Recent Development in Perturbative QCD for LHC

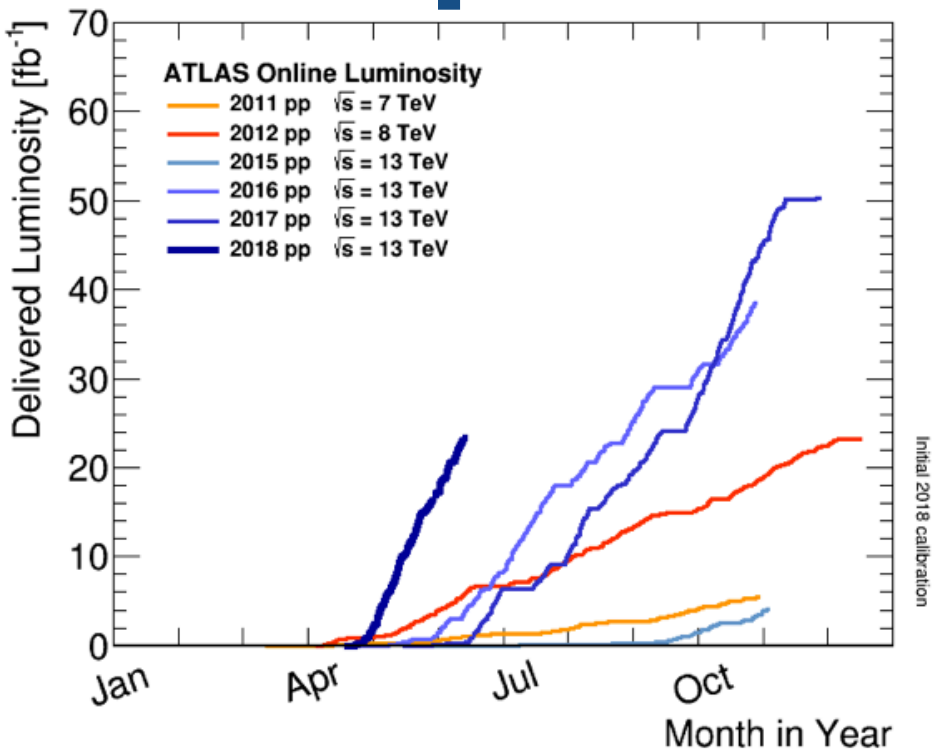
Hua Xing Zhu (朱华星)

Zhejiang University

中国物理学会高能分会年会

上海交大和李政道研究所, 6月23日, 2018

pQCD in the LHC era

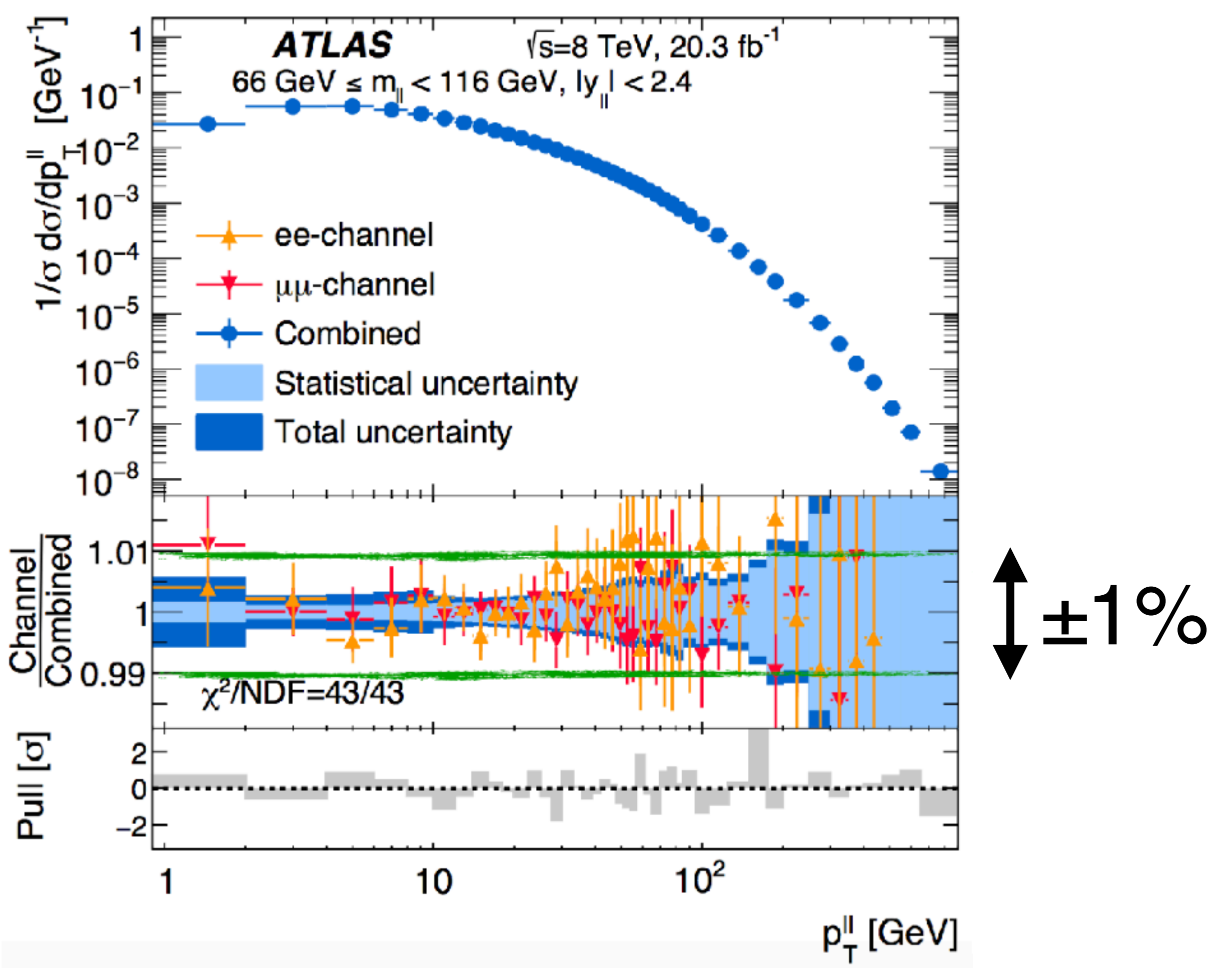


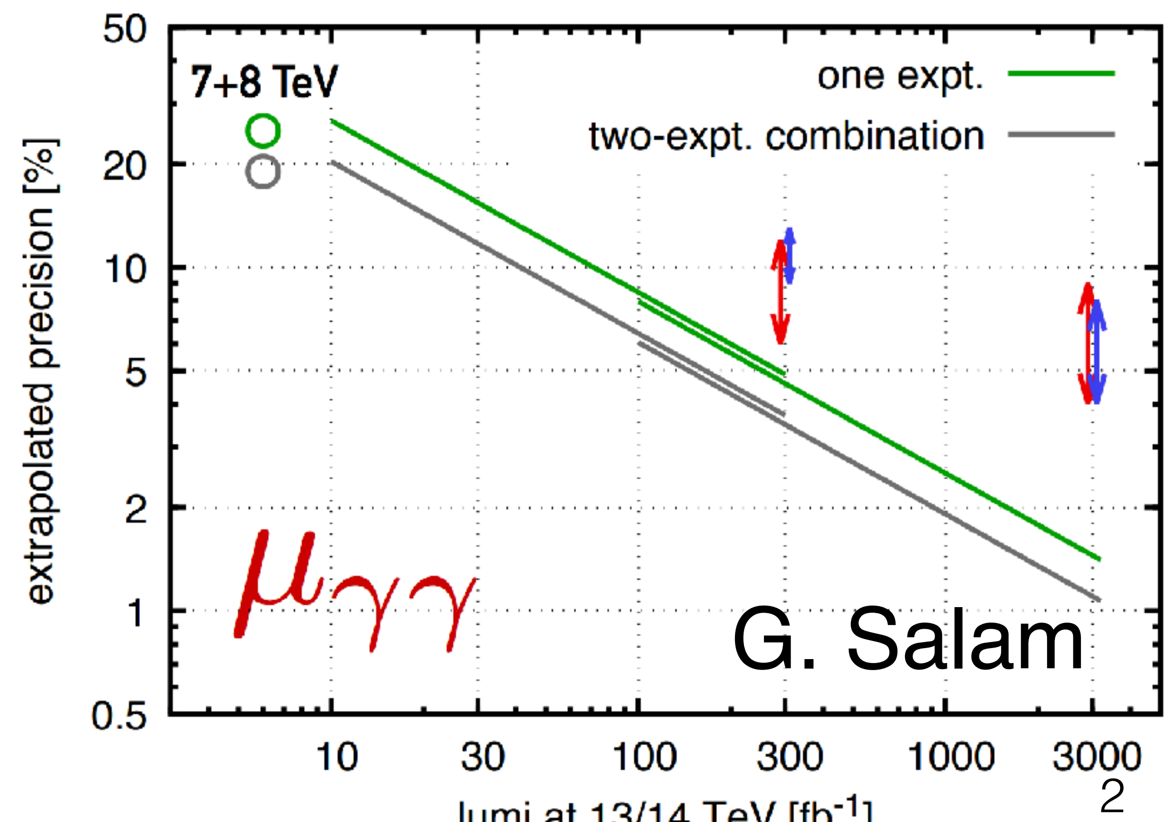
Today

- **20 fb^{-1} @ 8 TeV**
- **~110 fb^{-1} @ 13 TeV**

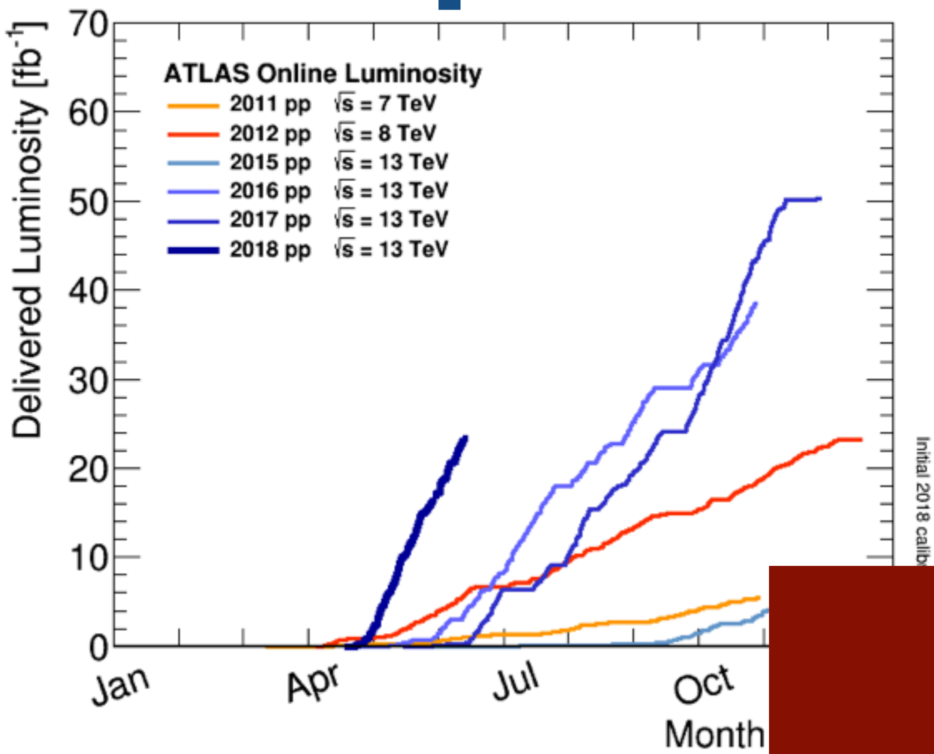
Future

- **2023: 300 fb^{-1}**
- **2035: 3000 fb^{-1}@14 TeV**





pQCD in the LHC era



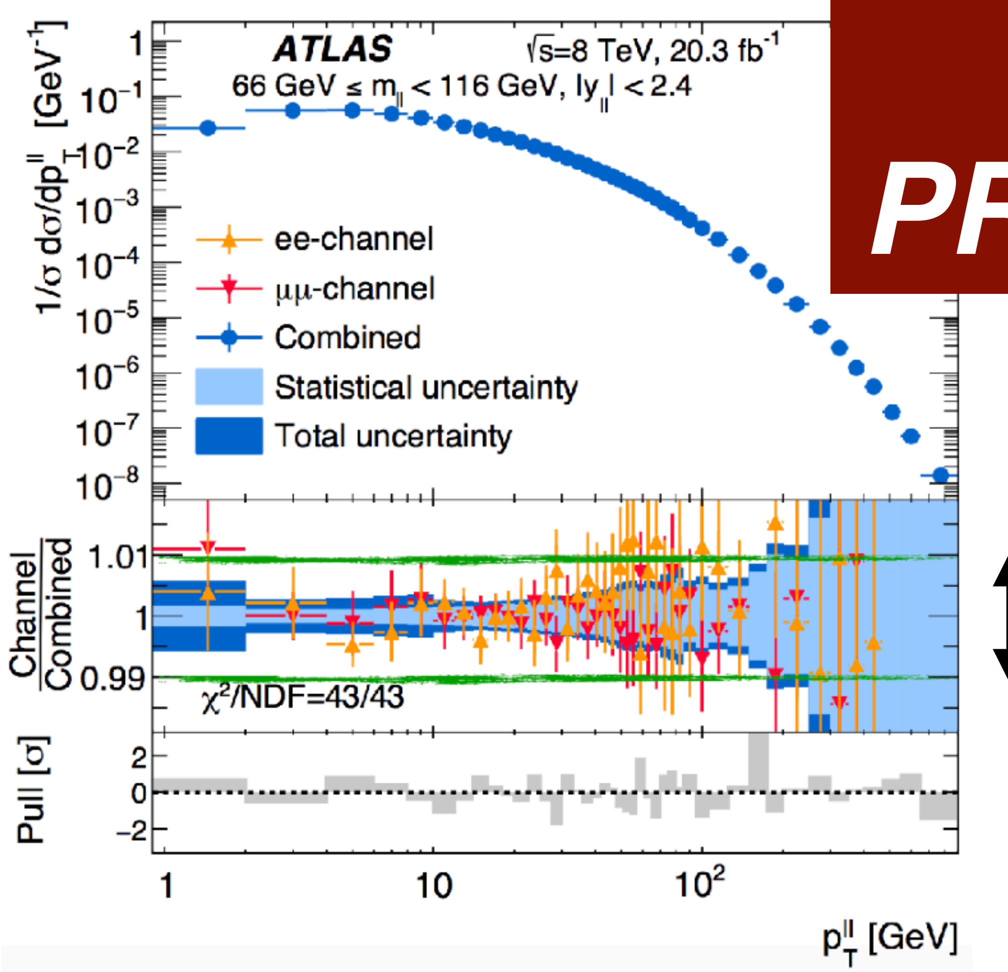
Today

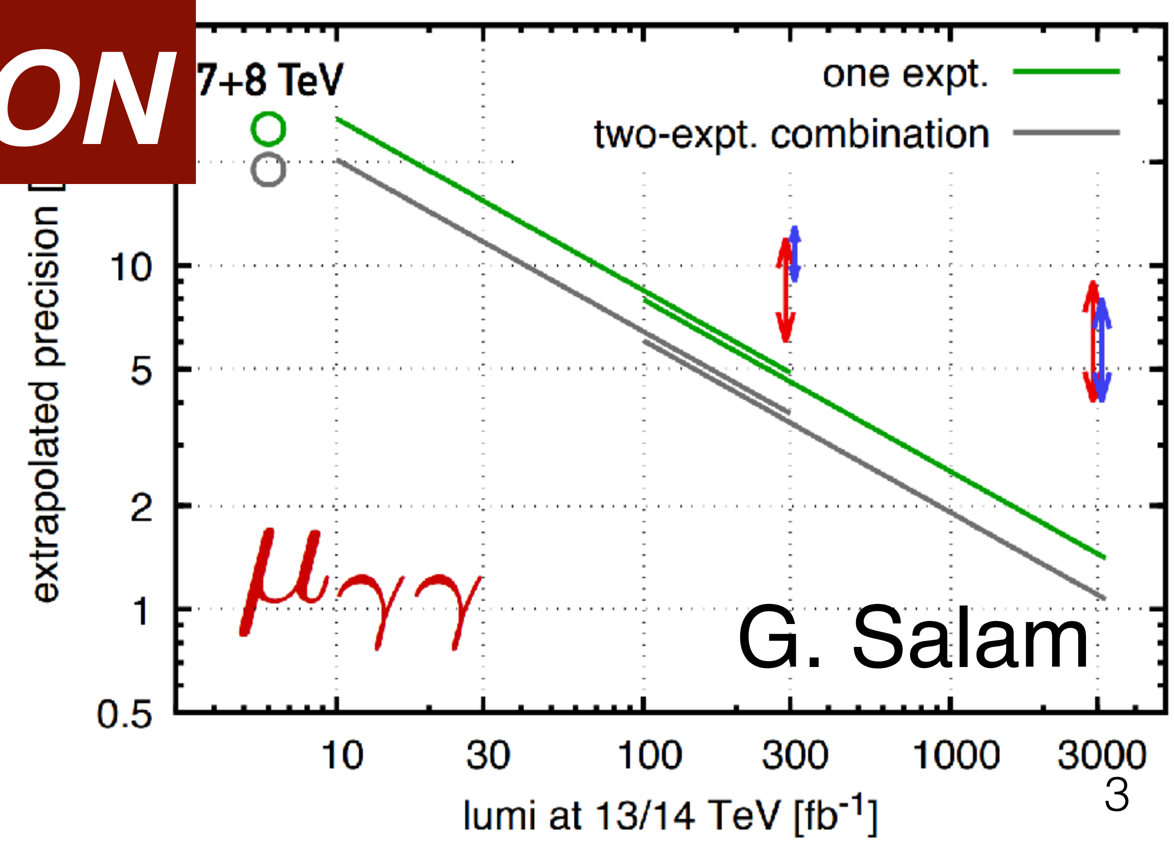
- **20 fb^{-1} @ 8 TeV**
- **~110 fb^{-1} @ 13 TeV**

Future

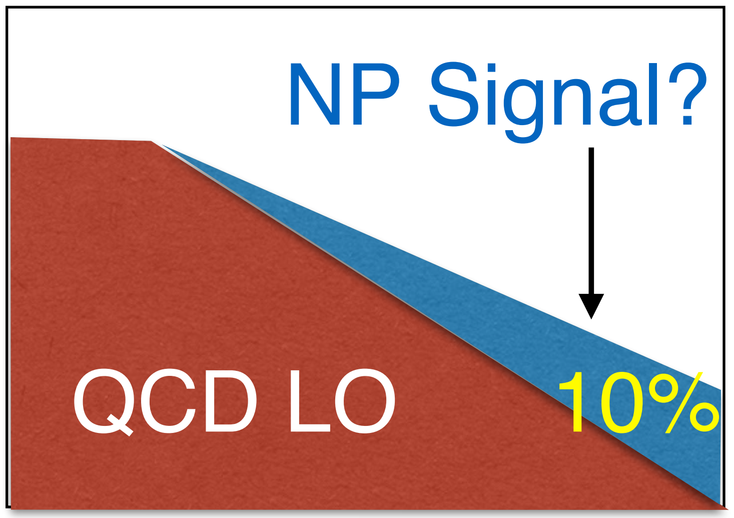
- **2023: 300 fb^{-1}**
- **2035: 3000 fb^{-1}@14 TeV**

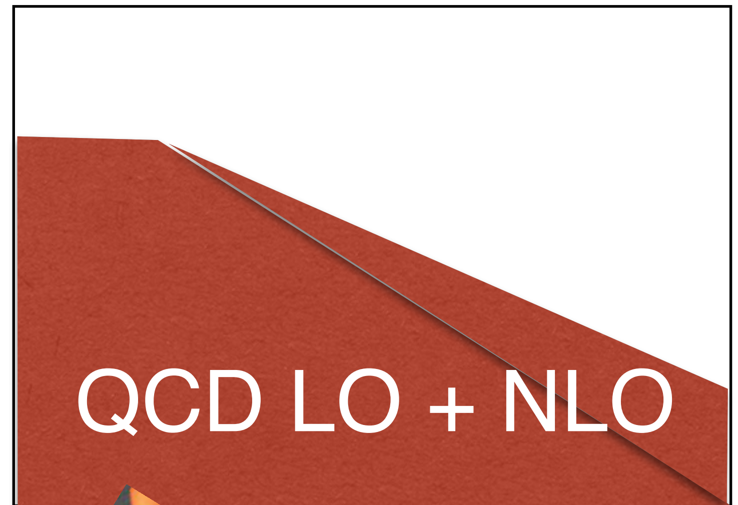
AGE OF PRECISION





Why precision QCD





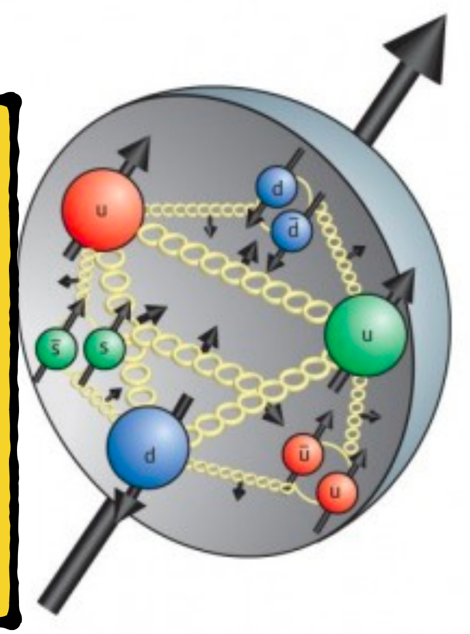
Precision for Discovery

Precision knowledge of background is crucial in declaring discovering

See also H. Zhang's talk

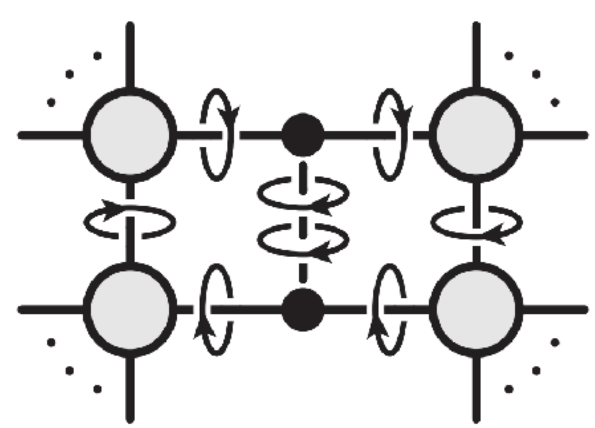
Precision for understanding QCD

- Structure of proton
- α_s determination
- splitting/fragmentation dynamics
- power corrections
- light-ray operator
- ……



