Fixed Order QCD corrections

Daniel de Florian
ICAS - UNSAM
Argentina

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ICAS

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Outline

- Introduction
- NLO
- NNLO
- N^3LO
- TH Uncertainties
- Conclusions

EXP

We measure XXX and the observable is in agreement with the Standard Model predictions

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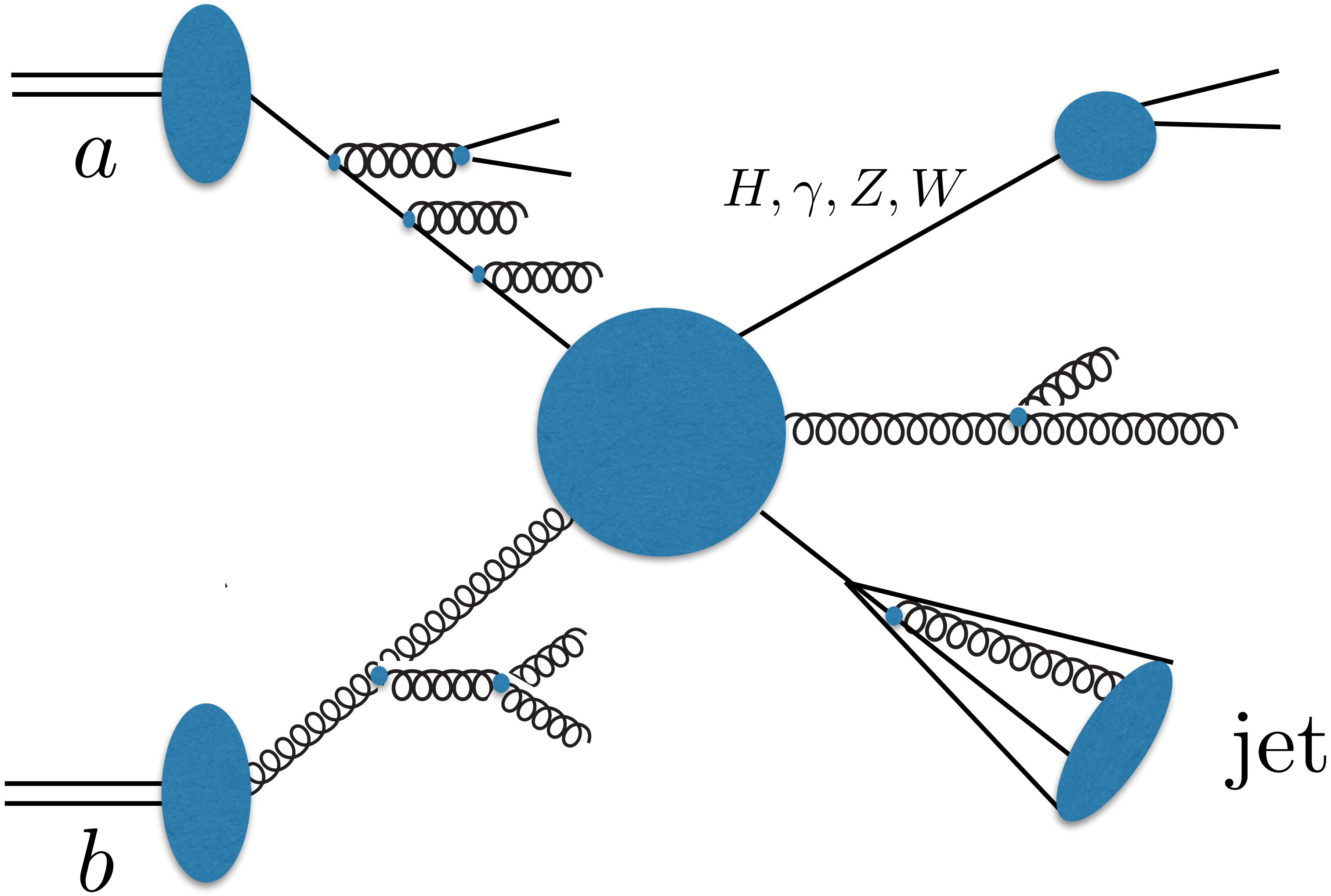
TH

We compute XXX at **$N^{i}LO$** and find a considerable reduction in scale dependence and a better description of the data

In the LHC era, QCD is everywhere!



non-perturbative parton distributions

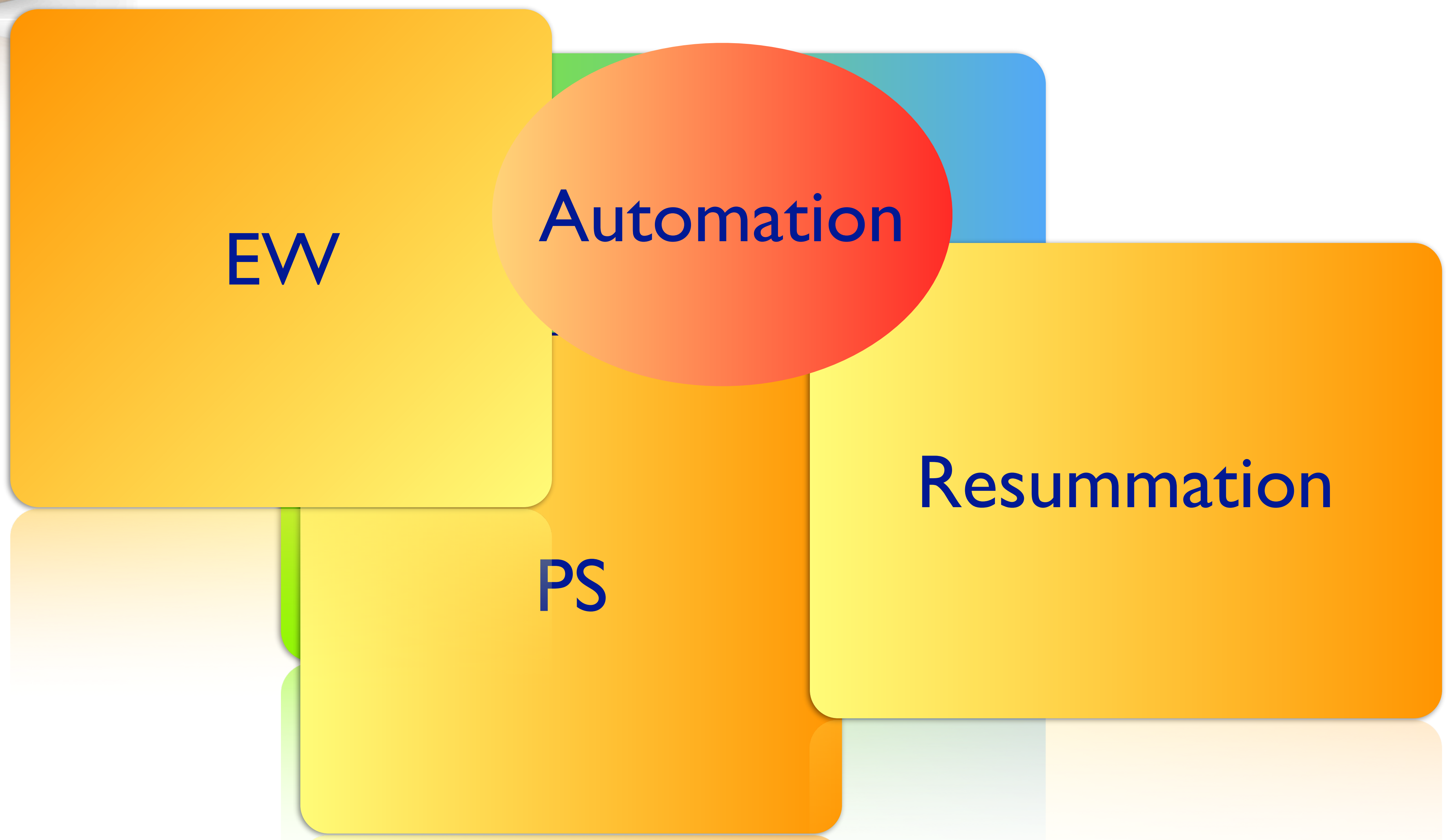
$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^m\right)$$

perturbative partonic cross-section

- Require precision for perturbative and non-perturbative contribution

The perturbative toolkit for precision at colliders

Everything starts with a fixed order calculation



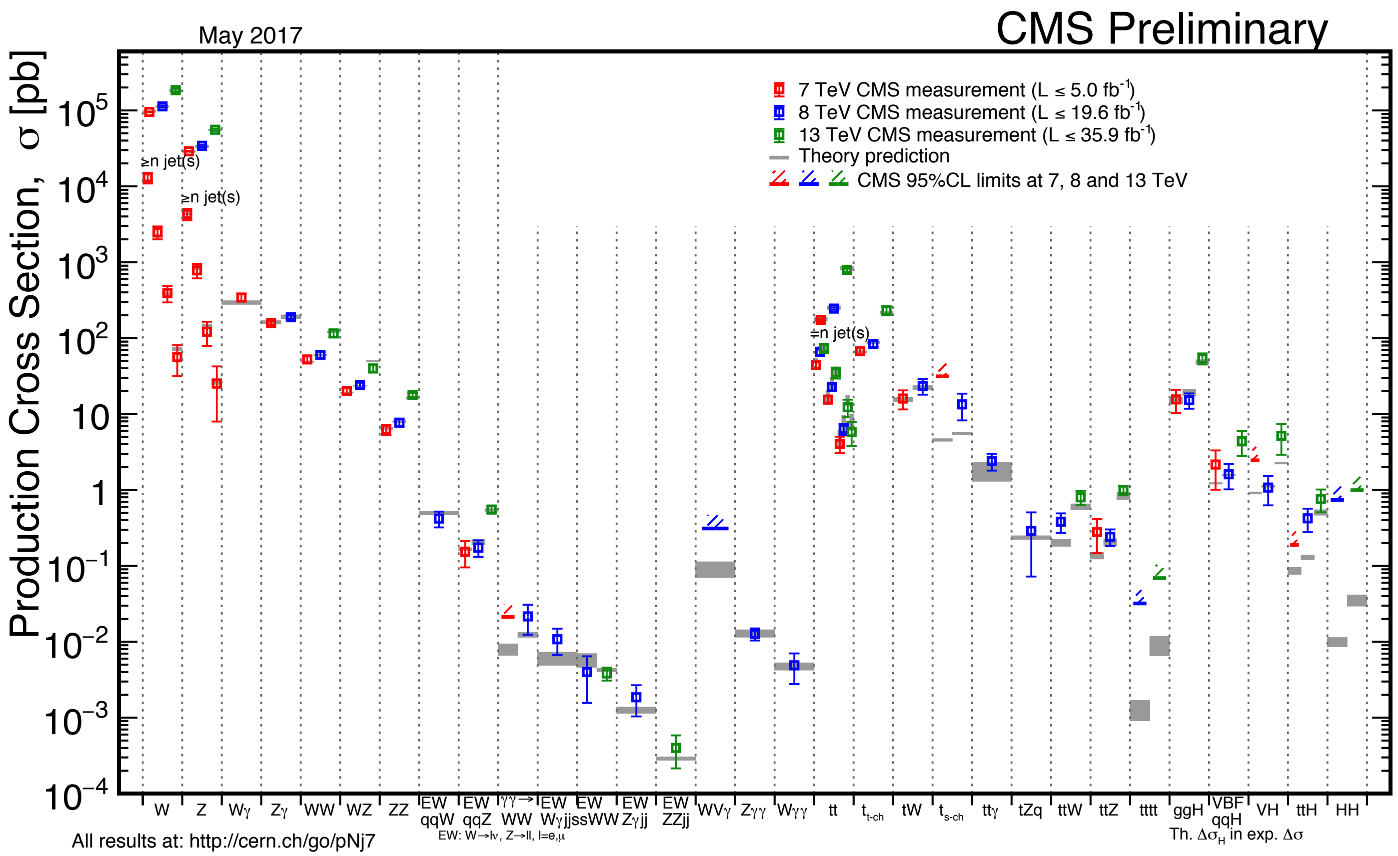
The perturbative toolkit for precision at colliders

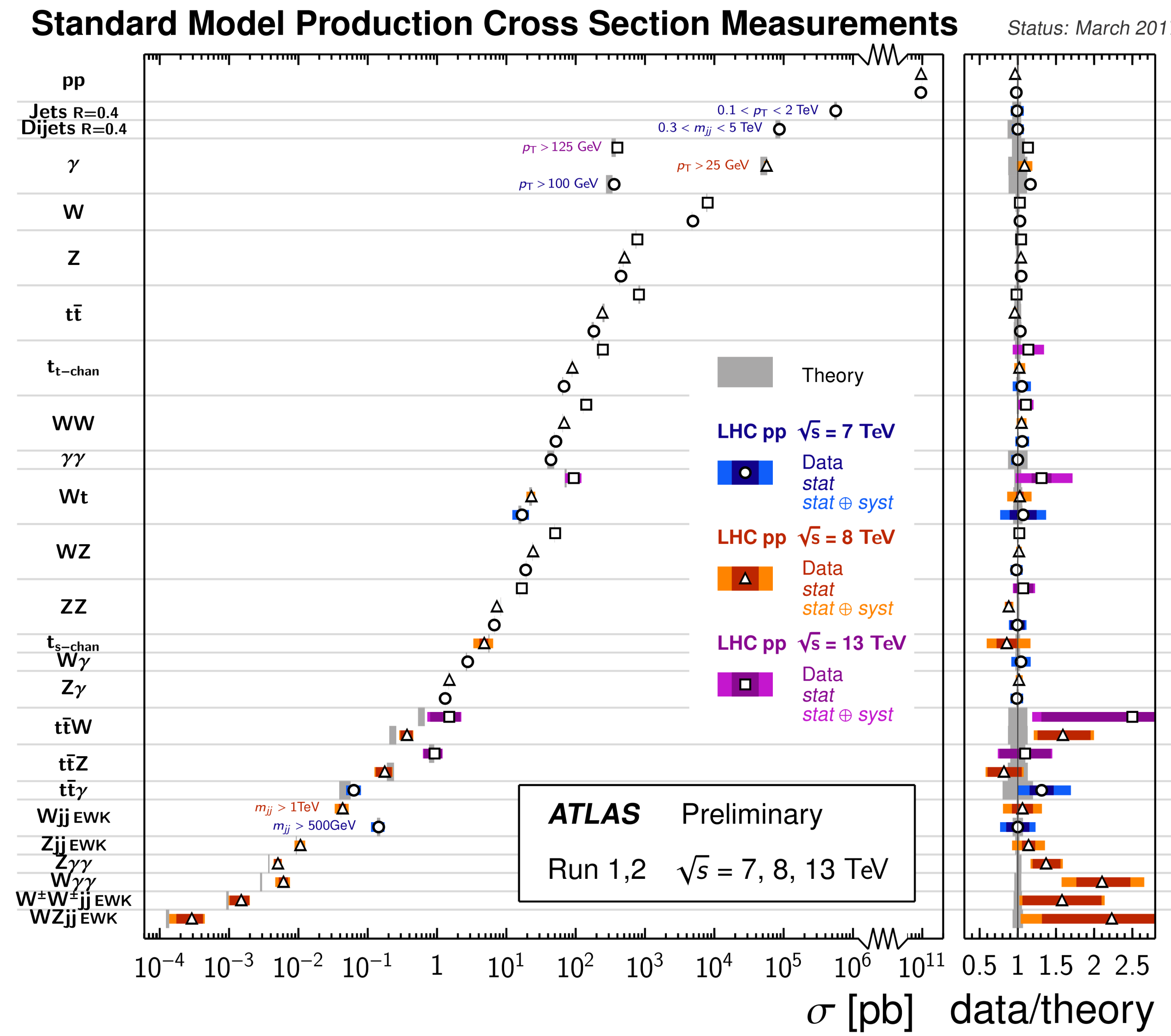
Everything starts with a fixed order calculation

- Partonic cross-section: expansion in $\alpha_s(\mu_R^2) \ll 1$

$$d\hat{\sigma} = \alpha_s^n \, d\hat{\sigma}^{(0)} + \alpha_s^{n+1} \, d\hat{\sigma}^{(1)} + \ldots$$

LHC incredibly successful at 7 , 8 & 13 TeV (Runs I and II)





Everything SM like (including Higgs)

Why higher order corrections?

