Precision phenomenology for 2→3 scattering at the LHC: Wbb and γjj final states

based on:
2205.01687 and 2209.03280 [hep-ph] (with R. Poncelet, A. Popescu, S. Zoia)
2304.06682 [hep-ph] (with S. Badger, M. Czakon, R. Moodie, T. Peraro, R. Poncelet, S. Zoia)

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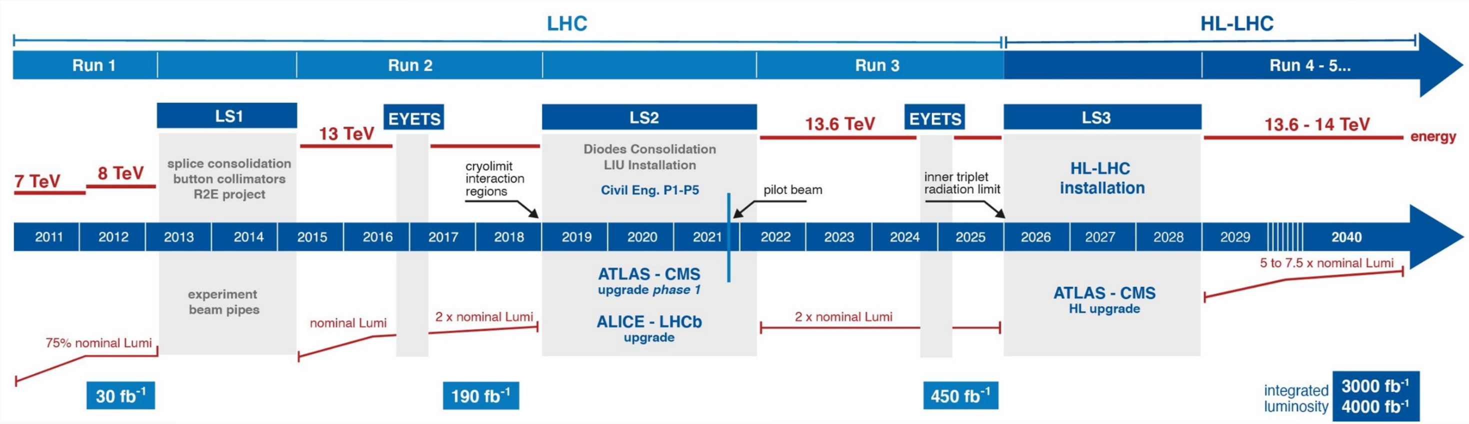
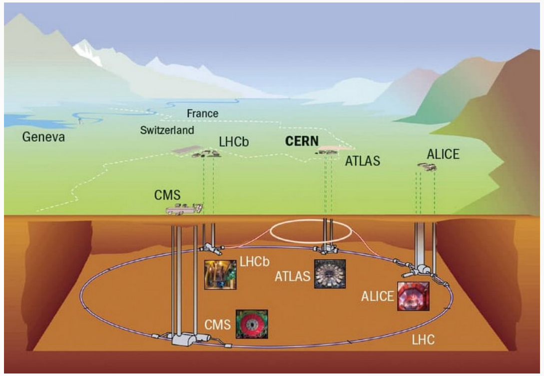
Demokritos-APCTP Meeting and HOCTOOLS-II mini-workshop
October 3rd, 2024



(https://hilumilhc.web.cern.ch/content/hl-lhc-project)



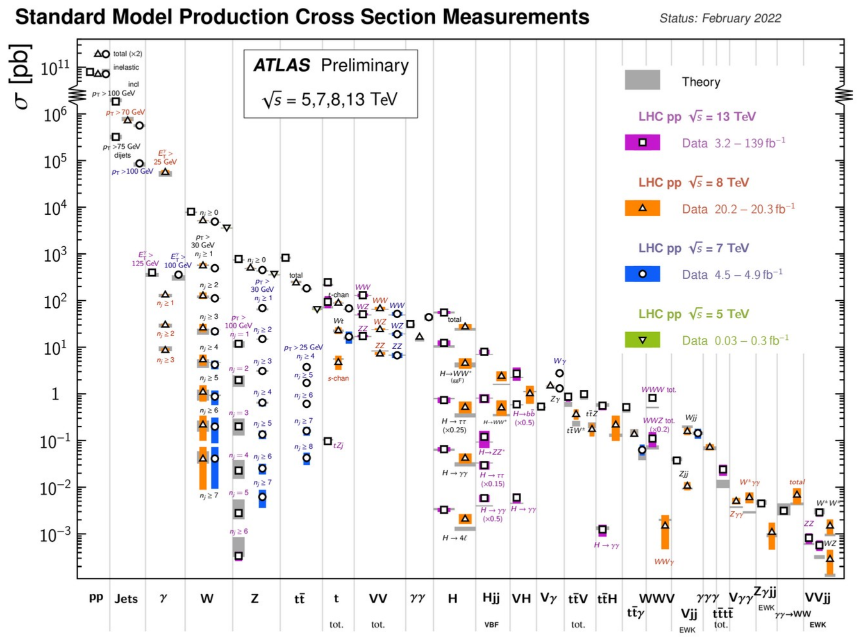
(https://physicsworld.com/a/on-the-road-to-discovery)

LHC as a precision machine

Run 1+2+3 and HL-LHC ⇒ huge amount of data

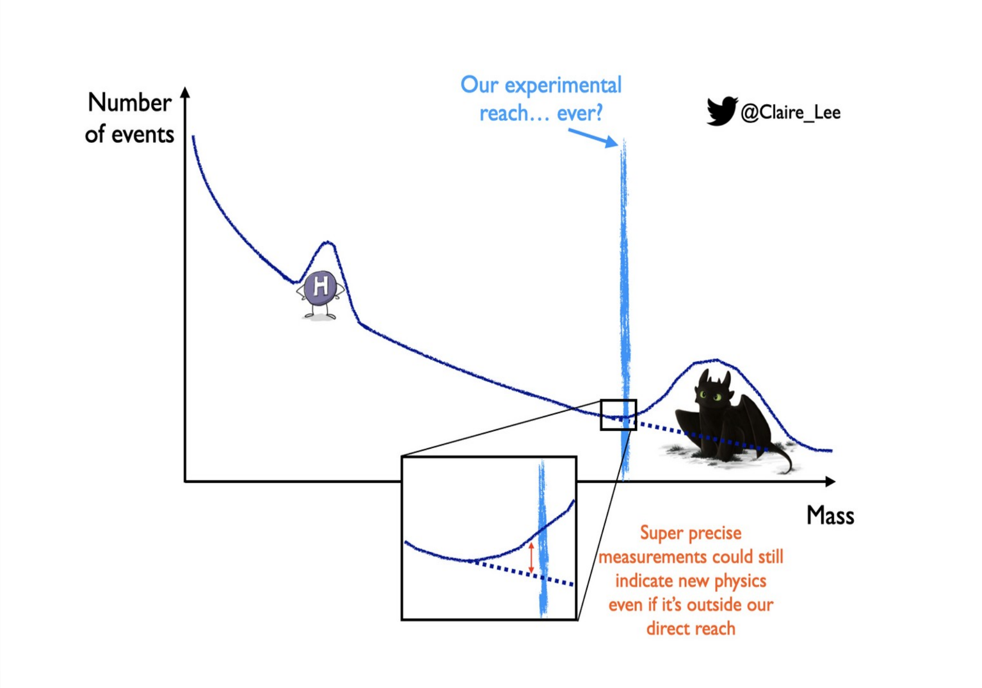
→ Small uncertainties on experimental measurements (some may reach % level accuracy)

→ Observe rare processes

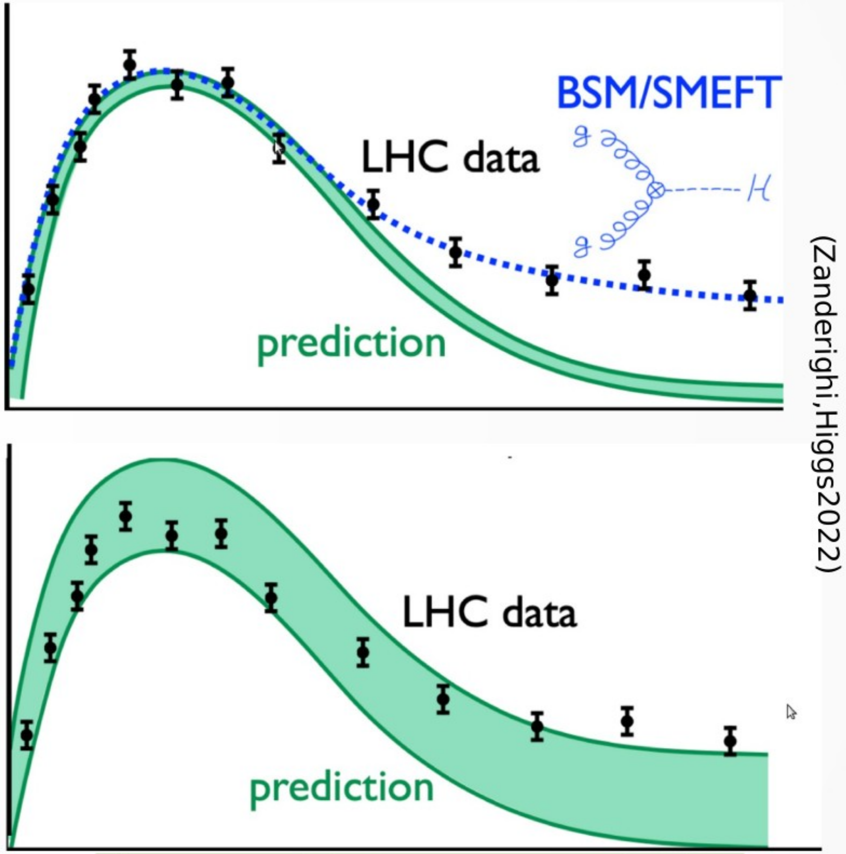


Searching for New Physics at the LHC

So far: no clear new physics signal at the current energy reach of LHC



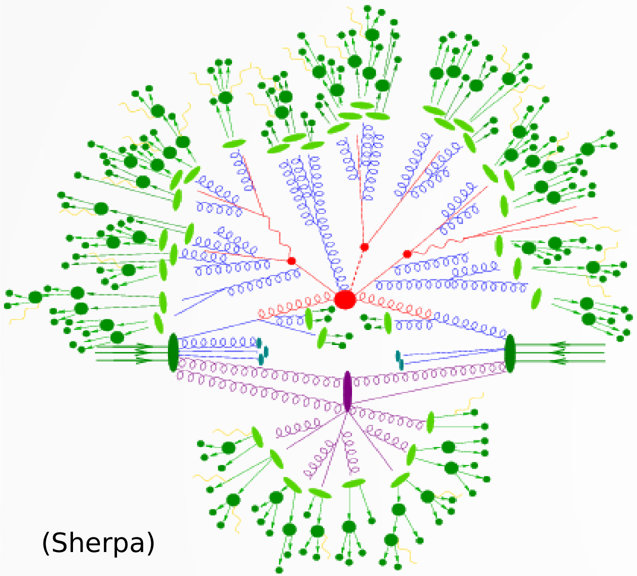
looking for deviations from SM predictions through precision measurements



theory with 5x uncertainties

(Zanderighi,Higgs2022)

