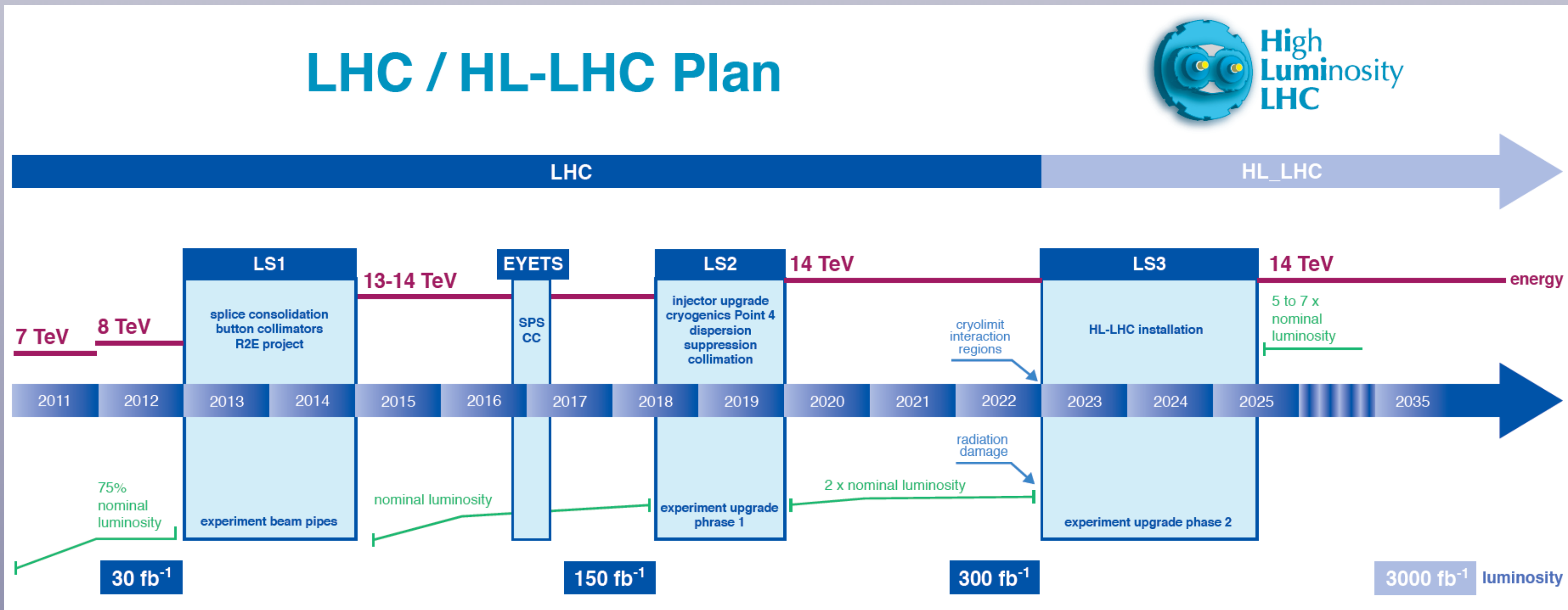
- However, at the LHC we might be heading towards a **change of paradigm**:

  - ☑ Thanks to recent impressive **theoretical and experimental progress,** we are getting close to achieving **precision physics at the LHC**

  - ☑ In the absence of new particle discoveries, **high-precision comparisons between data and theory** might be the key to unveil **new beyond the Standard Model dynamics**

  - ☑ Unclear when/if new high-energy lepton colliders **will be built**

We have 20 years of exciting LHC physics in front of us
And perturbative QCD could be the key for new discoveries!



Outstanding Questions in Particle Physics *circa* 2014

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- Is m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry ?
- does it regularize the divergent $W_L W_L$ cross-section at high $M(W_L W_L)$? Or is there a new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate *CP* ?
- cosmological EW phase transition

Quarks and leptons:
- why 3 families ?
- masses and mixing
- *CP* violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

Neutrinos:
- ν masses and and their origin
- what is the role of $H(125)$?
- Majorana or Dirac ?
- *CP* violation
- additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or modification of gravity theory ?

Many of these crucial questions will be addressed at the Large Hadron Collider

from Ian Shipsey

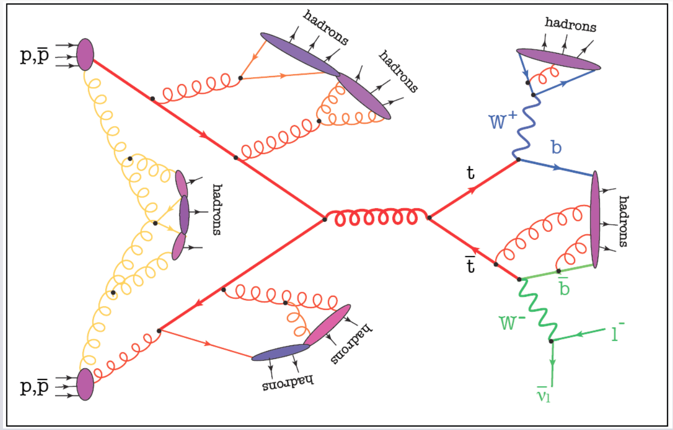
Pushing the boundaries of pQCD at the LHC

- In the **first part of the talk** I will provide some examples of the role of **recent progress in pQCD** in **improving the prospects of BSM searches at the LHC:**

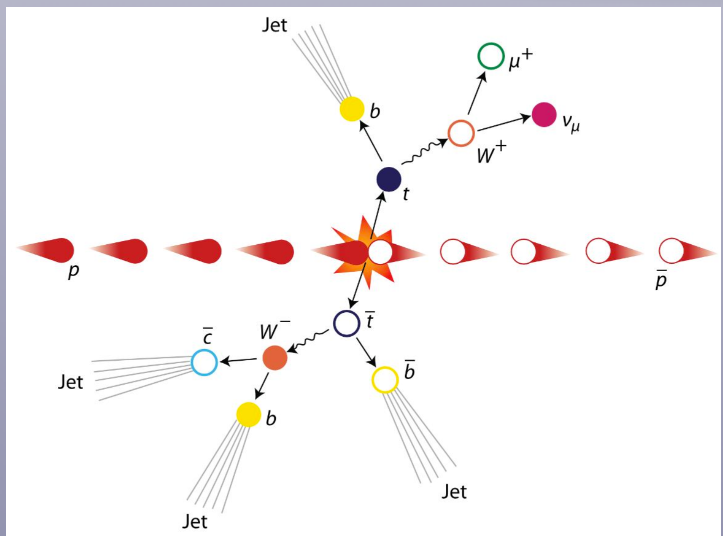
  - ☑ **Parton Distributions Functions (PDFs)**: Higgs characterization and W mass measurement
  - ☑ **Higher-order matrix elements**: Higgs characterization and supersymmetric top searches
  - ☑ **Modelling of final states**: jet reconstruction in the boosted regime

- Then in the **second part of the talk** I will present recent results on three topics that I have been working on recently that further emphasize some of the above topics:

  - ☑ PDFs with threshold resummation and **state-of-the-art squark and gluino cross-sections**
  - ☑ **Higgs pair production** and determination of Higgs couplings with jet substructure
  - ☑ **Charm production at LHCb** and improved predictions for neutrino telescopes

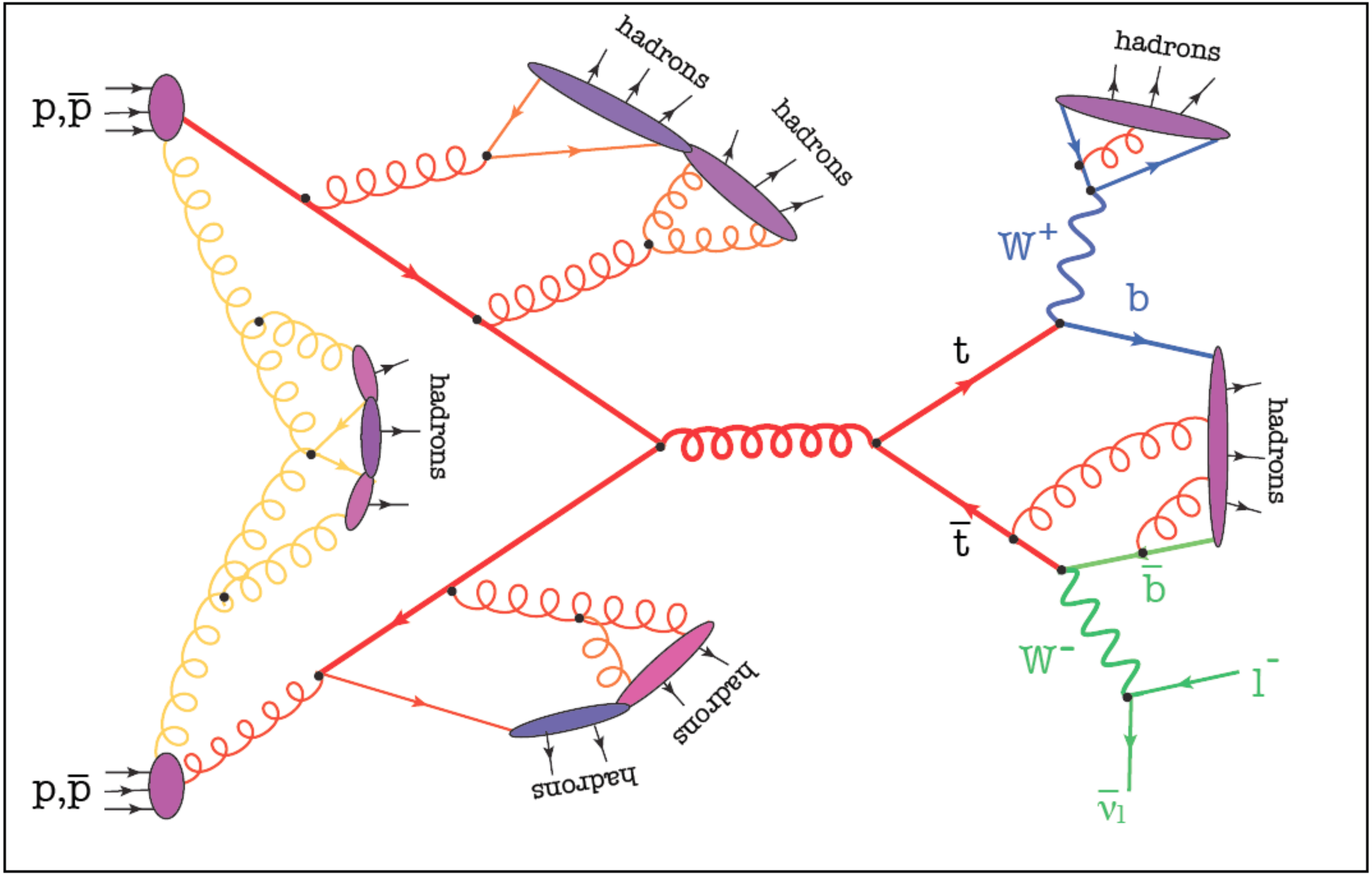


Pushing the boundaries of perturbative QCD



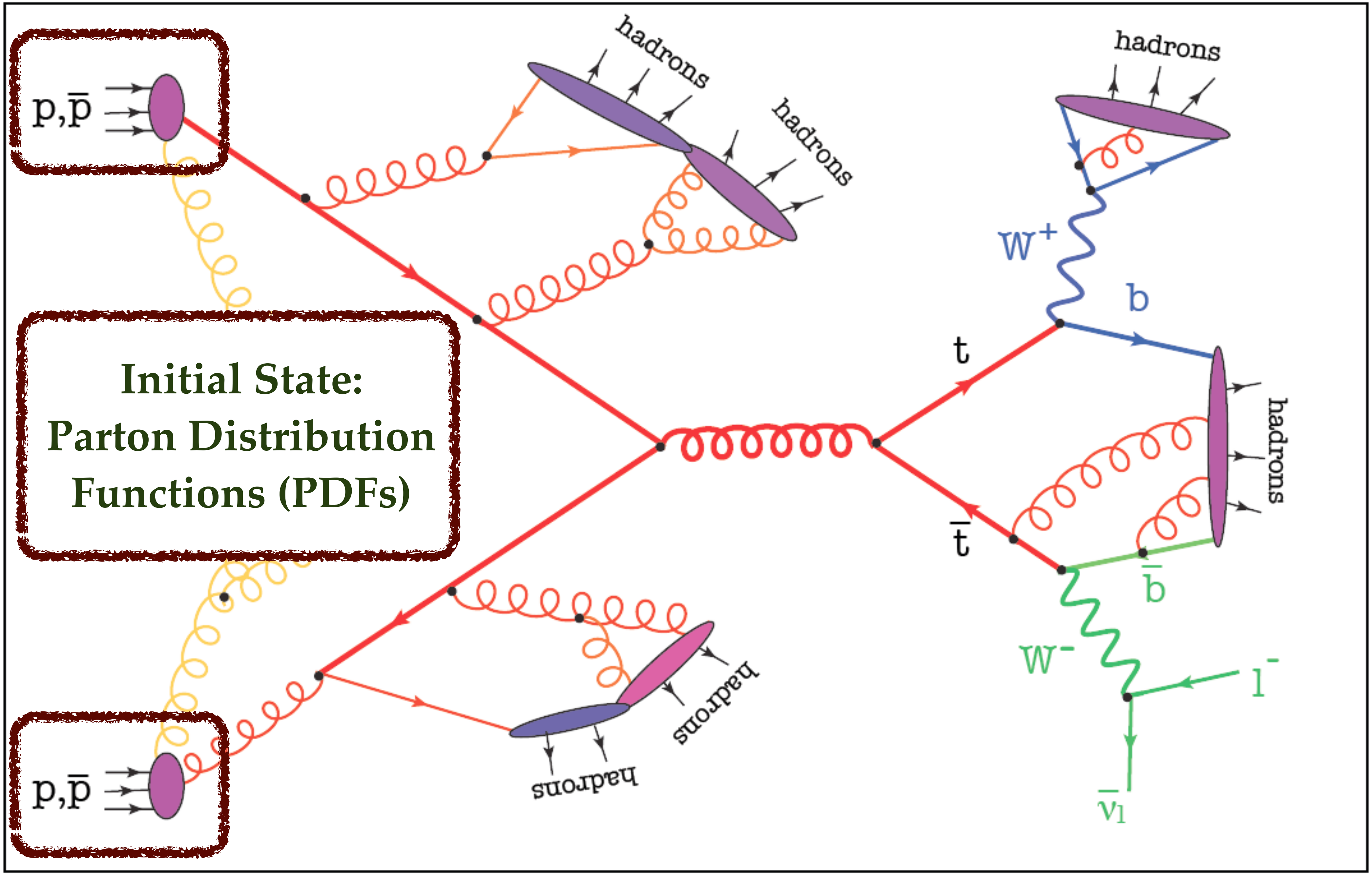
Barcelona, 29/10/2015

Perturbative QCD at the LHC



Drawing by K. Hamilton

Perturbative QCD at the LHC



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Higgs coupling characterization

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Future LHC data: measure H couplings at 2-8% level (cf 20-50% today), and to access rare decays such as $H \to \mu\mu$

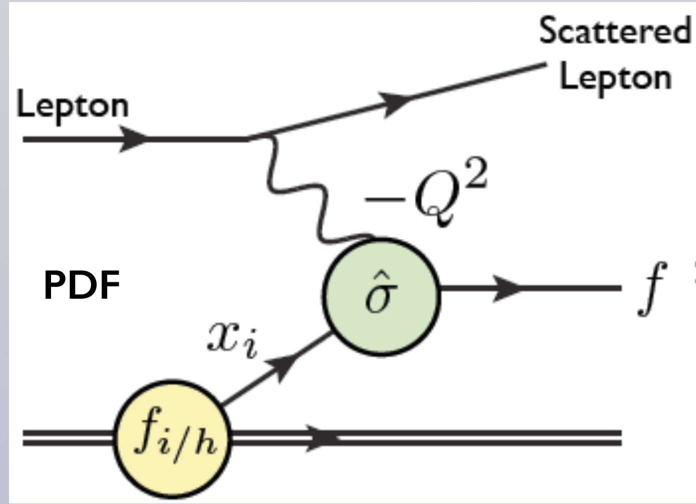
Parton Distributions Functions

- **QCD Factorization Theorem:** separate the hadronic cross section into a **perturbative, process dependent partonic cross section** and **non-perturbative, process independent, Parton Distributions (PDFs),** which encode the internal proton dynamics

- In **lepton-proton scattering** (DIS) we have

$$F_i(x,Q^2) = x\sum_i \int_x^1 \frac{dz}{z} C_i\left(\frac{x}{z},\alpha_s(Q^2)\right) f_i(z,Q^2).$$

Hadron-level cross section Parton-level cross-section Parton Distribution

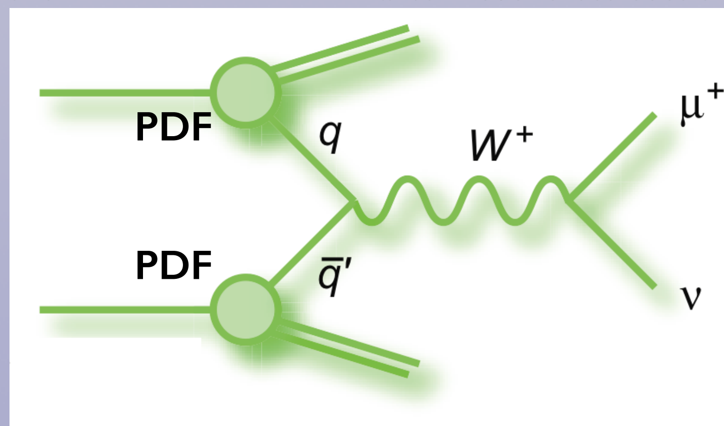


- The **Factorization Theorem** allows to use same **PDFs for predictions for collisions at the LHC:**

$$\sigma_X(s,M_X^2) \quad = \quad \sum_{a,b}\int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1,M_X^2) f_{b/h_2}(x_2,M_X^2)\hat{\sigma}_{ab\to X}\left(x_1x_2s,M_X^2\right)$$

Hadron-level cross section (2) Parton Distributions Parton-level cross-section

To make sense of **LHC collisions**, we need first of all to **determine the parton distributions of the proton** with high precision!

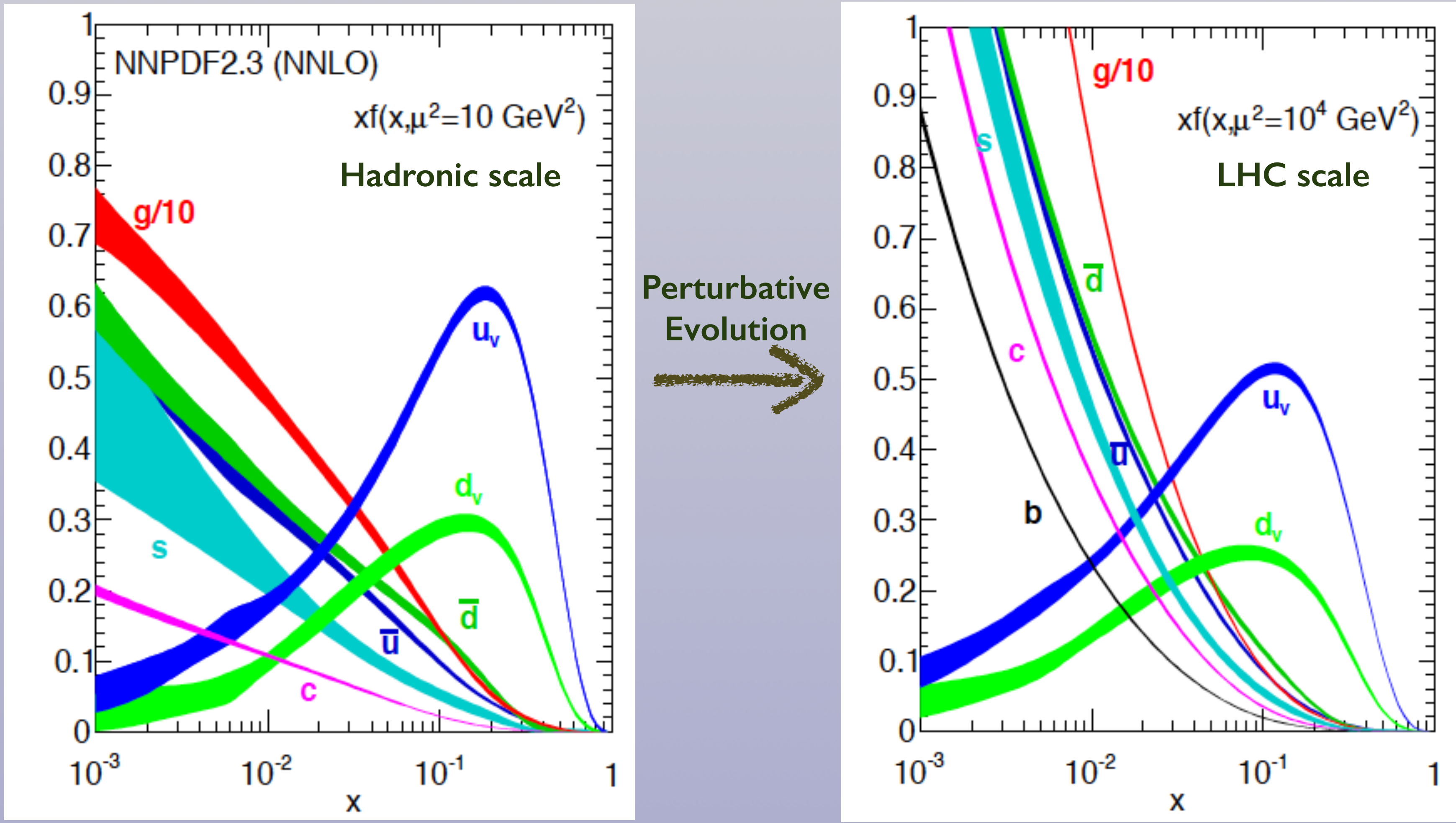


Parton Distributions Functions

- The dependence of PDFs on **Bjorken-x (momentum fraction) is determined by non-perturbative QCD dynamics**, but that on the **scale Q^2 (resolution)** is instead known from perturbative QCD: the **DGLAP evolution equations**

$$\frac{\partial q_i(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s\left(Q^2\right)}{2\pi}\int_x^1 \frac{dz}{z} P_{ij}\left(z,\alpha_s\left(Q^2\right)\right) q_j\left(\frac{x}{z},Q^2\right)$$

