Resummation and phenomenology of the Higgs transverse momentum distribution

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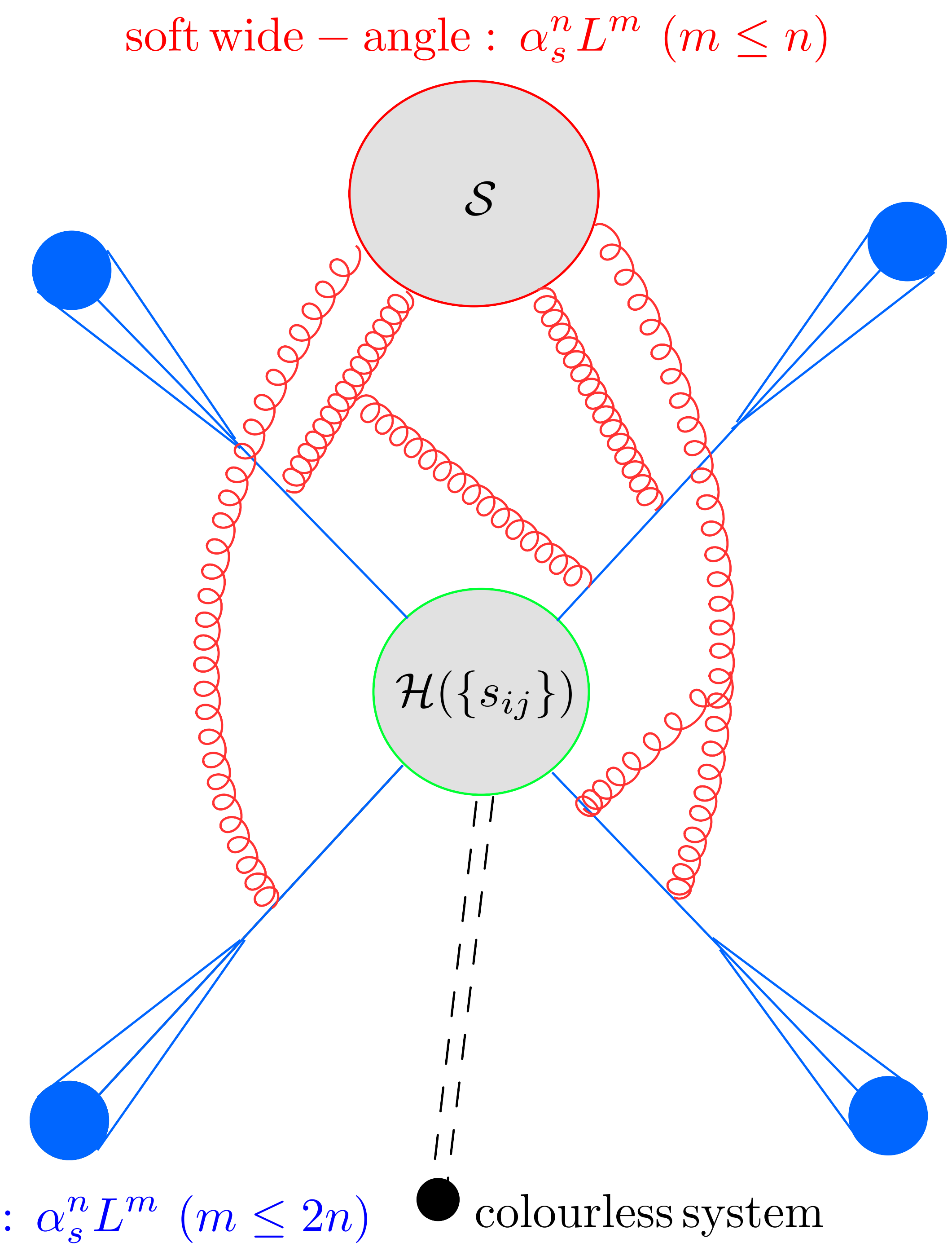
Outline

- Introduction
- rIRC safety and resummation of global observables at NNLL
- Observables with additional zeros away from the Sudakov limit
- Case study: the Higgs pT distribution
    - geometric divergences
    - generalisations and multi-differential resummations
- Light-quark Yukawa couplings from differential shapes in the production of H+jets
- Summary and conclusions

Factorisation of amplitudes in the IR

- Consider a IRC observable $V = V(\{\tilde{p}\}, k_1, ..., k_n) \leq 1$ in the Born-like limit $V \to 0$
- In this limit radiative corrections are described exclusively by virtual corrections, and collinear and/or soft real emissions (singular limit) — QCD squared **amplitudes factorise** in these regimes w.r.t. the Born, up to regular corrections
- Different observables are sensitive to different singular modes which determine the logarithmic structure of the perturbative expansion (e.g. (non) global, hard-collinear logarithms, …)
- In the limit of large logarithms and all-order treatment is necessary - effects often propagate far from the singular limit



$\mathrm{soft-collinear:}\ \alpha_s^n L^m\ (m \leq 2n)$

$\mathrm{hard-collinear:}\ \alpha_s^n L^m\ (m \leq n)$

Cases of collinear factorisation breaking due to exchange of Glauber modes found at high orders in multi-leg squared amplitudes

[Forshaw, Kyrieleis, and Seymour ’06-’09]

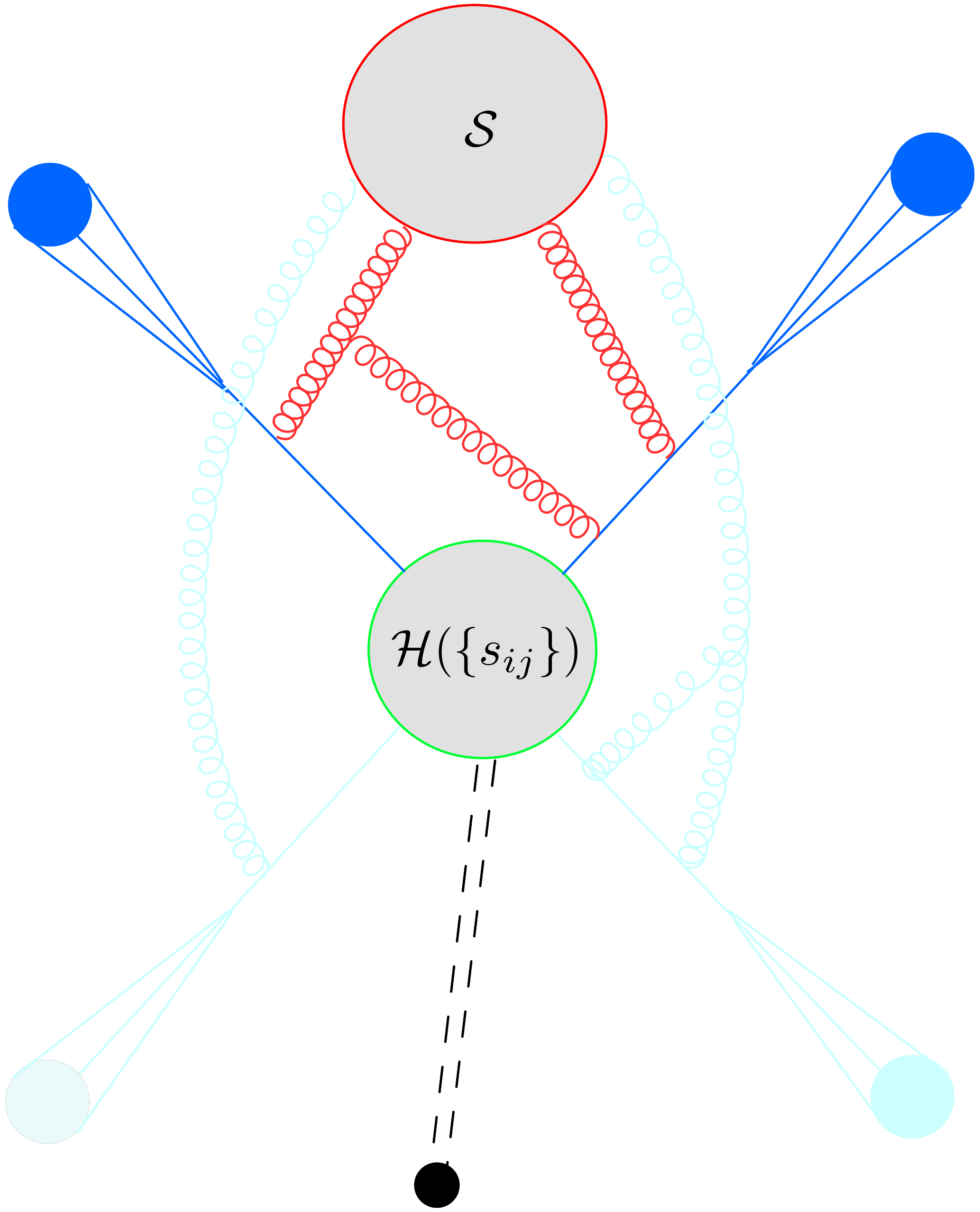
[Catani, de Florian, and Rodrigo ’12]

[Forshaw, Seymour, and Siodmok ’12]

[Angeles-Martinez, Forshaw, and Seymour ’15-‘16]

Two-emitter processes

- The strong angular separation between different modes ensures they evolve independently at late times after the collision
- The structure of the coherent soft radiation at large angles (interference between emitters) gets increasingly complex with the number of emitting legs



Two-emitter processes

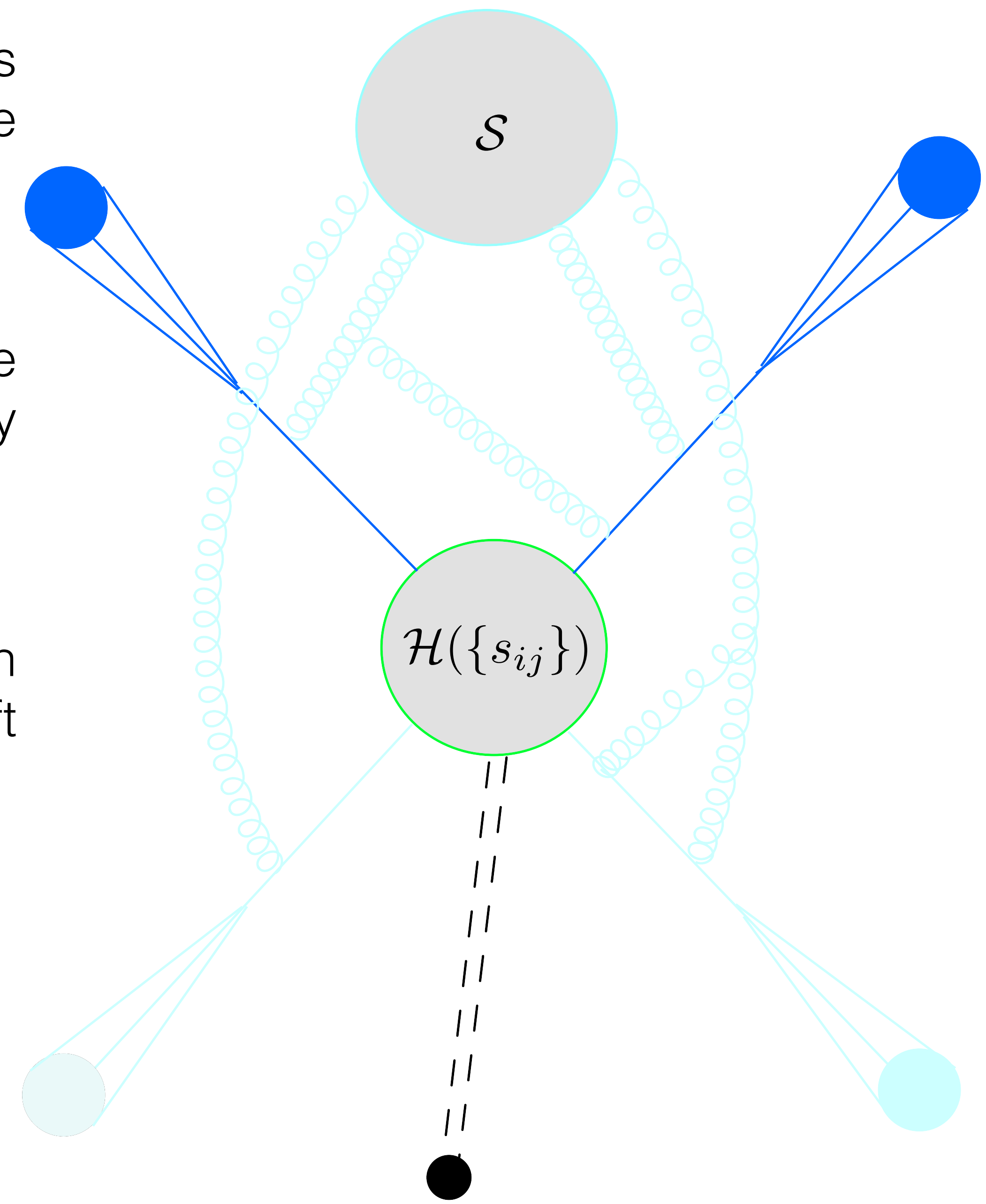
- The strong angular separation between different modes ensures they evolve independently at late times after the collision

- The structure of the coherent soft radiation at large angles (interference between emitters) gets increasingly complex with the number of emitting legs

- For continuously global observables in processes with two emitters, colour coherence forces the effect of soft modes exchanged with large angles to vanish

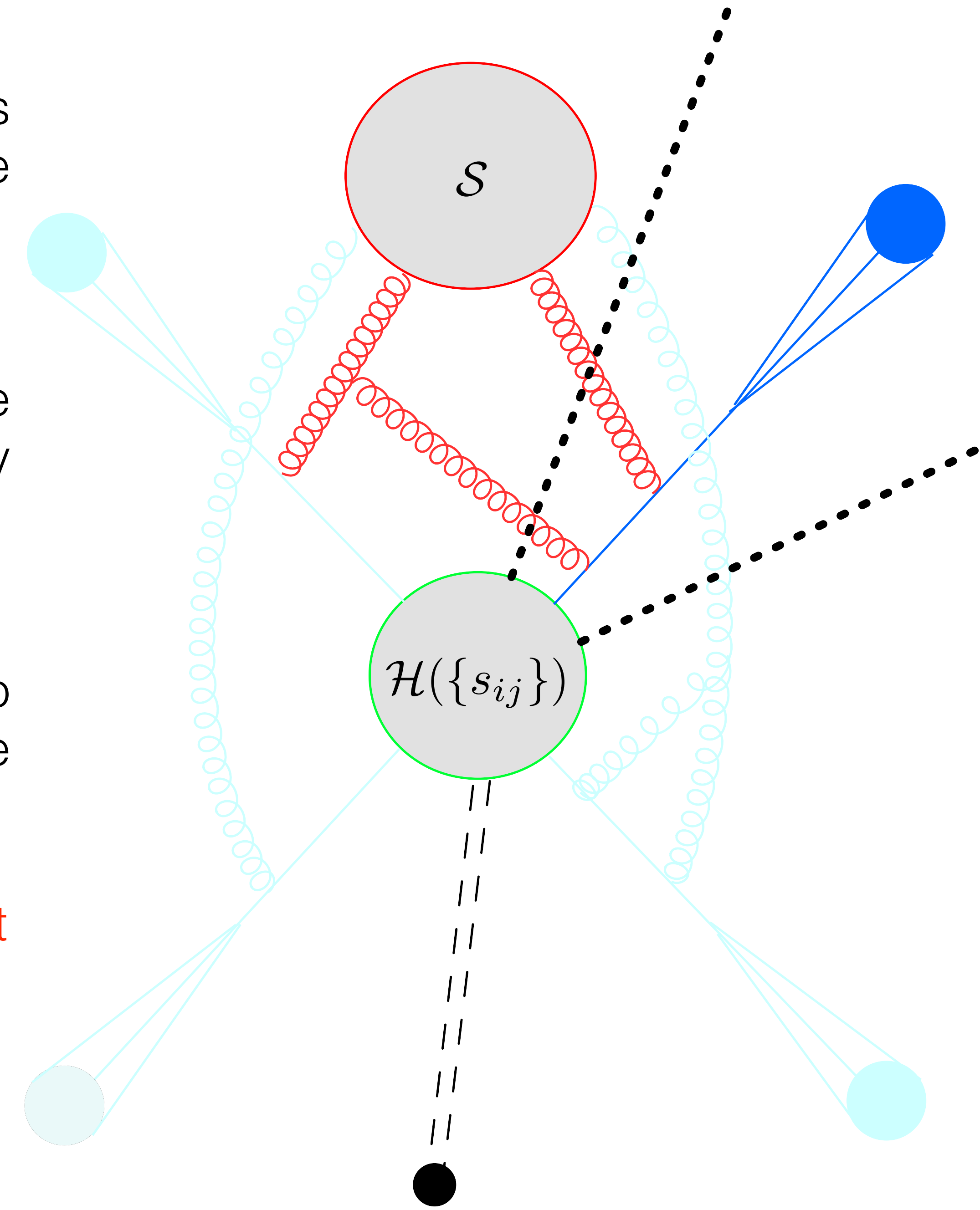
    - Only collinear (soft/hard) modes effectively remain

