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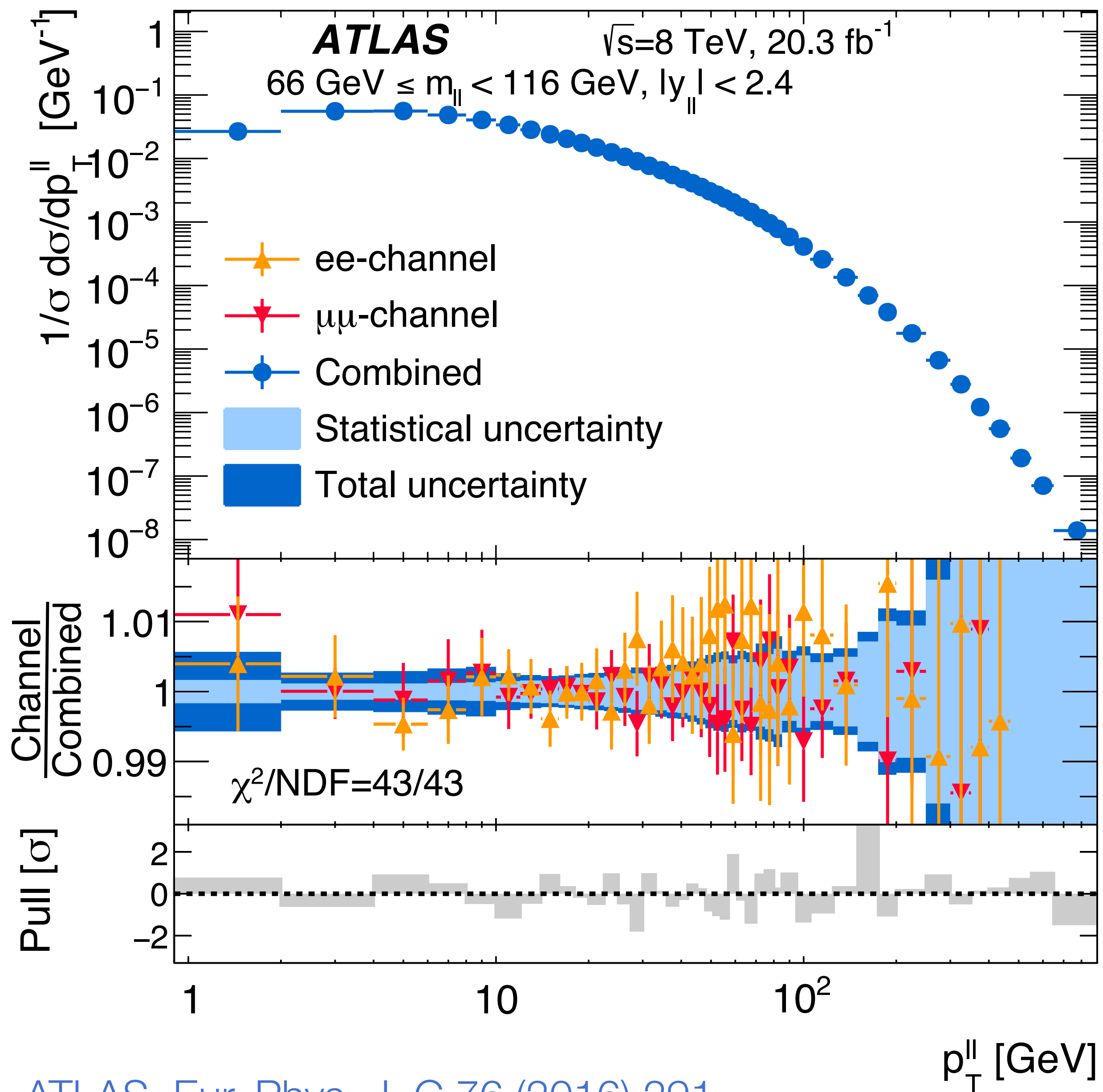
FOR FUNDAMENTAL PHYSICS

Automated, Resummed and Effective: Precision Computations for the LHC

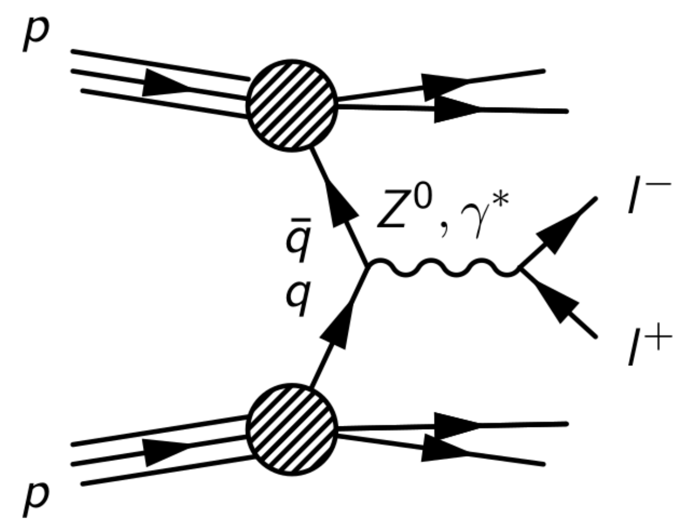
Thomas Becher
University of Bern

Freiburg, February 7, 2019

Precision measurements at the LHC



ATLAS, Eur. Phys. J. C 76 (2016) 291



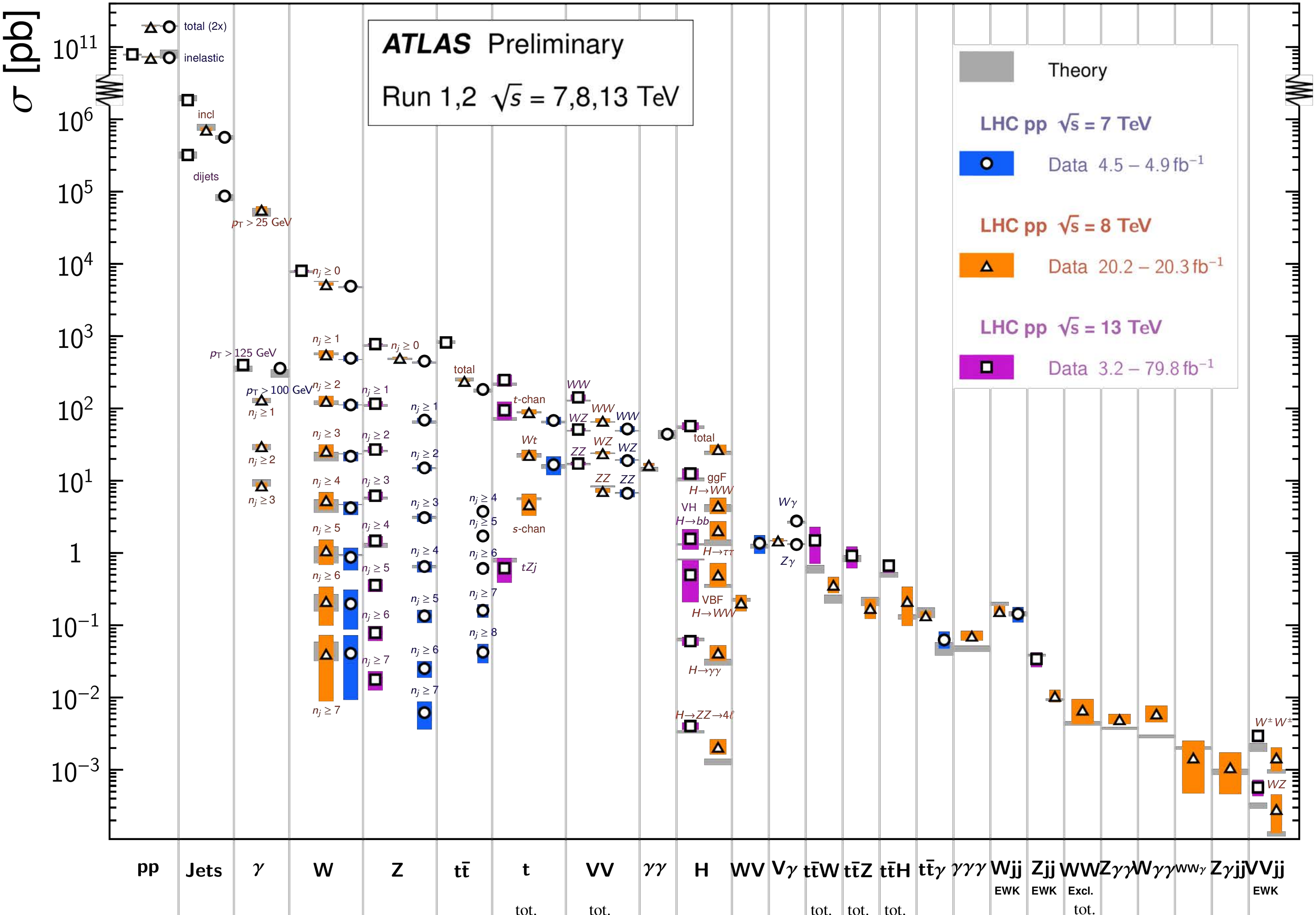
Sub-percent accuracy
over large range of energies and
many orders of cross section!

transverse momentum of the lepton pair

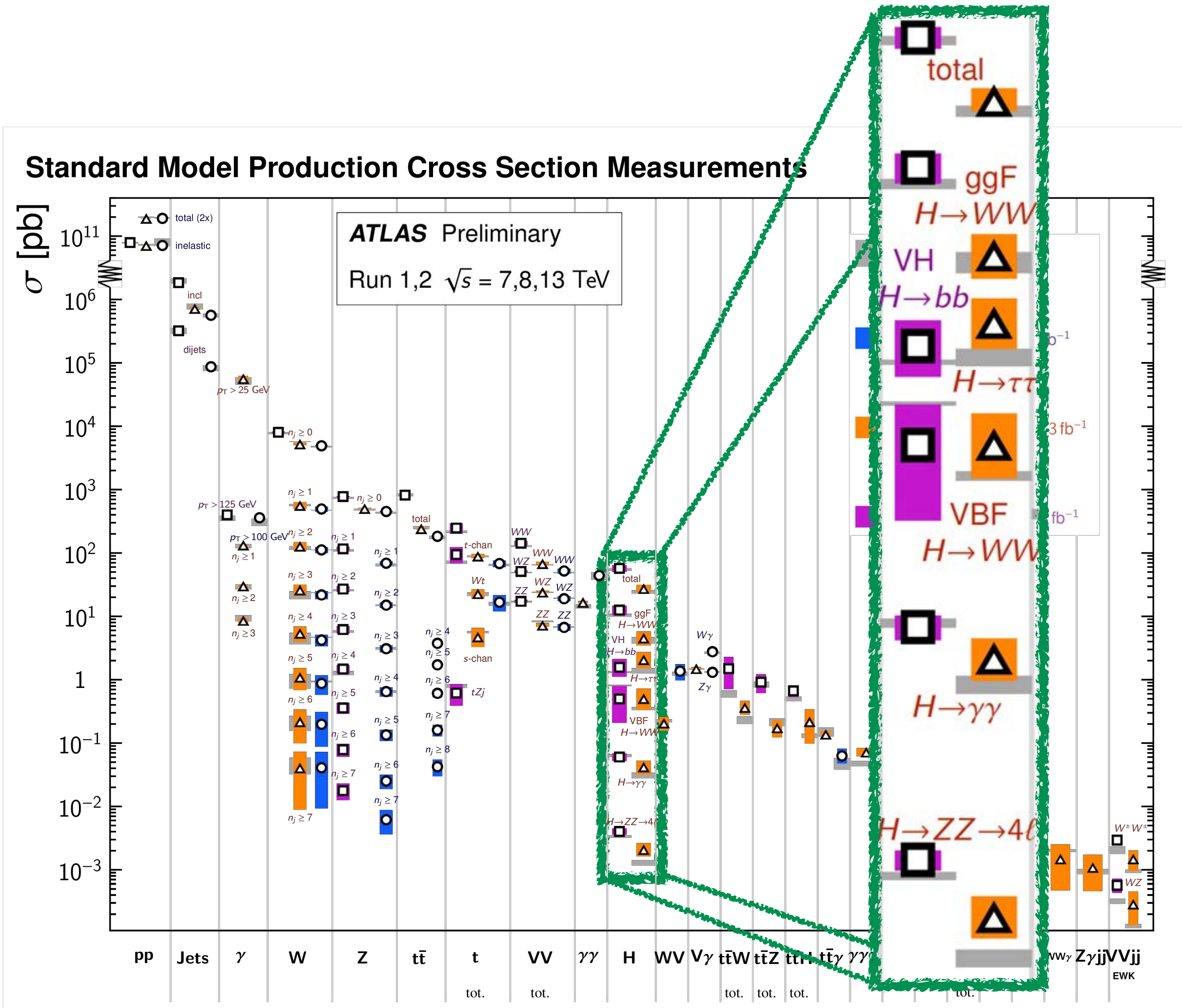
A huge challenge for theory!

Standard Model Production Cross Section Measurements

Status: July 2018



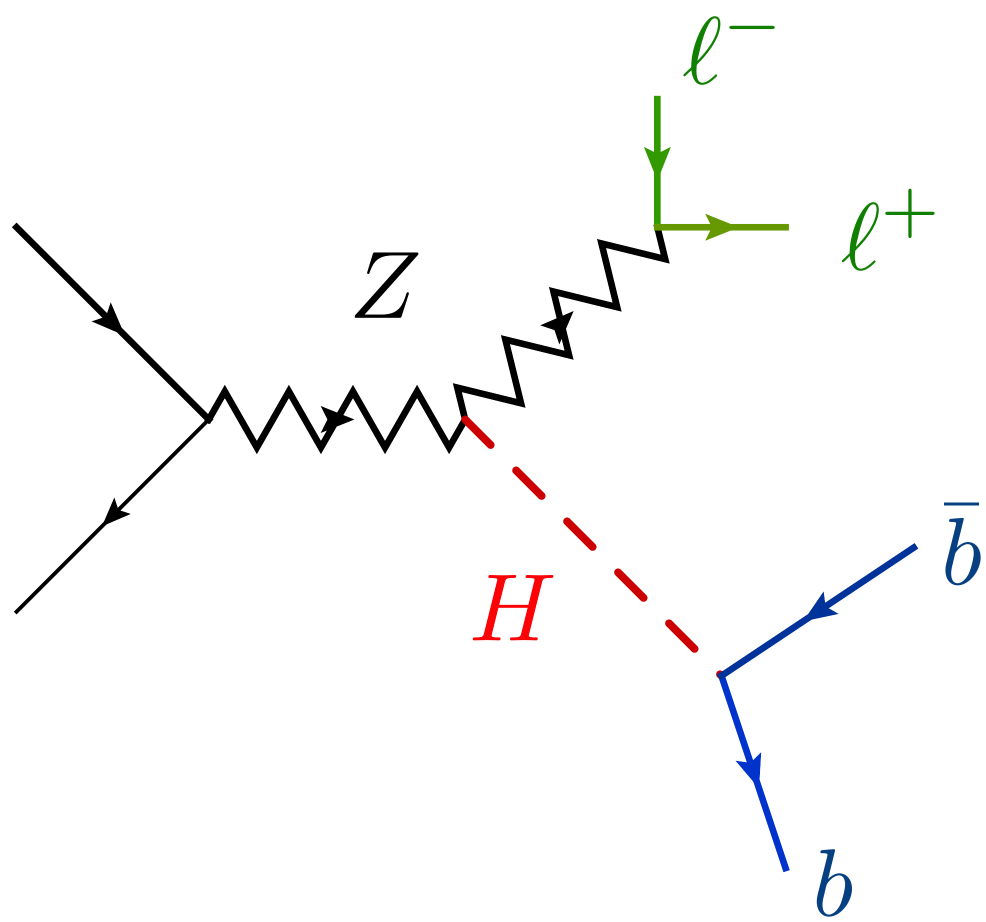
Higgs interactions: the fifth force

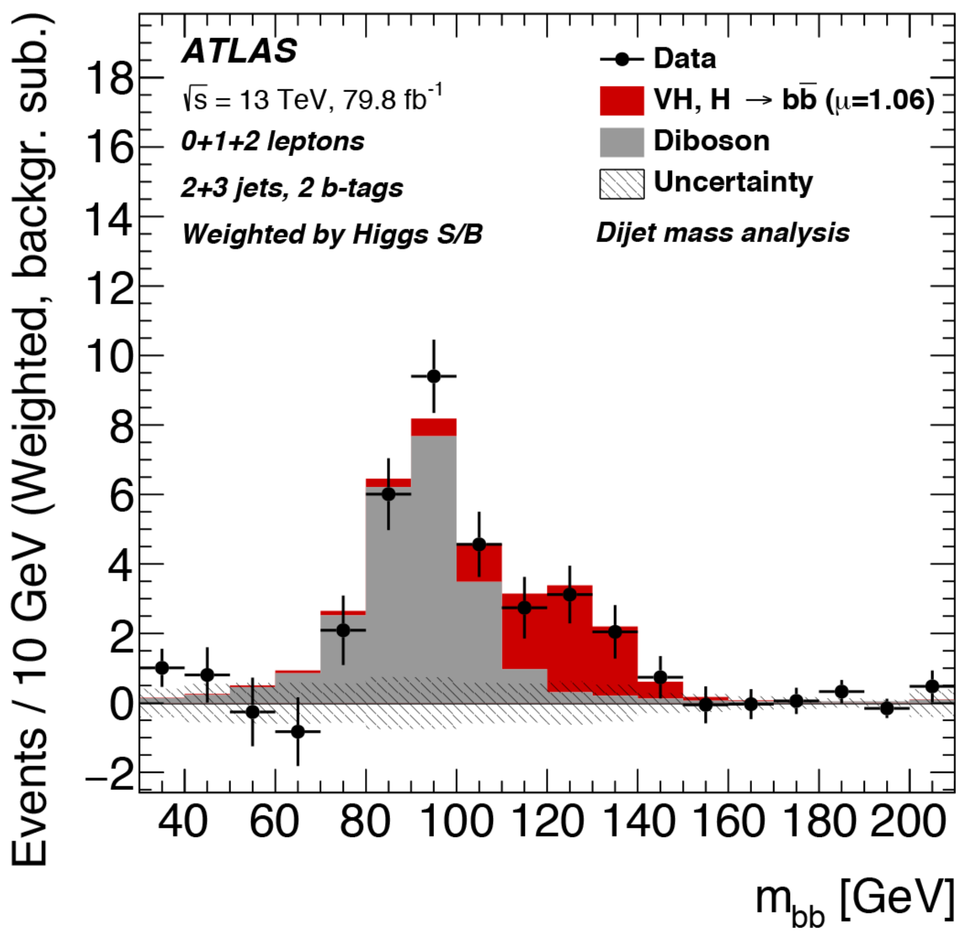


$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \Psi + h.c. \\
& \boxed{\begin{aligned} & + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi) \end{aligned}}
\end{aligned}
$$

A rich program of Higgs-boson physics, probing its interactions and searching for deviations from the SM.

e.g. Higgs coupling to b-quarks





Last year, ATLAS and CMS observed $H \to b\bar{b}$ for the first time. Extremely challenging due to the huge background from QCD processes.