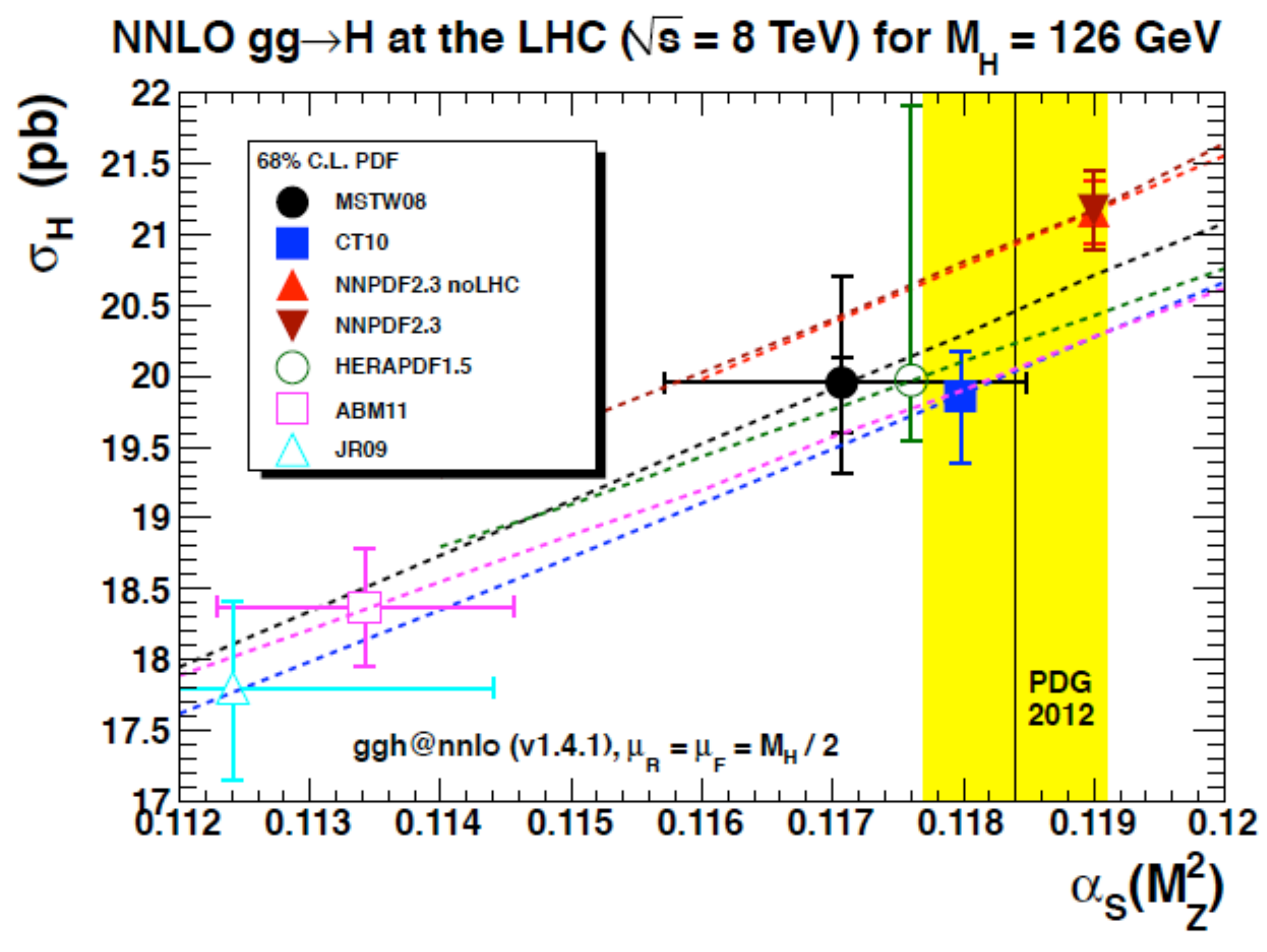
- Once x-dependence **$q(x,Q^2_0)$ extracted from data**, **pQCD determines PDFs** at other scales **$q(x,Q^2)$**

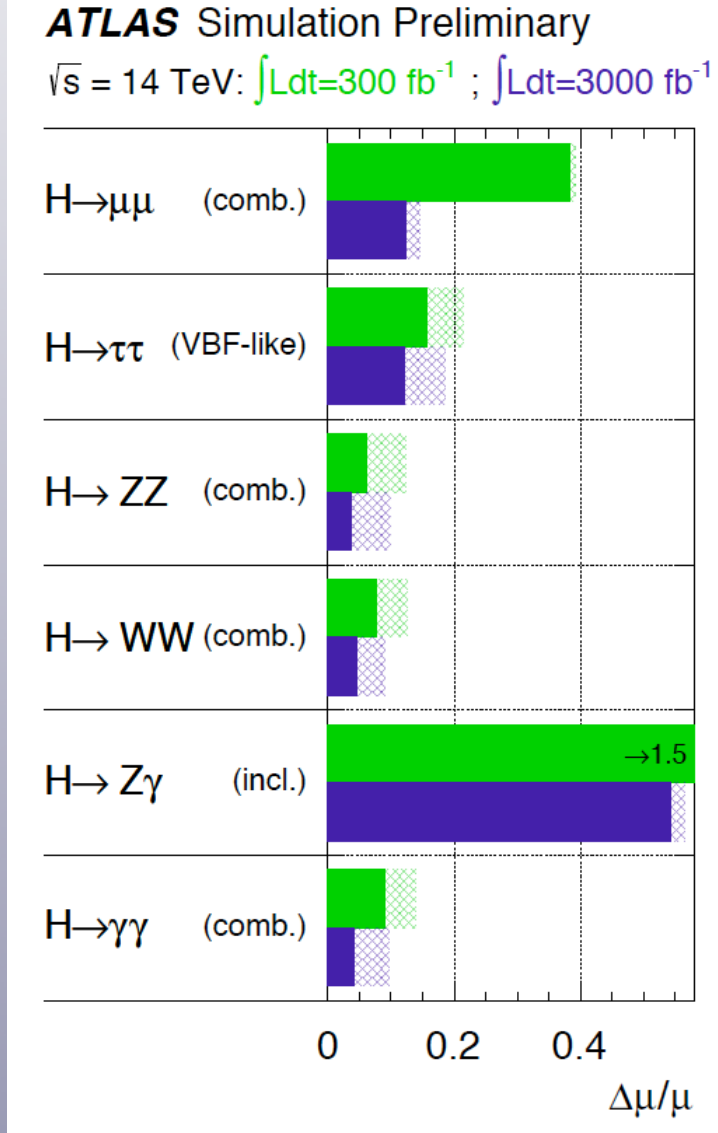


Higgs coupling characterization

Parton distributions: fundamental limit for Higgs boson characterisation in terms of couplings

Solid: no TH unc
Hatched: with TH unc

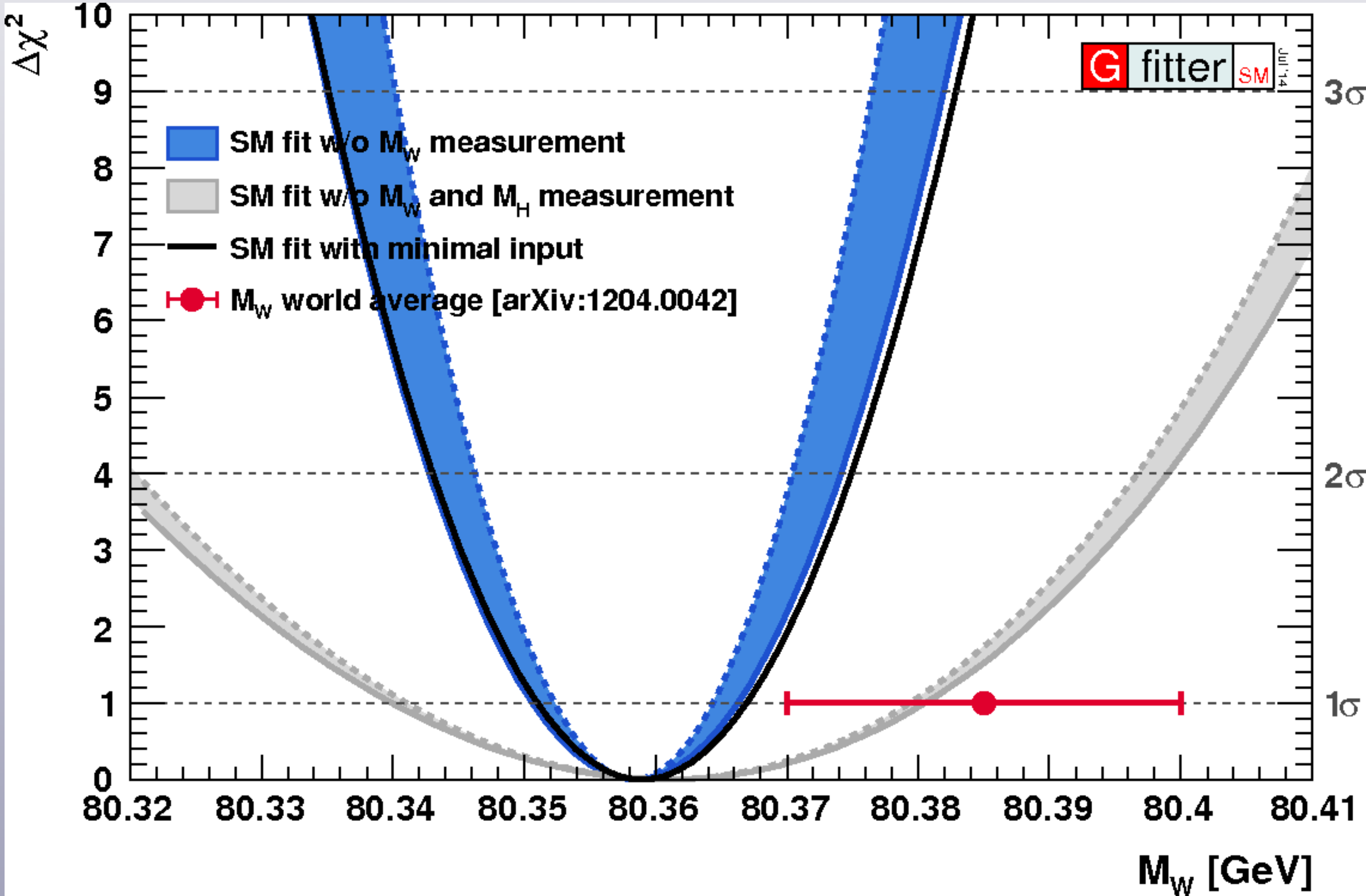




Even with ``perfect" measurements, our ability to look for **new physics in the Higgs sector** will be limited by the accuracy of **pQCD calculations**

PDFs and the global electroweak fit

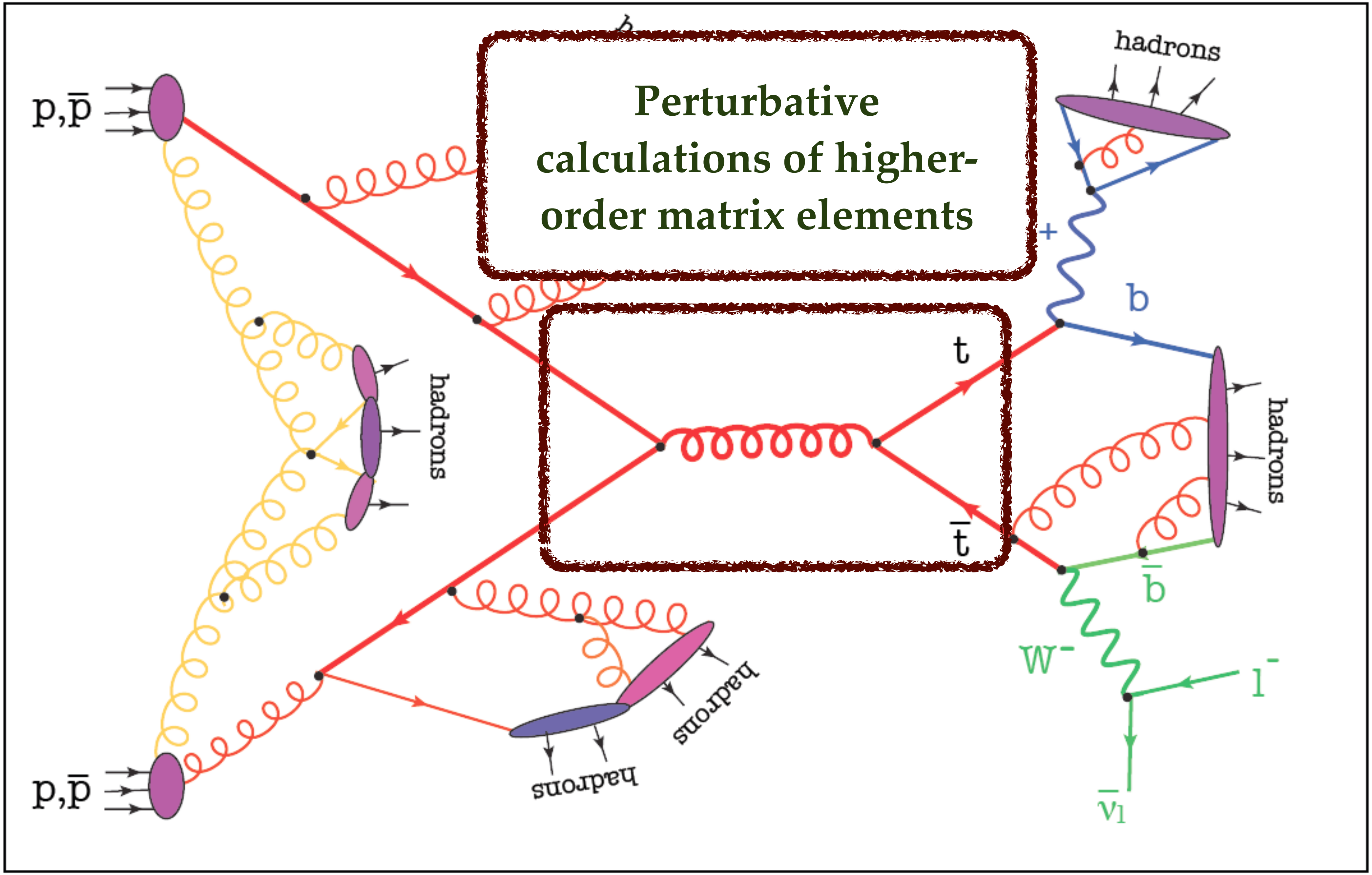
PDFs dominant systematic for precision measurements, like W boson mass, that provide consistency stress-tests of the Standard Model



- Reducing TH systematics could lead to **indirect BSM discovery** from precision measurements
- Precision in M_W will **improve by a factor 3** in 10 years
- If SM confirmed, **ruled out a broad class of BSM scenarios**

1.8-sigma tension between direct M_W measurement and global EW fit

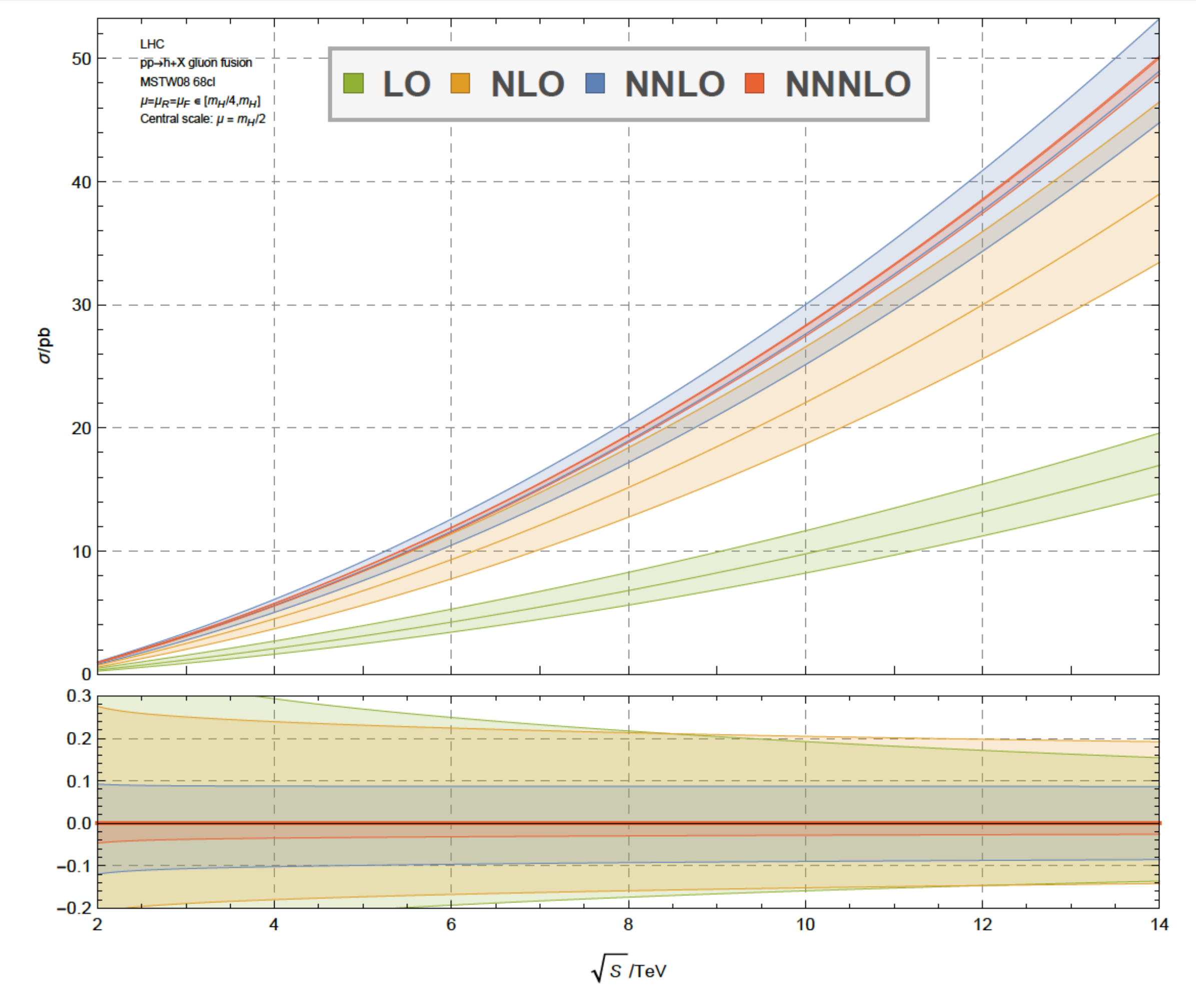
Perturbative QCD at the LHC

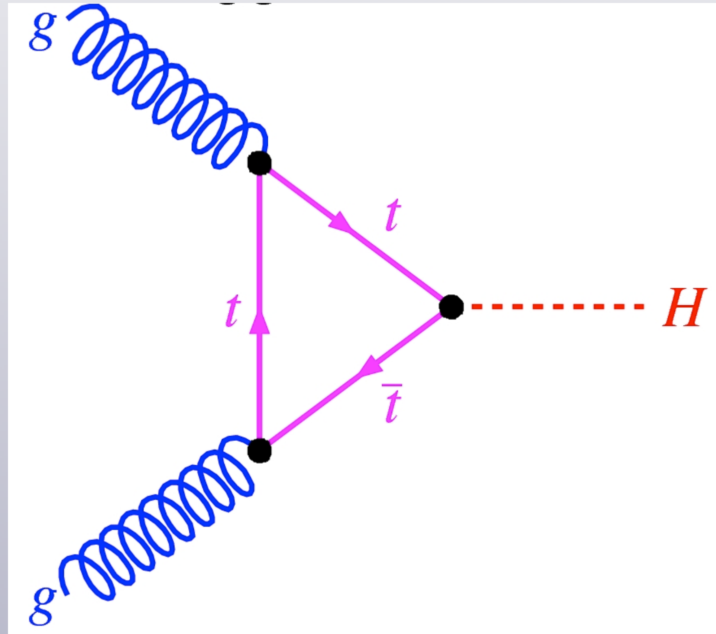


Drawing by K. Hamilton

Progress in (N)NNLO calculations

- Recently **massive progress of NNLO higher-order calculations ...**
- Now even **Higgs gluon fusion cross-section at N3LO! Scale uncertainties down to 2%!**