    - Soft modes can be absent in specific cases



Non-Global observables

- The strong angular separation between different modes ensures they evolve independently at late times after the collision
- The structure of the coherent soft radiation at large angles (interference between emitters) gets increasingly complex with the number of emitting legs
- For non-global observables one is always sensitive to the full evolution of the soft radiation outside of the resolved phase-space region
  - In general both soft and collinear modes are present
  - Collinear modes are absent for some observables



[Dasgupta, Salam '01; Banfi, Marchesini, Smye '02]
[Caron-Huot '15-'16; Larkoski, Moult, Neill '15; Becher, Neubert, Rothen, Shao '15-'16]

IRC safety

- Parametrisation for single emission and collinear splitting

$$V(\{\tilde{p}\}, \kappa_i(\zeta_i)) = \zeta_i\,; \qquad \kappa_i(\zeta) \to \{\kappa_{ia}, \kappa_{ib}\}(\zeta, \mu)\,,\ \mu^2 = (\kappa_{ia} + \kappa_{ib})^2/\kappa_{ti}^2$$

- The standard requirement of IRC safety implies that

$$\lim_{\zeta_{m+1}\to 0} V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \dots, \kappa_m(\bar{v}\zeta_m), \kappa_{m+1}(\bar{v}\zeta_{m+1})) = V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \dots, \kappa_m(\bar{v}\zeta_m))$$

$$\lim_{\mu\to 0} V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \dots, \{\kappa_{ia}, \kappa_{ib}\}(\bar{v}\zeta_i, \mu), \dots \kappa_m(\bar{v}\zeta_m)) = V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \dots, \kappa_i(\bar{v}\zeta_i), \dots \kappa_m(\bar{v}\zeta_m))$$

rIRC safety

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- Impose the following conditions, known as recursive IRC (rIRC) safety

$$\lim_{\bar{v} \to 0} \frac{1}{\bar{v}} V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \ldots, \kappa_m(\bar{v}\zeta_m)) \qquad (1)$$

  - The above limit must be well defined and non-zero (except possibly in a phase space region of zero measure)

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$$\lim_{\mu\to 0} \lim_{\bar{v}\to 0} \frac{1}{\bar{v}} V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \ldots, \{\kappa_{ia}, \kappa_{ib}\}(\bar{v}\zeta_i, \mu), \ldots \kappa_m(\bar{v}\zeta_m))$$

$$= \lim_{\bar{v}\to 0} \frac{1}{\bar{v}} V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \ldots, \kappa_i(\bar{v}\zeta_i), \ldots \kappa_m(\bar{v}\zeta_m)) \qquad (2.b)$$

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- Impose the following conditions, known as recursive IRC (rIRC) safety

- These conditions imply the existence of an observable-independent cutoff below which emissions are unresolved. They lead to:
  - the exponentiation of the IRC divergences and allow one to subtract them at all orders at once
  - the existence of a logarithmic ordering in the real-emission squared amplitudes that allows one to devise a resummation machinery

$$\lim_{\mu\to 0}\lim_{\bar{v}\to 0}\frac{1}{\bar{v}}V(\{\tilde{p}\}, \kappa_1(\bar{v}\zeta_1), \dots, \{\kappa_{ia}, \kappa_{ib}\}(\bar{v}\zeta_i, \mu), \dots \kappa_m(\bar{v}\zeta_m))$$

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Resummation of global observables

- A generic cumulative cross section can be parametrised as

$$\Sigma(v) = \sigma_0 \int \frac{dv_1}{v_1} D(v_1) P(v|v1), \qquad D(v_1) = e^{-R(v_1)} R'(v_1)$$

Probability of emitting the hardest parton v1 = v(k1)

Probability of secondary radiation given the first emission, and the observable's value v

- Assume that the integral is dominated by v1~v (true for most observables)

$$\Sigma(v) \simeq \sigma_0 e^{-R(v)} \int \frac{dv_1}{v_1} R'(v) \left(\frac{v_1}{v}\right)^{R'(v)} P(v|v_1) = \sigma_0 e^{-R(v)} \left(\mathcal{F}_{\rm NLL}(v) + \dots\right), \qquad P(v|v_1) = f\left(\ln \frac{v}{v_1}\right)$$

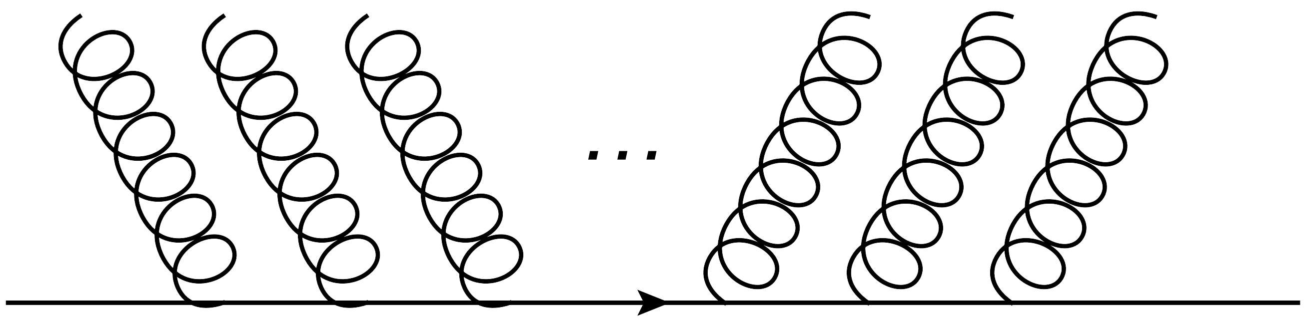
Integral over v1 evaluated analytically (neglect any subleading effects)

Higher-order corrections

- rIRC safety guarantees:
  - the cancellation of IRC singularities at all orders in the probability $P(v|v1)$
  - all leading logarithms $(\alpha_s^n \ln^{n+1}(1/v))$ exponentiate $\rightarrow e^{-R(v)}$
    - the multiple-emission function $\mathcal{F}_{\rm NLL}(v)$ is at most NLL
  - a logarithmic hierarchy in the real emission probability (e.g. see backup) —> At NLL only independent emissions contribute to $\mathcal{F}_{\rm NLL}(v)$

Resummation of global observables

- NLL general answer: ensemble of soft-collinear gluons independently emitted and widely separated in rapidity



[Banfi, Salam, Zanderighi '01-'04]

$$= \int d\mathcal{Z}[\{R'_{\mathrm{NLL},\ell_i}, k_i\}]\,\Theta\left(1 - \lim_{v\to 0}\frac{V_{\mathrm{sc}}(\{\tilde{p}\},\{k_i\})}{v}\right)$$

$$\mathcal{F}_{\mathrm{NLL}}(v) = \langle\Theta(1 - \lim_{v\to 0}\frac{V_{\mathrm{sc}}(\{\tilde{p}\},\{k_i\})}{v})\rangle$$

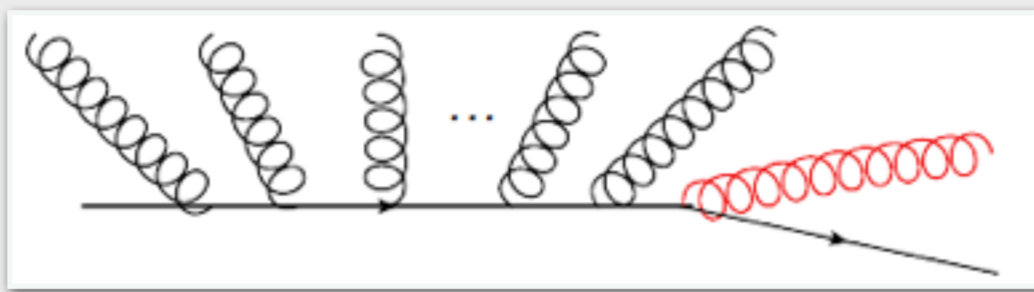
- Structure of NNLL corrections more involved: probe less singular kinematic configurations in the amplitudes and phase space

[Banfi, McAslan, PM, Zanderighi '14-'16]

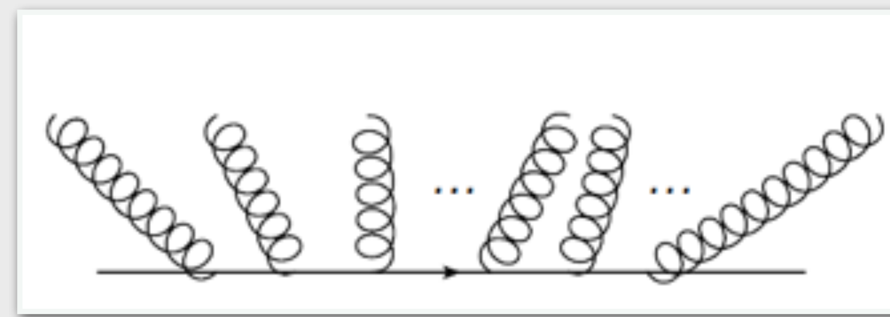
$$\Sigma(v) = \sigma_0 e^{-R(v)}\left[\mathcal{F}_{\mathrm{NLL}} + \frac{\alpha_s}{\pi}\left(\delta\mathcal{F}_{\mathrm{rap}} + \delta\mathcal{F}_{\mathrm{wa}} + \delta\mathcal{F}_{\mathrm{hc}} + \delta\mathcal{F}_{\mathrm{rec}} + \delta\mathcal{F}_{\mathrm{clust}} + \delta\mathcal{F}_{\mathrm{correl}}\right)\right]$$

General structure of NNLL

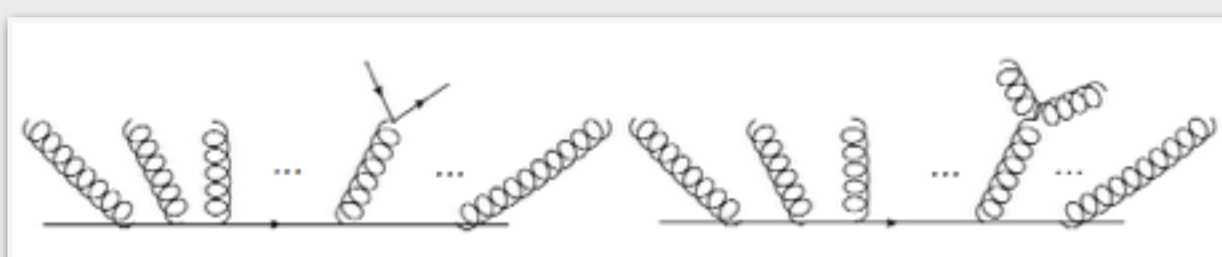
- (at most) one collinear emission can carry a significant fraction of the energy of the hard emitter (which recoils against it)
  - correction to the amplitude: hard-collinear corrections
  - correction to the observable: recoil corrections



- (at most) one soft-collinear emission is allowed to get arbitrarily close in rapidity to any other of the ensemble (relax strong angular ordering)
  - sensitive to the exact rapidity bounds: rapidity corrections
  - different clustering history if a jet algorithm is used: clustering corrections



- (at most) one soft-collinear gluon is allowed to branch in the real radiation, and the branching is resolved (correction to the CMW scheme for the running coupling)
  - correlated corrections



- (at most) one soft emission is allowed to propagate at small rapidities
  - soft-wide-angle corrections

- Non-trivial abelian correction (~Cf^n, Ca^n) for processes with two emitting legs at the Born level (it simply amounts to accounting for the correct rapidity dependence for one emission) - non-abelian contribution entirely absorbed into running coupling

- Non-abelian structure more involved in the multi leg case due to quantum interference between hard emitters (general formulation at NLL, still unknown at NNLL)

General structure of NNLL

- (at most) one collinear emission can carry a significant fraction of the energy of the hard emitter (which recoils against it)
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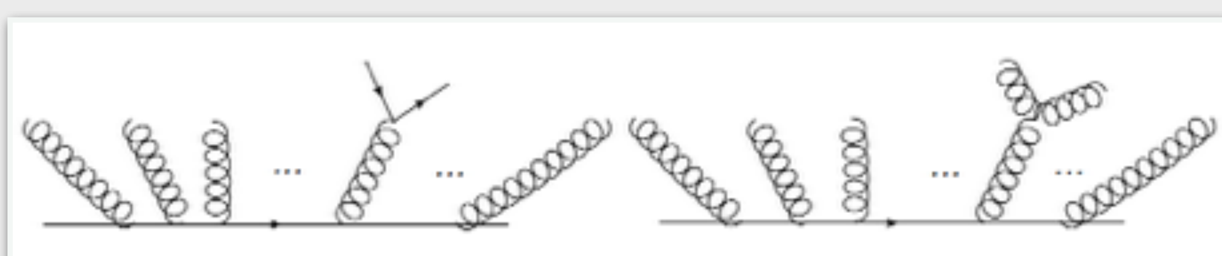
- use strategy of regions on amplitudes and observable to single out each contribution avoiding double-counting
- all corrections finite in four dimensions -> subtraction of IRC singularities local
- Fast numerical implementation and natural automation for any rIRC safe observable
- Extension to processes with more than 2 legs requires a more general treatment of the soft-wide-angle region



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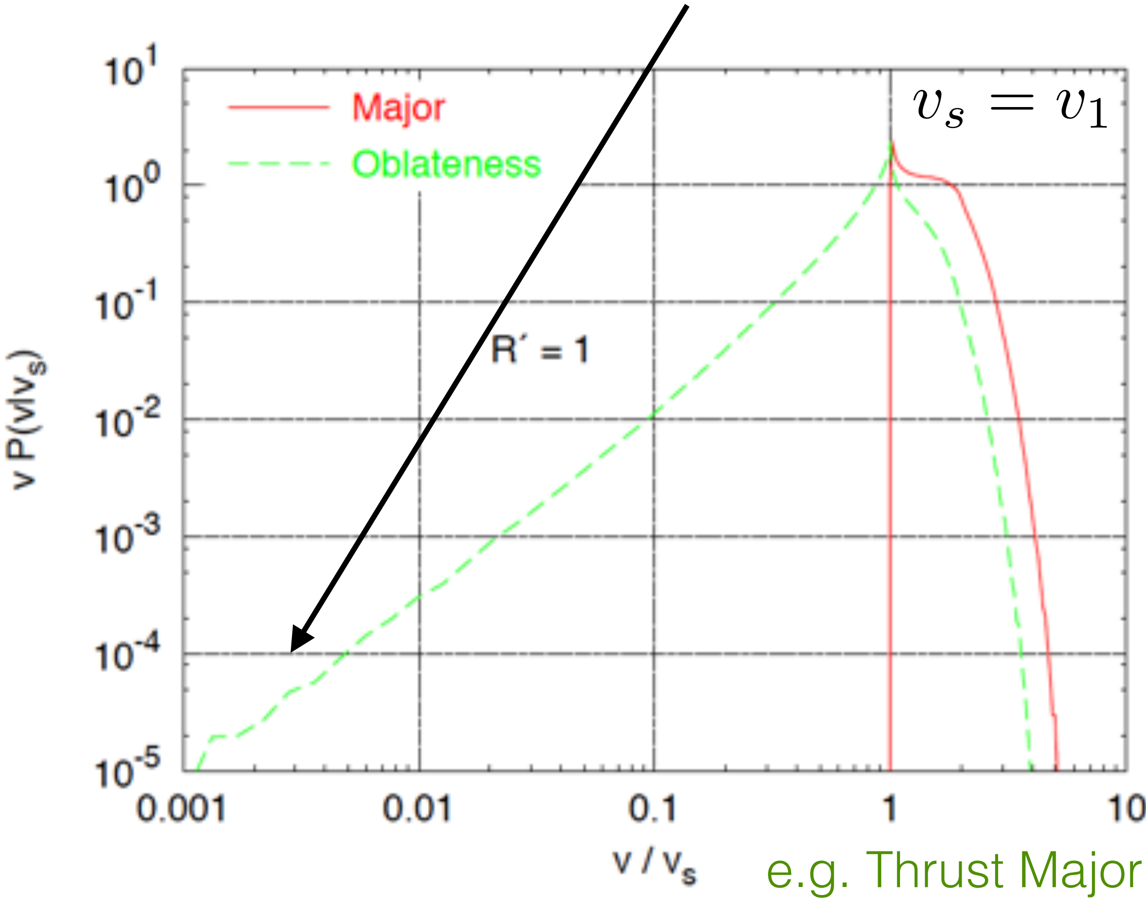
Away from the Sudakov limit