See also B.W. Xiao's talk

Precision ⇔ beauty in gauge theory

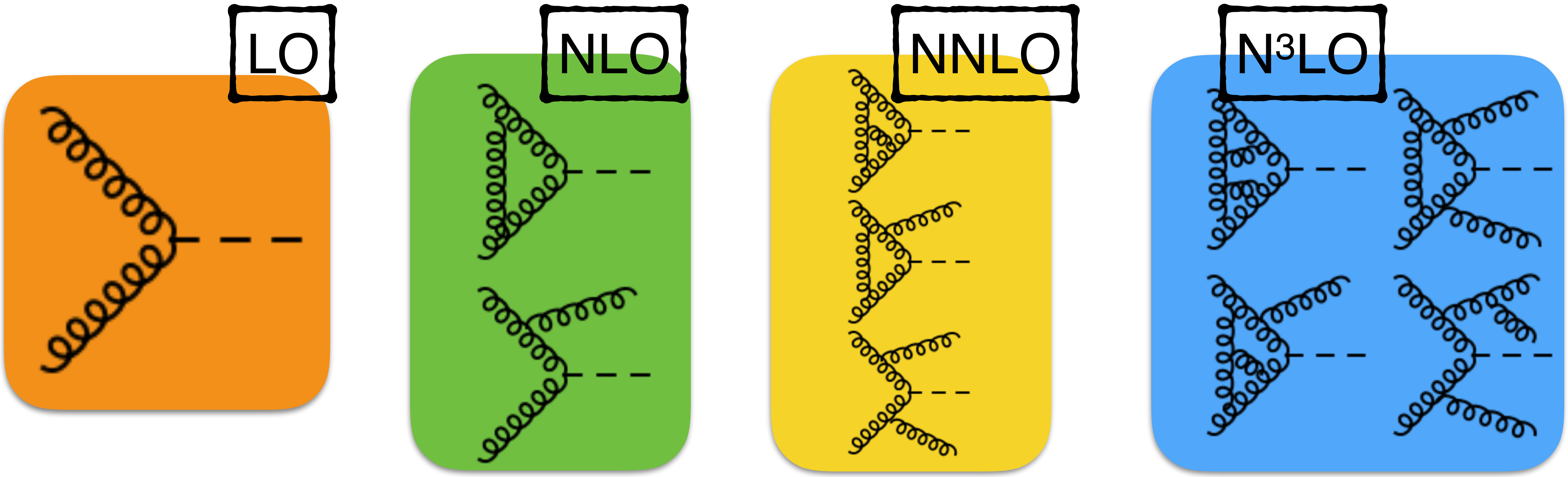


- Polylog & elliptic polylog
- iterative integral
- generalized unitarity
- scattering equatoin
- integrability
- amplituhedron
- positive geometry
- ……

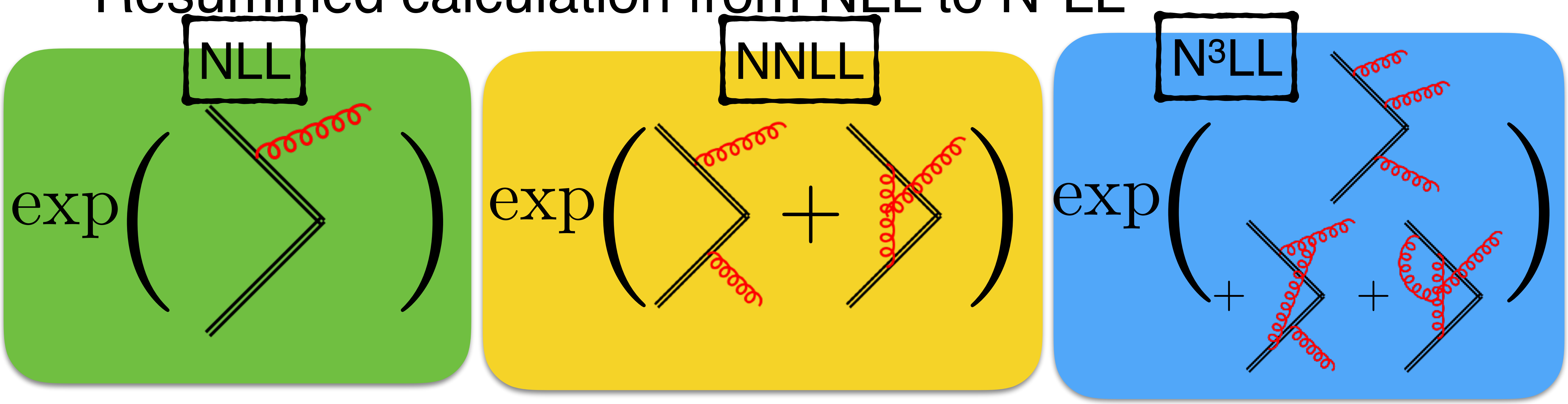
See also S. He and Y.Q. Ma's talk

Anatomy of perturbative calculation

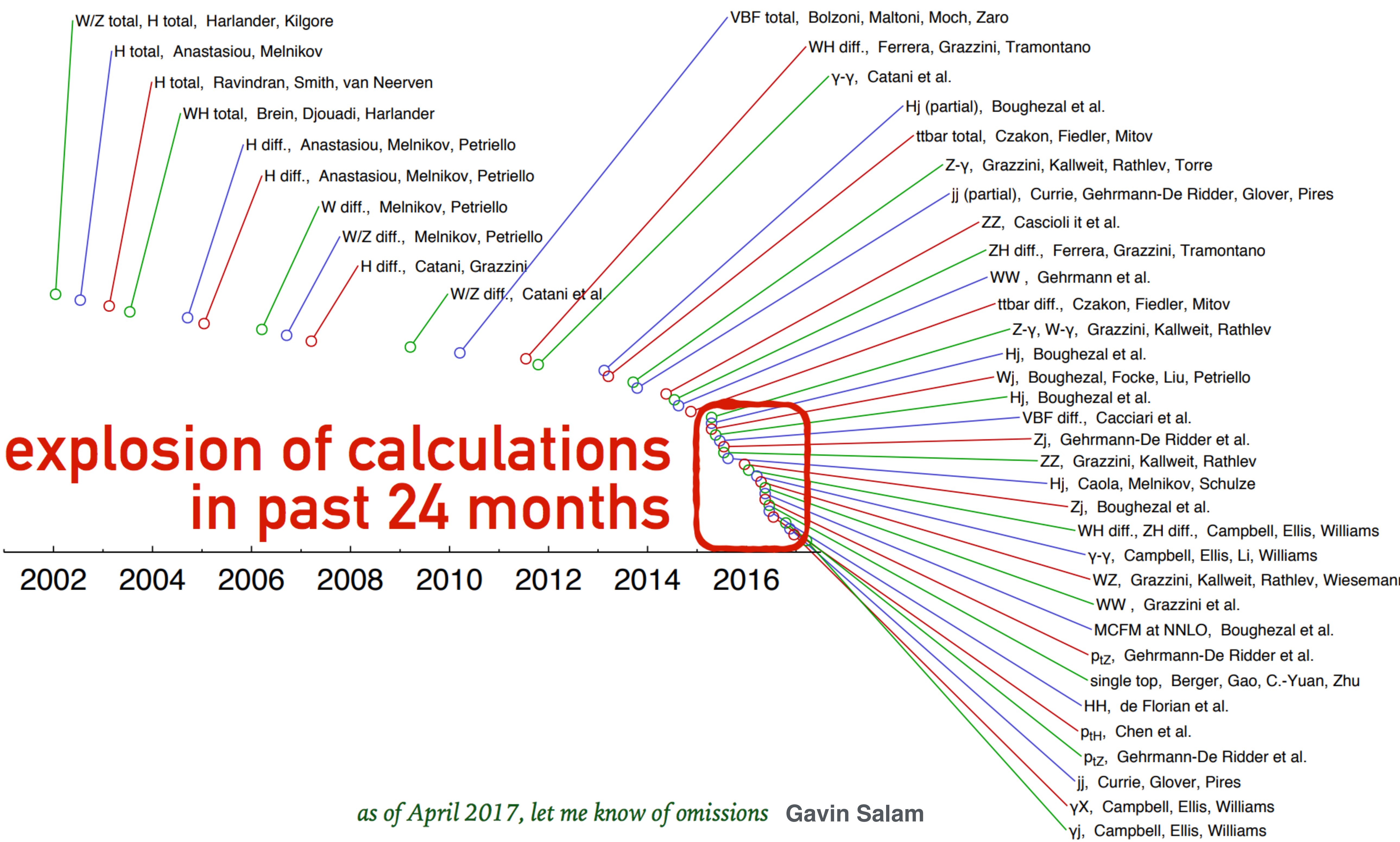
- Fixed-order calculation from LO to N³LO



- Resummed calculation from NLL to N³LL



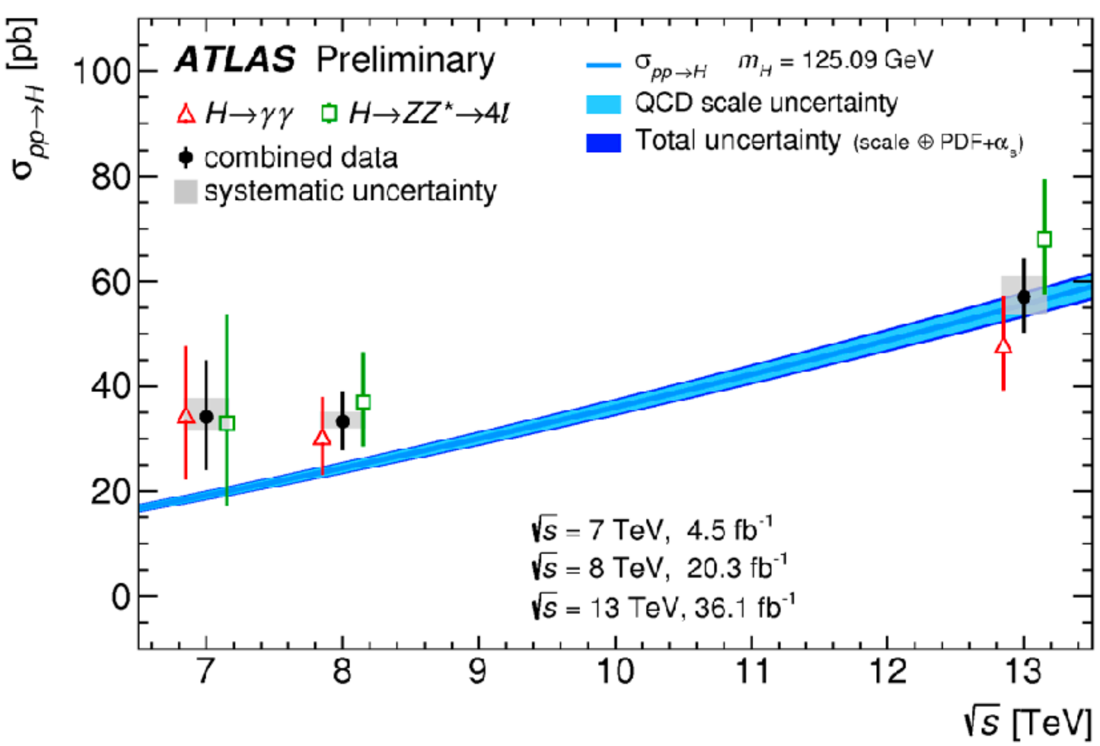
Explosion of NNLO calculations



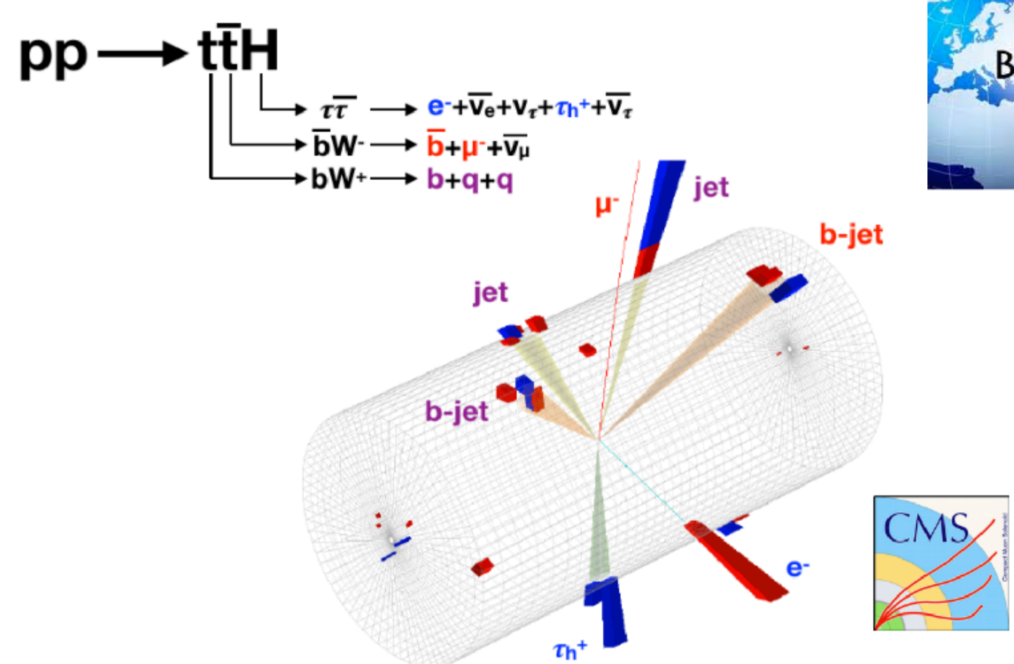
as of April 2017, let me know of omissions **Gavin Salam**

The Higgs boson

- The discovery of the Higgs boson is just the beginning of a long journey
- **The only fundamental scalar in the SM:** mass origin, vacuum stability, portal to new physics, etc
- **O(10^8) Higgs produced during the LHC life time**: a precision era await



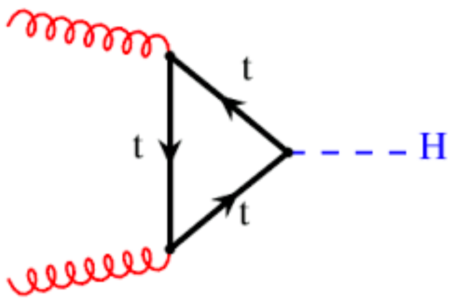
H inclusive cross section



NLO QCD+EW corrections including decay
Y. Zhang, W.G. Ma, R.Y. Zhang, C. Chen, L. Guo, 1407.1110

Inclusive cross section prediction

- **90%** of Higgs produced through **gg** fusion at the LHC
- Notorious **slowly convergent** perturbative series

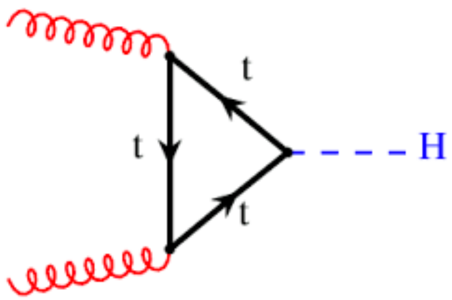


$$\sigma_H = 16 \text{ pb} + 20.6 \text{ pb} + 9.79 \text{ pb} + ?$$

LO | δNLO | δNNLO | δN^3LO

Inclusive cross section prediction

- **90%** of Higgs produced through **gg** fusion at the LHC
- Notorious **slowly convergent** perturbative series



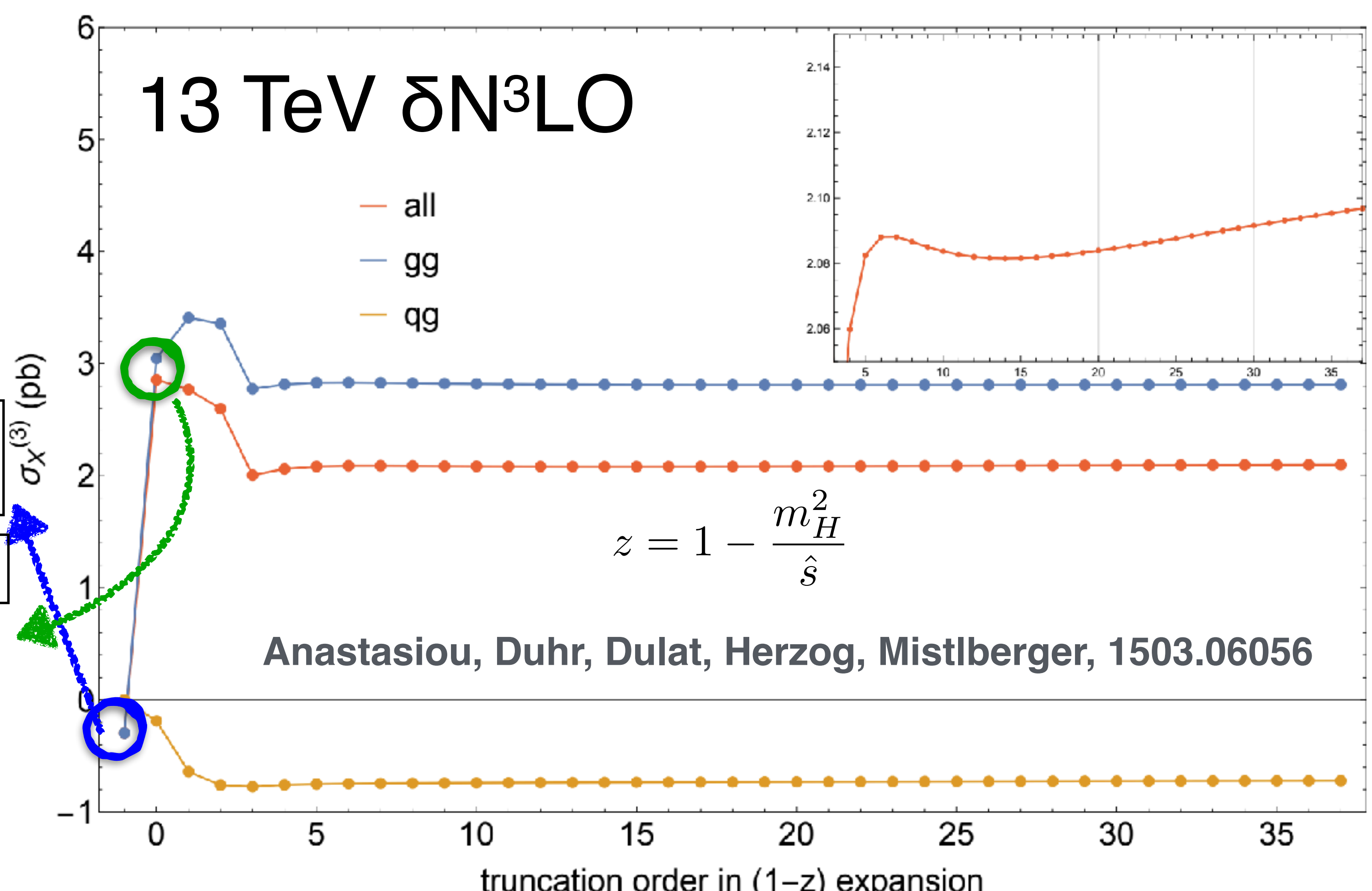
$$\sigma_H = 16 \text{ pb} + 20.6 \text{ pb} + 9.79 \text{ pb} + 2 \text{ pb}$$

LO δNLO δNNLO δN³LO

- Success application of **near threshold soft expansion**
- First N3LO hadronic cross section
- Crucial for precision Higgs program

Anastasiou, Duhr, Dulat, Furlan, et al., 1403.4616
Y. Li, von Manteuffel, Scharbinger, HXZ, 1412.2771

Anastasiou, Duhr, Dulat, Furlan, et al., 1411.3584



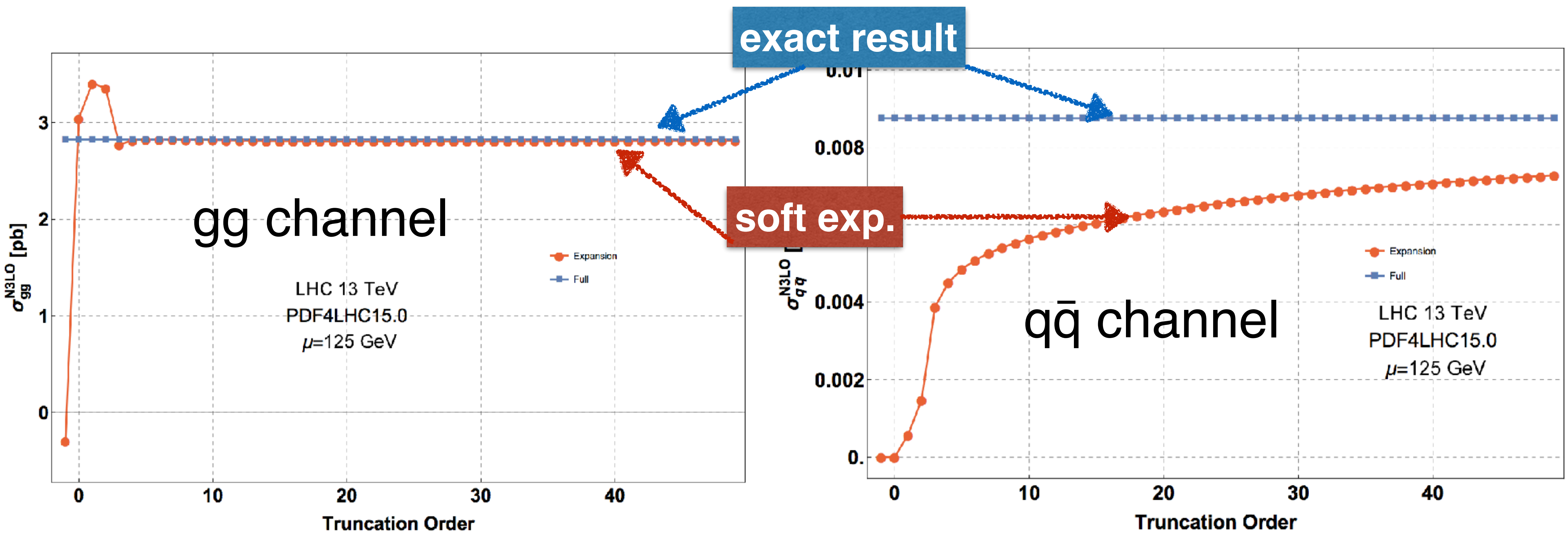
Alternative approach:
principle of maximum conformality applied to Higgs production/decay

S.Q. Wang, X.G. Wu, Brodsky, Mojaza, 1605.02572
J. Zeng, X.G. Wu, S. Bu, J.M. Shen, S.Q.Wang, 1801.01414

