High-p_T Physics

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Summary

- The new world average from PDG on $\alpha_s(M^2_Z)$ is 0.1179 ± 0.0010
- Elastic scattering of electrons on protons:
  - "Simplest" elastic approximation: Rutherford scattering
    - Has one independent variable, e.g. θ or Q^2
  - Mott scattering includes energy transfer from electron to nucleon and spin-1/2
  - Rosenbluth formula introduces internal structure of the proton; electric and magnetic form factors
- Inelastic scattering requires two independent variables, e.g. scaling variable x and momentum transfer squared Q^2
- Can be converted to other combination with inelasticity y and hadron final state mass squared W^2
- Lorentz-invariant description involves structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$

$$F_1(x) = \frac{F_2(x)}{2x}$$

- Depend mostly on x, not Q^2: Spin-1/2 partons lead to Callan-Gross relation

DIS cross section

Rosenbluth formula can be rewritten to include inelastic scattering.

Most general Lorentz-invariant and parity conserving expression:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right] \qquad Q^2 \gg M_p^2 y^2$$

$F_1(x,Q^2)$ and $F_2(x,Q^2)$ are structure functions incorporating the form factors (and kinematic ones, τ), but cannot be related to Fourier transforms any more since dependent on x.

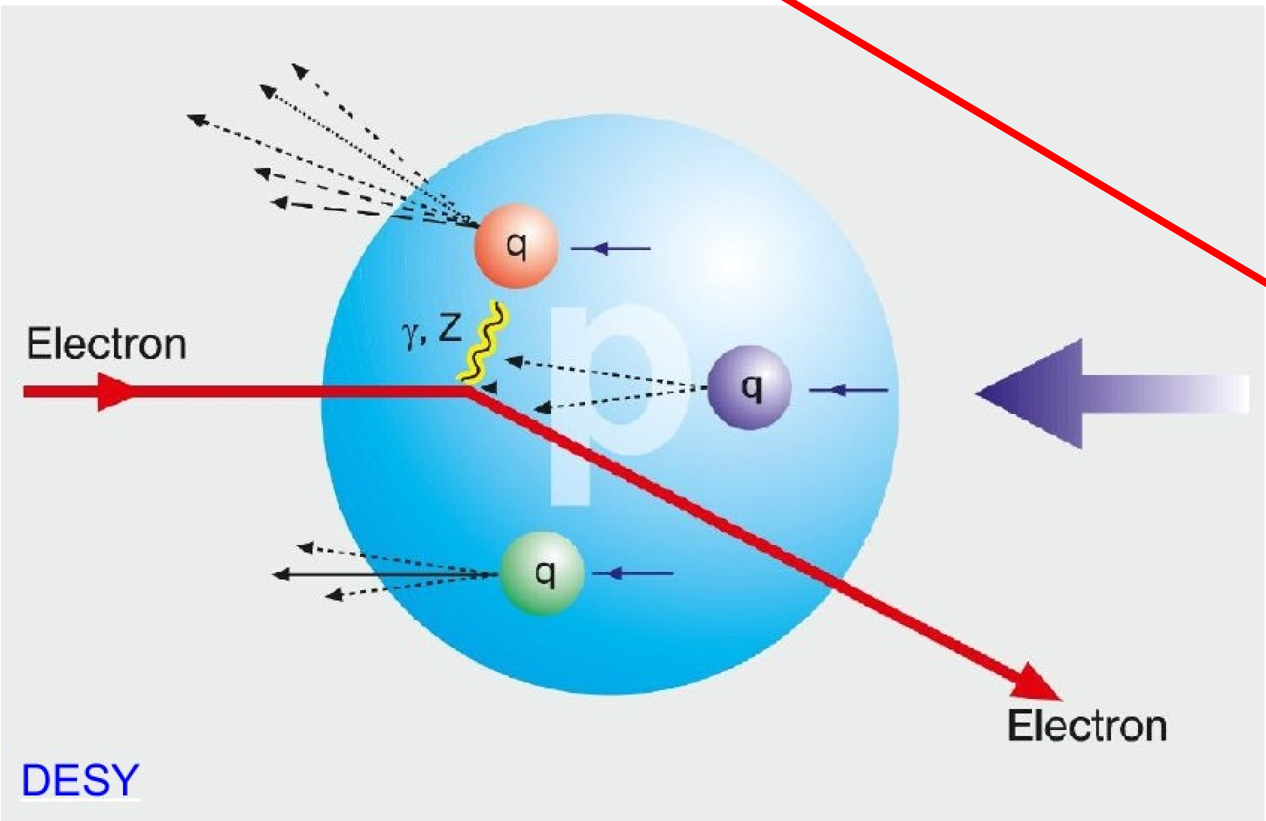
Still, $F_1(x,Q^2)$ is of purely magnetic origin, while $F_2(x,Q^2)$ originates from both, electric and magnetic effects.

What do they mean?

Quark-Parton-Model

J.D. Bjorken, R.P. Feynman 1969:

- **Infinite momentum frame**
  - incoherent superposition of elastic scatterings with point-like “partons”
  - scale invariant, i.e. independent of resolution ~ q^2, no natural length scale
  - partons have spin 1/2



Bjorken scaling:

$$F_1(x, Q^2) \to F_1(x)$$
$$F_2(x, Q^2) \to F_2(x)$$

Callan-Gross relation:

$$F_1(x) = \frac{F_2(x)}{2x}$$

Spin 0 would give:

$$F_1(x) = 0$$

Quark-Parton-Model

Modern writing:

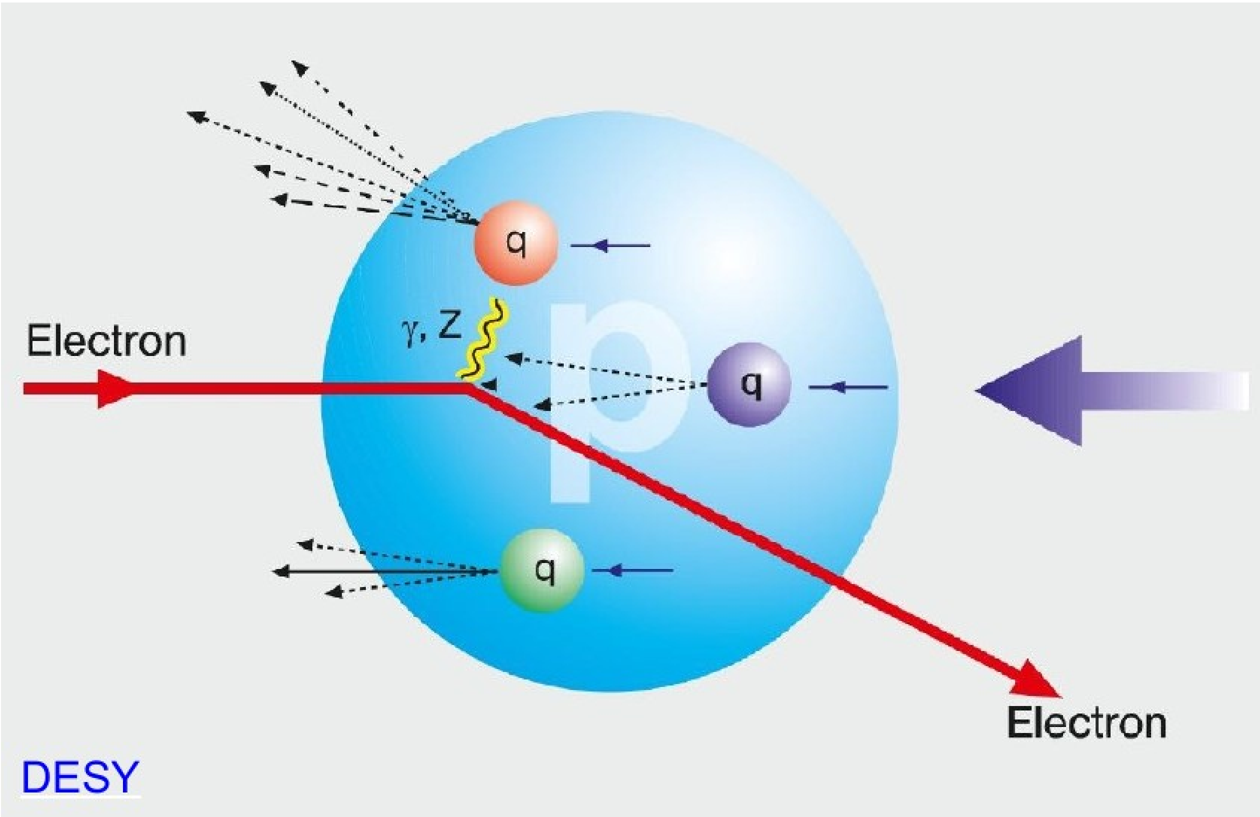
$$F_2(x) = x \sum_i e_i^2 \left[q_i(x) + \overline{q_i}(x) \right]$$

quark charges

anti-quark momentum distribution

quark momentum distribution

q_i : parton distribution functions (PDFs)



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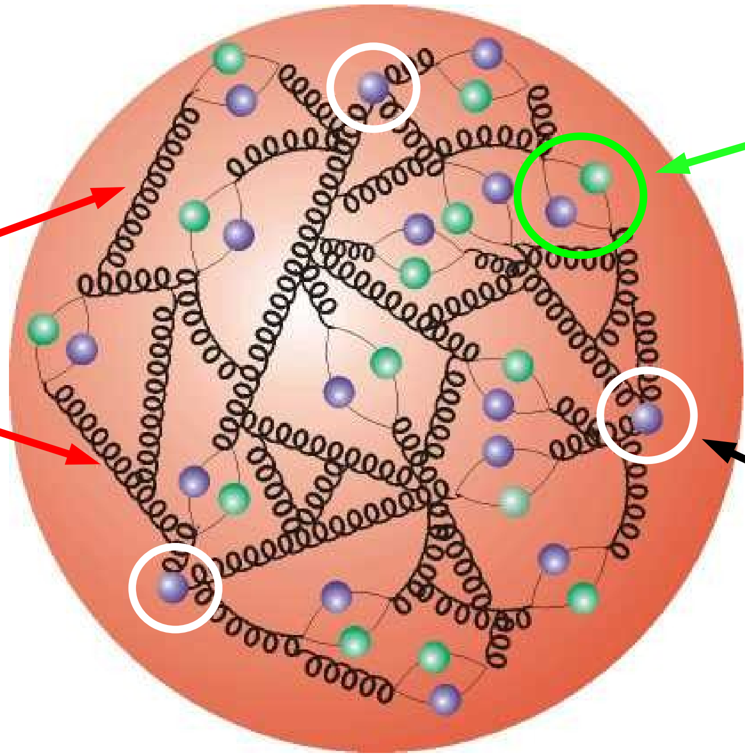
Proton structure



- Example of generic functional form of proton structure:

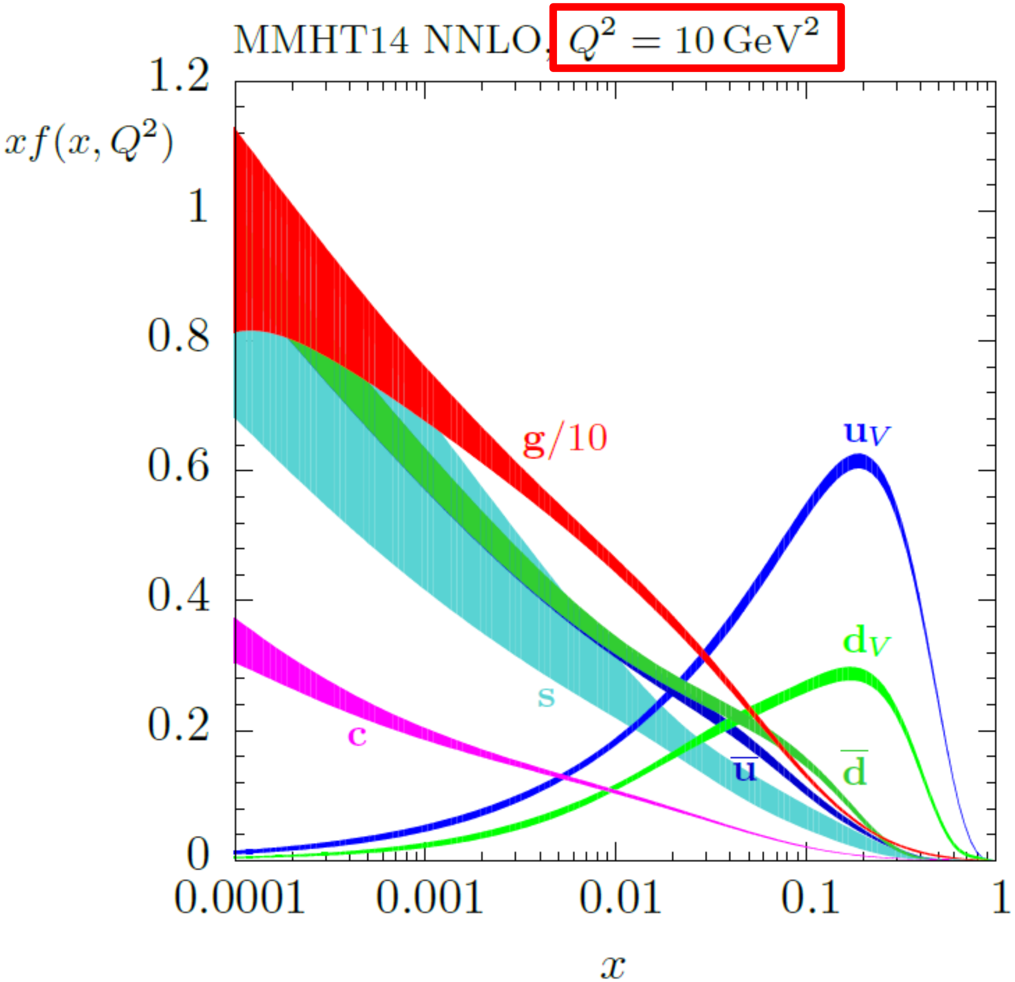
$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

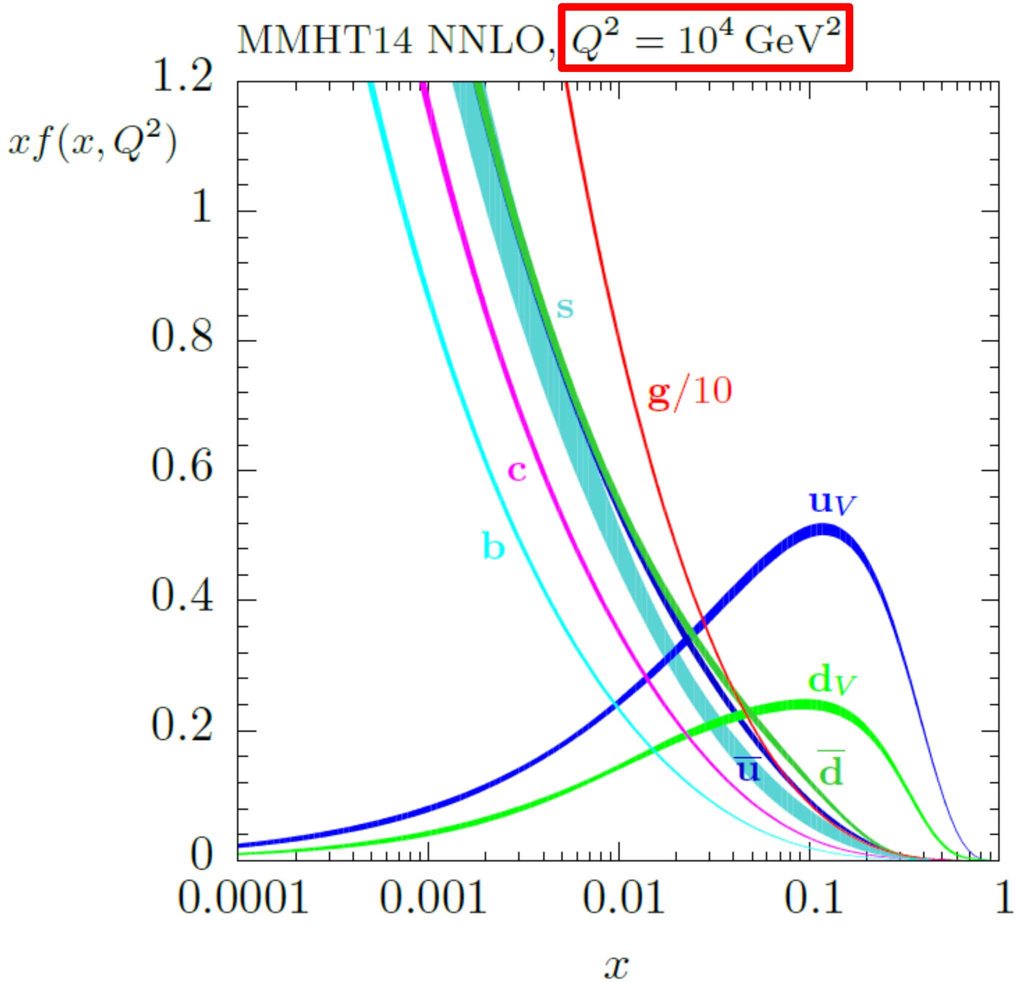
Normalisation (A) | Behaviour for x → 0 (B) | Behaviour for x → 1 (C) | Middle region largest variability (D, E)