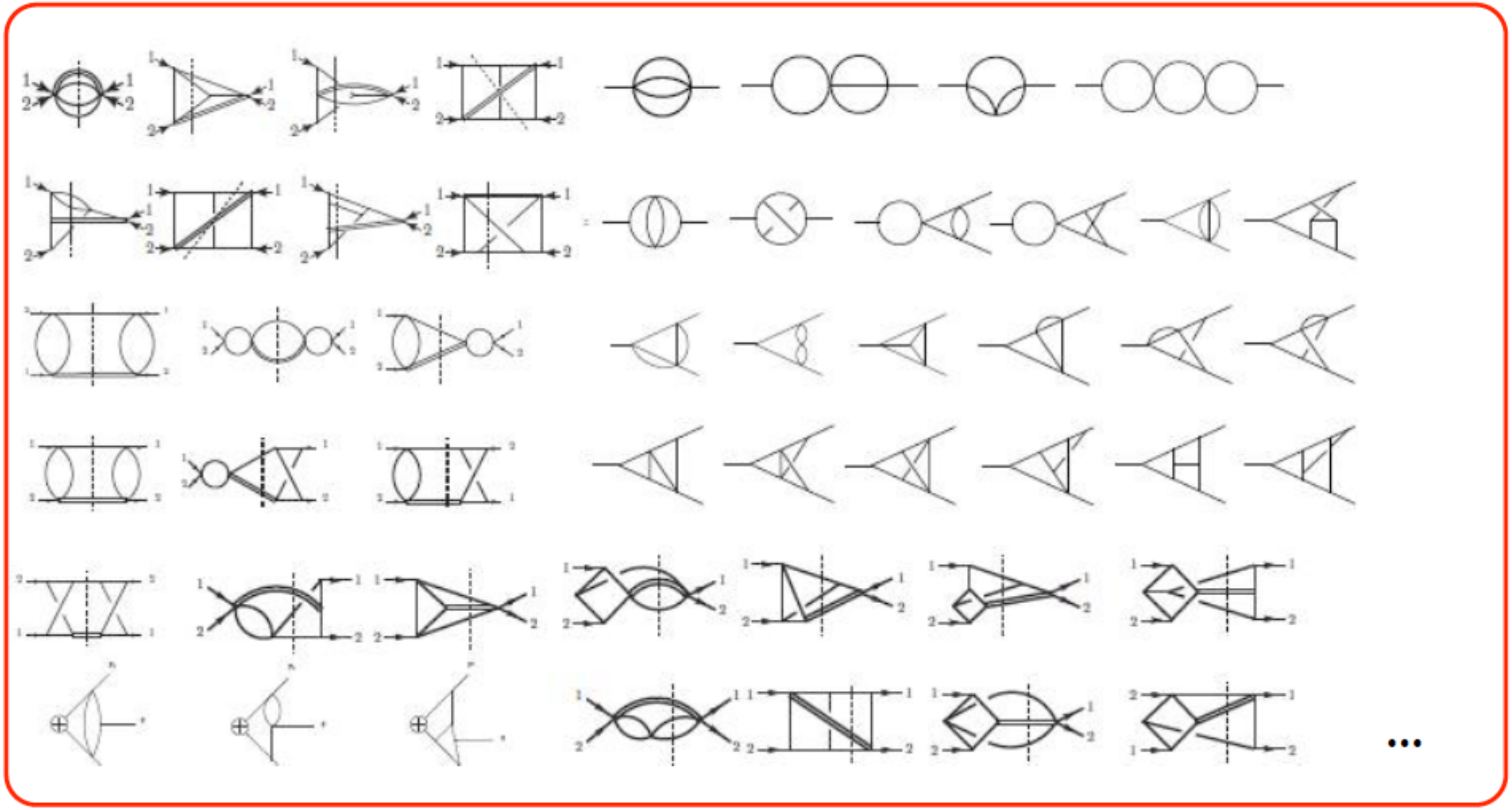
- NLO **δσ≃25%**
- NNLO **δσ≃10%**
- N3LO **δσ≃2%**

Anastasiou et al, arxiv:1503.06056

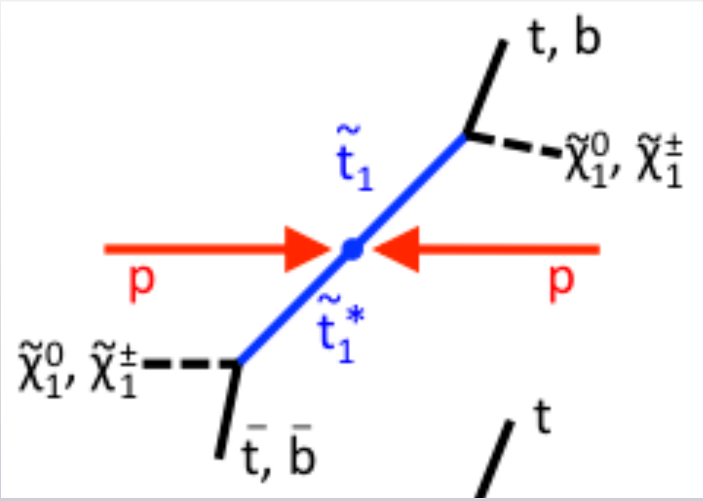
- **Few-percent accuracy (or better)** is becoming the **new standard for LHC calculations.**
- Essential ingredient of New Physics searches *i.e.* in **Higgs coupling extractions**

N3LO calculations are not easy ...

- O(100000) interference diagrams (1000 at NNLO)
- 68273802 loop and phase space integrals (47000 at NNLO)
- about 1000 master integrals (26 at NNLO)



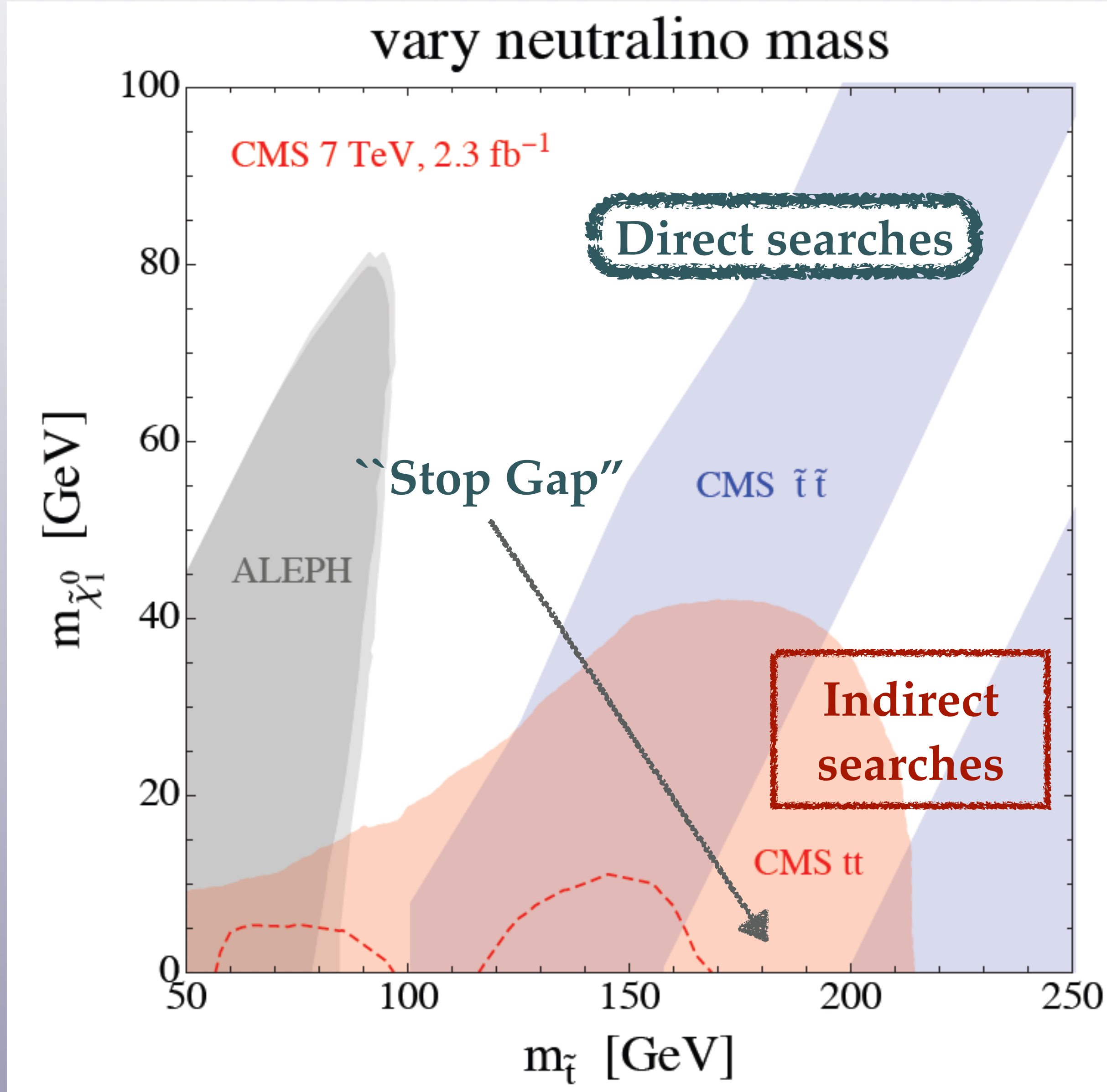
Closing the stop gap with NNLO calculations



- Light supersymmetric top quarks are frequent in **weak-scale natural realisations of supersymmetry**

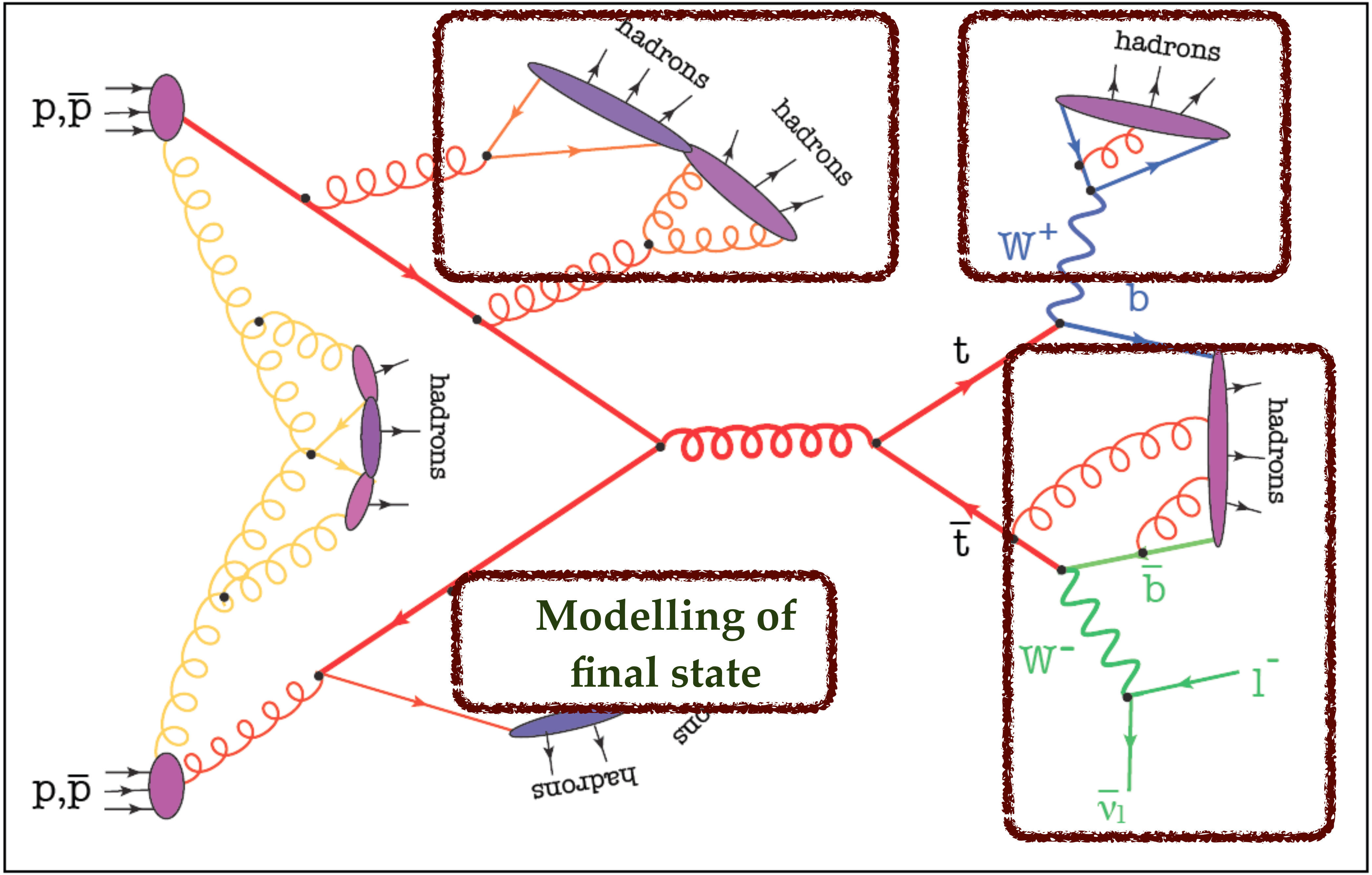
- Current **direct searches** have a **gap close to the top quark mass**, due to final state similarities with SM ttbar (*ie* little missing E_T from neutralinos)

- Thanks to **NNLO calculation of σ(tt)**, with a **few percent residual theory error**, one can close this gap by comparing SUSY predictions with **measurements of the total cross-section**



Czakon et al, arxiv:1407.1043

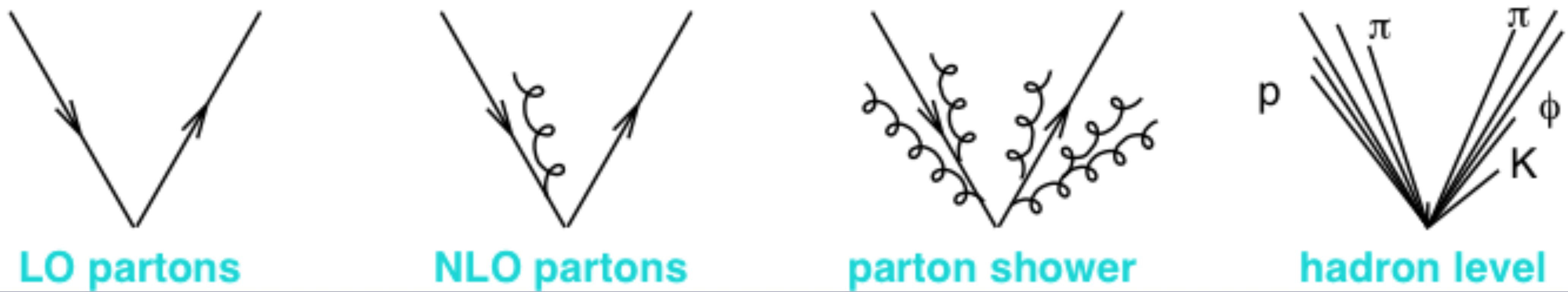
Perturbative QCD at the LHC



Drawing by K. Hamilton

Jets in hadron collisions

- QCD calculations are provided in terms of **quarks and gluons in the final state**
- After hard scattering, quarks and gluons follow a **branching process** and then **hadronize**, leading to a collimated bunch of hadrons as characteristic signal in the detector: **a QCD jet**
- A quantitative robust **mapping between final state hadrons**, observed in the detector, and **partons from** the hard-scattering, is required to compare theory with data: a **jet algorithm**
- **Jets are ubiquitous at the LHC,** present in almost every measurement



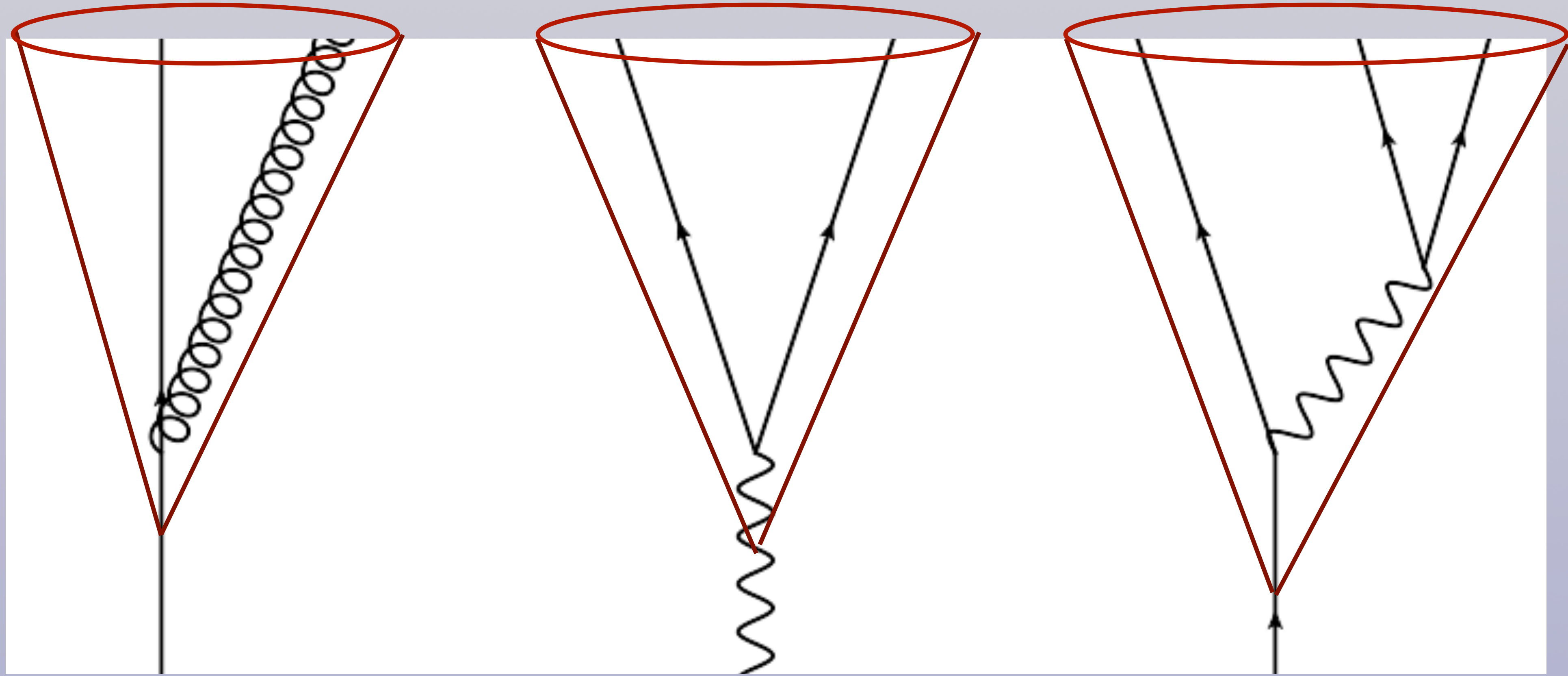
A jet is a fundamentally ambiguous concept

A jet algorithm is required to provide a jet definition

Jet algorithms should be applied to partons, hadrons and calorimeter cells

Jet substructure

- In the decays of a **massive resonances,** hadronic **boosted prongs** can often be collimated into a **single jet:** very difficult to separate from **overwhelming QCD background**
- The different **substructure in these jets** as compared to **QCD jets** can provide strong background suppression in **Higgs studies** and **BSM searches**



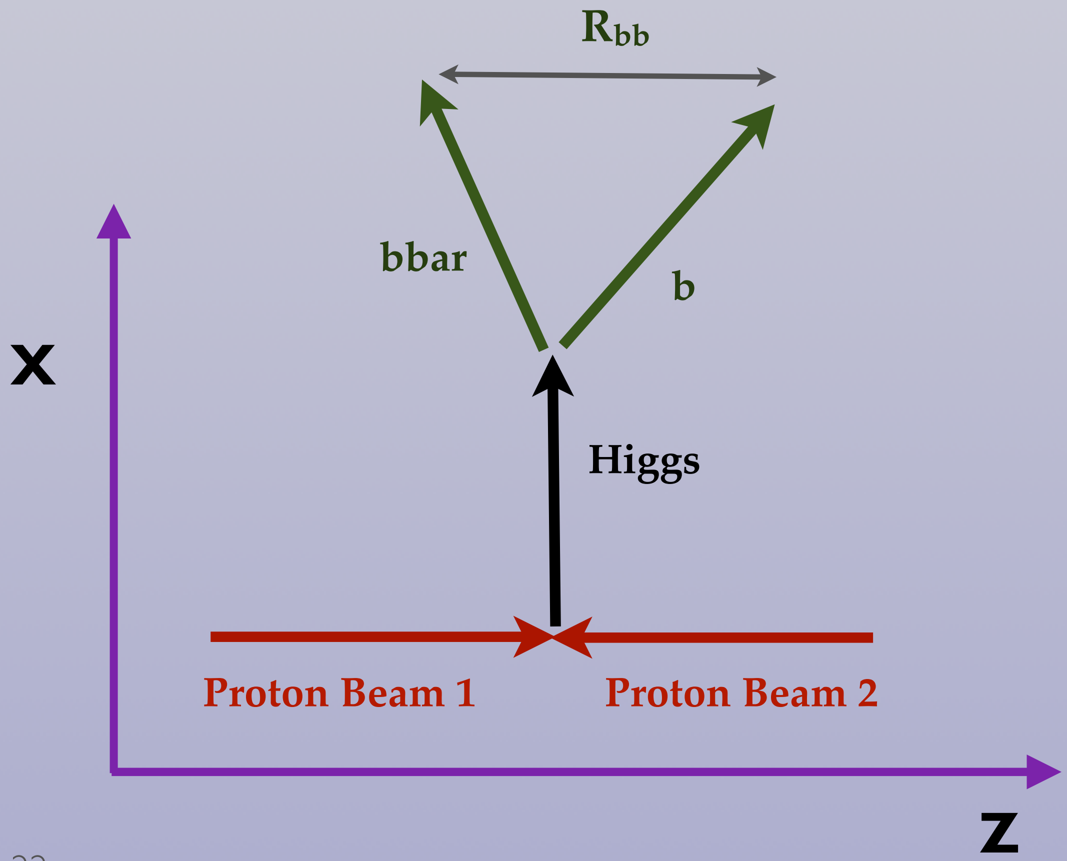
QCD jet **Boosted W jet** **Boosted top quark jet**