List of LHC measurements observing direct signals of New Physics

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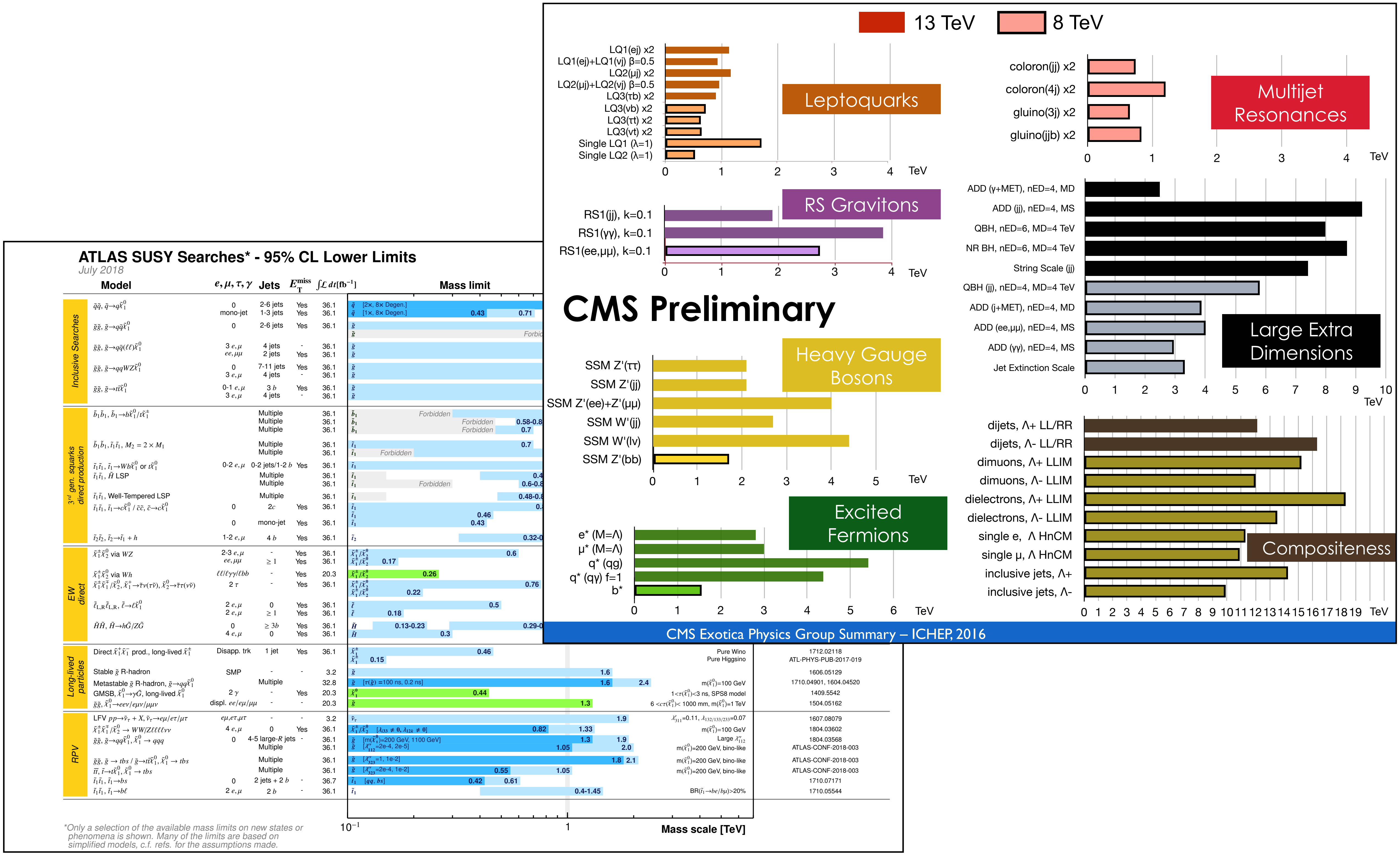
… and there were a lot of searches!



In the absence of direct signals, the focus shifts more and more on indirect searches, looking for small deviations from SM predictions.

Motivates work on precision predictions.

Effective field theory provides a systematic framework to study deviations from the SM.

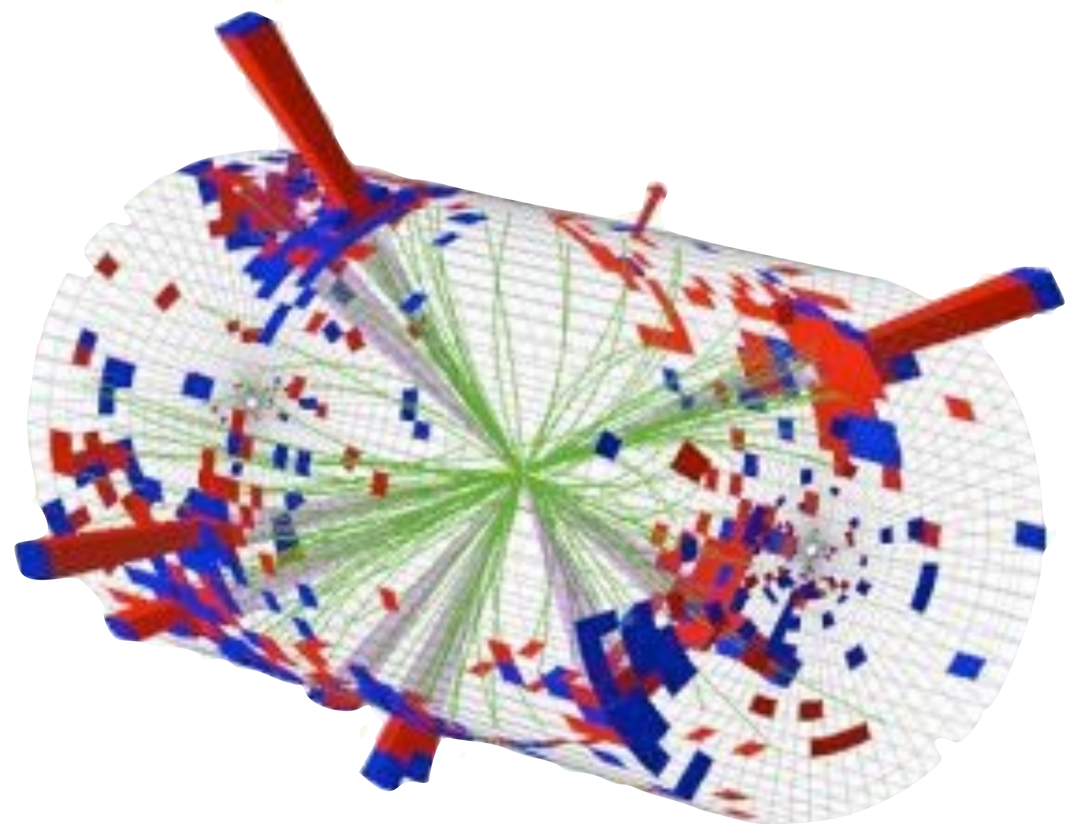
$$\mathcal{L}_{\mathrm{S}M} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right),$$

standard, renormalizable textbook SM Lagrangian

Wilson coefficients

additional operators induced by new heavy physics at scale Λ

Effective theory for LHC processes



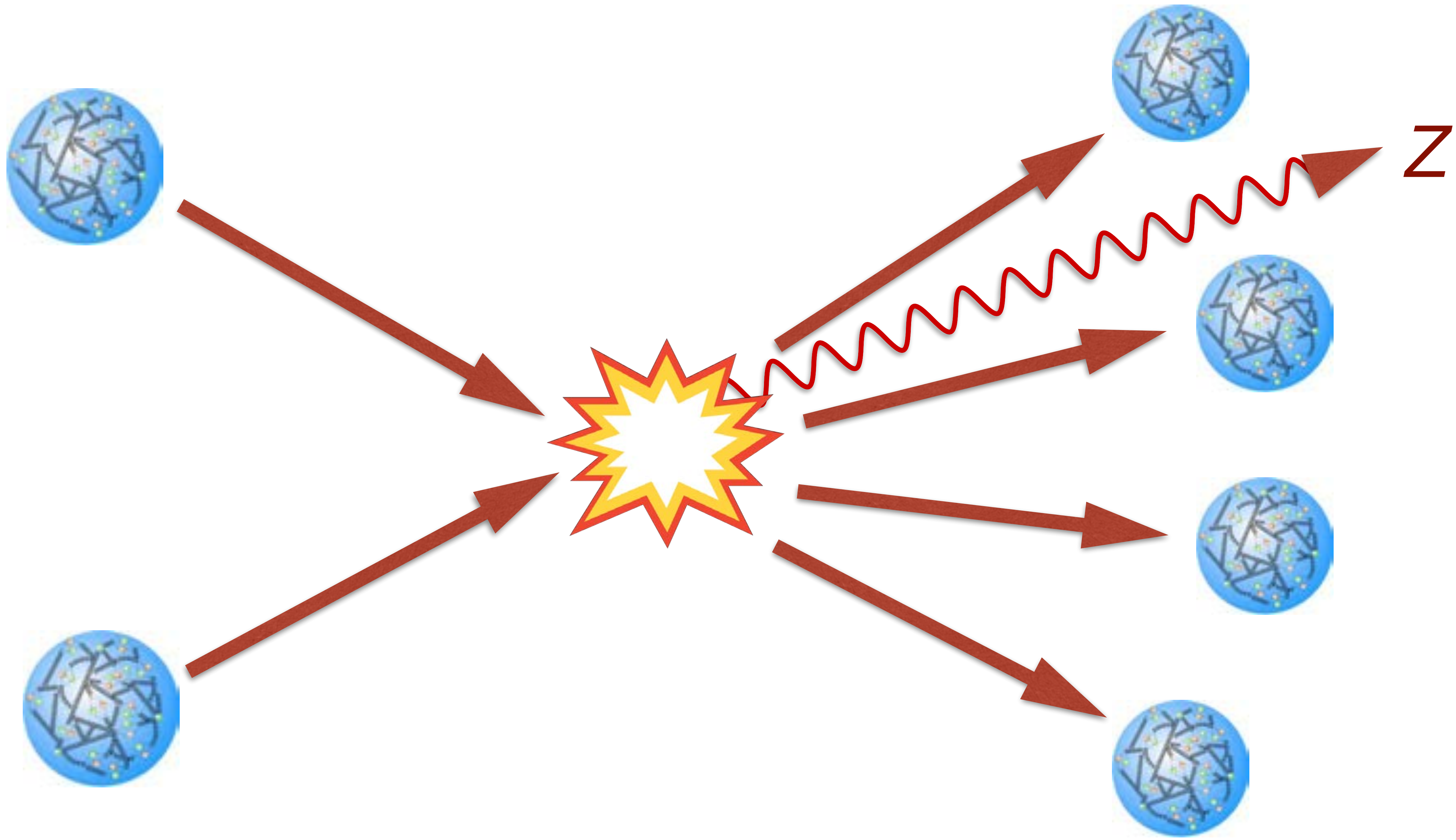
Many scale hierarchies!

$$\sqrt{s} \gg p^T_{\text{Jet}} \gg M_{\text{Jet}} \gg E_{\text{out}} \gg m_{\text{proton}} \sim \Lambda_{\text{QCD}}$$

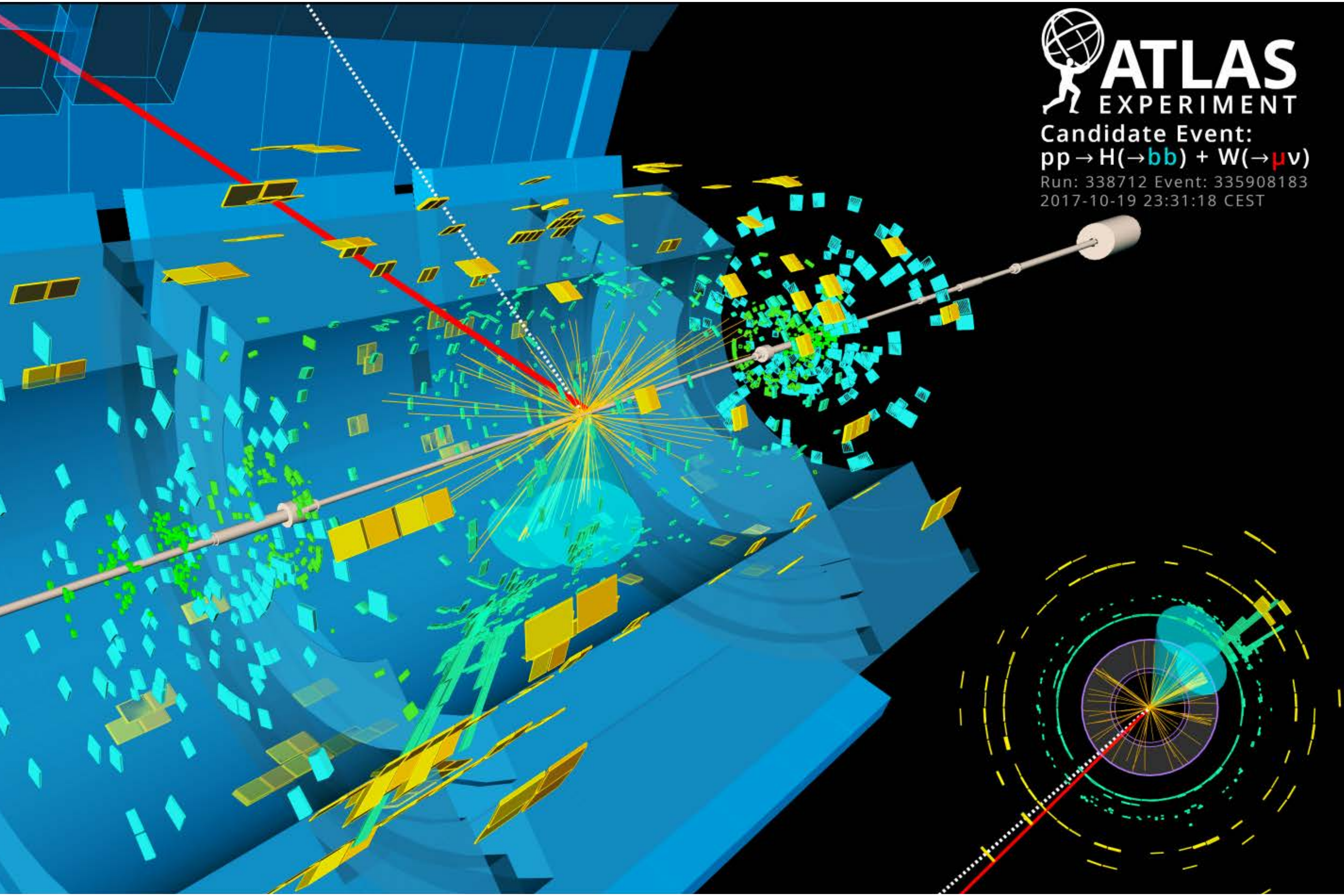
→ Soft-Collinear Effective Theory (SCET)

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke, Diehl et al. 2002; …

pp scattering



The challenge are QCD (strong interaction) effects


ATLAS
EXPERIMENT
Candidate Event:
pp → H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

What can be computed in perturbation theory in QCD?

What can be computed in perturbation theory in QCD?

Nothing.

PhD student (working on lattice QCD) at
Bern University during his thesis defense

What can be computed in perturbation theory in QCD?