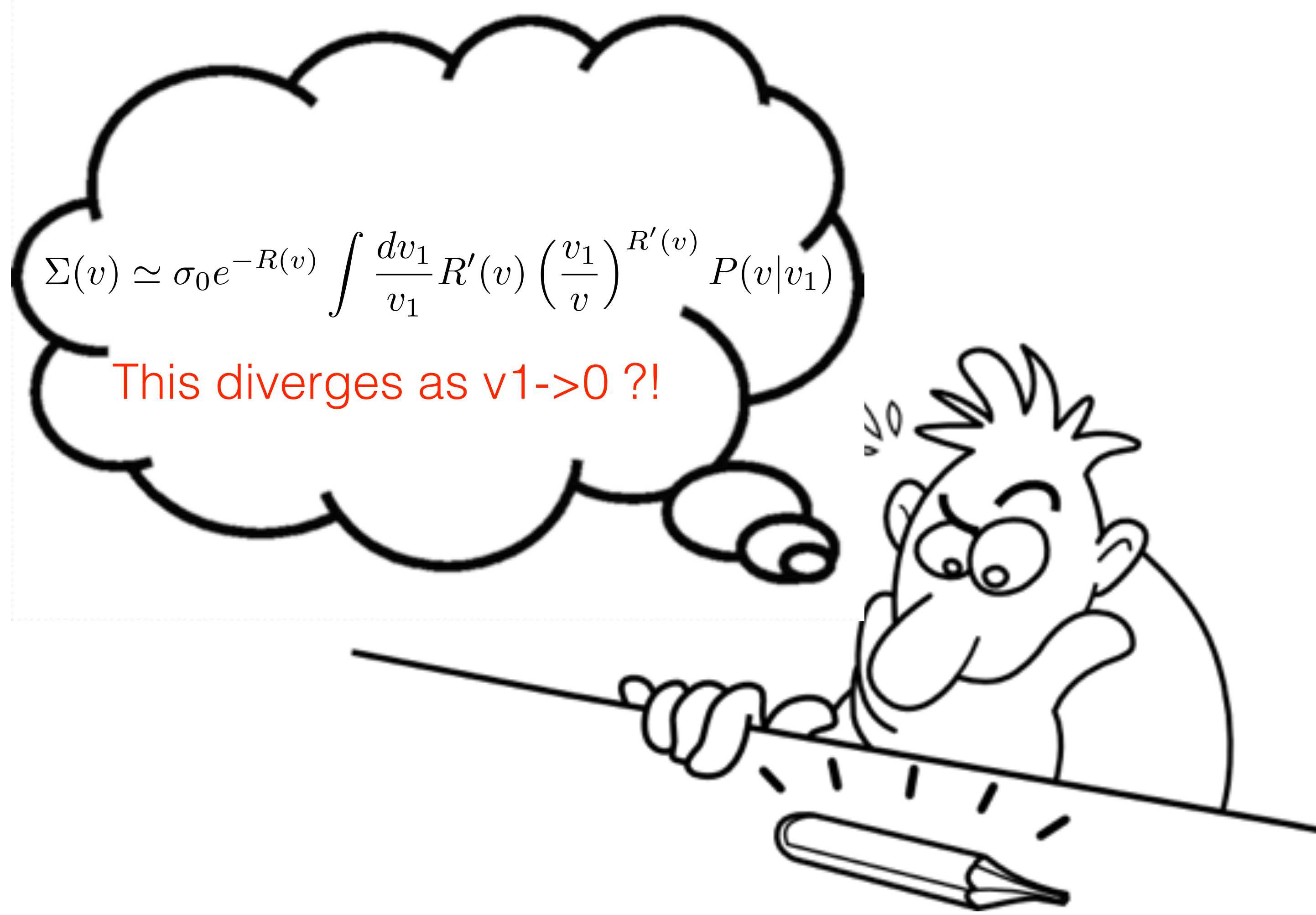
- Some observables vanish even if the real radiation is not completely unresolved (event not Born-like) due to kinematic cancellations; i.e. pT, phi* in DY, azimuthal decorrelation in pp->2 jets, oblateness in e+e-, etc.

- In this limit one of the assumptions made earlier is violated

  - Instead one has:

$$v_1/v \gg 1, \qquad P(v|v_1) \neq 0 \text{ for } v_1 > v$$





e.g. Thrust Major vs. Oblateness: [Banfi, Salam, Zanderighi 0112156]

A case study: Higgs transverse momentum

Resummation performed in impact-parameter space up to NNLL:
[Bozzi, Catani, de Florian, Grazzini '03-'05; Becher, Neubert '10]

- Toy model: consider ensemble of independent emissions; PDFs independent of energy scale

$$[dk]M^2(k) = \frac{dk_t}{k_t}\frac{d\phi}{2\pi}R'(k_t) \equiv \langle dk\rangle R'(k_t) \qquad \vec{q}_{n+1} = \vec{k}_{t,1} + \cdots + \vec{k}_{t,n+1}$$

$$\Sigma(p_t^{\rm H}) = \sigma_0 \int_0^\infty \langle dk_1\rangle R'(k_{t,1}) e^{-R(k_{t,1})}\epsilon^{R'(k_{t,1})}\sum_{n=0}^{\infty}\frac{1}{n!}\prod_{i=2}^{n+1}\int_{\epsilon k_{t,1}}^{k_{t,1}}\langle dk_i\rangle R'(k_{t,1})\Theta\Big(p_t^{\rm H} - |\vec{q}_{n+1}|\Big)$$

- By expanding $k_{t,1} \sim p_t^{\rm H}$, and neglecting effects beyond NLL one gets

$$\Sigma(p_t^{\rm H}) = \sigma_0 e^{-R(p_t^{\rm H})}\int_0^\infty \langle dk_1\rangle R'(p_t^{\rm H})\left(\frac{p_t^{\rm H}}{k_{t,1}}\right)^{-R'(p_t^{\rm H})}\epsilon^{R'(p_t^{\rm H})}\sum_{n=0}^{\infty}\frac{1}{n!}\prod_{i=2}^{n+1}\int_{\epsilon k_{t,1}}^{k_{t,1}}\langle dk_i\rangle R'(p_t^{\rm H})\Theta\Big(p_t^{\rm H} - |\vec{q}_{n+1}|\Big)$$

$$= \sigma_0 e^{-R(p_t^{\rm H})}e^{-\gamma_E R'(p_t^{\rm H})}\frac{\Gamma\left(1 - R'(p_t^{\rm H})/2\right)}{\Gamma\left(1 + R'(p_t^{\rm H})/2\right)} \sim \frac{1}{2 - R'(p_t^{\rm H})}$$

- The cross section features a geometric singularity at finite values of the transverse momentum if subleading effects are neglected
- However, at each order in the coupling the above treatment reproduces the correct logarithms —> non-logarithmic effect missing ?

[Parisi, Petronzio '78]
[Frixione, Nason, Ridolfi '98]
[Dasgupta, Salam '01]

Physical interpretation of the divergence

- The $p_t^{\mathrm{H}} \to 0$ limit is approached with two different kinematic mechanisms:
  - individual $k_{t,i} \to 0$ for all emissions: —> Exponential suppression

$$\text{e.g. } E_T = \sum_i |\vec{k}_{ti}| \qquad |\vec{k}_{ti}| \text{ generated w/ Sudakov probability}$$

  - finite $k_{t,i}$ which cancel against each other —> Power-law suppression

$$\Delta\phi \text{ cancellations with } \vec{k}_{ti}/|\vec{k}_{ti}| \text{ generated w/ uniform probability}$$

- Below a given pt the latter mechanism becomes the dominant one, therefore in this pt region it makes no sense to neglect logarithmically subleading effects

- Solution:the scale of the real radiation is set by the first emission $k_{t,1}$ instead of p_t^{H} —> Resum logarithms of $m_{\mathrm{H}}/k_{t,1}$ then integrate over $k_{t,1}$ [PM, Re, Torrielli '16]

In the Sudakov limit

$$k_{t,1} \leq p_t^{\mathrm{H}}$$

this corresponds to including subleading logarithmic terms

In the limit where cancellations kick in

$$k_{t,1} \gg p_t^{\mathrm{H}}$$

the real radiation is described correctly

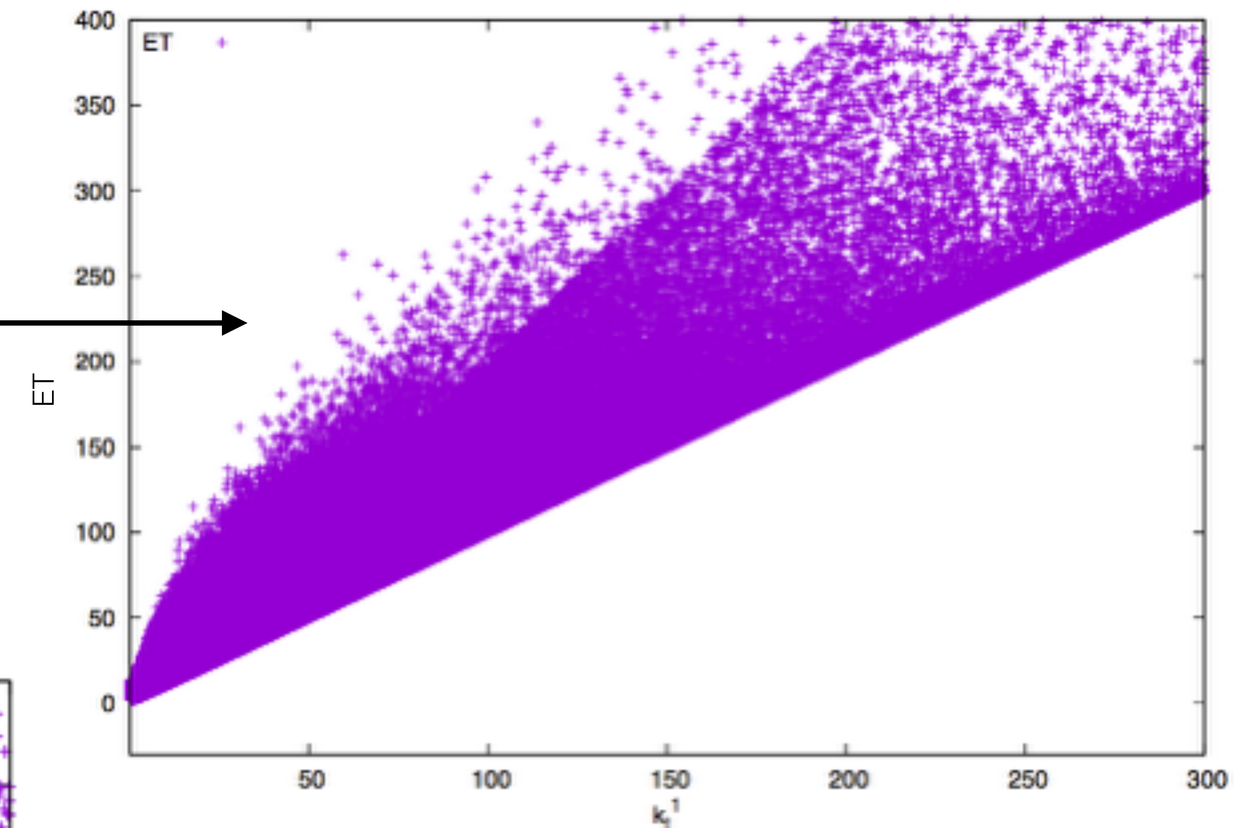
$$\Sigma(p_t^{\mathrm{H}}) \sim \sigma_0 \int_{\Lambda_{\mathrm{QCD}}}^{Q} \frac{dk_{t,1}}{k_{t,1}} e^{-R(k_{t,1})} \left(\frac{p_t^{\mathrm{H}}}{k_{t,1}}\right)^2$$

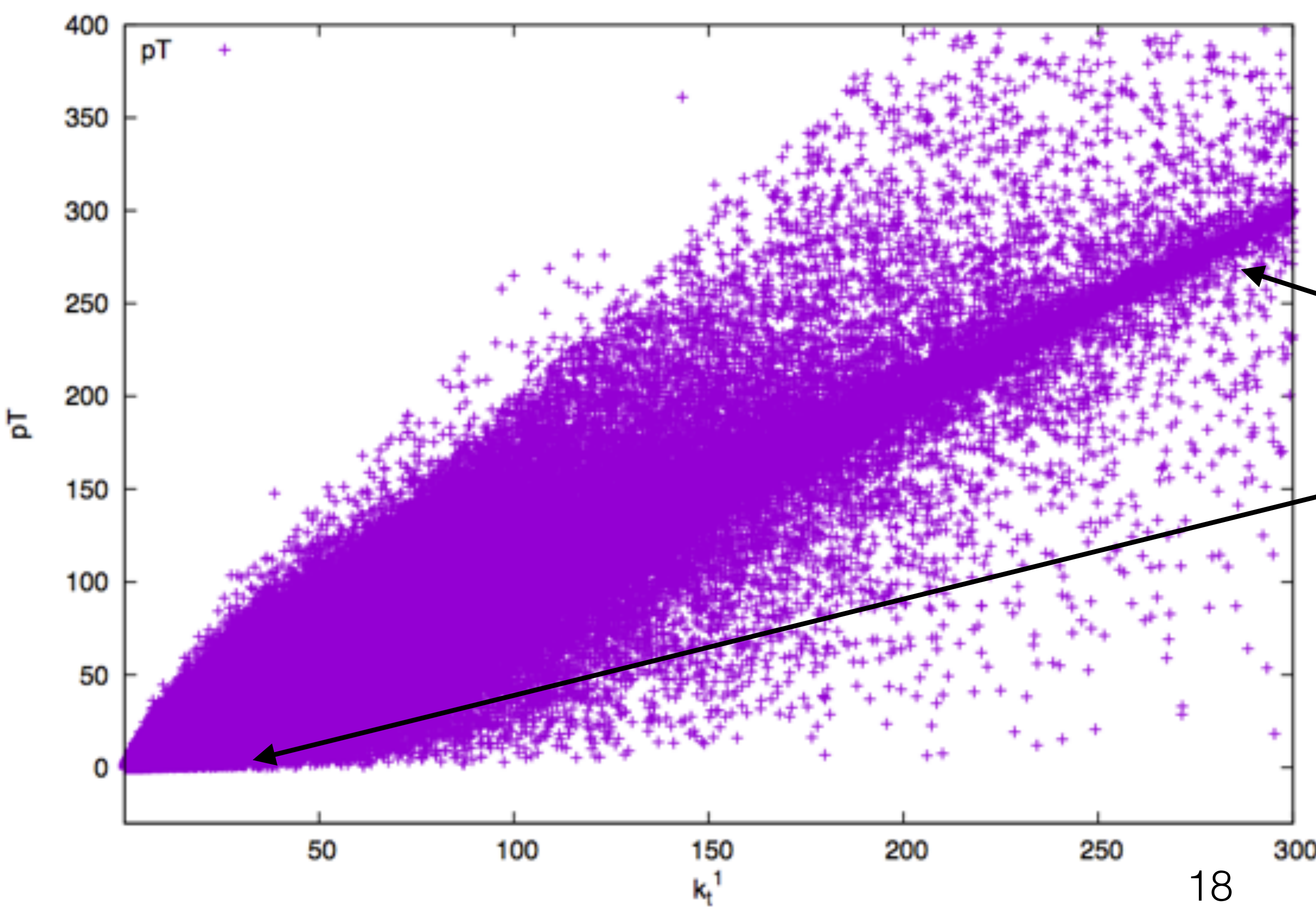
$$= \sigma_0 \, (p_t^{\mathrm{H}})^2 \, R_0(Q^2) + \cdots$$

[Parisi, Petronzio Nuclear Physics B154 (1979) 427-440]

pT vs. ET: dependence on the first emission

Transverse Energy: single (Sudakov) suppression mechanism for all values of kt1





Transverse Momentum:

$R'(k_{t1}) \ll 1$: few emissions $\rightarrow p_T \sim k_{t1}$

$R'(k_{t1}) \geq 2$: many emissions $\rightarrow$ azimuthal cancel.

