Models and Methods for Beyond Standard Model Physics at colliders

Lectures for the Ph.D. Program in Physics, XXXVI Cycle

13/04/2021

Vieri Candelise
University of Trieste

Chapter I-II

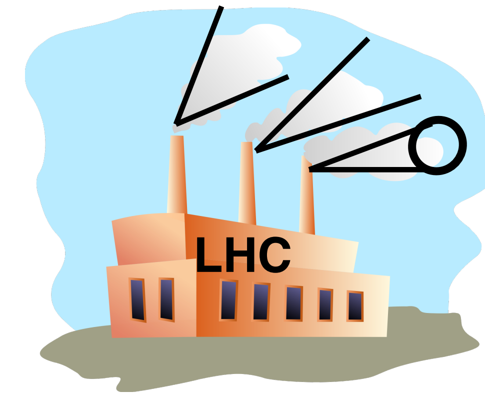
Modern SM phenomenology and measurements

[duration: 2h]

SM Physics @ LHC: Jets

LHC is the most efficient Jet Factory of the world!

Jets are the experimental signatures of quarks and gluons



what can we do with jets?

***pure*-QCD**

- Explore the pQCD in brand new energy regions
- Constrain the PDFs
- Probe and measure α_S
- Access the dynamics of heavy flavors
- Compare to NLO/NNLO predictions
- Tune Monte Carlo Generators

… much more!

***not-purely*-QCD**

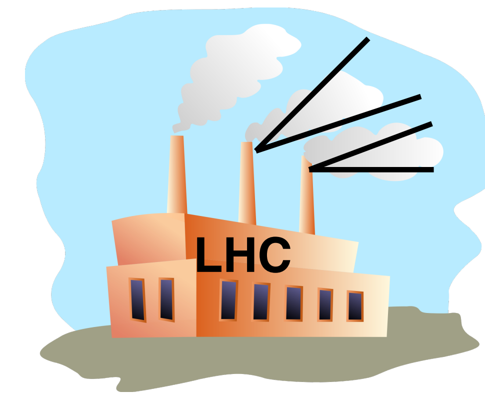
- Extensive test of the Standard Model: V+Jets, H+Jets, V+heavy flavors…
- Test the SM at NNLO precision
- Beyond the Standard Model:
  - dijet resonances
  - monojet & dark matter
  - new strongly produced states
  - hadronic resonances

… much more!

SM Physics @ LHC: Jets

LHC is the most efficient Jet Factory of the world!

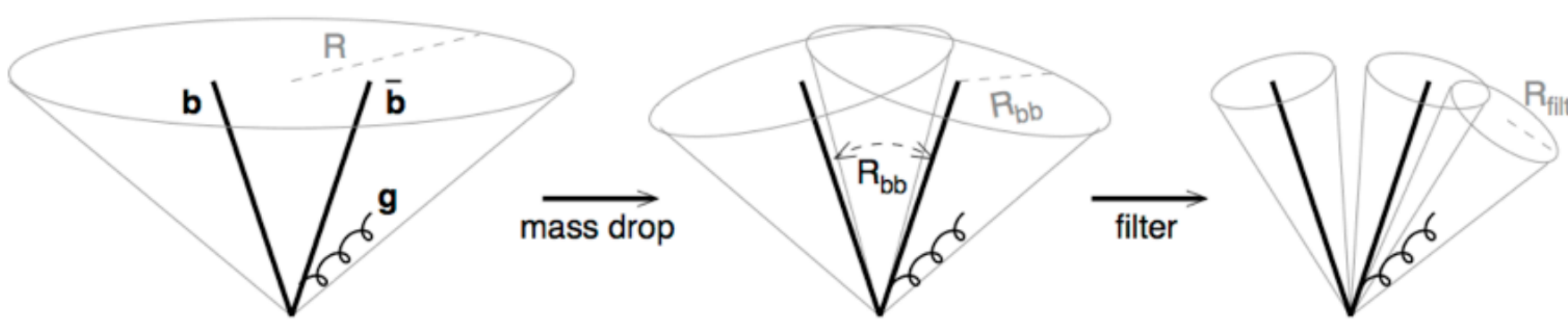
Jets are the experimental signatures of quarks and gluons



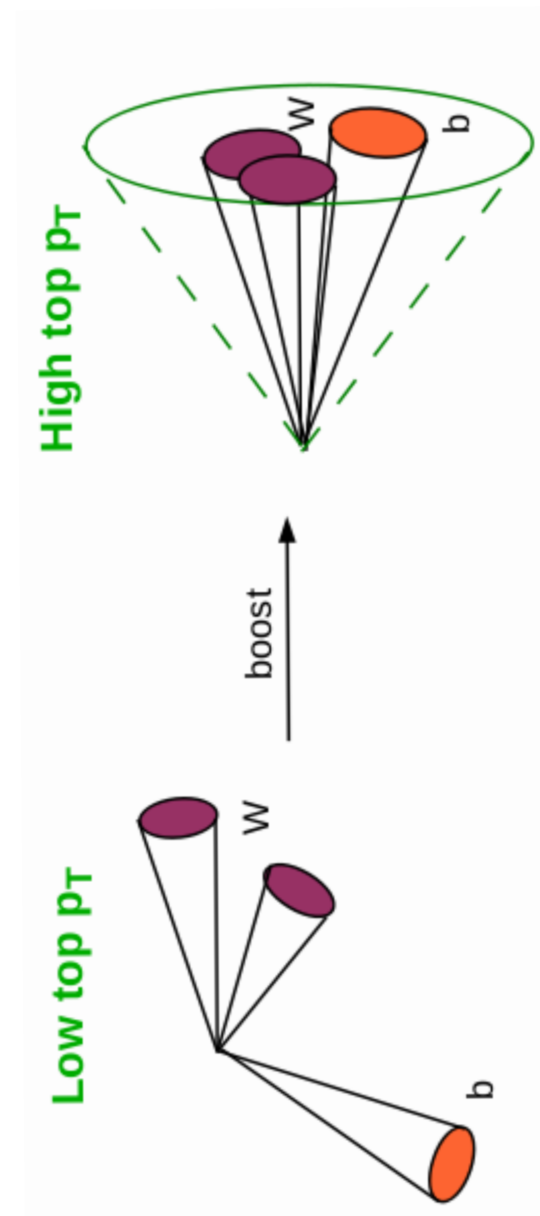
what can we do with jets?

explore substructure

- exploring the inner structure of jets



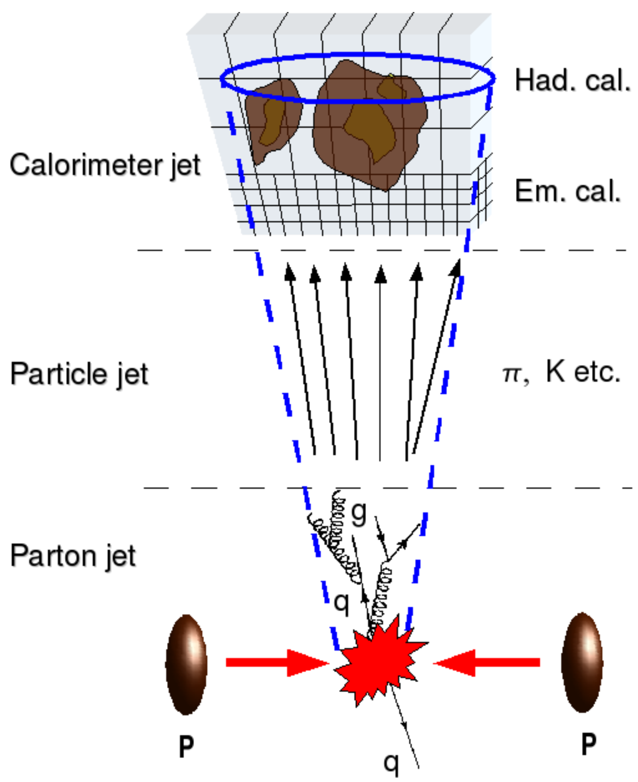
- highly boosted bosons reconstructed as jets
- using sub-jets as a powerful tool for measurements such as *H(bb) - jets*, *Z(bb) - jets*, *top-jets*…



SM Physics @ LHC: Jets

ATLAS

topological calorimeter-cell **clusters**



anti-k$_T$ clustering algorithm (infrared and collinear safe)

ATLAS/CMS: R=0.4 (Run II)

LHCb: R=0.5

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

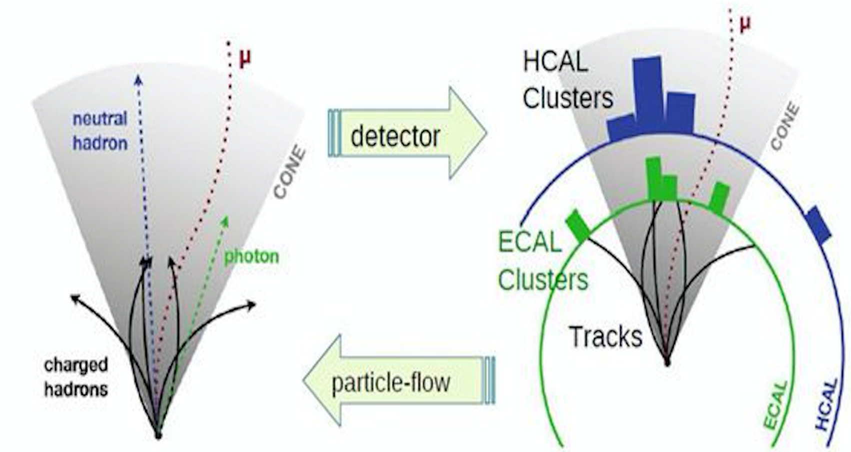
$$d_{iB} = k_{ti}^{2p},$$

← →

↓

CMS

particle-flow



uses all the sub-detectors information to reconstruct objects

LHCb

LHCb acceptance forward direction

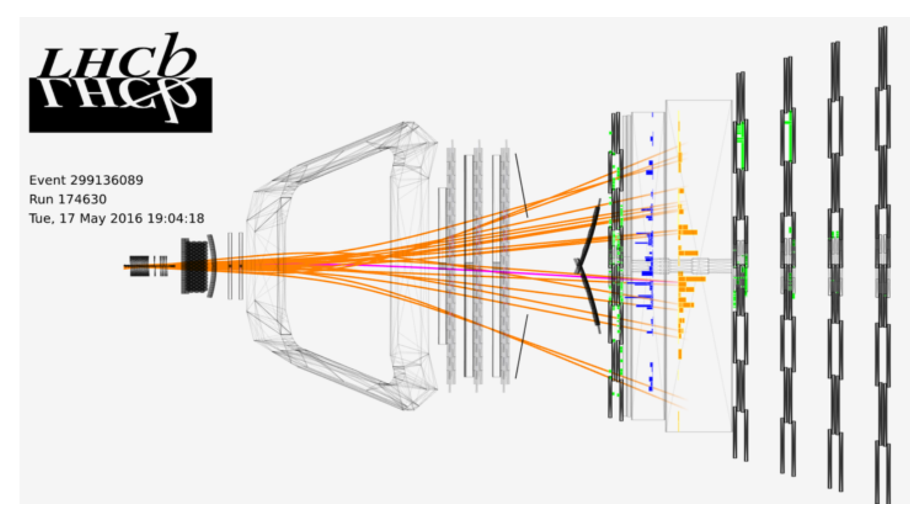
- **Particle Flow**

calo cell E$_T$~10 GeV saturation

↓

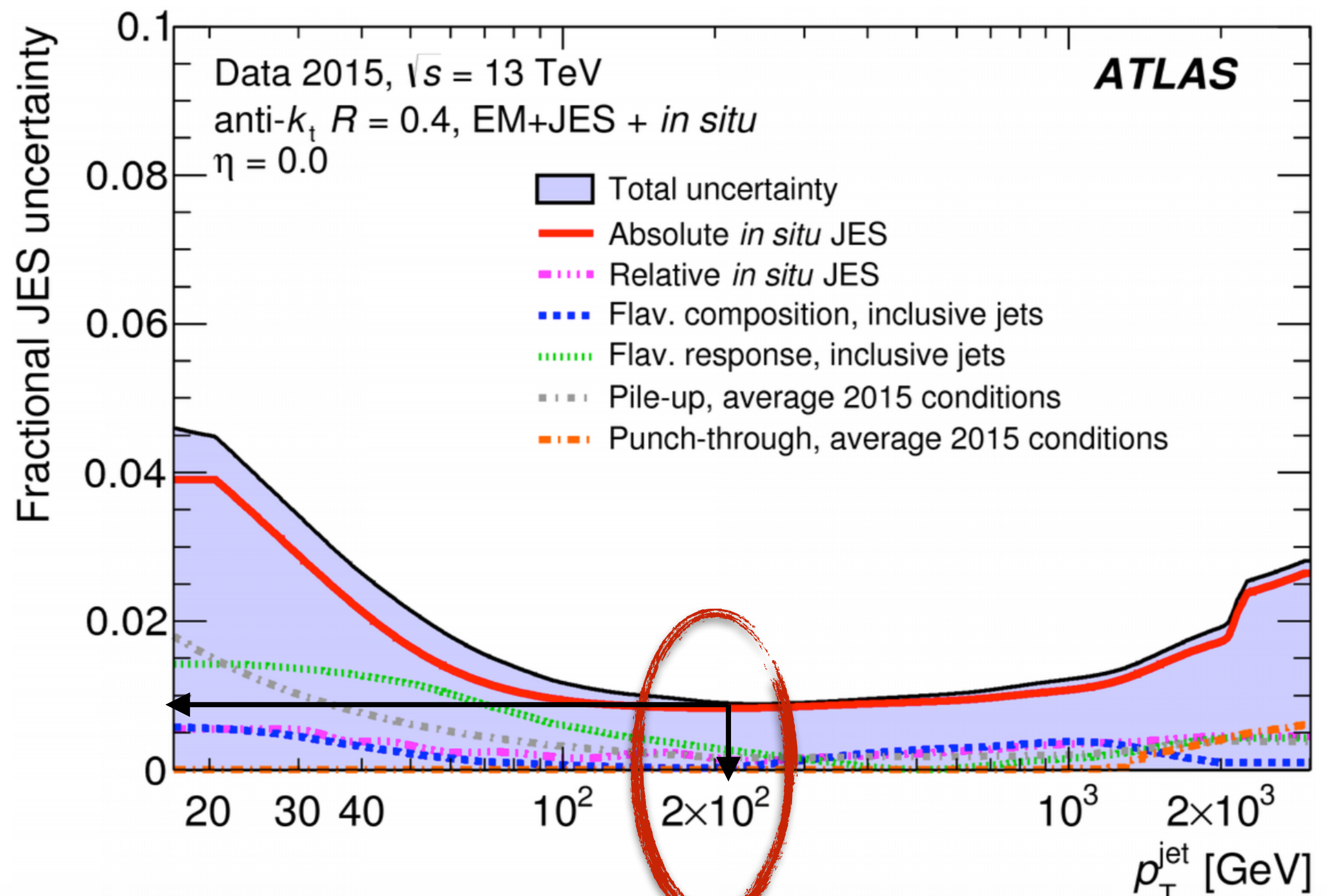
use the precise tracking information → use particles! (Λ,Ks,π,..)

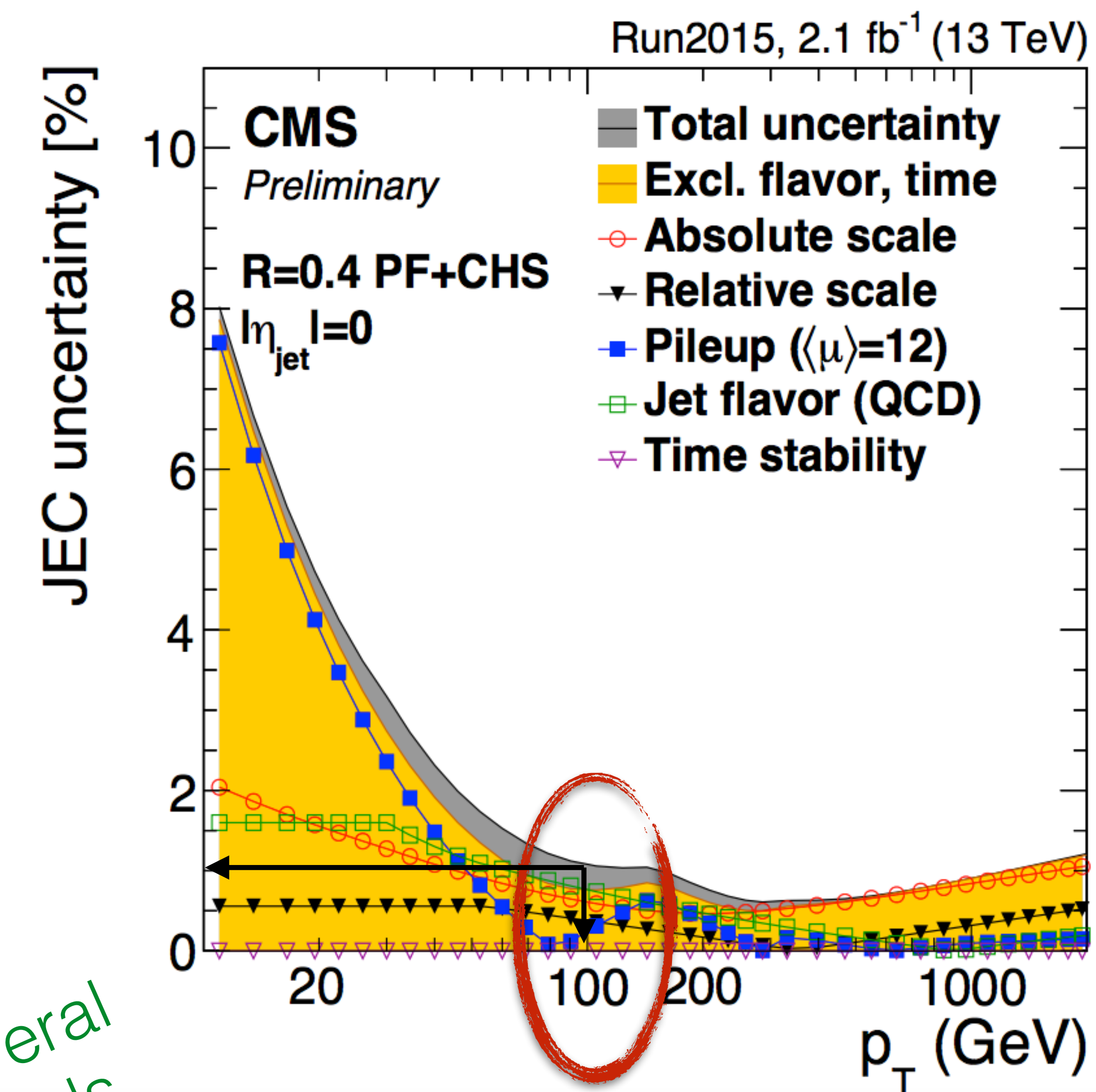
$(2 < \eta < 5)$



SM Physics @ LHC: Jets

ATLAS ← both deliver jet energy corrections → **CMS**





Correct for

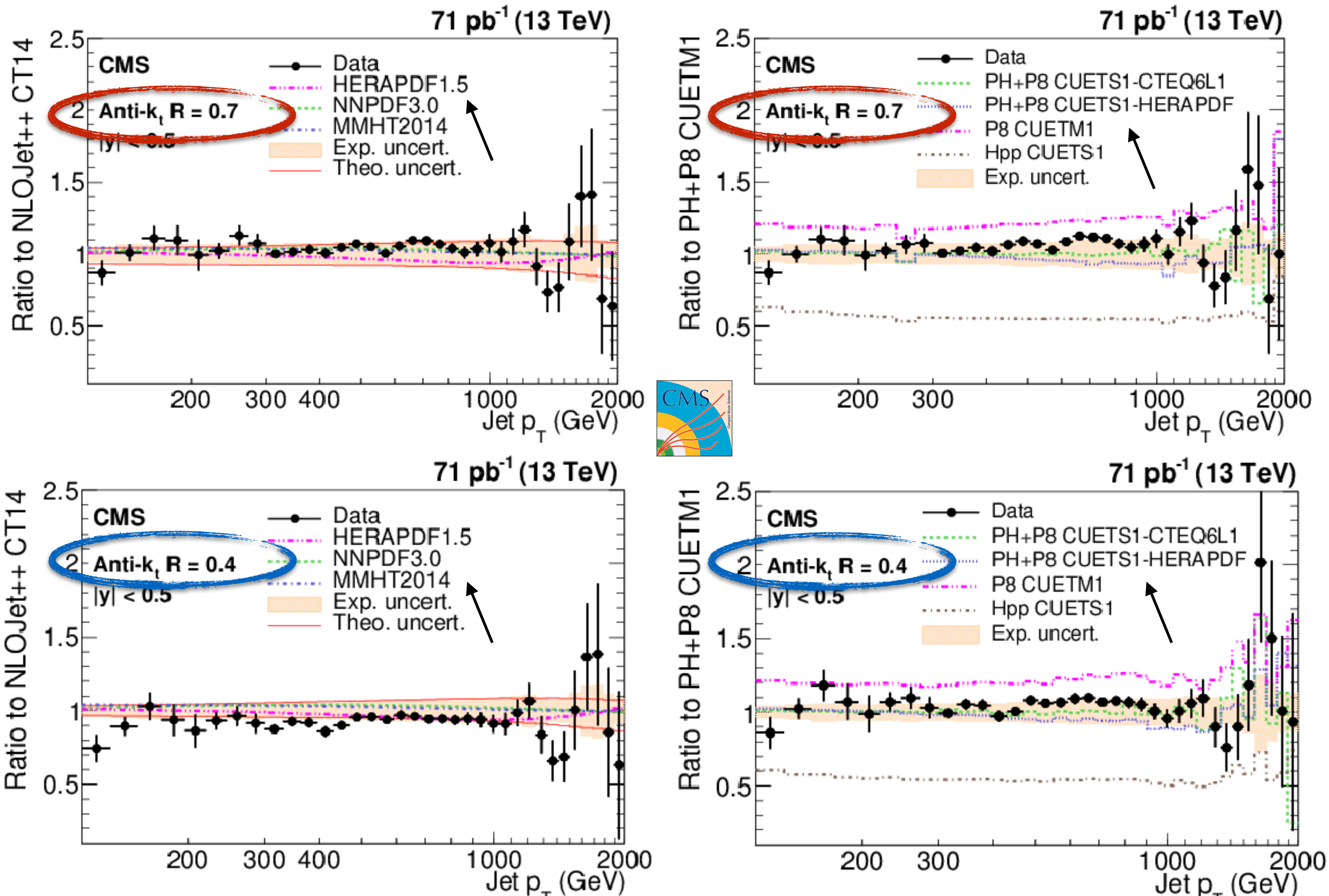
- Pile-Up
- Jet Flavor Composition
- Absolute/Relative Scale

thanks to several in-situ methods

Less than 2% in the region $p_T > 100$ GeV!