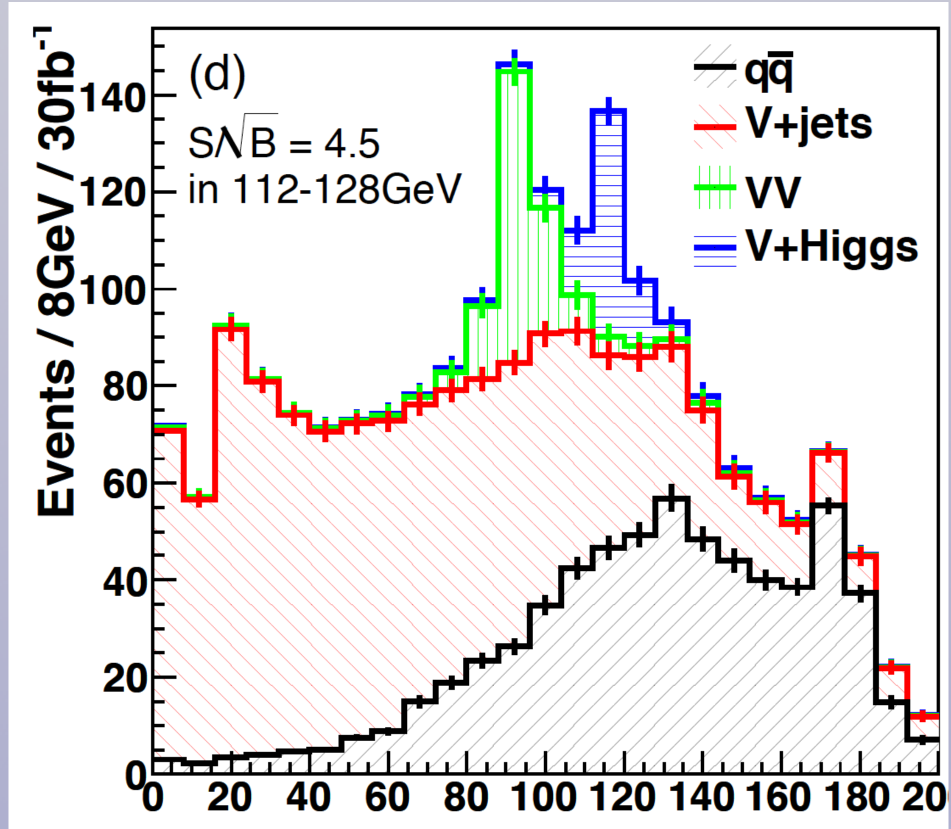
The onset of the boosted regime

- Consider for example **Higgs decays** into a **pair of bottom quarks**
- It is easy to compute that the **angular separation between the two bottom quarks**, **R_{bb}**, is

$$R_{b\bar{b}} = \frac{p_{z,b}}{p_{x,b}} - \frac{p_{z,\bar{b}}}{p_{x,\bar{b}}} = \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_{T,H}}$$

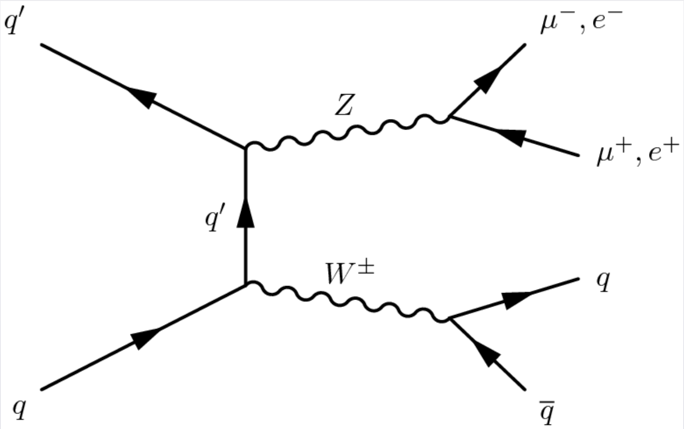
- For typical LHC value of **jet cone radius R=0.6**, the **boosted regime sets in for $p_{T,H} > 4\, m_H = 500$ GeV**
- Region is crucial in Higgs characterisation studies, *eg* to resolve **new particles in the gg->h loop**
- **Substructure methods** required to exploit this region



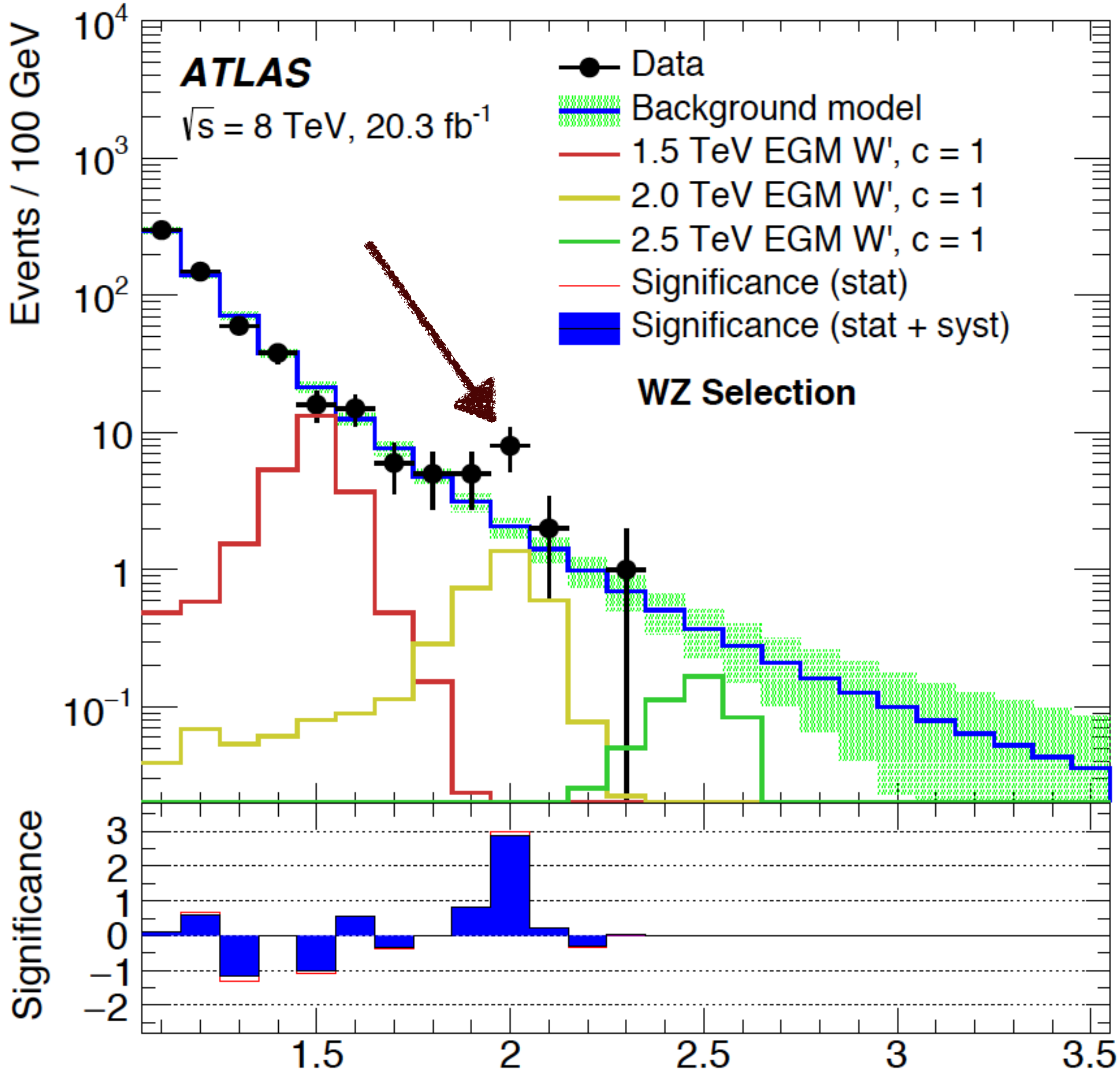


Butterworth et al, arxiv:0802.2470

Jet substructure and the LHC diboson excess



- Tantalising excesses over SM expectations from ATLAS and CMS in the **diboson channel** when the **two bosons decay hadronically**
- Local ATLAS significance of the **excess almost 4 sigma**
- Search relies crucially on **jet substructure techniques to tag the hadronic decays** of the boosted W and Z bosons



Invariant mass of the dijet system

Updated squark and gluino cross-sections with threshold-improved PDFs

Bonvini, Marzani, JR, Rottoli, Ubiali, Ball, Bertone, Carrazza, Hartland, arXiv:1507.01006
Beenakker, Borschensky, Kramer, Kulesza, Laenen, Marzani, JR, arXiv:1510.00375

All-orders resummations

Resummation is well-understood QCD technique to **improve precision of perturbative calculations**

fixed order

$$\frac{\sigma}{\sigma_0} = 1$$ LO

$$+ c_1\alpha$$ NLO

$$+ c_2\alpha^2$$ NNLO

$$+ \ldots$$

all order (L = some large logarithm)

$$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1}$$ LL

$$+ \alpha^n L^n$$ NLL

$$+ \alpha^n L^{n-1}$$ NNLL

$$+ \ldots$$

Various types of resummation used for LHC calculations

- **L = log(1-x):** threshold (soft-gluon) resummation
- **L = log(1/x):** high-energy (small-x) resummation
- **L = log(p_T/M):** transverse momentum resummation
- …….

All-orders threshold resummation

- The basic idea of **threshold resummation** methods is simple: start from the **factorised cross-section** and transform it to **Mellin (conjugate) space**

$$\sigma(x,Q^2) = x \sum_{a,b} \int_x^1 \frac{dz}{z} \mathcal{L}_{ab}\left(\frac{x}{z},\mu_F^2\right) \frac{1}{z}\hat{\sigma}_{ab}\left(z, Q^2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

$$\sigma(N,Q^2) = \int_0^1 dx\, x^{N-2} \sigma(x,Q^2) = \sum_{a,b} \mathcal{L}_{ab}(N,Q^2)\hat{\sigma}_{ab}\left(N,Q^2,\alpha_s\right)$$

- Then compute a **resummed coefficient function** that includes terms or the type $\boldsymbol{\alpha_S^k \ln^p N}$, corresponding to $\boldsymbol{\alpha_S^k \ln^r (1-x)}$, to **all orders in perturbation theory**

$$\hat{\sigma}_{ab}^{(\mathrm{res})}(N,Q^2,\alpha_s) = \sigma_{ab}^{(\mathrm{born})}(N,Q^2,\alpha_s)\, C_{ab}^{(\mathrm{res})}(N,\alpha_s)$$

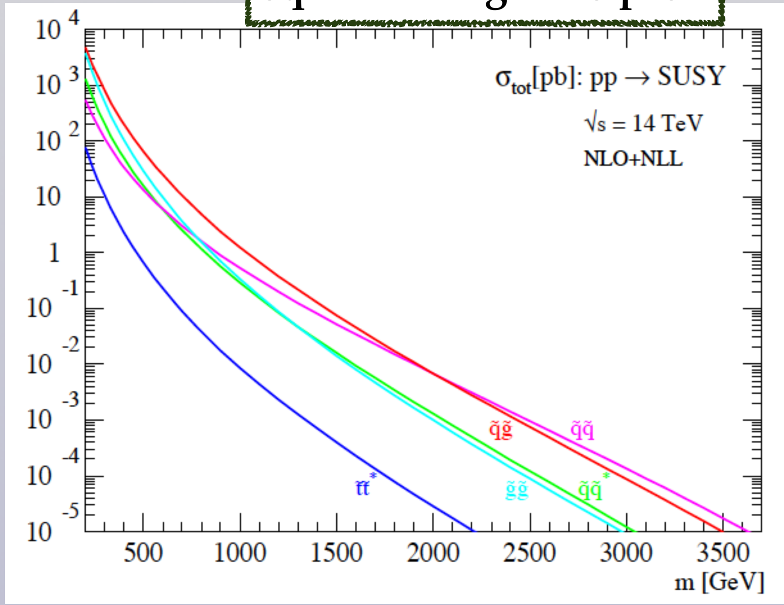
$$C^{(N\text{-soft})}(N,\alpha_s) = g_0(\alpha_s) \exp \mathcal{S}(\ln N, \alpha_s),$$
$$\mathcal{S}(\ln N,\alpha_s) = \left[\frac{1}{\alpha_s} g_1(\alpha_s \ln N) + g_2(\alpha_s \ln N) + \alpha_s g_3(\alpha_s \ln N) + \ldots\right]$$

- These terms are numerically large near the **partonic threshold x -> 1 (N -> ∞)**, and thus their resummation **improves the perturbative expansion**, reduces scale uncertainties and allows to **construct approximate higher-order results**

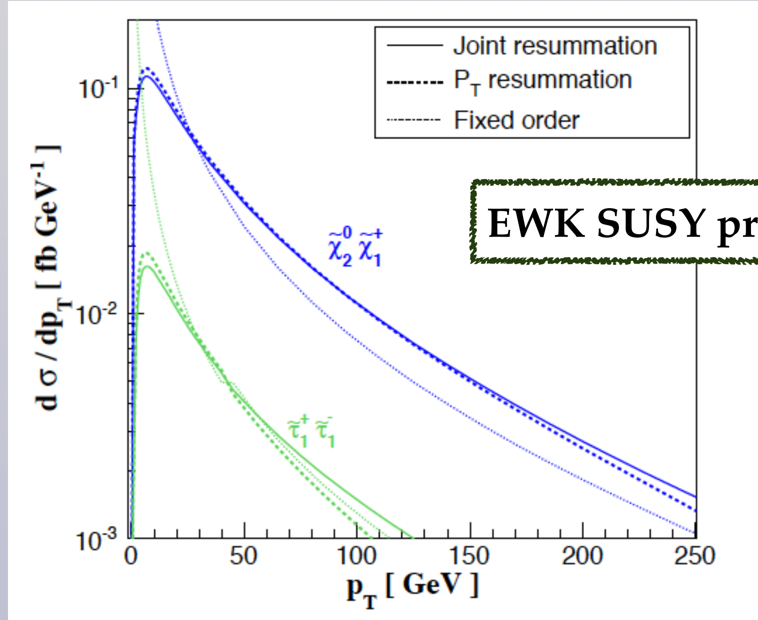
Why threshold resummation?

☑ **Threshold resummation of partonic cross-sections** extensively used in precision LHC phenomenology

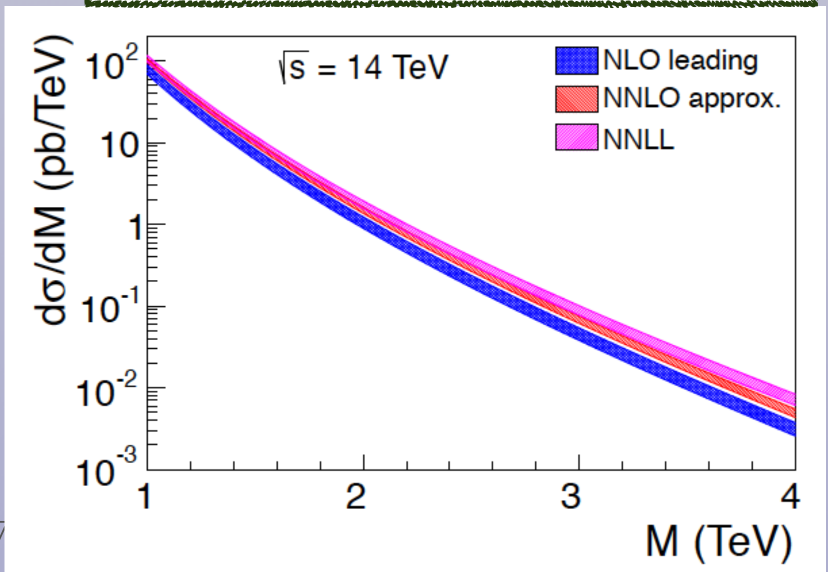
squark and gluino prod



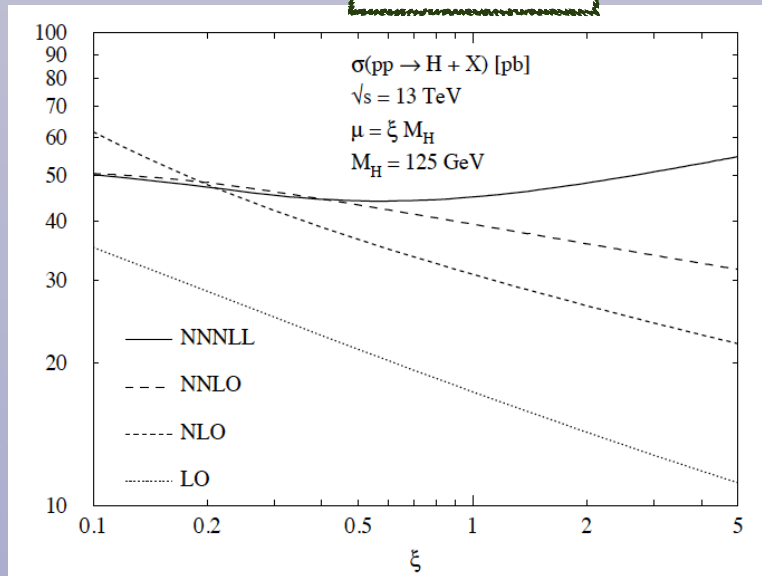
EWK SUSY prod



large mass top quark pair production



gg -> Higgs



Why threshold resummation?

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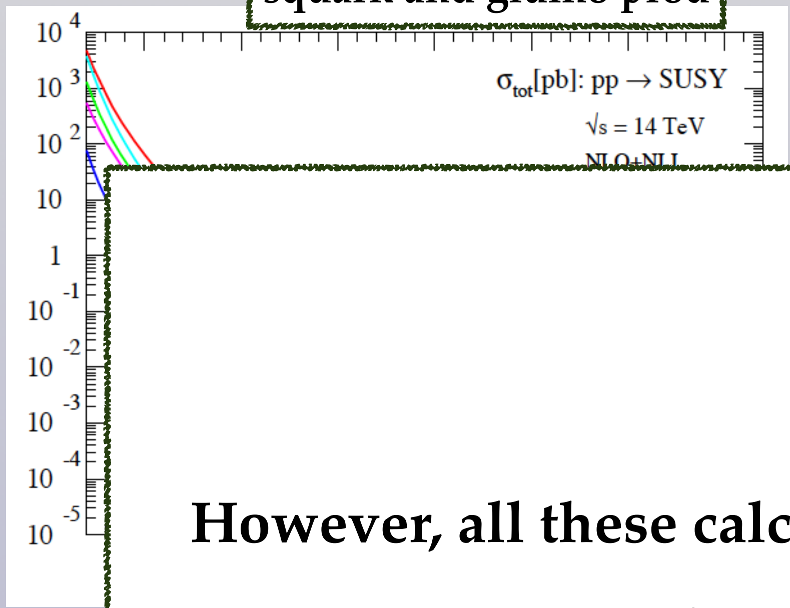
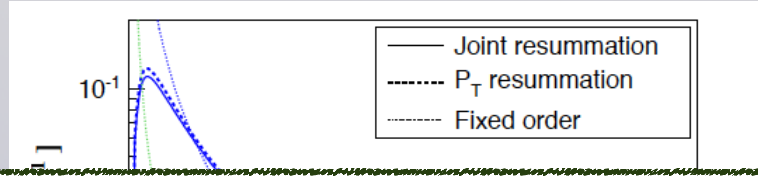
squark and gluino prod



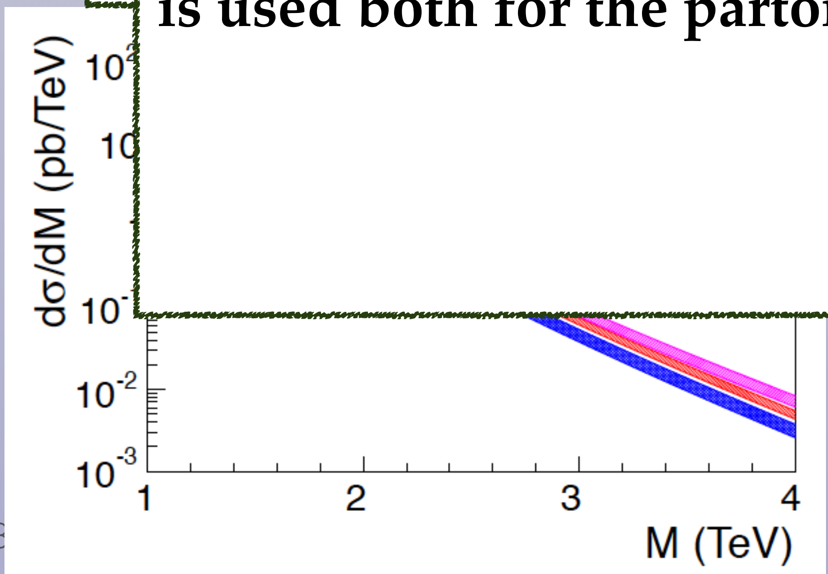


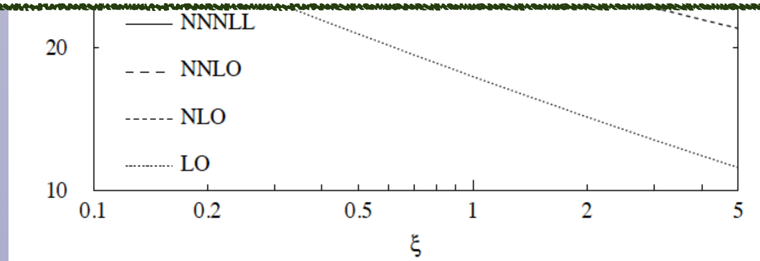
However, all these calculations use fixed-order NLO PDFs!