At some value of $R'(k_{t1})$ a transition takes place and the more likely way to get pT->0 becomes the second mechanism

NNLL cross section

- NNLL corrections to the logarithmic structure can be obtained by means of the aforementioned approach
    - In this case the observable is very inclusive, therefore just two NNLL corrections are non-trivial

$$R'(k_{t,1}) = \hat{R}'(k_{t,1}) + \delta\hat{R}'(k_{t,1}) + \cdots,$$
$$R''(k_{t,1}) = \hat{R}''(k_{t,1}) + \cdots,$$

Radiator from [Grazzini, de Florian '01; Becher, Neubert '10]

$$\Sigma(p_t^{\rm H}) = \int_0^\infty \langle dk_1 \rangle \left[\epsilon^{\hat{R}'(k_{t,1})} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon k_{t,1}}^{k_{t,1}} \langle dk_i \rangle \hat{R}'(k_{t,1})\right] \left\{\partial_L \left[-e^{-R_{\rm NNLL}(k_{t,1})}\mathcal{L}\right] \Theta\left(p_t^{\rm H} - |\vec{q}_{n+1}|\right)\right.$$
$$\left. + e^{-R(k_{t,1})}\hat{R}'(k_{t,1}) \int_{\epsilon k_{t,1}}^{k_{t,1}} \langle dk_s \rangle \left[\left(\delta\hat{R}'(k_{t,1}) + \hat{R}''(k_{t,1}) \ln\frac{k_{t,1}}{k_{t,s}}\right)\hat{\mathcal{L}} - \partial_L \hat{\mathcal{L}}\right]\left[\Theta\left(p_t^{\rm H} - |\vec{q}_{n+1,s}|\right) - \Theta\left(p_t^{\rm H} - |\vec{q}_{n+1}|\right)\right]\right\}$$

$$\mathcal{L} = \frac{\alpha_s^2(\mu_R)}{576\pi v^2}\tau \sum_{i,j} \int_\tau^1 \frac{dx_1}{x_1} \int_{x_1}^1 \frac{dz_1}{z_1} \int_{\tau/x_1}^1 \frac{dz_2}{z_2} \, [HCC]_{gg;ij} \, f_i\left(x_1/z_1, e^{-L}\mu_F\right) f_j\left(\tau/x_1/z_2, e^{-L}\mu_F\right), \; L = \ln\frac{Q}{k_{t,1}}$$

$$[HCC]_{gg;ij} = H_g^H(\alpha_s(\mu_R), \mu_R, Q, m_H)\left[C_{gi}(z_1; \alpha_s(k_{t,1}), \mu_R, \mu_F, Q) C_{gj}(z_2; \alpha_s(k_{t,1}), \mu_R, \mu_F, Q)\right.$$
$$\left. + G_{gi}(z_1; \alpha_s(k_{t,1}), \mu_R, \mu_F) G_{gj}(z_2; \alpha_s(k_{t,1}), \mu_R, \mu_F)\right]$$

O(as^2) coefficient functions from [Catani, Grazzini '11, Gehrmann, Luebbert, Yang '14]

- N3LL corrections to the real emissions can be included systematically. Only missing ingredients are the Sudakov anomalous dimensions

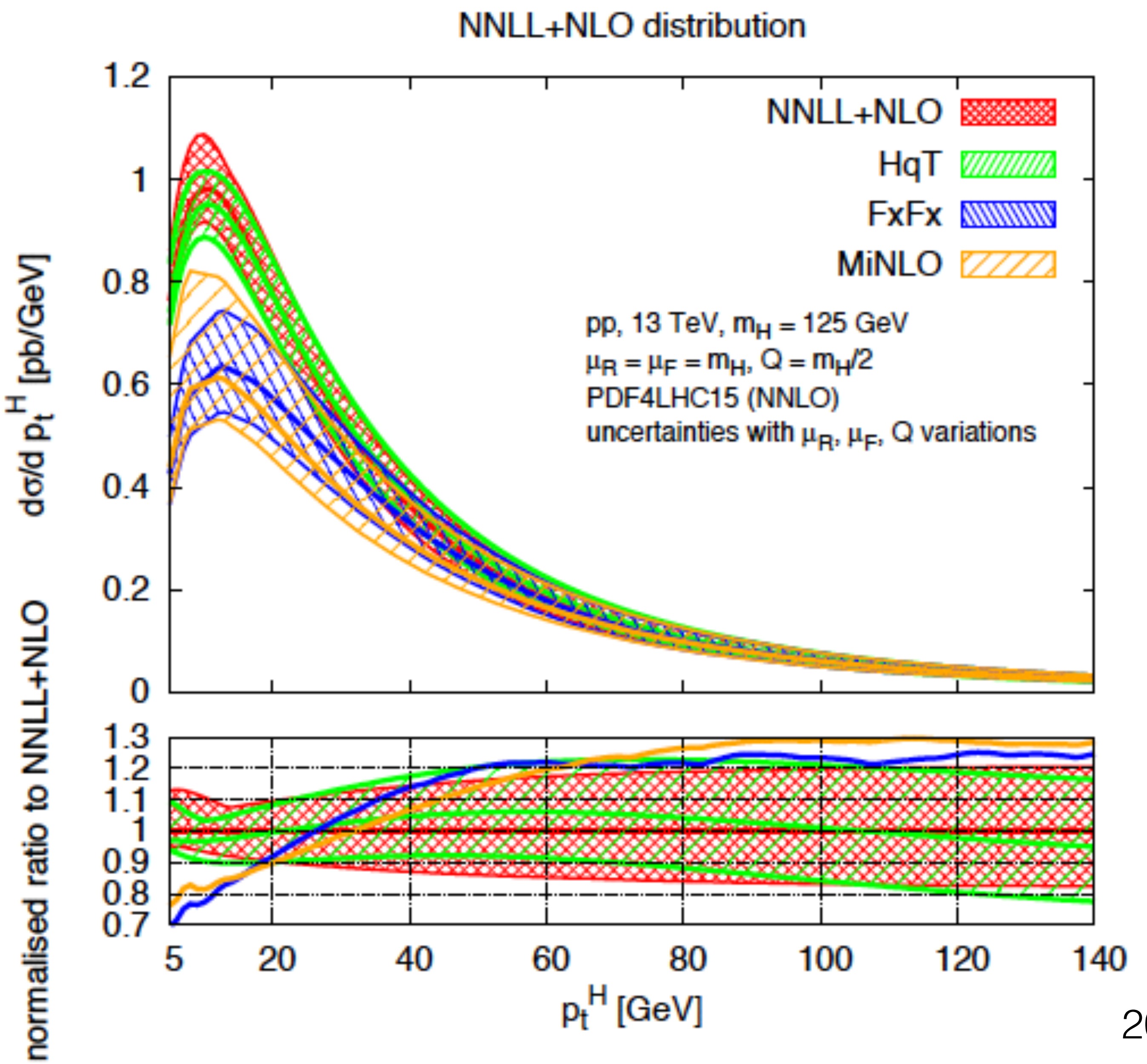
B3 in [Li, Zhu '16]

Spectrum at NNLL+NNLO

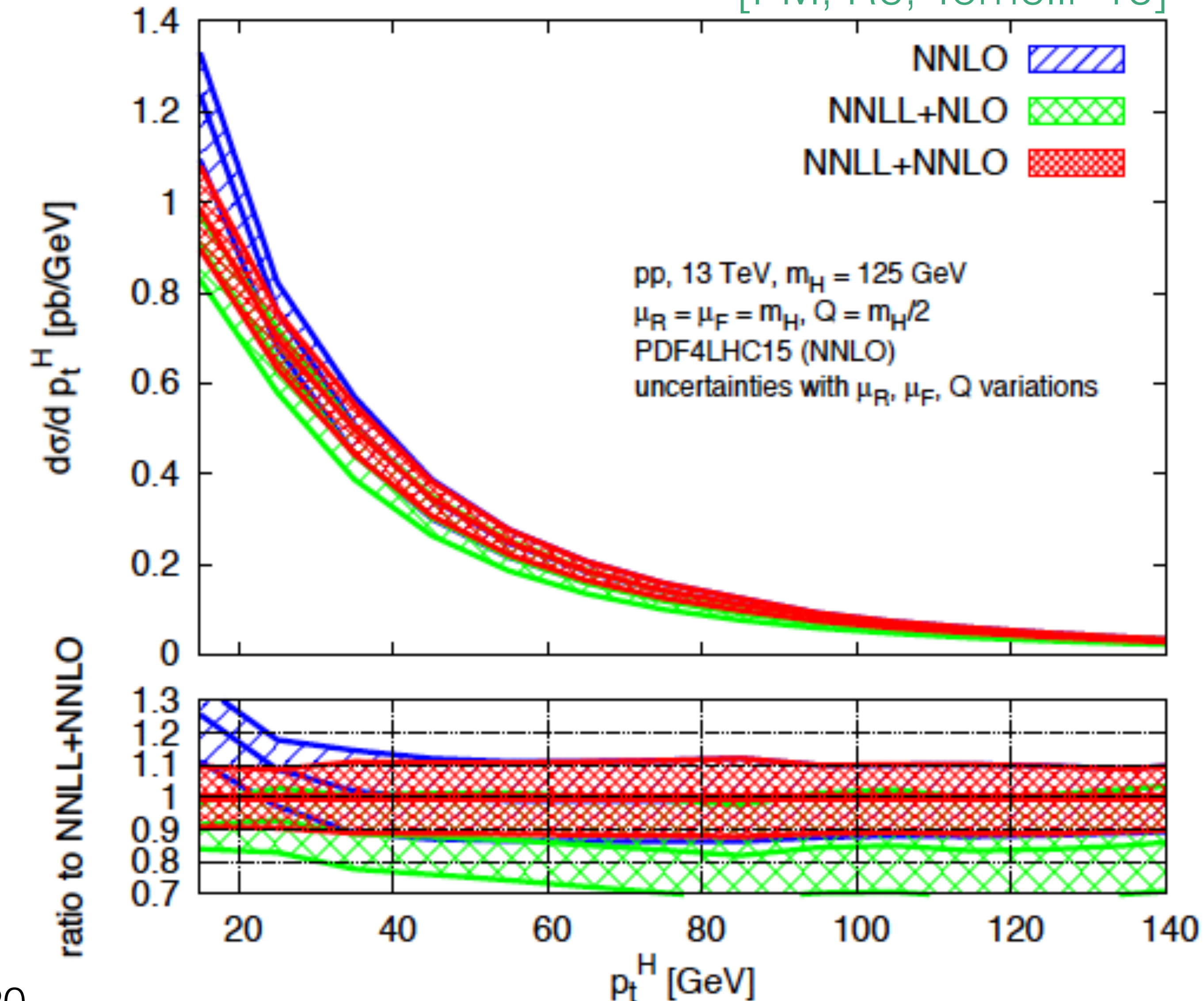
Fixed-order obtained combining N3LO cross section and H+1 jet @ NNLO

[Anastasiou et al. '15-'16] [Caola et al. '15; Boughezal et al. '15; Chen et al. '16]

- Master formula can be evaluated with fast MC methods (~5 mins for 500 bins), no integral transforms required (luminosity in momentum space)
- Sizeable effects of NNLL resummation at small pt (~20% at 20 GeV), uncertainty reduced from 15-20% to 10%
- Below this accuracy heavy-quark effects matter, comparable to N3LL corrections

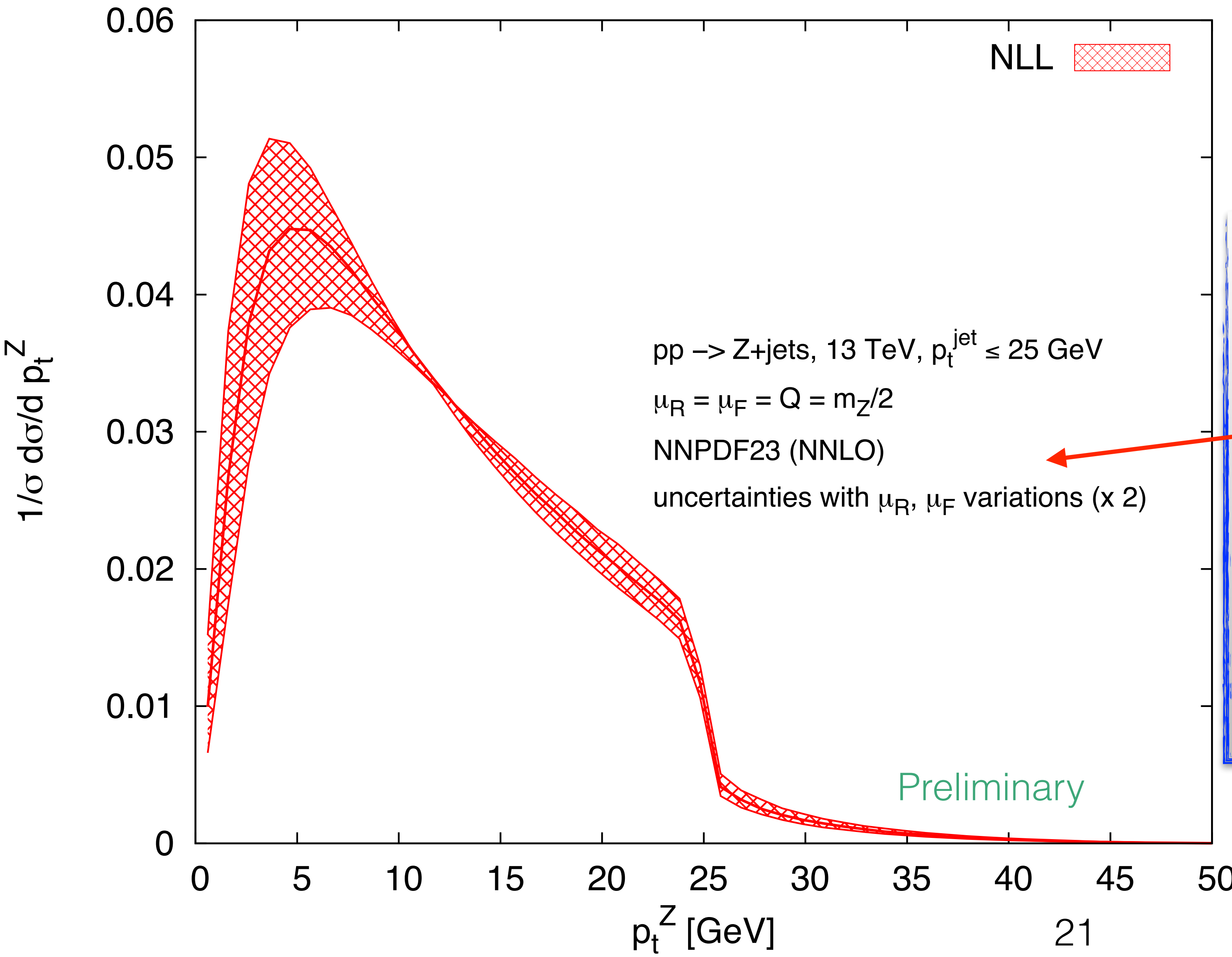


[PM, Re, Torrielli '16]



Generalisation and joint resummations

- The approach extends the treatment to all rIRC-safe observables featuring this type of cancellations: $k_{t,1} \to V_{\rm sc}(\{\tilde{p}\}, k_1)$ as a reference
- Observables with the same Sudakov radiator (i.e. same soft-collinear approximation for a single emission) can be resumed *simultaneously*:



- multi-differential distributions (matching to fixed order more involved)

  e.g. pt distribution in 0-jet bin
- Access to Sudakov shoulders [Catani, Webber 9710333]
- Study of correlations between observables