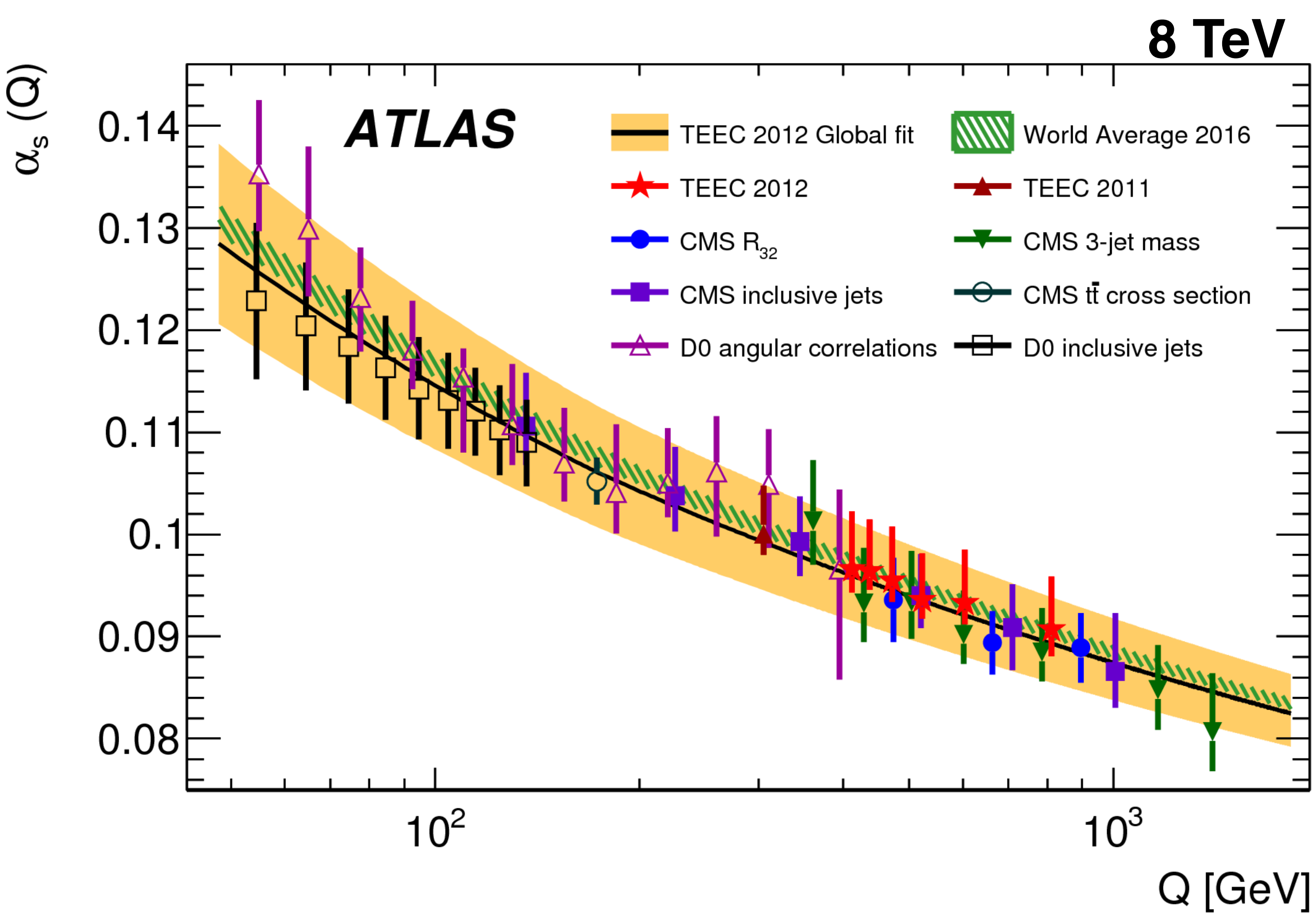
LHCb: ~10-15% for p_T of 10–100 GeV

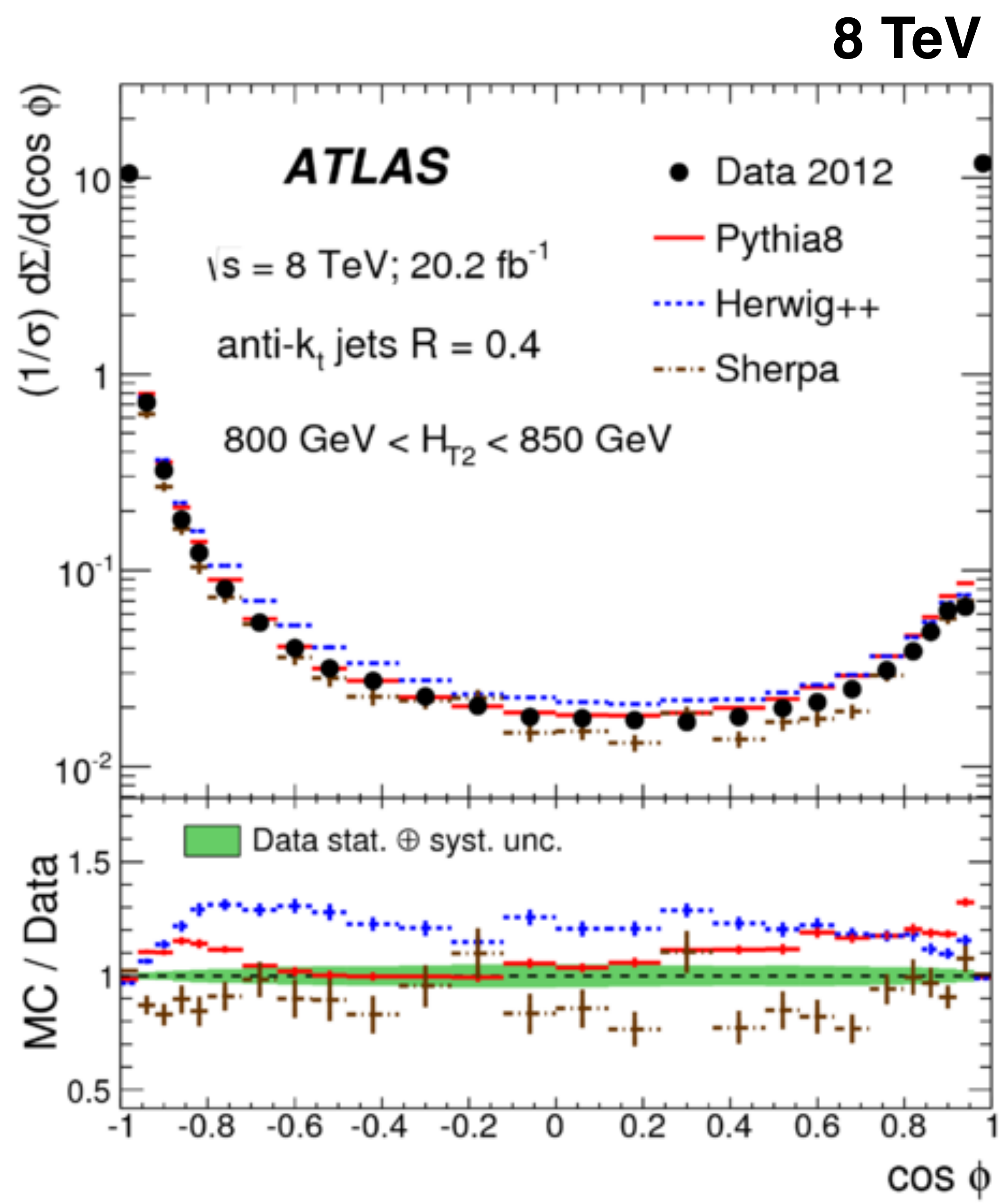
Inclusive jet differential cross section at 13 TeV



Determination of the strong coupling α_S

- p_T>100GeV, $|\eta|$<2.5, anti k_T - R=0.4
- energy-energy correlations and their associated asymmetries in multi-jet event
- bins of the scalar sum of the transverse momenta of the two leading jets
- fitted to NLO calculations

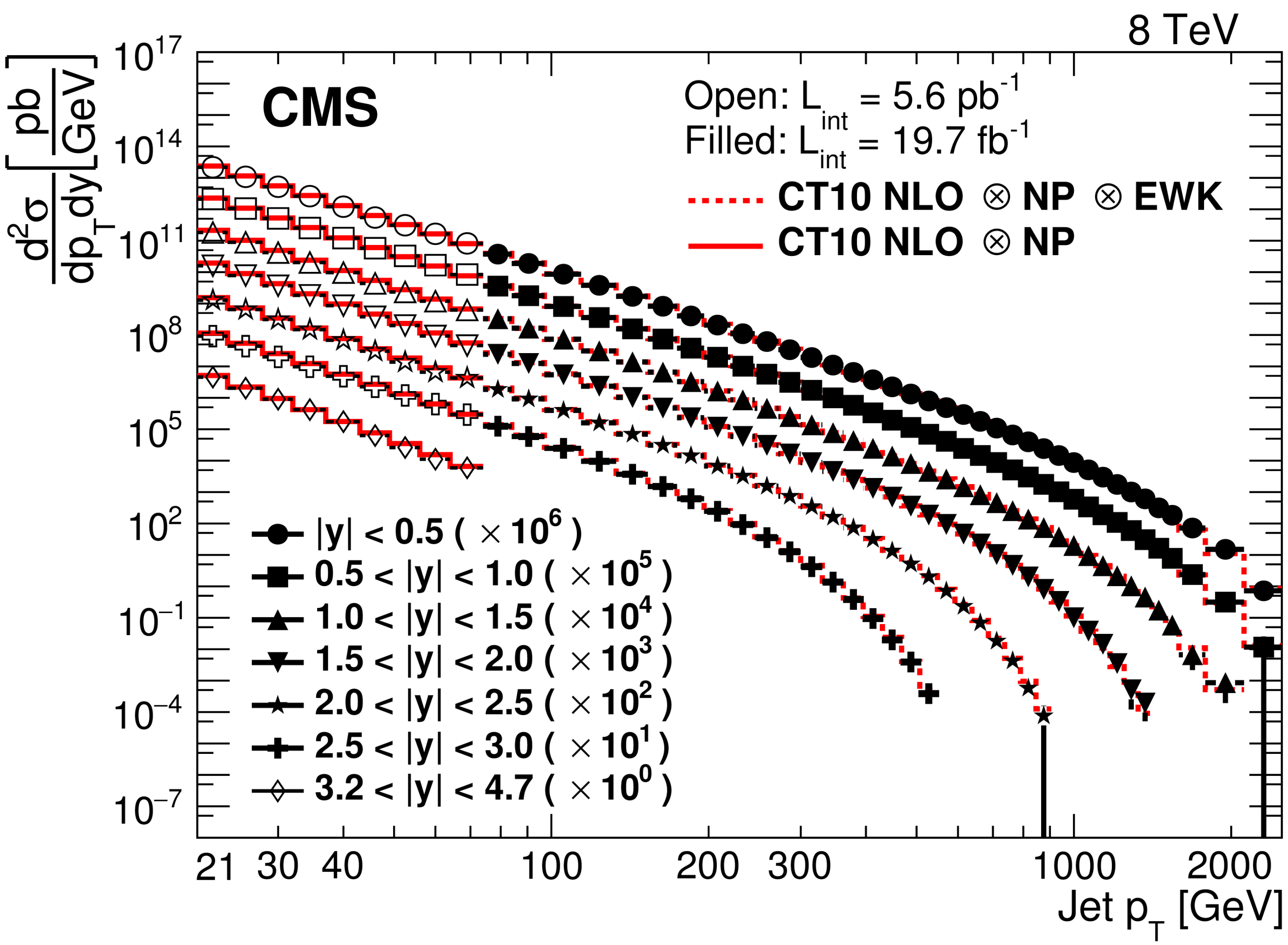


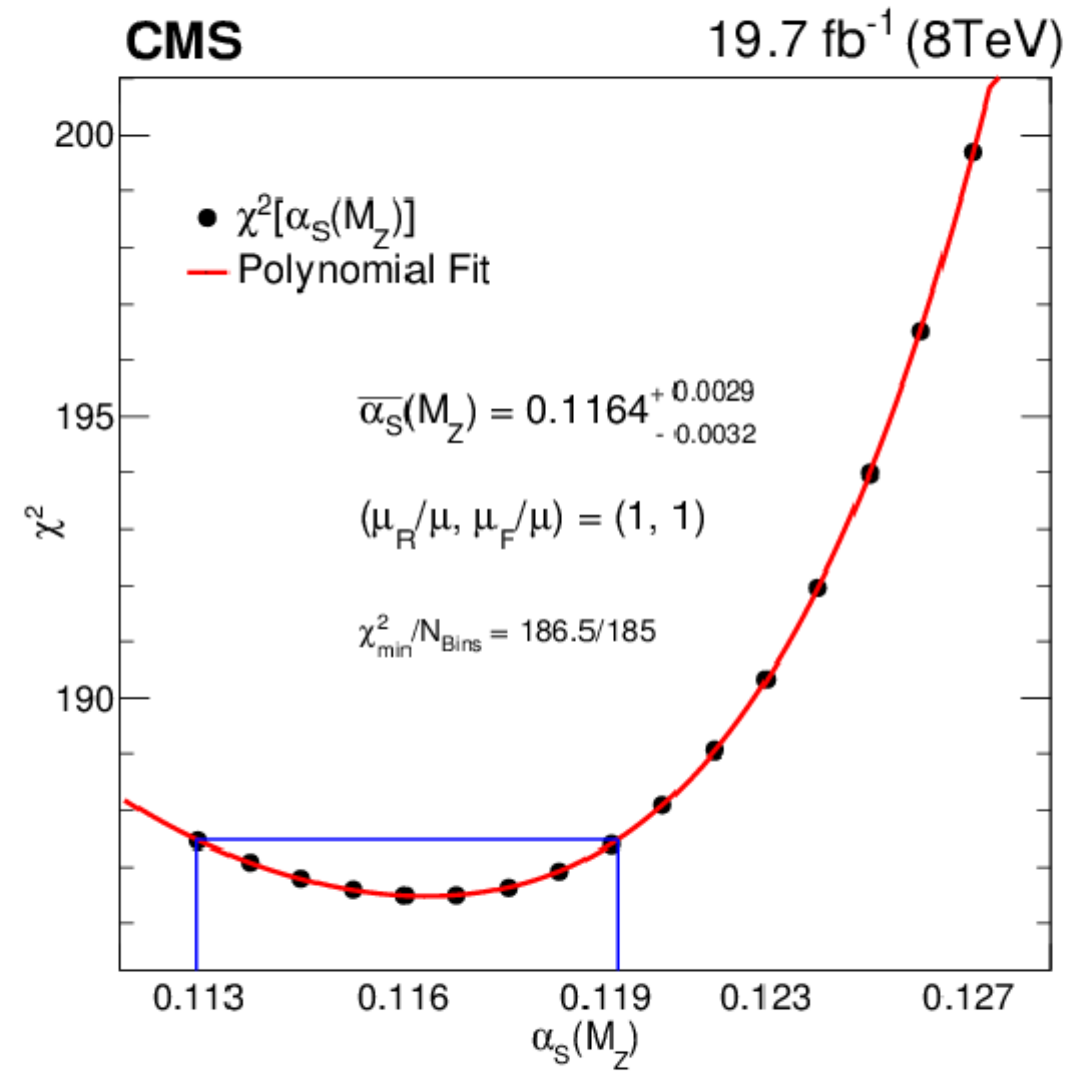


$$\alpha_S = 0.1162 \pm 0.0011(exp.) + 0.0084 - 0.0070(th.)$$

Determination of the strong coupling α_S

- coupling extracted from double-diff **σ** at 8 TeV
- measured jets up to 2.5 TeV and $|y|<4.7$



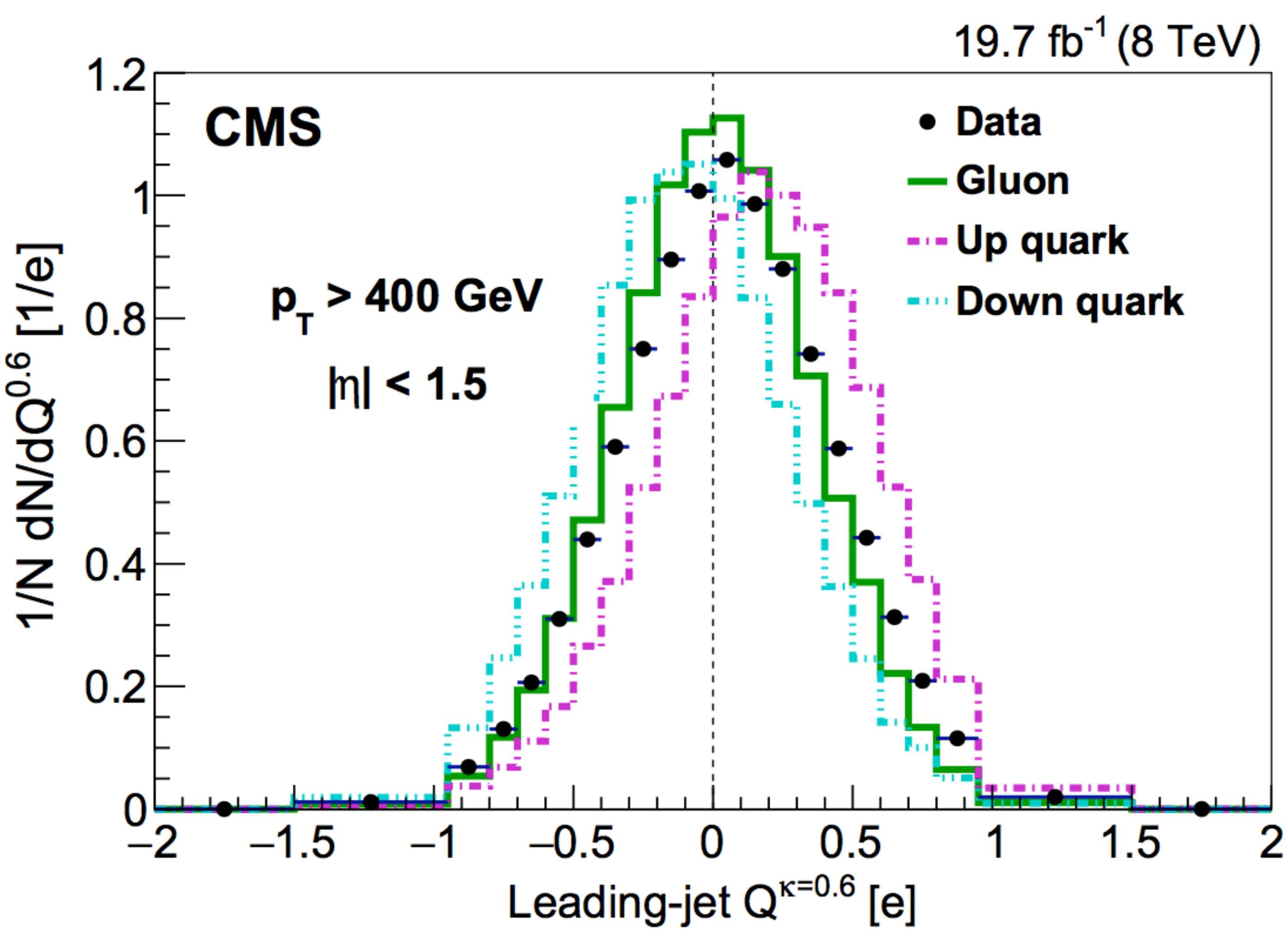


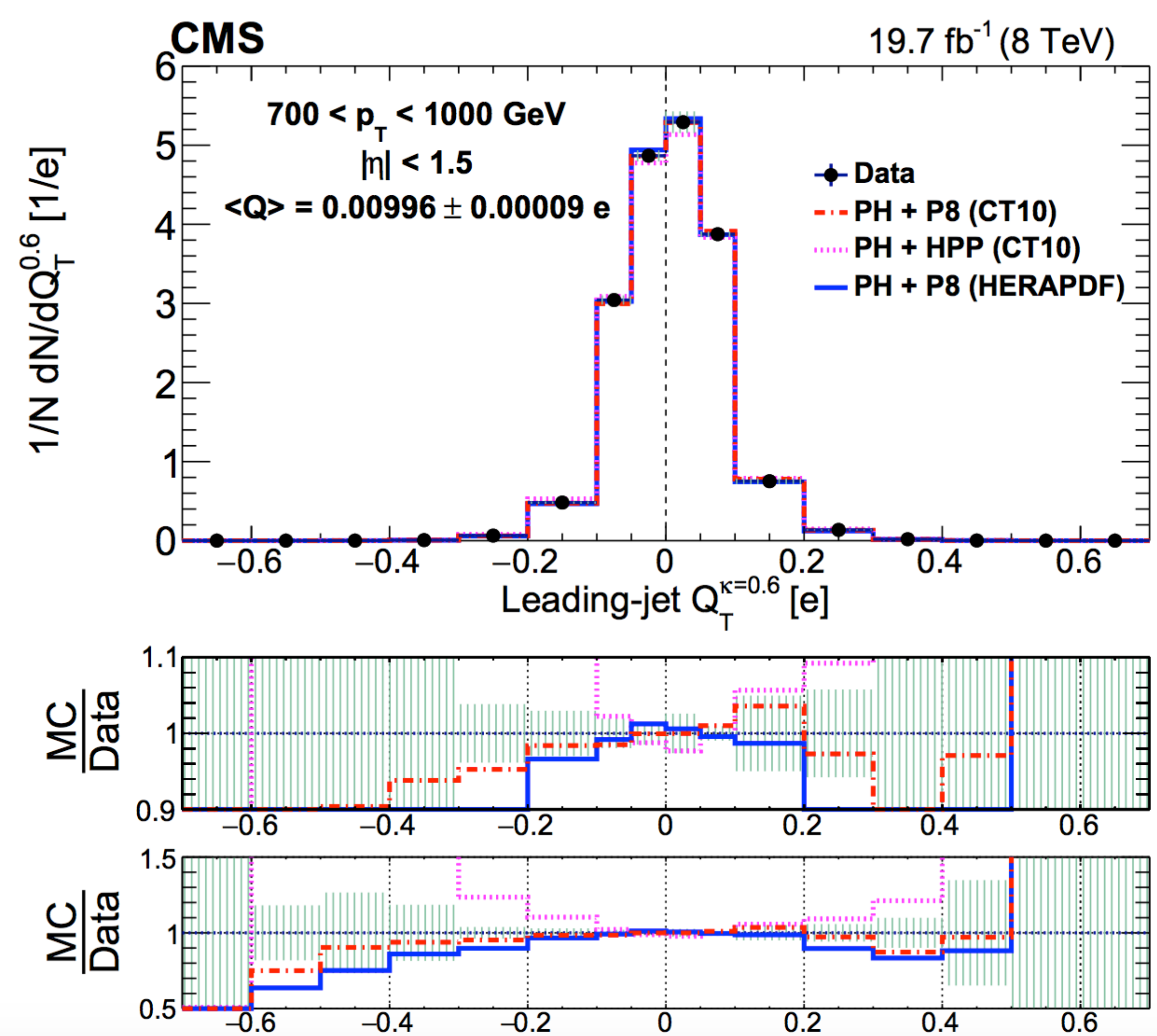
$$\alpha_S = 0.1164^{+0.0014}_{-0.0015}(exp.)^{+0.0025}_{-0.0029}(NP)^{+0.0053}_{-0.0028}(scale)$$

Measurement of the jet charge

access the initiated parton charge

$$Q^j = \frac{1}{p_T^j} \sum_k Q_k (p_T^k)^j$$



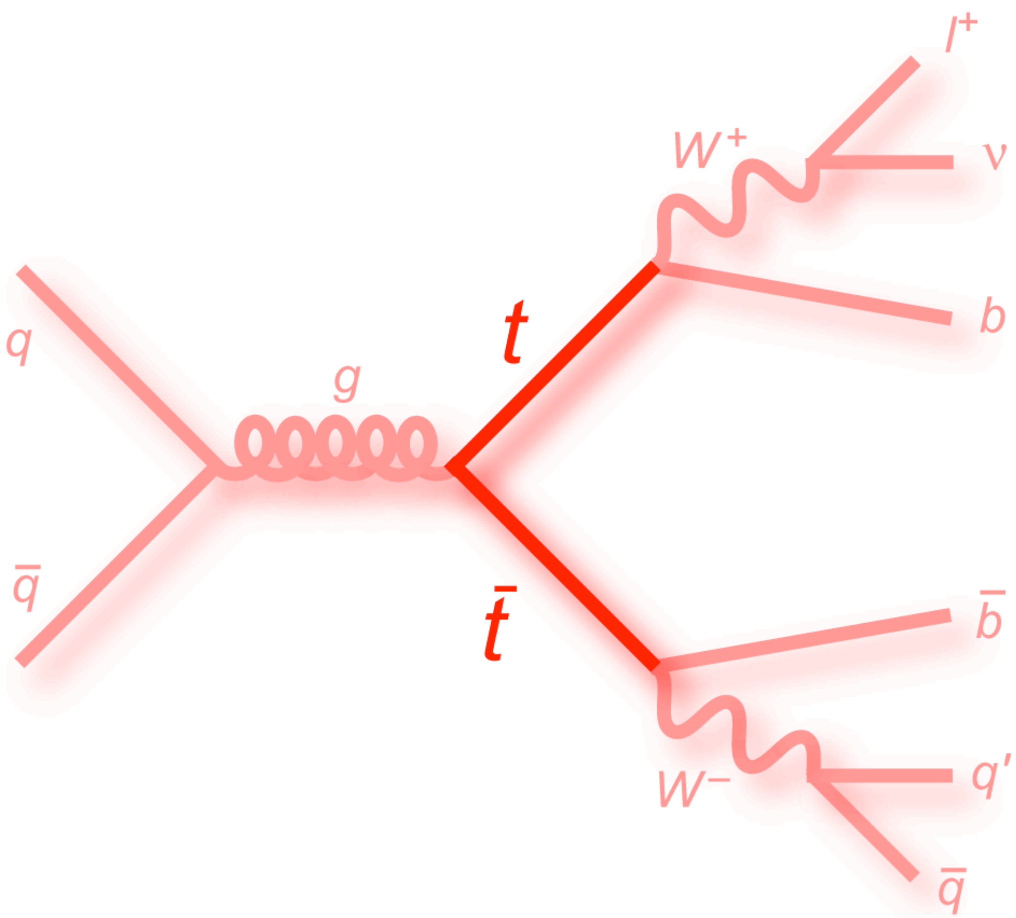


detector level jet charge

0,1,-1 = *g,u,d* quarks

unfolded jet charge, p_T> 400 GeV

SM Physics @ LHC: Top



key features

$|V_{tb}|\sim 1 \longrightarrow BR(t \longrightarrow Wb) \sim 100\%$

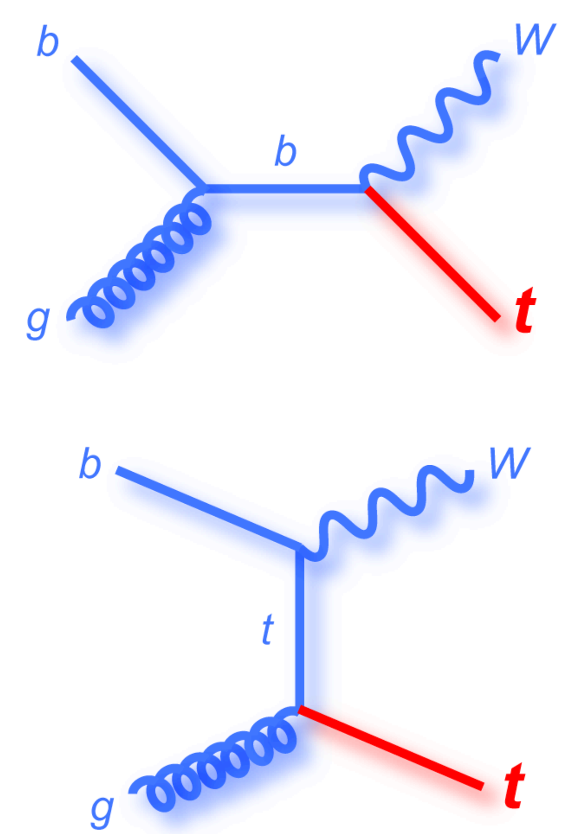
participate to all interactions

heaviest particle in the SM

$m_t \sim 175$ GeV

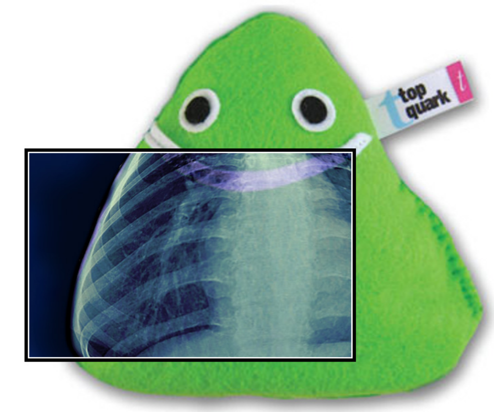
weights close to a Tungsten atom!