What happens if exactly the same theory (NLO+NLL)

is used both for the partonic matrix elements and for the PDFs?

la

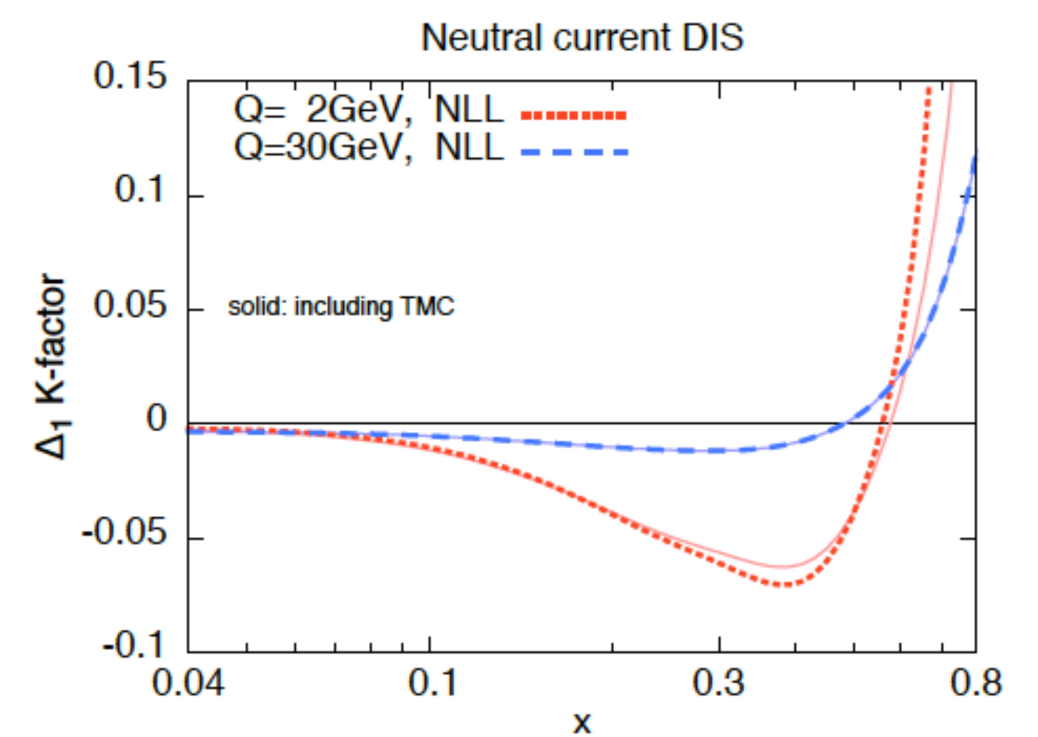


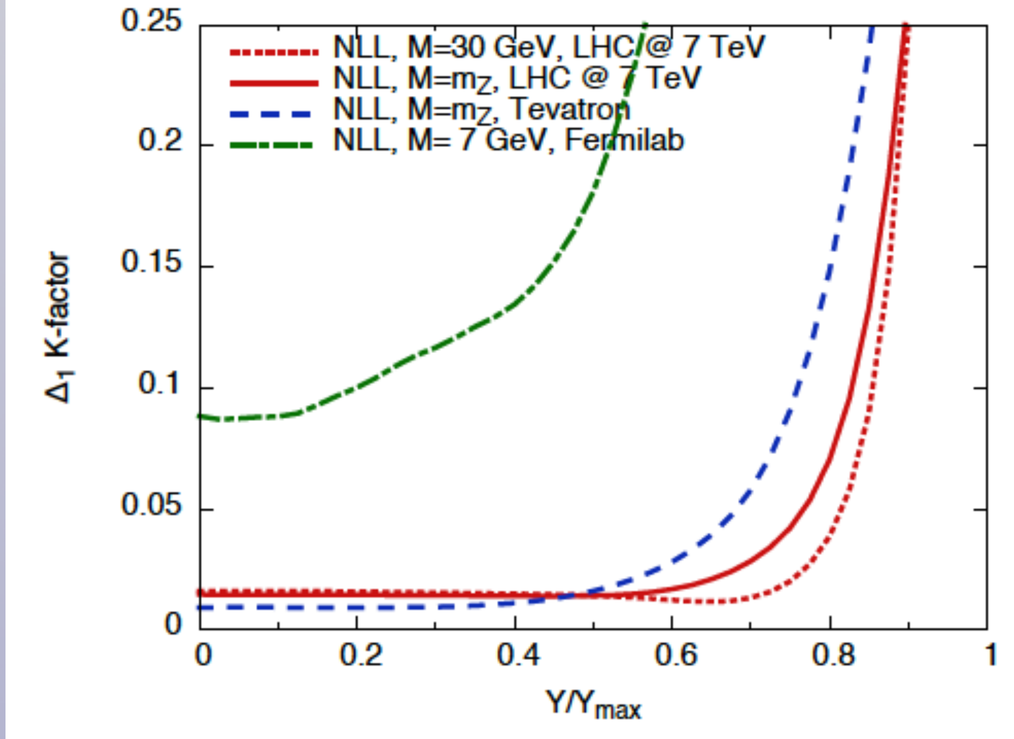


PDFs with threshold resummation

- **Threshold-resummed PDFs** will be suppressed as compared to the **Fixed-Order (FO) PDFs**
- Due to **enhancement in NLO+NLL xsecs** used in the fit for **DIS structure functions** and **DY distributions**

$$\sigma_{\mathrm{N}^j\mathrm{LO}+\mathrm{N}^k\mathrm{LL}} = \sigma_{\mathrm{N}^j\mathrm{LO}} + \sigma_{\mathrm{LO}} \times \Delta_j K_{\mathrm{N}^k\mathrm{LL}}$$

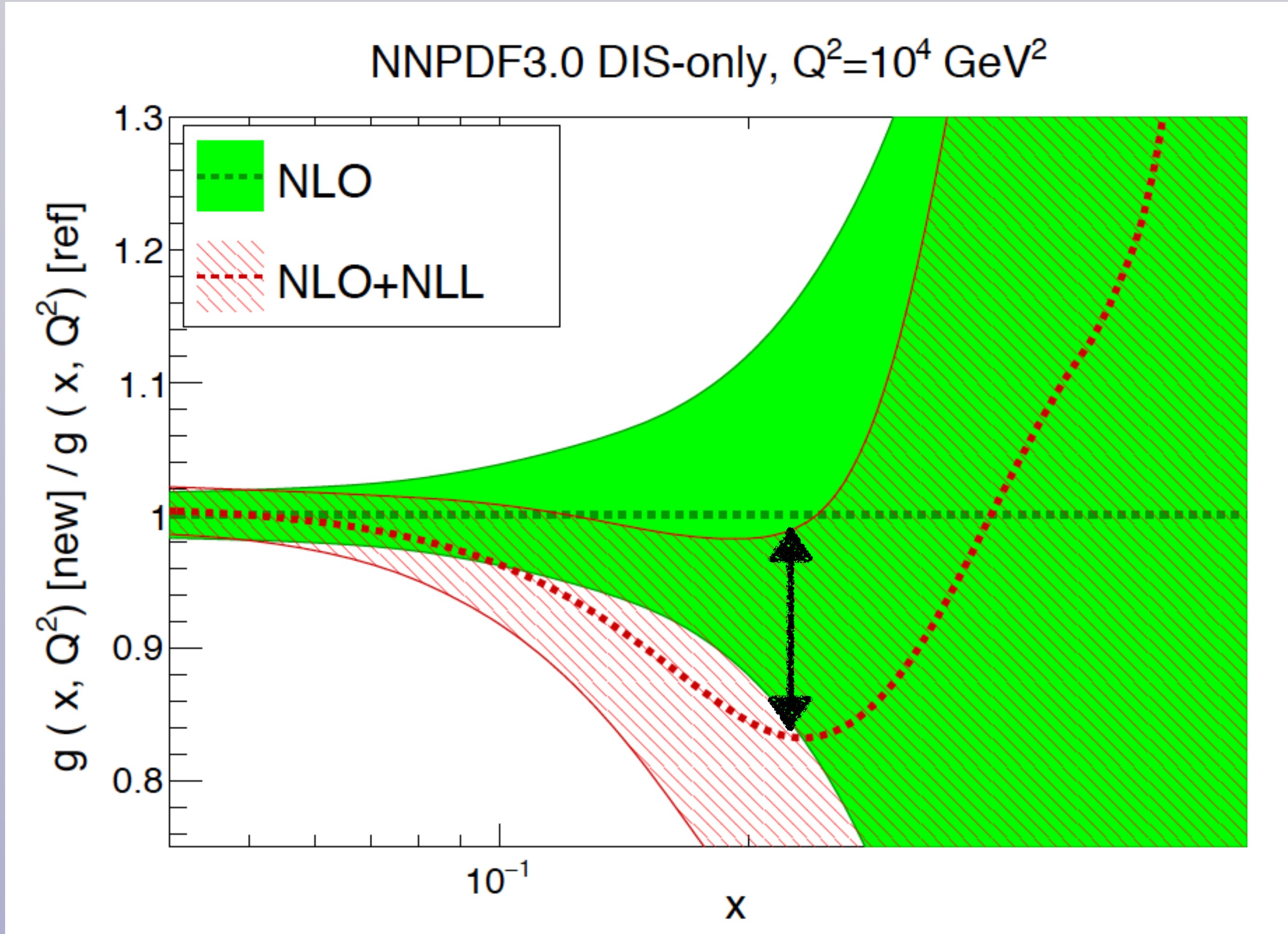




- **Phenomenologically most relevant:** this suppression will partially or totally compensate enhancements in partonic cross-sections for new processes (SUSY, Higgs, ttbar differential)

PDFs with threshold resummation

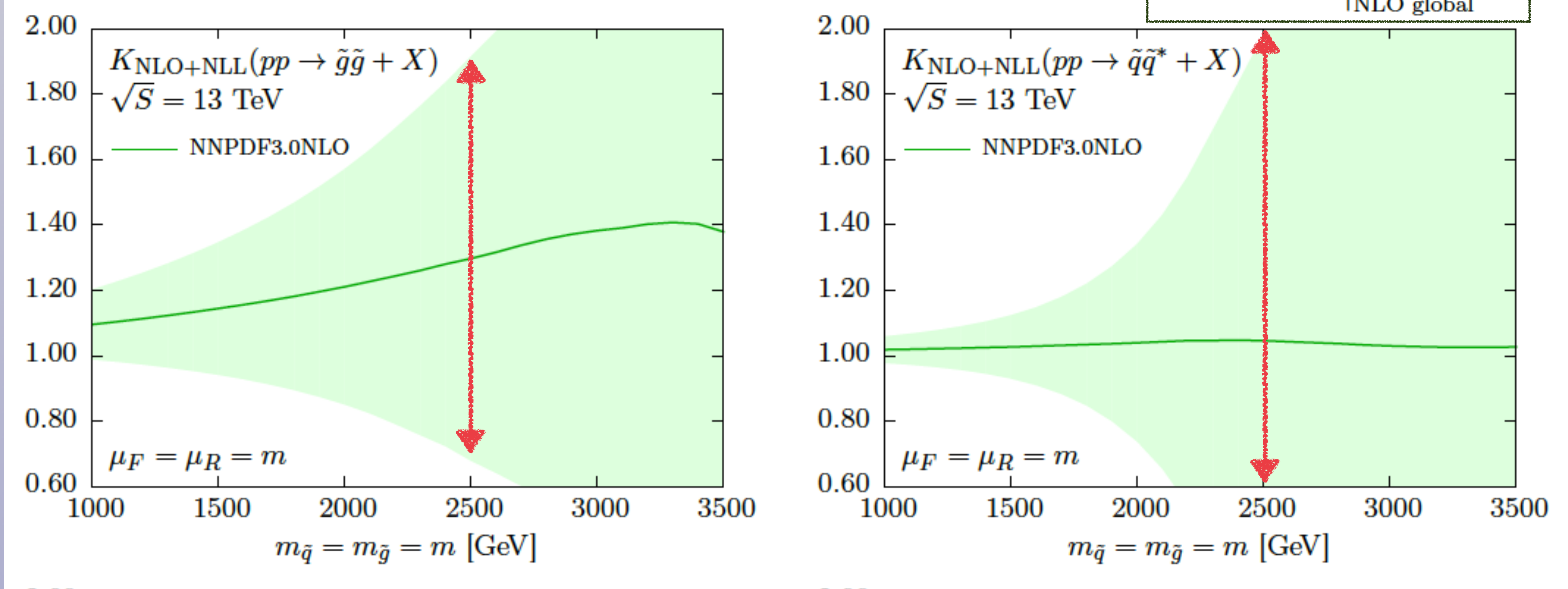
- Produced for the first time **threshold-improved PDFs at** NLO+NLL and NNLO+NNLL using a **variant of the NNPDF3.0 global PDF analysis**
- For medium and small-x, **resummed PDFs reduce to FO PDFs**, as expected
- At large-x, **resummed PDFs substantially suppressed** from enhancement in partonic matrix elements



Updated NLO+NLL cross-sections with NNPDF3.0NLO

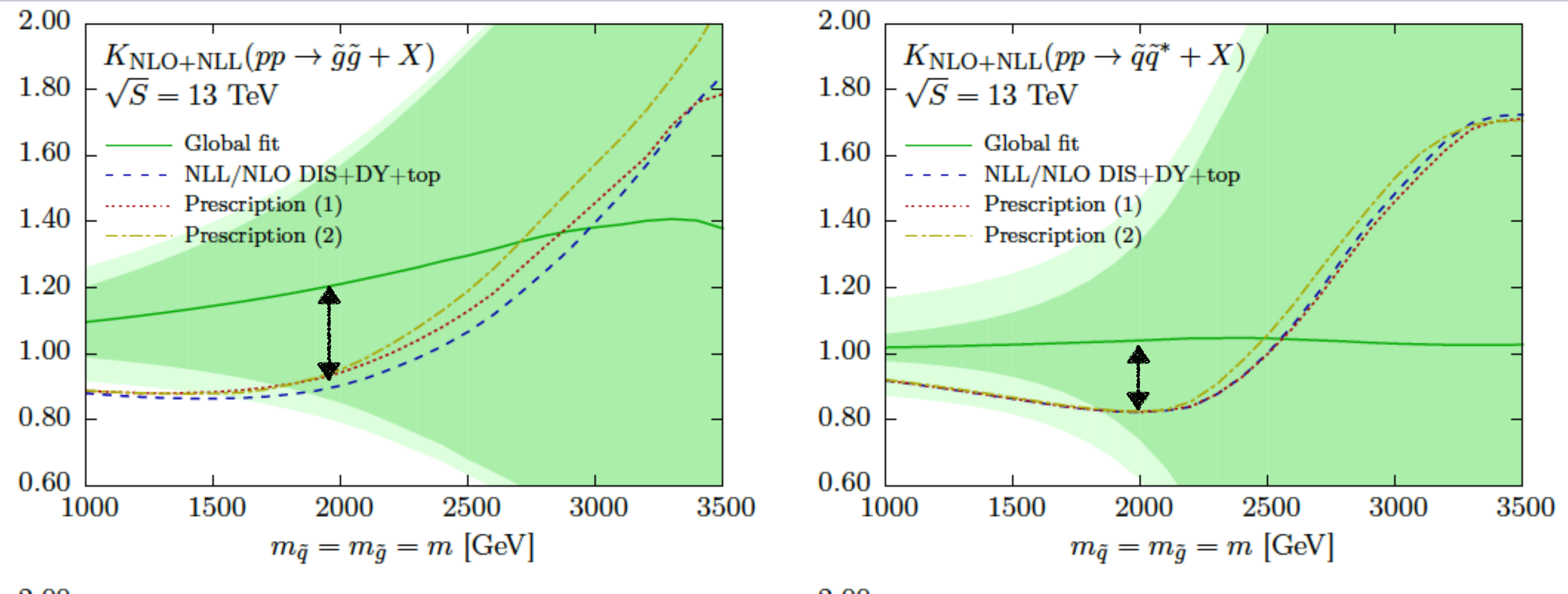
- **ATLAS and CMS** use the **NLO+NLL squark and gluino calculations** from **NLL-fast** to derive bounds on supersymmetric particles from their searches
- **Previous NLL-fast calculations** based on the old CTEQ6.6 and MSTW08 sets, latest version now updated to **NLO+NLL cross-sections with NNPDF3.0NLO**
- **PDF uncertainties blow up at large masses**, due to lack of experimental constraints on **large-x PDFs**
- Serious problem for **SUSY particle characterisation** in case of discovery!

$$K := \frac{\sigma^{\rm NLO+NLL}\big|_{\rm NLO\ global}}{\sigma^{\rm NLO}\big|_{\rm NLO\ global}} .$$



NLO+NLL SUSY xsecs with threshold-improved PDFs

- Now include the effect of **NLO+NLL threshold-improved PDF**
- Substantial shift, **changes qualitatively and quantitatively** the behaviour of NLO+NLL SUSY xsecs
- Shift within total theory band, so **current exclusion limits unaffected**
- But will become crucial if we ever need to **characterise SUSY particles from LHC data**, much in the same way as we do for the Higgs boson



solid band: PDF errors only. lighter band: scales+PDF errors added linearly

NLL-fast grids

- The **updated NLO+NLL squark and gluino** production cross-sections at the **LHC 13 TeV** using **NNPDF3.0** can be downloaded from the NLL-fast collaboration webpage
- Include a **complete characterisation of theory uncertainties** from PDFs, scales and string coupling

http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast

Squark and gluino production:

- Squark and Gluino Production at Hadron Colliders, W. Beenakker, R. Höpker, M. Spira, P.M. Zerwas, Nucl. Phys. B492 (1997) 51-103
- Threshold resummation for squark-antisquark and gluino-pair production at the LHC, A. Kulesza, L. Motyka, Phys. Rev. Lett. 102 (2009) 111802
- Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC, A. Kulesza, L. Motyka, Phys. Rev. D80 (2009) 095004
- Soft-gluon resummation for squark and gluino hadroproduction, Wim Beenakker, Silja Brensing, Michael Krämer, Anna Kulesza, Eric Laenen, Irene Niessen, JHEP 0912 (2009) 041
- Squark and gluino hadroproduction, W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, L. Motyka, I. Niessen, Int. J. Mod. Phys. A26 (2011) 2637-2664

Stop (sbottom) production:

- Stop Production at Hadron Colliders, W. Beenakker, M. Krämer, T. Plehn, M. Spira, P.M. Zerwas, Nucl.Phys. B515 (1998) 3-14
- Supersymmetric top and bottom squark production at hadron colliders, Wim Beenakker, Silja Brensing, Michael Krämer, Anna Kulesza, Eric Laenen, Irene Niessen, JHEP 1008(2010)098
- Squark and gluino hadroproduction, W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen, L. Motyka, I. Niessen, Int. J. Mod. Phys. A26 (2011) 2637-2664

When using NLL-fast version 3.1, please additionally cite:

- NLO+NLL squark and gluino production cross-sections with threshold-improved parton distributions, W. Beenakker, C. Borschensky, M. Krämer, A. Kulesza, E. Laenen, S. Marzani, J. Rojo

Code

Downloads

NEW: NLL-fast, version 3.1 (LHC @ 13 TeV)

- Main program and grids in one package nllfast-3.1. For grids for stop/sbottom production SUSY parameters other that stop/sbottom masses correspond to CMSSM benchmark point 40.2.5 as
- This version of NLL-fast is an update of version 3.0, now also including predictions with the NNPDF3.0NLO (NNPDF3.0LO for LO) set.
- Please note that the output format for the NNPDF predictions is slightly different, as the PDF and AlphaS error are already given in a combined format.