Theoretical Predictions for the LHC



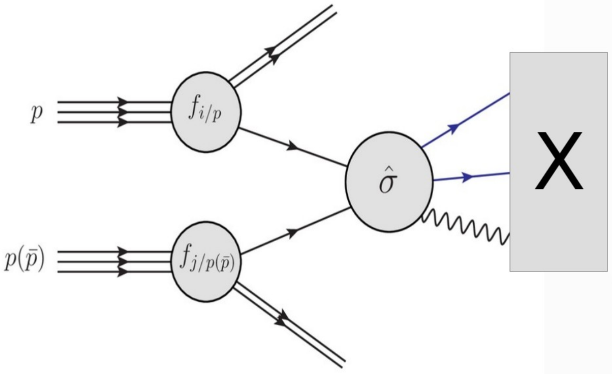
(Sherpa)

Hard scattering | Parton showers | Hadronization

Decay of Hadrons | EM bremsstrahlung | Underlying events

$\Rightarrow$ Monte Carlo event generator

Master formula for *pp* cross section:



$$d\sigma(pp \to X) = \sum_{ij} \int dx_1 dx_2 \, f_{i/p}(x_1) f_{j/p}(x_2) \, d\hat{\sigma}(ij \to X)$$

parton distribution functions (PDF) | partonic cross section

Perturbative QFT framework

Perturbative calculation of partonic cross sections

$$d\hat{\sigma} = \underbrace{d\hat{\sigma}^{(0)}}_{\text{LO}} + \underbrace{\alpha\, d\hat{\sigma}^{(1)}}_{\delta\text{NLO}} + \underbrace{\alpha^2\, d\hat{\sigma}^{(2)}}_{\delta\text{NNLO}} + \ \ldots$$

LO: Leading Order
NLO: Next-to-Leading Order
NNLO: Next-to-Next-to-Leading Order

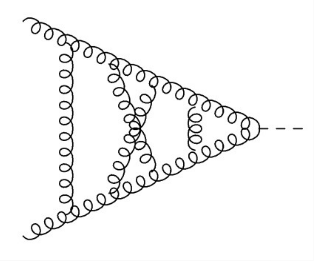
Large quantum corrections come from strong interaction (QCD) $\alpha_s\left(M_Z^2\right) \sim 0.1$

Main source of theoretical error ⇒ truncation of perturbative series (scale dependence)

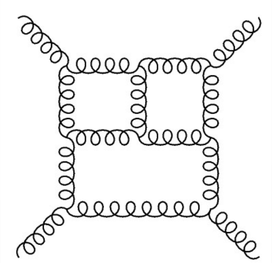
Typical theoretical error on :

LO > 50% NLO QCD ~20-30% NNLO QCD ~1-10%

Loop Frontiers

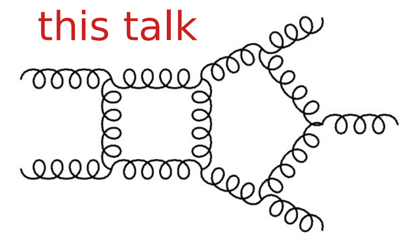


N4LO 2→1

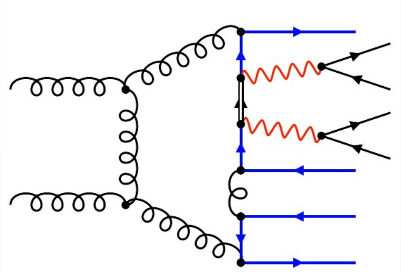


N3LO 2→2

Multiplicity Frontiers



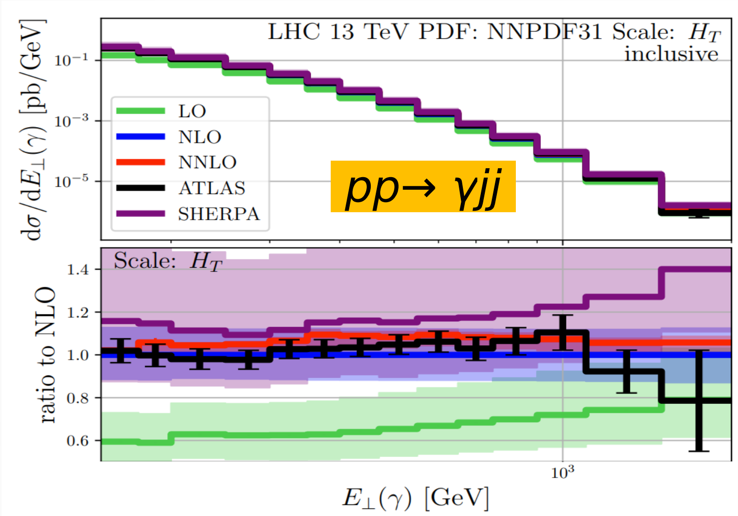
NNLO 2→3

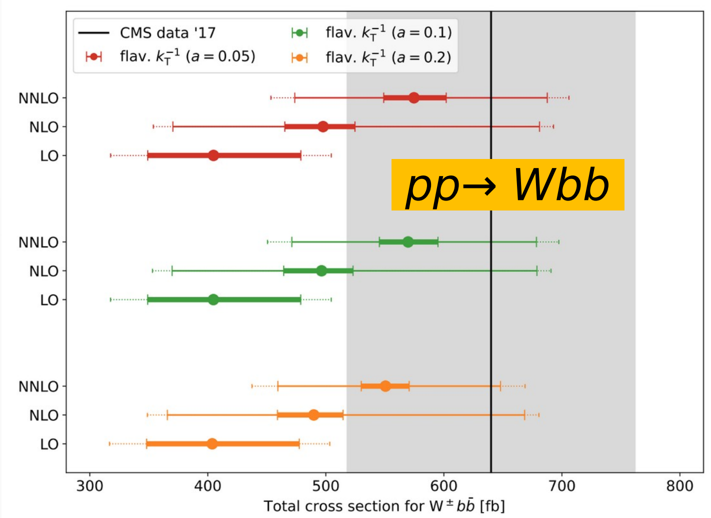


NLO 2→6

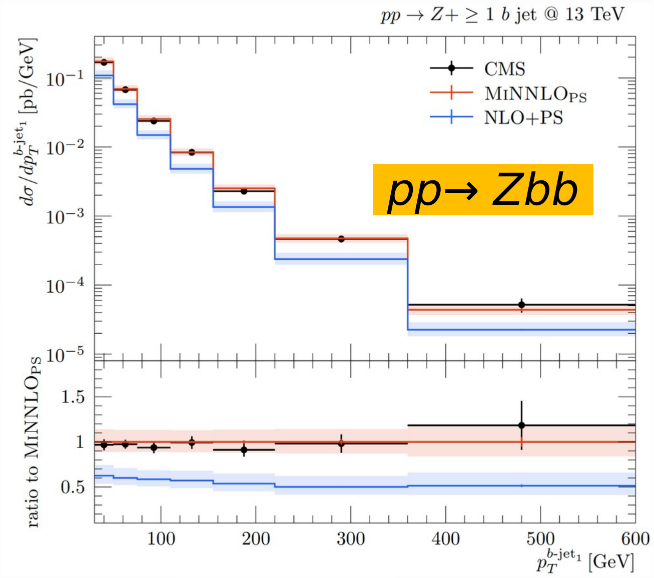
[Badger,Czakon,**HBH**,Moodie,Peraro,Poncelet,Zoia(2022)]

NNLO QCD calculation for 2→3 scattering processes

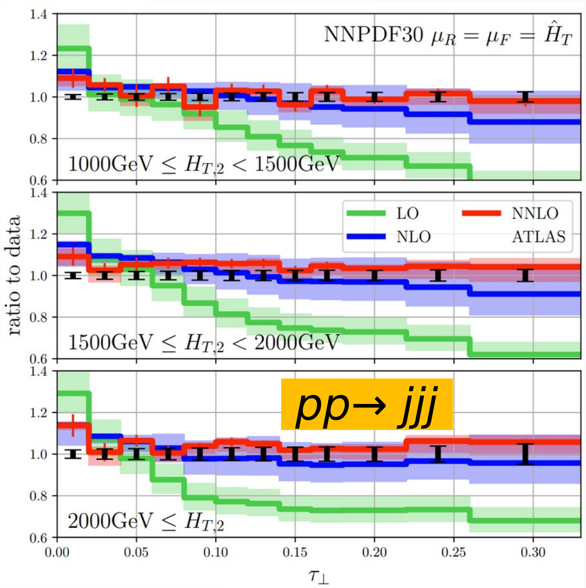




[**HBH**,Poncelet,Popescu,Zoia(2022)]



[Mazzitelli,Sotnikov,Wiesemann(2024)]



[Czakon,Mitov,Poncelet(2021)][Chen,Gehrmann,Glover,Huss,Marcoli(2022)]Alvarez,Cantero,Czakon,Llorente,Mitov,Poncelet(2023)]

also: *pp→γγγ, pp→γγj, pp→Wbb, pp→ttW, pp→ttH*

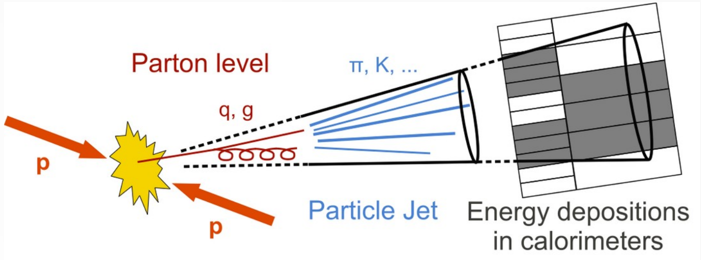
[Chawdhry,Czakon,Mitov,Poncelet(2019)][Kallweit,Sotnikov,Wiesemann(2020)]
[Czakon,Mitov,Poncelet(2020)][Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini(2022)][Buonocore,Devoto,Grazzini,Kallweit,Mazzitelli,Rottoli,Savoini(2022)]
[Catani,Devoto,Grazzini,Kallweit,Mazzitelli,Savoini(2020)]

Wbb production at NNLO QCD

HBH,Poncelet,Popescu,Zoia

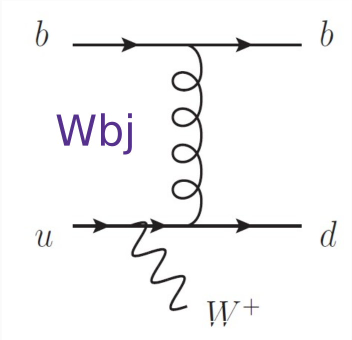
arXiv:2205.01687 and arXiv:2209.03280

W/Z+b-jets production at the LHC



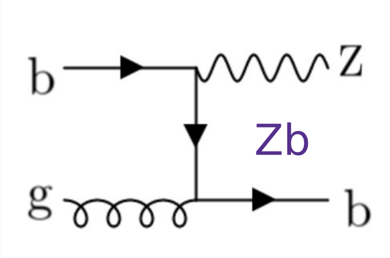
- Test perturbative QCD
- Modelling of flavoured jets (theory and experiment)
- Sensitivity to heavy flavour schemes: 4-flavour (4FS) vs 5-flavour (5FS) scheme

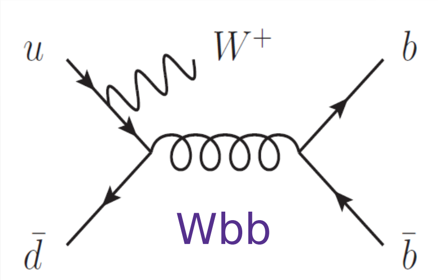
massive b (4FS) massless b (5FS)



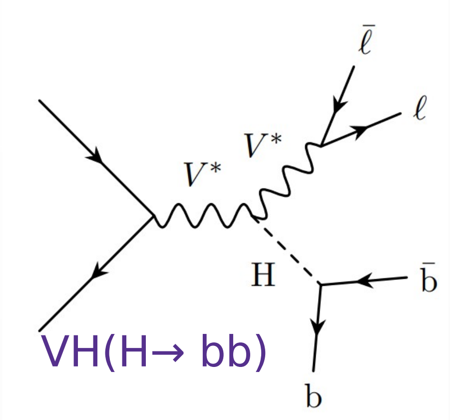
W/Z+1b jet: probe *b*-quark PDF

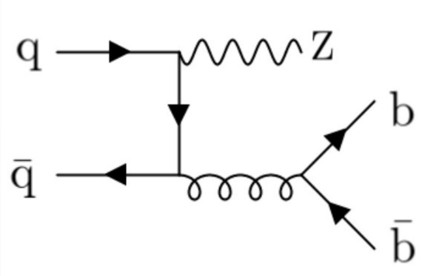
W+2b jets: background to single top production pp→bt(→bW)





W/Z+2b jets: background to VH(H→bb)



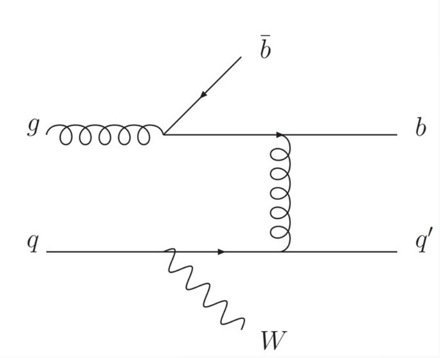


Zbb

Feynman diagrams taken from arXiv:1907.05836, arXiv:2112.09659.

W+2b+ ≤ 3j at NLO QCD

[Anger,Febres Cordero,Ita,Sotnikov;arXiv:1712.05721]

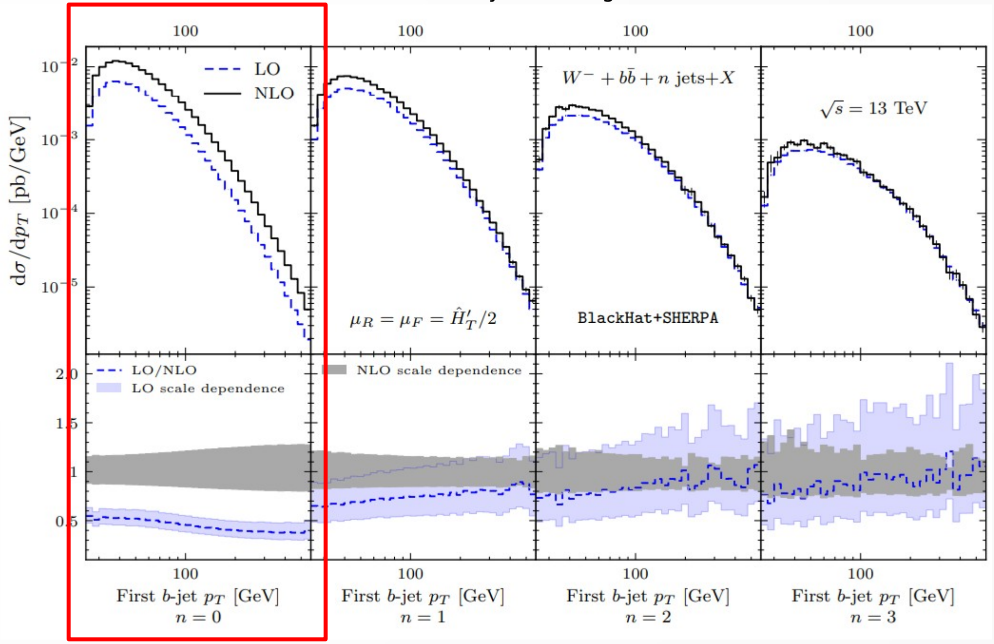


Feynman diagram from arXiv:1107.3714

Inclusive Wbb production (*pp→ Wbb+X*)

- large NLO corrections as well as large NLO scale dependence
- due to opening of qg channel (*qg→Wbb+q*)

jets	$W^- b\bar{b}$ LO	$W^- b\bar{b}$ NLO	K-factor
0	$0.33278(12)^{+0.0619}_{-0.0490}$	$0.67719(60)^{+0.1288}_{-0.1000}$	2.03
1	$0.36153(13)^{+0.1408}_{-0.0945}$	$0.50484(63)^{+0.0851}_{-0.0800}$	1.40
2	$0.18501(44)^{+0.1053}_{-0.0626}$	$0.22604(87)^{+0.0407}_{-0.0400}$	1.22
3	$0.07204(25)^{+0.0540}_{-0.0289}$	$0.08288(89)^{+0.0189}_{-0.0200}$	1.15



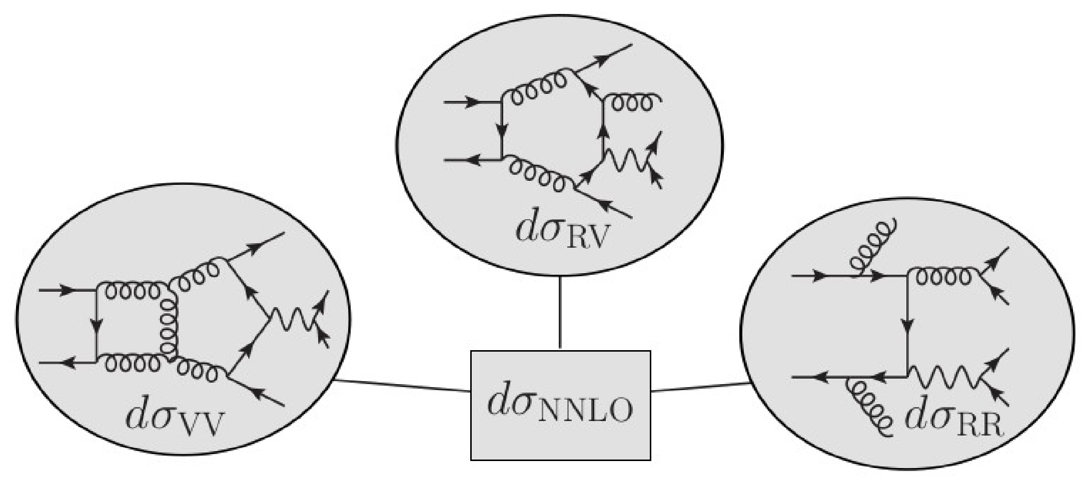
~100% NLO QCD corrections

scale dependence: 19% at LO, 20% at NLO

Calls for a NNLO QCD calculation!!

NNLO QCD corrections to W(→lυ)+bb in 5FS

NNLO QCD calculation for W+2b jets: massless b (5FS)[HBH,Poncelet,Popescu,Zoia(2022)] ← this talk
massive b (4FS)[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini(2022)]

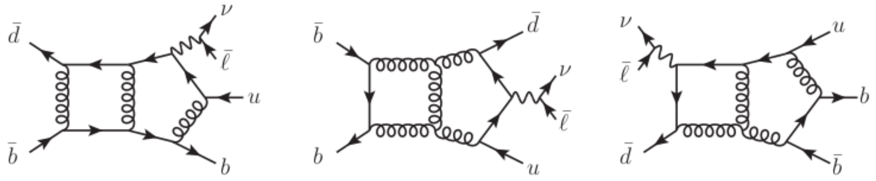


Amplitudes:

- Tree-level pp→W(→lυ)+bbjj: AvH library[Bury,van Hameren(2015)]
- One-loop pp→W(→lυ)+bbj: OpenLoops[Bucionni,Lang,Lindert,Maierhoefer,Pozzorini,Zhang,Zoller(2018,2019)]
- Two-loop pp→W(→lυ)+bb:[Abreu,Febres Cordero,Ita,Klinkert,Page(2021)][HBH,Poncelet,Popescu,Zoia(2022)]

NNLO subtraction scheme: Sector Improved Residue Subtraction Scheme (STRIPPER)[Czakon(2010)]

Two-loop amplitude for $u\bar{d} \to W^+(\to \bar{\ell}\nu)b\bar{b}$



⇒ leading colour approximation and massless b quark

⇒ compute squared matrix element

$$\sum \mathcal{M}^{(0)*}\mathcal{M}^{(2)} = M^{(2)}_{\mathrm{even}} + \mathrm{tr}_5\, M^{(2)}_{\mathrm{odd}}$$

$$\mathrm{tr}_5 = 4i\varepsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$$

employ CDR+Larin scheme to treat γ_5.

⇒ Incorporating $W \to \ell\nu$ decay

$$M_6^{(L)} = \sum_{\mathrm{spin}} A_6^{(0)\dagger} A_6^{(L)} = M_5^{(L)\mu\nu}\, \mathcal{D}_{\mu\nu}\, |P(s_{56})|^2$$

$$M_5^{(L)\mu\nu} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu} \qquad v_i^{\mu\nu} \in \{p_1^\mu, p_2^\mu, p_3^\mu, p_W^\mu\}$$

Derive analytic expressions of the finite remainders using finite-field reconstruction method

QGRAF[Nogueira], FORM[Vermaseren], LiteRed[Lee], FiniteFlow[Peraro], Mathematica

$$M_k^{(2)}(\{p\},\epsilon) = \sum_i c_{k,i}(\{p\},\epsilon)\, \mathcal{I}_{k,i}(\{p\},\epsilon)$$

↓ IBP reduction

$$M_k^{(2)}(\{p\},\epsilon) = \sum_i d_{k,i}(\{p\},\epsilon)\, \mathrm{MI}_{k,i}(\{p\},\epsilon)$$

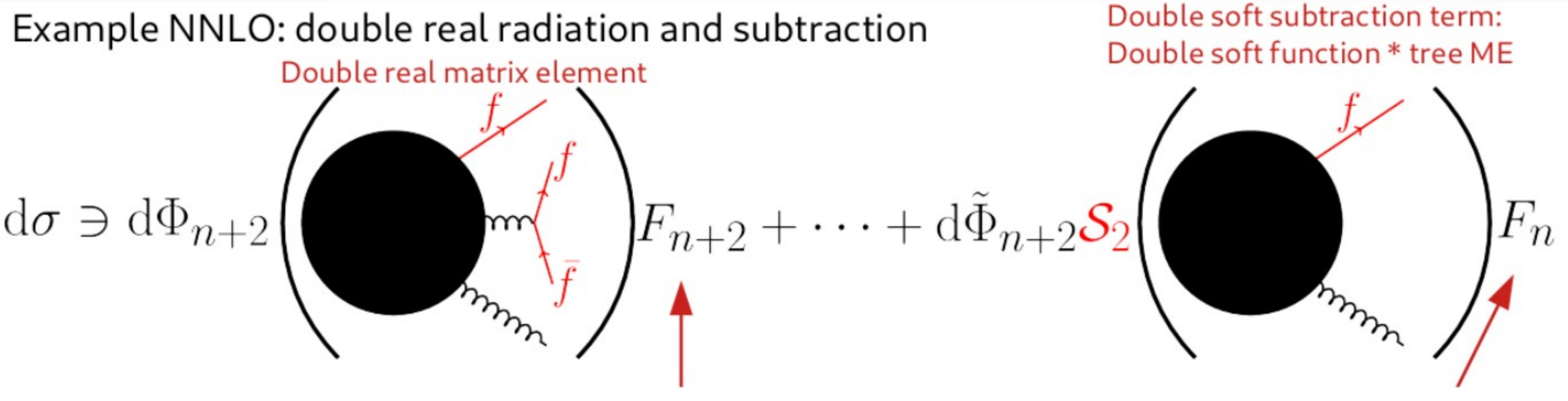
↓ map to special function basis

↓ subtract UV/IR poles

↓ ϵ expansion

$$F_k^{(2)}(\{p\}) = \sum_i e_{k,i}(\{p\})\, m_{k,i}(f) + \mathcal{O}(\epsilon)$$

Fixed-order flavoured jets beyond NLO

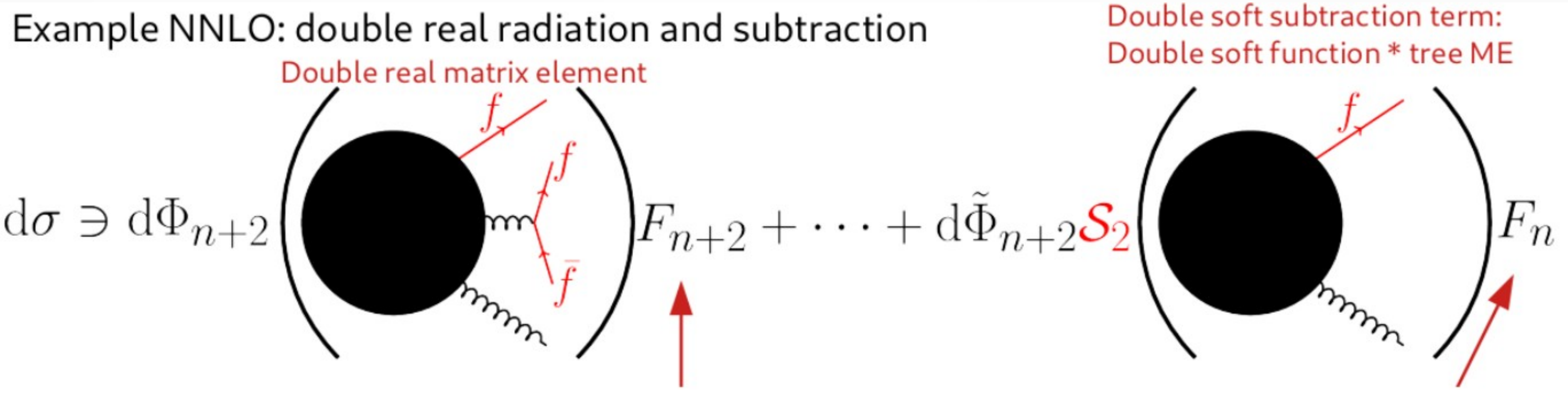


Mistreatment of flavour pair in F_{n+2} ⇒ mismatch w.r.t F_n ⇒ double soft singularity not subtracted

Solutions:

- Flavour-k_T jet algorithm [Banfi,Salam,Zanderighi(2006)] → data/theory comparison require unfolding
- Practical jet flavour through NNLO [Caletti,Larkoski,Marzani,Reichelt(2022)]
- Infrared-safe flavour anti-k_T jets [Czakon,Mitov,Poncelet(2022)]
- A dress of flavour to suit any jet [Gauld,Huss,Stagnitto(2022)]
- Flavoured jets with exact anti-k_T kinematics [Caola,Grabarczyk,Hutt,Salam,Scyboz,Thaler(2023)]

Fixed-order flavoured jets beyond NLO



Infrared-safe flavour anti-k_T jet algorithm [Czakon,Mitov,Poncelet(2022)]

→ introduce damping function to the standard anti-k_T jet algorithm

$$\mathcal{S}_{ij} = 1 - \Theta(1-x)\cdot\cos\left(\frac{\pi}{2}x\right) \leq 1 \qquad x \equiv \frac{1}{a}\,\frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2}$$

if i, j have the same non-zero flavour of opposite sign. a: tunable *softness* parameter

→ minimize the effect of unfolding

Setup (follows CMS measurement [arXiv:1608.07561])

→ **5FS**, LHC 8 TeV, PDFs: NNPDF31, cuts: $p_{T,l} > 30$ GeV, $|\eta_l| < 2.1$, $p_{T,j} > 25$ GeV, $|\eta_l| < 2.4$

→ jet algorithm: flavour-k_T [Banfi,Salam,Zanderighi(2006)] and flavour anti-k_T [Czakon,Mitov,Poncelet(2022)], R=0.5

→ central scale: $\mu_R = \mu_F = H_T$ where $H_T = E_T(l\upsilon) + p_T(b_1) + p_T(b_2)$

→ final state: inclusive (at least two b jets) and exclusive (exactly two b jets and no other jets)

→ scale uncertainties: inclusive → 7-pt variation ($\frac{1}{2} \leq \mu_R/\mu_F \leq 2$)

exclusive → 7-pt variation and uncorrelated prescription [Stewart,Tackmann(2012)]

Uncorrelated scale variations: $\sigma_{Wb\bar{b},\mathrm{exc}} = \sigma_{Wb\bar{b},\mathrm{inc}} - \sigma_{Wbbj,inc}$ $\quad \Delta\sigma_{Wb\bar{b},\mathrm{exc}} = \sqrt{\left(\Delta\sigma_{Wb\bar{b},\mathrm{inc}}\right)^2 + \left(\Delta\sigma_{Wbbj,inc}\right)^2}$

Leading colour approximation is only applied to scale independent double virtual finite remainder

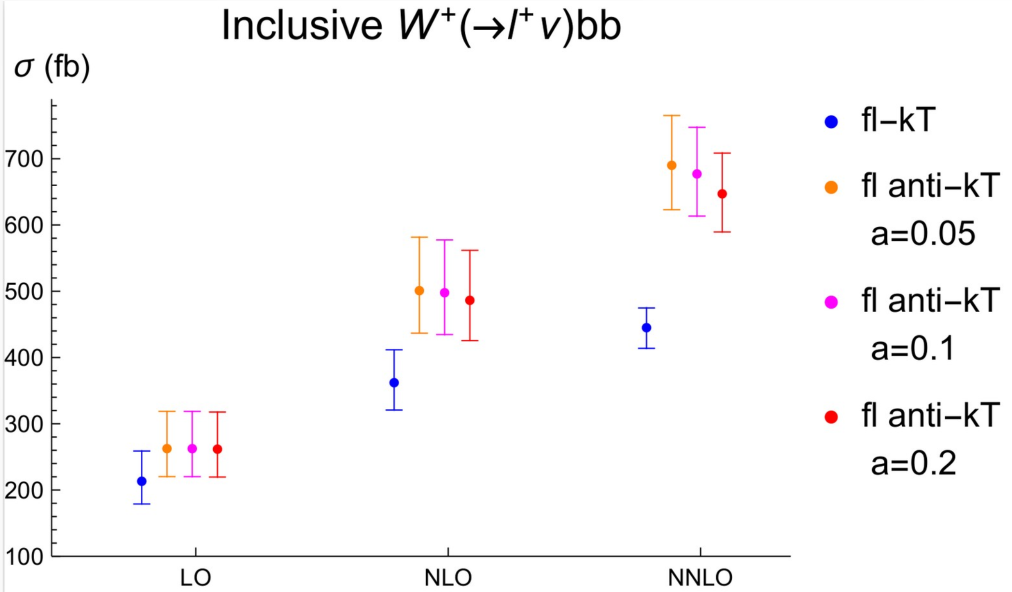
$$\mathcal{V}^{(2)}(\mu_R^2) = \mathcal{V}^{(2)}_{\mathrm{LC}}(s_{12}) + \sum_{i=1}^{4} c_i \ln^i\left(\frac{\mu_R^2}{s_{12}}\right)$$

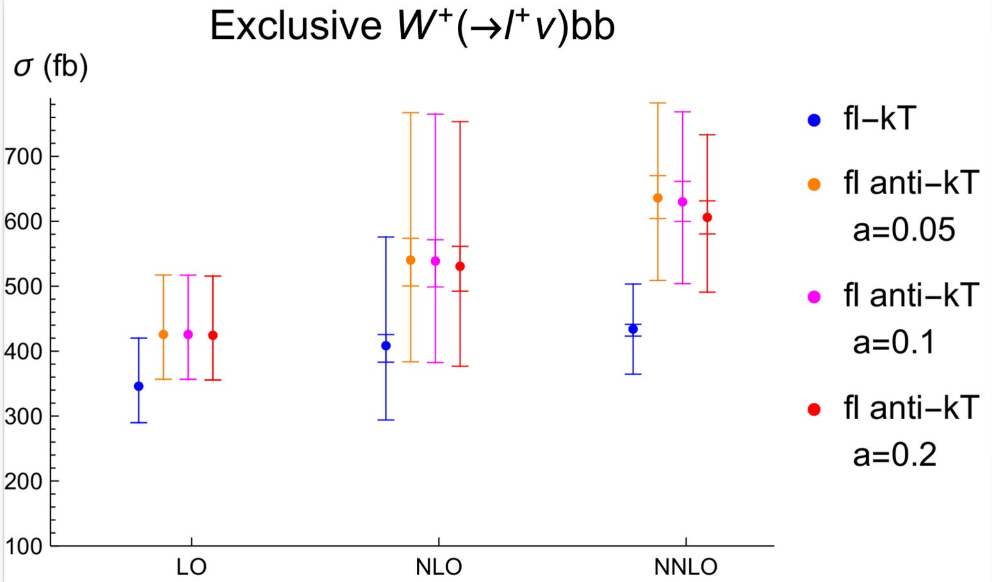
Double virtual contributions to σ: 5% (inc) 10% (exc), estimated SLC: 0.5% (inc) 1% (exc)

W+2b at NNLO QCD: massless b (5FS)

[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]

"K-factor" $\quad K_{NLO} = \sigma_{NLO}/\sigma_{LO} \quad K_{NNLO} = \sigma_{NNLO}/\sigma_{NLO}$





$$K_{\mathrm{NLO}}^{\mathrm{fl}-k_T} \sim 1.7, \quad K_{\mathrm{NLO}}^{\mathrm{fl}-k_T^{-1}} \sim 1.9$$

$$K_{\mathrm{NNLO}}^{\mathrm{fl}-k_T} \sim 1.2, \quad K_{\mathrm{NNLO}}^{\mathrm{fl}-k_T^{-1}} \sim 1.3-1.4$$

$$K_{\mathrm{NLO}}^{\mathrm{fl}-k_T} \sim 1.2, \quad K_{\mathrm{NLO}}^{\mathrm{fl}-k_T^{-1}} \sim 1.3$$

$$K_{\mathrm{NNLO}}^{\mathrm{fl}-k_T} \sim 1.1, \quad K_{\mathrm{NNLO}}^{\mathrm{fl}-k_T^{-1}} \sim 1.2$$

W+2b at NNLO QCD: massless b (5FS)

[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]

⇒ scale uncertainties: inclusive → 7-pt variation $1/2 \leq \mu_R/\mu_F \leq 2$

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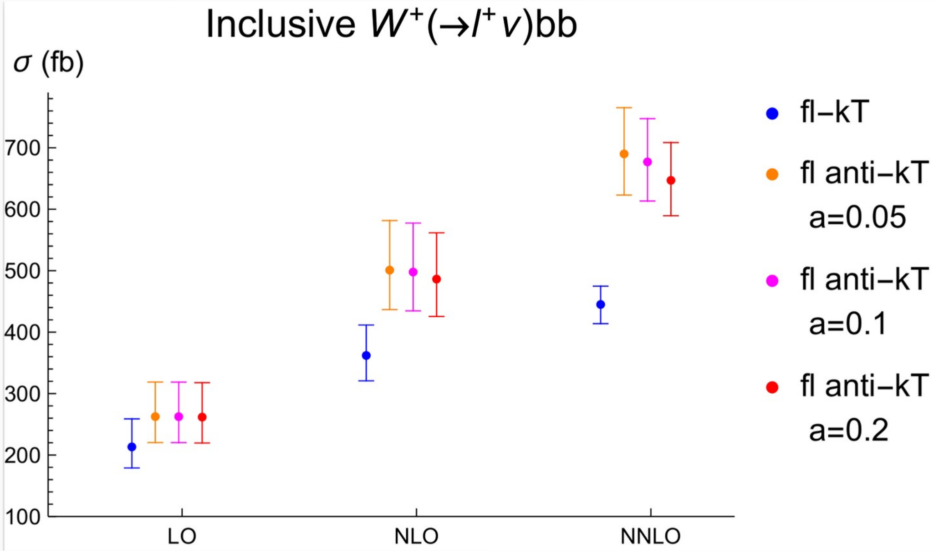
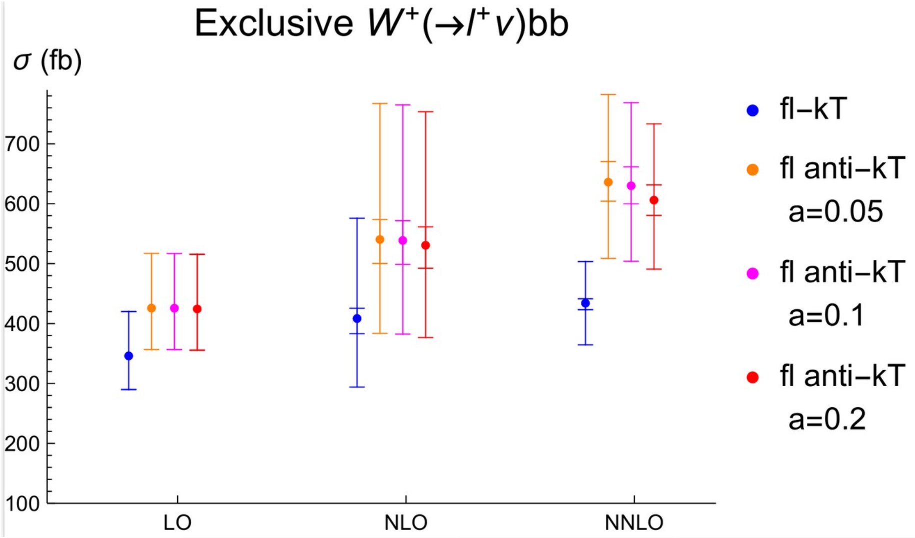
Uncorrelated scale variation $\sigma_{Wb\bar{b},\mathrm{exc}} = \sigma_{Wb\bar{b},\mathrm{inc}} - \sigma_{Wbbj,inc}$ $\Delta\sigma_{Wb\bar{b},\mathrm{exc}} = \sqrt{\left(\Delta\sigma_{Wb\bar{b},\mathrm{inc}}\right)^2 + \left(\Delta\sigma_{Wbbj,inc}\right)^2}$





$\delta^{\mathrm{fl}-k_T}_{\mathrm{scale}}$: 20%(LO), 13%(NLO), 7%(NNLO)

$\delta^{\mathrm{fl}-k_T^{-1}}_{\mathrm{scale}}$: 20%(LO), 15%(NLO), 10%(NNLO)

$\delta^{\mathrm{fl}-k_T}_{\mathrm{scale}}$: 20%(LO),6%(NLO), 3%(NNLO) → 7-pt

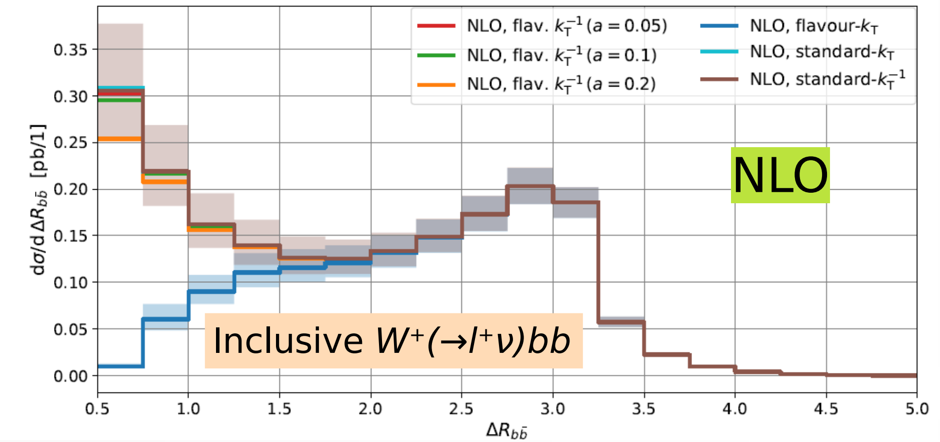
30%(NLO), 16%(NNLO) → correlated

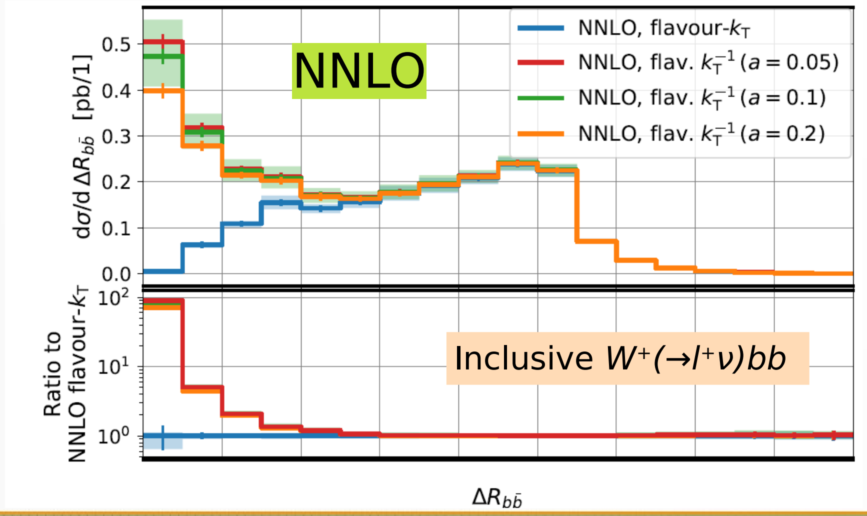
$\delta^{\mathrm{fl}-k_T^{-1}}_{\mathrm{scale}}$: 20%(LO),7%(NLO), 5%(NNLO) → 7-pt

35%(NLO), 22%(NNLO) → correlated

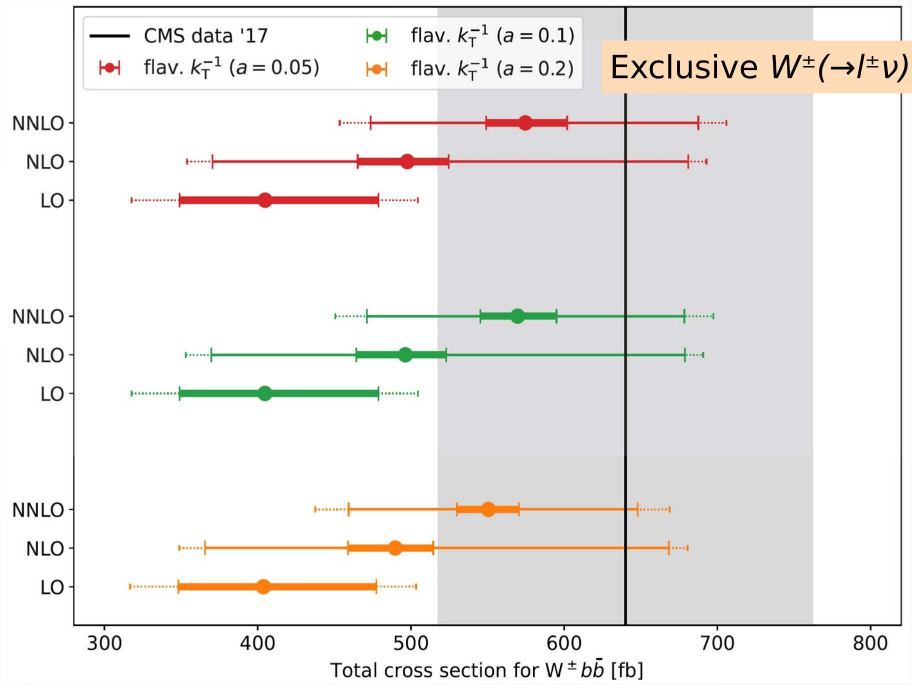
W+2b at NNLO QCD: massless b (5FS)

[HBH,Poncelet,Popescu,Zoia (arXiv:2205.01687,arXiv:2209.03280)]





- NLO: comparison to standard k_T/anti-k_T algorithm
- Supression at small ΔR_{bb} for flavour-kT algorithm



7-pt scale variation and uncorrelated presciption,
+ Hadronisation and MPI uncertainties

W+2b at NNLO QCD: massive b (4FS)

[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)]

- Two-loop amplitude with massive *b* is still out of reach
  → capture leading contributions in m_b/Q using "massification" procedure [Mitov,Moch(2007)]

$$\mathcal{M}_2^m = \mathcal{M}_2^{m=0} + Z^1_{[q]}\mathcal{M}_1^{m=0} + Z^2_{[q]}\mathcal{M}_0^{m=0}$$

Massless two-loop *ud→lνbb* amplitude from [Abreu,Febres Cordero,Ita,Klinkert,Page,Sotnikov(2021)]

$Z_{[q]}$: universal, perturbative factor, obtained from the ratio of massive to massless γ^*qq form factors

$$Z^l_{[q]} = f\left(\epsilon, \log m_b^2/Q^2\right)$$

power corrections in m_b and heavy loops contributions are not included

- Subtraction scheme: q_T slicing [Catani,Grazzini(2007)] $d\sigma_{\mathrm{NNLO}} = \mathcal{H}\otimes d\sigma_{\mathrm{LO}} + \lim_{r_{\mathrm{cut}}\to 0}[d\sigma_{\mathrm{R}} - d\sigma_{\mathrm{CT}}]_{r>r_{\mathrm{cut}}}$
- *b*-quark mass: regulates IR divergencies in the double soft limit
  → standard anti-k_T jet algorithm can be used at NNLO
- Fiducial setup follows ATLAS *VH(→bb)* boosted analysis (arXiv:2007.02873)

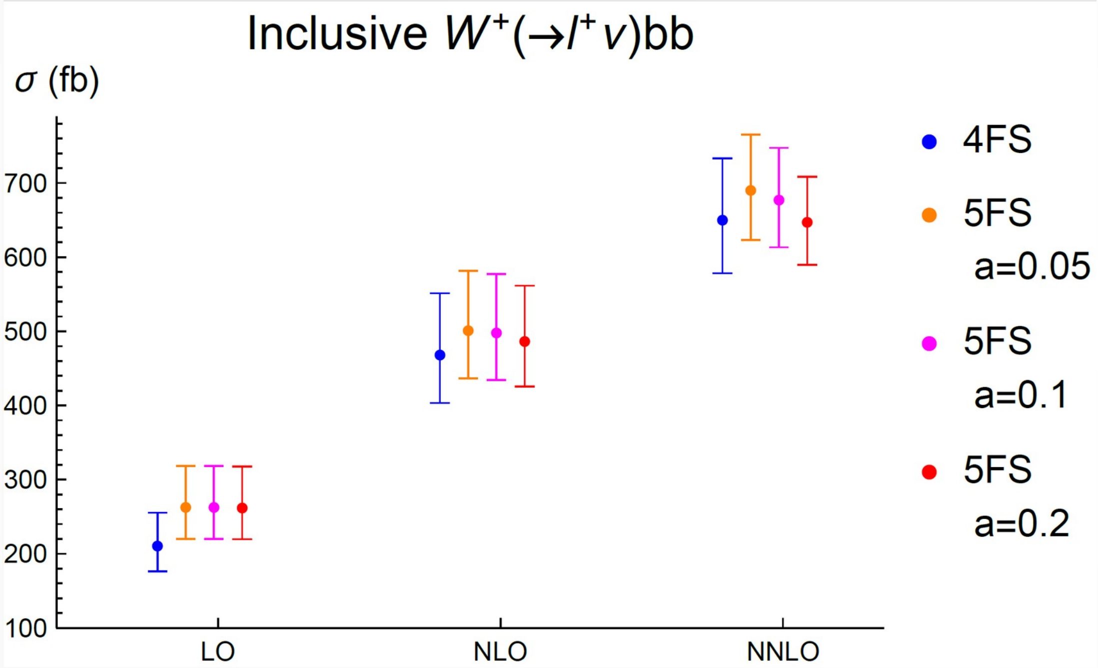
W+2b+X at 13.6 TeV, mb = 4.92 GeV, anti-k_T (and k_T) with R=0.4

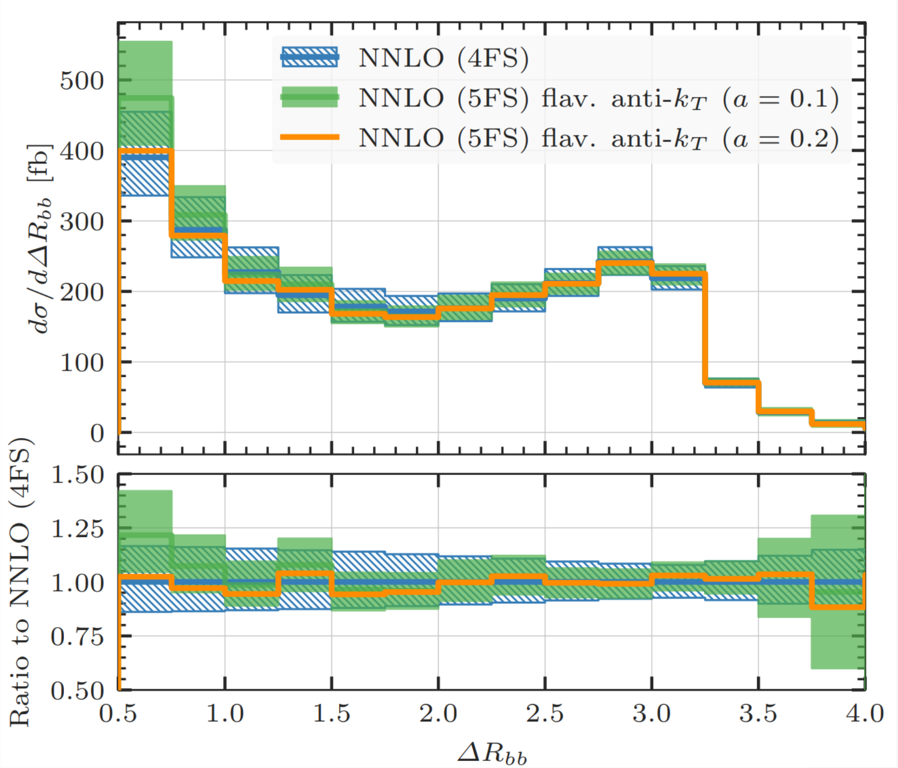
$n_b = 2$, $p_T(b_1) > 45$ GeV, $0.5 < \Delta R_{bb} < 2$

$p_T(l) > 25$ GeV, $|\eta(l)| > 2.5$, $p_T(W) > 150$ GeV, $p_T(j) > 20$ GeV if $|\eta(j)| < 2.5$ or $p_T(j) > 30$ GeV if $2.5 < |\eta(j)| < 4.5$

W+2b at NNLO QCD: 4FS vs 5FS comparison

[Buonocore,Devoto,Kallweit,Mazzitelli,Rottoli,Savoini (arXiv:2212.04954)]





→ good agreement within scale variations

γjj production at NNLO QCD

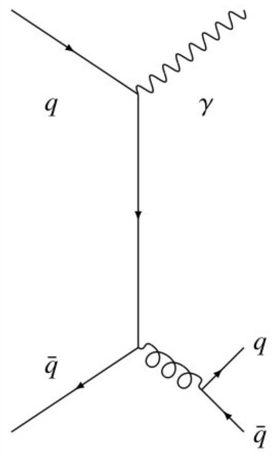
Badger, Czakon, **HBH**, Moodie, Peraro, Poncelet, Zoia

arXiv:2304.06682

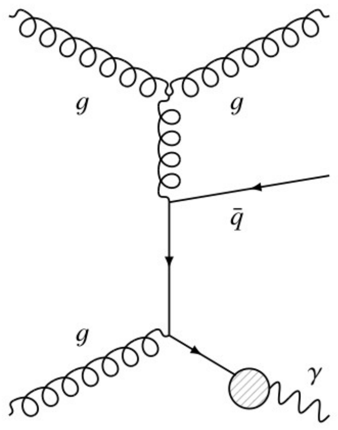
Photon production mechanisms

Prompt photon:

- photon directly produced from hard scattering
  → test of pQCD, PDF study, BSM background
- photon from fragmentation of QCD partons
  → collinear emission from final state quark
  → non-perturbative photon FF should be
  modelled/extracted from data



direct



fragmentation

Secondary photon: hadronic activities (e.g. $\pi^0 \to \gamma\gamma$) ⇒ dominant contribution!!

→ suppressed by imposing isolation cut. *Fixed-cone isolation* applied in experiment

$$E_T^{\mathrm{had}} \leq E_T^{\mathrm{max}}(p_T^{\gamma}) = \varepsilon p_T^{\gamma} + E_T^{\mathrm{thres}}$$

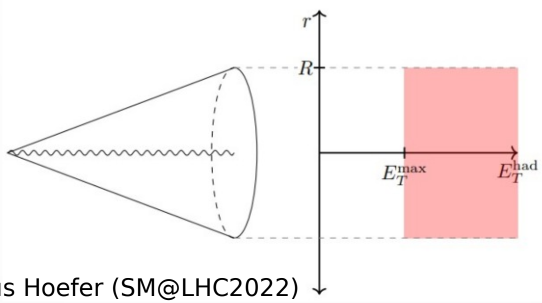
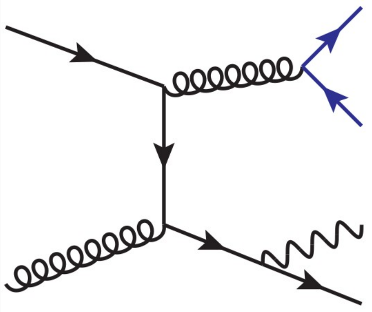


Image: Marius Hoefer (SM@LHC2022)

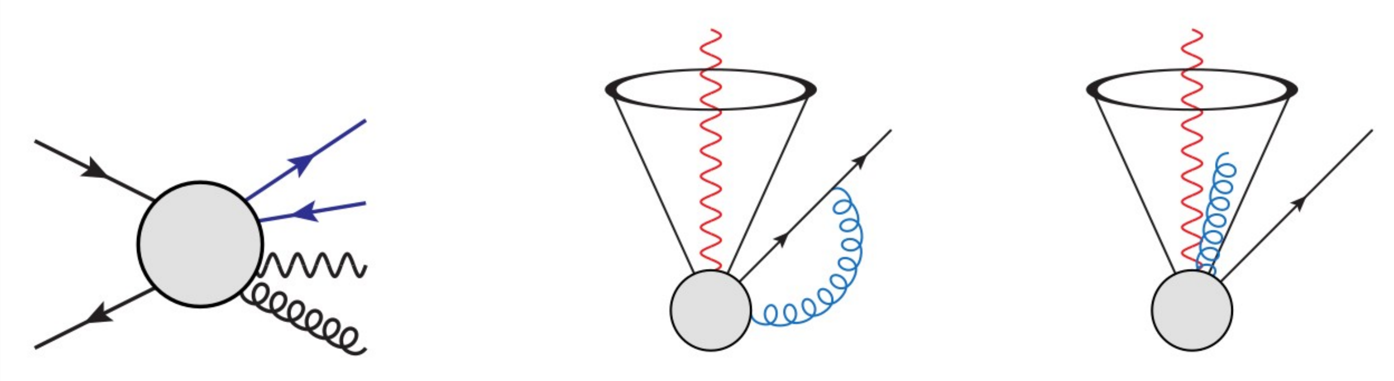
⇒ Non-vanishing fragmentation component

Quark-photon final state singularities

Real correction to pp→γjj at NLO



Vetoing radiation inside photon isolation cone (sending $E_T(max) \rightarrow 0$) leads to IR safety issue



Vetoing radiation inside photon isolation cone restricts gluon phase space, thus spoiling IR cancellation

Quark-photon final state singularities

Solution:

- Extract collinear singularities, absorb them in the photon fragmentation function

$$D_q^\gamma = -\frac{1}{\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu^2}{M_F^2}\right)^\epsilon \frac{\alpha}{2\pi} Q_q^2 P_{\gamma q}(z)$$

  The NLO cross section becomes

$$\sigma^\gamma_{NLO} = \sigma^\gamma_{NLO,\mathrm{direct}}(M_F) + \int_0^1 dz \sum_a \sigma_f^a D_{a\to\gamma}(z, M_F)$$

- Employ smooth cone isolation ala Frixione [arXiv:9801442]

$$\sum_{\mathrm{had}} E_T^{\mathrm{had}}\,\theta(R - R_{\mathrm{had},\gamma}) < \epsilon_h E_T^\gamma \left(\frac{1-\cos R}{1-\cos R_0}\right)^n \qquad \text{for all } R \le R_0$$

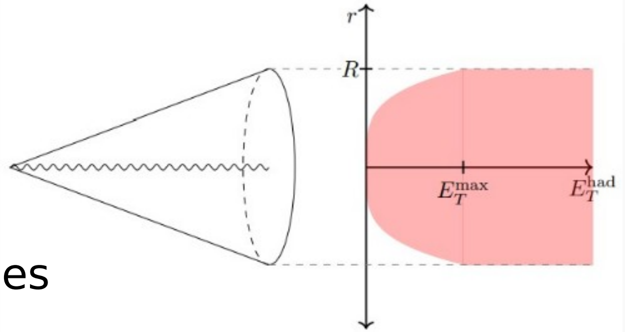


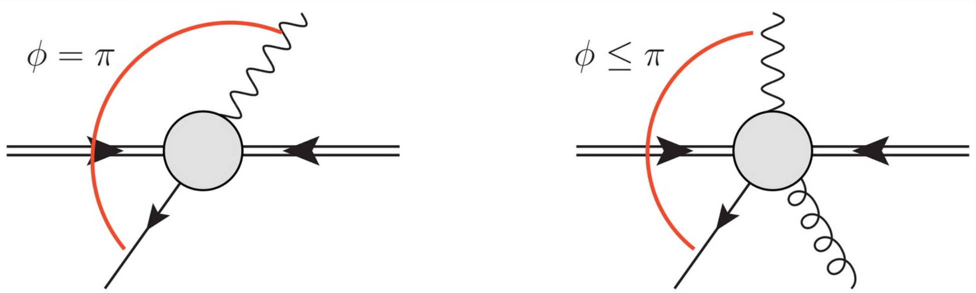
Image: Marius Hoefer (SM@LHC2022)

  - ✓ soft radiation allowed inside the cone but no collinear singularities
  - ✓ remove fragmentation contribution completely (convenient for theoretical calculation)
  - ✓ difficult to implement experimentally due to finite detector resolution

Photon + dijet production: motivation

- Access to angular correlations between photon and jets

  (photon and jet(s) are not back-to-back at tree level, similar to multijet processes)



- Study different phase-space regions due photon production mechanism

  $E_T(\gamma) > p_T(j_1)$: photon from hard interaction

  $p_T(j_1) > E_T(\gamma) > p_T(j_2)$: high z fragmentation (z: photon collinear mom fraction)

  $p_T(j_2) > E_T(\gamma)$: low z fragmentation

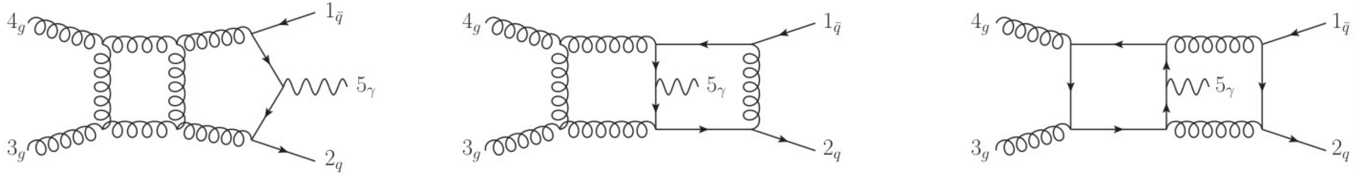
- Background to Beyond Standard Model (BSM) process

$$pp \rightarrow \gamma + Y(\rightarrow jj)$$

Two-loop QCD amplitudes for pp→γjj production

Two partonic channels: 0→qqggγ and 0→qqQQγ, computed in full colour.

Example:
0→qqggγ



$A^{(2),N_c^2}_{34;q}, A^{(2),N_c}_{\delta;q}$ — $A^{(2),1}_{34;q}, A^{(2),N_c}_{\delta;q}, A^{(2),1/N_c}_{\delta;q}$ — $A^{(2),N_c}_{34;l}, A^{(2),1/N_c}_{34;l}, A^{(2),1/N_c^2}_{\delta;l}$

Colour and (N_c,n_f) decomposition

$$\mathcal{M}^{(L)}(1_{\bar{q}}, 2_q, 3_g, 4_g, 5_\gamma) = \sqrt{2}\, e\, g_s^2\, n^L \left\{ (t^{a_3} t^{a_4})_{i_2}^{\;\bar{i}_1} \mathcal{A}^{(L)}_{34} + (t^{a_4} t^{a_3})_{i_2}^{\;\bar{i}_1} \mathcal{A}^{(L)}_{43} + \delta_{i_2}^{\;\bar{i}_1} \delta^{a_3 a_4} \mathcal{A}^{(L)}_{\delta} \right\}$$

$$\mathcal{A}^{(2)}_{34} = \mathcal{Q}_q N_c^2 A^{(2),N_c^2}_{34;q} + \mathcal{Q}_q A^{(2),1}_{34;q} + \mathcal{Q}_q \frac{1}{N_c^2} A^{(1),1/N_c^2}_{34;q} + \mathcal{Q}_q N_c n_f A^{(2),N_c n_f}_{34;q} + \mathcal{Q}_q \frac{n_f}{N_c} A^{(2),n_f/N_c}_{34;q}$$
$$+ \mathcal{Q}_q n_f^2 A^{(2),n_f^2}_{34;q} + \left(\sum_l \mathcal{Q}_l\right) N_c A^{(2),N_c}_{34;l} + \left(\sum_l \mathcal{Q}_l\right) \frac{1}{N_c} A^{(2),1/N_c}_{34;l} + \left(\sum_l \mathcal{Q}_l\right) n_f A^{(2),n_f}_{34;l}\,.$$

Amplitudes are written in terms of pentagon functions [Chicherin,Sotnikov(2019)]

analytic form of rational coefficients are derived using finite-field techniques

amplitude	helicity	original	stage 1	stage 2	stage 3	stage 4
$A^{(2),1}_{34;q}$	$-++-+$	94/91	74/71	74/0	22/18	22/0
$A^{(2),N_c^2}_{34;q}$	$-+-++$	58/55	54/51	53/0	20/16	20/0

Setup (follows ATLAS measurement)

Measurement of isolated-photon plus two-jet production in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector [arXiv:1912.09866]

Requirements on photon	$E_T^\gamma > 150$ GeV, $\lvert\eta^\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta^\gamma\rvert < 1.56$) $E_T^{\text{iso}} < 0.0042 \cdot E_T^\gamma + 4.8$ GeV (reconstruction level) $E_T^{\text{iso}} < 0.0042 \cdot E_T^\gamma + 10$ GeV (particle level)		
Requirements on jets	at least two jets using anti-k_t algorithm with $R = 0.4$ $p_T^{\text{jet}} > 100$ GeV, $\lvert y^{\text{jet}}\rvert < 2.5$, $\Delta R^{\gamma-\text{jet}} > 0.8$		
Phase space	**total**	**fragmentation enriched** $E_T^\gamma < p_T^{\text{jet2}}$	**direct enriched** $E_T^\gamma > p_T^{\text{jet1}}$
Number of events	755 270	111 666	386 846

Employ hybrid isolation

$$E_\perp(r) \leq E_{\perp\max} = 0.0042\, E_\perp(\gamma) + 10 \text{ GeV} \quad \text{for} \quad r \leq R_{\max} = 0.4$$

+

$$E_\perp(r) \leq E_{\perp\max}(r) = 0.1\, E_\perp(\gamma) \left(\frac{1-\cos(r)}{1-\cos(R_{\max})} \right)^2 \quad \text{for} \quad r \leq R_{\max} = 0.1$$

No fragmentation component, purely pQCD through NNLO

Focus on “inclusive” (total) and “direct enriched”

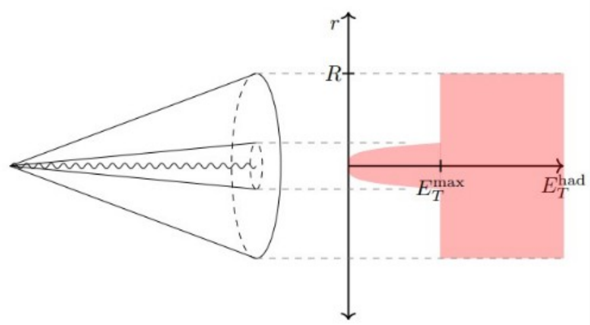


Image: Marius Hoefer (SM@LHC2022)

Data-theory comparison

$$\mu_R = \mu_F = H_T = E_\perp(\gamma) + p_T(j_1) + p_T(j_2)$$

$$\mu_R = \mu_F = E_\perp(\gamma)\ ,$$

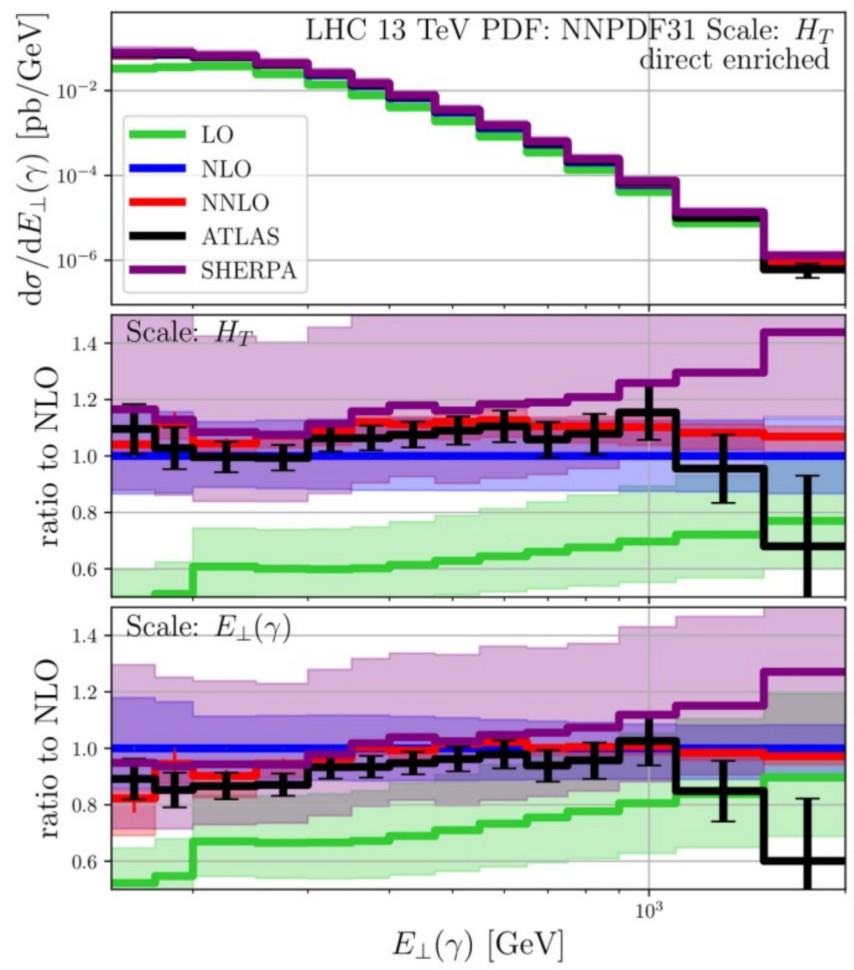
NNLO QCD prediction:

- Describe the data well
- Improved description of shape
- Small corrections
- Small scale dependence

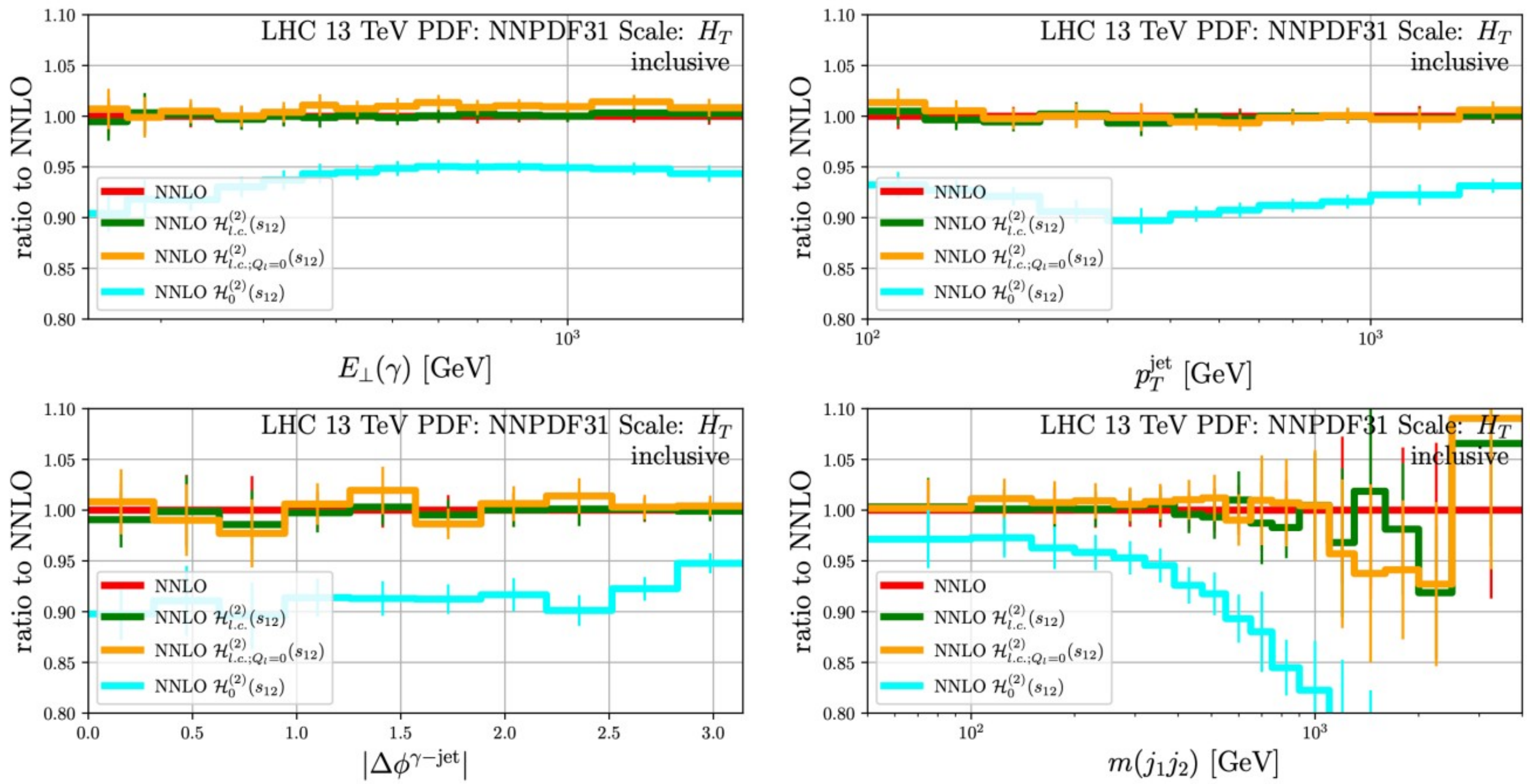
Discrepancy in the high-E_T tail:

→ due to missing EW corrections

Fragmentation contribution estimated at < 5%
⇒ from pp → γj (calculation with fragmentation vs hybrid isolation)



Double virtual corrections: subleading colour contributions



Summary

- NNLO QCD calculation for Wbb and γjj production
  → improve theoretical uncertainties, better agreement with data
- γjj production: first 2→3 NNLO QCD calculation with full colour two-loop amplitude
  → very small double virtual subleading colour contribution
- These calculations are possible thanks to:
  - (i) efficient NNLO subtraction method
  - (ii) availability of the two-loop amplitude
- Looking forward to explore other 2→3 scattering processes