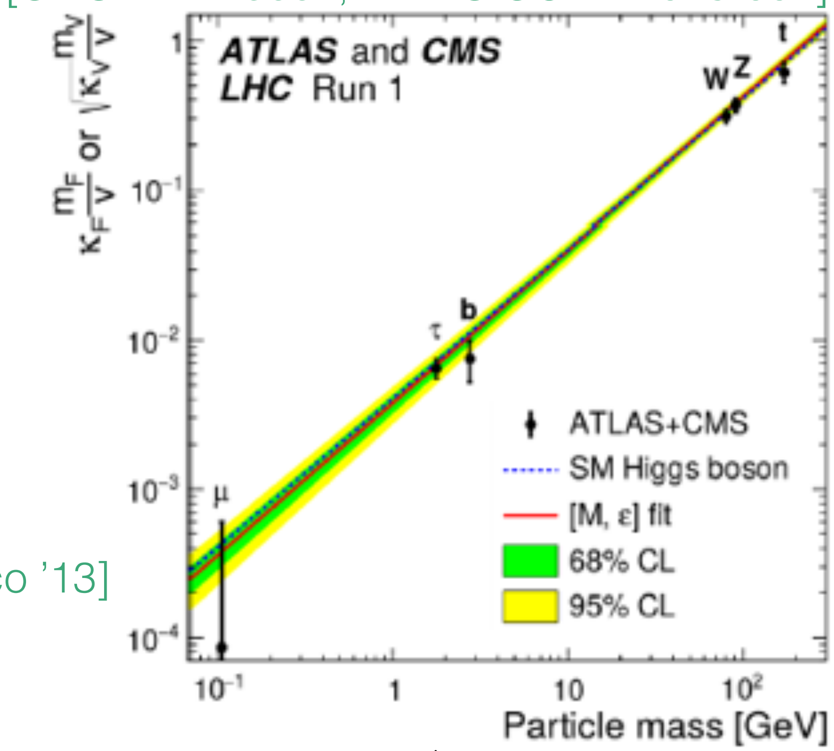
Light-quark Yukawa couplings from differential distributions

Probing light-quark Yukawa couplings

- Yukawa couplings to third-generation quarks compatible with SM values

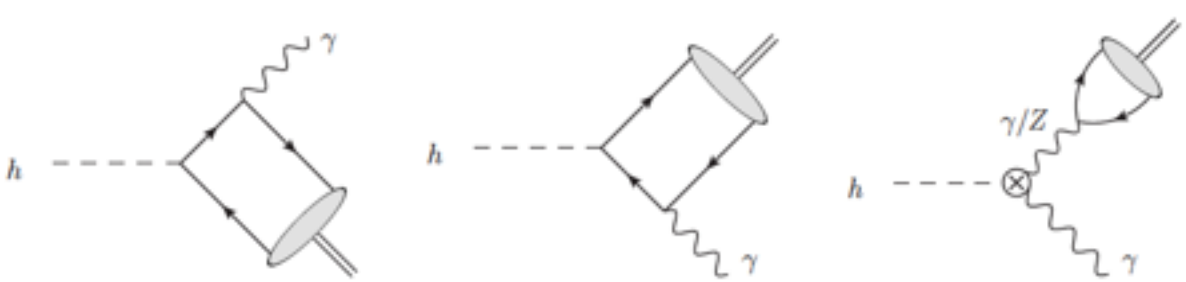
[CMS: 1412.8662; ATLAS-CONF-2015-007]

$$-\frac{m_f}{v} h \bar{f} f \to -\frac{m_f}{v} h \bar{f} \left(\kappa_f + i\tilde{\kappa}_f \gamma_5\right) f \qquad y_f^{\rm SM} = \sqrt{2}\frac{m_f}{v}$$



- No direct measurements for first and second generation yet. Possible methods:

  - Exclusive decays $h \to J/\psi\gamma\,;\Upsilon\gamma\,;\phi\gamma\,;\rho^0\gamma\,;\omega\gamma$



[Bodwin, Petriello, Stoynev, Velasco ’13]
[Kagan et al. ’14]
[Koenig, Neubert ’15]

$|\kappa_c| < 429\,(\text{Run I})\;\;(\text{expect O(few) at } 3\,\text{ab}^{-1})$

  - Recasting of $Vh(\to b\bar{b})$ (c-tagging): $|\kappa_c| < 234\,(\text{Run I})$ [Perez, Soreq, Stamou, Tobioka ‘15] [Delaunay, Golling, Perez, Soreq ‘13]

  - Constraints from total width (mass): $|\kappa_c| < 120 - 140\,(\text{Run I})$ [Perez, Soreq, Stamou, Tobioka ‘15]

  - $h\,c$ associated production (c-tagging): $(\text{expect O(few) at } 3\,\text{ab}^{-1})$ [Brivio, Goertz, Isidori ’15]

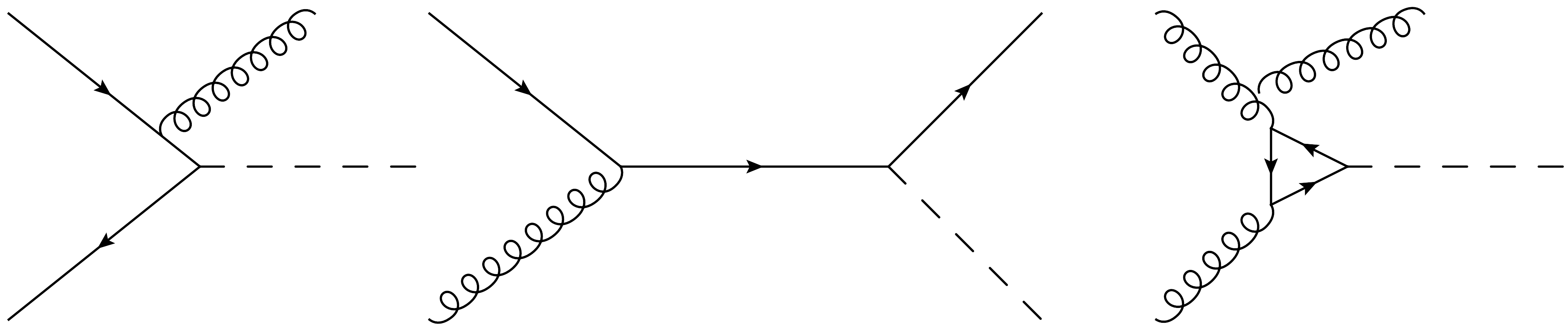
  - Global fit of signal strengths (very model dependent): $|\kappa_c| < 6.2\,(\text{Run I})$ [Perez, Soreq, Stamou, Tobioka ‘15]

Differential distributions in H+jet

[Bishara, Haisch, PM, Re ‘16]

- Interplay between different production modes in the region $m_q \leq p_\perp \leq m_H$

$\sim \kappa_q^2$ $\qquad$ $\sim \kappa_q^2$ $\qquad$ $\sim \kappa_q \frac{m_q^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_q^2}\right)$ (interference w/ top)



- Quark-induced production dominates for large Yukawa modifications (can be used for 1st generation) - no interference with gluon fusion

[Soreq, Zhu, Zupan ’16]

- Interference with heavy new physics suppressed (can be resolved by exploiting sensitivity in the tail)

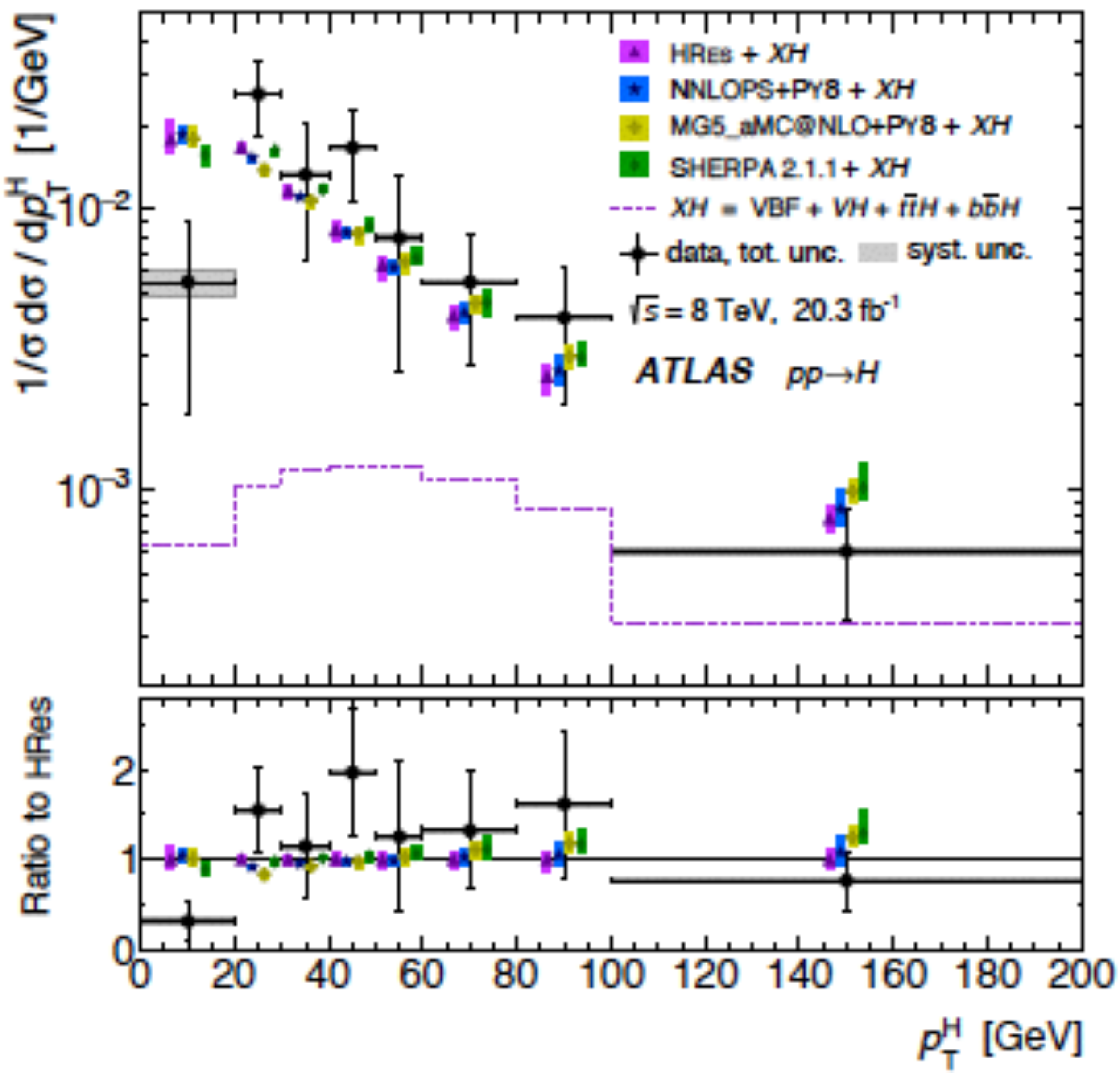
see e.g. [Banfi, Martin, Sanz ’13]
[Buschmann, Goncalves, Kuttimalai, Schoenherr, Krauss, Plehn ’14]
[Buschmann, Englert, Goncalves, Plehn, Spannowsky ’14] …

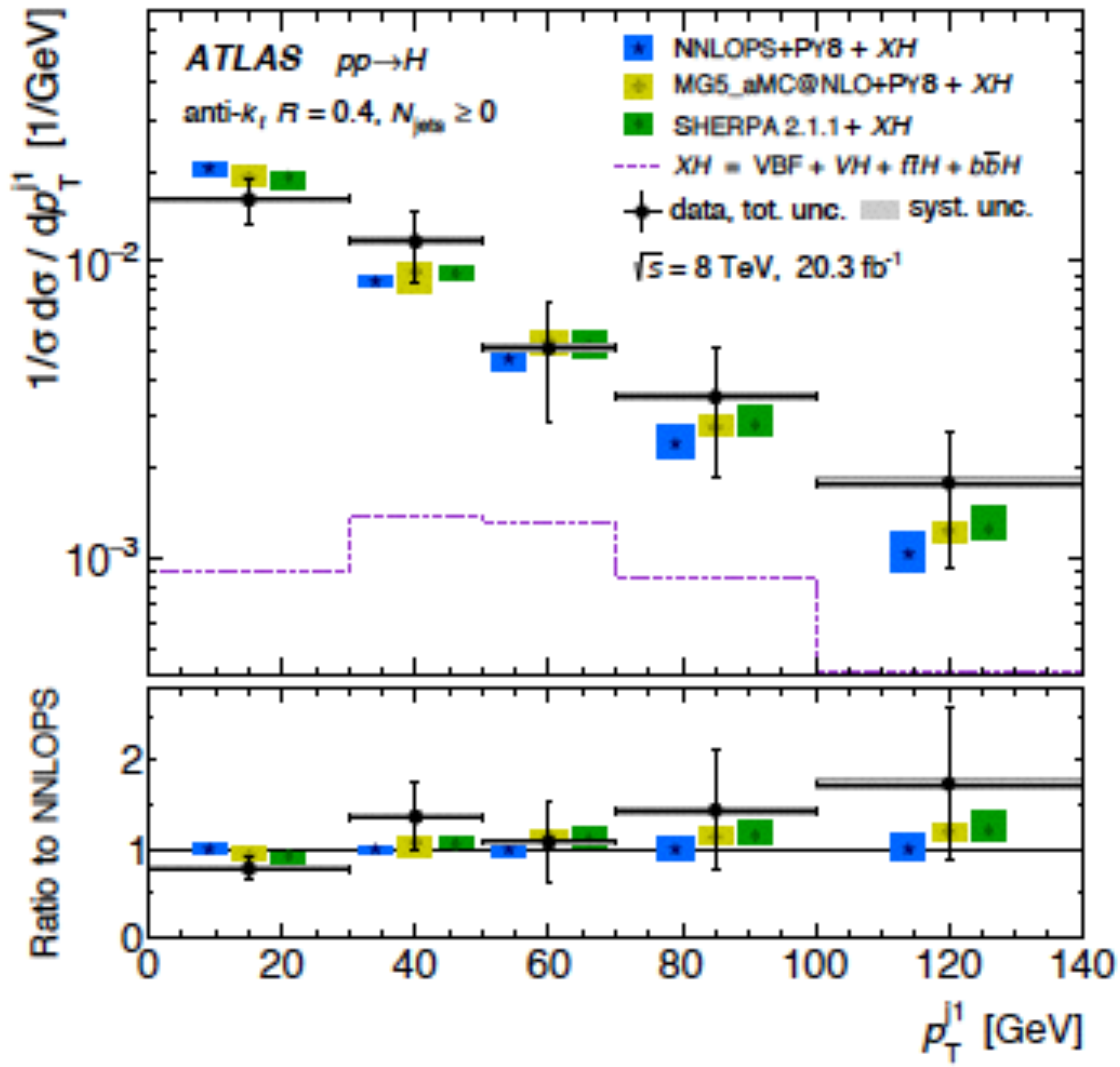
- Modifications can be probed through shape distortions
    - considering normalised distributions also divides out NP effects on the BR (Higgs width constraints require a global fit)

Experimental sensitivity

- Differential distributions measured at Run I and Run II for $h \to \gamma\gamma,\ 4\ell,\ 2\ell 2\nu$
- Experimental uncertainties dominated by statistical errors; systematics ~ 2%

[data from ATLAS 1504.05833 (gamma gamma + ZZ combination)]