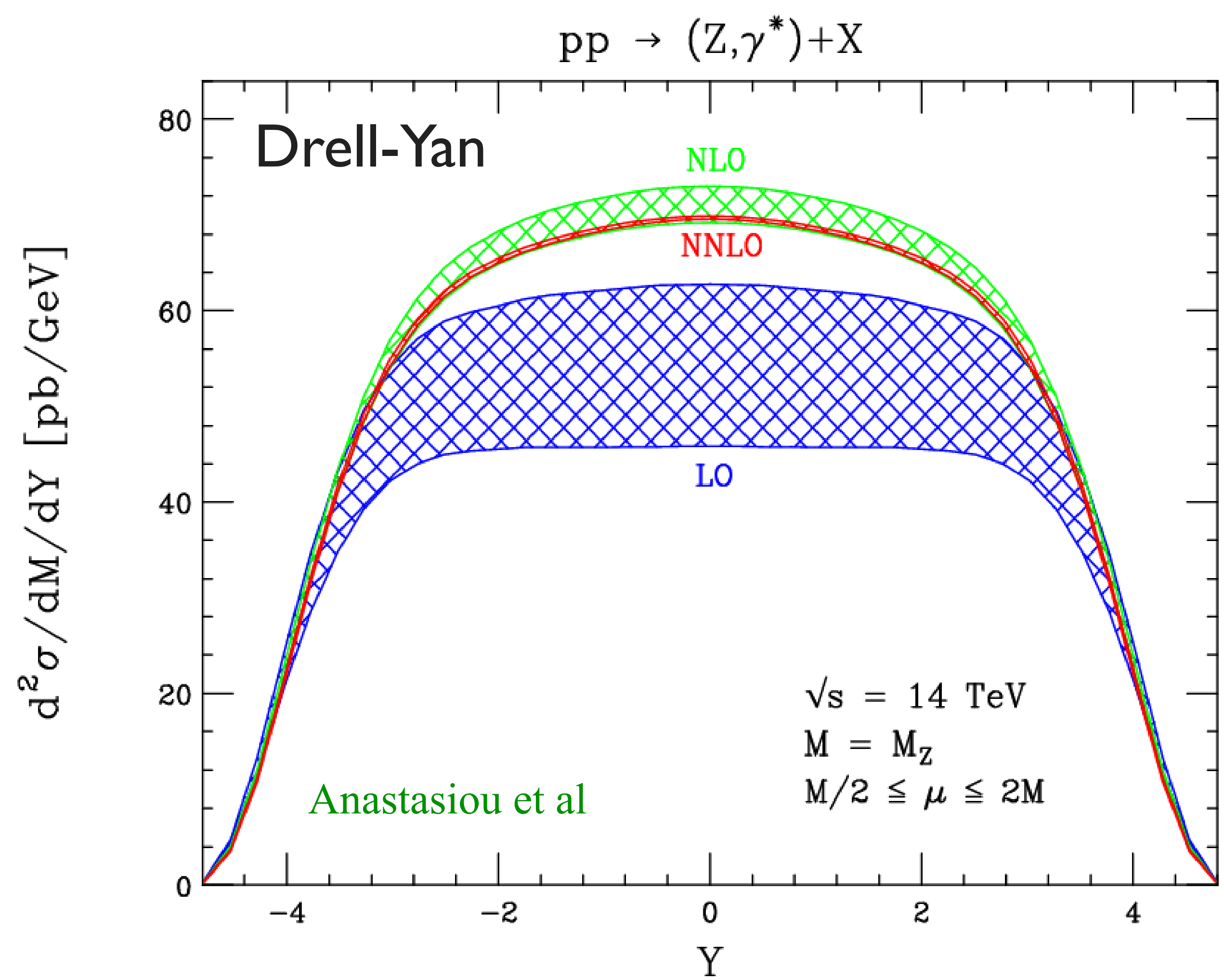
- Large Corrections : check PT $\alpha_s \sim 0.1$ → slow convergence
  shape and normalization

- Accurate Theoretical Predictions

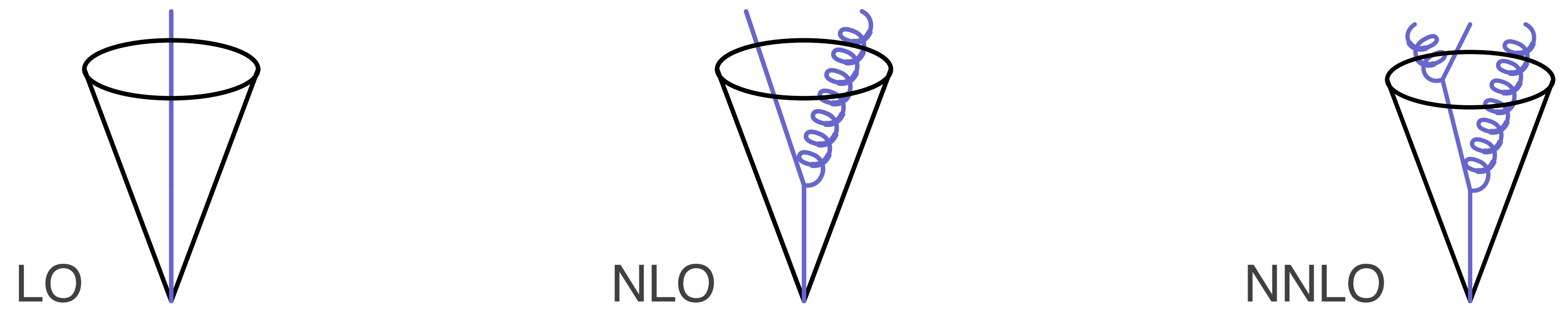
$$\sigma(p_1,p_2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1,\mu_F^2)\, f_{b/h_2}(x_2,\mu_F^2) \;\times\; \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

Scale dependence considerably reduced at higher orders

→ TH uncertainty



- Extra radiation : more partons result in better TH/EXP matching

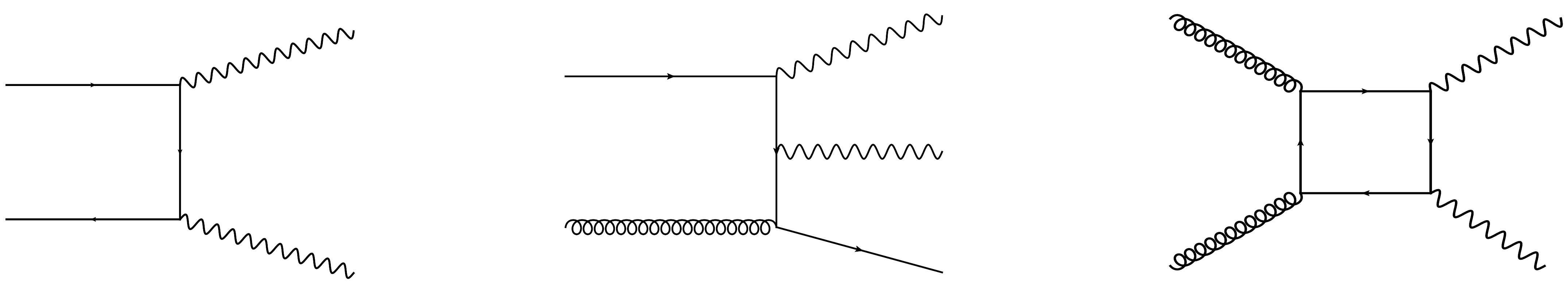


Description of jets, transverse momentum, etc

- Opening of new channels

Sometimes new channels at higher order provide large corrections due to parton luminosity (pdf, non-perturbative-pertubative interplay)

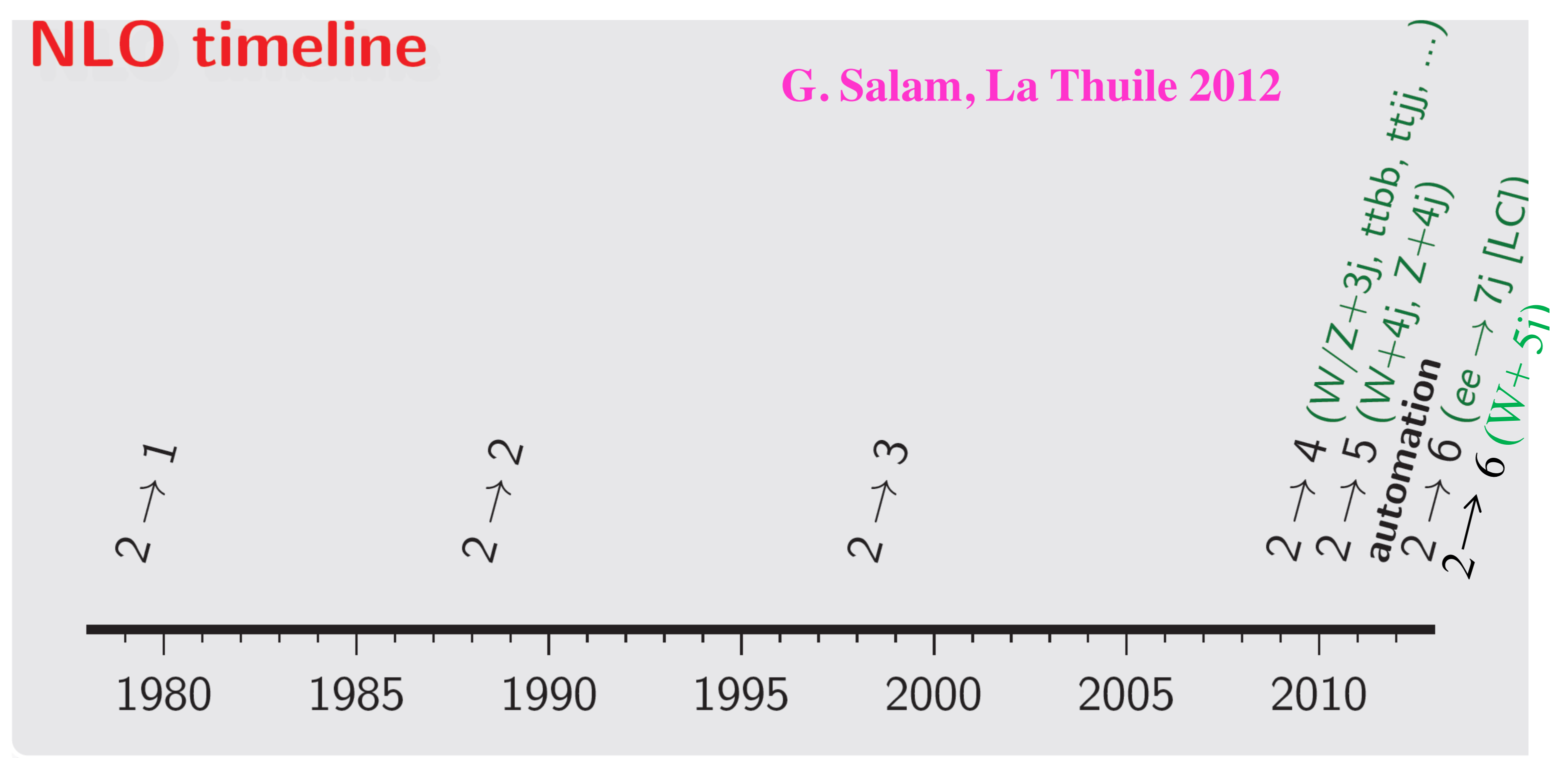
◉ Diboson production



$\mathcal{O}(\alpha_s^0)$ but $q\bar{q}$ Luminosity $\mathcal{O}(\alpha_s)$ but qg Luminosity $\mathcal{O}(\alpha_s^2)$ but gg Luminosity

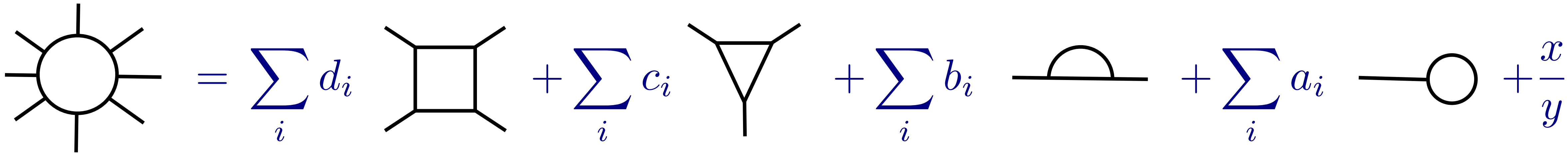
NLO

The NLO revolution



Revolution in calculation of 1-loop amplitudes

- Bottleneck was in the virtual contribution : large multiplicities



Feynmanian approach

Improvements in decomposition and reduction

Denner, Dittmaier; Pozzorini; Binoth, Guillet, Heinrich, Pilon, Schubert + many others

Unitarian approach

Use multi-particle cuts from generalized unitarity

Bern, Dixon, Dunbar, Kosower; Britto, Cachazo, Feng; Mastrolia; Forde; Badger; Ellis, Giele, Kunszt, Melnikov + many others

OPP Ossola, Papadopoulos, Pittau decomposition at the integrand level

J. Henn QCD@LHC17

- Final goal: Really automatic NLO calculations

zero cost for humans

  - Specify the process (input card)
  - Input parameters
  - Define final cuts

- Automatic NLO calculation "conceptually" solved
  - in a few years a number of codes

HELAC-NLO, Rocket, BlackHat+SHERPA, GoSam+SHERPA/MADGRAPH, NJet+SHERPA, Madgraph5-aMC@NLO, RECOLA, OpenLoops+SHERPA

  - compete on precision, flexibility, speed, stability, ...
  - many features : uncertainties, Parton shower, …

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How easy is NLO these days?

```
import model loop_sm-no_b_mass
define p = g u u~ c c~ d d~ s s~ b b~
define j = g u u~ c c~ d d~ s s~ b b~
generate p p > t~ t j [QCD]
output my_pp_ttj
calculate_xs NLO
```

pp⟶tt+j

e.g. MadGraph5_aMC@NLO v2.1.1
[Alwall et al. 1405.0301]

generation time ~ 5 mins
total cross section ~ 30 mins (20 cores)

Not everything solved at NLO yet… but constant progress

- EW corrections

A.Vicini QCD@LHC17

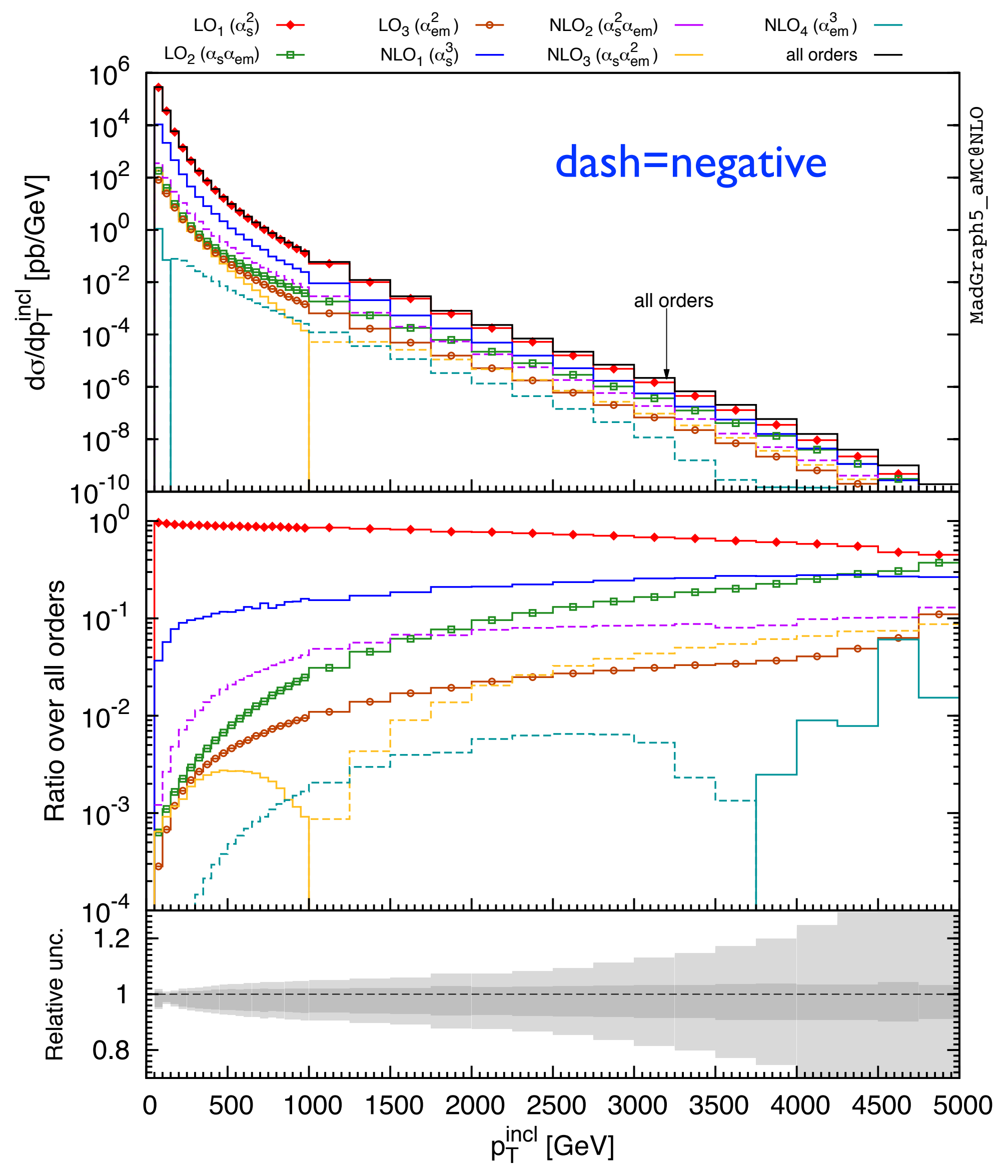
MadGraph5_aMC@NLO

- QCD dominant (except very large pT)
- Coupling hierarchy ~ respected
- Large cancellations in EW contributions
- No HB radiation

Sherpa+Recola B. Biedermann QCD@LHC17

Dijet production

Frederix, Frixione, Hirschi, Pagani, Shao, Zaro (2017)



