Particle Physics Phenomenology with proton-proton collisions at the LHC

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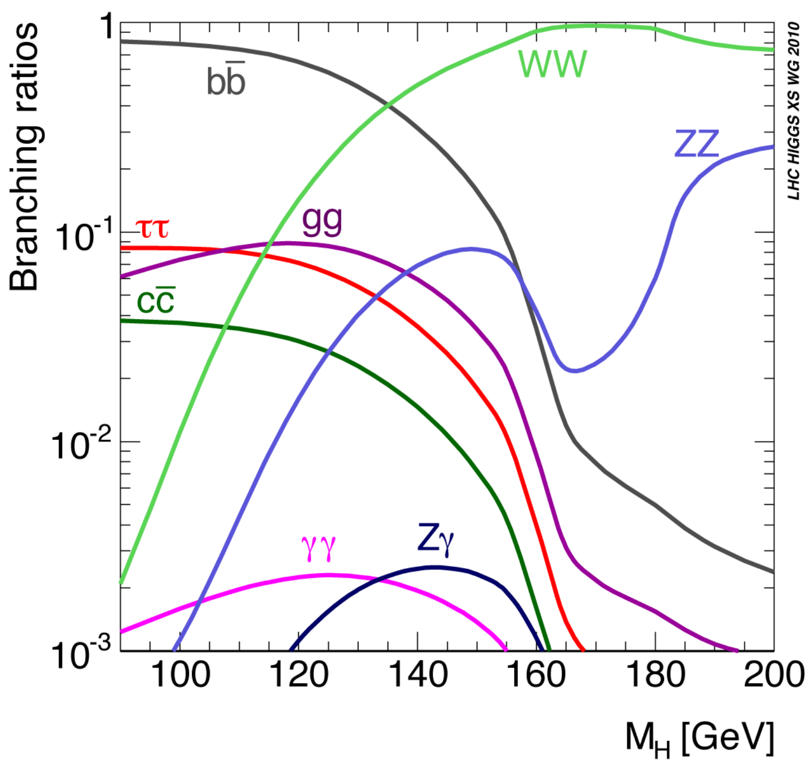
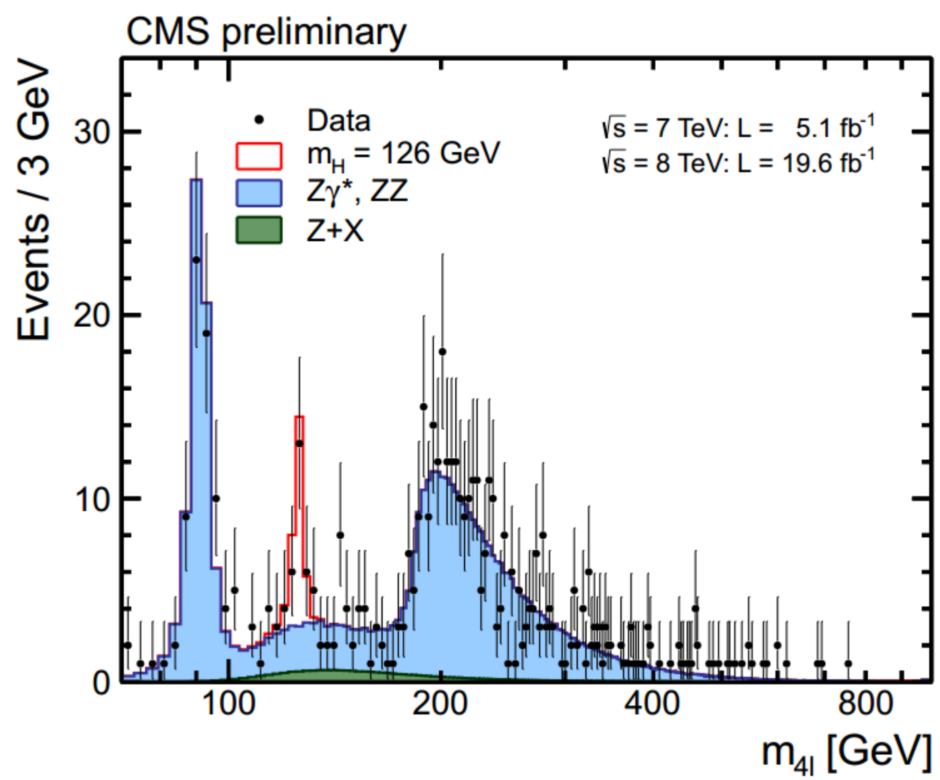
Phenomenology

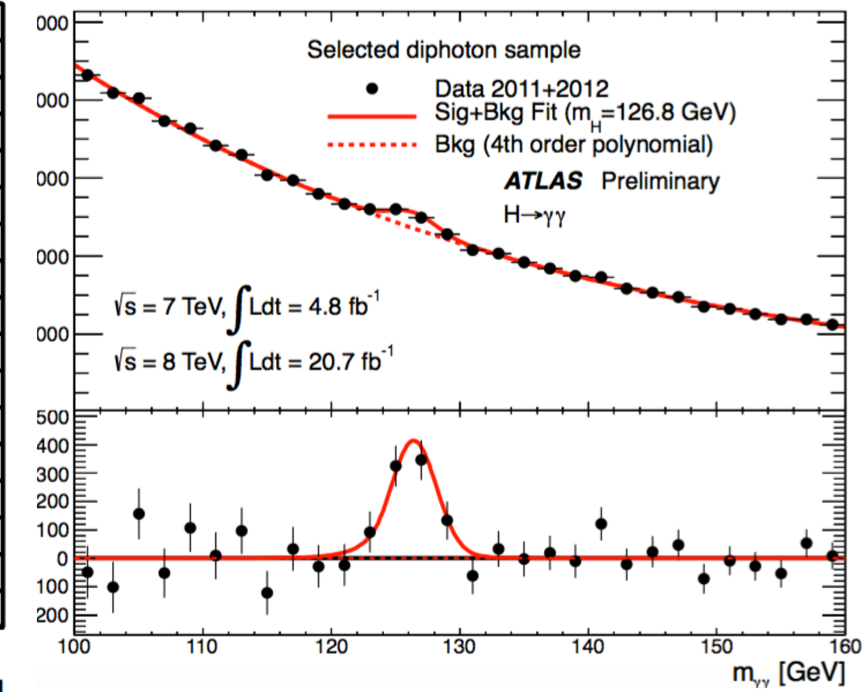
Bridge between our theoretical understanding of particle physics with the results of particle experiments



Higgs decay modes as function of M_H (Standard Model theory)



Higgs discovery plot in ZZ (CMS experiment at the LHC)



Higgs discovery plot in $\gamma\gamma$ (ATLAS experiment at the LHC)

- Quark Model and hadron phenomenology: theory and observation (Gernot)
- Beyond the standard model phenomenology: experimental consequences of New Physics (Igor)
- Standard Model Phenomenology → Theory calculations of detailed predictions for the experiments, at high-precision, including radiative corrections (João)

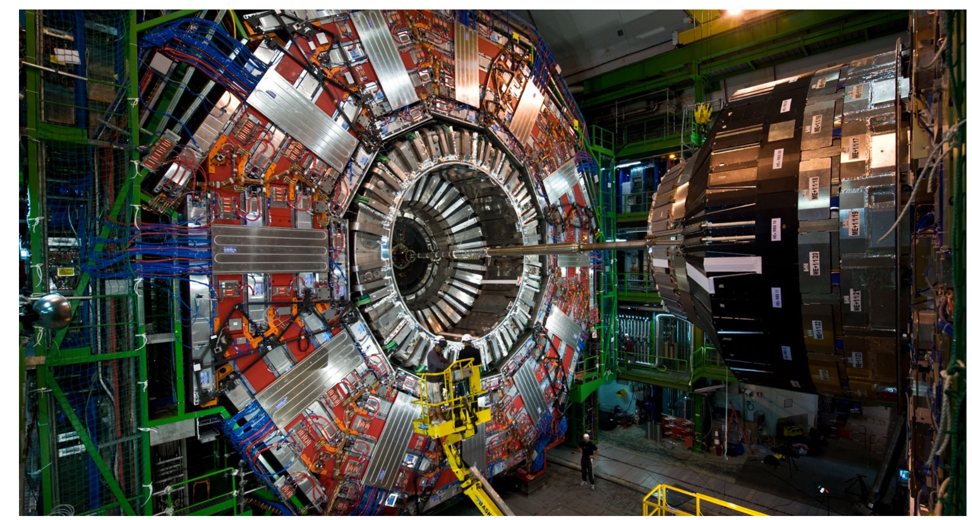
Proton-proton collisions at the LHC

High-energy physics data from the most powerful particle accelerator running in the world

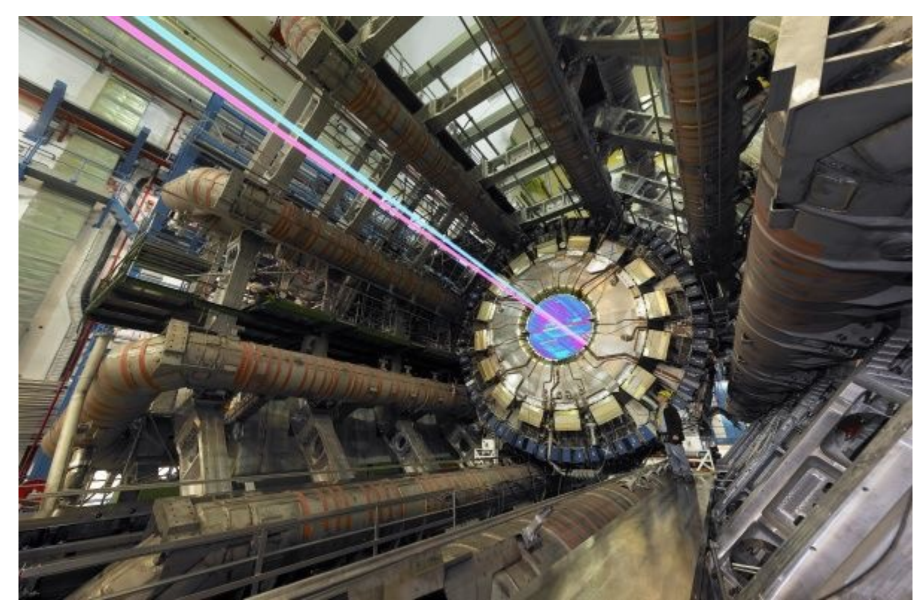
- Built in the CERN complex in Geneva, the LHC accelerates protons up 99.9999991% the speed of light to produce collisions in the interaction points where the detectors record the results of the collisions

Energy of the collision is transformed into matter in the form of new particles according to Einstein's special relativity $E=mc^2$