- highest yukawa coupling to H, most sensitive to EW symmetry breaking
- decays before hadronizing (lifetime~10^{-25} sec)
- m_t sensitive to the Universe destiny
- the top is a special particle



single-top also measurable at LHC in the s- t- and Wt- channels

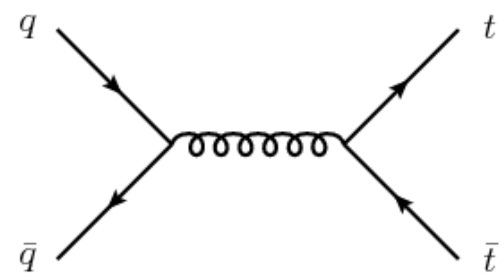
SM Physics @ LHC: Top



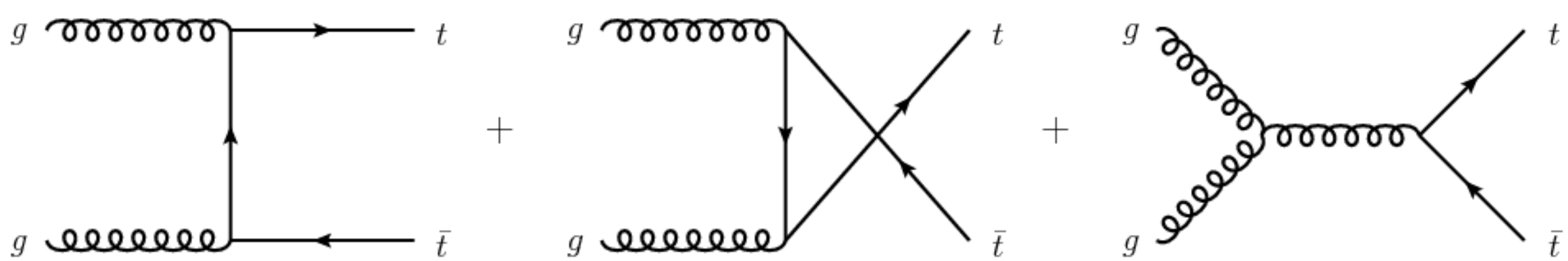
$t\bar{t}$ dominated by gluon fusion (qq/gg=10%/90%) at LHC

LO diagrams @ LHC

top Factory:
High rate of $t\bar{t}$ at LHC
(30m only in 2016)

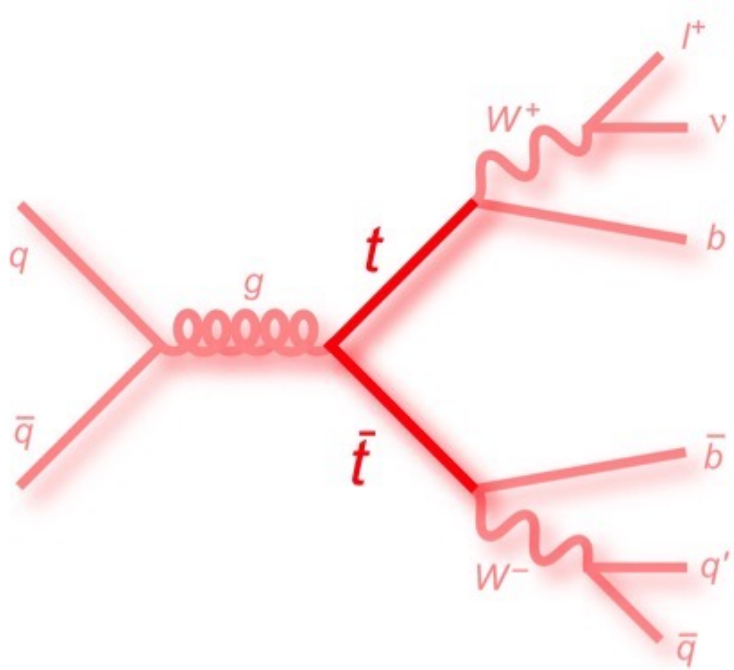


vast phenomenology: standard model, QCD calculation and new physics searches



calculations are challenging: NNLO/NNLL corrections important

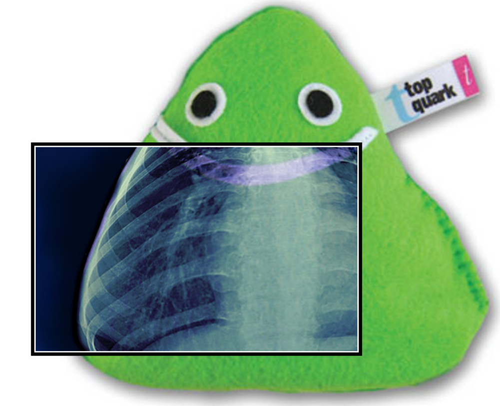
final states: • fully hadronic • dilepton • lepton+jets

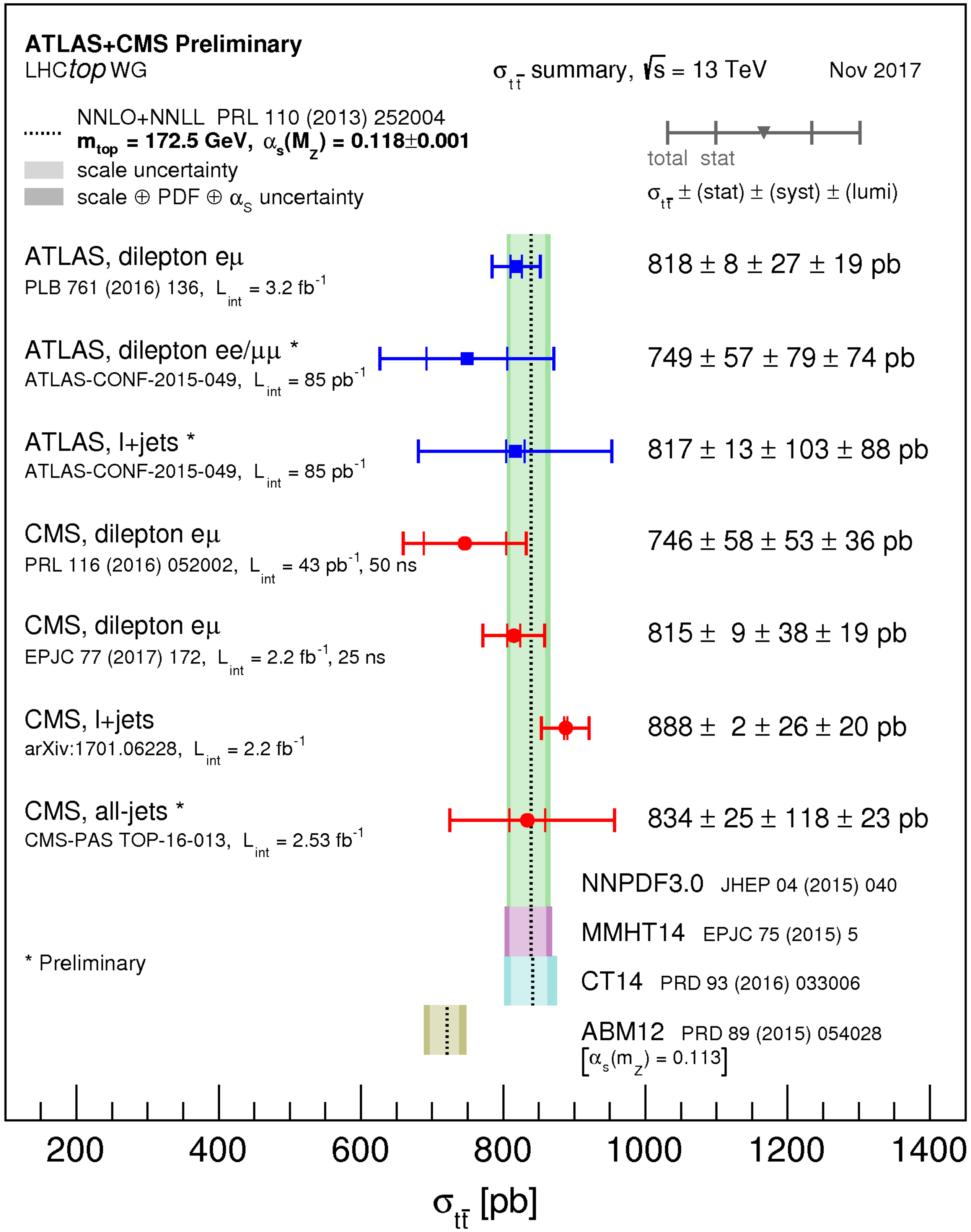


Present times top quarks general news

- $t\bar{t}$ production cross section @ 13 TV measured at ~5.5%(beyond NNLO+NNLL precision!)
- Jet substructure and shape observables @ 13 TeV
- first measurement of the forward production (LHCb)

State-of-Art of $t\bar{t}$ cross sections





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/

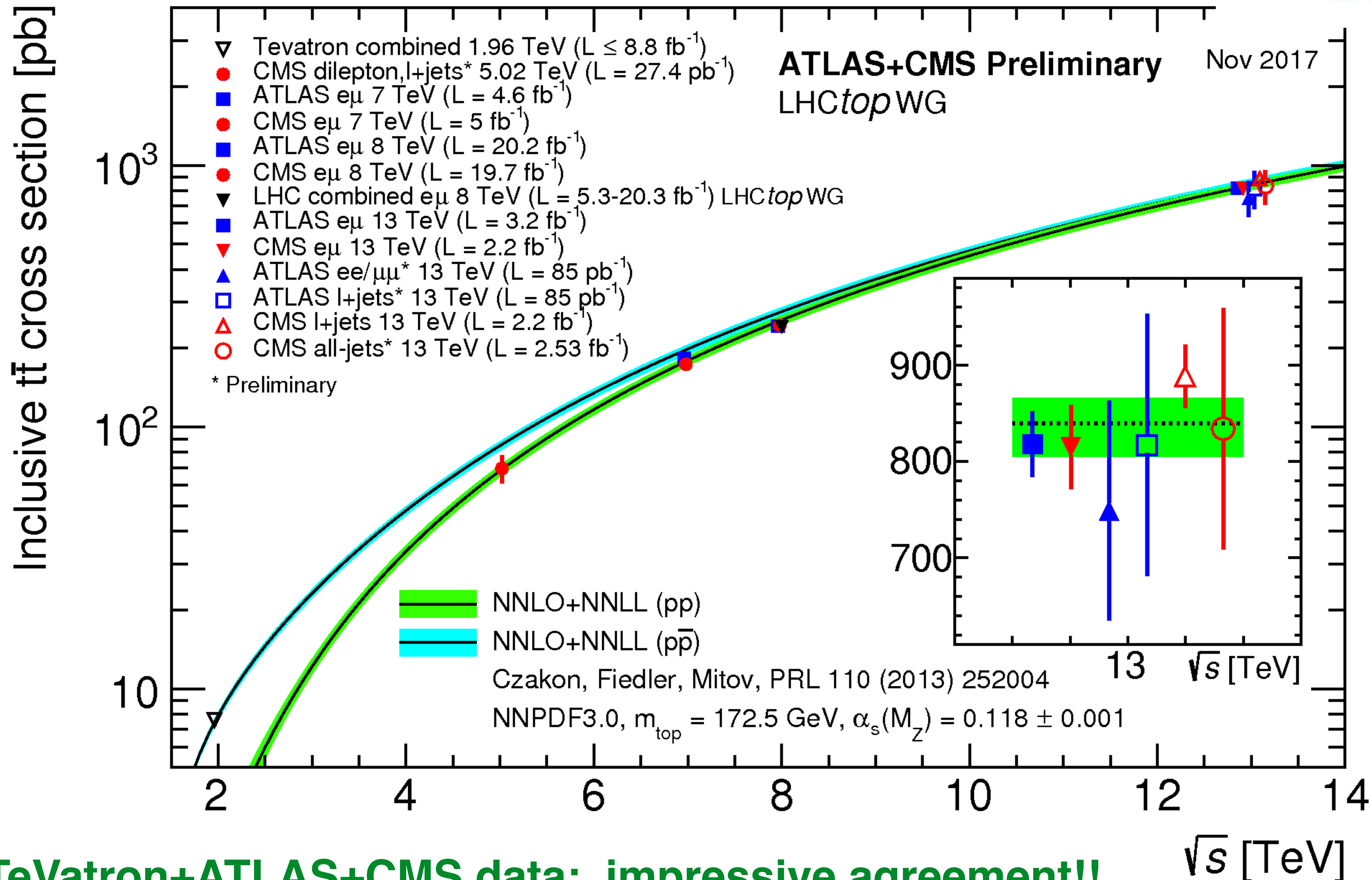
tt production cross section grand summary at 13 TeV for ATLAS+CMS

Most precise measurements from *eμ* at 7+8 TeV, and *l*+jets at 13 TeV

Individual analyses with precision of 3-4%

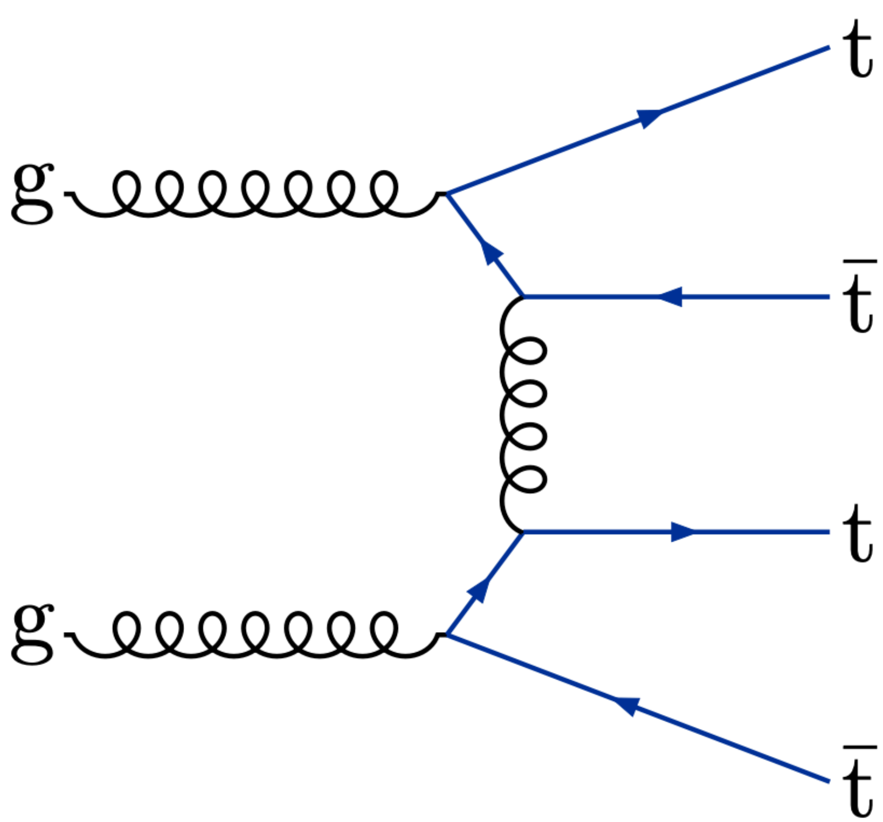
$t\bar{t}$ cross section and energy

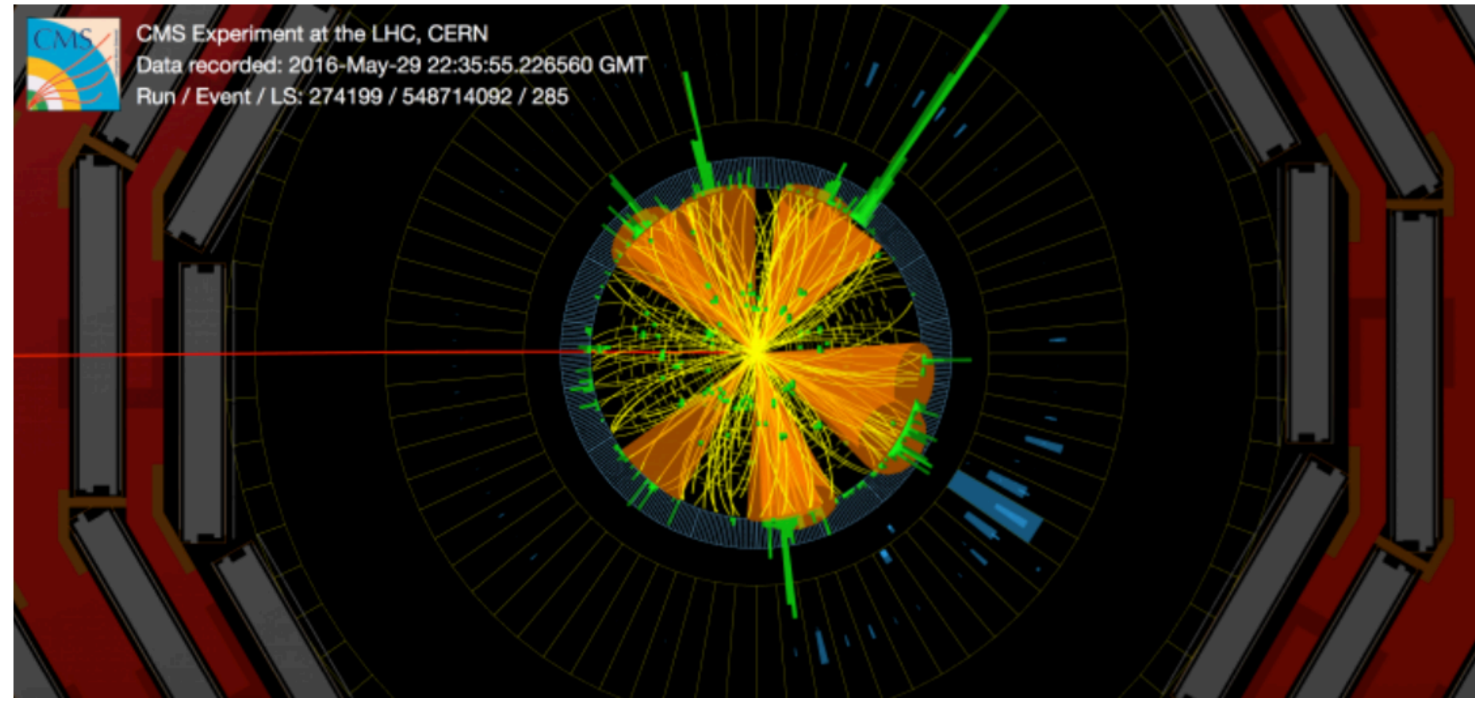
Measured $t\bar{t}$ cross section versus $\sqrt{s}$



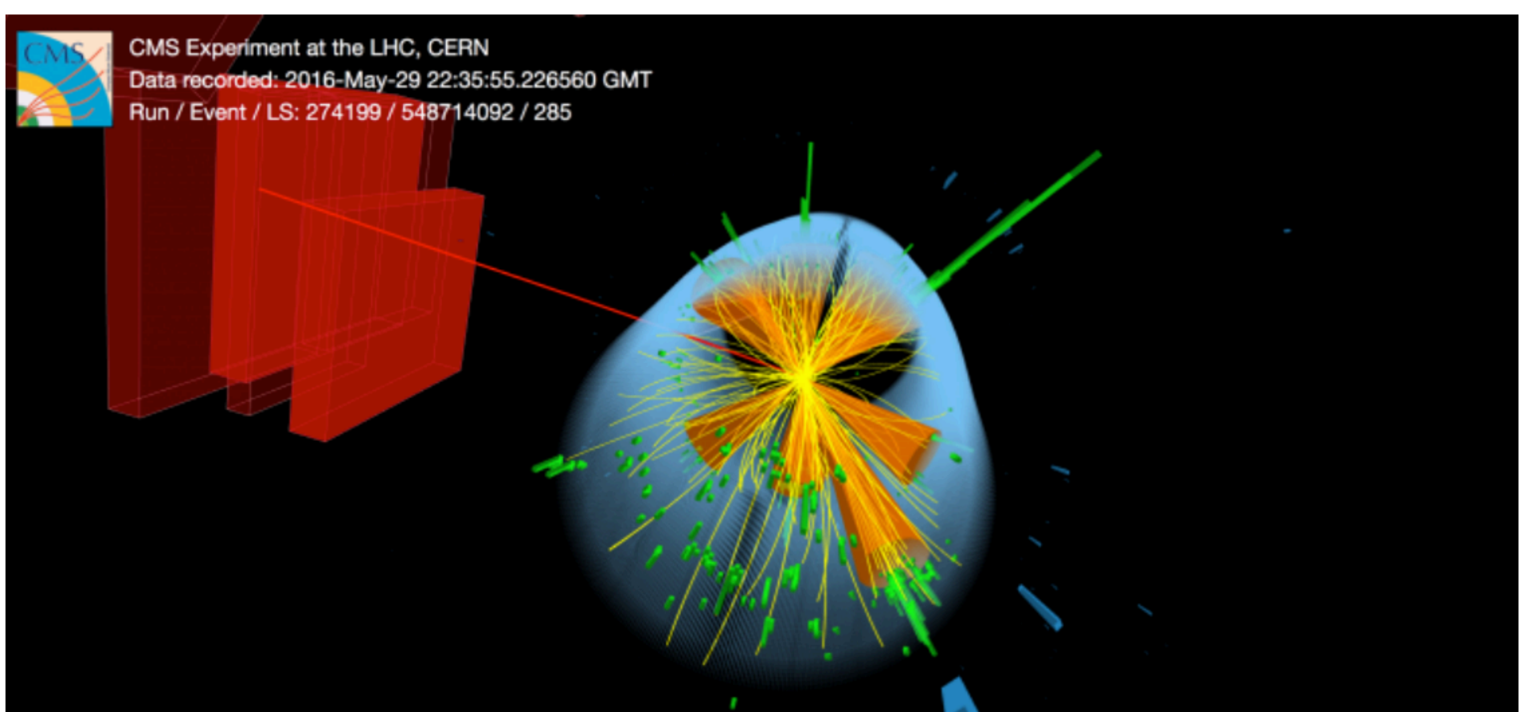
TeVatron+ATLAS+CMS data: impressive agreement!!