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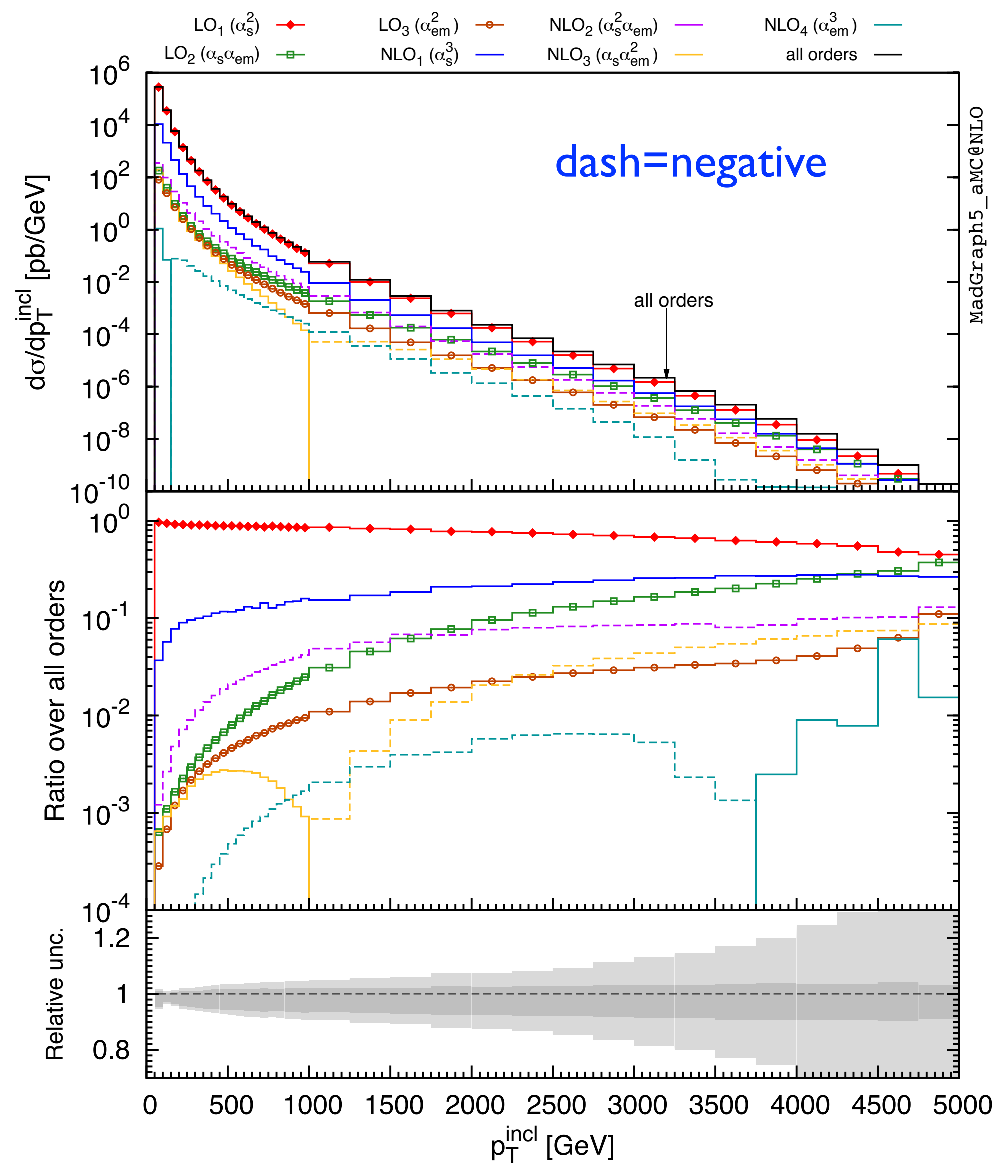


Off-shell effects

e.g., ttj Bevilaqua et al (2015)

- Large corrections in kinematical edges

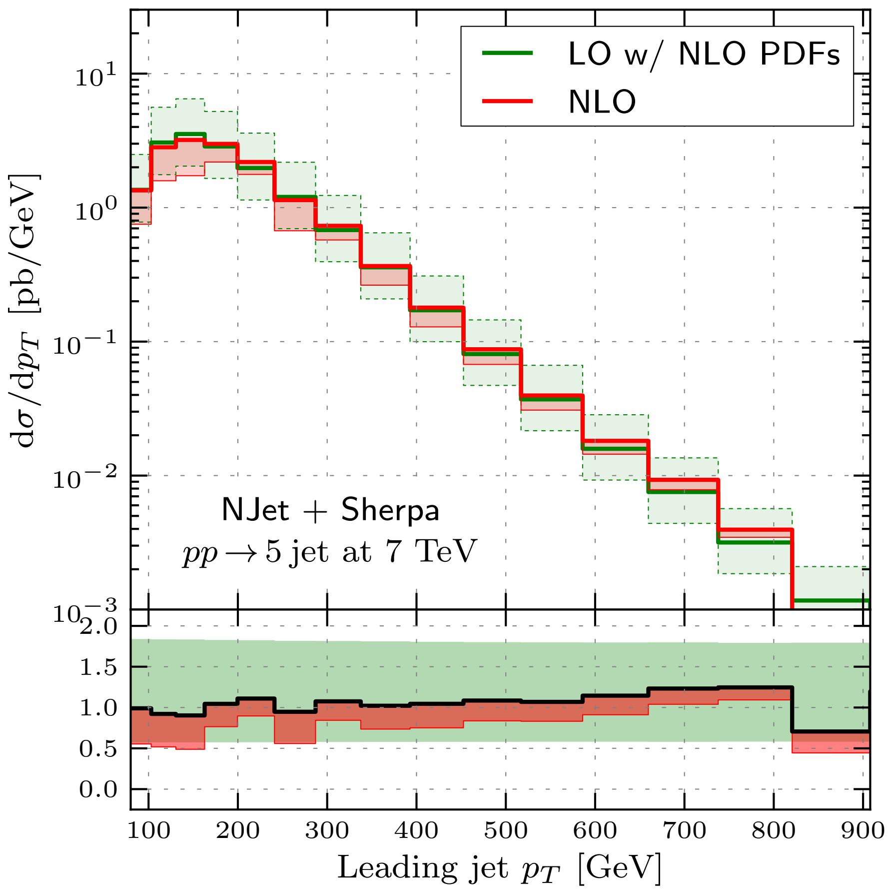
H. Hartanto QCD@LHC17

BSM (arbitrary, higher dimensional operators, etc)

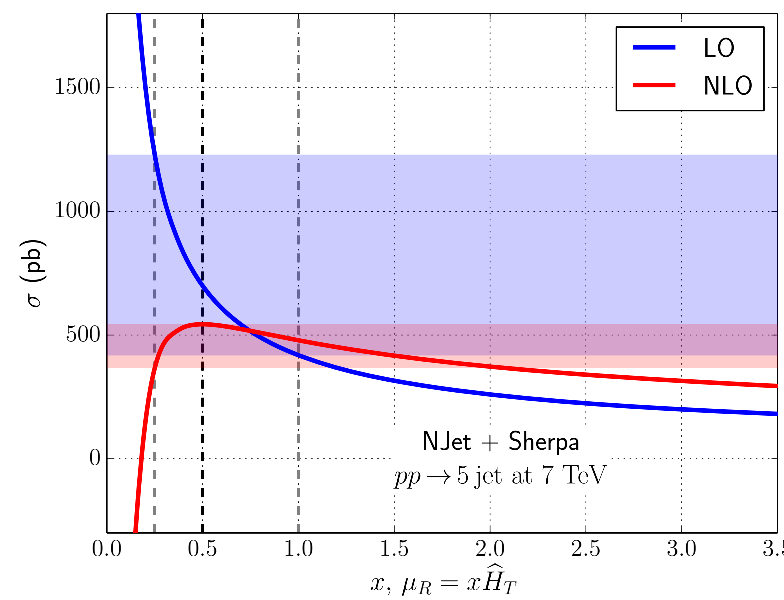
- Still limitations in numerical accuracy for processes with many particles (>4) in final state

Multi-jet production

$pp \to 5\,\text{jets at NLO}$

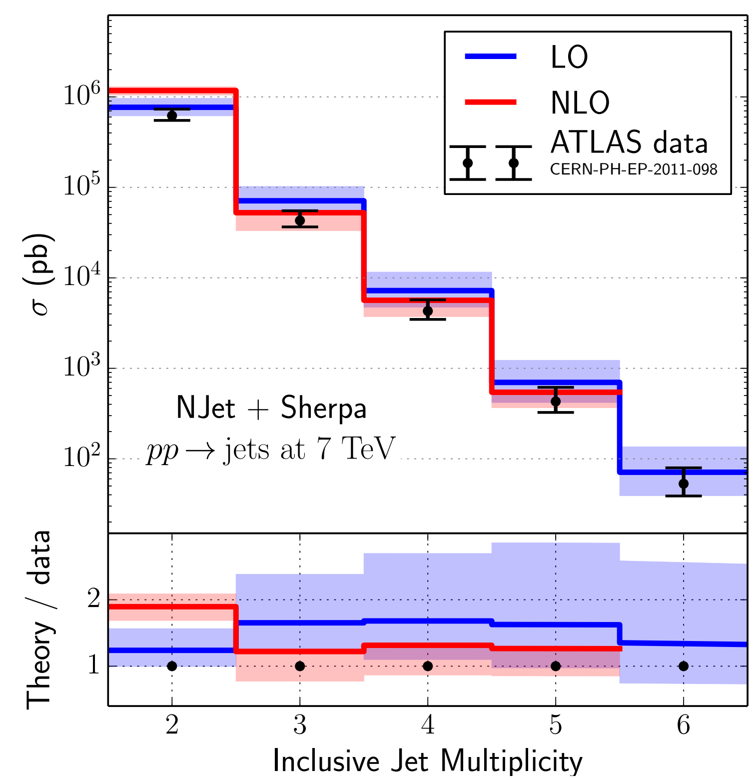


Njet+Sherpa (Badger, Biedermann, Uwer, Yundin)

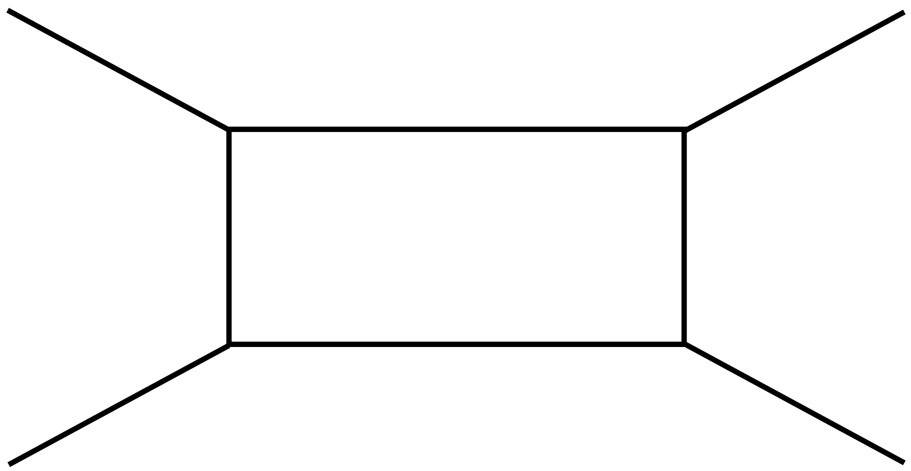


$$\widehat{H}_T = \sum_{i=1}^{N_{\text{parton}}} p_{T,i}^{\text{parton}}$$

- Better stability
- NLO in very good agreement with data!



NLO
Loop induced processes



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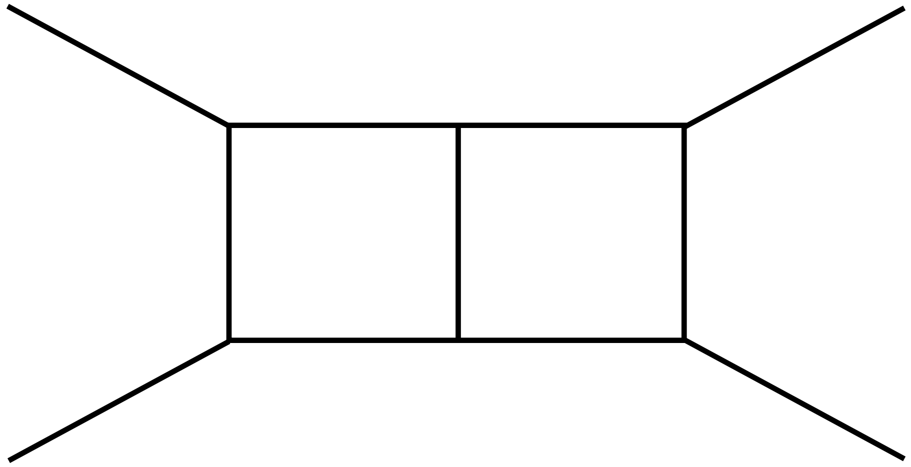
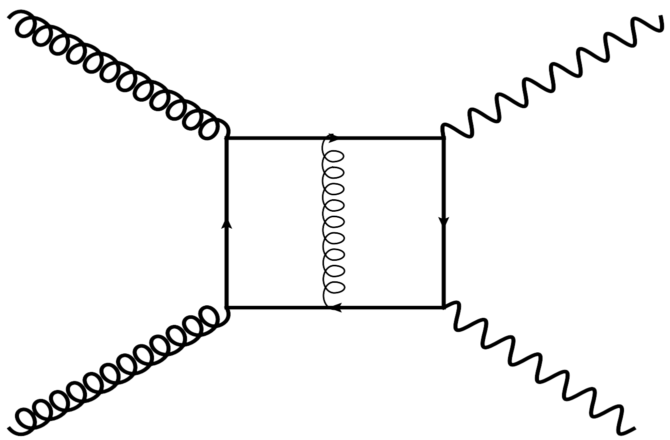


NLO = 2 loops for them…

Loop induced Processes : start at one loop at LO

- Enhanced by gluon luminosity
- Corrections for gg channel usually large (color, logs)



$gg \to VV$

H background

F. Caola, et al (2015-2016)
J. Campbell, K. Ellis, M. Czakon, S. Kirchner (2015)

$gg \to (H) \to VV$

signal-background interference

Higgs width

- Available only for massless partons @NLO (+$1/m_T$ expansion)
- But mass effects not-negligible (helicity flip in interference)

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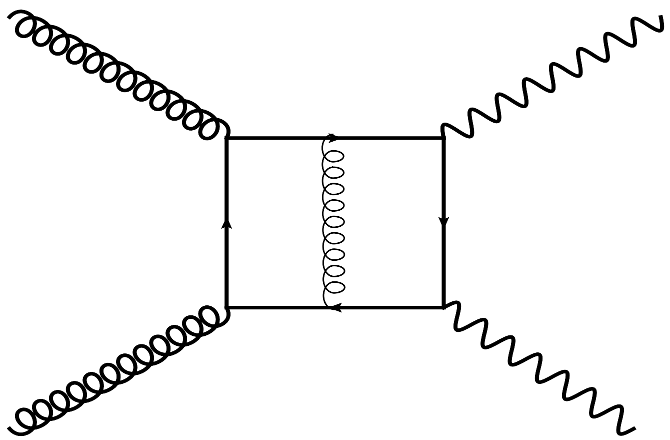

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$gg \to H + \mathrm{jet}$

- usually computed within EFT (large top mass limit)
- sensitive to top mass at large pT
- sensitive to top-bottom interference at low pT

40-50% correction
low mass approx.

J. Lindert, K. Melnikov, L. Tancredi, C. Wever (2017)

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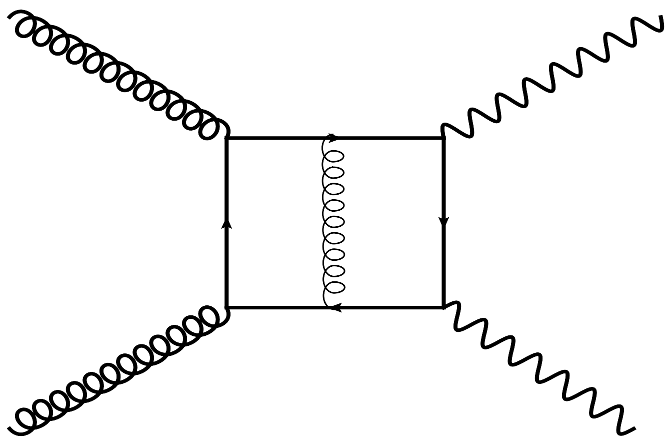

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H.Frellesvig QCD@LHC17

C.Weber QCD@LHC17

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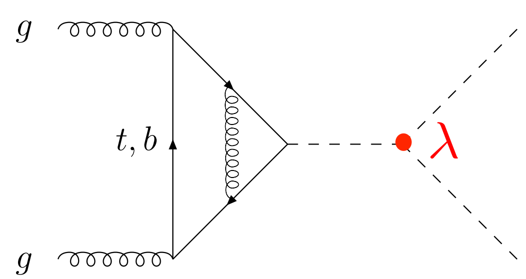
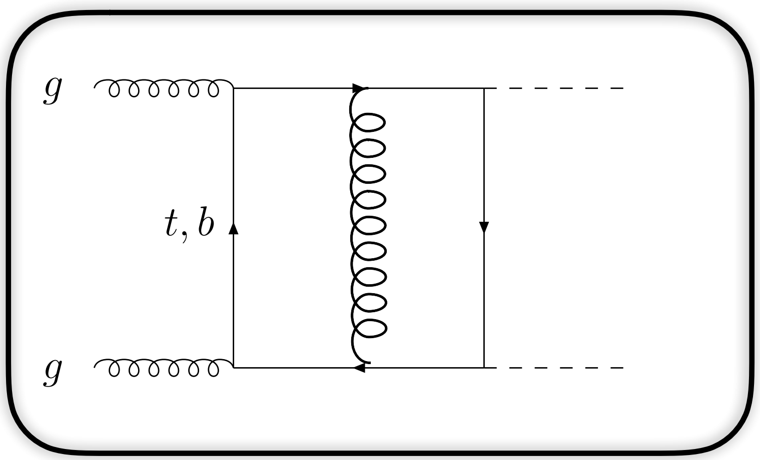
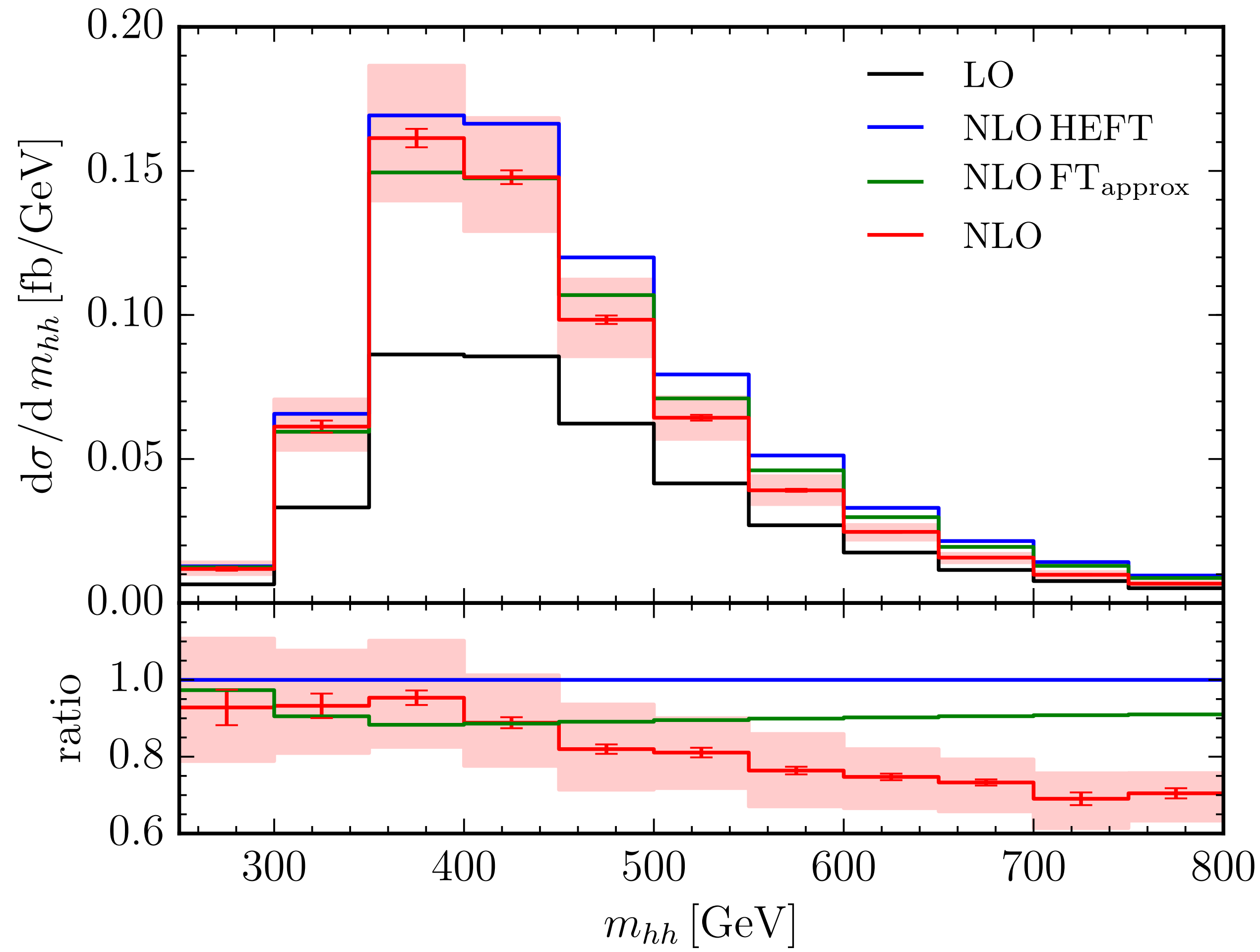
HH production in gg fusion

- Full NLO calculation — Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)
- 2 loop amplitudes computed numerically with SecDec







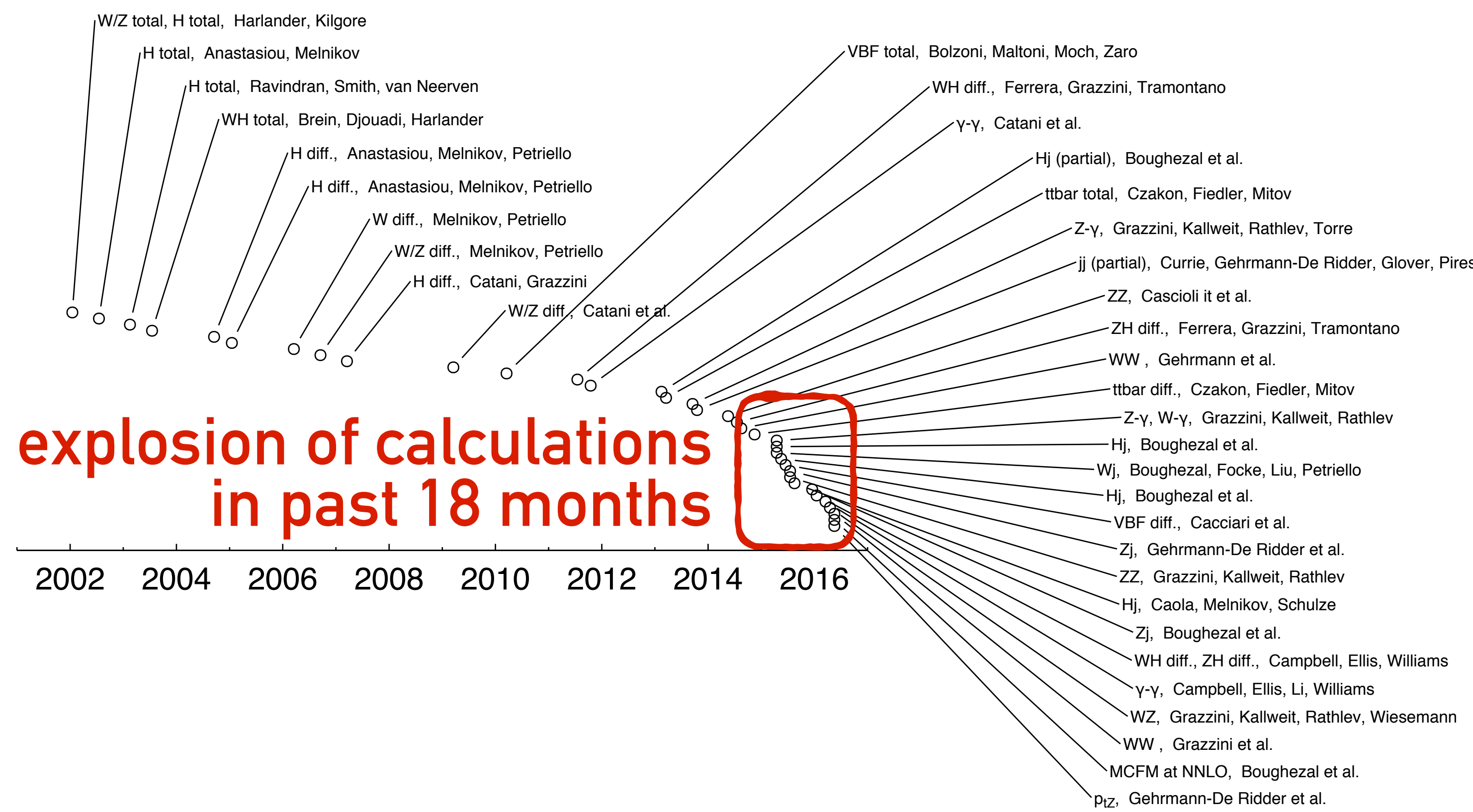
- -14% wrt EFT / bigger for large invariant masses
- NNLO available in EFT (learn about approx.) — deF, Mazzitelli (2014), deF et al (2016)
- Technique applicable for other observables?
  - 2-loop reduction/integrals out of analytic reach

NNLO

NNLO

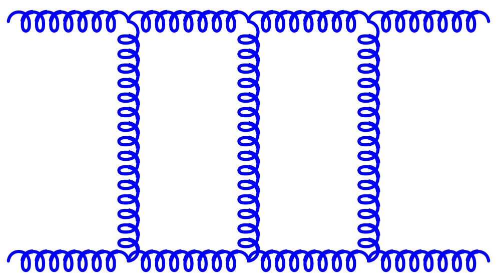
The NNLO revolution

G. Salam LHCP16



Degree of complexity at NNLO

- 2 loop

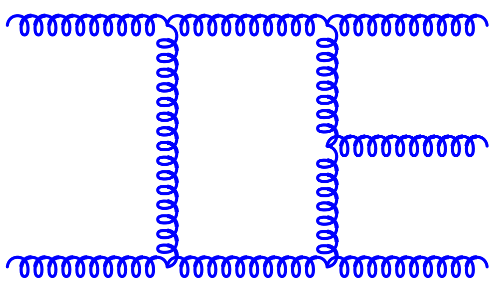


loop integrals → explicit infrared poles $\frac{1}{\epsilon^4}$

$2 \to 2$ available (even for VV production)

- Bottleneck for larger multiplicities?

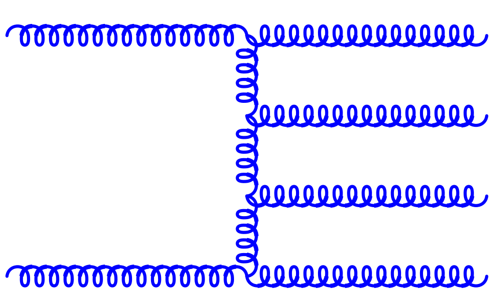
- 1 loop + single emission



"NLO complexity" : loop → $\frac{1}{\epsilon^2}$

singular emission → $\frac{1}{\epsilon^2}$

- Double real emission



Tree level — Trivial to compute Amplitudes
a Hell of infrared singularities

- Bottleneck for larger multiplicities?

after integration over unresolved partons → $\frac{1}{\epsilon^4}$ poles

Handling singularities $$\int |M_R|^2 dPS$$

Subtraction Method : need local subtraction counter-term

$$\int_0^1 (|M_R|^2 - \mathcal{S}) dPS + \int \mathcal{S}\, dPS + \int |M_V|^2 dPS'$$

Finite

Computed "analytically"
cancel divergences

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- The method used at NLO
- Subtraction can be fully local (better convergence, but not all)
- At NNLO many more singular configurations
- Integration of subtraction term quite complicated (can be numerical)

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different approaches

Sector decomposition Anastasiou, Melnikov, Petriello; Binoth, Heinrich

Antennae subtraction Gehrmann, Gehrmann-de Ridder, Glover

Sector-Improved residue subtraction Czakon, Boughezal, Melnikov, Petriello

CoLorFul subtraction Del Duca, Somogyi, Trocsanyi

Projection-to-Born Cacciari, Dreyer, Karlberg, Salam, Zanderighi

Phase space slicing : split phase space according to singular configurations

$$\underbrace{\int_\delta^1 |M_R|^2 dPS}_{} + \underbrace{\int_0^\delta |M_R|^2 dPS + \int |M_V|^2 dPS'}_{}$$

Regularized by cut-off (numerically involved)

Can be obtained from resummation framework

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Can be obtained from resummation framework

- Not used at NLO
- Generates large cancellations on cut-off (has to be checked)
- Simpler to implement (resummation)
- Count with faster computers for "smaller" correction
- Can use precise NLO calculations as basis (X+jet)
- Use local subtraction for NLO-like singularities

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• q_T and Jettiness to characterize "pure" NNLO configurations

q_T-subtraction   Catani, Grazzini; Catani, Cieri, deF, Ferrera, Grazzini

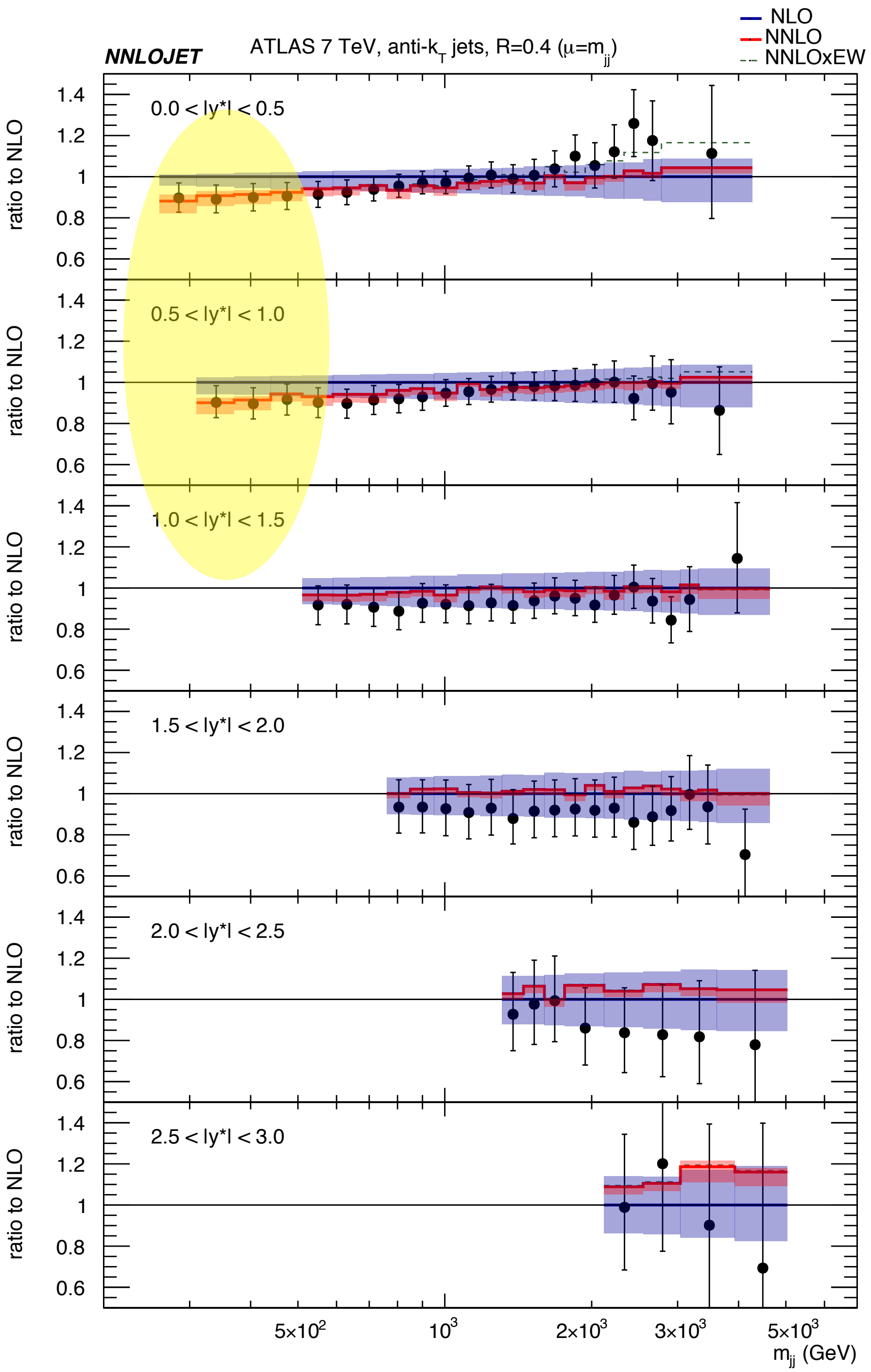
N-jettiness subtraction   Boughezal, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

• So far only "simpler" configurations : one/zero colored particle in f.s.

$pp \to 2\,\text{jets}$

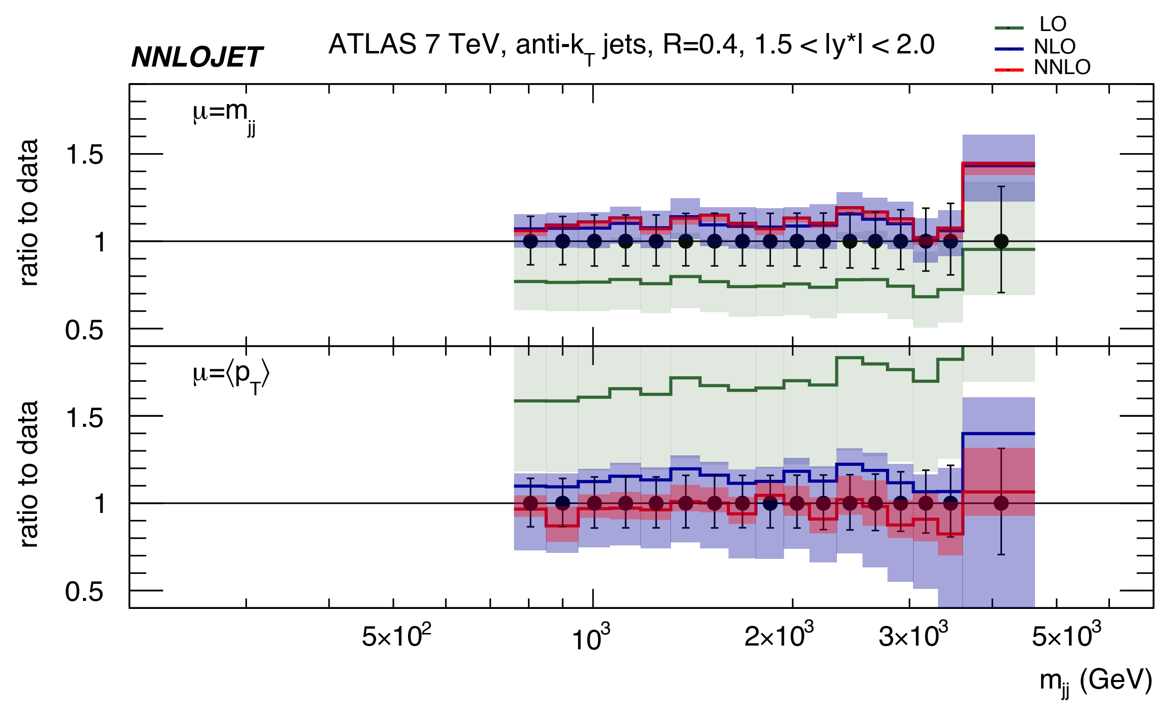
- Leading color using antenna subtraction : NNLOJET (1 and 2 jets)

J.Currie, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A.Huss, J.Pires (2017) J.Currie, E.W.N. Glover, J.Pires (2016)