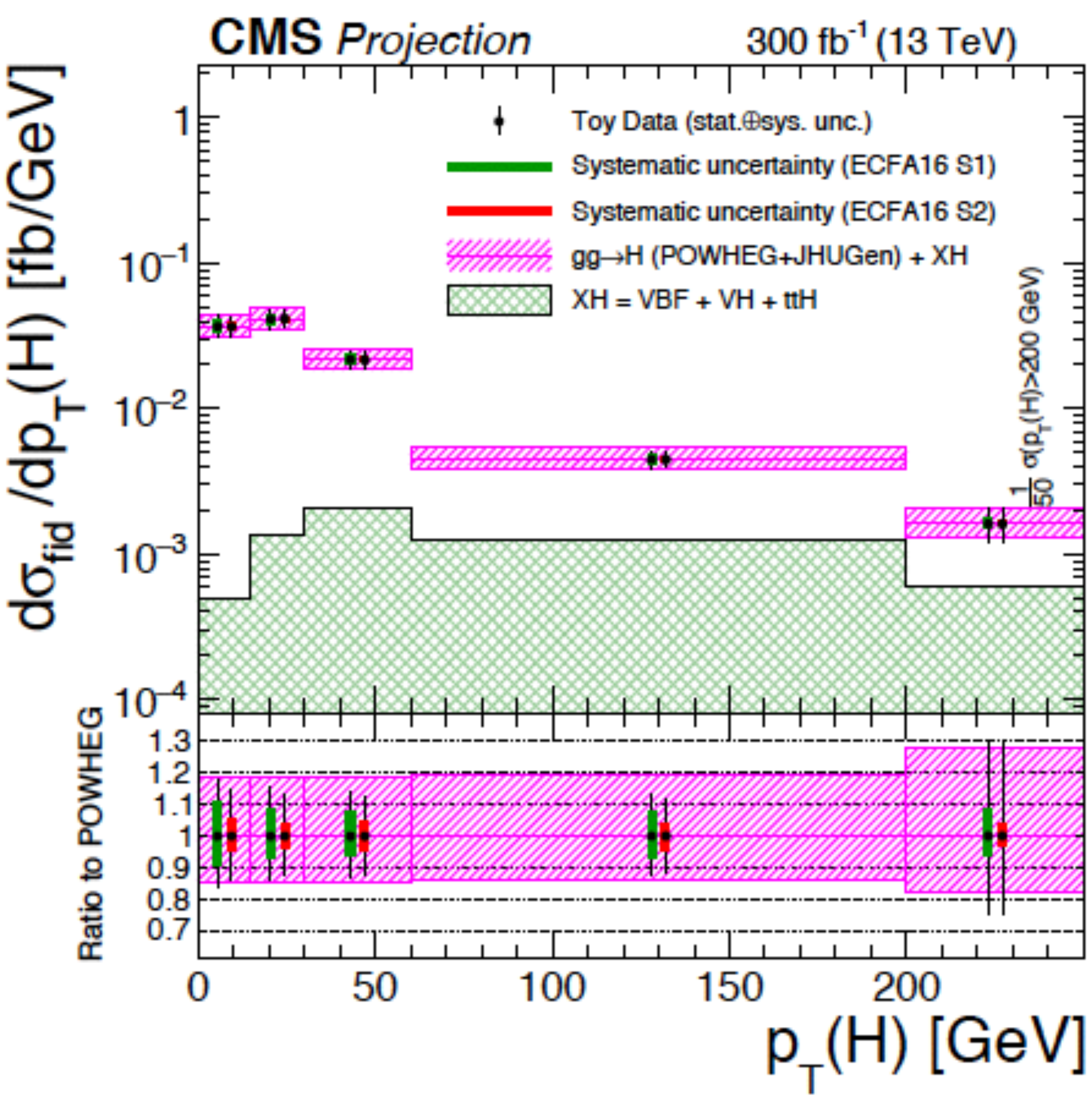


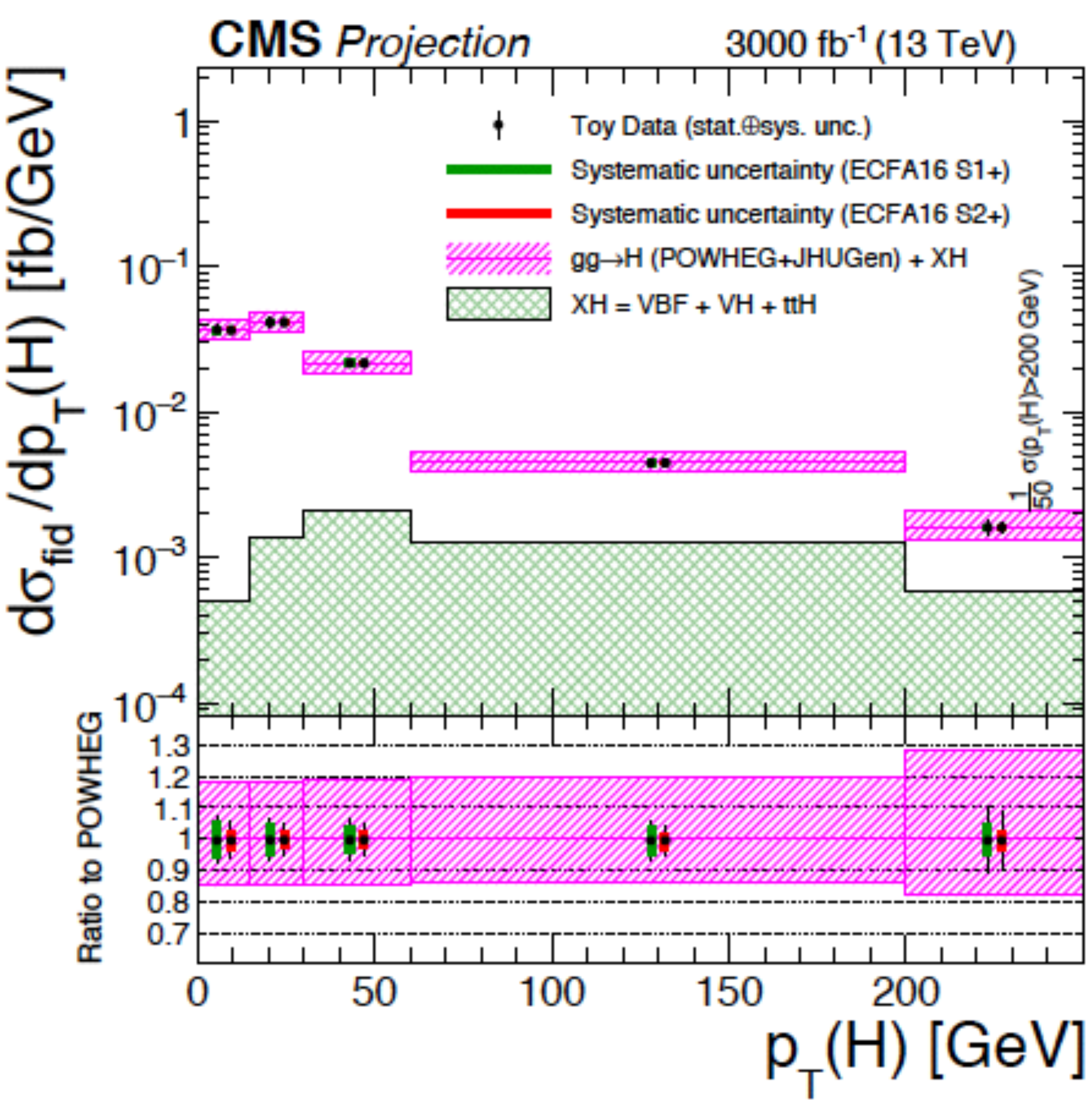


Experimental sensitivity

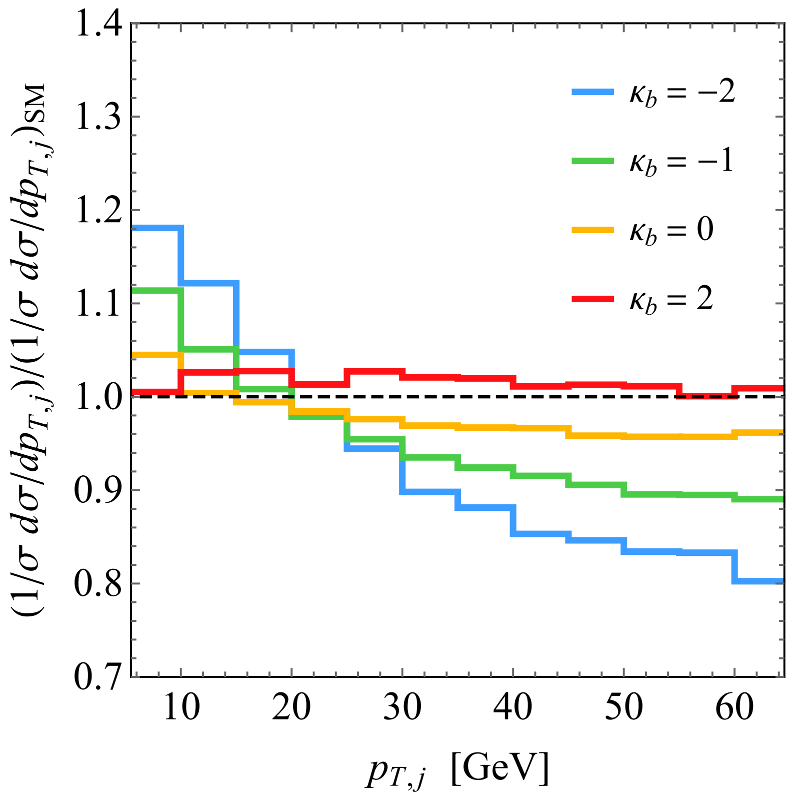
- Run II and High-Luminosity projections expect few-% systematics on unnormalised distribution - further reduced for the (normalised) shape
- Theory precision will become the limiting factor

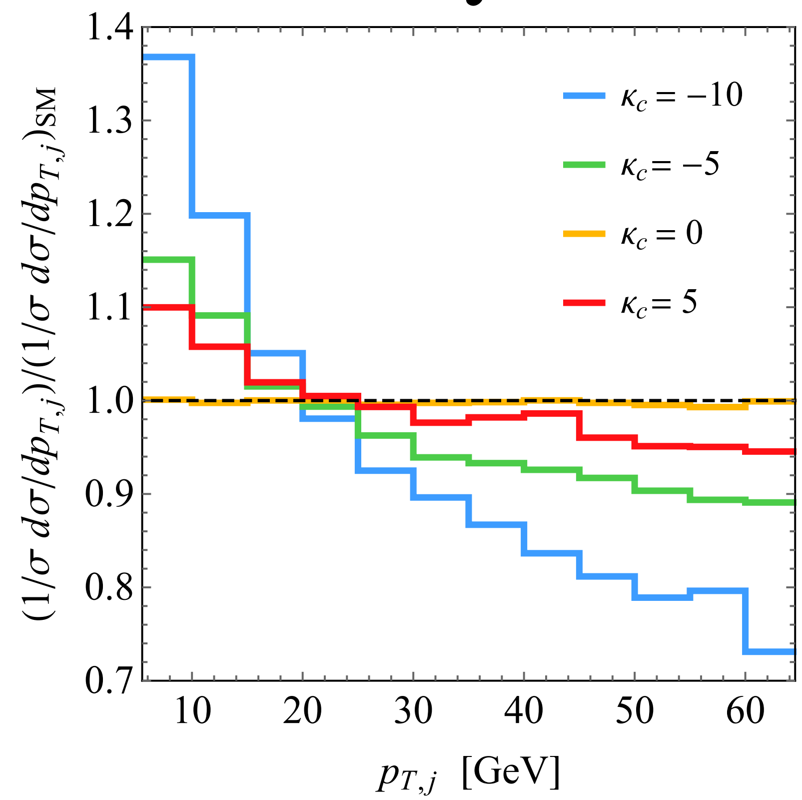
[H -> ZZ, M. Vidal's talk at ECFA 2016]





Theory sensitivity

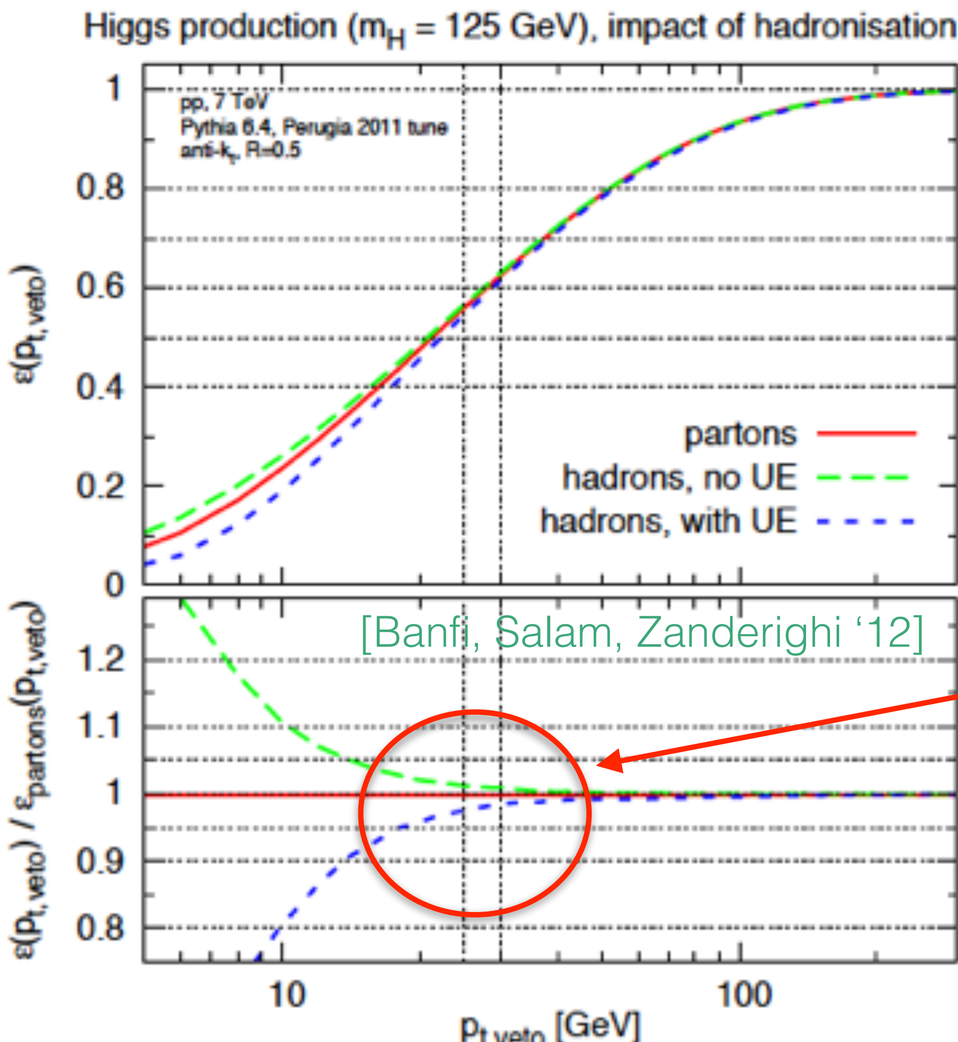




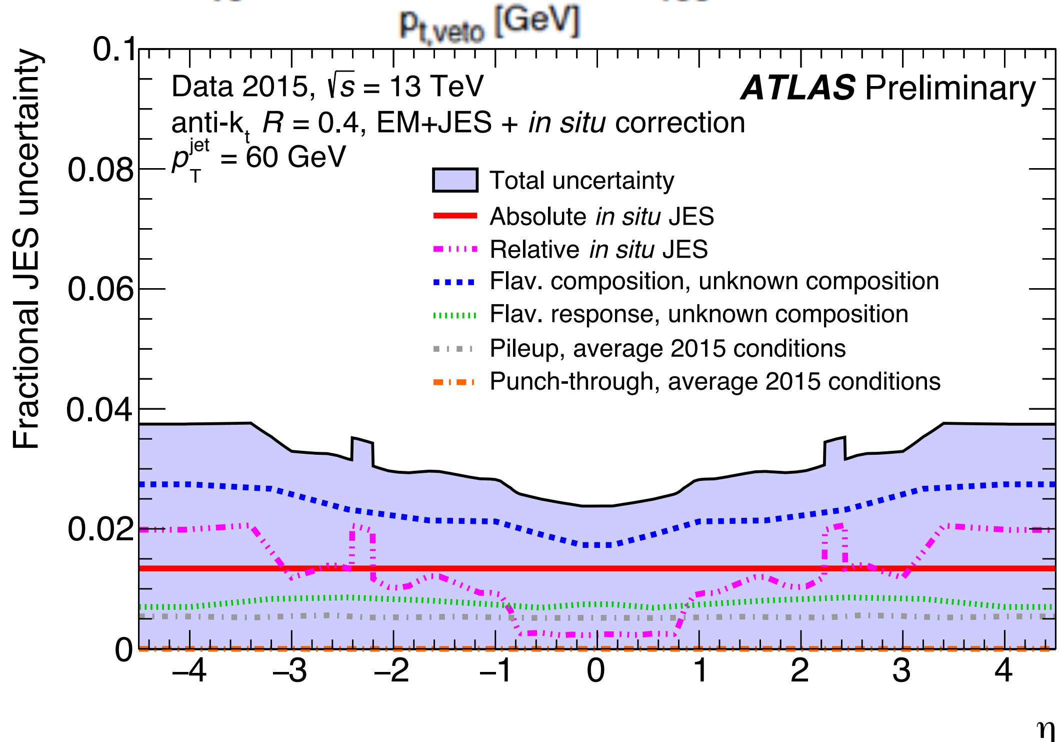
(Similar for ptH)