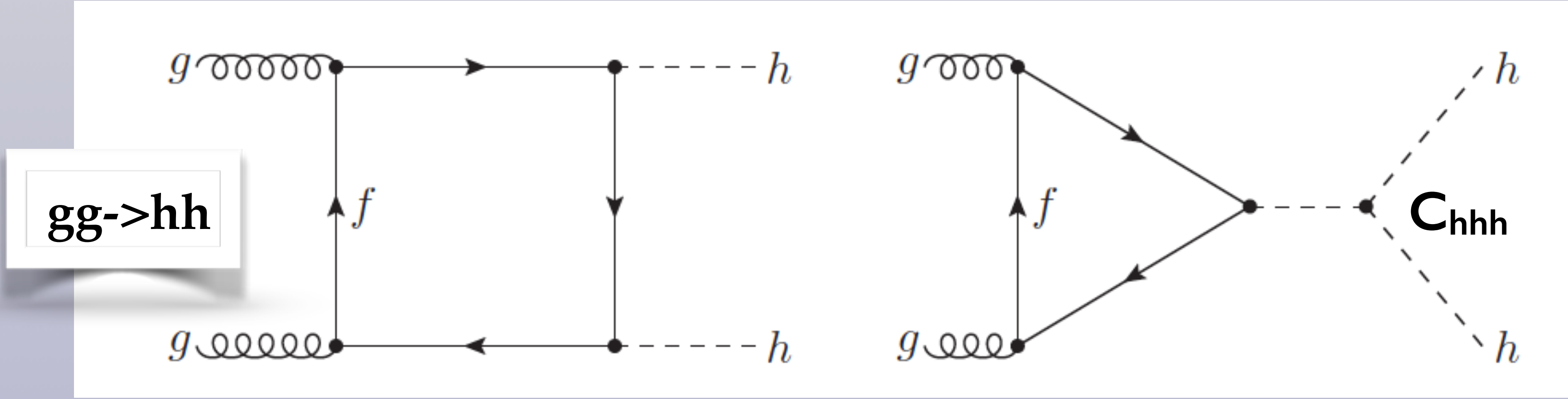
- In addition, **cross-sections using the threshold-improved NNPDF3.0** sets is available from the authors upon request.
- Important to use **up-to-date theory calculations** for the **interpretation of SUSY searches** at the LHC Run II

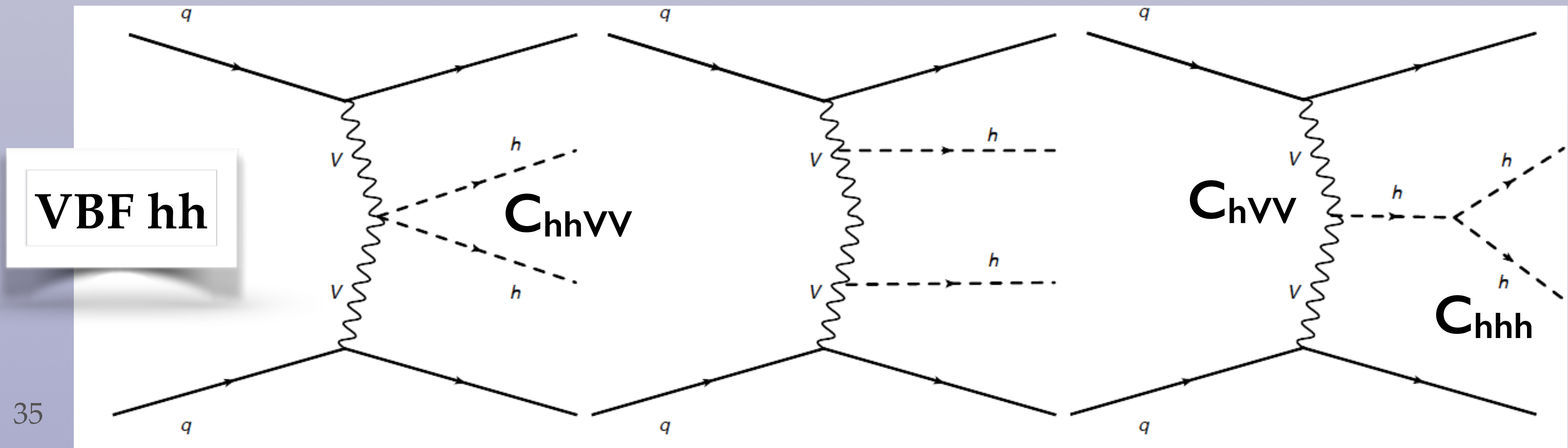
Higgs Pair Production with Jet Substructure

Gouzevitch, Oliveira, Rosenfeld, JR, Salam, Sanz, arXiv:1303.6636
Behr, Bortoletto, Frost, Issever, Hartland, JR, in preparation
Contino, JR, in preparation

Higgs Pair Production at the LHC

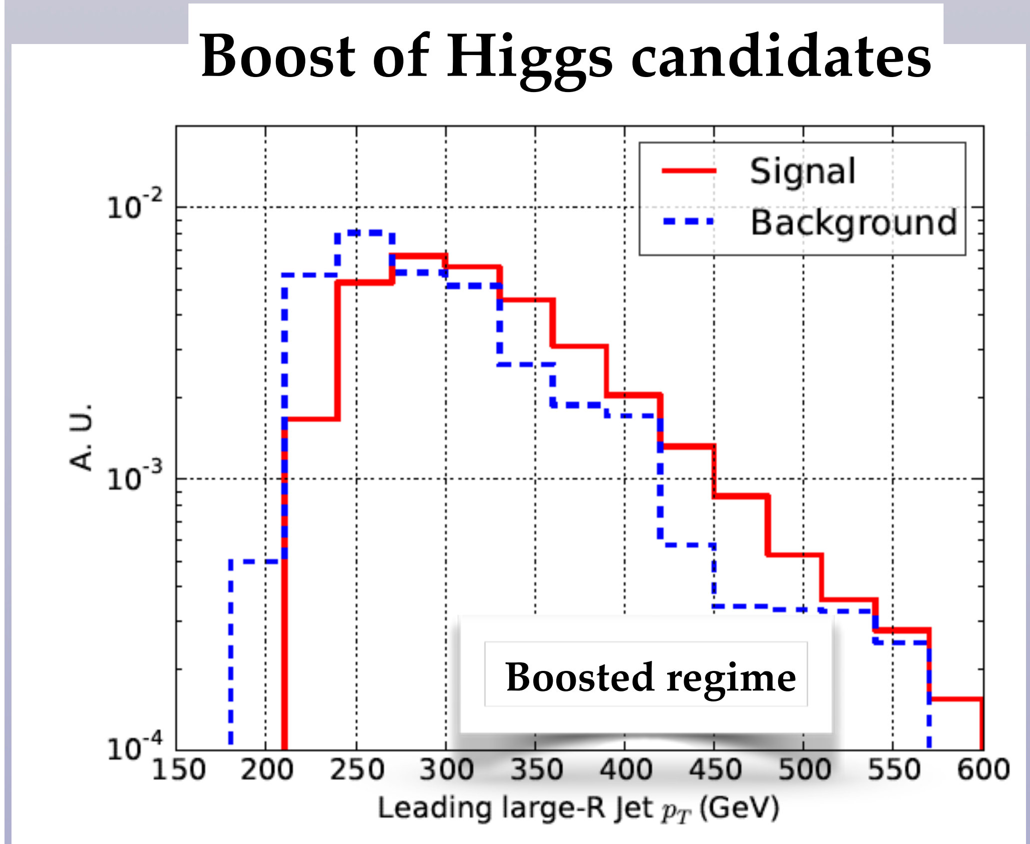
- As compared to single Higgs production, **double Higgs production** allows accessing crucial components of the Higgs sector, in particular the **Higgs self-coupling** and the **hhVV coupling**
- In the SM, **hh rates are small**, can only be probed at the **High-Luminosity upgrade of the LHC**
- Rates for double Higgs production are **generically enhanced in BSM scenarios**, and LHC searches in various final states have already started at Run I

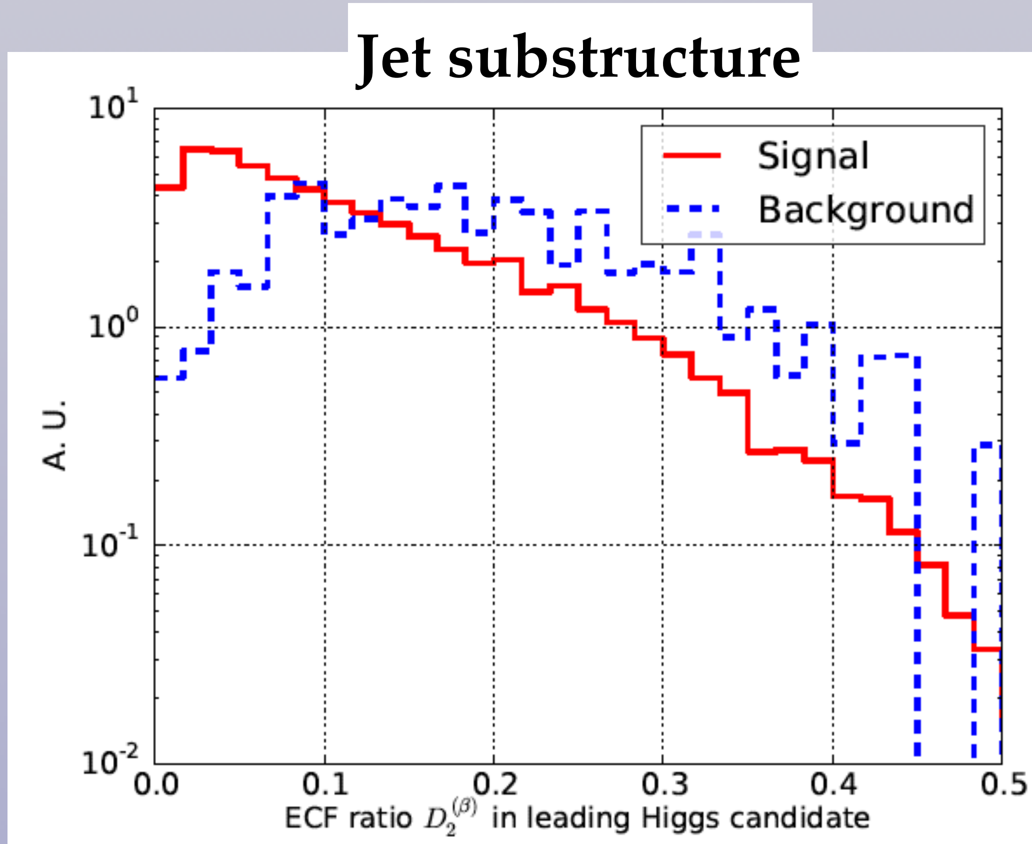




Boosting Higgs Pair Production

- The **hh->4b final state** yields the largest rates, but affected by **overwhelming QCD multijet background**
- Can be made competitive requiring the **di-Higgs system to be boosted** and exploiting kinematic differences between signal and QCD background for **jet substructure**
- In this final state, it is also mandatory to optimize the **boosted b-tagging techniques,** with impressive recent progress by ATLAS and CMS





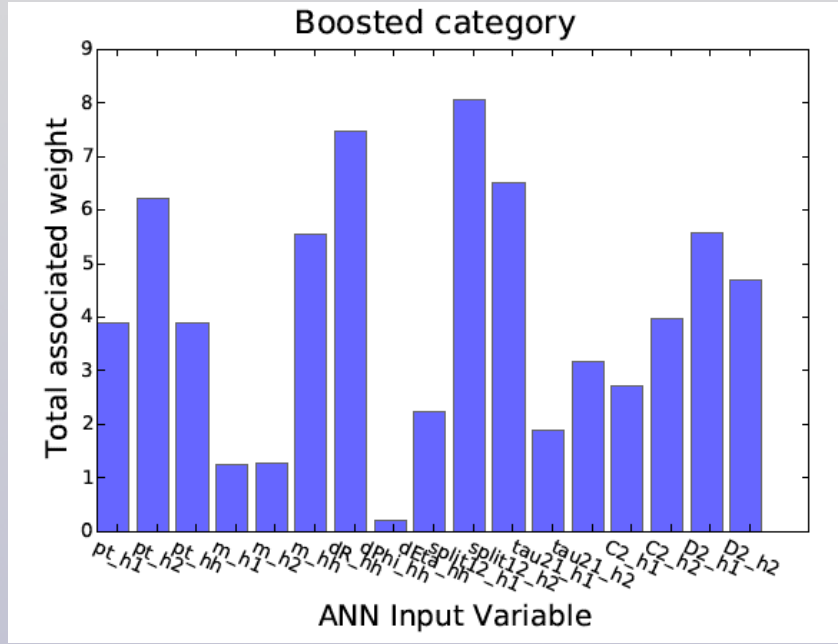
Multivariate techniques

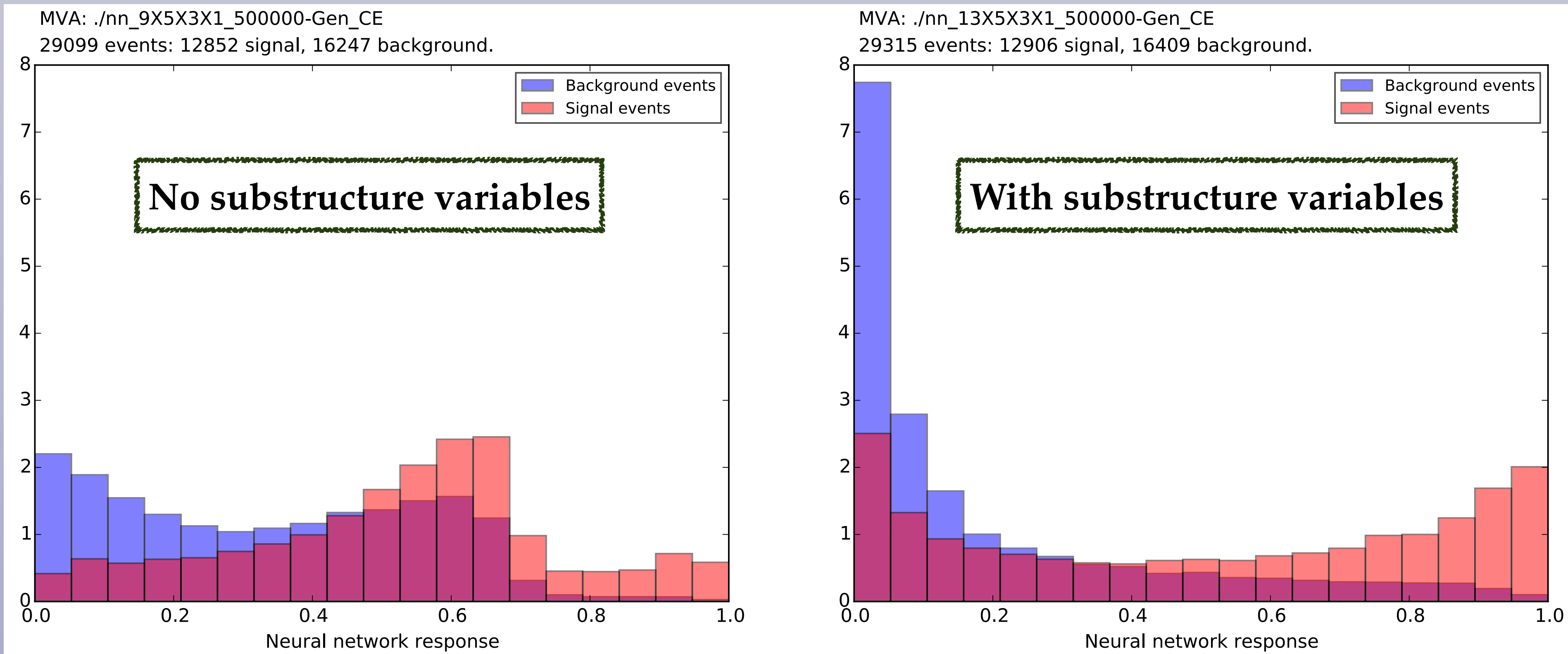
Even using jet substructure, **S/√B** remains small in a **cut-based analysis**

Can be improved using **multivariate techniques:**

- **Improve S/√B as compared to cut-based analyses**
- **Identify automatically** the kinematical variables with most discrimination power

Redundancy of **NN-based Multivariate Analysis** guarantees the optimisation of signal/background separation





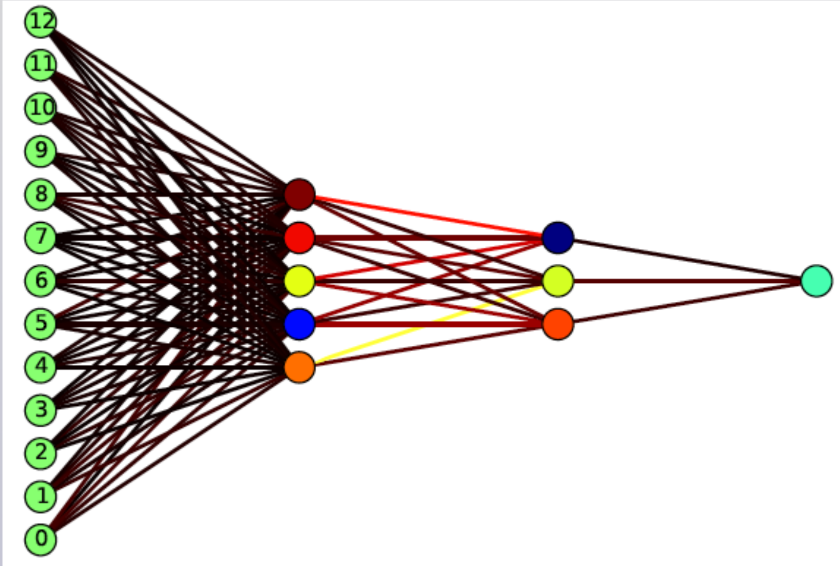
Results for gg->hh->4b

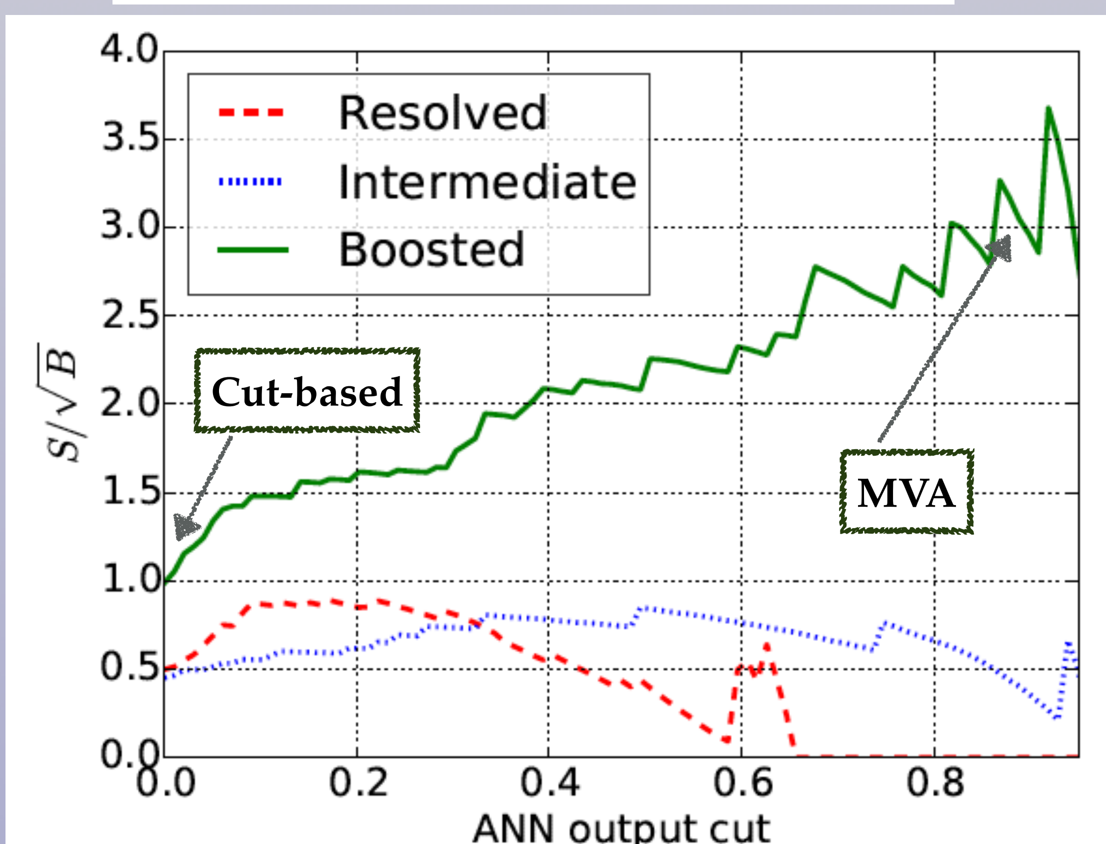
- The use of **multivariate techniques** allows to **substantially improve the signal significance** for this process as compared to a traditional cut -based analysis

- The significance would be enough to be able to **claim evidence of Higgs pair production at the HL-LHC** with a single final state

- We assumed SM production, next step to quantify **sensitivity in BSM scenarios**

Behr, Bortoletto, Frost,
Issever, Hartland, JR, in preparation





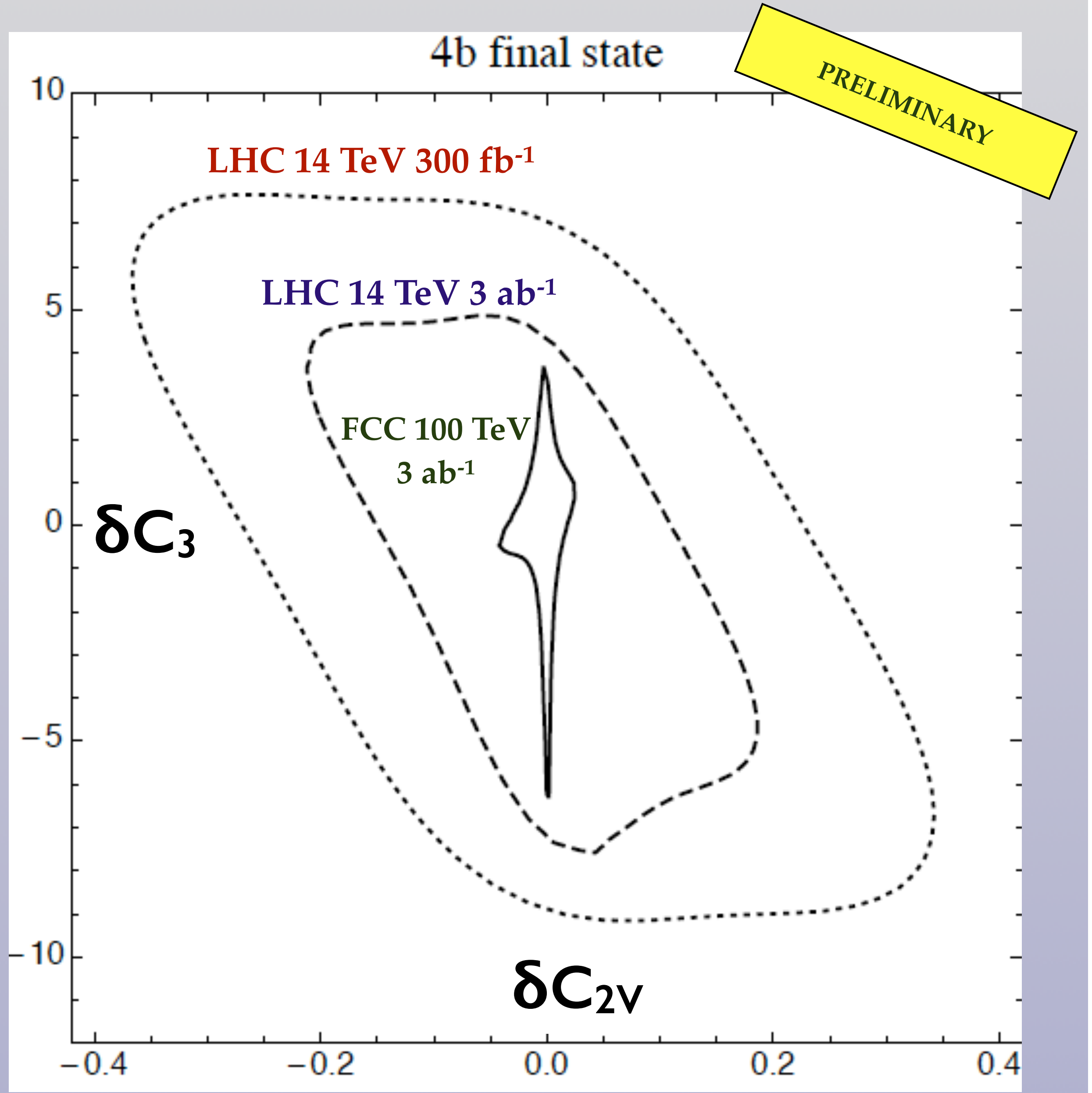
Results for VBF hh->4b

- In the **4b final state,** 14 TeV with 300 fb^{-1} (3000 fb^{-1}) the **hhVV** coupling can be measured with **good precision: ~25-30% (10-15%)**