Example for PDFs

MMHT 2014 PDFs

Resolution scale



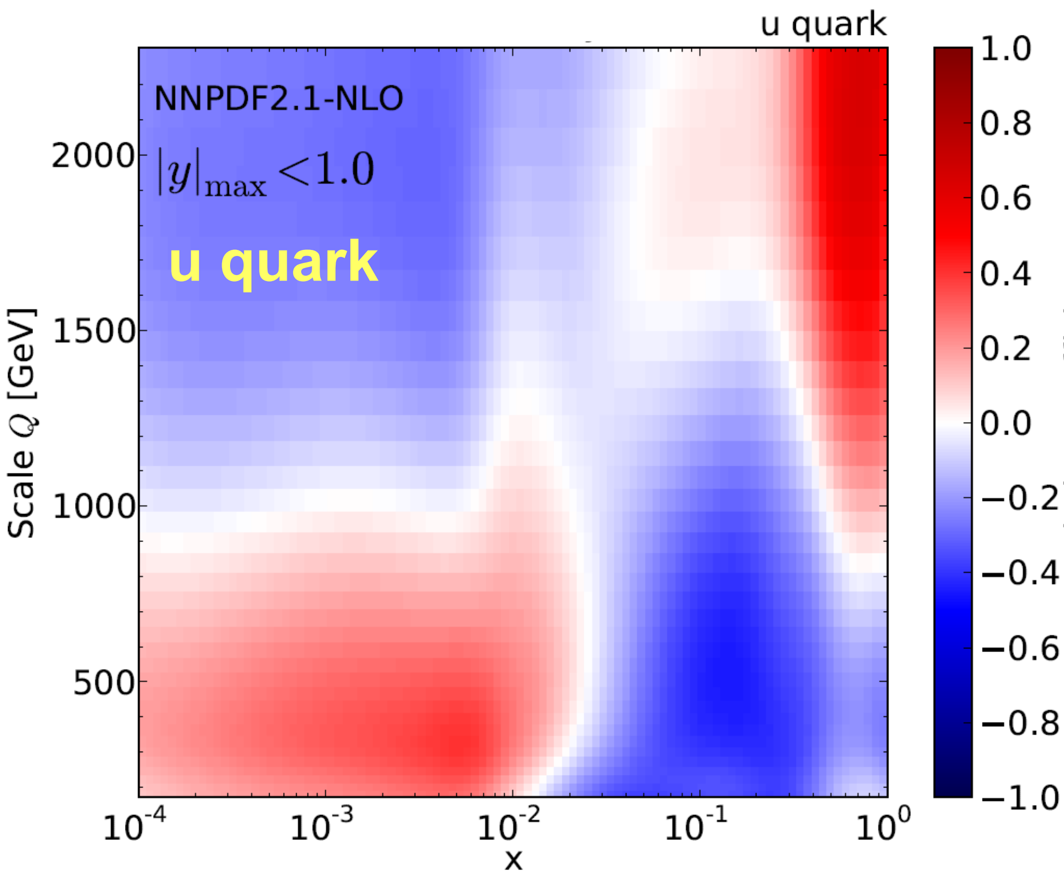


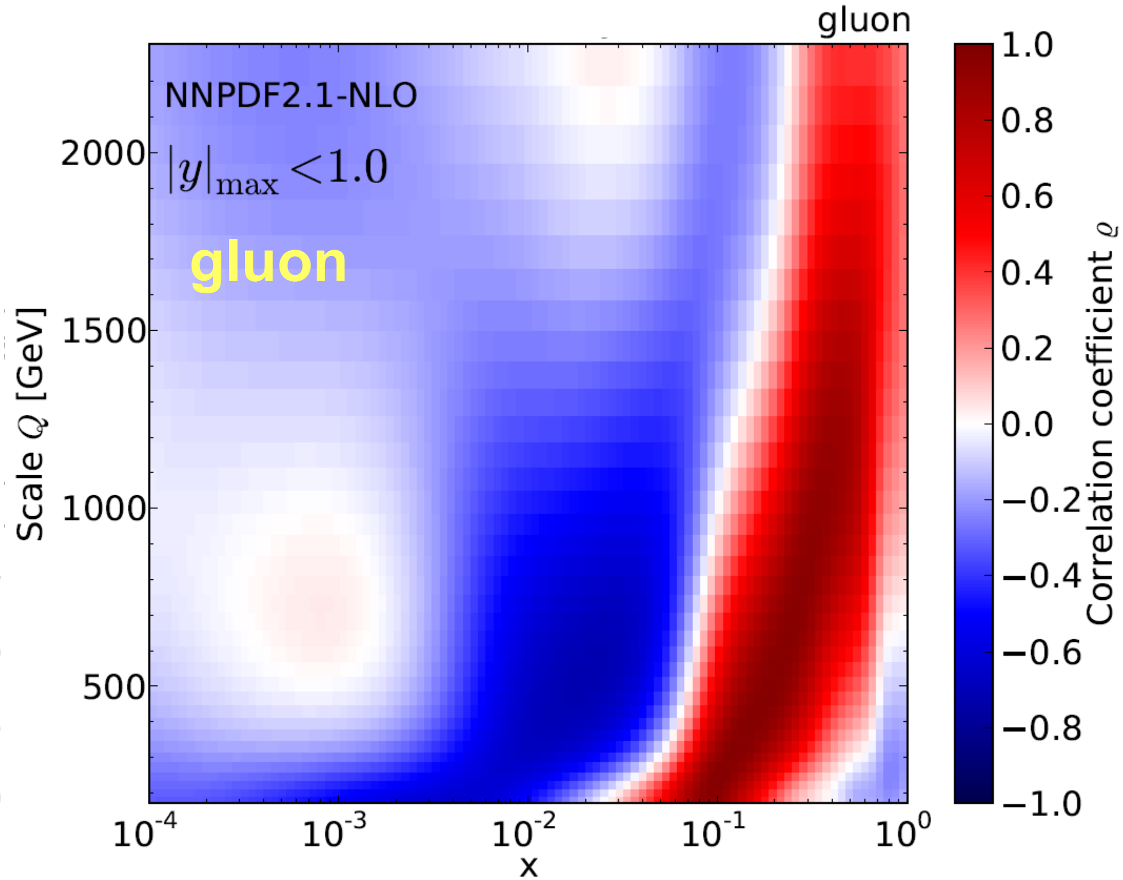
R. Thorne, 13.04.2015
PDF4LHC Meeting

Example: Measurement of high pT jets and gluon content of the proton:

- **Gluon distribution at high x (> 0.1)**
- **Quark distribution at high x (> 0.3)**

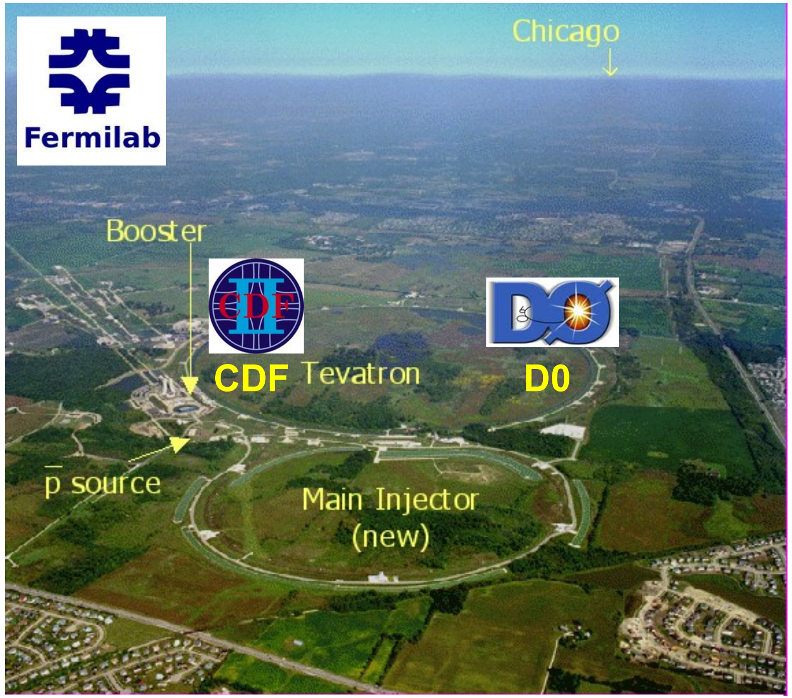
$$\varrho_f(x,Q) = \frac{N}{(N-1)} \frac{\langle \sigma_{\text{jet}}(Q)_i \cdot xf(x,Q^2)_i \rangle - \langle \sigma_{\text{jet}}(Q)_i \rangle \cdot \langle xf(x,Q^2)_i \rangle}{\Delta_{\sigma_{\text{jet}}(Q)} \Delta_{xf(x,Q^2)}}.$$





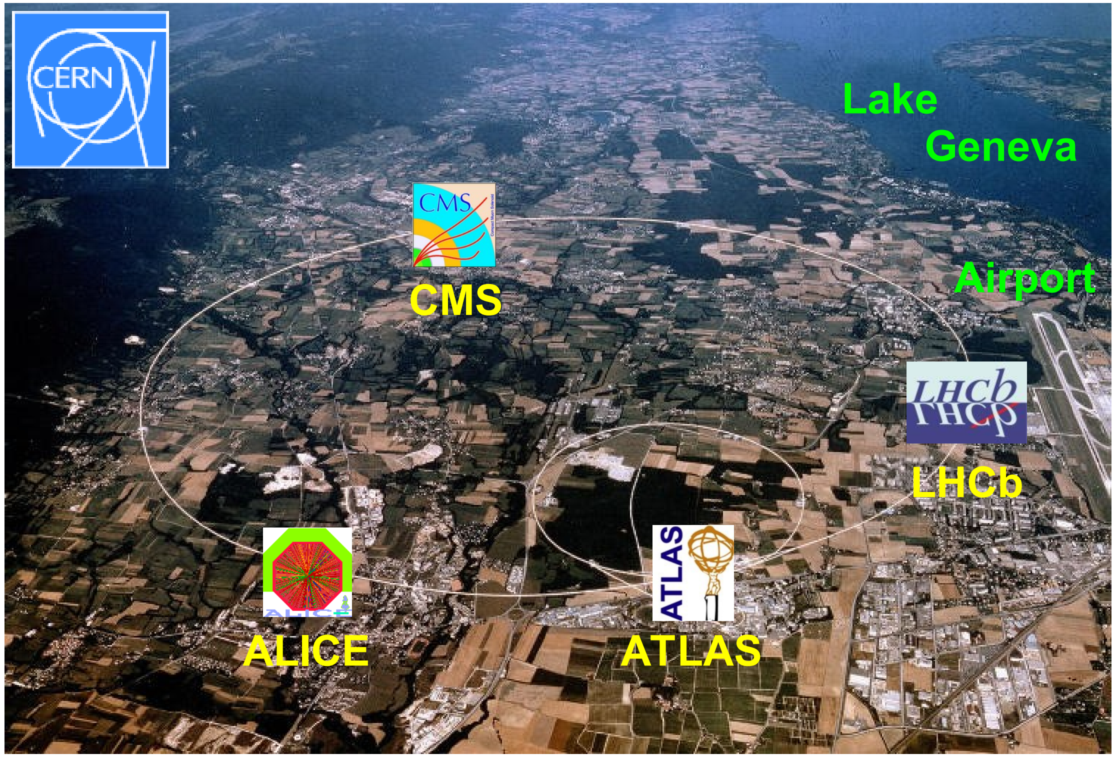
Hadron Colliders

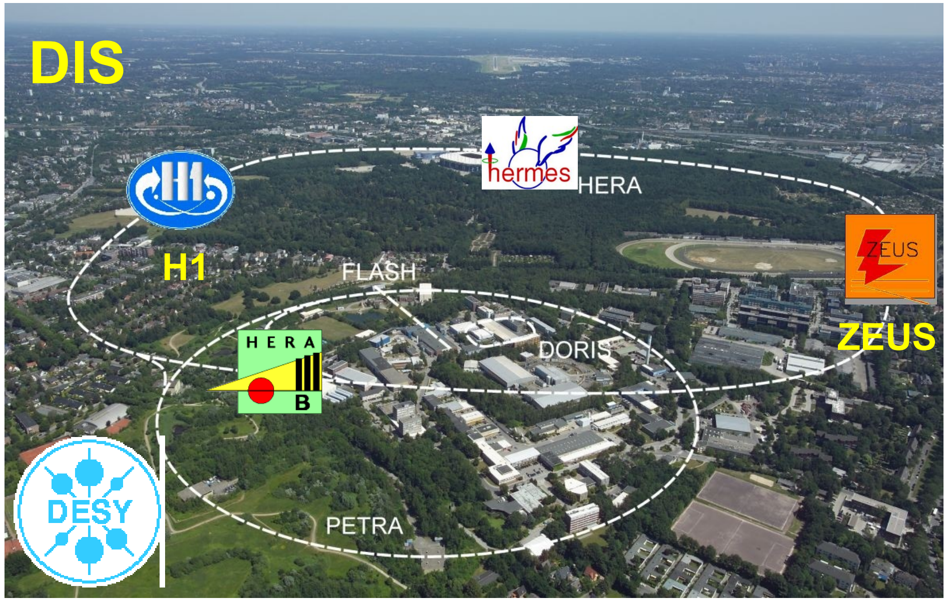
Tevatron: 1986 – 2011
Collisions of p anti-p
Run II: E_{cms} =1.96 TeV
Run II: Record luminosity: 4.3 x 10^{32} $cm^{-2}s^{-1}$



LHC: 2009 – present
Collisions of p-p, Pb-Pb, and p-Pb
E_{cms} = 0.9, 2.36, 2.76, 5.02, 7, 8, 13 TeV
Peak inst. Luminosity: ~ 2 x 10^{34} $cm^{-2}s^{-1}$

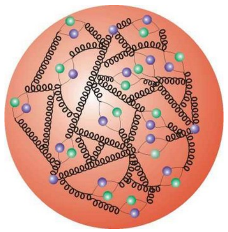
HERA: 1992 – 2007
Collisions of e^{+}-p, e^{-}-p
HERA II: E_{cms} = 319 GeV

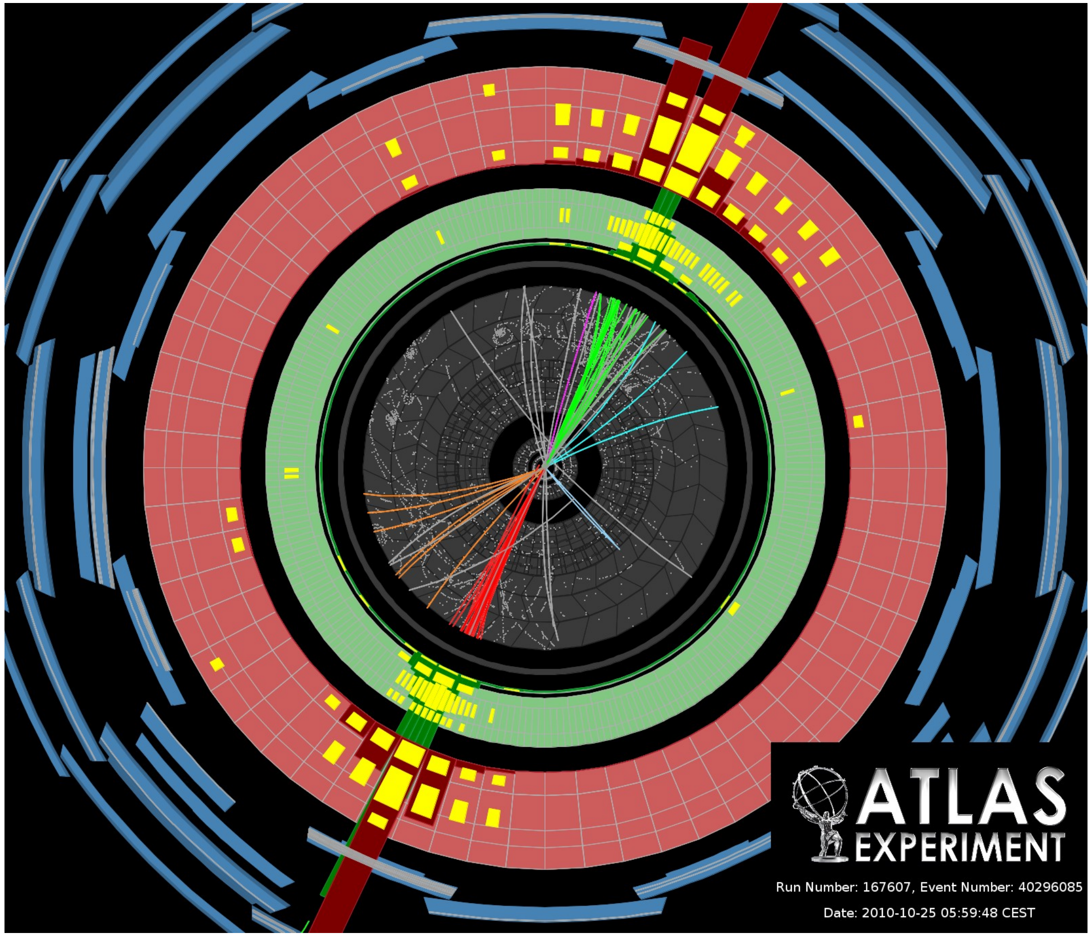


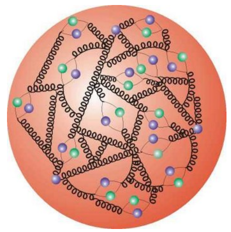


Hadron-hadron collisions

"Broadband beams" of various parton types with various energies
→ QCD parton collider!





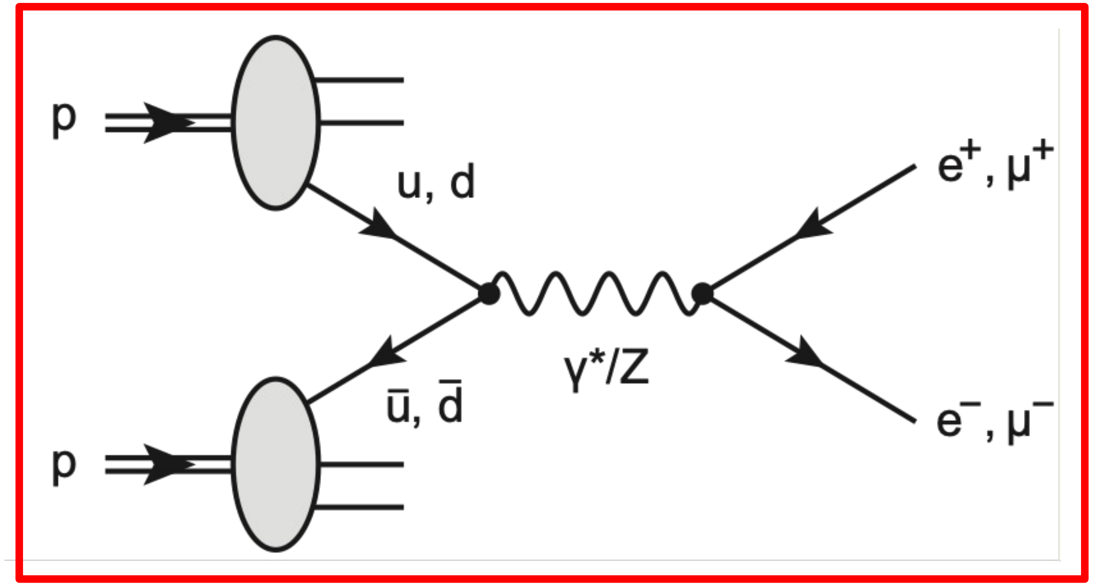


Challenge: Reliable calculations of observables

Prototype process: Drell-Yan

$pp \to l^+ l^- + X$

- **Hadro-production of lepton pairs**
  - **at large center-of-mass energies**
  - **with large invariant mass**
  - **color-neutral final state (except proton remnants) → no hadronisation**



Not a Feynman diagram

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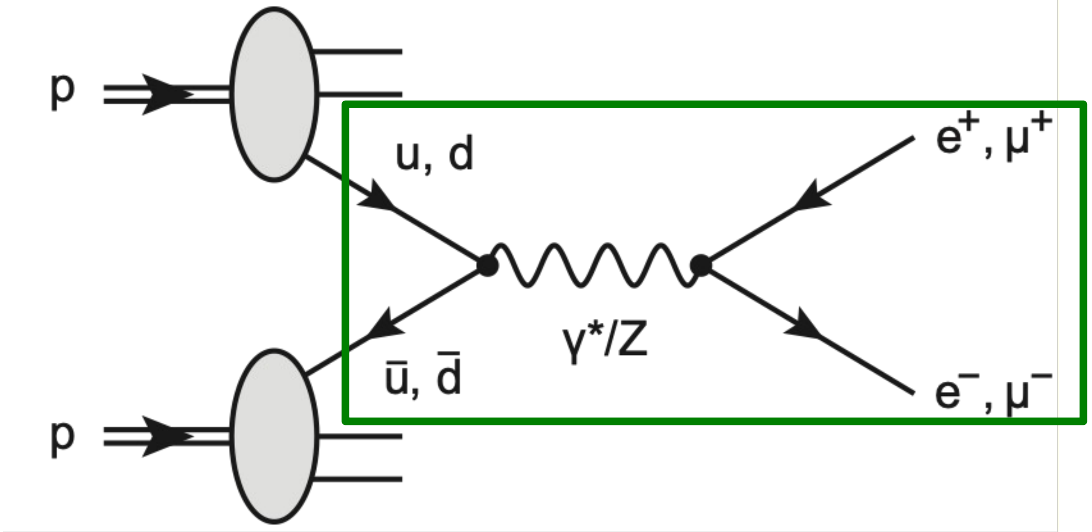

Partonic Feynman diagram
→ calculable in perturbative QCD

Prototype process: Drell-Yan

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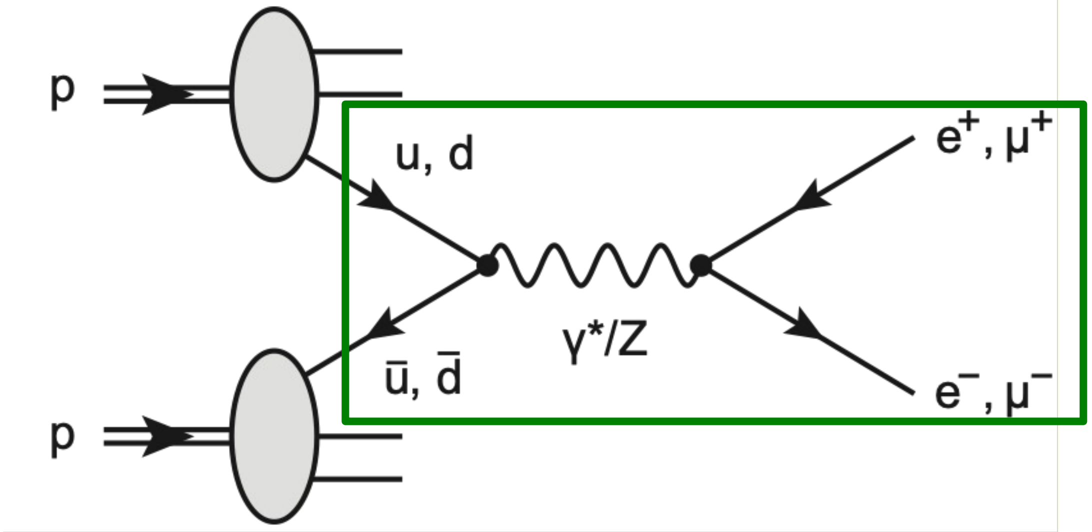

- **Factorisation theorem of QCD:**
  - Process can be calculated by factorising "hard" and "soft" components
    - Calculate hard partonic subprocess
    - Weight cross section with probability to find partons with momenta x_1, x_2 inside hadrons
    - Integrate over all possible parton momenta
    - Sum over all possible parton flavors

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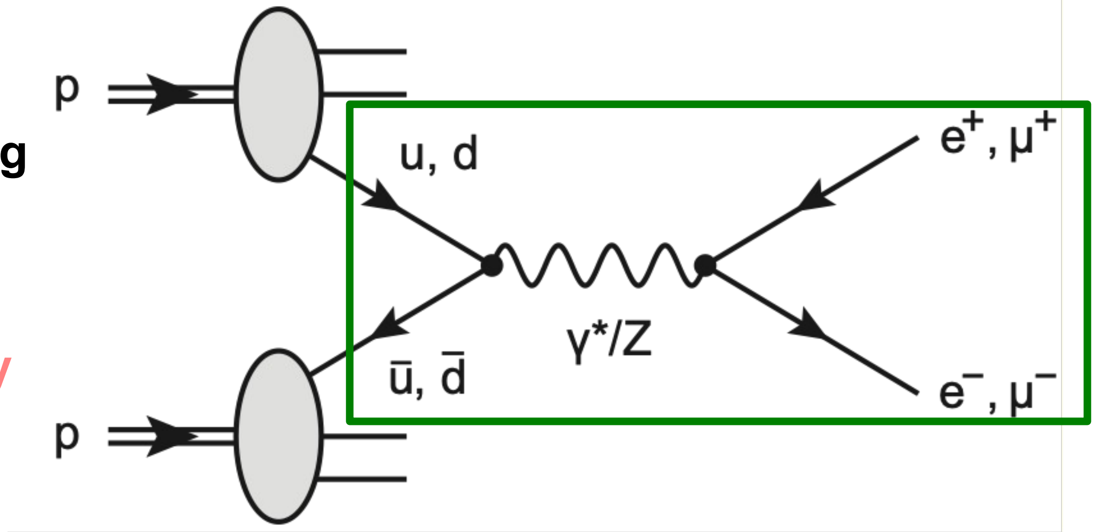
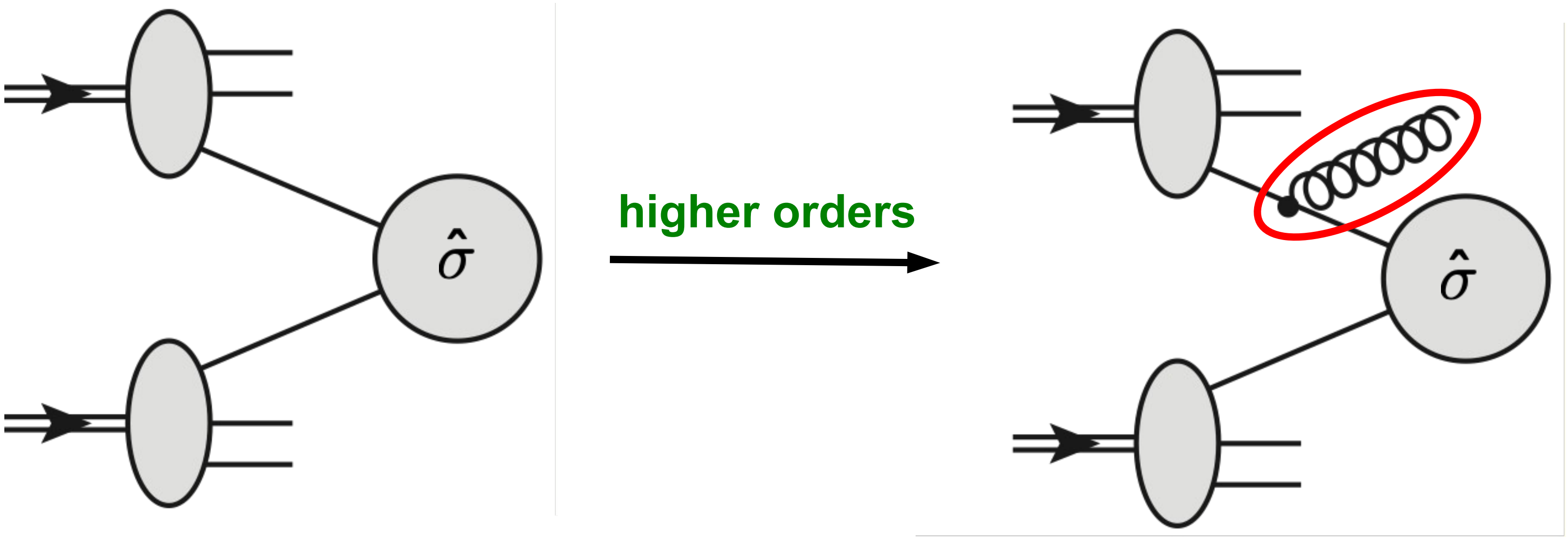


$$\sigma_{\mathrm{DY}} = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i(x_i) f_j(x_j) \cdot \hat{\sigma}(q_i q_j \to l^+ l^-)$$

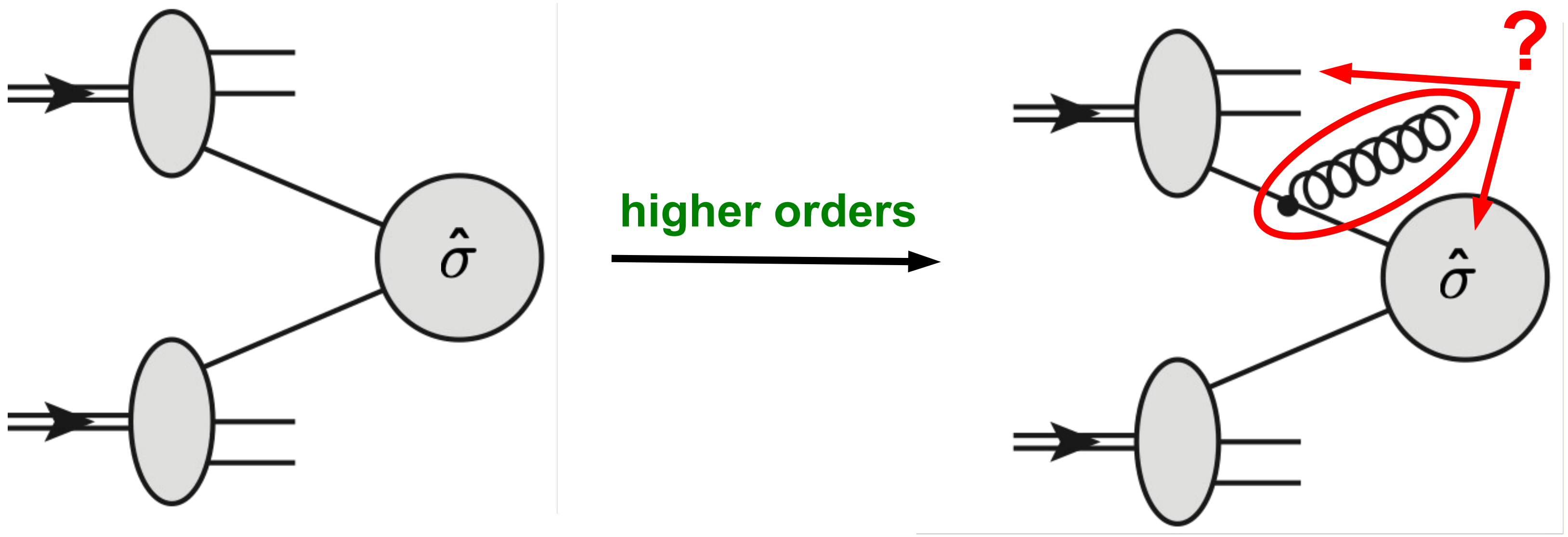
PDFs $f_i(x_i)$ are universal; can be measured independently e.g. in DIS!

Factorisation scale



Where does this belong to?

Factorisation scale



Where does this belong to?

The PDF?

Or the parton process?

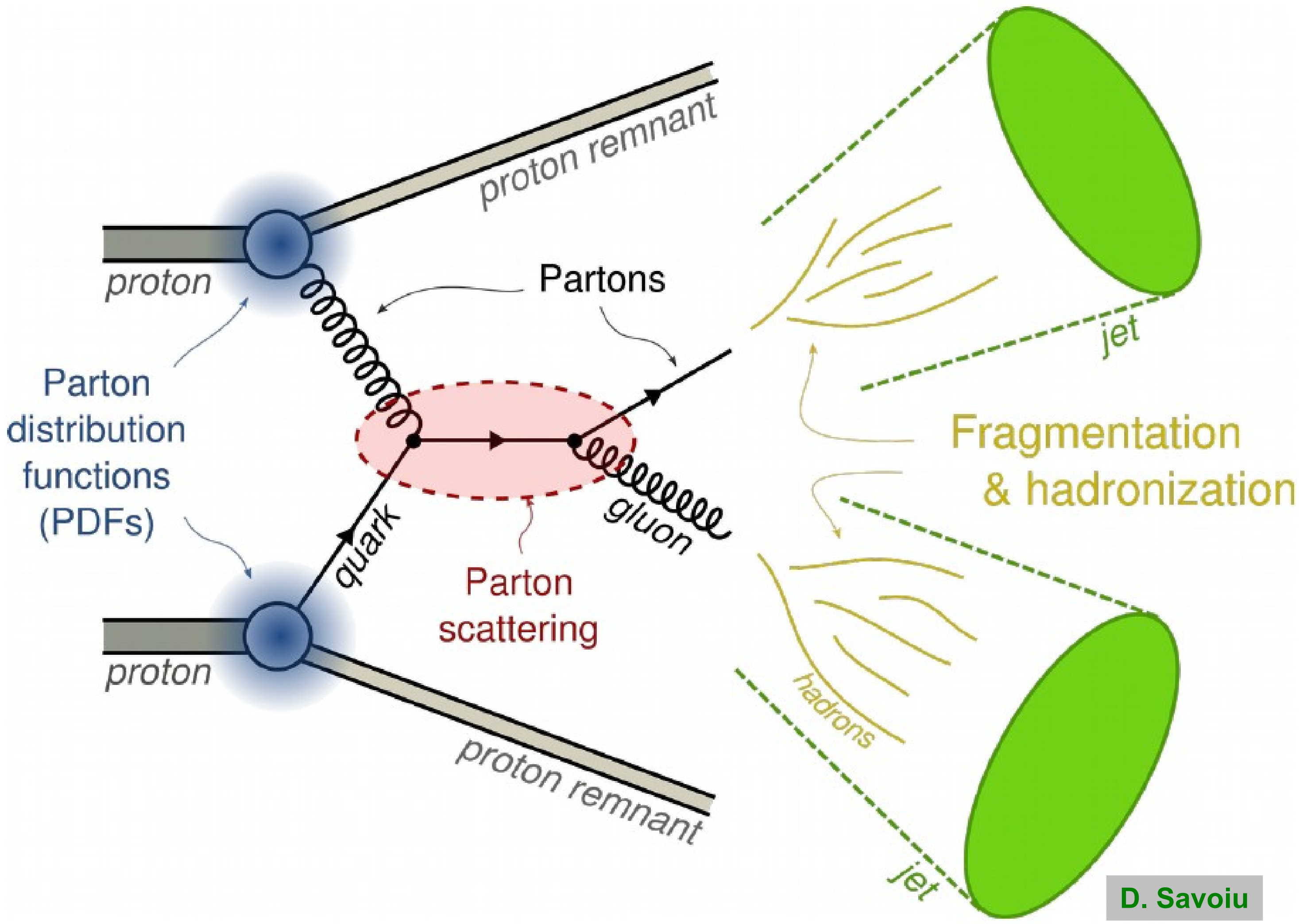
- **Attribution ambiguous:**
  - **Leads to soft and/or collinear divergences (long-distance effects!)**
  - **Solution: Introduce a new scale to separate short- and long-distance effects**
    - **Factorisation scale μ_f**
    - **All soft and collinear divergences (long-distance effects) are absorbed into the PDFs determined from experimental measurements**

$$f_i(x_i) \rightarrow f_i(x_i, \mu_f^2)$$

$$\hat{\sigma}_{ij}(x_i, x_j, \mu_r^2, \alpha_s(\mu_r^2)) \rightarrow \hat{\sigma}_{ij}(x_i, x_j, \mu_f^2, \mu_r^2, \alpha_s(\mu_r^2))$$

Hadron-hadron cross sections

Factorisation valid also for more general final states, e.g. jet production!



Event rates at the LHC

Total cross section

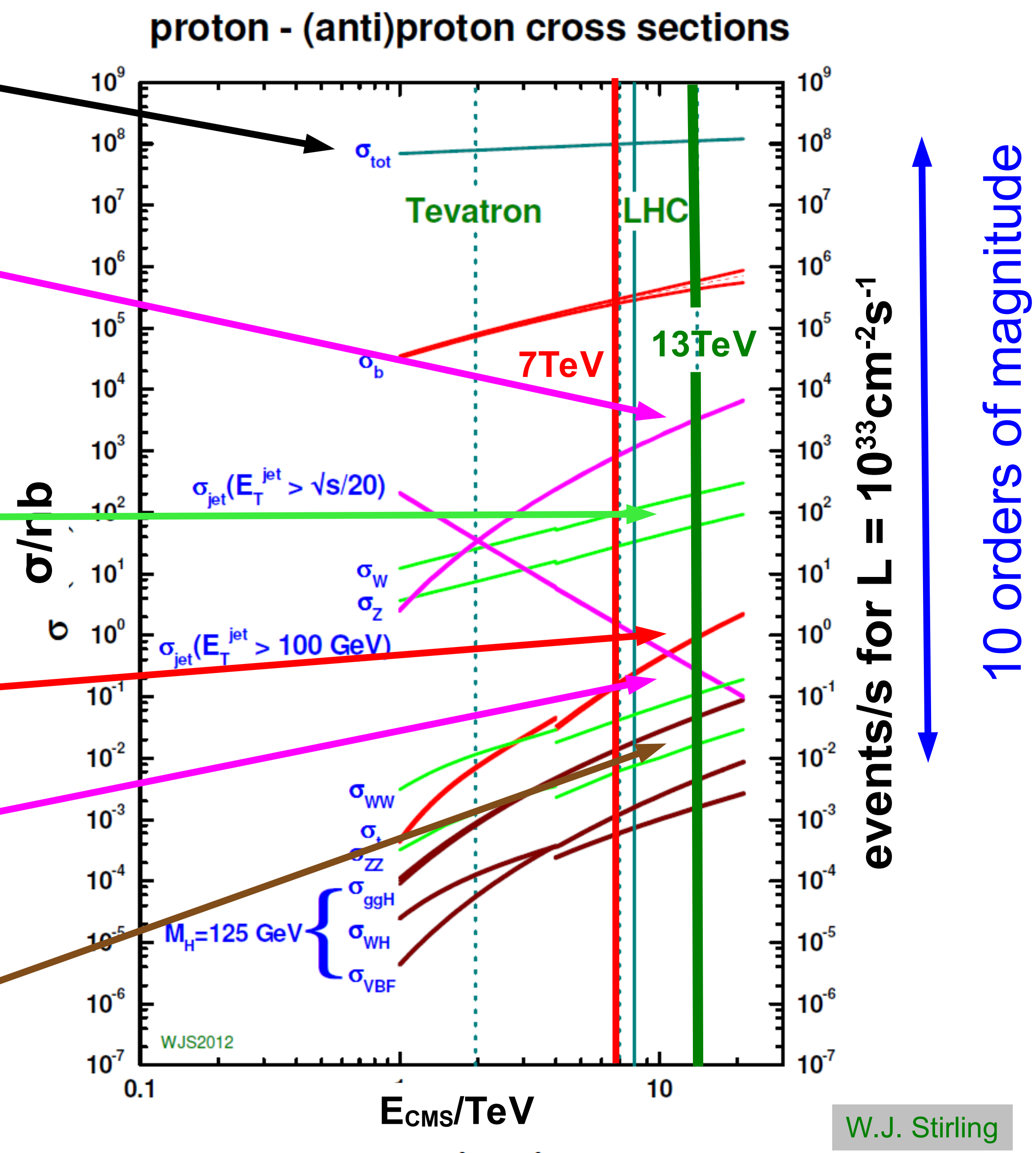
Jets: $\sigma_{jet}(E_T^{jet} > 100\text{GeV})$
~ 2000 / s

W & Z bosons: σ_W, σ_Z
~ 200 / s, 50 / s

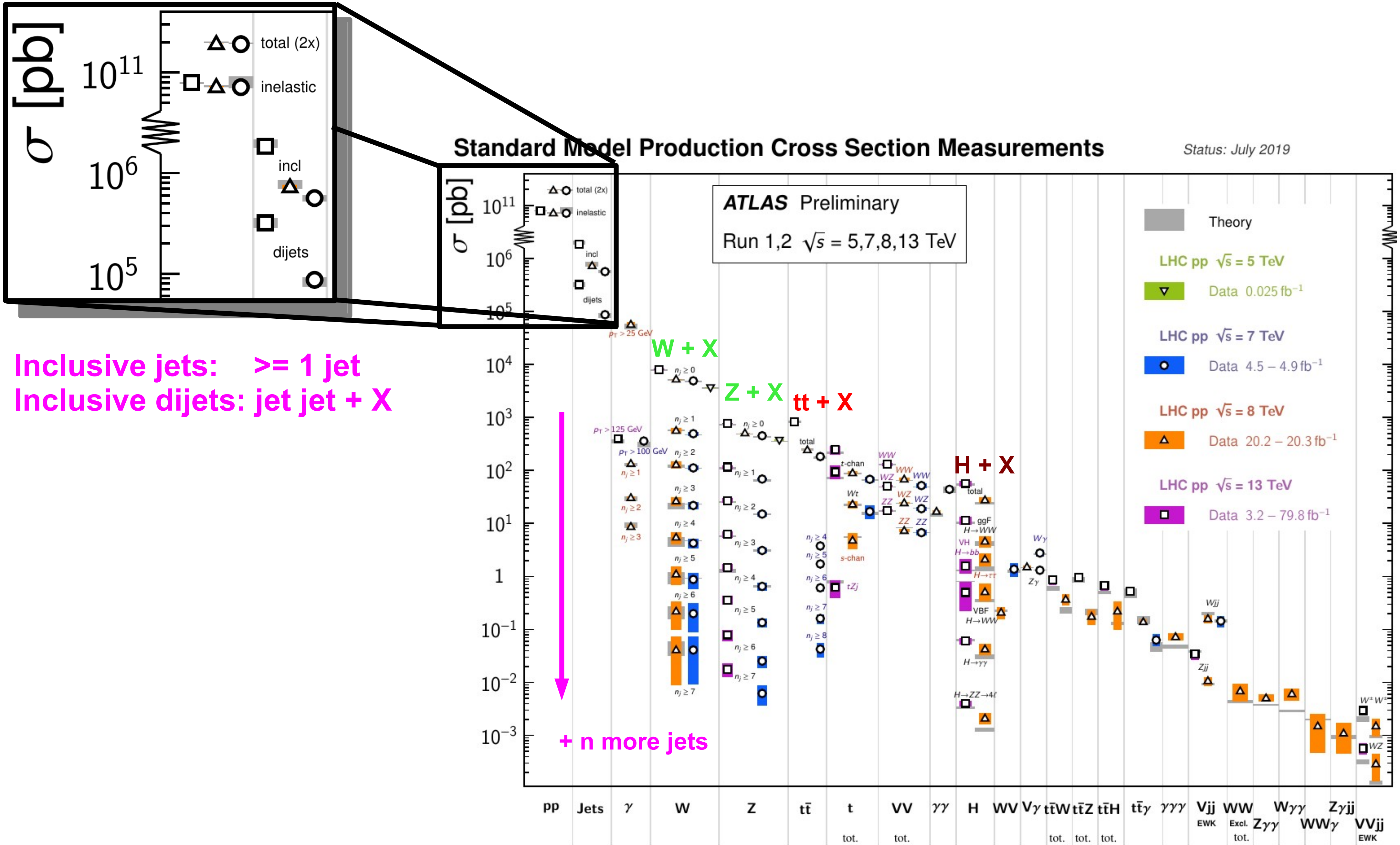
Top quarks (σ_{tt})
~ 1 / s

Jets: $\sigma_{jet}(E_T^{jet} > 650\text{GeV})$
~ 18 / min

Higgs Bosonen (σ_{ggH}, σ_{WH}, σ_{VBF})
~ 150 / h



Jets at the LHC

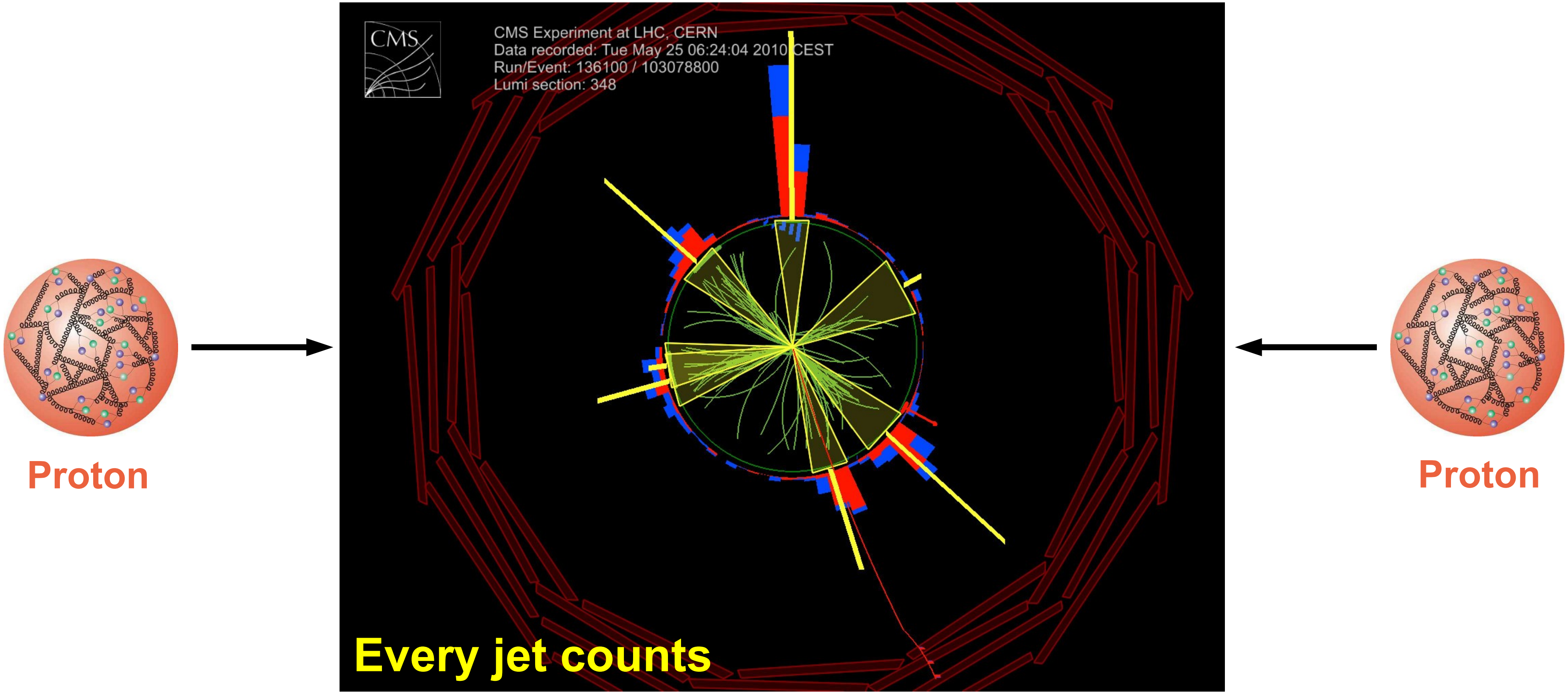


Inclusive jets: >= 1 jet

Inclusive dijets: jet jet + X

All inclusive

Large transverse momenta



Proton

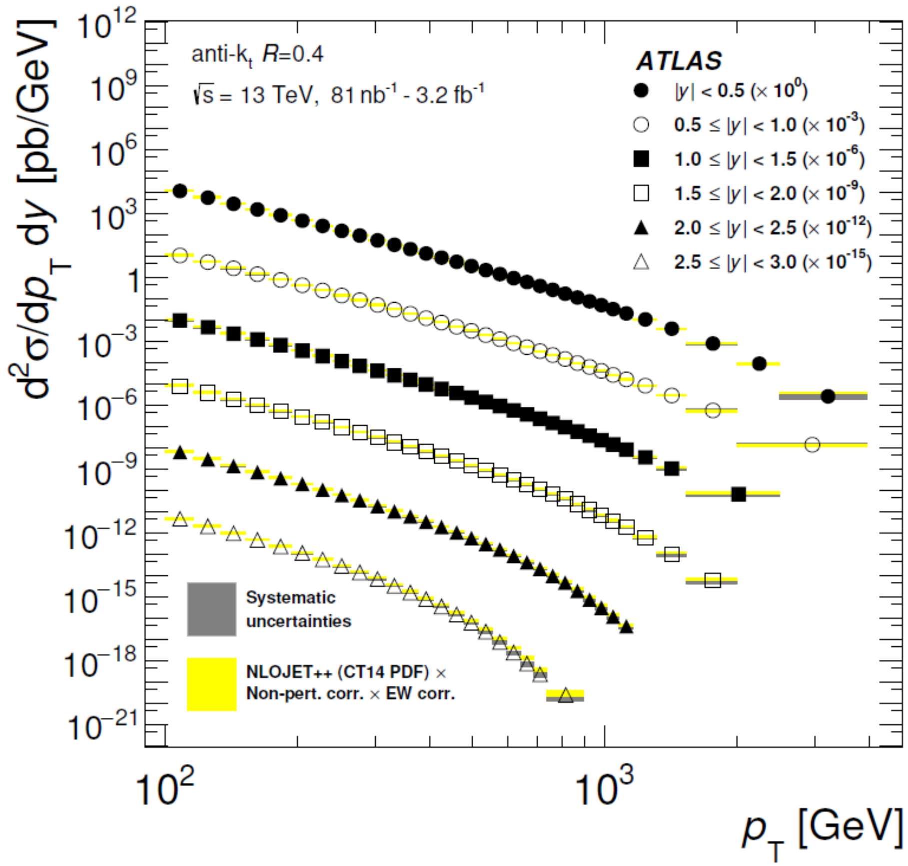
Proton

Inclusive jet cross section

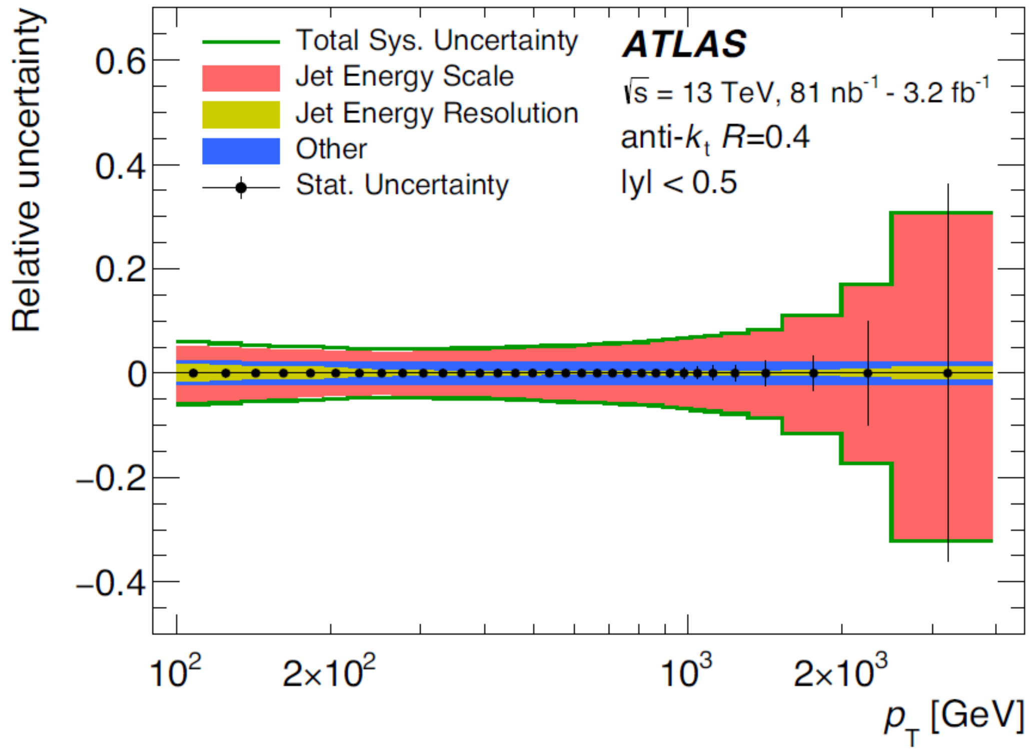
Overall agreement with predictions of QCD at NLO over many orders of magnitude in cross section and even beyond 2 TeV in jet p_T and for rapidities |y| up to 3 ~ 5 at $\sqrt{s}$ = 2.76, 7, 8, and 13 TeV.

$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

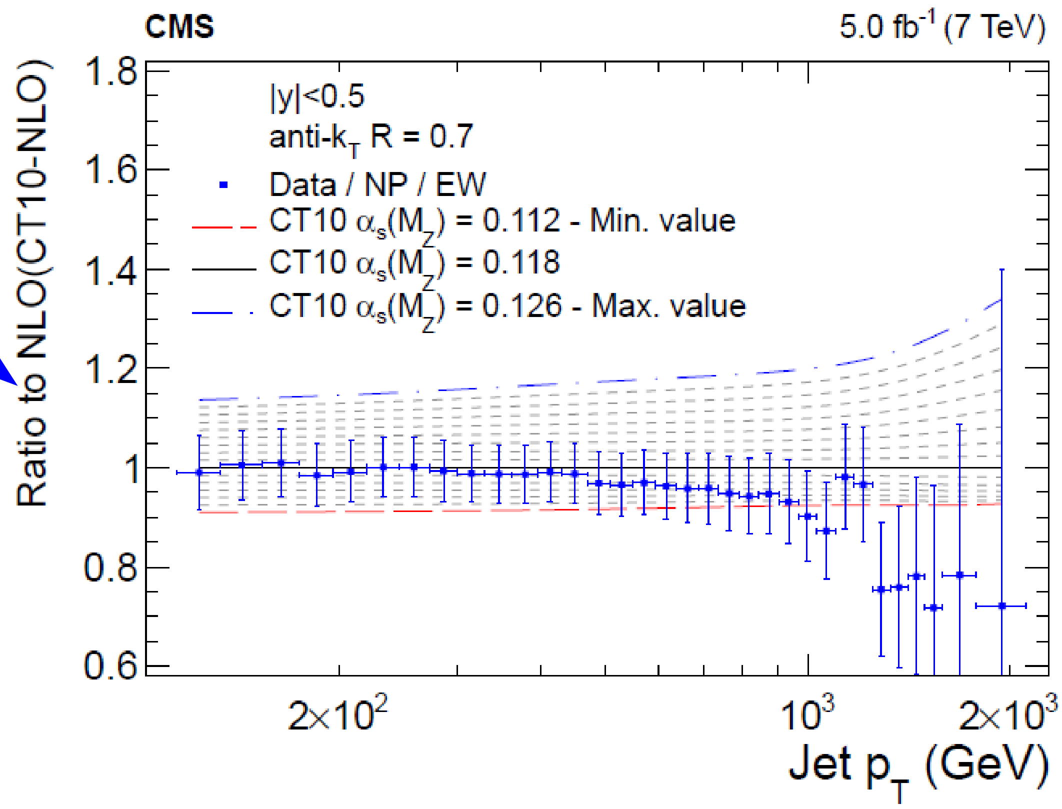
Data vs. NLO pQCD x non-pert. x EW corrections



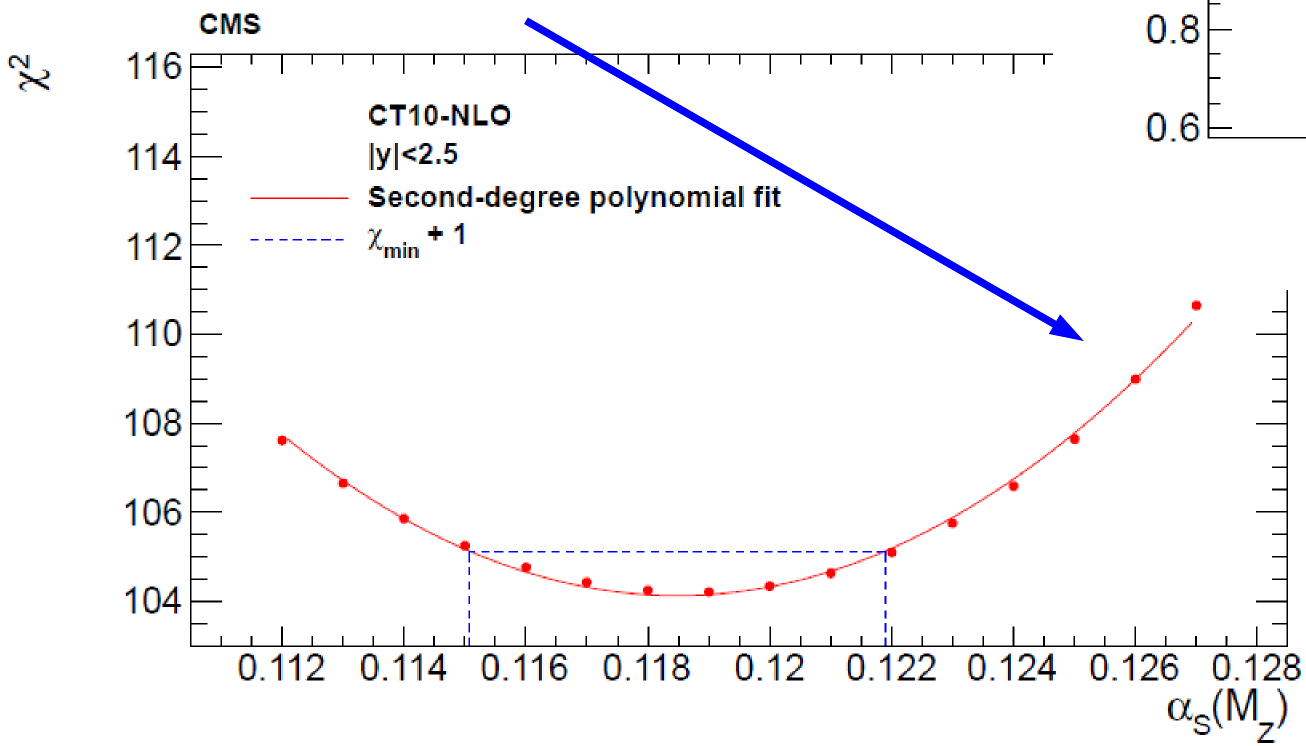
Exp. uncertainties for |y| < 0.5



Sensitivity of inclusive jet cross sectiom to α_s



Example of χ2-fit



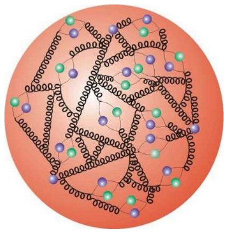
Much more on jet analyses in:

Particle physics II – Top quark and jet physics at the LHC

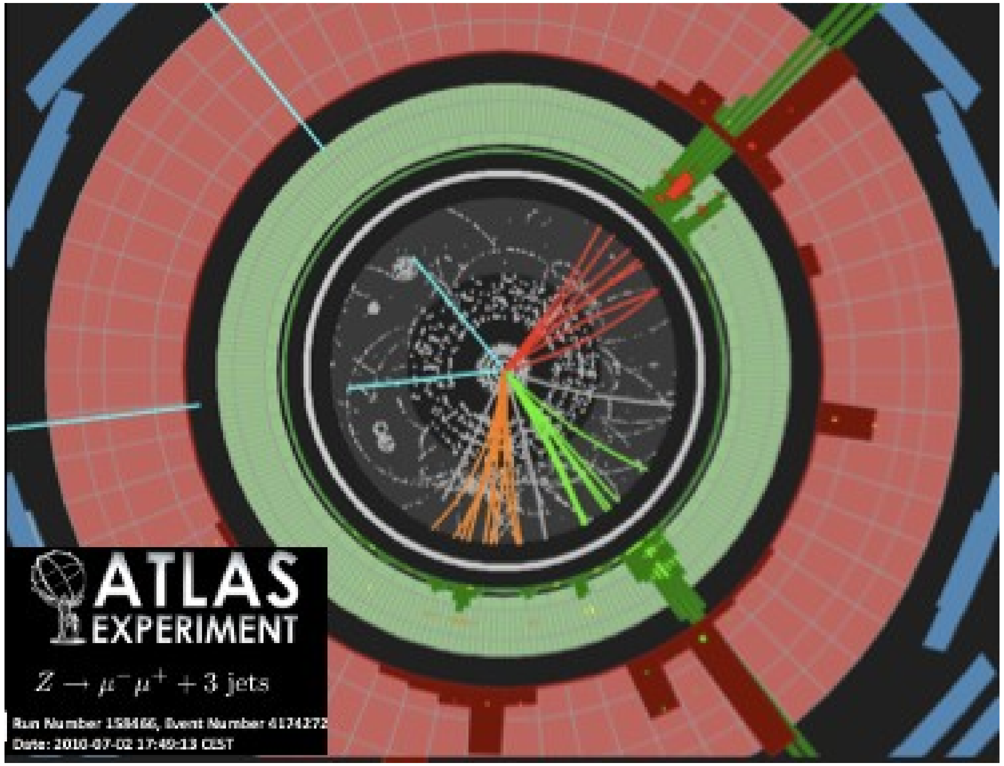
KR + A. Meyer

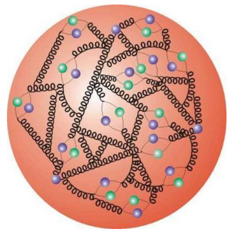
W and Z bosons

Standard Candles



Proton





Proton

W and Z bosons at high p_T

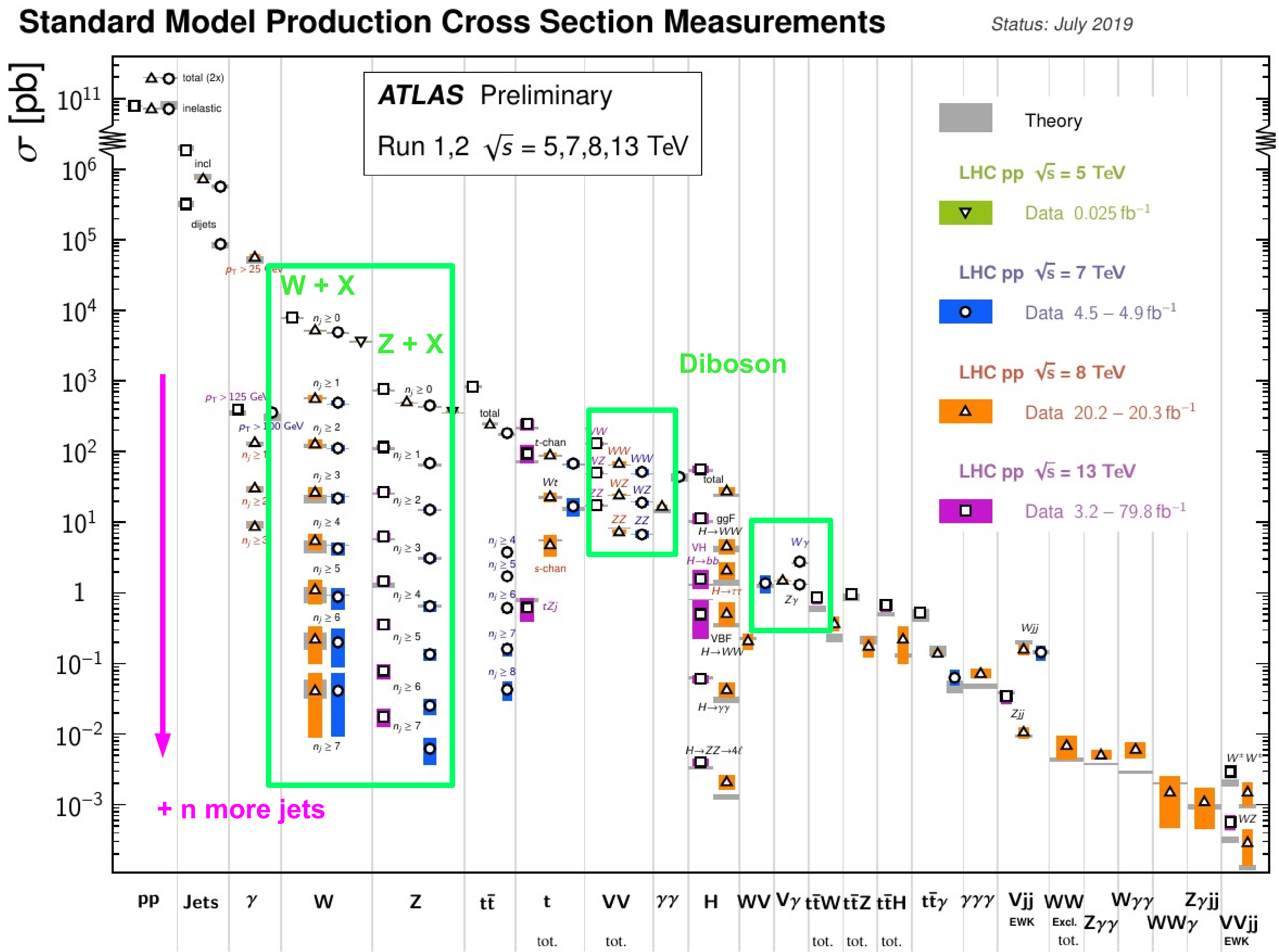
- **Hadro-production of leptons pairs from W, Z decays**
  - **large invariant mass**
  - **high p_T of leptons, but not necessarily of W, Z**
  - **high p_T of W, Z requires balancing object → most frequently jets**
    - **Very interesting to study: W, Z p_T distribution**
    - **Also: di- and triple-vector boson production**
- **Further interest:**
  - **Masses of W and Z bosons: Important SM parameters**
  - **W and Z boson couplings in production and decay**
    - **E.g. asymmetries in production**

Much more on W, Z analyses in:

Particle physics II – W, Z and Higgs physics at the LHC

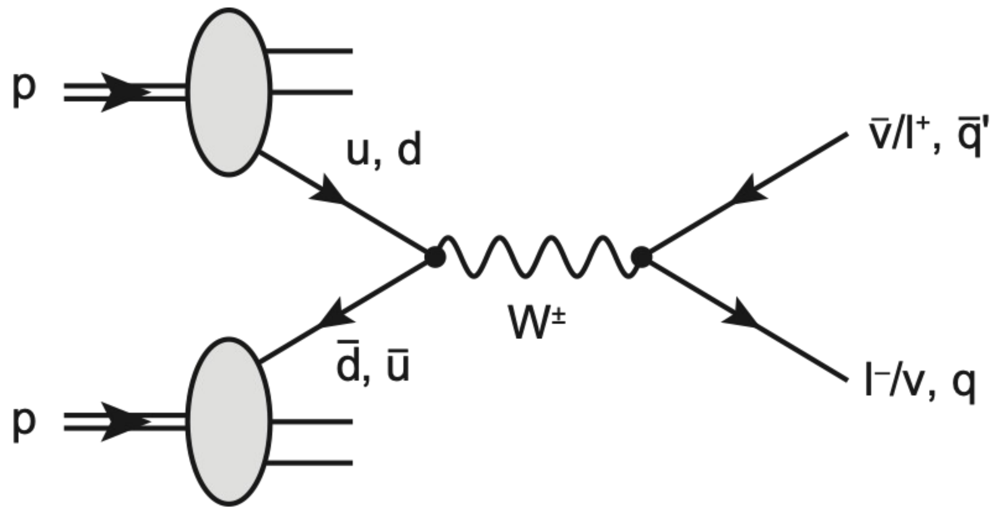
M. Schröder, R. Wolf

W and Z at the LHC



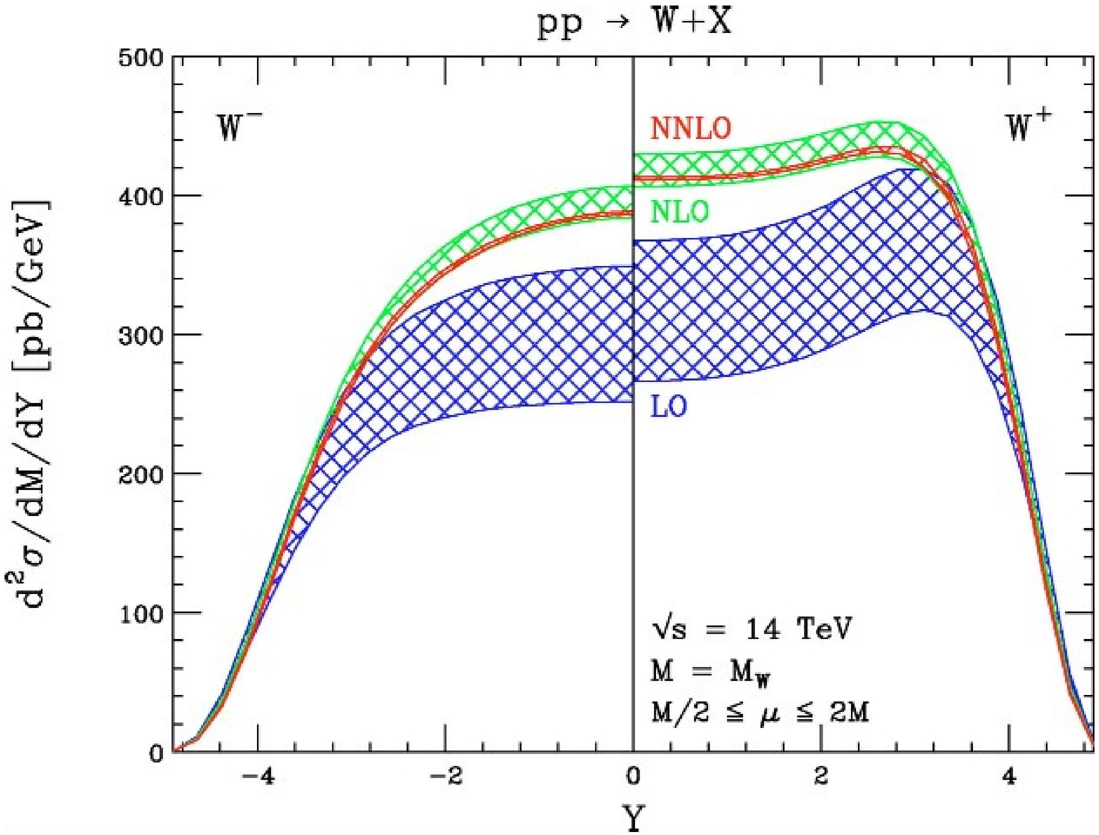
W boson production

Proton-proton collisions, all p_T:



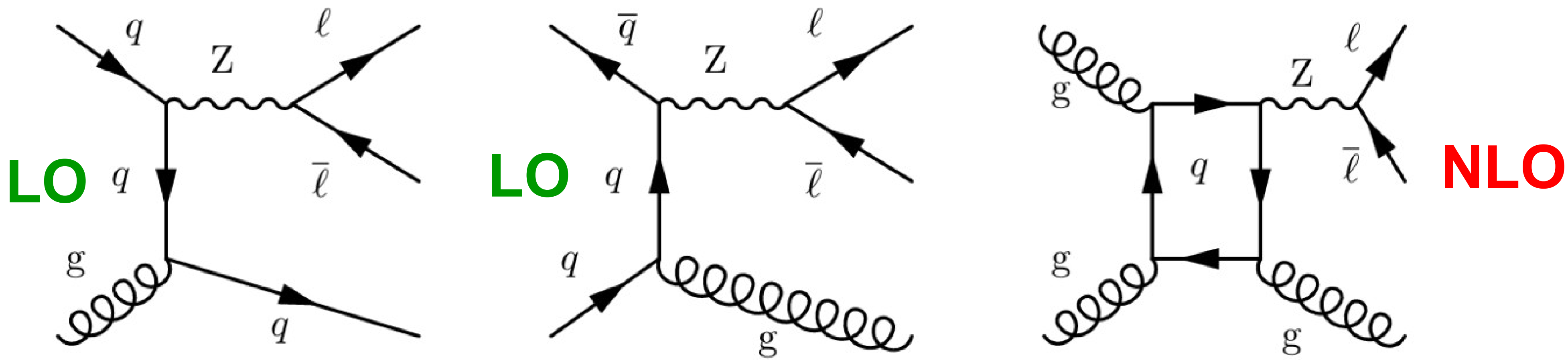
Theory known up to NNLO, 1st order independent of α_s

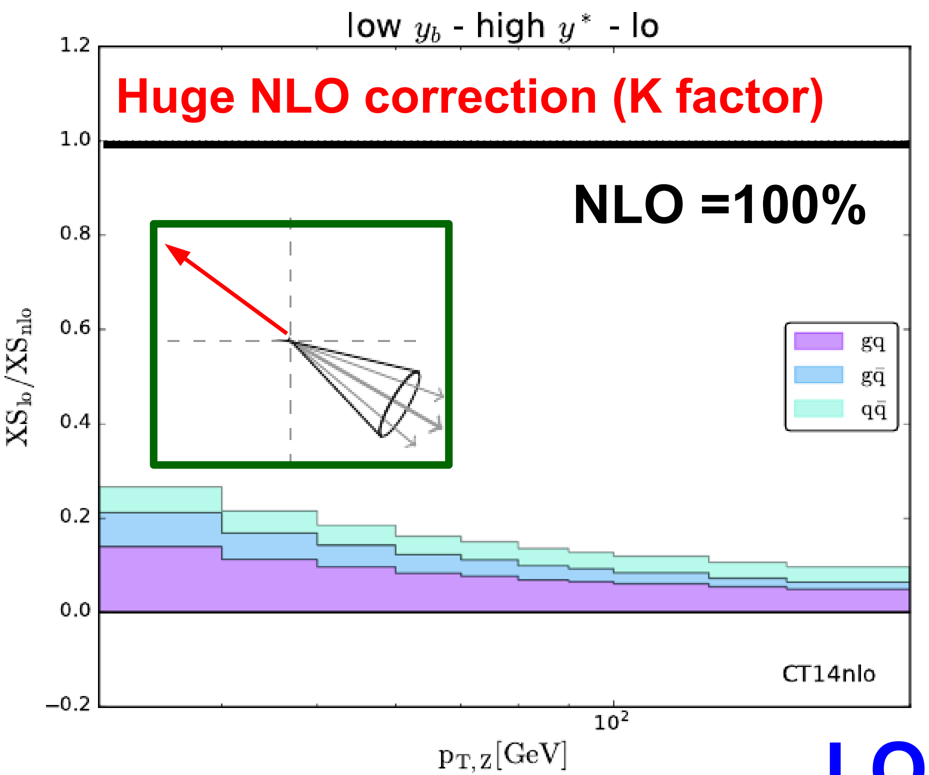
Only W^- shown   Only W^+ shown

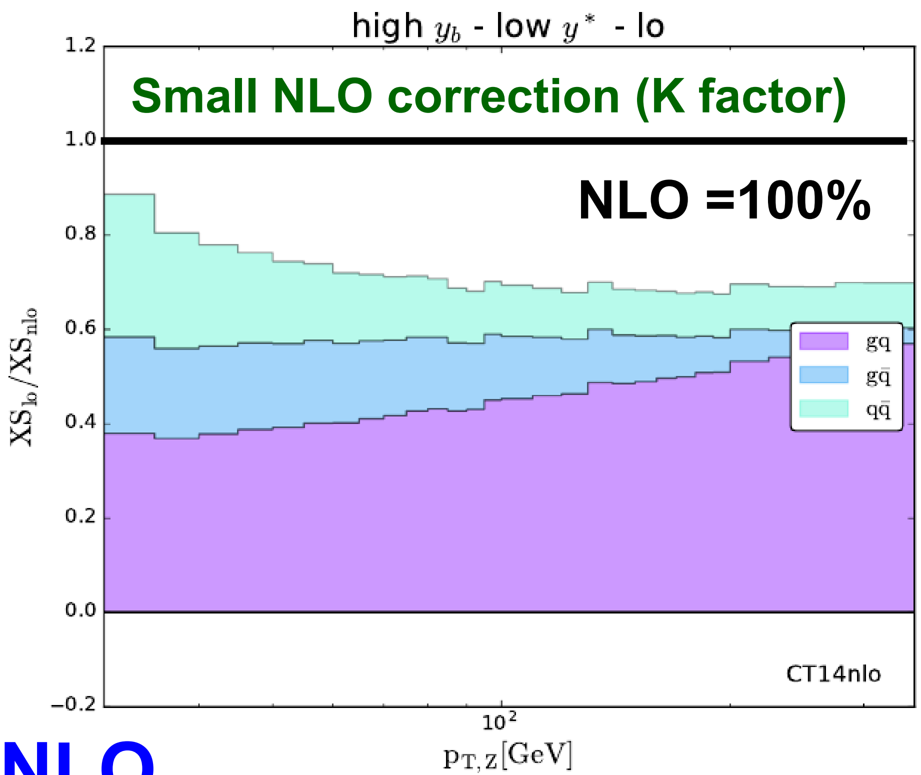


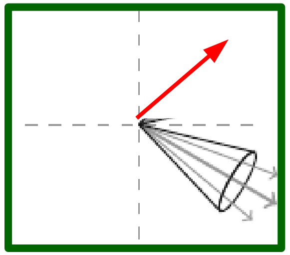
- **Production of W bosons vs. rapidity y**
  - **symmetric around zero for W^+, W^-**
  - **BUT: W^+ different from W^-**
  - **Proton content different for u and d!**

Z+jet production





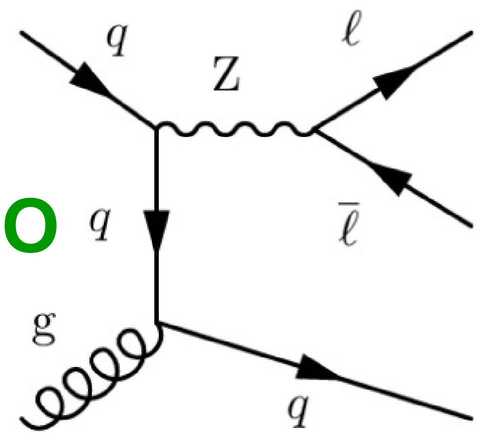




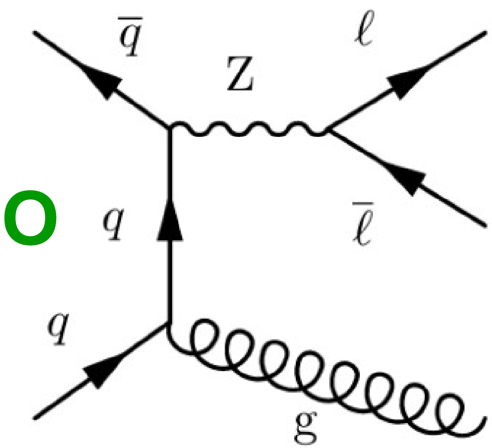
LO/NLO

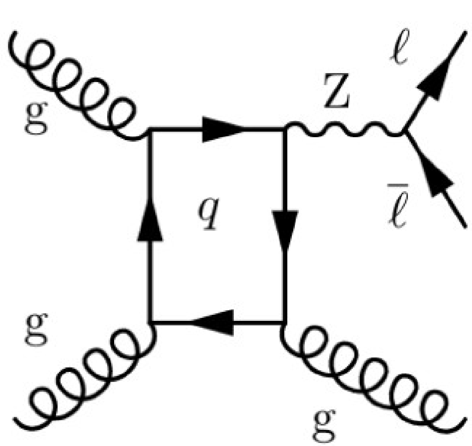
Z+jet production

LO

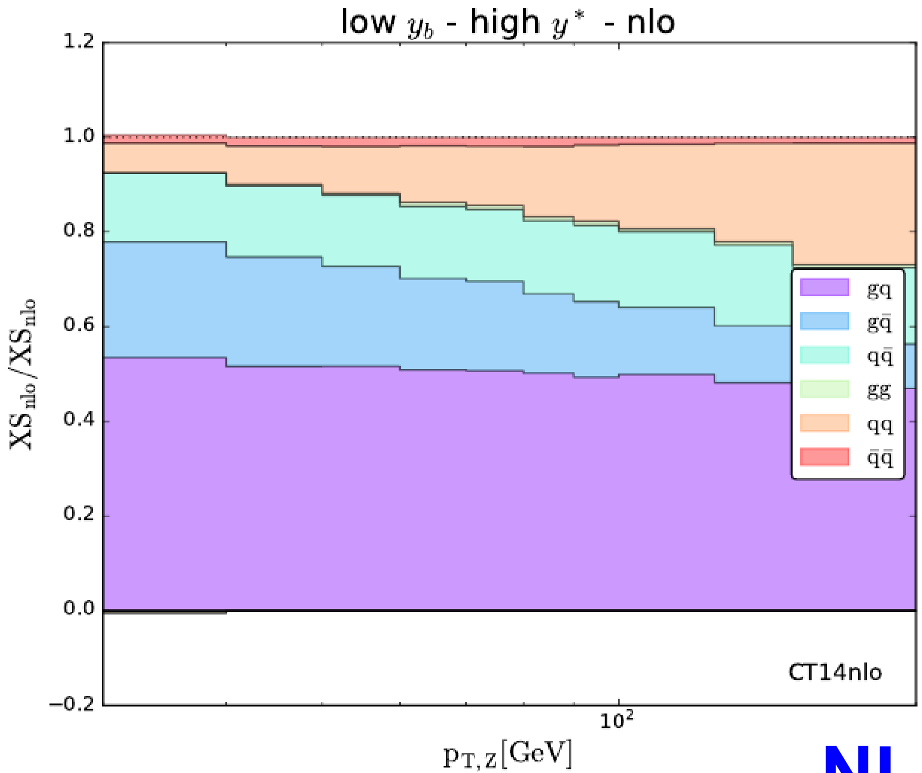


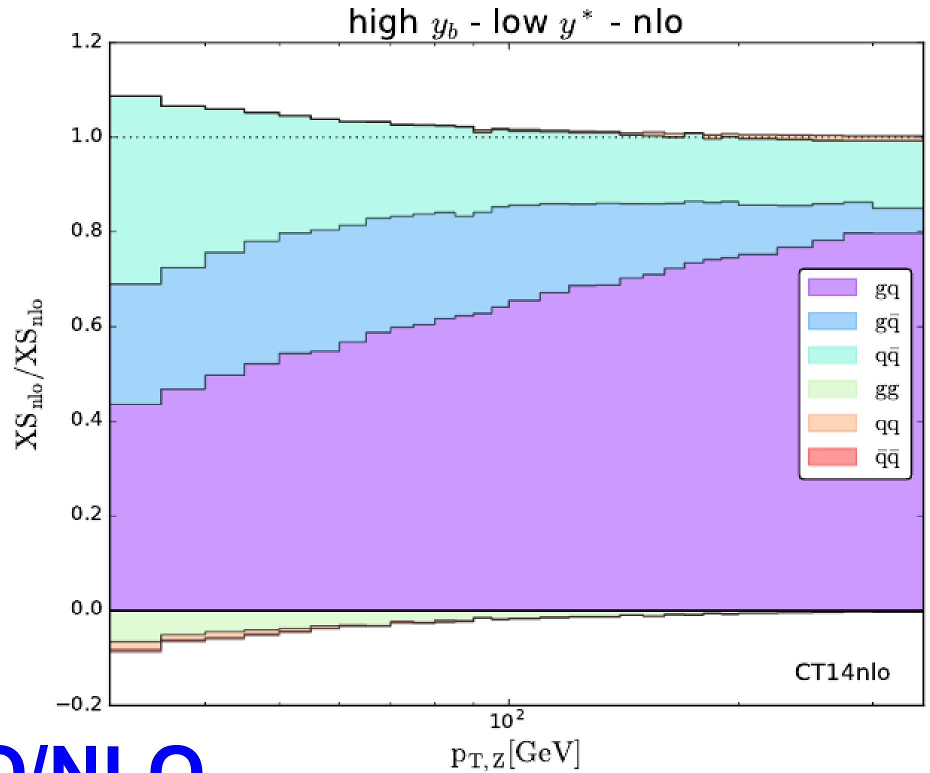
LO





NLO

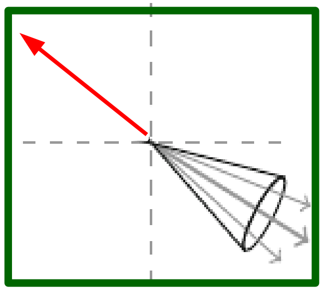




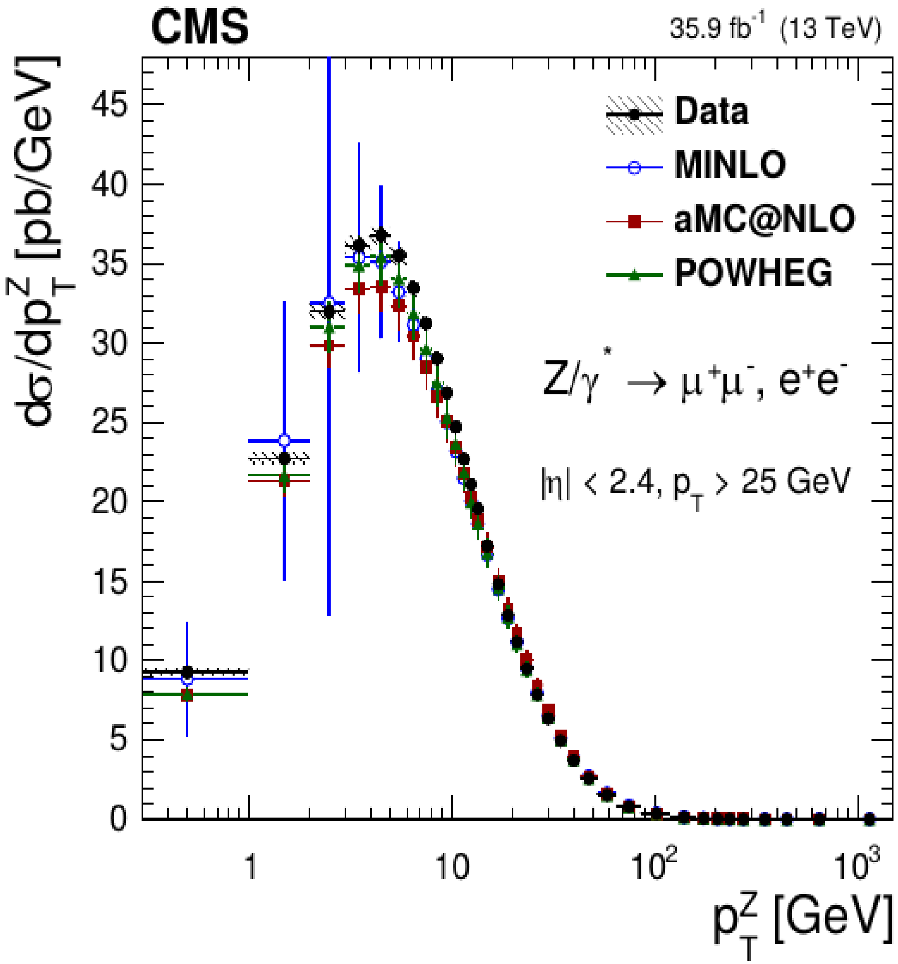
NLO/NLO

Z+jet production

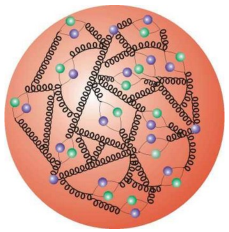
- **Theory for forward-backward topology**
  - **starts being precise only at NNLO**



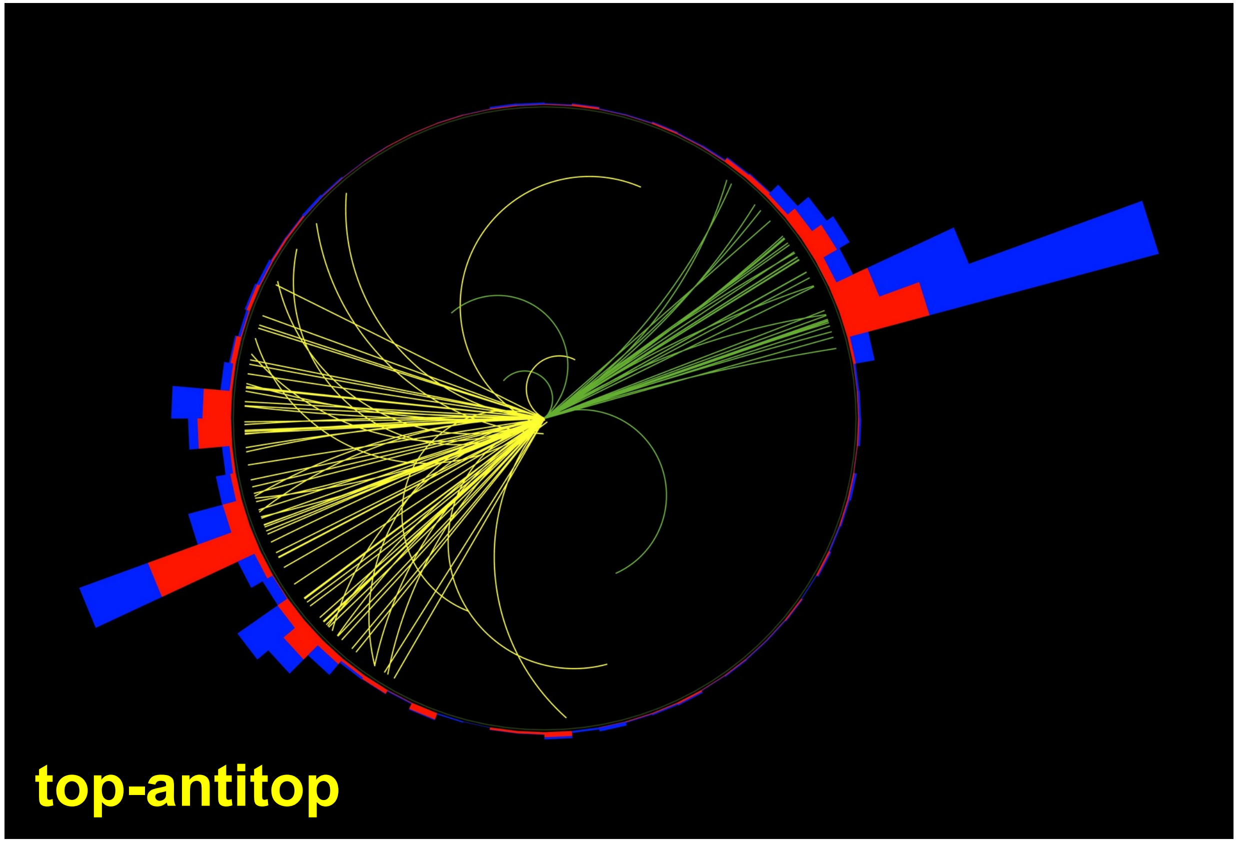
- **Z p_T distribution:**
  - **Z p_T balanced by jets at high p_T**
  - **At small p_T multiple soft gluon radiation must be considered, fixed-order pQCD insufficient**
    - **Resummation of leading terms to all orders**
    - **Parton showers**
  - **Description by MC generators with showers and/or resummation ok**

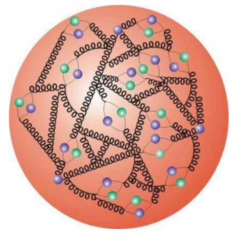


Heavy quarks



Proton



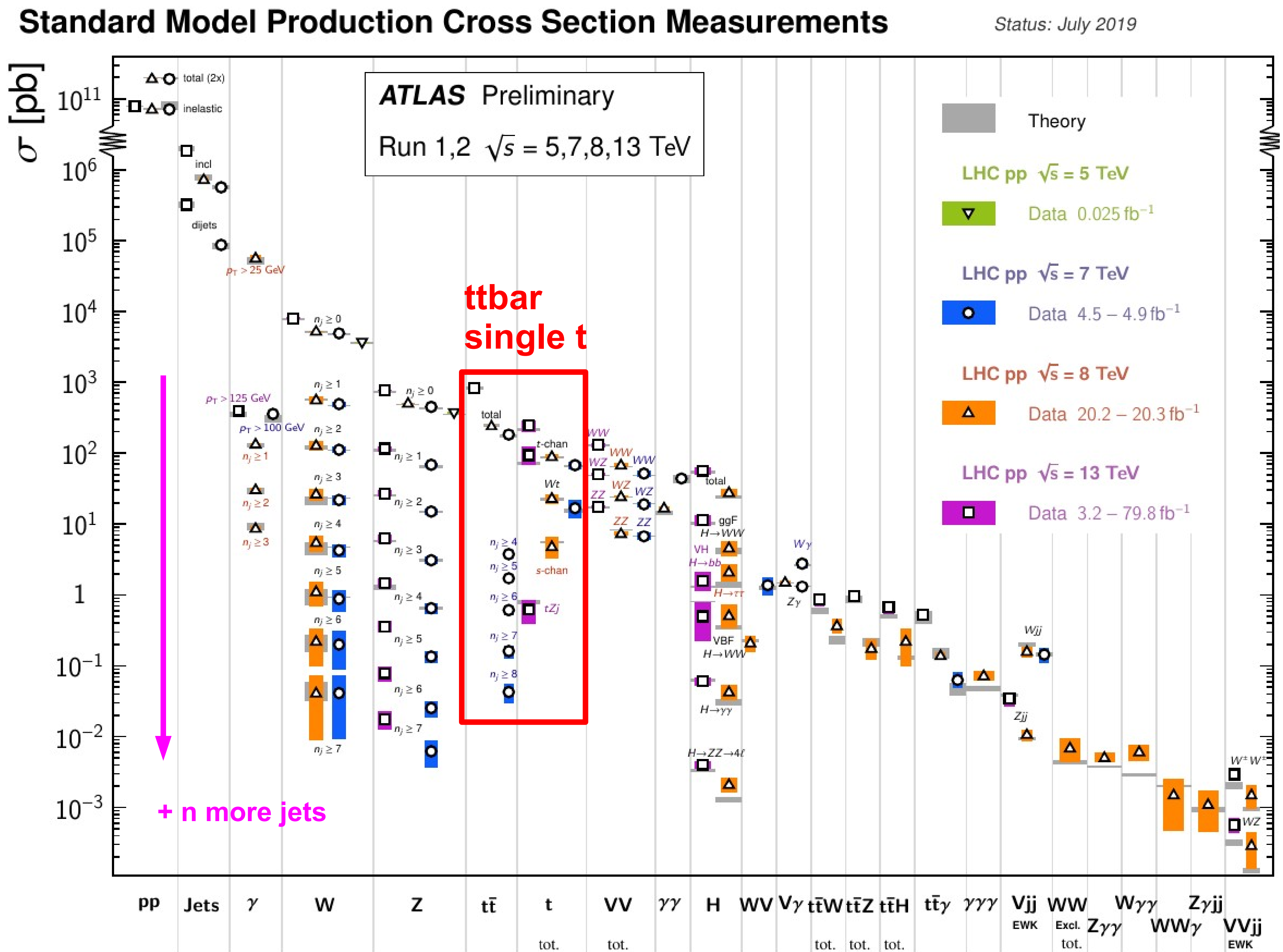


Proton

Relevant CMS measurements:

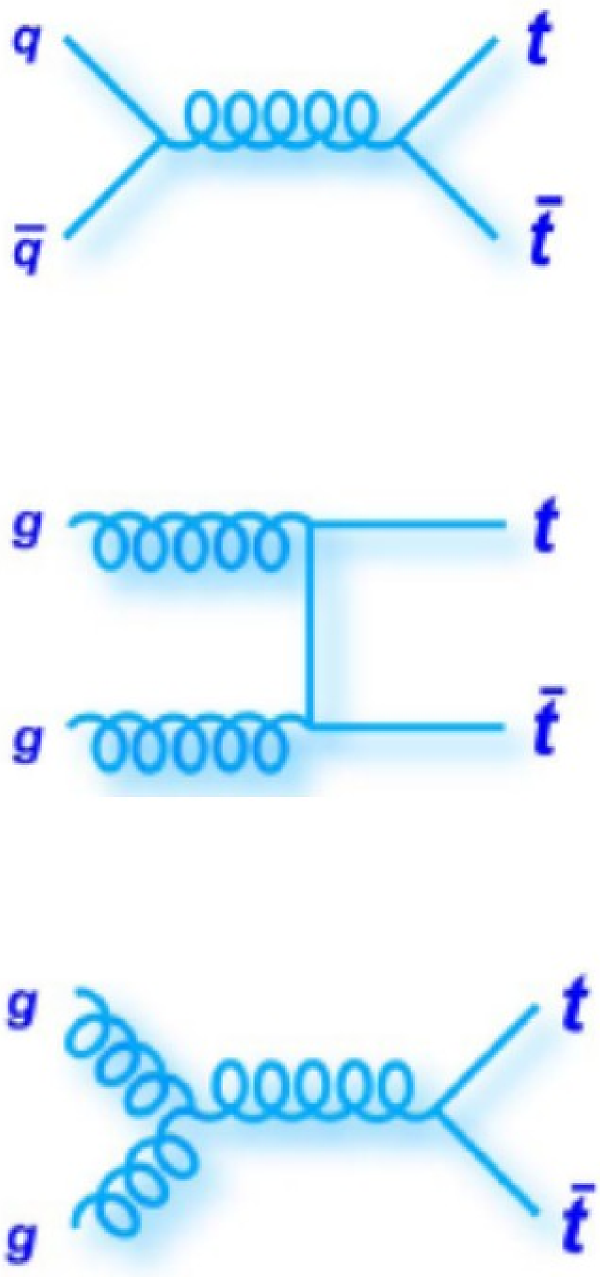
PLB 728, 496 (2013), JHEP 11, 067 (2012) [Erratum: PLB 738, 526 (2014)], CMS-TOP-17-001, arXiv:1812.10505 CMS-PAS-TOP-18-004.

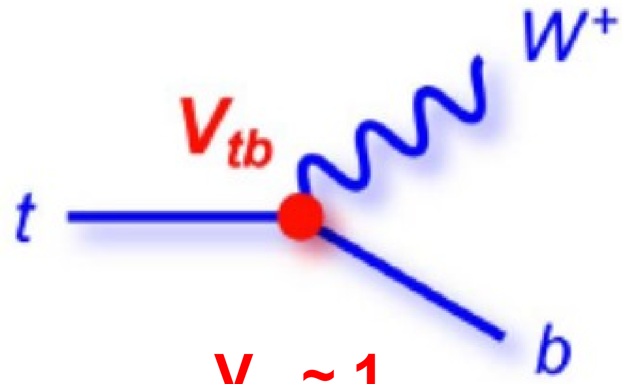
ttbar at the LHC



Top quark in the Standard Model

- **top like a normal quark**
  - **Spin 1/2**
  - **Couples to color**
  - **Produced "strongly", predominantly via gluon-gluon process at the LHC**
  - **Decays "weakly" to ~100% via t → Wb**
  - **No flavor-changing neutral currents**



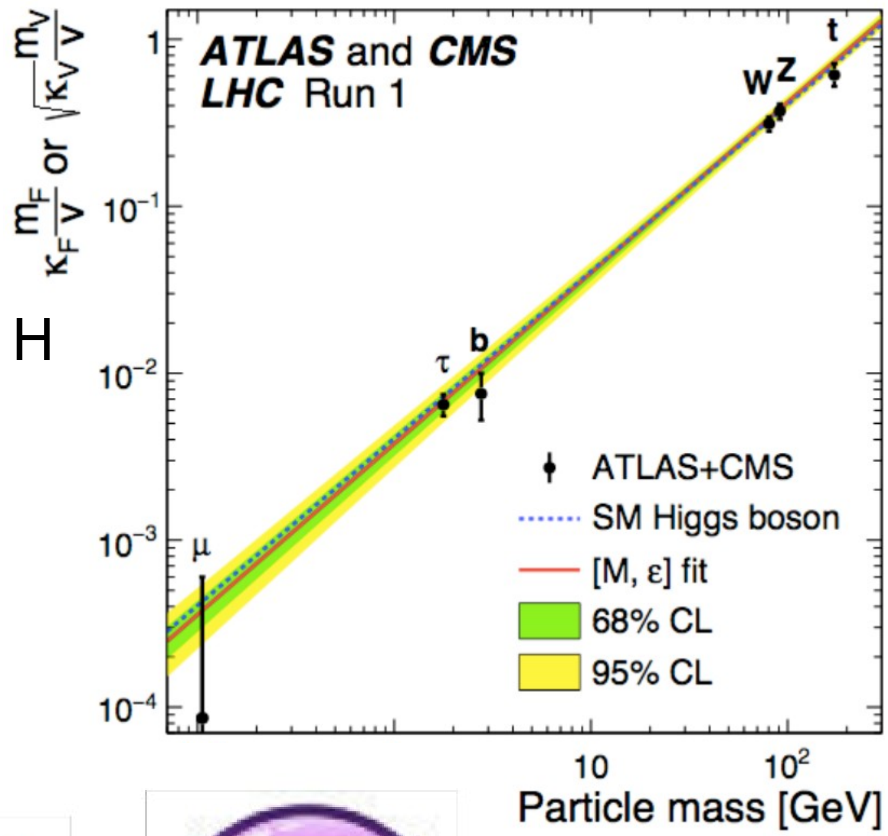


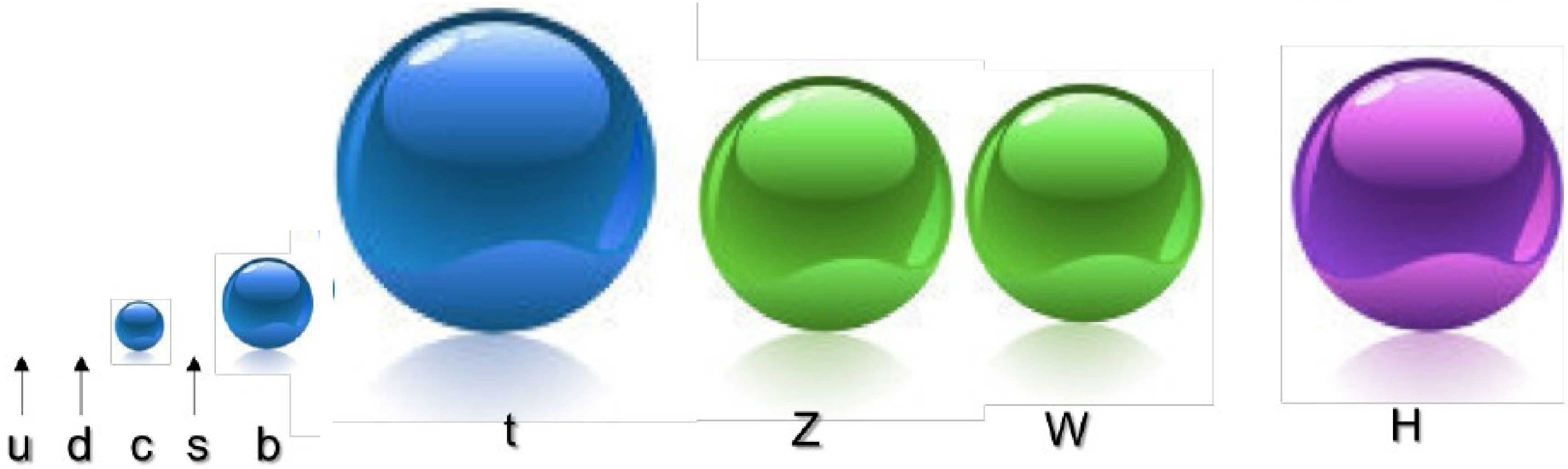
$V_{tb} \sim 1$

	d	s	b
u	0.97434	0.22506	0.00357
c	0.22492	0.97351	0.0411
t	0.00875	0.0403	0.99915

CKM matrix

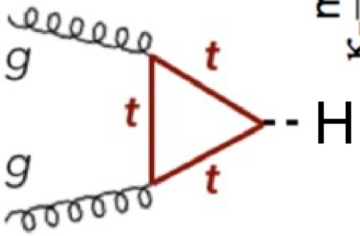
- **top not a normal quark**
  - **Heaviest known elementary particle**
    m_{top} = ~173 GeV

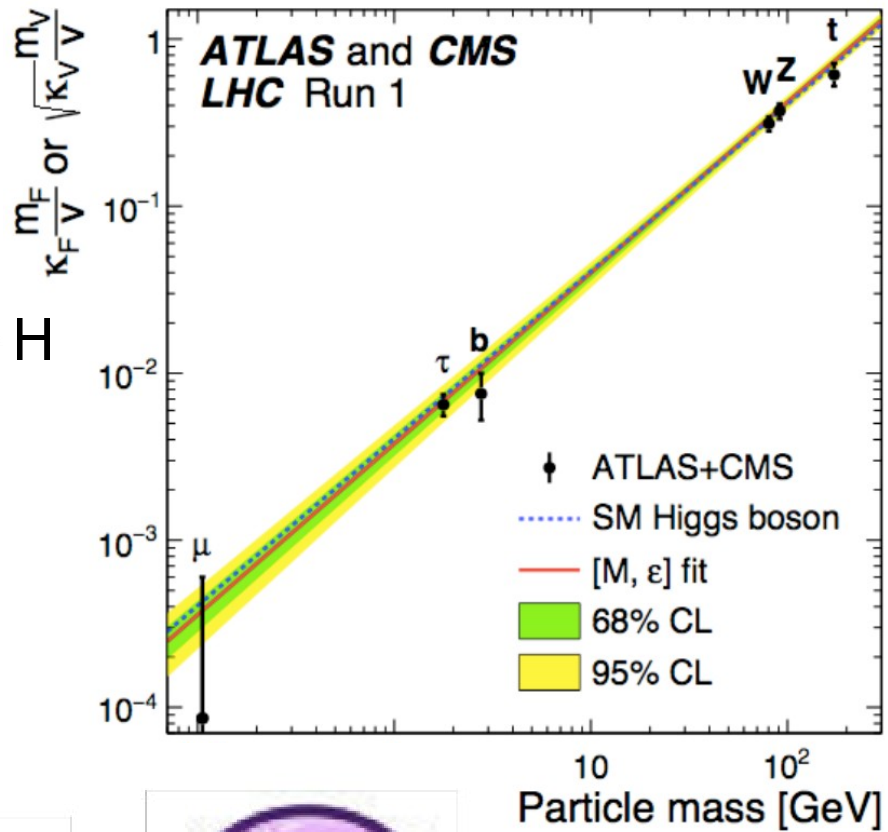


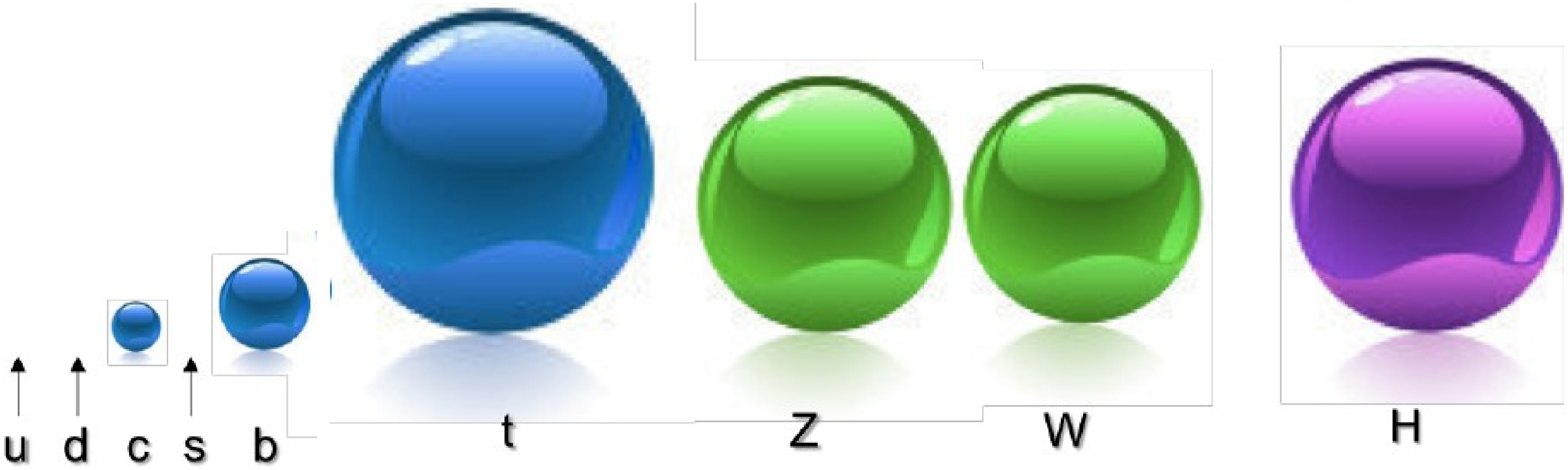


Top quark in the Standard Model

- top not a normal quark
  - Heaviest known elementary particle m_{top} = ~173 GeV
  - Dominant loop graph for Higgs production

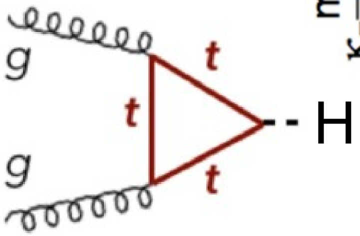


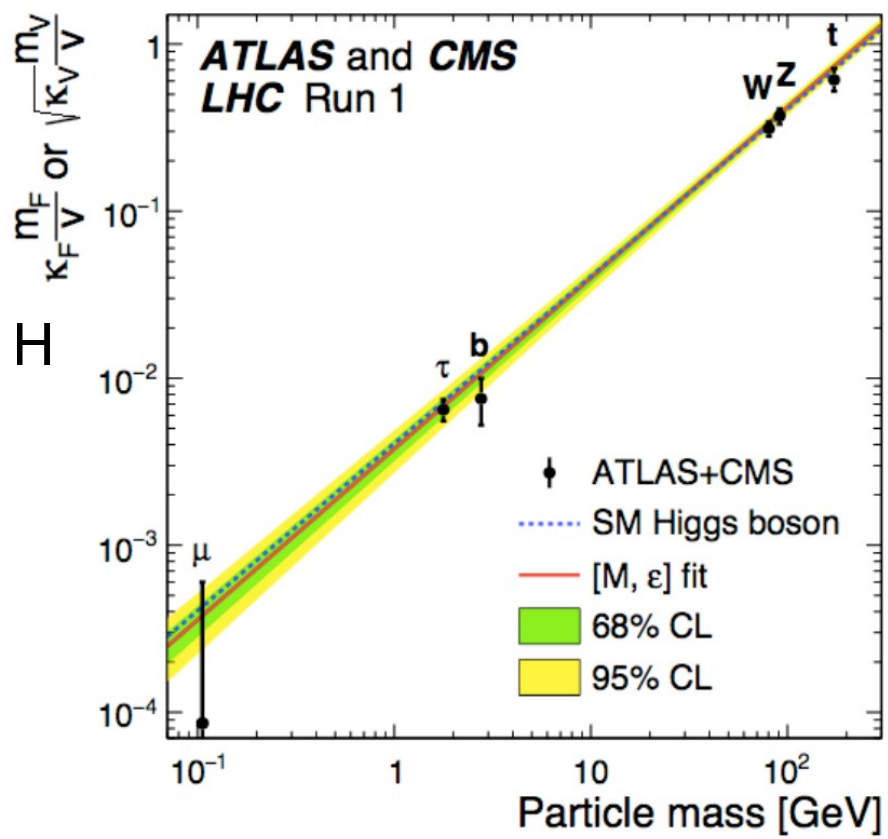




Top quark in the Standard Model

- top **not a normal quark**
  - **Heaviest known elementary particle m_{top} = ~173 GeV**
  - **Dominant loop graph for Higgs production**
  - **Very short lifetime τ ~ 5 10^{-25} s**
  - **Decays before forming hadrons**
  - **Allows to measure spin correlations**

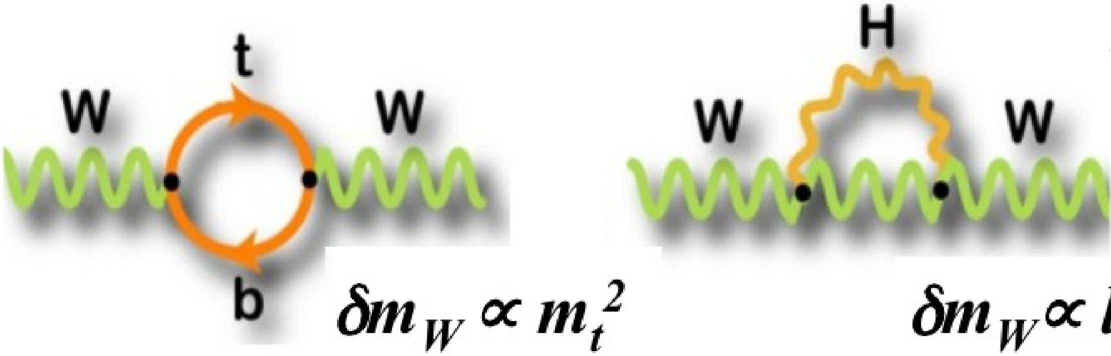




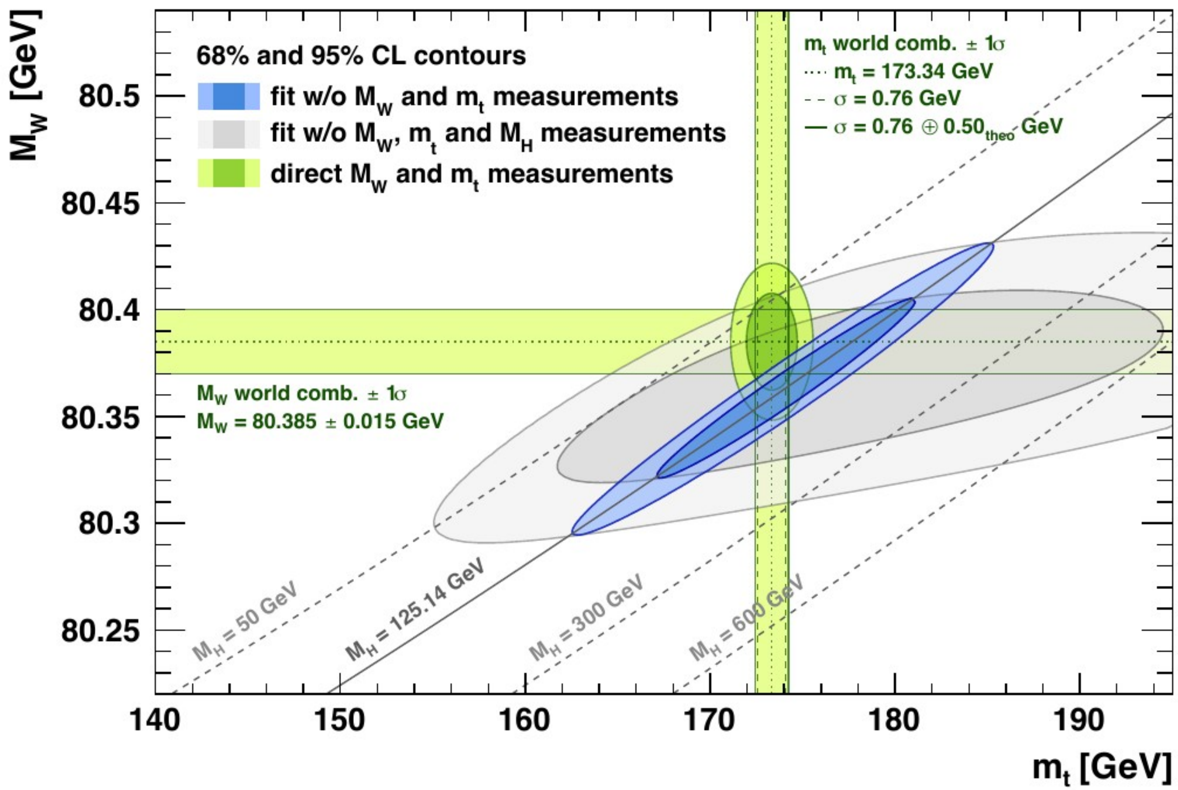
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}}$$

top, W, and Higgs mass

- top mass connected to W and Higgs mass via loop corrections
- Production as single-top can provide input to PDFs
- Background to many searches for new physics



$\delta m_W \propto m_t^2$ $\quad$ $\delta m_W \propto \ln(m_H)$



arXiv:1407.3792

Much more on top analyses in:

Particle physics II – Top quark and jet physics at the LHC

KR + A. Meyer

Summary

- Collisions including hadrons such as protons in the initial state require knowledge of the hadron’s internal structure
- Protons are described by parton distribution functions (PDFs) describing the probability to find a parton i with momentum fraction x at a scale μ_f
  - The x dependence cannot be derived in perturbative QCD, but is universally usable in scattering processes once determined from data
  - The scale dependence is calculable in perturbative QCD, TP II Top & Jets
- Through the factorisation theorem of QCD cross sections involving hadrons can be derived separating soft/collinear effects into PDFs and high-pT parton scatters in partonic matrix elements
- Examples for high-pT processes at the LHC are
  - Inclusive jet production → determination of the strong coupling constant
  - W production → asymmetry in W^+ W^- rapidity distribution
  - Z+X production → process decomposition vs. rapidity; Z pT from low to high
  - ttbar production → top quark mass, lifetime, ...

Backup