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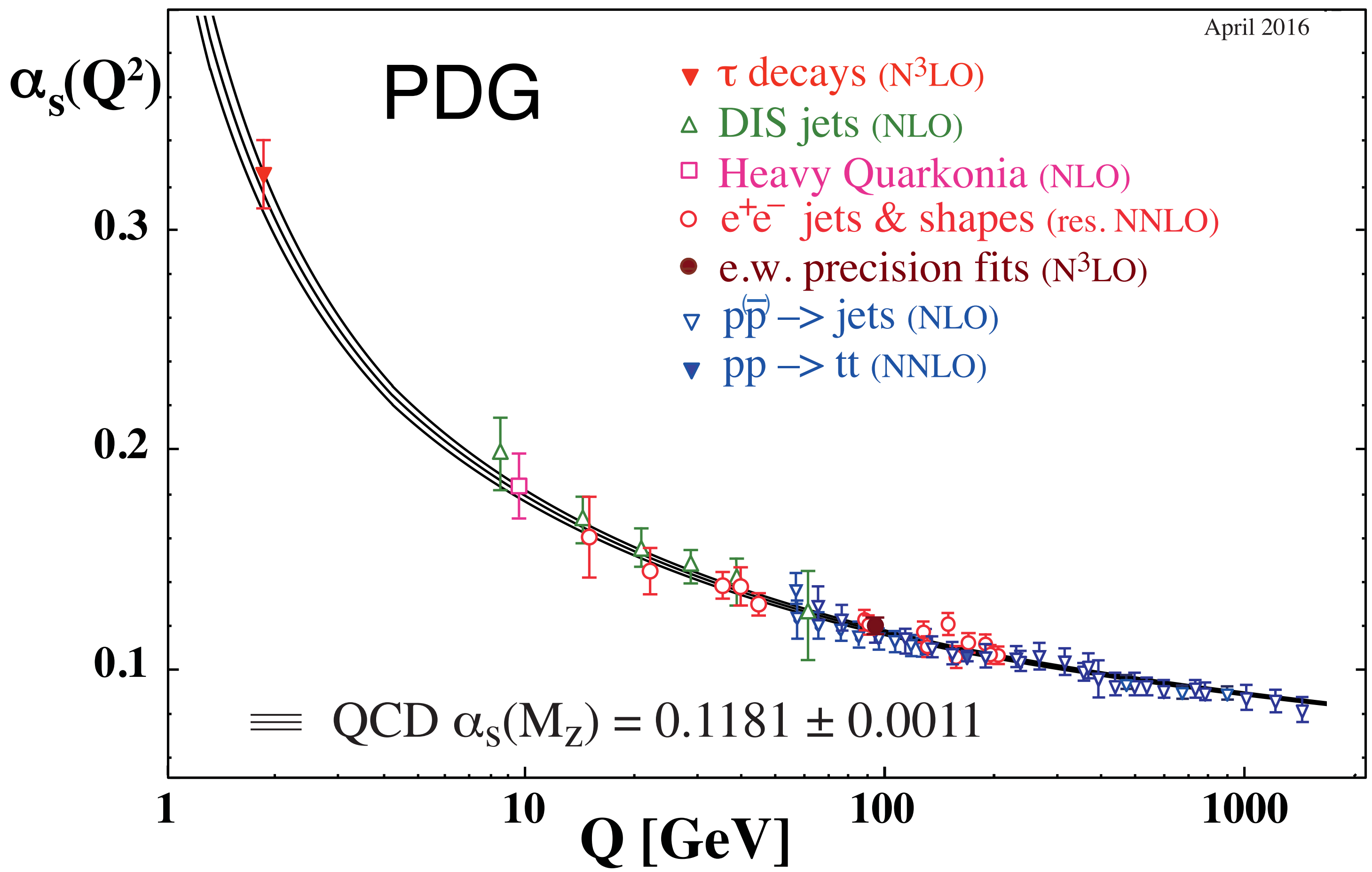
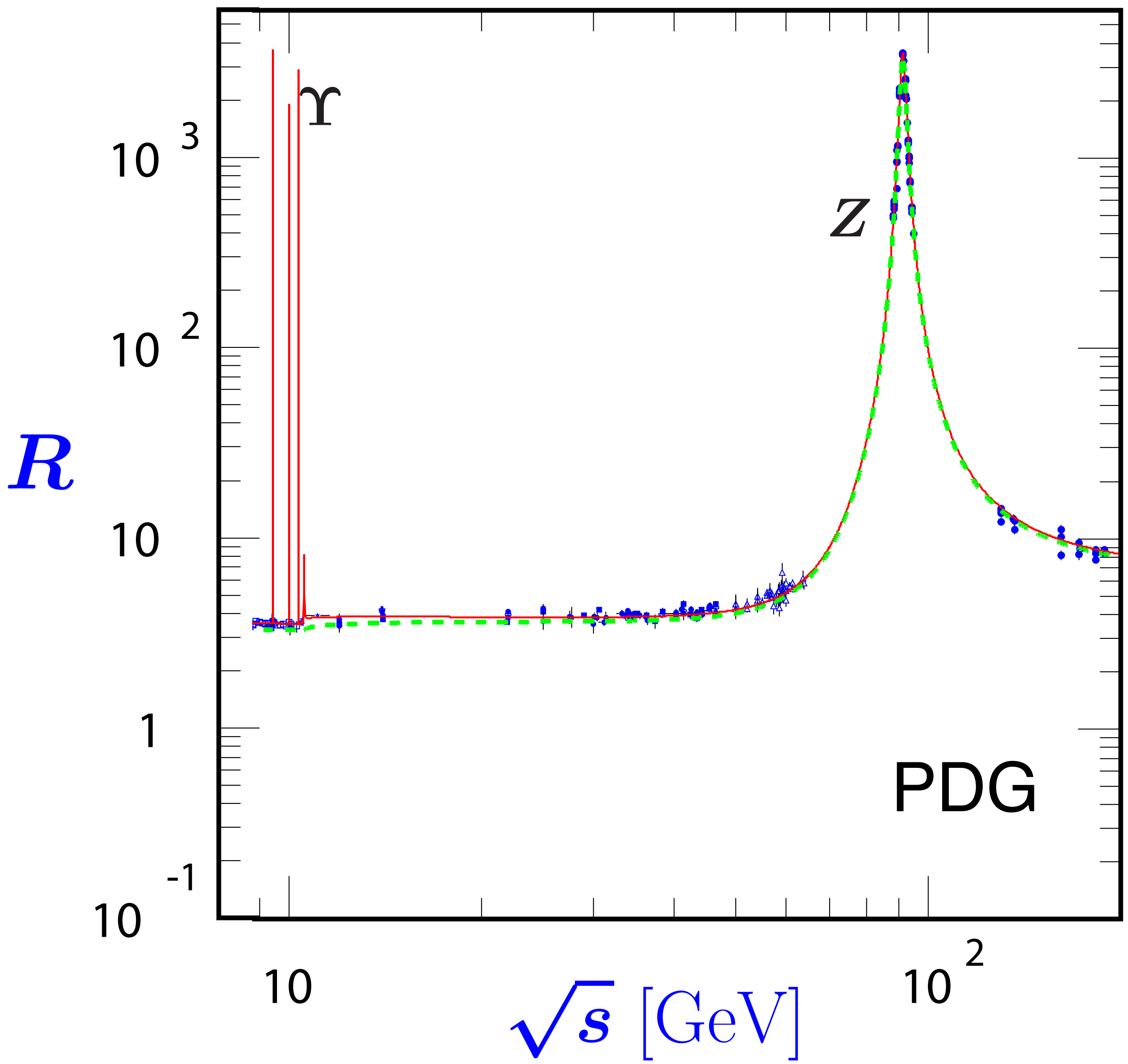
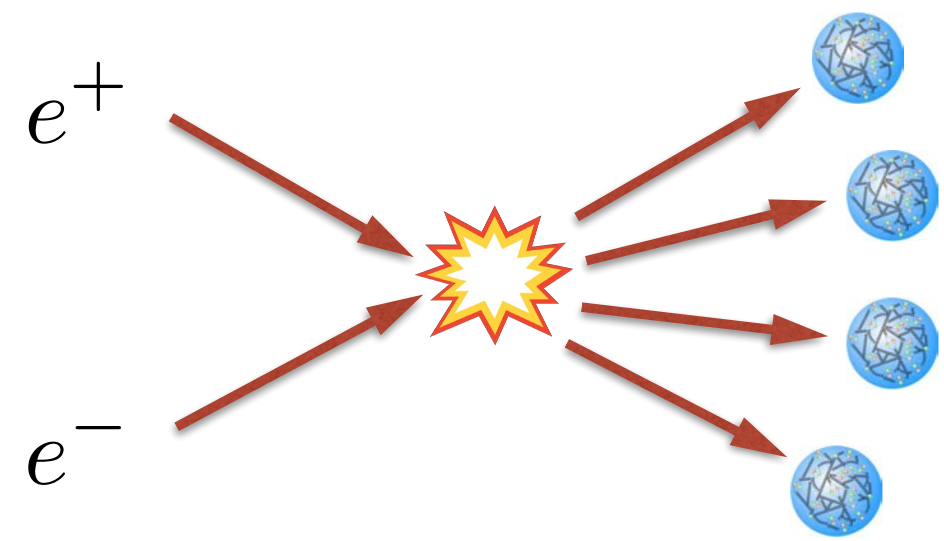


More educated answer: High-energy processes.
QCD coupling becomes weak at high energy because of asymptotic freedom.





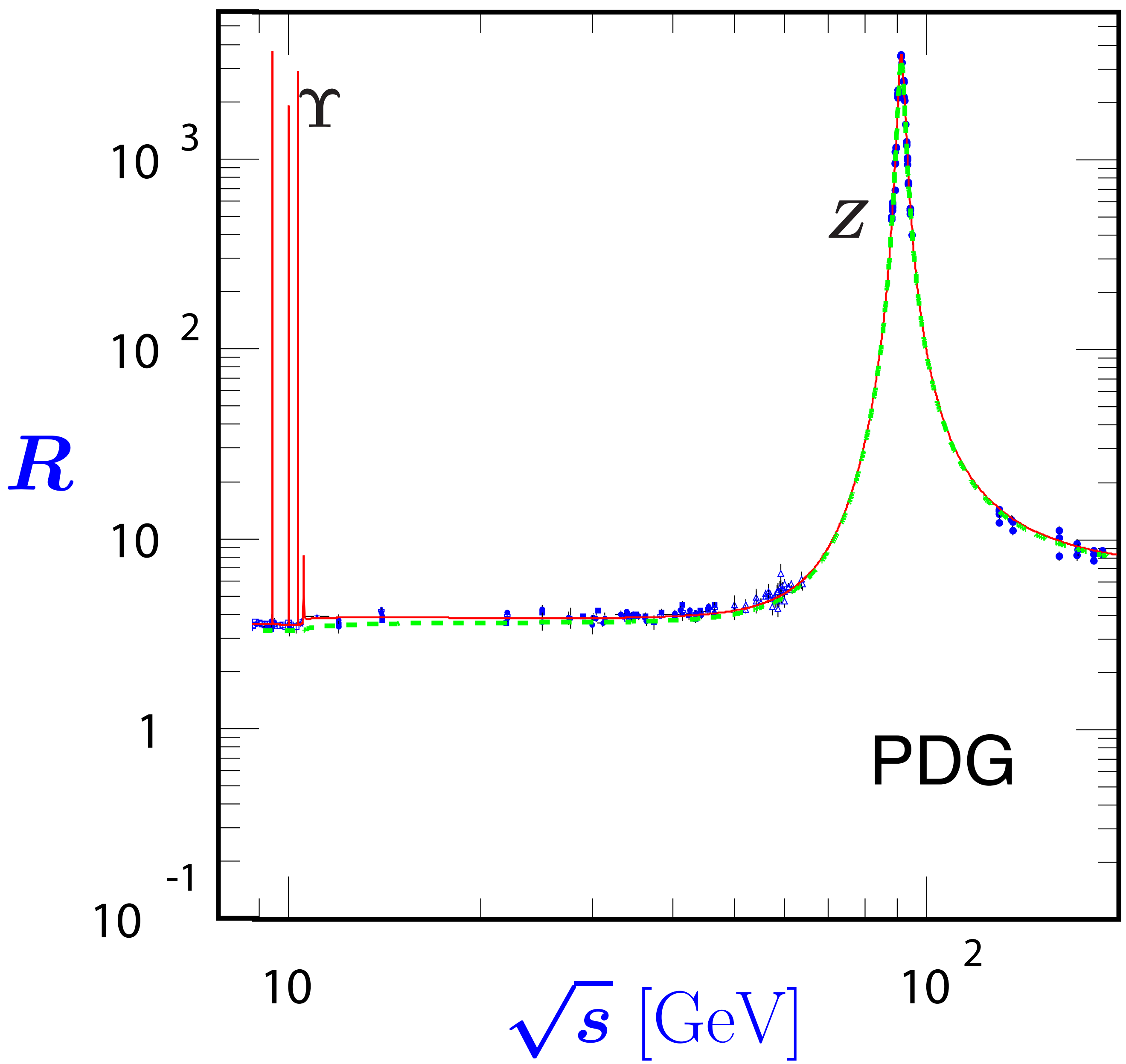
measurement

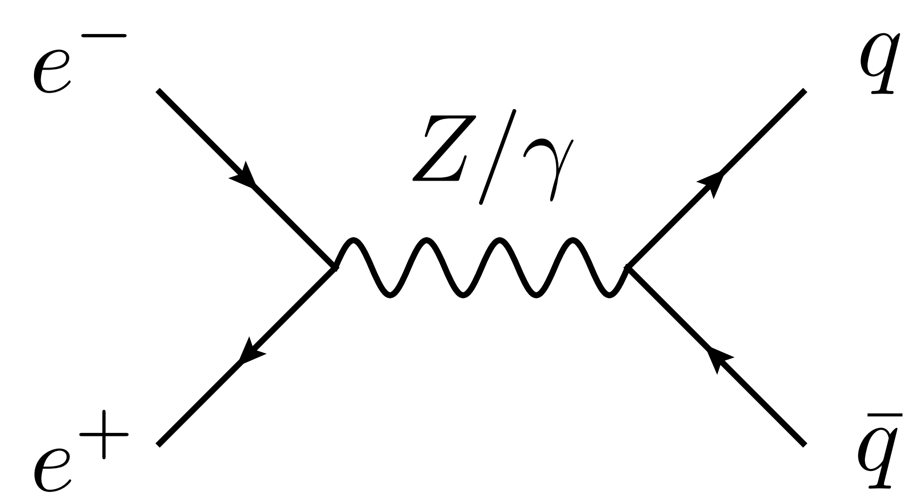
$$R = \frac{\sigma(e^+e^- \to Z/\gamma^* \to \mathrm{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

theoretical expression
w/o Z-boson exchange

Blue: experimental measurements

Green and red lines theoretical predictions





sum over colors and flavors of quarks

$$R_{\text{pert}} = \frac{\sigma(e^+e^- \to Z/\gamma^* \to q\bar{q})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

Dashed green: LO perturbation theory

Solid red: $\mathrm{N^3LO}$ perturbation theory

Remarkable agreement with data!

The **Operator Product Expansion (OPE)*** explains why the computation using quarks and gluons works. Factorizes low and high energy contributions

$$R(s) = C_1(s)\,\langle 0|\,1\,|0\rangle + C_{q\bar{q}}(s)\,\langle 0|\,m_q\bar{q}q\,|0\rangle + C_{GG}(s)\;\langle 0|\,G^2\,|0\rangle + \ldots$$

* see e.g. Peskin & Schröder p.615

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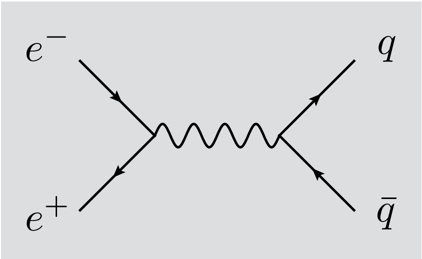

Wilson coefficients:
high-energy physics
independent of states

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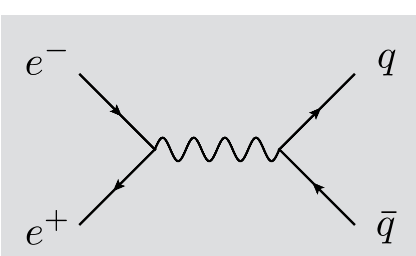

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Matrix elements:
non-perturbative,
hadronisation effects

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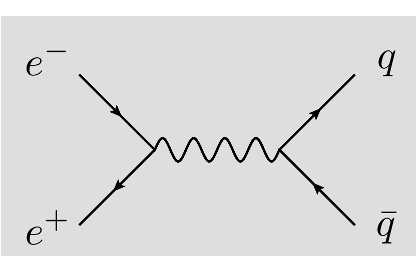

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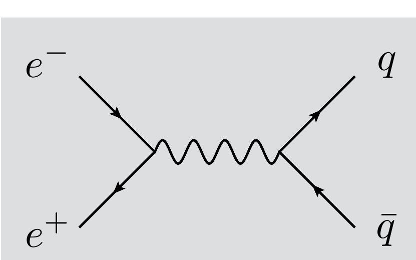

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The computation of the R-ratio is based on an expansion in the scale ratio Λ_{QCD}^2/Q^2.

A systematic method to separate physics at different scales and perform expansions in scale ratios is Effective Field Theory (EFT)

- Construct general effective Lagrangian describing low energy physics.
- High energy physics enters the Wilson coefficients (``couplings”) of the effective Lagrangian.

Soft-Collinear Effective Theory (SCET) is the EFT for collider processes

- A family of EFTs for different kinematic situations

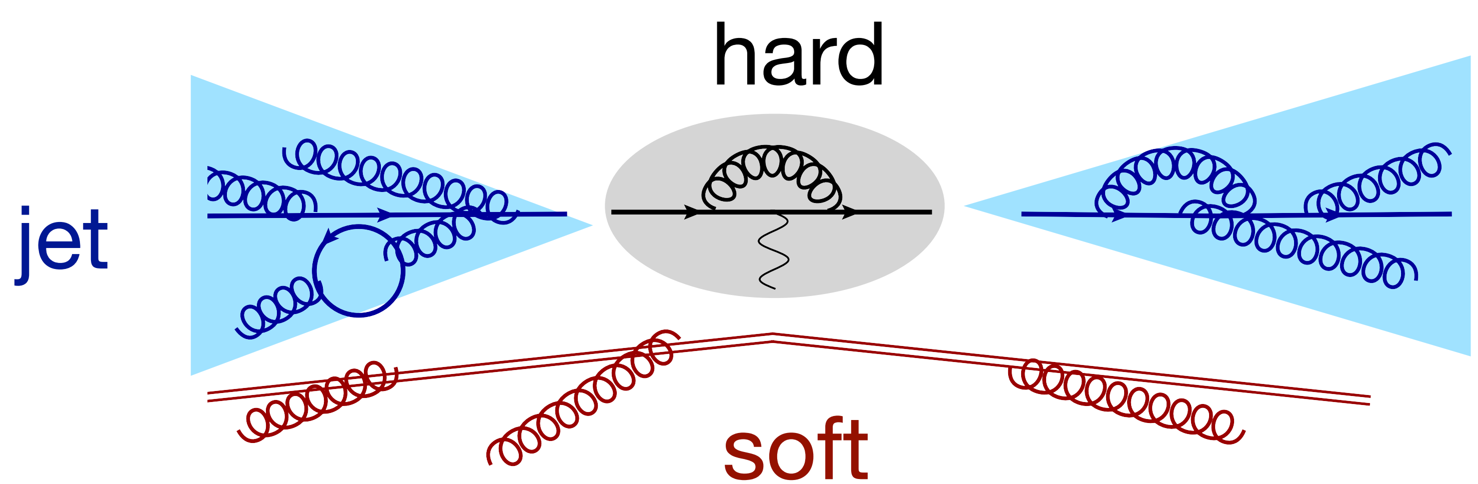
Soft-Collinear Effective Theory (SCET)

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke, Diehl et al. 2002; ...

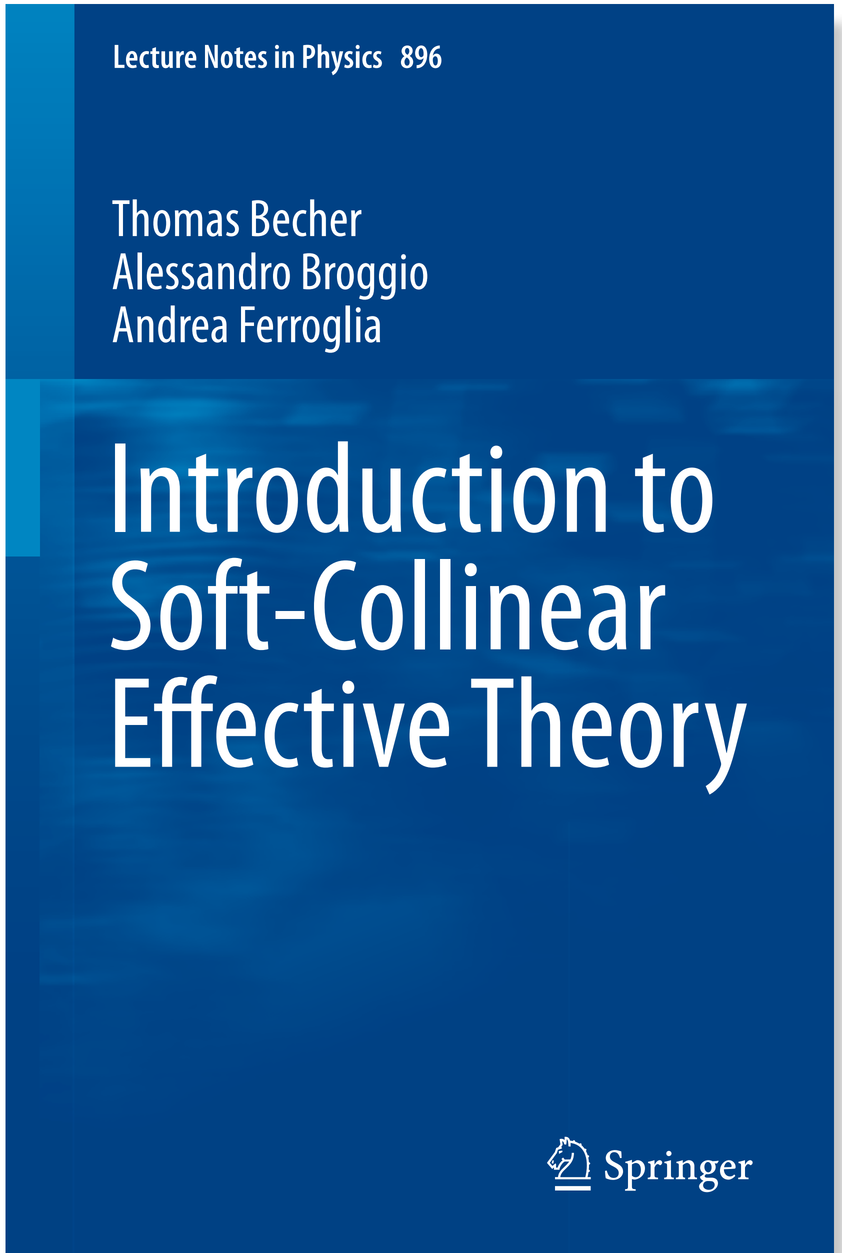
Implements interplay between soft and energetic collinear particles into effective field theory

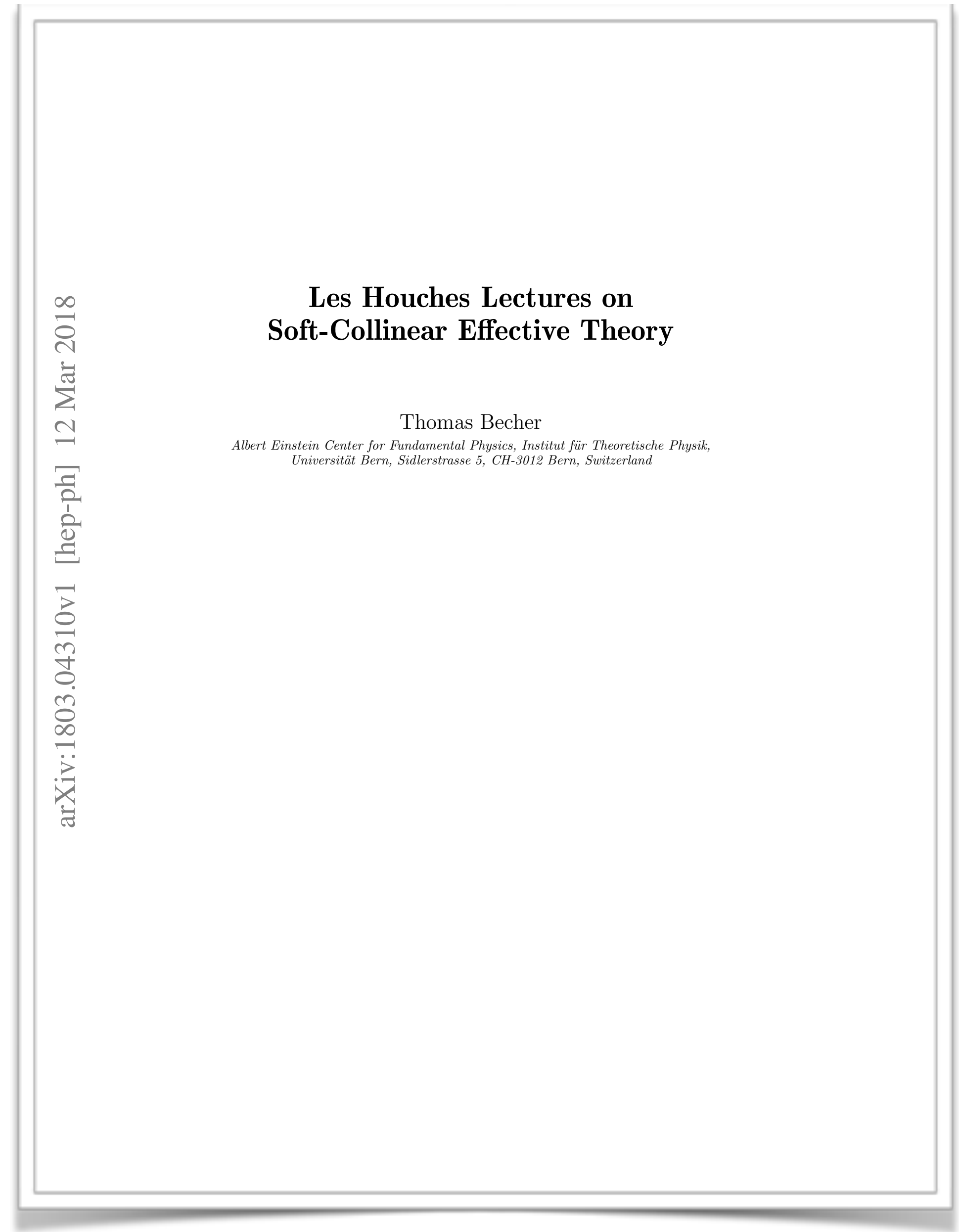
Hard } **high-energy**

Collinear *fields*
} **low-energy part**
Soft *fields*



Allows one to analyze factorization of cross sections and perform resummations of large Sudakov logarithms.

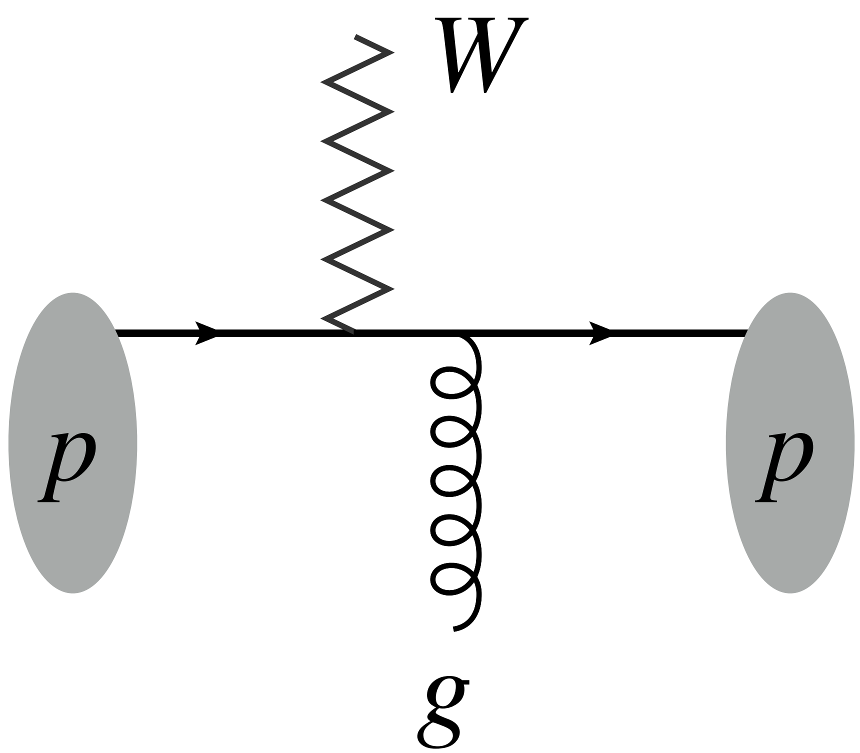




arXiv:1410.1892

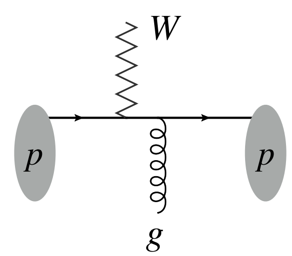
arXiv:1803.04310

Sketch of a hadron collider process



Hard scattering at short distances: perturbation theory

Sketch of a hadron collider process



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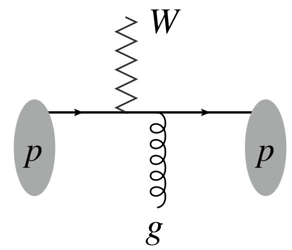

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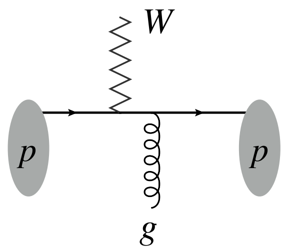

Hard scattering at short distances: perturbation theory

Soft and collinear emissions: parton shower, resummation, SCET

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Hadronisation, hadron decays:
modelled by MCs

Sketch of a hadron collider process

Hard scattering at short distances: perturbation theory

Soft and collinear emissions: parton shower, resummation, SCET

Hadronisation, hadron decays: modelled by MCs

This picture can be misleading: it depends on the observable to which aspect of QCD one is sensitive!

For inclusive observables, sensitive only to a single high-energy scale Q, we have*

$$\sigma = \sum_{a,b} \int_0^1 dx_1 dx_2\, \hat{\sigma}_{ab}(Q, x_1, x_2, \mu_f)\, f_a(x_1, \mu_f)\, f_b(x_2, \mu_f) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)$$

* for Z-production: Collins, Soper and Sterman '84

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partonic cross sections: perturbation theory

parton distribution functions (PDFs): nonperturbative

* for Z-production: Collins, Soper and Sterman '84

The right way to look at this formula is (soft-collinear) effective field theory

$$\sigma = \sum_{a,b} \int_0^1 dx_1 dx_2\, C_{ab}(Q, x_1, x_2, \mu) \langle P(p_1)|O_a(x_1)|P(p_1)\rangle\, \langle P(p_2)|O_b(x_2)|P(p_2)\rangle + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)$$

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Wilson coefficient:
matching at $\mu \approx Q$
perturbation theory

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low-energy proton matrix elements
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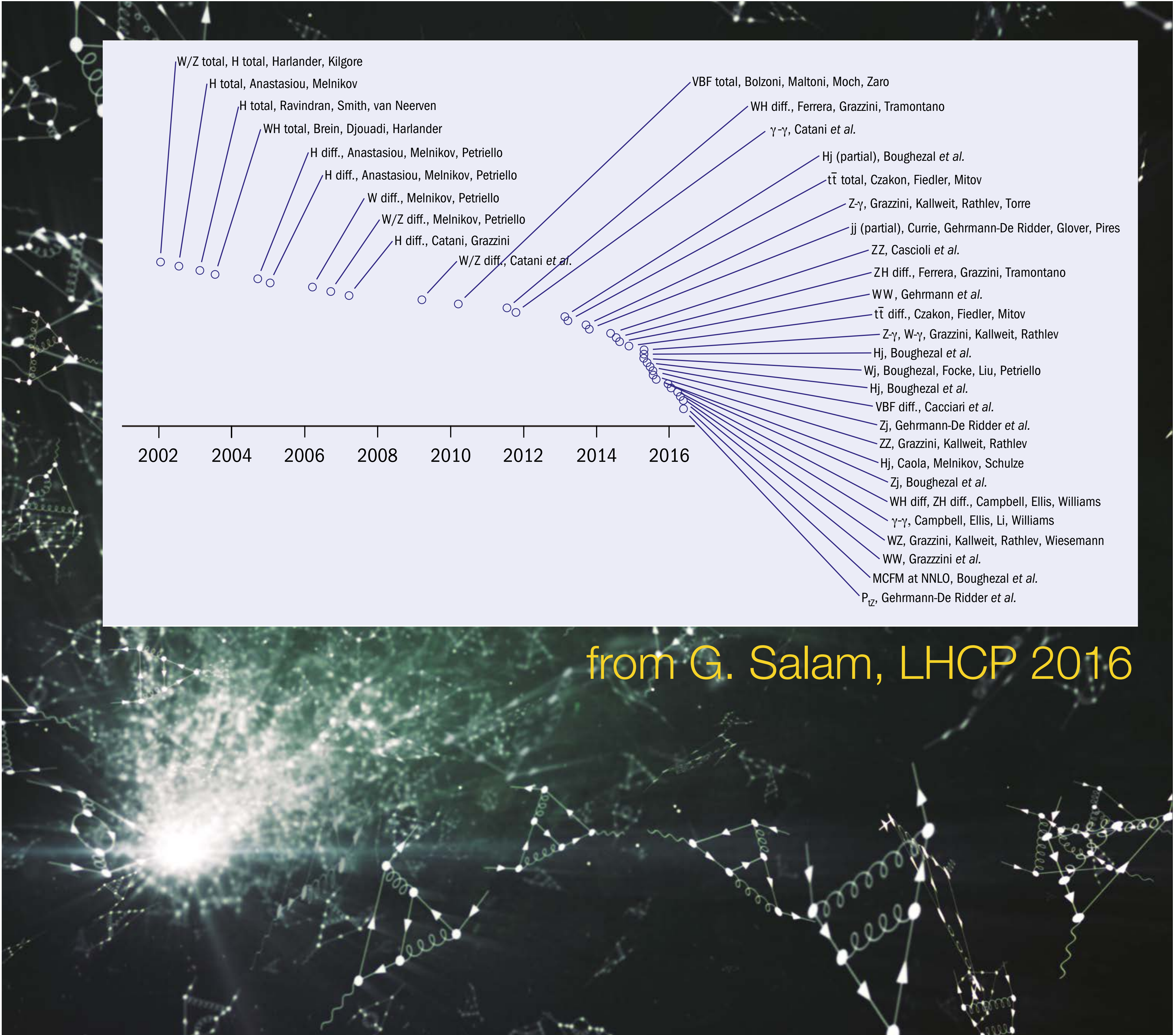
power suppressed operators



Theory

The two-loop explosion

During the past two years there has been a burst of activity in next-to-next-to-leading order calculations to ensure that theory keeps up with the increasing precision of LHC measurements.

Studying matter at the highest energies possible has transformed our understanding of the microscopic world. CERN's Large Hadron Collider (LHC), which generates proton collisions at the highest energy ever produced in a laboratory (13 TeV), provides a controlled environment in which to search for new phenomena and to address fundamental questions about the nature of the interactions between elementary particles. Specifically, the LHC's main detectors – ATLAS, CMS, LHCb and ALICE – allow us to measure the cross-sections of elementary processes with remarkable precision. A great challenge for theorists is to match the experimental precision with accurate theoretical predictions. This is necessary to establish the Higgs sector of the Standard Model of particle physics and to look for deviations that could signal the existence of new particles or forces. Pushing our current capabilities further is key to the success of the LHC physics programme.

Underpinning the prediction of LHC observables at the highest levels of precision are perturbative computations of cross-sections. Perturbative calculations have been carried out since the early days of quantum electrodynamics (QED) in the 1940s. Here, the smallness of the QED coupling constant is exploited to allow the expressions for physical quantities to be expanded in terms of the coupling constant – giving rise to a series of terms with decreasing magnitude. The first example of such a calculation was the one-loop QED correction to the magnetic moment of the electron, which was carried out by Schwinger in 1948. It demonstrated for the first time that QED was in agreement with the experimental discovery of the anomalous magnetic moment of the electron, g_e-2 (the latter quantity was dubbed "anomalous" precisely because, prior to Schwinger's calculation, it did not agree with predictions from Dirac's theory). In 1957, Sommerfeld and Petermann computed the two-loop correction, and it ▷

Next-to-next-to-leading order (NNLO) Feynman diagrams relevant to the LHC physics programme. (Image credit: Daniel Dominguez, CERN.)