- At a 100 TeV **FCC,** the **hhVV** coupling can be pinned down with **very high, few percent precision**

- Encouraging to begin to explore **Higgs pair production in VBF** already at the **LHC Run II**

- Unique probe of the Higgs mechanism to **unitarize electroweak symmetry breaking**

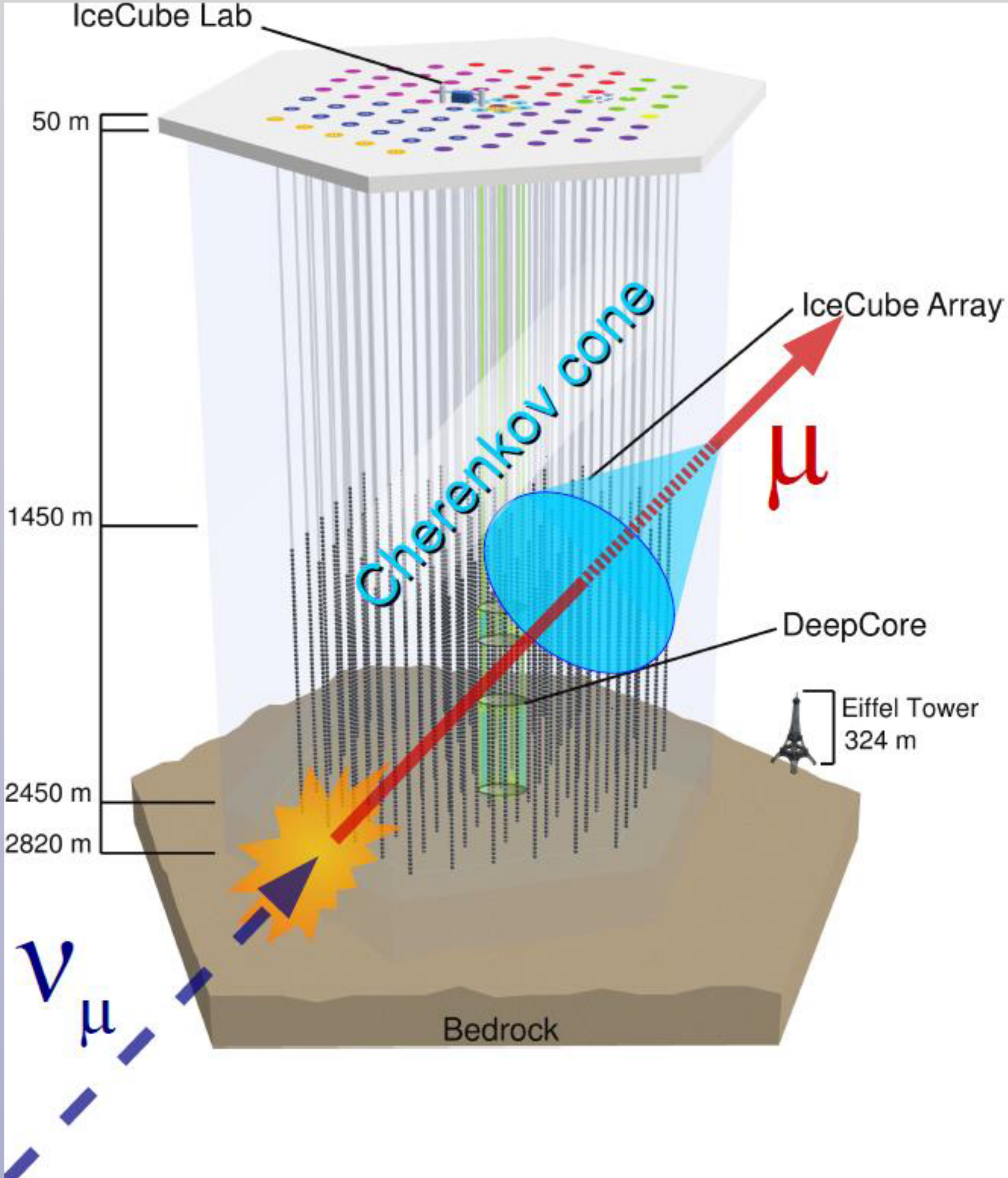


Contino, JR, in preparation

From LHC measurements to neutrino telescopes

Gauld, JR, Rottoli, Talbert, arXiv:1506.08025
Gauld, JR, Rottoli, Sarkar, Talbert, arXiv:1511.aaaaa

Neutrino Astronomy at IceCube



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

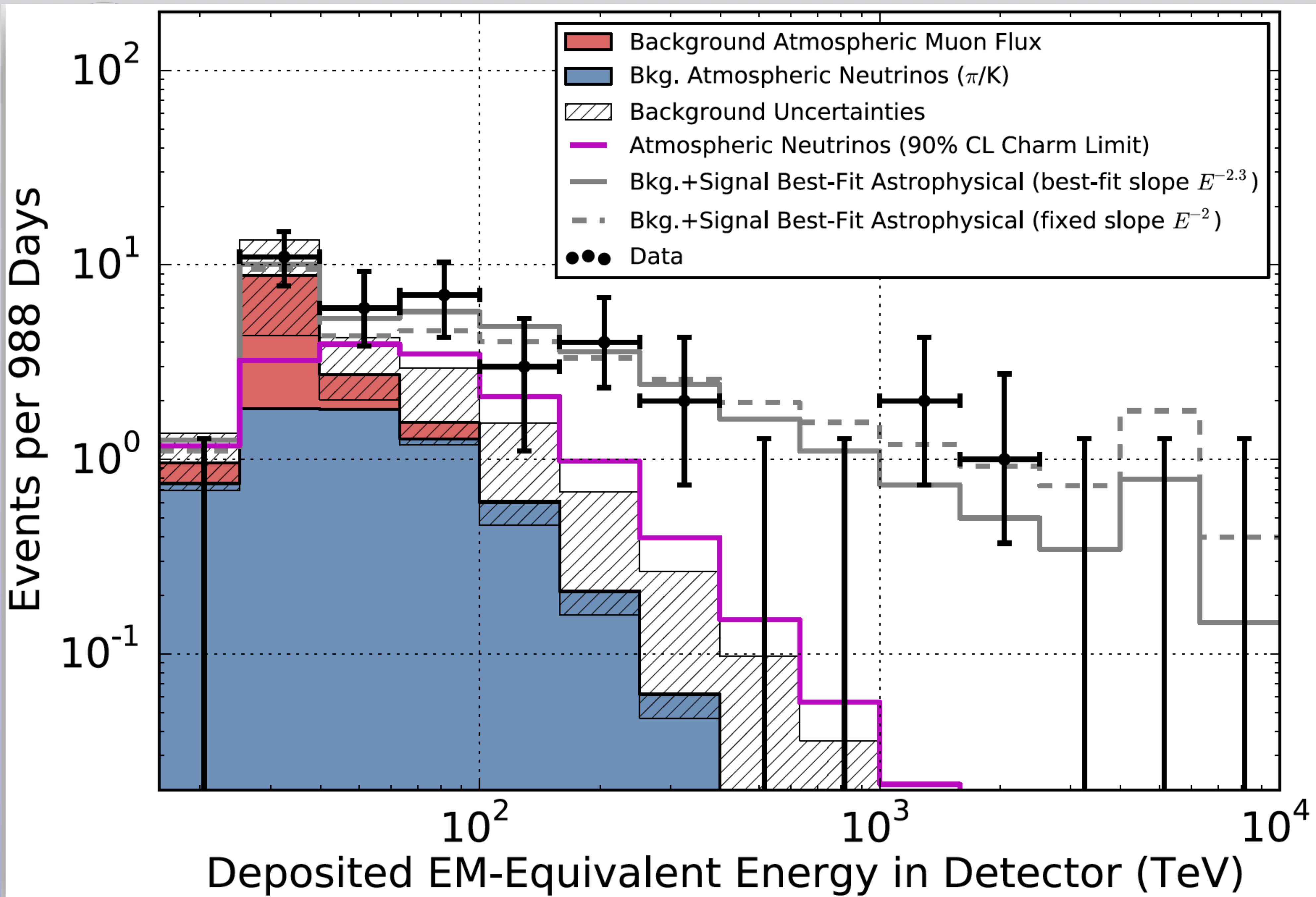
- The recent discovery by the **IceCube neutrino telescope** of **ultra-high energy neutrinos** heralds the **beginning of neutrino astronomy**

- The main **background for astrophysical neutrinos at IceCube** is the flux of neutrinos from the **decays of charm mesons** in cosmic ray collisions in the atmosphere

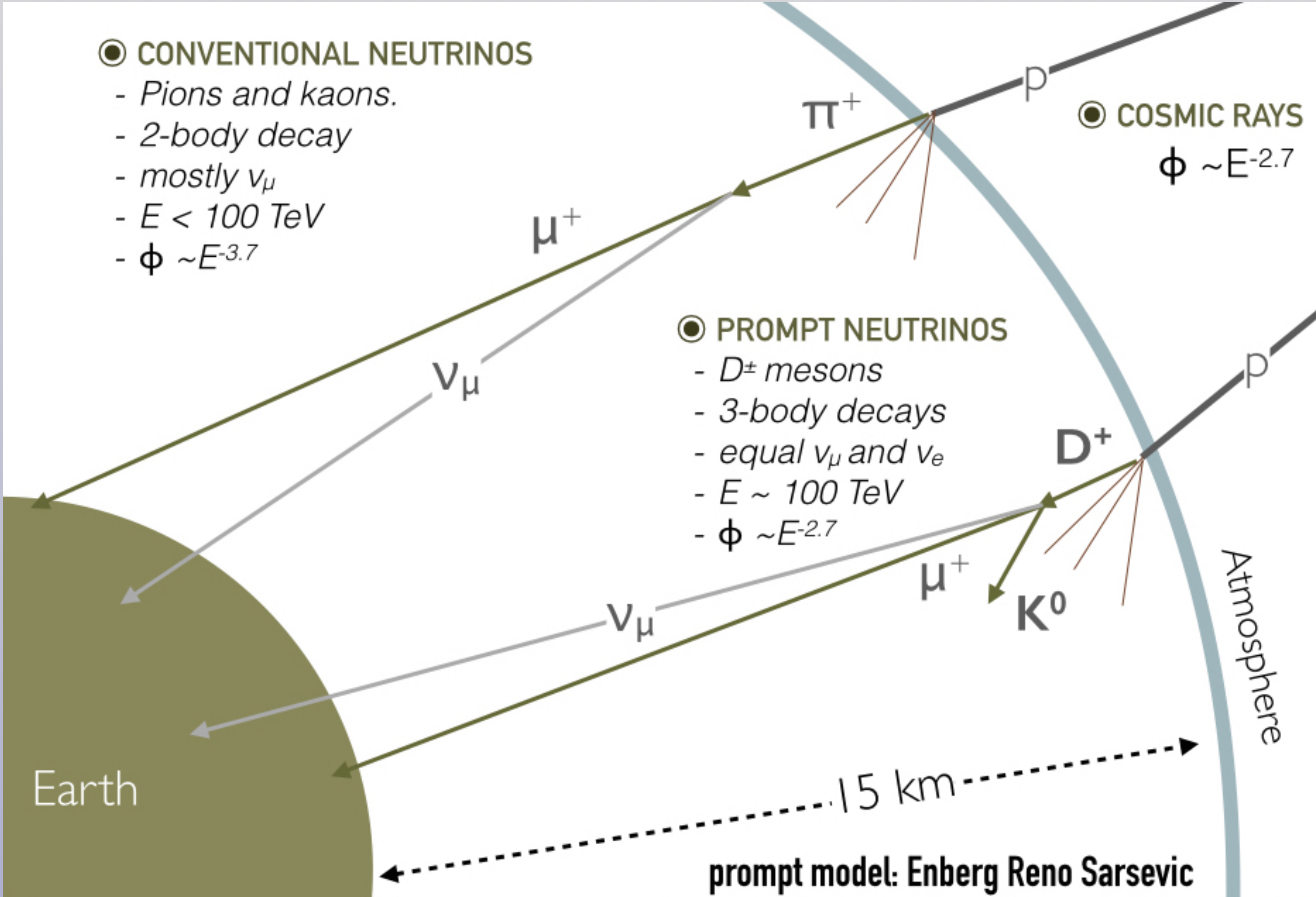
- Theoretically, this **prompt neutrino flux** is affected by large uncertainties: can we **trust perturbative QCD** there?

- Strategy: use **LHC data to validate our calculations** of the prompt neutrino flux

Neutrino Astronomy at IceCube



Neutrino Astronomy at IceCube



Charm production and LHC kinematics

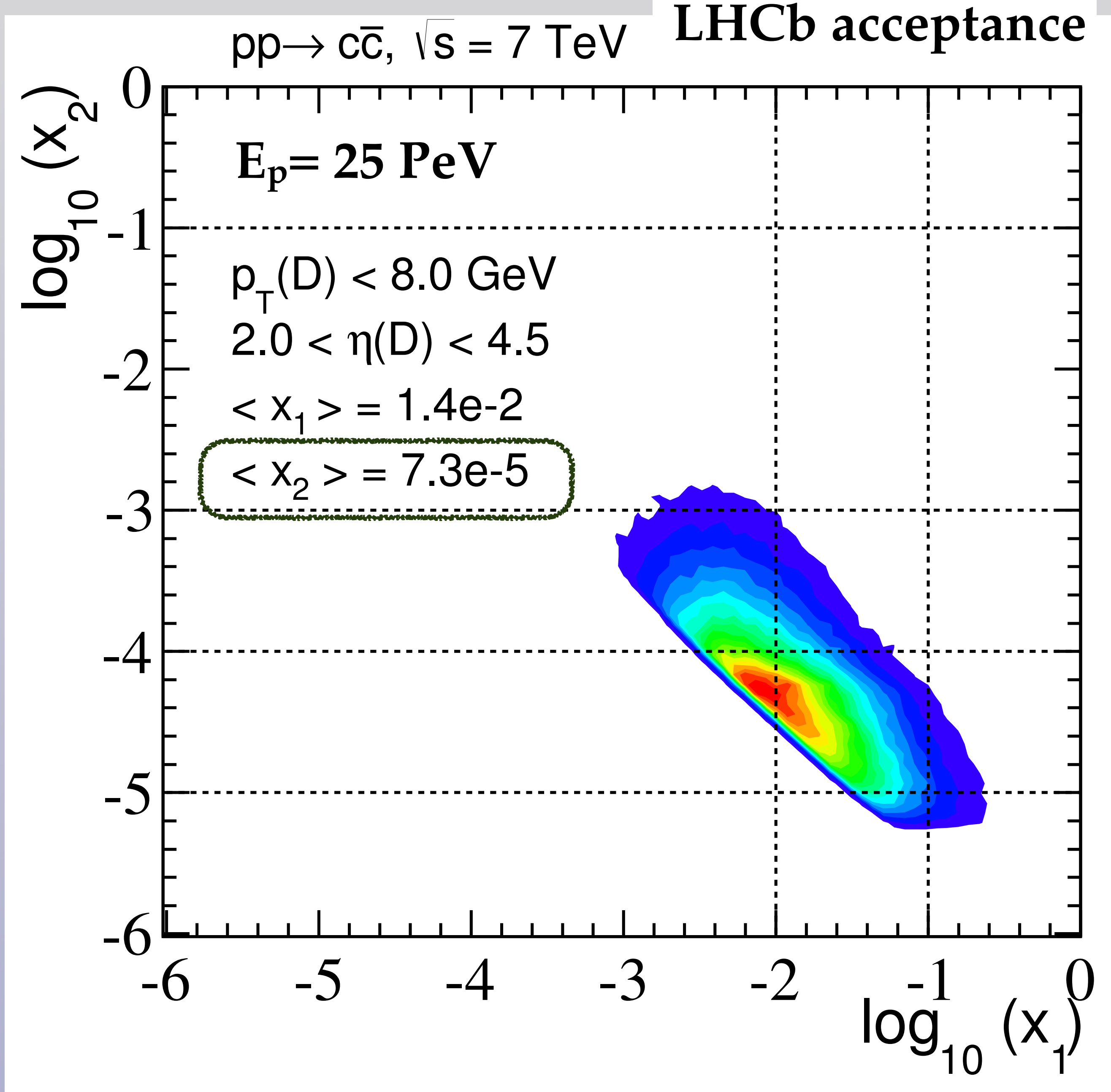
- **Collisions of cosmic rays** in the atmosphere with **energy E_p** correspond to **LHC collisions with center-of-mass energy $\sqrt{s} = \sqrt{(2 E_p m_p)}$**

- Icecube has detected neutrinos up to **several PeV**.

- The prompt flux at these energies originates from collisions of cosmic rays with E_p in the EeV range, **so $\sqrt{s}$=O(10-20) TeV,** covered by LHC data

- The **forward coverage of LHCb** is particularly useful to cover the **small-x region** where theory uncertainties are the largest

LHCb acceptance

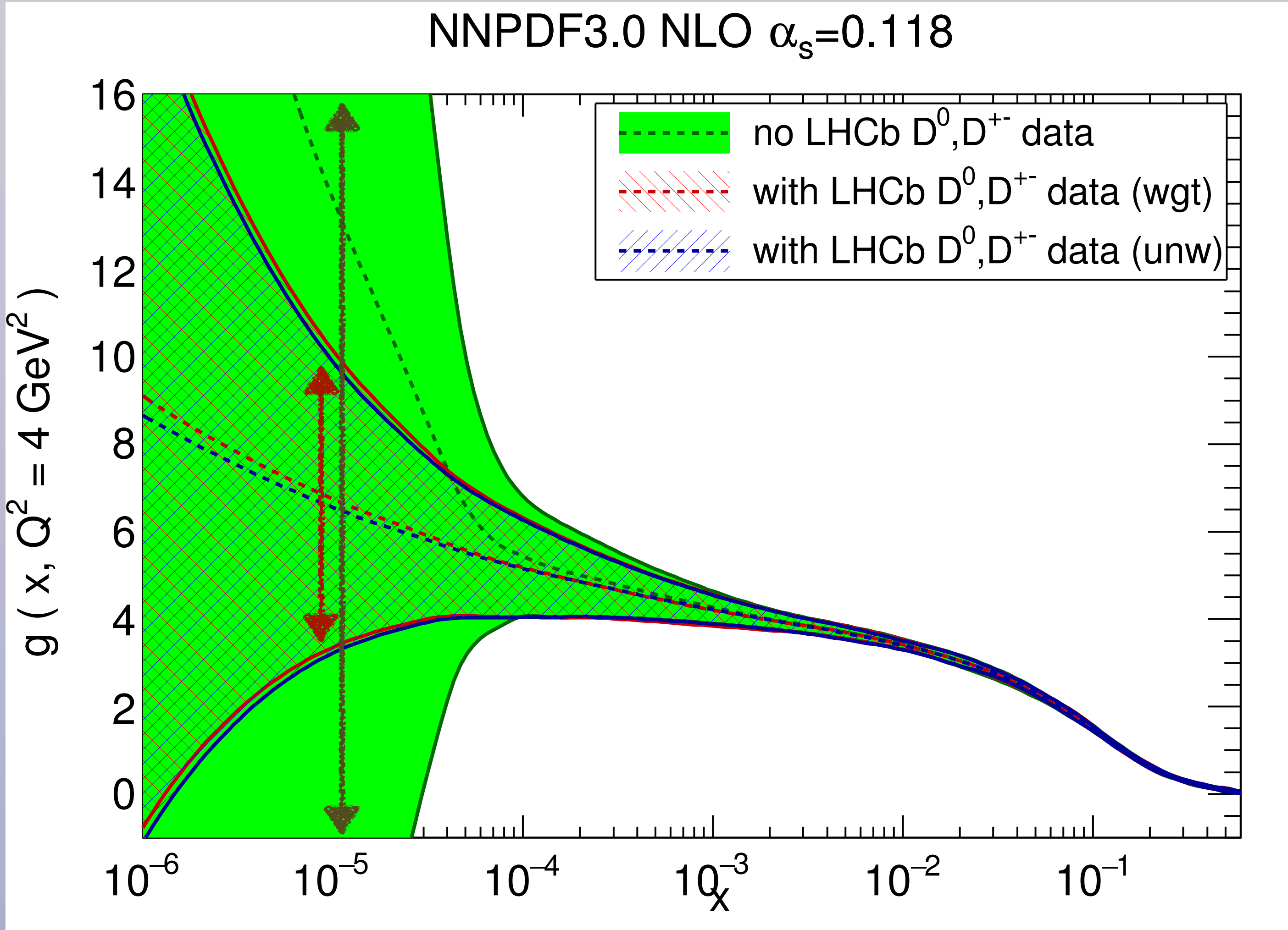


Charm production and the small-x gluon

- The production of **charm and bottom mesons in the forward region** can be used to constrain the **small-x gluon**, where **PDF uncertainties are huge** from lack of direct constraints

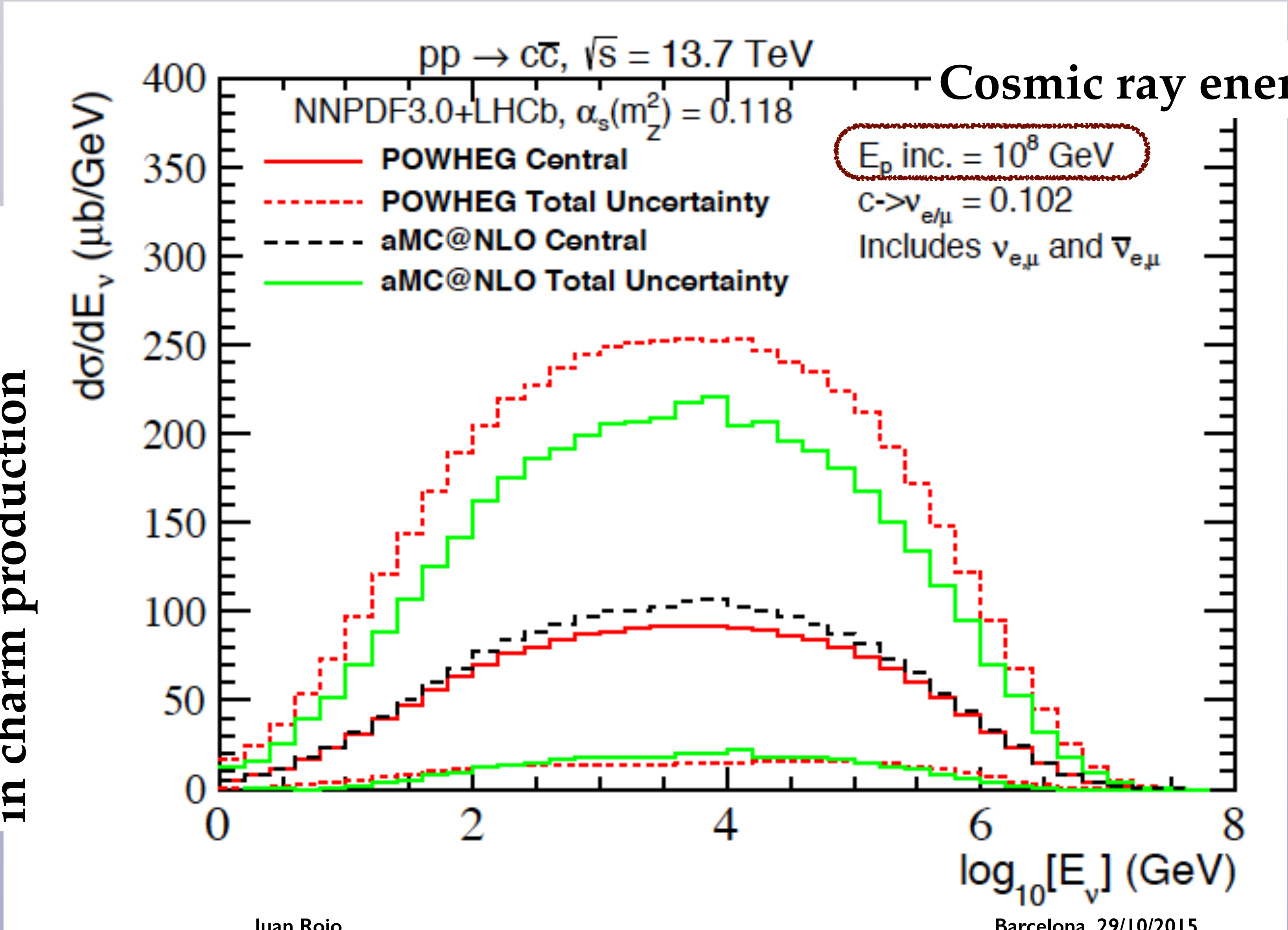
- Using the **FONLL calculation** and **normalised LHCb 7 TeV D meson data**, we have included these measurements in **NNPDF3.0 NLO** and found a **substantial reduction of PDF errors**

- Semi-analytical **FONLL** results validated with **POWHEG** and **aMC@NLO** calculations



Charm production and the small-x gluon

- **With improved NNPDF3.0+LHCb set,** provided predictions for wide range of cosmic ray energies
- Excellent agreement between three codes: **POWHEG**, **aMC@NLO** and **FONLL**



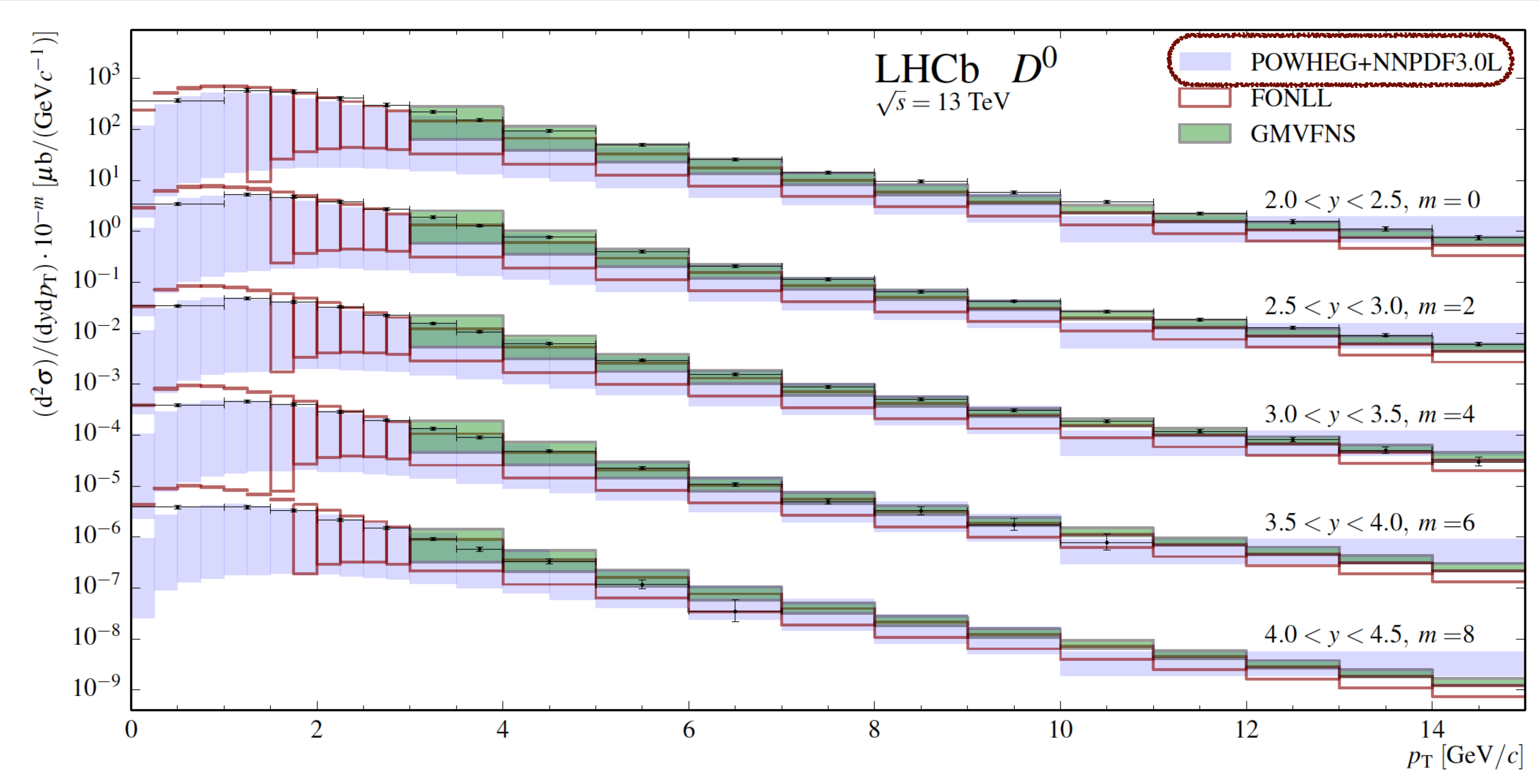
Cosmic ray energy

Neutrino energy spectrum in charm production

Comparison with LHCb 13 TeV data

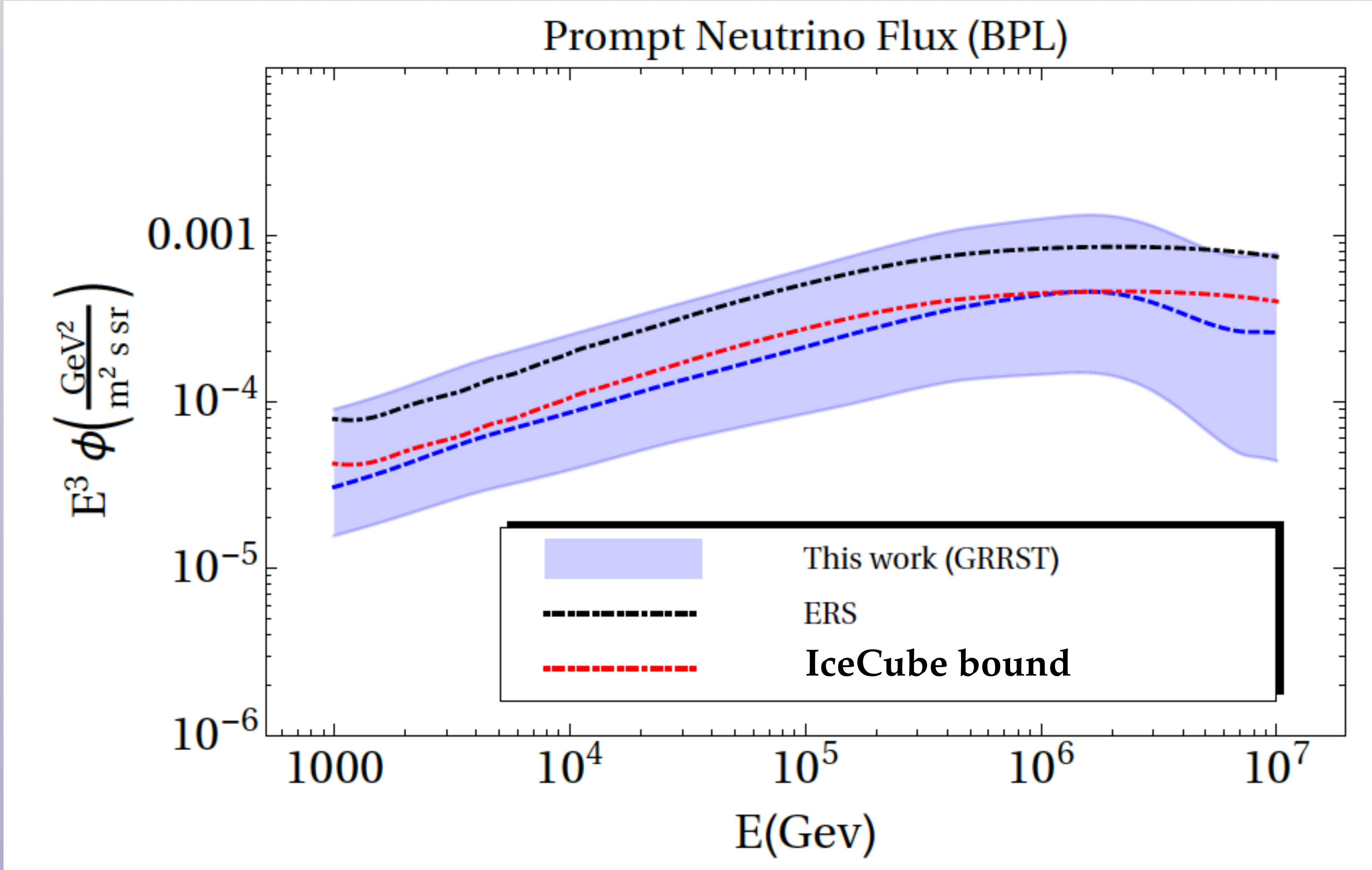
- Using the **improved small-x PDFs with 7 TeV LHCb charm data**, we also provided predictions for 13 TeV, very recently published

- **Good consistency** between our **predictions** (POWHEG+NNPDF3.0L) and the **LHCb 13 TeV** data within theory uncertainties, which further strengthens the **robustness of our approach**



Charm production and the small-x gluon

Preliminary results for the **expected prompt lepton fluxes at IceCube** in our framework (GRRST) compared with previous calculations and with the **direct IceCube bounds on the prompt flux**



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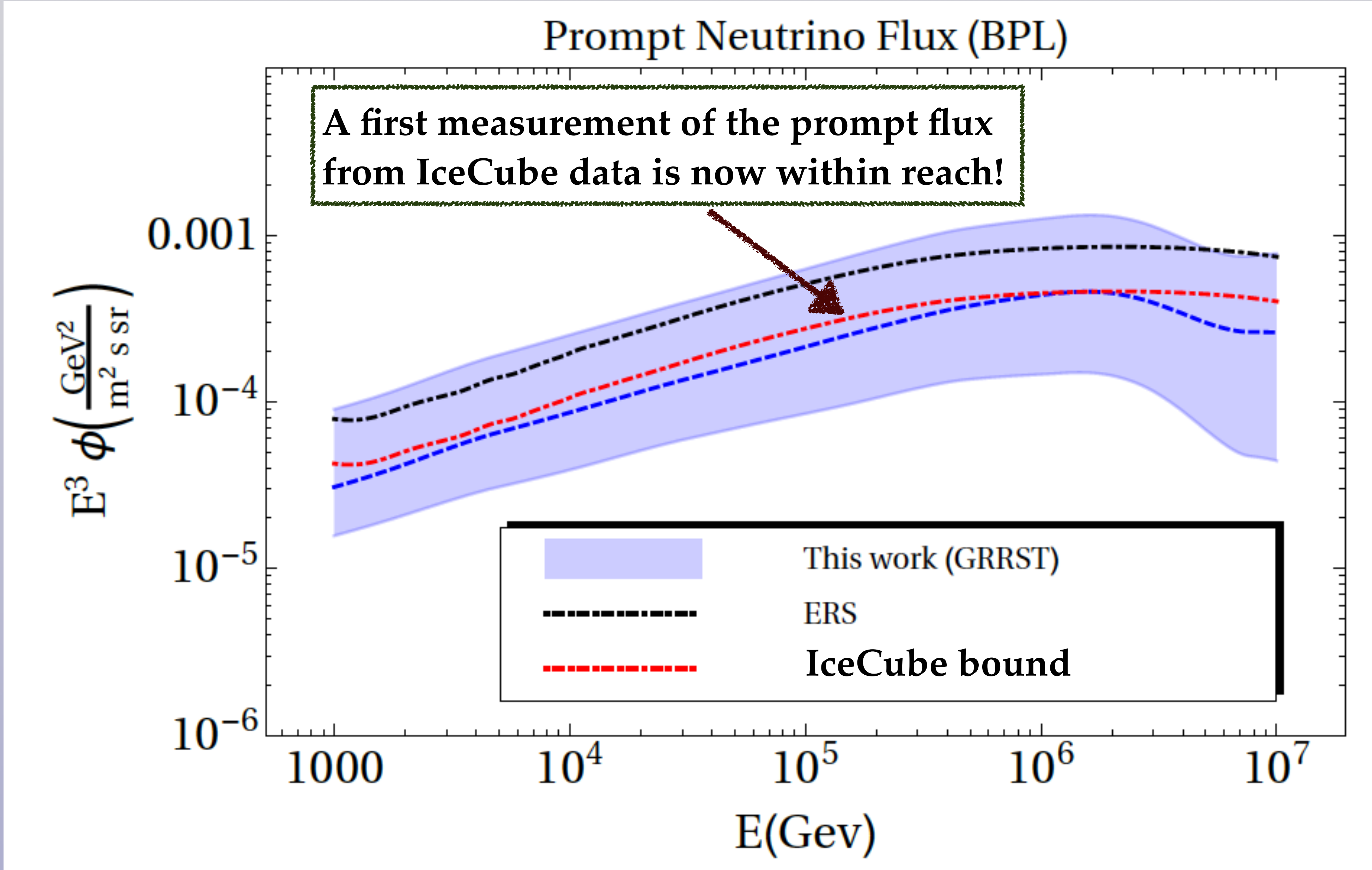


Summary & Outlook

pQCD at the LHC Run II

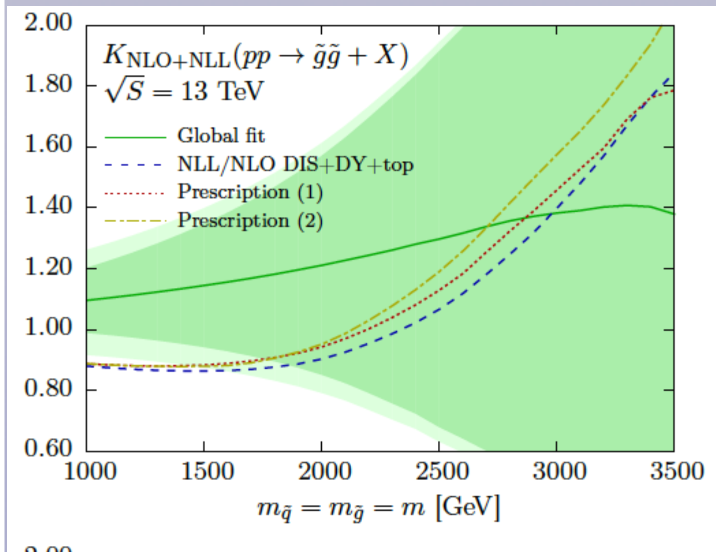
- **Recent breakthroughs** in **theoretical methods** and **experimental techniques** indicate that **precision physics is within reach at LHC Run II,** and **perturbative QCD** is central in this program

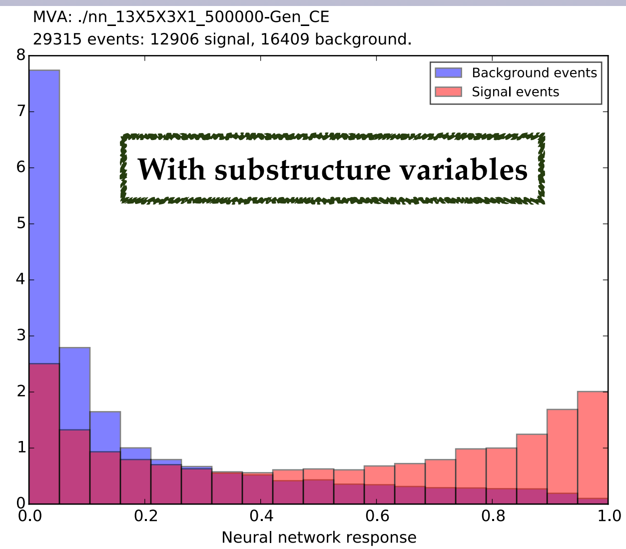
- In the **absence of clear New Physics signals**, a program of **global precision comparisons between theory and data** could be the best strategy to unveil BSM dynamics

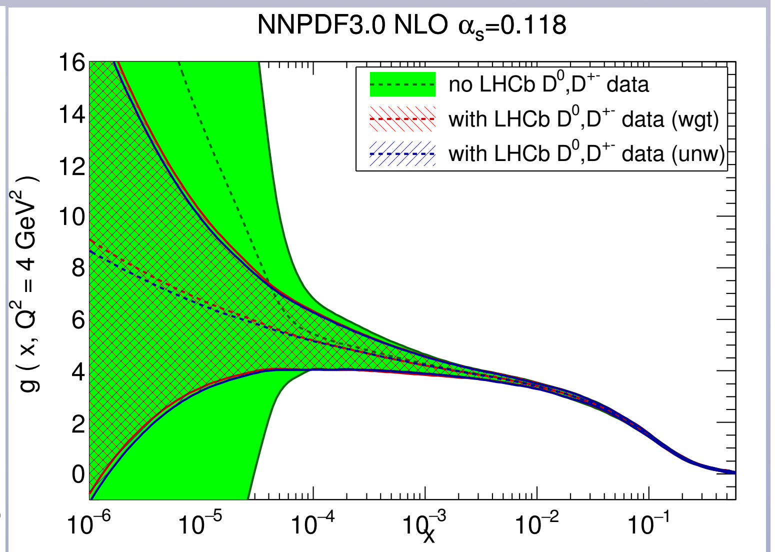
- **Parton Distributions** are crucial ingredient in many LHC processes, from **Higgs characterisation** to **high-mass squark and gluino production**

- **Jet substructure** is the key to exploit **the TeV scale at the LHC**, and some of the most exiting hints on BSM physics at Run I are based on substructure methods

- Progress in perturbative QCD can also find applicability in unexpected domains, such as **neutrino astronomy at IceCube**







pQCD at the LHC Run II

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Thanks for your attention!