On the edge of the top: 4tops final states





$$\sigma(pp \to t\bar{t}t\bar{t}) = 12.0^{+2.2}_{-2.5}\,\text{fb}$$

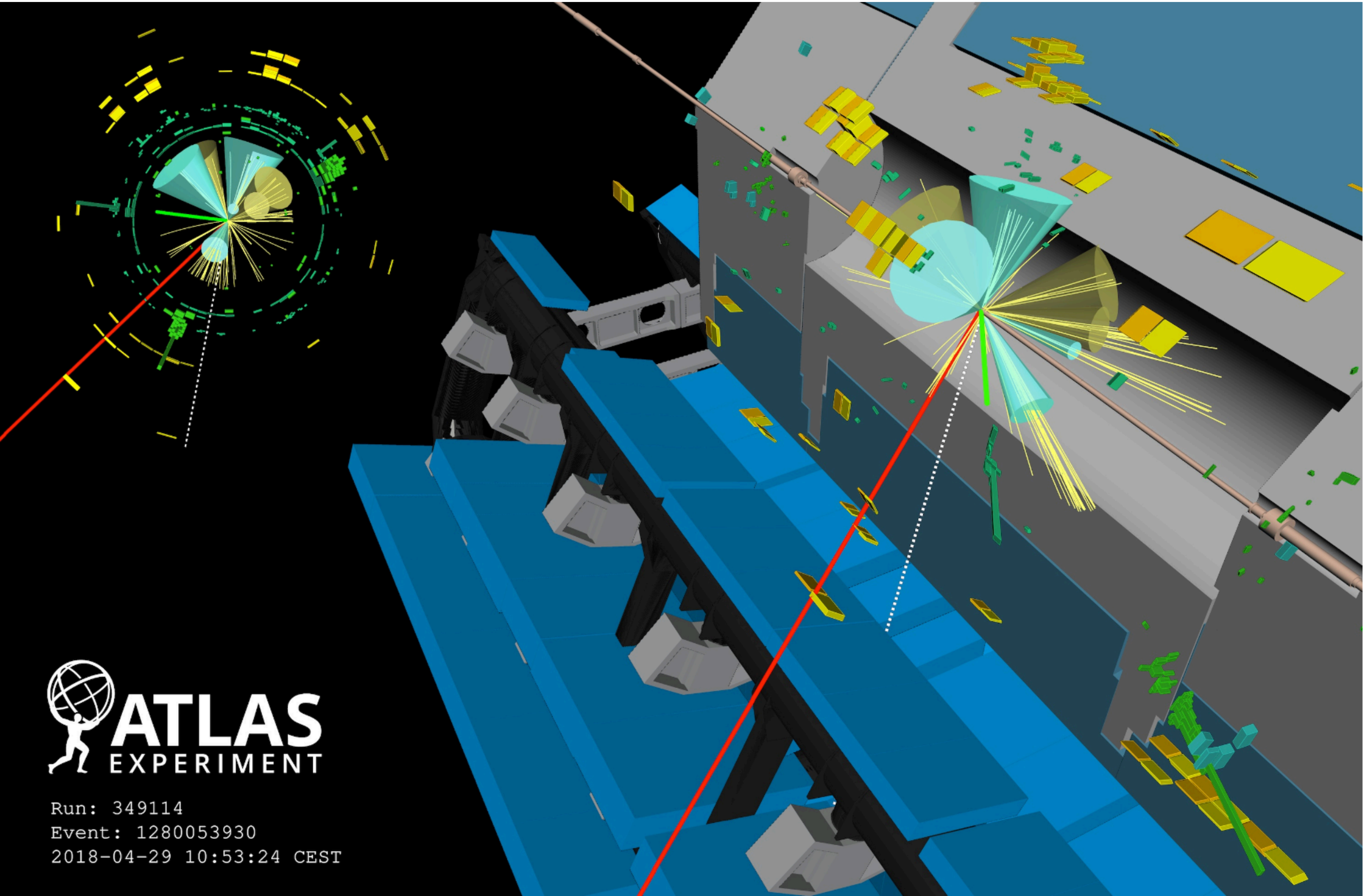


constrain the Yukawa coupling of the top quark to the Higgs boson

challenging: WWWWbbbb

4b + 4lep + missing energy

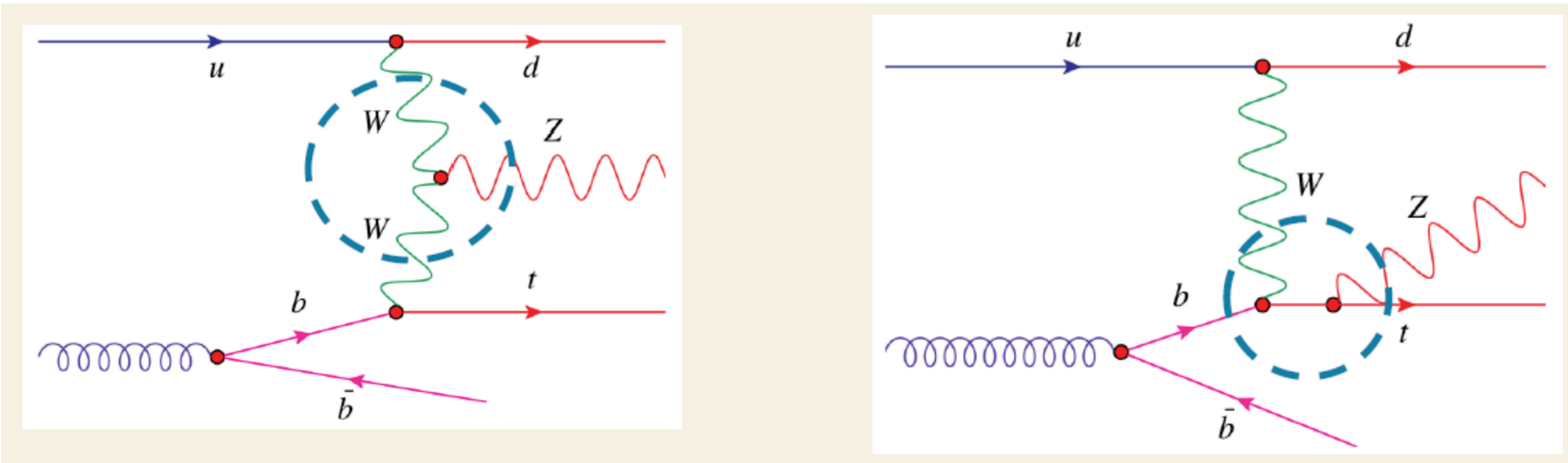
On the edge of the top: 4tops final states



On the edge of the top: tZq and tγq

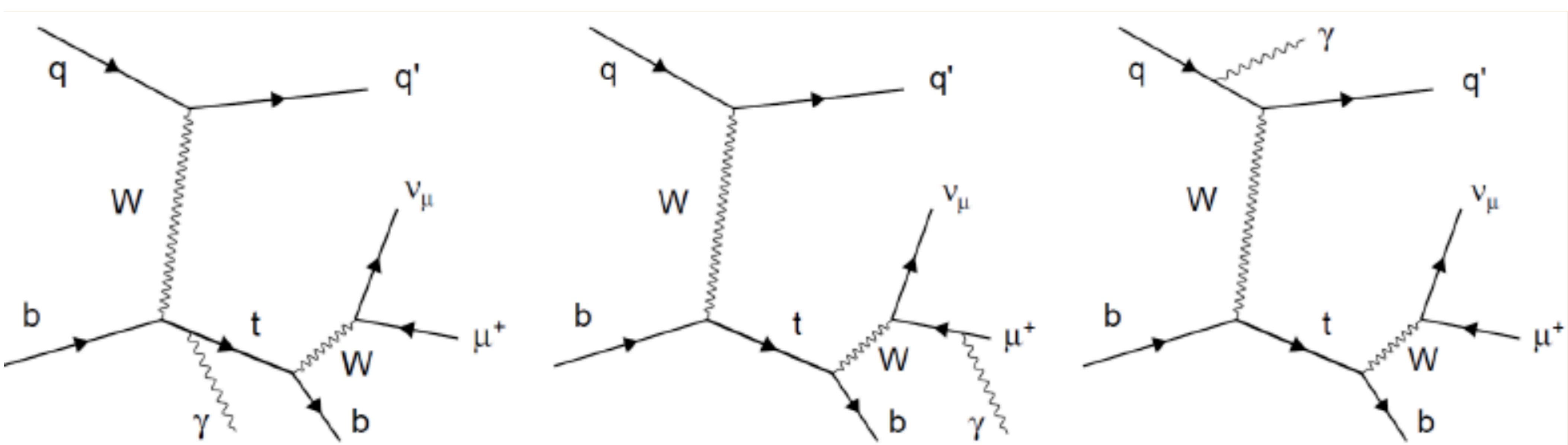
σ(pp→tZq→tℓ+ℓ−q)= =111 ± 13 (stat) +11(syst) fb

SM expectation 94.2±3.1 fb



σ(pp→tγj)B(t→μνb)= 115 ± 17 (stat) ± 30 (syst) fb

SM expectation 81±4 fb

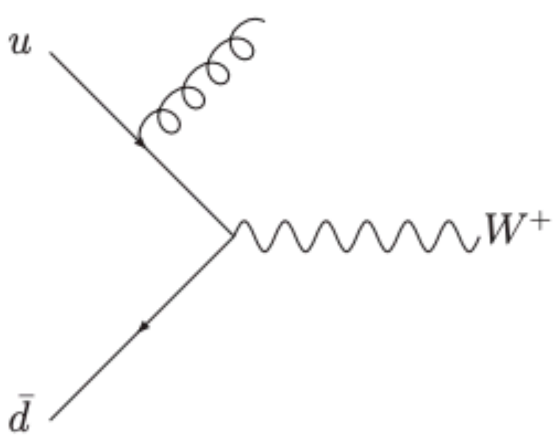


ultra-rare SM processes!!

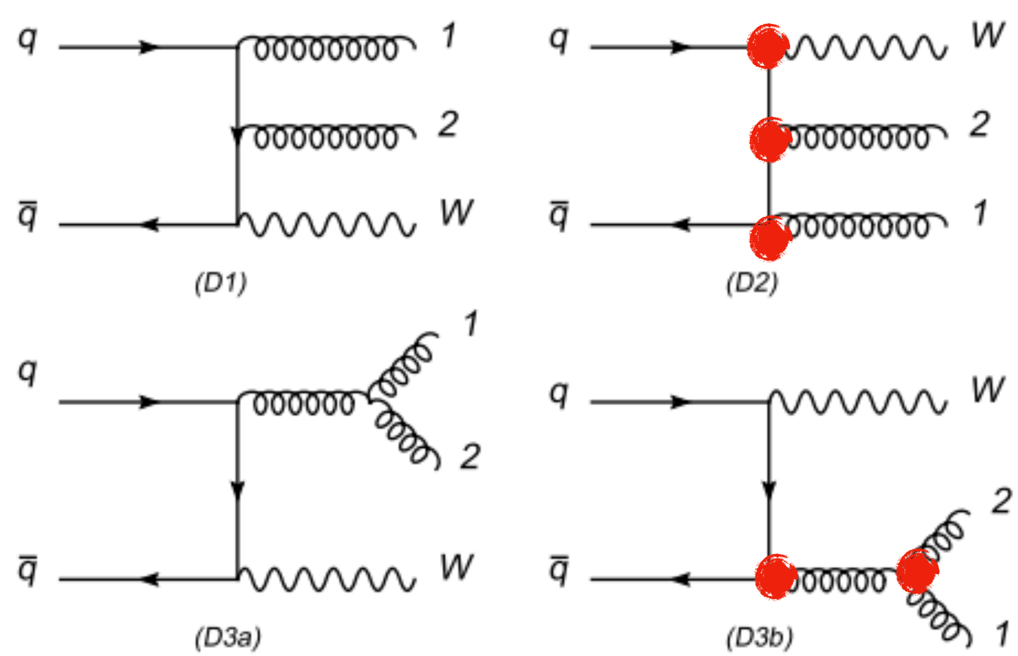
SM Physics @ LHC: DY

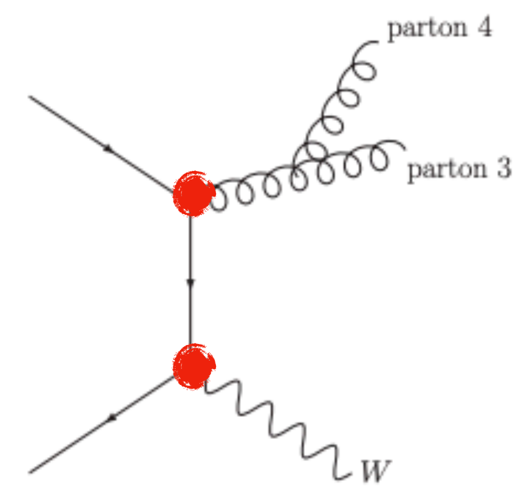
Electroweak Physics: W and Z production

Thousands of W/Z produced at the LHC, vector boson factory!



W+jets





= $O(\alpha_S)$ each vertices contributes to an extra perturbative order in QCD/EW

Measurements of cross sections and spectra are a benchmark for the test of the Electroweak sector (and QCD when jest are produced!) and of the detector performance (leptonic Z decay is the cleanest signature)

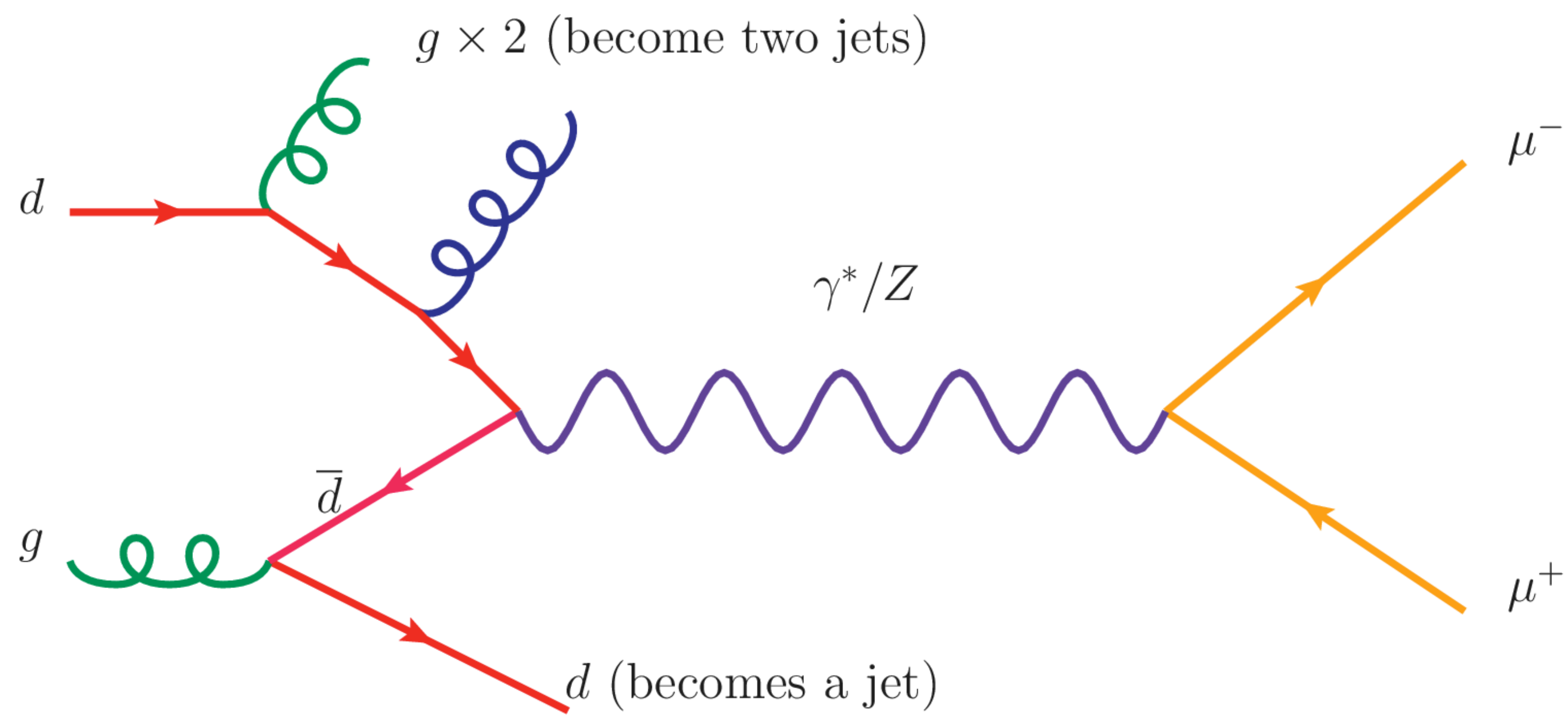
Vector boson plus jets: powerful validation and test of the QCD and tuning of the Monte Carlo predictions

SM Physics @ LHC: DY

Electroweak Physics: W and Z production

Thousands of W/Z produced at the LHC, vector boson factory!

Z+jets



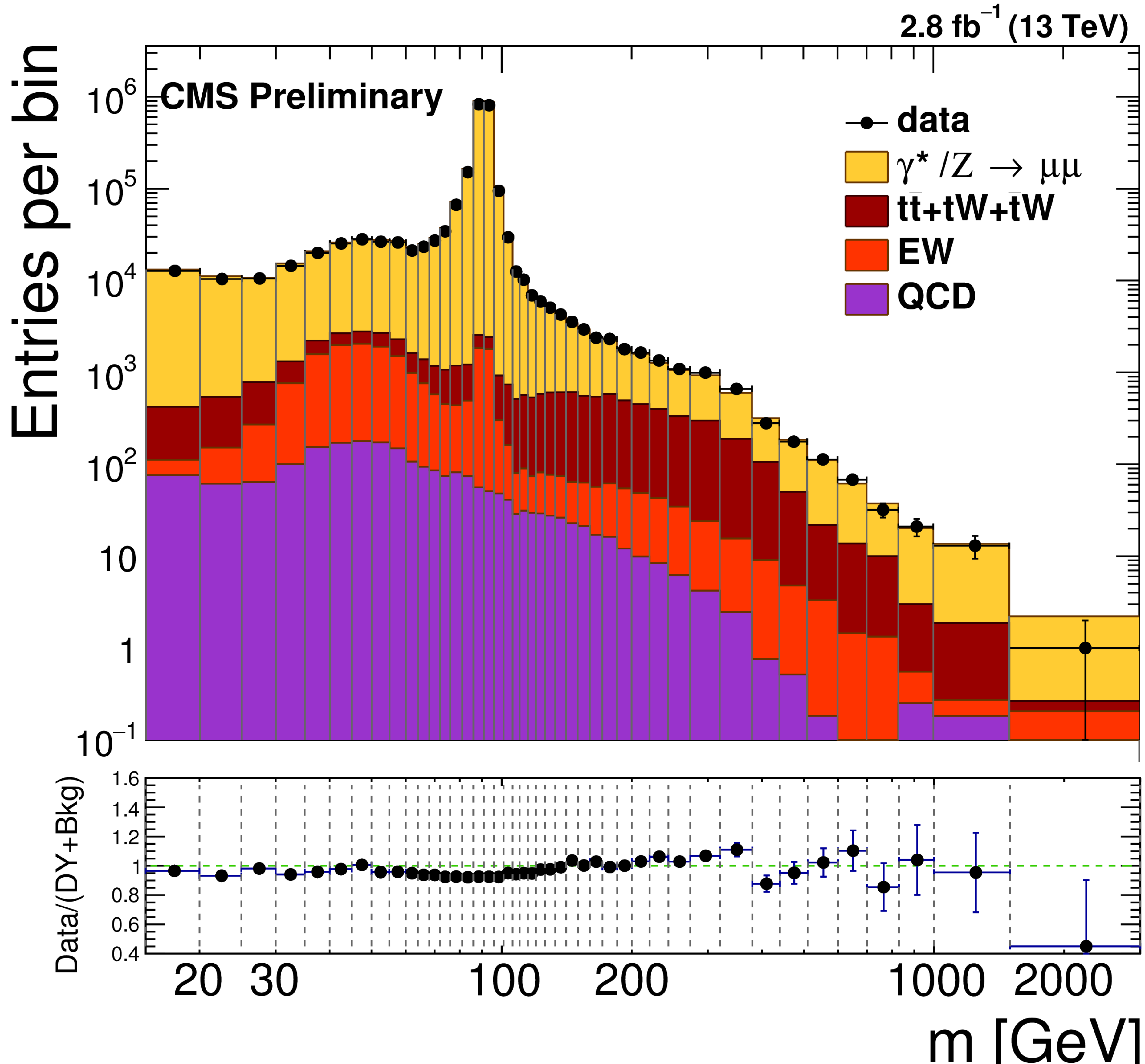
Drell-Yan

Measurements of cross sections and spectra are a benchmark for the test of the Electroweak sector (and QCD when jest are produced!) and of the detector performance (leptonic Z decay is the cleanest signature)

Vector boson plus jets: powerful validation and test of the QCD and tuning of the Monte Carlo predictions

