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Chiral Dynamics 2015
Pisa, Italy, 29 June 2015

Pion production in NN collisions near threshold: complete NNLO calculation in chiral EFT

in collaboration with
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Outline:

- Why is pion production interesting?
- High accuracy pion production operator
- Convolution with NN wave functions
- Summary and outlook

Phys.Rev. C 85 (2012) 054001
Phys.Rev. C 88 (2013) 064003

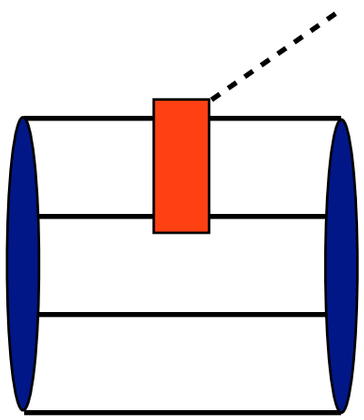
Why is pion production interesting?

- First inelastic process in nucleon-nucleon interactions
- Several channels:
  $pp \to pp\pi^0$ and $pp \to d\pi^+$ cross sections differ by an order of magnitude

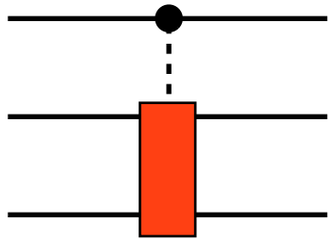
$$\sigma_{\rm tot}(pp \to pp\pi^0) \simeq 3\,\mu b \qquad \sigma_{\rm tot}(pp \to d\pi^+) \simeq 43\,\mu b \qquad T_{\rm lab} = 293.5\ {\rm MeV}$$

COSY-TOF (2003)

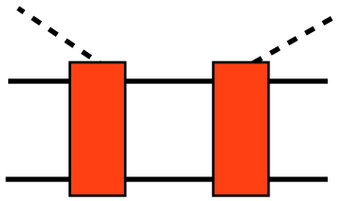
- Charge symmetry breaking (CSB) in $pn \to d\pi^0$
- Important prerequisite for more complicated processes:



CSB in $dd \to \alpha\pi^0$



3N forces



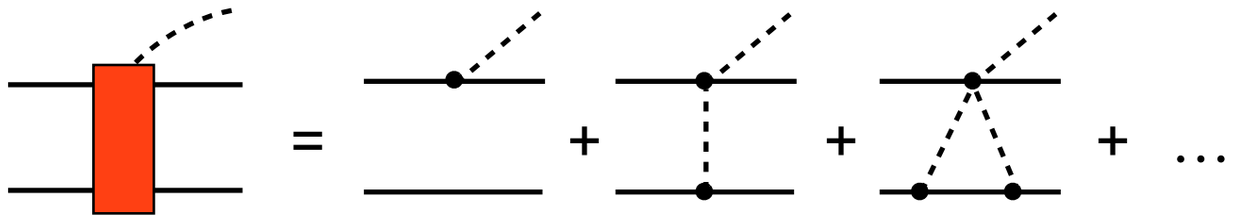
pionic deuterium
$\pi d \to NN \to \pi d$

Goal: Study $NN \to NN\pi$ in chiral effective field theory

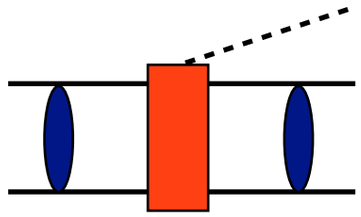
Strategy of NN→NNπ study

We use **'Hybrid' chiral EFT method**:

1. Calculate irreducible production operator perturbatively in chiral EFT



2. Convolute it with non-perturbative NN wave functions

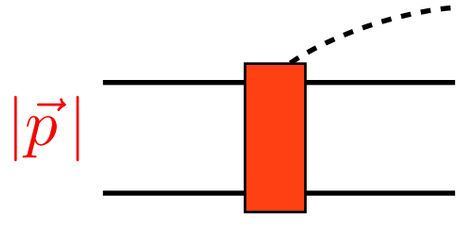


Phenomenological NN wave functions: CDBonn, AV18, Nijmegen, …

Chiral NN wave functions [Epelbaum, Krebs, Meißner 2014]

- calculated up to N4LO
- describe phase shifts up to pion production
- several versions available with different R-space cutoff: 0.8-1.2fm
  (approximately correspond to momentum cutoff 330-500 MeV)

Pion production operator



Main specifics:

- NN momenta in CMS are large enough to produce a pion

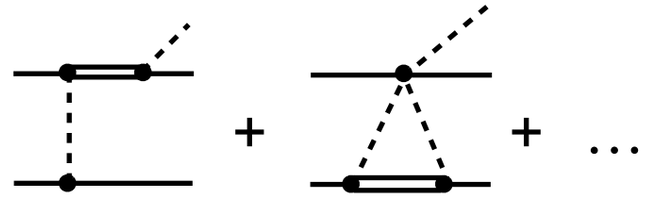
  $|\vec{p}\,| \sim \sqrt{m_\pi m_N} \sim 360\ \mathrm{MeV}$ – new soft scale

  Special counting: Momentum Counting Scheme (MCS)

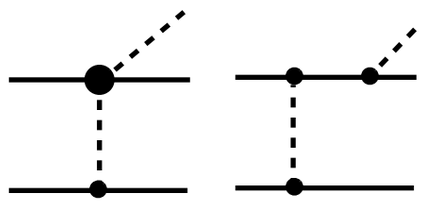
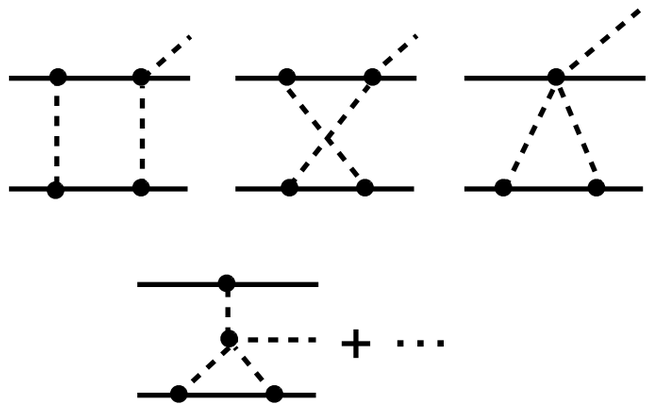
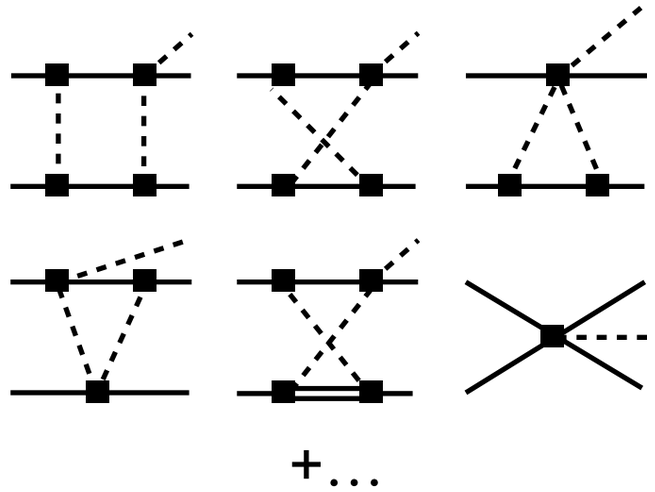
  expansion parameter: $\chi_{\mathrm{MCS}} \sim \dfrac{|\vec{p}\,|}{\Lambda_\chi} \sim \sqrt{\dfrac{m_\pi}{m_N}}$

- Delta(1232)-resonance is close $m_\Delta - m_N \sim 280\ \mathrm{MeV} \sim |\vec{p}\,|$

  => Include additional operators with explicit delta



Part 1: s-wave pion production operators

		LO	NLO	NNLO this work
exp				
43μb	$pp \to d\pi^+$	big contribution Koltun et al. (1966)	0 Lensky et al. (2006)	small, correction to LO
3μb	$pp \to pp\pi^0$	almost negligible Cohen et al. (1996), Park et al. (1996)	0 Hanhart and Kaiser (2005)	small, but main contribution (!)

⇒ NNLO effects are crucial to understand cross section puzzle

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		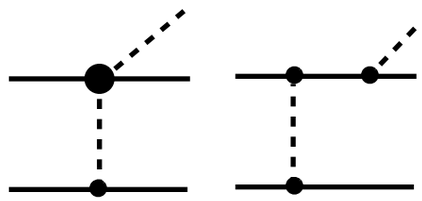	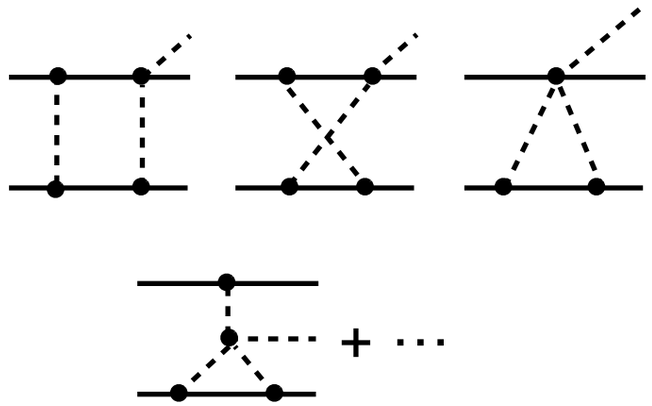	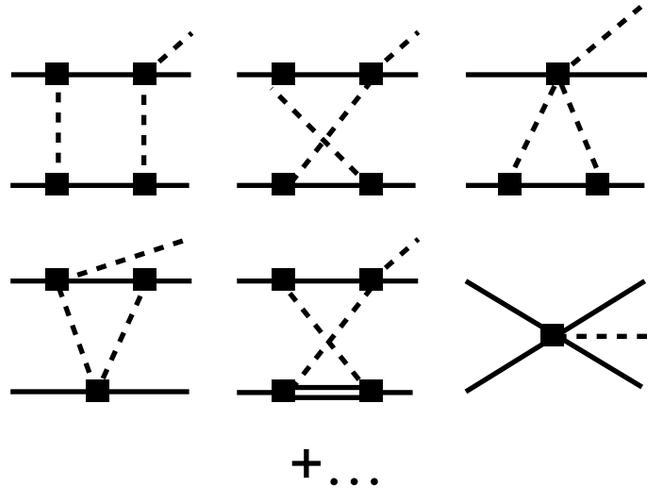
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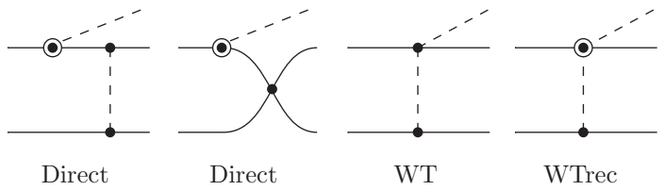
⇒ NNLO effects are crucial to understand cross section puzzle

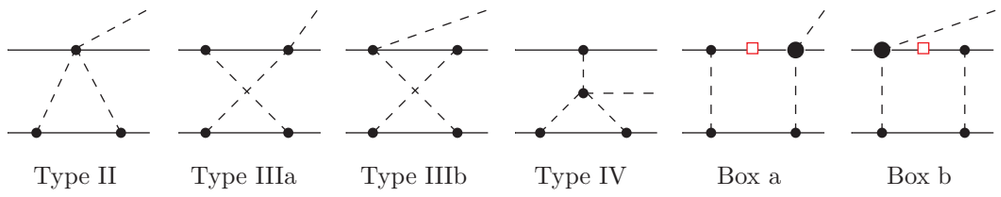
Pion production operator at NNLO — Results

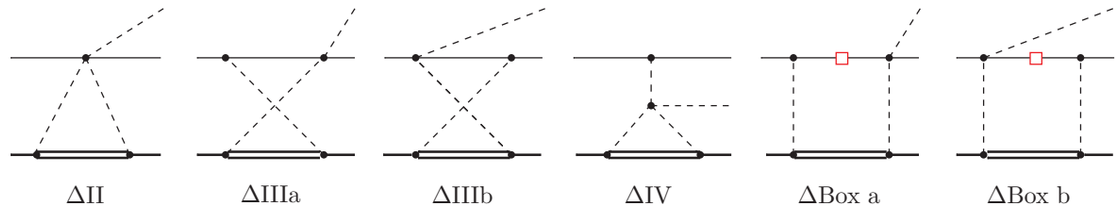
- We calculated full pion production operator at NNLO [AF et al. 2012, 2013]
  - Lots of cancellations found
  - Finite contribution remains

LO:

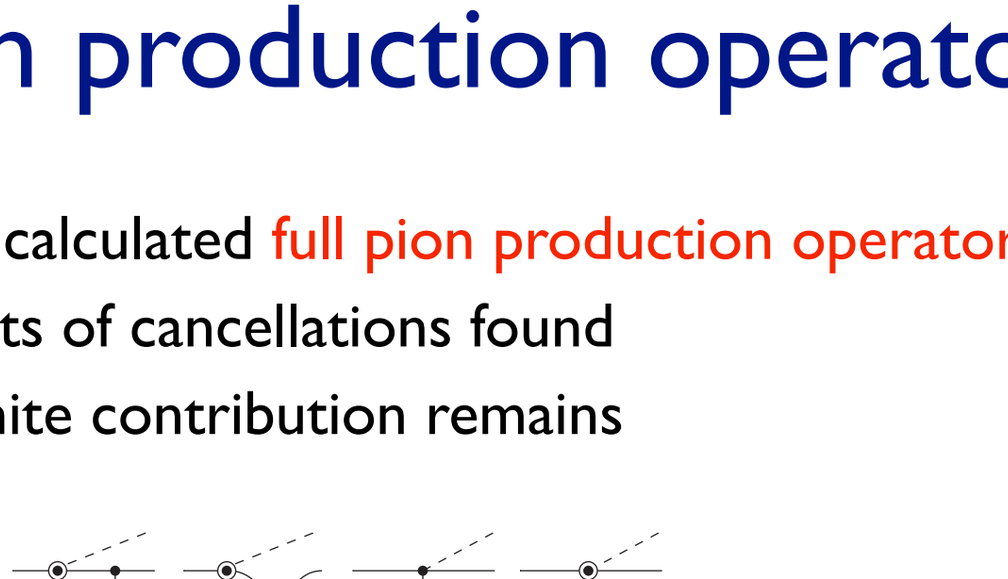


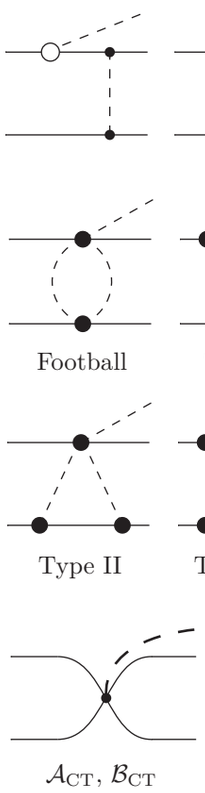
NLO:





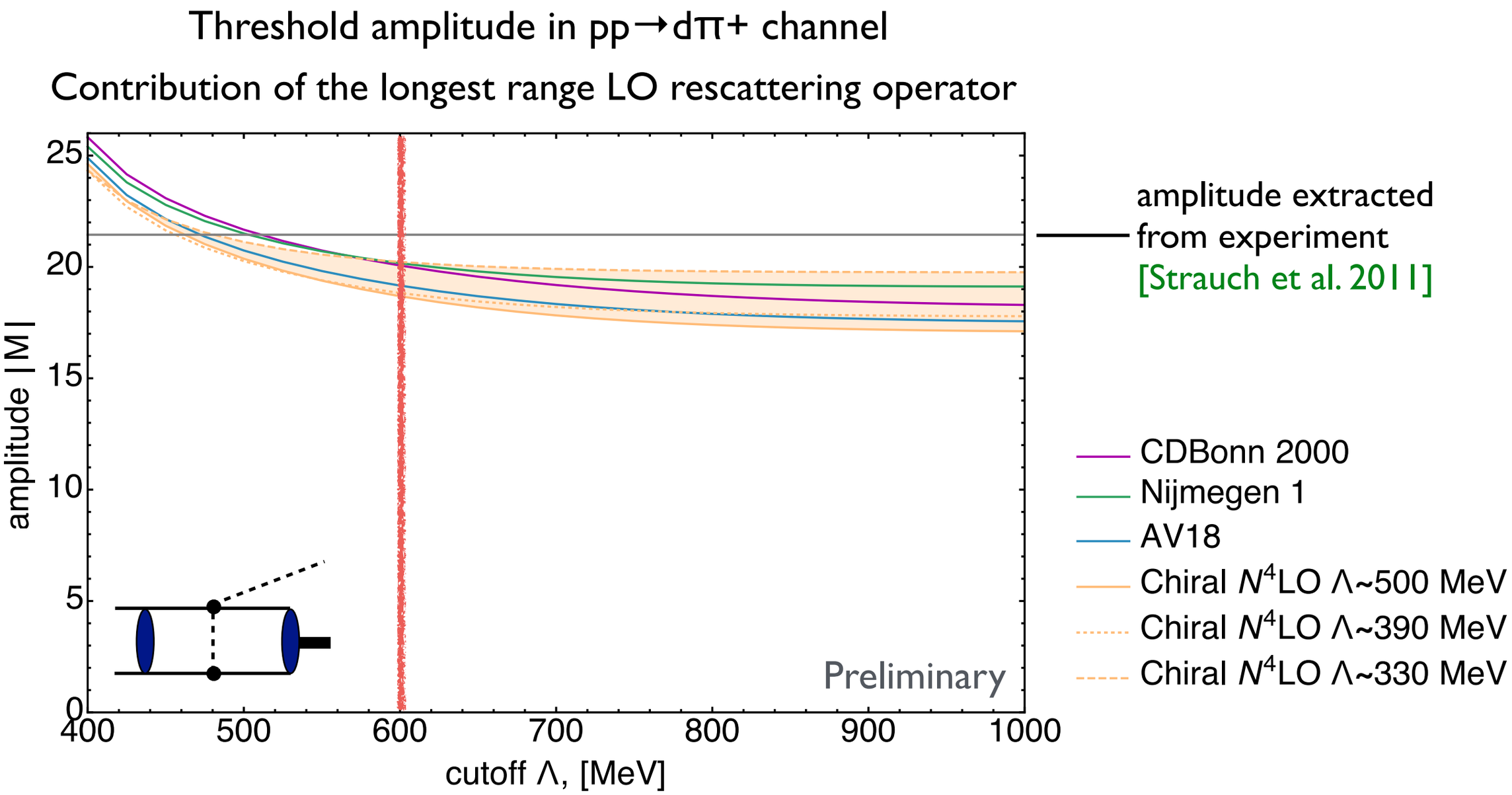
NNLO:





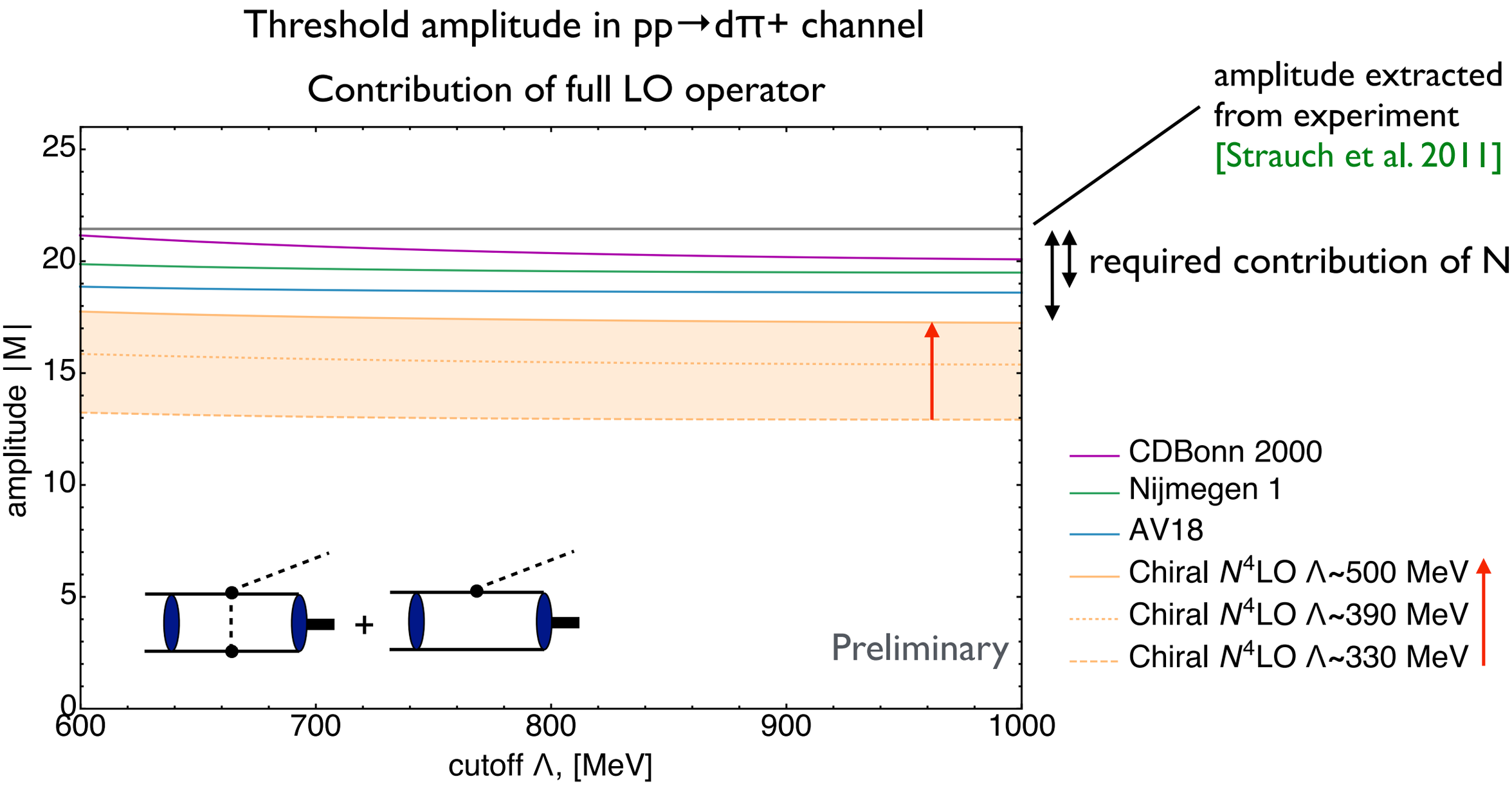
+ ...

Convolution: pp→dπ+ channel



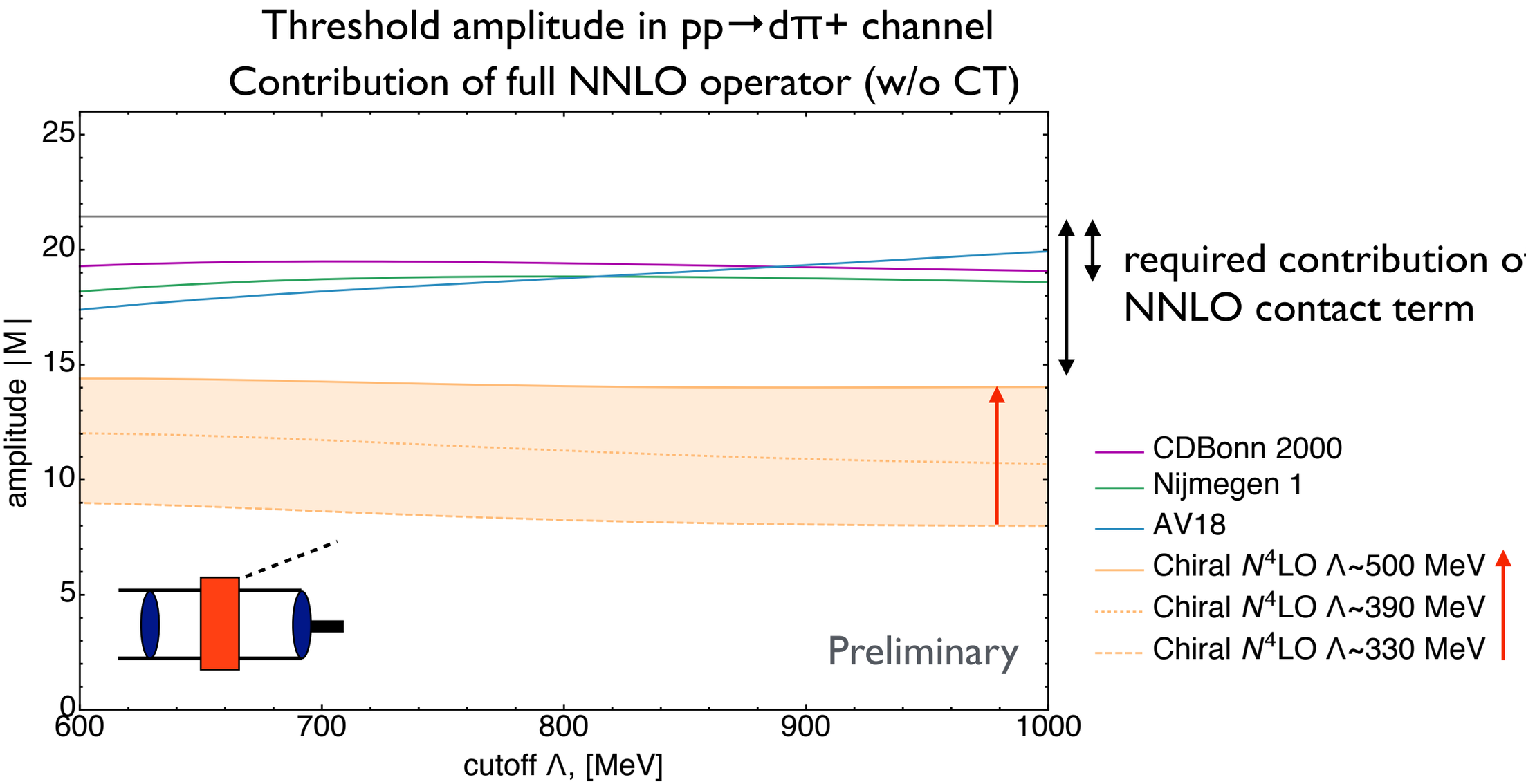
- Cutoff-independence for Λ > 600 MeV (Soft scale is 360 MeV)
- Agreement for all phenomenological as well as chiral potentials

Convolution: pp→dπ+ channel



- Consistent result for all phenomenological potentials
- Chiral WF cut intermediate momenta, which are kept in phenomenological WF

Convolution: pp→dπ+ channel



NNLO corrections give small (natural) contribution — consistent with our power counting

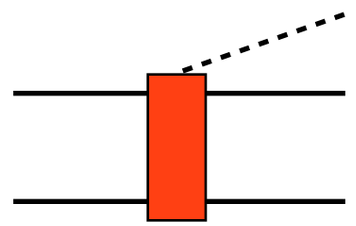
Summary and outlook

Study of NN→NNπ in Chiral EFT

- Test of chiral EFT at intermediate energies
- Tool to study charge symmetry breaking ($pn \to d\pi^0$)
- Building block for more complicated reactions ($dd \to \alpha\pi^0$, 3NF,...)

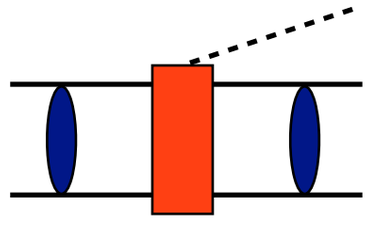
Current results:

- s-wave pion production operator at threshold
  up to N^2LO MCS (6%) including explicit Delta(1232)



- convolution with nucleon-nucleon wave functions in $pp \to d\pi^+$
- hybrid calculations with all phenomenological potentials give consistent results
- since pion production probes intermediate distances
  the use of phenomenological WF for pion production is preferred

Next step



- Convolution with nucleon-nucleon wave functions
  and calculation of the observables in $pp \to pp\pi^0$

spares

Convolution: pp→dπ+ channel

Threshold amplitude in pp→dπ+ channel
Contribution of full NNLO operator (w/o CT)