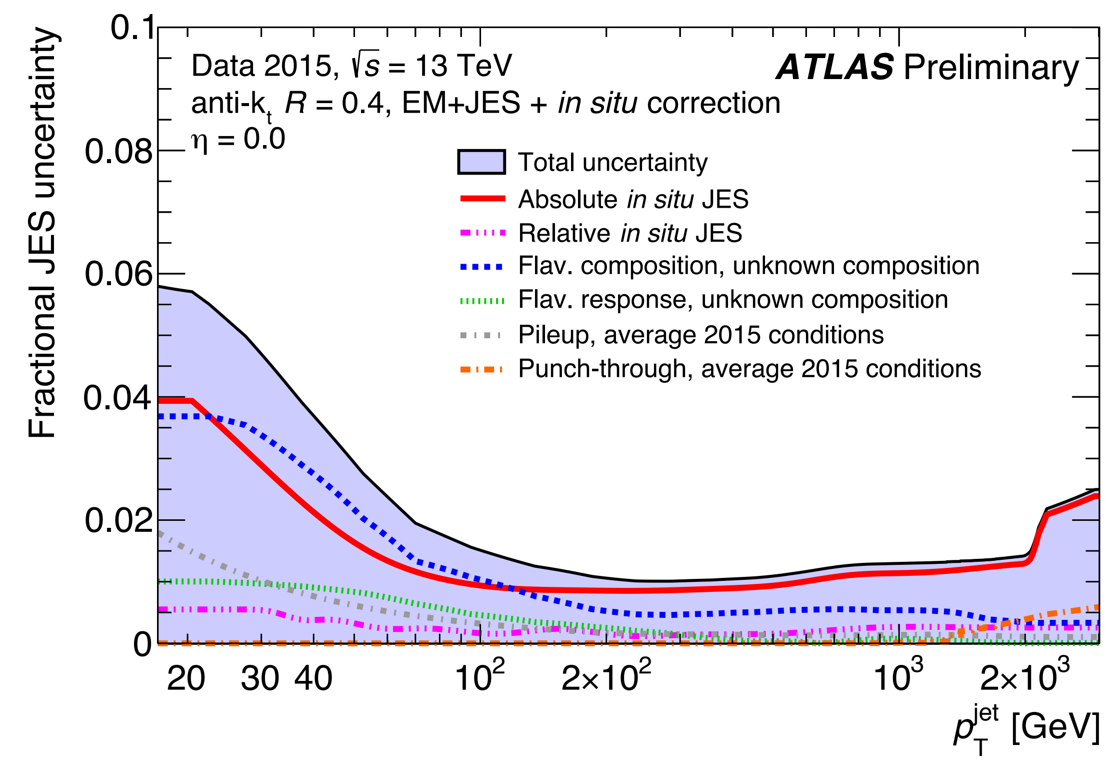
- Achievable precision via perturbation theory:
  - quark-initiated spectrum (i.e. non-ggF mediated) known at NN(N)LL+NLO in 5FS [Campbell, Ellis, Maltoni, Willenbrock '02] [Harlander, Ozeren, Wiesemann '10] [Harlander, Tripathi, Wiesemann '14] [Harlander, Kilgore '03] [Buehler, Herzog, Lazopoulos, Mueller '12]
  - ggF spectrum known at NN(N)LL ($\ln(m_H/p_t)$)+LO in the full SM [Ellis, Hinchliffe, Soldate, van der Bij '88] [Baur, Glover '90]
    - NLO mass effects necessary for ~5% precision in this pT region [gg->h g in Melnikov, Tancredi, Wever '16]
    - light-quark mass logarithms $\ln(p_t/m_q)$ might not require resummation for bottom and charm quarks [Melnikov, Penin '16]
  - coupling uncertainty at most ~ 2% for gluon fusion
  - PDFs uncertainty relevant for b and c quarks, but much reduced in the shape

Non-Perturbative effects in distributions



- Jet pt more sensitive to NP radiation:
  - in-to-out (hadronisation)
  - out-to-in (und. events + pile-up)
- Sensitivity to Yukawa modifications similar to the Higgs pt, but hard to get a very robust theory control with a first bin finer than 20 GeV
- JES uncertainty might be a problem too

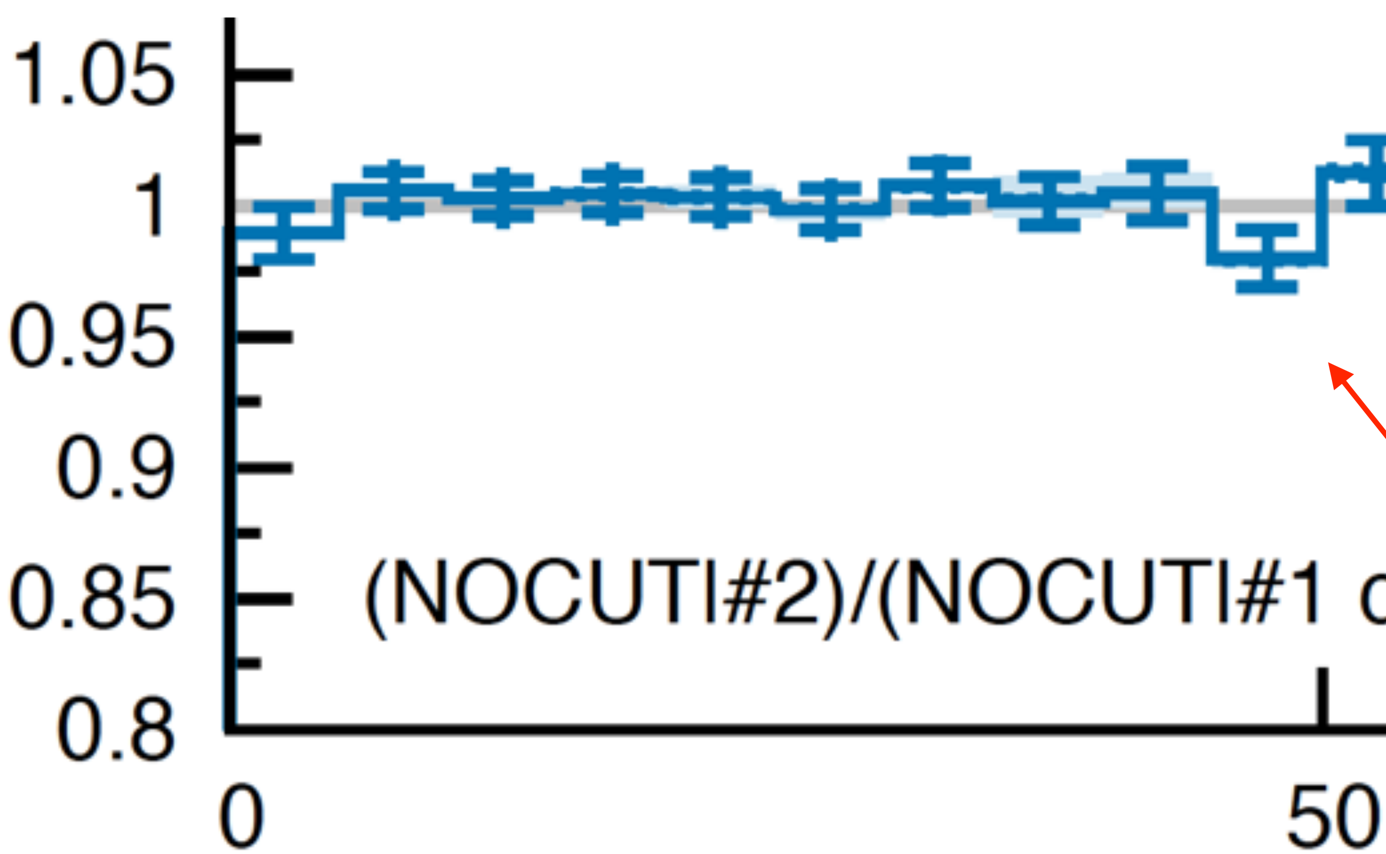


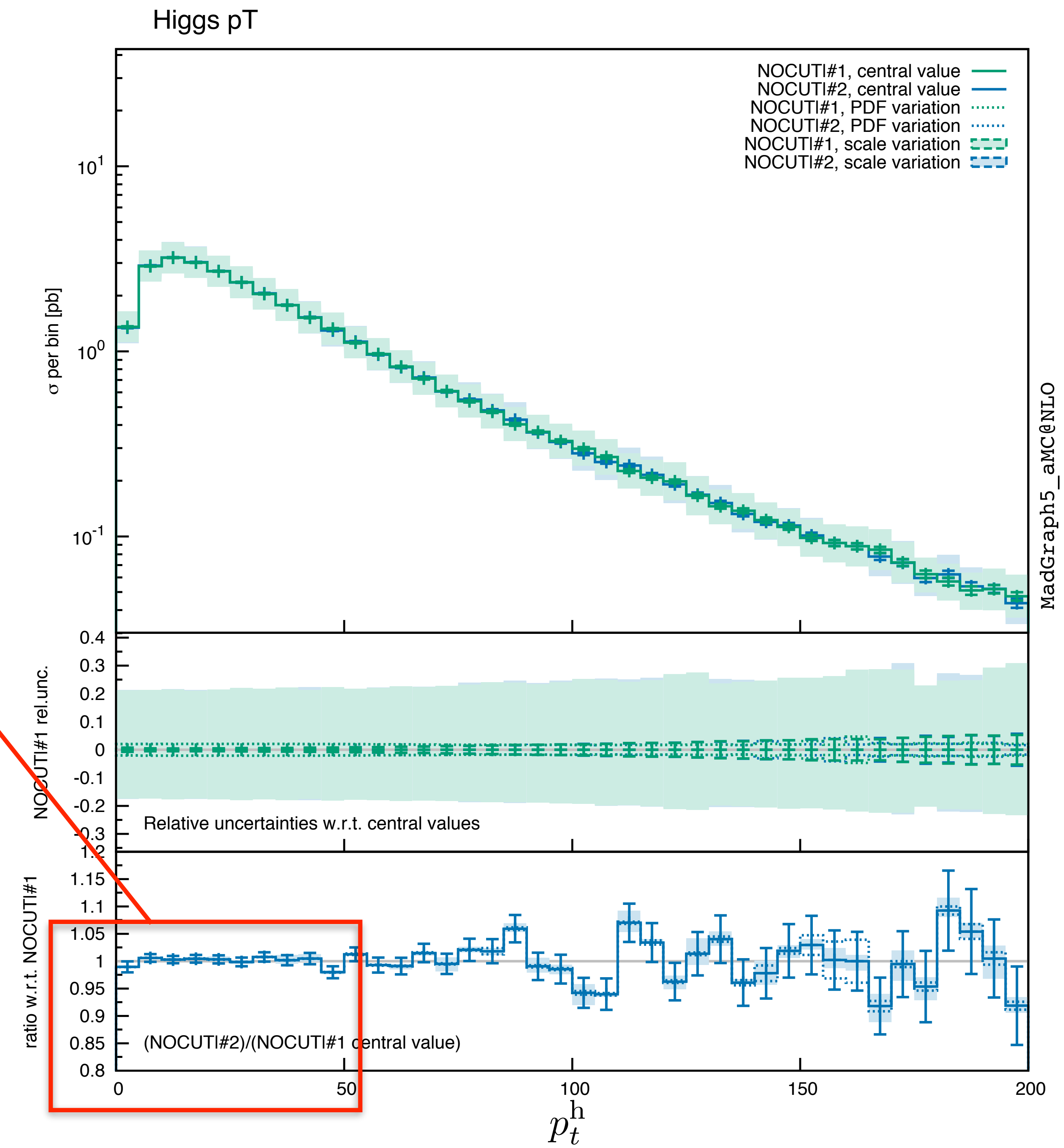


[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2016-010/]

Non-Perturbative effects in distributions

- Higgs pt only feels the recoil from low pt (non perturbative) emissions
- This effects is comparable to the one due to intrinsic transverse momentum of initial-state partons
- Moderate impact $\leq 2\%$

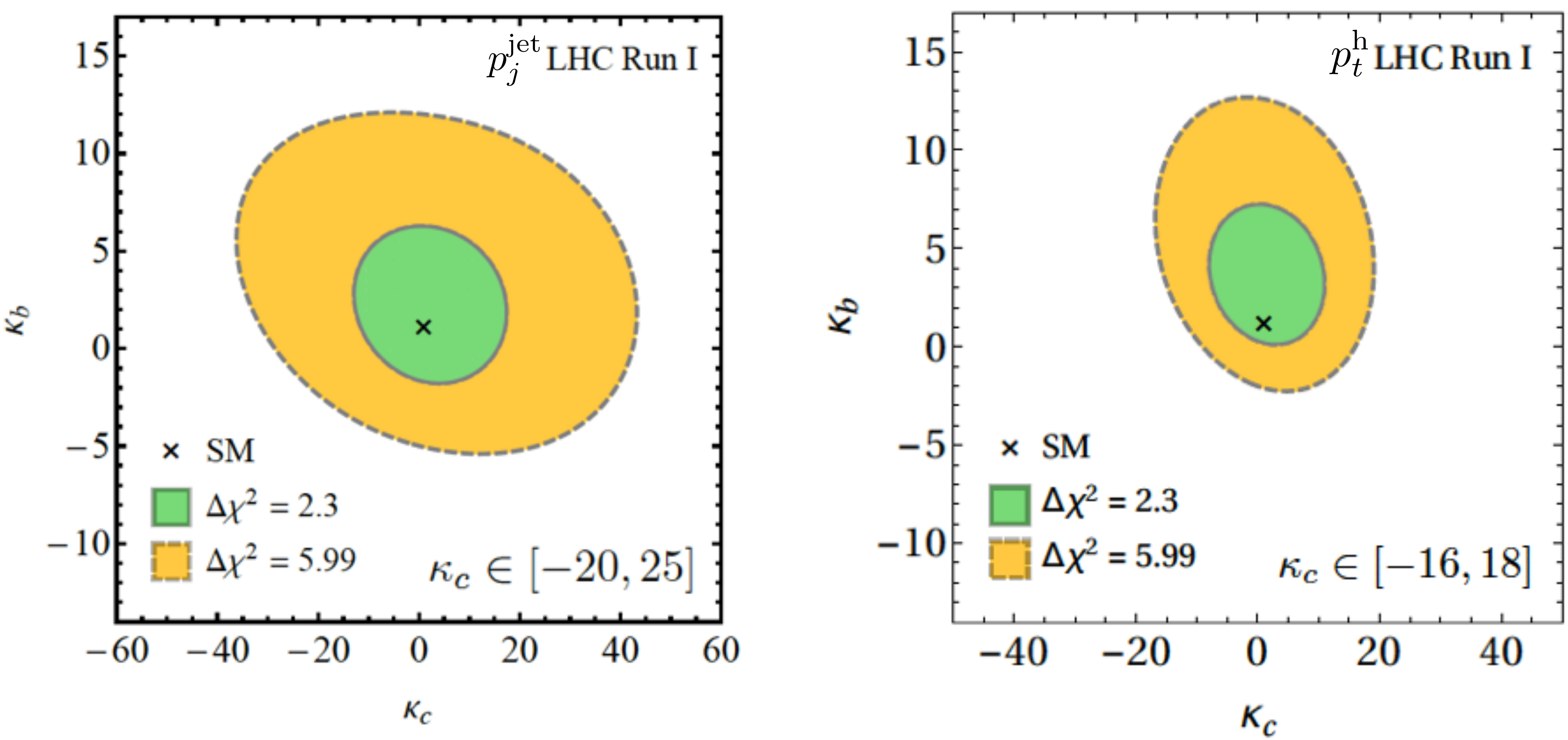




Run I bounds

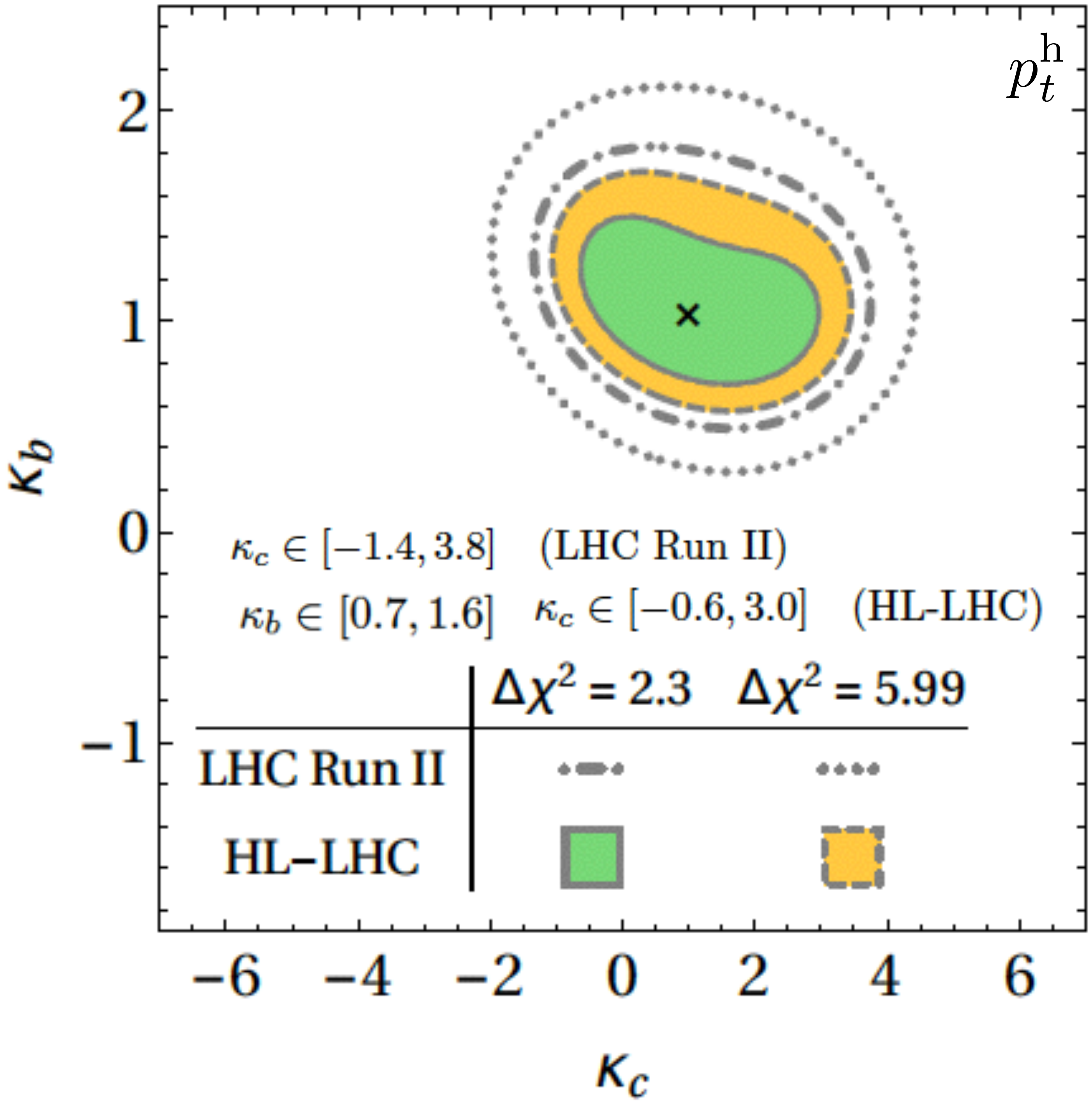
- Use all bins in the range [0,100] GeV and experimental correlations
- Predictions:
  - ggF at NNLL+NLO (full mass to LO, NLO corr. in HEFT)
  - quark-initiated processes with MG5_aMC@NLO