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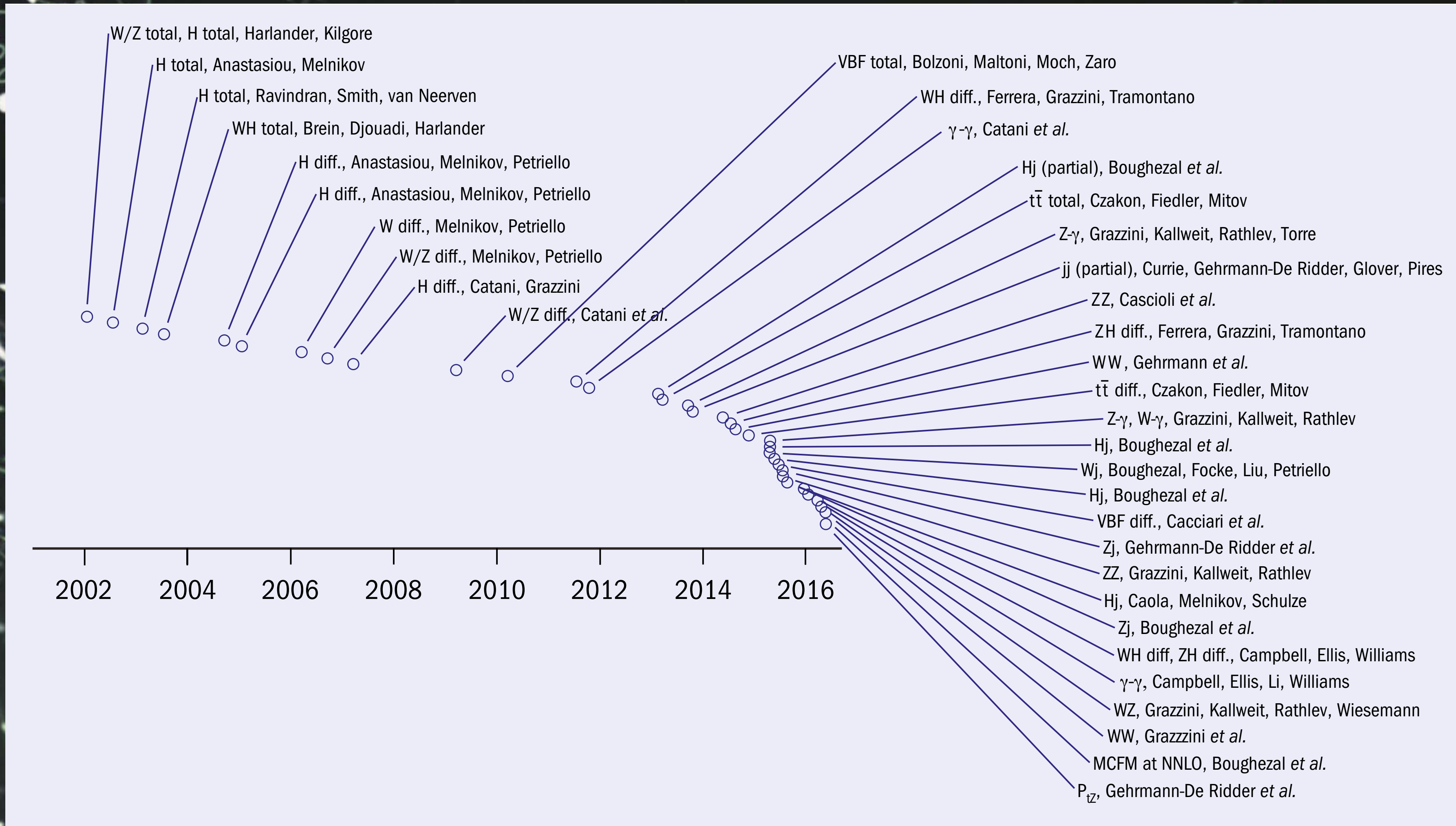

from G. Salam, LHCP 2016

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...n diagrams ...credit: Daniel

Note: Many computations based on effective field theory (q_T and N-jettiness subtractions):

NNLO (QCD) ≈ NNLO (SCET) + NLO (QCD)

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If disparate hard scales are present, one encounters large logarithms in the matching coefficient.

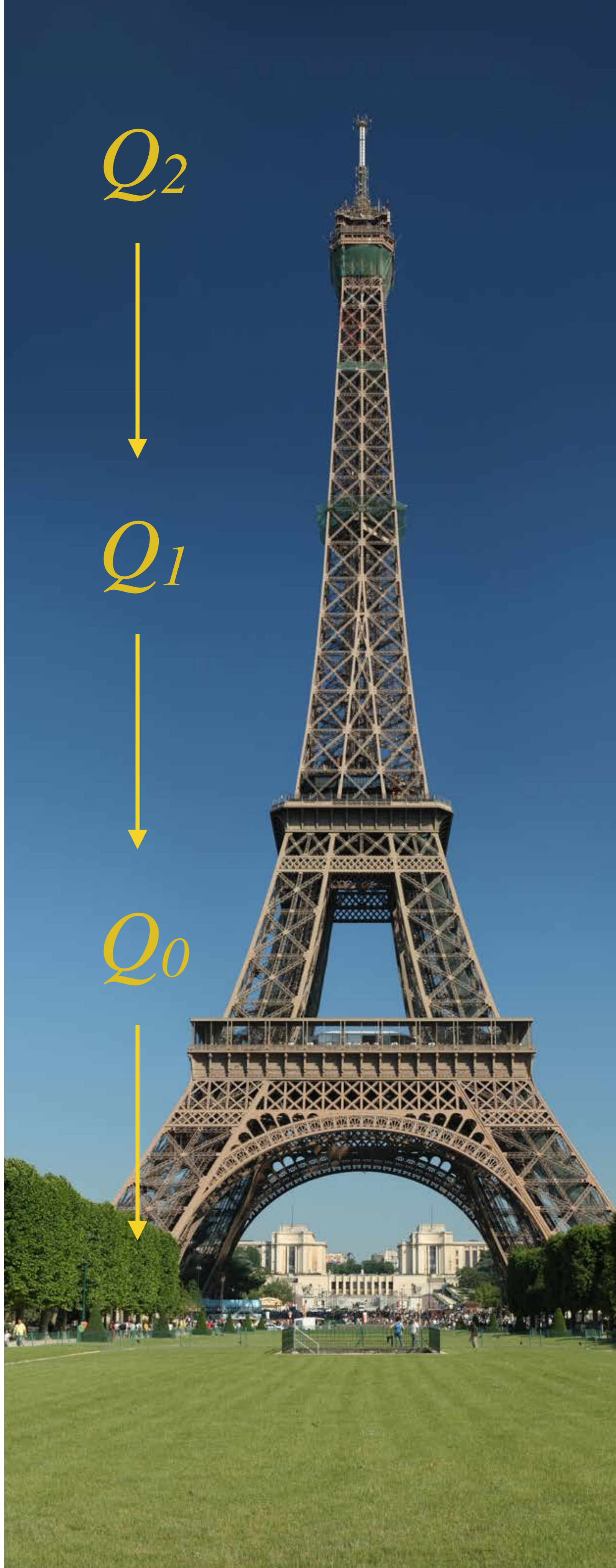
- Can spoil convergence of perturbation theory

Solution: use a tower of effective theories. Integrate out the contributions at the different scales, one after another.

- Resummation by RG evolution

Challenges

- Need the EFT relevant for the given kinematics. By now, we know how to handle many kinematic situations.
- Need to compute and match the results in different hierarchies, e.g. for $Q_1 \to Q_2$

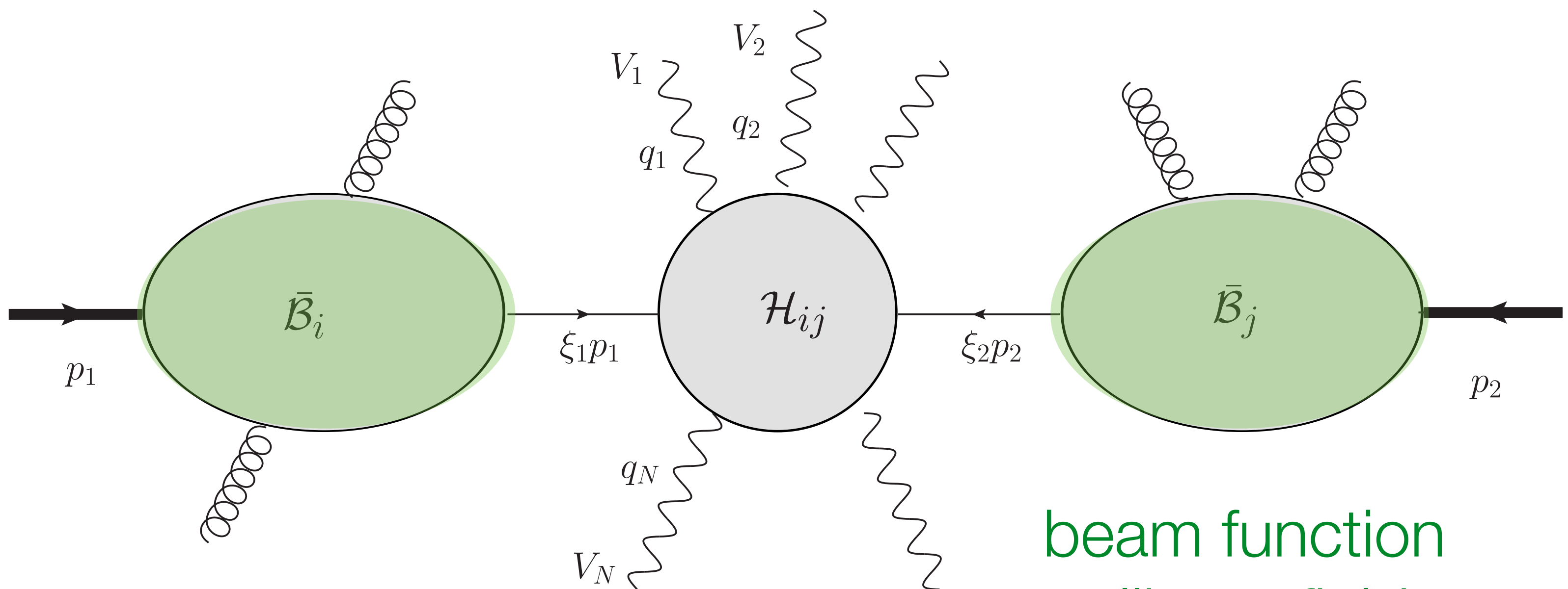


Example: Two-step factorization in SCET for EW-boson production at small transverse momentum q_T

in SCET: TB, Neubert ’10; diagrammatically: CSS ‘85

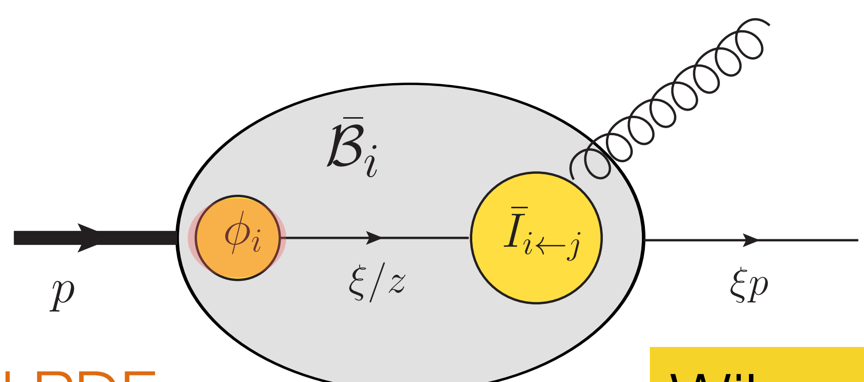
1.) $q_T \ll M$

Hard function



beam function
collinear fields

2.) $\Lambda_{QCD} \ll q_T$



standard PDF

Wilson coefficient
perturbative

M

↓

q_T

↓

Λ_{QCD}

Resummation

Using RG evolution between the different scales resums large logarithms in the cross section of the form

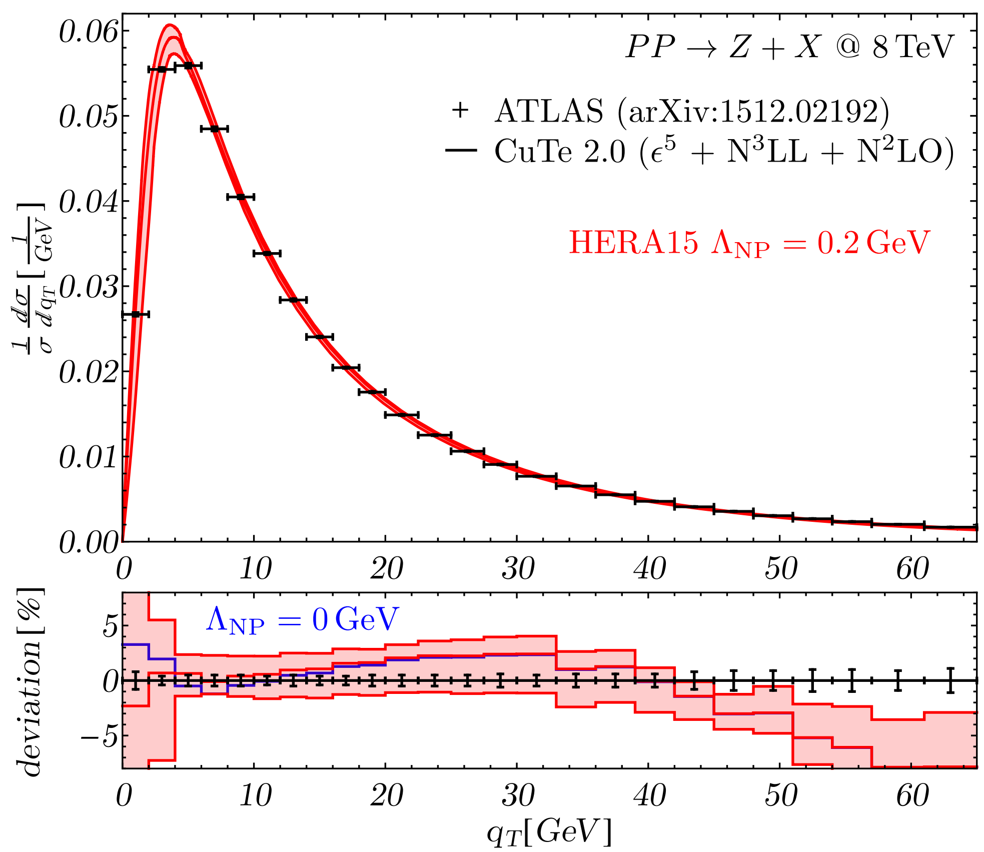
$$\alpha_s^n \ln^m \left(\frac{q_T^2}{M^2} \right)$$

LL: $m=2n$
NLL: $m=2n-1$
NNLL: $m=2n-2$

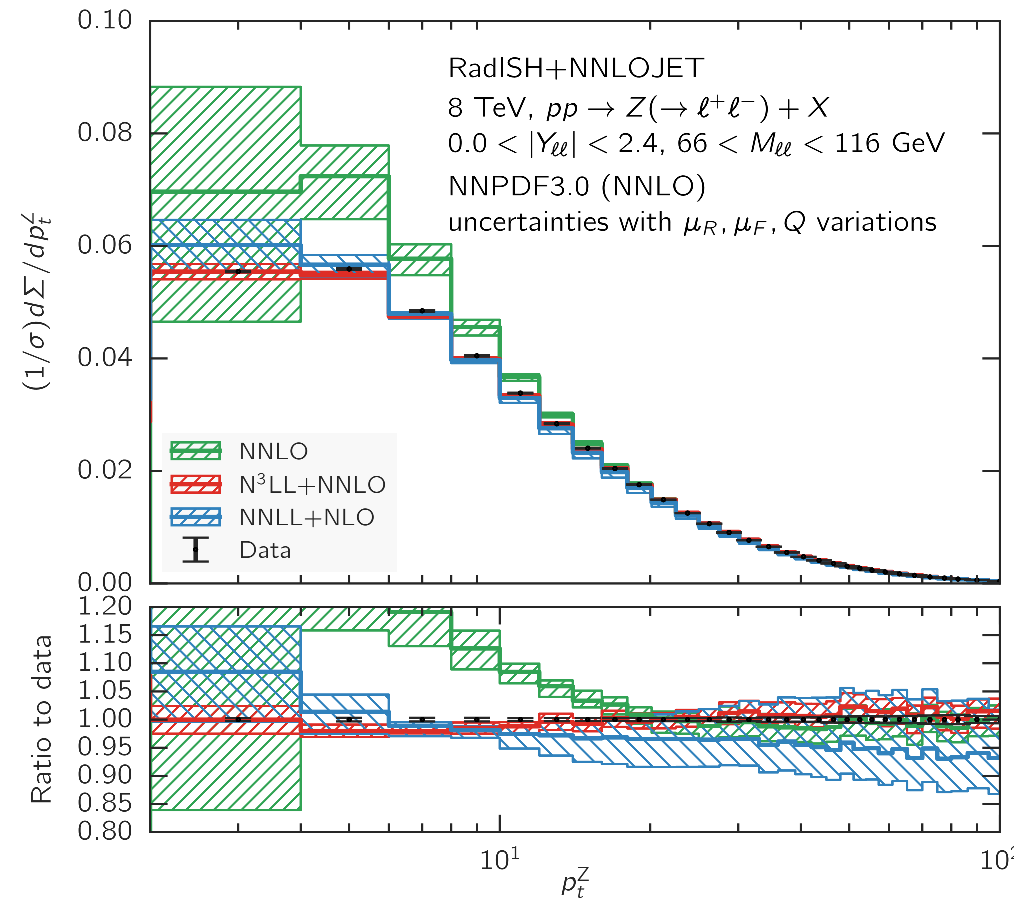
which spoil the perturbative expansion.

N³LL resummation: four-loop cusp anomalous dimension Moch et al. ’18, Henn et al. ’19, Lee et al. ‘19 three-loop regular anomalous dimensions Li, Zhu ’16; Vladimirov, ’16 and two-loop results for beam functions Catani, Grazzini et al. ‘12; Gehrmann, Lübbert, Yang ’12 ’14.