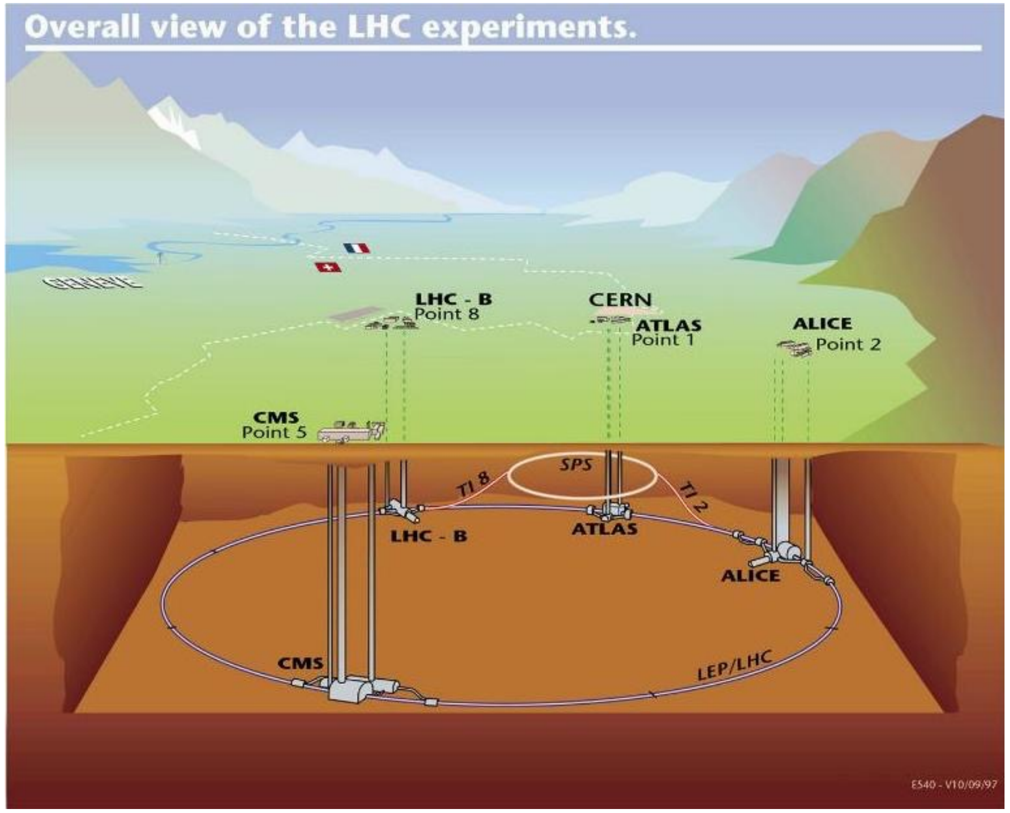
LHC tunnel length = 27 km

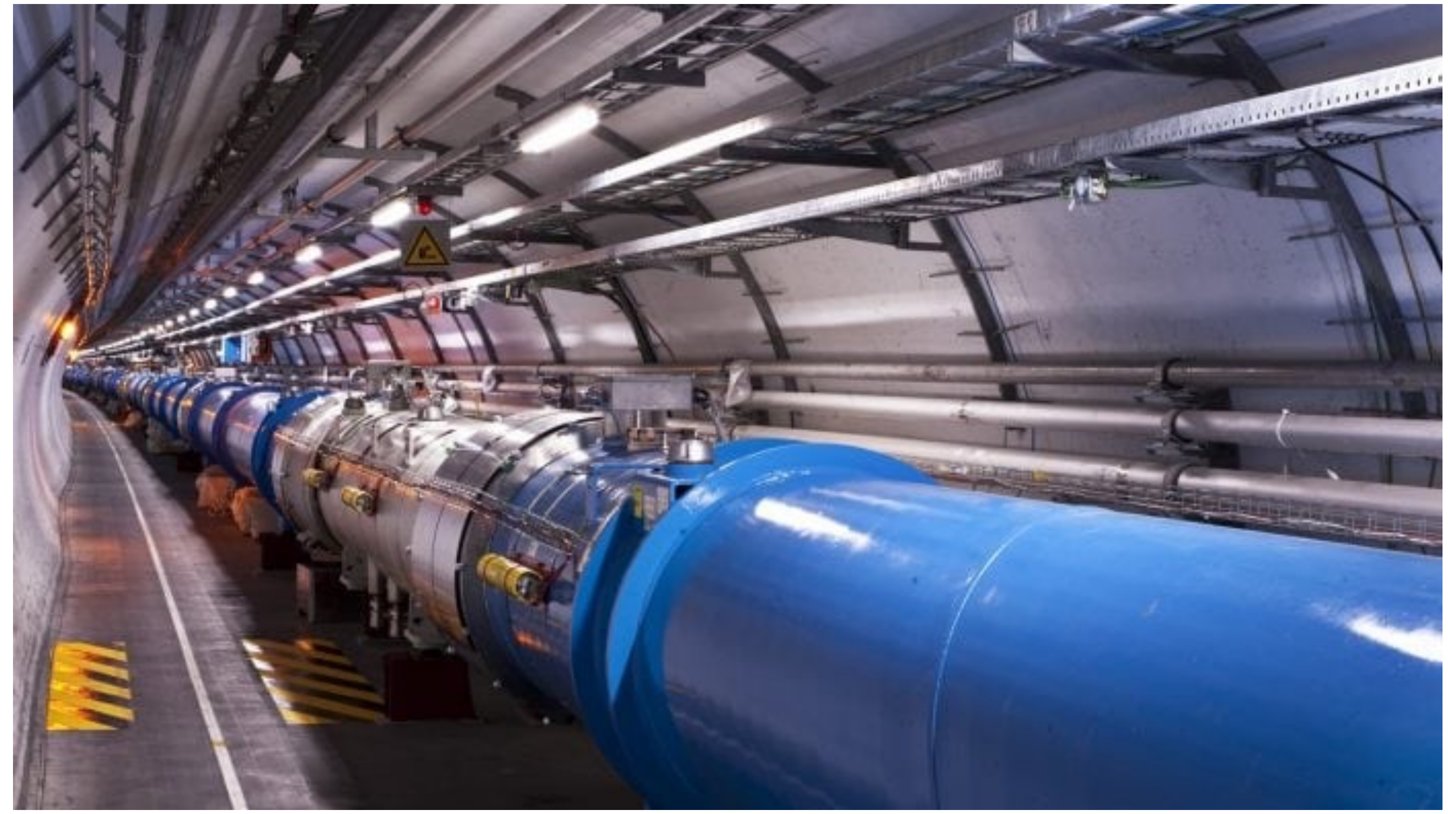


CMS detector



ATLAS detector

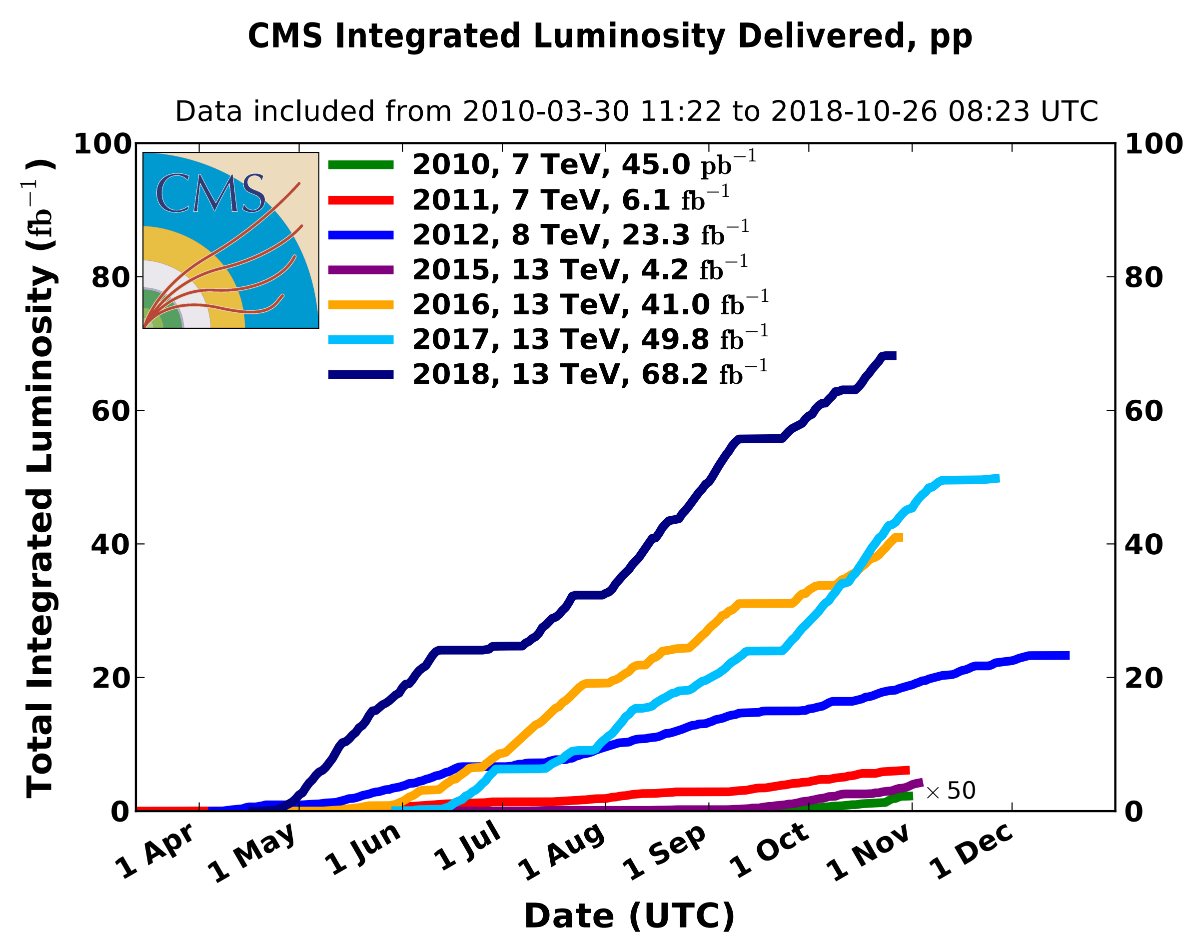




Experiments hosted 100m underground

<u>*LHC status:*</u>

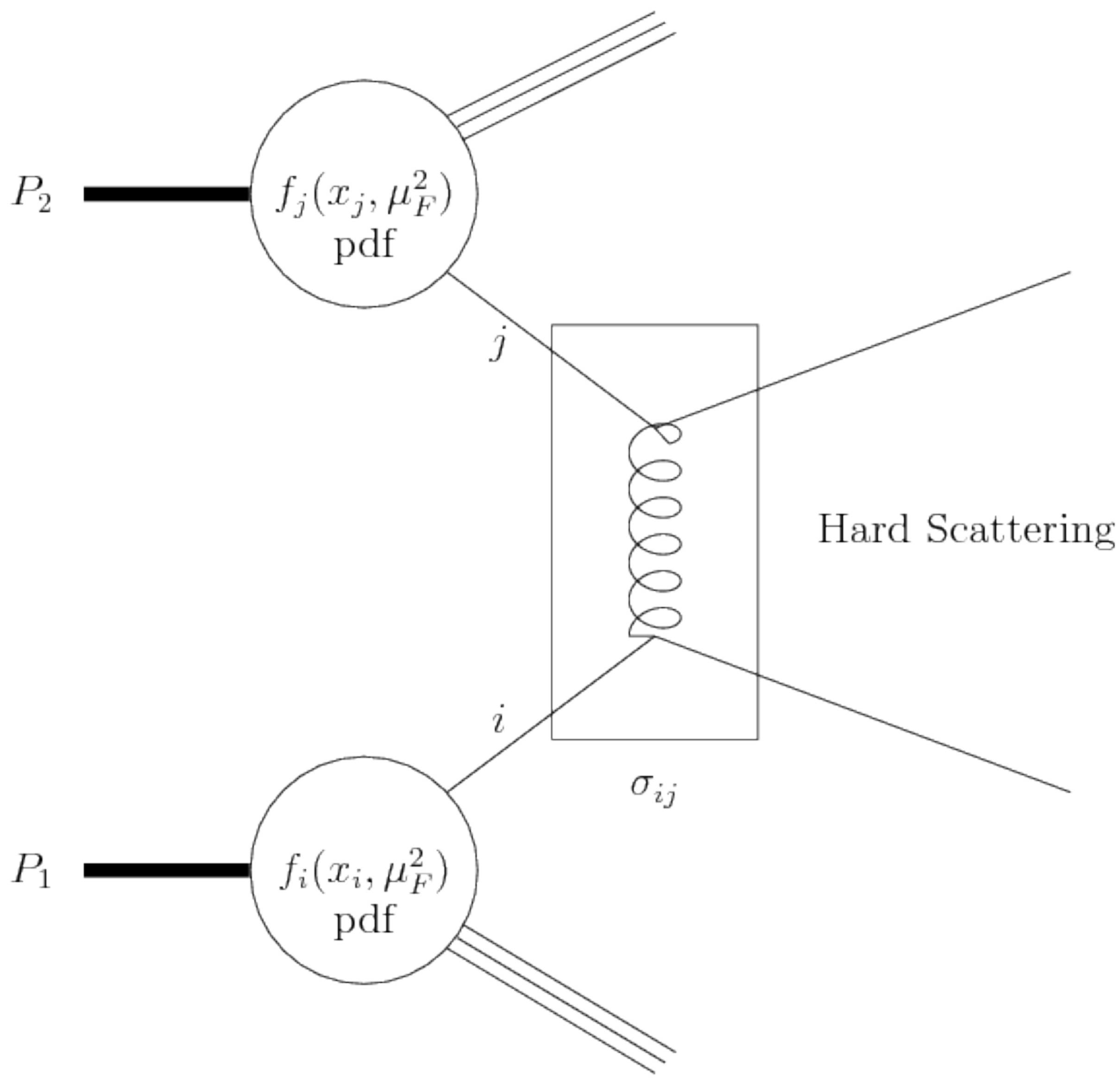
- reached end of run II phase [2015-2018] with *pp* collisions at $\sqrt{s}$=13 TeV and heavy ion collisions
- datasets measured in units of inverse fentobarn L=150 fb^{-1} → $\mathcal{O}(10^{14})$ collisions recorded
- excellent performance from both the accelerator and the detectors → expect many new measurements and physics results → ***N.Castro's talk***
- expect to resume *pp* collisions in 2021 to begin LHC run III at $\sqrt{s}$=14 TeV