[data from ATLAS 1504.05833 (gamma gamma + ZZ combination)]



Future perspectives

assume combination of $h \to \gamma\gamma$, 4ℓ, $2\ell 2\nu$



Two future scenarios (data SM like):

- Run II (300 fb^-1, 5 GeV bins):
    - syst (exp) 3%; theory 5%
- HL-LHC (3000 fb^-1, 5 GeV bins):
    - syst (exp) 1.5%; theory 2.5%
- Important impact of correlations
- It might be useful to study the complementarity with other strategies for an optimal bound (different directions in the plane)
- It can be used to set bounds on the strange Yukawa of O(30) (although harder to get a good theory control)

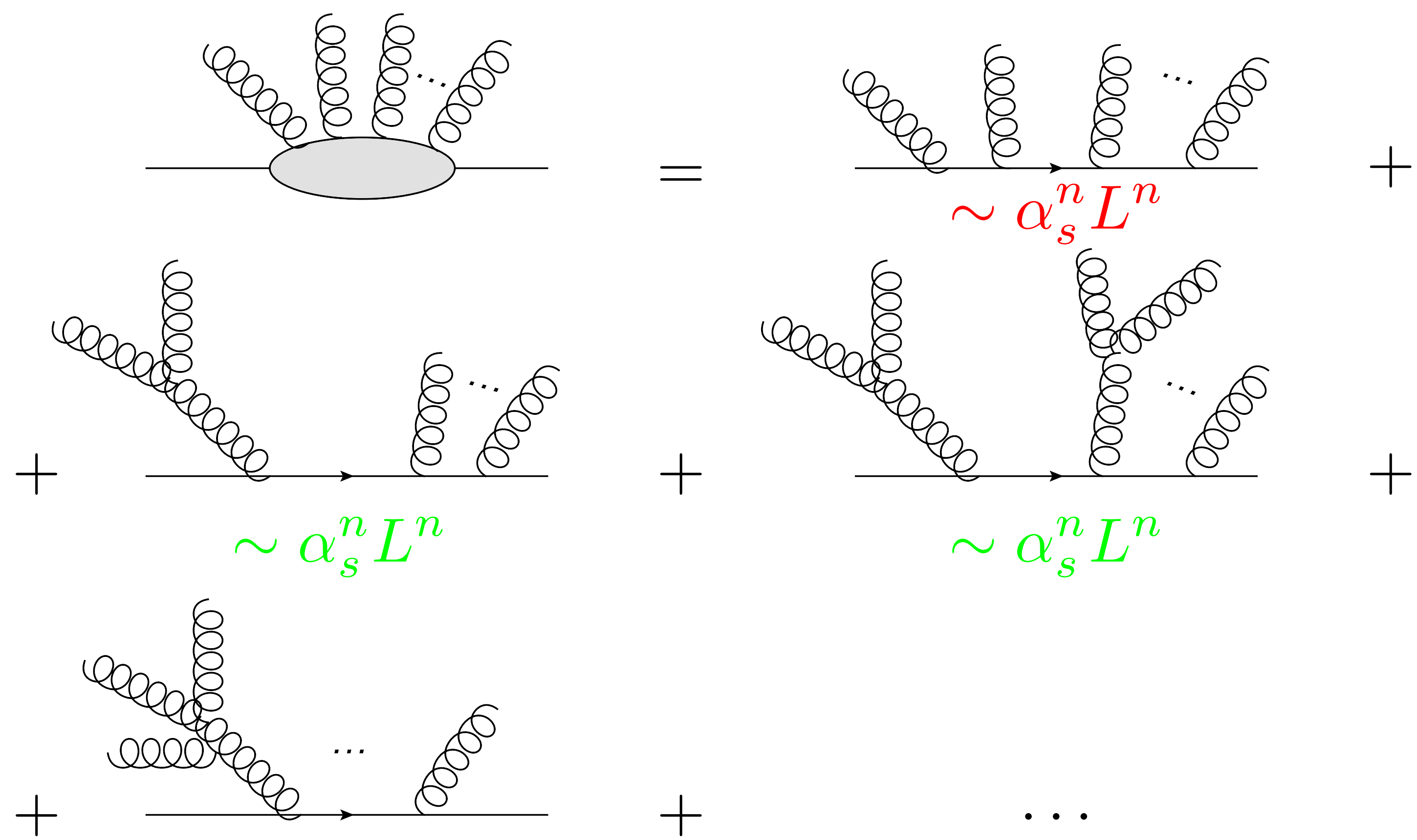
Conclusions

- I discussed a general method for the resummation of global rIRC observables at NNLL:
    - formulation complete for two-scale problems in reactions with 2 hard Born emitters
    - It can handle complex non-factorising observables - in principle extendable to higher orders
- Treatment of observables with cancellations away from the Born-like limit
    - First hints on how to handle joint resummations at NNLL and problems with more than two scales
- ptH distribution is sensitive to modifications of the hcc coupling due to the different functional dependence of different production modes
    - Sensible deviations can be probed already at Run II with very little model dependence

Thank you for your attention

Hierarchy in real emissions

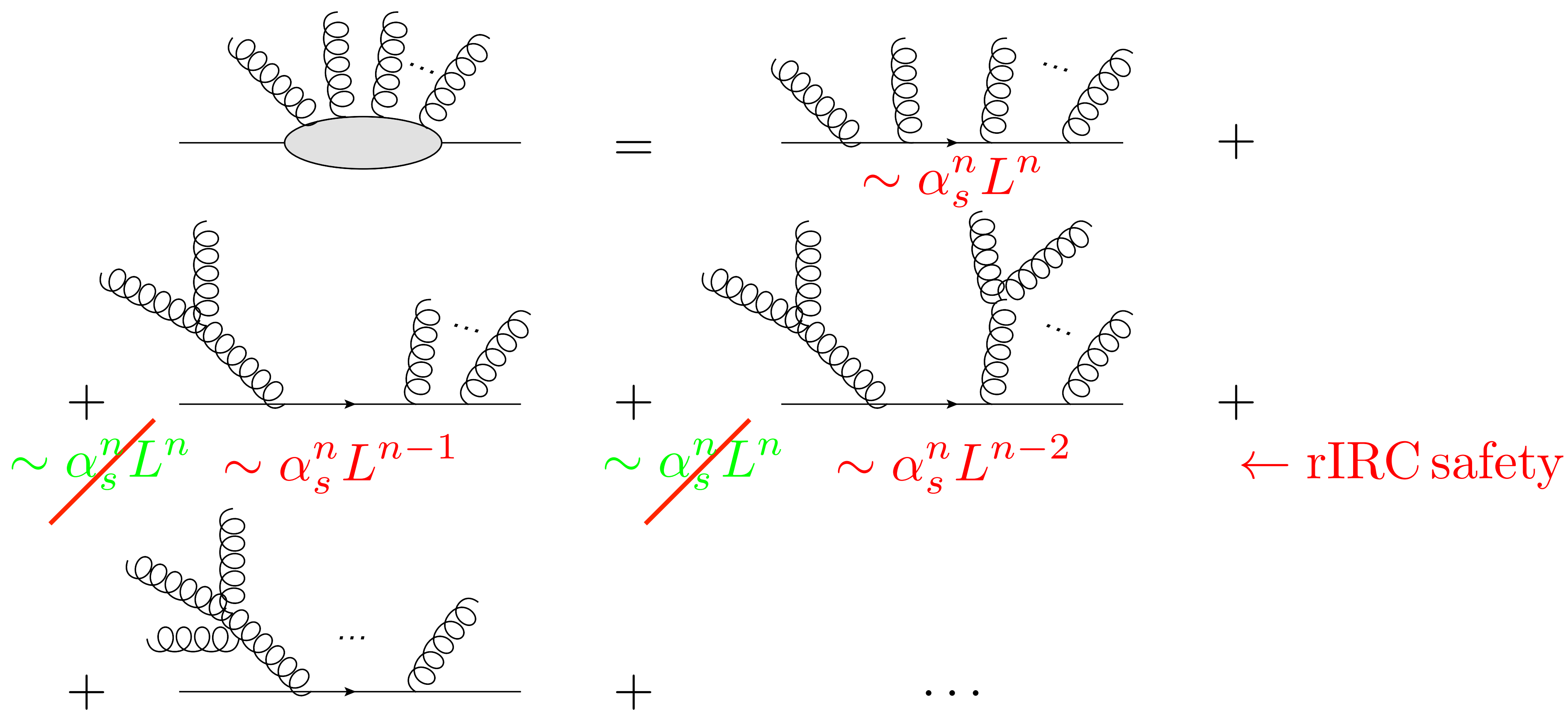
- It is useful to decompose the matrix element for n soft / collinear emissions as a sum of terms with an increasing number of colour-correlated emissions (i.e. non-abelian contributions)



- Which diagrams do we need to achieve NLL, i.e. neglect terms of order $\alpha_s^n L^{n-1}$?

Hierarchy in real emissions

- It is useful to decompose the matrix element for n soft / collinear emissions as a sum of terms with an increasing number of colour-correlated emissions (i.e. non-abelian contributions)



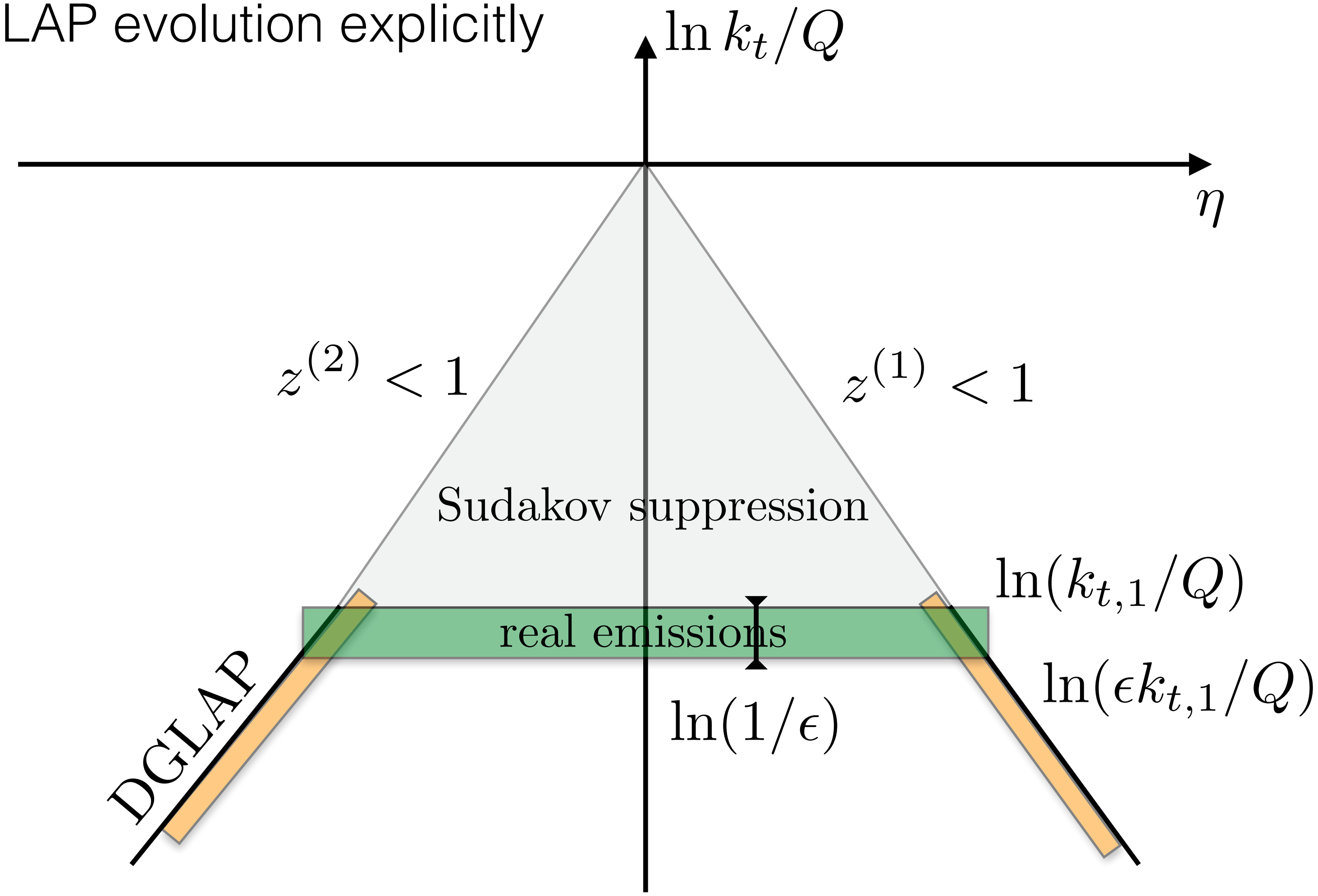
- At NLL only independent soft emissions in the multiple-emission function
- With two real emitters the non-abelian contribution is fully inclusive in the secondary branchings (contributing to the radiator)

Treatment of initial state radiation

[PM, Re, Torrielli in preparation]

- At NLL real radiation is soft and collinear, therefore there's no overlapping with the DGLAP evolution (hard collinear radiation -> larger rapidities)

- At NNLL a single real hard-collinear emission is allowed; need to resolve the last step of DGLAP evolution explicitly



- i.e. expand around the IR cutoff of the last resolved emission

$$q(x, \epsilon k_{t,1}) = q(x, k_{t,1}) - \frac{\alpha_s(k_{t,1})}{\pi} P(z) \otimes q(x, k_{t,1}) \ln \frac{1}{\epsilon} + \mathcal{O}(\mathrm{N^3LL})$$

cutoff dependence cancels against the real counterpart

Extrapolation strategy for future scenarios

[M. Vidal's talk at ECFA 2016]

Public results are extrapolated to larger data sets 300 and 3000 fb^{-1}. In order to summarize the future physics potential of the CMS detector at the HL-LHC, extrapolations are presented under different uncertainty scenarios:

	systematics unchanged	exp. sys. scaled* $1/\sqrt{L}$	theo. sys. scaled 1/2	high PU effects
ECFA16 S1	✓	✗	✗	✗
ECFA16 S1+	✓	✗	✗	✓
ECFA16 S2	✗	✓	✓	✗
ECFA16 S2+	✗	✓	✓	✓

(*) until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector.