Higgs plus jet at NNLO

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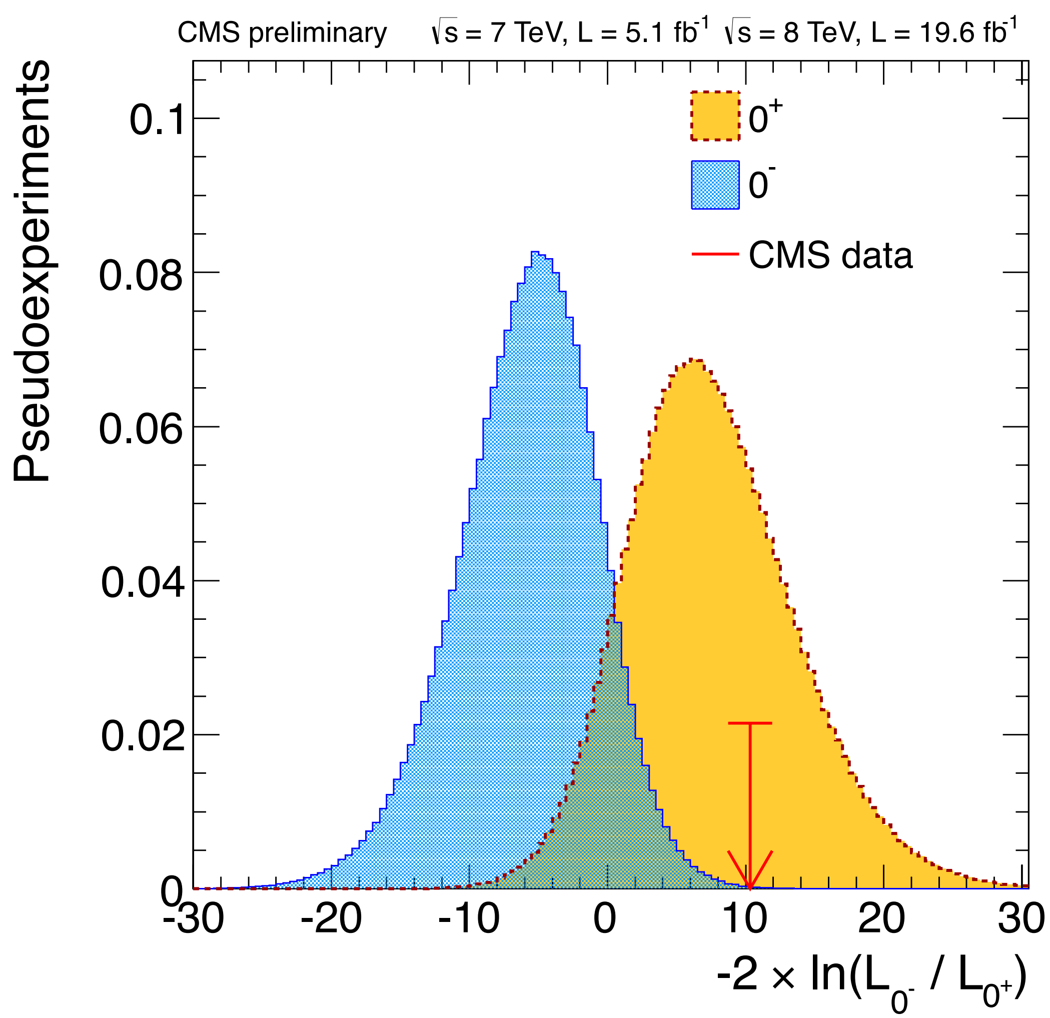
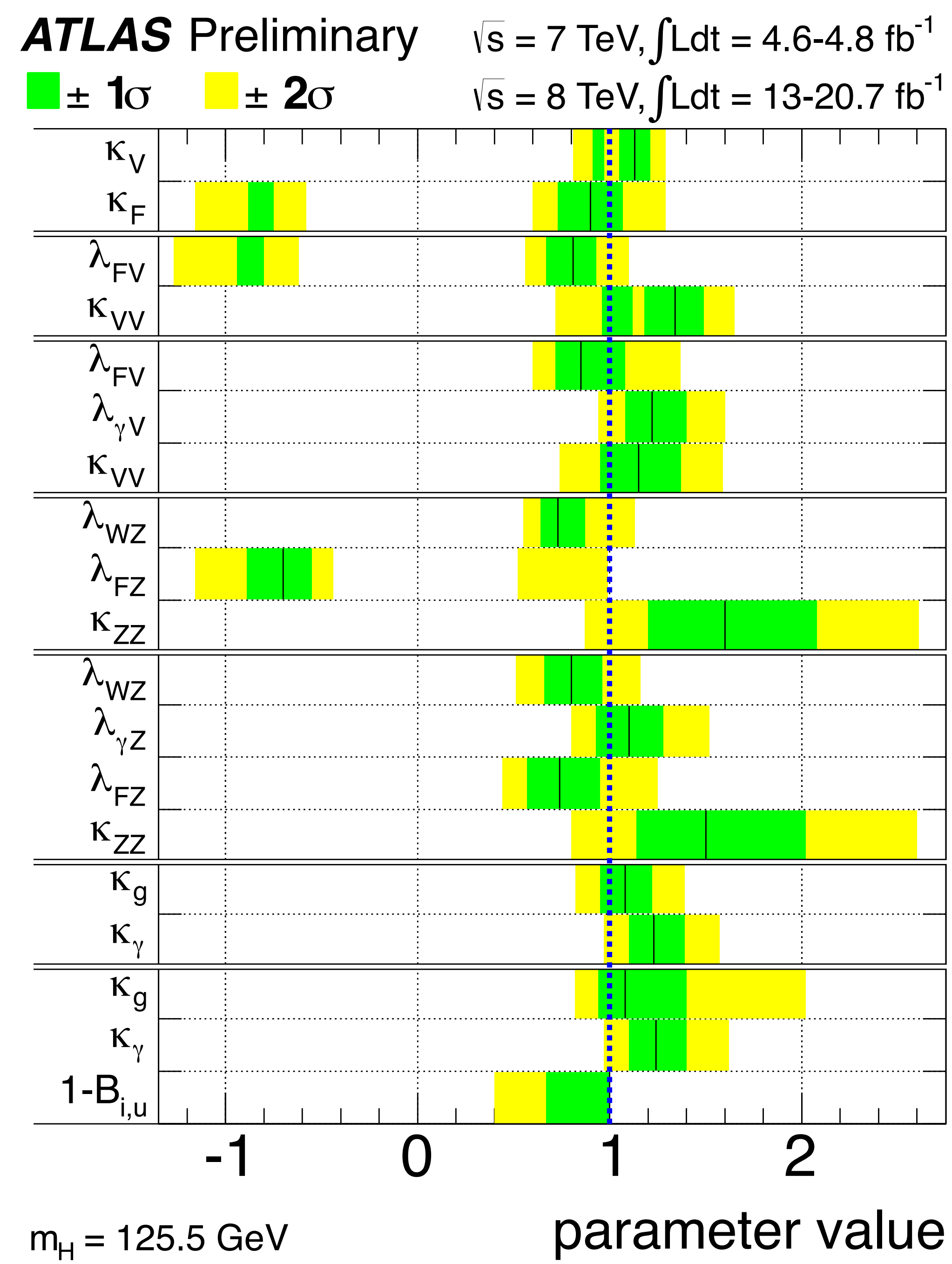
The Higgs Boson:
moving fast towards precision physics

Properties of the new particle



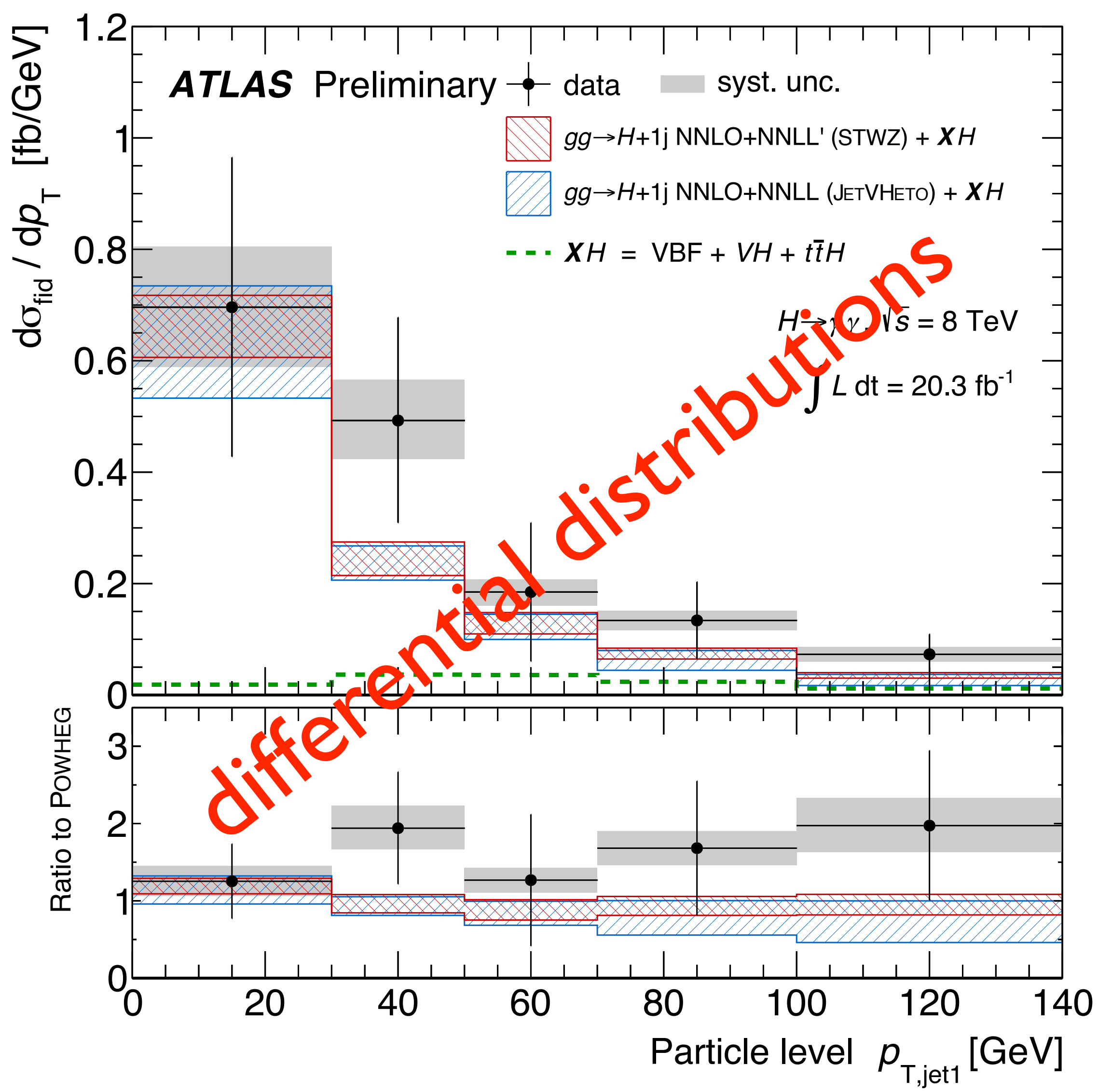
Spin-parity

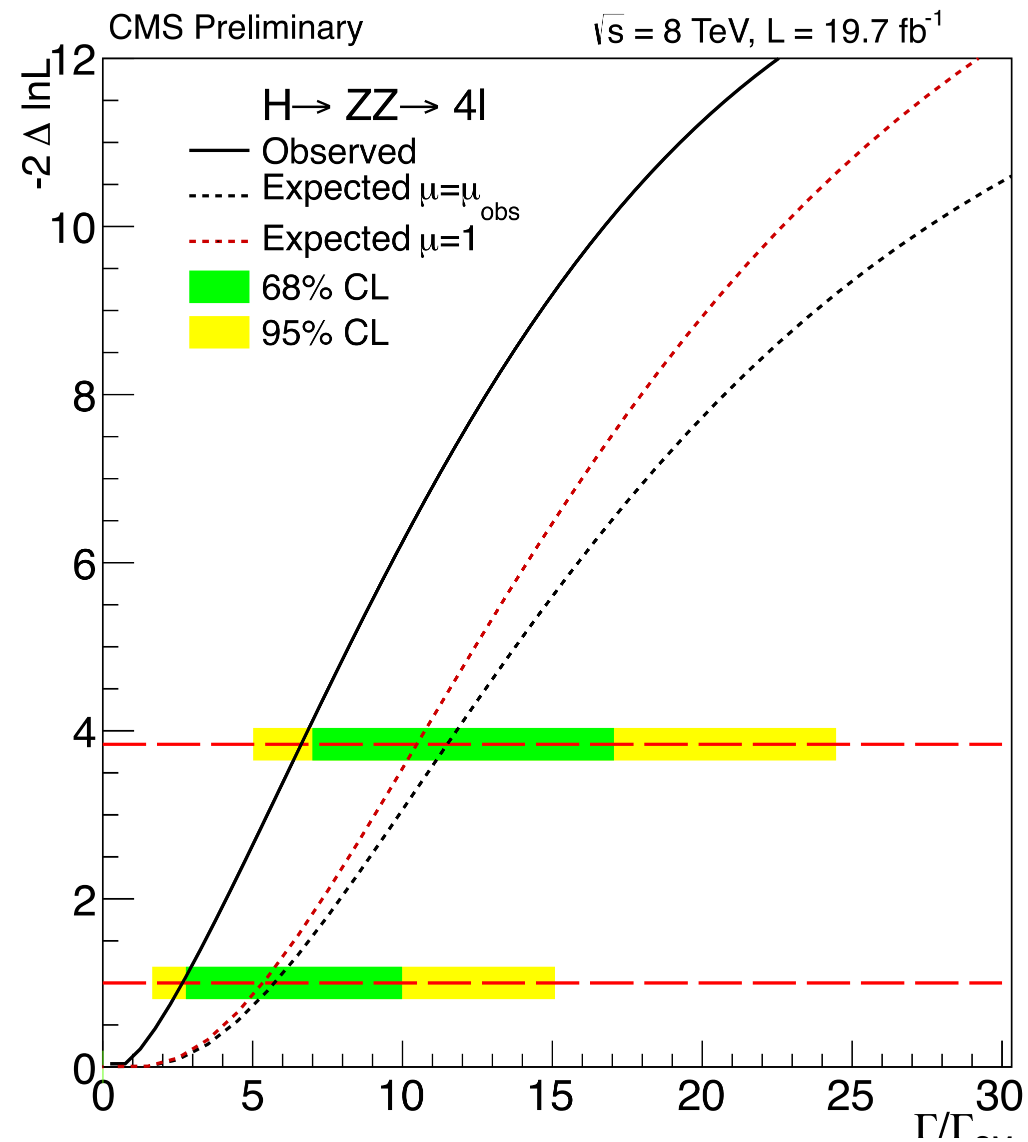


Couplings (SM-like)

The Higgs Boson: moving fast towards precision physics

Challenging analysis are already possible

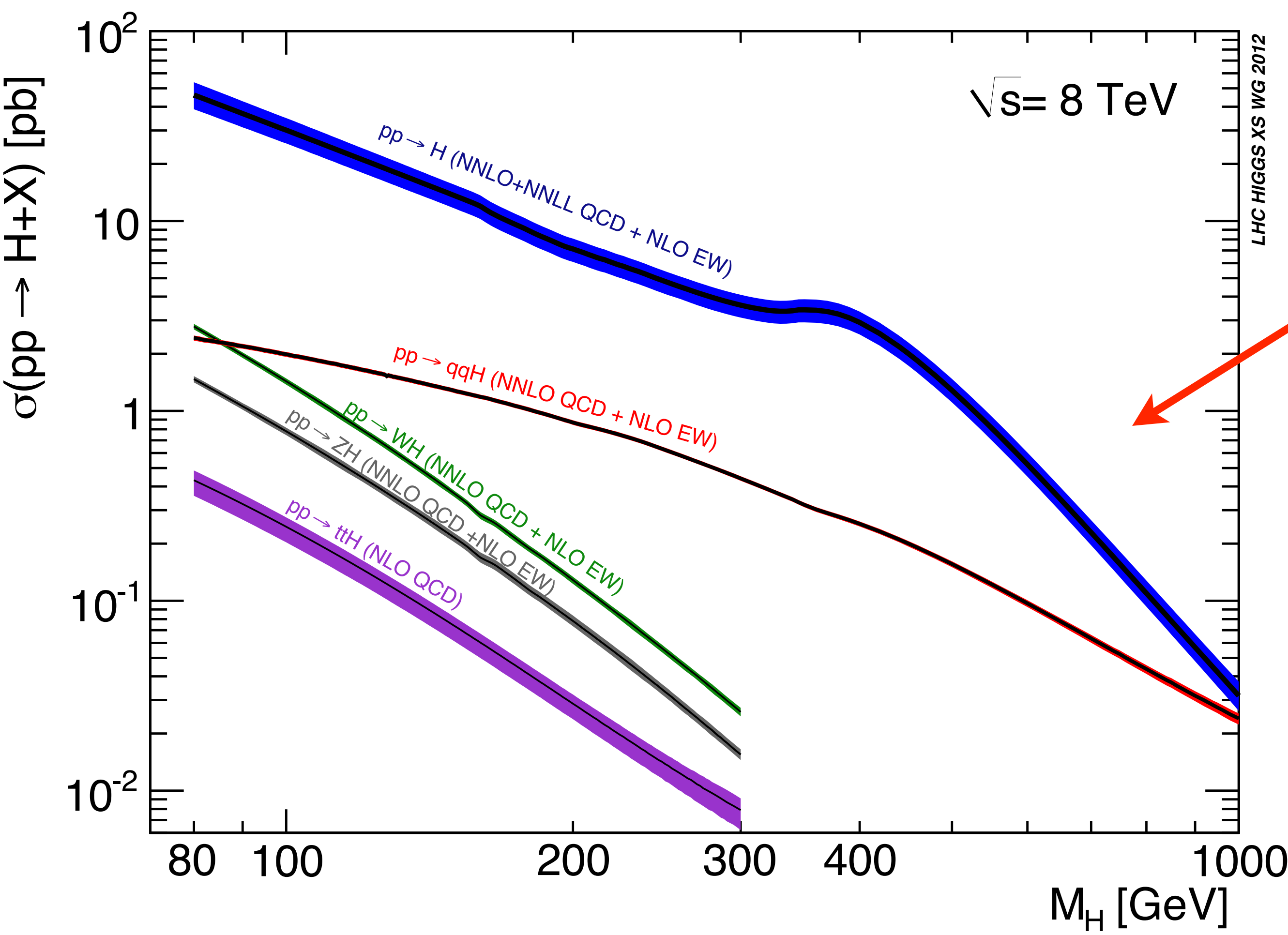




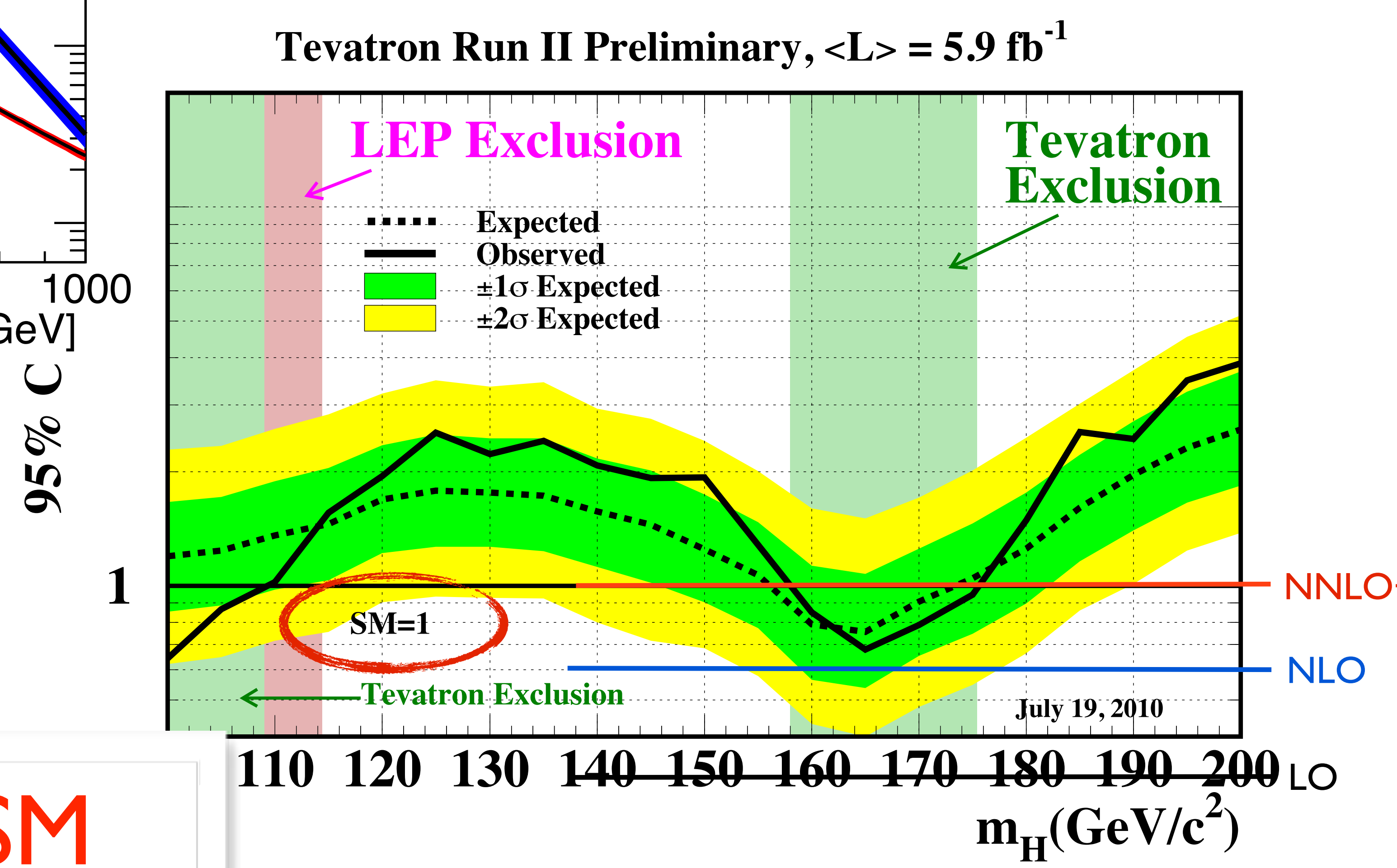
On/off-shell correlations

So far: (very) SM-like

The role of theory: quest for precision



- Higher-order perturbative computations
- Resummation program
- Reliable tools (PS, PDFs...)



Higgs program requires very sophisticated theory predictions

Even more so since BSM effects are so far well hidden

[Harlander, "First three years of the LHC"]

Higgs physics: search for small deviations

Pushing collider pheno to the boundaries

To the edge of pQCD: N^3LO

- towards the full result
  [Anastasiou et. al, Höschele et al; Buheler, Lazopoulos (2013-2014)]
- approximation from soft-collinear and Regge behavior
  [Ball, Bonvini et al. (2013)]

Going exclusive: cope with jet-bin analysis (H->WW, ττ)

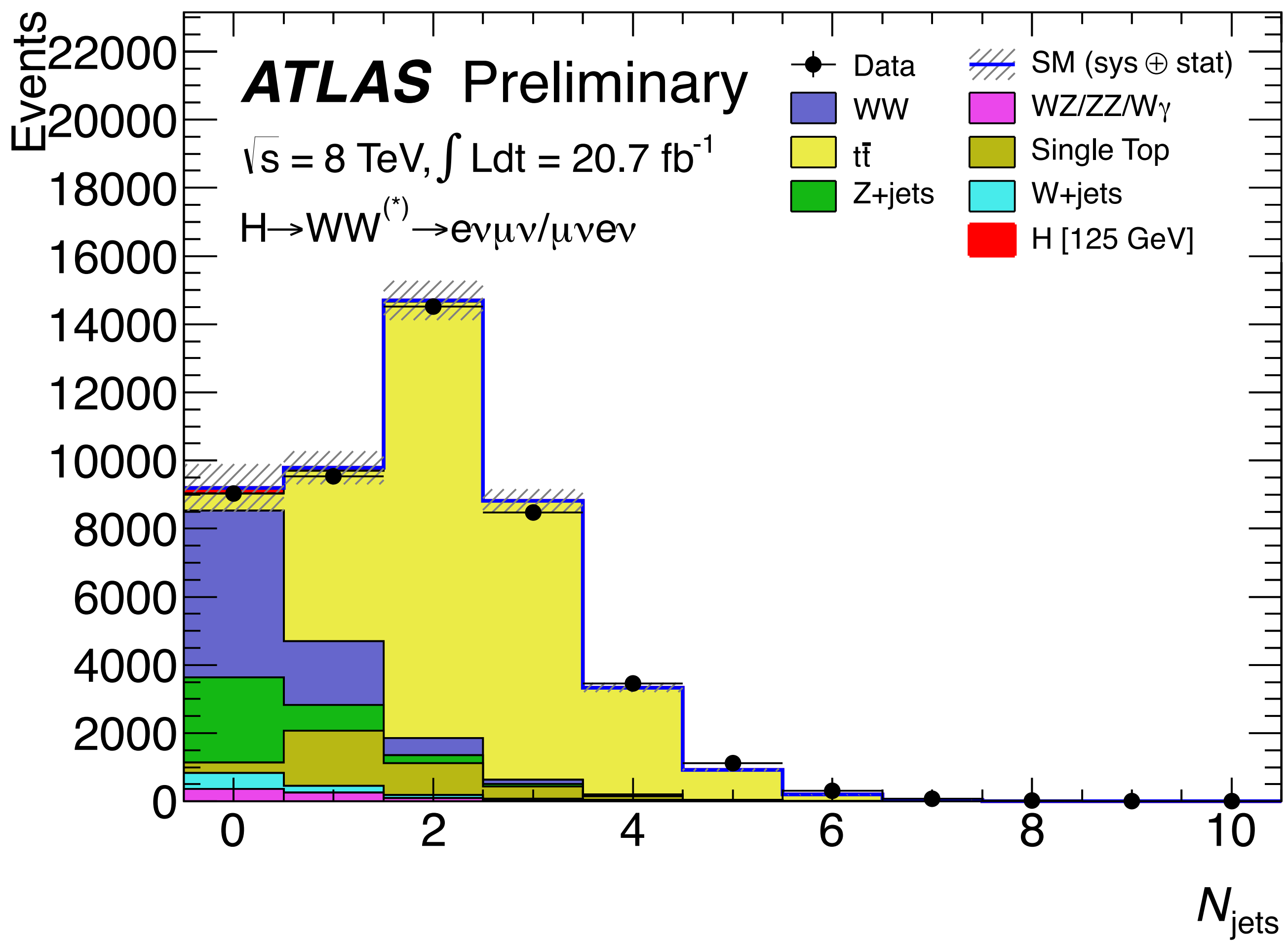
- resumming jet vetoes [Stewart, Tackmann et al; Banfi, Monni et al (2013)]
- Higgs+Jet @ NNLO
- Higgs+JJJ @ NLO [Cullen at al, (2013)]

Always improving our tools:

- beyond $m_t \to \infty$, $m_b \to 0$ [Harlander et al, (2012); Grazzini, Sargsyan (2013)]
- parton shower matching @ NNLO [Hamilton, Nason et al, (2013)]

Higgs plus jet: why NNLO

Experimental analyses for $pp \to H \to WW$:
binned according to jet multiplicity (different systematics)

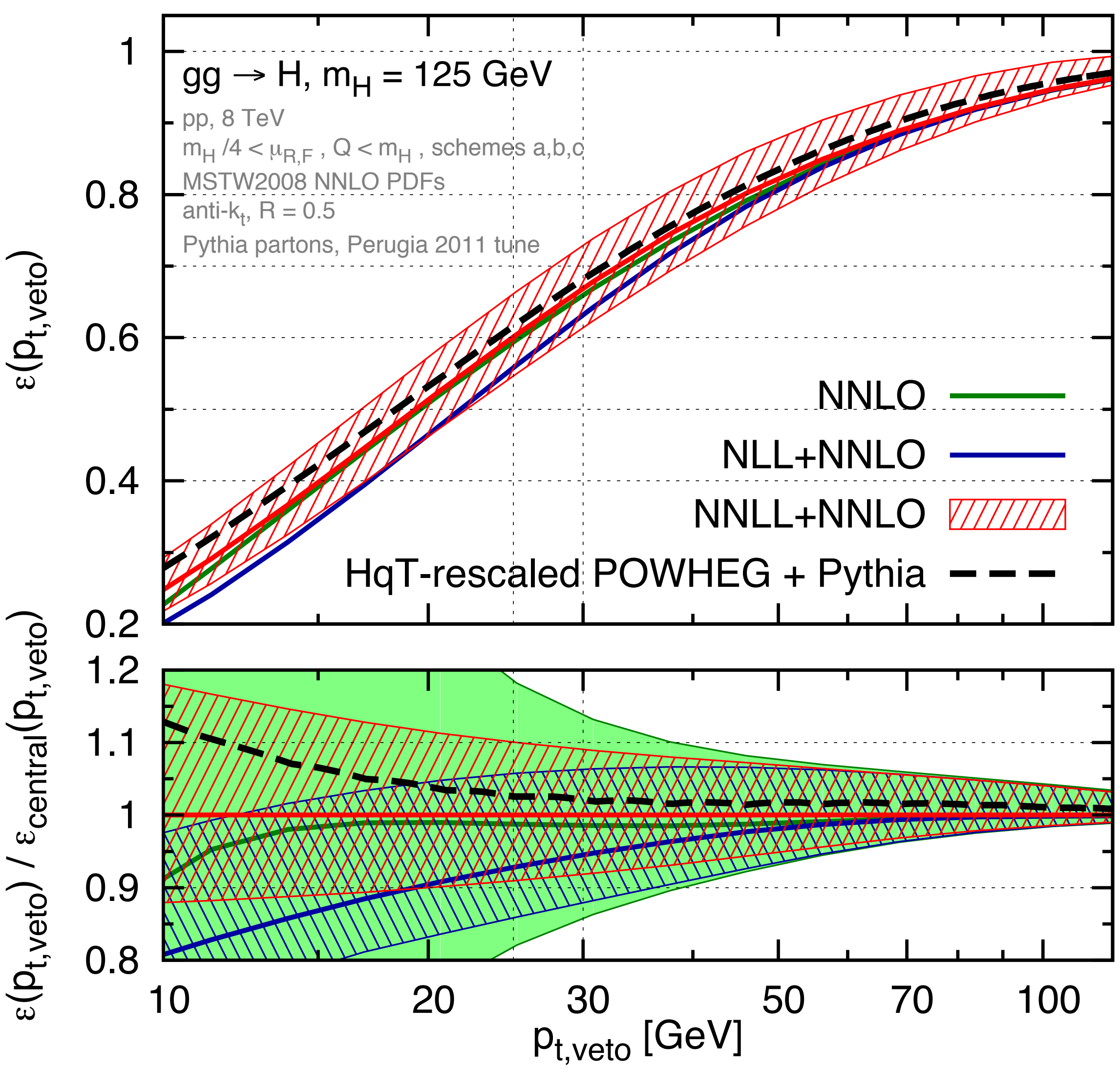


- Signal/background ratio for H+1, H+2 jets: $\sim 10\%$
- Significance in the H+1jet bin smaller, but not much smaller, than significance in the H+0 jet bin
- LARGE THEORY ERROR

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{\text{jet}} = 1$	9527	9460 ± 40	97 ± 1	1660 ± 10	270 ± 10	4980 ± 30	1600 ± 20	760 ± 20	195 ± 5
$N_{b\text{-jet}} = 0$	4320	4240 ± 30	85 ± 1	1460 ± 10	220 ± 10	1270 ± 10	460 ± 10	670 ± 10	160 ± 4
$Z \to \tau\tau$ veto	4138	4020 ± 30	84 ± 1	1420 ± 10	220 ± 10	1220 ± 10	440 ± 10	580 ± 10	155 ± 4
$m_{\ell\ell} < 50$	886	830 ± 10	63 ± 1	270 ± 4	69 ± 5	216 ± 6	80 ± 4	149 ± 5	46 ± 2
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	728	650 ± 10	59 ± 1	250 ± 4	60 ± 4	204 ± 6	76 ± 4	28 ± 3	34 ± 2

Higgs plus jet: need for improvement

0-jet bin: $\sigma_0 = \sigma_{\rm tot} - \sigma_{\geq 1}$



Large uncertainties even after NNLL resummation

[Banfi et al. (2012-2013); Tackmann et. al (2012-2013)]

1- and 2-jet bin

State of the art: NLO for H+1,2,3 jets

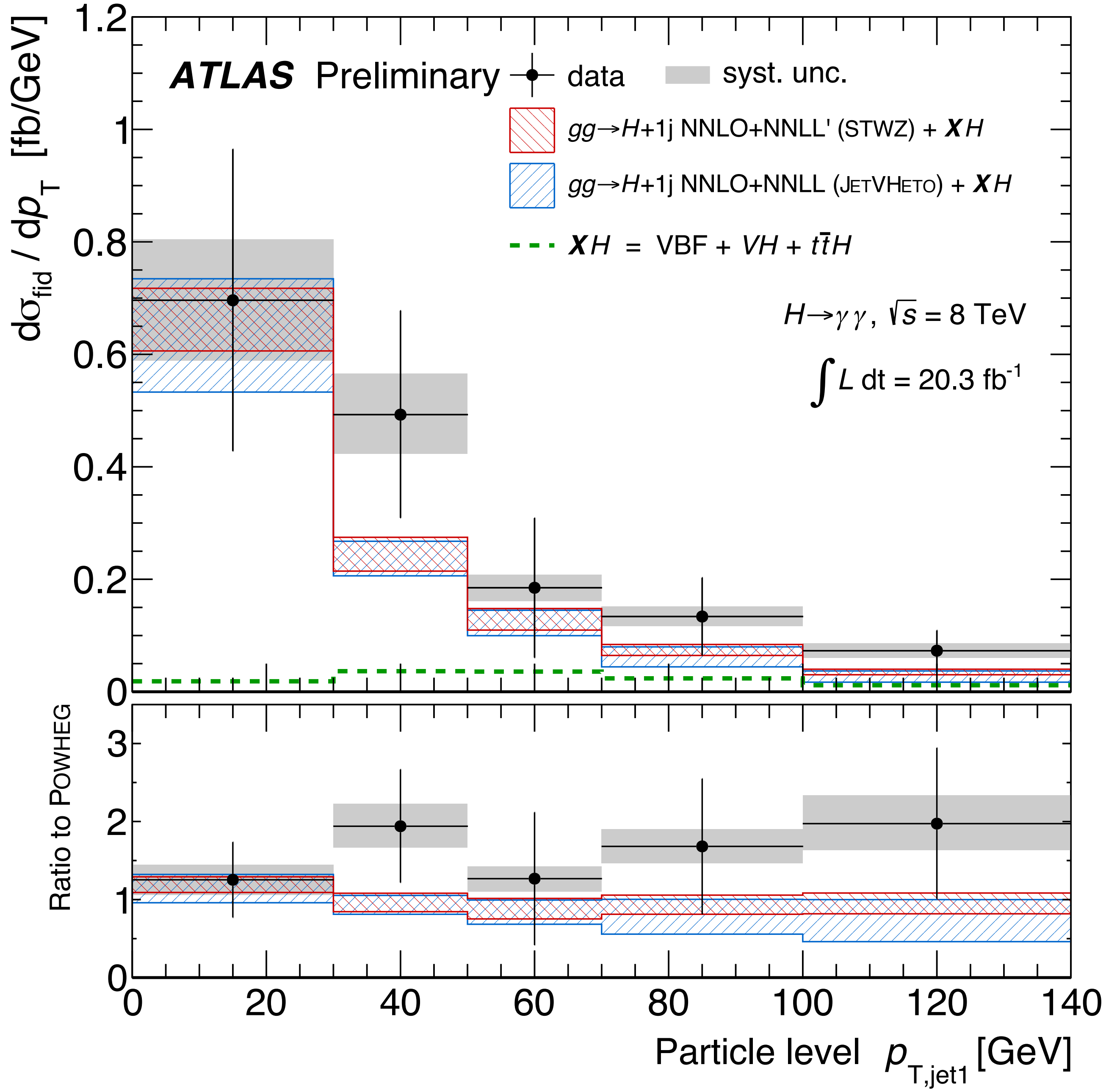
Source (1-jet)	Signal (%)	Bkg. (%)
1-jet incl. ggF signal ren./fact. scale	27	0
2-jet incl. ggF signal ren./fact. scale	15	0
Missing transverse momentum	8	3
W+jets fake factor	0	7
b-tagging efficiency	0	7
Parton distribution functions	7	1

ATLAS

Large K-factors, error dominated by missing higher orders

UNCERTAINTY CAN BE REDUCED BY IMPROVING FIXED ORDER H+JETS PREDICTIONS

Higgs plus jet: need for improvement



Soon we will require good control of the HIGGS PT SPECTRUM

Powerful probe of the Hgg coupling

- high log accuracy ✓
- finite m_t ✗
- genuine NNLO description

H+J @ NNLO REQUIRED FOR RELIABLE HIGGS PHENO

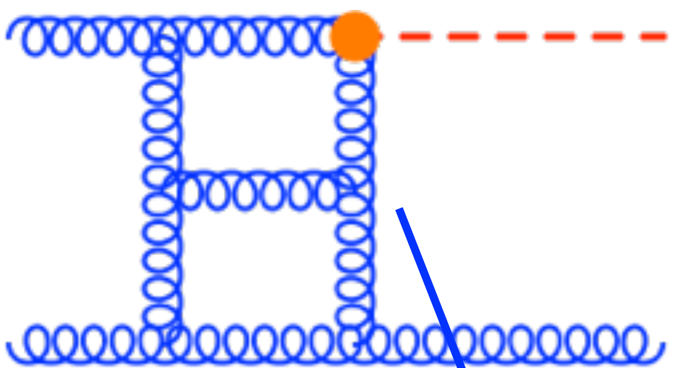
Higgs plus 1 jet at NNLO

Anatomy of a NNLO computation

- For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission
- This problem has now been solved both in theory (antenna subtraction, sector decomposition+FKS, semi-analytic subtraction) and in practice for 2->2 processes (top-pair, dijet, H+jet, single-top…)
- Now the problematic part is computing two-loop amplitudes. State of the art:
  - Numerically: 2->2 with 1 extra mass-scale (tt)
  - Analytically: 2->2 with two external mass scales (VV*)

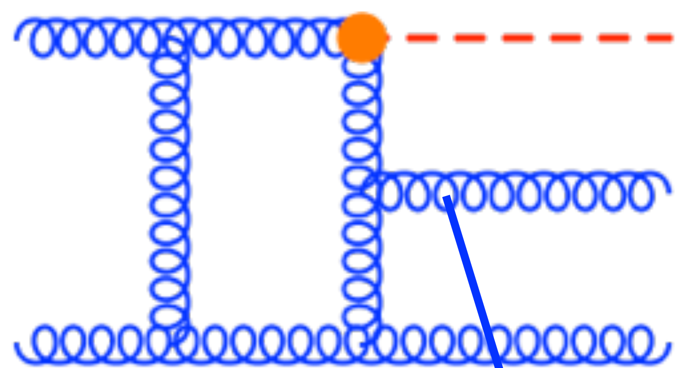
H+J: building blocks

VV



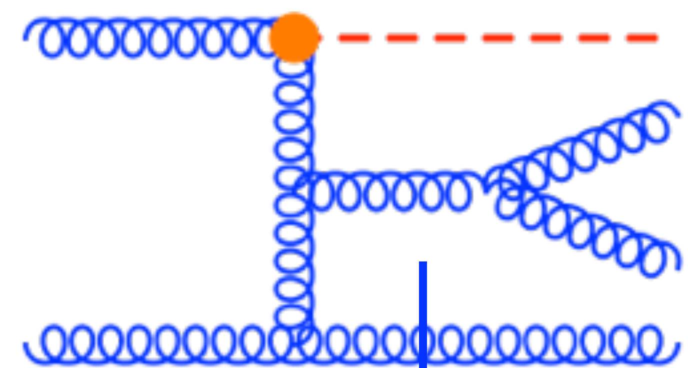
[Gehrmann et al. (2011)]

RV



[Badger et al. (2011)]

RR



[Del Duca et al., Dixon et al. (2004)]
[Badger]

$$\int \left[\frac{\mathrm{vv}_4}{\epsilon^4} + \frac{\mathrm{vv}_3}{\epsilon^3} + \frac{\mathrm{vv}_2}{\epsilon^2} + \frac{\mathrm{vv}_1}{\epsilon} + \mathrm{vv}_0 \right] d\phi_2$$

$$\int \left[\frac{\mathrm{rv}_2}{\epsilon^2} + \frac{\mathrm{rv}_1}{\epsilon} + \mathrm{rv}_0 \right] d\phi_3$$

$$\int [\mathrm{rr}_0]\, d\phi_4$$

Problematic part is to extract implicit IR poles from RV and RR in a FULLY-DIFFERENTIAL way, i.e. without doing the PS integration

OUR APPROACH: SECTOR DECOMPOSITION + FKS

[Czakon (2010), Boughezal, Melnikov, Petriello (2011)]

H+j: building blocks and credits

Computation done in full CDR

- not necessary in principle -> see D. Heymes talk
- however less prone to implementation bugs
- gives some extra handles for checks (disappearance of unph. amps)

We then require the following process-dependent ingredients

- tree-level H+3j [Del Duca et al., Dixon et al. (2004)], [Badger]
- tree-level H+2j [Badger et al. (2011)] up to $\mathcal{O}(\epsilon)$
- tree-level H+1j up to $\mathcal{O}(\epsilon^2)$
- one-loop H+2j [Badger et al. (2011)]
- one-loop H+1j up to $\mathcal{O}(\epsilon)$
- two-loop H+1j [Gehrmann et al. (2011)]

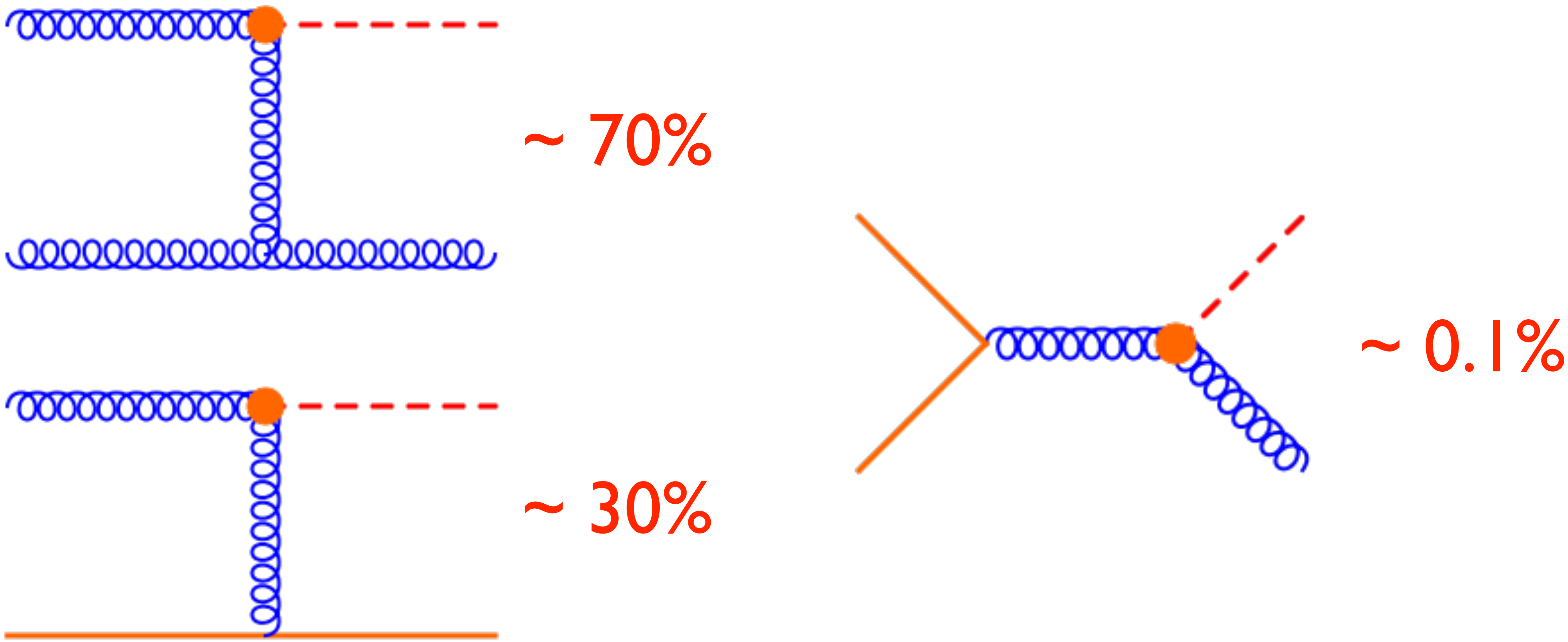
Amplitudes need to be FAST and STABLE

ANALYTIC RESULTS, SPINOR-HELICITY FORMALISM

EXTREMELY GRATEFUL TO MCFM FOR PROVIDING EXCELLENT AMPLITUDES ALREADY AS A FORTRAN CODE!

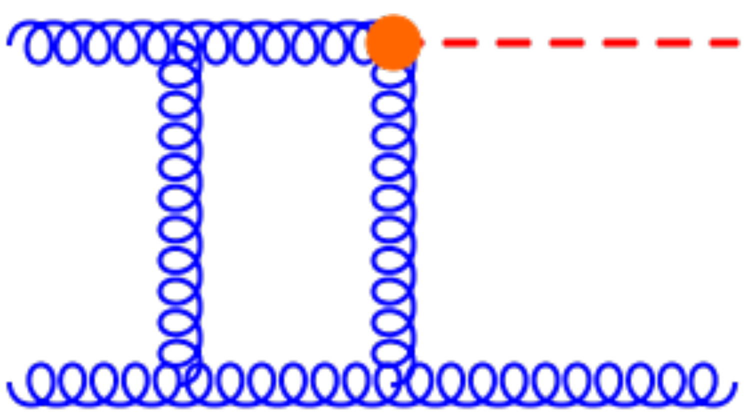
Higgs plus 1 jet at NNLO: our computation

Partonic Channels: LO

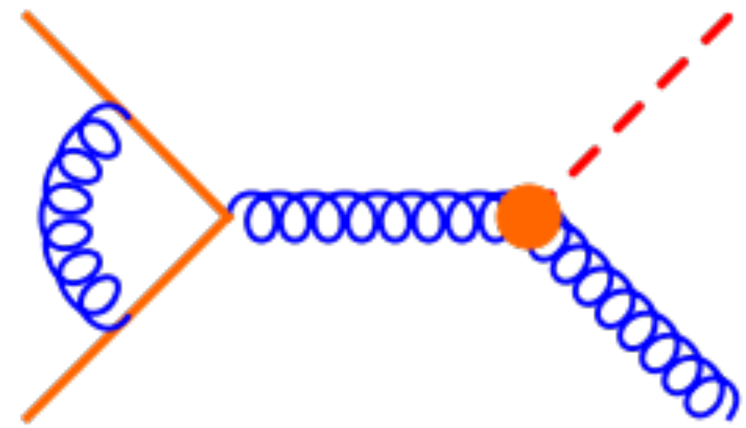


- gg is by far the most important
- qg is relevant as well
- qqb is negligible

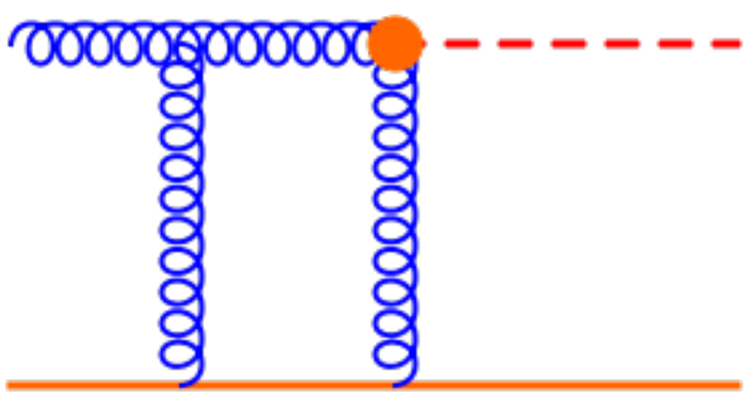
Partonic Channels: NLO



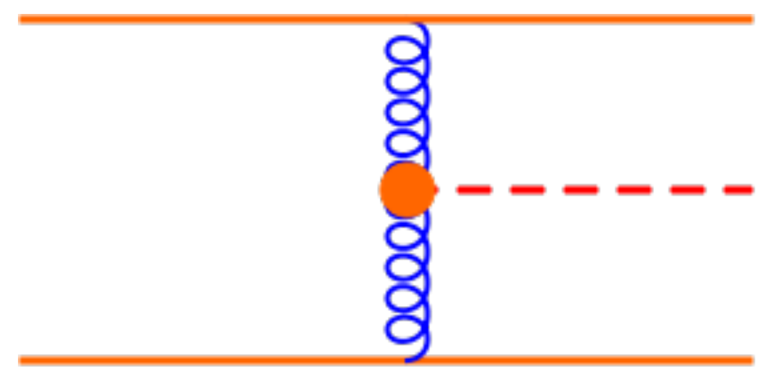
~ 70%



~ -0.5%



~ 30%



Again, gg and qg are the most relevant

Partonic Channels: recap

LO and NLO:

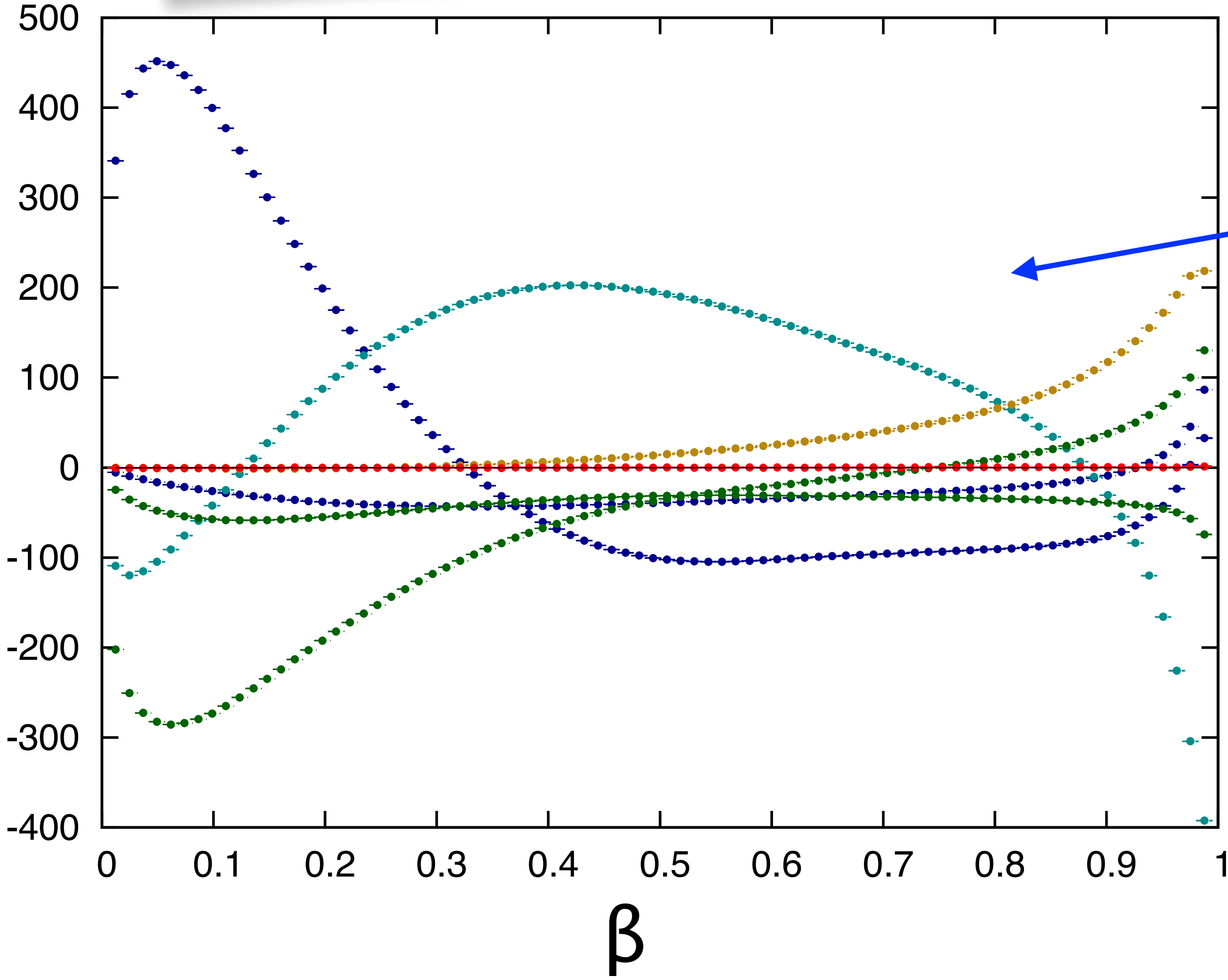
- gg ~ 70% full result
- qg ~ 30% full result
- qq is negligible
- pattern persists for Hjj@NLO (qq~2%) (same ingredients of Hj@NNLO)

At NNLO, we ONLY CONSIDER GG AND QG

- we must compute everything at NLO, as all channels mix under PDF renormalization

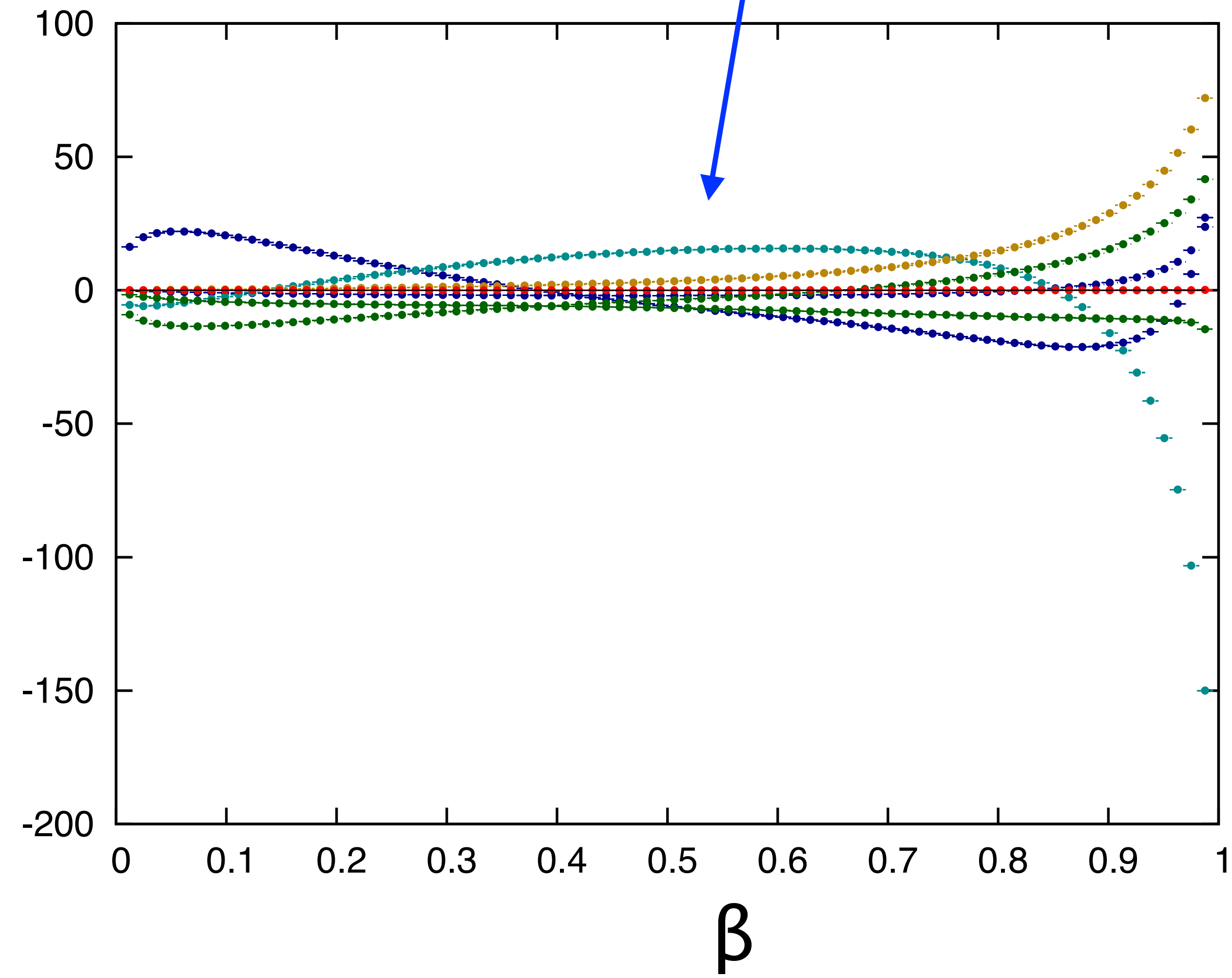
Checks: cancellation of 1/ε poles

NUMERICAL CANCELLATION between
renormalization and coll. couterterms, RR, RV, VV



gg

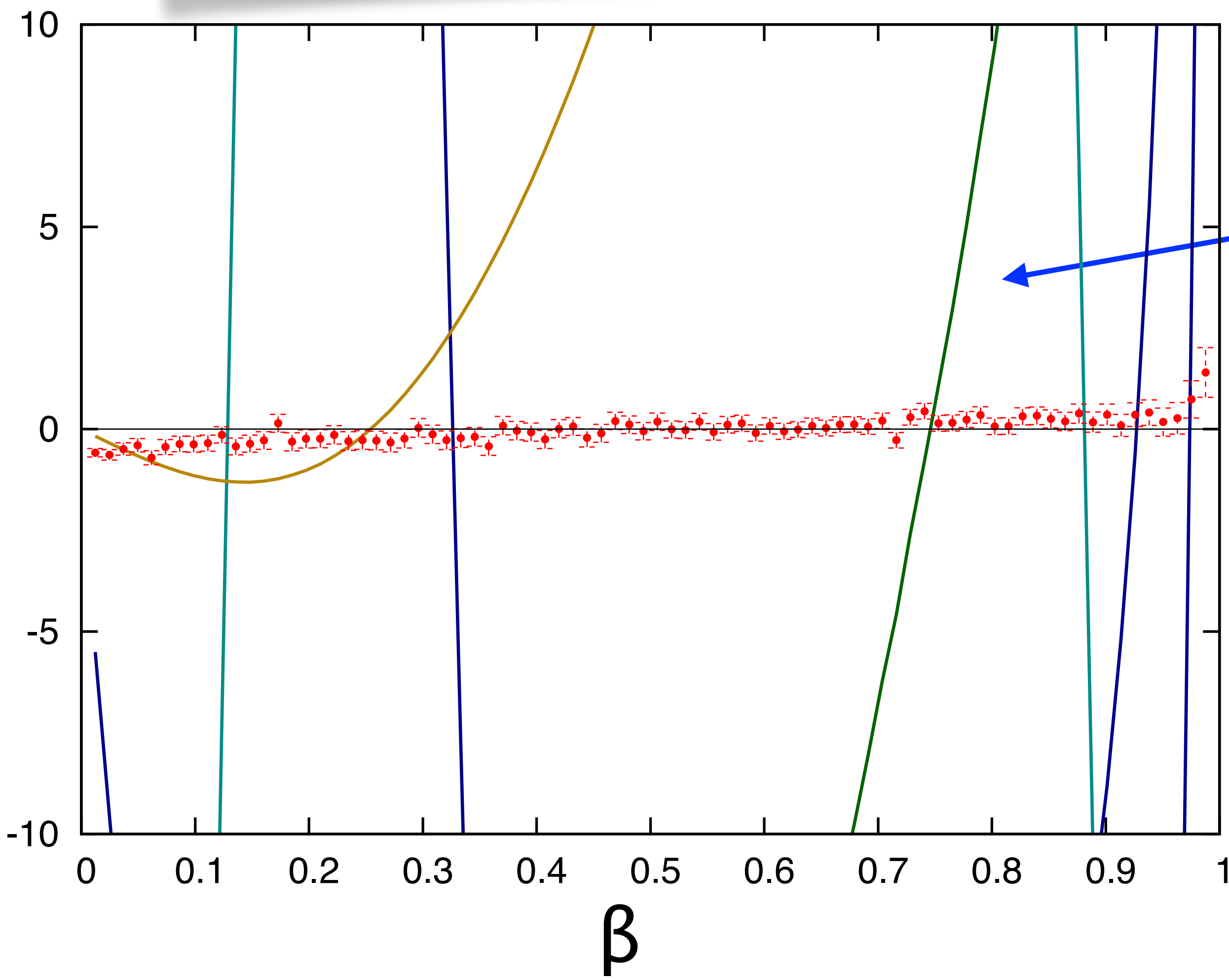
qg

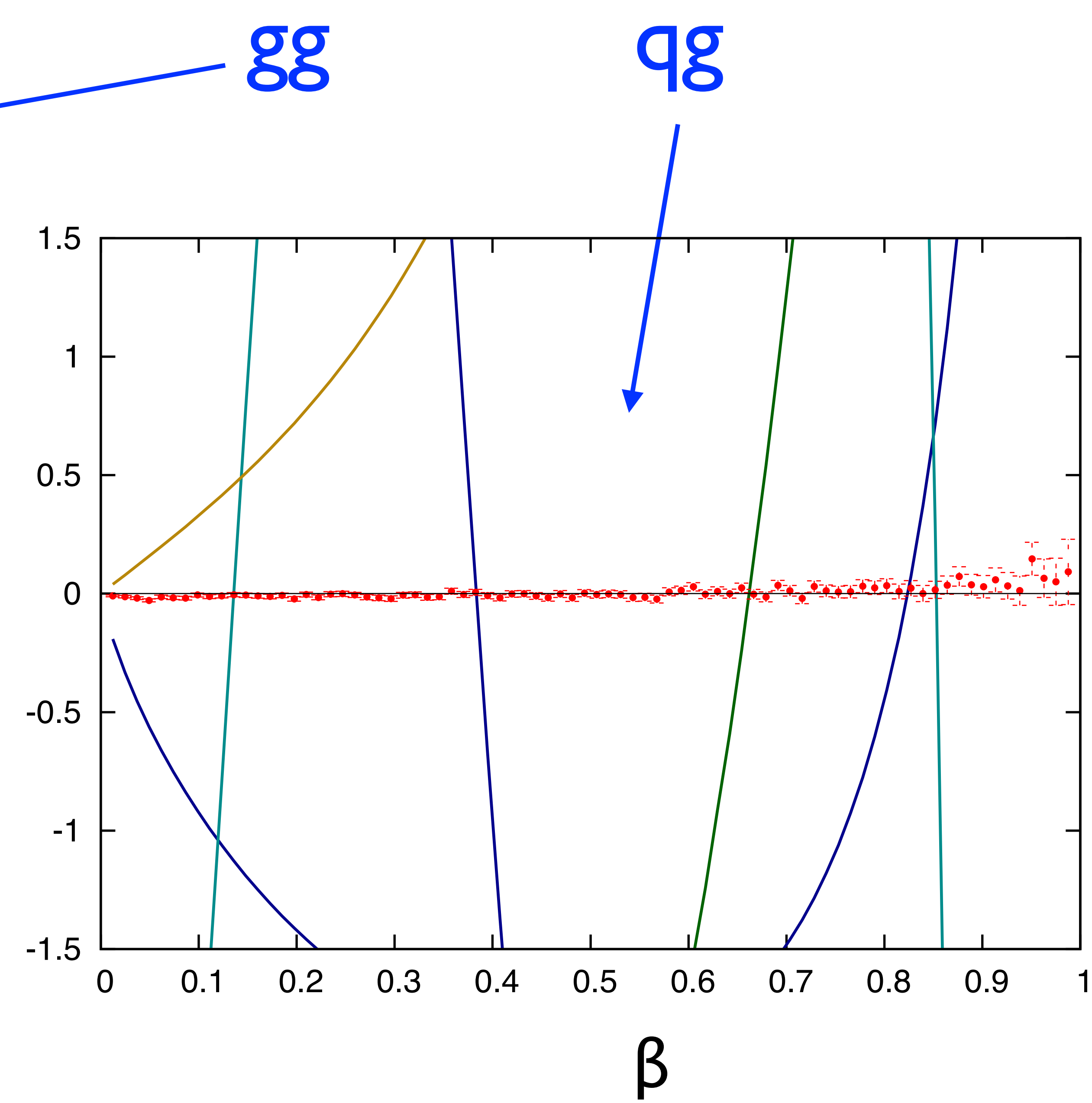


$$\beta = \sqrt{1 - \frac{s_{th}}{\hat{s}}}$$

Checks: cancellation of 1/ε poles

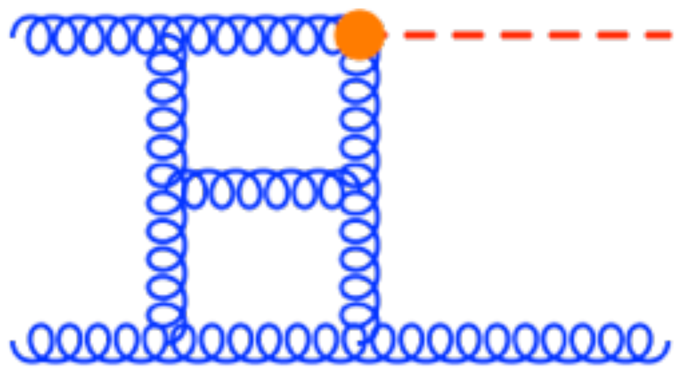
NUMERICAL CANCELLATION between renormalization and coll. couterterms, RR, RV, VV

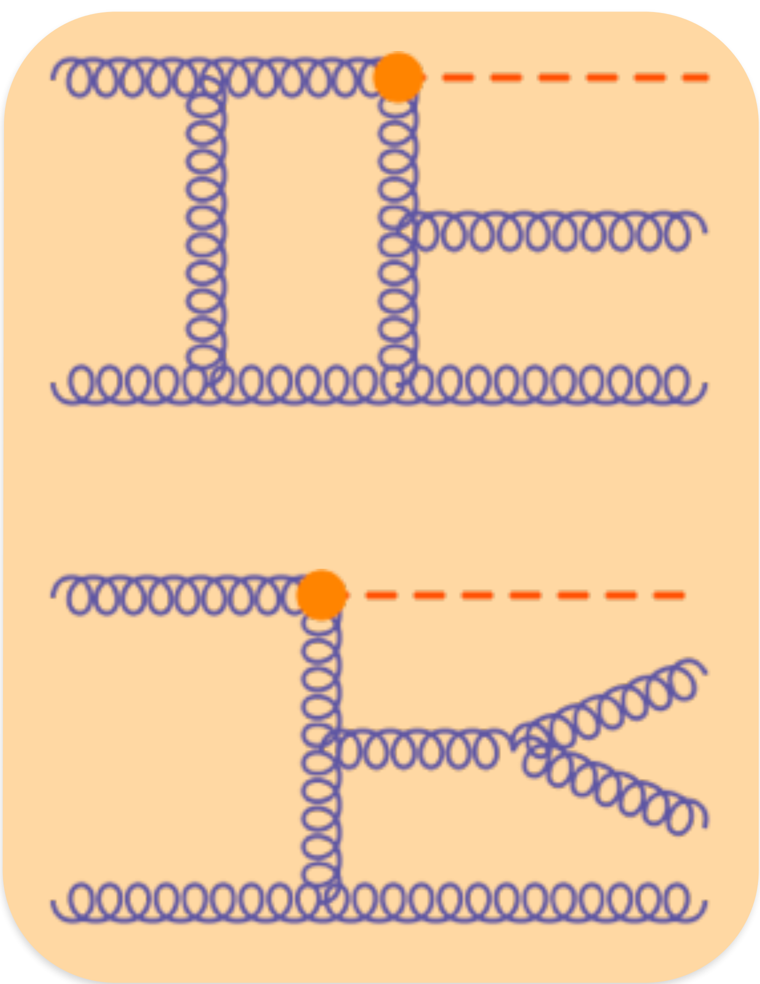




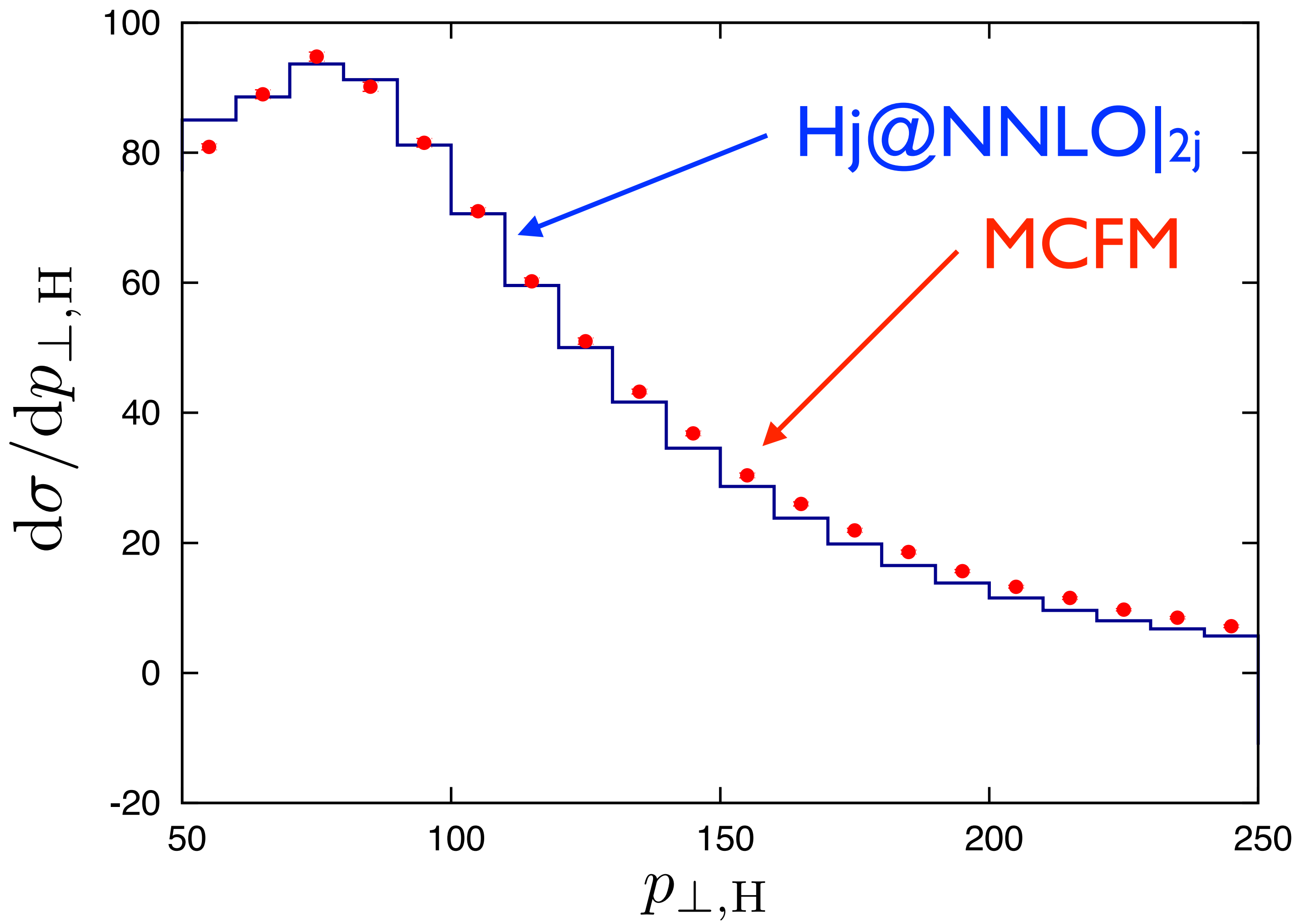
Better than per mill cancellation at 1/ε

Checks: p_T spectrum in the 2-jet bin



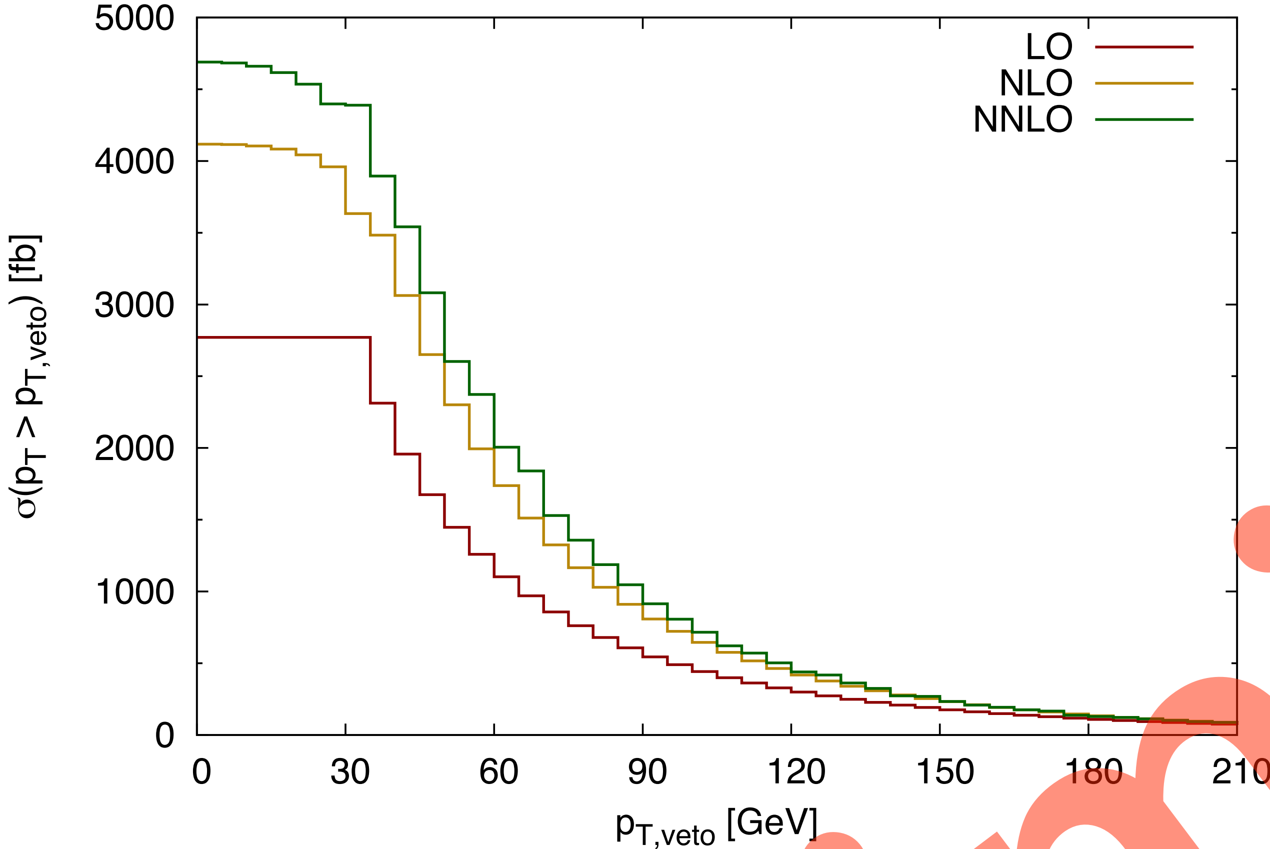


H+j @NNLO ∈ H+jj@NLO

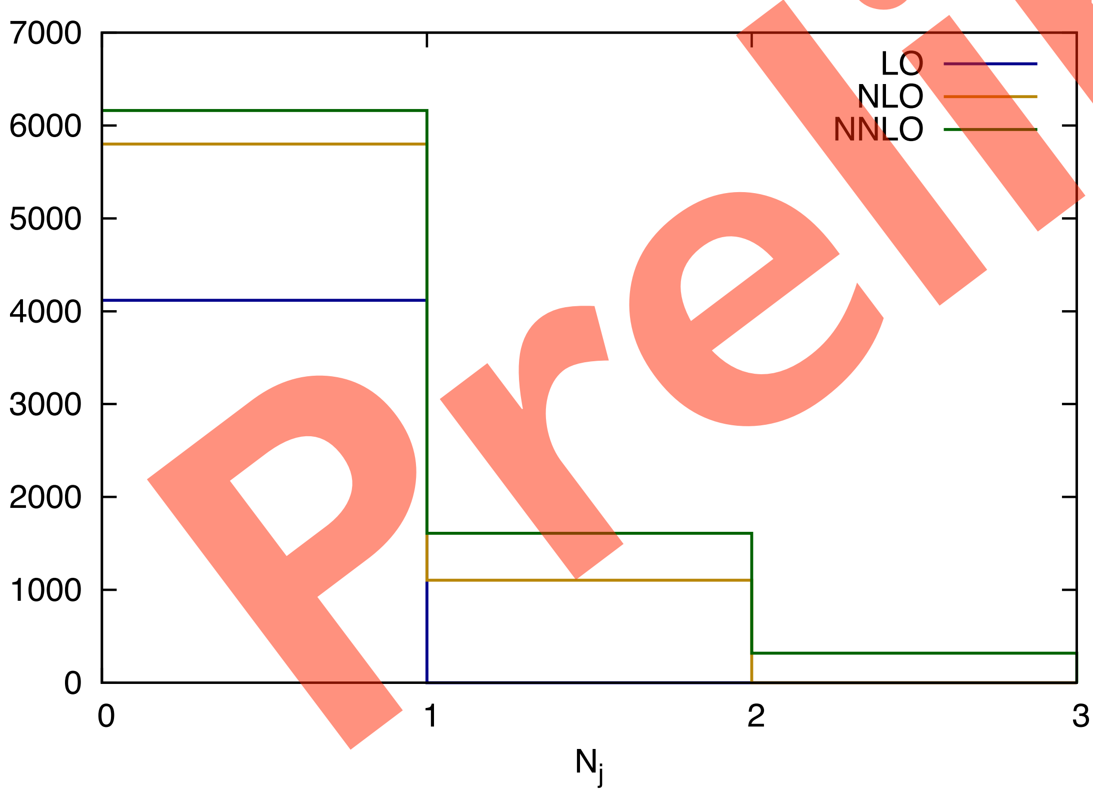


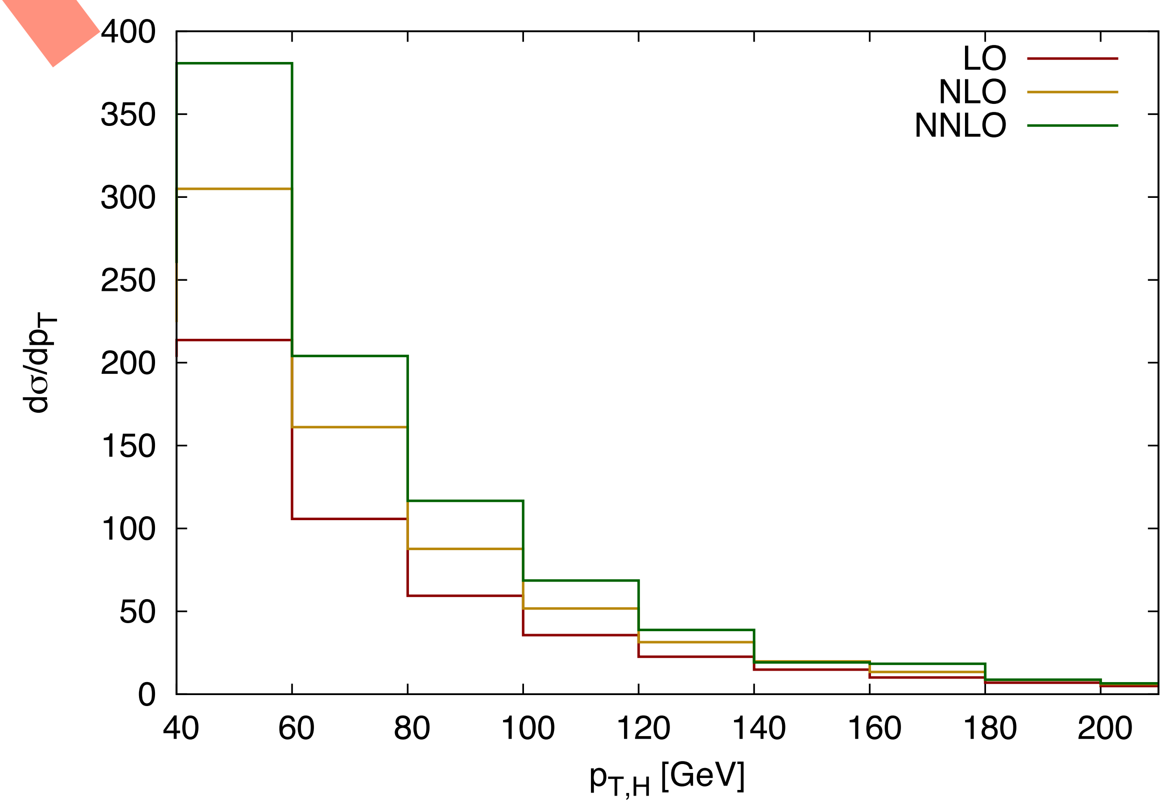
Good agreement with MCFM

Some (VERY PRELIMINARY) results



Can compute IR safe obs on the fly





Conclusions

All channels preliminary results for H+1j @ NNLO

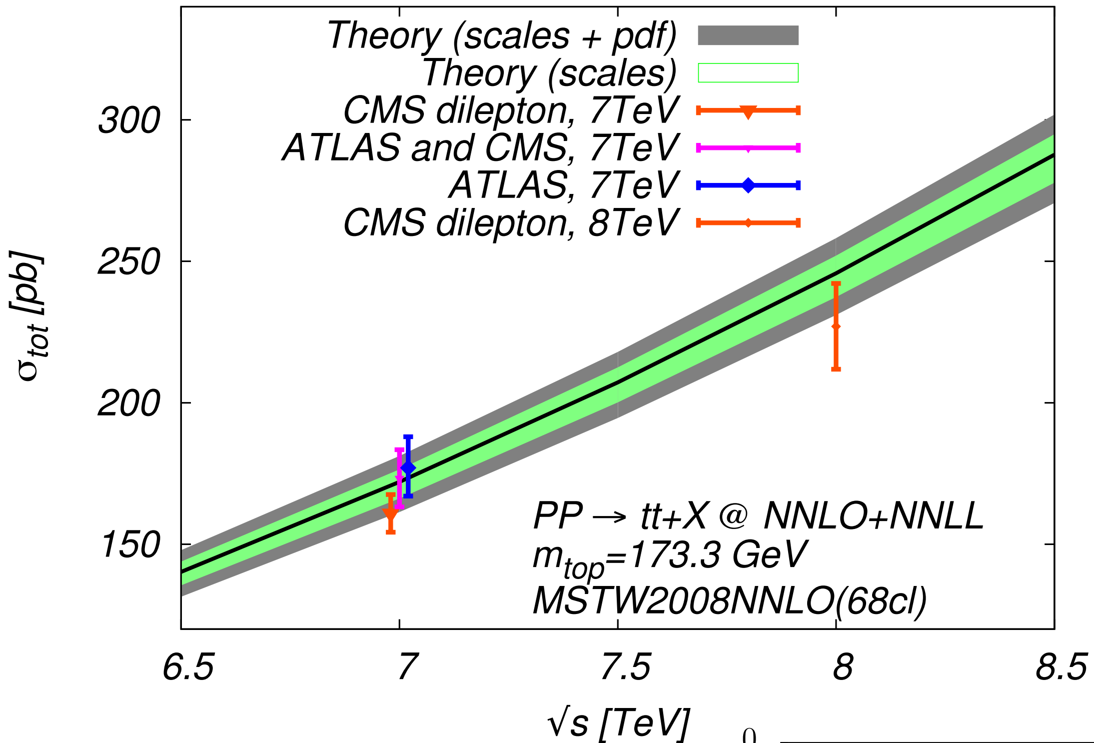
- Computation completed for all relevant channel ✓
- Differential distributions implemented ✓
- Cancellation of IR singularities ✓
- Code fully validated ✗ [our priority, almost there + see next talk]

Work in progress:

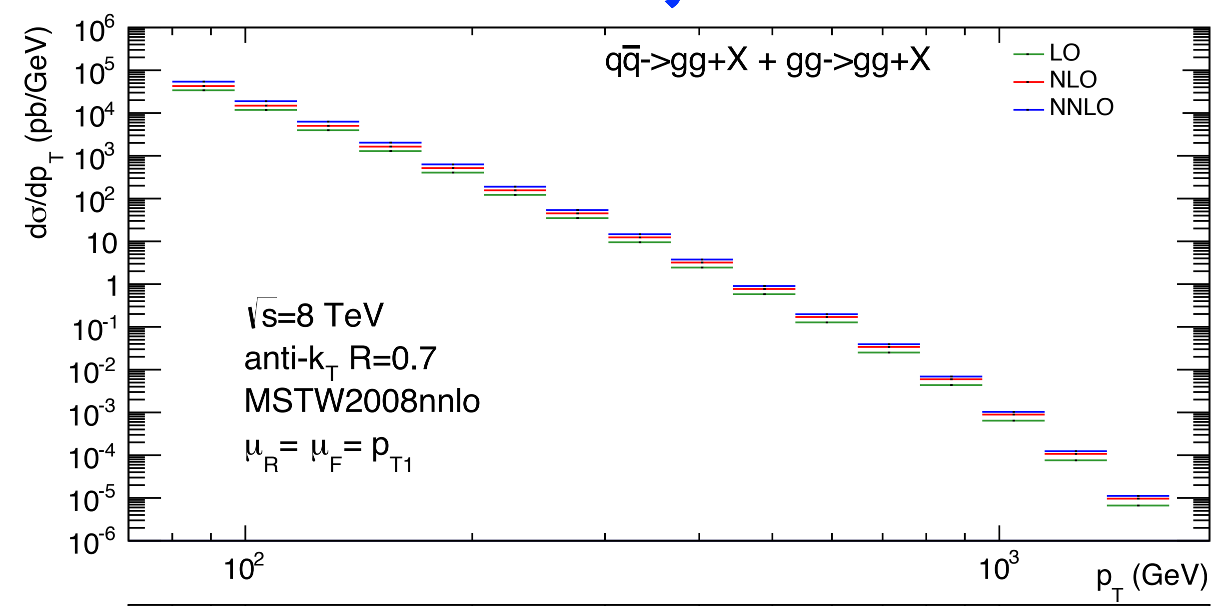
- Higgs decay (WW/γγ) ~ ✓
- Dynamical scale $\mu_R, \mu_F = (m_H + p_{T,lj})/2$ ~ ✓
- Systematic scale variation / PDF error [META PDFs promising!]
- Higgs p_T distribution and vetoed cross section@LHC
- WW background @ NNLO [see J.M. Henn's talk]

Colorful 2 -> 2 NNLO phenomenology is a reality

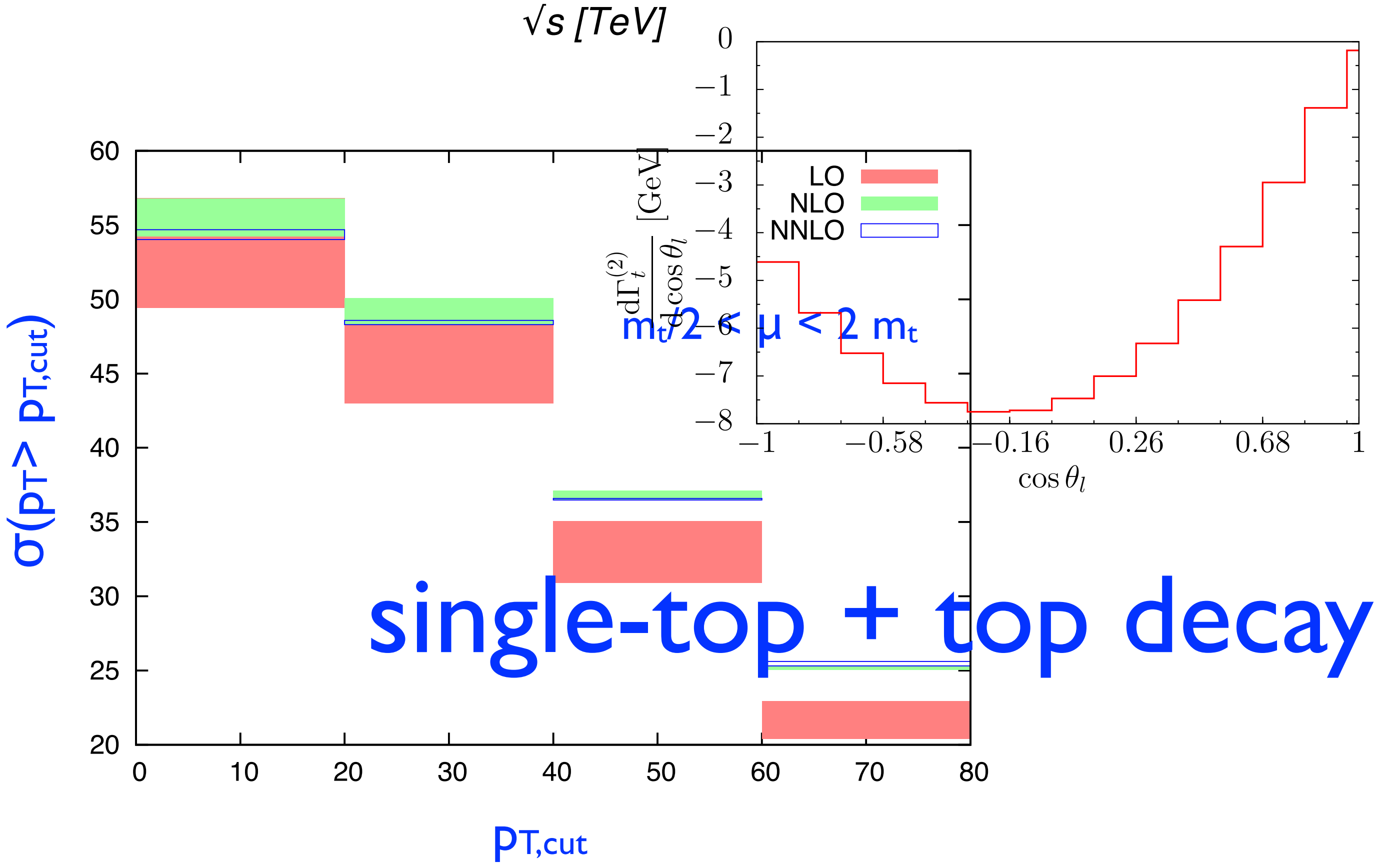
ttbar



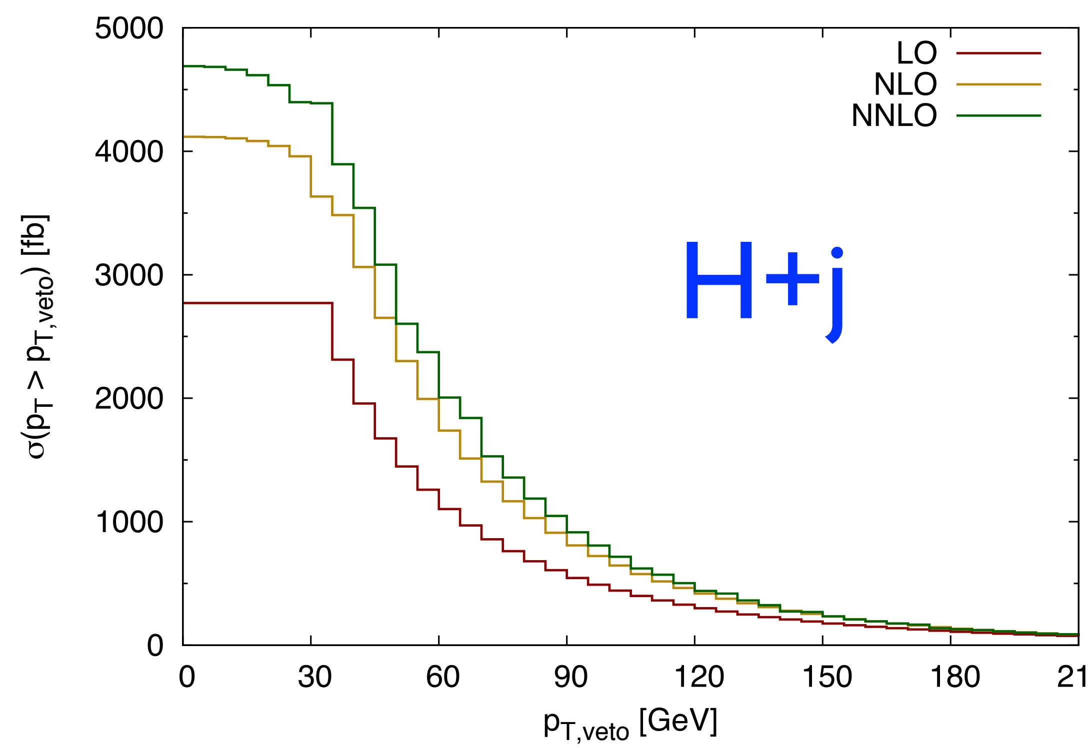
dijet



single-top + top decay



H+j

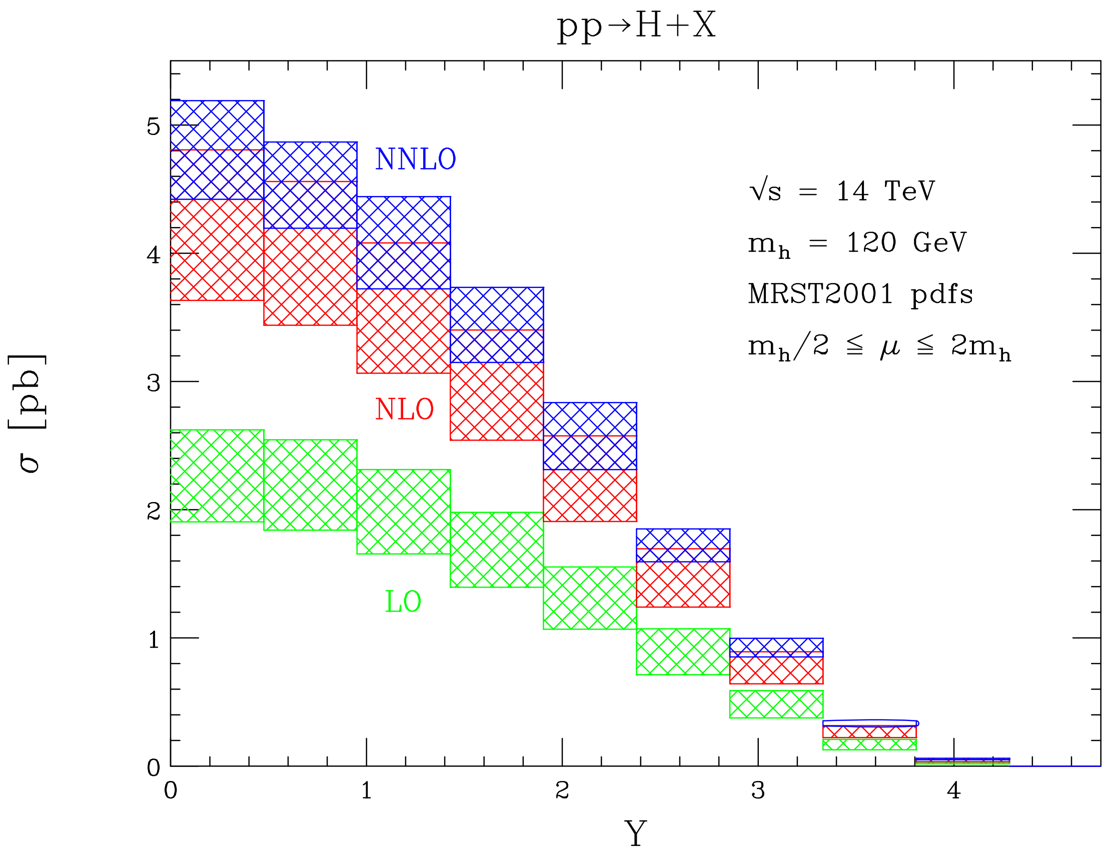


Thank you for your attention!

A successful strategy for simpler processes: SECTOR DECOMPOSITION

[Binoth, Heinrich; Anastasiou, Melnikov, Petriello (2004)]

Basic idea: CLEVER PARAMETRIZATION of the phase space which makes IR SINGULARITIES MANIFEST



Powerful tool for fully differential NNLO:

- dijet production at LEP [Anastasiou, Melnikov, Petriello (2004)]
- Higgs production at hadron colliders [Anastasiou, Melnikov, Petriello (2005)]
- DY production at hadron colliders [Melnikov, Petriello (2006)]
- bb->H [Bühler, Herzog et al (2012)]

BUT

Parametrization becomes challenging for more complicated processes

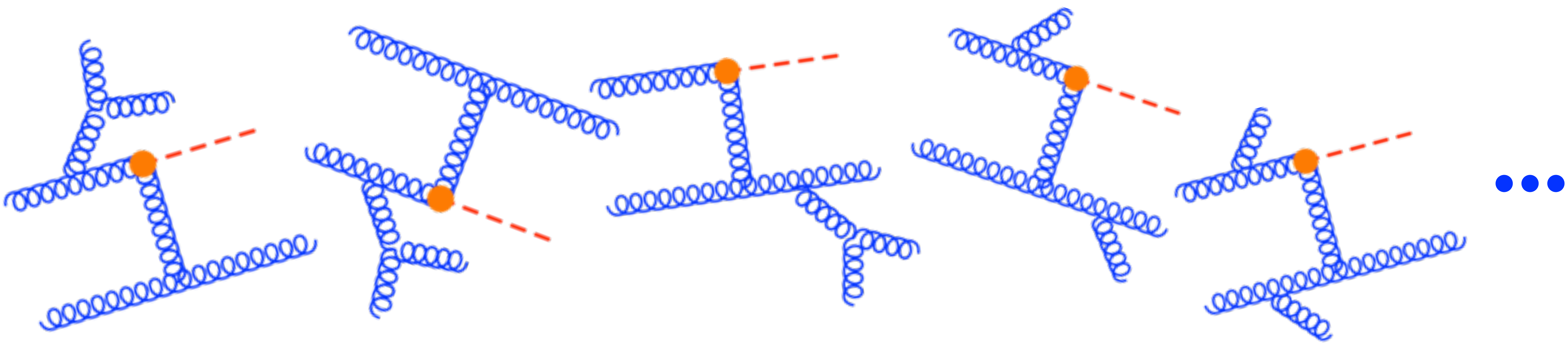
Parametrization known only for ONE COLLINEAR DIRECTION

As it is, highly process-dependent framework

Sector-improved subtraction scheme

[Czakon (2010)]

Combining sector decomposition and FKS partitioning makes extraction of singularities systematic and process-independent



- Basic NNLO building block: double unresolved configuration with two partons soft/collinear to hard directions

Sector-improved subtraction scheme

[Czakon (2010)]

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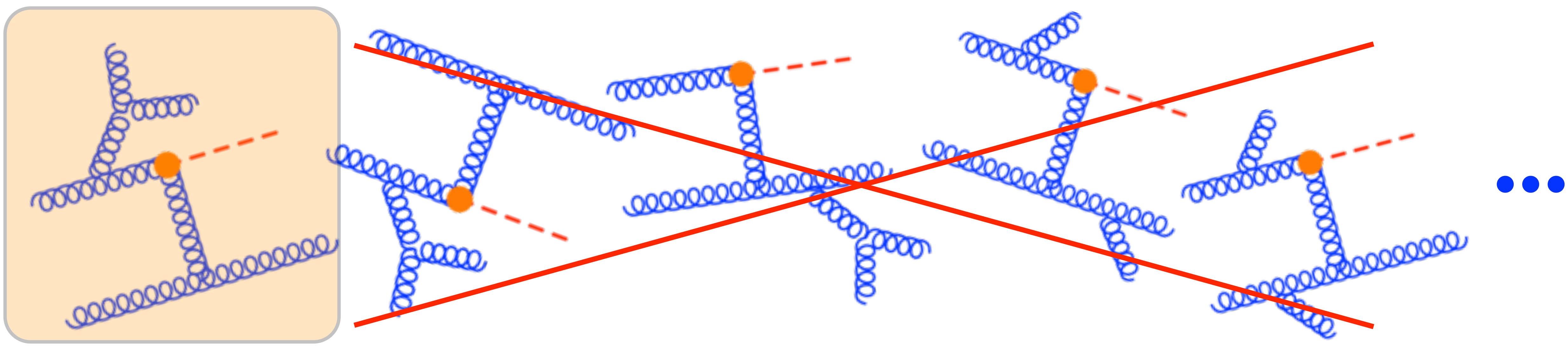

- Basic NNLO building block: double unresolved configuration with two partons soft/collinear to hard directions
- FKS: partition the phase space such that in each partition unresolved partons can be collinear only to a single hard direction (triple collinear),

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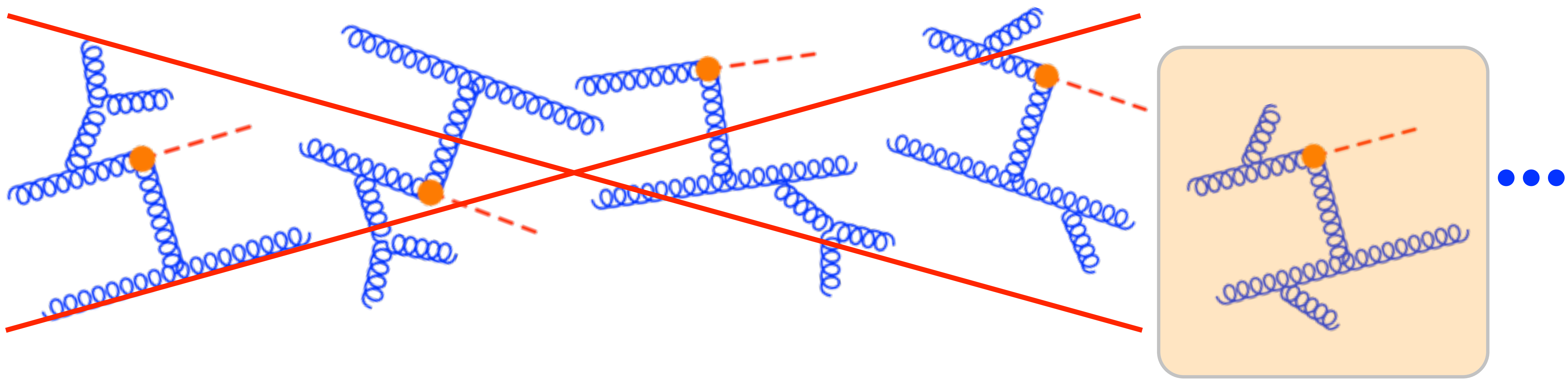

- Basic NNLO building block: double unresolved configuration with two partons soft/collinear to hard directions
- FKS: partition the phase space such that in each partition unresolved partons can be collinear only to a single hard direction (triple collinear), or a single pair of hard directions (double collinear)
- Use a local sector decomposition in each partition

Bonus: parametrization in terms of energy/angles ⟶ physical singularities related to known eikonals/splitting functions