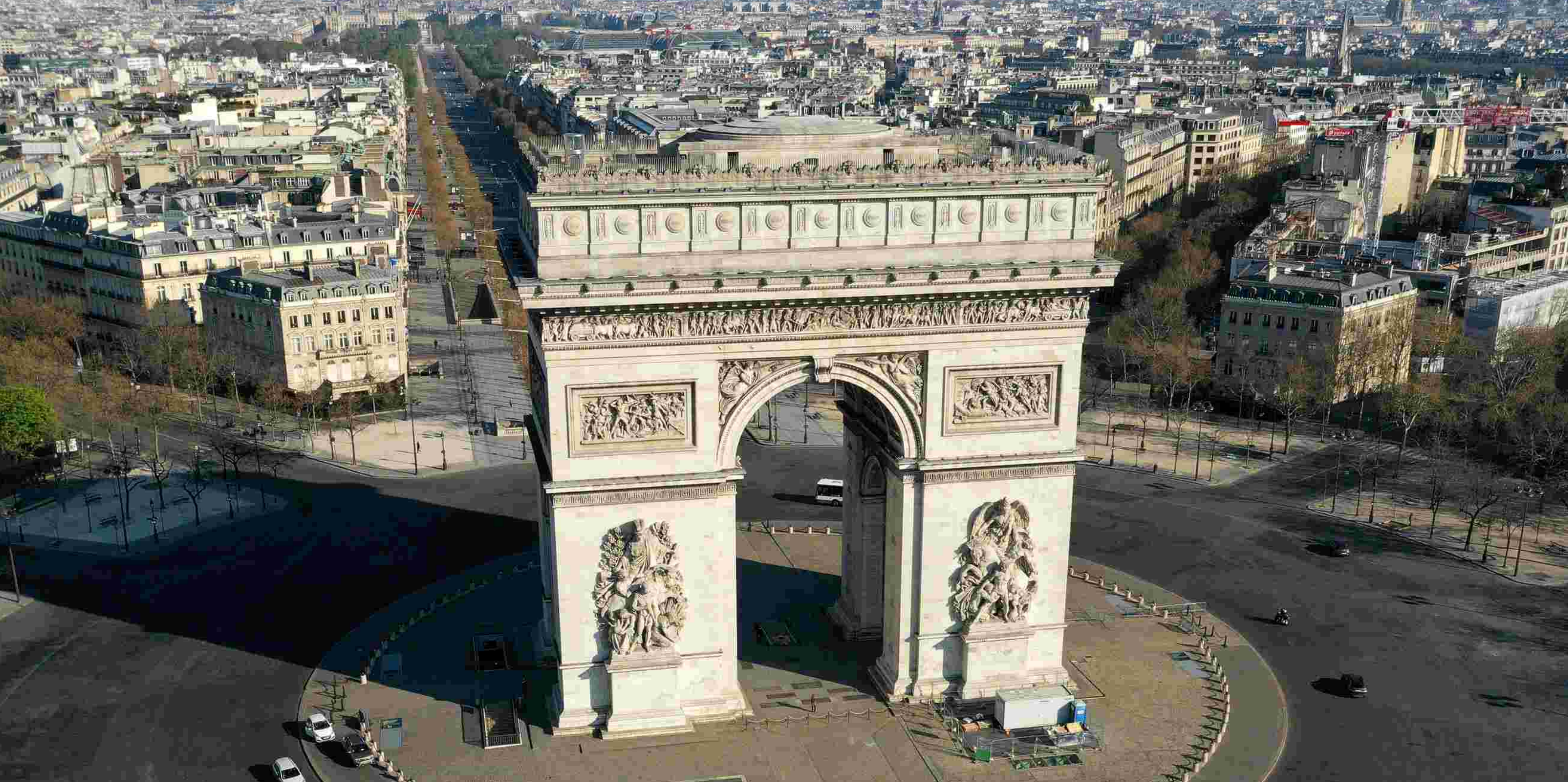


PRECISE PREDICTIONS FOR BOOSTED HIGGS PRODUCTION

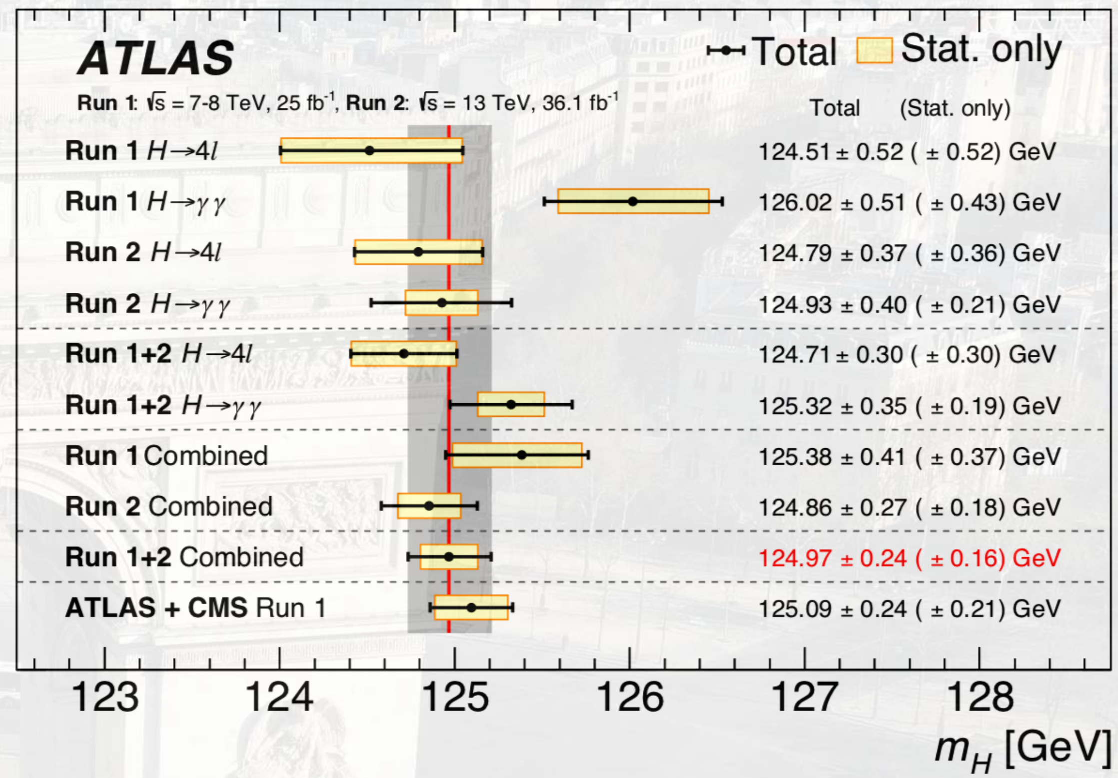
THE 8TH LHCP CONFERENCE (ONLINE)

Universität Zürich[UZH]

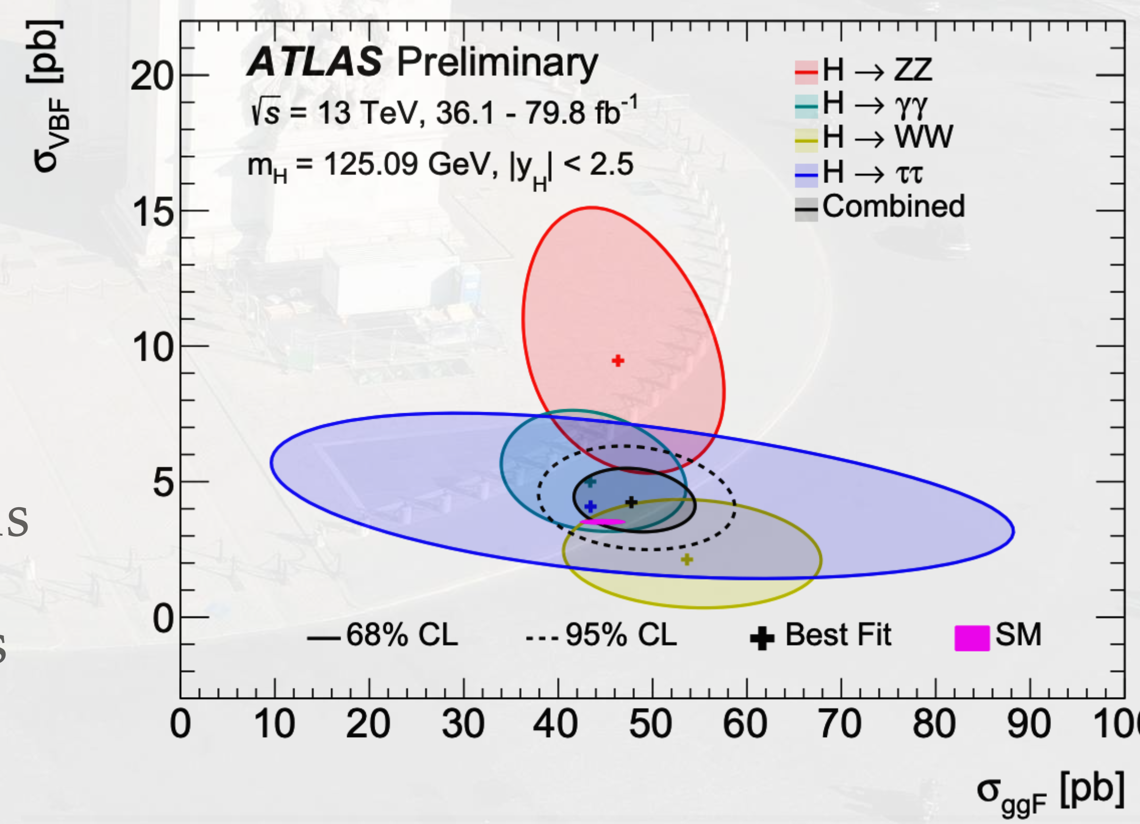
Xuan Chen
Physik-Institut, Universität Zürich
Zoom, May 26, 2020

SUCCESS OF LHC HIGGS EXPERIMENTS

- Higgs boson properties in agreement with SM
  - Bosonic (Run I) and 3rd generation fermionic couplings (Run II) observed with current precision on coupling ±10-20% (EPS2019)
  - Higgs mass uncertainty at ±0.2% level
  - Fiducial total cross section measured with ± 9% accuracy (Run I + II)
  - 2nd generation fermion couplings still to be established
  - HH signal with 10 times SM exclusion limit
- Adventure to explore full potential of the LHC
  - Differential in production and decay channels
  - New targets of precision and fiducial regions
  - Accelerate searches of new physics



ATLAS 1806.00242

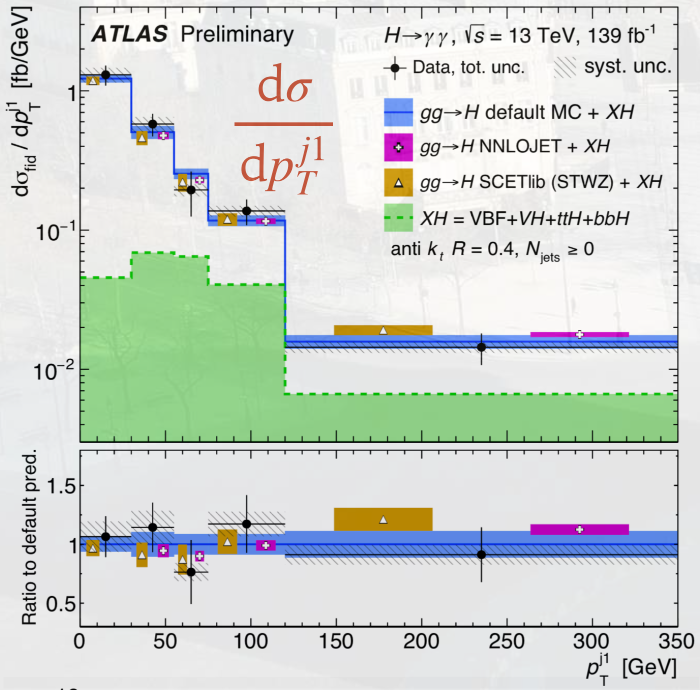


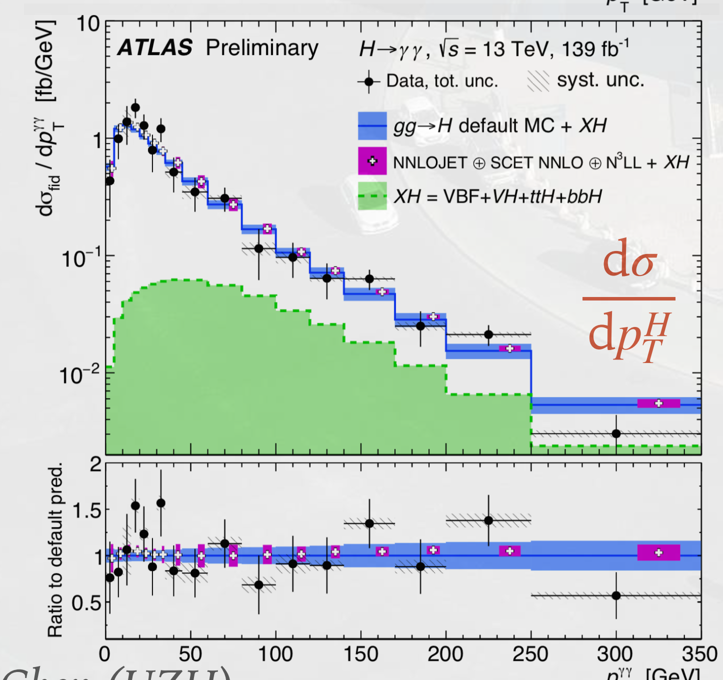
ATLAS-CONF-2018-031

INGREDIENTS OF HIGGS PRODUCTION AT LHC

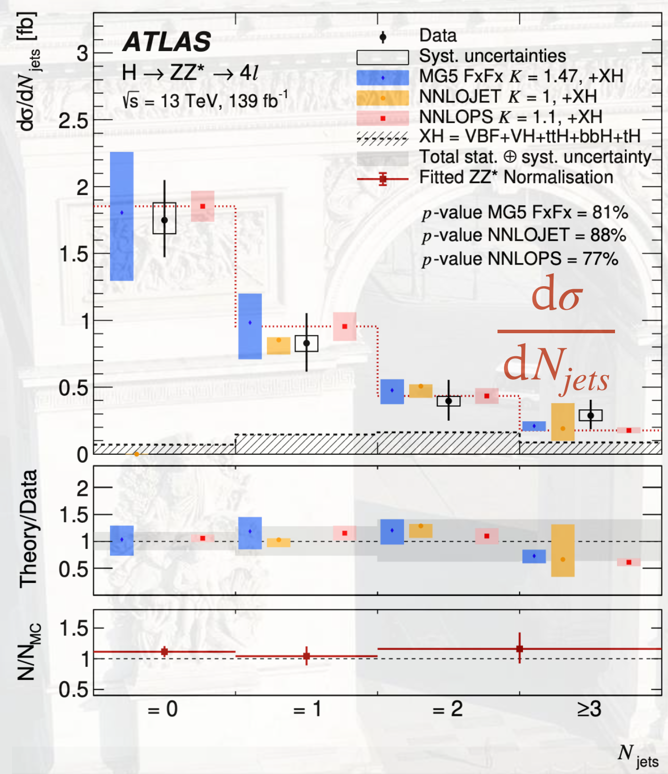
- Higgs Boson produced at the LHC with four main production channels
- Total cross section accuracy is currently at NLO QCD + EW and above with: ggF@N3LO QCD, VBF@N3LO QCD, VH@NNLO QCD

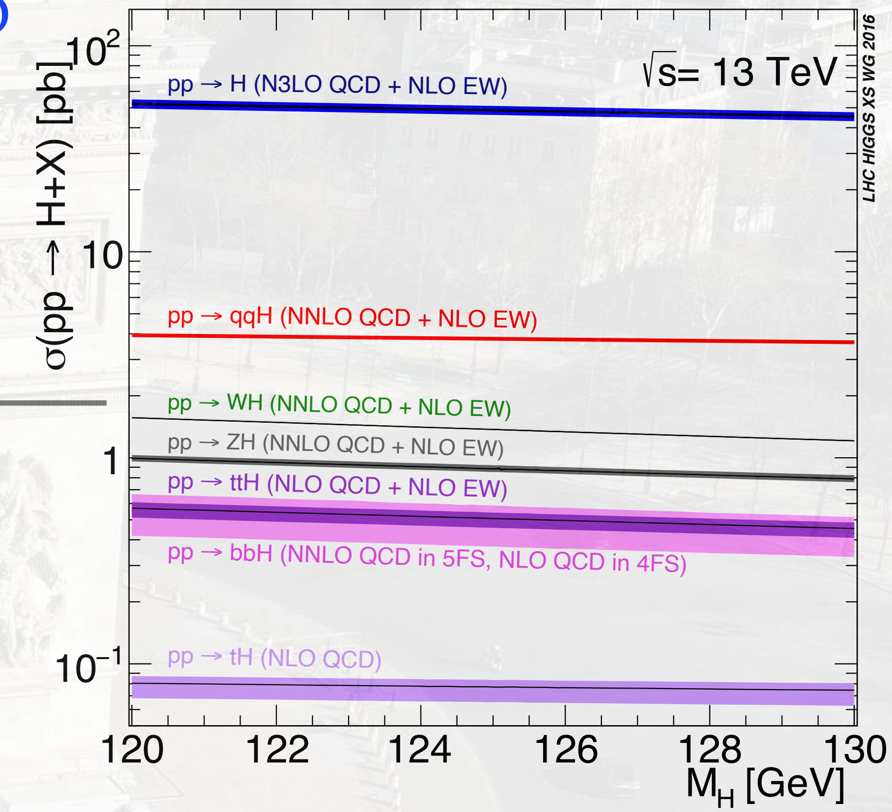
ATLAS-CONF-2019-029





ATLAS 2004.03969



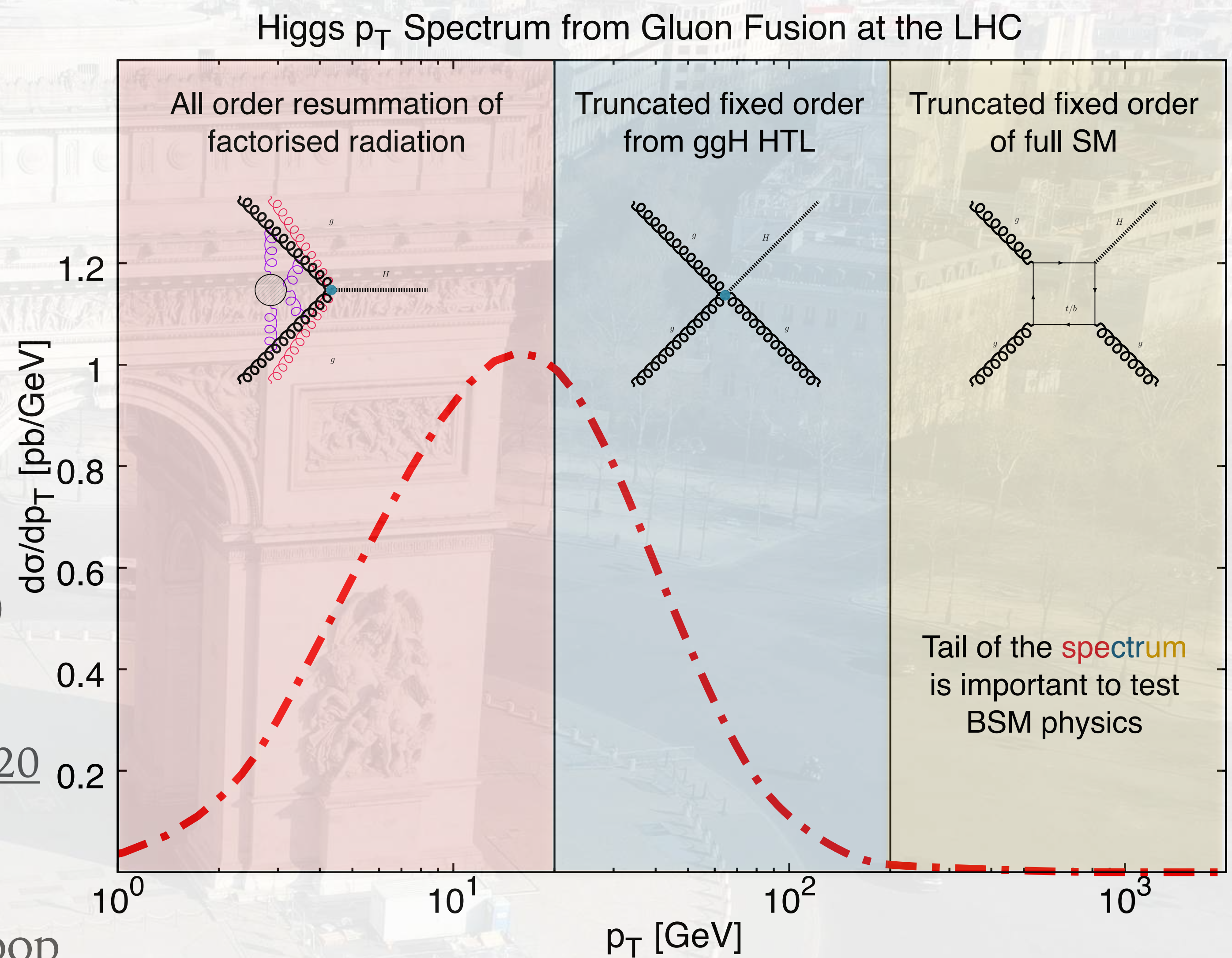


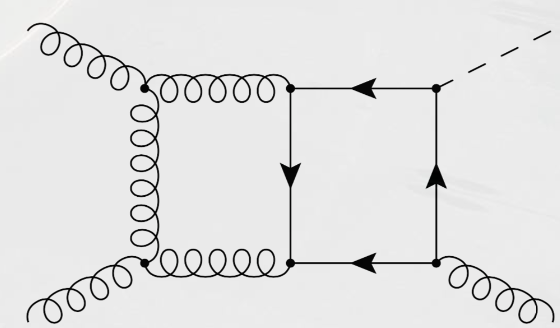
HXSWG 1610.07922

- Differential cross section reveal more details of Higgs properties
- $\frac{d\sigma}{dp_T^H}$ $\frac{d\sigma}{d|y^H|}$ $\frac{d\sigma}{dp_T^{j1}}$ $\frac{d\sigma}{dN_{jets}}$
- Uncertainties at differential level: EXP ~ 20% and TH ~ 10%
- Bulk of distributions is dominated by ggF channel, good agreement between LHC data and TH predictions

HIGGS TRANSVERSE MOMENTUM SPECTRUM

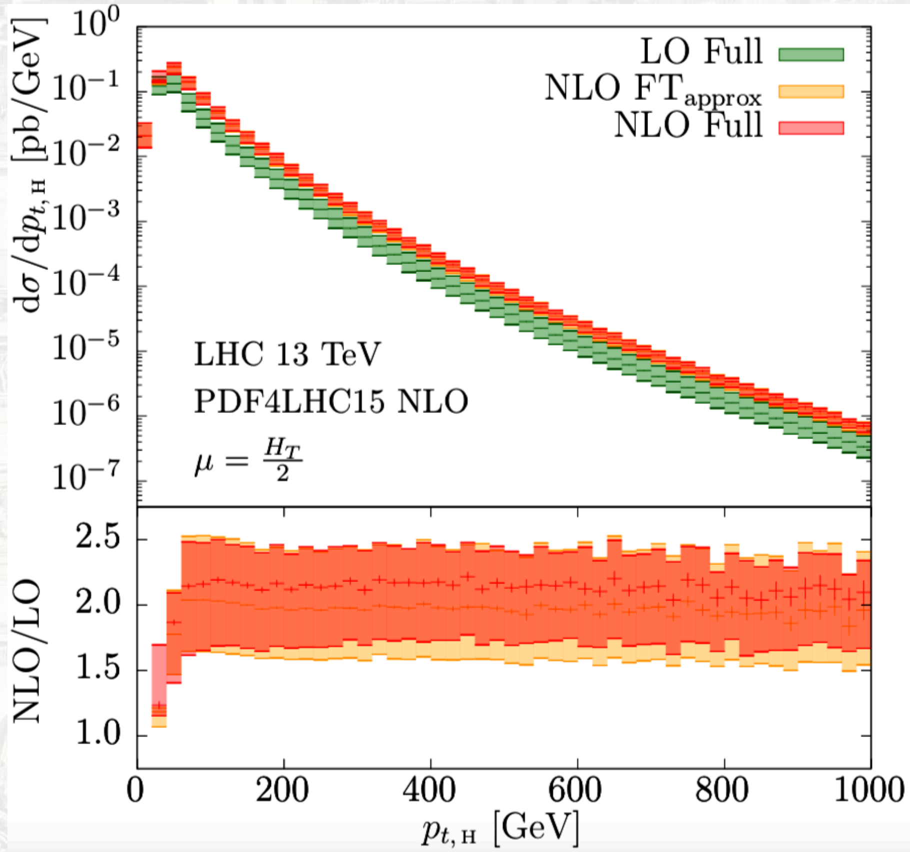
- Higgs pT spectrum tests SM in various aspects
- Small pT (< 20 GeV ggF dominant):
  - Singular log divergence $\ln^k(m_H^2/p_T^2)/p_T^2$ require resummation and matching to fixed order
  - Current precision is N3LL+NNLO 1705.09127, 1805.00736, 1805.05916
- Medium pT (20 ~ 200 GeV ggF dominant):
  - Reliable with heavy top limit (HTL or EFT)
  - Current precision is H+J NNLO HTL 1504.07922, 1607.08817, 1505.03893, 1906.01020
- Boosted pT (> 200 GeV)
  - Energy scale resolve mass effect of quark loop
  - Best ggF precision is H+J at NLO SM (1802.00349)
    - Sharply failing statistics in wide kinematic fiducial regions
      - Challenge for both EXP and TH for systematic error estimation
      - Sensitive to BSM like extra generation of quarks, off-shell effects and etc.



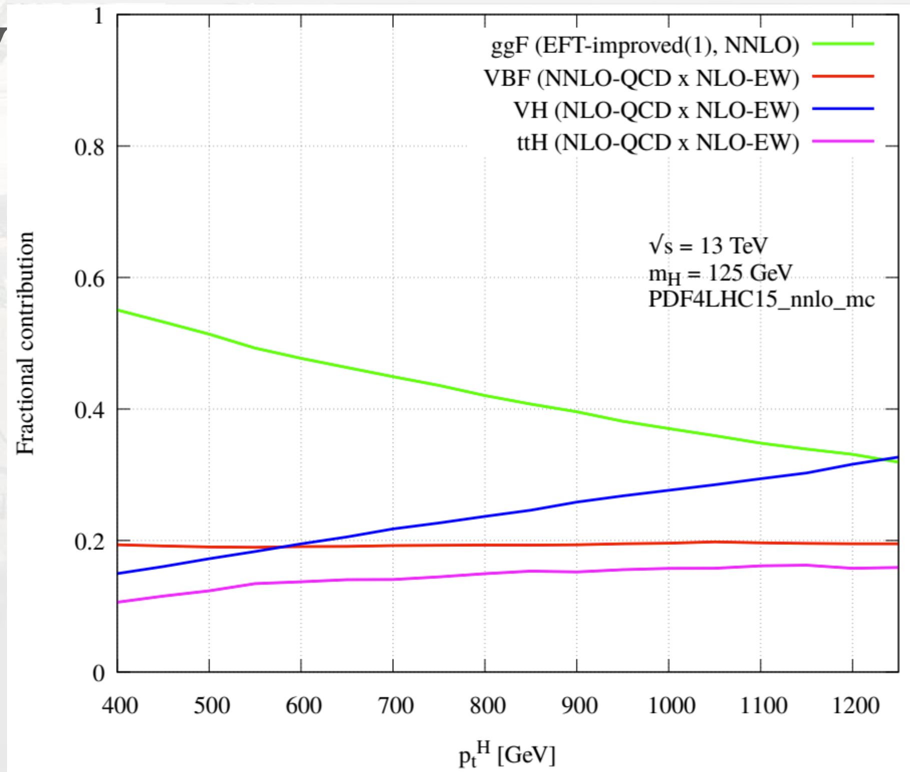


HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION

- Two approaches to include top mass effects
  - Expansion valid for $m_H^2, m_t^2 \ll |s| \sim |t| \sim |u|$ 1703.03886, 1802.02981
  - Exact results at NLO SM (numerical in SecDec) 1802.00349
  - Joint effort in HH: exact numerical+expansion 1907.06408
- Precision challenge from EXP and TH
  - ggF channel NLO SM scale uncertainties ~ 20%
  - Run II statistics has > 50% error above 350 GeV
- **ggF channel is not the full picture**
  - Boosted Higgs enhanced by quark PDFs
  - VH dominants over ggF at 1.2 TeV (~1/3)
  - ttH and VBF channels contribute about 1/3.
  - Joint effort is needed to include all channels



1802.00349



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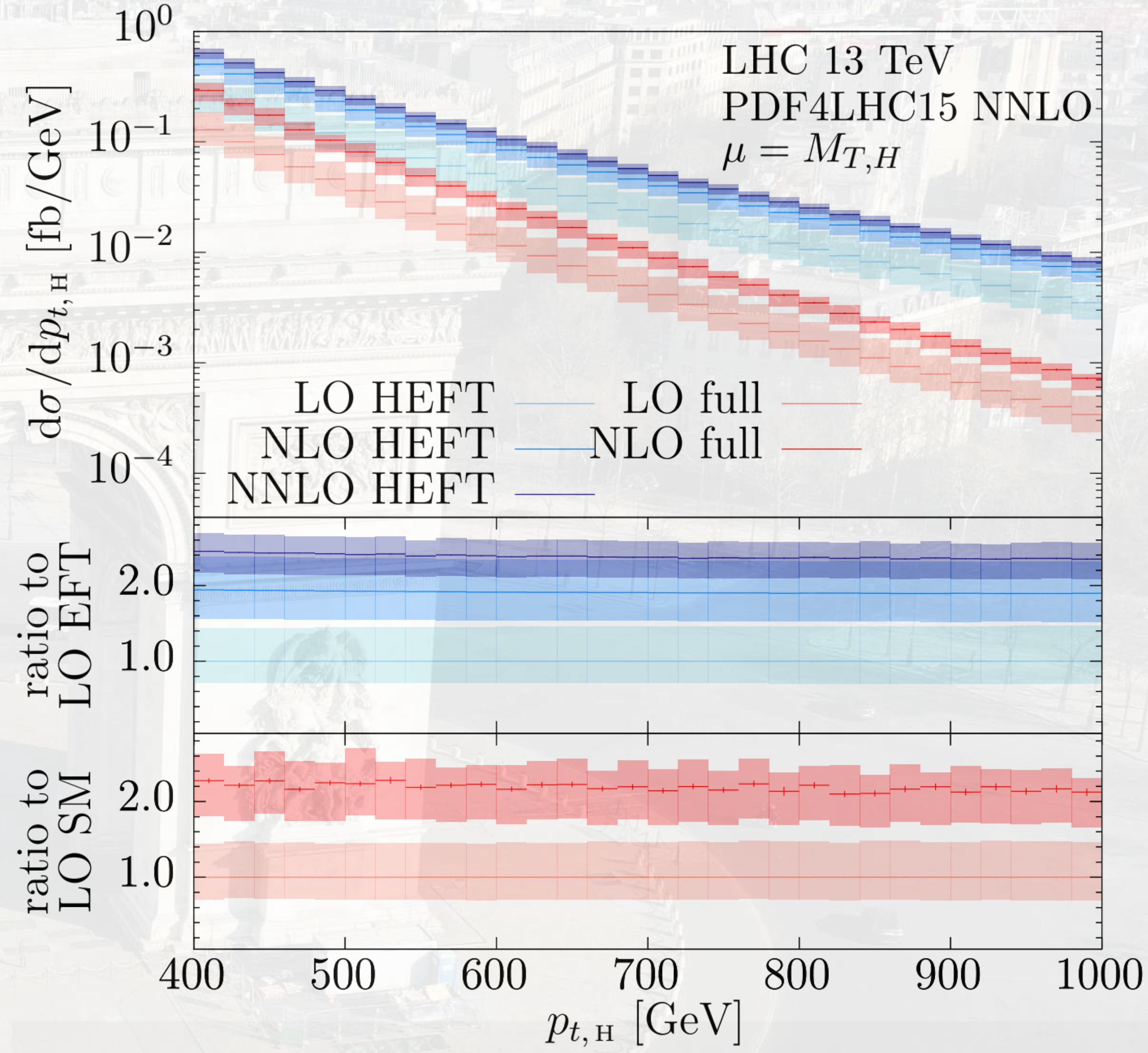
HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION (GGF)

- Joint efforts in ggF channel, EFT and SM: HXSWG 2005.07762
  - m_H=125 GeV, m_t=173.2 GeV, $\sqrt{s}$=13 TeV
  - 5F scheme with PDF4LHC15_nnlo_mc
  - Seven scales centred at $M_{T,H} = \sqrt{m_H^2 + p_T^2}$
  - On-shell top mass scheme
- Remarkable K-factors:
  - SM (NLO/LO) ≈ EFT(NNLO/LO)
  - Nearly flat at large pT
- Combine EFT and SM:
  - Ideally, we need NLO SM accuracy and NNLO EFT precision
  - With assumption that NNLO SM also has flat K-factors at large pT, we rescale:



$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) \equiv \frac{\Sigma^{\text{SM, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})} \Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$

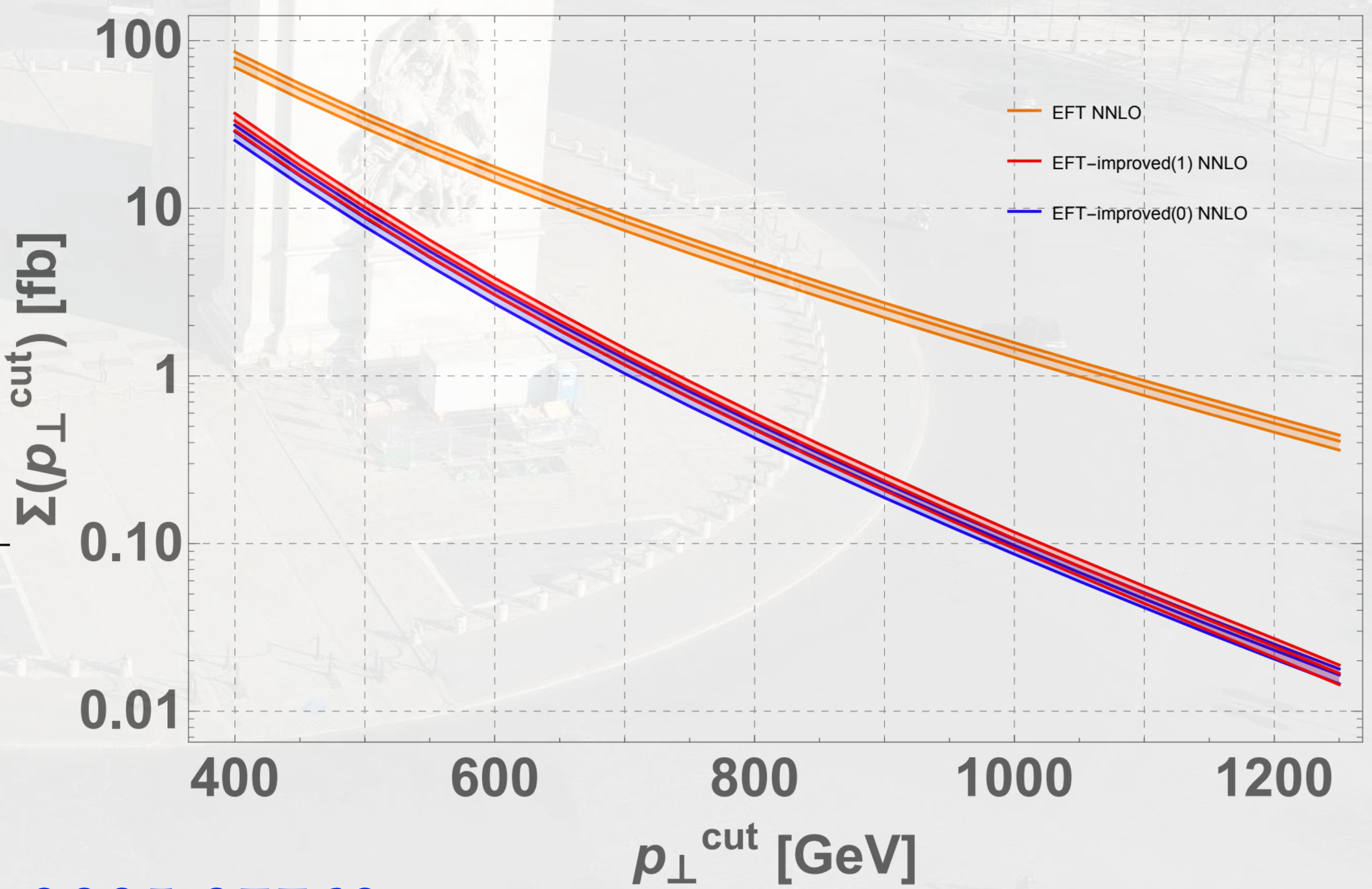
HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION (GGF)

- Error estimation of EFT-improved NNLO predictions:
  - From scale variation of $\Sigma^{\text{SM, NLO}}/\Sigma^{\text{EFT, NLO}}$ and $\Sigma^{\text{EFT, NNLO}}$
    - Independent 7-point scale variation then combine quadrature or linearly
  - From top mass correction to NNLO EFT :

$$\delta_{\text{NNLO},\, m_t} \equiv \frac{\delta\Sigma^{\text{SM, NLO}} - \delta\Sigma^{\text{improved(0), NLO}}}{\delta\Sigma^{\text{EFT, NLO}}} \times \delta\Sigma^{\text{EFT, NNLO}}$$

- Current best prediction:
  - "EFT-improved (1) NNLO"
  - TH error combined in quadrature
  - Under control at 10% level

$p_\perp^{\text{cut}}$	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	$\text{NNLO}^{\text{approximate}}_{\text{lin.unc.}}$ [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$33.3^{+15.1\%}_{-17.4\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	$23.0^{+14.9\%}_{-17.2\%}$
450 GeV	$18.1^{+10.8\%}_{-12.8\%}$	$18.1^{+14.9\%}_{-17.2\%}$



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HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION (GGF)

- Comparison among public event generators in HXSWG 2005.07762:

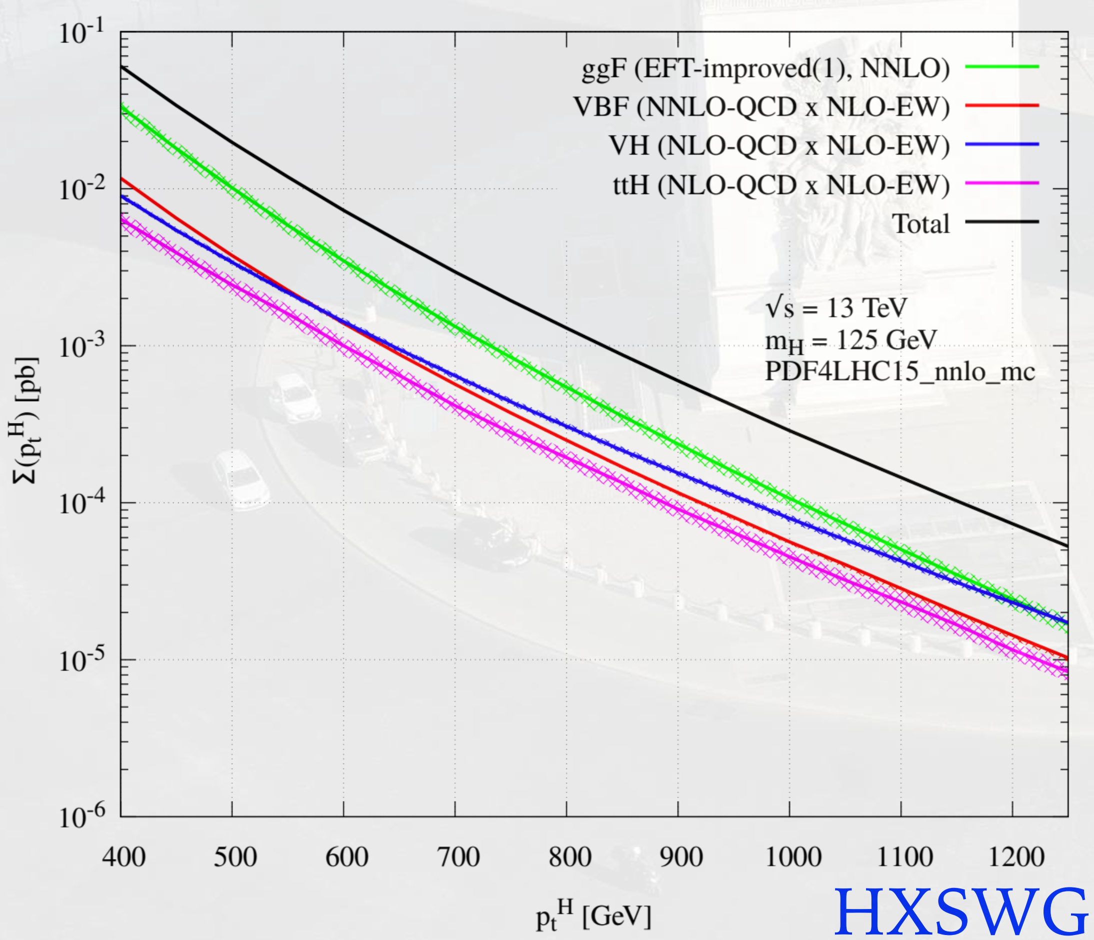
Fixed order level	Total	$p_\perp^{\rm cut} > 400$ GeV	$p_\perp^{\rm cut} > 450$ GeV	$p_\perp^{\rm cut} > 500$ GeV
$\mathtt{ggh}^{\rm hfact=104}_{m_t=\infty}$	$30.3^{+6.1}_{-4.7}$	$0.0829^{+0.0451}_{-0.0266}$	$0.0577^{+0.0325}_{-0.019}$	$0.0408^{+0.0236}_{-0.0137}$
HJ $m_t=\infty$, 5 GeV gen. cut	–	$0.0651^{+0.0156}_{-0.0131}$	$0.0417^{+0.01}_{-0.0084}$	$0.0279^{+0.0067}_{-0.0057}$
HJ $m_t=\infty$, 50 GeV gen. cut	–	$0.0651^{+0.0156}_{-0.0131}$	$0.0418^{+0.01}_{-0.0085}$	$0.0278^{+0.0066}_{-0.0056}$
HJ-MiNLO $m_t=\infty$	$32.1^{+11}_{-4.9}$	$0.0803^{+0.9087}_{-0.0164}$	$0.0524^{+0.0118}_{-0.0107}$	$0.0353^{+0.0078}_{-0.0072}$
HJ-MiNLO $m_t=171.3$ GeV	$33.8^{+11.4}_{-5.2}$	$0.029^{+0.007}_{-0.006}$	$0.0161^{+0.0036}_{-0.0033}$	$0.0091^{+0.0021}_{-0.0018}$

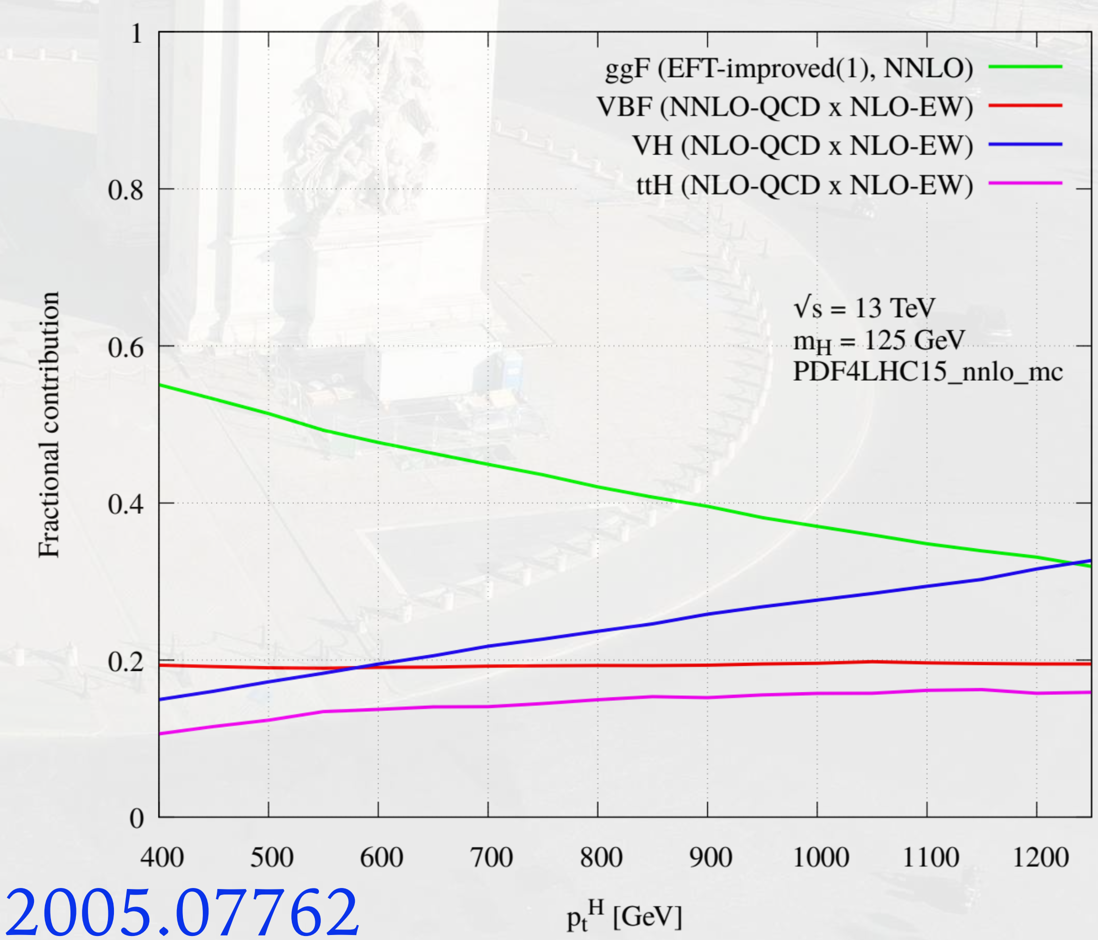
  - POWHEG gg_h: NLO EFT accuracy for total cross section, LO EFT accuracy for pT 0812.0578
  - POWHEG HJ: NLO EFT accuracy for pT 1202.5475
  - HJ-MiNLO: NLO EFT accuracy for pT with "EFT-improved (0) NLO" rescale feature 1212.4504
  - MG5_MC@NLO: (N)LO SM accuracy for pT with EFT virtual rescaled by LO SM 1604.03017, 1405.0301
  - POWHEG and HJ-MiNLO are matched to Pythia 6 parton shower. hep-ph/0603175
- Comparison with the current best:
  - General good agreement
  - +20% correction to NLO SM
  - Uncertainty reduced by 70~100%

$p_\perp^{\rm cut}$	$\mathrm{NNLO}^{\rm approximate}_{\rm quad.unc.}$ [fb]	HJ-MINLO [fb]	MG5_MC@NLO [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$18.1^{+10.8\%}_{-12.8\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

HIGGS TRANSVERSE MOMENTUM FROM VH, VBF AND TTH

- Transverse momentum contributions from VH, VBF and ttH channels:
  - ZH, $W^{\pm}$H: NLO accuracy from POWHEG-BOX-V2 with 3-point scale variation 1306.2542, 1002.2581
  - VBF: NNLO accuracy with structure function approach with 3-point scale variation 1506.02660
  - $t\bar{t}H$: NLO accuracy from Sherpa+OpenLoops with 7-point scale variation 0811.4622, 1111.5206
  - EW correction: NLO photonics corrections from Sherpa+OpenLoops 0811.4622, 1111.5206, 1412.5157, 1712.07975, 1907.13071





HXSWG 2005.07762

HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION (ALL)

- Channel breakdown of Higgs transverse momentum at boosted region
  - Dominant uncertainties from ggF and ttH channel at 10%
  - NLO VH uncertainties at 5% and the state-of-the-art NNLO correction further reduce to 2%
  - ggF, VH and ttH uncertainties stays flat while VBF uncertainties increase at large pT
  - EW corrections are substantial at large pT but is currently unknown for ggF channel
  - New physics effects could affect various channels differently, recommendation for STXS

$p_\perp^{\mathrm{cut}}$ [GeV]	$\Sigma_{\mathrm{ggF}}^{\mathrm{NNLO}_{\mathrm{quad.unc.}}^{\mathrm{approximate}}}(p_\perp^{\mathrm{cut}})$ [fb]	$\Sigma_{\mathrm{VBF}}^{\mathrm{NNLO}}(p_\perp^{\mathrm{cut}})$ [fb]	$\Sigma_{\mathrm{VH}}^{\mathrm{NLO}}(p_\perp^{\mathrm{cut}})$ [fb]	$\Sigma_{t\bar{t}H}^{\mathrm{NLO}}(p_\perp^{\mathrm{cut}})$ [fb]
400	$33.30^{10.89\%}_{-12.91\%}$	$14.23^{+0.15\%}_{-0.19\%}$	$11.16^{+4.12\%}_{-3.68\%}$	$6.89^{+12.62\%}_{-12.97\%}$
450	$18.08^{10.78\%}_{-12.79\%}$	$8.06^{+0.24\%}_{-0.23\%}$	$6.87^{+4.6\%}_{-3.49\%}$	$4.24^{+12.84\%}_{-13.15\%}$
500	$10.17^{10.67\%}_{-12.74\%}$	$4.75^{+0.33\%}_{-0.29\%}$	$4.39^{+4.43\%}_{-4.04\%}$	$2.66^{+12.85\%}_{-13.22\%}$
550	$5.87^{10.54\%}_{-12.60\%}$	$2.90^{+0.34\%}_{-0.36\%}$	$2.87^{+4.44\%}_{-3.74\%}$	$1.76^{+14.23\%}_{-13.93\%}$
600	$3.48^{10.35\%}_{-12.49\%}$	$1.82^{+0.41\%}_{-0.39\%}$	$1.91^{+5.22\%}_{-4.71\%}$	$1.11^{+12.99\%}_{-13.4\%}$
650	$2.13^{10.23\%}_{-12.45\%}$	$1.17^{+0.49\%}_{-0.39\%}$	$1.30^{+4.67\%}_{-4.28\%}$	$0.72^{+12.6\%}_{-13.26\%}$
700	$1.32^{10.03\%}_{-12.32\%}$	$0.77^{+0.57\%}_{-0.45\%}$	$0.90^{+4.15\%}_{-5.4\%}$	$0.47^{+11.42\%}_{-12.74\%}$
750	$0.84^{10.05\%}_{-12.31\%}$	$0.51^{+0.69\%}_{-0.56\%}$	$0.62^{+5.15\%}_{-4.66\%}$	$0.32^{+11.53\%}_{-12.84\%}$
800	$0.54^{9.91\%}_{-12.24\%}$	$0.35^{+0.71\%}_{-0.6\%}$	$0.44^{+5.64\%}_{-4.13\%}$	$0.22^{+11.42\%}_{-13.3\%}$

VBF	VH	$t\bar{t}H$
−17.80%	−19.05%	−6.95%
−19.43%	−20.83%	−7.75%
−21.05%	−22.50%	−8.49%
−22.34%	−24.07%	−9.11%
−23.73%	−25.56%	−9.91%
−25.03%	−26.98%	−10.67%
−26.29%	−28.30%	−11.37%
−27.35%	−29.60%	−11.94%
−28.42%	−30.83%	−12.51%

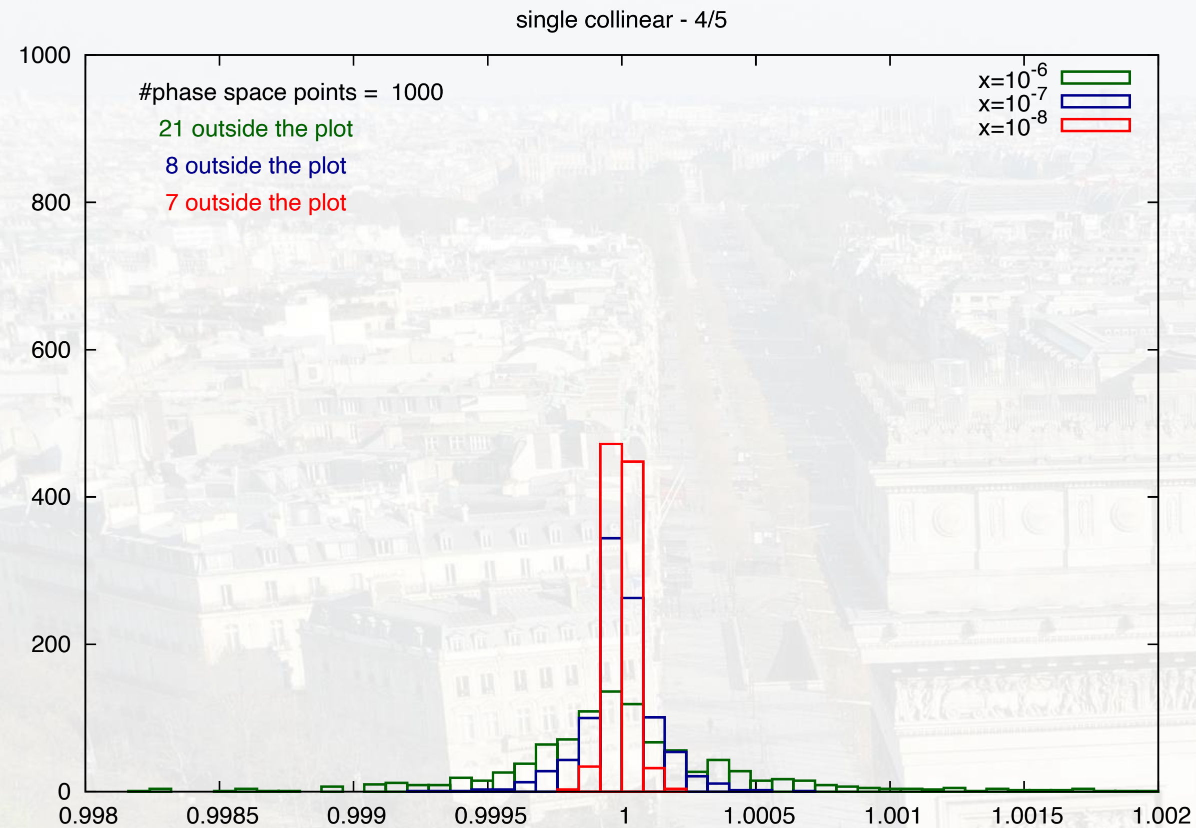
HXSWG 2005.07762

FUTURE WORK AND CONCLUSION

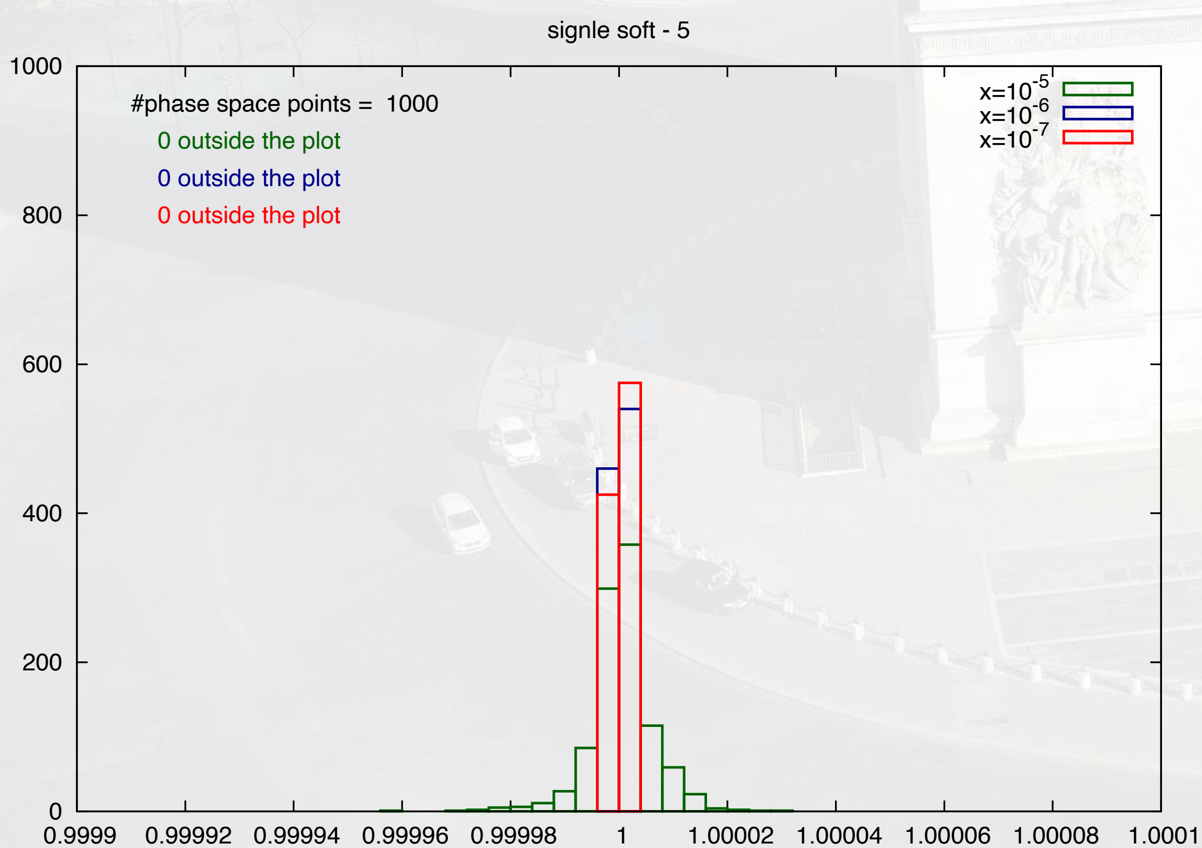
Thank you!

- Higgs boson precision measurements focus on differential observables and distinguishing production and decay channels
- Higgs boson precision predictions focus on reducing uncertainties from all sources. FO QCD corrections, EW at large scale, Parton Shower effects etc.
- Boosted Higgs is becoming the focus to improve EXP and TH precision to accelerate searches for new physics
- Higgs properties are different in boosted than in the bulk of the fiducial regions. Theory uncertainty is at 10-15% level for pT > 400 GeV.
- New source of theory uncertainties to be studied in the future
  - Top mass schemes (Substantial @ LO, reduced considerably @ NLO)
  - PDF and couplings uncertainties (Systematically improvable)
  - More reliable rescaling for quark mass effect (Event by event rescaling)
  - Upgrade VH and VBF predictions at NNLO and N3LO.

TEST NUMERICAL STABILITY OF MATRIX ELEMENTS



Single collinear limit 4//5 with $x \sim 10^{-8}$



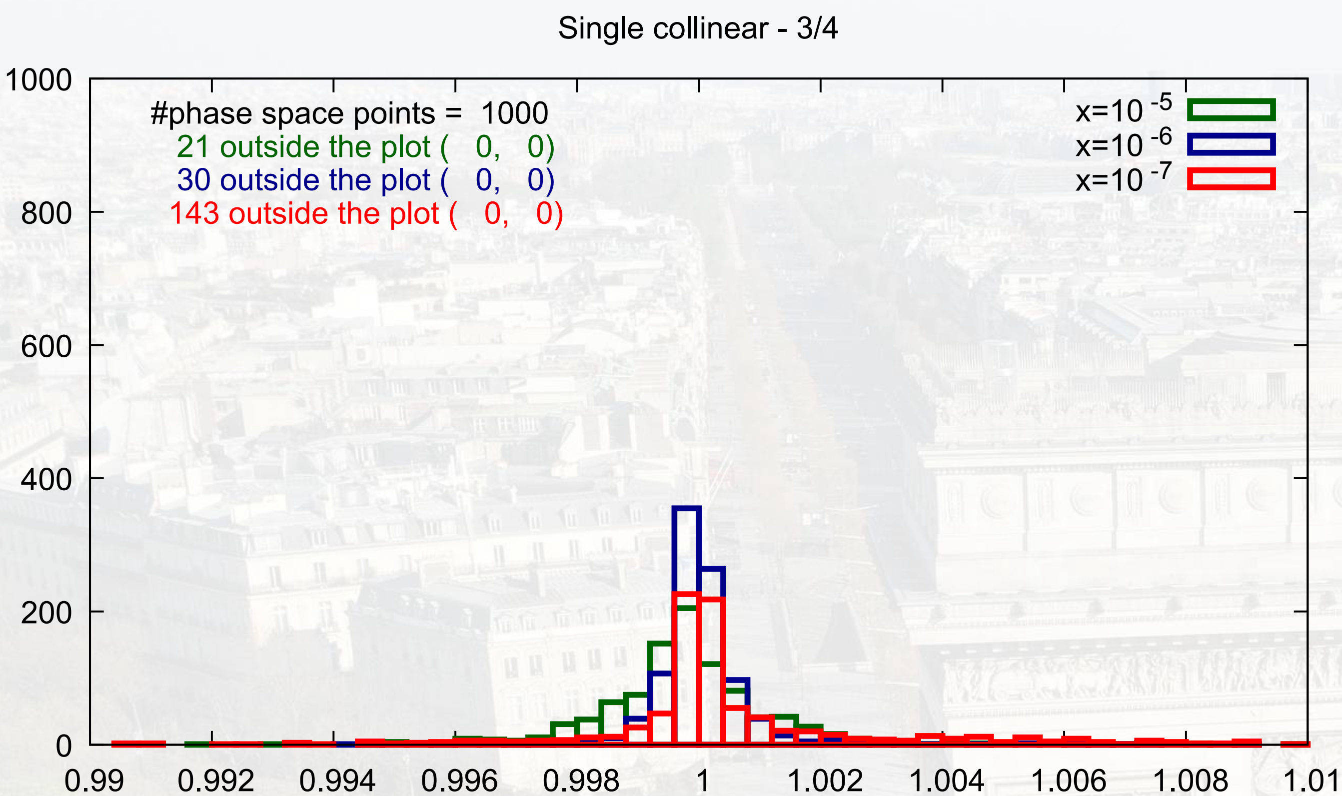
Single soft limit $5 \to 0$ with $x \sim 10^{-7}$

- Construct antenna subtraction terms (ATS) to mimic unresolved limits of matrix elements (ME)
- Test function (tree level): $R = \dfrac{ME^0}{AST^0}$
- R ~ the horizontal axis (centre at one near the unresolved region)
- Number of P.S. points in each bin ~ the vertical axis
- Controlling singular region correctly will achieve spike plots
- For example: $p_1 + p_2 \to p_3 + p_4 + p_5$

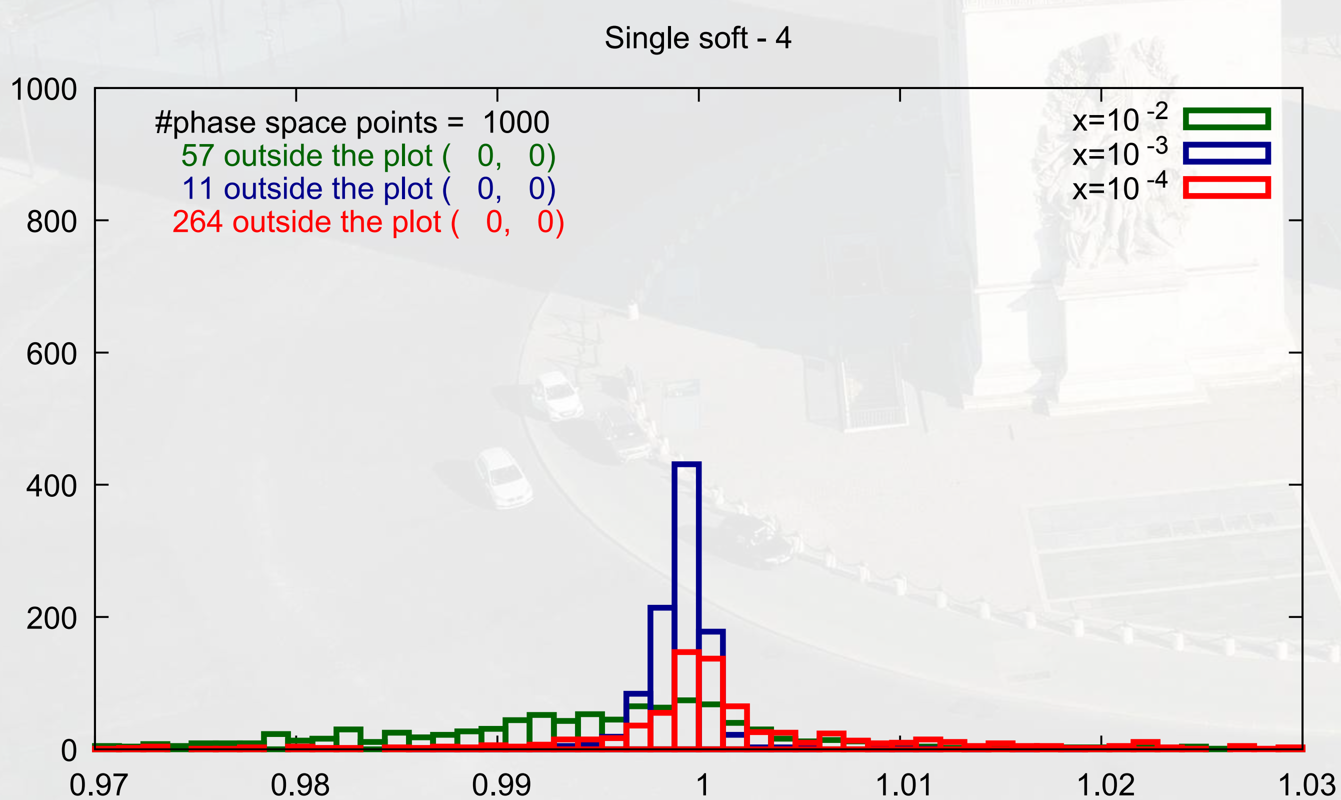
Single collinear limit: $x = \dfrac{s_{45}}{s}, \quad x \sim 10^{-8}$

Single soft limit: $xs = s_{35} + s_{45}, \quad x \sim 10^{-7}$

TEST NUMERICAL STABILITY OF MATRIX ELEMENTS



Single collinear limit 3//4 with $x \sim 10^{-6}$



Single soft limit $4 \to 0$ **with** $x \sim 10^{-3}$

- Ideally we would like to use ME from automated tools
- However, not many of them are numerical stable in IR singular regions
- OpenLoops2 is one of the best auto-tools optimised in IR singular regions
- However for a loop-induced process: $g_1 + g_2 \to \gamma + \gamma + g_3 + g_4$
- Test function (loop induced):

$$R = \frac{ME^1}{AST^1}$$

- We observe spikes break down at
  single collinear limit: $x \sim 10^{-7}$
  single soft limit: $x \sim 10^{-4}$