Beyond soft expansion: analytic

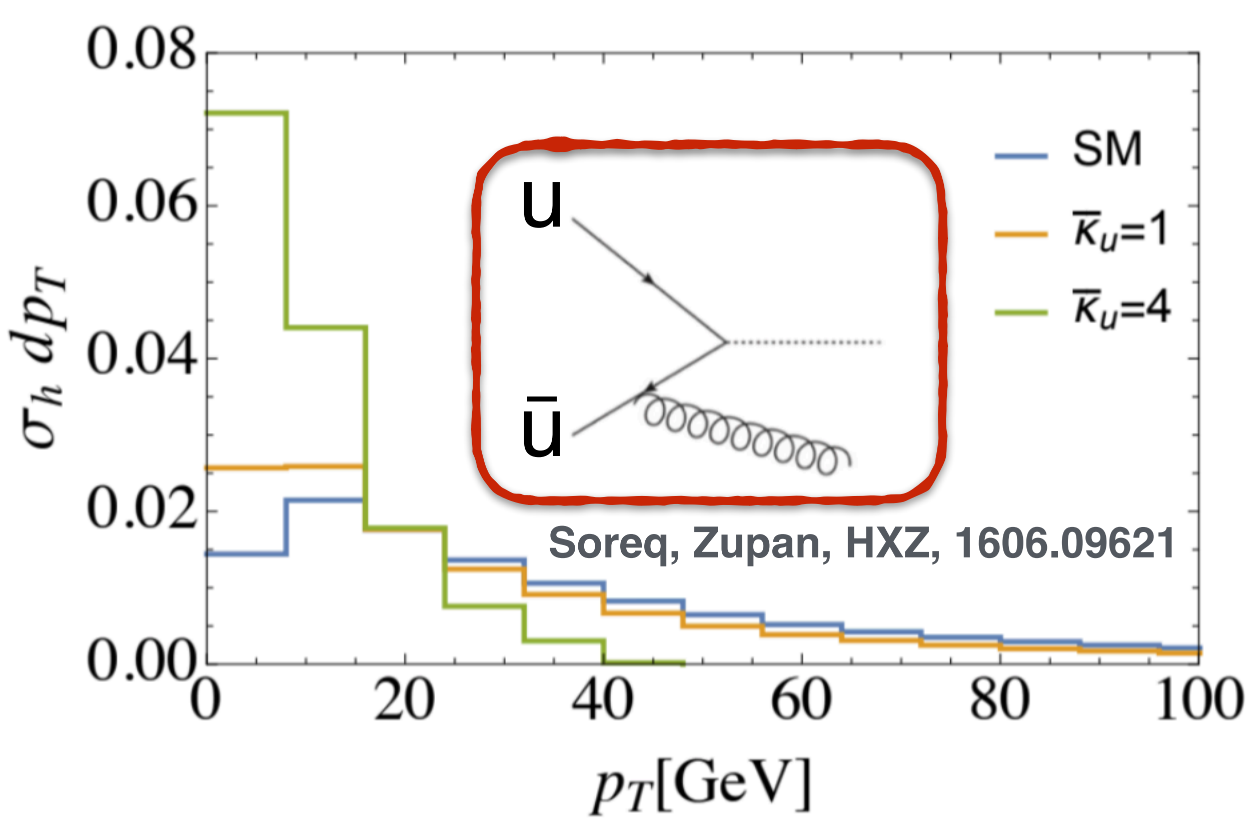
Mistlberger, 1802.00833

- Full analytic expression recently obtained
- O(1000) Feynman integrals, **elliptic integrals** involved
- **First analytic hadronic cross section with elliptic integrals**
- Excellent convergence for gg channel, much worse for qq
- Results will facilitate N^{3}LO calculation for **Drell-Yan**

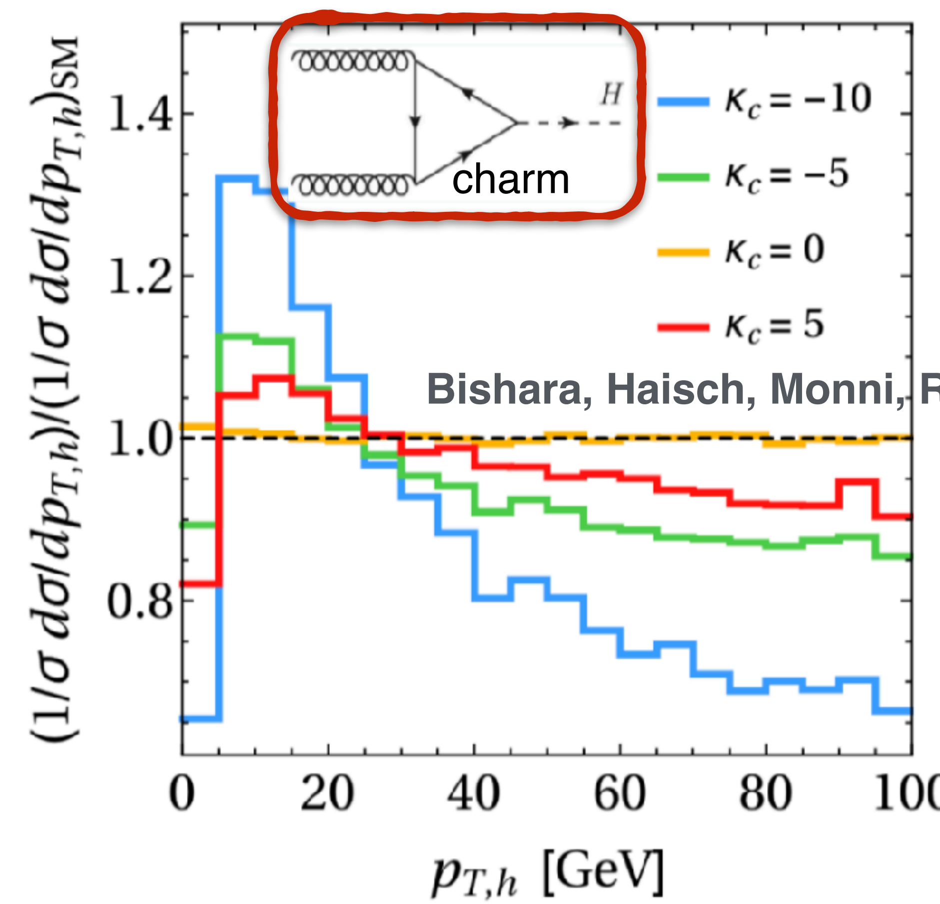


Higgs differential distribution

- 80fb^{-1} run-2 data analyses, about **4 million Higgs**, precision become possible even for differential dist.
- Differential distribution (pT, jet-bin Xsec,…) allows more detailed scrutiny of Higgs properties
- One example: **light quark Yukawa through Higgs pT**



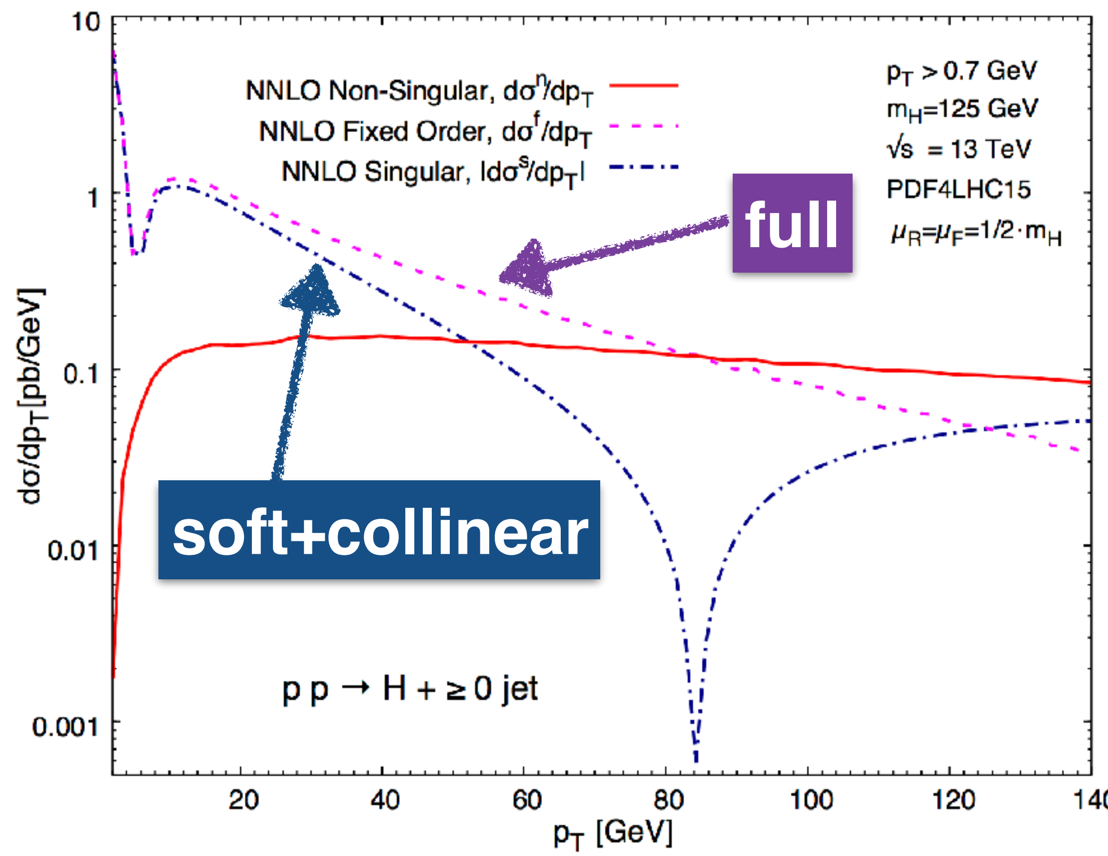
Soreq, Zupan, HXZ, 1606.09621

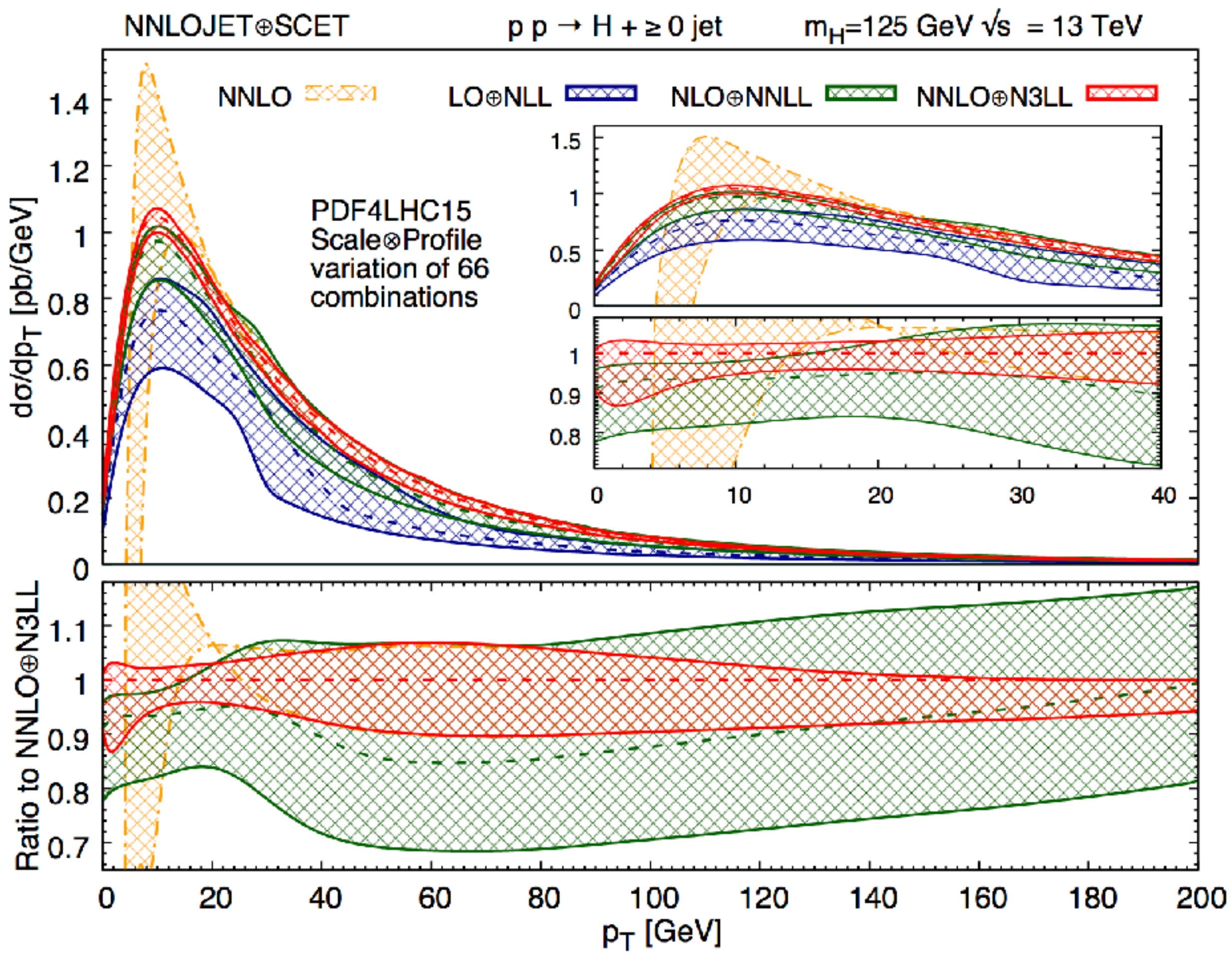


Bishara, Haisch, Monni, Re, 1606.09253

Higgs pT spectrum prediction

- Differential pT distribution for Higgs exhibits **large logarithms** $\ln^k(p_T)/p_T$
- Several different approaches for their resummation
  - Collins-Soper-Sterman formula
  - TMD factorization (Ji-Ma-Yuan, hep-ph/0404183)
  - Soft-Collinear Effective Theory



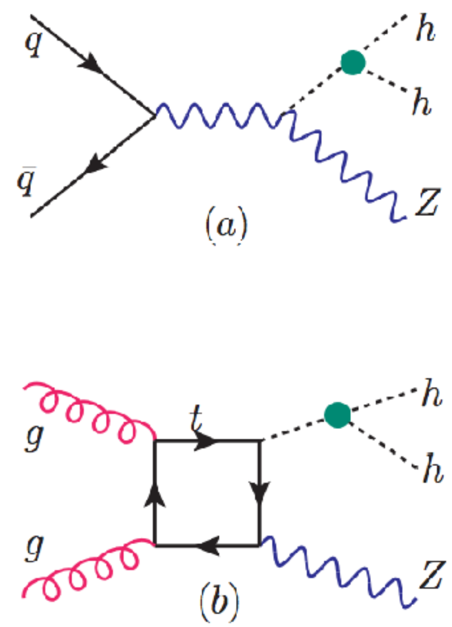


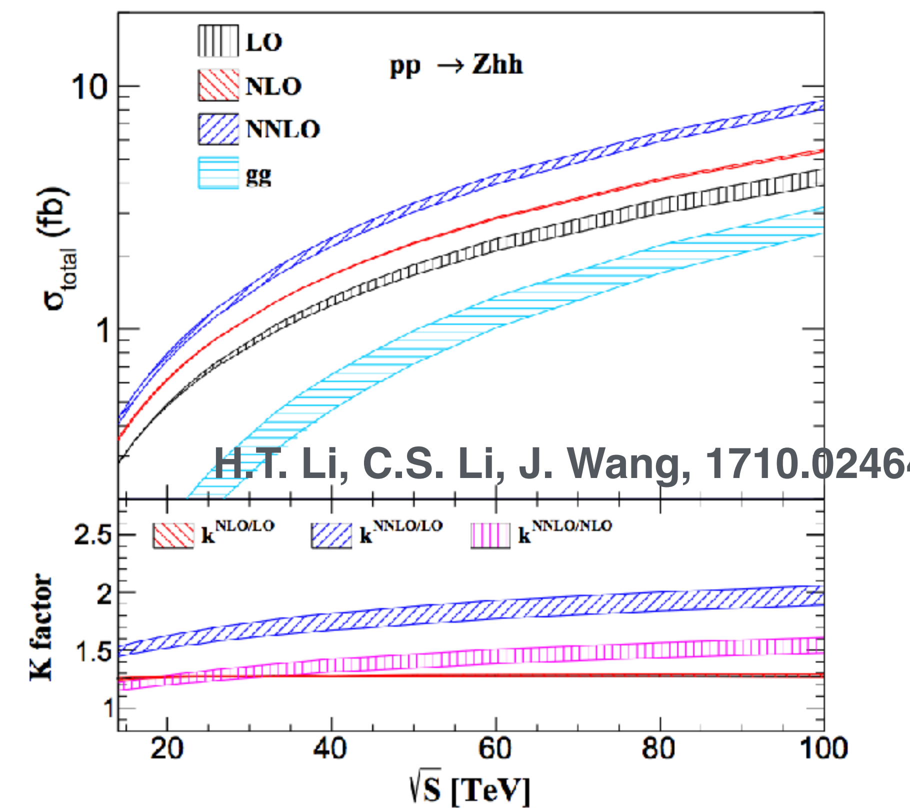
- Recently first pT resummation calculation at **NNLO + N3LL** with high resolution
- Many years of calculation efforts in fixed order, anomalous dimension, matching coefficients
- **Continuous reduction of theoretical uncertainties**: demonstrate power of pQCD

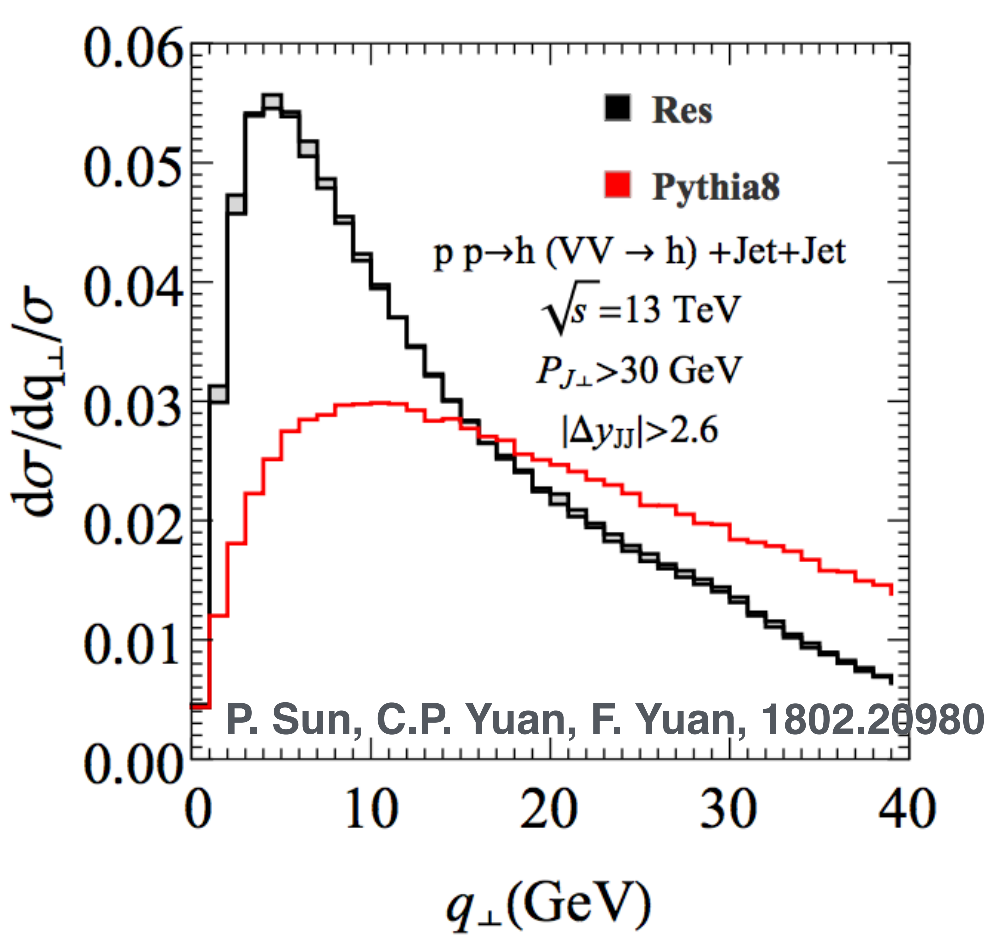
X. Chen, Gehrmann, Glover, Huss, Y. Li, Neill, Schulze, Stewart, HXZ, 1805.00736

Higgs associated production

- Higgs pair production associated with Z
- Sensitive to Higgs trilinear coupling
- **Large K factor** at NNLO



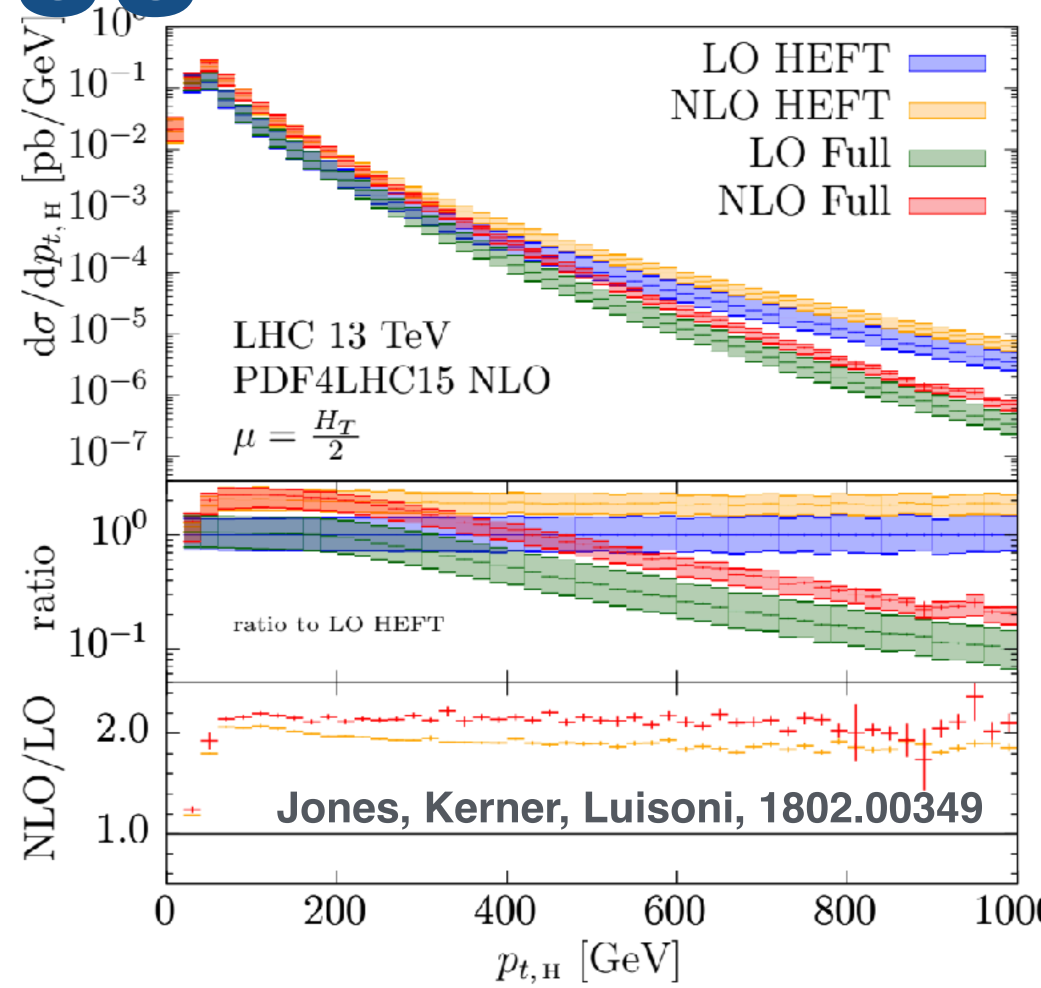




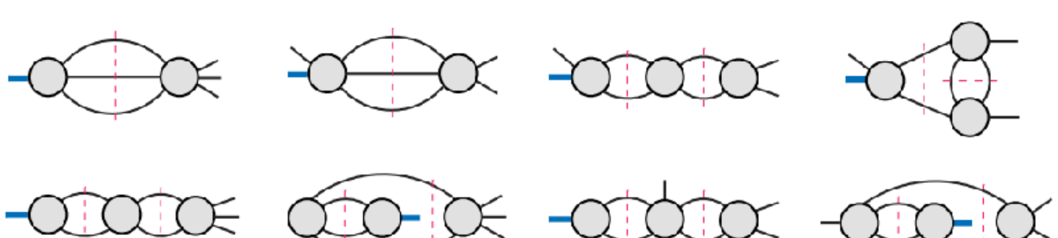
- Higgs VBF production
- Resummation of qT for **Higgs + di-jet system**
- **Significant difference** between resummation and Pythia
- Important to understand the origin of difference

Beyond Higgs EFT

- Higgs + jet production at NLO with **full top mass dependence**
- Numerical calculation of two-loop diagrams
  - **Quasi Monte-Carlo** for Feynman Integrals **[Z. Li, J. Wang, Q.S. Yan, X.R. Zhao, 1508.02512]**
- Full mass corrections become important for pT>200 GeV



$$O_1 = H\mathrm{Tr}(G_\mu{}^\nu G_\nu{}^\rho G_\rho{}^\mu)\,,$$
$$O_2 = H\mathrm{Tr}(D_\rho G_{\mu\nu} D^\rho G^{\mu\nu})\,,$$



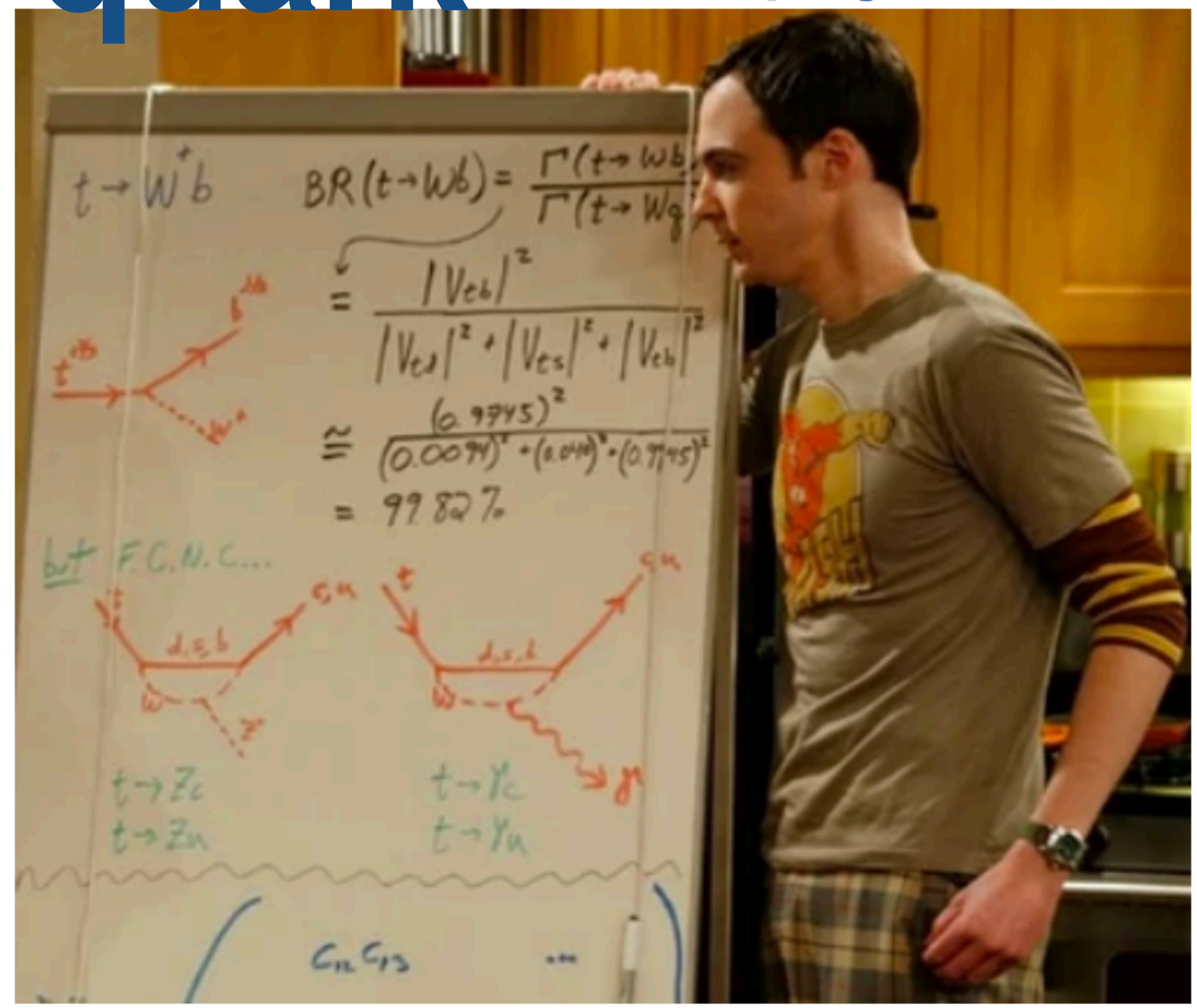
$$\Omega^{(2)}_{\mathcal{O}_1;4} = -\frac{3}{2}\mathrm{Li}_4(u) + \frac{3}{4}\mathrm{Li}_4\left(-\frac{uv}{w}\right) - \frac{3}{2}\log(w)\mathrm{Li}_3\left(-\frac{u}{v}\right) + \frac{\log^2(u)}{32}\left[\log^2(u)+\log^2(v)+\log^2(w)-4\log(v)\log(w)\right] + \frac{\zeta_2}{8}\left[5\log^2(u)-2\log(v)\log(w)\right] - \frac{1}{4}\zeta_4 - \frac{1}{2}\zeta_3\log(-q^2) + \mathrm{perms}(u,v,w)\,. \qquad (23)$$

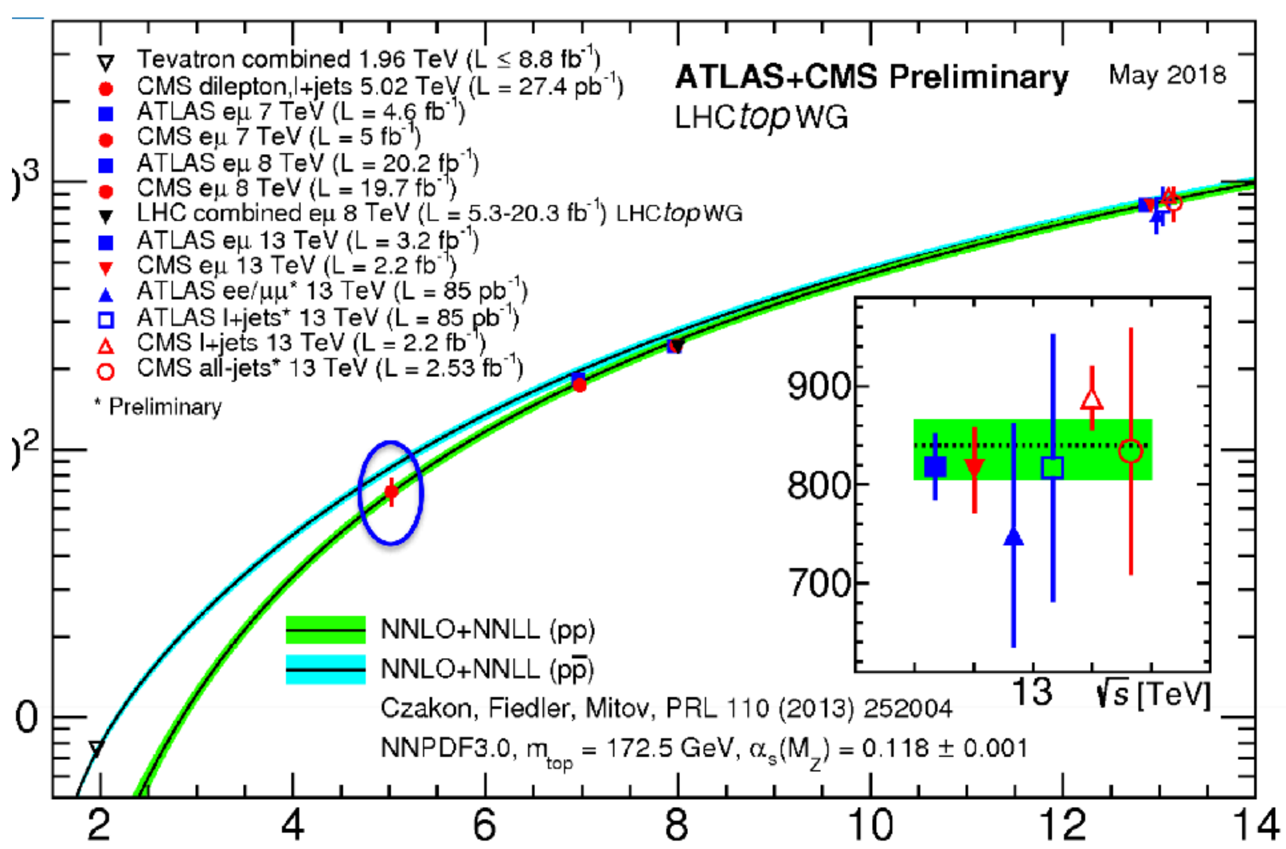
Q.J. Jin, G. Yang, 1804.04653

- Mass effects can be partially taken into account by including higher dim. operator
- **Two-loop form factor** calculated for EFT operator up to dimension 7
- Maximal transcendental part resemble N=4 SYM; lower transcendental part also in compact form
- Important ingredient for NNLO H+jet with dim. 7 operator

The top quark

- The **heaviest** particle in the SM
- **Largest contribution** to fine tuning problem in the SM
- **Top mass** and the fate of the universe
- **Abundantly produced** at the LHC: ideal arena for precision
- Frequently appear as **background** in new physics searches



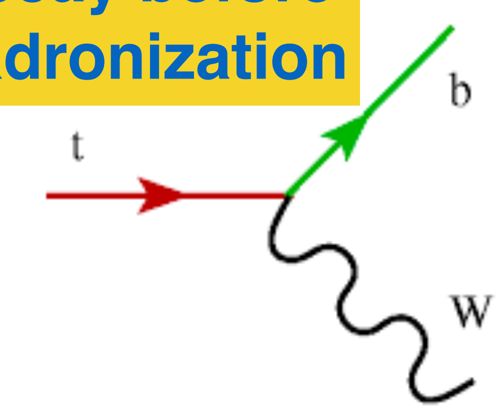


Impressive agreement up to now..

Javier Fdez.

lifetime of ≈ 0.5×10^{-24} s

decay before hadronization



top quark decay

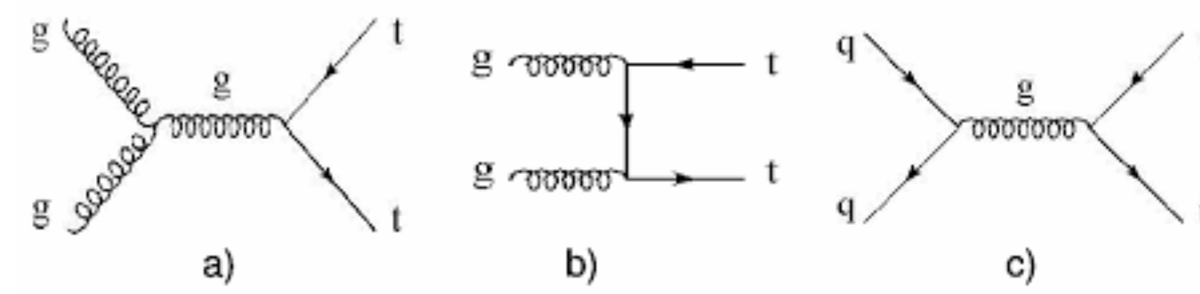
NLO QCD:
C.S. Li, Oakes, T.C. Yuan, 1991

NNLO QCD + NLO EW:
J. Gao, C.S. Li, HXZ, 1210.2808
Brucherseifer, Caola, Melnikov, 1301.7133

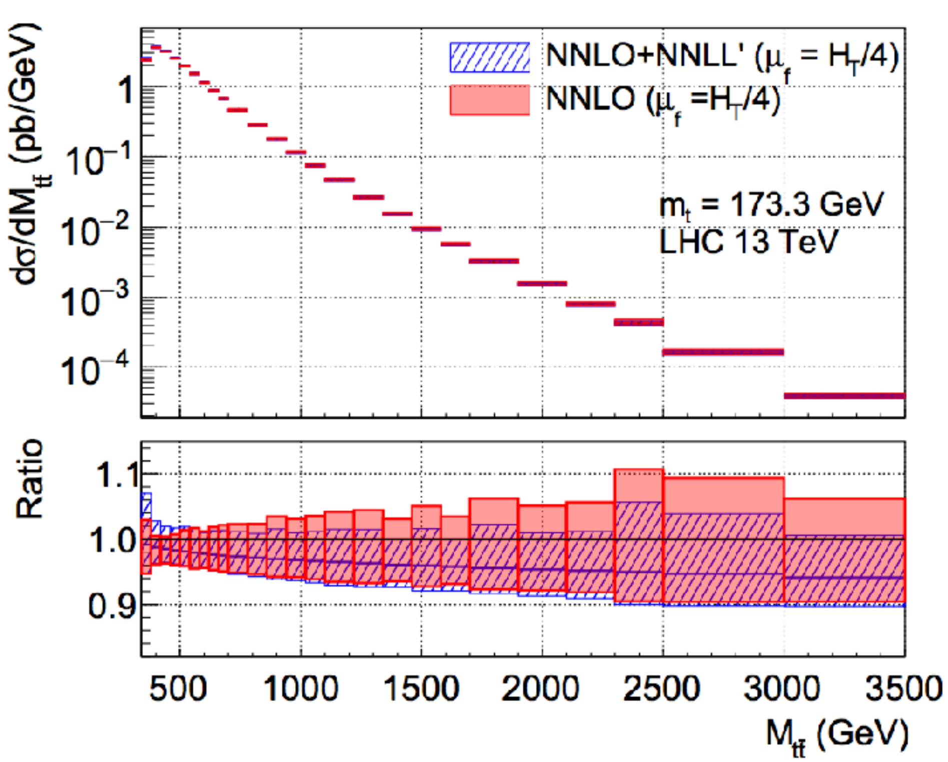
NLO FCNC decay:
J.J. Zhang, C.S. Li, J. Gao, H. Zhang, Z. Li, C.-P. Yuan, T.C. Yuan, 0810.3889
Durieux, Maltoni, C. Zhang, 1412.7166

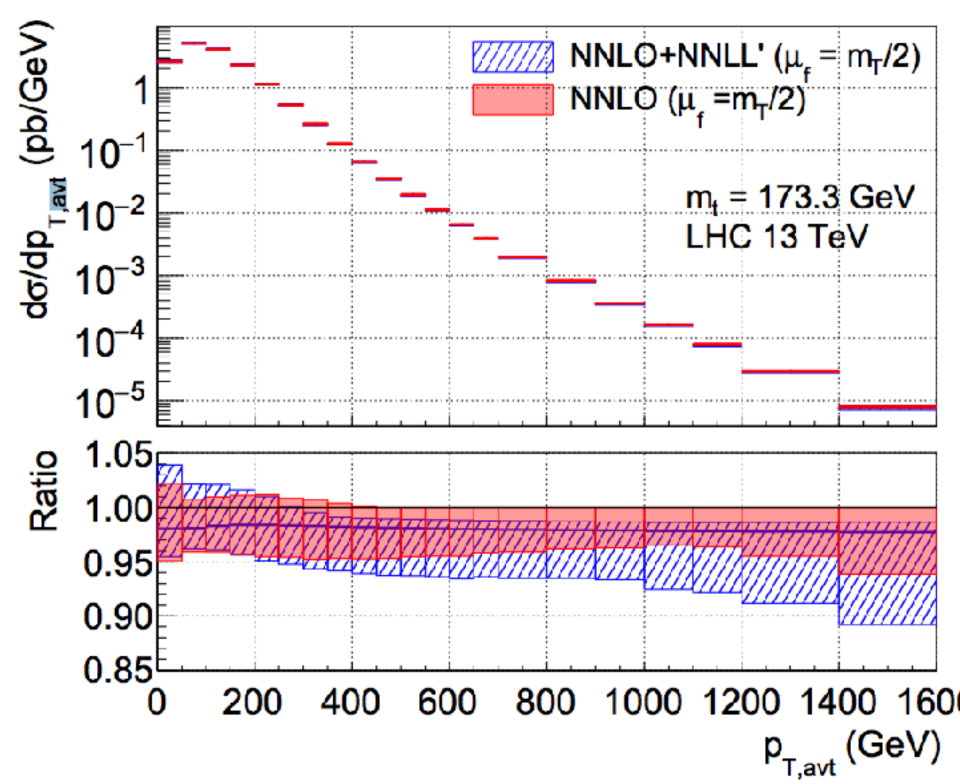
Boosted $t\bar{t}$ production

- Resummation for (boosted) $t\bar{t}$ at **NNLO + NNLL'**
- Combine **fixed order, threshold resummation, and high energy top mass logs resummation**
- Optimal kinematical scale choice



NLO spin correlation:
Bernreuther, Brandenburg, Z.G. Si, Uwer, hep-ph/0107086
NLO QCD production + decay:
Bernreuther, Brandenburg, Z.G. Si, Uwer, hep-ph/0403035
NLO EW:
Bernreuther, Fuecker, Z.G. Si, hep-ph/0610334
NNLO QCD:
Czakon, Fiedler, Mitov, 1303.6254
……

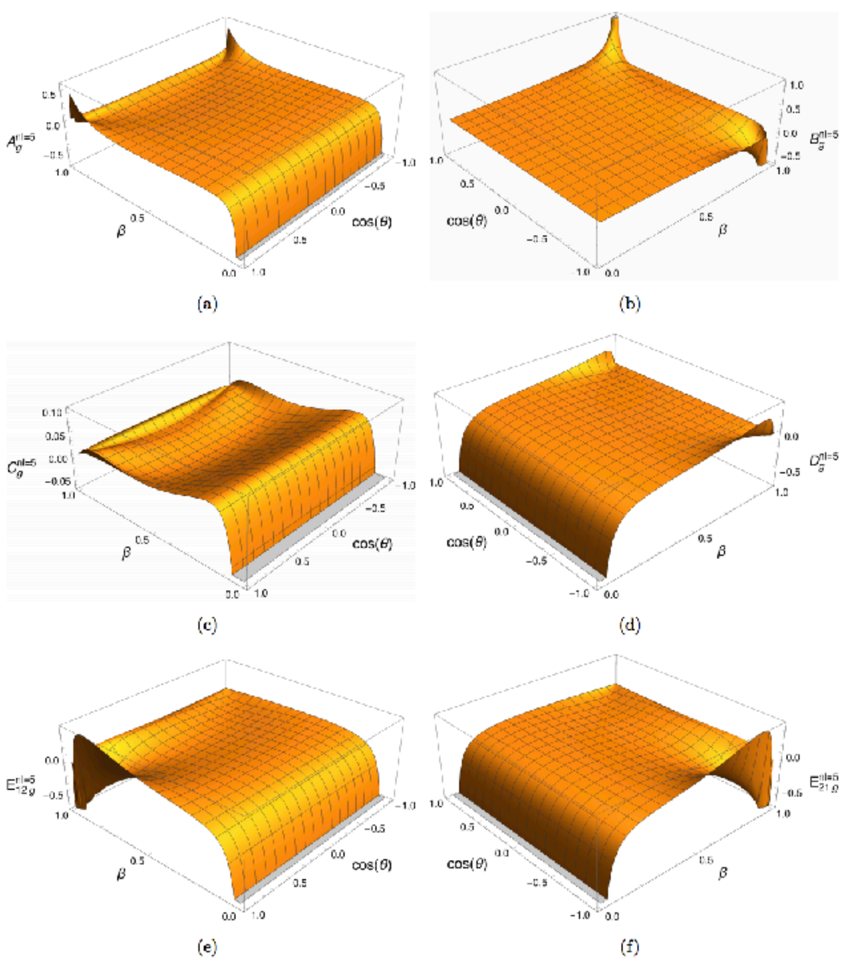




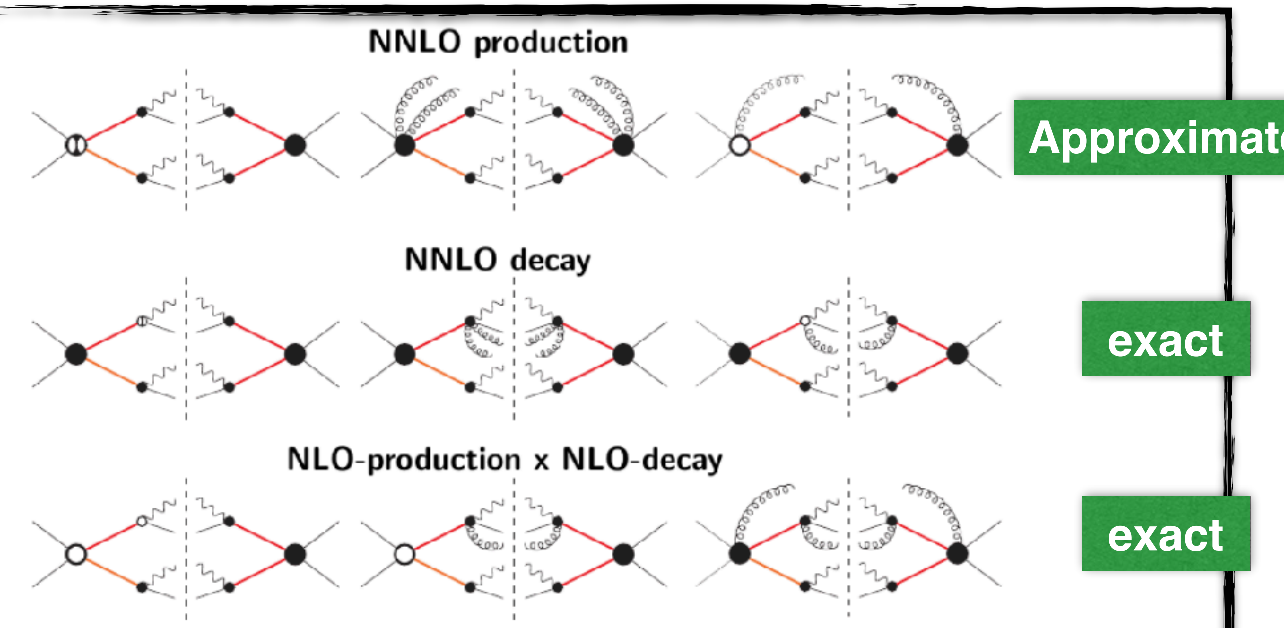
Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, X. Wang, L.L. Yang, 1803.07623

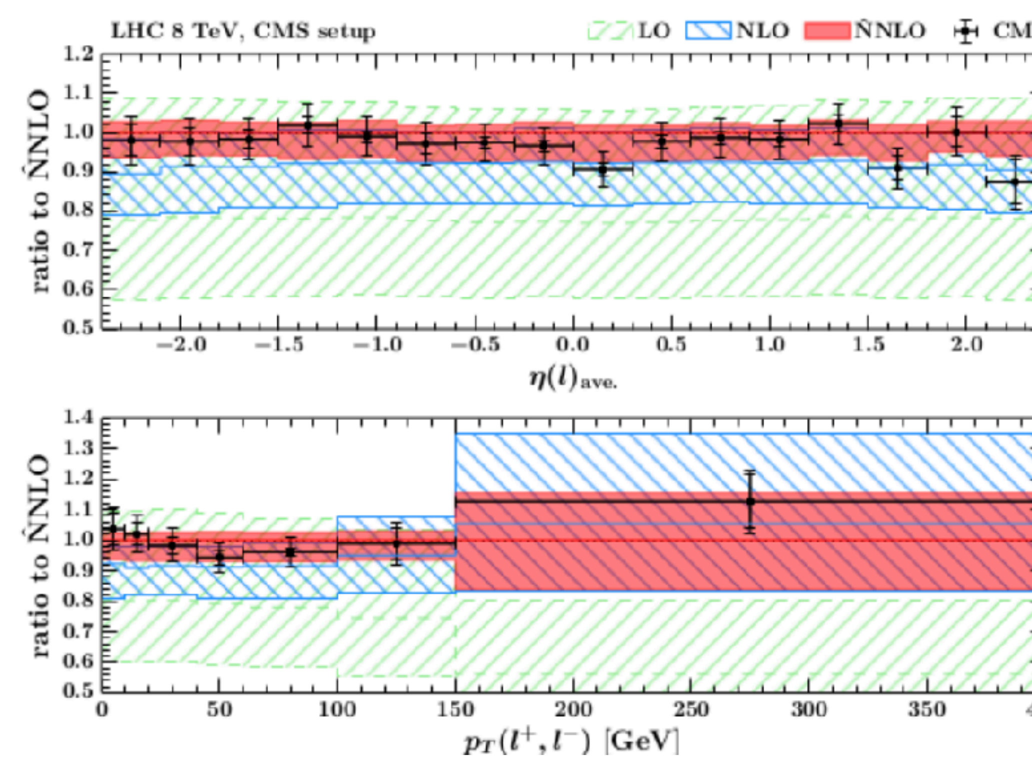
Towards $t\bar{t}$ production and decay@NNLO

- **Two-loop polarized amplitudes** for $t\bar{t}$ production
- Essential ingredient for NNLO production + decay
- **422 master integrals** with three scales, **elliptic integrals** involved
- Solved by numerical differential equation



L. Chen, Czakon, Poncelet, 1712.08075



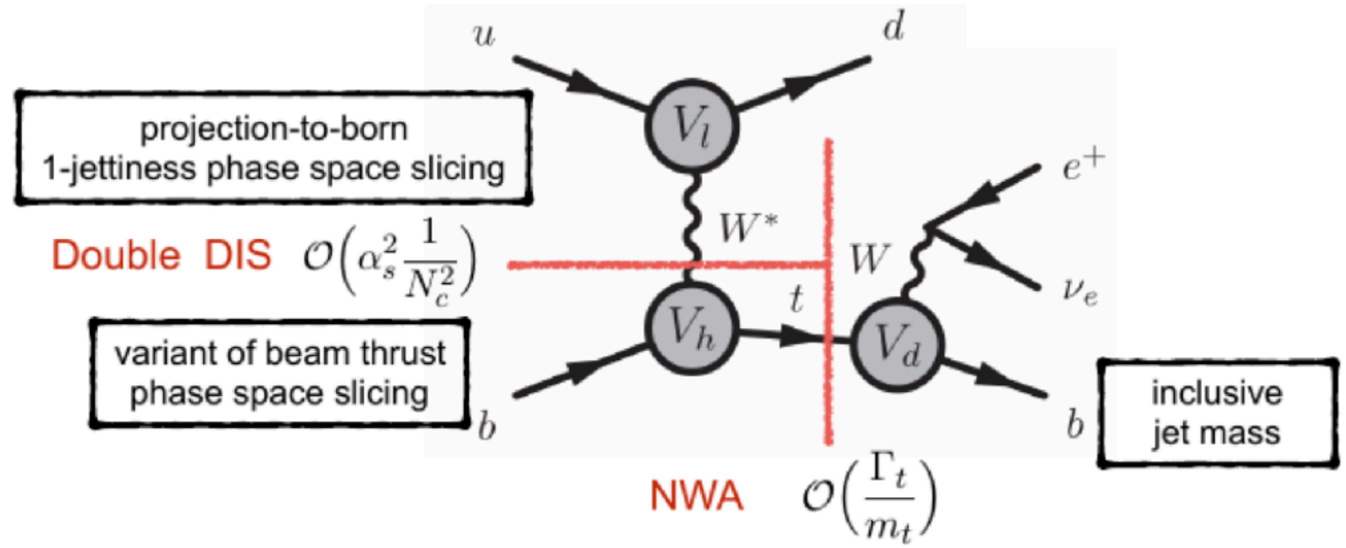


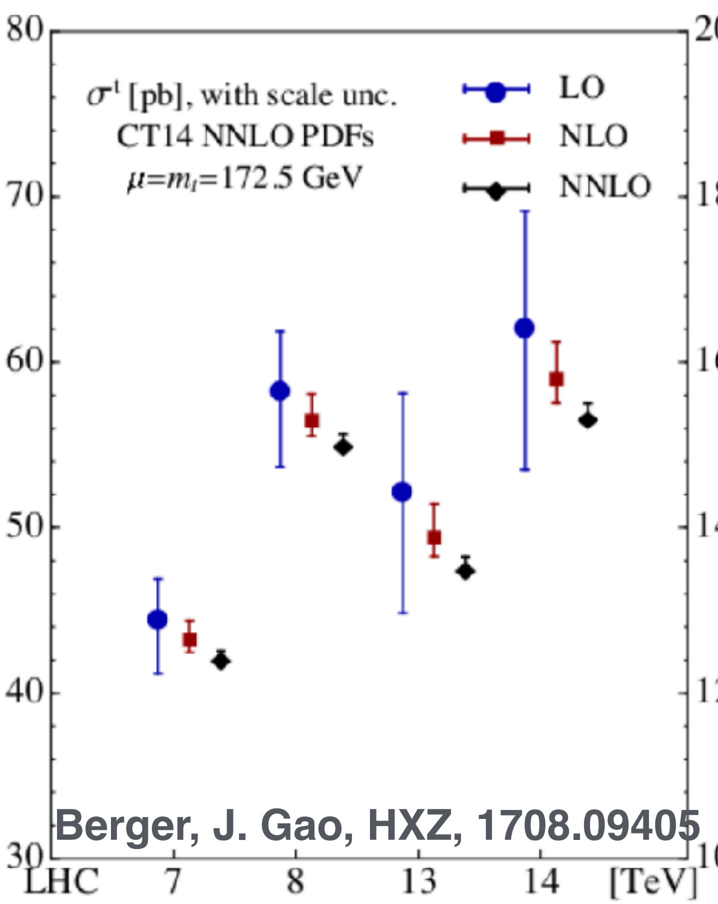
- **Approx. NNLO production + full NNLO decay**
- **Fully differential**. Significant corrections to fiducial distribution

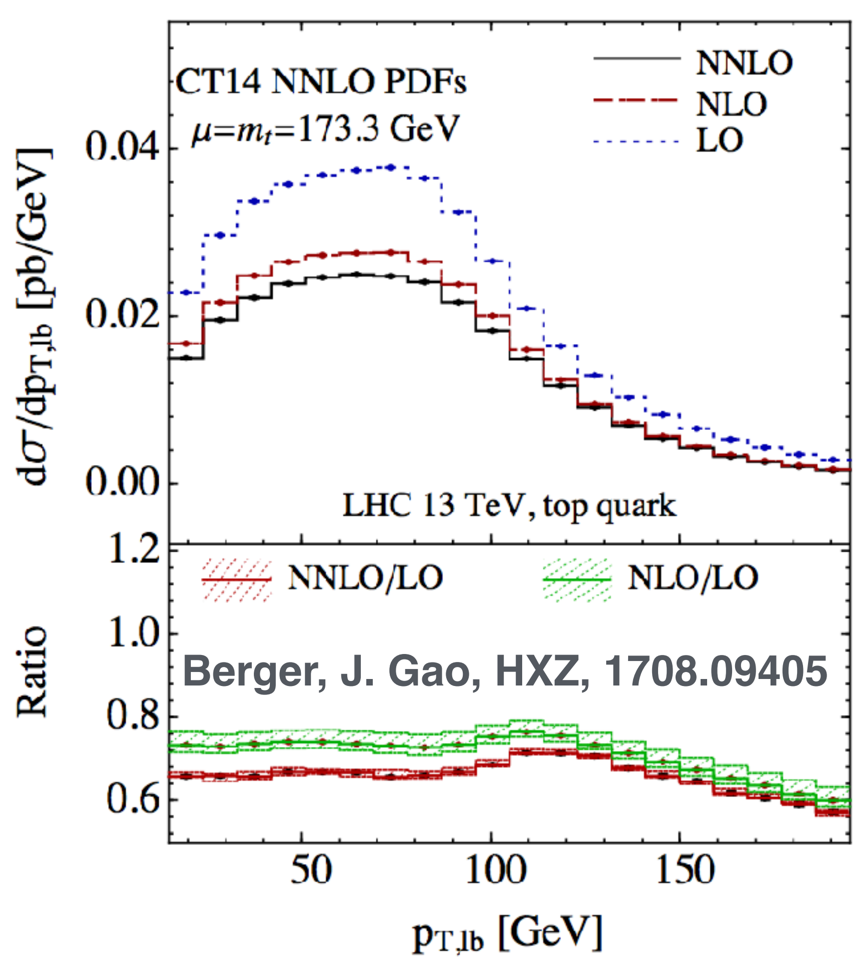
J. Gao, Papanastasiou, 1705.08903

Single top production and decay

- Sensitive to CKM element V_{tb}
- Large Xsec (~210pb@13TeV)
- Large background from $t\bar{t}$. Severe phase space cut
- Need accurate prediction for **fiducial distribution**





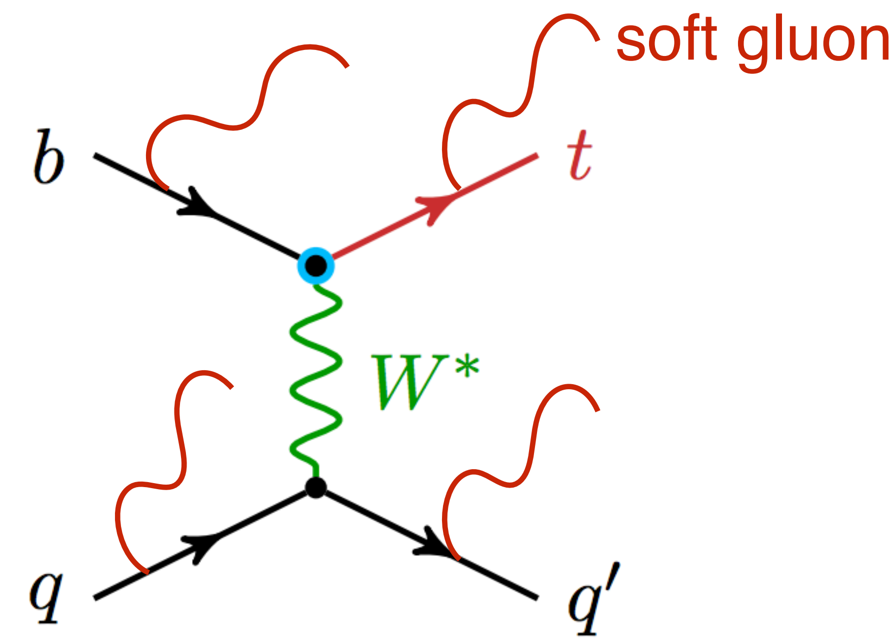


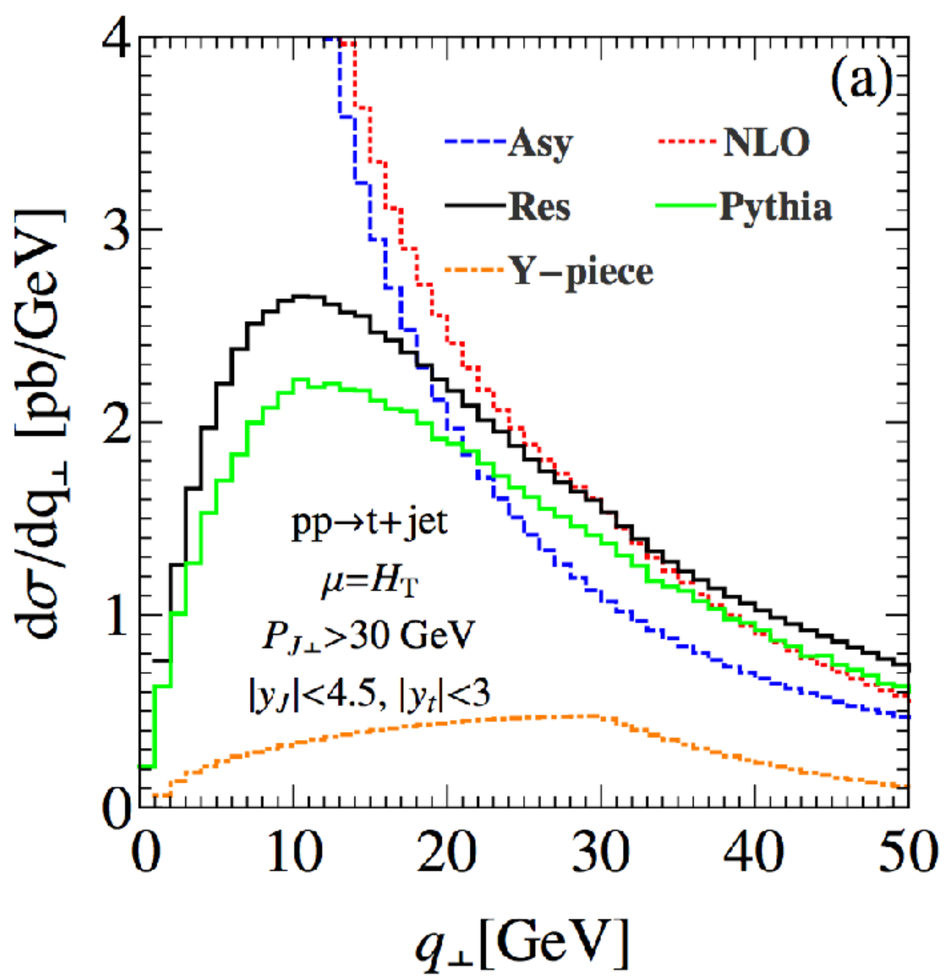
NLO QCD prod. + decay:
Q.H. Cao, Schwienhorst, Benitez, Brock, C.P. Yuan, hep-ph/0504230
NNLO QCD production only:
Brucherseifer, Caola, Melnikov, 1404.7116
NNLO QCD prod. + decay:
Berger, J. Gao, C.P. Yuan, HXZ, 1606.08463
Berger, J. Gao, HXZ, 1708.09405

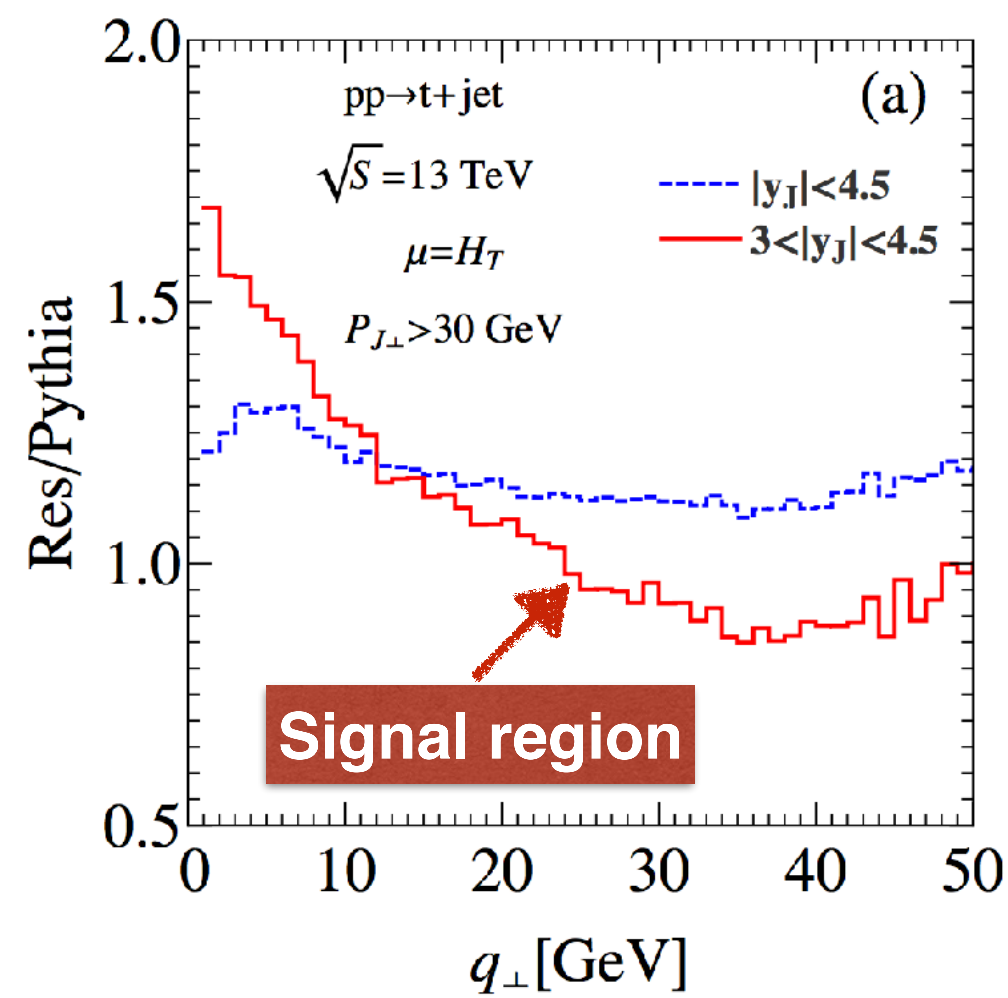
FIRST NNLO PROD. + DECAY CALCULATION FOR TOP !

Top + jet pT distribution

- The total transverse momentum of **top+jet** in single top is sensitive to ISR and FSR
- Resummation prediction can be used to **calibrate Monte-Carlo generator**
- **Substantial difference** with Pythia in the signal region ($3<|y_J|<4.5$)
- Must be careful when using event generator to calculate IR sensitive observable



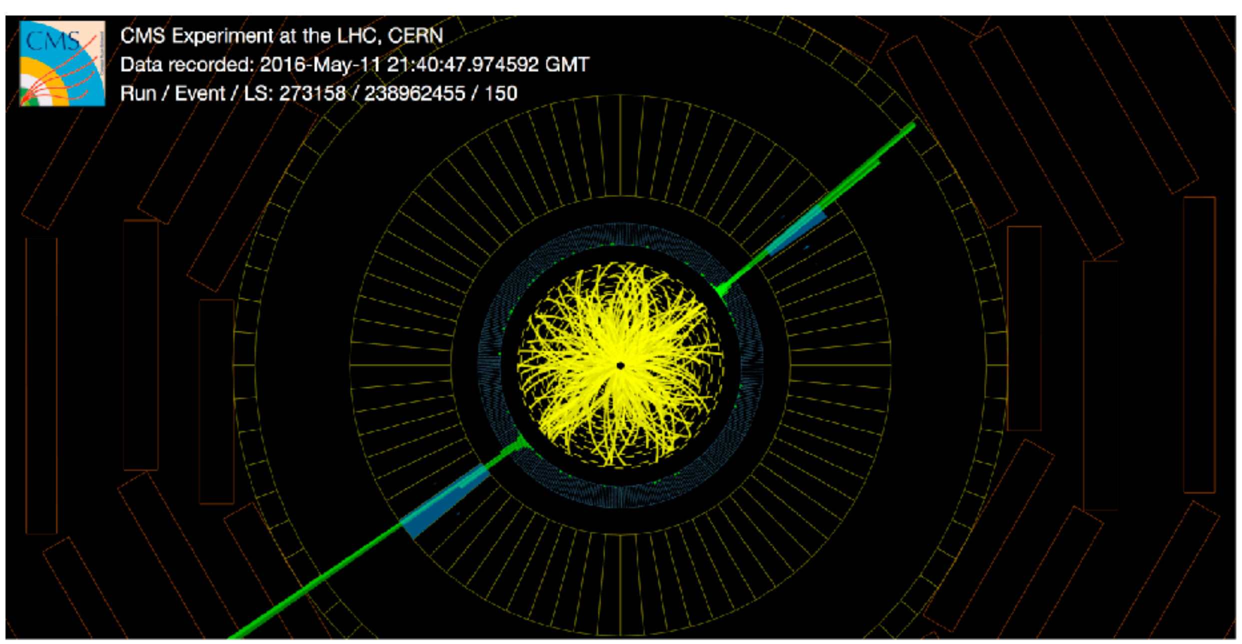




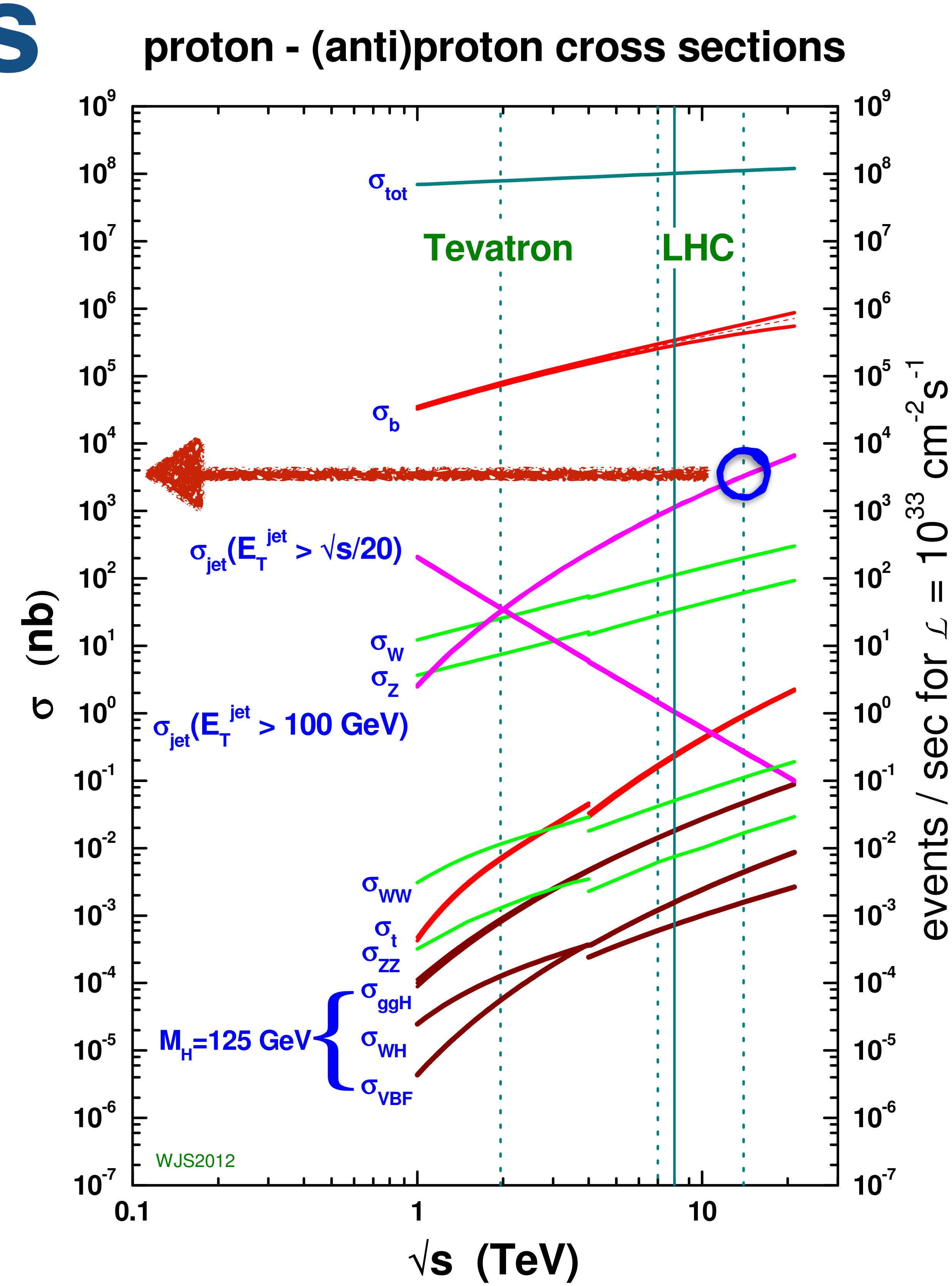
Q.H. Cao, P. Sun, B. Yan, C.P. Yuan, F. Yuan, 1801.09656

Jets

- **Largest** Xsec in hard processes
- Important signal/background for new physics
- Precision α_s extraction
- Sensitive to gluon PDF at large x
- LHC cover **large kinematical range** in p_T: pressure test for pQCD

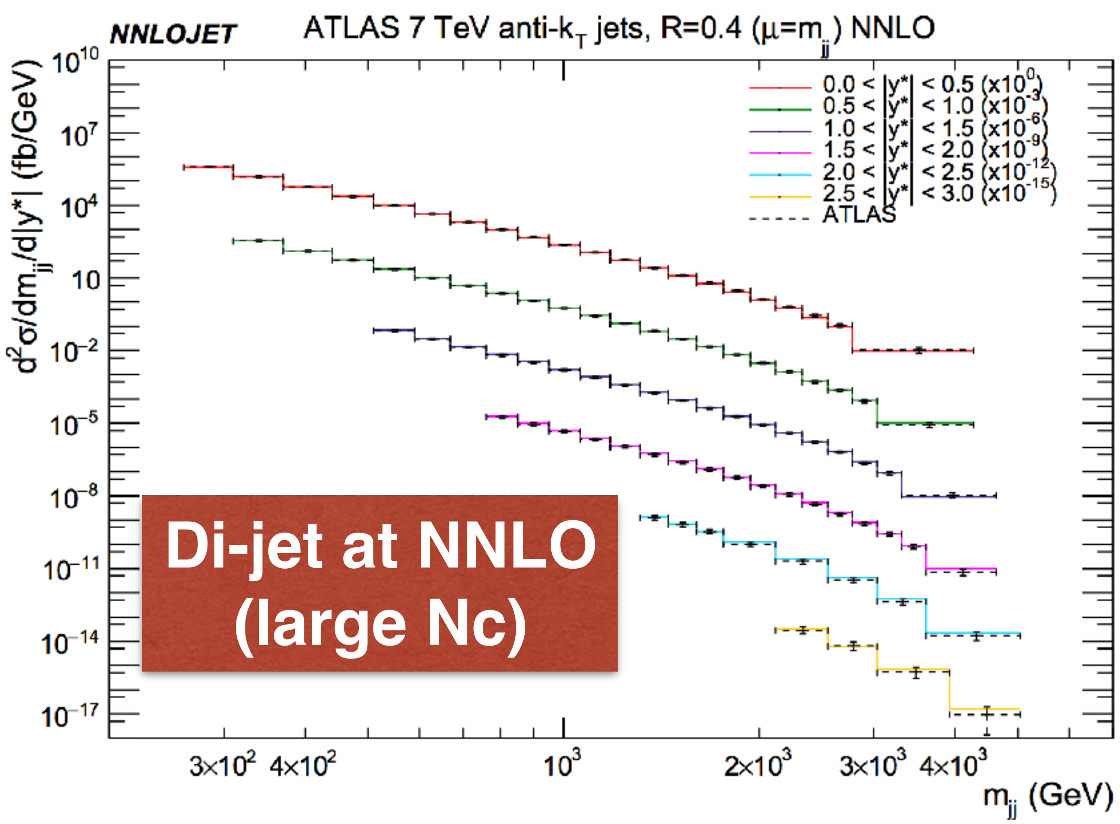


$$M_{JJ} = 7.7 \text{ TeV}$$



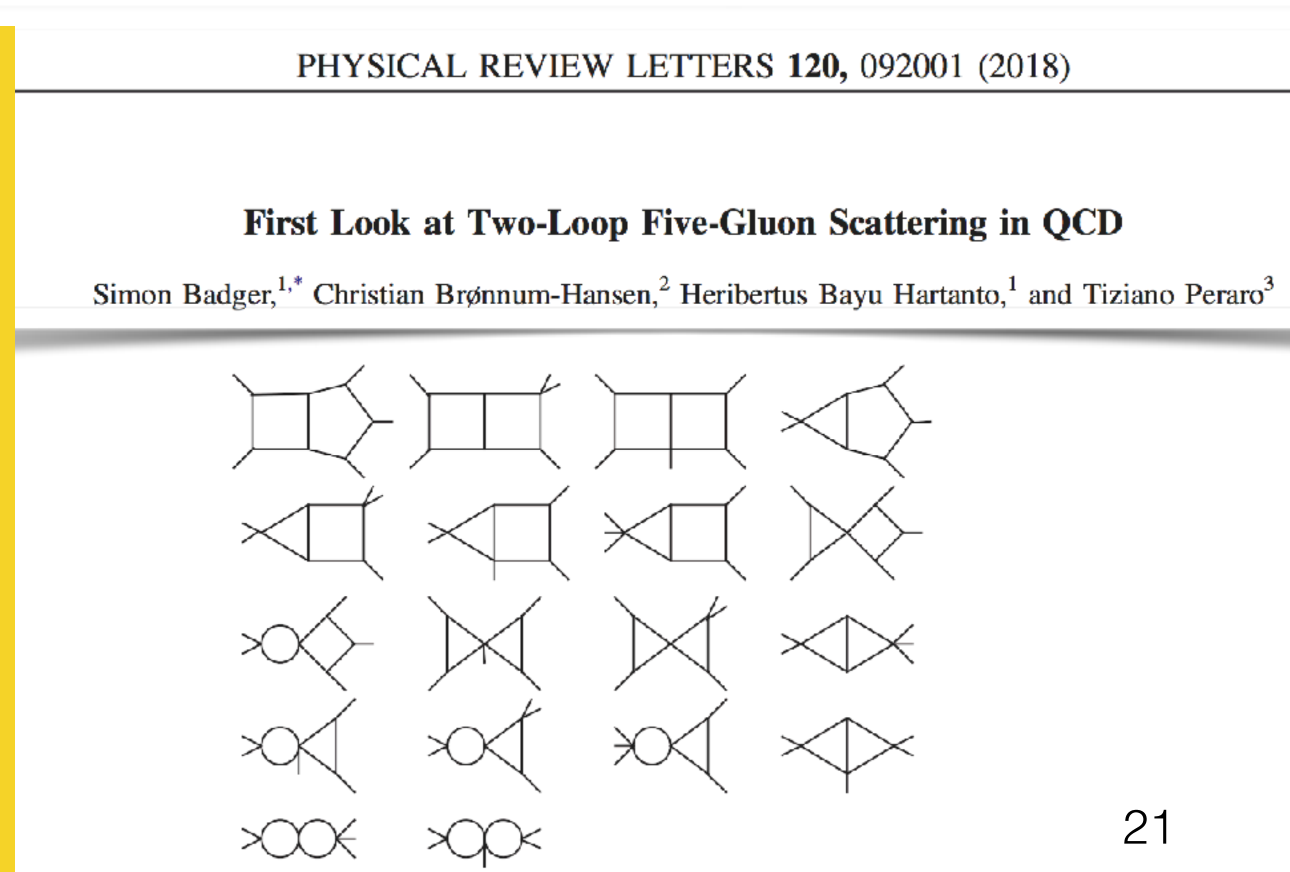
W. J. Stirling

Jet production



- Data span over **22 order of magnitude**
- The theoretical efforts towards NNLO results also span **over decades**
  - Two-loop virtual amplitudes: Smirnov, 1999; Tausk, 1999; Glover, et al, 2001-2003; Bern et al, 2002-2003
  - Infrared subtraction: Gehrmann-De Ridder, 2005-2013
  - Currently only leading color NNLO corrections available: Currie, Glover, Pires, 1611.01460
  - Phenomenology: Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires, 1705.10271

- Towards **three-jet production** at NNLO: heroic efforts of many
- Generalized unitarity: Bern, Britto, Cachazo, Dixon, B. Feng, Kosower, Ita, …
- integrand reduction: Badger, Frellesvig, Mastrolia, Ossola, Papadopoulos, Pittau, Peraro, Y. Zhang ……
- two-loop five-point planar integrals: Gehrmann, Henn, Lo Presti, Papadopoulos, Tommasini, Wever, …
- Two-loop planar amplitudes: Abreu, Cordero, Badger, Boels, Brønnum-Hansen, Hartanto, H. Luo, Ita, Jaquier, Page, Peraro, M. Zeng, Y. Zhang, ……
- And many others


PHYSICAL REVIEW LETTERS **120,** 092001 (2018)

First Look at Two-Loop Five-Gluon Scattering in QCD

Simon Badger,[1,*] Christian Brønnum-Hansen,[2] Heribertus Bayu Hartanto,[1] and Tiziano Peraro[3]

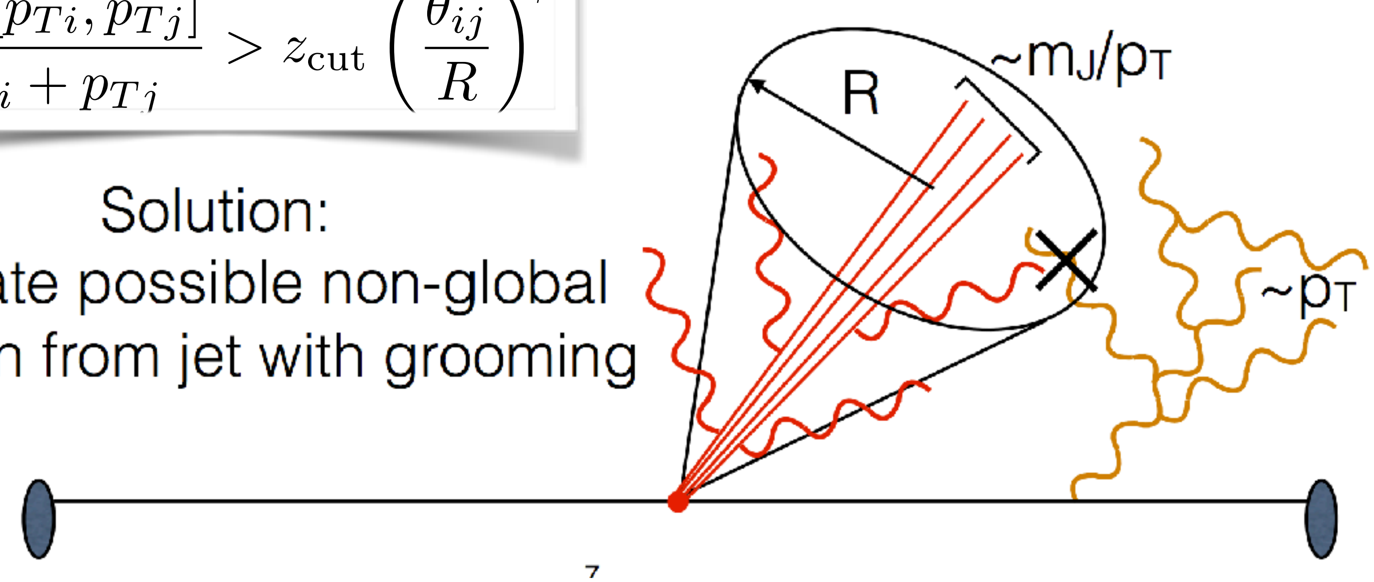
Jet substructure at the LHC

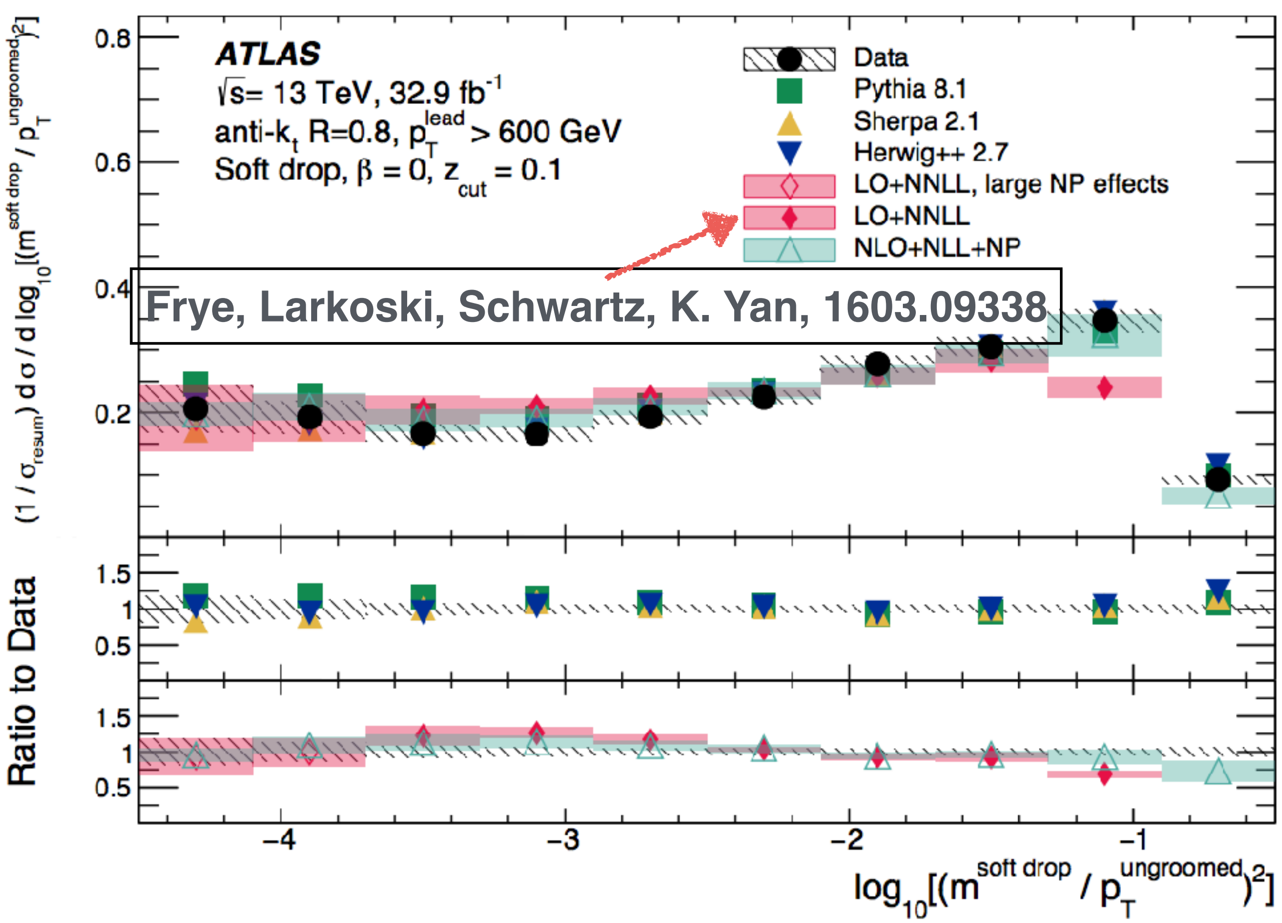
- **Jet mass**: best studied jet substructure observable. Useful for **boosted particle tagging**
- Contamination by soft radiations out side the jet
- Jet Grooming: entering the precision era

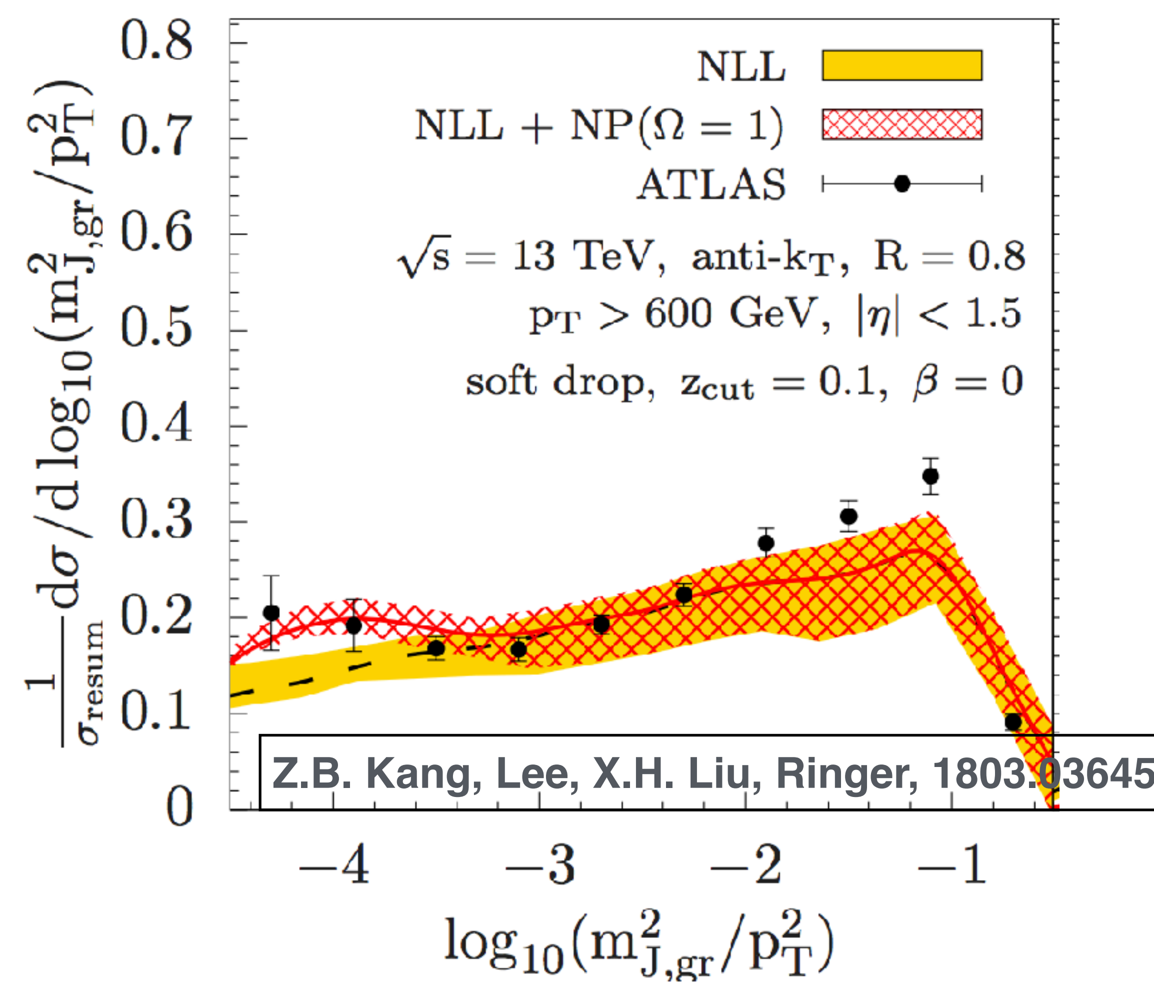
$$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti}+p_{Tj}} > z_{\text{cut}} \left(\frac{\theta_{ij}}{R}\right)^{\beta}$$

From Larkoski in LHCP 2018

Solution:
eliminate possible non-global radiation from jet with grooming

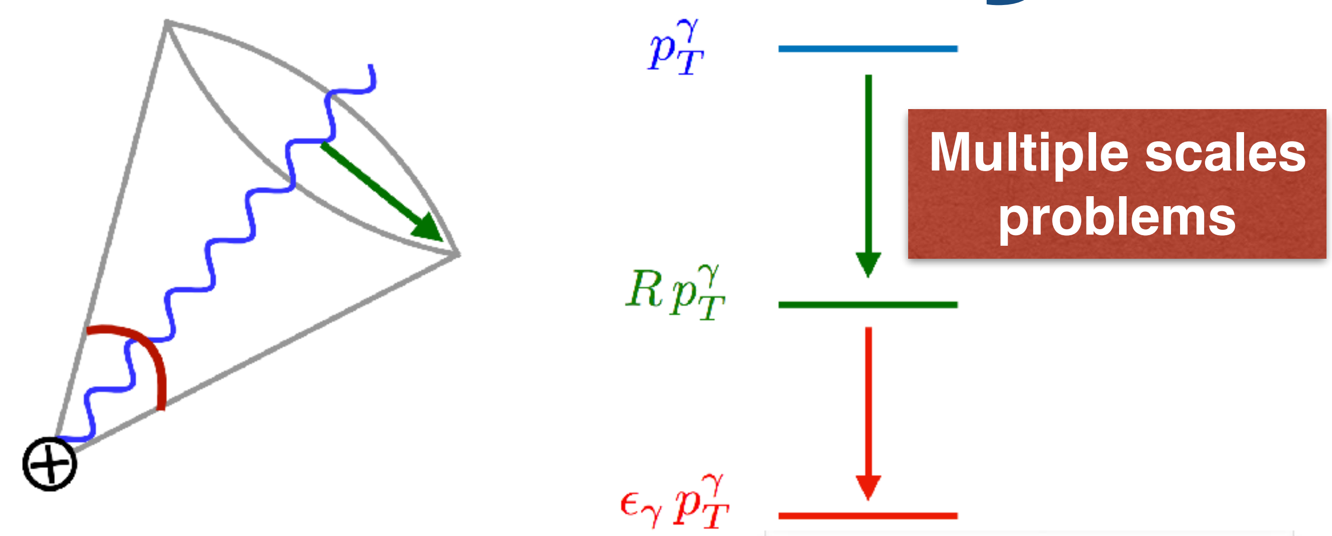






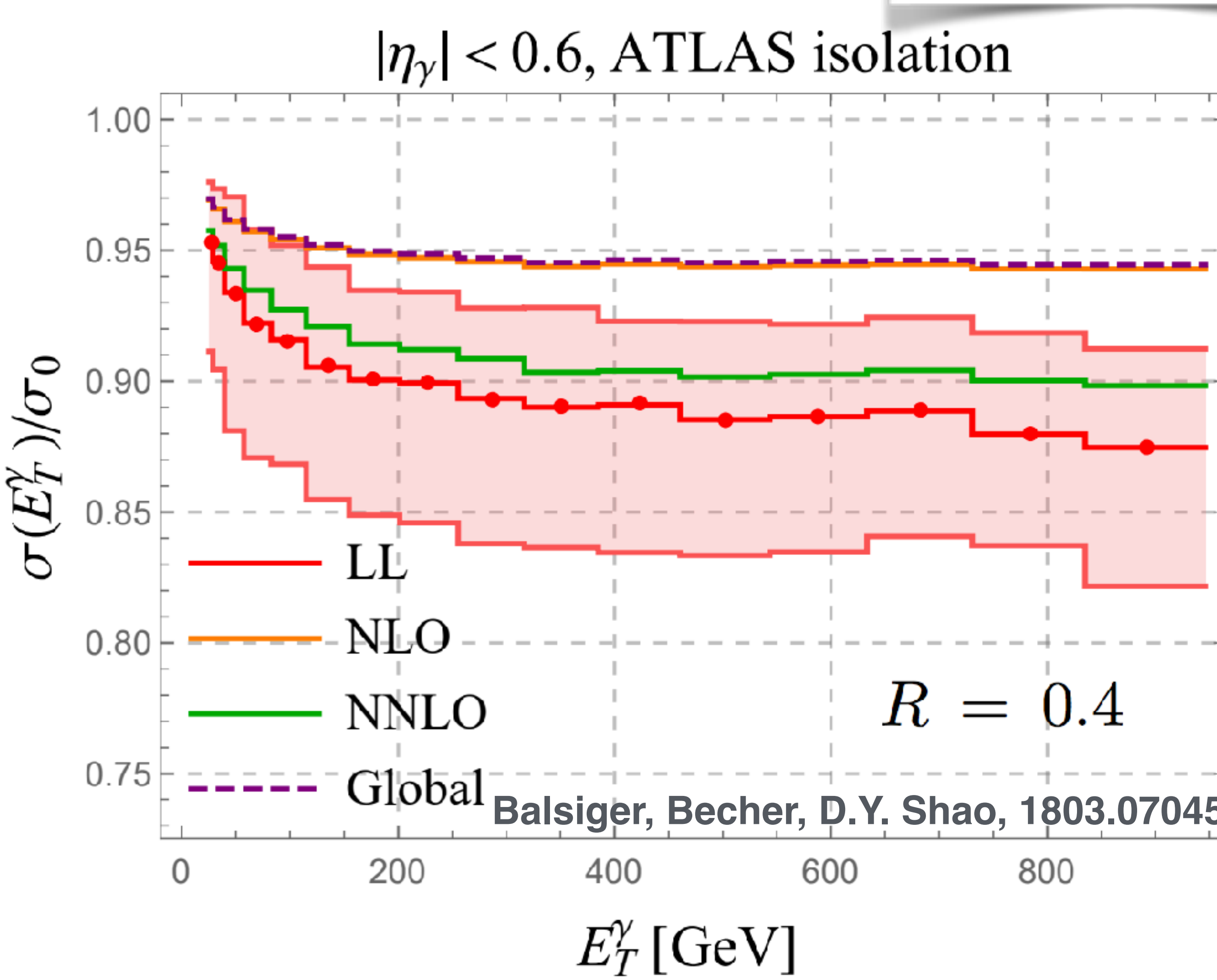
Jet vetos and Non-Global Logs

- Unlike new physics search, in precision QCD quite often experimentalists are **well ahead of theorists**
- Experiments use isolation criteria to define **isolated photons** $\sum_{\text{had}\in\mathcal{C}(R)} E_T^{\text{had}} \leq \epsilon_\gamma E_\gamma^T$
- **Important in H→γγ measurements**
- When R and ϵ_γ small, large logarithms (**Non-global logarithms**)
- LL resummation by solving **infinite dimension** evolution equation by Monte-Carlo method



$R^2 \times \alpha_s^n \ln^n \epsilon_\gamma \ln^{n-1} R$

See D.Y. Shao's talk

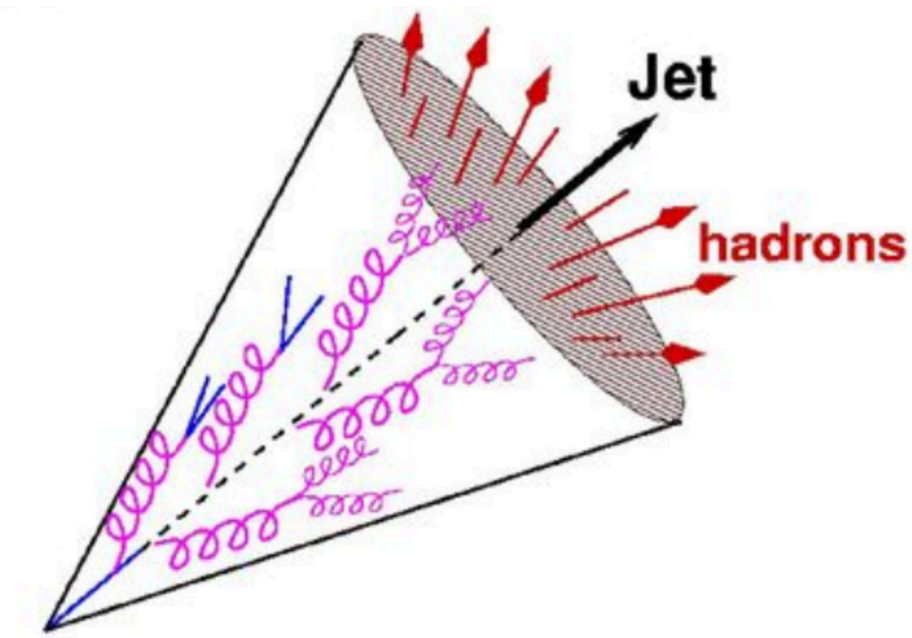


Balsiger, Becher, D.Y. Shao, 1803.07045

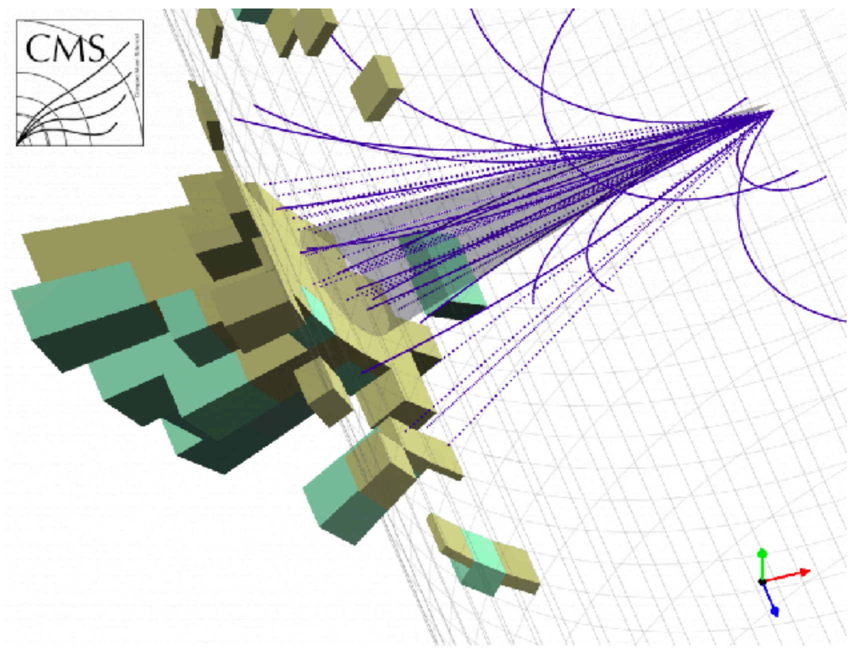
12%!

Detailed look into “jets”

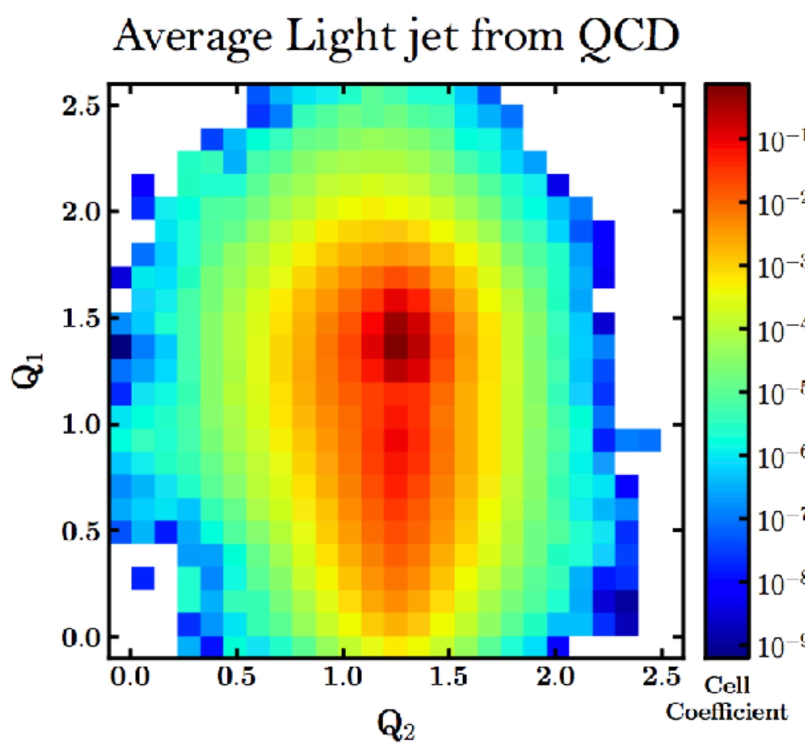
- **Huge amount of data** sample will be available
  - LHC O(10^{13}) jet with pT > 200GeV
  - for CEPC at 250 GeV: ~ 1 di-jet event per second



Feynman diagram



event display



energy deposition

- Current paradigm uses jet algorithm to define jet
- Example: the sequential clustering algorithm

> As usual, one introduces distances d_{ij} between entities (particles, pseudojets) i and j and d_{iB} between entity i and the beam (B). The (inclusive) clustering proceeds by identifying the smallest of the distances and if it is a d_{ij} recombining entities i and j, while if it is d_{iB} calling i a jet and removing it from the list of entities. The distances are recalculated and the procedure repeated until no entities are left.
>
> **Cacciari, Salam, 0802.1189**

- While jet algorithm is extremely useful in practice, it obscure the connection between physical observable and fundamental objects in quantum field theory

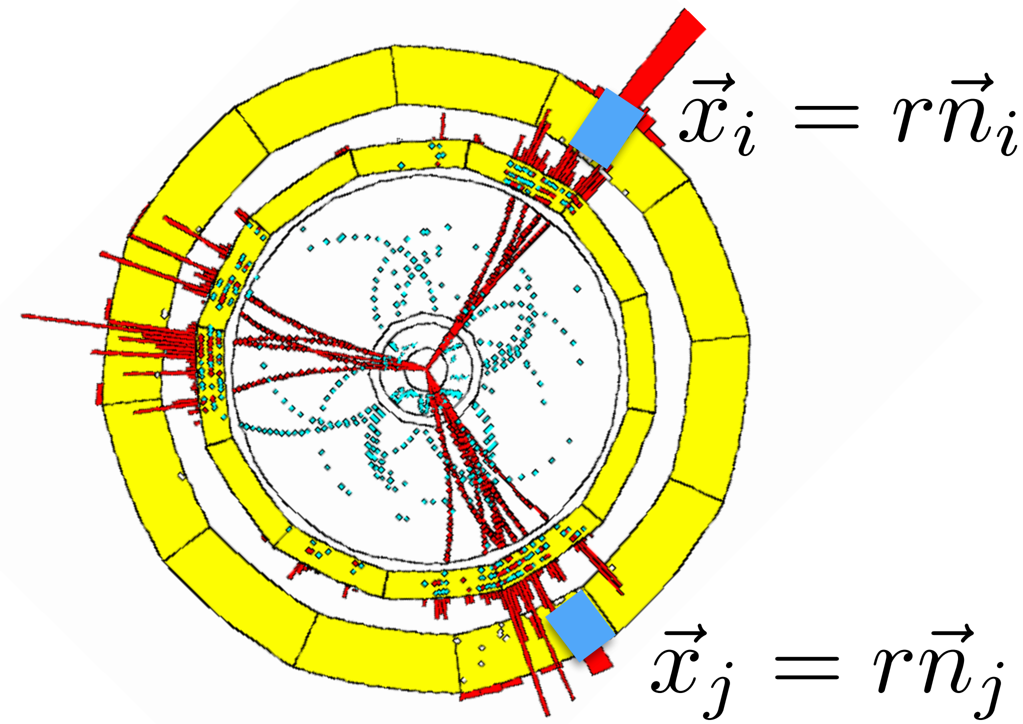
Is there a physical observable that measures the jetty nature of QCD, while admits simple field theory interpretation?

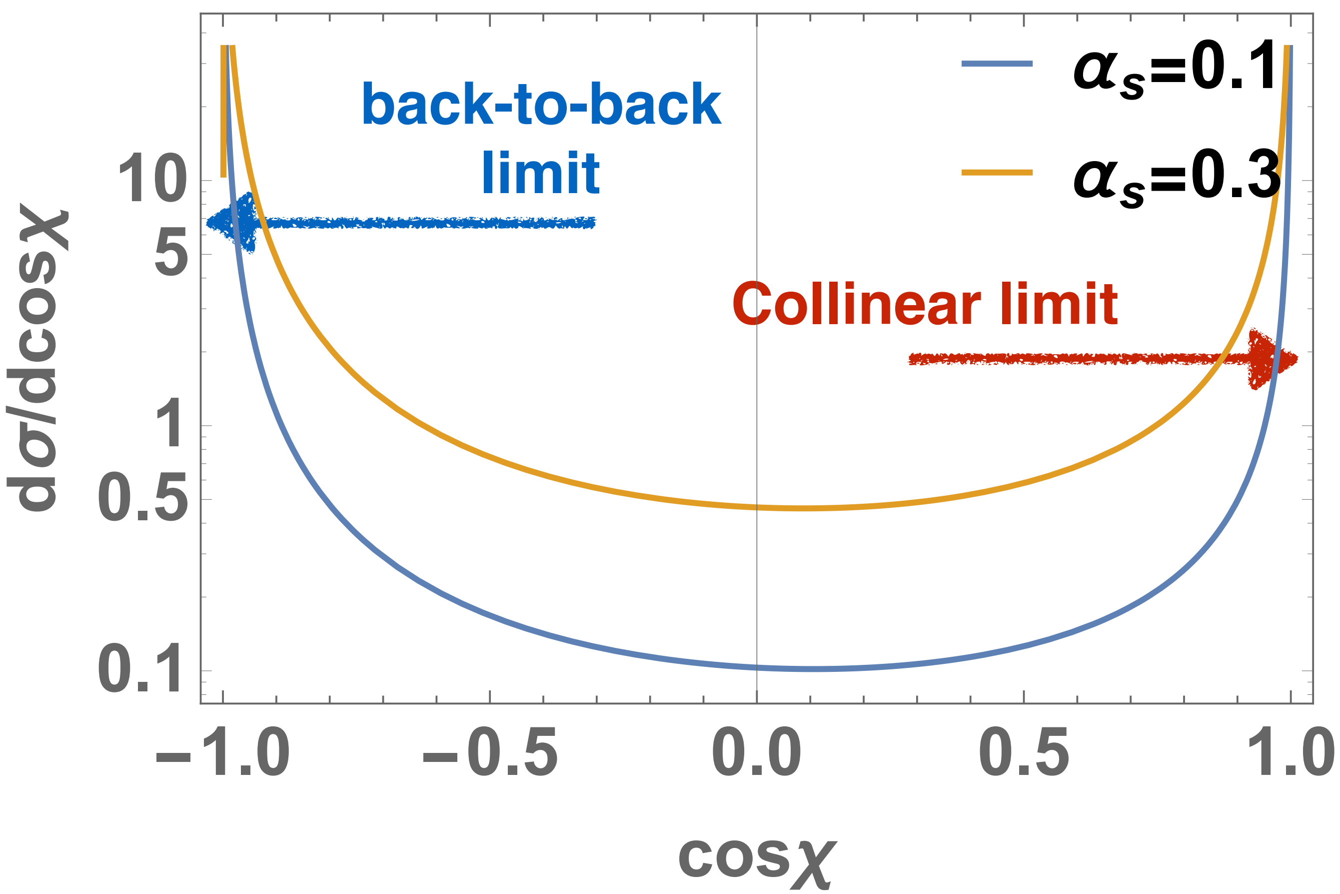
Energy-Energy Correlation (EEC)

- Energy correlation of a pair of detector calorimeter at fixed angle χ, sum over all pairs

Basham, Brown, Ellis, Love, 1978

$$\frac{1}{\sigma}\frac{d\Sigma_{\rm EEC}(\chi)}{d\cos\chi} = \frac{1}{\Delta\chi N_{\rm events}} \sum_{N_{\rm events}} \sum_{ij} \frac{E_i E_j}{E^2}$$





- In the weak coupling limit, the di-jet nature of the event appear as **peak at the end point**
- As coupling becomes strong, the distribution is **flatten**

Field theoretic definition for EEC

- EEC defined as (light-cone) **four point correlation function**

Hofmann, Maldacena, 0803.1467
Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, 1309.0769

$$\mathrm{EEC} \sim \underbrace{\int d^4x\, e^{iqx}}_{\text{Fourier}} \underbrace{\int_0^\infty dt_1 dt_2 \lim_{r_i\to\infty} r_1^2 r_2^2}_{\text{Detector limit}} \underbrace{\langle 0|O^\dagger(x)\, T_{0\vec{n}_1}(x_1) T_{0\vec{n}_2}(x_2)\, O(0)|0\rangle_W}_{\text{Wightman correlation function}} \Big|_{x_i=(t, r\vec{n}_i)}$$

Energy-Momentum tensor

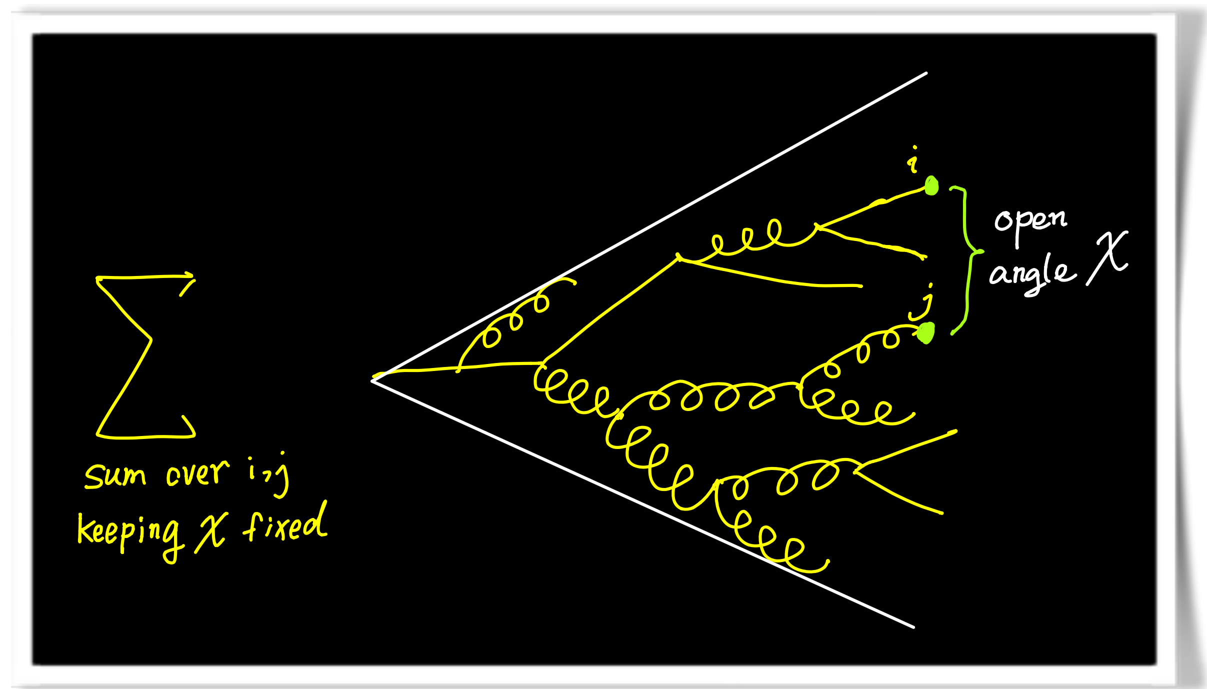
Operator that create QCD excitation

$$O(x) = \bar{\psi}\gamma^\mu\psi(x)$$

- In the collinear limit $\chi\to 0$, EEC measures energy correlation **within a jet**
- Can be studied by light-cone OPE

$$\langle \mathcal{E}(\vec{y})\mathcal{E}(0)\rangle \sim \sum |y|^{-2+(\tau_a-2)} c_a \langle \mathcal{U}_a \cdots \rangle$$

- U_a are spin 3, twist 2 operator

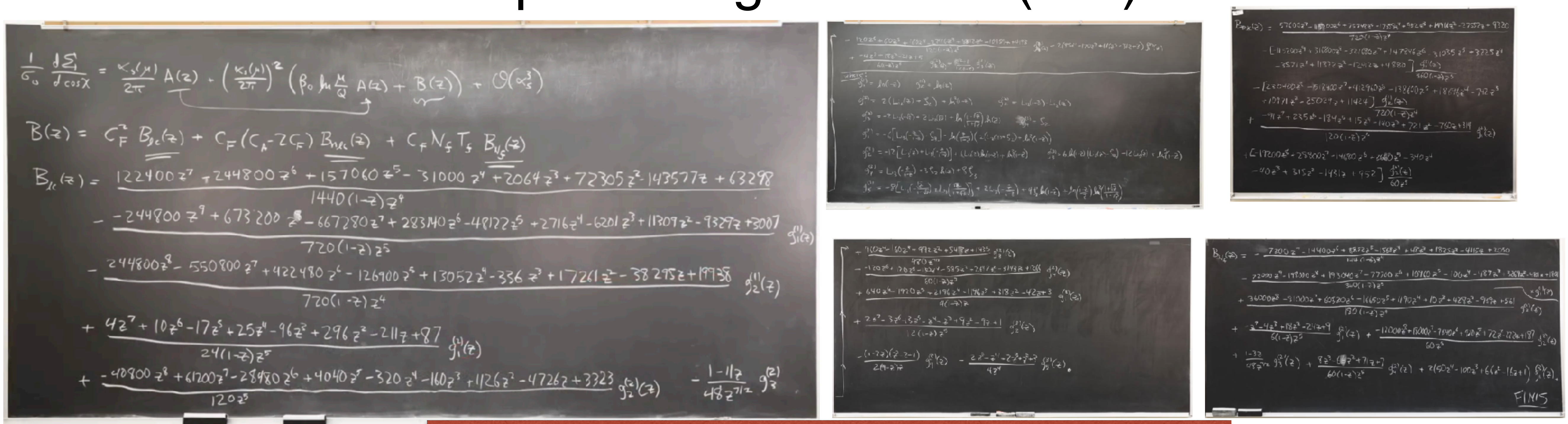


- Despite having nice field theoretic definition, the study for EEC is far from complete
    - Operator product expansion in the collinear limit
    - Non-perturbative power corrections
    - Correlation function definition for EEC and lattice calculation
    - EEC for precision α_s extraction
    - ……

Analytic NLO calculation for EEC

Dixon, M.X. Luo, Shtabovenko, T.Z. Yang, HXZ, 1801.03219

- Final result is simple enough to fit on (five) blackboards



First analytic QCD event shape distribution!

- In the collinear limit

$$\left.\frac{d\sigma}{d\chi}\right|_{\chi\to 0} = \frac{\alpha_s}{2\pi}\frac{3C_F}{4\chi} + \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{1}{\chi}\left[\left(\frac{25}{8}C_F^2 - \frac{107}{30}C_F C_A + \frac{53}{60}C_F n_f t_f\right)\ln\frac{\chi}{2}\right.$$

$$\left. + C_F^2\left(-2\zeta_3 + \frac{43}{36}\pi^2 - \frac{8263}{864}\right) + C_F C_A\left(\zeta_3 - \frac{25}{36}\pi^2 + \frac{17683}{1350}\right) - \frac{4913}{1800}C_F n_f t_f\right]$$

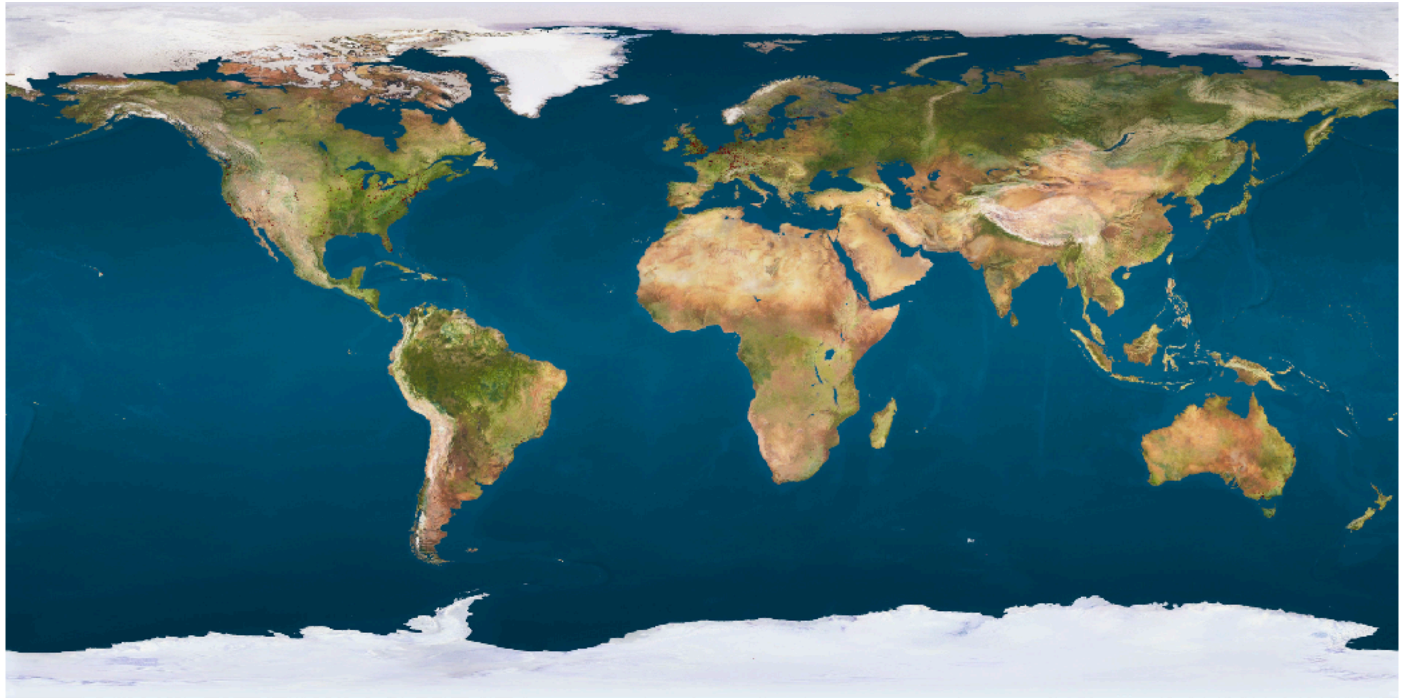
known from jet calculus

New results!

Conclusion

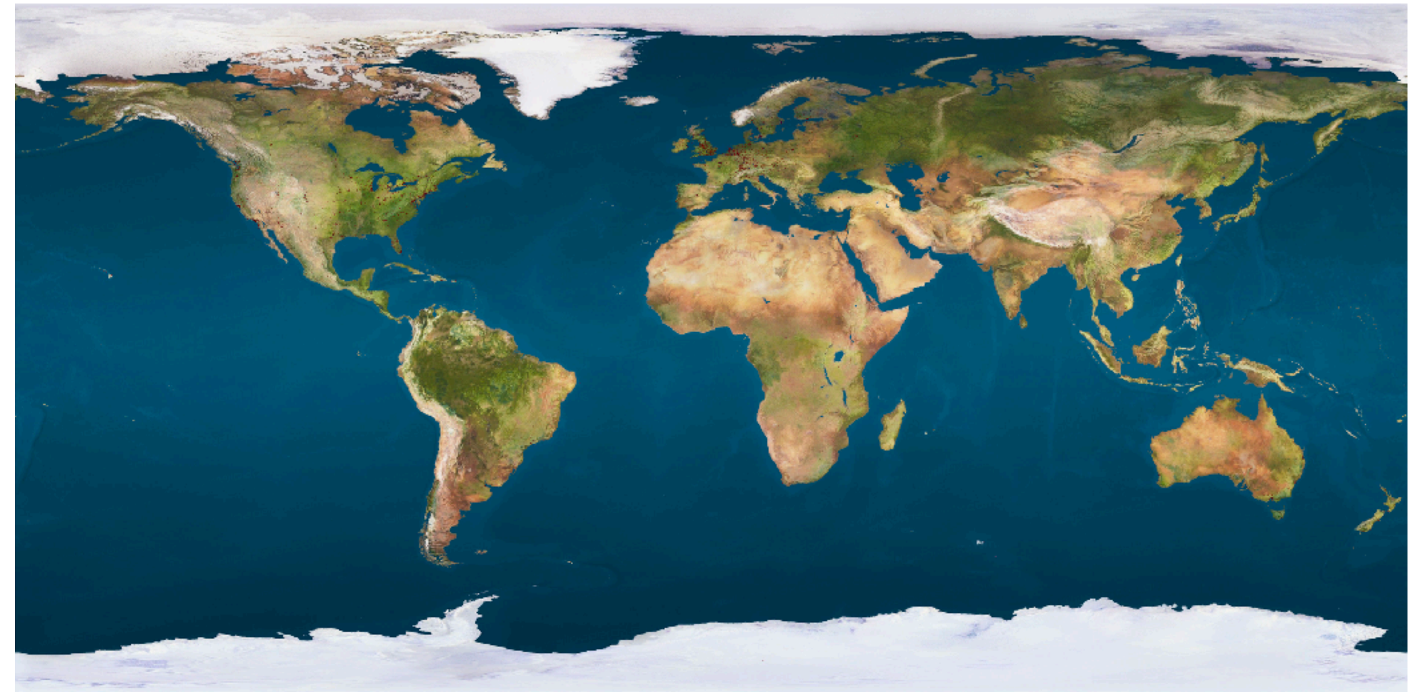
明洪武二十二年

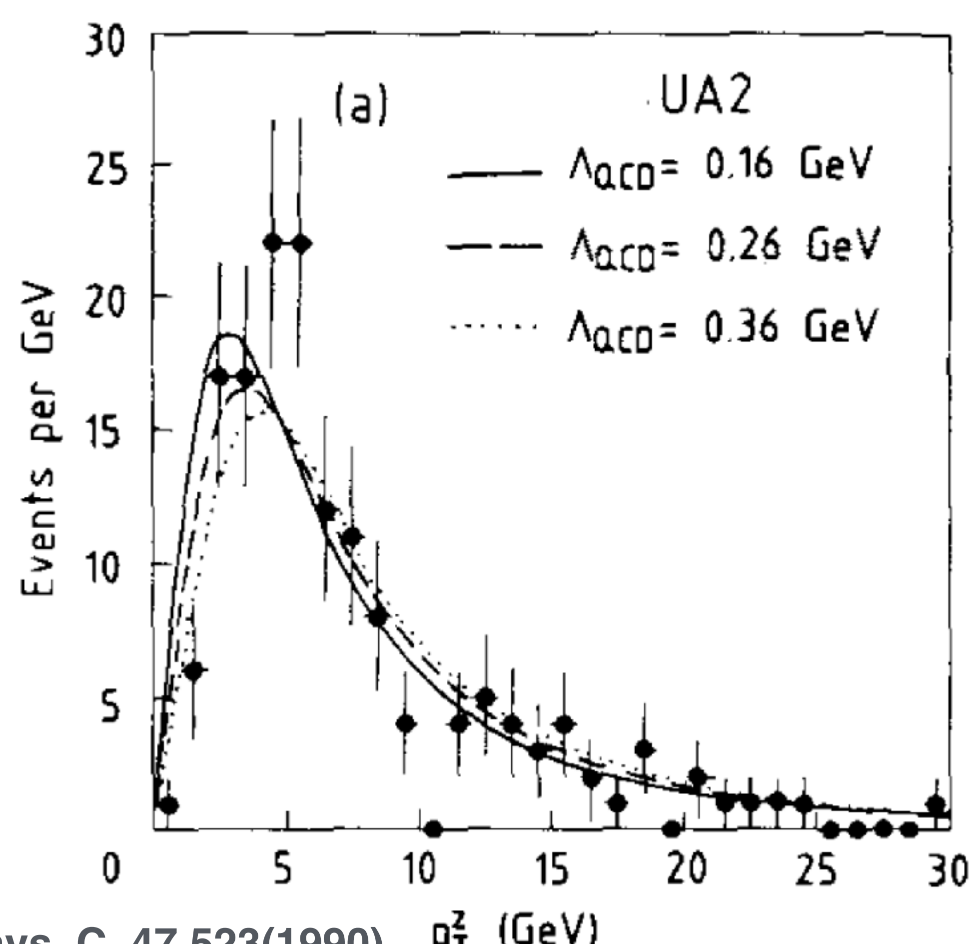
明洪武二十二年



Z. Phys. C, 47,523(1990)

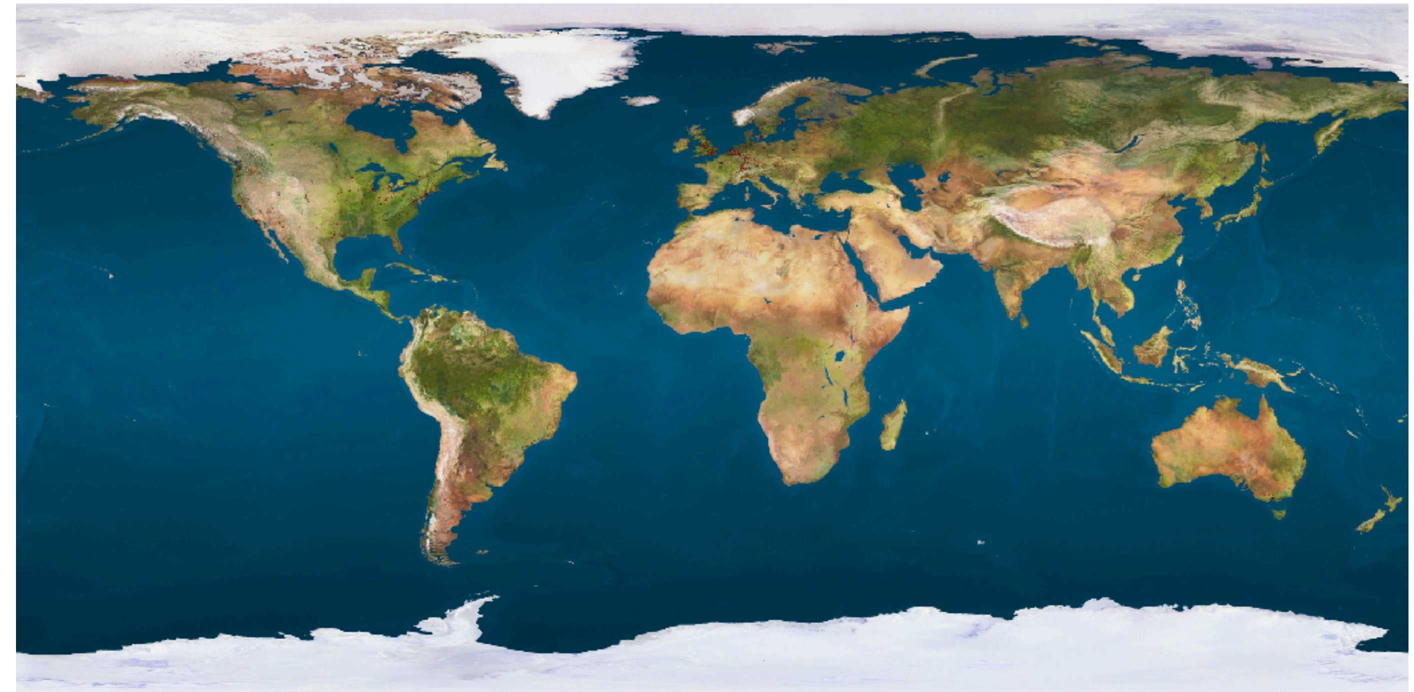
明洪武二十二年

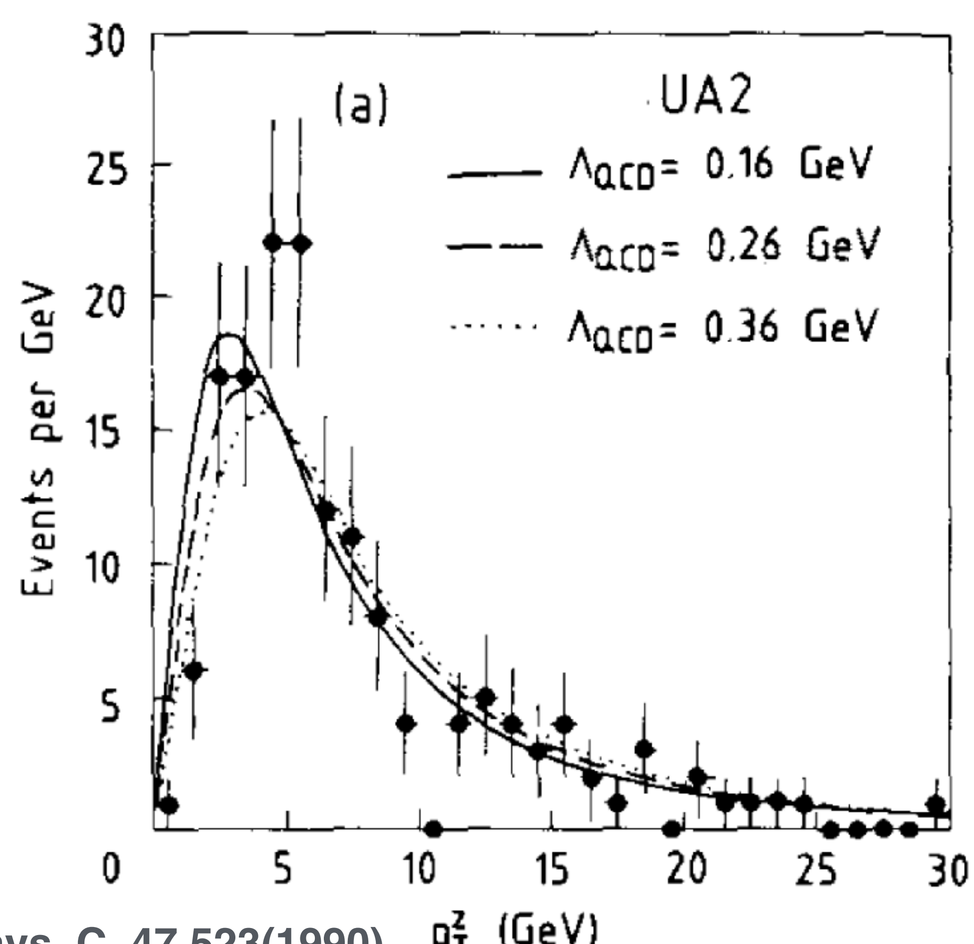




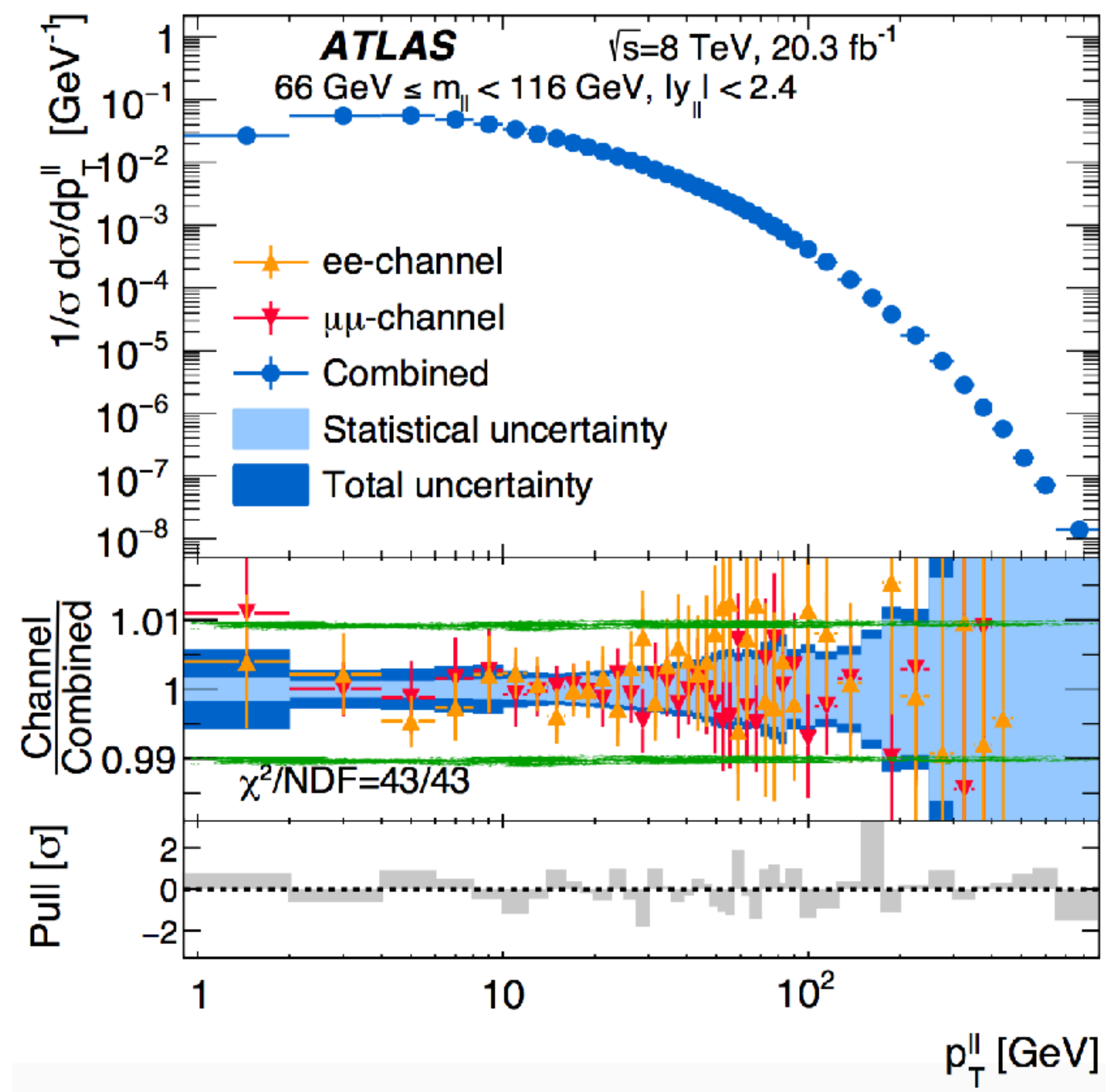
Z. Phys. C, 47,523(1990)

明洪武二十二年





Z. Phys. C, 47,523(1990)



Thank you!