Z production $q_T \ll M_{Z,H}$



CuTe 2.0 TB, Lübbert, Neubert, Wilhelm



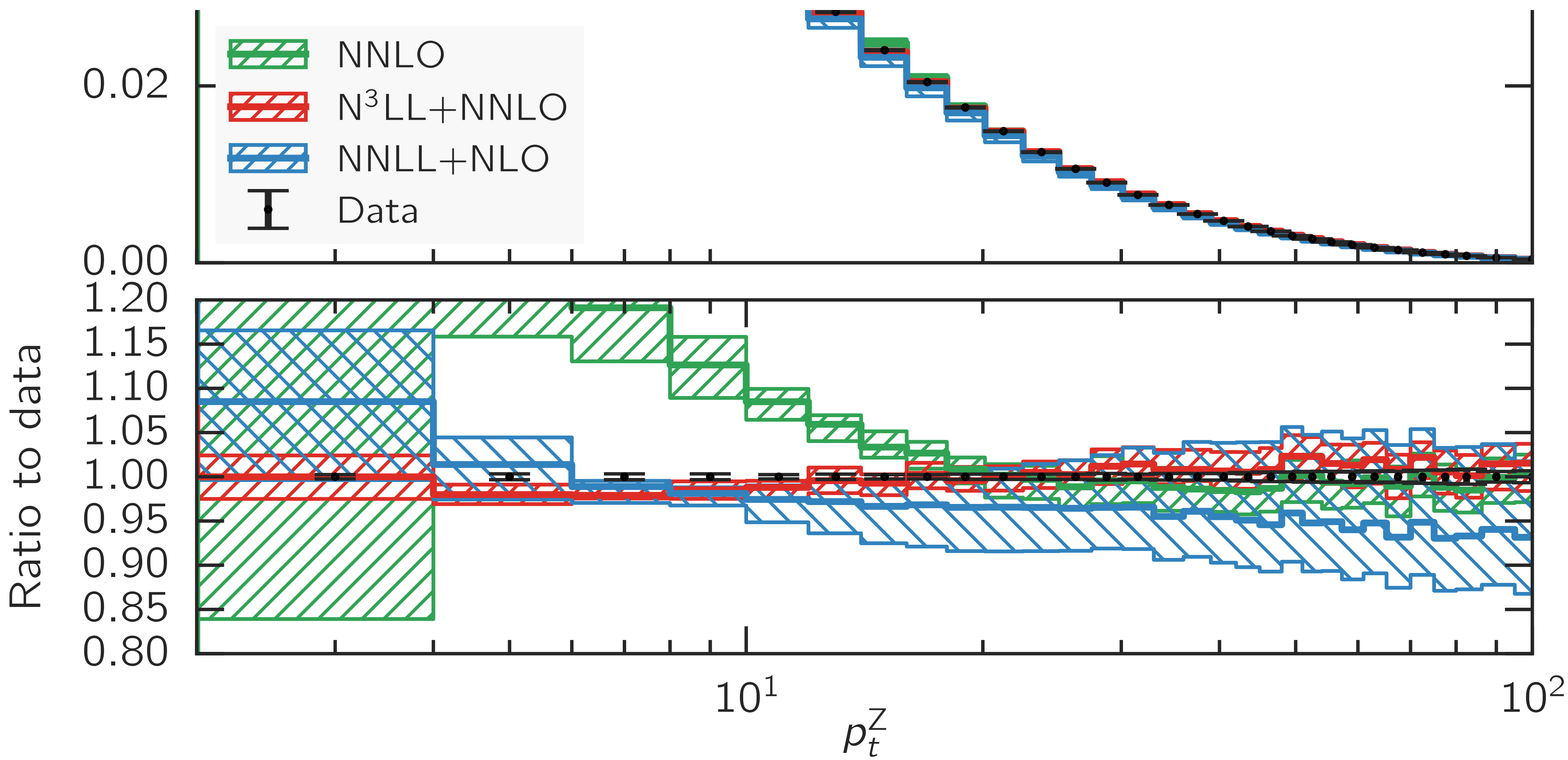
Bizon et al. ‘18

Bizon, Monni, Re, Rottoli and Torrielli, ‘17

State of the art result from RadISH generator on the right includes

- resummation to N^{3}LL accuracy,
- matching to $O(\alpha_s^3)$ fixed order result at higher q_T,
- and takes into account all experimental cuts.

Z production $q_t \ll M$



- few per-cent theoretical precision
- resummation is crucial

S

- and takes into account all experimental cuts.

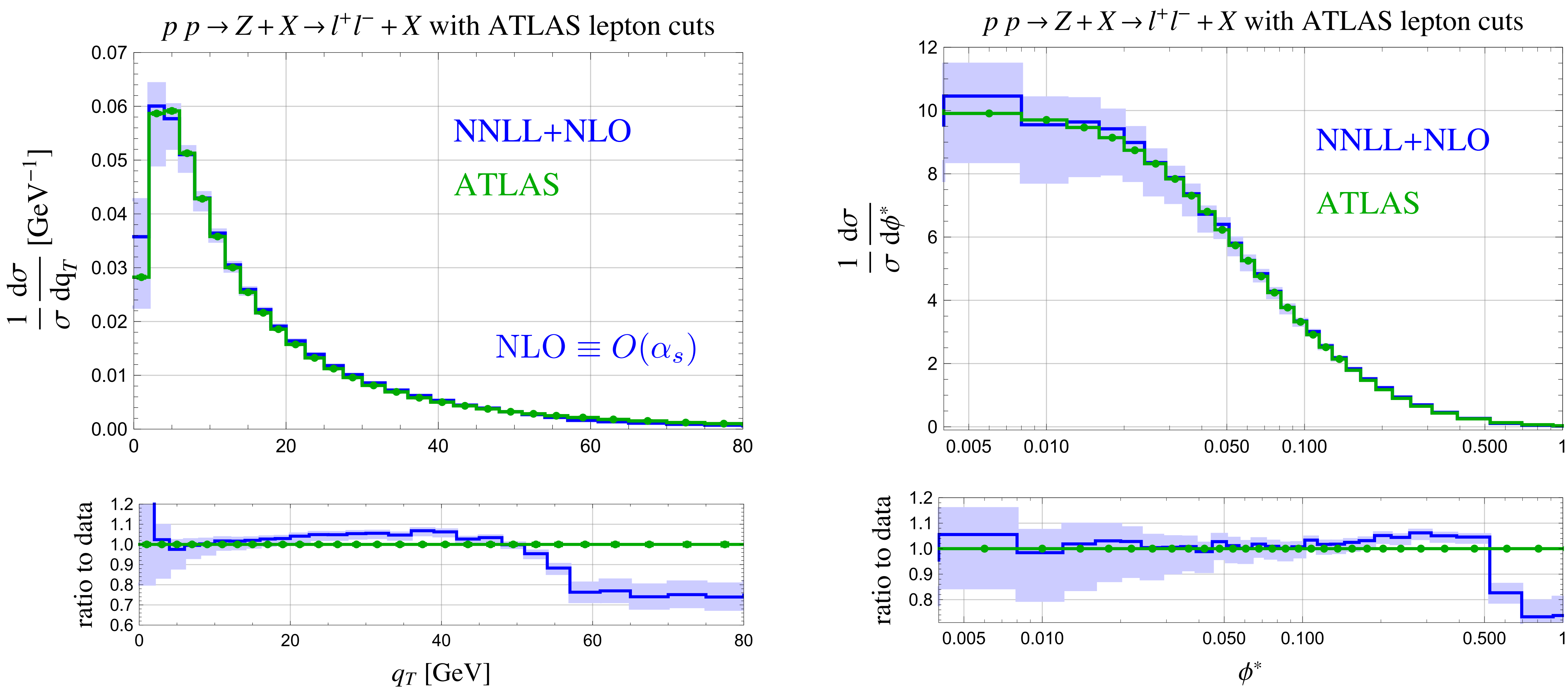
Event-based q_T resummation

TB, Hager, in preparation

While fixed-order computations have been automated up to NLO, resummations are typically done analytically, observable by observable.

Have automated q_T resummation

- Generate hard function as event file using Madgraph tree-level event generator.
- Reweight to obtain a sample of resummed events with different q_T values.
- Analyze sample, putting cuts on vector bosons and their decay products.



- Include ATLAS cuts on the final state leptons
- Obtain also related observables such as ϕ^* (right plot)
- Same code also computes *W*, *ZW*, *WW*, *ZZ*, …

TB, Hager, in preparation

Automation

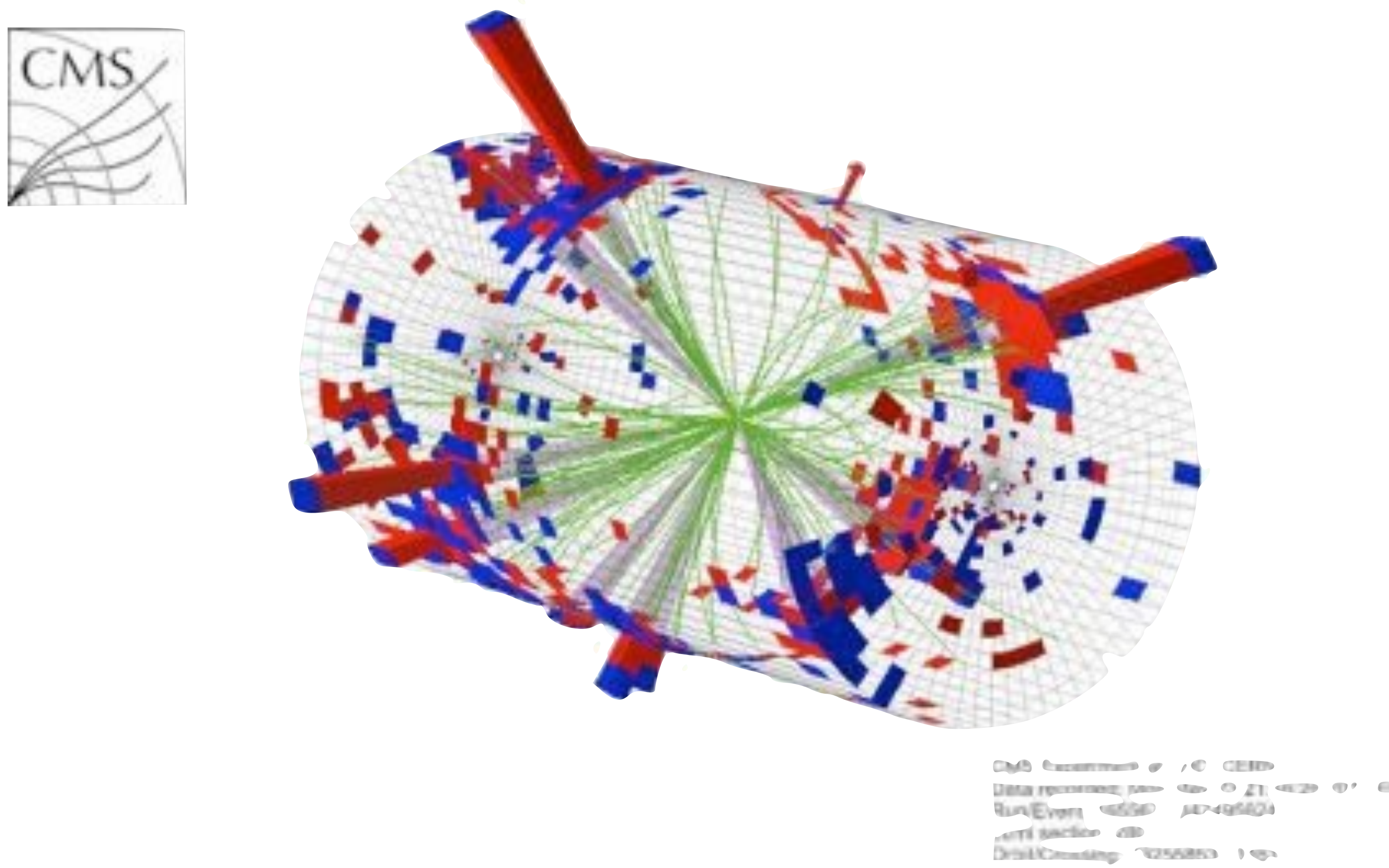
There are several more examples for automated resummations, both based on SCET and other methods

- Hadronic event-shapes, CAESAR Banfi, Salam, Zanderighi ’04; ARES Banfi, McAslan, Monni, Zanderighi ’15; CAESAR+SCET Bauer, Monni ‘18

- Jet-veto cross sections, TB, Frederix, Neubert, Rothen ‘15

- Threshold resummations for top production Broggio, Ferroglia, Ossola, Pecjak, Signer, Yang, … ’16-’19

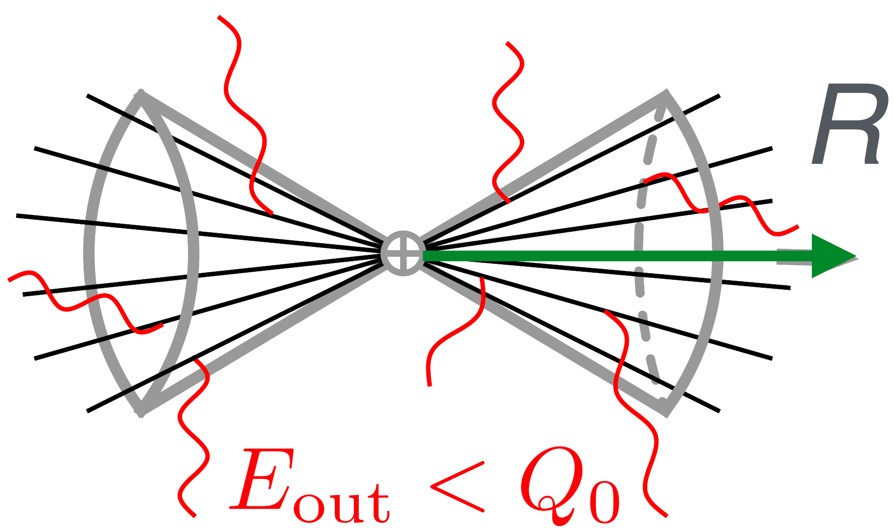
- Automated computation of soft functions SOFTSERVE Bell, Rahn, Talbert ‘18



Jet Effective Theory

Hadronically inclusive observables are insensitive to hadronisation effects. More exclusive observables with the same property?

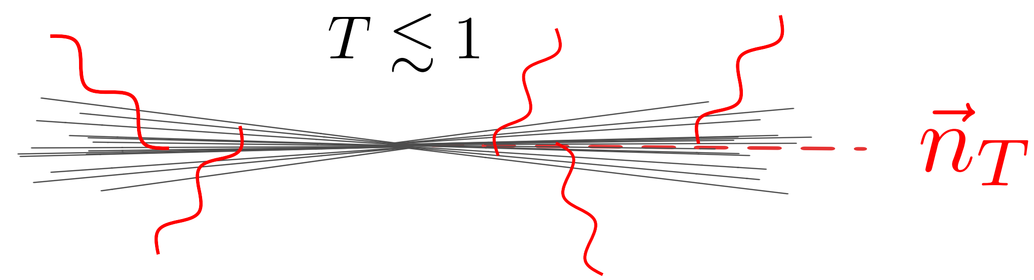
Jet cross sections



scales: Q, Q_0, QR, Q_0R

collision energy

Event shapes



e.g. thrust $T = \max_{\mathbf{n}} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}|}{\sum_i |\mathbf{p}_i|}$

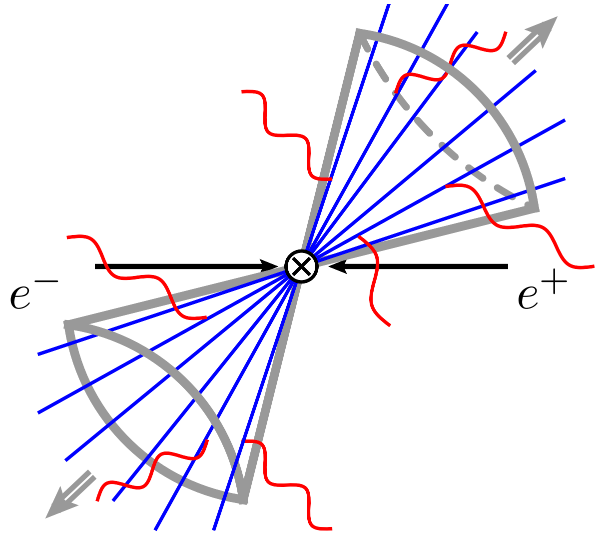
scales: Q, $Q(1\text{-}T)$, …

Higher-logarithmic resummations up to N^{3}LL for event shapes, but jet observables exhibit a much more complicated pattern of

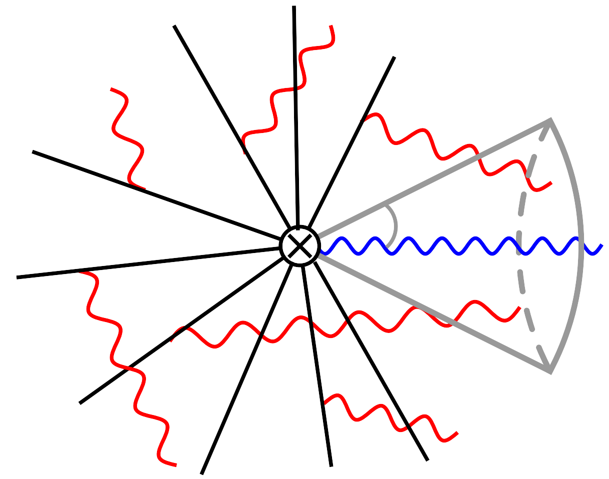
non-global logarithms

discovered by Dasgupta and Salam '01. A lot of recent progress towards higher logarithmic resummation

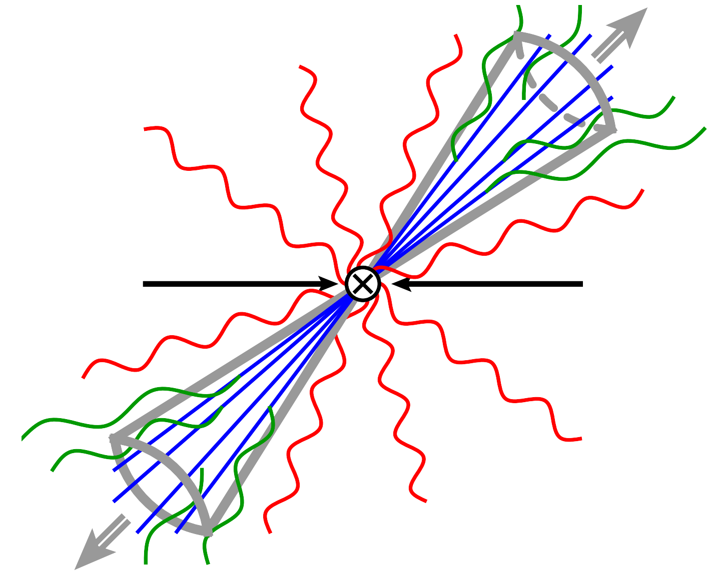
- Color density matrix, Caron-Huot, JHEP 1803, 036 (2018) [1501.03754], …
- Dressed gluon exponentiation, Larkoski, Moult and Neill, JHEP 1509, 143 (2015), …
- Jet Effective Theory, TB, Neubert, Rothen and Shao, PRL 116,192001 (2016), …



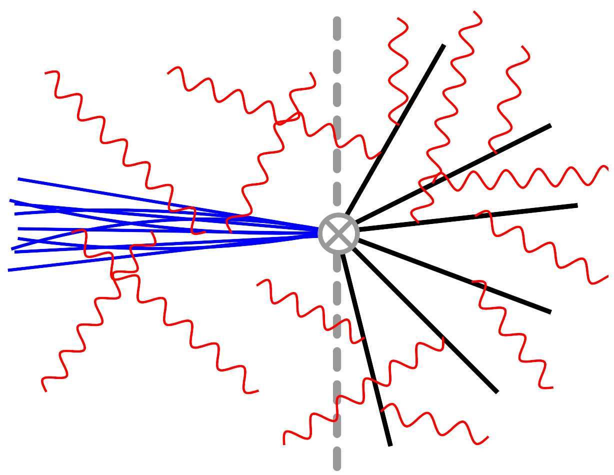
1.) 2.) cone jets,
gaps between jets



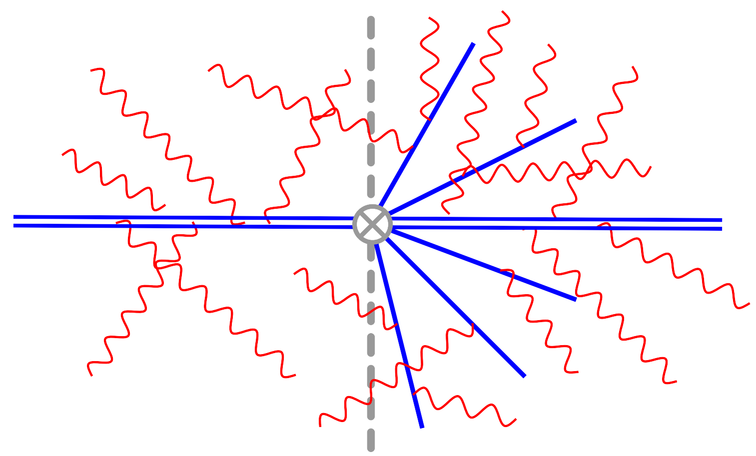
5.) isolation cones



1.) narrow jets



3.) light-jet mass
4.) narrow broadening



3.) hemisphere
soft function

1.) 2.) TB, Neubert, Rothen, Shao ’15 ’16

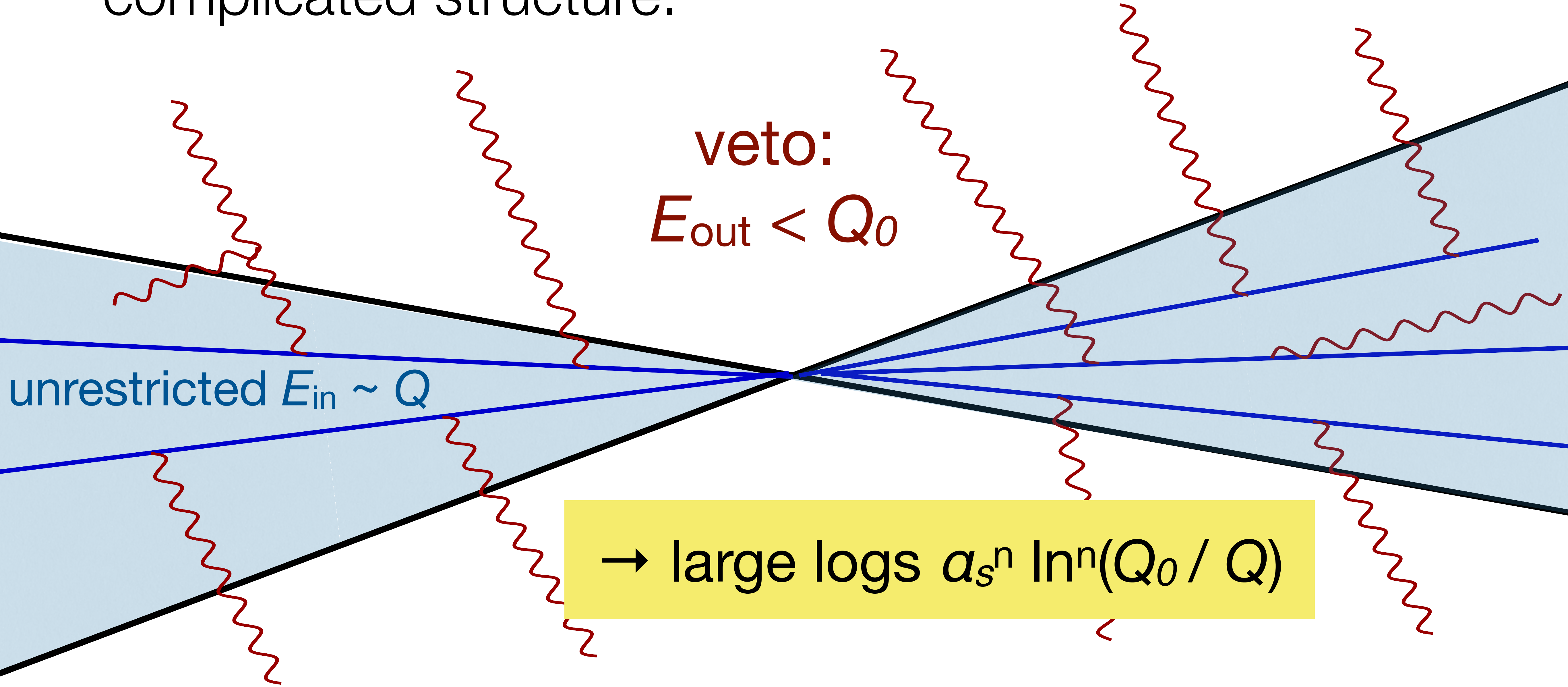
3.) TB, Pecjak, Shao ’16

4.) TB, Rahn, Shao ’17

5.) Balsiger, TB, Shao, ‘18

Effective field theory for (non-global) jet observables!

Soft radiation in jet processes has in general a very complicated structure.



→ large logs $\alpha_s^n \ln^n(Q_0 / Q)$

Hard partons (quarks and gluons) inside jets act as sources: soft radiation pattern depends on color-charges and directions of all hard partons!

Factorization for interjet energy flow

TB, Neubert, Rothen, Shao '15 '16, see also Caron-Huot '15

Hard function
m hard partons along
fixed directions $\{n_1, \ldots, n_m\}$
$\boldsymbol{\mathcal{H}}_m \propto |\mathcal{M}_m\rangle\langle\mathcal{M}_m|$

Soft function
squared amplitude with
with m Wilson lines

$$\sigma(Q, Q_0) = \sum_{m=2}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, Q_0, \mu) \big\rangle$$

color trace

integration over directions

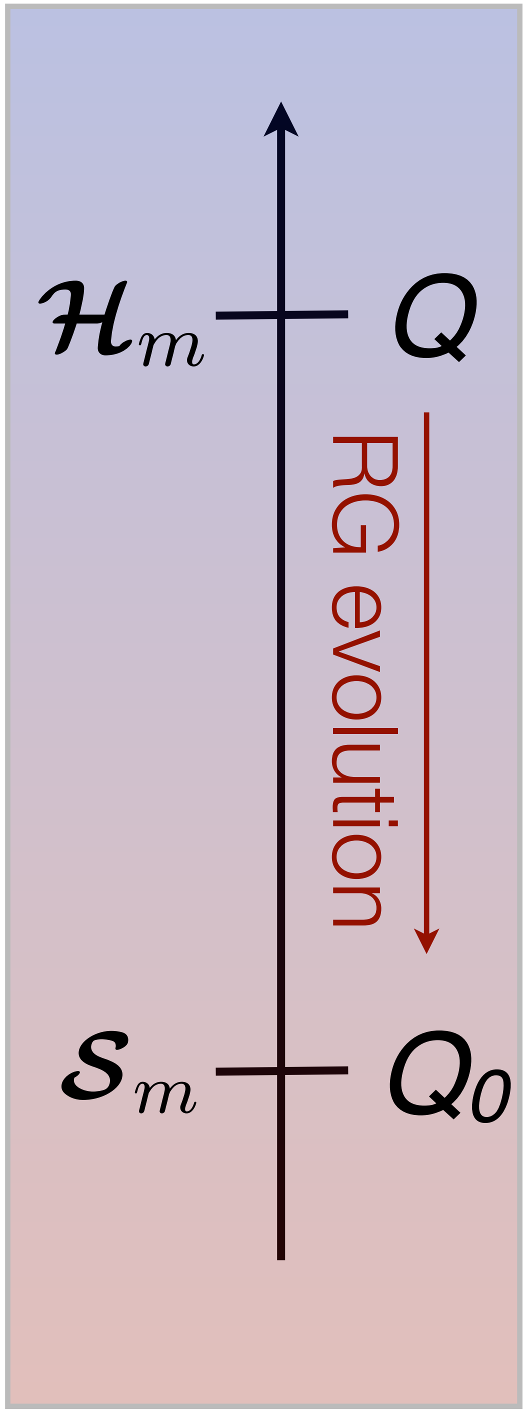
Achieves scale separation! Can resum logs by solving RG.

Resummation by RG evolution

Wilson coefficients fulfill renormalization group (RG) equations

$$\frac{d}{d\ln\mu}\boldsymbol{\mathcal{H}}_m(Q,\mu) = -\sum_{l=2}^{m}\boldsymbol{\mathcal{H}}_l(Q,\mu)\,\boldsymbol{\Gamma}^H_{lm}(Q,\mu)$$

1. Compute $\mathcal{H}_\mathrm{m}$ at a characteristic high scale $\mu_h \sim Q$
2. Evolve $\mathcal{H}_\mathrm{m}$ to the scale of low energy physics $\mu_s \sim Q_0$
3. Evaluate $\mathcal{S}_\mathrm{m}$ at low scale $\mu_s \sim Q_0$



Avoids large logarithms $\alpha_s^n \ln^n(Q/Q_0)$ of scale ratios which spoil convergence of perturbation theory.

RG = Parton Shower

- Ingredients for LL

$$\boldsymbol{\mathcal{H}}_2(\mu = Q) = \sigma_0$$
$$\boldsymbol{\mathcal{H}}_m(\mu = Q) = 0 \text{ for } m > 2$$
$$\boldsymbol{\mathcal{S}}_m(\mu = Q_0) = 1$$

$$\boldsymbol{\Gamma}^{(1)} = \begin{pmatrix} \boldsymbol{V}_2 & \boldsymbol{R}_2 & 0 & 0 & \dots \\ 0 & \boldsymbol{V}_3 & \boldsymbol{R}_3 & 0 & \dots \\ 0 & 0 & \boldsymbol{V}_4 & \boldsymbol{R}_4 & \dots \\ 0 & 0 & 0 & \boldsymbol{V}_5 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- RG

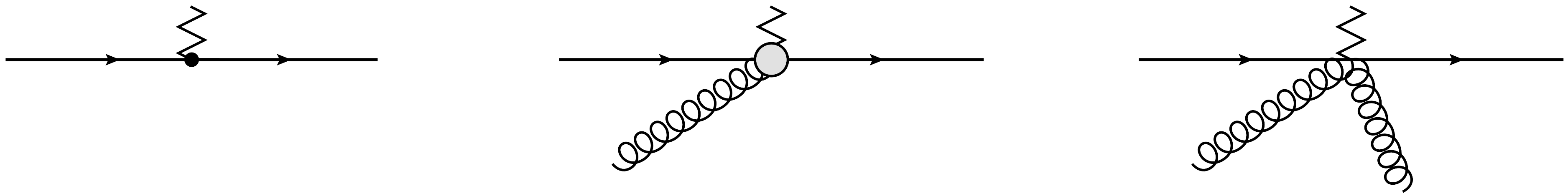
$$\frac{d}{dt}\boldsymbol{\mathcal{H}}_m(t) = \boldsymbol{\mathcal{H}}_m(t)\boldsymbol{V}_m + \boldsymbol{\mathcal{H}}_{m-1}(t)\boldsymbol{R}_{m-1}\,.$$

shower evolution time

$$t \equiv t(\mu_h, \mu_s) = \int_{\alpha_s(\mu_s)}^{\alpha_s(\mu_h)} \frac{d\alpha}{\beta(\alpha)}\,\frac{\alpha}{4\pi}$$

- equivalent to parton shower equation

$$\boldsymbol{\mathcal{H}}_m(t) = \boldsymbol{\mathcal{H}}_m(t_1)e^{(t-t_1)V_n} + \int_{t_1}^{t} dt' \boldsymbol{\mathcal{H}}_{m-1}(t')\boldsymbol{R}_{m-1}e^{(t-t')\boldsymbol{V}_n}$$



$$\mathcal{H}_2(t_0) \longrightarrow \mathcal{H}_3(t_1) \longrightarrow \mathcal{H}_4(t_2) \qquad \boldsymbol{\mathcal{S}}_m^{(0)} = \mathbf{1}$$

$$\sigma_{\rm LL}(Q, Q_0) = \sum_{m=2}^{\infty} \langle \boldsymbol{\mathcal{H}}_2^{(0)} \otimes \boldsymbol{U}_{2m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(0)} \rangle$$

$$= \langle \boldsymbol{\mathcal{H}}_2^{(0)}(t) + \int \frac{d\Omega_3}{4\pi} \boldsymbol{\mathcal{H}}_3^{\rm LL} + \int \frac{d\Omega_3}{4\pi} \int \frac{d\Omega_4}{4\pi} \boldsymbol{\mathcal{H}}_4^{\rm LL} + \dots \rangle$$

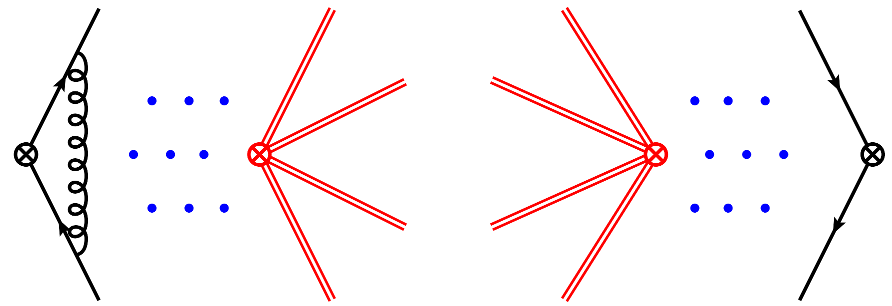
LL shower equivalent to Dasgupta Salam '01. Have flexible implementation for general *k*-jet processes

- uses LHE event files from Madgraph for LO $\mathcal{H}_k$
- used different forms of collinear cutoff
- studied gap fractions and photon isolation cones, both in ***e⁺e⁻*** and ***pp*** collisions

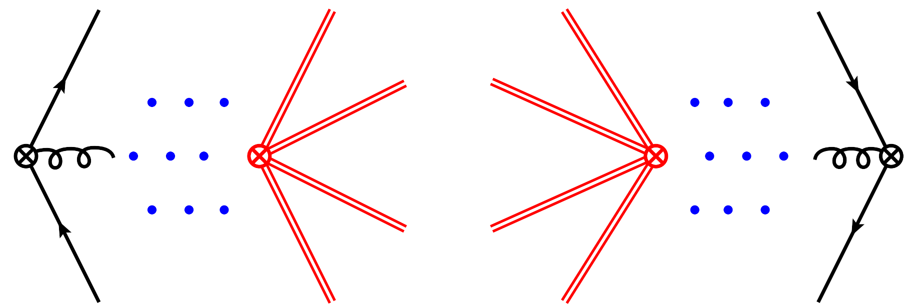
Balsiger, TB, Shao, JHEP 1808 (2018) 104

$O(\alpha_s)$ corrections at LL′

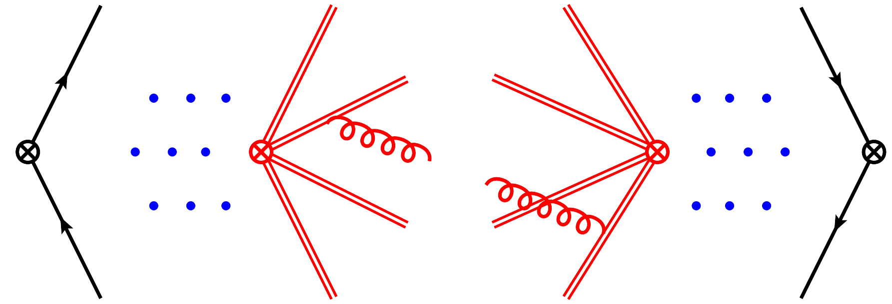
Balsiger, TB, Shao 1901.09038



$$\sim \quad \boldsymbol{\mathcal{H}}_2^{(1)} \otimes \boldsymbol{U}_{2m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(0)}$$



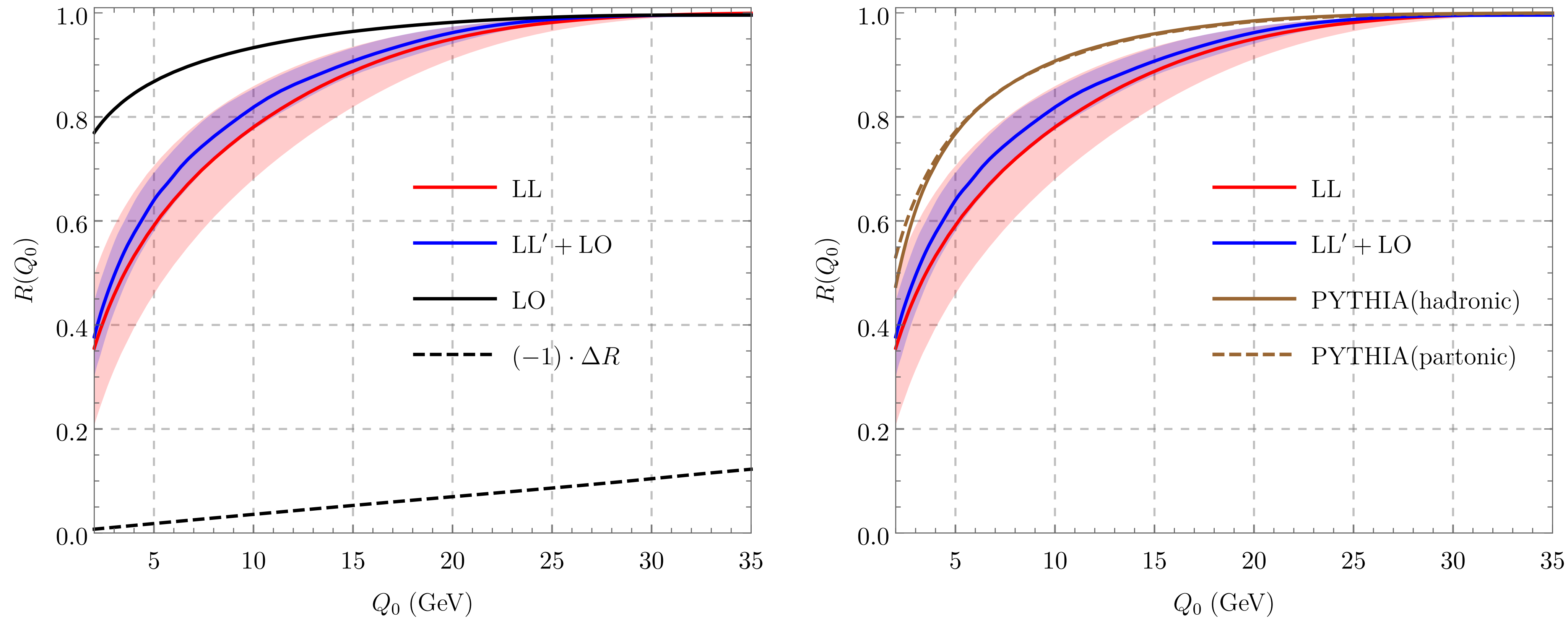
$$\sim \quad \boldsymbol{\mathcal{H}}_3^{(1)} \otimes \boldsymbol{U}_{3m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(0)}$$



$$\sim \quad \boldsymbol{\mathcal{H}}_2^{(0)} \otimes \boldsymbol{U}_{2m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(1)}$$

- Implemented these: a systematically improved parton shower!
- Need to add two-loop evolution for full NLL accuracy.