Theoretical framework

Inclusive cross section formula for hard scattering process initiated by two hadrons:
Factorization theorem

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), s/\mu^2, s/\mu_F^2)$$



To apply:

- initial state: proton bound state of quarks of gluons
- require large momentum transfer scale of the reaction $Q^2 \gg \Lambda_{hadronic} \approx 200$ MeV, e.g, M_H=125 GeV
- quarks and gluons (proton constituents) behave as free particles in the collision → ***hadron-hadron*** cross section ***factorizes*** into ***parton-level*** cross section $\boldsymbol{\sigma_{ij}}$ between elementary point-like particles convoluted with ***parton distributions***
- compute partonic cross section $\boldsymbol{\sigma_{ij}}$ in perturbation theory from first principles → work in the perturbative region where the coupling constant of the theory QCD,EW is small

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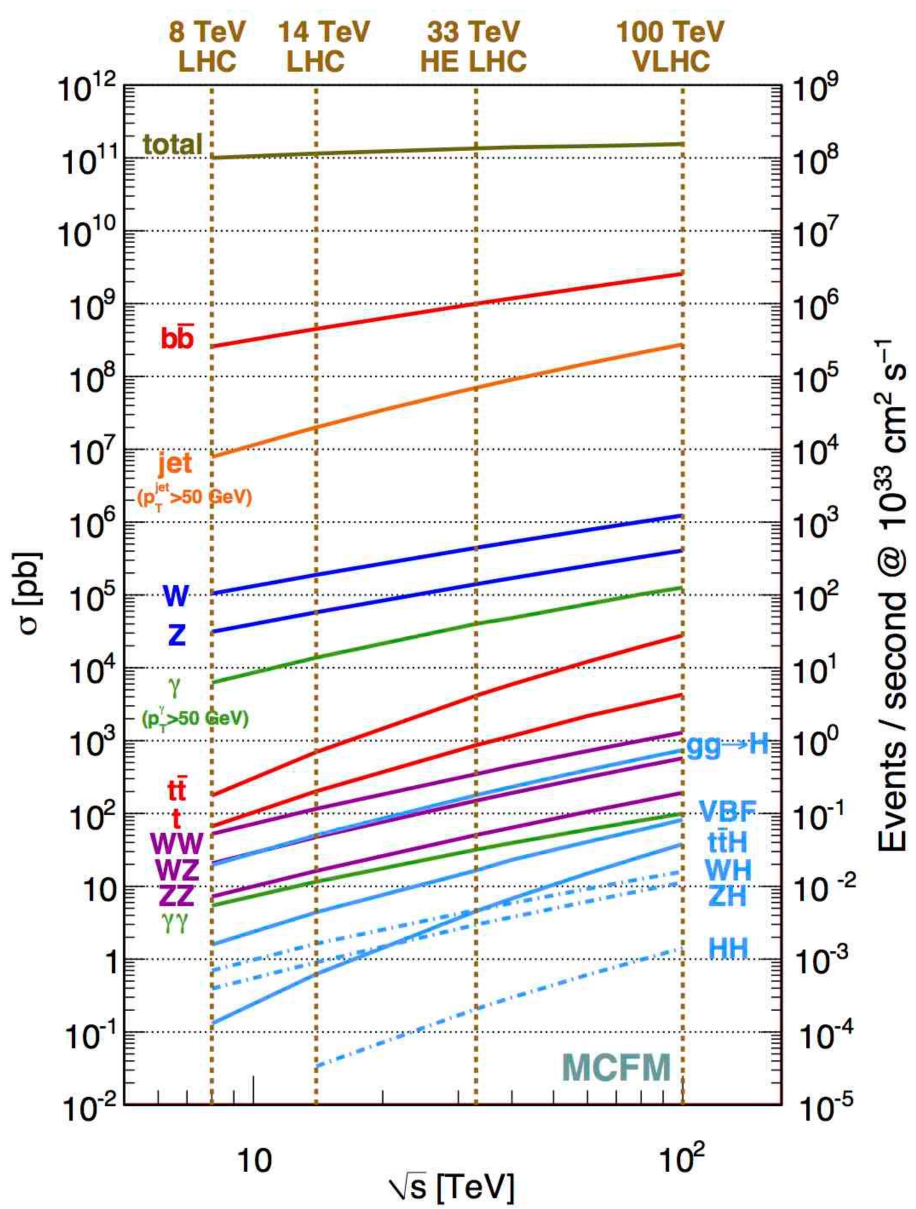

<u>*Theoretical uncertainties:*</u>

- ***Parton distributions:*** probability distribution of quarks and gluons in the proton with fraction *x of* proton momentum → ***universal but non perturbative*** → extracted from data

$$f_i(x,\mu_F^2)$$

- ***Hard partonic cross section: process dependent contributions dictated from the SM Lagrangian and the Feynman diagrams of the process → computable in perturbation theory***

$$\hat{\sigma}_{ij\to X}(Q^2)$$

Special relativity kinematics

- At High-Energy Particle LHC collisions, particles move at speeds close to the speed of light
  → classical relationship for the kinetic energy no longer valid

$$\text{kinetic energy} \neq mv^2/2$$

Postulates of special relativity:

- Laws of physics are invariant in all inertial systems (non-accelerating frames of reference)
- The speed of light in free space is the same in all inertial frames of reference

→ Derive new Lorentz transformations for the conversion of coordinates and times of events between two frames S and S' moving at relative velocity *v*

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$$\begin{aligned} t' &= \gamma\left(t - vx/c^2\right) \\ x' &= \gamma\left(x - vt\right) \\ y' &= y \\ z' &= z, \end{aligned}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\Rightarrow (ct')^2 - (x')^2 - (y')^2 - (z')^2 = (ct)^2 - x^2 - y^2 - z^2$$

Lorentz Invariant !

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- Laws of physics are invariant in all inertial systems (non-accelerating frames of reference)
- The speed of light in free space is the same in all inertial frames of reference

→ Obtain the relativist form for kinetic energy and momentum

$$K = (\gamma - 1)mc^2 \approx mv^2/2 \qquad v \ll c$$

$$E = K + mc^2 = \gamma mc^2$$

$$p = \gamma mv$$

$$\Rightarrow m^2c^4 = E^2 - p^2c^2$$

<u>Lorentz Invariant !</u>

Relativistic phase space integral

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Postulates of special relativity:

- Laws of physics are invariant in all inertial systems (non-accelerating frames of reference)
- The speed of light in free space is the same in all inertial frames of reference

→ Obtain the relativist form for the phase space

$$E' = \gamma(E - vp_x)$$
$$p'_x = \gamma(p_x - v/c^2 E)$$
$$p'_y = p_y$$
$$p'_z = p_z$$

$$\frac{dp'_x}{dp_x} = \gamma\left(1 - \frac{v}{c^2}\frac{dE}{dp_x}\right) = \gamma\left(1 - v\frac{p_x}{E}\right) = \frac{E'}{E}$$

$$\Rightarrow \frac{dp'_x}{E'} = \frac{dp_x}{E}$$

$$R_n(E) = \frac{1}{(2\pi)^{3n}} \int \prod_{i=1}^{n} \frac{d^3 p_i}{2E_i} (2\pi)^4 \delta^4(P - \sum_{i=1}^{n} p_i)$$

QCD Lagrangian

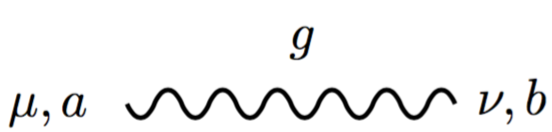
- Theory to describe the interactions between quarks and gluons charged under color

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - g_s\bar{\psi}\gamma^{\mu}T^{a}G^{a}_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}G^{a}_{\mu\nu}G^{a,\mu\nu}$$

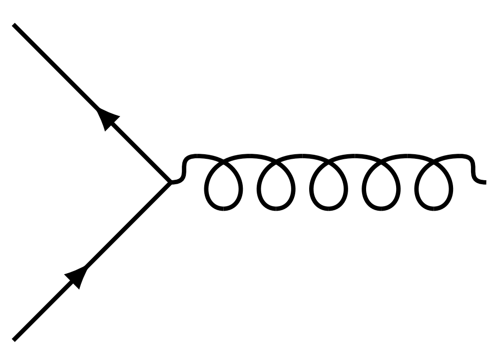
- Lorentz Invariant with $\psi - \text{quark field} \quad ; \quad G_{\mu} - \text{gluon field}$

- The Feynman rules follow

$$(\gamma^{\mu}p_{\mu} - m)u(p) = 0$$



$$: -\frac{ig_{\mu\nu}\delta^{ab}}{q^2}$$



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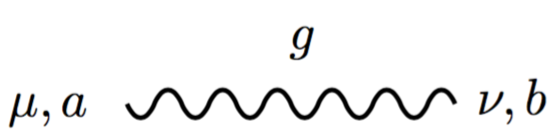

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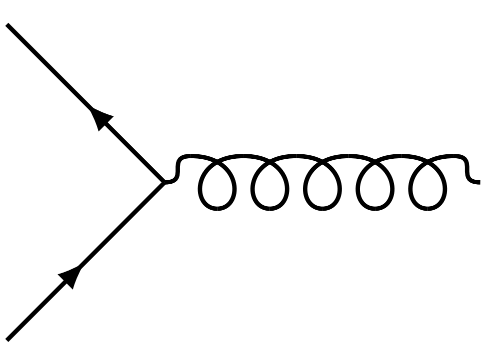
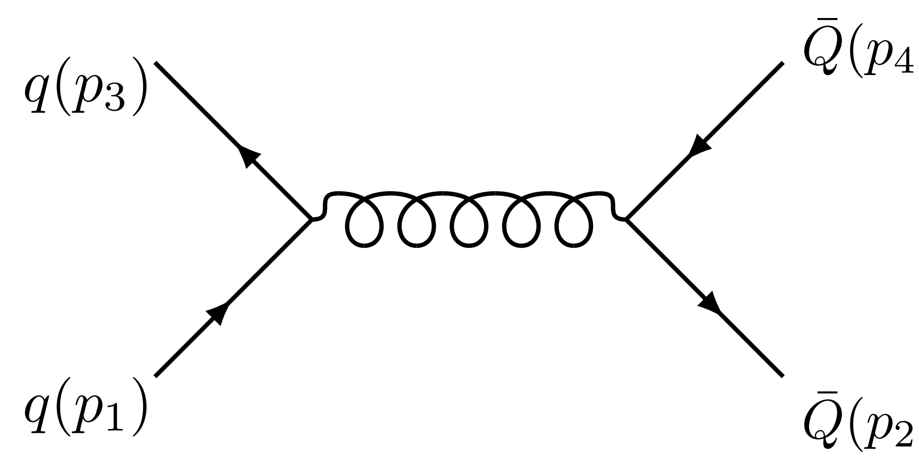


$$: iT^a_{ij}\gamma^{\mu}$$

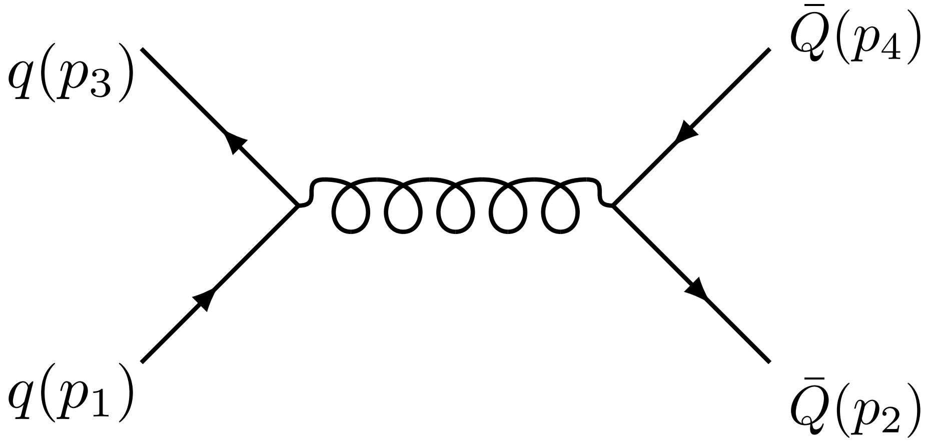
- quark-antiquark scattering amplitude

$$q(p_1)\bar{Q}(p_2) \to q(p_3)\bar{Q}(p_4)$$



$$\mathcal{M} = -g_s^2 \frac{1}{(p_1 - p_3)^2}[\bar{u}(3)\gamma^{\mu}u(1)][\bar{v}(2)\gamma_{\mu}v(4)]\ (T^a_{i_1 i_3}T^a_{i_4 i_2})$$

- quark-antiquark scattering amplitude $q(p_1)\bar{Q}(p_2) \to q(p_3)\bar{Q}(p_4)$



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- squaring the amplitude yields a double trace over the fermion lines

$$\begin{aligned} |\mathcal{M}|^2 &= (N^2-1)\frac{g_s^4}{(p_1-p_3)^4}[\bar{u}(3)\gamma^\mu u(1)][\bar{u}(1)\gamma^\nu u(3)][\bar{v}(2)\gamma_\mu v(4)][\bar{v}(4)\gamma_\nu v(2)] \\ &= (N^2-1)\frac{g_s^4}{(p_1-p_3)^4}\, Tr(\gamma^\mu \not{p}_1 \gamma^\nu \not{p}_3)\, Tr(\gamma_\mu \not{p}_4 \gamma_\nu \not{p}_2) \\ &= (N^2-1)\frac{g_s^4}{(p_1-p_3)^4}\, 8\; ((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)) \\ &= (N^2-1)\; g_s^4 \; \frac{2(s^2+u^2)}{t^2} \end{aligned}$$

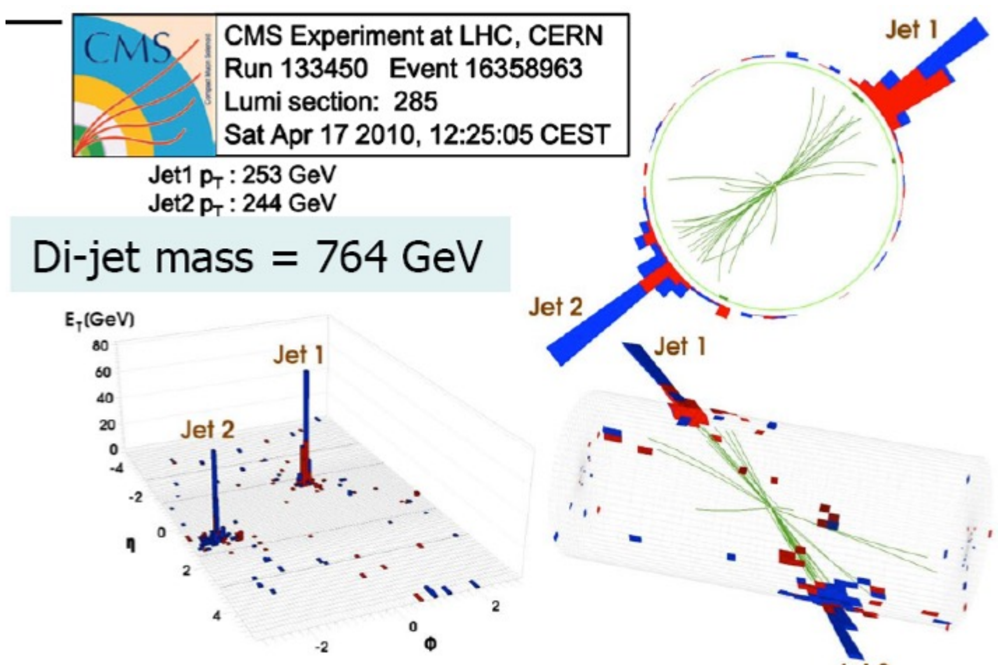
- using momentum-conservation and defining

$$s = (p_1+p_2)^2$$
$$t = (p_1-p_3)^2$$
$$u = (p_2-p_3)^2$$

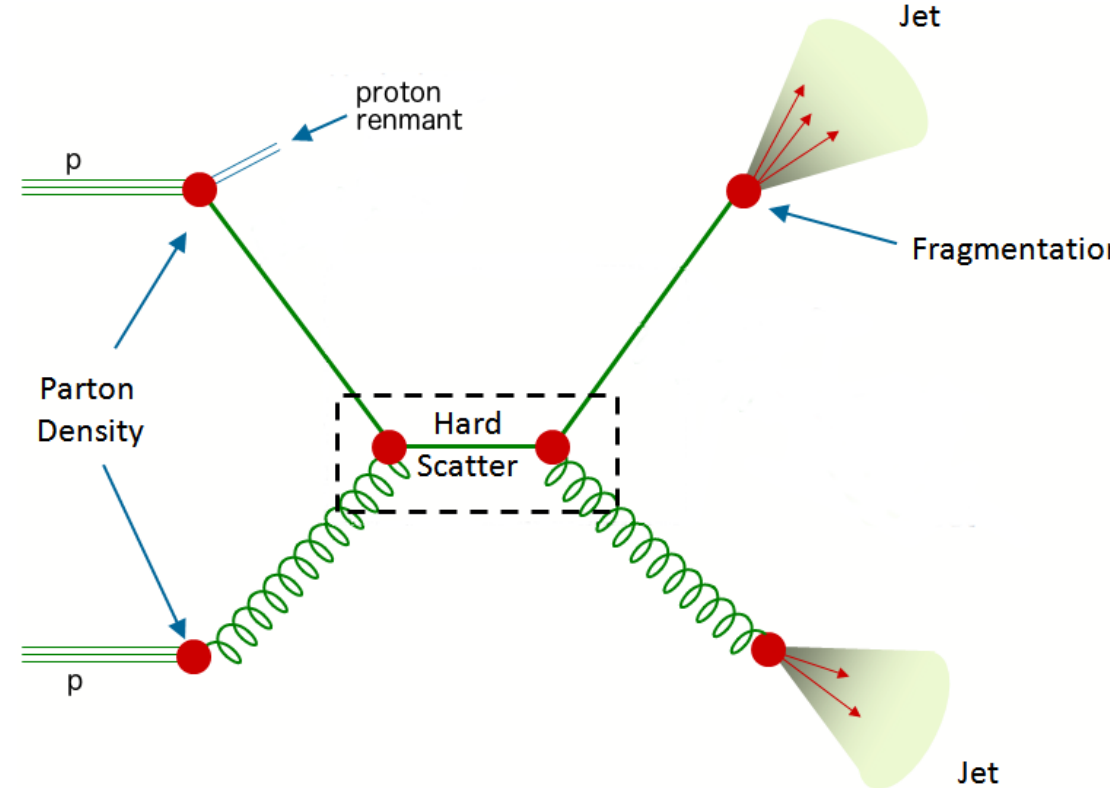
Jet cross section prediction at the LHC

Scattering with large transverse momentum outgoing quarks/gluons produce QCD radiation forming a spray of collimated charged particles → Jet

2-jet event recorded by the CMS detector



what we measure



what we calculate

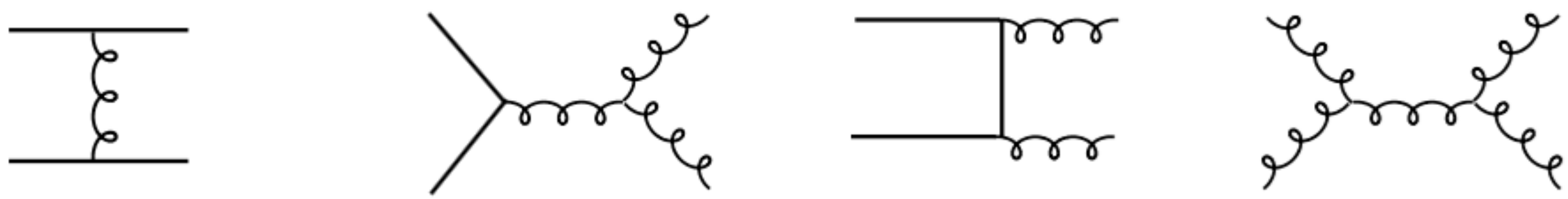
- Using the tools developed in the previous slides can now make the connection between the experimental measurement and the theory prediction

Jet cross section prediction at the LHC

Scattering with large transverse momentum outgoing quarks/gluons produce QCD radiation forming a spray of collimated charged particles → Jet

- Identify all partonic subprocesses

$$q\bar{q} \to q\bar{q}\ , \quad q\bar{q} \to gg\ , \quad qg \to qg\ , \quad gg \to gg\ , \ldots$$



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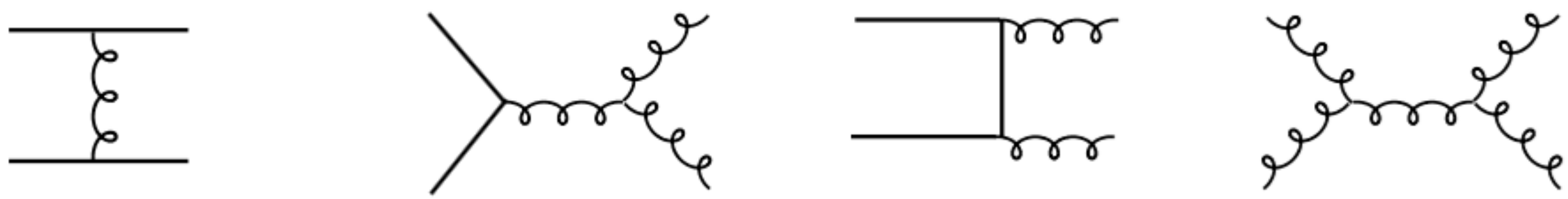

- For each one obtain the matrix element

$$\mathcal{M}_{ij\to kl}(p)$$

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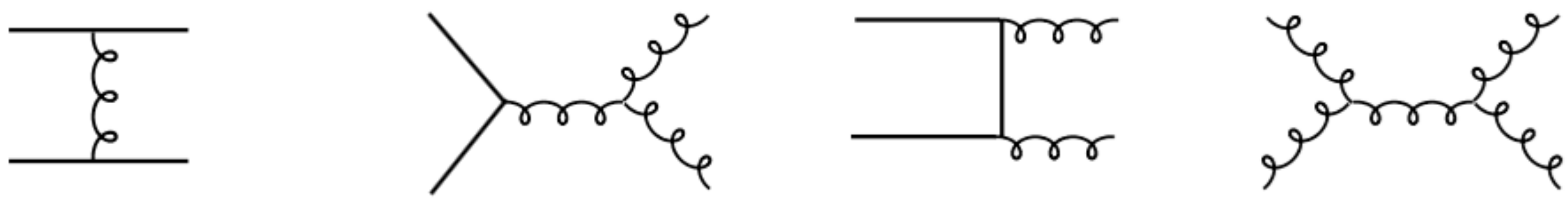

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- Square the matrix element, sum over spins and color, integrate over the phase space

$$d\hat{\sigma} = \frac{1}{2\hat{s}} \sum |\mathcal{M}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \frac{dp_3^3}{2E_3(2\pi)^3} \frac{dp_4^3}{2E_4(2\pi)^3}$$

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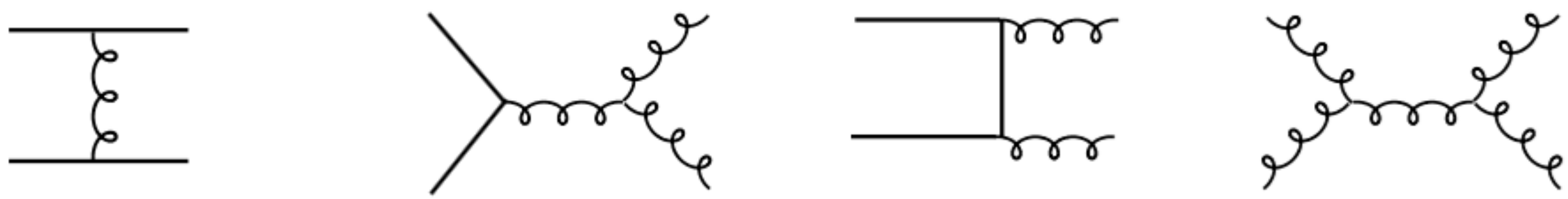

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- Convolute partonic cross section $\mathrm{d}\hat{\sigma}$ with the parton distribution functions $f_i(x, \mu_F^2)$ according to the factorization theorem → Monte-Carlo code for event generation/theory - data comparison

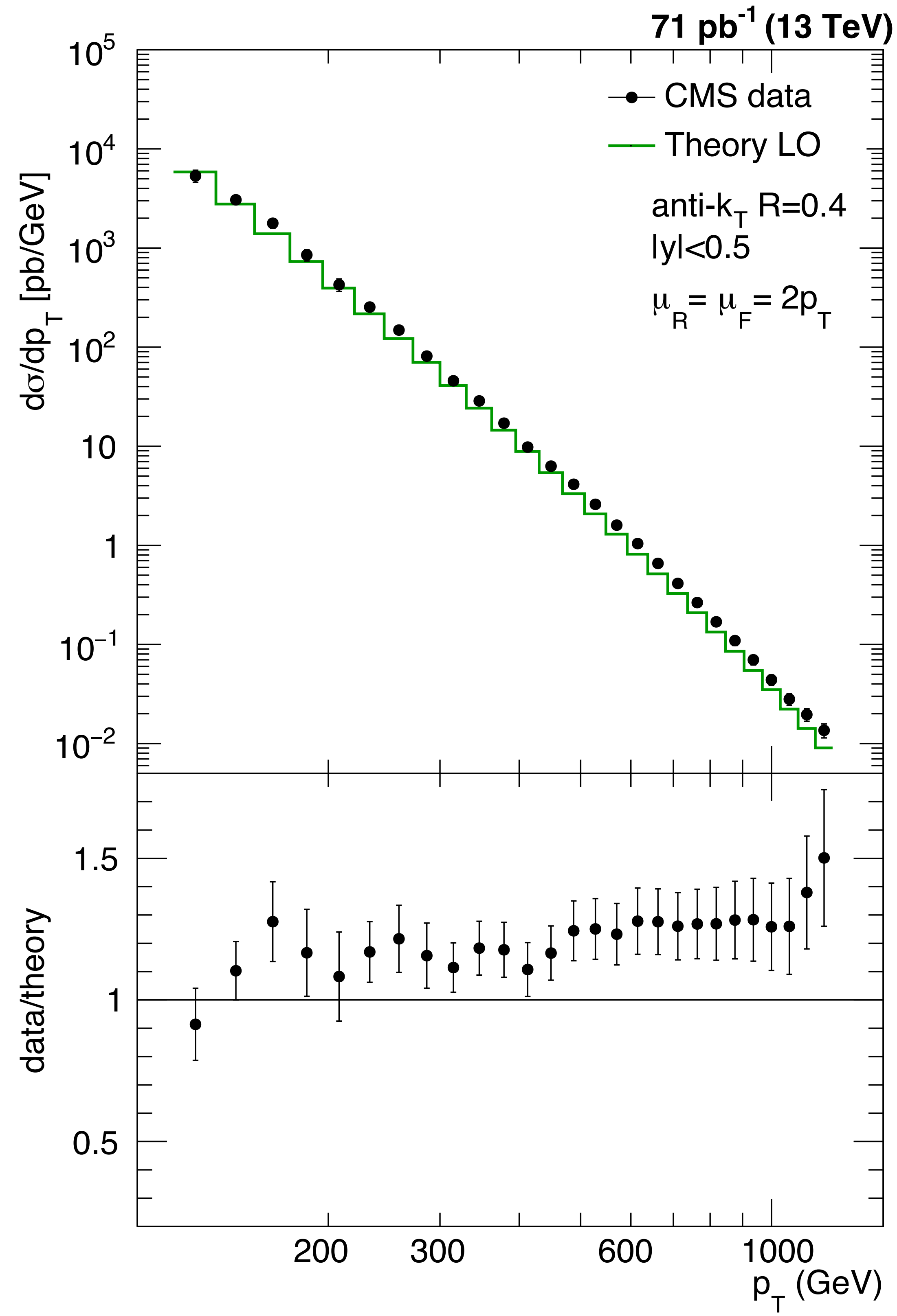
Comparison with LHC data

- Measurement of the jet p_T cross section by the CMS collaboration

run-II data at 13 TeV !

- Steeply falling p_T spectrum over 6 orders of magnitude

- At high-p_T data shows an excess over the theory prediction



Jet p_T distribution

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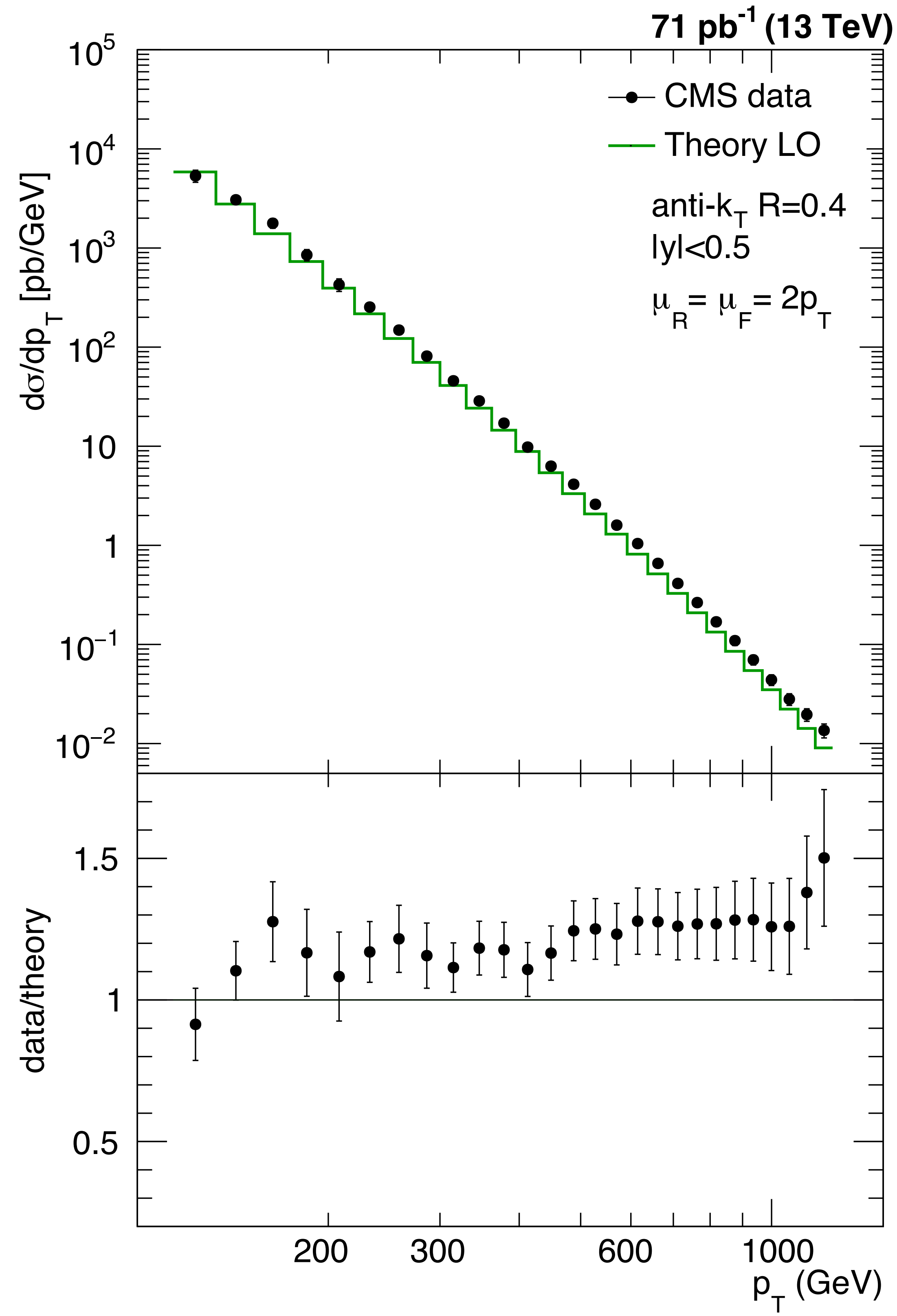
<u>Assuming the measurement is correct:</u>

A: new physics contribution ?

B: problem in the theory calculation ?

*<u>Need phenomenology for **A** and **B** !</u>*



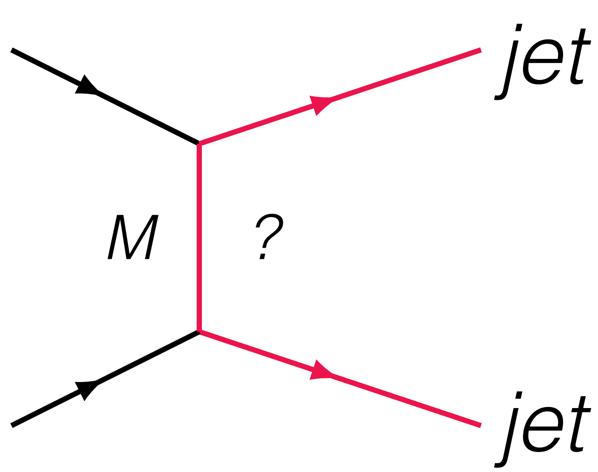
Jet p_T distribution

A: new physics contribution ?

Adding a new physics contribution of the type:

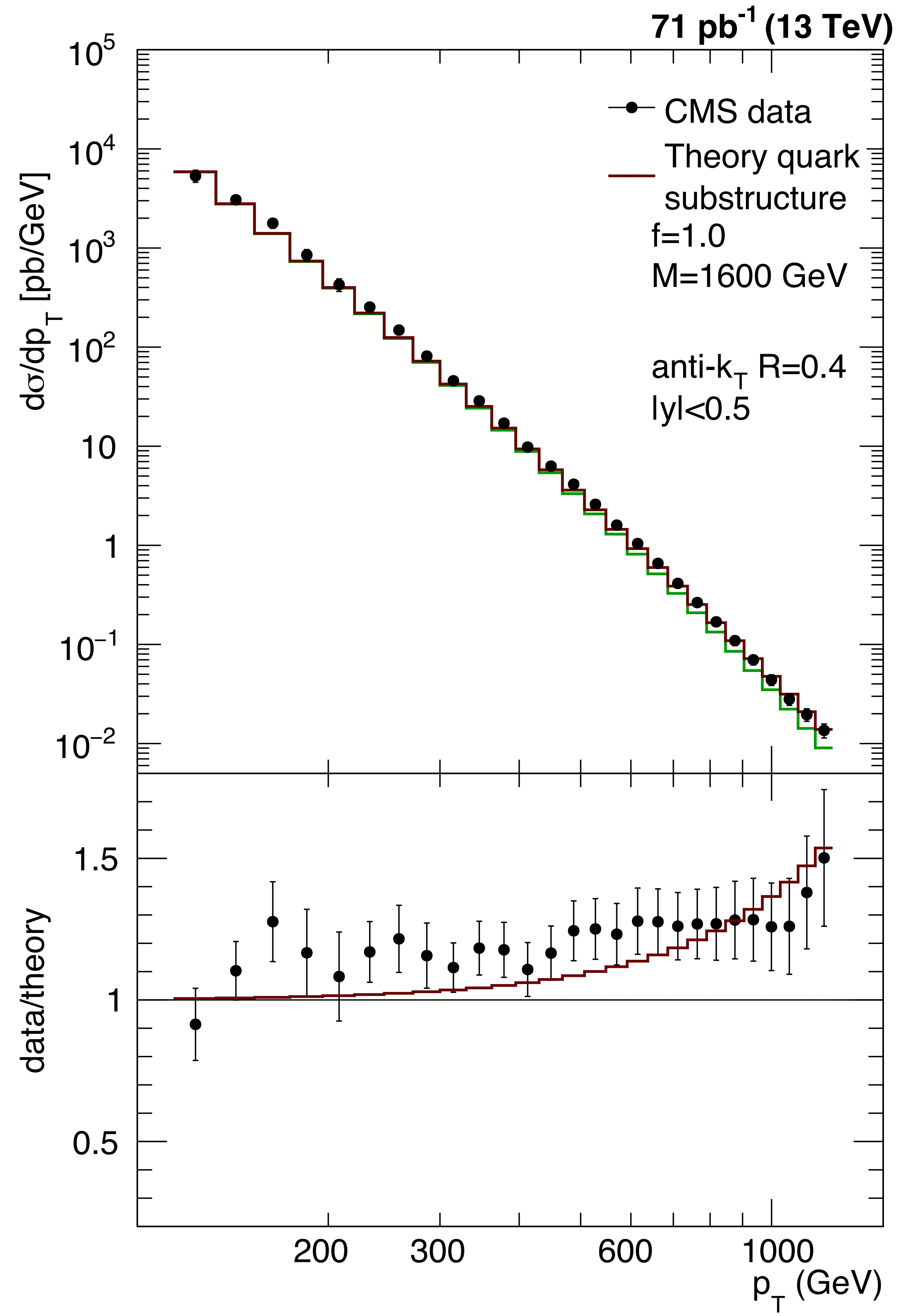
$$\Delta\mathcal{L} = \frac{f^2}{M^2}\bar{\psi}\gamma^\mu\psi\,\bar{\psi}\gamma_\mu\psi$$

- leads to four fermion interactions due to exchange of a new particle of mass *M* → excitation of internal quark substructure



- leads to an enhancement of the theory prediction at large p_T (ex: *f=1* and *M*=1.6 TeV)

$$\Delta\sigma \sim f^2\frac{p_T^2}{M^2}$$

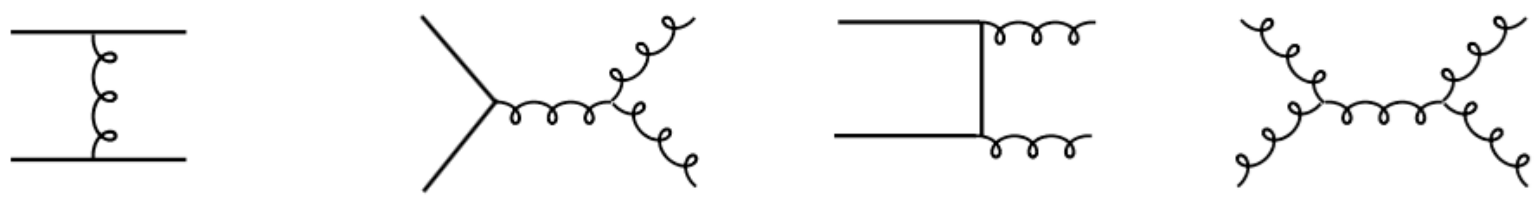


Jet p_T distribution

B: problem in the theory calculation ?

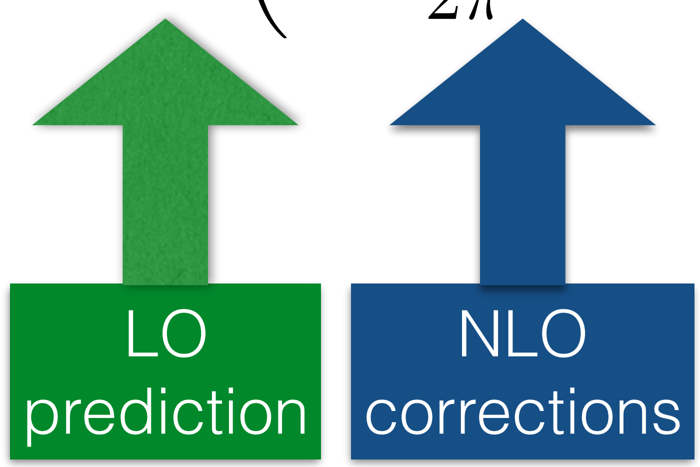
$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), s/\mu^2, s/\mu_F^2)$$

- Identify all partonic subprocesses



- parton-level cross section can be computed as a series in perturbation theory

$$\hat{\sigma}(p_1, p_2) = \sigma_{LO} \left(1 + \frac{\alpha_s}{2\pi}\sigma_1 + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma_2 + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma_3 + \ldots\right) \quad \alpha_s(M_Z) = 0.118$$



- NLO corrections suppressed by α_s but NLO diagrams contribute to the observable we are measuring

B: problem in the theory calculation ?

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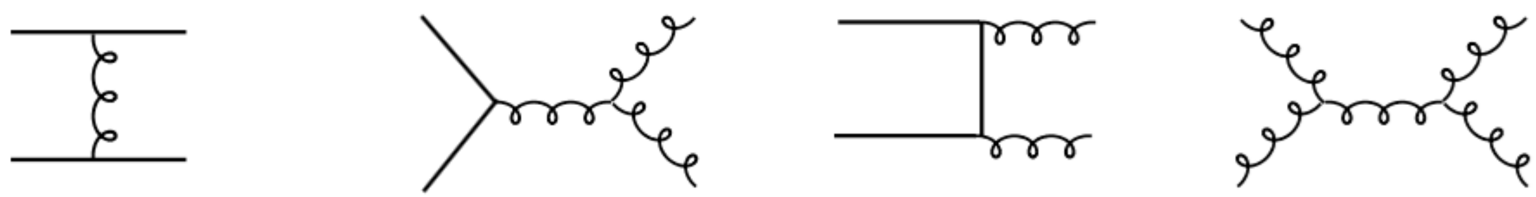
- Identify all partonic subprocesses



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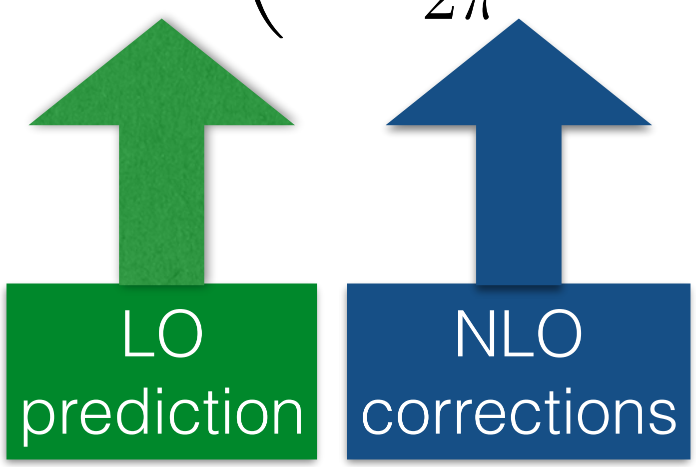
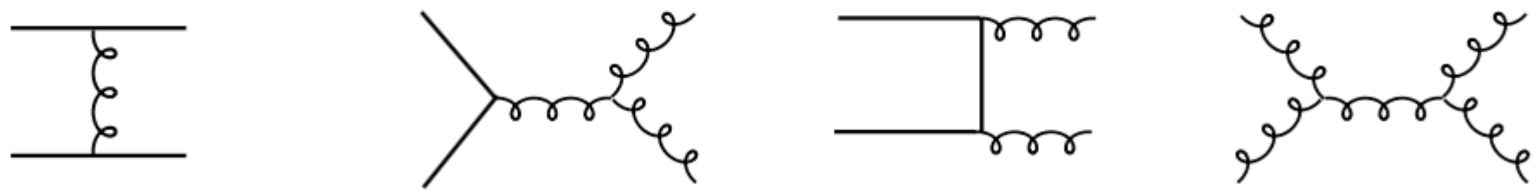


- NLO corrections suppressed by α_s but NLO diagrams contribute to the observable we are measuring

LHC data always measures the result of the full series, independent of our ability to calculate it or not!

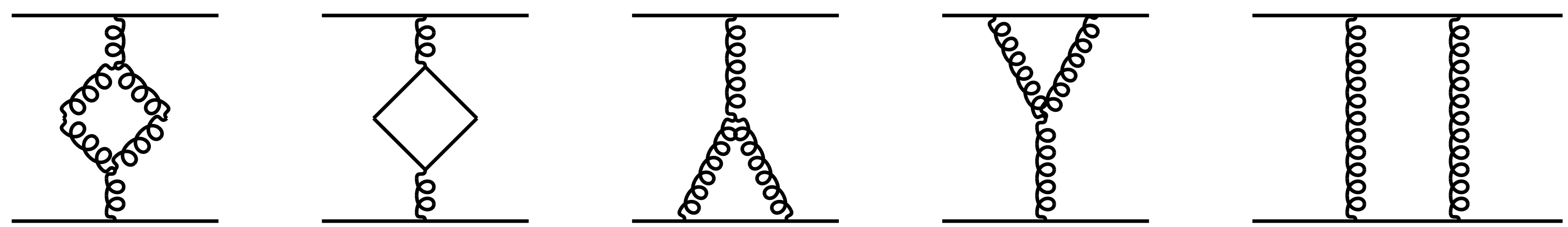
$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2 f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2)\hat{\sigma}_{ij}(p_1,p_2,\alpha_s(\mu^2),s/\mu^2,s/\mu_F^2)$$

- Identify all partonic subprocesses



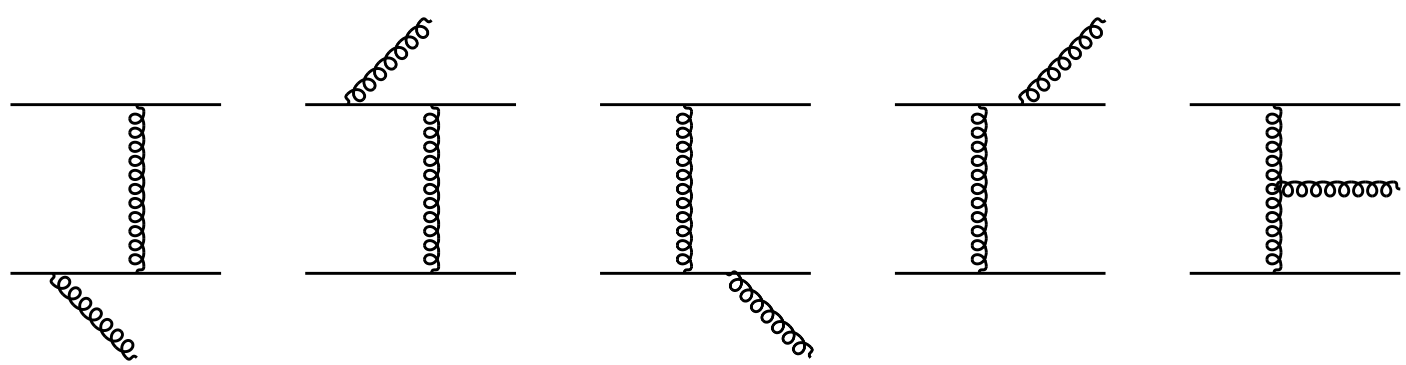
QCD corrections at NLO

virtual



. . .

real



. . .

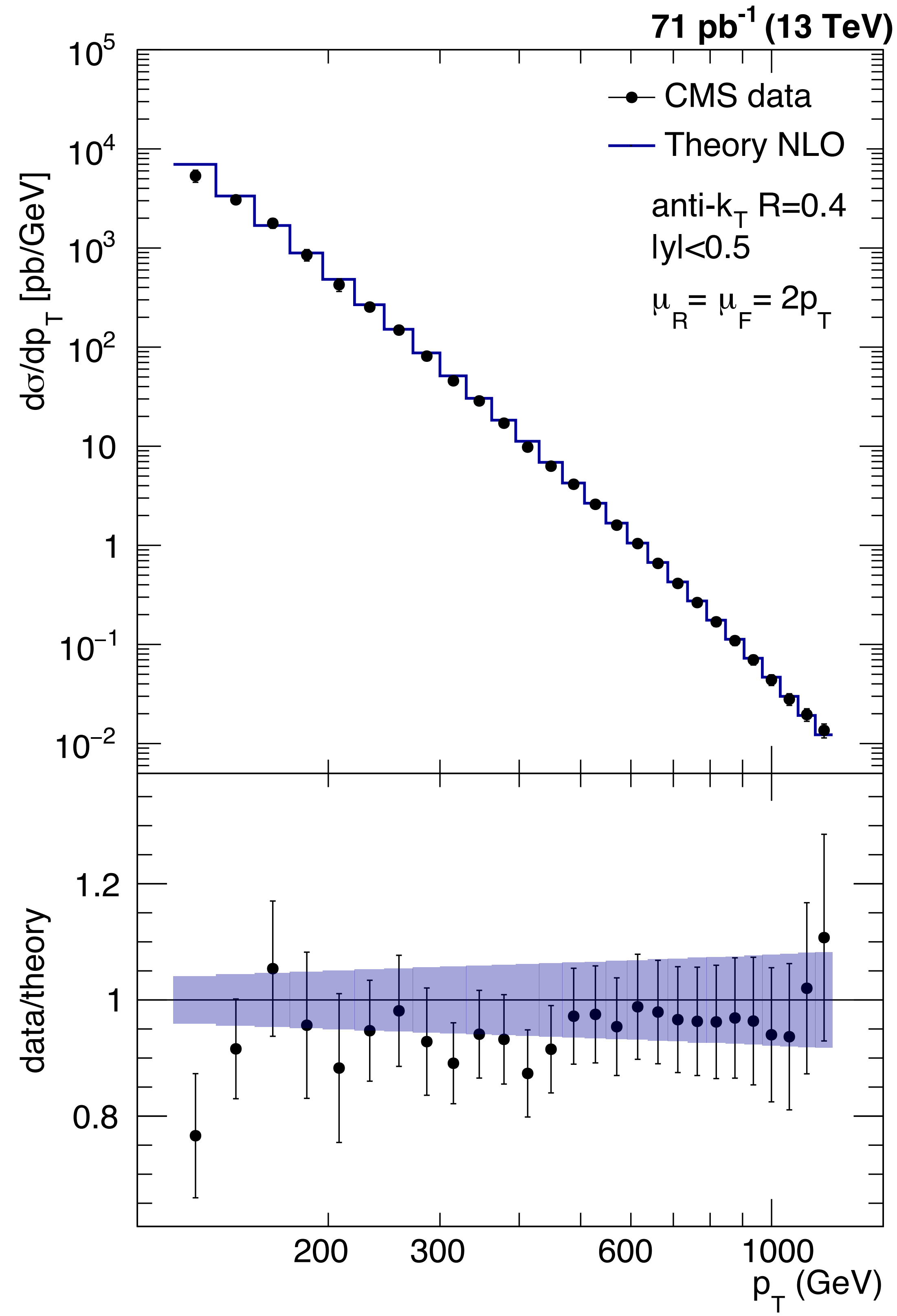
- In the limit of soft/collinear emission NLO diagrams contribute to the 2-jet final state!
- Including higher corrections improves predictions and reduces theoretical uncertainties

Comparison with LHC data

- Measurement of the jet p_T cross section by the CMS collaboration

run-II data at 13 TeV !

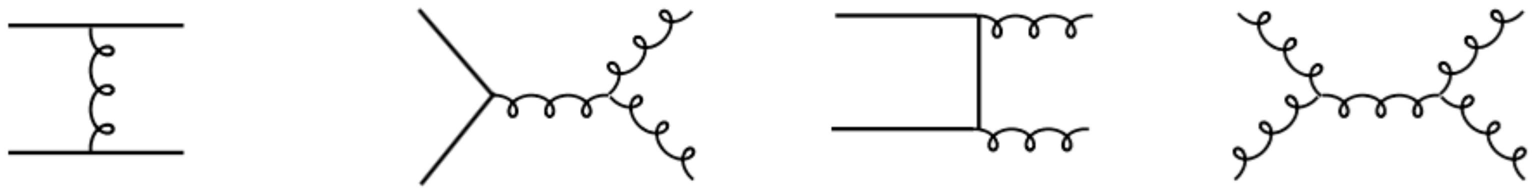
- Steeply falling p_T spectrum over 6 orders of magnitude
- Significant improved agreement between the data and the NLO prediction
- Blue band estimates the uncertainty of the theory prediction



Jet p_T distribution

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), s/\mu^2, s/\mu_F^2)$$

- Identify all partonic subprocesses

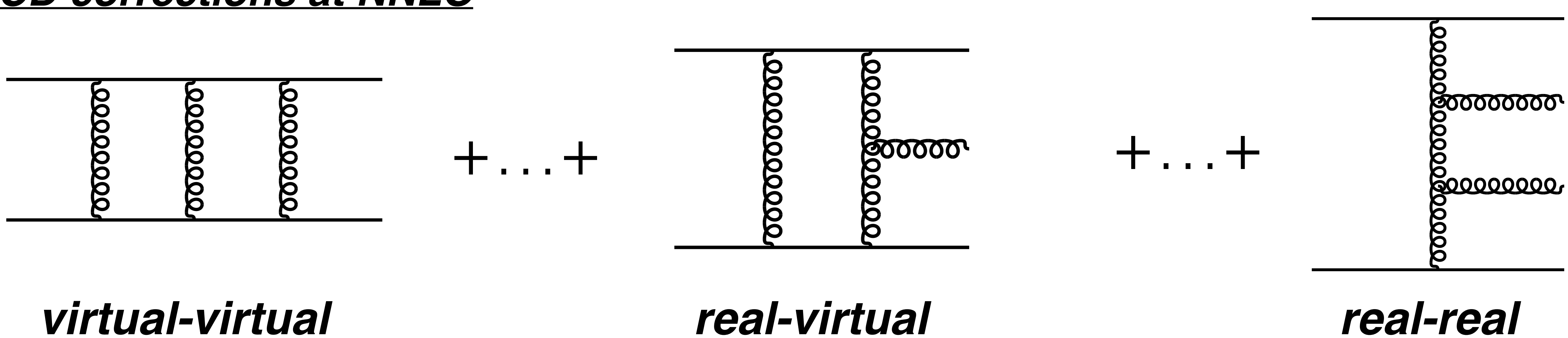


$$\hat{\sigma}(p_1, p_2) = \sigma_{LO} \left(1 + \frac{\alpha_s}{2\pi}\sigma_1 + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma_2 + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma_3 + \ldots\right) \qquad \alpha_s(M_Z) = 0.118$$

J.Currie, E.W.N.Glover, J.Pires
Phys. Rev. Lett.118, 072002 (2017)

J.Currie, T.Gehrmann, A.Gehrmann-De Ridder, N.Glover, A.Huss, J.Pires
JHEP 1810 (2018) 155

QCD corrections at NNLO



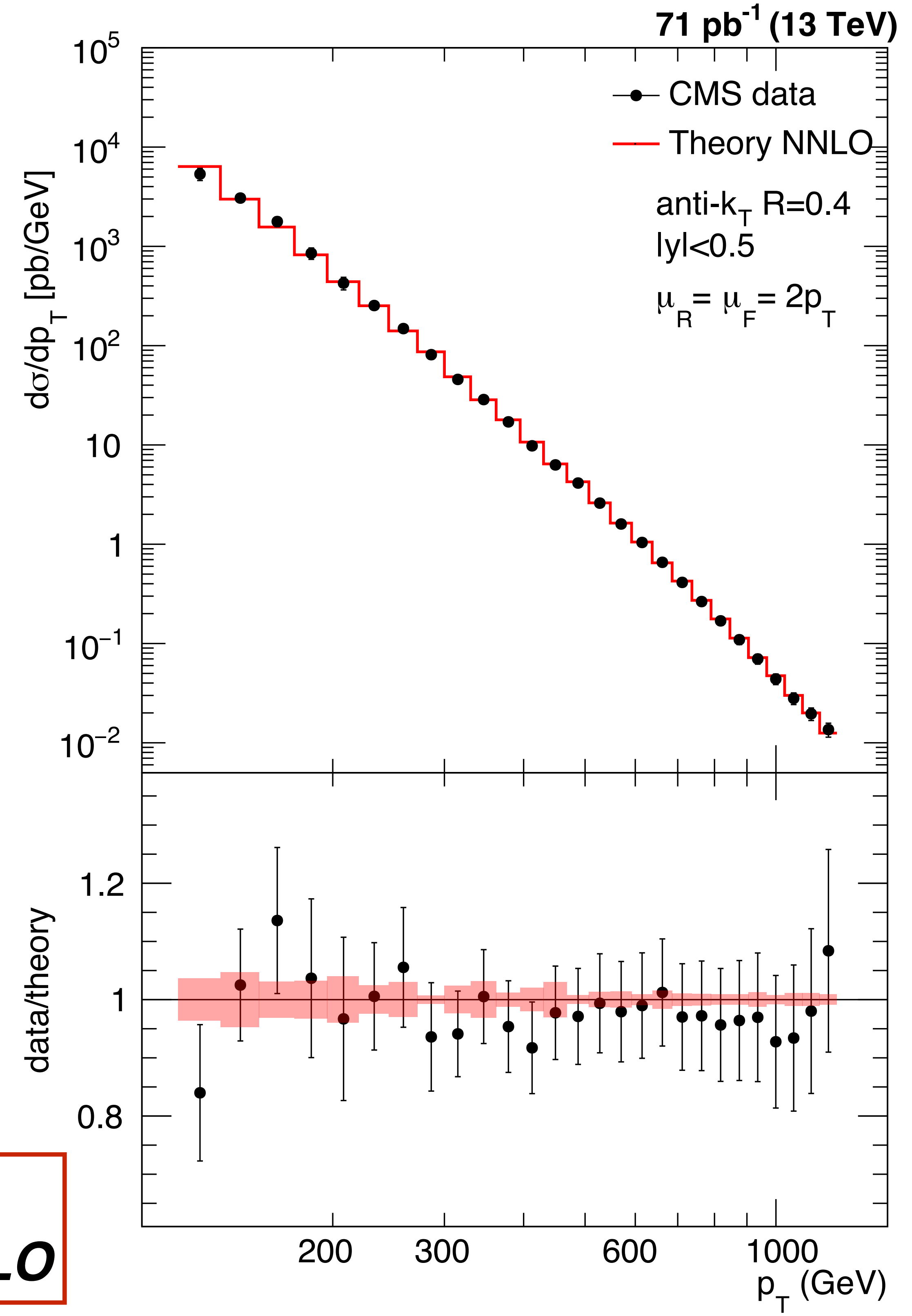
Comparison with LHC data

- Measurement of the jet p_T cross section by the CMS collaboration

run-II data at 13 TeV !

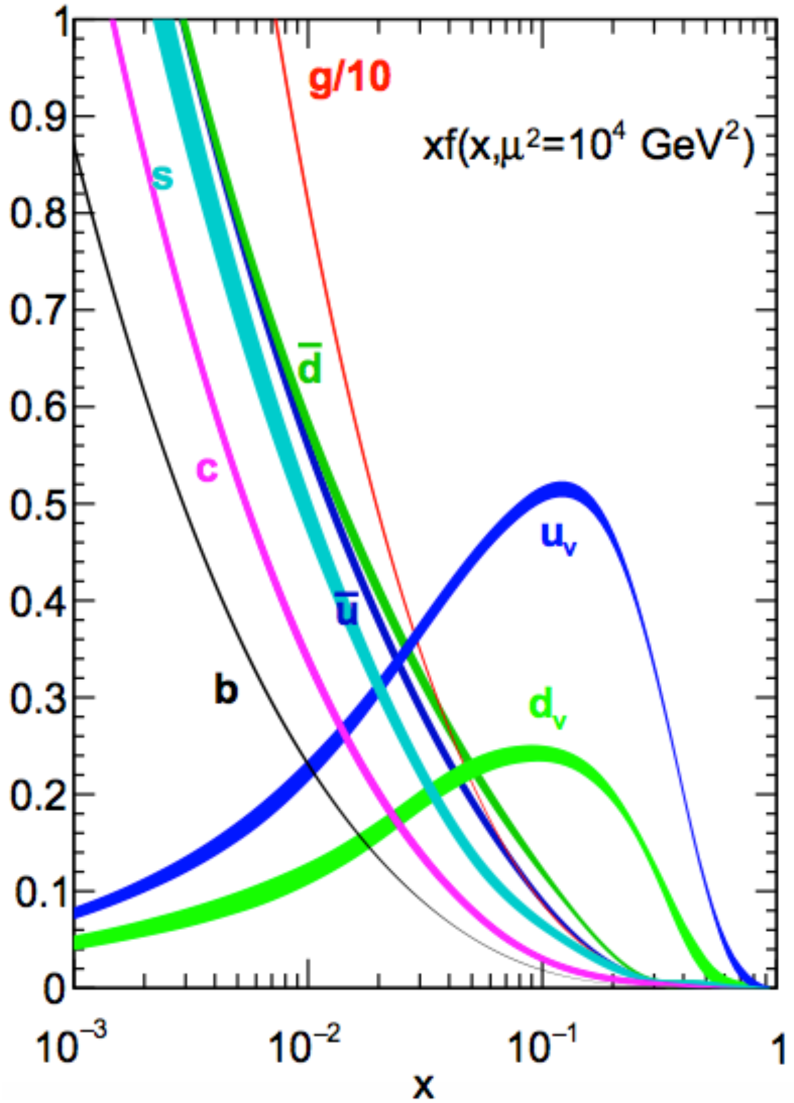
- Steeply falling p_T spectrum over 6 orders of magnitude
- Data well described by the NNLO prediction
  → *eliminates evidence for New Physics*
- Significant reduction of the theory uncertainty with respect to NLO (δ_{th} below 5%)

Ongoing: use good description of data to constrain parton distribution functions at NNLO

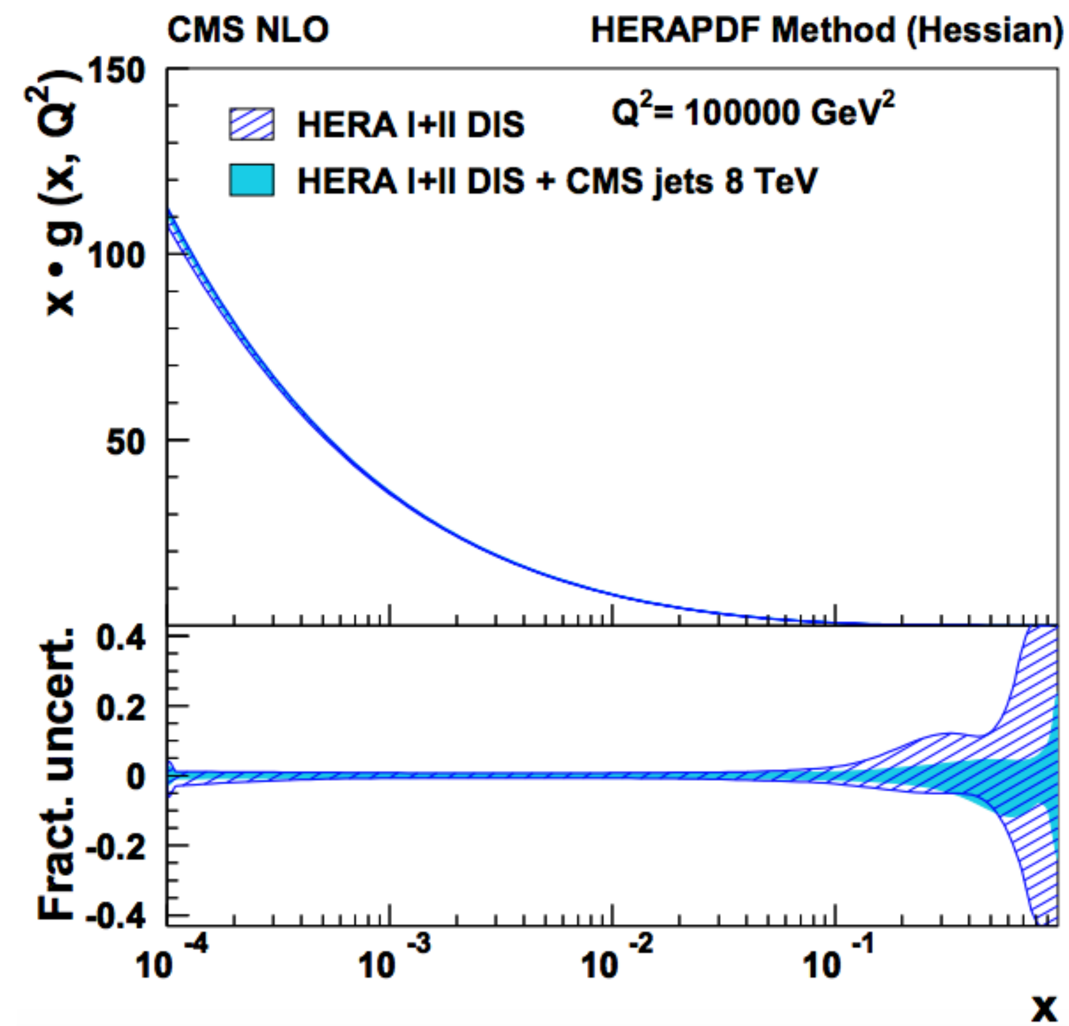


Jet p_T distribution

Ongoing: use good description of data to constrain parton distribution functions at NNLO



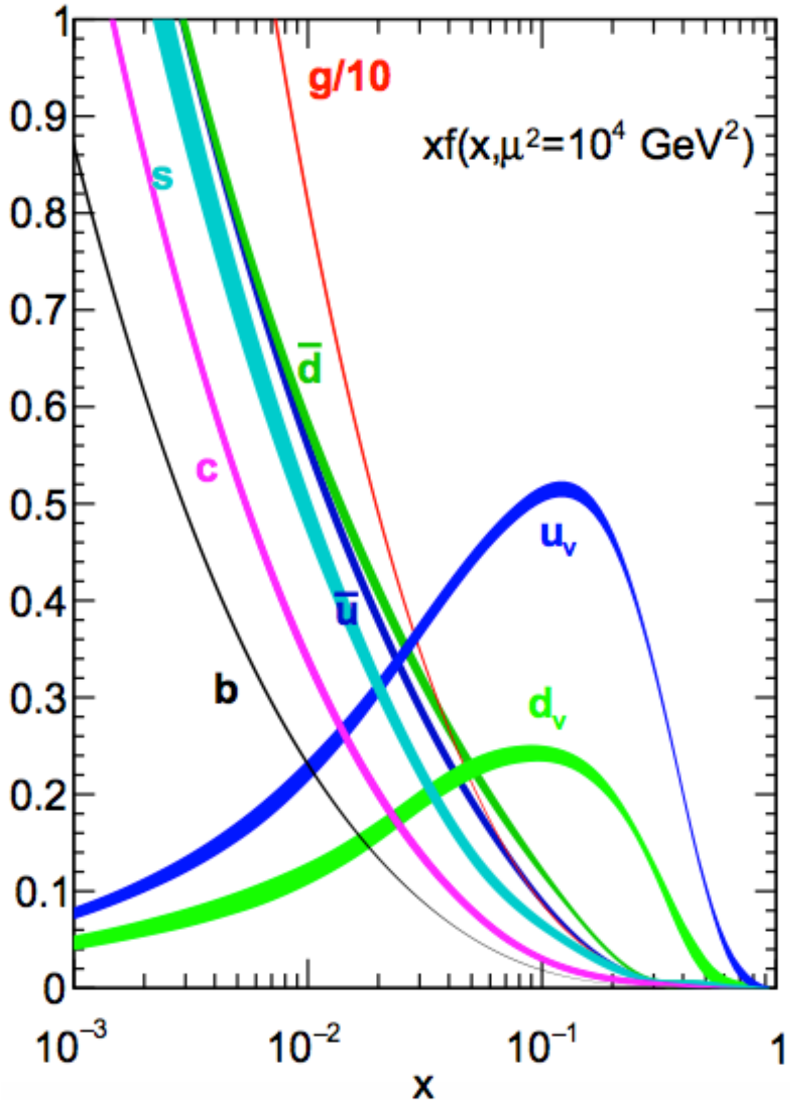
PDFs from NNPDF3.1 (arXiv:1706.00428)



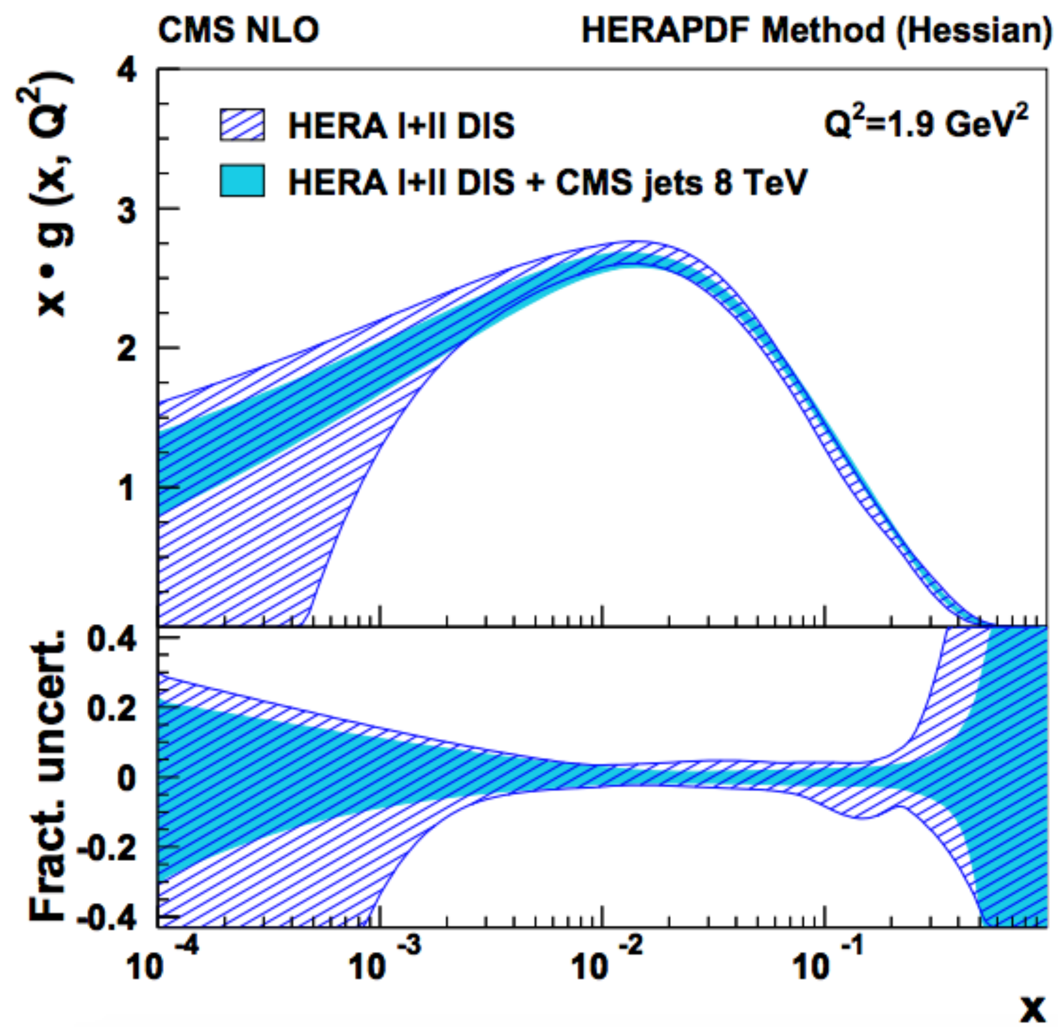
Gluon PDF fractional uncertainty with LHC jet data included CMS (arXiv:1609.5331)

gluon at large-x high-Q^2 needed to study gg fusion to Higgs

Ongoing: use good description of data
to constrain parton distribution functions at NNLO



PDFs from NNPDF3.1 (arXiv:1706.00428)



Gluon PDF fractional uncertainty with LHC jet data included CMS (arXiv:1609.5331)

gluon at large-x high-Q^2 needed to study gg fusion to Higgs

small-x PDFs $x \sim 10^{-6}$ low-Q^2: needed to the study high-energy $E_\nu >\sim 1$ PeV flux of prompt atmospheric neutrinos → background to astrophysical neutrino flux