- Moderate NNLO corrections (<10%)
- Improve description of data for low M_{jj}/y^*
- Invariant mass natural scale (better convergence)
- Cures pathological NLO behavior for $\langle p_T \rangle$

$$\mu = m_{jj} \qquad \mu = \frac{1}{2}(p_{T_1} + p_{T_2})$$



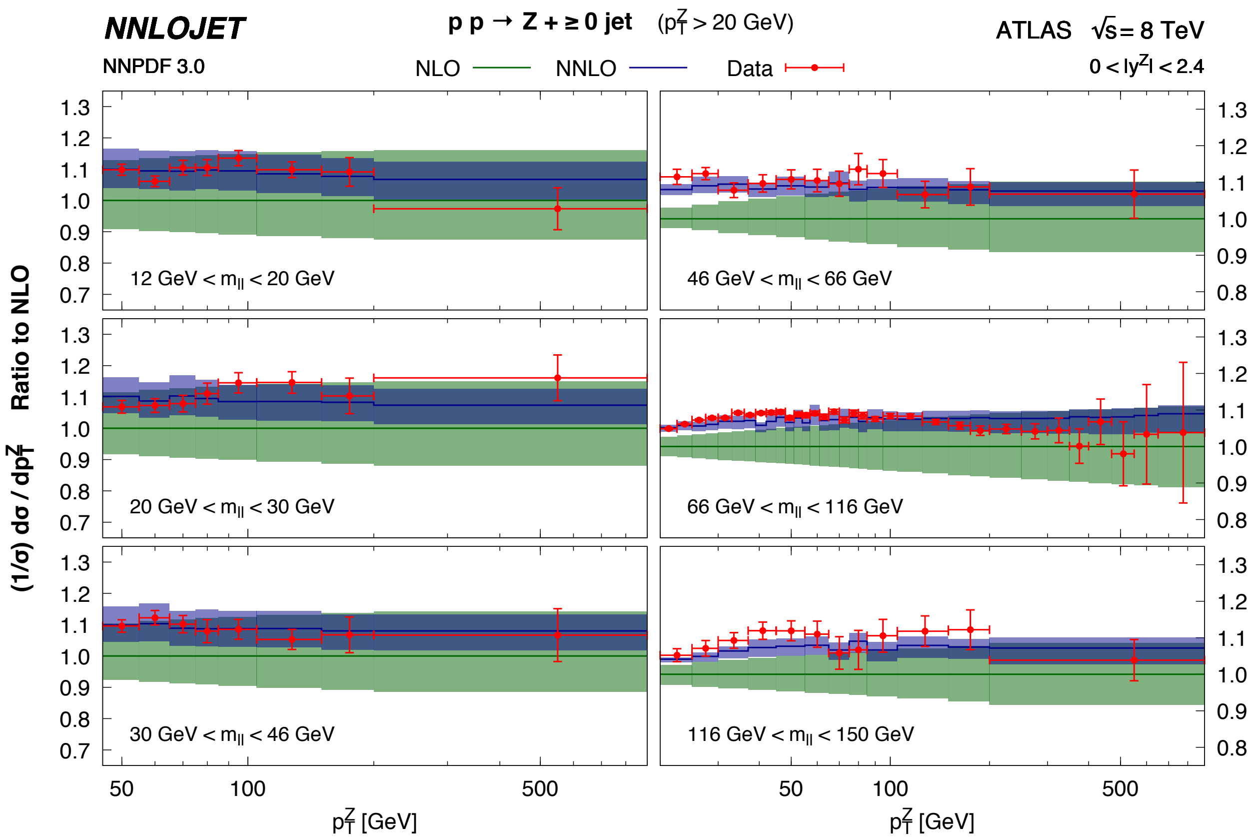
- NNLO scale dep. smaller than EXP errors
- NLO underestimates uncertainty

$pp \to Z + \text{jets}$

- Experimental Uncertainties at the 1% level or below
- Phenomenological interest : PDF's, luminosity normalization, (W mass)

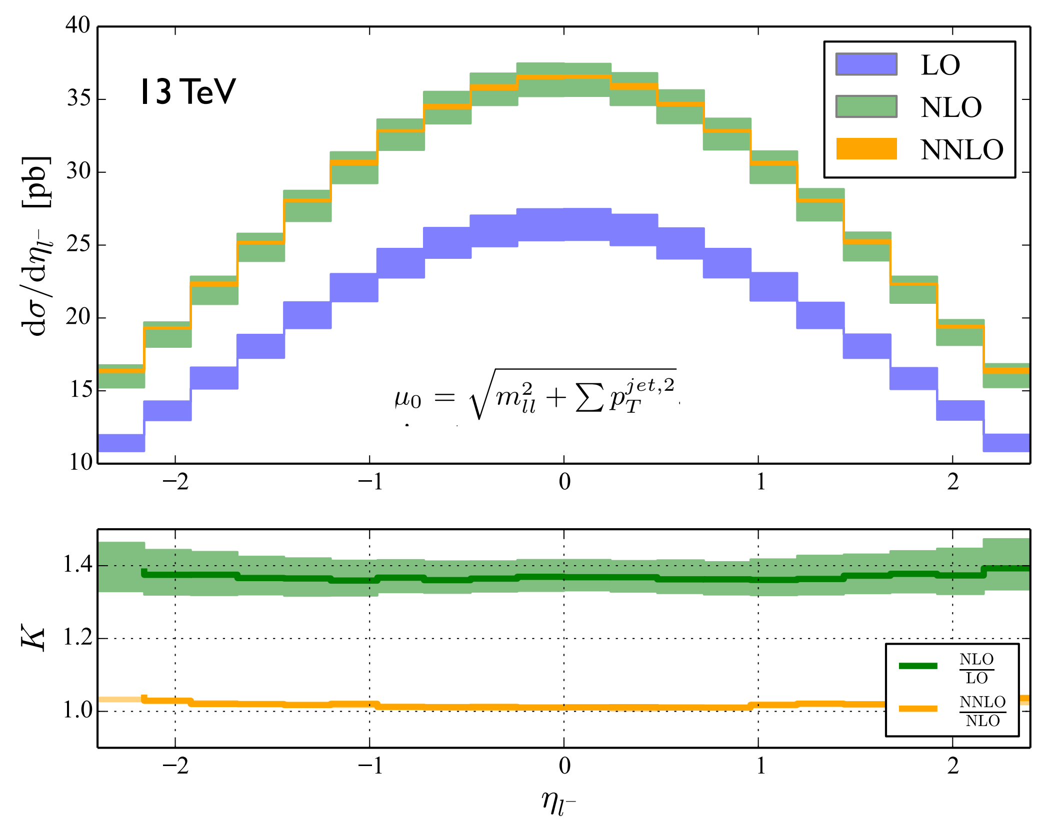
Antennae subtraction

A.Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A.Huss, T.A.Morgan (2016)



N-Jettiness

R. Boughezal, J. Campbell, K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello(2016)



- significant reduction in scale dependence
- substancial improvement in agreement with data
- W+ jet available R. Boughezal, X. Liu, F. Petriello(2016)

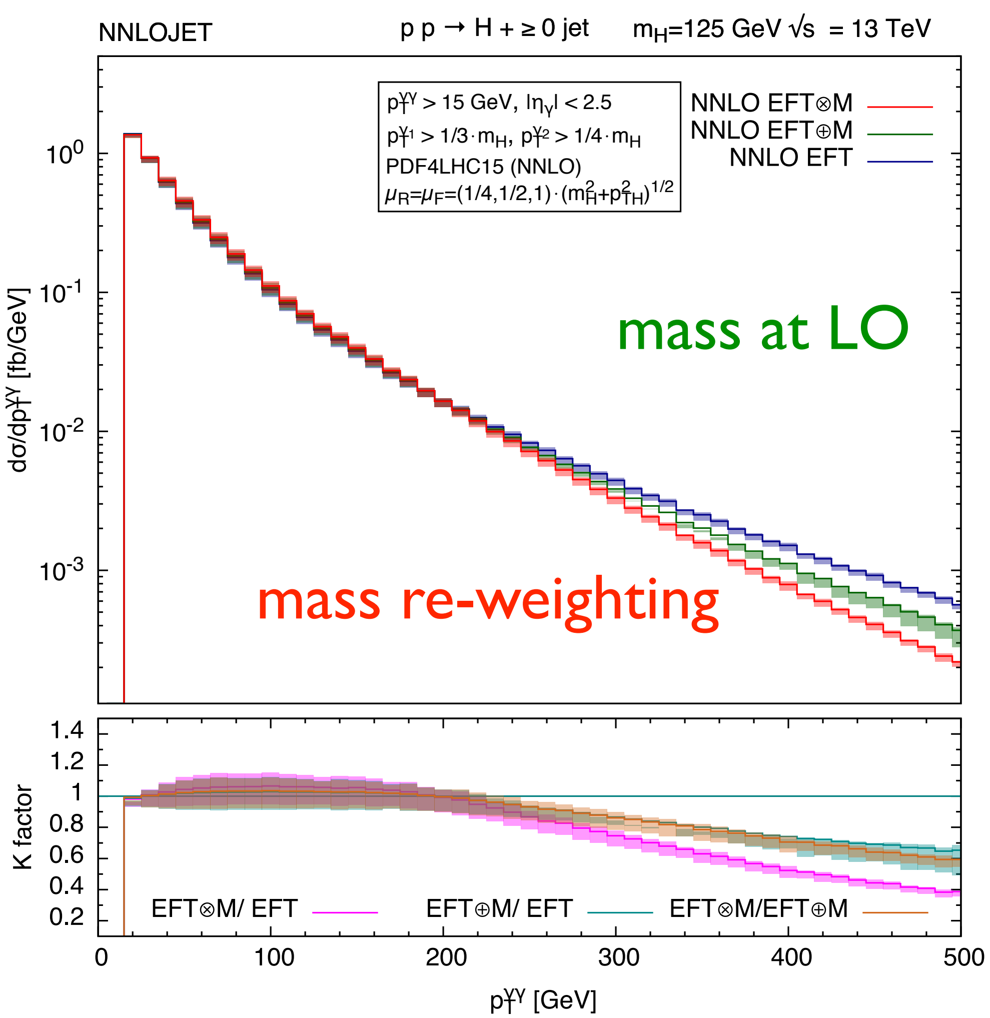
$pp \to H + \text{jets}$

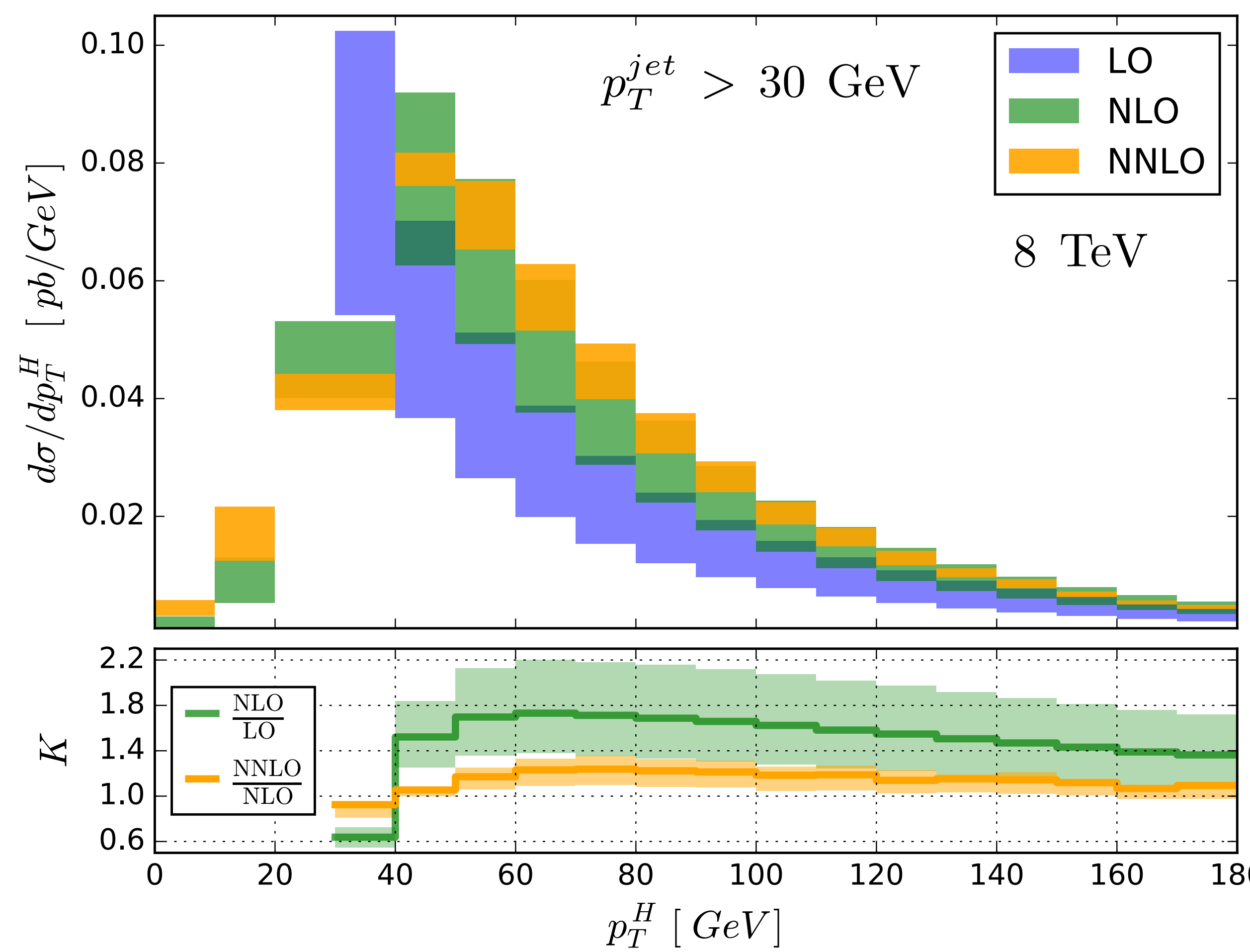
- Higgs moving from inclusive to fiducial/exclusive distributions

Antennae subtraction
X. Chen, J. Cruz-Martinez, T. Gehrmann, E.W.N. Glover, M. Jaquier (2016)

N-Jettiness R. Boughezal, C. Focke, W. Giele, X. Liu, F. Petriello(2015)

Sector dec. R. Boughezal, F. Caola, K.Melnikov, F. Petriello, M. Schulze (2015)





- Within approx. of EFT : missing HQ effects

H.Frellesvig QCD@LHC17

- Need full mass dependence at NLO (massive two loop)

Towards automation @ NNLO

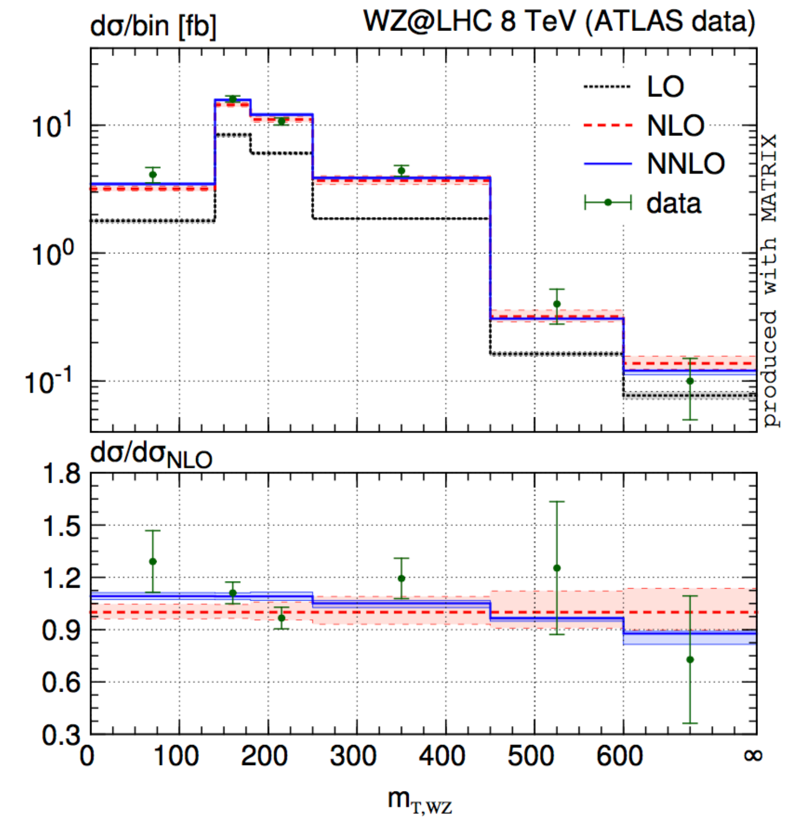
Matrix @ NNLO

M. Grazzini, S. Kallweit, D. Rathlev, M. Wiesemann (2016)

- $pp \to Z/\gamma^*$ ($\to l^+l^-$) ✅
- $pp \to W(\to l\nu)$ (✅)
- $pp \to H$ ✅
- $pp \to \gamma\gamma$ ✅
- $pp \to W\gamma \to l\nu\gamma$ ✅
- $pp \to Z\gamma \to l^+l^-\gamma$ ✅
- $pp \to ZZ(\to 4l)$ ✅
- $pp \to WW \to (l\nu l'\nu')$ ✅
- $pp \to ZZ/WW \to ll\nu\nu$ ✅
- $pp \to WZ \to l\nu ll$ ✅
- $pp \to HH$ (✅)

NNLO parton level generator with several processes in unique framework (di-boson)

- qt subtraction
- Open-Loops : X+1 parton
- Will include qT resummation
- So far, colored singlet final state
- Public version soon



Towards automation @ NNLO

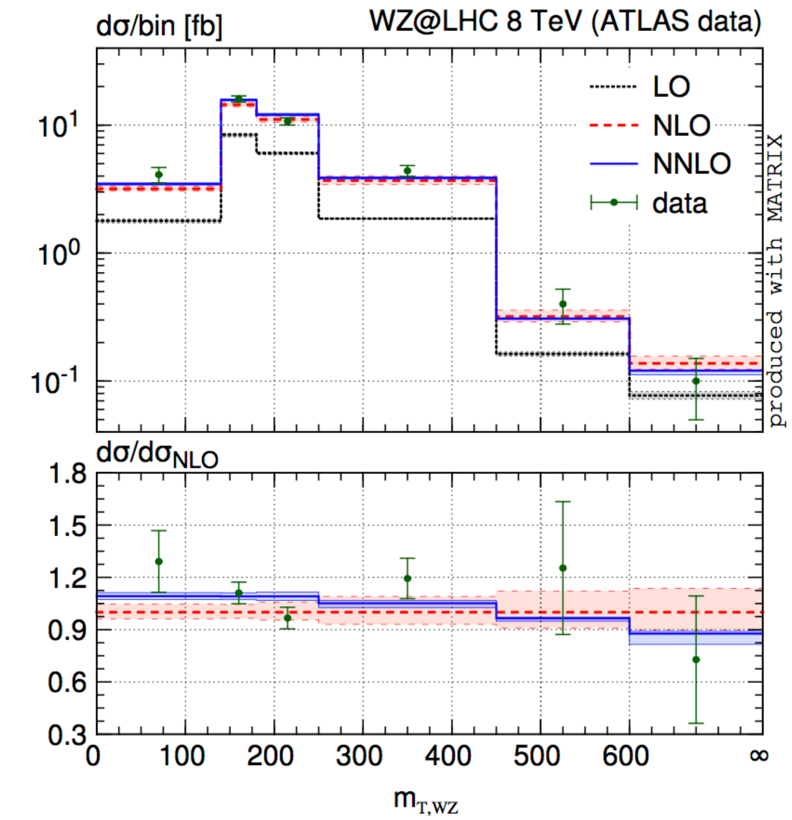
Matrix @ NNLO

M. Grazzini, S. Kallweit, D. Rathlev, M. Wiesemann (2016)

- pp→Z/γ* (→l+l-) ✅
- pp→W(→lν) (✅)
- pp→H ✅
- pp→γγ ✅
- pp→Wγ→lνγ ✅
- pp→Zγ→l+l-γ ✅
- pp→ZZ(→4l) ✅
- pp→WW →(lνl'ν') ✅
- pp→ZZ/WW →llνν ✅
- pp→WZ →lνll ✅
- pp→HH (✅)

▸ NNLO parton level generator with several processes in unique framework (di-boson)

- qt subtraction
- Open-Loops : X+1 parton
- Will include qT resummation
- So far, colored singlet final state
- Public version soon



MCFM@ NNLO

R. Boughezal, J. Campbell, K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello (2016)
J. Campbell, T. Neumann, C. Williams (2017)

- N-Jettiness
- Less processes available yet : V+1 jet done

W^+
W^-
Z
H
$\gamma\gamma$ $Z\gamma$
W^+H
W^-H
ZH

Towards automation @ NNLO

- Sector-decomposition + FKS : Stripper

R. Poncelet QCD@LHC17

Towards automation @ NNLO

- Sector-decomposition + FKS : Stripper

R. Poncelet QCD@LHC17

- 3 jet production in e+e- and event shapes: CoLoRFulNNLO

Z. Tulipánt QCD@LHC17
Z. Ször

Del Duca, Duhr, Kardos, Somogyi, Ször, Trócsányi, Tulipánt (2016)

- Fully differential results for ttbar Czakon, Heymes, Mitov(2015-2016)

A. Mitov QCD@LHC17

- t-channel. Single-top + top-decay (NW) Berger, Gao, Yuan, Zhu (2016)

Slicing (N-jettiness) + subtraction (P2B)

- VBF at NNLO : projection to Born method

Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)

- $H \to b\bar{b}$ @ NNLO Del Duca, Duhr, Somogyi, Ször, Tramontano, Trócsányi (2015)

- \+ many more computations in just a few years

N^3LO

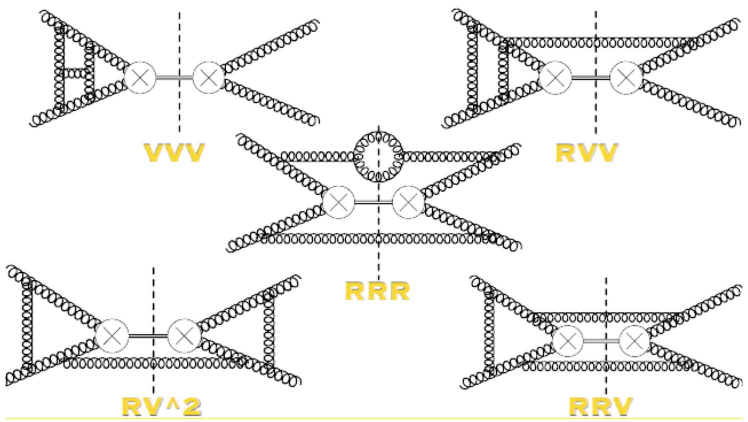
The new Frontier

Higgs at N^3LO

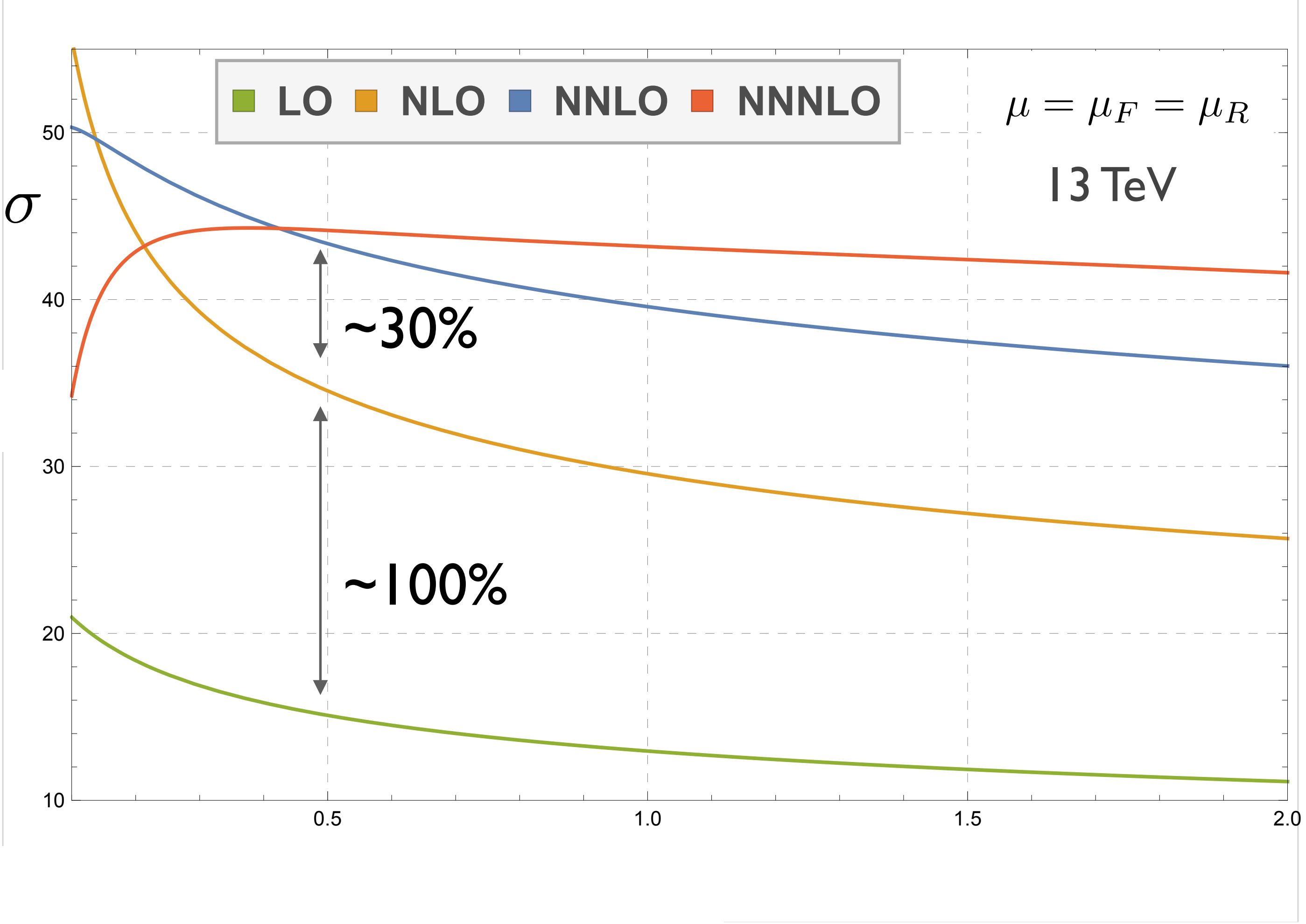
C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger (2015)

- Very relevant observable called for higher orders (slow convergence)
- Impressive calculation : new techniques
  - Threshold expansion (very high order)
  - Within (excellent) heavy top approximation
  - Could be used for DY
  - Differential distributions

S. Lionetti QCD@LHC17



68273802 loop and phase space integrals

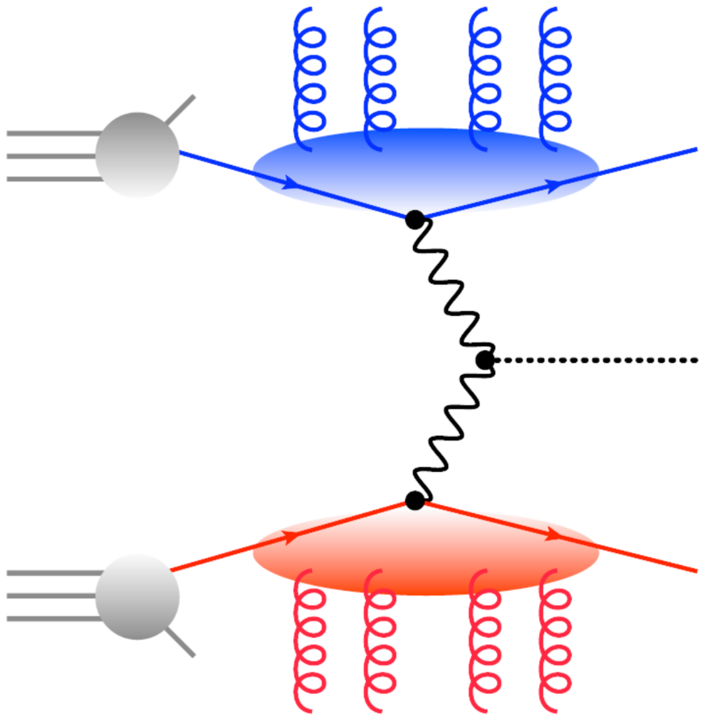


C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog, A. Lazopoulos, B. Mistlberger (2016)

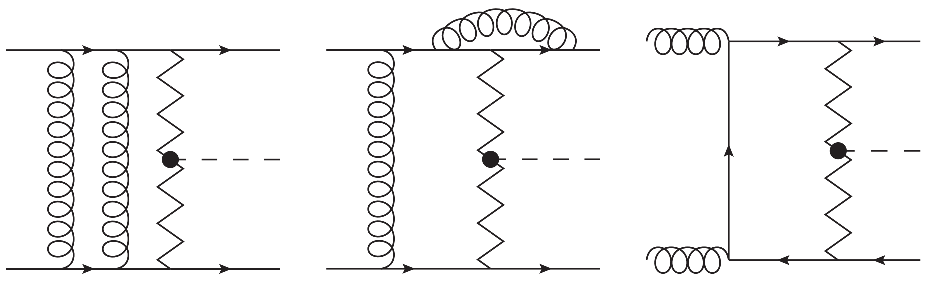
- Inclusive over parton radiation
- Observe stabilization of expansion
- Small correction (2% at $M_H/2$)
- Scale variation at N^3LO ~2%

VBF at N^3LO

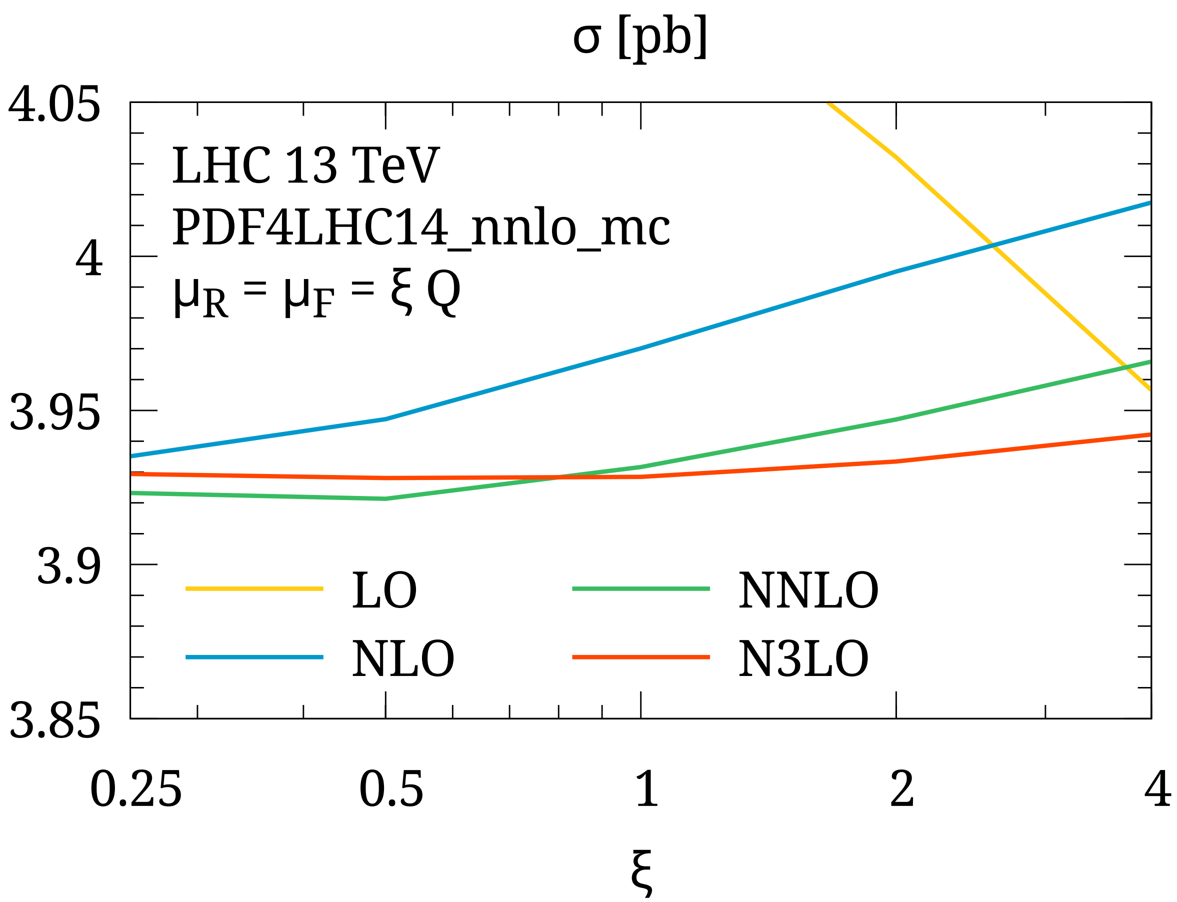
F. Dreyer, A. Karlberg (2016)



- DISxDIS like approach ~1% accurate picture



neglect exchange between lower and upper legs



- Inclusive on parton radiation
- small corrections ~1-2%
- within NNLO band
- sizable reduction in scale dep.

- Exclusive at NNLO

M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi (2015)

NNLO differential larger (5-10%) than for inclusive (1%) and beyond NLO band

N3LO Splitting functions

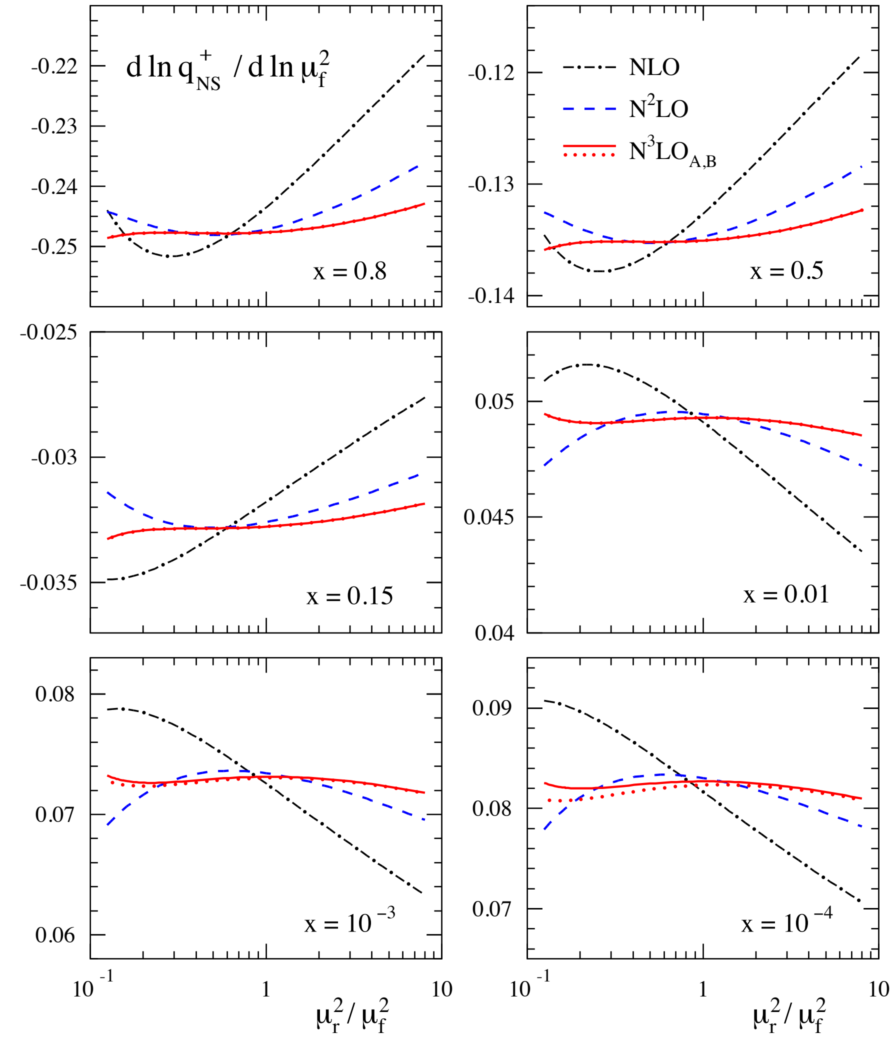
S. Moch, B. Ruijl, T. Ueda, J. Vermaseren, A. Vogt (2017)

- Non-Singlet 4 loop splitting function

- N=20 Mellin moments (large Nc)
- Enough to provide a reconstruction in terms of Harmonic sums
- N=16 beyond large Nc
- Precise for $x \gtrsim 10^{-4}$

$$xq_{\rm ns}^{\pm,\rm v}(x,\mu_0^2) \;=\; x^{0.5}(1-x)^3$$

$$\alpha_{\rm s}(\mu_0^2) \;=\; 0.2$$



- Visible improvement of scale stability

Singlet and Gluon splitting functions feasible

QED corrections G. Sborlini QCD@LHC17

TH Uncertainties

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF+}\alpha_s)$$

what is the meaning of that?

- Usually obtained by performing scale variations

$$\log\frac{Q}{\mu} \qquad \log\frac{\mu_F}{\mu_R} \qquad \log\frac{Q}{\mu_{F,R}}$$

keep logs small

$$\mu_{F,R} = \left(r, \frac{1}{r}\right) Q$$

- Lack of probabilistic framework : how to combine with other?
- Several examples showing that "*r*=2" might be short to account for true uncertainties

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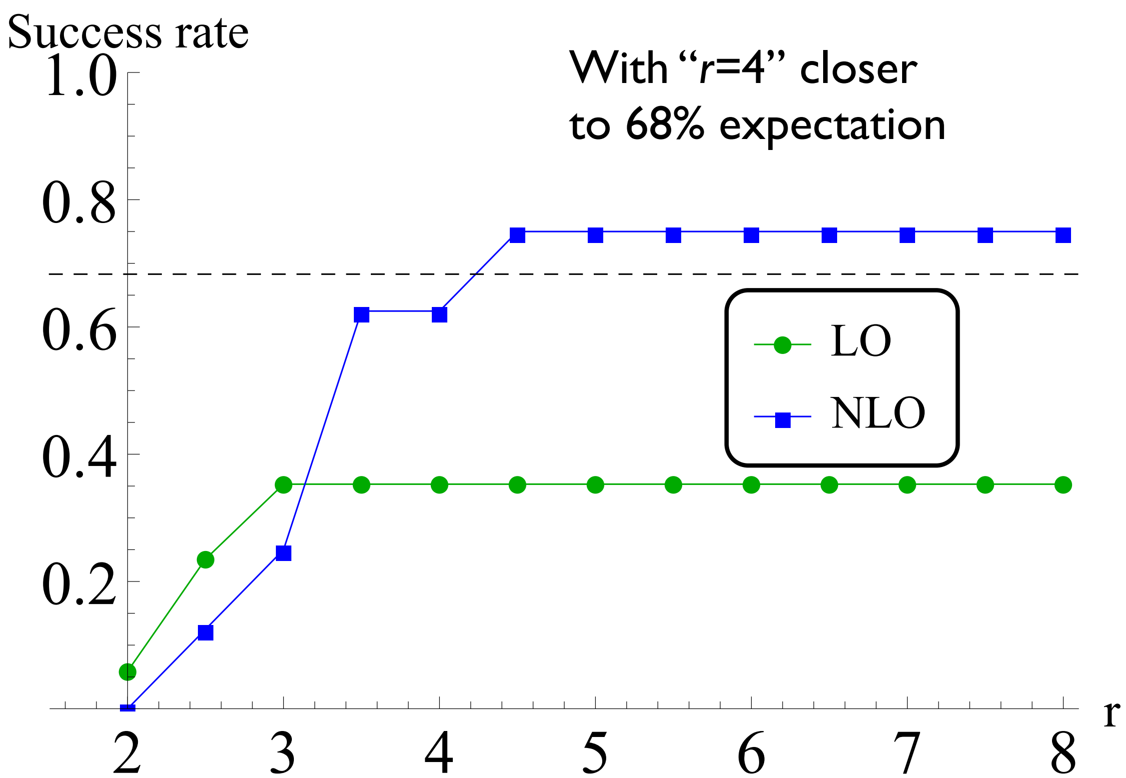
- Lack of probabilistic framework : how to combine with other?

- Several examples showing that "*r*=2" might be short to account for true uncertainties

  - Fraction of hadronic observables (~15) whose h.o. correction is contained in the scale variation interval

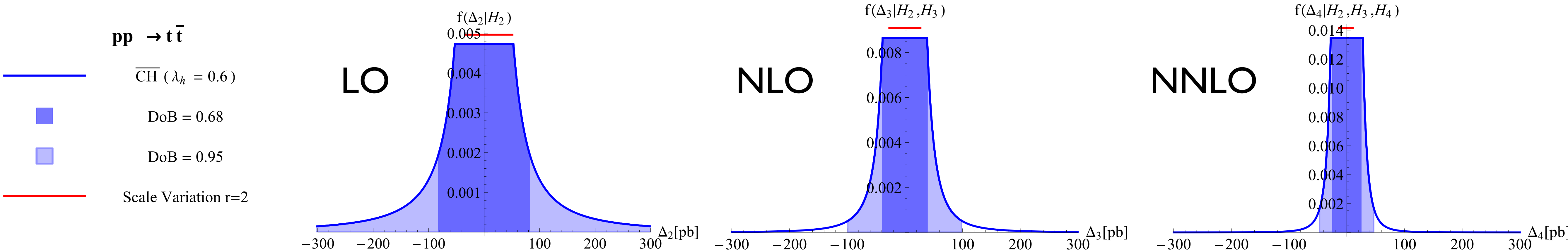
    E. Bagnaschi, M. Cacciari, A. Guffanti, L. Jenniches (2014)

  - But *rescaling* depends on order: might be better from NNLO



- Bayesian approach: Introduce condicional density compute credibility interval with degree of belief (68%, 95%)

M. Cacciari, N. Houdeau (2011); E. Bagnaschi, M. Cacciari, A. Guffanti, L. Jenniches (2014)



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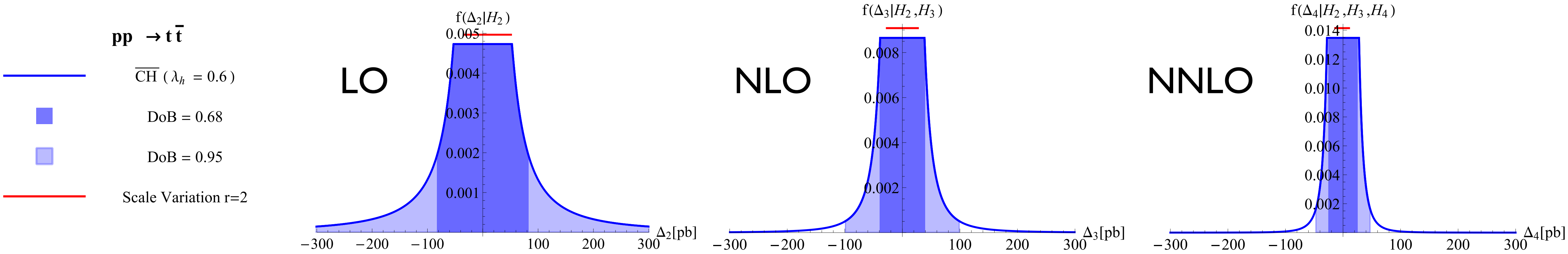

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- Series acceleration: estimate some unknown terms using analytical structure of expansion and sequence methods A. David, G. Passarino (2013)

- Evaluate "higher order" terms from resummation framework

DdeF, J. Mazzitelli, S. Moch, A. Vogt (2014)
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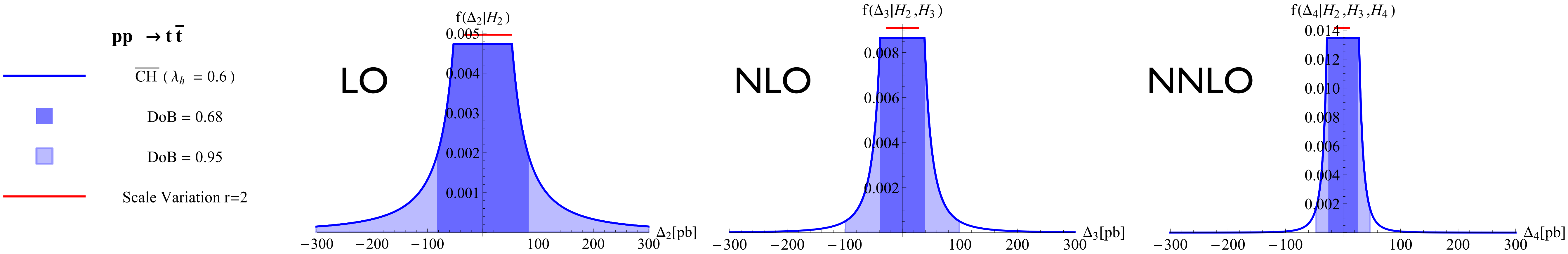

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Too much effort to reach N^nLO to avoid the search for a more rigorous handling of TH uncertainties in perturbative calculations

Conclusions

- Amazing progress in fixed order calculations during the last (>) decade

  Automation of NLO

  Several NNLO processes $2 \to 2$ ✓

  Even N^3LO for simpler kinematics and first set of splitting functions

  Driven by LHC

- But… Reaching new bottlenecks

- Large multiplicity at NLO still needs *manual*-work

- Loop induced processes (massive) yet hard to tackle

- NNLO very difficult for more than 2 particles in final state

  - Virtual amplitudes (massive)
  - Real radiation not trivial (numerical infrared treatment)

  Will need significant development

- Need a more rigorous treatment of TH uncertainties

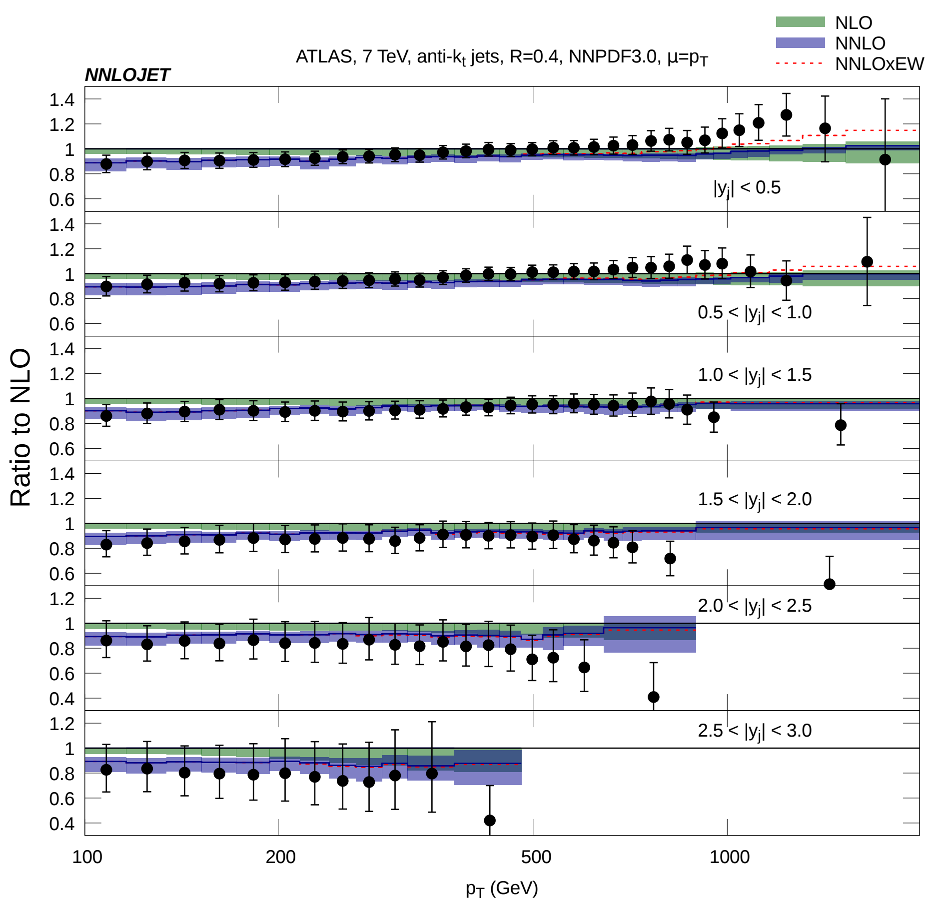
Thanks to Costas Papadopoulos and Marco Zaro for discussions

Backup slides

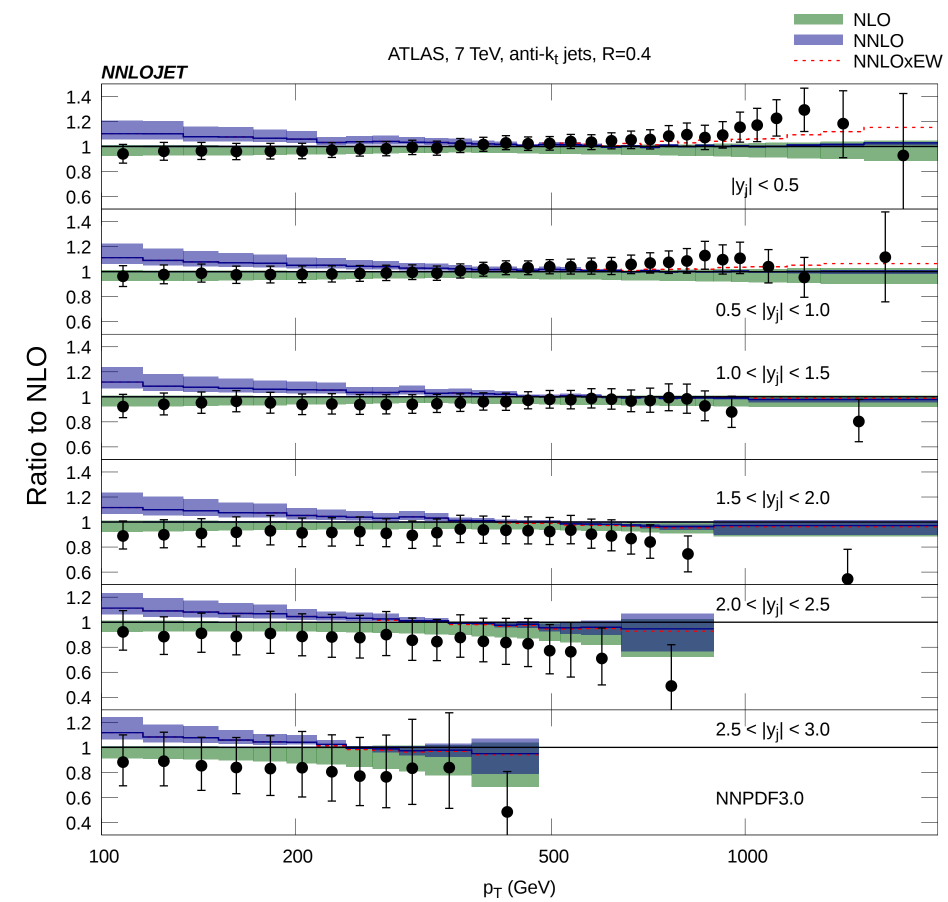
Single-jet production

- Leading color using antenna subtraction : NNLOJET

J.Currie, E.W.N. Glover, J.Pires (2016)   J.Currie, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A.Huss, J.Pires (2017)



$\mu = p_T$



$\mu = p_{T_1}$

- Moderate NNLO corrections
- Two different central scales: leading jet vs individual jet

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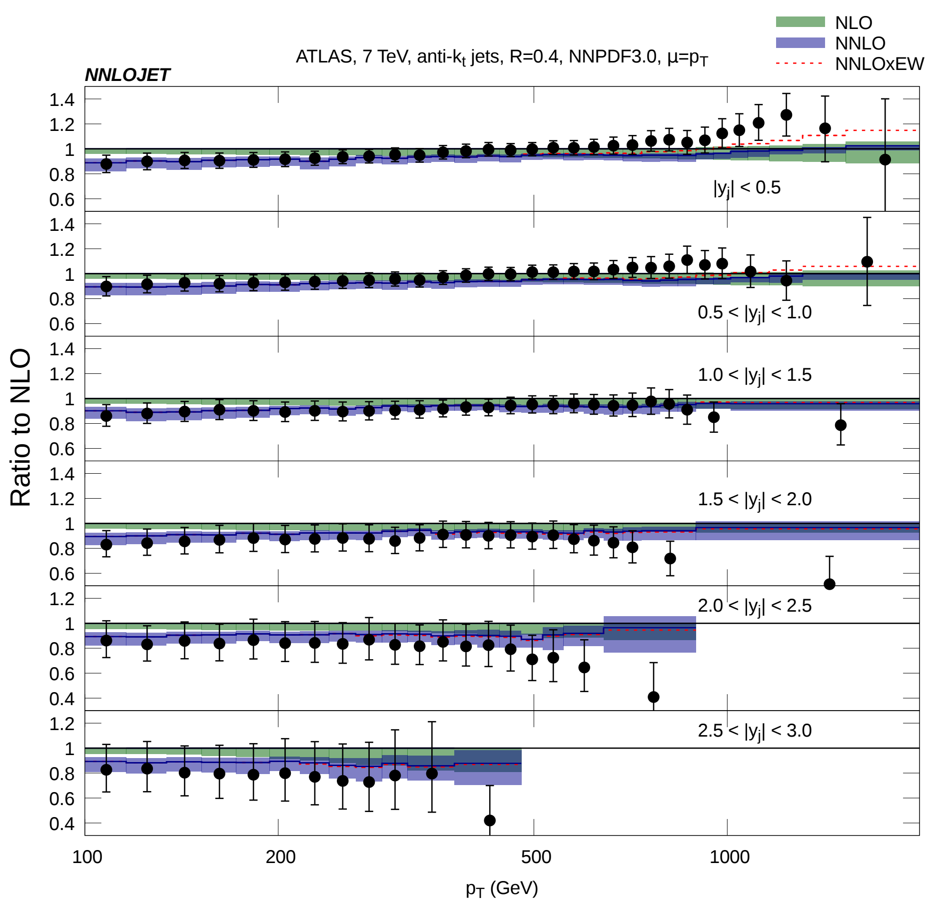

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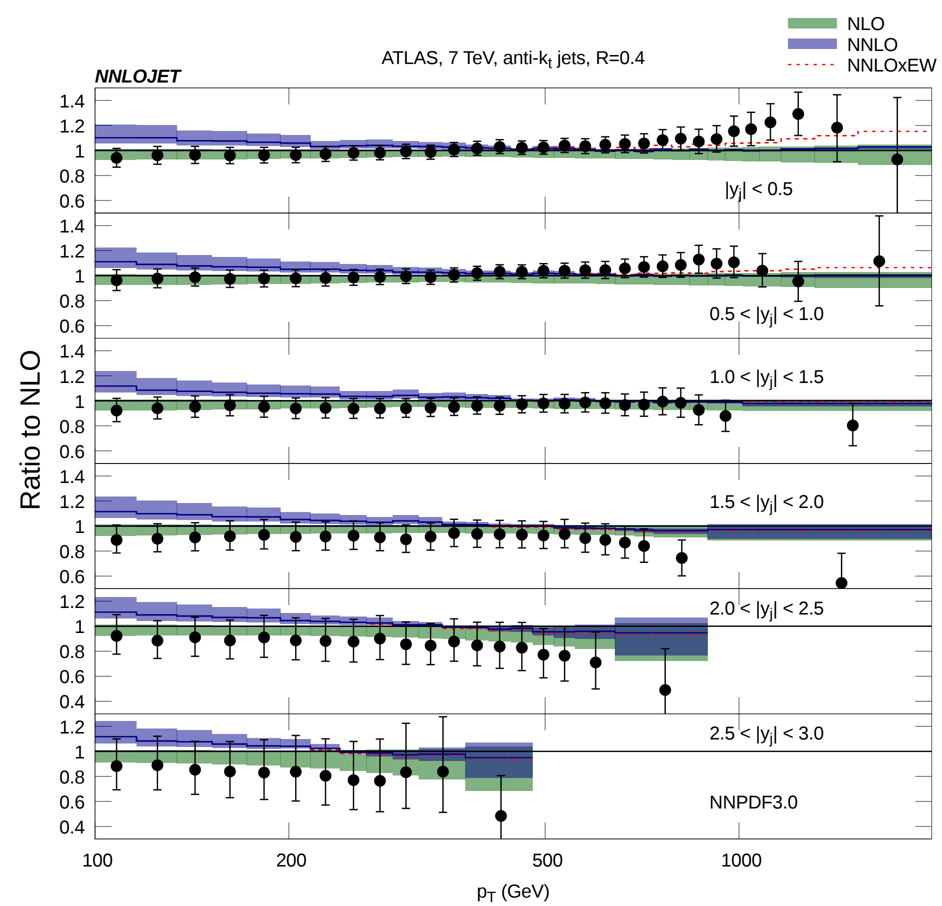


$\mu = p_{T_1}$

- Moderate NNLO corrections
- Two different central scales: leading jet vs individual jet
  - Equivalent at large transverse momentum
  - Differences outside scale band at low momentum
  - p_T provides better description (with larger corrections and scale dep.)
  - Requires further studies to LHC data (scale, shape, cone, pdfs)

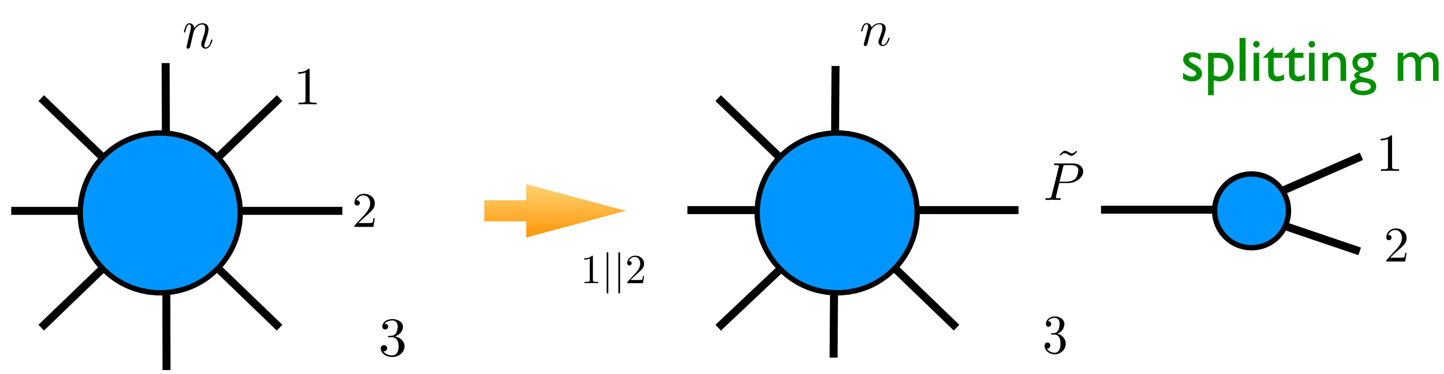
Infrared Structure of QCD

- H.O. computations possible: understanding infrared structure of amplitudes
- Key for cancellation of singularities : factorization of amplitudes

Strict factorization in collinear limit

splitting matrix

n particle amplitude



universal and process independent
independent of non-collinear partons

2 collinear

n-1 particle amplitude

$$\mathbf{P}^{(0,R)} = \left(\boldsymbol{Sp}^{(0,R)} \right)^{\dagger} \boldsymbol{Sp}^{(0,R)}$$

$$|\mathcal{M}^{(0)}(p_1, p_2, \ldots, p_n)\rangle \simeq \boldsymbol{Sp}^{(0)}(p_1, p_2; \widetilde{P}) \; |\mathcal{M}^{(0)}(\widetilde{P}, \ldots, p_n)\rangle$$

AP kernel

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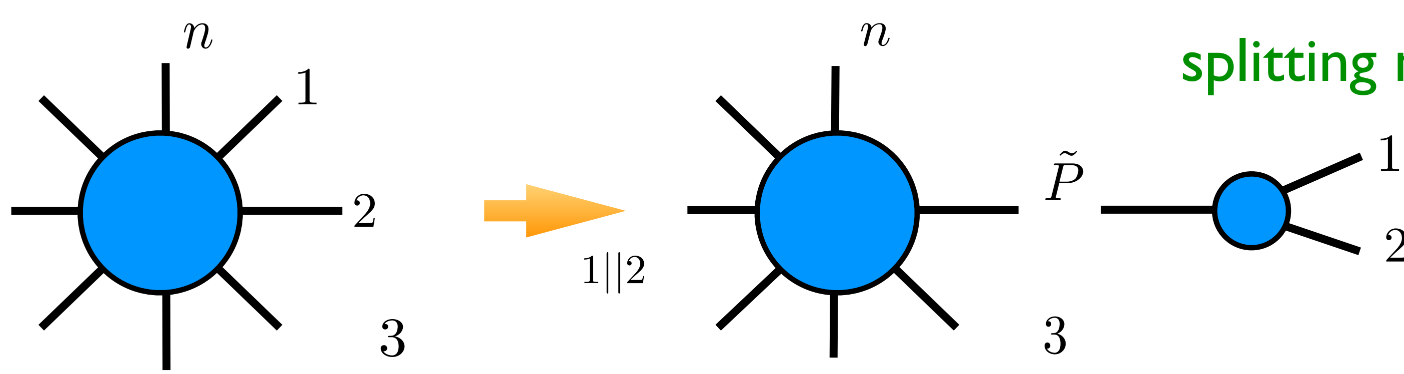

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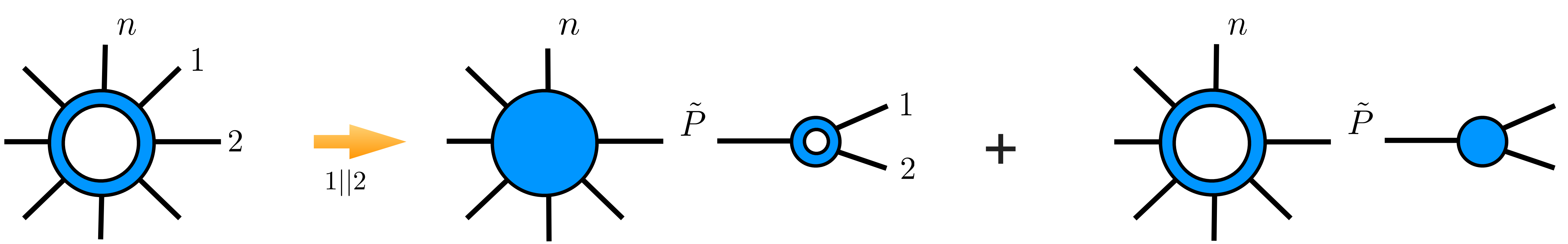
AP kernel

- Similar approach for virtual amplitudes

$$|\mathcal{M}^{(1)}(p_1, p_2, \ldots, p_n)\rangle \simeq \boldsymbol{Sp}^{(1)}(p_1, p_2; \widetilde{P}) \; |\mathcal{M}^{(0)}(\widetilde{P}, \ldots, p_n)\rangle + \boldsymbol{Sp}^{(0)}(p_1, p_2; \widetilde{P}) \; |\mathcal{M}^{(1)}(\widetilde{P}, \ldots, p_n)\rangle$$

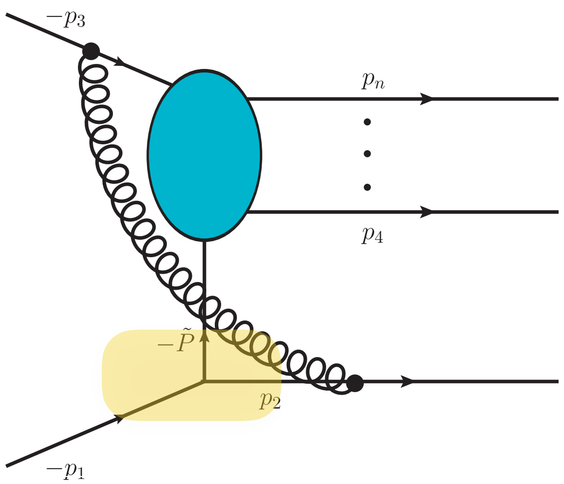


Factorization fails in space-like region: hadronic colliders

Catani, deF., Rodrigo (2012)

$\boldsymbol{Sp}^{(1)}(p_1, p_2; \widetilde{P}; p_3, \ldots, p_n)$ depends on non-collinear partons

➡ Violation of strict factorization for one loop amplitudes



fact. breaking divergent part

$$\Delta^{(1)}_{mC}(\varepsilon) = \frac{\alpha_S(\mu^2)}{2\pi} \frac{i\pi}{\varepsilon} \sum_{\substack{i \in C \\ j \in NC}} \mathbf{T}_i \cdot \mathbf{T}_j \, \Theta(-z_i) \, \text{sign}(s_{ij})$$

- Cancels in TL (and DIS) due to color Coherence
- Absorptive (Imaginary): cancels in cross section

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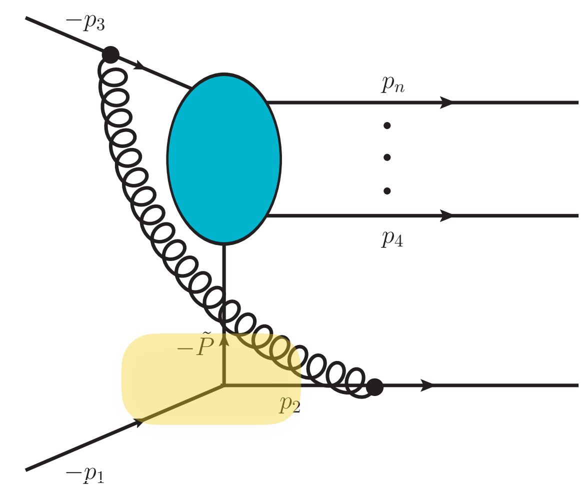

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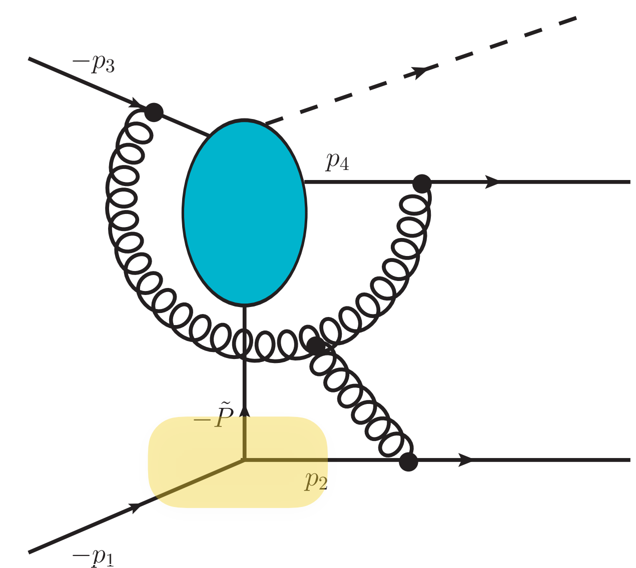

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Forshaw, Seymour, Siódmok (2012)
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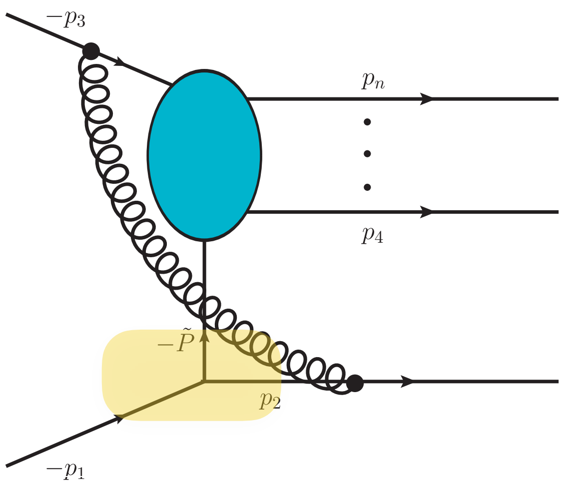

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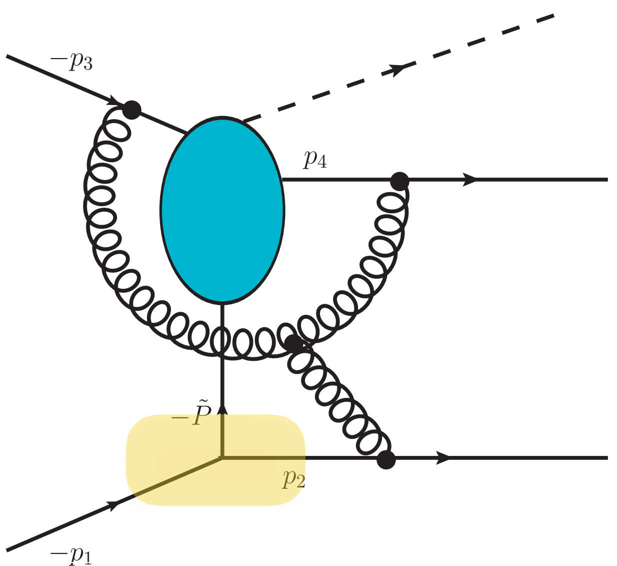

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- Factorization fails in space-like region: hadronic colliders — Catani, deF., Rodrigo (2012)

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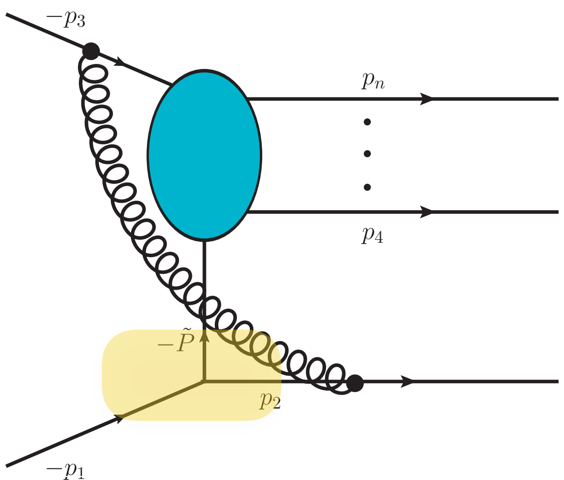

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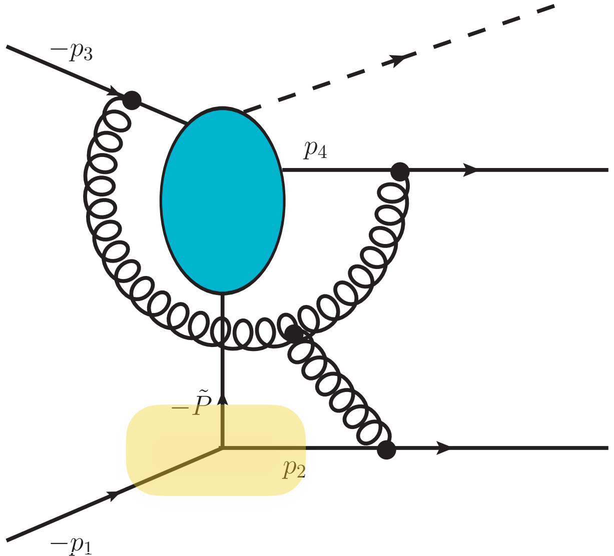

- Challenges collinear mass factorization and higher order calculations: cancellation with other contribution
- Produces super-leading logarithms in 'gaps–between–jets' cross sections