Gap fraction $R(Q_0)$ at $Q=M_Z$

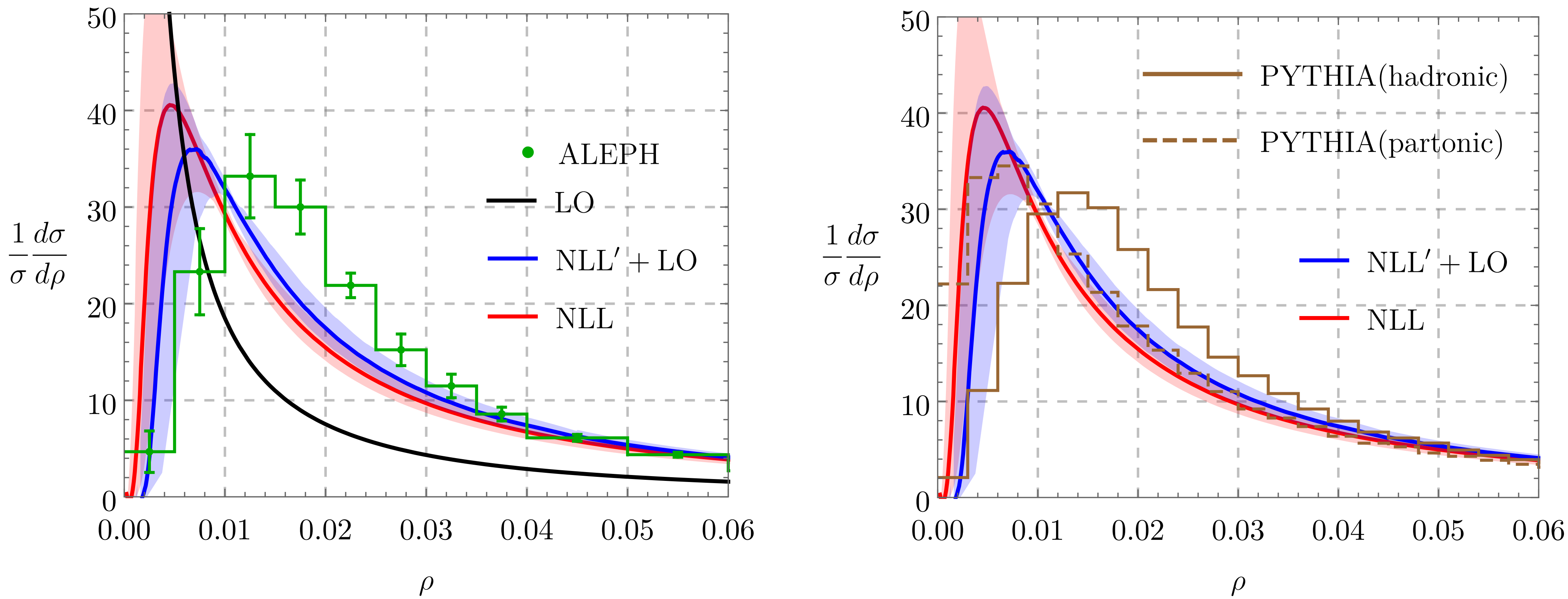


- Bands from variation of hard and soft scales by factor 2.
- By construction $R(Q_0) = 1$ at end-point Q_0=$Q/2$. we match to fixed order and use a profile function function to switch off resummation.
- Unfortunately there is no exp. data.

$$R(Q_0) = \int_0^{Q_0} dE_s \, \frac{1}{\sigma_{\rm tot}} \frac{d\sigma}{dE_s}$$

***E*$_s$** = energy in gap

NLL′ results for jet invariant mass



- Jet mass is double logarithmic variable. Double logs can be subtracted and resummed analytically.
- Exp. result from combining ALEPH light- and heavy-jet mass data.
- Peak at $\rho \approx 0.006$ corresponds to $\mu_s \approx 0.5$ GeV. Non-perturbative effects are important and shift the peak, see PYTHIA.
- Partonic PYTHIA is close to NLL′.

Hadronisation, MPI, pile-up, …

Additional soft radiation from different sources

- Pile-up. Additional soft scatterings during the same bunch crossing (~50 at run II, up to ~200 at HL-LHC).
- Multi-Parton Interaction (MPI). Parton showers generate additional radiation from the proton remnants.
  - Power suppressed? Glauber gluons?

Due to these effects, there is a lot of additional energy dumped into jets, isolation cones, …

Pile-up and MPI mitigation

- Methods to correct for pile-up

  see review by Soyez 1801.09721

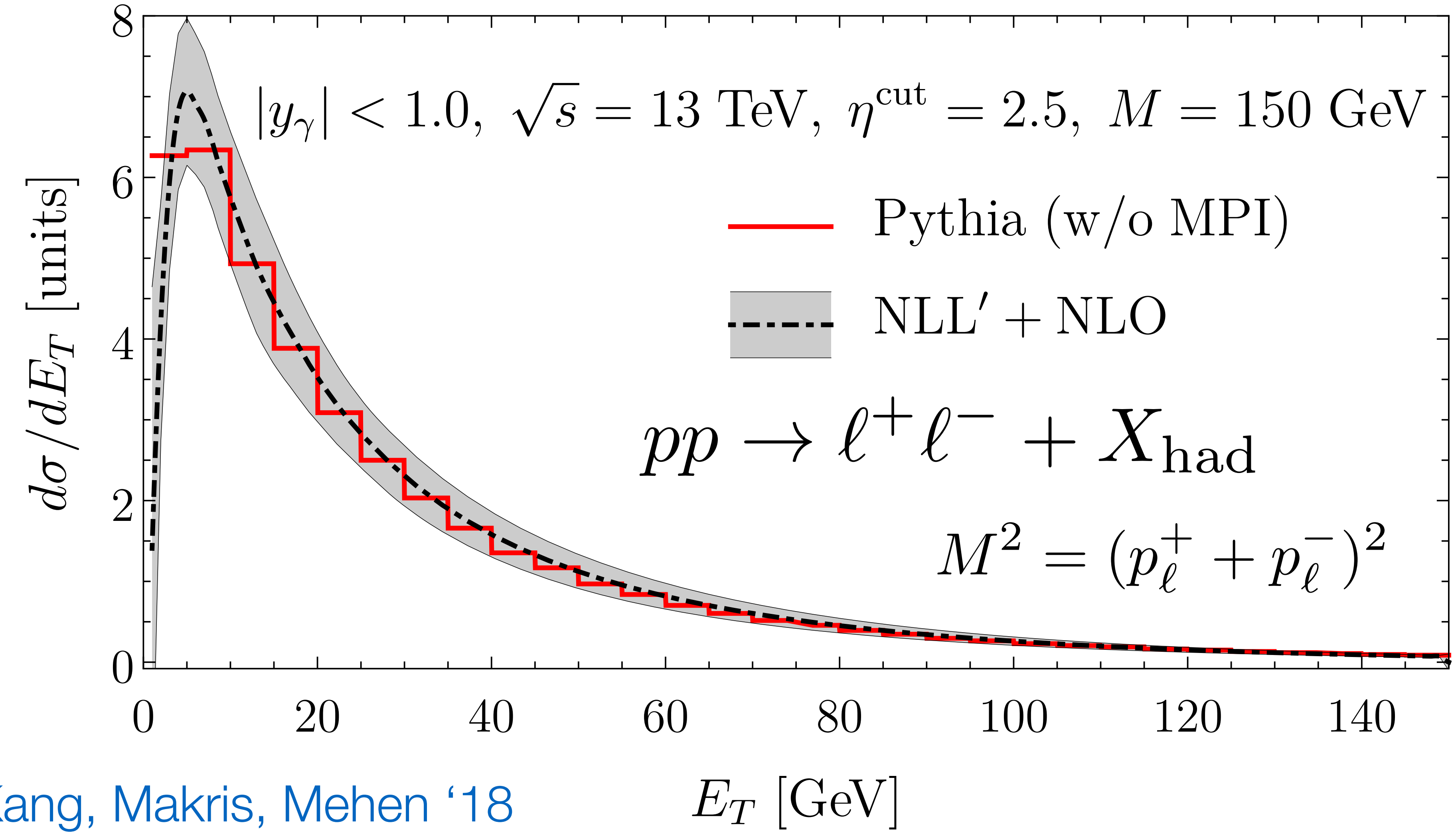
  - Area–median technique, SoftKiller, Jet Cleansing, PUPPI, …

- Observables which are insensitive to soft radiation

  - Jet substructure techniques to remove soft radiation: Grooming, soft-drop, mass-drop, …

    see introduction by Marzani, Soyez and Spannowsky 1901.10342
    review by Larkoski, Moult and Nachman 1709.04464

Transverse energy $E_T = \sum_i |\vec{p}_{T,i}|$

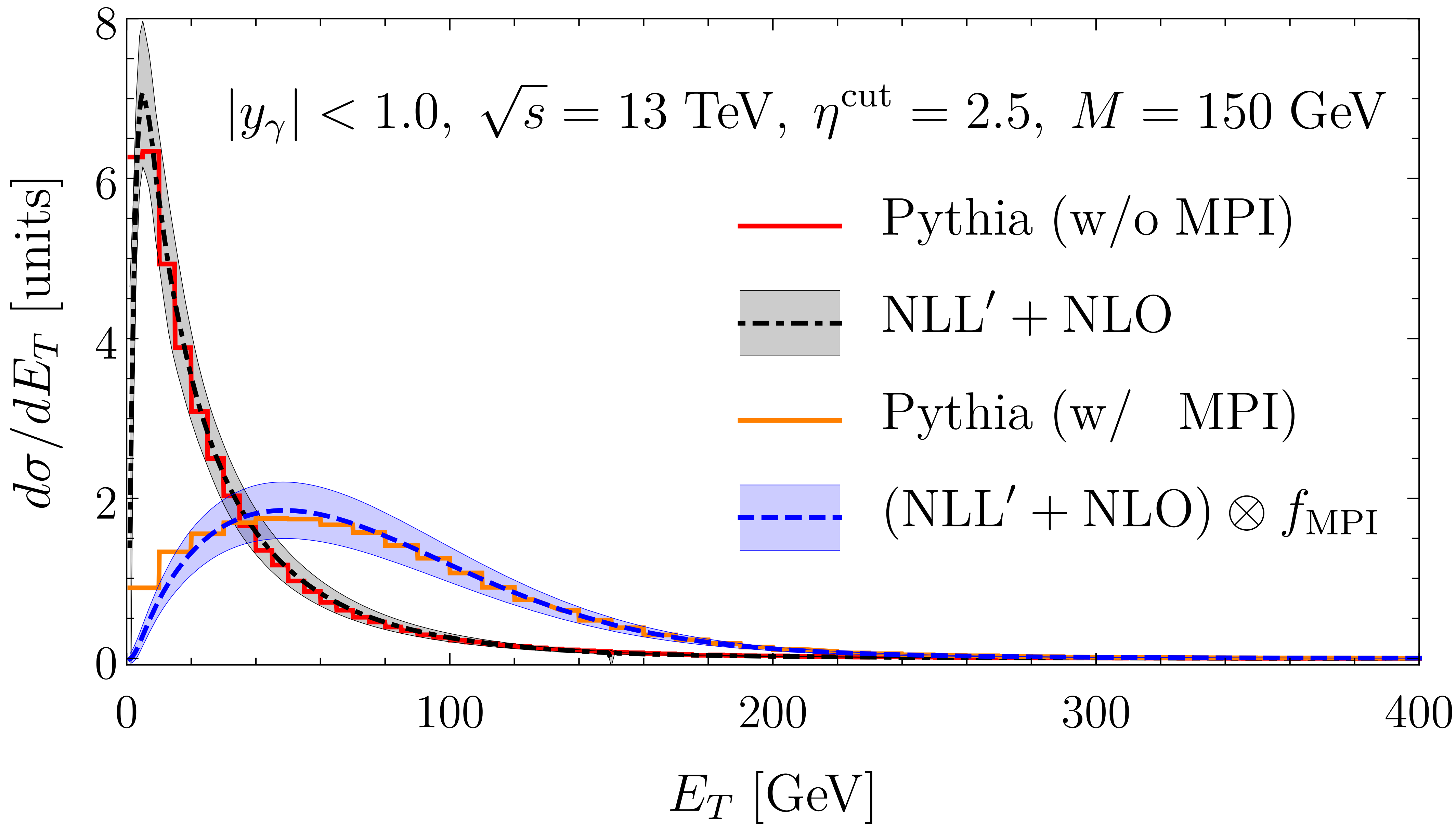


Kang, Makris, Mehen '18

- E_T is very sensitive to soft radiation.
- NLL$'$ resummation using SCET agrees with PYTHIA w/o MPI

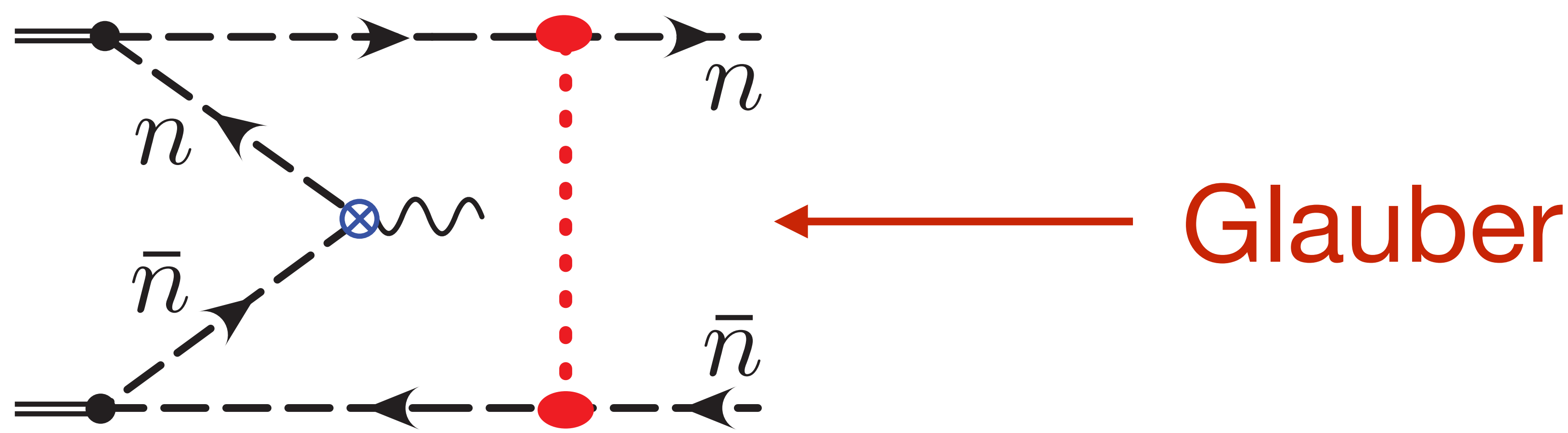
MPI effects in E_T

Kang, Makris, Mehen '18



- Dramatic change after MPI is switched on!
- Can reproduce Pythia with model function f_{MPI}

MPI = Glauber gluons?



Proton collisions include forward component (proton remnants). EFT for *pp* collisions must describe forward scattering.

- Absence of factorization-violation due to Glauber gluons is important element of factorization proof for Drell-Yan process. E_T will likely involve Glauber contributions.
- SCET with Glauber-gluons now available Rothstein and Stewart ‘16

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Summary

A lot of progress in first-principles computations of collider processes using effective theory methods

- High-precision computations for simple observables
- Automated resummations
- Factorization and resummation for more exclusive observables such as jet processes
  - interesting connection to MC parton showers

At the same time open issues and challenges

- MPI, hadronisation, factorization violation, Glauber gluons …