SM Physics @ LHC: DY

DRELL-YAN

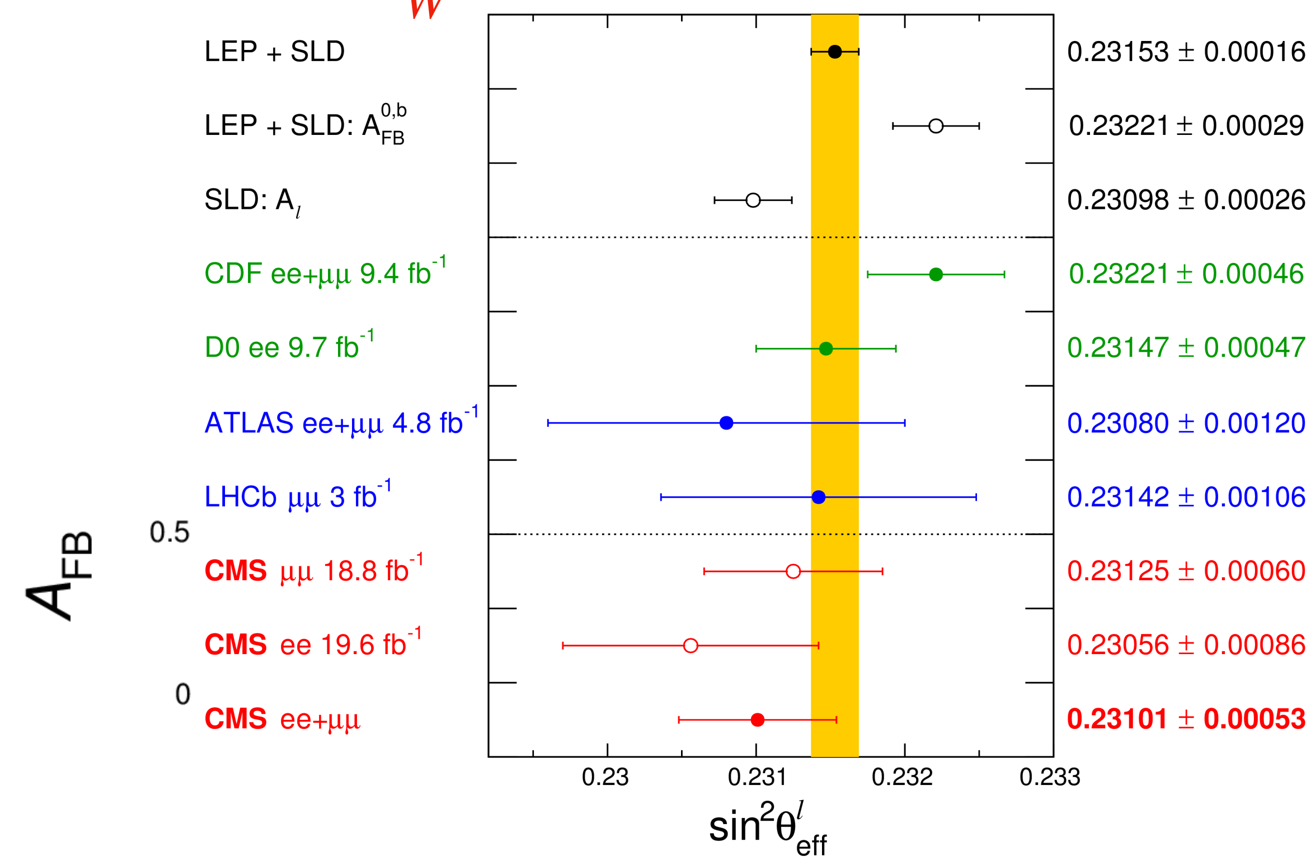


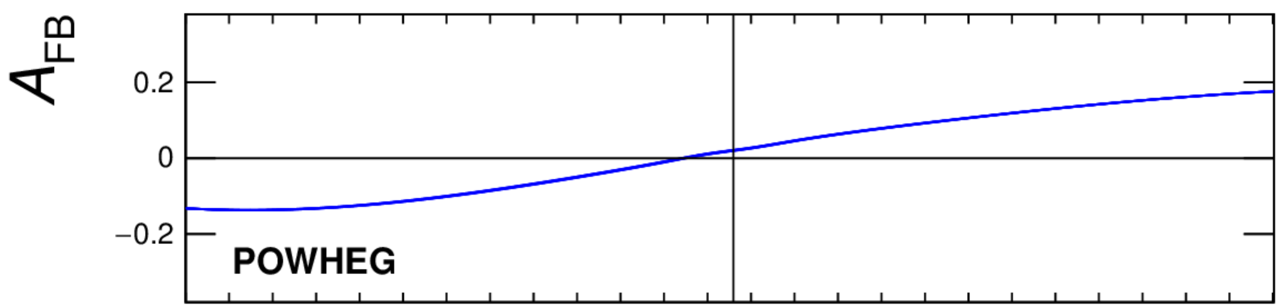
SM Physics @ LHC: $sin^2\theta_W$

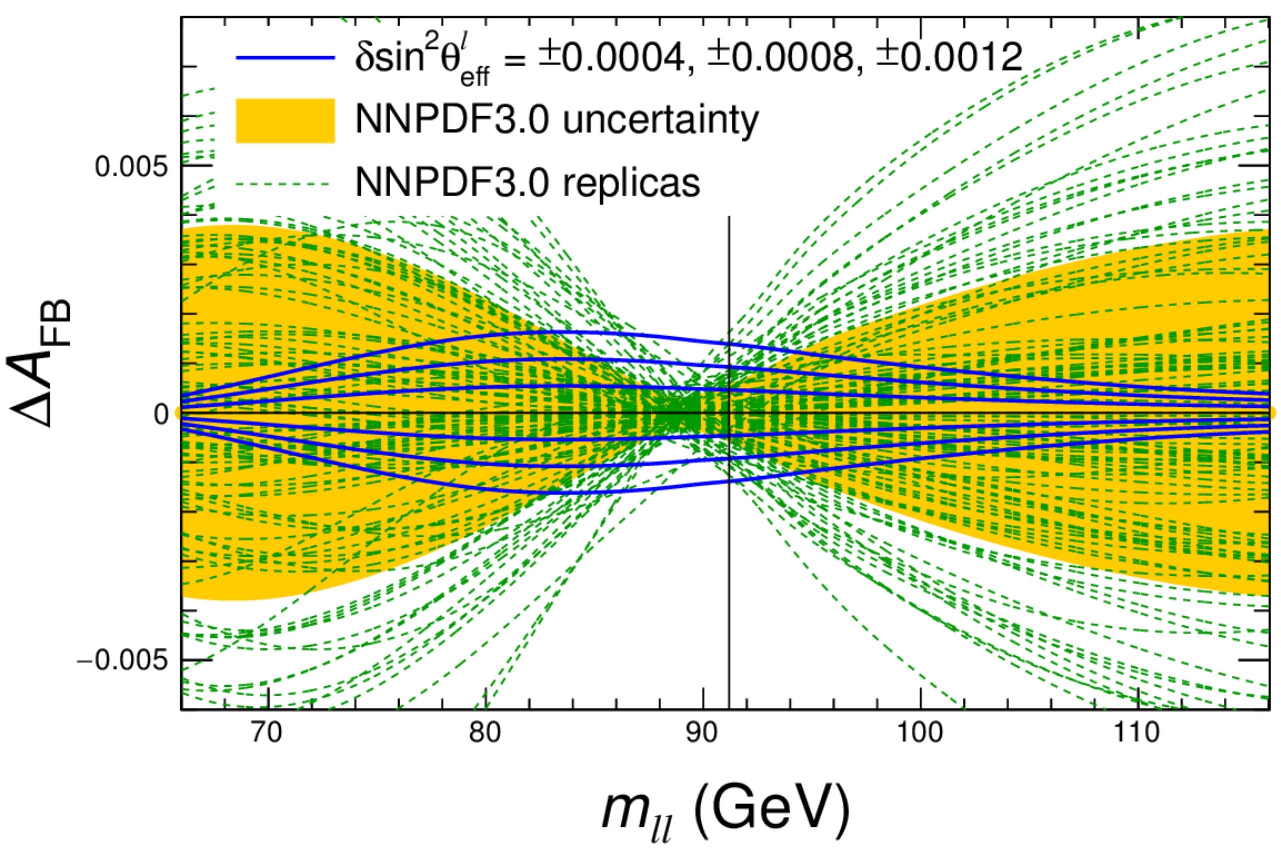
asymmetry due to interference of V-A currents => $sin^2\theta_W$!

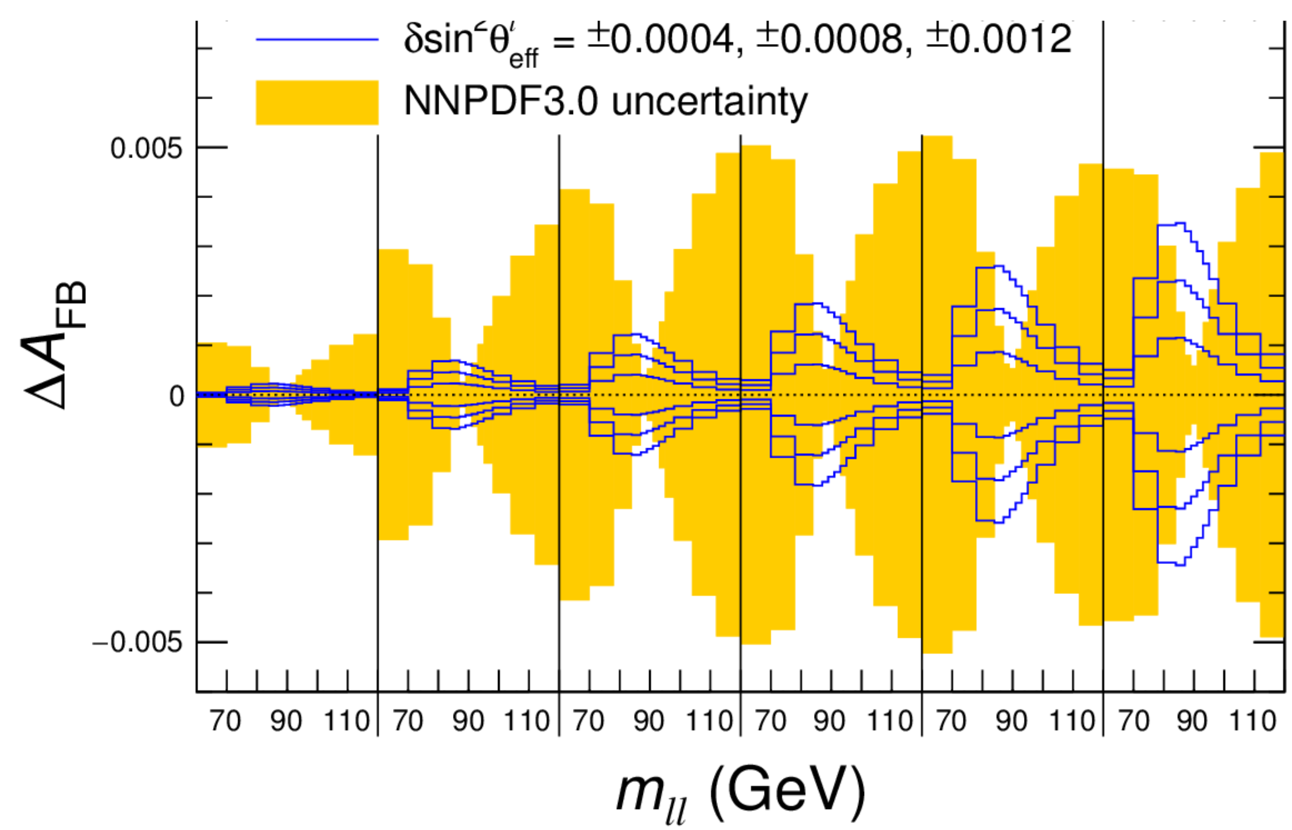
$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4\cos\theta^*$$

$$A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$









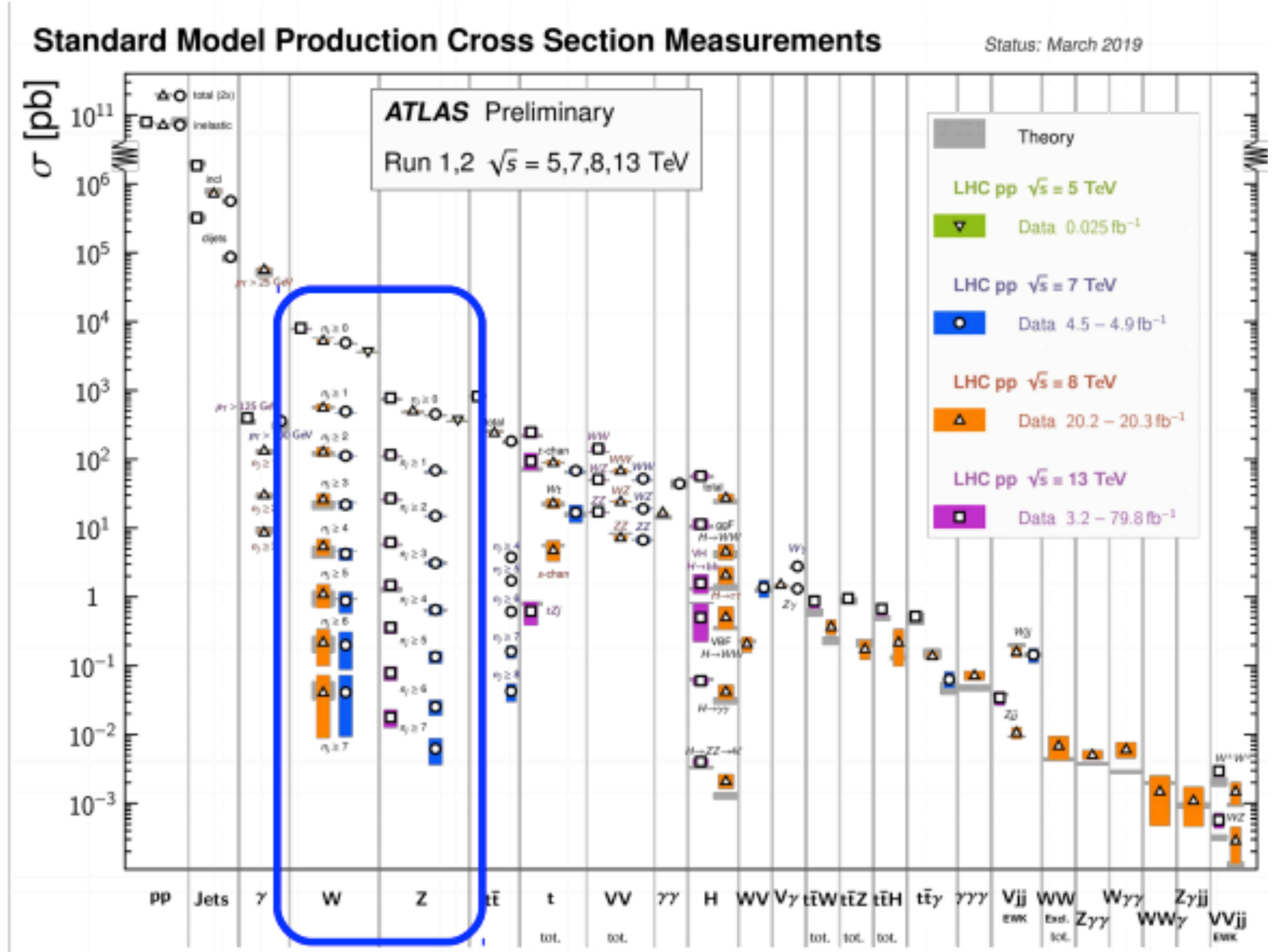
SM Physics @ LHC: V+Jets

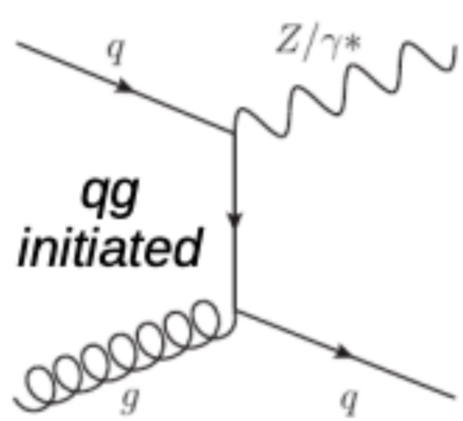
W or Z plus jets at LHC:

- Abundant QCD production spanning several orders of magnitude of cross-section
- Wide range of measurements now available at different energies and conditions thanks to CMS and ATLAS

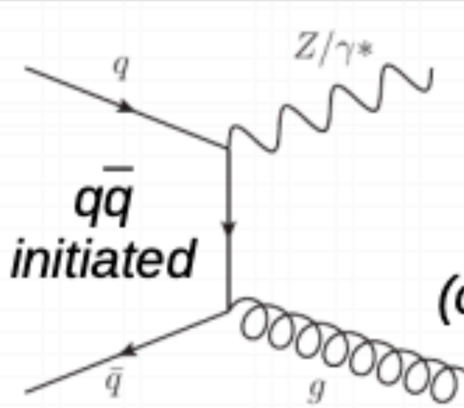
Measurements are test of:

- *MC modeling* ⇒ key for Higgs, BSM, EWK etc.
- Perturbative QCD (*pQCD*) predictions
- *Proton PDFs* ⇒ Thanks to dominant *qg* interaction



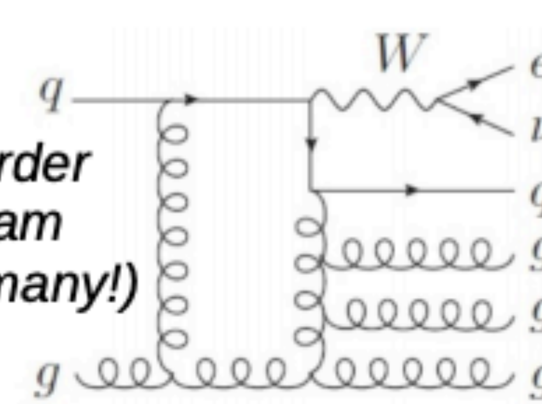


qg *initiated*



$q\bar{q}$ *initiated*

high-order diagram (one of many!)



SM Physics @ LHC: differential cross sections

to make meaningful comparisons with theory and in order to "come back" to the particles that we see in the Feynman diagrams we need to pay special attention when we make differential measurements

example: pp -> Z+b-quarks + X

inclusive cross section: typical expression

$$\sigma(Z(\rightarrow \ell\ell)+\geq 1b) = \frac{(N^{sign}_{Z+b} - N_{t\bar{t}} - N_{VV} - N_{charm} - N_{light})}{\epsilon_\ell \cdot \epsilon_b \cdot \int L dt}$$

signal event (definition)

efficiencies (can be the product of N sources)

integrated luminosity

background

SM Physics @ LHC: differential cross sections

to make meaningful comparisons with theory and in order to “come back” to the particles that we see in the Feynman diagrams we need to pay special attention when we make differential measurements

example: pp -> Z+b-quarks + X

inclusive cross section: typical expression

$$\sigma(Z(\rightarrow \ell\ell)+\geq 1b) = \frac{(N_{Z+b}^{sign} - N_{t\bar{t}} - N_{VV} - N_{charm} - N_{light})}{\epsilon_\ell \cdot \epsilon_b \cdot \int L dt}$$

differential cross section: explore the kinematics of the event

$$\frac{d\sigma}{dx} =$$

- leading b-jet p_T
- leading b-jet η
- Z boson p_T
- $H_T = \sum_{jet} p_T$
- $\Delta\phi\,(Zb)$

shapes give a complete understanding of the process, lots of information on pQCD and EWK

SM Physics @ LHC: Unfolding Spectra

Need to deconvolve the measured distributions from

- detector effects
- efficiencies
- smearing effects
- bins migration

in order to give a reliable comparison to the theoretical predictions

$$g(y) = \int K(y,x) f(x) \mathrm{d}x$$

unfolded data

measured data

$$y = \mathrm{A(y,x)} \cdot x$$

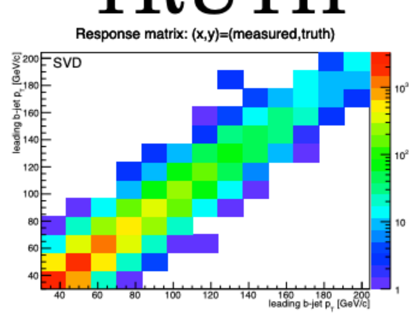
response matrix

Two algorithms → Iterative - application of the Bayes Theorem
→ Singular Value Decomposition (SVD)

→ regularized by a parameter k

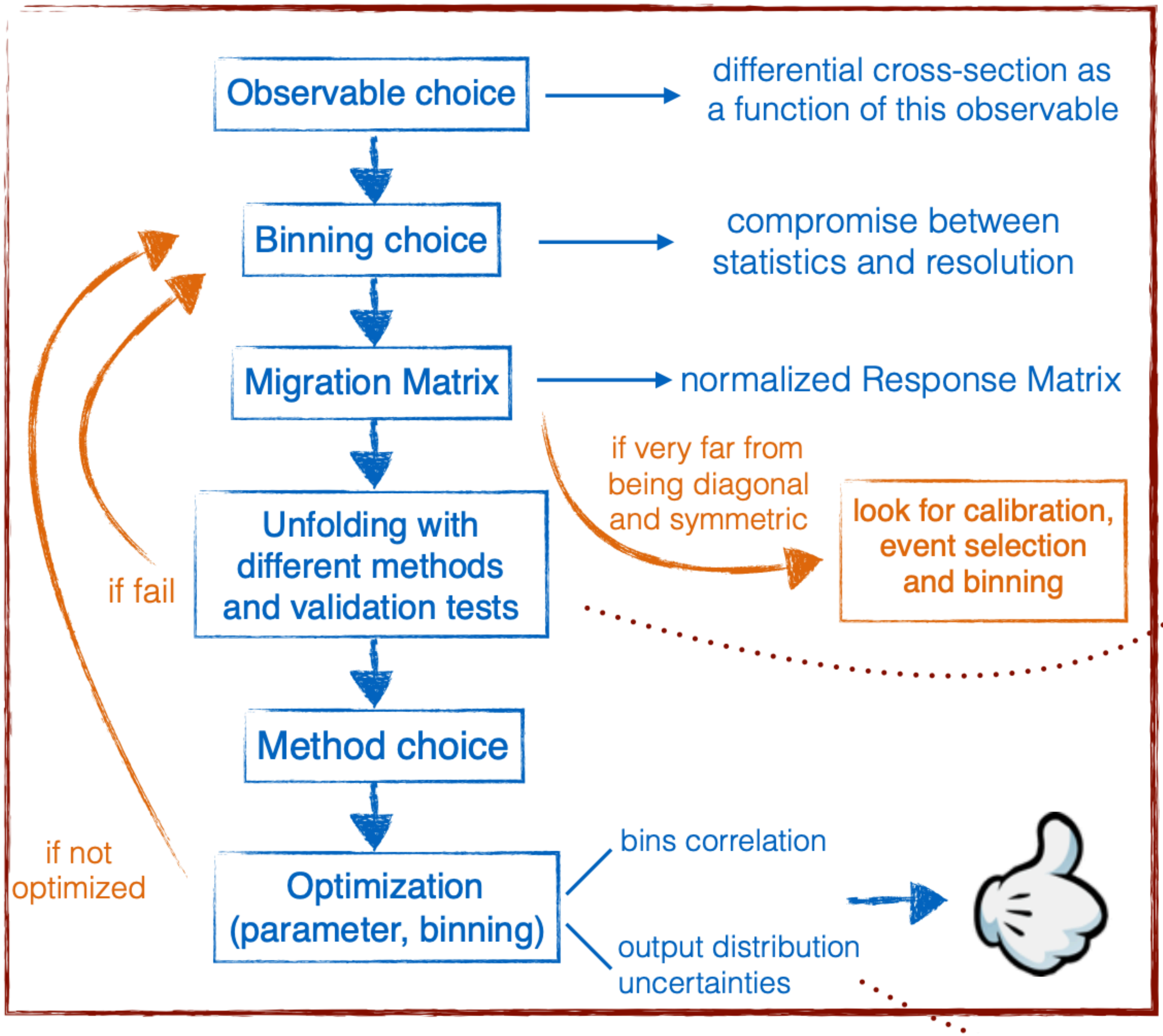
$0 < k < N(\text{bins})$

DATA *folded* [MC TRUTH RECO] → DATA *unfolded*



SM Physics @ LHC: SVD Unfolding

How to proceed



$\mu = M^{-1} v$

Inversion of a finite system of equation rarely admits an exact solution:

- ➡ **different techniques** calculating approximate solutions
- ➡ **regularization** needed to overcome potential instability of the approximated solutions

Treatment of uncertainties with unfolding

- ➡ **statistical uncertainties**
  - Poisson bin-per-bin fluctuation of the reconstructed spectrum
  - Bootstrap replicas
- ➡ **systematics uncertainties**
  - Gaussian smearing (different choice, see next slides)

SM Physics @ LHC: Unfolding algorithms

https://arxiv.org/abs/hep-ph/9509307

BAYESIAN WAY

applies Bayes' Theorem using "true" , "reco" and "measured" distributions as probabilities to enter the formula

- needs a prior
- needs to be iterated

https://arxiv.org/abs/1010.0632

SVD WAY

singular values decomposition of the response matrix

- needs to be regularized (dependence on a parameter)
- more difficult calculations

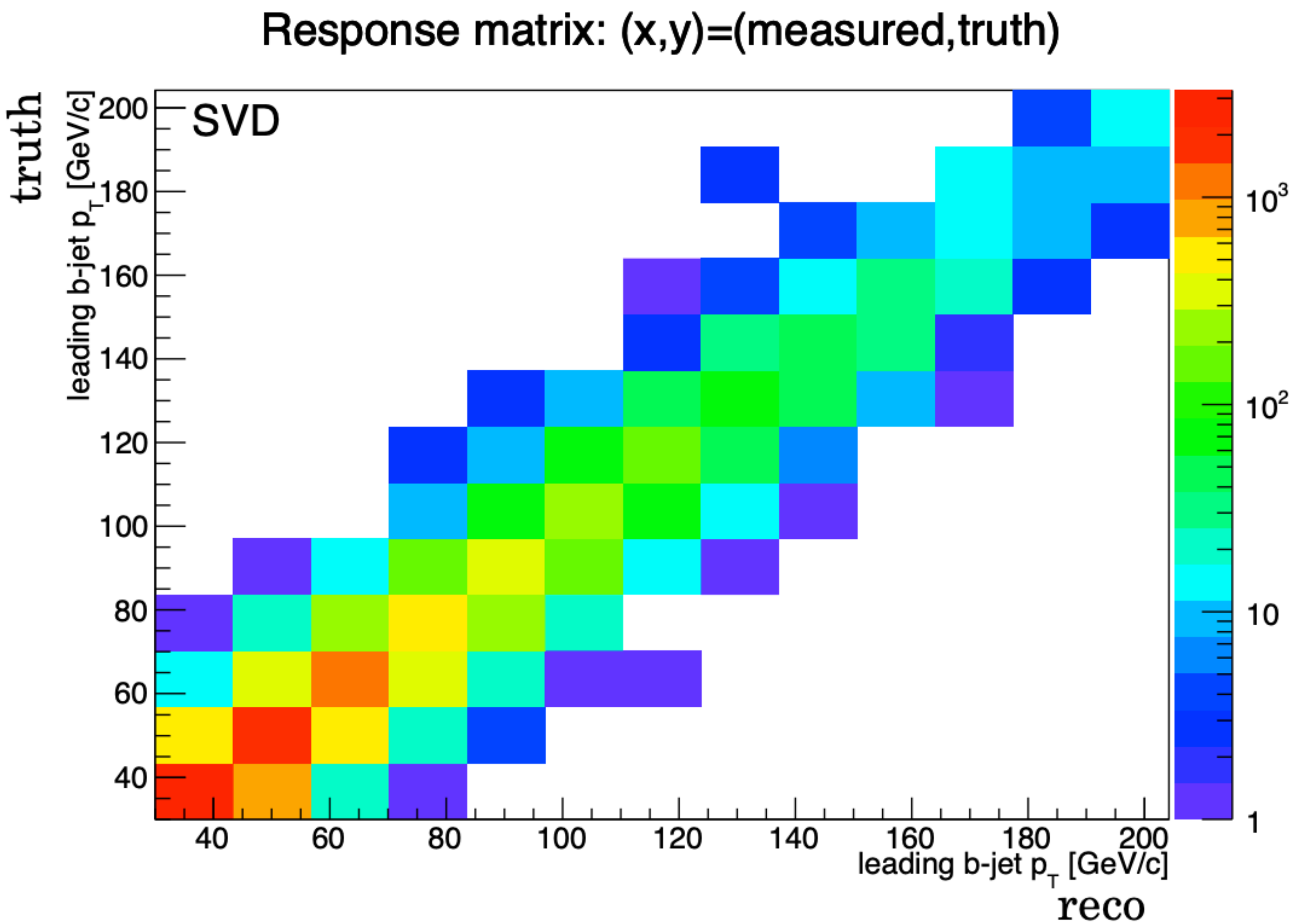
PRACTICAL WAY: calculate the "reco" and "truth" distributions for a given observable and give it to RooUnfold

http://hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html

BAYESIAN AND SVD INCLUDED

SM Physics @ LHC: Unfolding Spectra

The Response Matrix



MC reco is MadGraph+Pythia as default

k (SVD) = N (bins) / 2

leading b-jet momentum

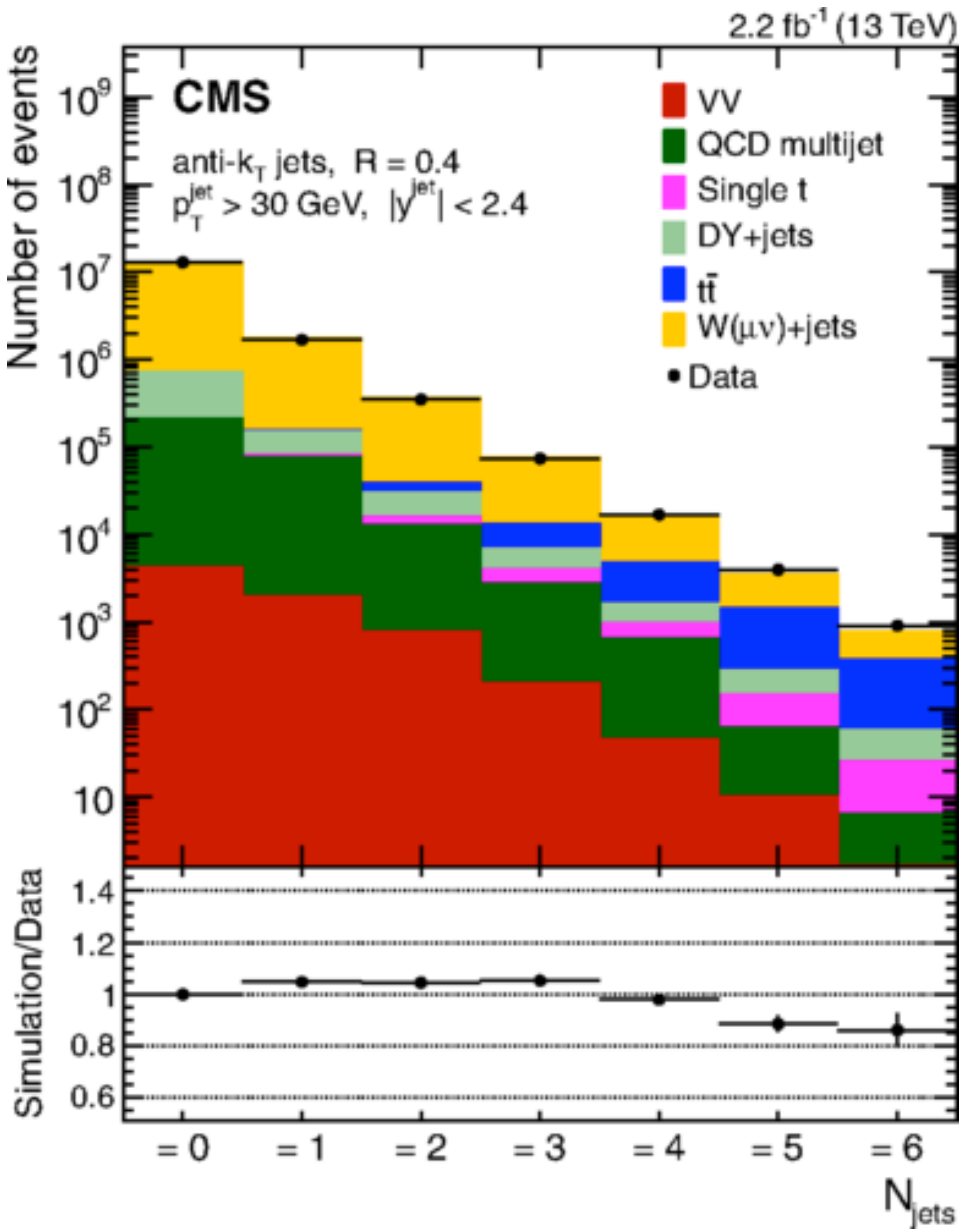
$p_T > 30$ GeV ; $|\eta| < 2.5$

- y axis : generator-level (truth) b-jet momentum
- x axis : Monte Carlo reco b-jet momentum
- matching (truth - reco) jets $\Delta R < 0.5$ in the eta-phi space

several tests to validate the procedure

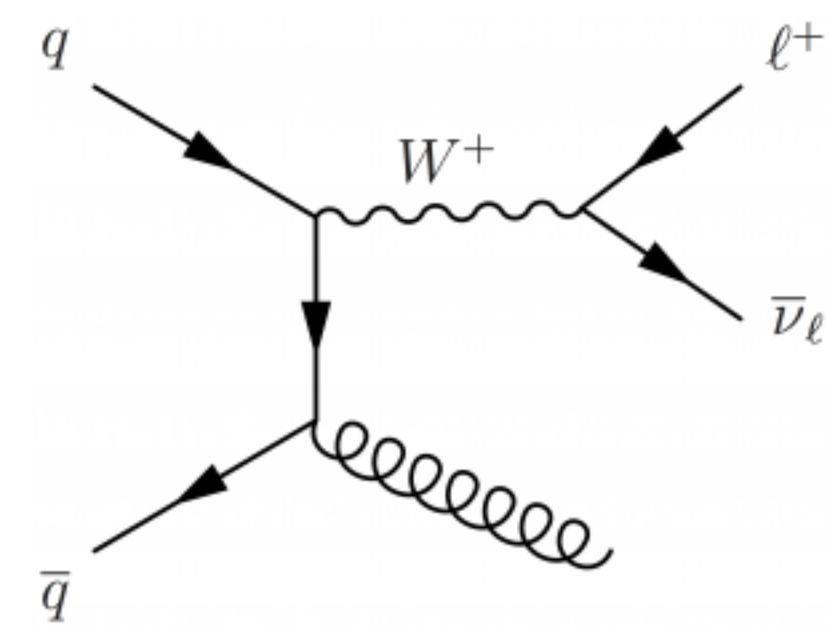
* identity chek
* dependence on different MC
* Bayes-SVD compatibility

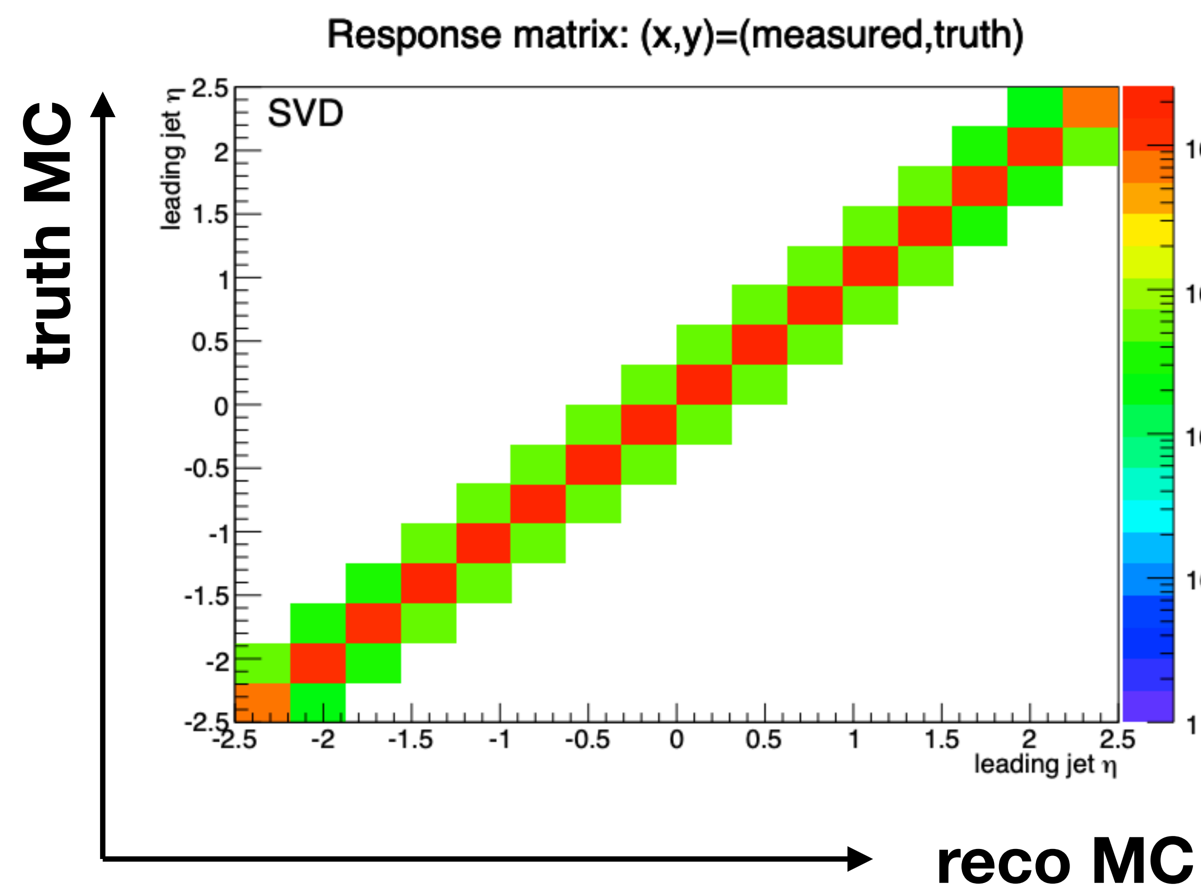
SM Physics @ LHC: W+Jets



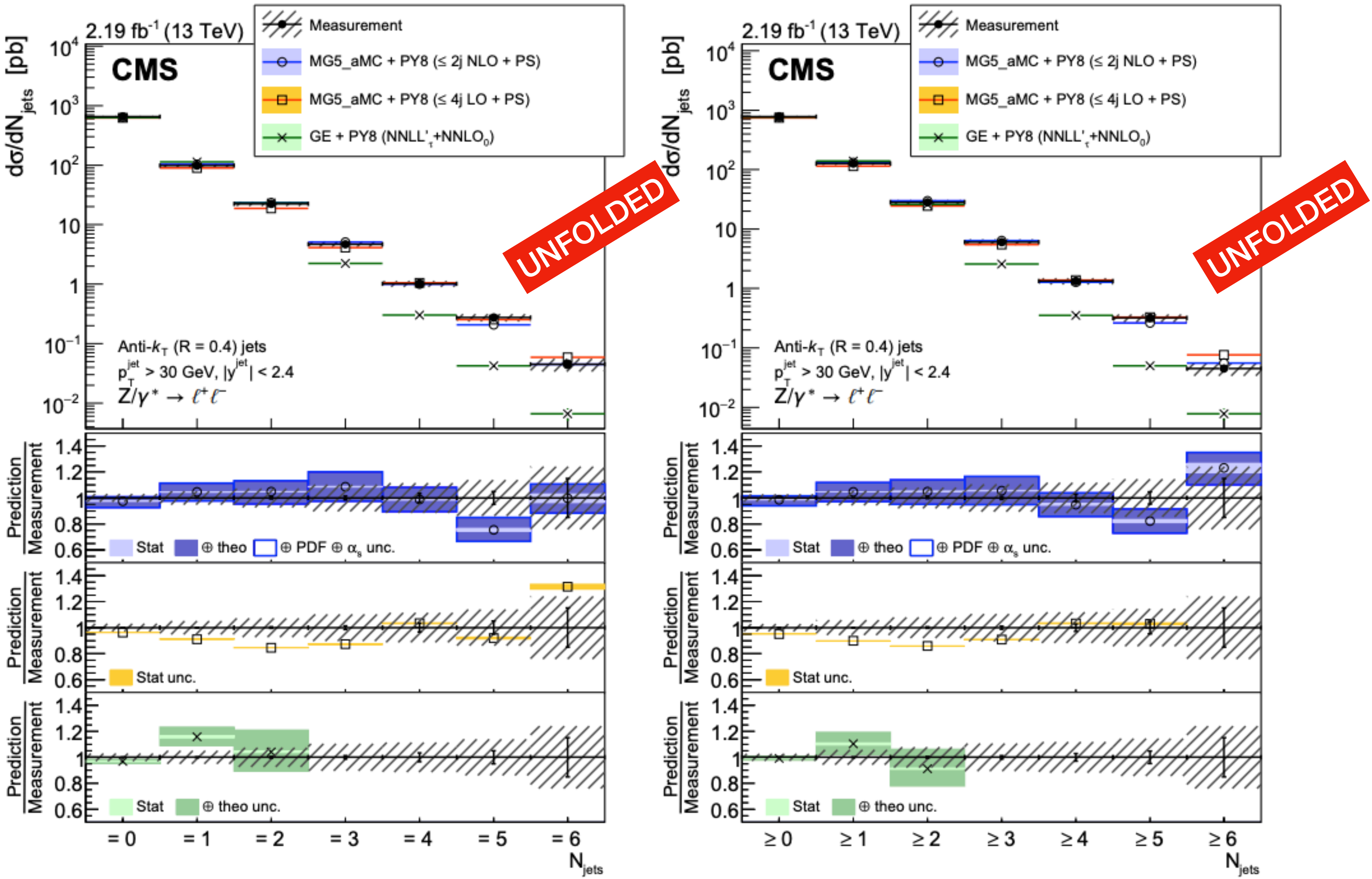
DETECTOR LEVEL

UNFOLD

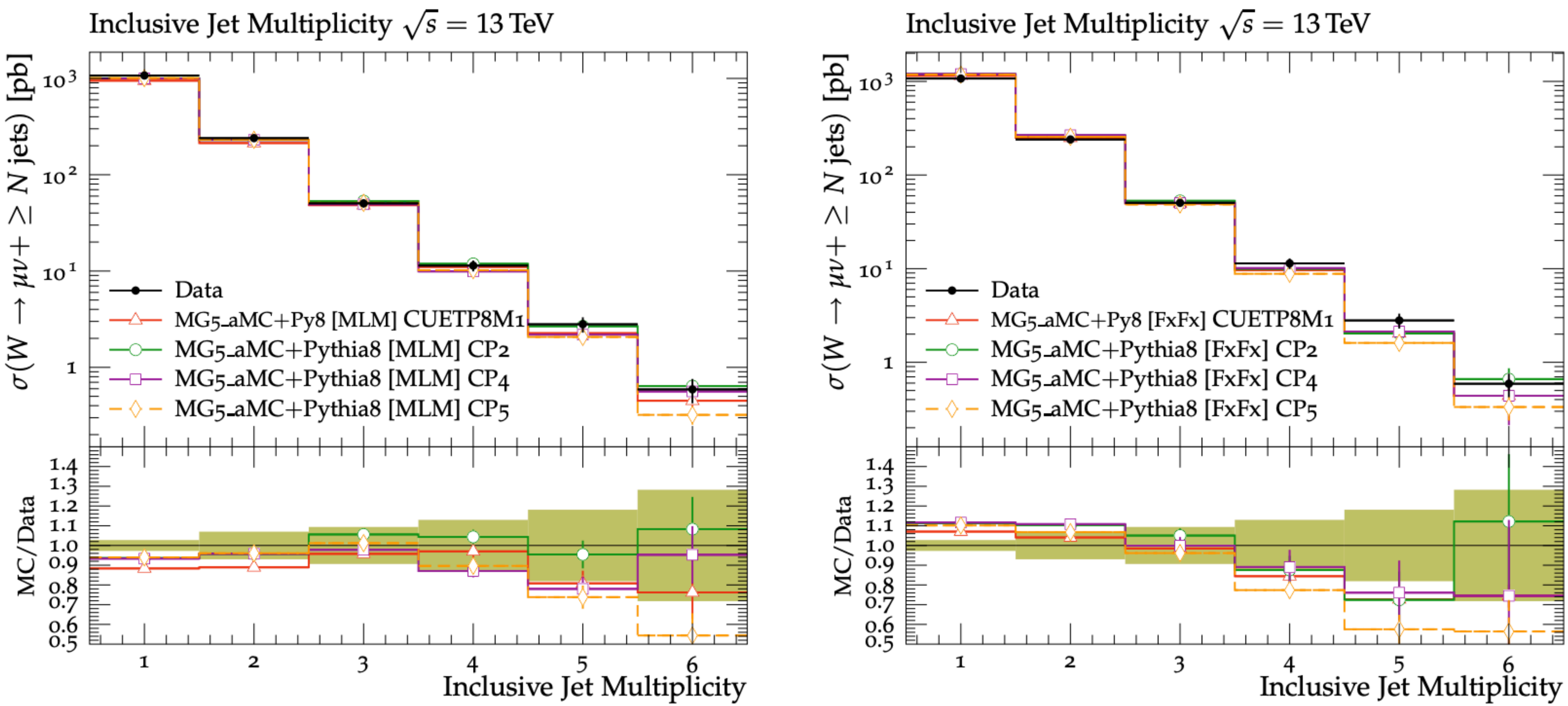




SM Physics @ LHC: Z+Jets



SM Physics @ LHC: W+Jets



strong dependence on the QCD / parton shower modelling in generators!

Physics of W/Z + heavy flavors at LHC

perturbative QCD

- *Wc :* access the strange quark content of the proton
- *Zb :* understand the production mechanism
  - tree level vs NLO
  - 4FS ($m_b \neq 0$) vs 5FS ($m_b = 0$)
- PDF studies, NLO effects

Electroweak Measurements

- Higgs background *HZ*, *HW*
- Differential Cross sections
- *Zb* polarization asymmetry $\sin^2\Theta_W^{eff}$, couplings

Beyond the Standard Model

- 4th generation heavy *b',t'* quarks decaying to *Vb*
- Multi Higgs-doublets Models
- supersymmetry with *sbottoms*

SM Physics @ LHC: V+HF

$Z + b$

selection criteria

- ≥1 antiKT05 jet with $p_T > 30$ GeV, $|\eta|<2.4$
- b-tagging: exploiting SV mass discriminator
- ≥1/2 b-tagged jet with $p_T > 30$ GeV, $|\eta|<2.4$
- dilepton mass $71 < M(ll) < 111$ GeV

background

- ttbar: ***data-driven*** estimation in an eμ+jets control sample: extract both shape and normalization

- *Z+c, Z+light-* flavor MC templates extracted from SV mass fit and subtracted

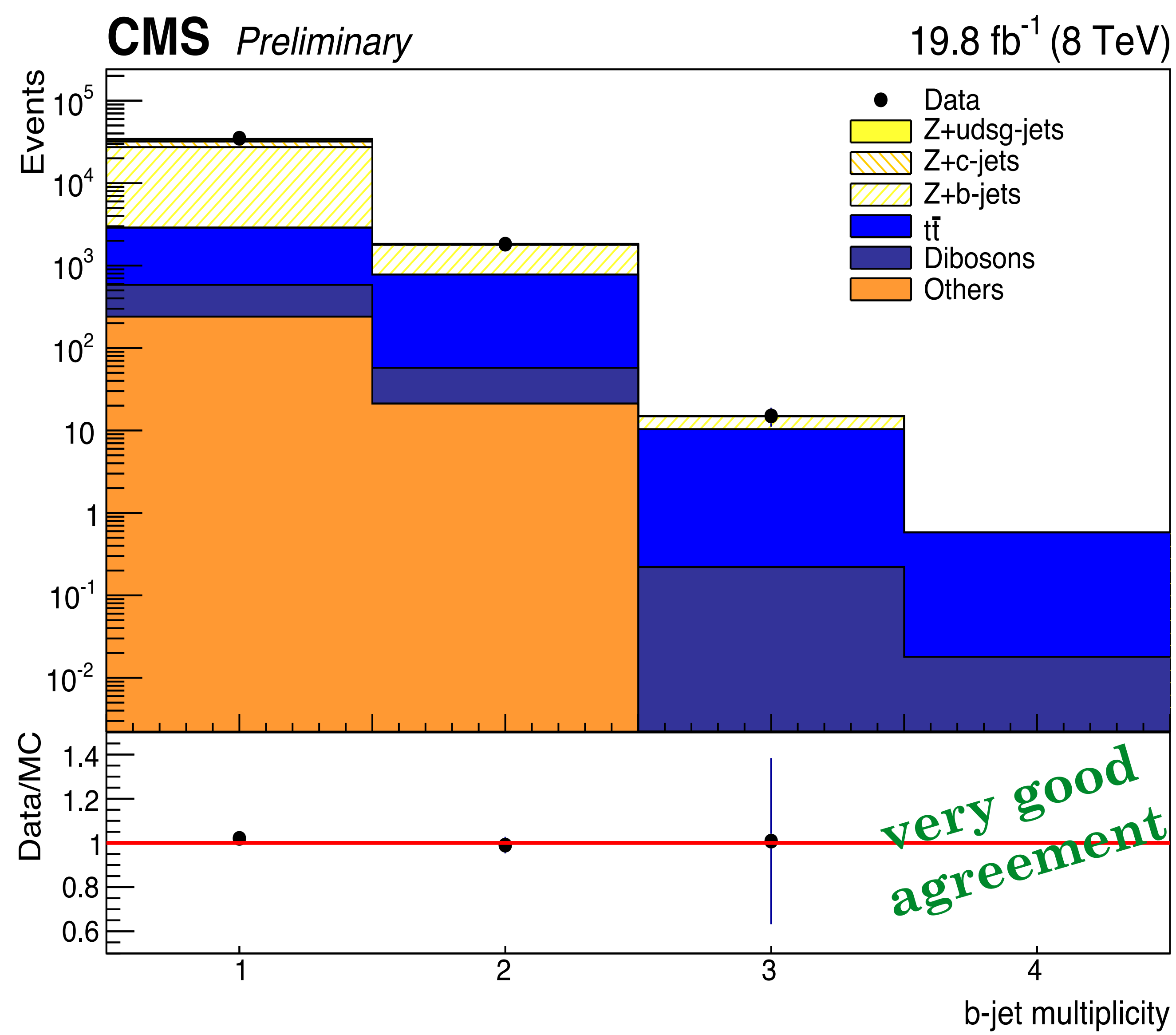
- *dibosons taken from MC*

cross sections

- *unfolded* (SVD) data compared with:
  - MadGraph5+Pythia6 (LO) 5FS
  - MadGraph5 4FS
  - Powheg (NLO for 1jet)

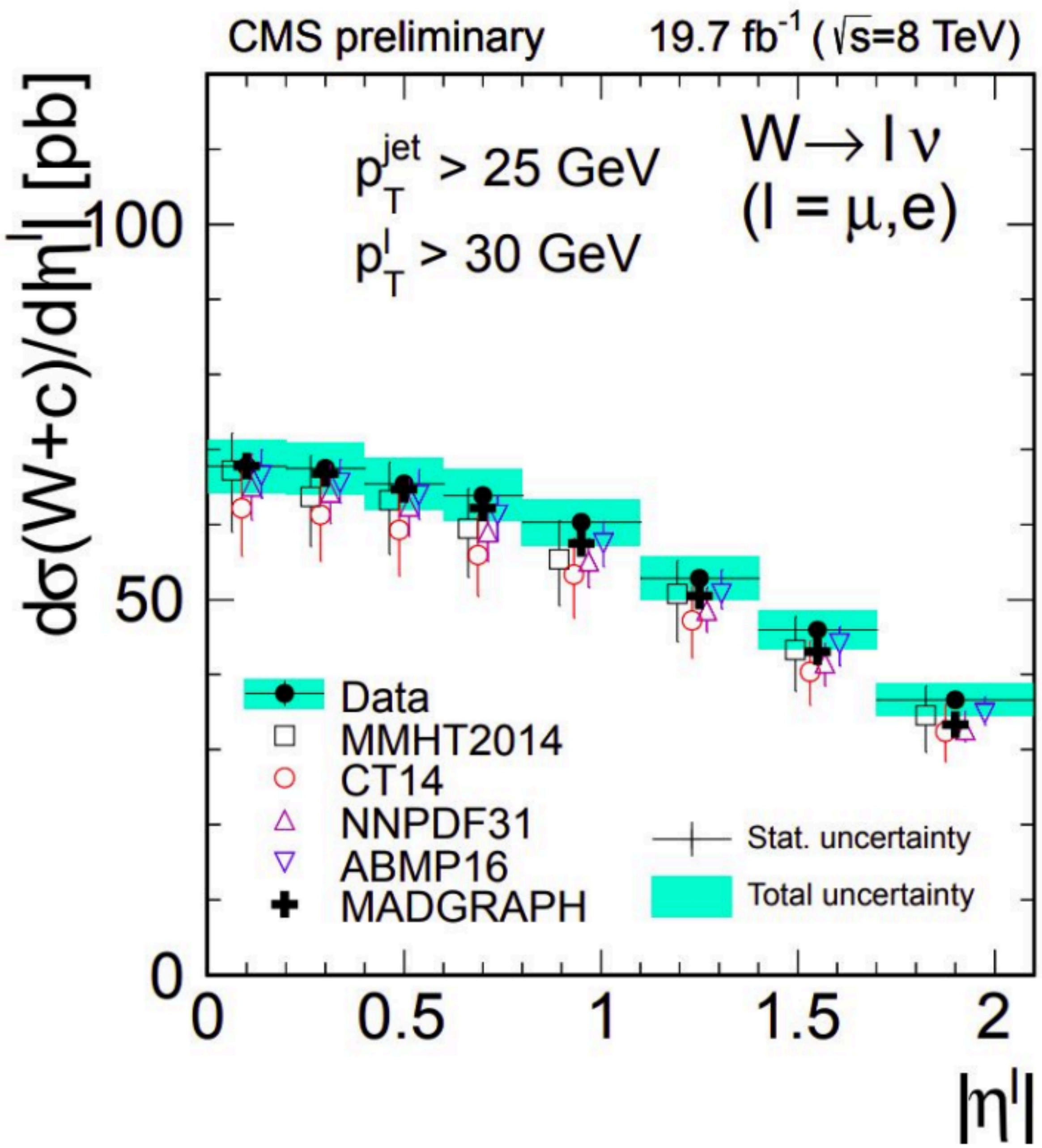
systematics
- Jet Energy Correction
- Unfolding

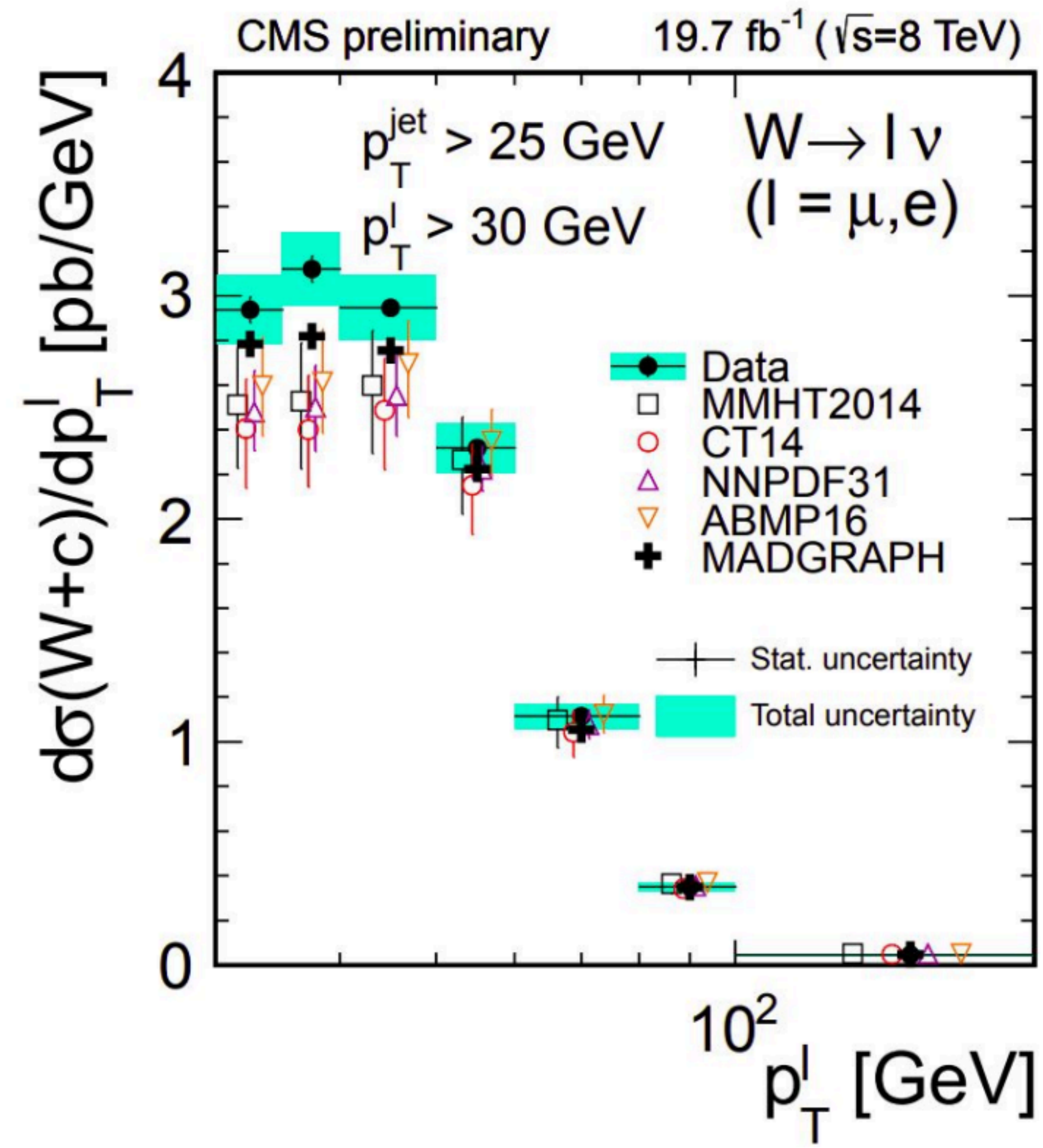
- important test of pQCD with heavy flavors: 4 flavor scheme (b massive) and 5 flavor schemes (b massless)
- important background for new physics and Higgs: HZZ, SUSY, 4th generation…



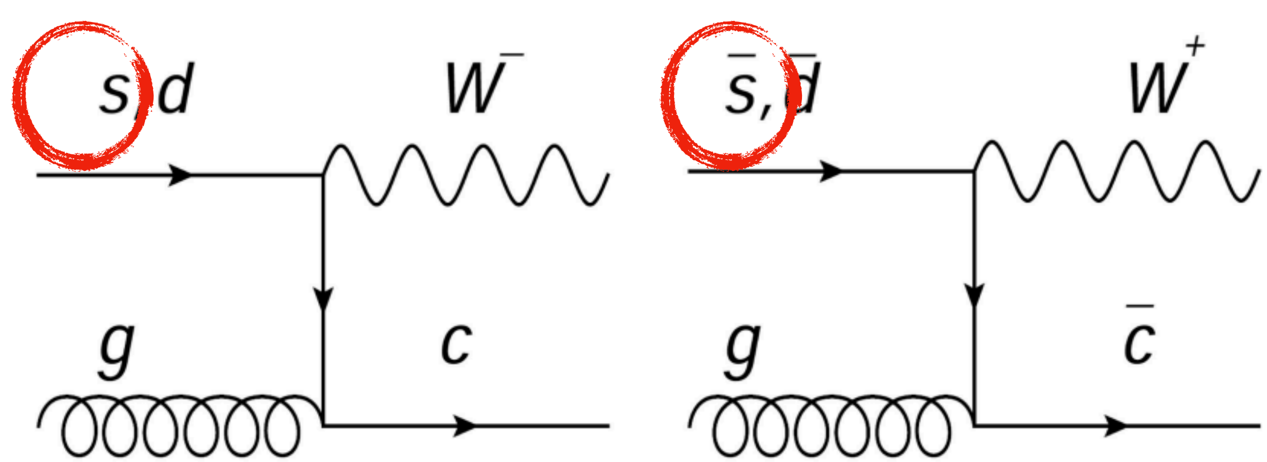
detector-level inclusive b-jet multiplicity

SM Physics @ LHC: V+HF





W+c

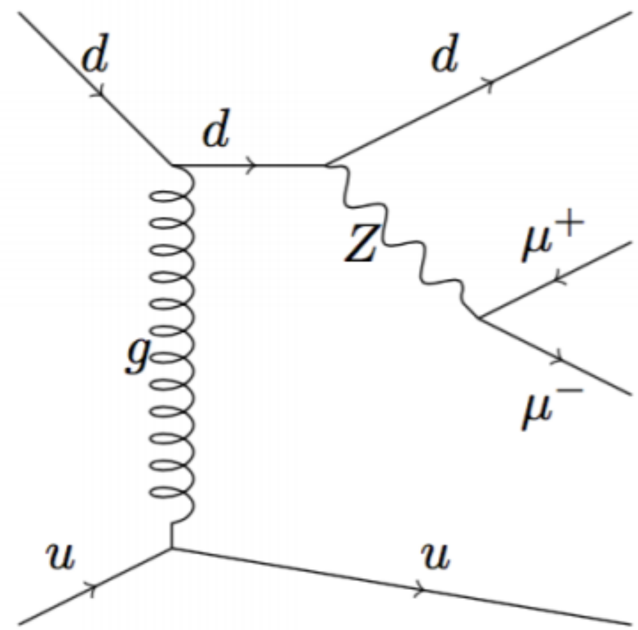


allows to access the strange sea!

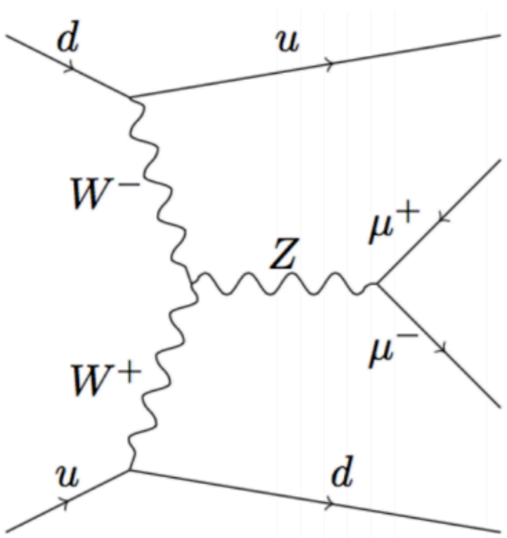
SM Physics @ LHC: VBF & VBS modes

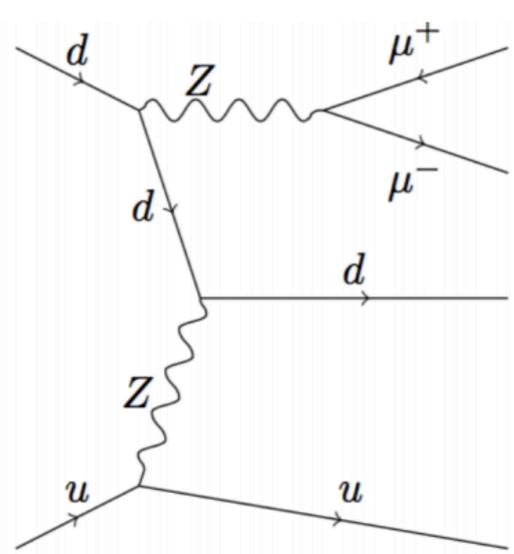
- pure EW production: order α^4_{EW} versus Drell-Yan order $\alpha^2_{QCD}\ \alpha^2_{EW}$

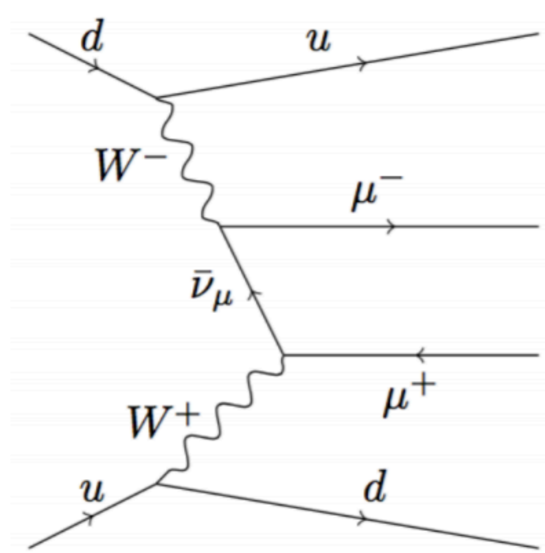
- includes diagrams with VBF processes: highly sensitive to EWSB and potential New Physics

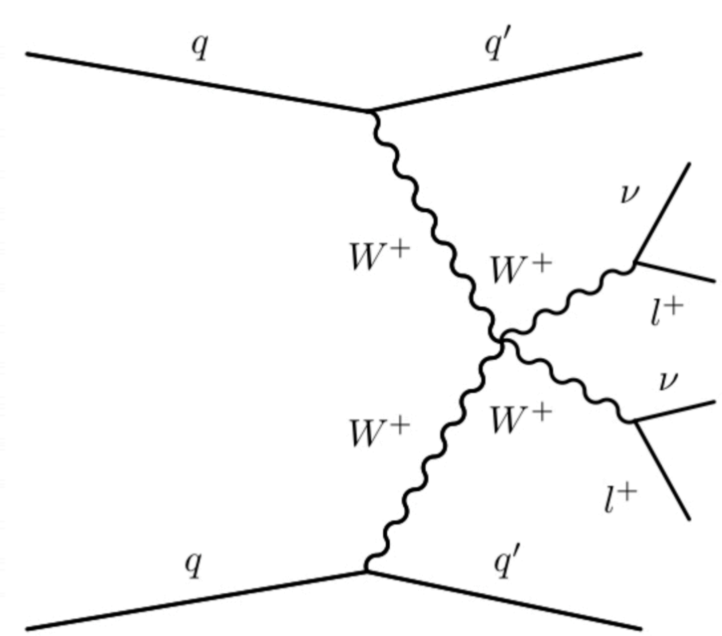


DY background







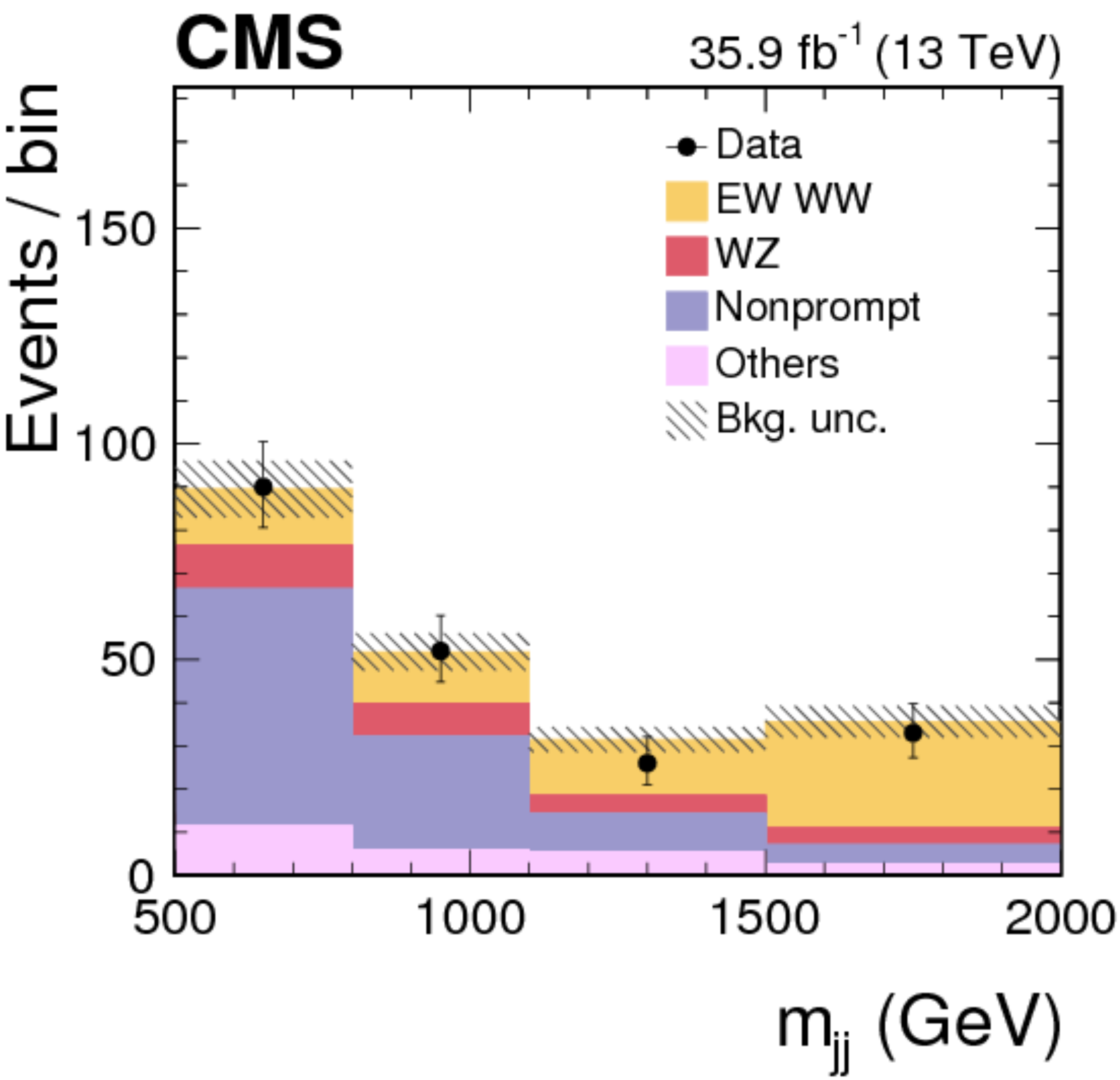


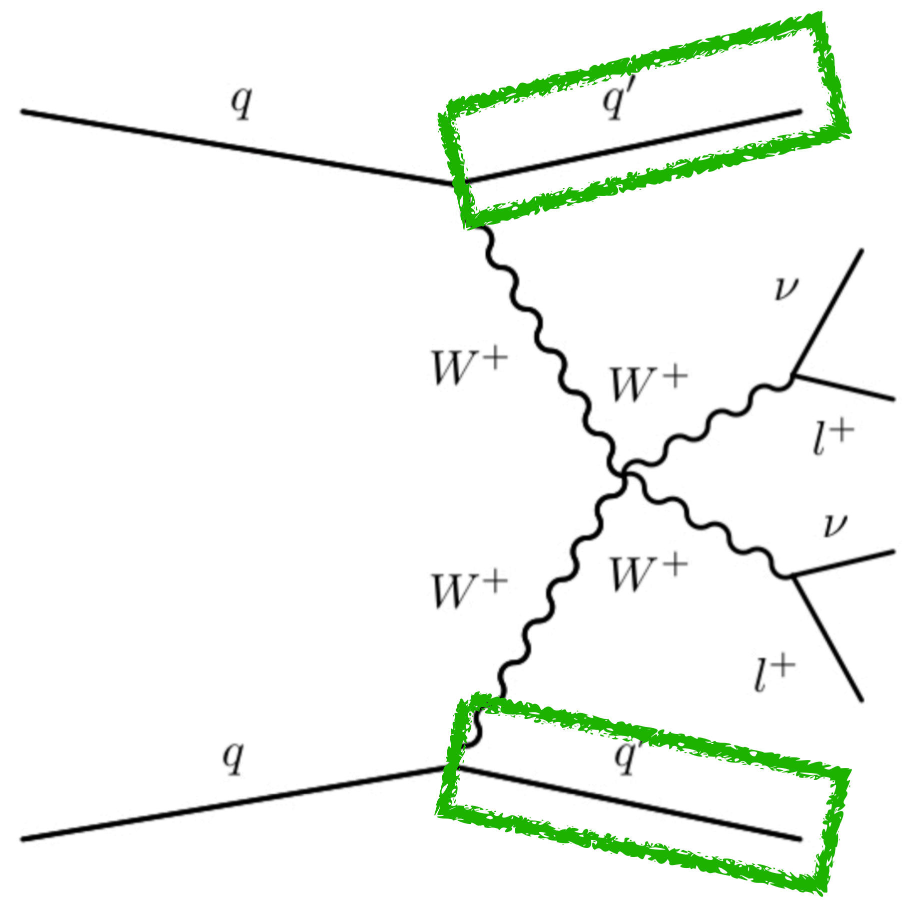
VBF Signal
***WWZ* vertex**

Pure Electroweak

VBS Signal
***WWWW* vertex**

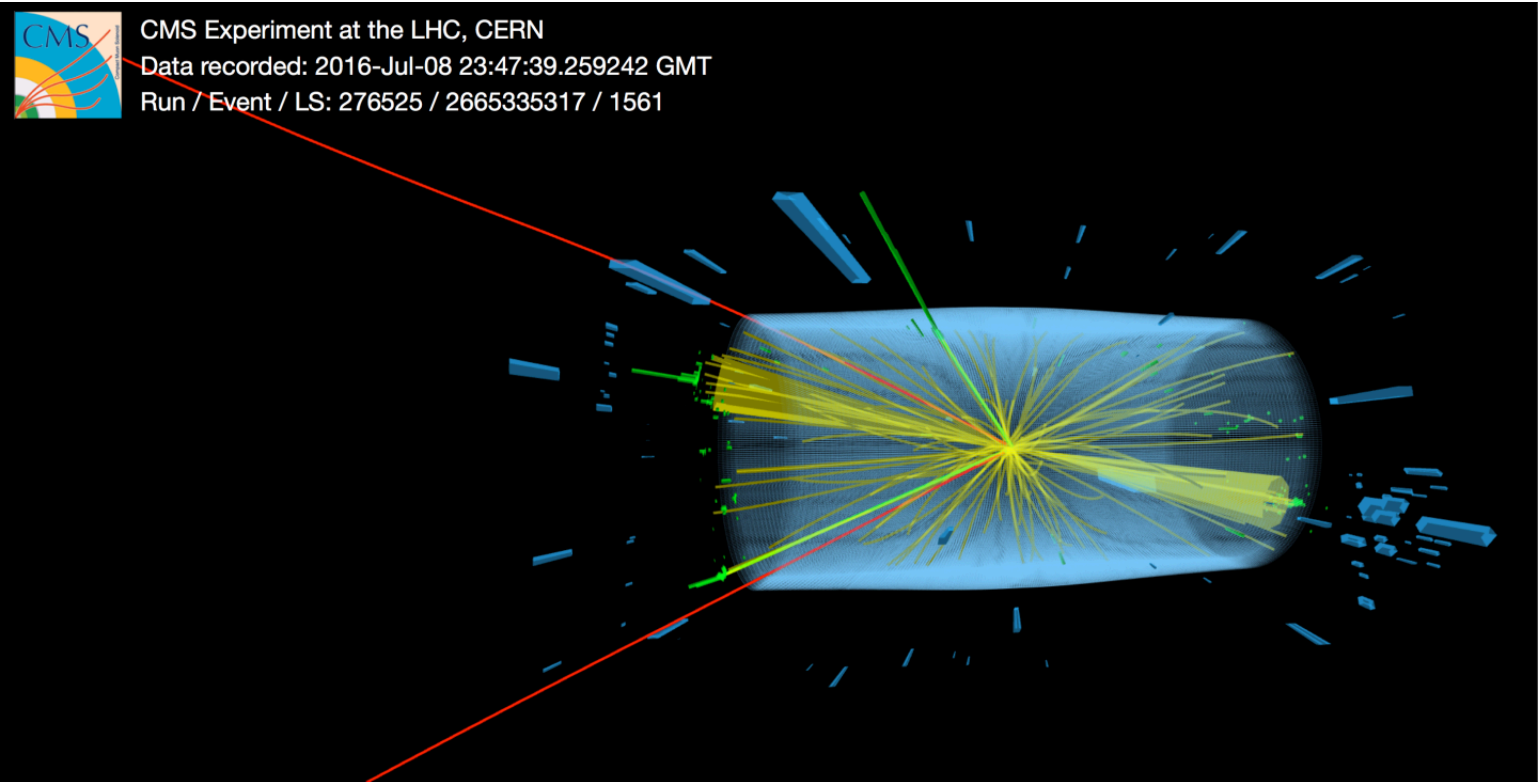
SM Physics @ LHC: VBF & VBS modes





Typical VBS selection:
2 jets with $p_T > 30$ GeV
$m_{JJ} > 500$ GeV **$|\Delta\eta_{JJ}| > 2.5$**

SM Physics @ LHC: VBF & VBS modes

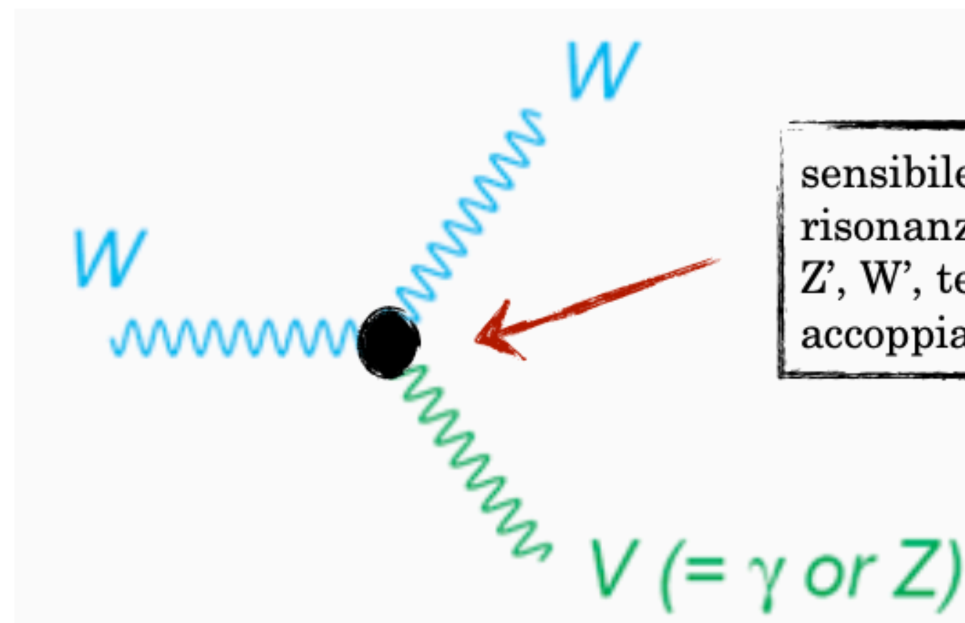


Why making bosons scatter and fuse? aGC

Exploiting the non-Abelian nature of the SU(2)XU(1) symmetry group: vector bosons interact!

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - ig f^a_{bc} A^b_\mu A^c_\nu$$

- conseguenza della non abelianità di $SU(2)_L \times U(1)_Y$
- interazioni elettrodeboli predicono vertici WWV (*TGC*)
- Test del Modello Standard



sensibile a nuova fisica
risonanze in WW
Z', W', technicolor
accoppiamenti anomali

parametrizzazione Lorentz-invariante piu generale

$$\begin{aligned} i\mathcal{L}^{WWV}_{eff} = \; & g_{WWV}\Big[g^V_1 V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \\ & \frac{\lambda_V}{m^2_W} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + i g^V_5 \varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right)V^\sigma \\ & + i g^V_4 W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m^2_W} W^-_{\rho\mu} W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\Big], \end{aligned} \tag{1}$$

~~CP~~ = 0 nello SM

~~C~~ = 0 nello SM

~~P~~ = 0 nello SM

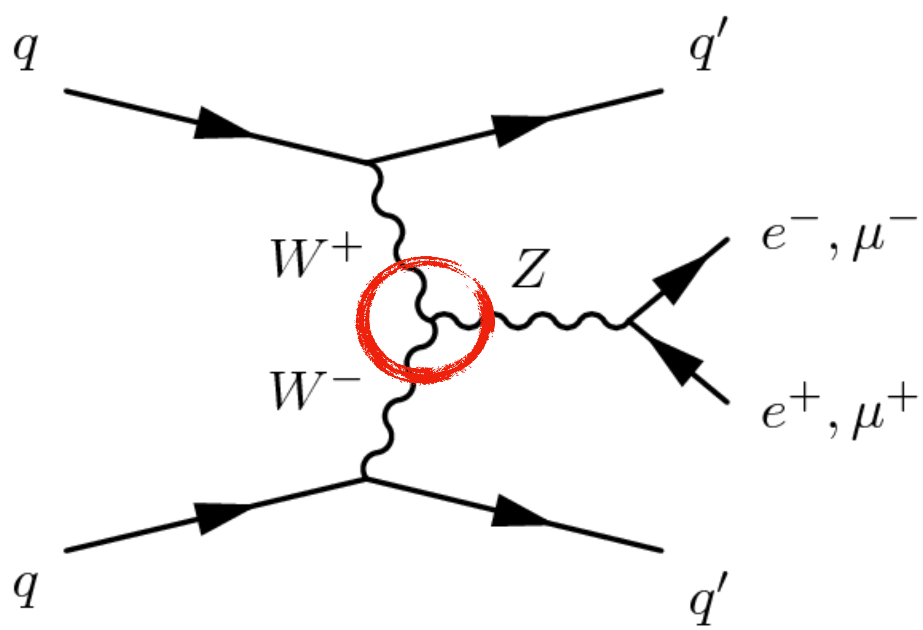
da 14 a 6 parametri

Why making bosons scatter and fuse? aGC

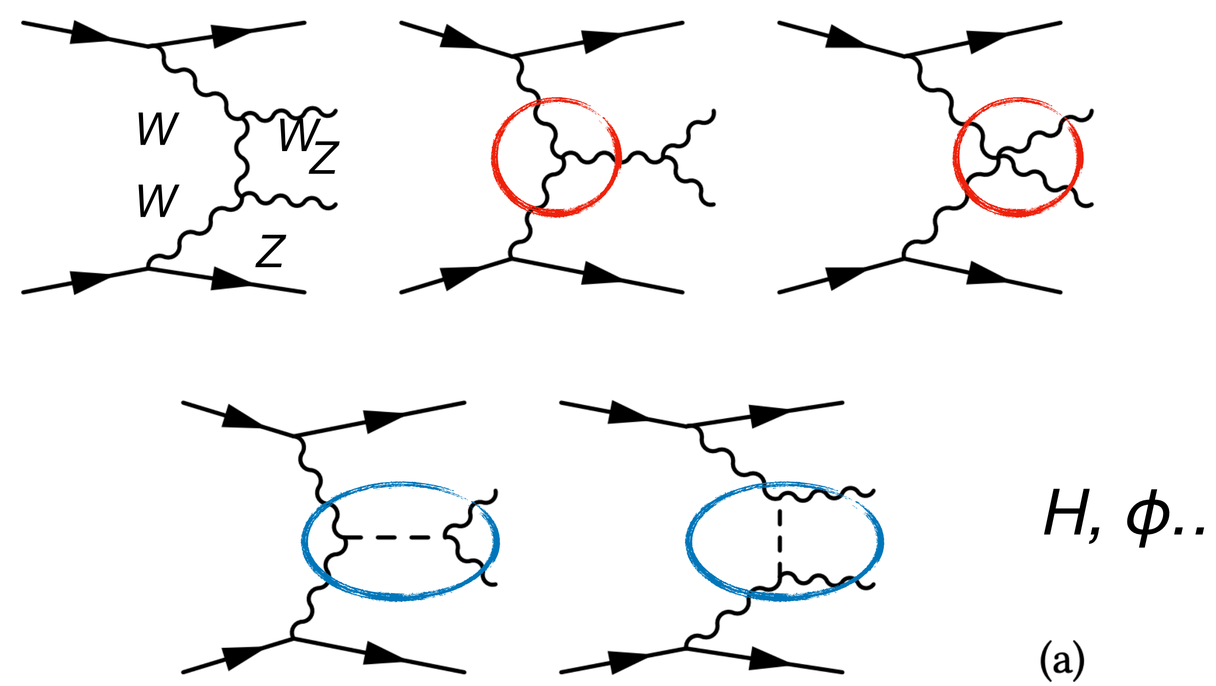
Exploiting the non-Abelian nature of the SU(2)XU(1) symmetry group: vector bosons interact!

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - igf^a_{bc}A^b_\mu A^c_\nu$$

single boson



diboson



very clean signature at colliders: 2 isolated leptons + 2 high energy jet highly separated in Δη

- pure EW production: order α^4_{EW} versus Drell-Yan order α^2_{QCD} α^2_{EW}
- includes diagrams with VBF processes: highly sensitive to EWSB and potential New Physics
- constrain SM-forbidden diagrams including higher order operators: anomalous triple/quartic gauge couplings

$$\mathscr{L}_{aQGC} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \dots$$

A model-independent way of searching for New Physics

Why making bosons scatter and fuse? aGC

Extend the SM Lagrangian with higher order operators: the most simple EFT

$$\mathscr{L}_{aQGC} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \ldots$$

The expansion operators are proportional to the "anomalous" boson couplings *fi*

$$\begin{aligned}
\mathcal{O}_{WWW} &= \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}, \\
\mathcal{O}_{W} &= \frac{c_W}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi), \\
\mathcal{O}_{B} &= \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi), \\
\widetilde{\mathcal{O}}_{WWW} &= \frac{\widetilde{c}_{WWW}}{\Lambda^2} \widetilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}, \\
\widetilde{\mathcal{O}}_{W} &= \frac{\widetilde{c}_W}{\Lambda^2} (D^\mu \Phi)^\dagger \widetilde{W}_{\mu\nu} (D^\nu \Phi),
\end{aligned}$$

Several Tensor-Vector operators relative to different topologies: ZZZ, $Z\gamma\gamma$, $\gamma\gamma\gamma$…

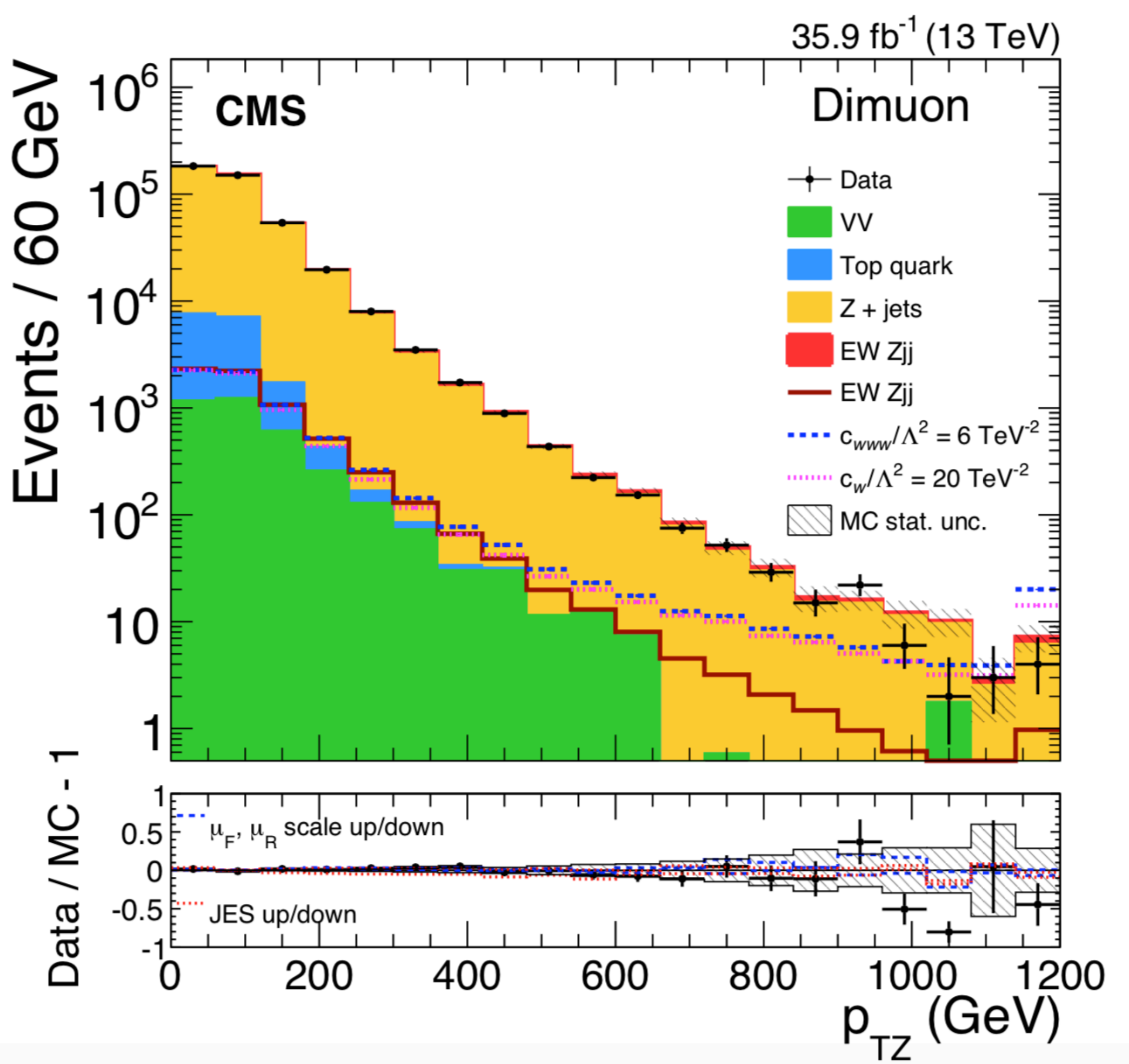
Why making bosons scatter and fuse? aGC

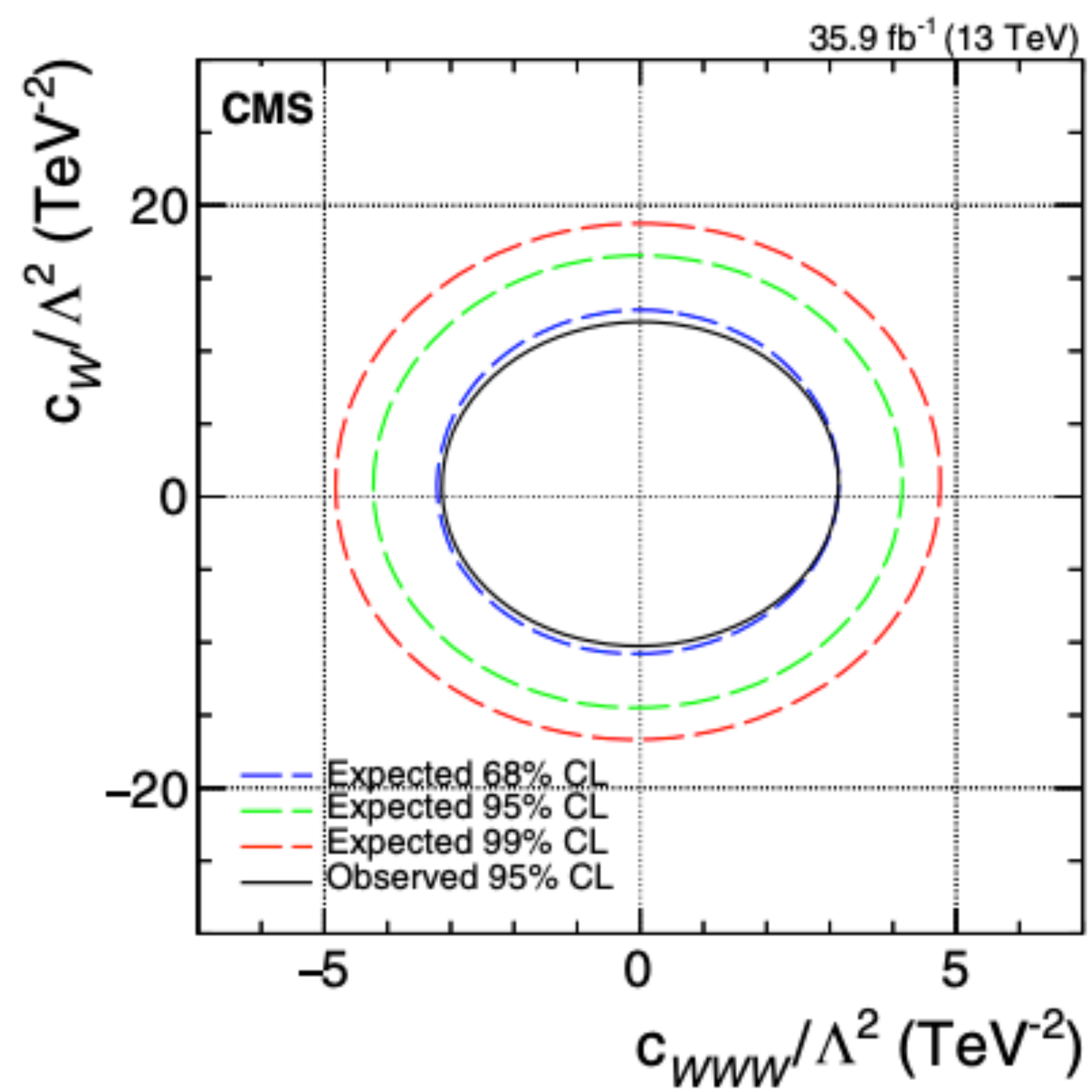
Write down a fully simulated MC with events weighted for the aGC

compare the signal strength with the zero hypothesis as the SM

Use Profiled Likelihood to make 95% CL exclusions

WZ+2J





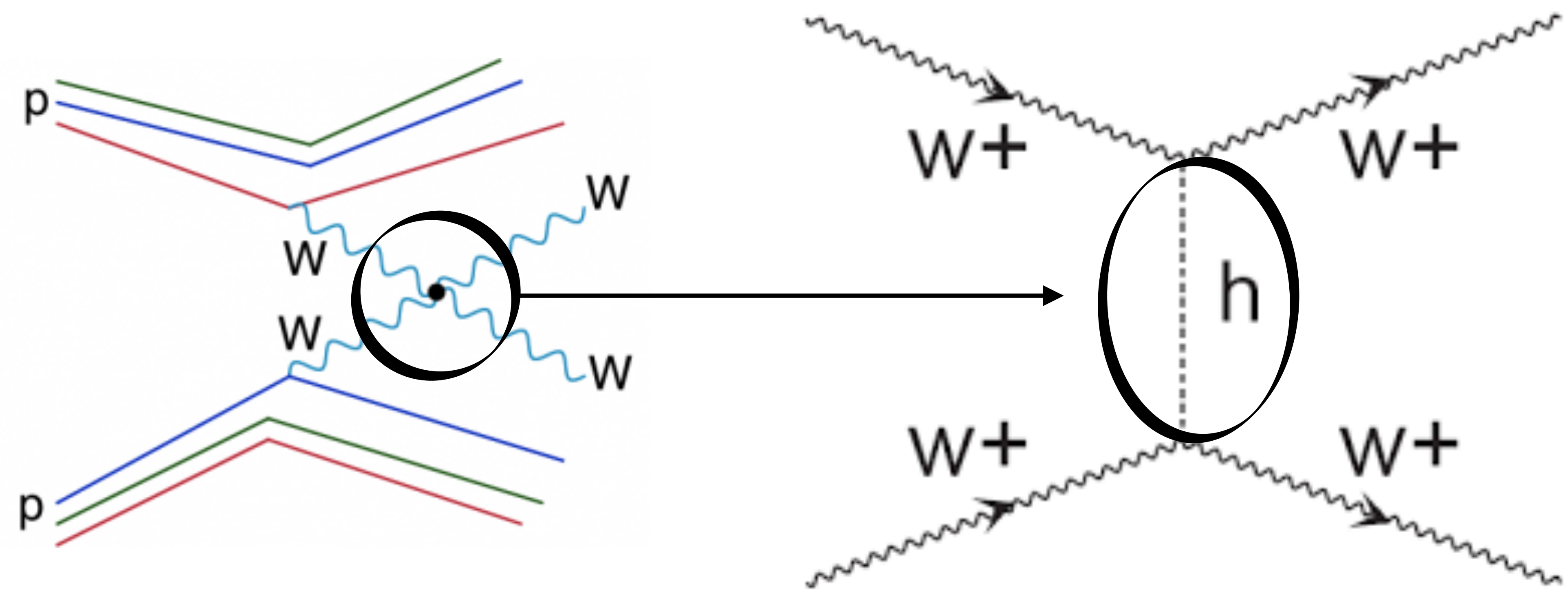
we will get into this
later with the statistics part

Why making bosons scatter and fuse? The Higgs

Let's take the $WW \rightarrow WW$ scattering

The cross section diverges at
$\sqrt{s} = 1.2$ TeV

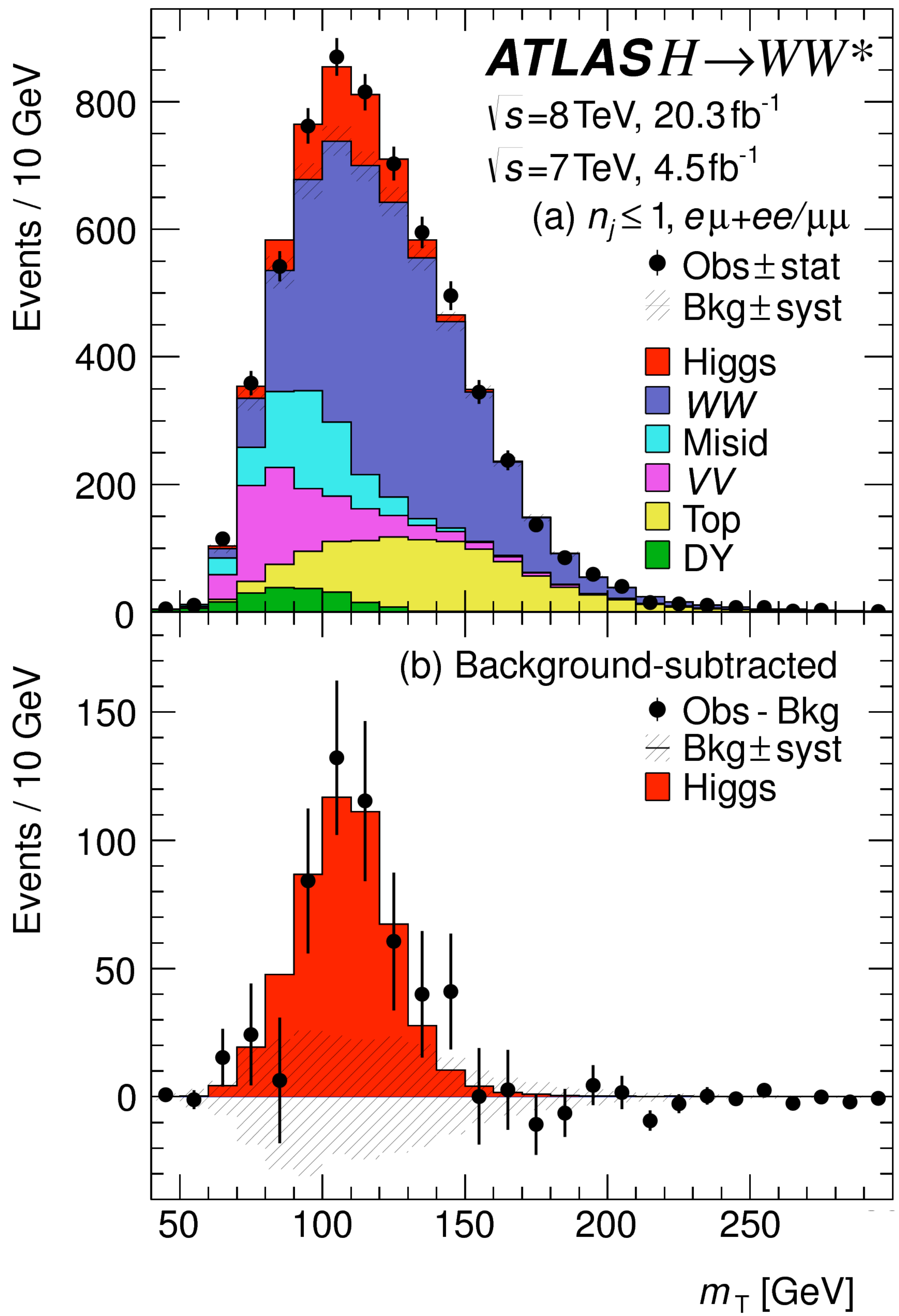
diverges means that
$P \propto |M|^2 > 1$

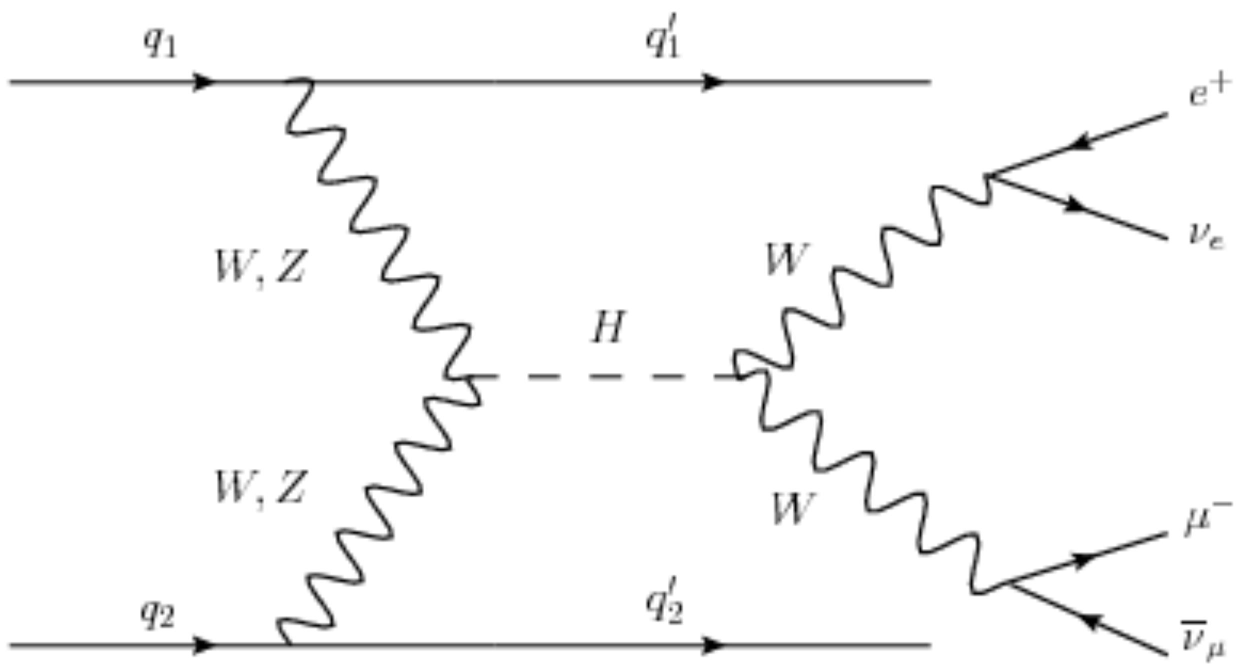


at the heart of the fusion

The $WW \rightarrow WW$ needs a heavy scalar to restore the unitarity of the cross section!

Towards the Higgs





We will focus on the Higgs in the next lecture…